Plasma-Based Upgrades for Linear Colliders: Opportunities at C^3 Demo Facility

Spencer Gessner

Future US Colliders Workshop

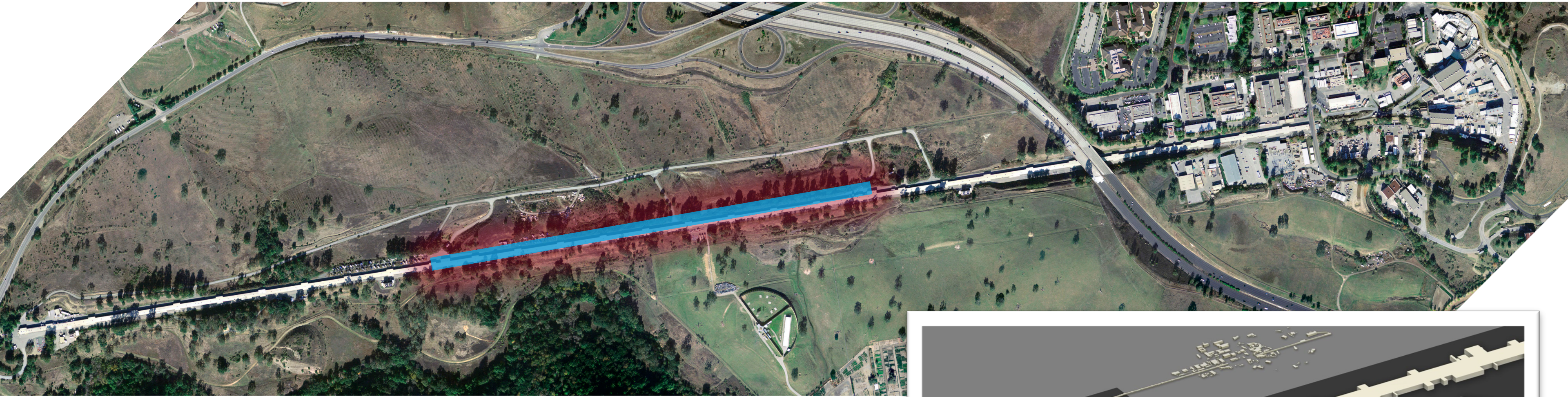
January 20, 2022

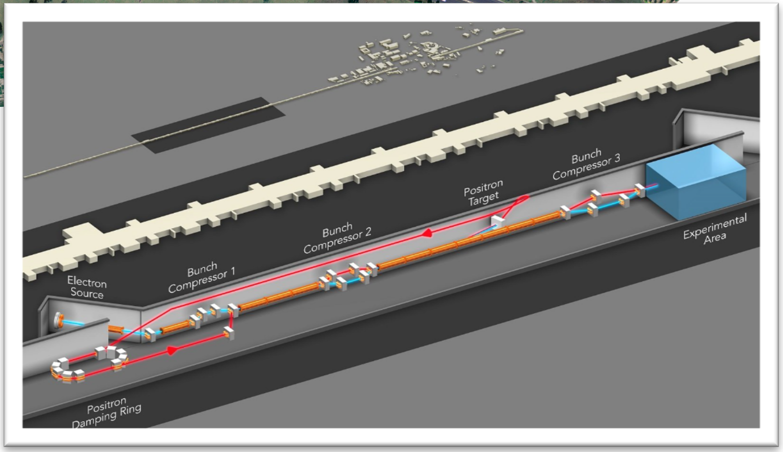
U.S. DEPARTMENT OF ENERGY | Stanford University

SLAC NATIONAL ACCELERATOR LABORATORY

FACET-II

SLAC





At FACET-II, we are pursuing studies that are relevant to a Plasma-based Linear Collider:

- Single-stage, high-quality acceleration.
- Low-emittance beams from plasma.
- Focusing with plasma lenses.
- Positron acceleration.

Topics

- Increasing center of mass energy with plasma acceleration
  - Afterburner: *Repetition-rate challenge*
  - Plasma Staging

- Beam Delivery Systems
  - Plasma lenses for focusing
  - Machine-Detector Interface with plasma

Plasma Afterburner Energy Upgrade

"Just" add plasma to the end of the accelerator!

This concept is simple and makes use of the existing infrastructure and linac.

There are several challenges with this approach, but I will focus on one: *Does it work for bunch trains?*

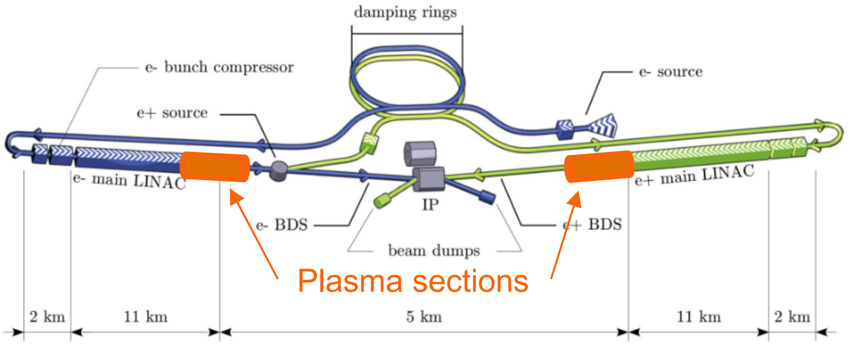


Figure: ILC 500 GeV layout with dimensions (not to scale)

For some considerations on the plasma afterburner, see for example T. Raubenheimer, AIP Conf. Proc. 2004.

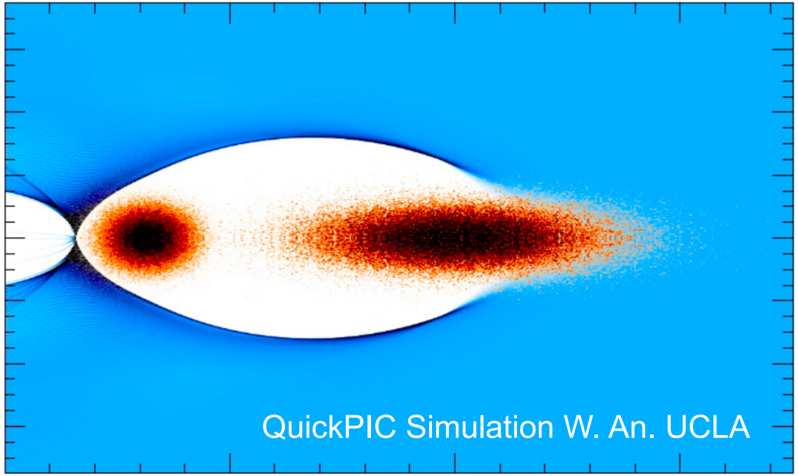
Plasma Wakefield: $Q = 1$

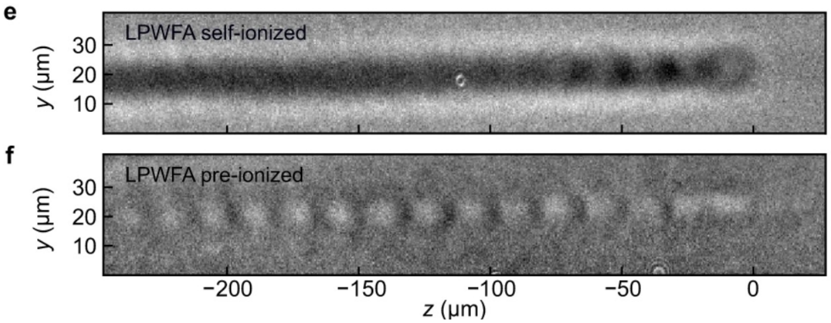
SLAC

The blowout regime plasma wakefield is ideal for accelerating electron beams, but only the first cycle of the wake is used.

The wake decoheres rapidly due to thermal effects and plasma electron phase mixing.

The timescale for decoherence is sub-ns.





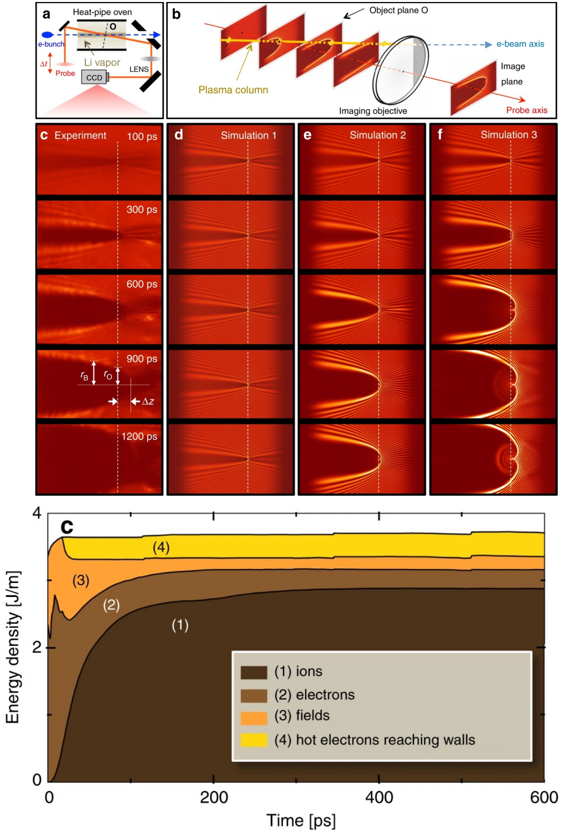
T. Kurz et al. Nat. Comm. 12:2895 (2021)

How long before the plasma recovers?

At FACET, we studied the evolution of the plasma after the passage of the drive electron beam.

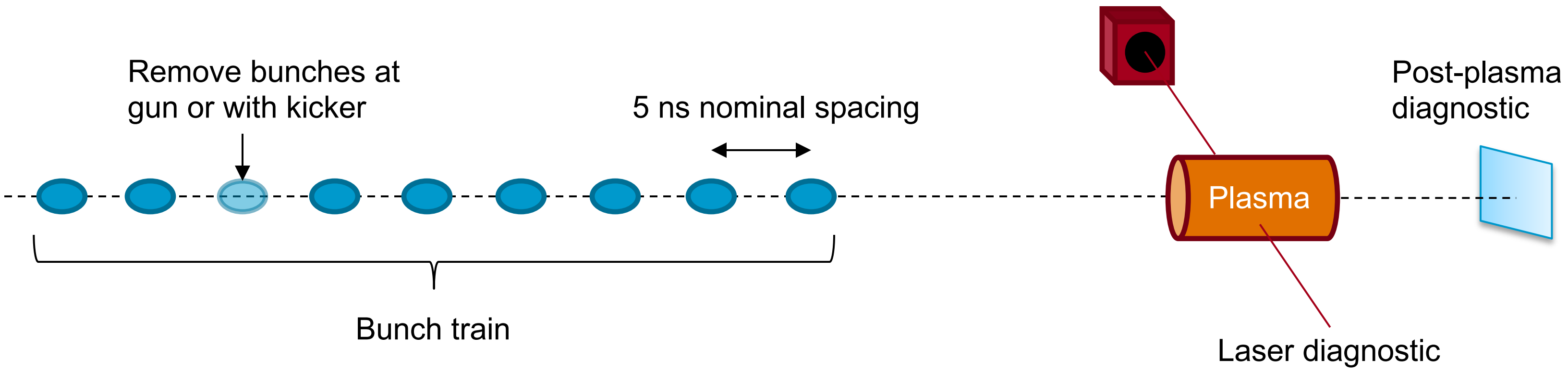
Energy left in the wake is primarily stored in the motion of plasma electrons, but is quickly transferred to the plasma ions.

The ions remain in a heated state for many nanoseconds.



R. Zgadzaj et al. Nat. Comm. 11:4753 (2020)

Studies at Demo Facility

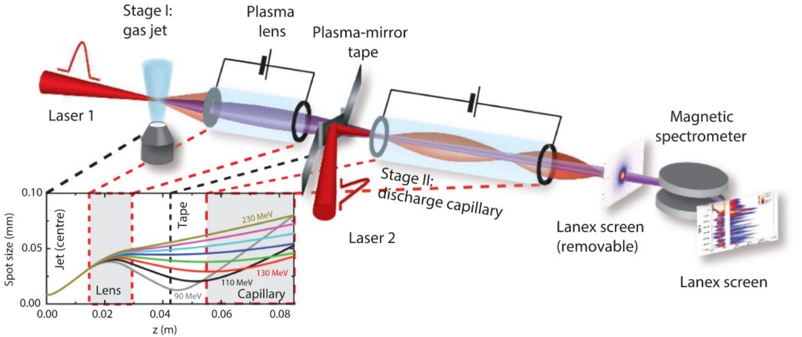


By sending bunch trains through a plasma, we can study both the evolution/equilibration of the plasma, as well as the effectiveness of wakefield acceleration in a heated plasma.

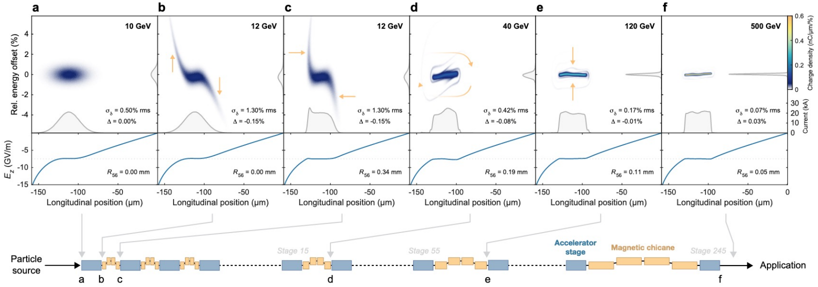
Staging Energy Upgrade

With staged plasma acceleration, multiple *drive* beams are used to accelerate a single *main* beam.

This has been demonstrated for laser wakefield acceleration, but not beam-driven plasma acceleration, in part because the beam and optics requirements are challenging!

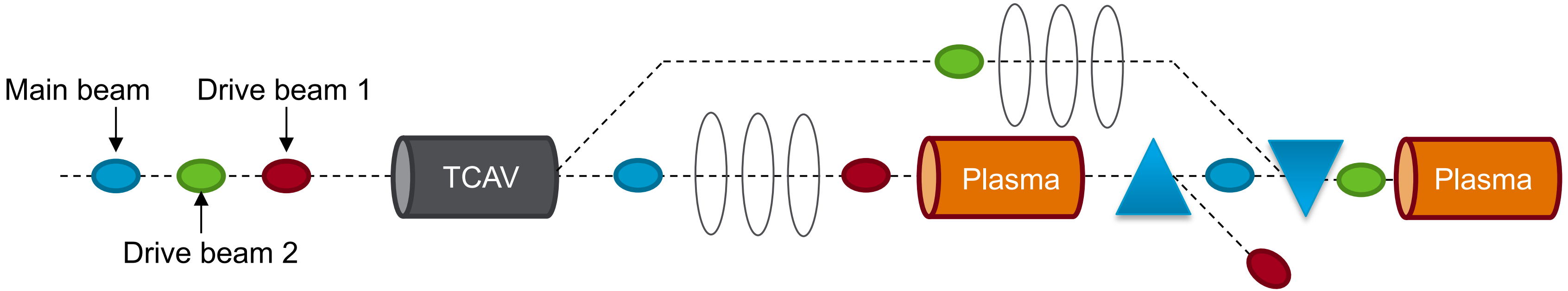


S. Steinke et al. Nature 530:190 (2016)



C. A. Lindstrom. arXiv 2104.14460 (2021)

Studies at Demo Facility

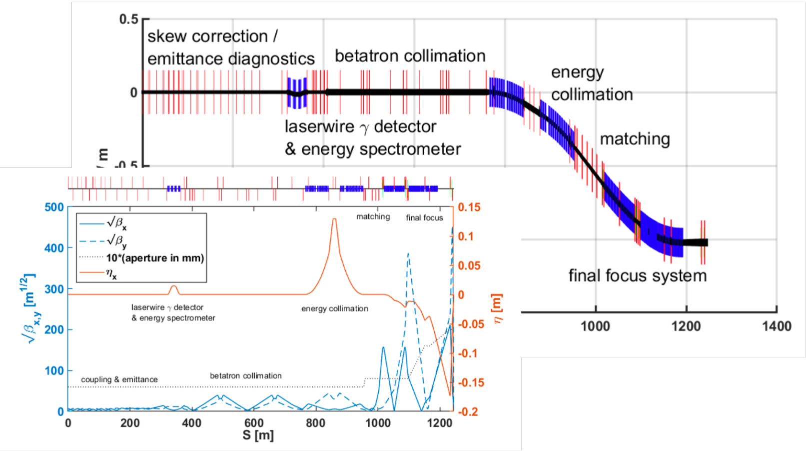


The C^3 demonstration facility could provide the much-needed platform for studying plasma staging. There are currently no facilities (existing or planned) with this capability.

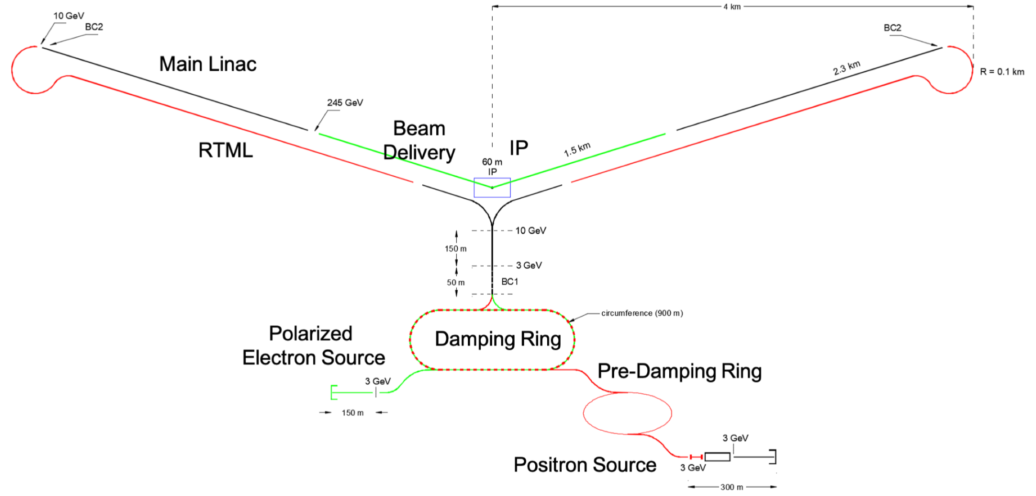
Beam Delivery System

SLAC

C^3 - Investigation of Beam Delivery Adapted from ILC/NLC

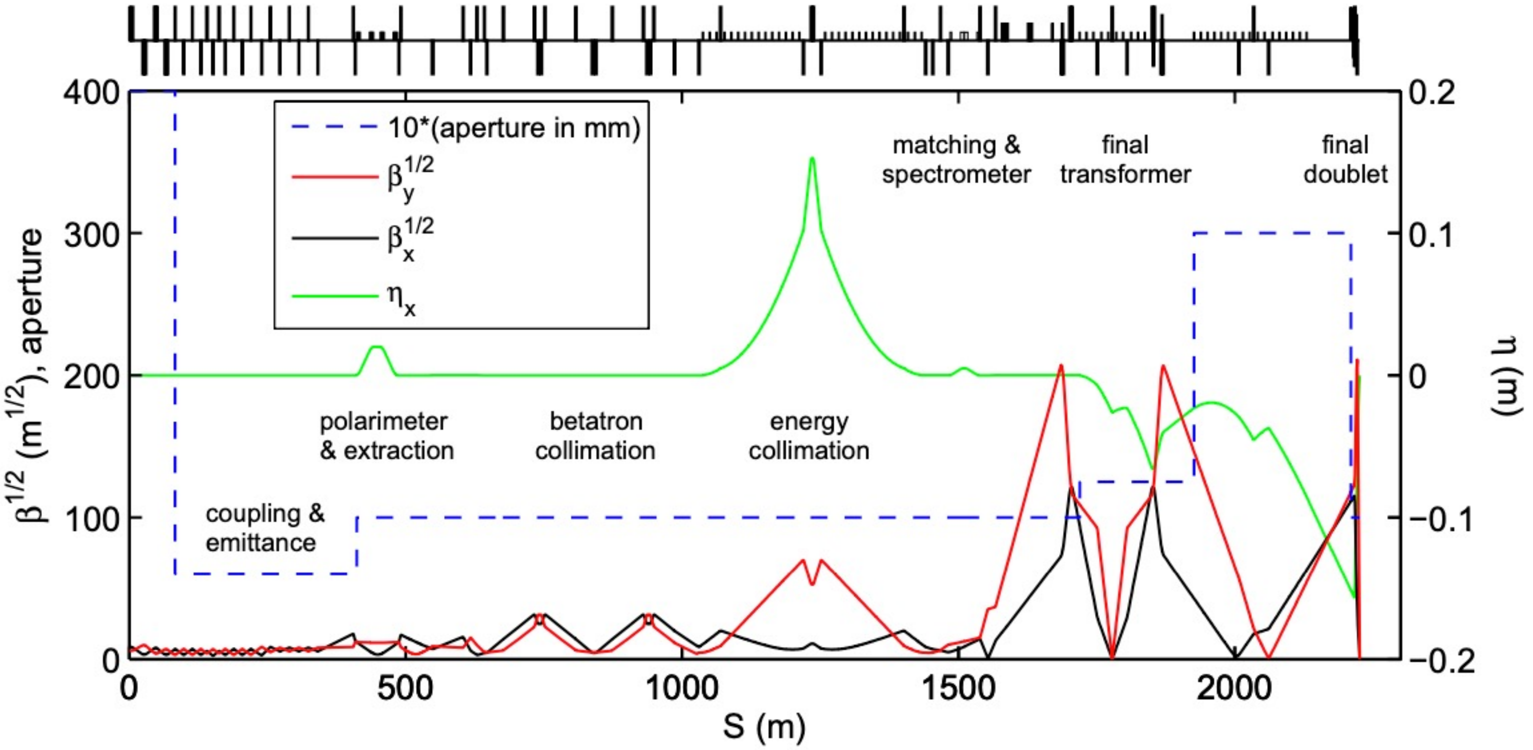


C^3 - 8 km footprint for 250/550 GeV



Assuming we can increase the beam energy with plasma acceleration, we still need to bring the beam to the IP for collisions.

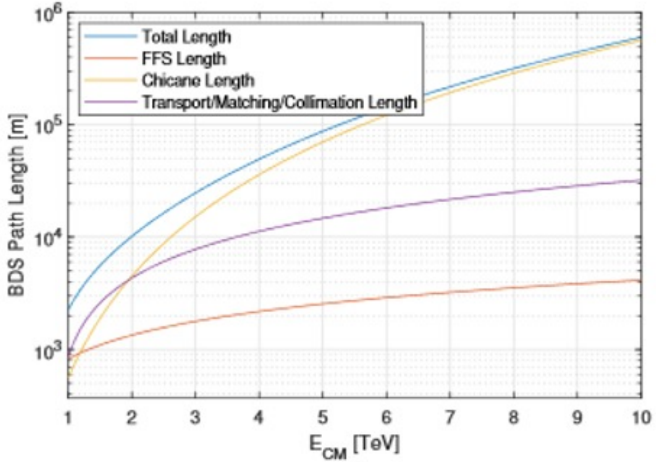
BDS Design Considerations



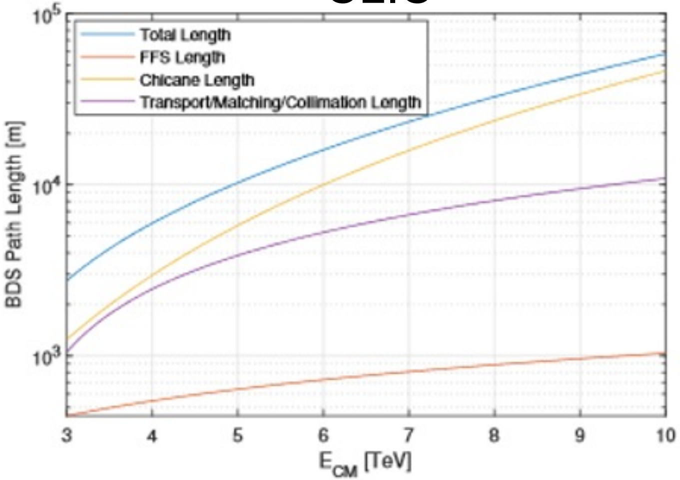
G. White's Presentation on Tuesday

BDS Length Scaling with Beam Energy

ILC



CLIC



	ILC E_{cm} = 1 TeV	CLIC E_{cm} = 3 TeV
FFS	826	446
Bending Sections	562	1250
Other	866	1054
Total	2254	2750

=> L ~ $E^{7/10}$ (Original Raimondi/Seryi paper)

$\Delta\gamma\epsilon \approx (4\times 10^{-8} m^2 GeV^{-6}) E^6 \sum_i \frac{L_i}{|\rho_i|^3}\mathcal{H}_i$ (ISR) **=> L ~ E^3**

L ~ E

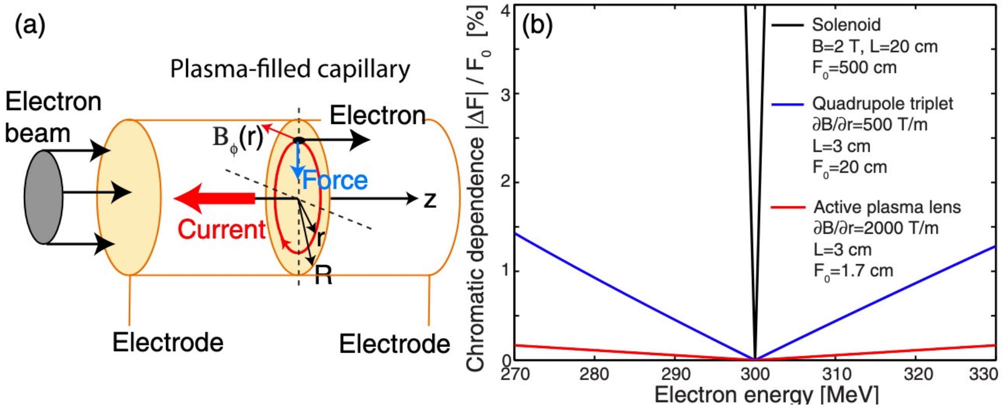
An (entirely wrong) estimate of BDS length scaling with energy based on either ILC or CLIC baseline designs (Lumi ~ E)

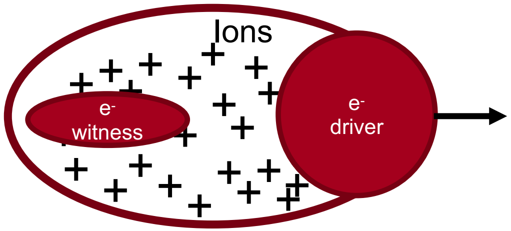
Plasma Lens Solutions

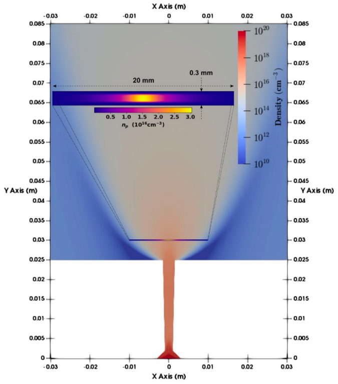
Plasma lens systems offer two main advantages:

1. Focusing gradients are orders of magnitude larger than what can be achieved with traditional systems.
2. Axisymmetric focusing strongly reduces chromatic effects.

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







C. Doss et. al., PRAB 22, 111001 (2019)

The L^* Challenge

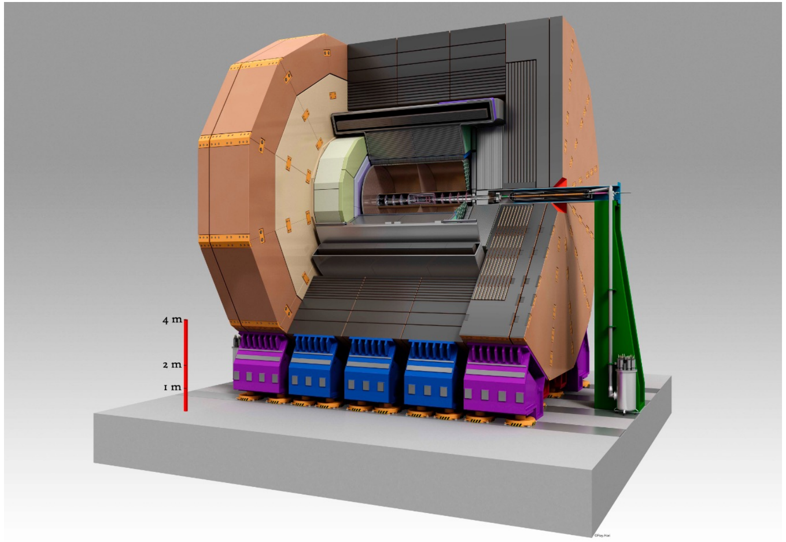
The evolution of the beam size in vacuum is given by:

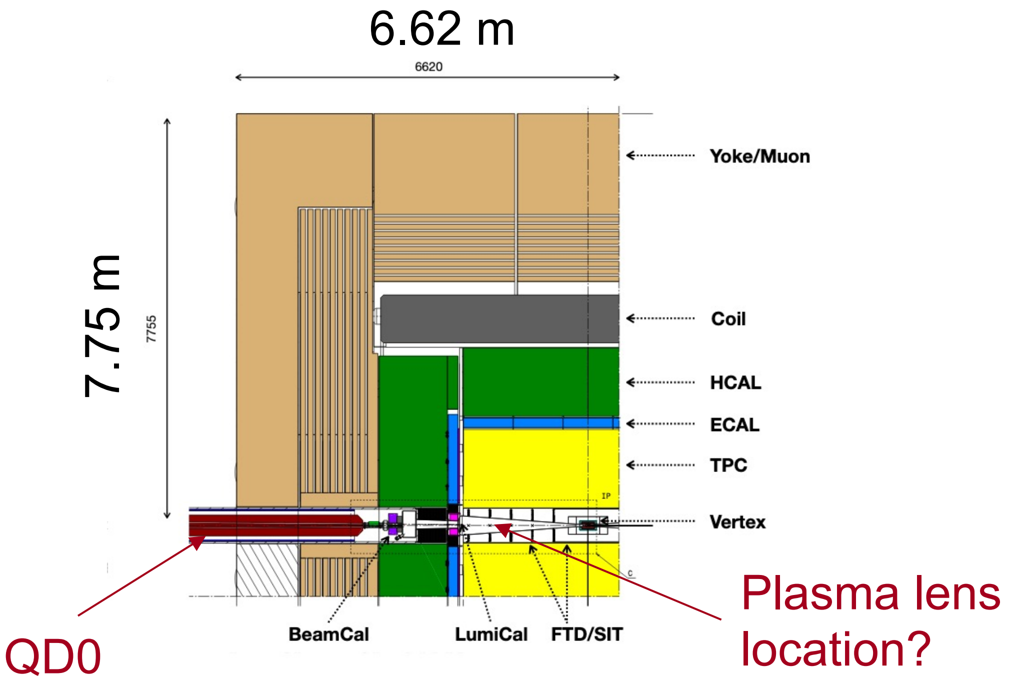
$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

$$L^* \approx \sqrt{\beta_{end}\beta^*}$$

We can use plasma lenses to reduce β^*, but this *necessitates* a small L^*.

Studies at Demo Facility





Can we study plasma lens integration with a detector at a demo facility?

Conclusion

- Plasma technology has the potential to extend the physics reach of future linear colliders.

- A C^3 Demonstration Facility would provide the opportunity to study staging, something which can't be done anywhere else in the world!