IMPACT OF THE GREAT PROJECT ELI (EXTREME LIGHT INFRASTRUCTURE) ON MEDICAL CARE AND ON NEW TECHNOLOGY FOR INDUSTRY

a) Medicine: Application to HadronTherapy

High-power laser systems as proposed in the ELI project afford new and unique possibilities of producing of intense particle beams with energies in the MeV to GeV region. Particular advantages of laser-driven accelerators are their compact size (‘table-top’ devices) and low cost – both investment and operation costs – which would significantly reduce the size and cost of hospital-based proton and light-ion cancer treatment facilities. Furthermore, laser technology may offer much more elegant and cost-saving solutions for the rotating gantry structures, which at present are very heavy and bulky devices allowing beam delivery to the patient at all angles. For these reasons, laser technology is expected to revolutionize the field of particle radiotherapy and make very compact treatment units available. As a result, much more patients would benefit from highly precise and effective radiation treatment with energetic particle beams. At present, twenty-five proton and three carbon-ion treatment units are in operation world-wide, these using either cyclotron or synchrotron RF accelerators.

In Europe a number of new facilities are coming up soon or in the near future: RPTC Munich (protons), HIT Heidelberg (light ions), CNAO Milan (light ions), MED-AUSTRON Vienna (light ions), ETOILE Lyon (light ions), and RKA Marburg (light ions). These facilities will be the first clinical-based ion therapy centres in Europe. In view of the promising clinical results recently obtained with carbon-ion radiotherapy at HIMAC/Japan and GSI Darmstadt/Germany, there is a strong demand for new treatment facilities with much higher patient capacity. Laser-driven accelerators are therefore expected to have a strong impact on the next generation of treatment facilities.

The typical and most critical requirements for particle beams used for cancer treatment are briefly discussed in the following:

The major physical advantage of charged-particle beams in radiotherapy is their excellent inverted depth-dose profile (Bragg curve) offering most favourable conditions for the treatment of deep-seated tumours. In contrast, to photons the energy deposition increases for particles with depths up to a pronounced maximum (Bragg peak) at the end of range. For example, the Bragg peak of a 330 MeV/u monoenergetic carbon-ion beam penetrating 20 cm into tissue has a half-width (FWHM) of only 5 mm and the peak dose is a factor of about 4.5 higher than the plateau dose. The width of the Bragg peak is mainly caused by the unavoidable energy-loss straggling. By varying the particle energy, the depth of the Bragg peak in the target volume can be precisely adjusted to the location prescribed by the treatment plan. With scanning systems, the target volume is irradiated slice-by-slice in steps of typically 1 - 2 mm in depth by moving pencil-like ion beams over each target slice in strict accordance with the prescribed contour and dose pattern.

Both the absolute kinetic energy and the energy spread of the incident ion beam are of key importance for radiotherapy applications. In the example above, an energy shift of ±1% would shift the Bragg peak location by ±3.3 mm. At least at higher energies, the energy spread of the primary beam should therefore be better than 1%. The recent finding of narrow peak structures of laser-generated electron beams (Nature Vol. 431, Sept.2004) was an important step demonstrating that favourable beam characteristics such as narrow beam energy spectra can be achieved by the laser-foil technology. Laser-generated carbon-ion beams with an energy spread of 25% at 3 MeV/u have been produced experimentally. PIC-simulations predict a much smaller energy spread (order of 1%) at higher laser power.

The treatment of deep-seated tumours requires beam energies in the range of about 50 – 430 MeV/u for carbon-ions. Ideally, the selected energy is delivered directly by the accelerator. Alternatively, passive degraders (range-shifters) can be used for energy selection, but this causes contamination of the primary beam by secondary fragmentation products, in particular neutrons, with long ranges. These particles can be removed by proper shielding and cleaning magnets before reaching the treatment area, but only at the expense of increased space and cost requirements.

Another important question is how to control the beam intensity and number of ions delivered, which is directly related to the dose deposited in a patient. Scanning beam systems (such as operational at GSI) require intensities in the range of 10^6 – 10^8 carbon ions per second, the scanning speed being limited by the magnet power supplies. Such systems require beams with a well-defined average intensity and can tolerate only small fluctuations. For a laser-driven system, control and regulation of the dose rate would require either a sufficiently high pulse repetition rate (100 – 1000 Hz) or stretching of the ultra-short pulses. This could be achieved by injecting the short particle pulses into a stretcher ring which would also serve as an accumulator ring. From this ring particle beams with well-defined beam energy could be slowly extracted and distributed to several treatment rooms.

The basic requirements for particle beam applications used in radiotherapy are:
-type of ion proton: He, Li, B, C, O
-contamination level: < 1%
-Energy range protons He 30 – 220 MeV/u
-C 50 – 430 MeV/u
-O 50 – 500 MeV/u
-energy spread: 0.1 – 1%
-intensity range: 10^6 – 10^8 ions/s
-selectable intensity levels, small fluctuations
-time structure: 100 – 1000 Hz rep. cycle required for dose control or pulse stretching
-beam interrupt: fast (< 1 ms)

Although these requirements can not yet be fully met by laser-driven systems, solutions to specific problems might be possible in the near future. The requirements for scanning beam systems are higher than those for passive beam delivery systems. However, scanning beam systems are clearly superior, giving optimum three-dimensional conformation of the dose to the target volume and thus taking full advantage of the clinical benefits of light-ion beams.

Replacement of the LINAC section by a laser-driven accelerator (as proposed by M. Roth) will represent a very important first step towards laser-generated ion beam applications in radiotherapy and is essential for demonstrating the feasibility and potential advantages of such systems. This would require particle beams of a few MeV/u, which have already been produced by existing laser-driven systems. Such a test facility would permit thorough investigations of all beam parameters relevant to applications in radiotherapy, in particular the stability and reproducibility of the particle energy as well as long-term behaviour and safety aspects.

b). Understanding fundamental aging processes in nuclear power plant material

ELI will be a powerful tool for generating secondary beams, among which intense, ultra-short particle bunches may prove particularly useful for material sciences. Let us recall that with present-day lasers it has already been demonstrated that electrons with hundreds of MeV, protons and carbon ions with several MeV, and even 2.5-MeV neutrons can be obtained in short (sub-picosecond) and intense ($>10^{12}$ particles) pulses. It is reasonable to expect that a ×1000 increase of the power available will result in much more intense pulses for such particles, higher energies, and also the possibility of accelerating heavier ions.

Obviously, however, having access to short pulses of high-energy ions synchronized with laser pulses affords hope o realizing a brand new type of experiments, viz. ion (pump)- laser (probe) experiments. Indeed, the mechanisms leading to defect creation or phase transformation in materials subjected to low or high-energy ions involve as initial steps ultrafast processes whose elucidation is still a challenge: in the case of elastic scattering, collision cascades – at present observed only through atomistic simulations – or intense and short-lived electronic excitation in the case of high-energy ions – for which essentially two models were proposed long ago; and there is no clear answer yet concerning their respective validity. It is essential in both cases to obtain observations of the state of the target in the first few picoseconds after passage of the particles, and only laser-based sources can make such observations possible. It would, in principle, be possible either to observe directly the instantaneous electron distribution just after irradiation (in laser-laser experiments, time resolutions of a few 10^{-14} s are currently being achieved) or, with the use of a second derived source as a probe (e.g. an X-ray source, for X-ray diffraction experiments), to observe the onset of the disorder induced in the material with unequalled resolution.

It must be clear, however, that, if demonstration experiments can be started very soon, clean experiments will require such control of the ion beam quality as is still beyond reach for the time being. In particular, it will be necessary to control the ion charge state and the energy spectrum, while keeping the pulse as short as possible – i.e. well below one picosecond - at the sample position. This is a serious challenge the ion-beam community, and the availability of intense sub-picosecond ion pulses resulting from the completion of the ELI project could thus boost technical progress way beyond the laser community. In this respect, it is not too early to start thinking of solutions for recompressing an ion pulse to durations of less than one picosecond.

A final remark concerning experiments of this type is that they should bring decisive progress in a field (radiation physics) that is at the heart of the economic and environmental performances of major technologies, such as the production of electronuclear energy, and the associated fuel cycle.

b) Positron microscope

Intense and short pulses of positrons could also be particularly interesting. Positrons are used in several techniques of material analysis: The lifetime of the positrons in solids, this being in the range of picoseconds, is inversely proportional to the electron density. Positrons are easily trapped at vacancy-type defects, where the positron lifetime is prolonged. The lifetime spectrum, therefore, tells about the type and density of the defect distribution in solids. On this basis, it has been possible, for instance, to build a positron microscope able to observe inside a material the appearance of clusters of vacancies located at the head of a scratch. In addition, the chemical surroundings can be analyzed from the Doppler shift of the annihilation radiation. The Doppler effect can also be used to analyze the momentum distributions of the electrons in the solid in great detail.

Many of the techniques associated with positrons rely on measurement of their lifetime, which are in the range of hundreds of picoseconds. It is usually measured as the time elapsing between a start signal associated with penetration of the positron into the solid and detection of the gamma photons emitted in their annihilation with one material electron. This works because of the low intensity of the positron beams used so far (on the nanosecond time scale, they can be considered as isolated). This is also true in the case of the short bunches of positrons generated in existing machines, as well as in those still being planned (there are several such projects in Europe as well as in Japan), which produce pulses with durations of typically 100 ps at a high (tens of MHz) repetition rate, but with on average one positron only per pulse.

c) Positron sources for Bose-Einstein condensate

The progress that can be expected from a laser-produced positron source does not, however, arise mainly from the pulse shortness, since this will be extremely difficult to maintain in the necessary handling of the beam (which, in particular requires a moderation" stage followed by re-bunching of the positrons), but from the opportunity of obtaining intense pulses. One can consider first extensions of the applicability of present applications. For example, if it is possible to saturate all vacancies and vacancy clusters in the irradiated zone, the lifetime measurements could provide not only identification of the type of defects present in the sample but also, by virtue of the change in the lifetime occurring on saturation, a measurement of their absolute density. But entirely new physics could also emerge from high intensity positron sources, e.g. the possibility of realizing Bose-Einstein condensates of positronium: in a cavity with a volume of 1000 nm^3, such a condensate could be obtained with 100 positronium "atoms" only. But if 10^{10} positronium atoms could be trapped in a 1-cm-long cavity 1 µm in diameter, some recent theoretical predictions suggest the possibility of realizing in this way a 511-keV X-ray laser.

d) Improving environment: transmutation and nuclear waste treatment

Transmutation, i.e. using nuclear reactions to change very long-lived radioactive elements into less radioactive or shorter-lived products – is a concept for nuclear waste management being developed in several countries. Very long-lived iodine-129 has a half-life of 15.7 million years, high radiotoxicity and mobility, and is an important constituent of nuclear waste – making it one of the primary risk considerations in the nuclear industry. It currently has to be sheathed in glass and buried deep underground. Handling of iodine is also difficult since it is corrosive and volatile. Through the laser-induced photo-transmutation process, this long-lived isotope is transmuted first to the short-lived isotope, iodine-128, which then decays with a half-life of 25 minutes to the stable inert gas, xenon-128. The experiments demonstrate the feasibility of transmuting radioactive iodine-129; limitations to scaling up this technique may be the high energy consumption of the laser and the low cross-sections of the elements in question, resulting in low transmutation efficiencies. By focusing the high-power laser onto a tantalum metal target, the beam generates a plasma with temperatures of ten billion degrees. The electrons in the plasma generate gamma radiation intense enough to induce nuclear reactions in the iodine target.