Discussion on Plasma Lenses for Linear Colliders

Spencer Gessner

Snowmass CPM Session 187

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U.S. DEPARTMENT OF ENERGY | Stanford University

SLAC NATIONAL ACCELERATOR LABORATORY

Introduction

- Plasma lenses provide strong, *axisymmetric* focusing.

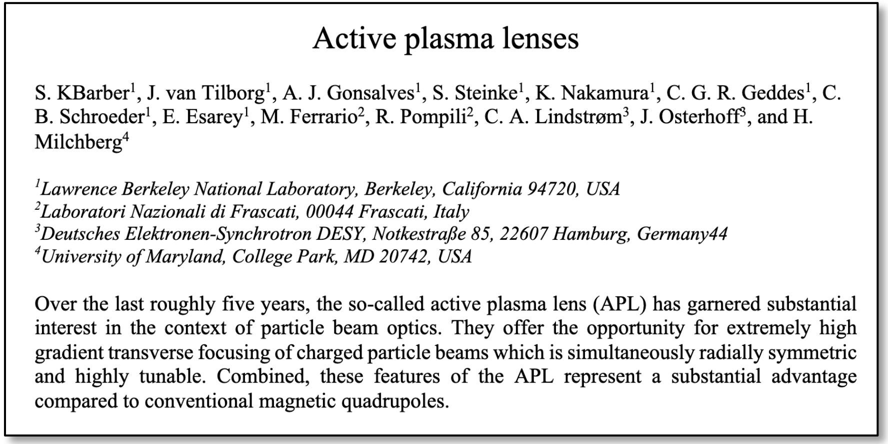
- Active plasma lenses (APL) have emerged as a critical tool in advanced accelerator technologies, specifically in LWFA staging.

- Passive plasma lenses (PPL) have been theorized as a route to the Oide limit and were experimentally tested at SLAC in the early 2000s.

- In this talk:
  - What are the merits of plasma lenses?
  - What are the drawbacks/limitations?
  - What role can they play in a future collider?

Snowmass LoIs on Plasma Lenses

Active Plasma Lenses



Active plasma lenses

S. KBarber[1], J. van Tilborg[1], A. J. Gonsalves[1], S. Steinke[1], K. Nakamura[1], C. G. R. Geddes[1], C. B. Schroeder[1], E. Esarey[1], M. Ferrario[2], R. Pompili[2], C. A. Lindstrøm[3], J. Osterhoff[3], and H. Milchberg[4]

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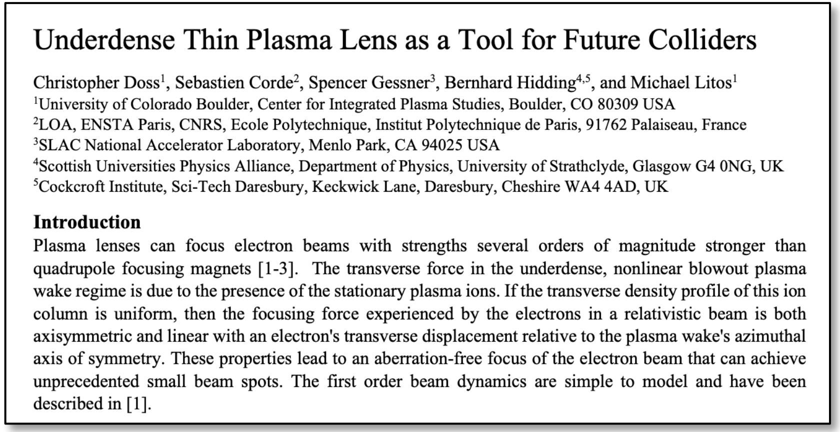
[2]*Laboratori Nazionali di Frascati, 00044 Frascati, Italy*
[3]*Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg, Germany44*
[4]*University of Maryland, College Park, MD 20742, USA*

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.

S. Barber et. al.
https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF6_AF0_Barber-196.pdf

Passive Plasma Lenses



Underdense Thin Plasma Lens as a Tool for Future Colliders

Christopher Doss[1], Sebastien Corde[2], Spencer Gessner[3], Bernhard Hidding[4,5], and Michael Litos[1]
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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].

C. Doss et. al.
https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF6-011.pdf

Active Plasma Lenses

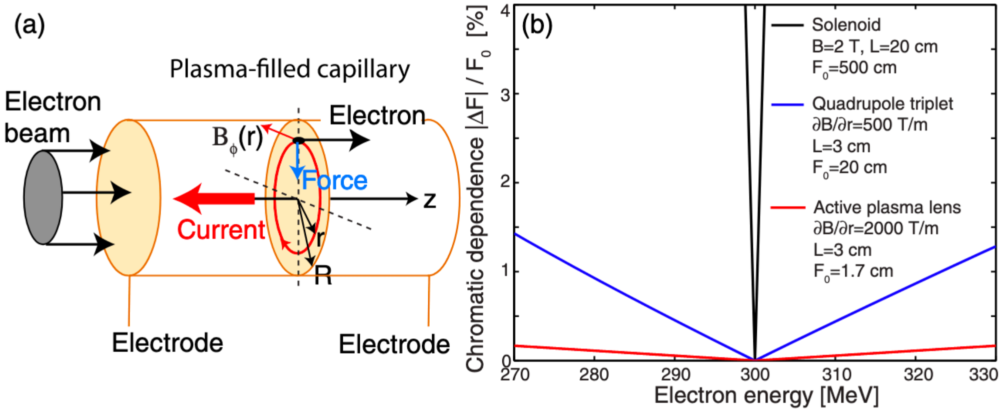
Active Plasma Lenses

An active plasma lens is made from a gas filled capillary with electrodes at either end. A large voltage is applied which ionizes the gas in the capillary and drives a current through the plasma. The advantages of the APL can be seen immediately:

$$g_{\mathrm{APL}} = 200\frac{I[\mathrm{kA}]]}{(R[\mathrm{mm}])^2}\ \mathrm{T/m}$$

The field gradient is independent of *r* (just like a quadrupole), *and* it provides simultaneous focusing of the *x* and *y* planes.

Plasma lenses offer field gradients of order 10 times greater than the strongest PMQs



J. van Tilborg et. al., PRL115,184802 (2015)

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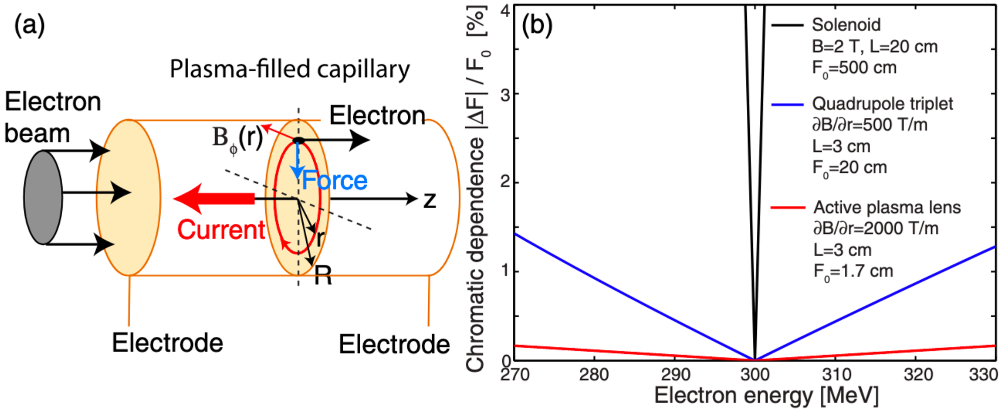

Important point #1:

The focusing does not depend on the beam shape. Works for both round and flat beams.

J. van Tilborg et. al., PRL115,184802 (2015)

Active Plasma Lenses

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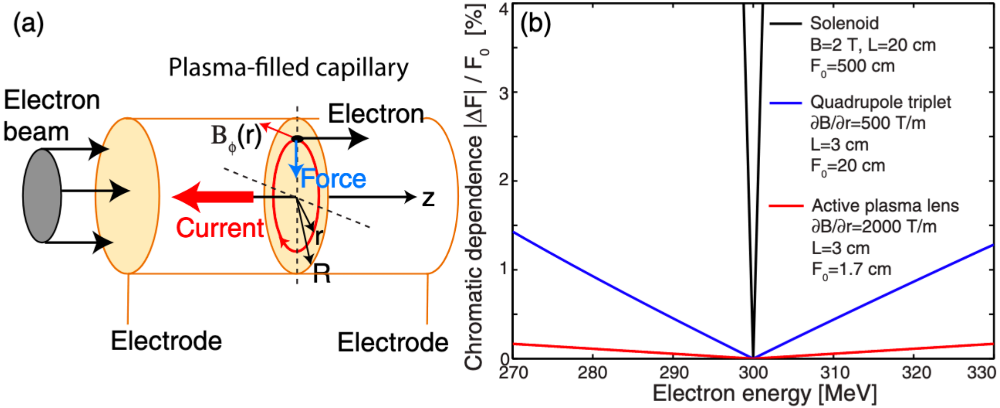


Important point #2:

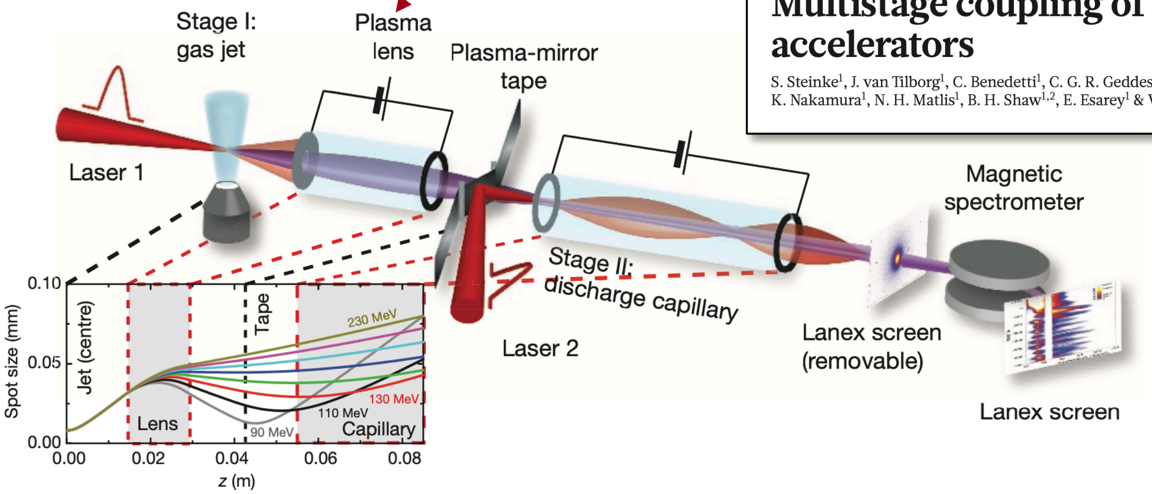
Since the focusing comes from the plasma current, it works for both electron and positron beams.

J. van Tilborg et. al., PRL115,184802 (2015)

Do they work?

Yes!

The APL is placed close to the first stage to capture the beam




LETTER

190 | NATURE | VOL 530 | 11 FEBRUARY 2016

doi:10.1038/nature16525

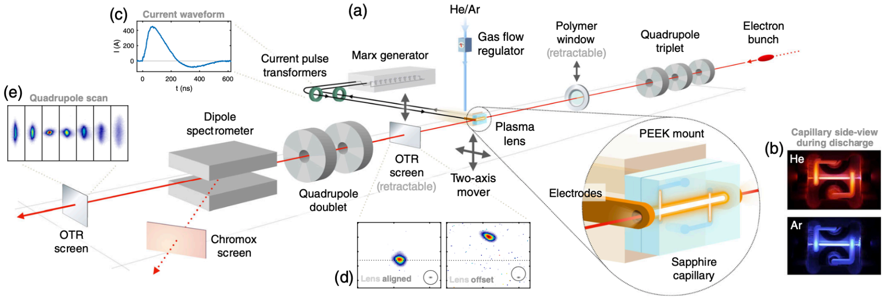
Multistage coupling of independent laser–plasma accelerators

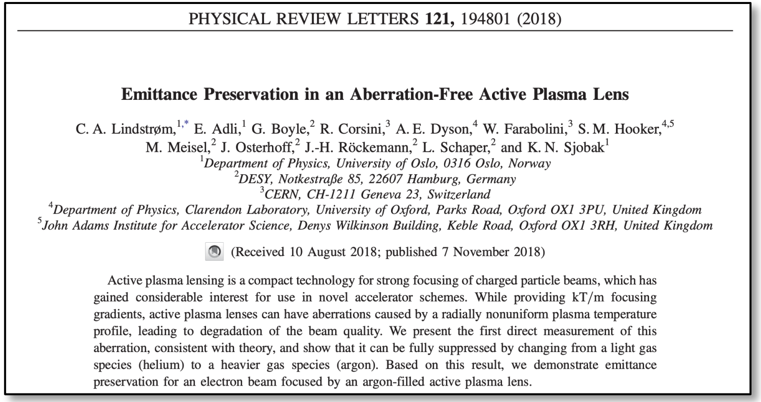
S. Steinke[1], J. van Tilborg[1], C. Benedetti[1], C. G. R. Geddes[1], C. B. Schroeder[1], J. Daniels[1,3], K. K. Swanson[1,2], A. J. Gonsalves[1], K. Nakamura[1], N. H. Matlis[1], B. H. Shaw[1,2], E. Esarey[1] & W. P. Leemans[1,2]

The APL was a critical component of the LWFA staging experiment at Berkeley.

Do they preserve emittance?

Yes!




PHYSICAL REVIEW LETTERS **121,** 194801 (2018)

Emittance Preservation in an Aberration-Free Active Plasma Lens

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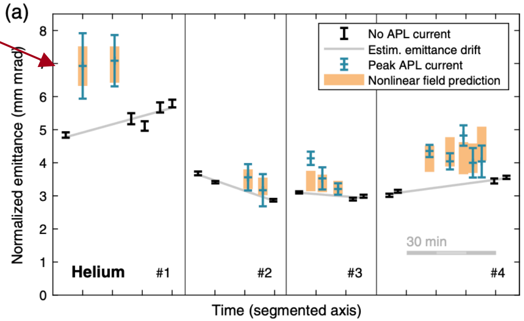
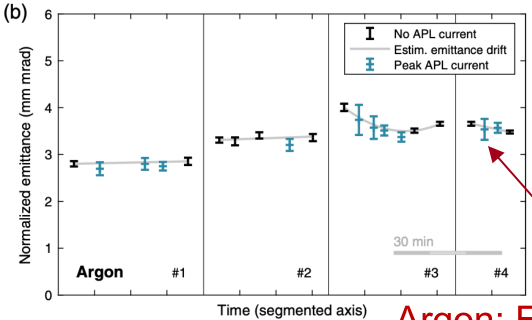
(Received 10 August 2018; published 7 November 2018)

Active plasma lensing is a compact technology for strong focusing of charged particle beams, which has gained considerable interest for use in novel accelerator schemes. While providing kT/m focusing gradients, active plasma lenses can have aberrations caused by a radially nonuniform plasma temperature profile, leading to degradation of the beam quality. We present the first direct measurement of this aberration, consistent with theory, and show that it can be fully suppressed by changing from a light gas species (helium) to a heavier gas species (argon). Based on this result, we demonstrate emittance preservation for an electron beam focused by an argon-filled active plasma lens.

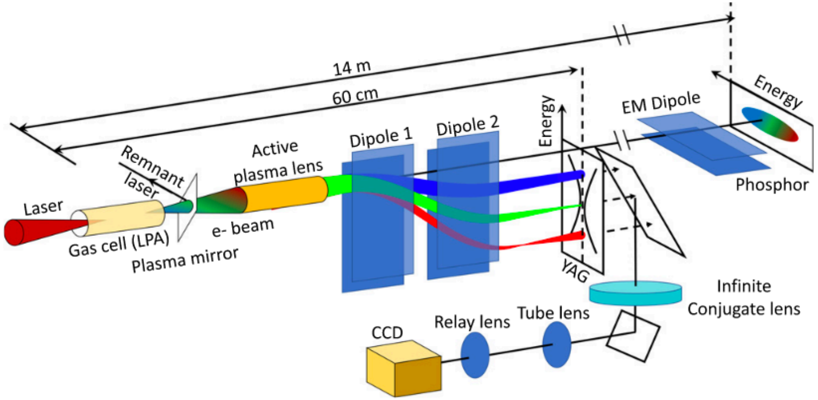
Helium: Emittance dilution due to non-uniform plasma current.

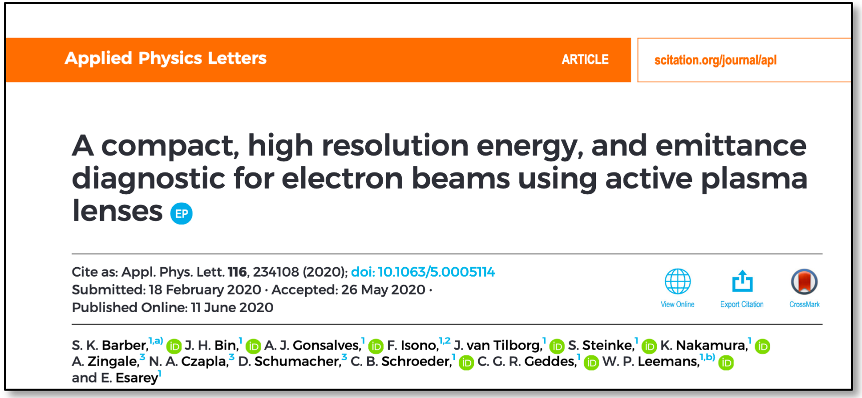




Argon: Emittance preservation with uniform plasma current.

What else are they good for?

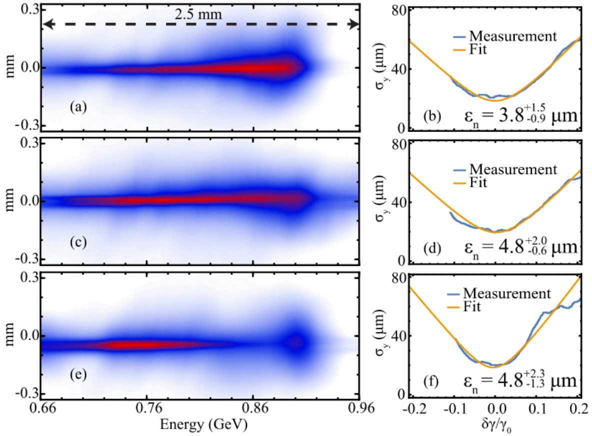



Applied Physics Letters ARTICLE scitation.org/journal/apl

A compact, high resolution energy, and emittance diagnostic for electron beams using active plasma lenses

Cite as: Appl. Phys. Lett. **116**, 234108 (2020); doi: 10.1063/5.0005114
Submitted: 18 February 2020 · Accepted: 26 May 2020 ·
Published Online: 11 June 2020

S. K. Barber,[1,a)] J. H. Bin,[1] A. J. Gonsalves,[1] F. Isono,[1,2] J. van Tilborg,[1] S. Steinke,[1] K. Nakamura,[1] A. Zingale,[3] N. A. Czapla,[3] D. Schumacher,[3] C. B. Schroeder,[1] C. G. R. Geddes,[1] W. P. Leemans,[1,b)] and E. Esarey[1]



Because APLs are much smaller than an equivalent quadrupole triplet, they allow for compact diagnostics of beams from laser wakefield accelerators.

Challenges for APLs

- The main assumption of the APL is that the focusing comes entirely from the plasma current. There is no plasma wakefield. This implies $n_b \ll n_0$, where n_b is the beam density and n_0 is the density of the gas (plasma) in the capillary.

- If beam density is comparable to the plasma density, the beam drives a wake with a ξ-dependent transverse focusing force.

- How “bad” is this effect? The answer is complicated because there are many parameters to be considered!
  - Bunch length, bunch radius, bunch charge, plasma density, APL current, APL radius

- Finally, what is the contribution to beam emittance due to scattering in the APL?

Emittance Growth due to Scattering

The change is RMS divergence due to scattering is given by*:

$$\frac{\partial\langle\theta^2\rangle}{\partial z} = \frac{2k_p^2 r_e Z}{\gamma^2}\log\left(\frac{\lambda_D}{R}\right)$$

For the case we are considering, the beam is not matched to the plasma, so we simply use the betafunction in the APL to calculate the change in emittance:

$$\frac{\partial\varepsilon_n}{\partial z} = \frac{\gamma\beta}{2}\frac{\partial\langle\theta^2\rangle}{\partial z} = \frac{\beta k_p^2 r_e Z}{\gamma}\log\left(\frac{\lambda_D}{R}\right)$$

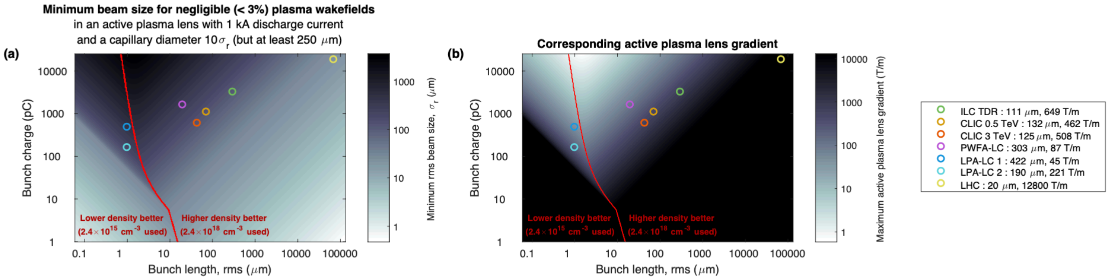
Two factors limit the emittance growth: high energy and small betas.

*C. B. Schroeder, et. al. Phys. Rev. ST Accel. Beams 13, 101301 (2010)

Wakefield Limitations in APLs

A study by C. Lindstrom and E. Adli looked at active plasma lenses for Linear Collider final focus systems, with the assumption that the focusing due to the wakefield is much smaller than focusing of the APL.

They find that the beam must have a large transverse size and betafunction when entering the APL.



Collider	**ILC**	**CLIC**	**CLIC**	**PWFA-LC**	**LP-LC**	**LP-LC**	**LHC**
	TDR	0.5 TeV	3 TeV	1 TeV	Ex. 1	Ex. 2	13 TeV
Final beam energy (GeV)	250	250	1500	500	500	500	6500
Charge per bunch (pC)	3200	1088	595	1600	480	160	18400
Bunch length, rms (μm)	300	72	44	20	1	1	7.6×10^4
Normalized emittance, x/y (μm rad)	10/0.035	2.4/0.025	0.66/0.02	10/0.035	1/0.01	1/0.01	3.75
Considerations for an active plasma lens with 1 kA discharge current and a minimum diameter 250 μm							
Min. beam size for negligible (< 3%) wake (μm)	111	132	125	303	422	190	20
Max. APL gradient with negligible wake (T/m)	649	462	508	87	45	221	12800
Required beta function $\sqrt{\beta_x\beta_y}$, final energy (m)	1.0×10^4	3.5×10^4	4.0×10^5	1.5×10^5	1.7×10^6	3.5×10^5	0.74

The large betafunction leads to emittance growth due to scattering in the APL. Snowmass is an excellent forum for examining this issue.

C. Lindstrom, E. Adli, “Analytic plasma wakefield limits for active plasma lenses” [arXiv:1802.02750], 2018.

Passive Plasma Lenses

Passive Plasma Lenses

- In a passive plasma lens (PPL), the focusing is provided by the wakefield.

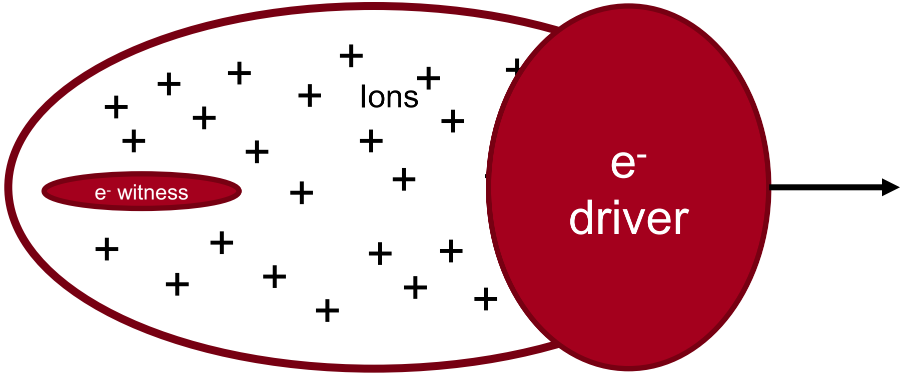
- There are two regimes for PPLs:
  - Overdense $n_b \ll n_0$: The beam drives a linear wakefield, which is focusing for some phases of the wake.
  - Underdense $n_b \gg n_0$: The beam drives a non-linear wakefield and an ion bubble forms. The focusing is provided by the plasma ions. Note that lasers can also be used to drive underdense PPLs (see for example: C. Thaury et. al. *Nat. Comm.* 6:6860).

- The benefit of the overdense regime is that it works for electrons and positrons, but it has many drawbacks because it is hard to tailor the beams to create wakes which provide uniform focusing.

- We will focus on the underdense (blowout) regime.

Passive Plasma Lenses

The nominal blowout regime produces an ion bubble which focuses electron beam particles.



We assume that the electron driver is transversely large and creates a wide bubble which reduces sensitivity to small offsets between the beam and driver.

Applying Gauss's law to the ions in the bubble gives:

$$E_r = \frac{e n_0 r}{2\varepsilon_0}$$

We can derive an engineering formula for the field gradient of a PPL in the blowout regime:

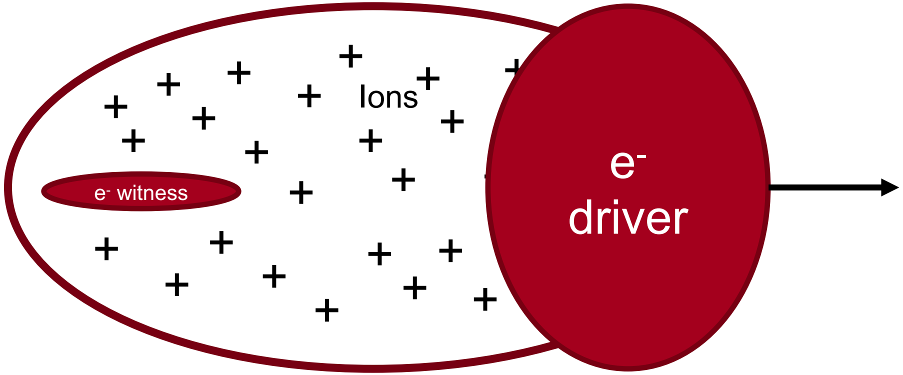
$$g_{\mathrm{PPL}} = 30\ n_0[10^{18}\ \mathrm{cm}^{-3}]\ \mathrm{MT/m}$$

This is at least 3 orders of magnitude larger than APLs in use today.

Passive Plasma Lenses

Important point #1:

The focusing for the witness beam does not depend on the witness beam shape. Works for both round and flat beams.



Important point #2:

Because we are operating in the blowout regime, the wakefield is saturated. We are not concerned about the witness beam being “too dense.”

Important point #3:

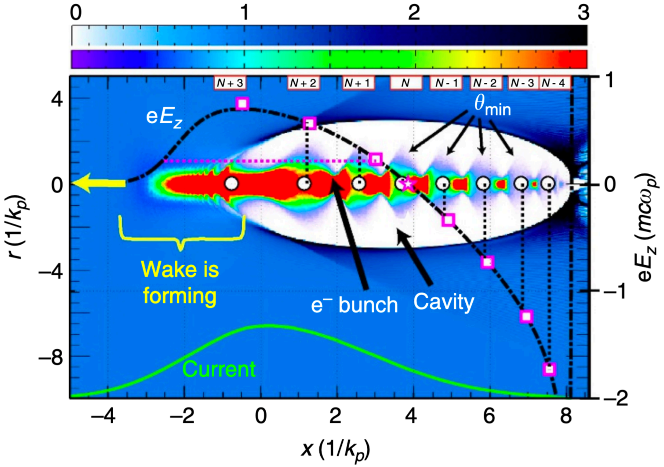
This does not work for positron beams. 😔

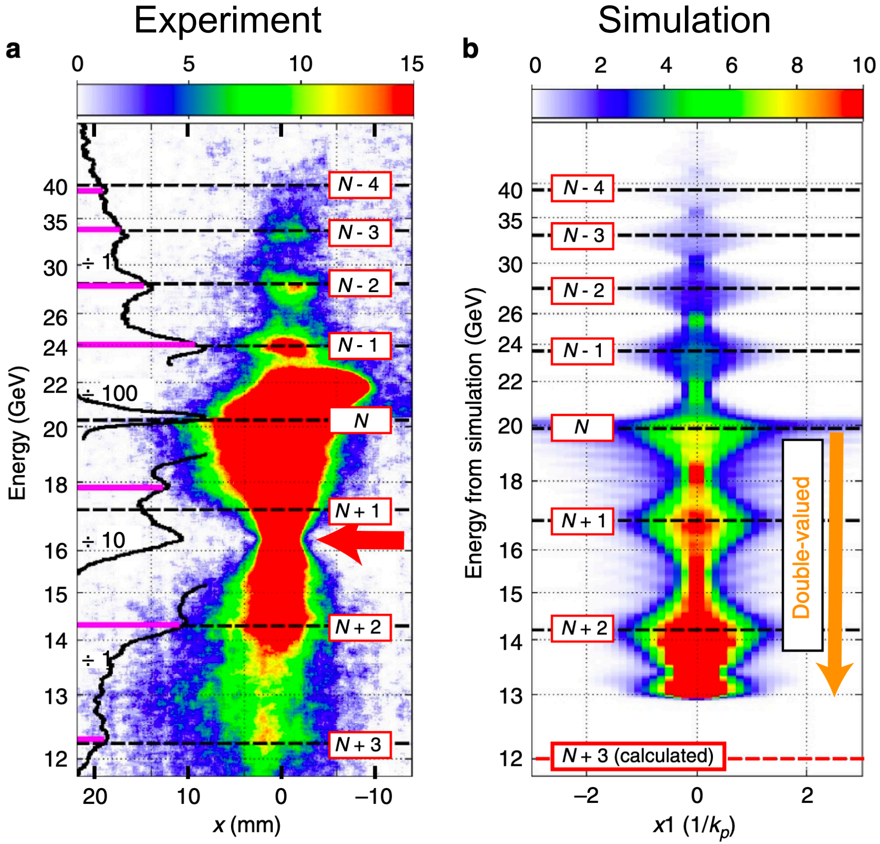
Do they work?

Yes*

*Modern PWFA experiments operate in the blowout regime. The bubble acts as a lens and keeps the beam focused as it transits the plasma.

Simulation





C. Clayton et. al., Nat. Comm. 7:12483 (2016)

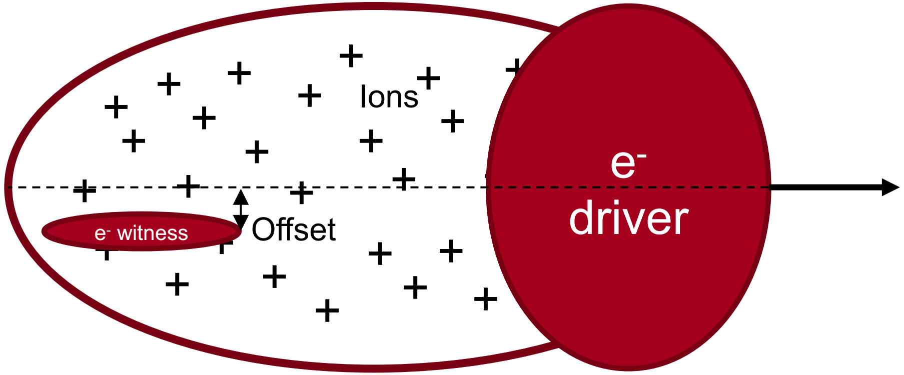
Challenges for PPLs

Offset considerations

The PPL requires a driver to create the wake. If there is an offset between the drive and the witness, this will lead to the witness beam exiting the plasma at an angle and "missing" the IP.

This problem has been studied in detail:

- G. R. White, T. O. Raubenheimer, "TOLERANCES FOR PLASMA WAKEFIELD ACCELERATION DRIVERS" WEYBA3, NAPAC 2020.
- G. R. White, T. O. Raubenheimer, "TRANSVERSE JITTER TOLERANCE ISSUES FOR BEAM-DRIVEN PLASMA ACCELERATORS" THPGW087, IPAC 2020.

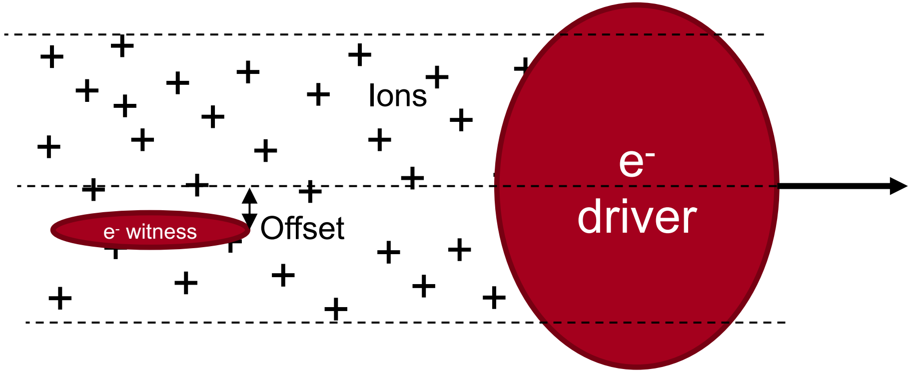


These studies conclude that "heroic" alignment is needed to avoid missing the IP.

Possible solution: Finite plasma column

If plasma is limited to a finite region of space (produce by a jet or in a capillary), and the driver is wide compared to the capillary, then the relative offset between the driver and witness is not important.

There is still the issue of the offset of the witness bunch w.r.t. the ion column, but the same is true of a beam entering FF magnets.

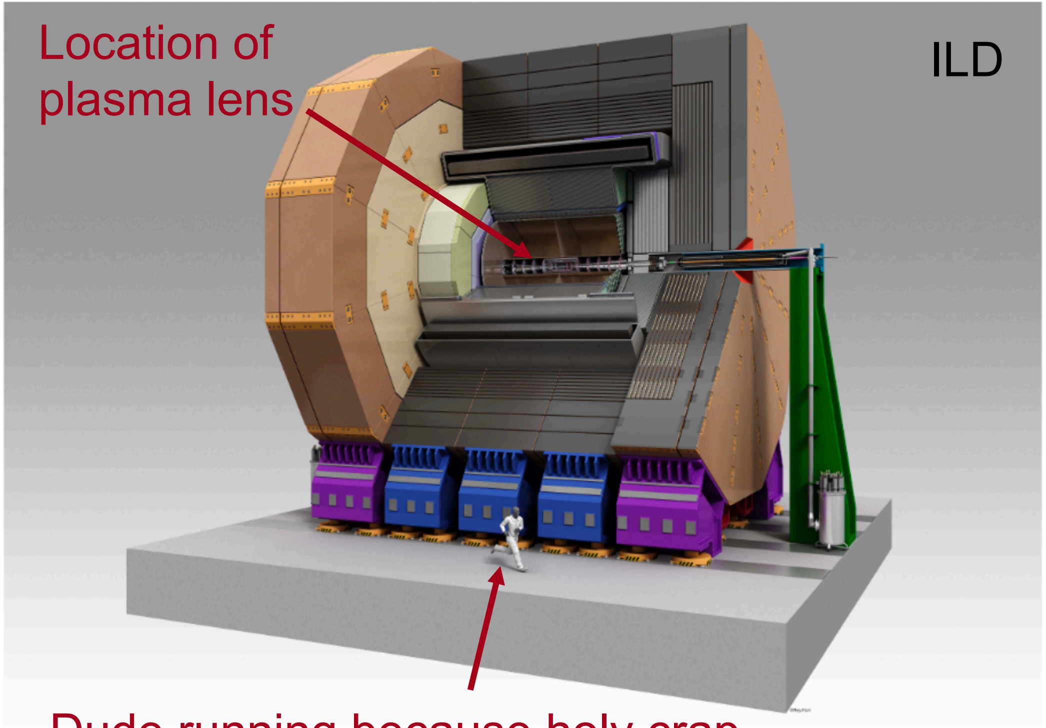


Machine Detector Interface Challenges

With L^* = 22 cm, the plasma lens will be *inside* the detector.

What kind of backgrounds will the plasma lens produce?

How do we isolate the plasma to a finite region inside the detector?



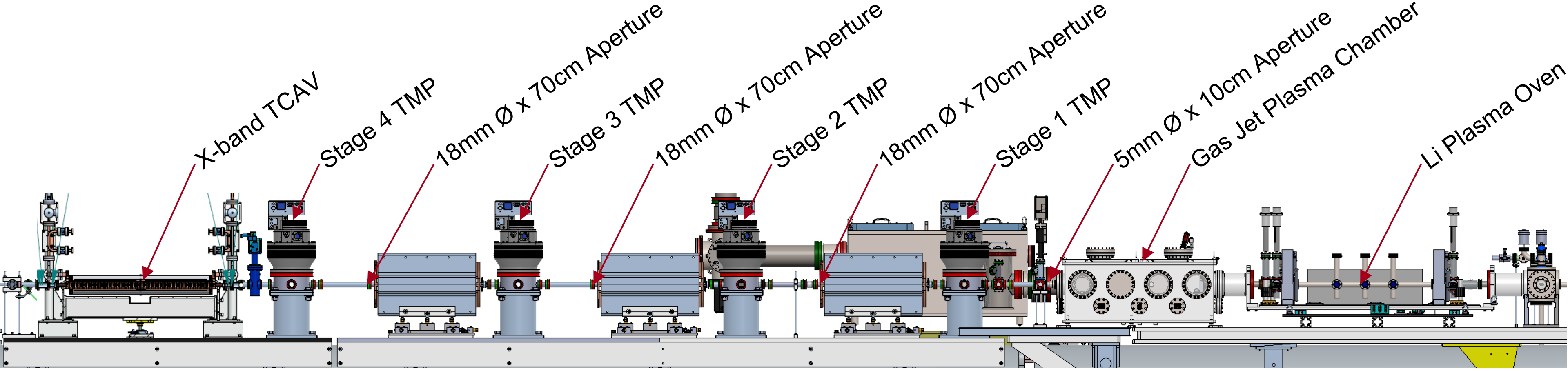
Dude running because holy crap they're about to turn on a 1 TeV beam.

Differential Pumping at FACET-II

D. Storey, SLAC

- Intercepting vacuum windows cannot be used due to extreme beam intensity
- Differential pumping is required to isolate the RF deflecting cavity from the experimental gases - up to 5 Torr He or H_2, and to limit scattering
- Four stages of molecular turbopumps preceded by conductance limiting apertures reduce the pressure by 9 orders of magnitude within <6 m

Stage:	Pressure
Experiment	5 Torr
1	10^{-2} Torr
2	10^{-5} Torr
3	10^{-8} Torr
4	$< 10^{-9}$ Torr



Experiments at FACET-II

Mike Litos from CU Boulder is leading the E308 experiment at FACET-II which will investigate thin, passive plasma lenses (TPL).

The first stage of the experiment will study the optimization of beam matching into and out of the plasma accelerator.

The second stage of the experiment will investigate the focusing and chromatic properties of the TPL in the context of a FF-type application.

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 111001 (2019)

Laser-ionized, beam-driven, underdense, passive thin plasma lens

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(Received 20 August 2019; published 7 November 2019)

We present a laser-ionized, beam-driven, passive thin plasma lens that operates in the nonlinear blowout regime. This thin plasma lens provides axisymmetric focusing for relativistic electron beams at strengths unobtainable by magnetic devices. It is tunable, compact, and it imparts little to no spherical aberrations. The combination of these features make it more attractive than other types of plasma lenses for highly divergent beams. A case study is built on beam matching into a plasma wakefield accelerator at SLAC National Accelerator Laboratory's FACET-II facility. Detailed simulations show that a thin plasma lens formed by laser ionization of a gas jet reduces the electron beam's waist beta function to half of the minimum value achievable by the FACET-II final focus magnets alone.

Last thing: Beating the Oide Limit

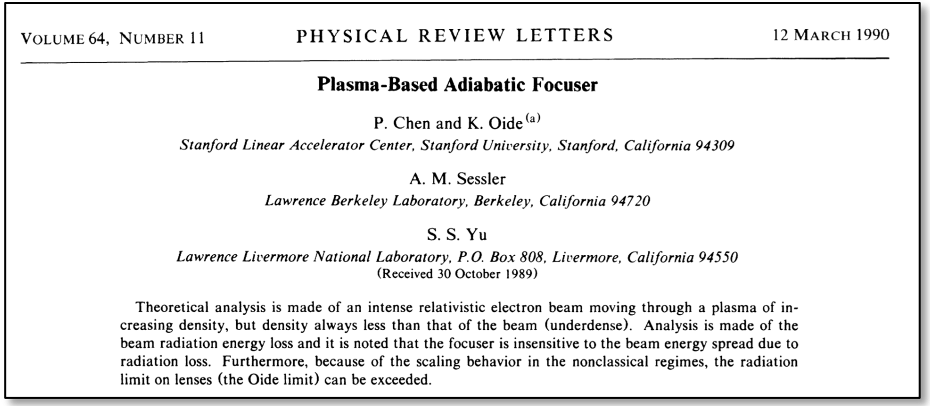
The Oide limit says that if you bend the beam too hard in the FF magnets, it will radiate like crazy and increase the energy spread of the beam, leading to a larger spot size. The limit is a function of the incoming beam emittance:

$$\sigma^*_{y\,\mathrm{min}} = \left(\frac{7}{5}\right)^{1/2}\left[\frac{275}{3\sqrt{6\pi}}\, r_e \bar{\lambda}_e F(\sqrt{K}L, \sqrt{K}l^*)\right]^{1/7}(\epsilon_{Ny})^{5/7}$$

In the paper by Chen et. al., they propose to beat this limit by making the beam radiate in the quantum regime.

$$\sigma_q \gg \left[\tfrac{1}{22}\,\bar{\lambda}_c \epsilon_n^2 (1+\alpha_0^2)\right]^{1/3} \times \exp\left[-3\left(\frac{\alpha_0^3}{(1+\alpha_0^2)^2}\,\frac{\bar{\lambda}_c}{\alpha^3 \epsilon_n}\right)^{1/3}\right]$$

This is achieved by making the beam as small as possible at the entrance of the plasma lens.



VOLUME 64, NUMBER 11 PHYSICAL REVIEW LETTERS 12 MARCH 1990

Plasma-Based Adiabatic Focuser

P. Chen and K. Oide[(a)]
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S. S. Yu
Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550

(Received 30 October 1989)

Theoretical analysis is made of an intense relativistic electron beam moving through a plasma of increasing density, but density always less than that of the beam (underdense). Analysis is made of the beam radiation energy loss and it is noted that the focuser is insensitive to the beam energy spread due to radiation loss. Furthermore, because of the scaling behavior in the nonclassical regimes, the radiation limit on lenses (the Oide limit) can be exceeded.

Conclusion

- Recent experiments have shown the usefulness of Active Plasma Lenses.
  - Critical tool for inter-stage coupling in a laser wakefield accelerator.
  - Allows for novel, compact emittance diagnostics.
  - Demonstrated to be emittance preserving.

- Passive Plasma Lens in the underdense regime have attractive properties for beam matching into and out of plasma stages, and they scale well to the high energies needed for Final Focus designs.
  - Experiments are planned at FACET-II.

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