Radiation Sources Based on Laser-Plasma Interactions

By D.A. Jaroszynski, R. Bingham, E. Brunetti, B. Ersfeld, J. Gallacher, B. van der Geer, R. Issac, S.P. Jamison, D. Jones, M. de Loos, A. Lyachev, V. Pavlov, A. Reitsma, Y. Saveliev, G. Vieux, S.M. Wiggins

University of Strathclyde, 107 Rottenrow, Glasgow, Scotland, UK

Plasma waves excited by intense laser beams can be harnessed to produce femtosecond duration bunches of electrons with relativistic energies. The very large electrostatic forces of plasma density wakes trailing behind an intense laser pulse provide field potentials capable of accelerating charged particles to high energies over very short distances, as high as 1 GeV in a few millimetres. The short length scale of plasma waves provides a means of developing very compact high energy accelerators, which could form the basis of compact next-generation light sources with unique properties. Femtosecond duration electron bunches from laser-driven accelerators could be used to produce tuneable femtosecond duration x-ray pulses useful for probing matter on unprecedented time and spatial scales. If developed to fruition this revolutionary technology could reduce the size and cost of light sources by three orders of magnitude and therefore provide powerful new tools to a large scientific community. Tuneable x-ray radiation and particle pulses with durations of the order of or less than 5 femtoseconds should be possible. We will discuss how a laser-driven plasma wakefield accelerator can be used to produce radiation with unique characteristics over a very large spectral range.

Keywords: Laser-Plasma Interactions, Advanced Accelerators, Radiation Sources

1. Introduction

Particle accelerators have become ubiquitous components of advanced light sources and essential tools for exploring the structure of matter. The particle energies required for these respective applications is quite different: synchrotron light sources and x-ray free-electron lasers (FELs) require electron energies in the 100 MeV to few GeV energy range, while high energy particle physics research requires TeV energies. However, both require accelerators capable of producing very high brightness beams. This imposes a huge challenge on the scientific community developing accelerators, and usually leads to very expensive facilities, partly because of the size of conventional RF accelerator components. A vigorous search for ways to make them more compact has driven investigations into new methods for accelerating particles to replace conventional RF cavities. Plasma has long been recognised as having the potential of providing acceleration gradients that are three orders of magnitude large than conventional RF accelerators (Tajima and Dawson, 1979; Bingham, 2005), which are limited by electrical breakdown of the cavity struc-

tures and multipaction. Harnessing plasma waves excited by the light forces of intense laser pulses is creating a revolution in accelerator technology. Researchers have already demonstrated gradients in excess of 100 GV/m (Modena et $al.$, 1995; Coverdale et $al.$, 1995; Nakajima et $al.$, 1995) in plasma using terawatt class laser pulses. Tenuous plasma with a density, n_e, in the range of 10^{18} cm^{-3} to 10^{19} cm^{-3} can potentially accelerate particles to GeV energies in a few millimetres. However, until very recently, electron beams were produced with a 100 % Maxwellian energy spread due to plasma wavebreaking (Malka et $al.$, 2002), which has limited the usefulness of plasma based accelerators and has been a major impediment to their development. However, a recent breakthrough by several groups (Mangles et $al.$, 2004; Geddes et $al.$, 2004; Faure et $al.$, 2004) reporting the acceleration of relatively high charge (10 - 500 pC) electron bunches to more than 100 MeV in less than 1 mm, thus unequivocally demonstrating a gradient of more than 100 GV/m. What was most surprising about these observations was that electrons were launched into the plasma wake from the background plasma, and were accelerated with a relatively small energy spread, $\delta\gamma_e/\gamma_e \approx 1$ - 3 %, where $\gamma_e = (1-\beta^2)^{-1/2}$ is the Lorentz factor and $\beta = v_e/c$ (c and v_e are the respective velocities of light and the bunch in vacuum). Simulations (Martins et $al.$, 2005) indicate that injection is rapidly shut off by beam loading (Trines et $al.$, 2001), which results in both a small energy spread and an extremely short electron bunch, of the order of 10 fs or less. Although ultra-high accelerating gradients have now been unambiguosly demonstrated, the length of the plasma, which is typically 1 mm, and dephasing of the electrons in the accelerating potential limit the final electron energy. This work is stimulating investigations into ways of controlling acceleration and exploring the source of pointing and shot-to-shot energy fluctuations (Mangles et $al.$, 2004; Geddes et $al.$, 2004; Faure et $al.$, 2004),

Coherent and incoherent electromagnetic radiation sources have become very important research tools for both scientists and industrialists. X-ray radiation from synchrotron light sources has become one of the most successful tools of science and is used by a large user community. New light facilities providing coherent radiation based on free-electron lasers have also been built but in spite of the huge advances in their development, they are still restricted to wavelengths longer than 30 nm (Ayvazyan et $al.$, 2002). However, excellent progress is being made to extend the spectral range of self amplification of spontaneous emission (SASE) FELs to less than 6 nm. The cost of light sources is determined by size of conventional accelerator structures and their radiation shielding infrastructure. This is creating a need to make them more compact. The recent progress in the development of wakefield accelerators is thus providing a realistic opportunity to dramatically reduce both their size and cost and therefore make them available to any medium sized university or research establishment. Furthermore, as will be discussed below, the ultra-short electron bunches from wakefield accelerators would make light sources unique and enable the production of brilliant electromagnetic pulses of only a few femtoseconds in duration, and over a wide spectral range from x-rays to terahertz frequencies. The ultra-short "pre-bunched" electron bunches should also enable the sources to emit coherently thus opening up the possibility of producing single cycle pulses in the mid-infrared and millimetre spectral range and attosecond pulses at shorter wavelengths. These sources would provide excellent tools for time resolved studies while at the same time create an opportunity to build facilities incorpo-

rating femtosecond lasers that are synchronised with electron beam based sources and ideal for two-colour and two-type (electron-photon) pump-probe time resolved studies. If radiation sources based on wakefield technology is developed to maturity it could possibly revolutionise the way science is done.

In this paper we report on progress towards producing a laser wakefield driven accelerators and radiation source, and explore some of the challenges that need to be met. As an illustration we will describe the United Kingdom Advanced Laser Plasma High-energy Accelerators towards X-rays (ALPHA-X) project (Jaroszynski and Vieux, 2002) which is applying the technology to driving compact, ultra-short pulse, tuneable, bright electromagnetic sources extending from terahertz frequencies to X-rays. Fig. 1 shows a schematic of the main components of the ALPHA-X project.

2. The laser-driven plasma wakefield accelerator

Electrostatic forces of a plasma with a density of $n_e \approx 10^{18}$ cm^{-3} are of the order of 100 GV/m (Tajima and Dawson, 1979), which is three orders of magnitude larger than that attainable with conventional RF cavities. The ponderomotive force (Kruer, 1988) of an intense laser pulse drives a plasma wave in the form of a wake travelling at the group velocity, v_g ($\equiv c(1 - \omega_p^2/\omega_0^2)^{1/2} \approx c(1 - \omega_p^2/2\omega_0^2)$), of the laser pulse in the plasma, where $\omega_p = \sqrt{e^2 n_e/\epsilon_0 m}$ is the plasma frequency and ω_0 is the radiation frequency. The Lorentz factor associated with the wake velocity is $\gamma_w = \omega_0/\omega_p$. As the wavelength of these plasma waves is very short, (≈ 33 μm for $n_e \approx 10^{18}$ cm^{-3}), they provide an opportunity to harness their electrostatic forces to produce a very compact travelling wave accelerating "structure". These structures have dimensions that are approximately λ_p^3, where $\lambda_p \approx 2\pi c/\omega_p$, which is $\approx 4 \times 10^{-5}$ cubic millimetres for the above density. Furthermore, as the accelerating medium is fully ionised i.e. already broken down, it is extremely robust. As with conventional RF accelerator cavities, the accelerating potential has both longitudinal forces, which give rise to acceleration, and transverse forces, which cause focussing or defocussing of the electron bunches, thus many of the techniques of conventional RF accelerator physics can be applied to plasma based accelerators. However, the small dimension of the plasma "structures" implies several significant challenges for harnessing the waves to accelerate charged particles. The most stringent of these is the requirement that electron bunches must be injected into the accelerating part of the electrostatic wave, which requires bunches to be much shorter than 100 fs for the above density. Electrons should also be injected precisely into the structure at a velocity close to the phase velocity of the wake i.e. at the group velocity of the laser pulse, thus implying that initially $\gamma_w \approx \gamma_e$ (typically $\gamma_w = 10$ - 50). For a plasma wave of relative amplitude, $\delta n_e/n_e$, electrons of the correct phase velocity are accelerated until they gain an energy $\gamma_e = 2\gamma_w^2 \delta n_e/n_e$ over a distance $l_d = \gamma_e \lambda_p = 2\gamma_w^2 \lambda_p/\pi$, after which deceleration occurs. The rapid longitudinal variation of the accelerating potential also increases the resulting energy spread and can cause fluctuations of the mean energy of accelerated electrons. The production of high quality electron beams with a reproducible mean energy and small energy spread implies bunch durations and synchronism between plasma wake of around 10 fs, for $\delta\gamma_e/\gamma_e < 1\%$, where γ_e and $\delta\gamma_e$ are the respective mean and dispersion of the electron bunch energy. The maximum energy acquired by an injected electron

bunch is inversely proportional to the plasma density and thus it is an advantage to accelerate particles over longer lengths using low density plasma. The maximum charge that can be accelerated is proportional to the background plasma density (Chiou and Katsouleas, 1998; Reitsma et al., 2000, 2005; Wilks et al., 1987), giving a maximum of $\approx$ 100 pC and 1 nC for 10^{18} cm^{-3}. At this density the dephasing length is of the order of one centimetre. Because diffraction limits the interaction length, it is necessary to guide the laser pulse in some form of plasma waveguide to fully utilise the accelerating potential (Butler et al., 2002; Spence and Hooker, 2001). To achieve sufficiently high intensities to drive a substantial plasma wave the normalised vector potential, $a = eA/mc$ (where A is the field potential) of the laser should be ≥ 1, which implies a laser spot size of the order of 50 μm for a 20 terawatt 800 nm laser pulse. The optimum pulse duration for driving the wake is $\tau_l \approx \lambda_p/2c$ (Fritzler et al., 2004), the resonant regime, though it has become clear that laser pulses with a duration longer than $\lambda_p/2c$ will evolve to an optimum dimension for driving the wake because of the space and time varying permittivity of the wake. The laser power rapidly evolves to the threshold for self focussing, P_{crit}[GW] $\approx 17(\omega_0/\omega_p)^2$, which leads to a further increase in the laser intensity.

3. Electron Injection

Currently two general approaches to the injection of electrons into wakefield accelerators are being considered. These are injection of an externally produced ultra-short electron bunch, an approach which goes back more than a decade, and the more recent "all-optical injection" method (Mangles et al., 2004; Geddes et al., 2004; Faure et al., 2004), where electrons are extracted from the background plasma. Both of these injection techniques are being explored in the ALPHA-X project. However, we will only discuss the former in this paper as the latter approach is discussed in detail in an accompanying paper (Krushelnick, 2005), in these proceedings.

(a) External Injection

Conventional electron beam injectors are usually based on RF photoinjector accelerators (van der Wiel, 2005). In these devices ultra-short bunches of electrons are extracted from a photo-cathode and accelerated in the electric fields of microwave cavities. However, producing electron bunches with durations of the order of 10 fs from photoinjectors is currently not possible because space-charge forces cause electron bunches to rapidly expand longitudinally and transversely.

A number of methods have been suggested to counteract space charge effects, some of which show promise (Luiten et al., 2004). However, it is generally accepted that the goal of achieving 10 fs electron bunches is still far away. State-of-the-art photoinjectors are only able to produce electron bunches of the order of 100 fs. New strategies for pre-bunching to compress the injected bunches to 10 fs or less are required. As will be discussed later, one approach adopted has been not to worry about the problem and live with a long bunch while allowing the focussing and defocussing parts of the plasma wakefield accelerator to naturally select a segment or segments of the injected electron bunches (Gordon et al., 2005). This has the disadvantage of increasing the absolute energy spread, but is still useful for accelerators achieving 1 GeV and higher because the relative energy spread shrinks

with increase in energy. Conventional pre-bunching strategies used in RF accelerators usually require several accelerating structures to produce an electron energy phase correlation or chirp which is subsequently used to compress the bunches in a dispersive magnetic buncher (Raubenheimer, 1995; Saldin *et al.*, 2002, 2004; Zholents, 2003). In this paper we describe a novel bunch compressor to achieve sub 100 fs electron bunches from a conventional RF accelerator and also methods of compressing electron bunches in the wake of a laser wakefield accelerator. As we will see below, maintaining a very short electron bunch is not possible in a beam transport system that includes strong focussing elements, such as quadrupoles or solenoid fields, because of path length dispersion. However, the problem can be turned into an advantage to compress electron bunches from a photoinjector while avoiding space-charge problems and emittance growth, as will be shown below.

(i) *Alpha-X photoinjector*

Figures 1 and 2 shows schematically the Alpha-X photoinjector and the beamline. The injector consists of a 2.5 cell S-band RF photoinjector (McDonald, 1988) with an axial RF input coupler, similar to the one described in (Kwiet, 2003; van der Wiel, 2005). A 10 MW klystron and modulator provides microwave power to the accelerating cavity, which has an on-axis electric field gradient of 100 MV/m capable of accelerating electrons emitted from a copper photocathode to 6.25 MeV. Elliptically shaped irises reduce the field on the iris surface to below that of the cathode field to reduce breakdown problems. The electron beam in the photoinjector is transported with a constant radius by a 0.25 T solenoid field and a bucking coil nulls the magnetic field on the cathode surface. After traversing a beam path of 1.5 m, the beam is focussed by a 0.5 T solenoid magnet to a spot-size of $\approx 50 \mu$m at the entrance of a plasma capillary, as shown in Fig. 2.

(ii) *Reducing bunch lengthening of injection electrons*

The current approach to create femtosecond bunches with reasonable charge is to accelerate picosecond electron bunches to high energy, in the order of 100 MeV, introduce an energy chirp by off-crest acceleration and then compress them magnetically in a chicane. High-power femtosecond UV lasers allow ultra-short (30-50 fs) electron bunches to be created directly inside a RF photoinjector. Unfortunately, these bunches can not easily be transported due to space-charge forces. Even assuming prompt response of the cathode (e.g copper) the bunch is stretched by space-charge forces to nearly a picosecond for reasonable bunch charge (10 - 100 pC). To illustrate this we have modelled the beam transport for the ALPHA-X beam line using the particle tracking code, GPT (de Loos and van der Geer, 2005). The simulation results shown in Fig. 3 and Fig. 4, of a 50 fs duration electron bunch starting with a large initial radius clearly show that the bunch is distorted by both space charge and path length dispersion which results in very long bunches. Space charge forces can be reduced by lowering the density, which is easily achieved by increasing the beam diameter to form a thin "pancake-shaped" bunch. However, increasing the bunch radius has two deleterious effects - i) the emittance of the beam will increase because $\epsilon_n = \sigma \sigma' \gamma_e$, where σ and σ' are the radius and angular dispersion respectively, and ii) the bunch will lengthen because of path length dis-

persion. All focussing systems introduce path length differences which cause bunch lengthening. This is insignificant for picosecond bunches and usually neglected. As path-length differences scale with the beam radius squared they quickly become the dominant effect at large initial radius for femtosecond bunches. There is a trade-off between space-charge induced bunch-lengthening and path-length induced lengthening. The optimum initial radius of 1.8 mm results in 330 fs bunches for ALPHA-X parameters, which is unacceptably long.

One way of compensating for path length dispersion is to shape the cathode surface and give it a curvature which precisely compensates the path length dispersion introduced by the focussing elements and accelerating fields. When this is done the focussing element behaves as a radial bunch compressor, with the advantage that the radially correlated phase delay appears as a geometric correction at the cathode, unlike velocity bunching techniques. Apart from compensating for path length induced dispersion, the curved cathode also has another very important advantage in extending the electron bunch dimensions into a domed pancake shape with a relatively large diameter hereby drastically reducing space charge effects.

To illustrate the variation of beam parameters we have carried out simulations using the GPT code (de Loos and van der Geer, 2005), of the beam transport through the RF photoinjector accelerator to the final focus at the capillary entrance. A 1 mm initial radius bunch produced by the 30 fs laser pulse is stretched to $\approx$400 fs due to space-charge forces, as shown in Fig. 3 and Fig. 4. The geometrically induced path-length dispersion leads to significant stretching of the bunch for large initial radii. Any focusing/defocusing of the electron beam, also near the irises of the cavity, and cyclotron motion of the bunch in the focusing solenoid result in longer path lengths. The bunch lengthening od a focussing element for relatively small beam diameters ($D << f$) is given by $\delta t = D^2/4fc$, where D is the beam diameter and f is the focal length. As an example, for the ALPHA-X beam final focus onto the entrance to the plasma channel the bunch is stretched by about 120 fs, where we have assumed a beam diameter of 5 mm and a focal length of 17 cm. Further stretching occurs in the accelerating cavities.

To obtain short electron bunches it is necessary to simultaneously minimise space charge forces while compensating geometrical path length dispersion. Space charge forces can be reduced by lowering the charge density or by using relatively complicated space-charge compensation schemes such as suggested (Luiten et al., 2004). The lower charge density is achievable by increasing the radial dimension to produce a "pancake shaped" bunche from the cathode. However, this comes at the cost of increasing the geometric dispersion, as discussed above. It is thus necessary to pre-disperse the electron in bunch radial phase-space by altering the cathode shape. A radius of curvature on the cathode of $\approx$ 8 cm is required to alter both the initial radial phase space distribution of the electron bunch and to compensate for differences in the accelerating field close to the cathode. The dramatic improvement possible with a curved cathode is illustrated in Fig. 3, where the beam transport from the cathode to final focus at the position of the plasma-channel has been simulated and the radial phase-space projection is shown at the focus. The curved cathode reduces the bunch length from 330 fs to less than 100 fs FWHM, while simultaneously reducing the spot-size, energy spread and paradoxically the emittance, as can be seen in Fig. 5, which plots the transverse emittance evolving along the beam line. The reduction of emittance is because the "slice emittance" is much

smaller than the total emittance. For shorter bunches the spherical concave cathode should be replaced by an elliptical shape to compensate for higher order effects.

(b) Injection and plasma based bunch compression

As mentioned above, injection of electrons into the plasma wake should occur close to the wake phase corresponding to the maximum acceleration potential. Furthermore, the electrons should have a duration much less than the plasma wavelength for the production of low emittance and energy spread beams. These requirements are very challenging. All-optical injection could provide a possible solution to these stringent requirements. However, much work needs to be done to control all optical injection to provide a reproducible injection source. It is thus prudent to explore both external and all-optical injection techniques. This is dual approach has been adopted in the ALPHA-X project and all-optical injection techniques are discussed in detail (Krushelnick, 2005). Here we will discuss two bunching techniques utilising the plasma wave which require externally injected electron bunches of the order of the plasma wavelength. Two distinct regimes are distinguished by the position relative to the wake at which electrons are injected. We will see below that for electron bunches with a duration $\tau_l \geq \lambda_p$ injected directly into the wake, the bunch is compressed by a large factor at the expense of charge loss and a a relatively large absolute energy spread (Gordon et al., 2005). An alternative method where low energy electron bunches are injected ahead of the wake, and compressed by a combination of longitudinal and transverse repulsion forces at the head of the wake is discussed in Khachatryan et al. (2004) and references therein.

(i) Long pulse injection and plasma based bunch compression

Considering the difficulty of producing an injection electron bunch with a duration substantially shorter than the plasma wavelength it is worth evaluating options for bunch compression. It is clear that reducing the bunch length using conventional RF and magnetic bunchers represents a substantial technological challenge, as we saw above. Promising but lossy bunch compression occurs when an electron bunch overlaps the whole of the accelerating and decelerating parts of the wakefield potential (Gordon et al., 2005). The repulsive parts of the accelerating fields filter out electrons which would otherwise produce a long low energy tail. As an example we assume an electron bunch with a duration of approximately 100 fs injected into the wake of a tenuous plasma. To model the plasma pre-buncher we have solved the quasi-static fluid equations, and have included space charge evolution of the electron beam in the wake. Modelling of the electron bunch evolution in three dimensions has, as a first attempt, been carried out using the GPT code (de Loos and van der Geer, 2005), where the accelerating field has been modelled as $E(r, z) = E_0 \cos\left(k_p(z - v_g t) + \varphi\right) \exp\left(-r^2/r_0^2\right)$, where r_0 is the transverse size of the wake and E_0 is the field strength. We have simulated a 300 μm diameter plasma channel (described below) with a density of 7×10^{17} cm^{-3}, giving $\lambda_p \approx 33$ μm, resonantly driven by a laser field with a potential $a_0 = 1$. An electron energy and charge of 7 MeV and 10 pC, respectively, has been chosen to be consistent with the ALPHA-X photo-injector describe above. Fig. 6 and Fig. 7 show snapshots of the electron bunch energy and spatial distributions at the entrance to the capillary,

8

after 1 mm and when they have gained 250 MeV. It is clear from the simulations that the λ_p segments of electron bunch are rapidly chopped by the interaction into $\lambda_p/2$ segments and then bunched both longitudinally and radially.

The wake accelerating structure can be used to bunch the beam by appropriately choosing the phase velocity of the wake, or alternatively, by matching electron beam energy and laser Lorentz factors. A significant fraction of electrons with the appropriate phase velocity can be trapped and electrons in the repulsive parts of the wake, expelled. Adjusting the phase velocity can be used as a way of controlling the trapping fraction, compression factor and the final energy spread. Compression of the trapped electrons into a small region of phase space leads to both a reduction in bunch length and energy spread, by reducing the potential difference across the electron bunch. Because the trapped charge fraction depends on the phase velocity of the injection electrons, so do beam loading effects (Reitsma *et al.*, 2005). There is an optimal beam charge which will cause the wake variation to be ironed out and therefore lead to significantly smaller energy spreads (Reitsma *et al.*, 2005; Gordon *et al.*, 2005).

By placing the electrons in a part of the wakefield where the accelerating force at the back of the bunch is larger than the force at the front, one can effectively compress the electron bunch: the strongest compression occurs if the bunch is injected around a zero of the longitudinal field. This is essentially the same mechanism that is used to compress electron bunches in RF cavities. The reason for using plasma-based compression, rather than a conventional method, is the same reason why plasma-based acceleration is attractive, namely that the gradients are so much higher. The disadvantage of the plasma-based compression scheme is that the initial bunch length must not exceed the plasma wavelength, which for a plasma density as low as 10^{17} cm^{-3} is still a challenging requirement.

A laser pulse and an electron bunch are injected into a short region of low plasma density, which is immediately followed by a somewhat longer region of higher density. The first stage is used for compression of the electron bunch: the low density is used to accept a somewhat longer electron bunch ($\lambda_p \propto n_p^{-1/2}$). The second stage is used for acceleration because of the higher gradient and shorter dephasing length offered by a higher plasma density. This assumes that the dephasing length associated with acceleration in the low density plasma is too long to be practical.

Beam loading effects are essential to describe the energy transfer from the plasma wave to the electrons: accelerated electrons can extract plasma wave energy efficiently only if the amplitude of the bunch wakefield is a significant fraction of the amplitude of the laser wakefield. 3-D effects also play a role in the evolution of energy spread, due to the finite bunch width and the dependence of the accelerating forces on the transverse coordinates. All these effects are taken into account in our numerical model. Fig. 9 shows the influence of the electron beam wake on the radial F_r and longitudinal F_z forces, which clearly demonstrates the flattening of the accelerating force in the region of the bunch. Beam loading leads to a reduction in the energy spread and emittance. The bunch electrons induce a wakefield that is decelerating and focusing, as shown in Fig. 8. The magnitude of the decelerating and focusing forces is zero at the front of the bunch and increases along the bunch from front to back. The deceleration of the back of the bunch hinders longitudinal bunch compression. The decelerating forces also causes a decrease of the average energy with increasing bunch charge.

Two stage buncher. Design a system with a two section plasma channel, with the first 4 mm with a density of 1.7×10^{17} cm^{-3} and a second stage with a density of 5.4×10^{17} cm^{-3}. The buncher compresses to $\tau_{final} = 2\tau_{initial}^2\omega_p/2\pi$, therefore if we inject close to the peak of the wave the bunch length compresses in a plasma from 42 fs to 14 fs with an energy gain of 8 MeV to 33 MeV after 1.2 cm, as shown in Fig. 10.

In conclusion, we have found several trade-offs involved in our two-stage scheme which uses a low density plasma for compression and a higher density plasma for acceleration of the electron bunch, in comparison with a scheme in which the same low density plasma is used for compression and acceleration (which takes a much longer plasma channel). Firstly, due to the reduction of plasma wavelength in the second stage, it is harder to get a small energy spread. Secondly, because the bunch has to cross a defocussing region of the wakefield, the transverse emittance degrades if the bunch propagates through the density transition. Our simulation results show that both these adverse effects are mitigated by beam loading Reitsma et al. (2005). Finally, we have found that the efficiency of energy transfer in the high density region is compromised, because the beam loading in the low density region limits the amount of charge that can be accelerated. This effect can be mitigated by focussing the laser pulse and the electron bunch such that their width is small compared to the plasma wavelength of the low density region.

4. Plasma channels

An important part of a wakefield accelerator is the plasma medium which supports the plasma wake. It has recently been shown that suitably profiled plasma channels can guide a laser pulses over many Rayleigh lengths. One method of forming a plasma waveguide is to apply a high voltage discharge through a gas filled capillary (Butler et al., 2002; Spence and Hooker, 2001; Bobrova et al., 2002). The hot plasma rapidly cools close to the wall of a capillary with a radius $r = r_m$, and adopts a parabolic radial density distribution, $n_e(r) = n_e(0)+\Delta n_e(r/r_m)^2$, with a minimum $n_e(0)$ on axis and Δn_e the difference of the electron density across the channel radius (Bobrova et al., 2002). A Gaussian laser pulse propagates with a constant spot size w_M, through the waveguide provided $w_M = [r_m^2/(r_e\Delta n_e)]^{1/4}$, where r_e is the classical electron radius. The waveguiding properties make them an excellent medium for plasma wakefield acceleration.

(a) Development of robust capillaries for wakefield acceleration studies

Typical wakefield experiments require a capillary diameter of 200 - 300 μm. Commercially extruded capillaries have a typical roundness of $\pm10\%$ and a wall thickness of 150 - 300 μm. Unfortunately, their thin wall sections make capillaries very fragile and suseptible to damage. Minor laser beam misalignment results in ablation of wall material and catastrophic fracture due to shock waves. One solution to this problem is afforded by ablating semi-circular cross-sectioned channels in two identical substrates using a femtosecond laser and then join them to form a single hollow capillary channel, as shown in Fig. 11. This has many advantages including robustness, ease of handling and most importantly, the ability to form tapers and other hollow structures.

Femtosecond laser micro-machining with appropriate pulse lengths and incident fluence levels ensure a laser spot diameter small compared with the desired profile topology and thus allow a semicircular feature to be formed in the surface of any substrate with a few micron accuracy. Additional grooves machined in one of the substrates act as hydrogen gas feed lines to both ends of the capillary, as shown in Fig. 11. The main hydrogen feed lines consist of simple slots with a cross-sectional area three times greater than the total link feed line area, which in this case is $\approx 400 \times 400 \mu$m. This geometry ensures a static gas fill in the capillary and minimises the risk of the electrical discharge in the hydrogen feed line. The two completed alumina substrates are finally aligned and glued together using epoxy resin. A typical machined cross-section is within 2% of a calculated convolved Gaussian semicircle, which is substantially better than the 5% roundness of an extruded tube.

Plasma waveguides manufactured as described above have been extensively tested and have survived continuous usage as a plasma waveguide for more than one year ($> 10^6$ shots).

The waveguiding properties of the profiled capillaries have been explored using a 10 Hz CPA femtosecond laser delivering up to 250 mJ, 800 nm, 50 fs pulses (Jaroszynski et al., 2000a). The experimental set-up includes a suitable imaging system for examining the transverse profiles at the entrance and exit of the capillary. 95 % of a beam is transmitted through the plasma waveguide formed by fully ionising hydrogen gas with an electrical discharge. The capillaries are robust and do not suffer catastrophic failure due to beam misalignment. Fig. 12 shows the entrance face of a capillary after 10^6 pulses. Laser machining of the surface is evident but does not appear to detrimentally modify the waveguide. In fact, we observe that waveguiding efficiency improves from $\approx 80\%$ to more than 90% with use, which suggests that tapering of the entrance improves mode matching. Evidence of tapering has also been observed in the density measurements described below.

(b) Novel technique for measuring the plasma density in a channel

Interferometry techniques have been routinely used to map the plasma distribution but usually can only be applied to small-scale plasmas. These techniques determine the permittivity of the transparent medium using arrangements like Michelson, Mach-Zehnder and less often Fabry-Perot interferometers. The density is determined from the phase change calculated from shifts in the fringe pattern. The phase change is directly related to the line integrated density along the ray path. Thus a first limitation appears for these interferometry methods: they do not provide the local density of the plasma but rather an averaged value. Furthermore, some knowledge of the expected plasma distribution is required for the Abel transformation which is used to deduce the localised plasma density. Also, extended plasmas cannot be probed as the laser pulse starts to interact too strongly with the plasma and becomes modulated. Here we present a new technique based on broad-band Raman amplification to measure the density of plasmas. This method has several advantages over other methods. First, it provides a non invasive tool for determining the electron density and therefore the plasma remains essentially undisturbed. Secondly, the density is measured locally and at a fixed time relative to the evolving plasma distribution, in contrast with interferometry techniques

which provide averaged values. Finally, the plasma density is determined directly and does not require extended calculations.

Stimulated Raman scattering (SRS) is a three-wave parametric instability where an incident electromagnetic (EM) wave (ω_0, $\vec{k_0}$) resonantly decays into a backscattered EM wave (ω_1, $\vec{k_1}$) and a plasma wave (ω_p, $\vec{k_p}$) satisfying the resonance conditions $\omega_0 = \omega_1 + \omega_p$ and $\vec{k_0} = \vec{k_1} + \vec{k_p}$, where ω_i and $\vec{k_i}$ represent the frequency and wave vector of the waves respectively (Kruer, 1988). A seed pulse, injected into a column of under-dense plasma can therefore be amplified by a counter-propagating pump pulse. In the linear SRS regime, when the intensities of the seed and pump are moderate ($\leq 10^{15}$ Wcm^{-2} for 800 nm radiation), the amplitude of the seed grows as $g = e^{\Gamma t}$, where Γ is the growth rate and t the duration of the interaction. For monochromatic circularly polarised beams the duration of the interaction is given by the pump duration and the gain is given by $\Gamma = a_0(\omega_0\omega_p/2)^{1/2}$. This large exponential gain has led to the suggestion of stimulated Raman backscattering in plasma as an alternative parametric amplifying medium (Malkin *et al.*, 1999; Shvets *et al.*, 1997). In contrast with the SRS linear theory for long duration monochromatic beams, very interesting features also appear when broad bandwidth chirped seed and pump pulses with identical spectral bandwidths, broader than twice the plasma frequency. The gain factor becomes a function of the intensity of the pump beam (Vieux *et al.*, 2005; Ersfeld and Jaroszynski, 2005). Finally, if the intensity of the pump beam is much larger than the seed intensity, the plasma wave is strongly driven only when resonant excitation occurs between the central frequency of the pump ω_0, which is the most intense, and the frequencies of the seed detuned by $\pm\omega_p$. In the seed spectrum a gain peak occurs at $\omega_0 - \omega_p$ and a loss trough at $\omega_0 + \omega_p$. The separation between the peak and trough is equal to twice the plasma frequency and directly leads to a measure of the density $n_e = \left(\omega_p^2\epsilon_0 m/e^2\right)^{1/2}$. Furthermore, because the interaction time is limited to half the laser pulse length, a local measurement of the density at the position of the interaction is obtained. The timing of the collision given by the absolute and relative delays between seed and pump give a measure of the position localised both in space and in time.

To measure the plasma density a seed and pump laser beam from a Ti:sapphire laser system with a central wavelength $\lambda = 800$ nm, and a spectral bandwidth full width at half maximum $\Delta\lambda_{FWHM} \approx 20$ nm are focused into either side of a 300 μm diameter, $L_c = 4$ cm long plasma channel. A beam splitter partitions the energy between the two beams. 90% is used as the pump while the remaining 10% is used as a seed. A delay line is in the seed beam line varies the relative time of injection of the seed into the plasma compared to the pump. In this manner it is possible to choose the region of interaction and therefore the region where the density measurement will be performed. The SRS growth factor is estimated as $\Gamma = 4.2 \times 10^{12}$ s^{-1}. The duration of the interaction is limited to $t' = 48$ fs, leading to an expected gain of $\approx 36\%$ in intensity given by the numerical calculation. Gain measurements were obtained by recording seed spectra with and without the presence of the pump in the channel. $g(\omega)$ is calculated as $g(\omega) = (I'(\omega) - I(\omega))/I(\omega)$ and gain of $\approx 20\%$ on average is measuerd. The frequency difference between the Stokes and anti-Stokes satellites is observed to be constant over most of the measurement range, suggesting that the electron plasma density is constant. Fig.(13) presents the results of the electron density calculated from the frequency difference between the Stokes

and anti-Stokes satellites. The abscissae gives the relative delay to relative position of interaction inside the capillary.

As expected the density, within the error measurements, is constant inside the capillary and decreases at the extremities of the measurement length. The measured density is evaluated as 6.5×10^{17} cm^{-3}. The length over which it is possible to obtain experimental data is 22.5 mm, which is shorter than the actual capillary length. To explain this result it has to be remembered that a density gradient exists between the ends of the capillary and the vacuum chambers which can reduce the plasma density. Moreover this decrease in plasma density is accentuated by the tapering of the waveguide by the laser. The diameter of the capillary can reach 600 μm at both extremities which leads to a drop in density of by a factor of four at the end of the capillary. As the Raman gain is density and intensity dependent, there is a value below which it becomes experimentally not possible to observe the Raman satellites.

5. Radiation source development

The ALPHA-X project is focussed on LWFA in preformed plasma channels driven by 50 fs, 1 J, 800 nm laser pulses, and injected by 100 fs, 100 pC electron bunches derived from a conventional photoinjector described above. Alternative all-optical injection schemes are also being developed at RAL and Strathclyde. The goal will be to accelerate the short duration electron bunches to an energy of about 1 GeV. For these conservative estimates we hope to obtain an emittance $\epsilon_n < 1$ mm mrad (Fritzler *et al.*, 2004). The main challenge will be to realise an energy spread $\delta\gamma/\gamma \leq 0.01$, where is the FEL gain parameter (Bonifacio *et al.*, 1989, 1991), which is necessary to achieve a high single-pass gain in the proposed FEL amplifier. We have calculated the synchrotron radiation peak brilliance for a 6 fs electron bunch for a 17 kA beam with an emittance of 1π mm mrad and a relative energy spread $\delta\gamma/\gamma \approx 1\%$ is shown in Fig. 14.

The FEL (Colson, 2001) is a unique source of coherent electromagnetic radiation because of its simplicity: the amplifying medium consists of an electron beam in vacuum subject to a spatially periodic magneto-static field (undulator) which enables transfer of energy between electrons and electromagnetic wave. The ponderomotive force arising from the Lorentz force of the combined magnetic fields of electromagnetic wave and undulator gives rise to bunching of the electron beam, which results in coherent radiation at a Doppler up-shifted frequency. The absence of a solid or gaseous amplifying medium allows the FEL to attain extremely high powers and broad tuneability. Tuning of the FEL wavelength, which is given by $\lambda_u/2\gamma^2(1 + a_u 2)$, can be achieved by varying γ or the undulator parameters (a_u and λ_u, respectively). Several x-ray FELs are being developed as 4th generation light sources at centres throughout the world. The ultimate goal of these projects is to reach the water window and beyond using a self-amplification of spontaneous emission (SASE) FEL amplifier driven by a GeV electron beam. When complete, these x-ray sources will produce bright and coherent x-ray pulses with durations of the order of the electron bunch duration. One drawback of SASE amplifiers is that they are essentially noise amplifiers and have spiky and fluctuating outputs (Bonifacio, 2005; Bonifacio *et al.*, 2005) and it is not yet known whether they will have good spectral and temporal properties.

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However, superradiance (Jaroszynski *et al.*, 1997, 2000b; Jaroszynski, 1997), self-amplification of coherent spontaneous emission (SACSE) (McNeil *et al.*, 1999, 2000) and amplification of an injected signal are ways of improving the temporal characteristics of the x-ray pulses. As x-ray SASE FELs are extremely expensive devices it is very important that they produce useful output. If ways are found to produce an electron bunch microstructure with Fourier components at the resonance frequency, a large stable "spontaneous" coherent signal will act as an (intrinsic) injection source in the FEL amplifier (i.e. SACSE FEL) (Wiggins *et al.*, 2000). This may be achievable using future laser-plasma accelerators because their predicted electron bunch durations can approach one femtosecond or less. The growth in intensity of an injected or spontaneous field in a FEL amplifier is given by $I = I_0 \exp(gz)$, where z is the propagation distance, $g = 4\pi\rho 3^{1/2}/\lambda_u$, is the small signal gain and ρ is the FEL gain parameter (Bonifacio *et al.*, 1989, 1991) which is a function of the beam energy γ, peak current I_{pk} and normalised emittance ϵ_n. For a matched electron beam, the FEL parameter is given by $\rho = 1.1\gamma^{-1}B_u\lambda_u^{4/3}I_{pk}^{1/3}\epsilon_n^{-1/3}$, where $B_u(\approx 1\text{T})$ is the undulator magnetic field. The matched electron beam radius for electron beams from laser-plasma accelerators ($\epsilon_n < 1$ mm mrad) is of the order of the plasma wake wavelength, giving $\rho \approx 0.01$ to 0.02, for the electron beam parameters expected from a laser-plasma accelerator, and a gain length $L_g = \lambda_u/(2\pi\sqrt{3}\rho)$ of less than 10 undulator periods, which is sufficient to obtain saturation in a 200-period, $\lambda_u = 1.5$ cm, undulator should be achievable over a wide wavelength range. Need $\delta\gamma/\gamma < \rho$ and $\epsilon_n < 4\lambda\beta\gamma\rho/\lambda_u$ or $\epsilon_n < \gamma\lambda$ (matched). A 4 nm source assuming a 1 GeV beam with 100 pC charge and a duration of 10 fs we get a peak current of $I_{pk} = 10$ kA we get a $\rho \approx 0.005$, which gives a gain length of $10\lambda_u$ and a constraint on the energy spread of $\delta\gamma/\gamma \approx 1\%$, which may be achievable. To achieve saturation we need about 100 200 undulator periods. FEL sources at x-ray wavelengths are less compact because the dependence of the gain on electron energy, $\rho \propto \gamma^{-1}$ leads to a lower gain and therefore the requirement of a longer undulator to achieve saturation. The enhancement over the expected synchrotron radiation brilliance is shown in Fig. 14. To significantly shorten the undulator length SACSE could be used to enhance the start-up power. This has the additional benefit that the non-linear regime is entered promptly and the superradiant pulses should evolve self-similarly leading to very high efficiencies and extremely short, smooth and stable pulses. Pulses as short as several attoseconds should be feasible in future x-ray FEL sources because the gain bandwidth is automatically increased in this regime. Superradiance and SACSE will be examined in the proposed research programme.

6. Conclusion

Accelerators harnessing the electro-static forces of laser driven plasma waves have a promising future. They have the potential of producing bright, high peak current relativistic electron bunches with sub ten-femtosecond durations, which would be ideal for driving compact light sources. In addition to reducing the size of next generation accelerators by a factor of one thousand, they could also provide useful building blocks for high energy accelerators. We have reviewed some of the challenges that still need to be met, particularly in controlling the acceleration process and injecting electron beams into a single acceleration stage. We also discussed some of the issues of transporting ultra-short electron bunches between accelera-

tion stages. We examined several promising pre-bunching techniques which utilise a laser-driven plasma wave. The main challenge is to reduce the energy spread of wakefield accelerators so as to make them useful as drivers for future compact x-ray free-electron lasers. We have used various aspects of the UK ALPHA-X project to illustrate possible solutions to many of the challenges facing developers of light sources based on plasma wakefield accelerators.

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FIGURES
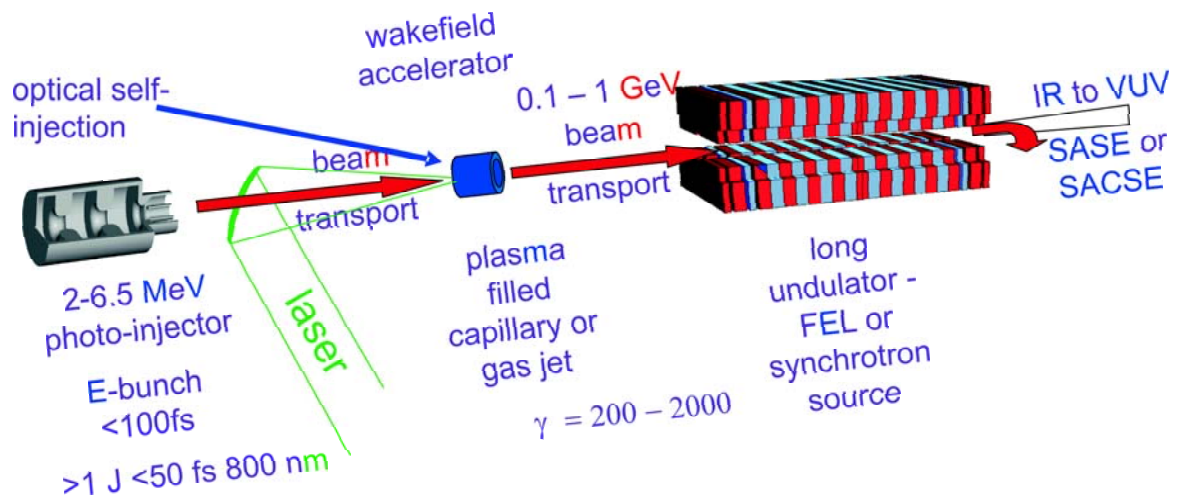
Figure 1. Schematic layout of Alpha-X
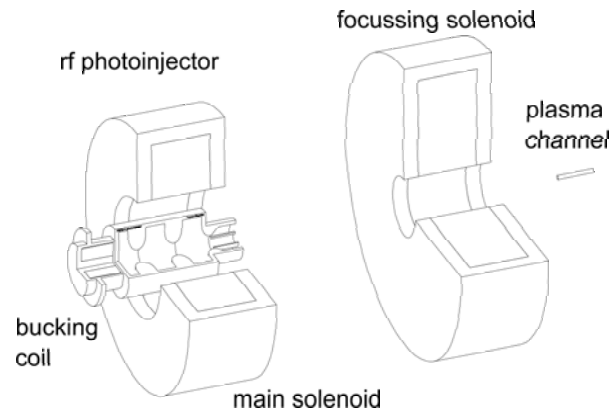
Figure 2. Schematic layout of the Alpha-X photoinjector and beam line
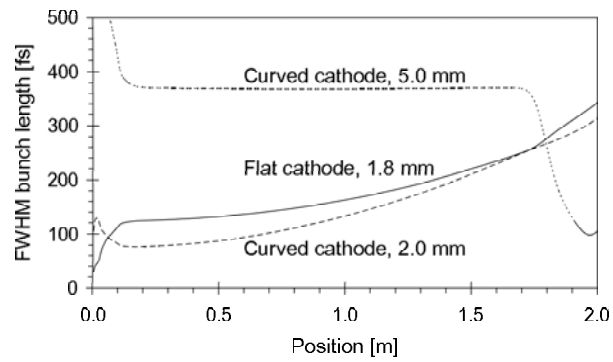
Figure 3. Comparison of bunch length evolution for flat and curved beams for 2 and 5 mm
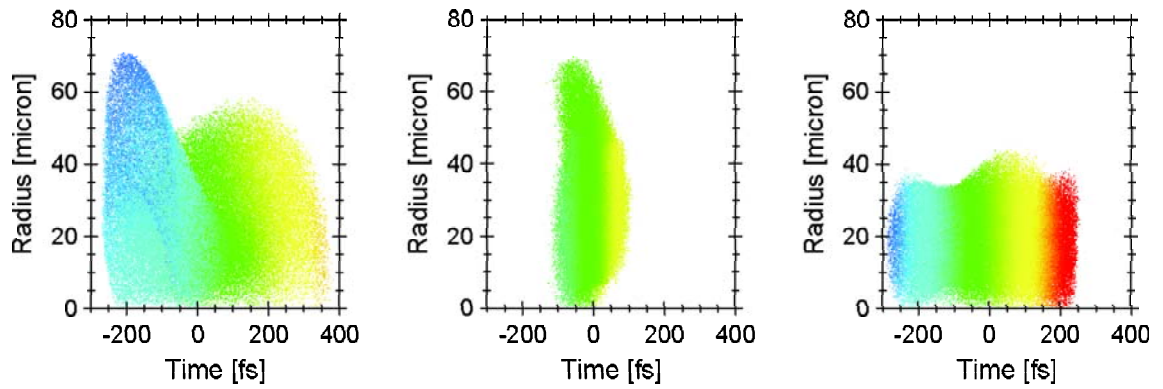
Figure 4. Simulated time-radius projection at the entrance of the plasma channel. Left: Flat cathode case, 2 mm beam radius. Centre: Curved cathode with 5 mm beam radius and 80 mm radius of curvature. Right: Curved cathode with 2 mm radius beam. The energy of particles are colour-coded to indicate their final energy.
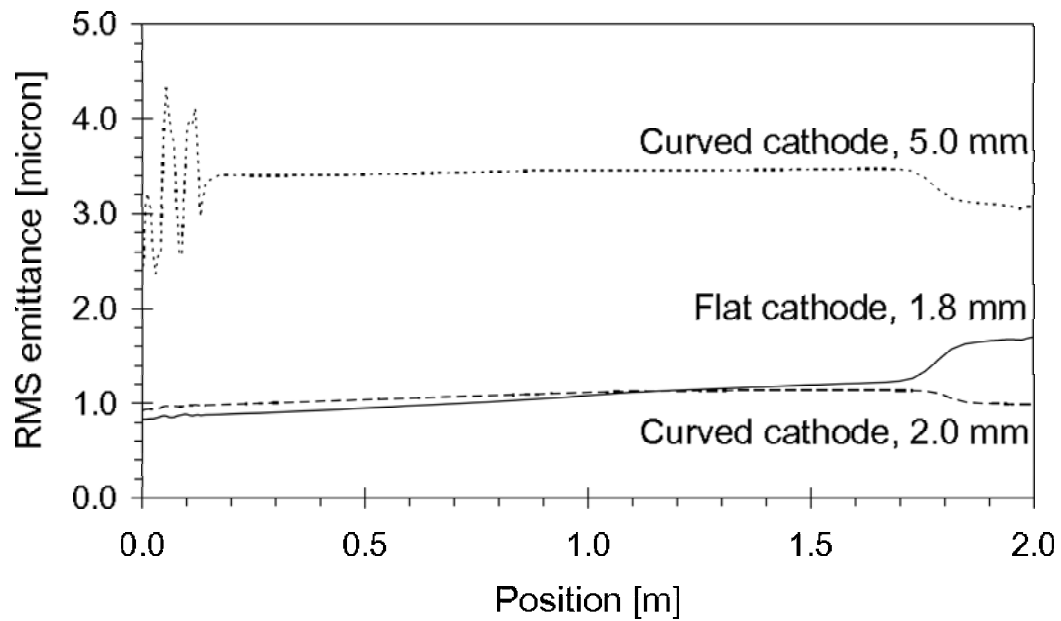
Figure 5. Simulated evolution of the emittance along the beam line with electron beam parameters as in Fig. 4
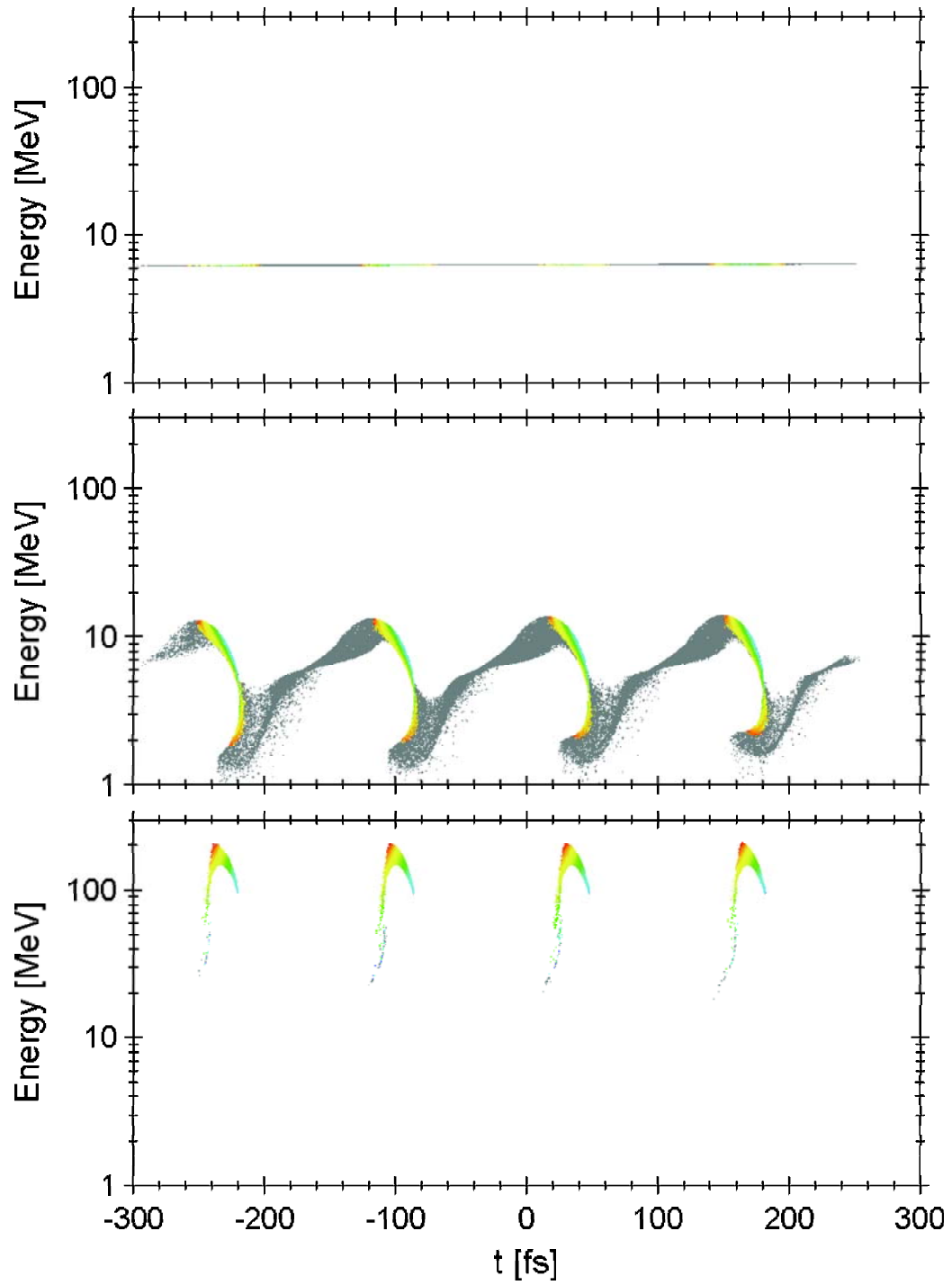
Figure 6. Simulated evolution of the beam energy in the plasma channel at the entrance
to plasma channel, 1 mm into channel and at 150 MeV
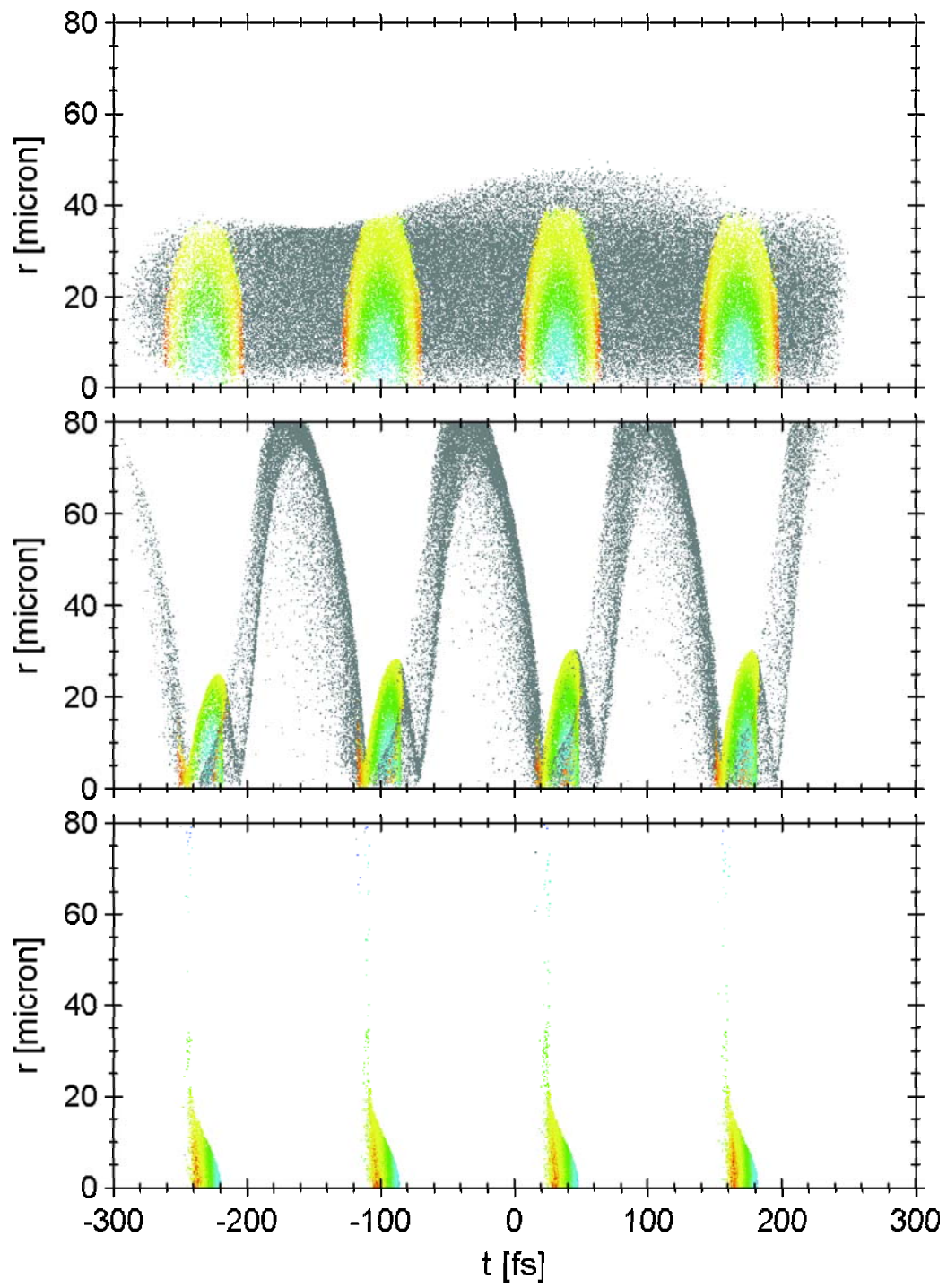
Figure 7. Simulated evolution of bunching in the plasma channel at the entrance to plasma channel, 1 mm into channel and at 150 MeV
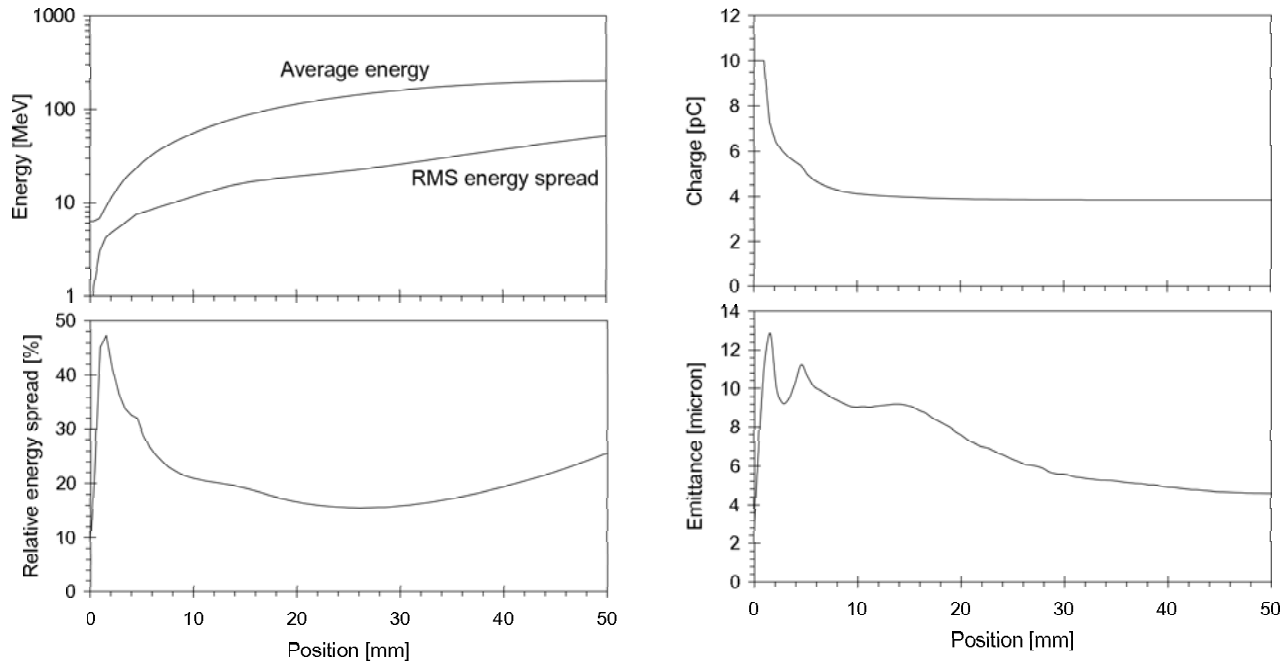
Figure 8. Simulated evolution of the bunch length, emittance, energy spread and mean
energy along the plasma channel
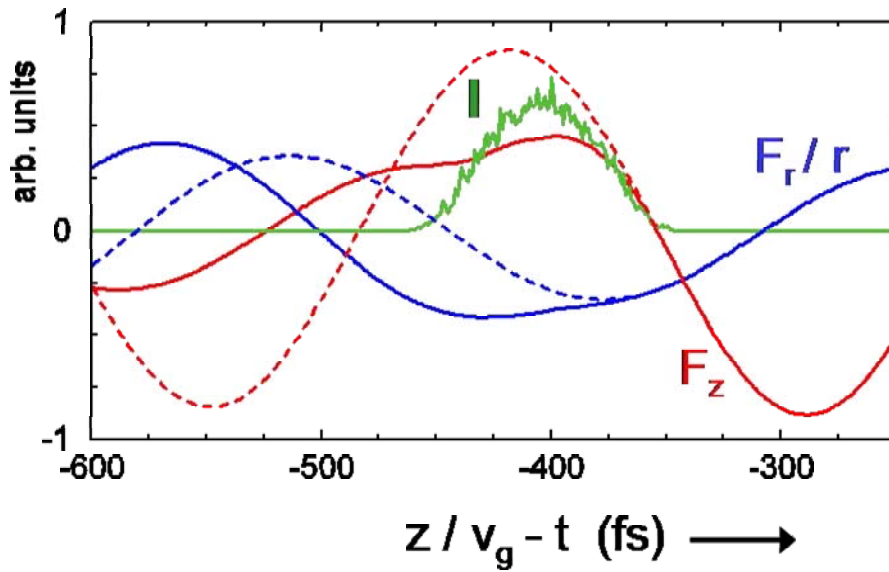
Figure 9. Beam loading. I represents the beam current, F_z the accelerating forces and F_r
the radial focussing forces. The solid and dotted lines are with and without beam loading
accounted for.
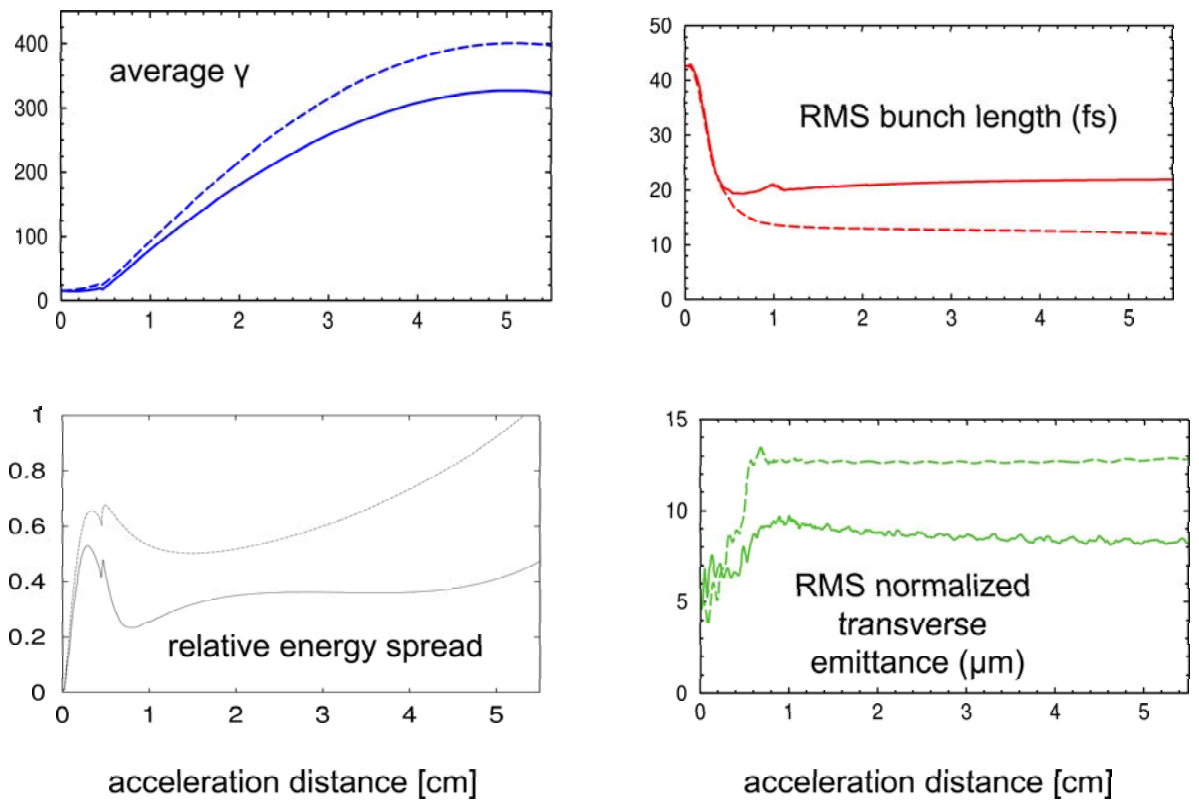
Figure 10. The average energy γ_e, relative energy spread, bunch length and normalised emittance for two staged buncher. The solid and dotted lines are with and without beam loading accounted for.
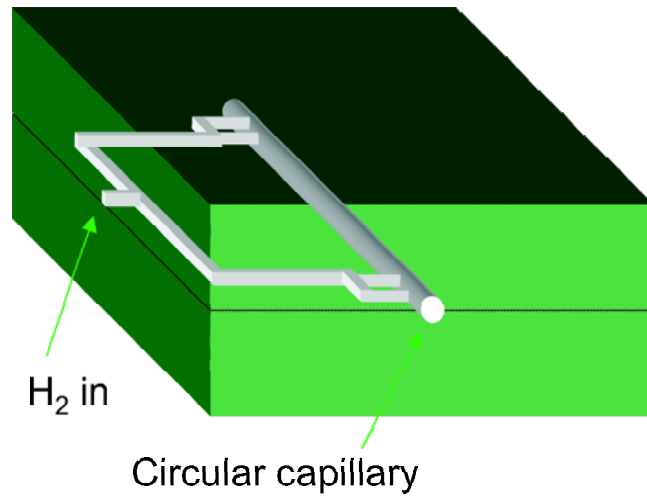
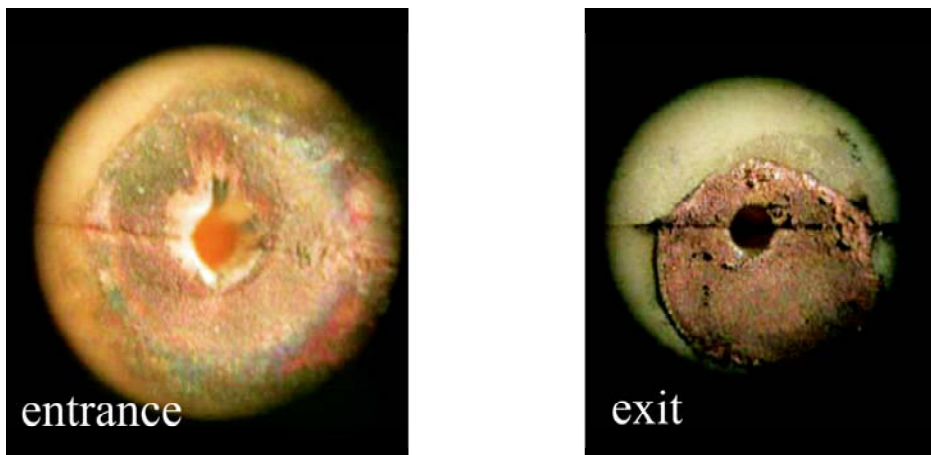Figure 11. Schematic of grooves machined into capillary block

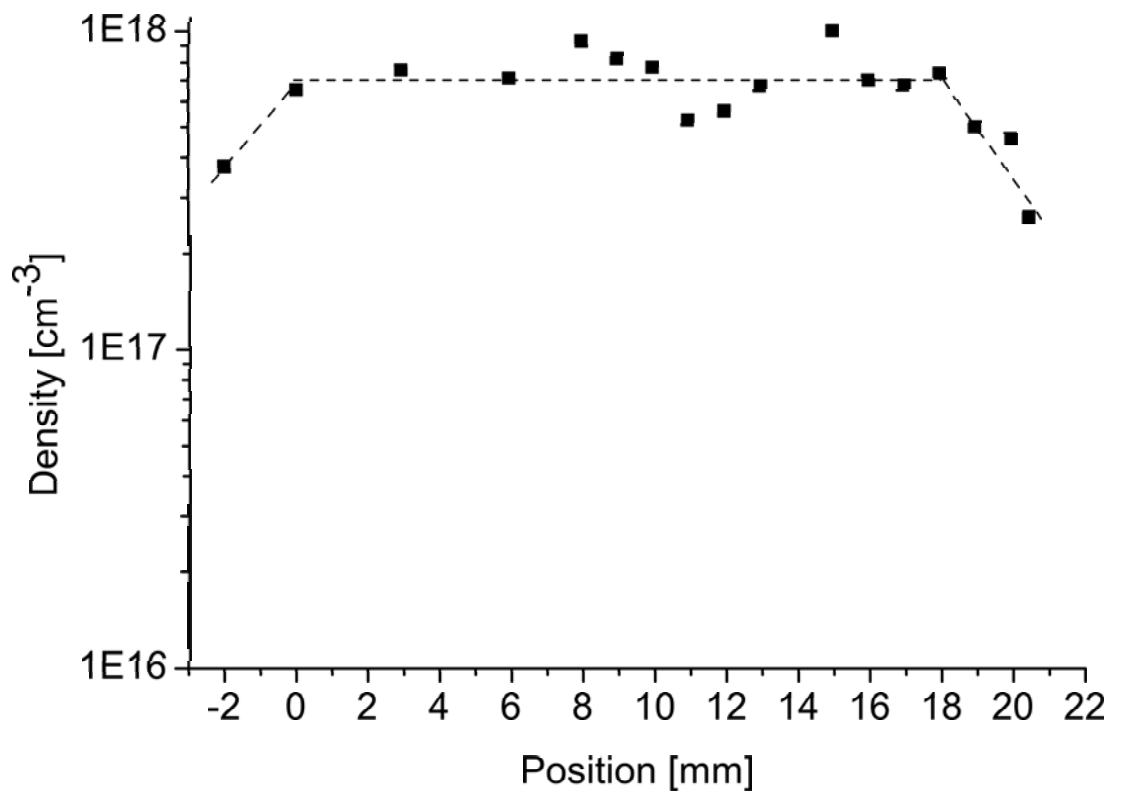Figure 12. Front and back face of capillary after 10^6 shots

Figure 13. Plasma density measured along capillary using Raman amplification
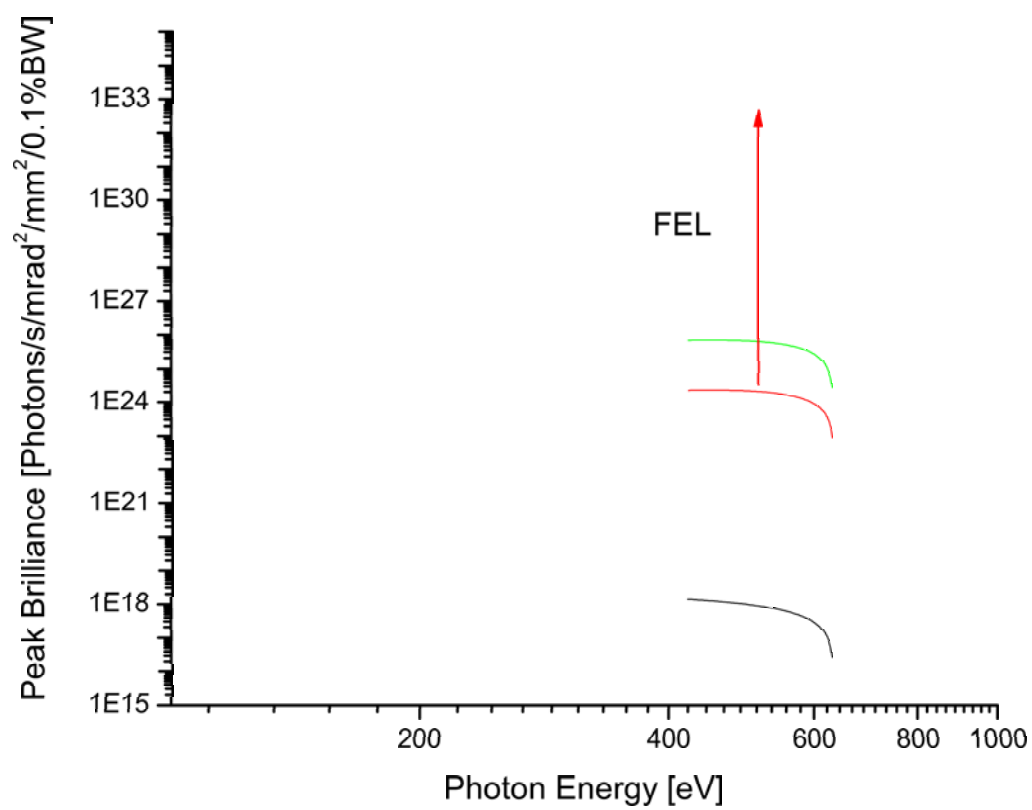
Figure 14. Calculation of the x-ray beam brilliance of synchrotron radiation and FEL
output as a function of photon energy for a 1 GeV beam.