Laser-driven particle and photon beams
and some applications

K W D Ledingham\textsuperscript{1,2} and W Galster\textsuperscript{1,3}

\textsuperscript{1} SUPA, Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK
\textsuperscript{2} AWE plc, Aldermaston, Reading RG7 4PR, UK
E-mail: K.Ledingham@phys.strath.ac.uk

Abstract. Outstanding progress has been made in high-power laser technology in the last 10 years with laser powers reaching petawatt (PW) values. At present, there are 15 PW lasers built or being built around the world and plans are afoot for new, even higher power, lasers reaching values of exawatt (EW) or even zetawatt (ZW) powers. Petawatt lasers generate electric fields of $10^{12}$ V m$^{-1}$ with a large fraction of the total pulse energy being converted to relativistic electrons with energies reaching in excess of 1 GeV. In turn these electrons result in the generation of beams of protons, heavy ions, neutrons and high-energy photons. These laser-driven particle beams have encouraged many to think of carrying out experiments normally associated with conventional nuclear accelerators and reactors. To this end a number of introductory articles have been written under a trial name ‘Laser Nuclear Physics’ (Ledingham and Norreys 1999 Contemp. Phys. 40 367, Ledingham et al 2002 Europhys. News. 33 120, Ledingham et al 2003 Science 300 1107, Takabe et al 2001 J. Plasma Fusion Res. 77 1094). However, even greater strides have been made in the last 3 or 4 years in laser technology and it is timely to reassess the potential of laser-driven particle and photon beams. It must be acknowledged right from the outset that to date laser-driven particle beams have yet to compete favourably with conventional nuclear accelerator-generated beams in any way and so this is not a paper comparing laser and conventional accelerators. However, occasionally throughout the paper as a reality check, it will be mentioned what conventional nuclear accelerators can do.

\textsuperscript{3} Deceased.
1. Introduction

1.1. Conventional nuclear instrumentation

Before dealing specifically with laser-driven particle and photon beams, it is appropriate to discuss conventional nuclear accelerators. This section is not meant to be exhaustive, which is beyond the remit of this paper but to put in context the laser-driven nuclear and particle phenomena.

The 20th century brought with it the scientific revolutions of quantum mechanics and relativity and in its wake followed a revolution in technology. The discovery of the atom and of its positively charged core, the nucleus, resulted in scientific interest, which led to the construction of the first particle accelerators, linear structures such as early Cockroft–Waltons and Van-de-Graafs, and cyclic structures such as fixed magnetic field cyclotrons and variable magnetic field synchrotrons driven by radio frequency (RF) fields. High particle energies demand very large magnets in a cyclotron limiting it to \( E < 500 \text{ MeV} \) proton beams, and thus ring structure synchrotrons using smaller magnets become advantageous for \( E > 500 \text{ MeV} \) \( u^{-1} \). Linear structures called linacs have a limited appeal beyond several tens MeV \( u^{-1} \) of particle energy as their length becomes excessive due to the limiting maximum electric field strength.
The use of superconductive cavities or magnets results in slightly higher field strengths ($10^7 \text{ V m}^{-1}$) than the ones obtained with room temperature devices and in a reduction in size but the technology remains complex and expensive.

The development of accelerator technology was accompanied by emerging new related instrumentation including nuclear detectors. Early emulsion and track films, bubble chambers, magnetic and electrostatic systems, gas counters and scintillator and solid-state detector arrays were developed, coupled to increasingly sophisticated electronic circuits for signal amplification. Out of necessity, detector and ‘electronics’ technology branched out into different science fields resulting in the specialization of state-of-the-art devices tailored to the various scientific uses and to the needs of applications in industry and clinical medicine, where nuclear techniques now play an important role in diagnostics and treatment of patients.

Within 70 years after Lawrence (1930, 1931), impressive advances had been achieved in both accelerator and detector technology for scientific studies in a wide range of fields but it also took tens of years of dedicated and patient work to reach the level of reliability, control and maturity needed for every day (non-scientific) applications, e.g. in industry and in clinical medicine following the early work of Wilson (1946). It is also important to realize that the evolution of accelerator and instrumentation technology has not resulted in one particular superior design but in a variety of tools best suited to specific applications in the sciences such as high-energy physics, nuclear and reactor physics, and in applications in industry, clinical medicine, etc.

Medical applications of protons and ions require relatively low beam intensities at the 1 nA level ($6.25 \times 10^9$ particles s$^{-1}$) that can be easily attained by conventional accelerators such as synchrotrons and cyclotrons and this was realized early on (Wilson 1946). In fact, cyclotrons achieve high currents >100 $\mu$A and might thus be considered an ‘overkill’ for applications that require at most a few nA. The required ($10^{10}$ particles s$^{-1}$) currents could also be achieved by multihundred-terawatt laser-driven table-top accelerators with 1–200 Hz repetition rate. For conventional accelerators used in clinical radiation therapy, it is stated (Alonso 2001) that the dose rate of 2 Gy min$^{-1}$ in 4 litres of tissue requires $\sim 10^{10}$ protons s$^{-1}$ or $\sim 3 \times 10^8$ $^{12}$Cs$^{-1}$. Linz and Alonso (2007) claim $10^{10}$ protons s$^{-1}$ and $\sim 10^{12}$ in total for 2 Gy in a 1 litre volume. Lower intensities are required for heavy ions ($Z > 1$) as the radiation damage caused by the ion scales with $Z^2$. Because the cell survival rate is nonlinear, dose accuracy in tumour treatment should be $\pm 2\%$. Typically, a fixed energy cyclotron is used for proton oncology and spreading out the Bragg peak through energy variation is achieved with degraders, which produce a large neutron flux requiring additional shielding and causing uncertainties in the dose calculations.

At present conventional accelerators used in industrial and clinical applications are electron linacs with >6 MeV for x-ray radiotherapy whose advances have been summarized by Bucci et al (2005). Fixed energy proton cyclotrons in the range of 10–30 MeV are used for positron emission tomography (PET) isotope production and $\sim 250$ MeV for proton oncology. Synchrotrons are used for light and heavy ion ($>400$ MeV u$^{-1}$) oncology and application beam lines are coupled to large-scale accelerators at established research centres, i.e. heavy ion medical accelerator (HIMAC in Chiba, Japan) and GSI (Darmstadt) use carbon ion beams and have a low repetition rate of $\sim 1$ Hz. More than 8000 electron linacs for cancer therapy using photons and more than 30 proton and heavy ion accelerator facilities are in use worldwide (Kinoshita et al 2006), where Germany and Japan promote $^{12}$C ions and the USA protons for oncology.
Recently, progress in accelerator technology centres on more compact, less expensive and mixed technology designs, e.g. non-scaling fixed field alternating gradient (FFAG) cyclotrons (an intermediate design using fixed magnetic field like the cyclotron but smaller magnets like a variable field synchrotron). FFAGs are more complex than synchrotrons and maximize their advantages by coupling several injector stages to reach the GeV regime for muon acceleration and neutrino factories (Koscielniak and Machida 2003, Trbojevic et al 2005) but can also deliver lower energies of interest to medical applications of protons (Mori 2003) and carbon ions (Keil et al 2003). The well-known and powerful spot scanning technology developed for hadron therapy with conventional accelerators is also well suited to the pulsed beam structure of FFAGs.

The lessons to be learned for the applications of laser-driven accelerators are that initial breakthroughs in novel concepts must be followed up by painstakingly dedicated efforts to render this novel technology suitable for specific applications. This should include the development of novel laser-driven particle accelerators providing monoenergetic particle beams as well as diagnostics and suitable detectors for such particle beams with $10^8 - 10^{12}$ particles in a 1 ps particle pulse at 1–200 Hz repetition rate. High repetition rates are needed in proton and ion beam therapy using the spot scanning technique (Keil et al 2003), which can be achieved with cyclotrons but not with synchrotrons or FFAGs.

It is perhaps not surprising that laser-driven beams have yet to achieve the quality of conventional RF accelerator beams since these have taken many tens of years to reach their present quality.

1.2. Laser history

After the invention of the laser in 1960, the power of lasers has increased dramatically over the years and indeed recent advances in laser technology have led to the development of compact multiterawatt and petawatt-pulsed laser systems in many laboratories worldwide. When focused to an area of a few tens of square microns or less, this laser radiation can reach intensities close to $10^{21}$ W cm$^{-2}$. Figure 1 illustrates the increase in achievable laser intensity since 1960. Arguably, the greatest advance was made in the mid-1980s with the introduction of ‘chirped pulse amplification’ (CPA) (Strickland and Mourou 1985). In CPA, a laser pulse of the order of femtoseconds or picoseconds is temporally stretched by three to four orders of magnitude using dispersive gratings, thus preventing damage to the laser-amplifying medium resulting from nonlinear processes at high intensities. After amplification, these laser pulses are recompressed to deliver about $10^3 - 10^6$ PW cm$^{-2}$ on target. Proposed techniques, including optical parametric CPA, OPCPA, (Dubietas et al 1992, Ross 1999) promise to continue to extend the boundaries of laser science in the foreseeable future and powers of exawatts ($10^{18}$ W) and zetawatts ($10^{21}$ W) are being discussed.

High-intensity laser radiation may now be applied in many traditional areas of science usually reserved to nuclear accelerators and reactors. As the laser intensity and associated electric field is increased then the electron quiver energy, the energy a free electron has in the laser field, increases accordingly as illustrated in figure 1. When laser radiation is focused onto solid and gaseous targets at intensities $>10^{18}$ W cm$^{-2}$, electrons quiver with energies greater than their rest mass (0.511 MeV) creating relativistic plasmas (Umstadter 2001).

In the 1970s, it was proposed (Tajima and Dawson 1979) that laser-driven electron acceleration was possible using intense laser light to produce a wake of oscillations in the plasma. It is very useful to compare laser accelerators (figure 1(A)) with conventional...
accelerators driven by alternating RF electric fields (figure 1(B)) in the so-called Livingstone plot (Panofsky and Breidenbach 1999). It should be noted that the electron beam energy of conventional accelerators has increased by a factor of 10 every 6 years over the last 70 years while the peak power of the laser has increased on average by an order of magnitude every three years recently. Moreover, there is a widely held view that the Livingstone plot for conventional accelerators will flatten off above 1 TeV whereas there is no apparent limitation for laser accelerators. It is perhaps a little naïve to compare the maximum energy of laser-driven electron beams with conventional accelerators because the existing properties of laser accelerators are still a long way from being of interest to particle physicists. However, the present completion date of the international linear collider is somewhere between 2020–2030 and there is the potential of laser accelerators playing a part in the final design. In the paper, dealing with the basis concepts of plasma accelerators (Bingham 2006), the author indicates how far the laser community must go before TeV electron energies are reached.

It is clear that the high-power laser has emerged as a new tool for investigating advanced physics under extreme conditions. Laser–plasma-based accelerators have the potential to deliver accelerating gradients more than 1000 times higher than in conventional accelerator technology and on a tabletop scale. When laser and conventional accelerators are compared, one of the main differences between the two technologies is the one of scale. This large increase in accelerating gradient for laser technology is the key to reducing the size and associated cost over conventional accelerators and in addition the shielding requirements are much reduced.

Through acceleration of a range of energetic particles and photons, intense laser–matter interactions may induce nuclear and particle processes. It should be emphasized that many of the applications that have been demonstrated on very large lasers as ‘proof of principle’ will
soon be carried out on the new generation of compact scale high-intensity, high repetition rate lasers being developed. Both types of lasers are needed to advance this field of research.

This paper aims to provide an overview of the range of exciting results from this emerging area of research. In order to review the field of laser nuclear and particle phenomena, it is necessary to introduce the laser properties and the laser–plasma interactions that produce the energetic beams for nuclear reactions. This is covered in detail in sections 2 and 3, respectively. Sections 4 and 5 review the laser nuclear science in more detail and give reference to the vast number of theoretical and experimental results to date.

2. High-intensity laser and laser–plasma interactions

2.1. High-intensity lasers

2.1.1. The generation of high-intensity laser pulses from large-scale facilities. The power in a laser pulse is defined to be the energy in the pulse divided by its time duration. Clearly, for the highest powers we need high pulse energies delivered in short pulses. Historically, it should be remembered that the drive to build powerful lasers was motivated by laser fusion research even before the advent of CPA. The pioneer in this respect was the Lawrence Livermore National Laboratory (LLNL) where a series of high-power lasers have been built since the 1970s up till the present time when ultimately the National Ignition Facility (NIF) will deliver a total of 1.8 MJ of laser energy in 192 laser beams. A number of large-scale facilities like NIF have been or are being built at CEA-Limeil (Megajoule), the FIREX project at the Institute of Laser Engineering at Osaka University in Japan, ORION, AWE Aldermaston, and the VULCAN laser facility at the Rutherford Appleton Laboratory in the UK.

Since specifically the Nd:glass laser VULCAN was used to perform many of the ‘proof of principle’ laser-induced nuclear reactions described in this paper, we shall describe this laser (figure 2) in greater detail (Danson et al 2004). In long-pulse mode (with pulses of nanosecond duration) the laser can deliver up to a total of 2.5 kJ (1.2 kJ) of laser energy at 1.053 µm wavelength (0.53 µm—frequency doubled) in eight beams. When it reached its present petawatt status in 2004, the CPA beam line delivered 423 J to target in the pulse duration of 410 fs at 1.03 PW power focused to an intensity of \(10^{21}\) W cm\(^{-2}\). Historically the first PW laser to reach intensities of \(10^{21}\) W cm\(^{-2}\) was the NOVA laser at LLNL (Bonlie et al 2000).

The energy that can be extracted from a laser amplifier chain is limited at short pulse duration by the intensity-dependent nonlinear refractive index of Nd:glass, which is one of the most commonly used laser materials. Normally, a beam of light is more intense in the middle than on its wings and hence above a certain intensity threshold, the laser beam will self-focus and cause catastrophic damage to the Nd:glass laser material. For many years this self-focusing effect limited the intensity of the light, which could be directed upon a target to the non-relativistic regime, i.e. the regime in which the oscillatory velocity of the electrons in the electric field of the focused laser was always much less than the speed of light. The invention of the CPA technique has overcome this limit (Strickland and Mourou 1985). This has resulted in a dramatic increase in the focused intensity on the target. Intensities of almost \(10^{21}\) W cm\(^{-2}\) have now been demonstrated with the VULCAN petawatt laser.

In implementing the CPA technique on a glass laser, an ultrashort pulse is stretched in time to become a longer pulse of typically nanosecond duration. Since by the uncertainty principle short pulses have a relatively large wavelength bandwidth, the pulse is stretched in time by
dispersing the different spectral components. Each component is arranged to travel a different distance prior to amplification. Diffraction gratings are normally used for this purpose. The stretched pulse is then amplified to higher energy but the longer pulse duration ensures that the intensity of the beam remains below the critical value for self-focusing. After amplification, the pulse is compressed in a similar manner to its stretching, resulting in a half picosecond duration laser pulse. In somewhat more detail, the baseline specification for the Vulcan upgrade is approximately 500 J delivered to target with pulse duration of 500 fs. This performance is not achievable by amplification solely by Nd:glass, since gain narrowing would reduce the pulse bandwidth to a value below the ~4 nm limit, which is required to support a 500 fs pulse duration. The approach taken for the petawatt project was to use an OPCPA preamplification system, which generates pulses of ~10 mJ at large bandwidth (1 mJ nm$^{-1}$) for injection into the Vulcan laser rod and disc amplifier chain. The amplifier chain is optimized for bandwidth using a combination of Nd:phosphate and Nd:silicate amplifying media. The preamplifier uses a customized 2 J, 1053 nm, 10 Hz YAG laser to generate a 4.5 ns frequency doubled 200–300 mJ pump pulse, which is approximately ‘top-hat’ in both space and time. This pumps a three-stage optical parametric amplifier that is seeded by the stretched oscillator pulse. The nonlinear medium used for the three amplification stages is ß-barium borate (BBO), each crystal being maintained in an oven at 40 °C.

To provide the 500 J laser energy required for the petawatt beamline an additional disc amplifier stage was commissioned. This comprised three ex-Nova (LLNL) 208 mm aperture disc amplifiers with gain isolation provided by a 208 mm aperture Faraday rotator and a single polarizer at the stage input. One of the 208 mm amplifiers was modified to operate with four flash-lamp circuits using an increased lamp bore to be compatible with Vulcan’s existing pulse power system. This modification indicated a saturation fluence of 4 J cm$^{-2}$, in close agreement with the calculated value, consistent with the requirements of the petawatt beamline and all the amplifiers were subsequently modified.
Figure 3. The petawatt target area complete with radiation shielding. It must be emphasized that before serious experimentation can be carried out using high-power lasers radiation with solid targets, shielding similar to that of conventional nuclear installations must be installed around the target area.

The use of a large aperture, 120 mm, adaptive optic module is essential to the petawatt facility. It is required both to improve the wavefront quality to produce the optimum focal spot on target and also to achieve the best possible recompression of the stretched pulse. The wavefront errors that need to be corrected arise from static aberrations of the optics in the beamline and distortions caused by the thermal gradients set up in the amplifiers during the course of firing laser shots throughout the day. A mirror was designed with 61 addressable elements in a two-dimensional (2D) array suitable for correcting these slowly varying aberrations. The adaptive (= deformable) mirror is installed after the rod amplifier chain and the wave-front sensor is positioned behind the final disc amplifiers before the petawatt spatial filter (SF).

The shielding requirements against radiation (γ-rays, x-rays, neutrons and accumulated activation) produced by petawatt laser shots on a range of target materials, very important for high-power laser assemblies, were calculated using experimental electron energy flux distributions and cross-checked by scaling data from earlier experiments on Vulcan and other facilities at intensities approaching $10^{20}$ W cm$^{-2}$. The design for medium and high-Z targets required a shield blanket of 15 cm lead and 10 cm of high-density polyethylene and a shielded fire escape door. A photograph of the target area prior to the installation of the shielding around the interaction chamber is shown in figure 2 and the completed shielding is shown in figure 3.

A 70 ton lead shield wall was installed surrounding the interaction chamber with gaps for access to the diagnostic ports. The 15 cm thick lead shield wall surrounding the chamber provides high γ-ray absorption and in combination with the 60 cm thick concrete walls surrounding the interaction area as shown in figure 3 gives an high attenuation of γ-rays, with a minimum direct attenuation of $2 \times 10^6$ for 4 MeV γ-rays. In addition to the γ-ray shielding, a neutron absorbing and moderating blanket is required. A 10 cm thick high-density polyethylene
shroud was added to the chamber to fulfill this requirement. A detailed description of the radiation shielding for the VULCAN petawatt and suitable for all petawatt lasers has recently been published (Clarke et al 2006a). The construction of shielding for the high-intensity laser was designed to carry out an extensive and disparate research programme.

However, a recent paper describes the shielding design for a laser-accelerated proton therapy system (Fan et al 2007). Although this shielding is specifically designed for proton therapy, the necessary considerations can be applied in general to high-power laser shielding. The authors describe that laser-accelerated protons emerging from a solid high-density target have a broad energy and angular distribution leading to dose distributions that are unsuitable for therapeutic applications. They have designed a special particle selection and collimation device necessary to generate the desired proton beam profiles for energy and intensity-modulated proton therapy. Large numbers of protons and electrons are stopped by this device that causes radiation-shielding problems. The authors have used particle-in-cell (PIC) to determine the energies of electrons and protons to be maximally 300 and 270 MeV, respectively, for laser intensities at about $2 \times 10^{21}$ W cm$^{-2}$. Monte Carlo simulations were used to calculate the best design of compact size of different materials for the collimator. In addition, the overall shielding to eliminate unwanted photons and neutrons to be below safe limits consisted of 4 cm of lead and 10–12 cm polythene. These figures are very similar to the radiation blanket around the VULCAN laser.

2.1.2. The generation of high-intensity laser pulses from compact table top lasers. Although large-scale facilities have essentially defined the ‘proof of principle’ experiments in the nuclear field described in this paper, such facilities are likely to be few world wide. Alternatively, it is expected that the compact, high repetition rate, table-top lasers with comparable intensity parameters will define the future for laser-driven nuclear and particle phenomena (Mourou et al 1998). It should be pointed out, however, that the specifications of these laser systems are normally 1–10 J pulses in 30–50 fs pulse lengths with pulse repetition rates of up to 10 Hz, providing intensities in the range of $10^{20}$–$10^{21}$ W cm$^{-2}$. The ‘proof of principle’ experiments carried out on large facilities operate with pulse energies of 100 J at similar intensities but with pulse repetition rate of a pulse every 30 min. Concerning the generation of nuclear phenomena, it is still uncertain how in detail compact lasers scale with large lasers at the same intensity but with very different energy and pulse width conditions. Recently, it has been pointed out (Fuchs et al 2006) that one would obtain more energy in a proton beam with a single shot at 10 J rather than by accumulating 10 shots at 1 J suggesting, that for isotope production and neutron production, 1 shot at 10 J is more efficient than 10 shots at 1 J. This is a contentious statement that has yet to find a satisfactory answer. The question of scaling efficiency concerning nuclear phenomena will be reconsidered in the following sections.

With respect to compact table top lasers, there exist a large number around the world in the 10–200 TW power regime yielding laser intensities between $10^{19}$–$10^{20}$ W cm$^{-2}$. In fact in 2004, HERCULES, a laser facility at the University of Michigan, claimed the world record in laser intensity (Bahk et al 2004). This laser is a custom-made Ti:Sapphire laser using CPA to generate ultrashort pulses with a power of 45 TW (27 fs, 1.2 J). The Michigan team used adaptive optics, a well-known technique for correcting wave-front distortion, to focus their pulses to the smallest spot possible ($<1 \mu$m). Pulses from HERCULES were reflected off a deformable mirror before being focused by a paraboloid mirror. Using the technique, the team managed to generate focused intensities of between 0.66 and $0.85 \times 10^{22}$ W cm$^{-2}$.

There are many table-top systems, which could be mentioned here and many have been covered in other recent reviews on high-intensity laser–matter interactions (Mourou et al 2006, Salamin et al 2006). We shall, however, only mention the compact laser systems that have been used extensively in experimentation on nuclear and particle phenomena: the 100 TW JanUSP laser (Allen et al 2004) of the Lawrence Livermore Laboratory with 10 J at 100 fs and intensities of $10^{20}$ W cm$^{-2}$; the 10 Hz, 100 TW high-intensity laser, with 2.5 J at 25 fs, $6 \times 10^{19}$ W cm$^{-2}$ at the Laboratoire d’Optique Appliquee, LOA (Malka et al 2004); the 100 TW laser at the Laboratoire pour l’Utilisation des Lasers Intense, LULI (Fuchs et al 2005), 30 J at 300 fs and intensities of $6 \times 10^{19}$ W cm$^{-2}$; the Jena Ti:Sa terawatt laser, JETI (Hidding et al 2006), 0.6 J at 80 fs with intensities of $5 \times 10^{19}$ W cm$^{-2}$ at 10 Hz; the Max Born Institute Laser (Ter-Avetisyan et al 2006) in Berlin, 40 fs, 0.75 J, 10 Hz and intensities of about $10^{19}$ W cm$^{-2}$.

2.2. Laser–plasma interactions

2.2.1. Introduction to ion acceleration mechanisms. The mechanism of the interaction of charged particles in intense electromagnetic (EM) fields has been considered for 60 years. This was one of the first explanations suggested by the early workers to explain the origin and the energies of cosmic rays (Fermi 1949, McMillan 1950, Menzel and Salisbury 1948). Simply, the idea is as follows. A charged particle in an intense EM field is accelerated initially along the direction of the electric field. The $v \times B$ force causes the particle’s path to be bent in the direction of the travelling wave (Maxwell 1873). In large fields, the particle’s velocity rapidly approaches the velocity of light and the particle travels with the EM wave-gaining energy from it. In astrophysical situations, the solar corona is thought to be one of the sources of the EM waves. Charged particles that are known to exist throughout the universe also become entrained in a long wavelength wave and galactic particles could be accelerated to energies as high as $10^{19}$ eV. These astrophysical phenomena were the counterparts of the terrestrial RF machines, cyclotrons, synchrotrons and linacs, built later to accelerate particles to high energies.

In 1971, the possibility of accelerating electrons in focused laser fields was first proposed (Feldman and Chiao 1971). They showed theoretically that an electron could gain energies as high as 30 MeV after a single pass through the focus of a diffraction-limited laser beam of power $10^{12}$ W and wavelength 1 $\mu$m. It was similarly calculated (Chan 1971) that an intense laser beam could be used as an energy booster for relativistic charged particles, showing that a 10 MeV electron can absorb 40 MeV from a laser beam (1 $\mu$m wavelength and an electric field of $3 \times 10^{10}$ V cm$^{-1}$) within a distance of 1.3 mm. The problem with these early schemes is that it is still not possible to maintain the required intensities over the necessary distances in vacuum, even with the highest energy laser systems in existence today.

In the late 1970s, this problem was overcome by the seminal work of Tajima and Dawson (1979) who realized that by focusing laser light into a plasma medium, much higher accelerating electric fields could be generated than by focusing into a vacuum alone. They proposed the construction of a laser–electron accelerator based on an intense laser pulse producing a wake of plasma oscillations (localized volumes of low and high densities of electrons). Similar to a boat creating a bow wave or wake as it moves through water, a bunch of high-velocity electrons creates a wake of plasma waves as it passes through the plasma. They demonstrated with computer simulations that existing glass lasers of $10^{18}$ W cm$^{-2}$ illuminating plasmas of densities $10^{18}$ cm$^{-3}$ could yield electrons of GeV energy per cm of acceleration length. It is known that conventional accelerators are limited by electrical breakdown to fields of about
20 MV per metre; at these fields the electrons are torn from the atoms in the accelerator’s support structure. Plasmas are already ionized gases and hence are impervious to electrical break down and thus these laser-driven plasma particle accelerators promise fields more than a 1000 times greater that those of the most powerful conventional accelerators (Dawson 1989).

2.2.2. Front and rear target surface ion acceleration driven by relativistic electron production. Since most of the nuclear phenomena, described in this paper, are generated by high-intensity laser interactions with solid targets, we shall concentrate on these although much work has been carried out on gas targets to generate beams of electrons. This will be discussed at greater length in the following section. Before we deal specifically with ion acceleration, we must first of all discuss electron acceleration since according to the present understanding, a principal role in the ion acceleration process is played by the relativistic electron production in the earliest phase of the laser–solid interaction (Passoni and Lontano 2004).

Laser light, like all EM waves, has associated with it perpendicular electric and magnetic fields with the direction of propagation being the vector cross-product of these. For a powerful laser pulse of intensity \( I = 10^{20} \, \text{W cm}^{-2} \), the associated electric field \( (E) \) is very large and \( E_\perp = 2.7 \times 10^{11} \, \text{V cm}^{-1} \) \( (I = 1/2\varepsilon_0cE_\perp^2 \) with \( \varepsilon_0 \) and \( c \) being the permittivity of free space and the velocity of light, respectively). This is a factor of \( \sim 400 \) greater than the field experienced by the electron of the hydrogen atom in its K-shell. At the same time, the varying magnetic field \( (B) \) is also very large being close to \( 10^9 \, \text{G} \) \( (I = 1/2cB^2/\mu_0 \) where \( \mu_0 \) is the permeability of free space). This is only a factor of 1000 smaller than the magnetic field of a typical black hole with 2–3 solar masses. The electric field is perpendicular to the direction of propagation, and hence no significant charged particle acceleration can take place in this direction (Hora et al 2000). However, the Lorentz force \(-e(v \times B)\) due to the laser interacting with charged particles produces a longitudinal force and hence electrons can be accelerated in the direction of laser propagation. It can be shown that the ponderomotive force along the direction of the laser propagation is proportional to the gradient of \( E_\perp^2 \) and in magnitude is equal to the \( v \times B \) force. Electrons readily oscillate in the electric field of a laser with a velocity known as the quiver velocity. For \( I\lambda^2 > 10^{18} \, \text{W cm}^{-2} \mu\text{m} \) (where \( I \) is the laser intensity in \( \text{W cm}^{-2} \) and \( \lambda \) is the laser wavelength in \( \mu\text{m} \)) these velocities become relativistic. The characteristic parameter (a) of this quiver motion is the normalized momentum \( (p) \) defined by \( a = p_{\text{osc}}/m_0c \) where \( m_0 \) is the rest mass of the electron (Wilks and Krueer 1997),

\[
a = \frac{p_{\text{osc}}}{m_0c} = \gamma v_{\text{osc}}/c = eE/m_0c\omega = \sqrt{(I\lambda^2/1.37 \times 10^{18})},
\]

(1)

\( \gamma \) is the relativistic factor \( 1/[1 - (v/c)^2]^{1/2} \), \( \omega \) is the laser angular frequency, \( I \) is the laser intensity in units of \( \text{W cm}^{-2} \) and \( \lambda \) is the laser wavelength in microns. The relativistic expression for the ponderomotive potential \( (U_p) \) using (1) is,

\[
U_p = m_0c^2(\gamma - 1) = m_0c^2(\sqrt{1 + a^2} - 1) = 0.511(\sqrt{1 + I\lambda^2/1.37 \times 10^{18}} - 1)[\text{MeV}].
\]

(2)

Assuming the electron energy distribution can be described by the relativistic equation \( E^2\exp(-E/kT) \) where \( k \) is the Boltzmann constant and \( T \) is the electron temperature, the average value of \( kT \) is found to be \( U_p \) (Malka et al 2004) and for a laser intensity of \( 10^{20} \, \text{W cm}^{-2} \) using equation (2) is \( U_p \sim 4 \, \text{MeV} \).

Of current interest are a number of mechanisms proposed, which can cause the electrons in plasmas to be accelerated to many times the value of the ponderomotive potential described.
above, such as wakefield acceleration (Amiranoff 1998, Tajima and Dawson 1979), plasma wave breaking (Modena et al 1995), $v \times B$ acceleration in the presence of an azimuthal magnetic field (Pukhov and Meyer-ter-Vehn 1998), and resonance absorption both classical (Wilks and Kruer 1997) and Brunel-type (Brunel 1987). The respective contributions of these mechanisms will depend on the type of target used and the length of the preplasma in front of the target. The electrons are emitted in a cone with a typical aperture of 10–30°. A summary of the electron acceleration mechanisms has been given by Amiranoff (2001). Relativistic laser–plasma interactions have been dealt with in great detail by Umstadter (2003) who includes an extensive bibliography.

Cerenkov radiation diagnostics (Brandl et al 2003) of hot electrons generated by fs laser interaction with solid targets has shown that there are two spatially separated beams, one along target normal and one close to the laser direction. The angular distribution of fast electron production has also been calculated (Sheng et al 2000). This has been corroborated by very recent work (Ter-Avetisyan et al 2008), which has also shown that in short (40 fs), high contrast and strongly relativistic laser pulse interaction with thin foil targets, two spatially separated electron populations were observed when the laser is at oblique incidence. The ponderomotive-driven electrons propagate in the laser direction, while the electrons driven by resonance absorption propagate in the target normal direction. On the other hand, protons driven by the two spatially separated sources are only observed along the target normal direction.

Measurements of proton emission from laser–solid interactions have been made as early as the 1980s (Gitomer et al 1986, Kishimoto et al 1983) using nanosecond CO$_2$ lasers. Later measurements using picosecond lasers (Beg et al 1997, Fews et al 1999) showed that protons of energies in the MeV range can be generated at $I \lambda^2$ up to $10^{19}$ W cm$^{-2}$ $\mu$m$^2$. In more recent experiments with $I \lambda^2$ up to $10^{20}$ W cm$^{-2}$ $\mu$m$^2$ (Clark et al 2000a, Krushelnick et al 1999, Santala et al 2001, Snively et al 2000) multiMeV protons have been observed.

The mechanisms responsible for ion acceleration are currently the subject of intensive research by many groups throughout the world. Simply, at the front side of the target the laser ponderomotive force, as has been described, forces the electrons created by the laser–solid interaction into the target. The ions are merely spectators at this stage but electric fields are created by the charge separation, which then drag the ions through the target. However, the main mechanism thought to be responsible for the generation of proton beams is the production of electrostatic fields due to space charge effects when the fast electrons exit the target. These fields cause surface molecules to be ionised by field emission. The details of the interaction physics are not yet fully understood, although probably Wilks et al (2001) have offered the most viable model to date. Proton beams have been observed both in front of the target (the ‘blow-off direction’) and behind the target (the ‘straight through’ direction). From where the proton beam in the straight through direction (at the rear surface) is originating, is still a major area of debate.

The hydrogen atoms responsible for the proton production are either from the bulk hydrocarbon molecules or from water vapour and hydrocarbon impurities on the target surfaces when metallic targets are used (Gitomer et al 1986). In the latter case, it has been asserted (Clark et al 2000a, Maksimchuk et al 2000) that the highest energy protons are generated from hydrocarbon impurity layers on the front of the target then travel through the target and out of the rear. Nemoto et al (2001) have shown by using deuterated targets that the accelerated deuterons appear to originate from the front surface. A number of authors on the other hand.
(e.g. Roth et al 2001, Snavely et al 2000) have argued that the energetic protons originate from the rear of the target. This issue has been discussed in detail by Zepf et al (2001, 2003) who concluded that the most energetic ions were emitted from the front, at least in the case of thicker targets. These authors acknowledged, however, that several acceleration mechanisms may be operating simultaneously. A difficult issue arises because of ring-like structures that can be seen on CR39 plates analysed by optical scanning techniques. These rings have been used by Zepf et al (2001, 2003) to conclude that the most energetic protons come from the laser target interface aided by the existence of transient multi megagauss magnetic fields within the target. In a recent paper, however, it has been suggested that the rings can arise quite naturally due to the saturation of CR39 by high fluxes of protons (Gaillard et al 2006). Their conclusion has been rebutted by the Imperial College group who showed that saturation did not occur in their experiment (Clark et al 2006). Recently, a comparison of laser proton acceleration from the front and rear surfaces of thin targets using nuclear activation techniques, which do not suffer the same problems as CR39 plates, has been carried out by Fuchs et al (2005) who concluded that the higher energy protons with smaller divergence come from the rear surface. Three-dimensional simulations of ion acceleration from foils also support the conclusion that ion acceleration from the front surface can scarcely reproduce the energies and directionality detected in recent experiments (Pukhov 2001). In a very recent paper (Fuchs et al 2007), comparing spectra and efficiencies of ions accelerated from the front and rear surfaces of thin solid foils, have come to the conclusion that for laser intensities up to $6 \times 10^{19} \text{W cm}^{-2}$, independent of pulse length, the rear surface acceleration is the dominant mechanism. However, at the time of writing this paper the controversy has yet to be resolved unambiguously.

2.2.3. Target normal sheath acceleration (TNSA). Most groups carrying out high-intensity laser production of proton beams generally accept the existence or some variant of what is called TNSA, a mechanism that is formed on the cold back surface of the target and which leads to highly laminar beams of low emittance (Wilks et al 2001, Hatchett et al 2000). A simple diagram of the TNSA mechanism is shown in figure 4.
In a recent review (Badziak 2007), it has been shown that the TNSA fields can be described by the following equation:

$$\varepsilon_{ac} = \frac{T_h}{\lambda_D},$$

where $\varepsilon_{ac}$ is the accelerating field, $T_h$ is the hot electron temperature, which depends on the laser intensity between $10^{17}$–$20$ W cm$^{-2}$ varying between 10 keV and 10 MeV, and $\lambda_D$ is the hot electron Debye sheath typically on the micron scale resulting in field strengths between $10^8$–$10^{11}$ V cm$^{-1}$. These fields can ionize the molecules on the back surface and then accelerate these ions over typical distances of $L_{ac} \sim 10 \mu$ to energies of $E_{ion} = Z e L_{ac} \varepsilon_{ac} = 100$ keV to 100 MeV depending on the charge state $Z$. The ions are accelerated typically along the target normal independent of initial laser direction with angular divergence (energy-dependent) of between 10–20$^\circ$. The suppression of transverse proton beam divergence has been simulated by controlled electron cloud in laser–plasma interactions. This is normally arranged by having a hole opposite the side, which is illuminated by the laser (Sonobe et al 2005).

Some recent results carried out at the 30 TW ‘Trident’ laser system at Los Alamos and the 10 TW beamline on the PHELIX laser system at GSI, Darmstadt, have shown that laser ion acceleration with microgrooved targets indicates that the TNSA process very much depends on the laser focus and target parameters such as the foil thickness (Schollmeier et al 2007).

Laser-produced particle beams are generally considered to be quasi-neutral. However, when the target is irradiated by a subpicosecond pulse the assumption of quasi-neutrality should be abandoned (Borghesi et al 2006) because the process of ion acceleration finds its origin precisely in strong charge separation at least in the early phase of the laser–solid interaction. After a few hundred microns, the energetic electrons cool down to reach a co-moving state with the protons. This is an area of theoretical study which is under intense scrutiny (Germillet et al 2002, Kovalev et al 2002, Passoni and Lontano 2004, Passoni et al 2004).

Ways of increasing the energies of the laser-induced ions by structuring the targets have been the subject of much experimental and theoretical work over the years (Albright et al 2006, Badziak et al 2001, Fourkal et al 2005, Kishimura et al 2004). These usually involve layering the targets using polymer-coated metal foils with the supportive substrate being made of high Z material.

2.2.4. Skin-layer ponderomotive acceleration (S-LPA). Badziak et al (2004, 2006) have carried out extensive research on a second promising method of generating light ion beams. This is called S-LPA, a mechanism established on the front surface of the target.

Simply, a laser prepulse of a factor $10^4$ lower in intensity than the main short high-intensity laser pulse produces a skin layer plasma of thickness 5 $\mu$m, which should be several times smaller than the laser spot diameter. This is an essential precondition. The main laser pulse, typically a few times $10^{17}$ W cm$^{-2}$, interacts with this plasma and drives two opposing plasma blocks, one into the target and the other towards the vacuum. Although the ion energies are shown to be very much smaller than in the TNSA mechanism, the ion beam brightness is likely to be much higher. Although S-LPA is still very much a theoretical concept, its authors believe that this approach could be very important in the future because table-top petawatt lasers with a high and controllable contrast ratio are well suited for applications, which require lower ion energies but high ion currents, e.g. PET isotope production and fast ignitor fusion.
3. Nuclear reactions using a laser accelerator source

A number of recent articles have described in detail how intense laser beams interact with the nucleus resulting in nuclear reactions (Takabe 2001, 2003, Yoneda 2001, Habs et al 2001, Salamin et al 2006). Essentially, there are three different ways in which high-intensity lasers can trigger nuclear reactions.

3.1. Nuclear processes induced by intense lasers interacting with solid and gaseous targets

As was described previously, when an intense laser beam interacts with a gas or solid target, beams of electrons, protons and heavy ions are formed both in front and behind the target with the protons principally being generated from impurity layers on the surface. Electrons also generate high-energy photons via bremsstrahlung processes which can cause further nuclear reactions. This is shown in the cartoon in figure 5.

The high-energy gamma rays produce secondary fluxes of neutrons via \((\gamma, xn)\) reactions and protons via \((\gamma, p)\) reactions as well as \((\gamma, pn)\) reactions. Furthermore, the high-energy gamma rays can cause \((\gamma, \alpha)\) and \((\gamma, \text{fission})\) reactions as well as electron–positron pair creation particularly in high \(Z\) targets. In principal, as the laser intensity increases so will the electron and photon energy increase with the possibility of pion production for energies greater than 140 MeV.

The giant dipole resonance (GDR) is a collective phenomenon in the nucleus when it absorbs energy from interactions with photons and particles. In this process, protons and neutrons oscillate in opposite directions to each other with the centre of mass remaining stationary. The peak of the resonance is in the 10–30 MeV region with the width being about 3–10 MeV depending on the mass and excitation energy of the nucleus. De-excitation can take place by emission of high-energy \(\gamma\)-rays, neutrons, protons and \(\alpha\)-particles, with the cross-section for neutron emission exceeding the one for proton emission especially in high \(Z\) neutron-rich nuclei where the coulomb field plays a prominent roll in suppressing charged particle

---

**Figure 5.** This diagram indicates self-focusing and all the nuclear radiation beams, which can be generated by intense lasers interacting with a solid (reproduced by kind permission of Ulrich Schramm).
Figure 6. The diagram shows a comparison of the \((\gamma, n)\) and \((\gamma, p)\) reactions in Zn. In higher Z neutron-rich nuclei the \((\gamma, p)\) cross-section is smaller than the \((\gamma, n)\).

emission. A diagram showing a comparison of the \((\gamma, n)\) and \((\gamma, p)\) reactions in Zn isotopes is shown in figure 6. Note that \((\gamma, n)\) cross-sections are obtained from measurements whereas \((\gamma, p)\) is obtained from statistical model calculations (Spohr et al 2008). This will be described in greater detail in sections 4.5.

3.1.1. Laser-driven electron production. By far the largest effort expended on laser-produced particle beams worldwide has been to generate electron beams (Wharton et al 1998). Typical high-intensity laser-produced electron beam spectra are shown in figure 7 (Cowan et al 2000a). In the early years of this research, most energy spectra obtained were largely exponential in shape as shown in figure 7 with PIC simulations also yielding similar results (Pukhov and Meyer-ter-Vehn 1999).

The high-energy electron spectra obtained when TW \((10^{19} \text{ W cm}^{-2})\) to PW \((10^{21} \text{ W cm}^{-2})\) lasers-irradiated plasmas with an exponential scale length of 10 \(\mu\)m (Pukhov and Meyer-ter-Vehn 1999) have been fitted by 3D simulations. Controlled preformed plasmas are a viable method for increasing the energies of electron beams. However, recent experimental results have yielded electron spectra which are far more energetic than predicted in these simulations.

Figure 8 shows the relativistic magnetic self-channelling of light in near-critical density plasmas. The simulation shows strong flows of relativistic electrons axially comoving with the laser pulse, which generate magnetic fields up to 100 MG. After an early phase of filamentation, a single-light channel with a width of 1–2 wavelengths is formed (Pukhov and Meyer-ter-Vehn 1996).

The difficulty of a large 100% energy spread of the electron beams was very much a problem in the early research of laser-driven electron acceleration. However, in 2004 under the title of ‘Dream Beams’, Nature published three papers by different groups who found a new physical regime of plasma density and laser intensity using short-pulse lasers in which electrons

were self injected in a narrow region of space and forced to accelerate as a single group with all particles reaching similar energies (Faure et al 2004, Geddes et al 2004, Mangles et al 2004). This phenomenon is shown diagrammatically in figure 9 (Katsouleas 2004).

However in 2006, it was shown experimentally (Hidding et al 2006) that quasi-monoenergetic electron bunches could also be generated by 80fs laser pulses. These monoenergetic bunches were characteristic of wakefield acceleration in the highly nonlinear wave-breaking regime, which was previously thought to be accessible only by much shorter laser pulses and in far less dense plasmas. In this experiment, the initially long laser pulse was modified in an underdense plasma to match the necessary conditions described previously. This picture was confirmed by semianalytical scaling laws and 3D-PIC simulations. Hidding’s results

Figure 7. Electron energy spectra produced at $90^\circ$ and $30^\circ$ from a gold target. Reproduced by kind permission of the authors and publishers (Cowan 2000a).

Figure 8. Perspective view of the self-focusing pulse at time 180 fs with a laser of intensity $10^{19}$ W cm$^{-2}$. The colours/greyscale refer to the maximum cycle-averaged light intensity in each $YZ$ plane. Reproduced by kind permission of the authors and publishers (Pukhov and Meyer-ter-Vehn 1996).

Figure 9. Wakefield acceleration. (a) In a plasma excited by a laser pulse, the wake potential rises until it steepens and breaks. Electrons from the plasma are caught in the ‘whitewater’ and surf the wave. (b) The load of the electrons deforms the wake, stopping further trapping of electrons from the plasma. (c) As the electrons surf to the bottom of the wake potential, they each arrive bearing a similar amount of energy. Reproduced by kind permission of the author and the publishers (Katsouleas 2004).

(2006) show that laser–plasma interaction can drive itself towards this type of laser wakefield acceleration (LWFA) even if the initial laser and plasma parameters are outside the required regime. Thus, monoenergetic electron beams now resemble more closely the output from a conventional RF-powered accelerator.

The ‘Dream Beam’ experiments reported in 2004 operated in the so-called bubble regime through a mechanism, in which electrons were ‘self injected’ into the wakefield allowing the trapping and the acceleration of quasi-monoenergetic bunches. In these experiments, a single laser pulse was responsible for trapping and accelerating electrons. This physics is highly nonlinear and can be explained as follows: the nonlinear evolution of the laser pulse via self-focusing and compression leads to an increase of the laser intensity and to the formation of an electron-evacuated cavity or bubble, filled with ions and surrounded by a dense wall of electrons. When the electron density at the walls reaches a threshold value, self-injection occurs at the back of the bubble. Injection stops when the charge density in the trapped bunch is comparable to the charge density at the bubble walls. This short and localized injection leads to the formation of a quasi-monoenergetic electron bunch. However, the efficiency and stability of this self-injection mechanism depends crucially on the shot to shot reproducibility of the laser pulses. The energies of the monoenergetic peaks, which have been reported above can differ considerably from shot to shot and indeed sometimes there is no monoenergetic feature at all. This is caused by electron injection into the wake at non-optimal times.

Recently, however, much more stable beams have been generated by tomographic techniques (Hsieh et al 2006), capillary discharges (Leemans et al 2006) and by colliding laser pulses (Faure et al 2006). Leemans et al. (2006) have shown (figure 10) that laser-driven electron energies up to 1 GeV can now be generated in capillary tubes.

Although Faure et al (2006) have not reached the energies achieved by Leeman’s group, the use of two colliding laser beams has resulted in superior shot-to-shot reproducibility, which is essential for the use of lasers in nuclear and particle physics applications. As emphasized, the French group has achieved quasi-monoenergetic tunable electron beams between 15–250 MeV with an energy spread of less than 10% with good shot to shot reproducibility.
Figure 10. (a) A laser is injected into a plasma in a 3 cm capillary tube to generate energetic electron beams, which are analysed by a magnet. (b) A graph of an electron beam reaching energies of 1 GeV. Reproduced by kind permission of the authors and the publishers (Leemans et al 2006).

The bubble regime described above to explain the monoenergetic electron beams was predicted theoretically as early as 2002 (Pukhov and Meyer-ter-Vehn 2002) and subsequently expanded in detail in other papers e.g. (Geissler et al 2006, Pukhov et al 2004). A 3D-PIC simulation of LWFA of electrons is shown in the figure 11 below.

3.1.2. Laser-driven proton and ion beams and ion reactions—(p,n), (p,xn) and heavy ion-type reactions. Before dealing with proton and heavy ion nuclear reactions it is useful to review the properties of laser-driven proton and heavy ion beams. We can again differentiate the proton spectra from large single pulse lasers like VULCAN, LULI and JanUSP with compact high repetition rate lasers like ASTRA, LOA, JETI, Lund, ATLAS and many others. Fast ion generation by high-intensity laser irradiation of solid targets and droplet targets has recently been reviewed (Borghesi et al 2006, Mendonca et al 2001, Nickles et al 2007, Wilks et al 2001).

Using large single-pulse lasers, a number of groups have produced proton beams up to about 60 MeV with 100% energy spread and indeed this seems to be an upper cut off energy for the beams at laser intensities of about $10^{21}$ W cm$^{-2}$. In early 2000, the first high-energy proton beams (18 MeV) were produced at the VULCAN laser with intensities of $5 \times 10^{19}$ W cm$^{-2}$ (Clark et al 2000a). At the same time petawatt laser experiments were carried out at Lawrence Livermore National Laboratory (Hatchett et al 2000) using several hundred joule pulses of 1 $\mu$m laser light in 0.5–5.0 ps pulses with intensities up to $3 \times 10^{20}$ W cm$^{-2}$ incident on solid targets. About 40–50% of the laser energy was converted to broadly beamed hot electrons. Protons with energies up to 55 MeV were observed with up to $3 \times 10^{13}$ protons per pulse, corresponding to ~6% of the total laser pulse energy. These numbers are typical and have been replicated by other groups using similar conditions (Allen et al 2003, Yang et al 2004a).

The proton beams have been shown to possess remarkable laminarity (Cowan et al 2004). For proton energies $>10$ MeV, the transverse and longitudinal emittances were respectively measured to be $<0.004$ mm mrad and $<10^{-4}$ eVs, i.e. at least 100 fold and perhaps as much as

Figure 11. Snapshots of electron density and electron energy spectra for two different laser intensities. (a) $a_0 = 3$ (below bubble threshold) and (b) for $a_0 = 5$ (above bubble threshold). Reproduced by kind permission of the authors and publishers (Geissler et al 2006).

$10^4$ fold better than conventional accelerator beams due to the small source size and short pulse duration. Using microstructured rear surfaces it was also shown that the protons propagated in almost straight lines from source to detector and by backward ray tracing one can determine from where the protons appeared to originate. Although there is no apparent physical meaning, this point is always located some 50–200 $\mu$m in front of the target (Roth et al 2005). The same authors have shown that the source size diminishes with increasing proton energies (figure 12).

The question of how the upper energy of the proton spectrum scales with intensity is also a very important one and has been well researched over the years. Probably the best accepted data on this point until recently is shown in figure 13 (Clark et al 2000b).

There have been two important recent publications on how the proton energy scales with laser intensity up to the highest petawatt laser–plasma interactions studied (Fuchs et al 2006, Robson et al 2007). Fuchs et al use the plasma-expansion model described by Mora (2003) to predict that a proton energy of 200 MeV could be achieved at an intensity of about $5 \times 10^{20}$ W cm$^{-2}$ (for a laser pulse of picosecond duration). Other groups have used PIC simulations to predict, e.g. energies up to 380 MeV at a peak laser intensity of $2 \times 10^{21}$ W cm$^{-2}$ (Malka et al 2004) and 173 MeV at $1.2 \times 10^{21}$ W cm$^{-2}$ (Schwoerer et al 2006). One of the important driving forces behind this work, which will be dealt with in the next section, is to identify the laser intensity and pulse energy necessary to generate the proton energies required for oncology namely about 250 MeV.

Figure 12. The source size at the rear surface decreases from 260 µm for 3 MeV protons to 80 µm for 10 MeV protons. Reproduced by kind permission of the authors and publishers (Roth et al 2005).

Figure 13. Maximum proton energy plotted as a function of $I\lambda^2$. Reproduced by kind permission of the authors and publishers (Clark et al 2000b).

The work of Robson et al (2007) has been slightly less optimistic than Fuchs et al (2006). Their recent experimental data up to the highest laser intensity recorded show that 200 MeV protons would require laser intensities of $4 \times 10^{21}$ W cm$^{-2}$ with 1 ps pulses. The earlier simple plasma expansion model of Mora (2003) had to be modified to provide a more realistic temperature-varying model. However, the new data and the modelling are close to the requirements predicted in the PIC simulations of Esirkepov et al (2006).
The proton spectra are also very much dependent on the target thickness (Ceccotti et al 2007, d’Humieres et al 2005) and contrast ratio (laser prepulse). Using the JanUSP laser, as the target thickness was reduced below a few microns, it was observed that the proton cut-off energy increased from a few MeV to about 20 MeV at a contrast ratio of $10^{10}:1$ (Mackinnon et al 2002). On the ATLAS laser, when the prepulse is lengthened this reduces the maximum proton energy (Kaluza et al 2004).

An analytical model for ion acceleration by high-intensity laser pulses has recently been published (Schreiber et al 2006). This describes a general expression for the maximum ion energy in experiments with thin foils irradiated by high-intensity laser pulses as a function of laser energy. The only parameters in this expression are the properties of the laser pulse and the target thickness. The dependence of maximum proton energy on the laser pulse duration for different laser energies is shown in figure 14. The model predictions are in good agreement with the maximum ion energies observed recently with high-intensity laser experiments on foil targets at $E_L = 0.7$ J.

The proton spectra generated by short pulse, compact lasers with typical pulse energies of 1 or 2 J exhibit lower maximum energy even though the laser intensities are similar to those in the large lasers. A number of laboratories have generated proton beams up to maximally about 10 MeV although <5 MeV is much more typical (Fritzler et al 2003, Matsukado et al 2003, Oishi et al 2005, Spencer et al 2003). Similar to the large laser systems, the maximum proton energies increase with decreasing target thickness and by minimizing the ASE intensity with contrast ratios up to $10^{10}:1$ utilizing plasma mirrors. Using the Lund laser system, maximum proton energies increased from about 1.5 MeV to almost 4 MeV as the aluminium targets were reduced in thickness from 10 to 0.1 $\mu$m (Neely et al 2006).

For applications like isotope production (covered in section 4) compact lasers produce radioactivity reduced by orders of magnitude compared with the large single-pulse lasers, although this can be compensated to some degree by integrating over many pulses since these

---

**Figure 14.** The figure shows the maximum proton energy as a function of laser pulse duration at four different constant pulse energies. The shaded part denoted laser intensities <1 PW. Reproduced by kind permission of the authors and publishers (Schreiber et al 2006).
Lasers have typically pulse repetition rates of 10 Hz. One of the principal advantages of table-top lasers is that careful, methodical work with high statistical accuracy can be carried out using the high-repetition rate lasers.

One of the very recent developments, which increases the efficiency of short-pulse laser-generated proton beams is the use of flat-top cone targets (Flippo et al 2008). These are nanofabricated devices made from copper or gold of thickness about 10 µ and with a flat top from which the contamination protons are accelerated by the normal TNSA mechanism. Spectra with proton energies up to about 40 MeV have been obtained from modest laser intensities of about $10^{19}$ W cm$^{-2}$. The laser is directed at the open ended base of the cone and apparently the high efficiency comes from the much hotter temperatures generated in comparison with the normal flat foil targets. The spectra are still exponentially shaped but with up to four orders of magnitude greater numbers of the higher energy protons.

Laser production of heavy ions was first researched systematically by the Imperial College team working on the VULCAN laser (Clark et al 2000b, Krushelnick et al 1999). Using gas targets (underdense helium, neon and deuterium), they observed ion energies up to 6 MeV primarily at 90° with respect to the laser direction. When laser–solid interactions were investigated, heavy lead ions were observed with energies up to 430 MeV with a focused laser of $5 \times 10^{19}$ W cm$^{-2}$. Other groups have also observed laser-driven heavy ion beams at similar laser intensities. Collimated jets of carbon and fluorine ions up to 5 MeV nucleon$^{-1}$ (up to 100 MeV) were observed from the rear surface of thin foils (Hegelich et al 2002). The normally dominant yield from proton acceleration could be suppressed by removing the hydrocarbon contaminants by resistive heating. Interestingly, it has been reported that proton spectra can be modulated by the presence of heavy ion beams (Allen et al 2003).

In a recent measurement (Brambrink et al 2006), the transverse characteristics of laser-produced heavy ion beams were compared with those for protons obtained under similar experimental conditions. It was demonstrated that excellent heavy ion beam quality (e.g. low emittance) similar to laser-generated proton beams existed. In their summary the authors claim this is an important result for future applications, where a good focusability and/or beam quality is essential. The size of the emitting area for ions is similar to values obtained for protons. The significantly lower divergence measured can be explained by the influence of the higher ion mass on the acceleration dynamics resulting in an emission angle scaling with the ion sound velocity in the surface region. The final important conclusion of this work is that the design of post acceleration and beam guiding, the less sophisticated results obtained for protons, can be scaled to the various ion species.

An experimental investigation of low and medium mass ion acceleration from resistively heated thin foils irradiated by ps laser pulses from VULCAN at intensities up to $5 \times 10^{20}$ W cm$^{-2}$ has recently been reported (McKenna et al 2007a). It was found that the spectral distributions of ions up to multiMeV/nucleon energies, accelerated from the rear surface of the target, are largely consistent with previously reported measurements up to $5 \times 10^{19}$ W cm$^{-2}$ intensities. Properties of the backward-directed beams of ions accelerated from the target front surface were also measured and it was found that compared with the rear surface, higher ion numbers and charges but similar energies were produced. A very recent paper has shown that lateral electron transport in high-intensity laser-irradiated foils can be diagnosed by ion emission (McKenna et al 2007b). This is a very interesting application of ion emission to investigate fundamental plasma properties.
Figure 15. (a) A laser with intensity $3 \times 10^{19} \text{ W cm}^{-2}$ is directed onto a proton-rich dot deposited on a titanium substrate. (b) The peaked proton distribution black dots and a PIC simulation red curve. The inset shows the peaked proton spectrum expected at $10^{21} \text{ W cm}^{-2}$. Reproduced by kind permission of the authors and publishers (Schwoerer et al. 2006).

As has previously been described, the recent publication of three high profile reports (Dream Beams) on the use of laser-based accelerators stimulated the production of high-energy quasi-monoenergetic electron beams of good quality and heralded a new age of laser applications in nuclear and high-energy physics. The race was now joined by taking the logical next step in the development of laser and target technology that is to generate similar quality beams of other species such as protons and heavy ions. In 2006, two papers were published on the generation of monoenergetic protons (Schwoerer et al. 2006, Toncian et al. 2006).

Schwoerer and his team produced quasi-monoenergetic protons from microstructured targets, an idea that had been suggested earlier (Esirkepov et al. 2002). These authors pointed out that the resulting proton spectrum has a strong correlation to the spatial distribution of the protons on the target surface as shown in figure 15(a). A terawatt laser beam is focused on the front side of a metal target generating electrons, which set up a Debye sheath on the back surface as described earlier. Applying a small hydrogen-rich dot on the back surface enhances the proton yield in the central part of the accelerating field, which is nearly homogeneous. This produces a quasi-monoenergetic bunch of protons. Figure 15(b) indicates the monoenergetic bunch and also the PIC simulation for the laser and target conditions used in the experiment. An inset in the figure estimates the proton peak energy when the laser intensity is increased to $10^{21} \text{ W cm}^{-2}$.

After publication of the above paper, a number of authors (e.g. Brantov et al. 2006, Robinson and Gibbon 2007, Robinson et al. 2006) pointed out that the previous theory (Esirkepov et al. 2002, 2004) was not sufficient to explain monoenergetic features. They emphasized that a pure proton microdot target does not by itself result in a quasi-monoenergetic proton beam. Such a beam can only be produced with a very lightly doped proton target in the presence of more abundant inert and heavier ions, which cause an electrostatic shock accelerating the protons away from the surface. Their simulations suggest that beam quality in current experiments could be considerably improved by choosing microdot compositions with a
Figure 16. (a) The black spectrum in the above picture shows the conventional exponential spectrum and the red peaked spectrum shows a monoenergetic peak from a dotted target, which had been cleaned by an ablation laser. (b) demonstrates a 2D-PIC simulation where the important point is that inert heavier ions are essential in the presence of a lightly doped proton layer. Reproduced by kind permission of the authors and the publishers (Pfotenhauer et al 2008).

5–10 times lower proton fraction. More recent experiments carried out in Jena (Pfotenhauer et al 2008) are shown in figures 16(a) and (b). These are spectra, that were replicated with high counting statistics after hundreds of similar spectra were collected. From this data, for the first time, the scaling of monoenergetic proton beams with pulse energy was obtained.

An innovative approach to proton acceleration, which might enhance existing proton energies by about 30%, has recently been suggested (Velchev et al 2007). The authors have called this a laser-induced Coulomb mirror effect and it effectively requires two laser pulses. Using the same dotted targets as described above the protons exit from target 1 on to a second proton-free target 2, which has been irradiated by a second laser. This allows the protons to experience the maximum acceleration field created by the laser. If only one laser is used the maximum TNSA field can never fully be realized. The authors also claim that although double-layer targets are undoubtedly beneficial, they are not really necessary since the timing between the two lasers generates a peaked distribution due to the filtering properties of the laser-induced Coulomb mirror. They emphasize that the second target should be devoid of hydrogen, which would generate thermal protons that would hamper the detection of higher energies.

A completely different approach was adopted by Toncian et al (2006). As shown in figure 17, two CPA lasers were used. CPA1 produced a broad spectrum of protons from the target, which were directed through a hollow metal cylinder irradiated by a second CPA2 laser beam.

The second laser beam causes transient focusing electric fields to be set up in the hollow cylinder, which allowed for a range of proton energies to be selected from the broad spectrum generated by the first laser beam, depending on the timing of the two lasers and on the flight time of the ions through the cylinder. This technique addresses two of the current drawbacks of
laser accelerated proton beams namely their broad energy spectrum and the source divergence. A similar outcome could be more easily achieved using small quadrupole or solenoid magnets, an approach that is being developed by several groups including the authors of this paper.

In 2006, the first papers published on quasi-monoenergetic heavier ions appeared (Hegelich et al 2006, Schnurer et al 2006, Ter-Avetisyan et al 2006). Hegelich and his team commented on the large energy spread of normal laser-produced ion beams and they argued that controlled treatment of foil targets before irradiation with the ultrahigh-intensity laser reduces adsorbed and absorbed proton contaminants to a negligible level, allowing higher-Z ions to become the dominant species. Using the correct treatment parameters and target materials, a very thin source layer of a few monolayers can be formed by catalytic processes. Specifically, they have demonstrated the acceleration of C$^{5+}$ and C$^{6+}$ ions from an ultrathin layer of graphitic carbon, formed by catalytic decomposition of adsorbed hydrocarbon impurities on a 20 $\mu$m palladium foil. The ions had a mean energy of 3 MeV nucleon$^{-1}$ (full width at half maximum (FWHM) = 0.5 MeV per nucleon) and a longitudinal emittance of less than $2 \times 10^{-6}$ eVs for pulse durations shorter than 1 ps. Such laser-driven, high-current, quasi-monoenergetic ion sources may enable significant advances in the development of compact MeV ion accelerators, new diagnostics, medical physics, inertial confinement fusion and fast ignition, some of which will be described in the following section.

The approach of Ter-Avetisyan (shown in figure 18) and his team was very different from all other monoenergetic ion experiments. They reported on the generation and laser

Figure 17. An ultrafast laser-driven microlens to focus and energy select MeV protons. This technique is in principal scalable to high-energy protons. Reproduced by kind permission of the authors and the publishers (Toncian et al 2006).
acceleration of bunches of energetic deuterons with a small energy spread at about 2 MeV. This quasi-monoenergetic peak within the ion energy spectrum was observed when heavy-water microdroplets were irradiated with ultrashort laser pulses of about 40 fs duration and high ($10^{-8} : 1$) temporal contrast, at an intensity of $10^{19} \text{ W cm}^{-2}$.

In a series of experiments, the Strathclyde team demonstrated that laser-induced primary protons and heavy ions could be used to produce secondary nuclear reactions (McKenna et al 2003a, b, 2004, Yang et al 2004a, b). All of this work was carried out using a primary target to produce protons and heavy ions. The primary ion beams then caused nuclear reactions in secondary targets placed at a small distance in front and behind the primary target irradiated by the laser. Laser-induced protons with energies up to 50 MeV produced (p,xn) reactions in secondary zinc and boron targets; primary iron targets produced protons and heavy ions, which produced fusion reactions in secondary carbon targets; $^{27}$Al, $^{12}$C and $^{16}$O ions from primary targets caused fusion reactions in secondary Al and C targets; finally using heated targets to eliminate the omnipresent proton beams, the heavy ion-induced reaction yields were considerably increased. This is shown in figure 19. During the course of this work the Monte Carlo code PACE 2 was used to determine the cross-sections for the possible fusion evaporation reactions (Gavron 1980).

Figure 18. Deuteron emission from laser-irradiated heavy water droplets. In the upper part (a) one observes the monenergetic deuteron feature along with parabolas from oxygen ions; the lower part (b) shows the deuteron spectrum. Reproduced by kind permission of the authors and the publishers (Ter-Avetisyan et al 2006).
Figure 19. Part of the $\gamma$-ray spectrum from carbon activation samples positioned at the front of the Fe foil target, which was (a) unheated and (b) heated to 860 °C. The counting time for each spectrum was 3 h. The effect of heating the target to get rid of the protons and hence maximize the heavy ion reactions is clearly seen since the gamma peaks in the hot spectrum are greatly enhanced.

In a recent article (Clarke et al 2006b) has described that as a diagnostics of high-intensity laser interactions $> 10^{19}$ W cm$^{-2}$, the detection of radioactive isotopes can be regularly used for the characterization of proton, neutron, ion and photon beam intensities. Normally this involves sample removal from the interaction chamber and time-consuming post-shot off-line analysis using NaI coincidence counting or Ge detectors, which limited the measurement to isotopes with half-lives greater than about 20 min. Clarke et al (2006b) described the use of in situ heavily shielded detectors (inside the vacuum vessel) to measure laser-driven (p, n) reactions in $^{27}$Al as an almost real-time diagnostic for proton acceleration. The $^{27}$Si isotope that is produced decays with a 4.16 s half-life predominantly by $\beta^+$ emission back to $^{27}$Al, producing a strong 511 keV annihilation peak detected by a NaI detector placed within the vacuum vessel. Recovery from the gamma flash was achieved by the detector, amplifier and electronics after one second and thus short half-lives of the order of 1 s can be measured online.

3.1.3. Laser-driven bremsstrahlung processes, $(\gamma, f)$, $(\gamma, p)$ and $(\gamma, n)$ reactions. As early as 1992 Kmetec et al (1992) demonstrated the production of MeV photons using a 0.5 TW, 120 fs Ti-Sapphire laser focused to intensities $> 10^{18}$ W cm$^{-2}$ on 1 mm thick tantalum targets. They estimated that about $10^6$ photons above 1 MeV were generated. Later in 1998 (Gahn et al 1998),
it was noticed that using a Ti–Sapphire laser (200 mJ and 130 fs) at an intensity of about $10^{18}$ W cm$^{-2}$ irradiating targets of various $Z$ numbers, hard $\gamma$-rays were formed with a maximum energy of about 2.5 MeV and with a maximum conversion efficiency of laser energy into MeV bremsstrahlung of $4 \times 10^{-6}$.

Since then a number of research groups have investigated the laser production of bremsstrahlung beams for a number of different applications. Early on it was realized that laser production of hot electrons from intense lasers with intensities greater than $10^{19}$ W cm$^{-2}$ could be diagnosed using bremsstrahlung-produced photonuclear reactions (Leemans et al 2001, Malka et al 2002, Norreys et al 1999, Phillips et al 1999, Spencer et al 2002).

Earlier in this chapter, it was described that a laser pulse of intensity $>10^{19}$ W cm$^{-2}$ interacting with solid targets produces electrons of energies of many tens of MeV are produced. In a high $Z$ target like, e.g. tantalum, the electrons generate an intense highly directional $\gamma$-ray beam that can be used to carry out photonuclear reaction studies. Assuming the flux of hard gamma rays above several MeV is sufficiently large then $(\gamma, \text{fission})$, $(\gamma, \text{p})$ and $(\gamma, \text{n})$ reactions are all possible via the GDR.

In 2000, two papers were published demonstrating for the first-time photonuclear fission of $^{238}$U at the VULCAN laser at RAL and the NOVA laser at Livermore at intensities between $10^{19}$–$20$ W cm$^{-2}$ (Cowan et al 2000a, Ledingham et al 2000). This experiment had already been suggested some 10 years earlier by a seminal theoretical paper predicting the possibility of optical induced nuclear fission (Boyer et al 1988). Fission was demonstrated by detecting the characteristic $\gamma$-rays from fission fragments. These measurements were carried out on single-pulse glass lasers with hundreds of joules in the pulses and with typically $10^6$–$7$ fission events per laser shot. Photofission experiments were also carried out on actinides using the Jena multiterawatt laser with laser pulses of about 1 J at similar intensities but integrating the spectra over $10^5$ shots (Ewald et al 2003, Schwoerer et al 2003).

In a seminal paper (Stoyer et al 2001) describing nuclear diagnostics for petawatt lasers in particular, it was shown that highly neutron deficient activation products could be produced by an intense laser of $3 \times 10^{20}$ W cm$^{-2}$ in the $^{191}$Au $(\gamma, 6\text{n})$ reaction, requiring gamma rays exceeding 50 MeV. For each extra neutron the photon threshold increases by about 10 MeV and hence this information and using known cross-sections could provide a measurement of the photon flux as is shown in figure 20.

In a very recent paper (Galy et al 2007) it has been pointed out that the outcome of accelerating electrons to energies over 200 MeV in these early experiments, led to the utilization of high-energy bremsstrahlung radiation for investigating laser-induced gamma reactions. However, no dedicated investigations have been reported with respect to the characterization of the generated bremsstrahlung in such experiments. As it is not experimentally feasible to measure directly a laser-produced bremsstrahlung spectrum, these authors described a dedicated series of calculations on the generated bremsstrahlung distributions from two experimental electron spectra measured using the giant pulse VULCAN laser and a gas jet target. This paper is highly recommended to those interested in laser production of bremsstrahlung beams for applications and there are two more papers dealing with bremsstrahlung production for photonuclear studies (Findlay 1989, 1990).

It has already been discussed that LWFAs have resulted in the generation of low divergence, hundred MeV, quasi-monoenergetic electron beams. The bremsstrahlung produced when these beams interact with high $Z$ converters have been used to induce photofission in natural uranium (Reed et al 2006). Gamma analysis of fission fragments have yielded $3 \times 10^5$ fission

Figure 20. A comparison of the photon flux as a function of photon energy for $^{197}$Au ($\gamma$, mn) activation products (points) and a Monte Carlo calculation. Reproduced by kind permission of the authors and the publishers (Stoyer et al 2001).

events per joule of laser energy, which the authors claim is more than an order of magnitude larger than previously obtained. These experiments were carried out using the Hercules laser at the University of Michigan with an intensity of $10^{19}$ W cm$^{-2}$ and with pulse widths of 30 fs focused on to a He gas jet after which was placed the uranium target of about 3 mm thickness.

3.1.4. Laser-driven neutron production. Since the first observation of neutrons by the fusion of fast deuterium ions in laser-produced plasmas (Floux et al 1970) using nanosecond pulses at intensities of about $10^{13}$ W cm$^{-2}$, much progress has been made in understanding the mechanism of laser-driven neutron production and the characterization of the emitted neutrons. The secondary reactions ($\gamma$, n), ($\gamma$, fission), (p, n), $d(d, n)^3$He and $d(t, n)^4$He are the most promising for generating neutrons using intense lasers.

Neutron production by lasers can again be differentiated when one considers neutron fluxes generated by single, high-energy-pulsed lasers such as VULCAN and compact, high repetition rate table-top lasers. A recent paper has reviewed laser-generated neutron sources (Zagar 2005). In this paper, they analysed recent data (McKenna et al 2005) showing that production levels in excess of $10^9$ neutrons per laser shot within a nanosecond pulse through (p, xn) reactions on lead targets are achievable. Yang et al (2004b) and Lancaster et al (2004) have also shown that neutron fluxes in excess of $10^9$ per shot can be produced by laser-induced (p, n) reactions using a number of different low and medium Z targets and pulse energies of about 200 J. Similar neutron fluxes have been produced at the Trident laser LANL and the PHELIX laser at GSI.
Although similar neutron production has not been carried out systematically using compact lasers, Pretzler et al (1998) have shown that neutron production of 140 neutrons per shot can be generated in fusion reactions using 0.2 J ultrashort laser pulses. Using a compact laser, Schwoerer et al (2001) generated 100 neutrons per pulse via photonuclear reactions. Zagar et al (2005) have also calculated that using current state-of-the-art table top, high repetition rate lasers with pulse energies of a few joules and laser intensities of a few $10^{19}$ W cm$^{-2}$, 10$^6$ neutrons can be generated per second from the (p,n) reaction on $^7$Li. These numbers are comparable with neutron yields produced when femtosecond laser pulses interact with deuterium clusters (Ditmire et al 1999, Hartke et al 2005, Zweiback et al 2000).

The fusion neutron yield from a laser irradiated heavy water (D$_2$O) spray target has also been studied recently (Ter-Avetisyan et al 2005) using a compact laser with 35 fs pulses at an intensity of $10^{19}$ W cm$^{-2}$. For each laser pulse of 0.6 J irradiating droplets of diameter 150 nm, $6 \times 10^3$ neutrons were produced from $10^{14}$ accelerated deuterons.

Detailed studies have been made of the neutron energy spectra produced when a solid CD$_2$ target was irradiated by 450 fs, 20 J, 1053 nm, pulses from the 30 TW Gekko MII laser at an intensity of $3 \times 10^{18}$ W cm$^{-2}$ (Youssef et al 2005). In another experiment (Youssef et al 2006) targets of LiF and CH-LiF were irradiated and laser-induced protons were generated at the front surface, which produced neutrons via the $^7$Li(p,n)$^7$Be reaction within the target. From the measured and calculated neutron spectra and using a 3D Monte Carlo code, the maximum energy, total number and slope temperature of the accelerated protons were determined. Thus neutron spectroscopy was used as a diagnostic tool to study proton acceleration. Observations of neutron spectra produced by fast deuterons generated by ultraintense laser interactions with deuterated plastic targets at higher intensities ($2 \times 10^{19}$ W cm$^{-2}$) have also been made. These yielded neutron fluxes of $7 \times 10^4$ neutrons per steradian (Izumi et al 2002).

The question of nuclear fusion in gases of deuterium clusters heated by femtosecond laser pulses has become an important topic over the last few years (e.g. Ditmire et al 2000, Madison et al 2004) because solid deuterium clusters provide a new type of target for laser–matter interactions. A theoretical study (Parks et al 2001) was presented describing the generation of laser-driven Coulomb explosions that create a hot fusion-producing ion tail. The derivation included an initial distribution function for the exploded ions, for an arbitrary cluster-size distribution, and solving the D–D neutron-production rate during the free expansion of these ions into a vacuum. It was found that good agreement existed between theory and the recent experiments.

The 14.1 MeV neutron energy spectrum from d–t fusion is similar to that produced in fusion reactors. Therefore the damage caused to the reactor walls by these neutrons may be studied using laser-induced d–t fusion neutrons under realistic conditions. Such studies would lead to a better understanding of the damage process, and the development and testing of more robust materials for reactor vessels and containers for storing nuclear waste. A target design has been described for d–t fusion reactions where under optimal conditions a neutron flux in the range $10^{14}$–$10^{15}$ neutrons cm$^{-2}$ s$^{-1}$ may be achieved with 100 J laser pulse energy operating at 100 Hz (Perkins et al 2000). This design has the capacity for producing high damage rates from a small neutron source volume at a relatively low cost with the potential for high experimental availability over long periods unlike reactor-based studies.

The merit of using ultrashort ion bunches produced by circular polarized laser beams to drive a source of fusion neutrons with a suboptical cycle duration has also been investigated (Macchi 2006). Using PIC simulations and analytical modeling, it is calculated that
for laser intensities of about $10^{19}$ W cm$^{-2}$ more than $10^3$ neutrons per joule can be generated within a time shorter than one femtosecond. A two-sided irradiation of a deuterated thin foil using two laser beams produced counter propagating deuterons, which collided to produce the femtosecond neutron burst.

The advancements in Ti–Sapphire laser technology have afforded the possibilities of practical applications of laser-generated neutrons. Neutron pulses are emitted from a small region and with time widths in the femtosecond to picosecond regimes. For example, in the center-of-mass system, the neutrons are produced with ‘monochromatic’ energies of 2.45 MeV in d–d and 14.1 MeV in d–t fusion reactions. The measured energy spread, determined primarily by the thermal velocity of the colliding ions, may be 10% or less. The 2.45 MeV d–d fusion neutrons in conjunction with the laser pulse or accompanying ultrashort x-ray pulse may be used as a pump or probe in time-resolved studies. This inherent capability is far beyond anything currently available but promises to open up a new field of ultrafast neutron spectroscopy for structure studies in material and biological sciences. ‘Monoenergetic’ neutrons may be used in time-resolved studies of materials. For example, it is expected that the passage of a neutron through a solid will create thousands of dislocations healing on nanosecond or shorter timescales. Studies of such transient damage in materials might involve measuring diffraction patterns of the neutron-irradiated sample with an ultrashort x-ray pulse created by the same laser pulse as used for neutron production. The variable delay between the neutron and the x-ray pulse would then provide the evolution with time of the healing process and lead to a better understanding of the underlying mechanisms. Other uses of fast neutron pulses may be in the study of biological materials and more generally in phenomena at sub-nanosecond timescale.

### 3.1.5. Laser-driven positron production.

The production of electron positron pairs by the interaction of relativistic superthermal electrons generated by ultraintense laser pulses with a high Z material was considered theoretically and has been reviewed (Galy et al 2007, Liang et al 1998, Marklund and Shukla 2006, Yoneda 2001). Indeed more than 10 years ago, it was demonstrated theoretically that positron and gamma-photon production could be generated by subterawatt femtosecond lasers using optimally designed targets (Shkolnikov et al 1997). They have shown that with a 10 kHz laser at $10^{21}$ W cm$^{-2}$, one could expect a laser-based source of $\sim 1$ Ci on a par with a $^{22}$Na source but with a much smaller radiation hazard.

Two processes are involved in pair creation after irradiating high Z targets with relativistic electrons (Takabe 2003):

- **Trident process**
  \[
  Z + e^{-} \rightarrow Z + 2e^{-} + e^{+}.
  \]

- **Bethe–Heitler process**
  \[
  Z + \gamma \rightarrow Z + e^{-} + e^{+} + \gamma.
  \]

Although the Trident process is a one step process and the Bethe Heitler is two step, having to create firstly a bremsstrahlung beam from the fast electrons, the latter cross-section is two orders of magnitude larger than the Trident process. In a paper, describing particle physics with petawatt class lasers (Karsch et al 1999), the authors have predicted (GEANT simulation) the production of $\gamma$ rays and of electron/positron pairs from a 8 mm thick tungsten target irradiated by a laser with intensity $10^{21}$ W cm$^{-2}$. This is shown in figure 21.

There have only been three experimental programmes to measure laser production of positrons. Firstly, using the Nova laser at focused intensities of $6 \times 10^{20}$ W cm$^{-2}$ (Cowan et al 2000b) on a 125 $\mu$ thick gold target, an electron–positron yield of about $10^{-4}$ of the primary...
electron yield was measured. The detectors used in the Nova experiment were nuclear emulsion detectors, which had to be scanned with great precision to exclude spurious tracks coming from scattered background events. The positron spectrum detected is shown in figure 22.

The second programme was carried out using a femtosecond table-top laser system (Gahn et al 2000, 2002). The production of positrons was demonstrated by generating multi MeV electrons in form of a collimated beam using 200 fs pulses from a laser with 1.2 TW and 10 Hz capability. The method uses the process of relativistic self-channelling in a high-density gas jet producing high electron energies. The laser–electron efficiency was estimated to be 5%. In a second step, utilizing the multi MeV electron beam, anti-particles, namely positrons, were successfully generated in a 2 mm Pb converter. The average intensity of this new source of positrons is estimated to be equivalent to a radioactivity of $2 \times 10^8$ Bq and it exhibits a very favourable scaling for higher laser intensities. The figure 23 shows the experimental arrangement and it should be emphasized that plastic scintillators, which were used to detect the positrons with mean energy 2 MeV must be very carefully shielded from laser-induced gamma background.

A very recent programme of relativistic positron production using short pulse lasers has been carried out at the Titan laser at the Lawrence Livermore National Laboratory using laser intensities up to $10^{20}$ W cm$^{-2}$ (Chen et al 2009). The positron intensity was measured to be $2 \times 10^{10}$ positrons per steradian with an energy peaking at about 7 MeV from mm thick gold targets. The positrons were produced predominantly by a Bethe–Heitler process.

A numerical study of pair creation by ultraintense laser systems irradiating a thin gold foil with 280 J pulses has been carried out (Nakashima and Takabe 2002) showing that as the laser intensity is increased from $10^{19}$–$21$ W cm$^{-2}$ the positron yield increased dramatically initially but eventually saturated around $10^{21}$ W cm$^{-2}$ at a yield of $5 \times 10^{10}$ positrons per pulse. Galy et al
Figure 22. Spectra of electrons and positrons measured in 600 J/0.5 ps shot on 125 µm Au target. Histograms show PIC simulation of electrons and corresponding prediction for positrons created by bremsstrahlung in the Au target. Reproduced by kind permission of the authors and publishers (Cowan et al 2000b).

Figure 23. Experimental arrangement for positron production. The laser interacted with a gas jet to generate high-energy electrons. These impinged on a high Z bremsstrahlung target, which created the electron–positron pairs. The positrons were deflected by a bending magnet and detected by a carefully shielded plastic scintillator. Reproduced by kind permission of the authors and publishers (Gahn et al 2000).

(2007) has shown that this positron flux is comparable with the one of presently existing long- and short-lived radioactive sources as well as to reactor and linac-produced positron sources.

It will be shown in section 5 that laser intensities are expected to increase to about $10^{22}$ W cm$^{-2}$ within the next year or two. When two laser beams, each of $10^{22}$ W cm$^{-2}$ are
incident on opposite sides of a very thin target in a ‘colliding beam’ geometry, the energy density
in the interaction volume is very high. Terabar pressures are created and using shaped focal plane
field distributions, TeV electron energies are expected to occur. At $10^{22} \text{W cm}^{-2}$ large numbers
of electron–positron pairs are generated, either through direct high-energy electron interaction
with a high $Z$ nucleus (Trident process), or through the interaction of bremsstrahlung produced $\gamma$-rays with the high $Z$ nucleus (Bethe–Heitler). Thus the possibility of exciting new laser-
induced particle physics is not far away.

3.2. Nuclear excitation of isomers using a laser accelerator source

Nuclear isomer research has the potential to lead to a series of novel ground-breaking
technologies in the near future. Firstly, isomers of stable nuclei may provide a clean and
switchable form of nuclear energy as they have a very high-energy per mass unit ratio in the
region of $\sim\text{MJ mg}^{-1}$ (Walker and Dracoulis 1999). Indeed some long-lived isomers can store
$10^4$ times more energy per gram than available from chemical compounds and may release
this energy cleanly without the production of radioactive by-products (Carroll 2001). Another
driving force behind this research is to identify suitable isomeric levels that can be laser pumped
to provide population inversion for three- and four-level gamma-ray lasers (Andreev et al 2001).

Laser-induced plasmas can cause many electrons to be stripped from atoms reducing the
total internal conversion rate of the transitions that can subsequently increase the lifetimes
from nanoseconds to microseconds equivalent to narrowing the linewidth of the transition. In
addition, the investigation of internal conversion processes in strongly ionized atoms could
lead to new and exciting nuclear physics, for example the investigation of higher order
processes, which couple atomic electrons to nuclear levels via so-called electronic bridge
mechanisms (Kekez et al 1985).

It has already been shown that the interaction of lasers with intensities $>10^{18} \text{W cm}^{-2}$ with
solid targets generates energetic electrons, photons, protons and ions. Less energetic laser beams
in the $10^{16}$–$10^{18} \text{W cm}^{-2}$ intensity range can also influence the nucleus by generating electrons
and x-rays in the keV energy range causing excitation of low-energy nuclear isomers (Letokhov
1974, Morita 1973). Hence, most laser experimental work to excite nuclear isomers has been
carried using lower intensity lasers.

Theoretical evaluations of Arutyunyan et al (1991a, b) predict a range of ultraintense
laser–plasma-induced processes that can lead to the excitation of isomeric nuclear levels.
The most prominent processes would be the nuclear excitation via photoabsorption, inelastic
scattering of plasma electrons (IS), inverse internal electron conversion (IIEC) and by electron
transitions (NEET). The efficiencies for these processes highly depend on the energy and
lifetime of the isomeric state. For the NEET process the atomic configuration of the emitting
nuclei has to be considered as well. The calculations predict that the excitation efficiencies of
the dominant processes increase steadily as a function of the electron plasma temperature for a
series of different isomeric states of stable nuclei. Consider for example the nuclear and atomic
electron levels of an element shown in figure 24(B).

An electron hole is produced in an atomic level by an electron or photon beam and is
filled by the photon emission transition $A$. If the multipolarity and energy of $A$ corresponds to
a nuclear absorption transition $B$ to an isomeric state then this transition can proceed efficiently
and is called nuclear excitation by electron transition (NEET). The isomeric state then de-
excites by emitting gamma rays or internally converted electrons. This was experimentally
Figure 24. (A) NEET excitation to an isomeric state and (B) laser excitation from an isomeric state, which could release large quantities of energy. In figure 24(B), if a long-lived isomeric state is populated, then laser-induced transitions to a higher excited state with a spin value between that of the isomeric and ground state could release large quantities of energies via a transition, e.g. (C) Some long-lived nuclear states can store $10^4$ more energy per gram than available from chemical compounds and release the energy cleanly without the production of radioactive by-products if the ground state is stable.

Demonstrated in the 1970s using electron and intense CO$_2$ laser beams (Otozai et al 1973, Izawa and Yamanaka 1979) to excite NEET isomeric transitions in $^{189}$Os and $^{235}$U and measuring the de-exciting internally converted gamma rays.

However, extensive theoretical and experimental studies on laser excitation of nuclear isomeric states (Andreev et al 2000) has shown that at laser intensities between $10^{16}$ and $10^{17}$ W cm$^{-2}$, the NEET processes can be neglected compared with the very much stronger plasma-produced electron impact and photoexcitation processes. Experimental studies of the excitation of the 6 keV transition in $^{181}$Ta using both dye lasers and subpicosecond Nd:glass lasers found an excitation efficiency of about $10^{-7}$. Other authors have tried to replicate this measurement in $^{181}$Ta without success (Hanvey 2004). A new experimental strategy to find unambiguous evidence for the direct laser-induced population of the short-lived $^{181m}$Ta has recently been suggested (Spohr et al 2006).

Probably the most comprehensive search for nuclear isomeric excitation has been carried in $^{235}$U (Claverie et al 2004, Gobet 2006). These authors have searched for the NEET of the isomeric level at 76 eV in $^{235}$U in a plasma induced by a YAG laser with an energy of 1 J and a FWHM time distribution of 5 ns, operating at an intensity of $10^{13}$ W cm$^{-2}$. A thorough description of the experimental conditions and analysis of the data is given. In this experimental situation, excitation of the isomeric level is not observed, a result that is at variance with a positive result reported by Izawa and Yamanaka (1979). An upper limit of $6 \times 10^{-6}$ per atom and per second averaged over the laser-pulse width has been set on the nuclear excitation rate.

Most existing experimental evidence indicates that the laser excitation of nuclear isomeric states has not yet been established unambiguously but the subject is sufficiently important to merit further studies.

3.3. Direct laser nuclear reactions

Direct laser-induced nuclear transitions were first considered theoretically more than 20 years ago and in particular laser-induced EM de-excitation of the nucleus (Kalman and Lovas 1987).
In this publication, the lifetime shortening of metastable nuclear states induced by a high-intensity laser beam was discussed.

At extremely high field strengths the laser can directly interact with the nucleus without the necessity of first producing secondary beams of electrons, photons, protons, heavy ions, neutrons and fission. Quantum optics demonstrates the direct interaction of high-intensity laser fields with nuclear fields enabling perhaps control or modification of nuclear dynamics. Generally speaking, direct interaction requires laser intensities of $5 \times 10^{28} \text{ W cm}^{-2}$ (2 mc$^2$ over the electron Compton wavelength $h mc^{-1}$). At these intensities one can observe electron–positron pair creation in the vacuum. These intensities however are much greater than can be achieved with any laser system envisaged at present although we shall again return to this subject in section 5.

In two recent papers (Burvenich et al 2006a, b) the direct interaction of nuclei with superintense laser fields was studied. It was shown that present and upcoming high-frequency laser facilities, especially when coupled with a moderate acceleration of the target nuclei to match photon and transition frequency, permit resonant laser–nucleus interactions to take place. These direct interactions may be utilized for the model-independent optical measurement of nuclear properties such as the transition frequency and the dipole moment, thus opening up the field of nuclear quantum optics. As an ultimate goal, the authors hope that direct laser–nucleus interactions could become a versatile tool to enhance preparation, control and detection in nuclear physics applications.

As has been described, direct laser interaction with the nucleus requires very high laser intensities. It is rather easy to show that a laser interaction with a free proton requires only intensities of about $10^{22} \text{ W cm}^{-2}$ to produce a quivering mode that carries off some tens of eV in energy. However, when the proton is bound inside the nucleus, it does not behave like a classical particle in a box. The shell structure and the Pauli exclusion principle allow only excitation from one discrete state to another. Since the transition dipole moments are typically less than 1 efm, the effect is dramatically reduced. The quantum Stark shift for laser intensities of as much as $10^{24} \text{ W cm}^{-2}$ is only fractions of an eV, which makes the effect very difficult to measure at least for the foreseeable future (Frauendorf 2008).

Although direct interaction studies of laser beams with nuclei may still be a long way off, a recent paper has shown that the acceleration of nuclear beta decay can be observed when a radioactive source is irradiated using an intense EM field (Reiss 2008). Although a laser was not used in this experiment, it is interesting to note that the first forbidden beta decay half-life of $^{137}\text{Cs}$ was modified by about $7 \times 10^{-4}$ relative to the natural rate when the source was irradiated by intense low frequency continuous EM fields. Theoretically, this was predicted in the 1980s (Reiss 1985 and all references therein), the idea being that the lifetime of beta processes is a function of the spins and parities of the nuclear levels involved. These spins can be modified by dressing them with photons from EM fields hence modifying the half-lives and such phenomena might be relevant for laser intensities above $10^{22} \text{ W cm}^{-2}$ (sections 5.2).

4. Applications for laser-driven photon and particle beams

4.1. Laser-induced transmutation studies

One of the major problems of the nuclear power industry today is the management and disposal of high-level radioactive waste with a long half-life. Vitrified high-level waste can be stored

for about 50 years before ultimate geological disposal. However, in many countries around the world much research effort is being expended in the possibility of partitioning and transmuting radioactive waste, which can reduce its toxicity by a factor of 100 (e.g. Bowman and Magill 2006, Magill et al 2003a). Recently, a number of roadmaps for nuclear waste transmutation using GeV energy light particle beams have been produced (e.g. Rubbia 2001).

Although the most frequently discussed methods involve transmutation by bombardment with neutrons from a reactor, there have been other suggested approaches to this problem, for example laser-driven high-brightness gamma generation for phototransmutation (Li et al 2002). Although such an approach does not include high-power short pulse lasers, this work has been included because high average power conventional lasers coupled to high-intensity linacs or storage rings constitute an alternative way of carrying out transmutation studies with lasers. The Japanese group have developed an approach of producing monoenergetic photons of 17.6 MeV by back scattering a CW Nd:YAG laser of wavelength 1.064 μm from a 1 GeV electron beam extracted from the New-SUBARU storage ring. The energy of the photon coincides with the maximum of the GDR cross-section for (γ,n) reactions. Initial studies have been shown to be encouraging and the experiments using the nuclear waste isotopes ¹²⁹I and ¹³⁷Cs will be carried out in the future (Li et al 2004, 2005).

Transmutation studies have also been carried out at two high-power laser centres, the large single-pulse laser centre at the Rutherford Laboratory and compact high repetition rate laser centre at the University of Jena. Firstly, the experiment carried out on VULCAN at the Rutherford Appleton Laboratory will be discussed (Ledingham et al 2003). This involved using the petawatt laser to drive the phototransmutation of long-lived ¹²⁹I with a half-life of 15.7 million years to ¹²⁸I with a half-life of 25 min. A laser-generated gamma ray is absorbed by the ¹²⁹I nucleus, which releases a neutron to undergo transmutation to ¹²⁸I. This GDR (γ,n) reaction is observed in ¹²⁹I and ¹²⁷I and the absolute activities of the reaction products ¹²⁸I and ¹²⁶I were used for the first time to determine the integrated cross-section for ¹²⁹I(γ, n)¹²⁸I from the known ¹²⁷I(γ, n)¹²⁶I cross-section.

The target arrangement on VULCAN was similar to that described earlier in section 3 where we were dealing with laser-driven bremsstrahlung processes. The laser-produced relativistic electrons then interacted with a 4 mm thick Au target to produce high-energy gamma rays. These photons irradiated iodine samples of 85% ¹²⁹I and 15% ¹²⁷I as shown in figure 25, which had been supplied by the Institute for Transuranium Elements, Karlsruhe, Germany.

The iodine samples were analysed using germanium detectors before and after laser irradiation of the gold target. The background spectrum in figure 26 was measured for 3 h and the principal lines observed resulting from the decay include ¹²⁵Sb. The background activity from the samples was of the order of 2.4 × 10⁸ Bq.

Figure 26 shows clear peaks at 443.3 and 527.1 keV, characteristic of the decay of ¹²⁸I. The decay rate of ¹²⁸I was determined by measuring the integrated area under the peaks over successive time intervals. The half-lives of the 443.3 and 527.1 keV peaks were 25.8 ± 1.0 and 25.5 ± 1.5 min, respectively, which agree well with the literature value of 25.0 min. In addition, the measured ratio of the area under the 443.3 and 527.1 keV peaks averaged over all of the measured spectra is 10.9, in good agreement with the literature value of 10.4. From the data, the total activity of ¹²⁸I produced at the time of the laser shot was deduced to be 1323 Bq. This corresponds to the production of ~2.9 × 10⁶ nuclei of ¹²⁸I for the 360 J laser shot.

The iodine samples contained 15% of the isotope ¹²⁷I. Observed weak peaks at 388.6 and 666.3 keV in the measured gamma emission spectra are attributed to the decay of ¹²⁸I, produced
Figure 25. The laser enters from the left interacting with an Au target to produce gamma rays, which irradiated the two iodine samples shown in the right-hand side of the picture.

Figure 26. Gamma emission spectra from one of the iodine samples measured before (background) and after laser irradiation of the gold target. Characteristic emission lines of $^{128}\text{I}$ at 443.3 and 527.1 keV are clearly observed.

by ($\gamma$, n) reactions on $^{127}\text{I}$. A similar analysis performed on those peaks illustrates the production of $1.7 \times 10^6$ $^{126}\text{I}$ nuclei.

A previous transmutation experiment was carried out at the compact high repetition laser JETI at the University of Jena using the same iodine sources (Magill et al 2003b). The Jena multi TW laser system generates pulses with an energy of 1 J, < 80 fs pulse width, at a repetition rate of 10 Hz with a centre wavelength of 800 nm. The pulses are focused onto the target, producing an average intensity of up to $10^{20}$ W cm$^{-2}$ within a focal area of 5 $\mu$m$^2$. The primary target is a 2 mm thick tantalum sheet, which acts as an electron source and bremsstrahlung converter. The iodine sample (21 g of PbI$_2$ with 17% of $^{129}\text{I}$) was placed directly behind the tantalum converter and the target was irradiated with 10 000 laser shots. After irradiation, $\gamma$-radiation from short-lived photoreaction products in the tantalum and iodine samples is detected by two germanium
Figure 27. The laser is directed at a helium gas jet and the fast electrons generated interacted with a thick high Z bremsstrahlung target. This arrangement was more efficient for nuclear reaction production than aiming the laser directly on the solid target (Liesfeld et al 2004). Reproduced by kind permission of the authors and Applied Physics B journal.

detectors. Spectra are taken in successive time intervals to monitor the characteristic decay times of the radioactive nuclei. With the efficiency calibration of the detectors absolute numbers of laser-induced reactions in units per laser shot are obtained. The number of \((\gamma, n)\) reactions in \(^{129}\text{I}\) was found to be 2 per laser shot.

In an improved experiment (Liesfeld et al 2004) demonstrated that if a high-energy electron beam was first generated in a He gas jet and then directed at a high Z target to produce the bremsstrahlung beam, the nuclear reaction rate of \(^{129}\text{I}\) increased by two orders of magnitude. This experimental arrangement is shown in figure 27.

However, by comparing the two experiments at VULCAN (300 J) and Jena (1 J) with similar laser intensities but with very different pulse energies \((E_l)\) there appears to be an \(E_l^2\) energy dependence of the nuclear reaction rate. It is realized that such a comparison is very naïve since the pulse widths and focal radii are very different; however, it does indicate that in order to obtain similar reaction rates with a compact laser many laser shots must be integrated.

The possibility of phototransmutation of the long lived nuclide \(^{135}\text{Cs}\) by an ultrashort, ultraintense laser has been analytically evaluated (Takashima et al 2005). The yield of the \(^{135}\text{Cs}(\gamma, n)^{134}\text{Cs}\) reaction was strongly dependent on the yield of bremsstrahlung photons in the giant resonance region. If a \(^{135}\text{Cs}\) source was illuminated at \(10^{21}\text{ W cm}^{-2}\) and 10 Hz for 30 min, the characteristic \(\gamma\)-ray counting from \(^{134}\text{Cs}\) was estimated to be 3 Bq.

4.2. High-intensity laser-driven medical applications

In 2000, the University of Strathclyde collaborating with the Rutherford Appleton Laboratory organized the first international workshop dealing with the potential of high-power laser technology in medicine. Two areas of high potential were identified; firstly, the production of PET isotopes and secondly, the production of laser-accelerated proton and heavy ion beams for therapy. The attendees, mainly clinicians and radiation physicists, emphasized that the laser community should concentrate on developing the laser and target technology for therapy rather
than on isotope production because of the potential advantages of lasers over conventional accelerator technology for that purpose. However, the physics community felt that to begin with the easier problem of isotope production should be attempted.

4.2.1. PET isotope production. PET is a powerful medical diagnostic/imaging technique requiring the production of short-lived (2 min to 2 h) positron-emitting isotopes. The PET process involves the patient receiving an injection of a pharmaceutical labelled with a short-lived $\beta^+\,$ emitting source that collects in ‘active’ areas of the body such as tumours. The principal tracers used in the PET technique are $^{11}\text{C}$, $^{13}\text{N}$, $^{15}\text{O}$ and $^{18}\text{F}$. Many chemical compounds can be labelled with positron-emitting isotopes and their bio-distribution can be determined by PET imaging as a function of time. However, the most commonly used radiopharmaceutical is 2-fluoro-2-deoxyglucose, 2-[18F]FDG. Over the last few years, the value of PET FDG in the management of cancer patients has been widely demonstrated. Figure 28 highlights the success rate of PET in diagnosing lung cancer compared with conventional x-ray computed tomography (CT) scanning (Ledingham 2006).

PET isotopes are generally produced using energetic proton beams produced by cyclotrons or Van-de-Graafs via (p, n) or (p, $\alpha$) reactions. Proton-induced reactions are favoured since the resultant isotope differs in atomic number from the reactant, thus simplifying the separation process and making it possible to produce carrier-free sources. The patient is then injected with the minimum amount of foreign material.

One of the main factors limiting the wider use of FDG PET imaging is the requirement for expensive infrastructure at the heart of which lies the cyclotron and the associated extensive radiation shielding. A simplified approach to isotope production would be to develop a miniaturized, on-site resource with capability similar to that of a cyclotron. As was stated previously, recent results show when an intense laser beam ($I > 10^{19}\text{ W cm}^{-2}$) interacts with solid targets, beams of MeV protons capable of producing PET isotopes are generated. Probably the first publication to suggest laser generation of positron-emitting radionuclides was an estimation using a 2D PIC simulation (Yamagiwa and Koga 1999). The calculation determined the laser production of protons and hence the generation of $^{18}\text{F}$ via the $^{18}\text{O}(p, n)^{18}\text{F}$ reaction. They found the instantaneous production rate of $^{18}\text{F}$ to be two orders of magnitude larger than by the standard method using a cyclotron.
A number of recent reports have been published using the high-power laser VULCAN both as a 100 TW laser and a petawatt laser (Ledingham et al 2004, Santala et al 2001, Spencer et al 2001). In addition, some preliminary work has also been carried out at the 10 Hz table-top ‘Salle Jaune’ laser at LOA (Fritzler et al 2003) estimating the strength of PET isotopes, which could be generated on a compact laser.

It should be pointed out that the laser approach at this stage is not intended to be a competitor of cyclotron sources but in the fullness of time, as the lasers develop and become smaller, this could become an alternative approach.

The experiments from both VULCAN and LOA will now be described in some detail beginning with the results from VULCAN. The PET isotope $^{18}$F is generated by a (p,n) reaction on $^{18}$O-enriched (96.5%) targets. The enriched $^{18}$O targets were irradiated in the form of 1.5 ml of $[^{18}$O$]_{2}O$ placed in a 20 mm diameter stainless steel target holder. For the production of $^{11}$C, the copper stacks described above were replaced by boron samples (5 cm diameter and 3 mm thick). After irradiation, the boron targets were removed from the vacuum chamber and the $^{11}$C activity produced in the (p,n) reaction on $^{11}$B was measured in the coincidence system about 2 h after the laser shot, a safety precaution because of the high activity. The counting rate was determined at time zero and converted to Bq using a calibrated $^{22}$Na source.

In order to determine the thickness of the primary target, which generated the highest activity sources, the $^{11}$C activity generated in the secondary $^{11}$B targets is measured as a function of sample material and thickness. The ratio of the back to front activities is shown in figure 29. This was carried out using the production of the PET isotope $^{11}$C rather than $^{18}$F because of the prohibitive cost of carrying out systematic work using the very expensive separated $^{18}$O isotope as a target. It is clear from figure 29 that very thin targets provide the highest activity sources.
when the total activity produced per laser shot is taken to be the sum of the back and front activities.

Figure 30 summarizes the measurements to date in this research programme into $^{11}$C and $^{18}$F PET isotope production on VULCAN. The red points ($^{11}$C) correspond to a number of different laser irradiances and pulse energies up to 300 J with pulse durations of 750 fs. The single blue triangle point is the activity from the $^{18}$F measurements at the highest laser pulse energy. The hatched area at the top of the graph provides an indication for the level of required $^{18}$F activity (1 GBq) from which an $^{18}$F-FDG patient dose would be generated and also the required $^{11}$C activity of 0.5 GBq, e.g. in the form $[^{11}$C]-Raclopride and $[^{11}$C]-Methiomin.

The results obtained at LOA (Fritzler et al. 2003) are arguably the more important ones to discuss since they represent what can be done using a compact laser, which is more likely to be the laser of choice for hospitals. Using 6 µm foil targets (both plastic and aluminium), a proton spectrum with energies of up to 10 MeV can be generated with the laser intensity of $6 \times 10^{19}$ W cm$^{-2}$ as is shown in figure 31.

The pulse energy on target was approximately 1 J in 40 fs. This spectrum was used to calculate the expected activities of $^{11}$C and $^{18}$F which indicated that activities between 2 and 12 Bq could be generated per shot. Thus, the LOA laser at pulse repetition rates of 1 kHz could generate between 300 and 1300 MBq in 30 minutes. This is sufficient for in-situ production since the typical patient dose is 200 MBq.

The production of the PET isotope $^{13}$N by the $^{12}$C(d, n)$^{13}$N reaction has been reported (Takahashi et al. 2005) using a 2.4 TW 50 fs table top-laser at a maximum intensity of $3 \times 10^{18}$ W cm$^{-2}$ incident on deuterated polystyrene to produce a deuterium beam, which then irradiated a secondary melamine resin target. At these laser intensities the radioactivity produced was only about 1 Bq.
In a very complete analysis of PET isotope production, an extensive numerical simulation has been carried out for laser-accelerated ions (Lefebre et al. 2006). Using numerical models for laser–plasma interaction and ion acceleration including ion transport codes and isotope production cross-sections, isotopic yields from such sources were calculated for various target thickness and laser intensity. Using 36 fs, $4 \times 10^{20} \text{ W cm}^{-2}$ at 1 kHz repetition rate, more than 100 GBq of $^{18}\text{F}$ is expected after an irradiation of 1 h. Such high yields would be sufficient to supply $^{18}\text{F}$ to PET facilities within reach of transport of several hours.

One interesting fact that can be tentatively drawn from a comparison between the activities gained on VULCAN and LOA is the scaling between large and compact lasers at roughly the same laser intensity. For a pulse of about 300 J the $^{11}\text{C}$ activity per shot on Vulcan was a few $10^6$ Bq. At LOA, for a pulse of typically 1 J the activity was about 10 Bq. The ratio of the activities is about $10^5$ with the ratio of the energies being 300. Thus, at roughly the same laser intensity, the activity scales approximately with the square of the pulse energy.

Although very encouraging progress was made in the laser production of PET isotopes in the last few years, a recent paper (Linz 2005) has questioned whether laser production of PET isotopes is ‘merely a modest proof of principle without direct practical applications’. Only time and scientific endeavour will determine whether this view will prevail or not. However, it should be emphasized with respect to the laser versus the conventional accelerator discussion that conventional accelerators have taken about 70 years to reach their present status while laser accelerators have only been a possibility for about 5 years.

4.2.2. Laser-driven electron beams for radiotherapy. Table-top LWFA, proposed theoretically by Tajima and Dawson (1979), have now generated individual electron bunches in the laboratory with considerable numbers of electrons above 10 MeV and the maximum energy reaching tens of MeV at a charge per laser pulse of 0.1 nC. This being so, the attained electron beam properties have stimulated discussions about the possible applications of LWFA to clinical radiation treatment, either directly or after conversion to x-rays. Clinical electron beam
applications require the selection of specific electron energies in the range of 6–25 MeV with a narrow energy spread ($\Delta E < 5$ MeV) for depth control, and a beam expansion to as much as $25 \times 25$ cm$^2$ for various tumour radiation treatments. Two detailed papers were published in 2004 (Chiu et al 2004, Kainz et al 2004), which discussed the feasibility of laser electron accelerators for radiation and in particular determined the dose properties of existing laser systems and their prospects for clinical application.

These authors reached the conclusion that present compact terawatt laser accelerators could produce therapeutic electron beams with acceptable pulse flatness, penetration and fall off depth dose but with pulse energies of typically 1 J, the predicted dose rates fall far short of the necessary clinical levels. Of course at the time of writing these papers, the energy spectra of the electrons were known to be falling off exponentially with energy but tailing off into a power-law distribution at higher energies.

A recent paper (Kinoshita et al 2006) has described the development of a laser-driven plasma cathode for medical applications. The specifications of the laser system were as follows: 11 TW, 38 fs pulse duration at a wavelength of 790 nm, 0.6 J pulse energy and 10 Hz repetition rate with ASE levels of $5 \times 10^{-7}$. The density of the gas jet can reach $1 \times 10^{20}$ cm$^{-3}$. This paper also describes the present status of radiation therapy in Japan and up-to-date medical accelerators are reviewed and compared with the potential of the laser accelerator.

Another recent paper dealing with radiotherapy using laser–plasma accelerators has employed a Monte Carlo simulation of the dose deposited by an experimental quasi-monoenergetic electron beam (Glinec et al 2006). They applied the most recent experimental results from laser–plasma accelerators. A narrow electron beam of $170 \pm 20$ MeV and charge $0.5 \text{nC}$ produced by a laser interacting with a gas jet is simulated. The dose deposition is calculated in a water phantom placed at different distances from the diverging electron source. Using magnetic fields to refocus the electron beam inside the water phantom improves the transverse penumbra. The electron beam is well suited for delivering a high dose on the propagation axis, namely a sharp and narrow transverse penumbra with a deep penetration.

4.2.3. Laser-driven proton and ion beams for hadron therapy. Hadrontherapy is a form of radiotherapy that uses protons, carbon and other heavy ions to irradiate cancerous tumours. The use of protons and carbon ions in radiotherapy has several advantages to the more widely used x-ray radiotherapy. Firstly, the proton beam scattering from the atomic electrons is greatly reduced, and thus, there is less irradiation of healthy tissues in the vicinity of the tumour. Secondly, the well-known Bragg peak for ions, where the energy loss $dE/dx$ increases drastically near the end of its path, can be used to good effect to coincide with the location of the tumour causing the deposition of the largest fraction of energy inside the tumour. The Bragg peak results in very little radiation being deposited after the tumour (spatially) and the oxygen enhancement ratio (OER) as well as the radiation toxicity are also reduced compared with x-ray radiotherapy. Recent advances in radiation therapy have resulted in intensity-modulated particle therapy (IMPT), which is similar in principle to intensity-modulated radiation therapy (IMRT) using x-rays (Bucci et al 2005). Tumour therapy using ion beams from conventional accelerators is a long established procedure and has been extensively reviewed (e.g. Amaldi 1999, Boyer 2002, Chalmers 2003, Jones 2005, Kraft 2000, Wilson 1946).

What is the perspective for the use of laser accelerated ions in hadrontherapy? Over the last few years a number of papers discussing the potential for laser hadron therapy have been published (Bulanov et al 2002a, b, c, d, Fourkal and Ma 2003, Fourkal et al 2003a, b).
These authors point out that proton beams with the required parameters can already be obtained using conventional accelerators of charged particles (synchrotrons, cyclotrons and linacs). However, the use of a laser-based accelerator is attractive for three reasons, it is compact, requires less radiation shielding and a large expensive positioning gantry is no longer required. Very recently, it has been realized that the simultaneous production of imaging beams is easier to achieve with laser technology than with conventional accelerator technology.

A possible way of using a laser accelerator can be envisaged as follows. The laser interacts with a target-generating energetic ions, which irradiate the tumour. Simultaneously produced electrons and energetic photons must be eliminated. The present laser-produced broad energetic ion beams may be used to some advantage since with conventional accelerators, the monoenergetic beams must be broadened to match the size of the tumour, before being used in therapy (spread out Bragg peak, SOBP). It is expected that proton beams with energies up to 250 MeV, which are a few MeV wide will be produced by future lasers with intensities of up to $10^{9}$–$10^{10}$ protons s$^{-1}$.

As has already been reported, in 2000, the University of Strathclyde collaborating with the Rutherford Appleton Laboratory organized the first workshop dealing with the potential of high-power laser technology in medicine. In 2007, the universities of Strathclyde and Paisley organized a follow-up meeting to identify the progress made in laser-driven proton and ion beam technology with applications leading to proton and ion beam therapy for deep-seated tumours. The conclusions and recommendations made by an international panel of experts for the future of laser-driven hadron therapy have been reported (Ledingham et al 2007). At the time of writing, the highest energy of protons generated by high-intensity lasers is still about 60 MeV. Proton therapy for deep-sited tumours requires proton beams of about 200 MeV. There are two compact laser systems presently constructed or nearing completion that conceivably will be capable of generating suitable proton energies assuming energies scale as present theory and experiments predict. Firstly, there is the Astra Gemini laser (Collier et al 2004) with specifications of $2 \times 500$ TW, 15 J, 30 fs focusable to $10^{22}$ W cm$^{-2}$ and 1–2 pulses min$^{-1}$ which became available to users in 2009. Secondly, the all diode pumped, high repetition rate compact laser Polaris (0.1 Hz) at the University of Jena with specifications $10^{21}$ W cm$^{-2}$, 150 J per pulse, 150 fs is about two years to completion (Hein et al 2006).

‘What will it take for laser-driven proton accelerators to be applied to tumor therapy’, has recently been discussed by Linz and Alonso (2007). These authors recognize that after many years of development using conventional accelerators, proton and ion beam therapy is gradually being accepted by clinicians. They acknowledge that the considerable costs involved are used to explain the slow market penetration and possible savings might occur if laser technology is used. Their objective of writing this paper was to discuss the very substantial developments, which they felt were still necessary before laser technology could be successfully applied to ion beam therapy. The necessary improvements facing the laser community are: (i) verifying scaling laws for proton energy with laser power, (ii) improving proton flux by at least an order of magnitude, (iii) improving shot to shot reproducibility to the few percent level, (iv) development of accurate dose control and (v) addressing quality assurance and patient safety. Although everyone who is working actively in the field of laser–plasma accelerators fully realizes the difficulties involved, it is not a bad thing to be subjected to a reality check from scientists working in the clinical field using conventional accelerators.

According to Linz and Alonso (2007), the radiation dose applied to patients in a single 1–3 min session is typically 2 Gy in the volume of 1 litre, which is equivalent to $10^{10}$ s$^{-1}$ or...
\[ \sim 10^{12} \text{protons in total}. \quad 1 \text{Gray} = 1 \text{J kg}^{-1} = 100 \text{rd (rad)} \text{ creating } \sim 2 \times 10^{11} \text{ ion pairs in } 1 \text{ cm}^3 \text{ of } \text{H}_2\text{O (tissue equivalent)}, \text{ and these intensities can be achieved in a single laser pulse. The spot scanning technique in ion therapy requires 200 Hz repetition rate which can be achieved with cyclotrons but not with synchrotrons (Keil et al 2003). Such high repetition rates, are not beyond reach of laser-driven proton or carbon ion accelerators.} \]

Although we are still a long way from generating laser protons for hadron therapy a number of groups are experimenting with low-energy laser proton sources up to a few MeV for biological studies, e.g. the demonstration of DNA double-strand breaking in cancer cells was recently demonstrated (Yogo et al 2009).

4.3. Laser-driven gamma-ray sources for radiography

In 1999, the Livermore group, using the Petawatt laser system at LLNL, published a paper (Perry et al 1999) describing how an intense laser (\( > 10^{21} \text{ W cm}^{-2} \)) could be used to generate hard x-rays, which could offer a new alternative to conventional accelerator bremsstrahlung sources. They argued that these laser-driven sources offered considerable simplicity in design and had the potential for much higher spatial and temporal resolution than had been achieved with accelerator sources. Absolutely calibrated sources extending up to 20 MeV and high-resolution radiographs were obtained.

Another programme of gamma-ray production for radiography was carried out using the VULCAN high-intensity laser at RAL (Edwards et al 2002). Using pulses of 1 ps and 90 J at intensities of about \( 5 \times 10^{19} \text{ W cm}^{-2} \), these authors characterized the gamma-ray source. The spectral and angular distributions of these gamma rays were measured using an array of thermoluminescent detectors for both an underdense gas target and an overdense solid target. It was found that the use of an underdense target in a laser–plasma accelerator configuration produces a much more intense and directional gamma source when the electrons irradiated a tantalum target. The peak dose was also increased significantly. A test object was irradiated namely a lead sphere (12 mm radius) surrounded by a tungsten sphere (35 mm radius). The lead ball was clearly visible inside the sphere.

A recent programme (Glinec et al 2005) using the compact Ti–Sapphire laser at LOA: 30 fs, 1.3 J and intensities of about \( 4 \times 10^{18} \text{ W cm}^{-2} \), irradiated a gas jet to produce energetic electrons, which were then slowed down in a tantalum converter. This was used to irradiate a 2 mm diameter tungsten object with cylindrical symmetry as shown in figure 32. This was the first evidence of achieving submillimetre resolution using a laser-driven electron accelerator.

Ultra short \( \gamma \)-ray sources can be used to measure fast moving objects or high-density compression visualization as well as to detect high \( Z \) materials for security purposes.

4.4. Laser-driven spallation

It has already been shown that laser-induced proton spectra from extended contamination layers on metal targets have normally a very wide energy distribution. McKenna et al (2005) has investigated whether this broad energy spectrum of laser-accelerated protons can be used for spallation-related physics. Using the petawatt arm of the Vulcan laser with pulse energies up to 400 J, a beam of protons was generated from a 10 \( \mu \text{m} \) thick aluminium target with a quasi-exponential shape up to about 50 MeV. This is shown in figure 33.

The laser-generated proton beam closely resembles the expected energy spectrum of evaporative protons (below 50 MeV) produced in GeV-proton-induced spallation reactions.
Figure 32. Radiographic image of a 2 mm diameter tungsten object with cylindrical symmetry, (a) experimental image and (b) computed image. Reproduced by kind permission of the authors and publishers (Glinec et al 2005).

Figure 33. (a) The laser-produced proton spectrum is shown in red. (b) Calculated cross-sections for secondary proton production via spallation evaporation and evaporation plus intranuclear cascade (INC) for different primary incident proton energies.
The protons are used to quantify the distribution of residual radioisotopes produced in a representative spallation target (Pb), and the results are compared with calculated predictions based on spectra modelled with nuclear Monte Carlo codes.

In general, the production of residues in spallation targets is complicated by the range of primary and secondary particles produced in competing spallation processes, and therefore codes are widely relied upon to calculate nuclide production due to specific processes. Low-energy (< 45 MeV) secondary protons are produced in both the INC and in the evaporative process and contribute significantly to residual nuclide production. This work illustrates that high-power laser-based accelerators, producing proton beams with broad energy distributions, can be used to experimentally determine residual nuclide generation arising from specific spallation processes, namely by evaporation rather than through INC. Potentially useful experimental data for the development of codes simulating nuclide production in spallation targets are obtained. Projected developments in laser–particle accelerators will enable these novel particle sources to be used for similar studies of other spallation processes in the future. Recent PIC simulations suggest that by carefully controlling the laser-irradiated target parameters it should be possible to tailor the shape of the energy spectrum of accelerated protons (Esirkepov et al 2002). Therefore, the low-energy evaporative part could be subtracted from the spectrum obtained in GeV interactions, which proceed mainly through INC processes. Furthermore, as focused laser intensities increase to between $10^{22}–10^{23}$ W cm$^{-2}$, protons with upper energies in the range 250 MeV–1 GeV are expected to be produced, facilitating laser-driven investigations of proton-induced fission and other intermediate and high-energy spallation processes.

4.5. Laser-driven photonuclear cross-section measurements

In an earlier paper (Stoyer et al 2001), it was pointed out that if ultraintense laser performance were more reproducible, better estimates of $(\gamma, n)$ and $(\gamma, p)$ integral cross-sections measurements would become possible. After 2001 the stability of lasers, particularly of the compact table-top variety, has become sufficiently reliable so that integral nuclear cross-sections can now be measured with confidence.

The first integral $(\gamma, n)$ cross-sections measurements employing laser-generated particles were carried out in 2003 and 2004 (Ledingham et al 2003, Liesfeld et al 2004). Both measurements focused on the $(\gamma, n)$ cross-section for $^{129}$I, which is an important isotope in transmutation studies.

The first experiment being published was carried out on the VULCAN laser at RAL (Ledingham et al 2003). The experimental arrangement has already been described earlier. Comparison of the yields from the $^{129}$I$(\gamma, n)^{128}$I and $^{127}$I$(\gamma, n)^{126}$I reactions produced in the same iodine sample determined the ratio of the integrated cross-sections for the two reactions. At a given gamma intensity $\Phi$, the number of nuclei $N_{128}$ of $^{128}$I and $N_{126}$ of $^{126}$I produced are given by: $N_{128} = \sigma_{129} \Phi N_{129}$ and $N_{126} = \sigma_{127} \Phi N_{127}$, where $N_{127} (= 3.5 \times 10^{22})$ and $N_{129} (= 1.8 \times 10^{23})$ are the initial number of nuclei of $^{127}$I and $^{129}$I, respectively, in the sample, and $\sigma_{129}$ and $\sigma_{127}$ are the cross-sections for the $^{129}$I$(\gamma, n)^{128}$I and $^{127}$I$(\gamma, n)^{126}$I reactions, respectively. Assuming the $Q$-value and width of the GDR, which dominates the cross-sections are similar, the ratio of the integrated cross-sections can be written as

$$\frac{\sigma_{\text{int}}^{129I}}{\sigma_{\text{int}}^{127I}} = \frac{N_{128}}{N_{126}} \frac{N_{127}}{N_{129}}.$$
The integrated cross-section for $^{127}$I($\gamma$, n)$^{126}$I is known, 309 mbarn, (http:IAEAND 2004) and the value for the $^{129}$I($\gamma$, n)$^{128}$I reaction was determined using four measured spectra to be $97 \pm 40$ mbarn. This is in good agreement with the theoretical cross-section given in the literature as 110 mbarn. The main uncertainty in the determined integral cross-section resides in the measured gamma-peak areas.

The $^{129}$I($\gamma$, n)$^{128}$I cross-section measurement was also carried out on the compact laser at the University of Jena (Liesfeld et al 2004) using the same $^{129}$I samples. The experimental arrangement has also been described earlier in sections 4.1. The cross-section was measured to be $250 \pm 100$ mbarn in fair agreement with the RAL measurement. The latter value was obtained using derived quantities from stable $^{127}$I and a theoretical equation for the GDR cross-section.

It thus became clear that a detailed programme of photonuclear cross-section measurements is best carried out on compact table-top lasers. To this end a number of photonuclear reactions were investigated using the high-power table-top laser at the University of Jena (Spohr et al 2008). The Jena JETI laser ($I \sim 5 \times 10^{19}$ W cm$^{-2}$) produced hard bremsstrahlung photons ($kT \sim 2.9$ MeV) via a laser–gas interaction, which served to induce ($\gamma$, p) and ($\gamma$, n) reactions in Mg-, Ti-, Zn- and Mo-isotopes. Several ($\gamma$, p) and ($\gamma$, n) decay channels were identified using nuclear activation techniques to determine their integral reaction yields. As the laser-generated bremsstrahlung spectra stretches over the energy regime dominated by the GDR, these yield measurements were used in conjunction with theoretical estimates of the resonance energies and their widths to derive the integral reaction cross-section $\sigma^{\text{int}}(\gamma, p)$ for $^{25}$Mg, $^{48,49}$Ti, $^{68}$Zn and $^{97,98}$Mo isotopes for the first time. This study enabled the determination of the previously unknown $\sigma^{\text{int}}(\gamma, n)/\sigma^{\text{int}}(\gamma, p)$ cross-section ratio of neutron to proton production for these isotopes. The experiments were supported by extensive statistical model calculations using a Monte Carlo code (Herman et al 2005, and the results were compared with the Thomas–Reiche–Kuhn (TRK) dipole sum-rule (Thomas 1925) as well as to experimental data in neighbouring isotopes, and a good overall agreement was observed. It was found that the Coulomb barrier and the neutron excess strongly influence the $\sigma^{\text{int}}(\gamma, n)/\sigma^{\text{int}}(\gamma, p)$ ratios for increasing target proton and neutron number.

A summary of published $\sigma^{\text{int}}(\gamma, n)/\sigma^{\text{int}}(\gamma, p)$ ratios as retrieved from the Atlas of Giant Dipole Resonances compiled by Valaramov et al (2000) and the six new ratios provided by this work (Spohr et al 2008) is shown in the figure 34. The x-abscissa is the Coulomb barrier for proton emission. The $\gamma$-coordinate represents the isospin projection $T_z$. The additional abscissa in the background showing the target atomic number $Z$ is to guide the eye. The colour code was chosen to pronounce the high ratio values among the 37 displayed isotopes. The three highest values for the neutron-rich nuclei $^{124}$Sn, $^{184}$W and $^{201}$Hg are suppressed by 1/8.

In explosive stellar events like supernovae, the temperatures are high enough for the production of heavy neutron-deficient nuclei, the so-called p-nuclei. Until now, the knowledge of the reaction rates of p-nuclei is based on theoretical parameterizations using statistical model calculations.

At the bremsstrahlung facility of the superconducting electron accelerator ELBE of FZ Dresden–Rossendorf, the photodisintegration rates of heavy nuclei have been measured experimentally. Photoactivation measurements on the astrophysically relevant p-nuclei $^{92}$Mo and $^{144}$Sm have been performed with bremsstrahlung end-point energies from 10 to 16.5 MeV (Nair et al 2008). In the near future further ($\gamma$, p) cross-sections will be measured in this sensitive region, which is bypassed by the more quiescent stellar neutron capture, and conventional electron linac-produced bremsstrahlung spectra will be used and compared with high-intensity laser-produced bremsstrahlung spectra.
5. Laser-driven beams in nuclear and particle physics—future directions

5.1. Future high-intensity lasers

At the time of writing, the highest laser intensity (published) in the world used the upgraded Hercules laser with 300 TW, 0.1 Hz repetition rate and 30 fs pulse width. By using adaptive optics and an f/1 parabola providing a 1.3 μm focal spot, an intensity of \(2 \times 10^{22} \text{ W cm}^{-2}\) was reached. This can be increased to \(5 \times 10^{22} \text{ W cm}^{-2}\) when an f/0.6 parabola is employed (Yanovsky et al. 2008). Similarly a 300 TW laser SILEX-I Ti:Sapphire laser system is operational in Miangyang, China and has the potential to operate at 500 TW and intensities of \(10^{22} \text{ W cm}^{-2}\) (Zhu et al. 2007). An exciting new laser system coming on song in 2009 at the University of Rochester is the OMEGA EP (extended performance). This is an addition to OMEGA and extends the performance and capabilities of the OMEGA laser system. It will provide pulses having multikilojoule energies, picosecond pulse widths, petawatt powers and ultrahigh intensities exceeding \(10^{20} \text{ W cm}^{-2}\).

The two new laser systems particularly suitable for proton oncology have already been described: Gemini at the Rutherford Appleton Laboratory and Polaris at the University of Jena. There are a number of other high-intensity laser systems at the planning stage and these shall now be described in detail.

Firstly, it is intended to upgrade the Vulcan petawatt laser system from 1 to 10 PW. This upgrade is shown in figure 35 and could lead to ion acceleration energies of almost 1 GeV, which will be described in the following section. The development will include a high-energy OPCPA system resulting in laser pulses of 300 J in 30 fs, i.e. 10 PW capable of providing pulses, which can be focused to an intensity of \(10^{23} \text{ W cm}^{-2}\).
There are two very powerful lasers, which will be nearing completion in a few years (2010–2012): the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory in California followed a few years later by the laser MegaJoule (LMJ) in France. Both aim to ignite a fusion reaction that turns a tiny pellet of hydrogen at the lasers’ focus into helium. Science at NIF will bring astrophysics into the laboratory by mimicking stars in a microcosm, and it might also potentially provide the basis for future inertia-driven fusion energy generation. However, the main rationale for NIF, and the reason it has been able to command the huge budget that it has, is to help the United States assure the operability and safety of its nuclear arsenal. Similar motivations lie behind the French LMJ facility. Both of these lasers are motivated by military concerns and will not be considered further here.

Although not involved in the military aspects of fusion research, the FIREX project in Japan has been designed to investigate fast ignition fusion up to the ignition temperature of 10 keV (Azechi 2006). It is expected that the FIREX-II facility will fulfil this prospect and be operational by 2011.

There are, however, two exciting civilian European projects at the planning stage, which could be completed by about 2015. In 2006, both of these projects were short listed for consideration under the European Roadmap for Research Infrastructures, a programme that provides money to help develop proposals for international projects.

In alphabetical order, the extreme light infrastructure (ELI) project (Gerstner 2007) will be described first. In the words of the authors led by Gerard Mourou of the Laboratory of Applied Optics near Paris, ELI would be the first infrastructure dedicated to the fundamental study of laser–matter interaction in a new and unsurpassed regime of laser intensity: the ultrarelativistic regime $> 10^{23}$ W cm$^{-2}$ with the possibility of reaching $10^{25}$ W cm$^{-2}$. At its centre would be an exawatt-class laser ~400 times more powerful than either the LMJ in France or the NIF in the US. In contrast to the former projects, ELI would attain its very high-power from the extreme shortness of its pulses (femtosecond and attosecond). In early 2007 the French government
announced that it would provide enough funding to allow a single 25 PW laser beam line (ILE) to be built at the Laboratoire d’Optique Appliquee in Paris. It is expected that ILE will be completed by 2011. This would be the essential forerunner for the 10 times more powerful upgrade to ELI specifications. The project would envisage the coherent combination of 10 ILE single beam lines to provide a 200 PW laser (0.2 EW) with a proposed pulse repetition rate of 1 shot min\(^{-1}\) and an implementation phase to be completed by 2014.

It was realized very early on in this preparatory phase that to be funded the science programme at this facility must be internationally leading. ELI is considered to be an outstanding tool for a number of different projects. Firstly, it will be able to provide femtosecond sources of particles with up to TeV electron bunches as well as very bright sources of x- and \(\gamma\)-rays. These intrinsically synchronized particle and photon beams are ultrashort and will offer unique possibilities for pump–probe studies in matter. Secondly, relativistic compression will offer the opportunity to exceed intensities of 10\(^{25}\) W cm\(^{-2}\), which would challenge the vacuum critical field. Although ELI is a long way from producing intensities of the order of 10\(^{29}\) W cm\(^{-2}\), the so-called ‘Schwinger’ limit (Schwinger 1951) where particles can be created from the vacuum, the experience gained on ELI at lower intensities is essential for carrying out the very difficult experiments close to the Schwinger limit. Finally, x-rays emitted by synchrotrons have been widely used in Biology, Chemistry and Physics for exciting and probing a large diversity of samples. Although these accelerators remain of great importance for users, new light sources such as ELI offer a completely new approach by shortening the pulse duration by a factor of about 10\(^5\) and by increasing the photon flux by nne orders of magnitude one gains access to attosecond/zeptosecond studies of the laser–matter interaction.

A second and much more costly proposal is high-power experimental research facility (HiPER). The HiPER project is a consortium of seven European countries at the national level (Czech Republic, France, Greece, Italy, Portugal, Spain, with the UK taking the coordinating role), two regional governments (Madrid and Aquitaine), industry, plus scientists from four other countries (Poland, Germany, Russia and USA) and international links to Japan, South Korea, China and Canada. This is a civilian equivalent to NIF and LMJ but using a subtly different path to fusion. Whereas NIF and LMJ use megajoule beams to reach fusion, HiPER would compress the fusion pellets much more gently with multiple long laser pulses but finally ignite fusion with an ultrashort intense laser pulse, a procedure, which is called fast ignition and which was first proposed by Tabak (1994). Other important references (Atzeni et al 2007, Dunne 2006, Honrubia and Meyer-ter-Vehn 2006) describe the HiPER facility and the physics involved in the fast-ignition approach.

In greater detail, HiPER aims to build upon the anticipated achievement of laser fusion energy gain on the US NIF. This event, anticipated in the period 2010–2012, will mark the culmination of roughly 50 years research. It will provide the scientific proof of principle to inspire focused programmes in both energy exploitation and the science under extreme conditions.

HiPER will make use of laser technology in a unique configuration, allowing fusion fuel to be compressed and then ignited to induce a propagating burn wave yielding energy gains of order 100 at a significantly increased efficiency and rate of production. As was indicated above this approach is made feasible by the advent of a revolutionary approach to laser-driven fusion known as fast ignition. The laser itself will deliver 200 kJ in a multinanosecond pulse to compress a deuterium–tritium pellet of fuel, combined with roughly 100 kJ in a multipicosecond pulse to ignite the compressed fuel. High repetition rate laser technology is being assessed,
combined with advanced target manufacture and handling techniques. One advantage of this approach argues Mike Dunne, of the Central Laser Facility, is that the laser can be fired much more frequently than by NIF or Megajoule.

HiPER has just completed a two-year conceptual design phase. It entered a three-year ‘preparatory phase’ project in 2008, with construction envisaged for the latter half of next decade. The facility will be the culmination of a strategic alliance of laser capabilities across Europe, for which the intermediate step, PETAL, is currently under construction near Bordeaux. An artist’s impression of the HiPER facility is shown in figure 36. HiPER will provide unprecedented tools for the creation and quantitative diagnosis of high-energy, high-density matter. The principal science areas range from: laboratory astrophysics to fundamental atomic physics; the unexplained field of warm dense matter; transient non-equilibrium nuclear physics; relativistic particle beam creation and application; turbulence; the physics of matter at extremes of temperature, density and pressure, or under extreme magnetic or electric fields; and systems whose behaviour is dominated by radiation or burn physics.

With many pulses at its disposal and freed from the demands of weapons research, HiPER could offer scientists far greater scope for non fusion research. Similar to ELI, HiPER could reach exawatt powers and focused intensities of $10^{25}$ W cm$^{-2}$.

The energy mission is aimed at establishing the case for the exploitation of laser-driven fusion. HiPER will illustrate the route to viable power generation by addressing the key research and development challenges—both scientifically and technologically. Governments throughout the world demand multiple energy solutions as a risk-balanced strategy for energy supply, with fusion possibly able to offer the ‘holy grail’ of energy sources—limitless fuel with no carbon or unmanageable radioactive by-products, energy security and a scale able to meet the long-term demand.

Another and much larger fusion project based on the Tokamak principle is the International thermonuclear experimental reactor (ITER) to be built at Cadarache in southern France.
5.2. Future ion experiments at laser intensities > $10^{21}$ W cm$^{-2}$

At present, high-power lasers have only reached intensities of about $10^{21}$ W cm$^{-2}$ and although electrons have been accelerated to energies above 1 GeV (Leemans 2006), relativistic ion energies are still far from being realized. Thus, the relativistic regime of the acceleration of particles heavier than electrons, which will now be discussed is purely theoretical.

In the proposed double-layer target, hydrogen is deposited on the surface of a high $Z$ substrate, and for the generation of high-quality laser-accelerated ion beams (Esirkepov et al 2002), the authors suggested that at $\alpha = 30$ (laser intensity of $\sim 1.2 \times 10^{21}$ W cm$^{-2}$ for $\lambda = 1 \mu m$) the proton energy would be monochromatic reaching about 60 MeV, being well separated from low-energy heavy ions, with a spectrum as shown in figure 37.

Remarkably, the low-energy protons that often dominate the proton yields are expected to be absent in this target design. It is thus entirely conceivable that this ion spectrum could be experimentally verified when Astra Gemini becomes operational in 2009. Although this energy is not sufficient for ion treatment of deep-sited tumours, it is sufficient for eye tumour treatment.

Much theoretical work has recently been carried out in the laser piston or radiation dominant regime, which for 800 nm lasers occurs at $10^{21-22}$ W cm$^{-2}$ (Bulanov 2004, Esirkepov 2004). This is a regime where laser-driven ions reach highly efficient relativistic energies and it has been predicted that a new epoch in charged particle acceleration will result (Bulanov 2006, Pegaro and Bulanov 2007). In this radiation pressure dominant regime, the ion acceleration is due to the radiation pressure of the light field on the electron component with the momentum being transferred to the ions through the electric field arising from charge separation. Apparently, the protons are predicted to move in the laser direction with the same velocity as the electron bunch and hence with a kinetic energy much greater than that of the electrons.

Also in this regime, the proton energy is proportional to the laser pulse energy. Using multiparametric PIC simulations, laser ion-acceleration scaling laws have been

---

Figure 37. A monoenergetic proton peak with a continuous distribution of heavy ions from the high $Z$ substrate, when a double-layer target is irradiated by a laser beam of intensity about $10^{21}$ W cm$^{-2}$ (Esirkepov et al 2002).
determined (Esirkepov et al 2006). These laws show how the maximum proton energies scale with pulse energy and power for optimal target thickness. With this scaling, laser-driven ion acceleration up to 200–300 MeV can be obtained with a petawatt laser of subpicosecond pulse duration. At laser intensities of $10^{22}$ W cm$^{-2}$, proton energies may reach several hundreds of MeV. This is shown in figure 38. It should be emphasized that these proton energies have some way to go to be confirmed experimentally.

Such experimental conditions are likely to be realized by exawatt lasers (Mourou et al 2006, Tajima and Mourou 2002), which are presently being designed and were described in sections 5.1.

5.3. Laser Wakefield Accelerators (LWAs)

In a conventional accelerator, the accelerating RF field is limited by field breakdown at which electrons are removed from the surrounding metal structures. However, the plasma is already broken down and hence can support much greater electric field strength than conventional accelerators by at least a factor of 1000. In principle, what a conventional particle accelerator needs kilometres to achieve, a compact PWFA has mastered in less than a metre (Bingham 2007).

The present energy frontier of high-energy physics is several TeV but colliders capable of reaching this regime (such as the Large Hadron Collider (LHC), and the International Linear Collider (ILC)) are costly and time-consuming to build. It is therefore important to explore new methods of accelerating particles to high energies. Plasma-based accelerators are particularly attractive because they are capable of producing accelerating fields that are orders of magnitude larger. In these novel accelerators, a drive beam (either laser or particle) produces a plasma wave (wakefield) that accelerates the charged particles. The ultimate utility of plasma accelerators will depend on sustaining ultrahigh accelerating fields over a substantial length in order to attain a significant energy gain. Recently, it has been shown that an energy gain of more than 42 GeV is
Figure 39. Energy spectrum of electrons observed in the 30–100 GeV range. Some of the electrons from the primary 42 GeV SLAC beam have been accelerated to 85 GeV in 1 m of plasma. Reproduced by kind permission of the authors and publishers (Blumenfeld et al. 2007).

achieved in a PWFA of 85 cm length. Driven by a 42 GeV electron beam at the Stanford Linear Accelerator Center (Blumenfeld et al. 2007), the resulting final energy is ∼85 GeV.

The results are in excellent agreement with the predictions of 3D PIC simulations. Most of the beam electrons lose energy to the plasma wave, but some electrons in the back of the same beam pulse are accelerated with a field of ∼52 GV m\(^{-1}\). This effectively doubles their energy, producing the energy gain of the 3 km long SLAC accelerator in less than a metre for a small fraction of the electrons in the injected bunch. Although the energy spectrum at about 85 GeV (figure 39) is far from a monoenergetic peak this is an important first step towards demonstrating the viability of plasma accelerators for high-energy physics applications.

The SLAC laser–plasma accelerator is of course a very large installation but one of the most important applications of this technology is likely to be the development of compact laser–plasma accelerators. Malka and his group (Malka et al. 2008) have recently reviewed the potential of laser-driven particle beams and have discussed the possibilities of using this technology to proton therapy and the detection of explosives and other environmentally hazardous materials.

6. Conclusions

Although high-power lasers have been now in operation around the world for about 25 years, their application to particle and photon beam production with possible applications to nuclear
and particle physics, the subject of this paper, has only taken place in the last 10 years. In scientific terms, this is a very short time indeed and so, as has been said elsewhere in this document, there is still much to do. This section will be written in the first person active to indicate that this is very much the opinion of the two authors of this paper but we know after many detailed discussions with colleagues that these views are widely held in our community although not necessarily with the same emphasis shown here.

We shall now attempt to draw together what has been achieved over the last 10 years and hopefully try to draw some conclusions as to where the field is heading. It has already been described that more than 15 PW lasers already exist or will soon be operative around the world. There exists probably twice that number of high-power, compact, high repetition rate lasers in the power range of a few TW to 200 TW. In section 5, we have described that multipetawatt and even exawatt lasers are being planned for completion in the next 10 years. The cost of these proposals are very high and probably will only be funded if the science carried out at these installations is sufficiently robust and imaginative and of an importance on a level equivalent to the discovery of the Higgs particle or gravitons at LHC in Geneva. Of course, the huge installations already reaching completion such as NIF and Megajoule are driven by military considerations and will continue over the next many years come what may. Further descriptions of future lasers will be resisted here because that is not the principal object of writing this paper. Suffice it to say that ‘proof of concept’ experiments will continue to be carried out using the high pulse energy, essentially single pulse lasers like VULCAN. On the other hand, the careful, quantitative experiments necessary to move our field forward will be largely carried out using the high repetition, compact lasers. However, it must be emphasized that the laser pulse power alone is not sufficient to reach exciting new areas of laser-driven nuclear and particle physics: there must be enough energy in the laser pulses and a focus on lasers dedicated for applications of this technology useful to society.

So where are we now? Firstly, we have described that laser-driven monoenergetic electron beams have reached GeV energies (Leemans et al 2006) although not necessarily with the shot-to-shot reproducibility that would excite particle physicists. However, this has already started to being addressed by operating counter-propagating laser beams (Faure et al 2006). Much of this work is being driven by the desire to generate high-energy electron bunches, which can be injected into undulators to generate x-ray pulses (Nakajima 2008, Schlenvoight 2008). As the lasers increase in power the energy of these electron beams will continue to increase to the multi GeV levels. To be of great interest to particle physicists, particularly those engaged in detector development, the electron numbers in the pulses need not be greater than pC and this has already been achieved. However, the pulses need to be reproducible in energy and generated from as compact a source as possible.

Ion production has not reached the stage of development that has been attained for electrons. The highest energy of laser-driven proton beams is still about 60 MeV (Snavely 2000) from large single-pulse lasers and over the last few years this maximum energy has not increased markedly. Indeed, this maximum is the upper limit of proton energy spectra with a thermal distribution and hence the proton yields at these high energies are still small. Thermal spectra from compact lasers have only reached levels of about 10 MeV (Fritzler 2003) while quasi-monoenergetic proton spectra using structured targets is only at the 1–2 MeV level. There is much eager anticipation that proton spectra could reach and surpass the 100 MeV level (Esirkepov et al 2002) when Gemini at RAL becomes operational in 2009 with a possible laser intensity of $10^{21–22}$ W cm$^{-2}$. This of course becomes potentially of great excitement to
those interested in proton oncology. The question of course of how to make the beams highly monoenergetic is still unresolved but a number of groups world wide are investigating the use of RF cavities (Noda et al 2006) and magnetic spectrometers extensively employed in conventional nuclear and particle technology exactly for this purpose (Chen et al 2008, Eichner et al 2007, Schollmeier et al 2008). Of course to permit the steering, detection and diagnostics of protons at energies of 200 MeV need the development of compact technology way beyond that currently in use with high-power lasers. It is, however, essential that the development of such technology goes hand-in-hand with laser development to deliver on applications. This has long been realized in the nuclear and particle community where costs and effort to deliver scientific output is put on an equal footing to the development of accelerators.

A prerequisite for the laser production of heavier ion beams is the elimination of parasitic proton beams produced by contamination layers of hydrocarbons and water vapour on the surfaces of the presently used targetry. This can of course be carried out using heated or laser-irradiated targets but probably it is also essential to improve the vacuum pressures presently being used in the target vessels (10\(^{-7}\) bar) by some orders of magnitude.

Laser-induced neutron production is still at an early stage of development but does hold a real potential in radiation-damaging studies. At present, the neutron flux from existing large single-pulse laser with pulse energies of several hundred joules per pulse yield numbers of about 10\(^9\) neutrons per pulse from (p, n) reactions. With table top lasers and pulse energies of close to a joule, the neutron numbers are reduced to about 100 per pulse using similar nuclear reactions and 80 fs pulse energies. Although it is very difficult to determine accurate scaling laws between large and compact laser because of their very different pulse lengths, it is probably reasonable to assume that at similar pulse powers there is a pulse energy (E) dependence for neutron numbers of about E\(^2\). Potentially for higher power lasers in the future, as we have already described, there exists a target design for t-d fusion reactions where under optimal conditions, a neutron flux in the range 10\(^{14}\)–10\(^{15}\) neutrons cm\(^{-2}\) s\(^{-1}\) may be achieved with 100 J laser pulse energy operating at 100 Hz (Perkins et al 2000). At these neutron intensities, radiation-damaging studies can be carried out on both material and biological samples. If this can be coupled to laser-induced x-ray production then time-resolved pump–probe experiments to identify the speed of mending of radiation-induced dislocations can be carried out.

Laser production of short-lived radioactive sources is at present very different for single-pulse lasers with pulse energies of hundreds of joules compared with compact laser with pulse energies of a few joules. Activities of up to about 10\(^7\) Bq per pulse (Ledingham 2004) can be generated using large lasers like VULCAN compared with about 10\(^2\) Bq per pulse from compact table top lasers at similar pulse powers. This of course can be increased considerably when using compact lasers by integrating the activity over thousands of pulses. It is by no means sure how isotope production will scale with laser power when higher powers lasers are used. Certainly, as the laser powers are increased the electron, photon and proton/ion energies will increase but the most important thing for isotope production is the number of particles close to the maximum of the nuclear dipole resonance cross section between 8–20 MeV.

The lessons to be learned from conventional instrumentation for laser science are that initial breakthroughs in novel concepts must be followed up by painstakingly dedicated efforts to render this novel technology suitable for useful applications. This should include the development of novel laser-driven particle accelerators as well as diagnostics and suitable detectors for laser-driven particle beams with 10\(^9\)–10\(^{12}\) particles in a 1 ps pulse at 1–200 Hz repetition rate.
Laser-driven accelerators need to be tailored and dedicated to specific applications (e.g. proton oncology), and the establishment of pilot facilities aiming at such specific applications, e.g. clinical medicine should be given priority. Repetition rates of up to 200 Hz are normally required for ion therapy using the spot-scanning technique (Smith 2006) but lower repetition rates of 1–10 Hz are also useful for therapy.

In an article in the Cern Courier, Joshi (2007), has argued that the several 100 TW laser facilities in Europe, the USA and Asia should advance LWFAs to provide GeV electron beams. However, to go beyond this, a high repetition rate 10 PW laser is needed to demonstrate a 100 GeV prototype facility of a laser-driven plasma accelerator. He also describes that 40 groups worldwide are working in the field of plasma-based acceleration. This provides a critical mass of trained scientists and students who are attracted to the field because it offers many chances to make unexpected discoveries. It is clear that many scientists are interested in developing laser-driven plasma–wave electron accelerators and this has recently been reviewed by Leeman and Esaray (2009). It has also been argued that present huge conventional accelerators like LHC do not have to get bigger if the promise of laser–plasma accelerators is realized (Mullins 2009). The time is now ripe to invest in appropriate facilities to take this field to the next level. Finally, although plasma physics will undoubtedly be advanced, this investment could also be a critical factor that makes the difference to the future of high-energy physics in the 21st century.

Finally, Gies (2009) has recently written a review article dealing with strong laser fields as a probe for fundamental physics. In particular, he maintians that the long-standing prediction of quantum-induced nonlinear self-interactions of macroscopic magnetic fields by Heisenberg and Euler (1936) has yet to be verified experimentally and high-intensity laser systems is a possible way forward. Gies also suggests that the ultra strong EM fields generated by lasers can search for new light but weakly interacting particles such as axion-like particles (ALPs) or minicharged particles (MCPs). He performs the first estimates of the accessible new-physics parameter space for the proposed new laser systems such as 10 PW upgraded VULCAN, HiPER and ELI.

Acknowledgments

We take great pleasure in acknowledging considerable help from many different people around the world and in many different laboratories during the writing of this paper. We thank Tom Cowan, Roger Dale, Mike Dunne, Stefan Frauendorf, Charlie Ma, Joe Magill, Victor Malka, Gerard Mouro, Wilfried Pilloy, Markus Roth, Ulrich Schramm, Heinrich Schwoerer, Hideaki Takabe and Roland Sauerbrey.

In particular, KWDL thanks Roland Sauerbrey who invited him to the Rossendorf Centre as an FZD fellow in 2007 and visiting scientist in 2009 where much of this paper was conceived and written. The freedom to complete this Herculean task is much appreciated.

References

Allen M et al 2003 Phys. Plasmas 10 3283
Amaldi U 1999 Nucl. Phys. A 654 375C

Andreev A V, Gordienko V M and Savel’ev A B 2001 Quantum Electron. 31 941
Arutyunyan R V et al 1991a Yad. Fiz. 53 36
Atzeni S, Schiava A and Bellei C 2007 Phys. Plasmas 14 052702
Badziak J 2007 Optoelectron. Rev. 15 1
Beg F N et al 1997 Phys. Plasmas 4 447
Bingham R 2006 Phil. Trans. R. Soc. A 364 559
Bingham R 2007 Nature 445 721
Blumenfeld I et al 2007 Nature 445 741
Borghesi M et al 2006 Fusion Sci. Technol. 49 412
Boyer A L et al 2002 Phys. Today 55 34
Brandl F et al 2003 Europhys. Lett. 61 632
Bulanov S V et al 2002c Med. Phys. 1 50
Carroll J J et al 2001 Hyperfine Interact. 135 3
Chen H et al 2009 Phys. Rev. Lett. 102 105001
Chiu C et al 2004 Med. Phys. 31 2042
Chalmers M 2003 Physics World 16 32
Clark E L et al 2000a Phys. Rev. Lett. 84 670
Clarke R J et al 2006b Appl. Phys. Lett. 89 141117
Cowan T E et al 2000a Phys. Rev. Lett. 84 903
Danson C N et al 2004 Nucl. Fusion 44 S239
d’Humieres E et al 2005 Phys. Plasmas 12 062704
Ditmire T et al 1999 Nature 398 489
Dunne M 2006 Science 312 374
Faure J et al 2004 Nature 431 541
Faure J et al 2006 Nature 444 737
Fermi E 1949 Phys. Rev. 75 1169
Flippo K A et al 2008 Phys. Plasmas 15 056709
Fourkal E and Ma C-M 2003 Med. Phys. 30 1448
Fourkal E et al 2003a Med. Phys. 30 1660
Fourkal E, Velchev I and Ma C-M 2005 Phys. Rev. E 71 036412
Frauenstock S 2008 private communication
Fritzler S et al 2003 Appl. Phys. Lett. 83 3039
Fuchs J et al 2006 Nat. Phys. 2 48
Fuchs J et al 2007 Phys. Plasmas 14 053105
Gahn C et al 1998 Appl. Phys. Lett. 73 3662
Gahn C et al 2000 Appl. Phys. Lett. 77 2662
Gahn C et al 2002 Phys. Plasmas 9 987
Geddes C G R et al 2004 Nature 431 538
Geissler M et al 2006 New J. Phys. 8 186
Germillet L, Bonnau G and Amiranoff F 2002 Phys. Plasmas 9 941
Gerstner E 2007 Nature 446 16
Glinec Y et al 2006 Med. Phys. 33 155

Habs D et al 2001 Prog. Part. Nucl. Phys. 46 375
Hegelich M et al 2006 Nature 439 441
Henn J 2006 Lecture Notes in Physics vol 694 (Berlin: Springer)
Hora H et al 2000 Laser Part. Beams 18 135
IAEND 2004 EXFOR nuclear reaction database http://IAEAND.IAEA.OR.AT/exfor
Johnston H 2006 Physicweb 21st November
Jones B 2005 Br. J. Radiol. 78 1
Kainz K K et al 2004 Med. Phys. 31 2053
Karsch S et al 1999 Laser Part. Beams 17 565
Katsouleas T 2004 Nature 431 515
Kinosita K et al 2006 Laser Phys. 16 660
Kishimoto Y et al 1983 Phys. Fluids 26 2308
Kishinou H et al 2004 Appl. Phys. Lett. 85 2736
Krushelnick K et al 1999 Phys. Rev. Lett. 83 737
Lanatser K L et al 2004 Phys. Plasmas 11 3404
Lawrence E O and Edelfsen N E 1930 Science 72 376
Lawrence E O and Livingstone M S 1931 Phys. Rev. 37 1707
Ledingham K W D and Norreys P A 1999 Contemp. Phys. 40 367
Ledingham K W D, Singhal R P, McKenna P and Spencer I 2002 Europhys. News 33 120
Ledingham K W D, McKenna P and Singhal R P 2003 Science 300 1107
Ledingham K W D 2006 Hyperf. Interact. 171 69
Ledingham K W D, Galster W and Sauerbrey R 2007 Br. J. Radiol. 80 855
Leemans W P et al 2001 Phys. Plasmas 8 2510
Leemans W P et al 2006 Nat. Phys. 2 696

Leemans W P and Esaray E 2009 *Phys. Today* March 44
Lefebre E et al 2006 *J. Appl. Phys.* 100 113308
Macchi A 2006 *Appl. Phys.* B 82 337
Madison K W et al 2004 *Phys. Plasmas* 11 270
Magill J et al 2003a *Nucl. Energy* 42 263
Malka G and Miquel J L 1996 *Phys. Rev. Lett.* 77 75
Malka G et al 2002 *Phys. Rev. E* 66 066402
Malka V et al 2008 *Nat. Phys.* 4 447
Matsukado K et al 2003 *Phys. Rev. Lett.* 91 215001
Maxwell J C 1873 *A Treatise on Electricity and Magnetism* (Oxford: Clarendon)
McKenna P et al 2003a *Phys. Rev. Lett.* 91 075006
McKenna P et al 2004 *Phys. Rev. E* 70 036405
McKenna P et al 2007a *Plasma Phys. Control. Fusion* 49 1
McMillan E M 1950 *Phys. Rev.* 79 498
Melone J 2009 private communication
Menzel D H and Salisbury W W 1948 *Nucleonics* 2 67
Mora P 2003 *Phys. Rev. Lett.* 90 185002
Mori Y 2003 *Proc. 17th Int. Conf. on Cyclotrons and Applications* vols 1–5 pp 3413–5
Morita M 1973 *Prog. Theor. Phys.* 49 1574
Mullins J 2009 *New Sci.* January 28
Nakajima K 2008 *Nat. Phys.* 4 92
Nemoto K et al 2001 *Appl. Phys. Lett.* 78 595
Noda A et al 2006 *Laser Phys.* 16 647
Norreys P A et al 1999 *Phys. Plasmas* 6 2150

Oishi Y et al 2005 Phys. Plasmas 12 073102
Otozai K et al 1973 Prog. Theor. Phys. 50 1771
Panofsky W K H and Breidenbach M 1999 Rev. Mod. Phys. 71 S121
Passoni M and Lontano M 2004 Laser Part. Beams 22 163
Passoni M et al 2004 Phys. Rev. E 69 02641
Perkins L J et al 2000 Nucl. Fusion 40 1
Pukhov A and Meyer-ter-Vehn J 1999 Laser Part. Beams 17 571
Pukhov A 2001 Phys. Rev. Lett. 86 3562
Reed S A et al 2006 Appl. Phys. Lett. 89 231107
Reiss H R 1985 Phys. Rev. C 31 2238
Reiss H R 2008 Europhys. Lett. 81 42001
Robson L et al 2007 Nat. Phys. 3 58
Ross I N 1999 Laser Part. Beams 17 331
Roth M et al 2005 Laser Part. Beams 23 95
Rubbia C A 2001 European Roadmap for Developing Accelerator Driven Systems for Nuclear Waste Incineration
ENEKA Report (Rome: ENEA)
Santala M I K et al 2001 Appl. Phys. Lett. 78 19
Schlenvoight H-P et al 2008 Nat. Phys. 4 130
Schnurer H et al 2006 Laser Part. Beams 23 337
Schwinger J 1951 Phys. Rev. 82 664
Schwoerer H et al 2003 Europhys. Lett. 61 47
Schwoerer H et al 2006 Nature 439 445
Sonobe R et al 2005 Phys. Plasmas 12 073104
Spencer I et al 2002 Rev. Sci. Instrum. 73 3801
Stoyer M A et al 2001 Rev. Sci. Instrum. 72 767
Tabak M 1994 Phys. Plasmas. 1 1626
Takabe H et al 2001 J. Plasma Fusion Res. 77 1094
Takabe H 2001 J. Plasma Fusion Res. 77 1097
Takashima R et al 2005 Appl. Phys. Lett. 86 011501
Ter-Avetisyan S et al 2005 Phys. Plasmas 12 012702
Thomas W 1925 Naturwissenschaften 13 627
Toncian T et al 2006 Science 312 410
Umstadter D 2001 Phys. Plasmas 8 1774
Velchev I et al 2007 Phys. Plasmas 14 033106
Walker P M and Dracoulis G 1999 Nature 399 35
Wilks S C et al 2001 Phys. Plasmas 8 542
Wilson R R 1946 Radiology 47 487
Yang J M et al 2004a J. Appl. Phys. 96 6912
Yang J M et al 2004b Appl. Phys. Lett. 84 675
Yanovsky V et al 2008 Opt. Exp. 16 2109
Yogo A et al 2009 Appl. Phys. Lett. 94 181502
Yonedo H 2001 J. Plasma Fusion Res. 77 1105
Youssef A et al 2005 Phys. Plasmas 12 110703
Zagar T et al 2005 New J. Phys. 7 253
Zepf M et al 2001 Phys. Plasmas 8 2323