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Investigation of plasma (Gabor) lenses for capture and focusing of laser-driven ions

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Laser-driven proton and ion acceleration has been identified as an alternative to conventional accelerators for certain applications, like isotope production or cancer therapy with hadrons, as it has the advantages of reduced size and cost over synchrotrons. In the regime of target normal sheath acceleration (TNSA) ions have been accelerated to kinetic energies of a few 10 MeV on the micrometre scale. The generated bunches have large energy spread and angular divergence, while also being characterised by small transverse emittance, short pulse duration and a large number of particles per bunch. In order to efficiently use the accelerated particles and generate a beam, it is critical to capture, transport and focus the ions with beamline elements that have high transmission and metre-scale focal lengths. For most applications it is also favourable to reduce the energy spread of the beam. Conventional optical systems such as large aperture pulsed high-field solenoids and dedicated compact permanent quadrupole magnet assemblies were successfully applied but may experience limitations in the transmission efficiency. Innovative laser plasma methods might be exploited for initial beam manipulation, but the capture, transport and focus of the generated ions remain a challenging task.

A cost-effective alternative is to employ a space charge (Gabor) lens. The lens consists of a trapped non-neutral electron plasma that creates a radially focusing force in both transverse planes simultaneously. The magnetic field required to confine the plasma is significantly reduced compared to that of a conventional solenoid with the same focusing strength. The focal length of the plasma lens is proportional to the energy of the particles entering the lens in contrast to conventional solenoid or quadrupole lenses in which the focal length is proportional to the square root of the particle energy. Thus, the Gabor lens is even more advantageous for focusing heavier ions like carbon or in the view of new laser-driven ion acceleration mechanisms that may allow acceleration to GeV energies.

The 'Laser-hybrid Accelerator for Radiobiological Applications', LhARA, is conceived as a uniquely flexible facility dedicated to the study of a completely new regime of radiobiology. LhARA is designed to employ Gabor lenses to capture and focus the particles produced in the laser-target interaction at energies up to 15 MeV, thus evading the space-charge limitations of current sources and enabling ultra-high instantaneous dose rates of up to 10^9 Gy/s. A first Gabor lens prototype for LhARA was built at Imperial College London and tested with a conventional proton beam. Particle-in-cell (PIC) and beam-tracking simulations were used to study the stability of the confined plasma and the effect of several instabilities on particle transport. The results will be presented together with the current efforts to design a second lens that can act as a reliable focusing device for LhARA. The main challenges in the operation of such a plasma lens are the confinement of a high-density space-charge (10^{15} m^{-3}), the control of the production mechanism of the plasma, and the use of non-destructive diagnostics.