# Underdense Thin Plasma Lens as a Tool for Future Colliders

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## Introduction

Plasma lenses can focus electron beams with strengths several orders of magnitude stronger than quadrupole focusing magnets [1-3]. The transverse force in the underdense, nonlinear blowout plasma wake regime is due to the presence of the stationary plasma ions. If the transverse density profile of this ion column is uniform, then the focusing force experienced by the electrons in a relativistic beam is both axisymmetric and linear with an electron's transverse displacement relative to the plasma wake's azimuthal axis of symmetry. These properties lead to an aberration-free focus of the electron beam that can achieve unprecedented small beam spots. The first order beam dynamics are simple to model and have been described in [1].

The underdense plasma lens can operate in either a two-bunch configuration where a “driver” electron bunch drives the nonlinear wake and a second, “witness” electron bunch is subsequently focused in the wake, or in a single-bunch configuration where the head of the single electron bunch is dense enough to drive the nonlinear wake and the bulk of the electron beam is focused. The plasma lens itself can be generated by laser ionization of gas, e.g. by focusing a femtosecond laser pulse into a gas jet. To minimize the longitudinal footprint, the laser pulse can propagate at 90° relative to the electron beam axis, reducing the space along the beam line required for the plasma lens to millimeters.

## Final Focus and the Oide Limit

Speculation about the potential use of plasma lenses for final focusing elements in a collider has existed for decades [2,3], although most incarnations of the plasma lens have failed to live up to the task. The strong, linear, axisymmetric focusing of the underdense plasma lens in combination with its ultra-compactness and “self-aligning” characteristics appear to make it perhaps the first truly viable candidate for this purpose. This may prove to be the case, although further study is still required. An important consideration is the scattering of the beam on the plasma ions, which may produce two problematic consequences: an increase in the beam emittance and a forward-directed shower of secondary particles. This could result in a reduced luminosity and increased background for particle detectors.

Oide in 1988 described the effect of hard synchrotron radiation on the emittance of an electron beam in the context of extreme focusing by a quadrupole magnet [4]. This emittance growth results in a minimum achievable final spot size, referred to as the Oide limit. Although this limit is known theoretically, it has yet to be demonstrated in experiment in the thirty-two years since Oide's paper. As collider technology improves towards being able to focus higher energy beams to smaller spot sizes, it will become necessary to study and understand this limit experimentally.

The Oide limit can be reached with a dense plasma lens operating in the underdense regime along with electron beam parameters that can be achieved at SLAC's upcoming FACET-II facility. If we consider an ideal passive plasma lens operating at a density $10^{18}\ \mathrm{cm}^{-3}$ with variable thickness, and a 10 GeV electron beam with 0.1% energy spread, normalized emittance $\varepsilon_N = 3\ \mu$m-rad, and vacuum waist beta function $\beta = 5$ m, the Oide limit will be reached with a lens of approximate thickness $L = 50\ \mu$m. At lower plasma lens thickness, the minimum rms spot size at the focus will be given by typical, ideal focusing predictions, while if the thickness is larger than L = 50 μm the rms spot size should follow Oide's model.

The beam parameters can be achieved at FACET-II, and laser-ionization of a plasma lens at $10^{18}$ $cm^{-3}$ is possible for thicknesses on the order of 10-200 μm based on the facility's experimental Ti:sapphire laser system parameters. A secondary, high peak-current drive beam traveling roughly 100 μm ahead of the main beam would be able to drive a sufficiently large nonlinear blowout wake in a plasma source of density $10^{18}$ $cm^{-3}$ to fully contain the main beam within the wake. Experimental planning to utilize this type of underdense thin plasma lens at FACET-II are currently underway.

## Plasma Lenses in Future Colliders

Apart from being a candidate for final focus optics, the strong, axisymmetric focusing of the underdense plasma lens has multiple applications in the context of a future plasma-based linear collider. In the case of plasma-based accelerators, plasma lenses can be used to "match" electron beams to the plasma [5]. If the beam is not matched to the plasma, it will experience irreversible emittance growth via chromatic filamentation, analogous to a mismatched beam in a synchrotron ring accelerator. The smaller footprint of the plasma lens also helps reduce the interstage distance between plasma acceleration stages as compared to the larger quadrupole magnets.

Plasma lenses can also be placed at the exit of a plasma-based accelerator to control the highly divergent matched beams that exit the plasma. It can be placed very close to the exit of the plasma thanks in part to its compactness, and it focuses axisymmetrically, simultaneously reducing the divergence of the electron beam in both transverse planes and mitigating chromatic emittance growth in the subsequent drift space. This feature is not only useful in the context of staging multiple plasma accelerators one after another, but it may also play a critical role in preserving the quality of ultra-high brightness beams that can be produced directly inside of a plasma accelerator. An example of this technique is the so-called "Trojan Horse" plasma photocathode injection method [6], which itself may prove to be a useful beam source for a future high-energy collider.

## Summary

The underdense plasma lens has many significant advantages over conventional magnetic focusing optics for high energy electron beams. It is orders of magnitude stronger, orders of magnitude more compact, and it focuses axisymmetrically. It may have potential for use as a final focus device for a future lepton collider, regardless of the accelerator technology used, and it will allow researchers to access the Oide limit in experiment for the first time at SLAC's FACET-II facility. Studying this effect will be critical in understanding the dynamics and limitations of any future collider's final focus system, which ultimately dictates what luminosities can be achieved. The underdense plasma lens can also be used to assist with matching beams into plasma accelerators and controlling the divergence of beams exiting plasma accelerators. At the same time, it can drastically reduce the distance required between plasma accelerator stages, significantly reducing the overall length of a plasma-based collider.

## References


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