Active plasma lenses

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Over the last roughly five years, the so-called active plasma lens (APL) has garnered substantial interest in the context of particle beam optics. They offer the opportunity for extremely high gradient transverse focusing of charged particle beams which is simultaneously radially symmetric and highly tunable. Combined, these features of the APL represent a substantial advantage compared to conventional magnetic quadrupoles.

APLs achieve these advantages through a drastically different approach to generating focusing fields. They consist of a gas filled capillary which is electrically discharged to produce a current that flows through the resultant plasma. The current is naturally associated with an azimuthal magnetic field with radially dependent amplitude. Thus, charged particle beams propagating axially through the plasma experience a focusing force arising from the radial magnetic field gradient. The strength of the focusing force is determined by the diameter of capillary and the amplitude of the discharge current and can easily approach several kT/m. For a given capillary geometry, the focusing strength experienced by a passing beam can be tuned either by reconfiguring the discharge circuit, or by adjusting the discharge timing relative to the arrival of the particle beam and making use of a time dependent current profile. The latter approach allows a very simple means for online adjustment comparable to conventional electromagnets.

Although the concept for APLs is not new, it dates back to 1950 [1], they have not widely been used for electron beams until recently [2]. Likely, this is due to a number of reasons. In order for an APL to be useful, the beam has to have transverse dimensions smaller than the capillary diameter, which is generally less than 1 mm. Such a small aperture is impractical for most transport lines. The use of plasma is also a concern for ultra-high vacuum environments found in most accelerators. Furthermore, the extreme focusing strengths available in an APL are generally only necessary for relatively high energy electron beams (>100 MeV).

However, the advent of plasma-based accelerators has ushered in a radically new type of electron beam source. In a laser plasma accelerator (LPA), electrons exit the plasma with energies of tens of MeV to several GeV with transverse dimensions on the micron scale and divergences on the mrad scale. For many applications envisioned for LPAs, it is critical to ensure rapid capture of the divergent beams in order to avoid irreversible chromatic emittance growth [3]. This presents the significant challenge of developing ultra-short focal length lens systems for very high energy electrons with low chromaticity which can be placed near an LPA source. APLs neatly address each of these challenges. It is straightforward to design an APL with a focal length of a few centimeters for e-beams with energies of up to 10 GeV and which fully captures a mrad divergence beam. An APL might be a crucial component in the transporting high quality beams originating from plasma accelerators.

From a practical standpoint, APLs have played, and will continue to play, a pivotal role in expediting fundamental research and development areas in advanced accelerators. For example, in 2016, the APL enabled the first demonstration of multi stage electron LPAs [4]. Staging of acceleration modules is critical for collider development and requires substantial research effort to better understand fundamental aspects like beam loading, instabilities, inter-stage emittance growth etc. APLs eliminate the complexity of developing an inter-stage e-beam transport system using conventional quadrupoles capable of focusing GeV class electron beams. Electromagnetic quadrupoles would be expensive, massive, and very difficult to integrate into most LPA labs. Permanent magnet-based quads mitigate most of those problems but come with the notable disadvantage of being limited in their tunability, a particular crippling limitation for LPAs which can easily be tuned to generate bunches with central energies spanning a wide range. As such, APLs offer an elegant solution to otherwise complex problem which facilitates rapid progress in the study of advanced accelerator concepts.

APLs are also gaining traction in the development novel diagnostics specifically tailored to handle the unique properties and environments inherent to multi GeV LPAs. A compact, high resolution spectrometer, which doubles as an emittance diagnostic, was recently demonstrated [5]. Other concepts, like characterization of ultra-intense e-beams, can be also enabled by APLs [6]. Applications such as these are critical for the continued development of plasma based accelerators; improved diagnostics allow experiments to push on the beam quality and control frontier.

There are, of course, a number of potential limitations of APLs which have been identified. Nonlinear focusing fields, which cause emittance growth, arise due to temperature gradients in the plasma resulting in nonuniform current distribution [7-9]. This effect is largely avoided by employing larger discharge currents so that the complete ionization of the gas is reached [10], or by using heavier gases rather than light gases like hydrogen or helium [11]. However, a heavier gas also means more Coloumb scattering, which also causes emittance growth. The suppression of the nonlinear fields has to be balanced against scattering effects for proper APL optimization. In addition to the two effects mentioned above, it is also possible for the beam to drive wakefields in the plasma. Wakefields driven by the e-beam passing through the plasma can also induce emittance growth related to head-to-tail focusing variation, which depends on the charge density of the beam as well as the density and length of the APL itself [12-13].

Active plasma lenses have drawn attention for a number of reasons. In the near term, practical implementations of emerging technologies like the APL are fundamental to enhancing and progressing the capabilities of advanced compact accelerators. Applications towards plasma-accelerator-based positron and proton/ion beams should also be considered. In the long term, APLs are being considered for plasma based collider designs in applications like interstage transport as well as for the final focus. Continued study and development of APLs is important. Improved understanding of sources of emittance growth and ways to mitigate them is needed. Technological developments are also needed to reach milestones such as high-repetition-rate discharging to focus kHz e-beams [14].

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