A Review of Plasma Lens Technologies for the Laser-hybrid Accelerator for Radiobiological Purposes (LhARA)

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First Year PG Report
27th February, 2025

Abstract

This report reviews the active plasma lens (APL) and Gabor lens for implementation on the beamline at LhARA. The Gabor lens currently suffers from plasma instabilities, limited effective radius, and electron loss, while the APL is limited to a smaller lens aperture due to z-pinching. By utilising developments from the electron trapping community, researchers are overcoming the challenges of the Gabor lens, making it the more viable option at present. However, recent research has suggested an improvement in the angular acceptance of the APL and the experiments planned at Peking University and at LIGHT should be closely followed.

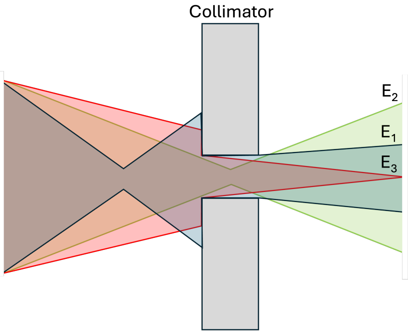

Figure 1: Side-view of energy collimator "selecting" E_2. The monoenergetic beams have energies $E_1 < E_2 < E_3$ and have been focussed by a lens upstream and the collimator is placed at the focal length for E_2.

1 Introduction

Particle Beam Therapy (PBT) takes advantage of the Bragg peak effect by utilising protons or light ions to deliver the same dose as conventional X-ray beams, but with less damage to the healthy tissue, [1]. However, PBT is performed mainly in high-income countries [2]. If PBT can be scaled down in cost and size, it will become accessible to mid/low-income countries. Furthermore, the processes behind particle radiotherapy are not fully understood [1]. With this motivation, the Laser-hybrid Accelerator for Radiobiological Applications (LhARA) is aiming to build a facility to study PBT [1]. LhARA employs a Laser-Driven (LD) proton source rather than conventional RF acceleration. In LD sources protons and light ions are accelerated through the Target Normal Sheath Acceleration (TNSA) produced by firing a high-power laser (100TW) at a target [1]. The achievable accelerating-voltage gradient for TNSA is four orders of magnitude greater than RF acceleration, so a facility's footprint can be greatly reduced [3].

LD beams have a wide energy spread and a large divergence. Therefore, a lens is required close to the source for optimal capture efficiency. Due to the energy spread, the lens will also be employed to select the required energy. By exploiting the chromaticity of a lens (the focal length varies with particle momentum [4]), a collimator can be placed at the focal length of the nominal energy to remove a large proportion of unwanted energies, as shown in Figure 1. Plasma lenses are compact and theoretically achieve the same focussing strength for a reduced magnetic field strength compared with conventional quadrupoles or pulsed high-field solenoids [4]. In the original proposed design for LhARA, non-neutral plasma lenses were chosen for implementation [1]. This lens, (also called a Gabor lens), consists of an electron cloud confined radially by a solenoid and longitudinally by end-cap electrodes, as shown in Figure 2. The cloud generates electrostatic focussing for a positively charged beam [5]. This review will explore and compare the suitability of the Gabor lens with the capillary discharge lens, (also known as an active plasma lens (APL) due to the use of an external driving current [6]). In an APL, shown in Figure 3, two electrodes on either end of a gas-filled cylindrical tube generate a current that produces an azimuthal magnetic field that can focus the beam.

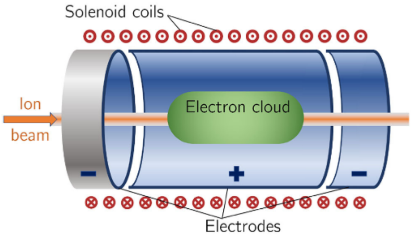

Figure 2: Schematic of a Gabor Lens. A central cylindrical anode and two end electrodes confine the electron cloud longitudinally, while the solenoid coils produce an axial magnetic field to confine the electrons radially.

2 Gabor Lens

2.1 Fundamental Principles

The defining features of a Gabor lens are the non-neutrality of the plasma and the azimuthal symmetry [7]. First proposed by Denis Gabor in 1947 [5] using a Penning-Malmberg trap to confine an electron cloud, the basic design is shown in Figure 2. From Gauss' law, the radial electric field, E_r, in a cloud with uniform density, n_e, is proportional to the distance from the central axis of the cloud, r, $E_r = -en_er/2\epsilon_0$. Assuming the thin lens approximation, when a beam of positively charged particles with atomic number, Z, mass, m, and momentum, p, passes through the cloud of electron density, n_e, it feels a perfect focussing force with strength

$$k = \frac{e^2 Zm\gamma n_e}{2\epsilon_0 p^2} \tag{1}$$

where γ is the relativistic lorentz factor. To confine the plasma, the potential across the two electrodes must be sufficient to balance the plasma space-charge potential providing a minimum voltage of

$$\Delta\phi = \frac{en_er_p^2}{4\epsilon_0}\left(1 + 2\ln\left(\frac{r_w}{r_p}\right)\right) \tag{2}$$

where r_p is the plasma radius, r_ω is the trap radius and n_e is the electron density. We have assumed a uniform density, rectangular density profile and an infinitely long trap. The last assumption means that for shorter lenses higher voltages than $\Delta\phi$ are often required.

The radial expansion of the plasma from its space-charge is counteracted by an axial uniform magnetic field, created by current-carrying coils wrapped azimuthally around the electron cloud. The required magnetic field to contain a certain density can be determined by the Brillouin limit equation [8],

$$n_\text{B} = \frac{\epsilon_0 B^2}{2m_e} = 4.8 \times 10^{18} B^2 \tag{3}$$

By combining equations (2) & (3), an "operation function" for the lens can be defined [9],

$$\Delta\phi = \frac{er_p^2}{8m_e}\left(1 + 2ln\left(\frac{r_w}{r_p}\right)\right)B_z^2 \tag{4}$$

The operation function defines, in an idealised state, the optimum configuration between the electrode potential $\Delta\phi$ and the axial magnetic field B to obtain the maximum plasma density. From equation (1), one can see that the focussing power of the lens depends on the electron density. Therefore, the Brillouin limit provides a maximum focussing power that can be achieved. However, the record density achieved in an electron plasma is $\sim 17\%$ of n_B [10].

2.2 Historical Review

Gabor originally proposed a non-neutral plasma lens in 1947 [5]. After Gabor, attempts to create the practical lens reported relatively successful results[11], but encountered issues such as large variations in focussing strength with time. In 1990 in Frankfurt [12], experiments showed negligible emittance growth of a 10keV He beam but a focal length four times larger than expected. After a measurement of the energy of the escaping ions from the lens, this was concluded to have been caused by a partially full lens.

A thesis was written on a prototype Gabor lens for the GSI[1] High Current Injector [9] in 2013. In their experiment two plasma instabilities were observed: a longitudinal instability that was causing a fluctuation in the ion current and the so-called diocotron instability [13], which results from a non-uniform radial density profile. This diocotron instability causes a shear in the adjacent azimuthal layers of the plasma, inducing vortices and distortions in the plasma column. The effect often leads to ring beams after focussing [4]. Similar to Frankfurt, there was also a difficulty in obtaining a uniform plasma across a large radius lens as required for GSI. Due to the finite plasma temperature, the plasma cools nearer to the electrode wall [9]. This causes the density profile to drop smoothly after some number of Debye lengths rather than a sharp drop-off. For high-quality focussing the effective diameter of the Gabor lens is the width of uniform density plasma, excluding the outer regions of varying density.

Studies in the LhARA group have reported similar issues in limited effective radius and plasma instabilities [14]. Furthermore, the studies, which used a prototype designed at Imperial College London and a test bench at the University of Swansea, also also found significant electron loss. For the electron cloud to be suitable as a beam focussing device, the confinement time must be significantly longer than the duration of bunch transit through the plasma. To avoid

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continuously refilling the lens, the electron cloud lifetime at a constant density must be greater than several ion bunch passes, i.e. of the order of seconds [4]. When testing the lens at Swansea, it was found to lose roughly half the electrons after one second. The electron loss was found to be radial, and it is known that radial loss is dependent on the ratio of L/B_z where L is the length of the trap [15]. Indeed, there were improvements with both an increased magnetic field and a shorter lens. It was estimated that to have a lifetime of the order of 100ms the lens would need to be a few 10s of centimetres [4].

The experiments at Frankfurt, GSI and in LhARA suffered from plasma instabilities, a radius limited by the width of the uniform plasma and electron loss. To produce the the electron cloud these experiments ionised the background gas in the trap, leading to little control over the plasma density profiles and the evolution of instabilities. To tackle the challenges a more controlled source of electron production is required along with an incorporation of active reduction of radial transport are required to produce a reliable lens.

2.3 Confinement Techniques

In the non-neutral plasma confinement community, stable and reliable confinement of non-neutral plasmas has been shown to work via two main operating principles: rotating-wall technique and evaporative cooling [16]. The plasma rotates at a natural frequency set by the $(\mathbf{E}\times\mathbf{B})$ drift combined with the diamagnetic drift [16]. Diamagnetic drift is due to the pressure gradients in the plasma. It has been shown that the frequency of rotation can be controlled by applying rotating electric fields at frequencies near the plasma's rotation frequency [17],

$$f = \left(\frac{e}{4\pi\epsilon_0 B_z}\right) n_e \tag{5}$$

The rotating electric fields are created by applying oscillating potentials phased with a time delay to each rotating electrode. It is a well-established technique, first done in 1997 by Huang et al [18]. In 2006 Danielson and Surko [19] found that plasma rotation can be further controlled when in the strong drive frequency regime. The strong-drive regime is when strong compression of the plasma is achieved by a significantly high rotating-wall amplitude [20]. Since the density of the plasma is linked to the rotating frequency this technique can control the density of the plasma.

The second technique employed is evaporative cooling. This provides control of the plasma potential by allowing the most energetic particles to escape by reducing the potential on one electrode. The particles left are cooler than the initial plasma, thereby allowing control of the plasma potential and via equation (2), the plasma radius.

The rotating-wall technique and evaporating cooling lead to competing effects. The rotating wall heats and compresses the plasma radially while cooling cools and expands [17]. This means that tuning of the potential well shape, rotating wall amplitudes and frequencies, and axial plasma positions relative to the rotating wall electrode is required. The paper [17] showed that once successfully tuned, one could control the electron density and the plasma potential, thus stabilising the plasma in terms of its density and number of particles.

2.4 Current Research

These techniques are now employed at the new test bench at the University of Swansea along with an electron gun source. The lens is 1m in length with a density of $4 \times 10^{15}\mathrm{m}^{-3}$. Solenoid coils produce a 40mT field. It incorporates the rotating wall technique and provides the necessary cooling using CO_2. This produced ions on collision with electrons which can be removed via evaporation when the electrodes are turned off. Further investigations are required to investigate the effects of the cooling gas, especially its pressure. There are also concerns that beam current might have an important impact on the reliability of the lens.

Furthermore, in 2023 a stable and reliable Gabor lens was designed for the transfer beamline to the HADES beamline at GSI [21]. 2m long Gabor lenses were inserted between quadrupoles in place of drifts. The lenses were employed to neutralise the space-charge effect and not for their focussing potential, meaning a higher electron density was not relevant, and the lens was easier to design than the version to be employed at LhARA. However, it is still promising to see the production of a reliable lens.

Overall, research into Gabor lenses has steadily increased and despite previous designs leading to lens aberrations, utilising the work of the non-neutral plasma confining community has led to significant breakthroughs towards the installment of a reliable lens.

3 Active Plasma Lens

3.1 Fundamental Principles

The simplest explanation of an APL is that a beam propagating along an external current, I, is radially focussed. According to Ampere's law this radial magnetic field gradient, g, for a discharge with radius, R, can be described by

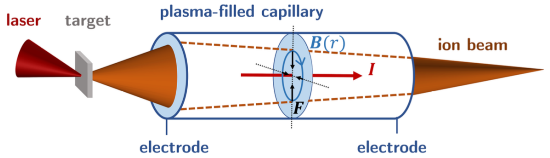

Figure 3: Schematic of a simple capillary-discharge APL. The current in the capillary generates a magnetic field, B and thus a focussing force, F.

$$g = \frac{\partial B_\theta}{\partial r} = \frac{\mu_0 I}{2\pi R^2} \tag{6}$$

where r is the distance from the central discharge current axis. Under this gradient, protons make a linear betatron motion [6], described by Hill's equation

$$\frac{d^2 r}{dz^2} + Kz = 0 \tag{7}$$

Where $K = \frac{e\mu_0 I}{2\pi R^2 p}$ is the focussing strength of an ideal APL acting on a beam with momentum, p. The discharge is of the order of nanoseconds, making APLs suitable for pulsed beams with short bunches like LhARA [4].

3.2 Historical Review

The first APL was constructed in 1950 by Panofsky and Baker [22] at Berkeley with a 7.62cm diameter tube. This experiment, along with experiments at Brookhaven National Laboratory (BNL) in 1965 [23] and CERN in 1987 [24], had large diameters ($\sim$ 40mm) and experienced the z-pinch effect. The z-pinch effect occurs when the magnetic pressure at the tube wall overcomes the plasma pressure,

$$\frac{B^2}{2\mu_0} = \frac{g^2 R^2}{2\mu_0} > n_e k_\mathrm{B} T_e \tag{8}$$

where n_e is the electron density and T_e is the electron temperature. This concentrates the current near the axis and if timed properly can focus a beam. However, these devices produce a non-linear magnetic focussing field [25]. In 1993, a "wall-stabilised" active plasma lenses was tested at GSI [26]. This is characterised by a skin depth, (the distance em waves can propagate in the plasma before their amplitude is reduced by a factor of 1/e), that is larger than the capillary diameter, allowing the pulsed current to flow homogenously across the whole capillary cross-section [26]. This stops the z-pinch effect and has several advantages over z-pinch lenses, including better focussing accuracy and longer stability over time [26]. This technique limits the radius and the discharge current to avoid z-pinching.

3.3 Experimental Progress

In 2017/18, APLs based on gas-filled discharge capillaries were employed on electron beamlines at Lawrence Berkeley National Laboratory (LBNL), INFN and Oxford [27]. The experiments showed several interesting results, including that APLs show little chromaticity making them useful for focussing the broad range of energies that occur from a LD source [28]. Although, this could also become a problem if the variation of focal length with energy is too small to allow energy selection after capture. The experiments identified two main challenges for APLs: the non-uniform plasma heating and the wakefields.

Due to finite temperature, the radius of linear focussing (or effective radius) is around half the lens radius [29]. This aberration leads to ring beams [30]. However, in Oxford it was found that employing a heavier gas increases the effective radius and removes the aberration. On the other hand, the use of heavier gas sees emittance growth due to scattering that increases almost quadratically with atomic number. This can be reduced with higher discharge current or by decreasing the lens radius [29]. At INFN it was found that a higher discharge current also reduced the non-uniformity.

Wakefields occur when the density of the plasma is not much greater than the density of the beam and can set up potentially very strong, nonlinear focussing fields [4]. To avoid wakefields, $n_p/n_b >> 1$ is required. By employing a larger transverse beam profile, thus reducing the beam density, the wakefield effects are significantly diminished [31]. However, the transverse beam profile is limited by the effective radius of the lens. It has been shown that wakefields can also be reduced by decreasing the length of the lens because the charge density does not grow sufficiently before it leaves the lens [32]. This is compensated for by increasing the discharge current and therefore the magnetic field gradient [33]. The shorter lens also has the benefit of reducing the number of collisions between the beam and the gas, which is important for heavier gasses, as mentioned previously [33].

Overall, the use of high current appears critical, but must be balanced by the possibility of re-introducing z-pinch effects, usually by reducing the trap radius. Proton beams, unlike electron beams, can be non-relativistic and more divergent, so that small apertures lead to unsatisfactory capture efficiency [4]. Therefore, one of the biggest hurdles between APLs and their successful installation on the LhARA beamline is the small lens aperture and subsequent transport efficiency.

3.4 Current Research

In 2022, the first attempts to install an APL on a proton beamline were undertaken [3]. An Argon-filled APL was used to focus protons on the 2MeV BELLA PW laser proton beamline at LBNL. Unfortunately, the lens suffered from poor transport efficiency at only 0.2% for energies above 1.5MeV. After this, the facility switched to a quadrupole configuration on the understanding that the radial acceptance and therefore the transport efficiency could not be scaled up from their previous attempt without encountering z-pinching, making this APL unviable [34].

At the same time, researchers at the University of Peking were designing an APL for another LD proton beam [35]. Again, a heavier gas was used to increase the effective radius. They concluded that the large divergence angle of LD protons is challenging to overcome for APLs. Furthermore, a limit was imposed on how close the APL could be placed to the source. If the APL is too near the source, then the gas discharge can damage the laser target. In addition, space for the electrode is required. The researchers did suggest mounting the laser target on the electrode to allow a smaller drift between source and lens, though this will require development of new technologies [35]. To address the transport efficiency issue, a simulation of a varying radius capillary tube was undertaken [6]. This found promising results with an increase in collection angle by 80%. Further experimental confirmation is required, but this simple geometric approach appears to be a potential new avenue for APLs on proton beam lines.

Finally, there are plans to test an APL for replacement of solenoids as the focussing element at the Laser Ion Generation, Handling and Transport (LIGHT) [36]. The outcome of the preliminary tests are awaited.

4 Conclusion

In summary, Gabor lenses and APLs both require significant research before reliable employment at LhARA can begin. Recent research into the confinement strategies of Gabor lenses indicates a promising resolution to electron loss and instabilities such as diocotron modes. Similarly, nonuniform current densities from wakefields and inadequate plasma heating in APLs have been overcome. In both cases the effect of the lens on the beam emittance is required to be investigated experimentally. However, for the lens to be employed at LhARA an angular acceptance of 50mrad is required [1] and while the simulations of varying-radius APL at University of Peking are promising, the current best experimental angular acceptance is 11mrad at the BELLA beamline.

The current lack of scalability of the radius of an APL due to z-pinching means the Gabor lens remains a more viable option for installation at LhARA. Nonetheless, the ongoing tests at LIGHT with APLs should be monitored and may provide useful insights into the potential of APLs and proton beams, as well as any further tests conducted in University of Peking.

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