Beam Delivery Systems for Future Linear Colliders

and

Extreme Bunch Compression Concepts

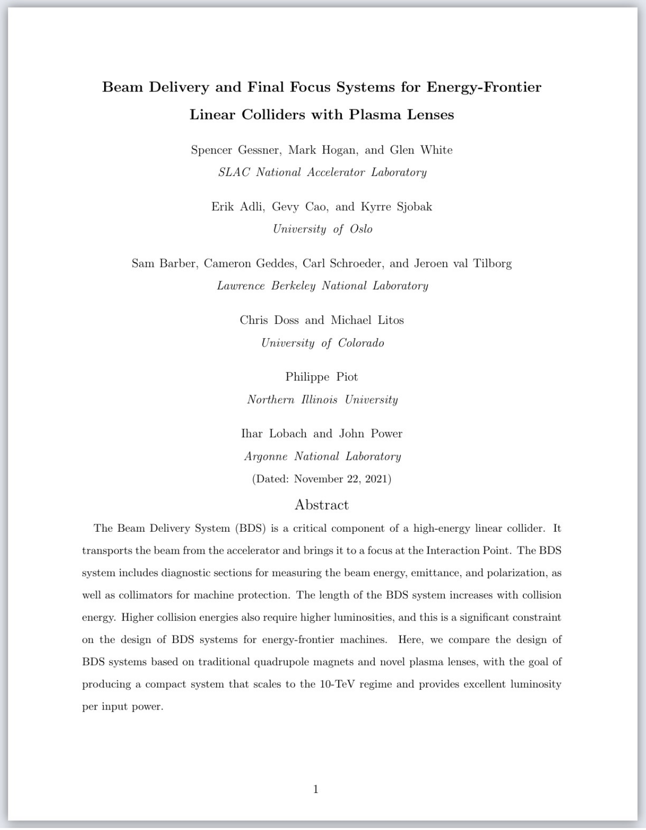
Spencer Gessner and Glen White

Snowmass AF1 Meeting

November 23, 2021

White Paper on BDS Systems

- There have been many discussions on Advanced Linear Colliders in AF6.
- The ultimate goal for these machines is to reach 10 TeV-scale CM energy and compete with FCC-hh and MCs in terms of physics reach.
- Colliding electron and positron beams at such high energies presents many challenges.
- If we can solve some of these challenges in the context of an Advanced Linear Collider, the broader LC community might benefit.



Beam Delivery and Final Focus Systems for Energy-Frontier Linear Colliders with Plasma Lenses

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University of Oslo

Sam Barber, Cameron Geddes, Carl Schroeder, and Jeroen val Tilborg
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University of Colorado

Philippe Piot
Northern Illinois University

Ihar Lobach and John Power
Argonne National Laboratory

(Dated: November 22, 2021)

Abstract

The Beam Delivery System (BDS) is a critical component of a high-energy linear collider. It transports the beam from the accelerator and brings it to a focus at the Interaction Point. The BDS system includes diagnostic sections for measuring the beam energy, emittance, and polarization, as well as collimators for machine protection. The length of the BDS system increases with collision energy. Higher collision energies also require higher luminosities, and this is a significant constraint on the design of BDS systems for energy-frontier machines. Here, we compare the design of BDS systems based on traditional quadrupole magnets and novel plasma lenses, with the goal of producing a compact system that scales to the 10-TeV regime and provides excellent luminosity per input power.

Figure of Merit

$$\frac{\mathcal{L}}{P_b}$$

The figure of merit for a linear collider is “Luminosity per beam power”.

Figure of Merit

$$\frac{\mathcal{L}}{P_b} \longleftarrow N_b\,,\ E_b\,,\ f$$

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Figure of Merit

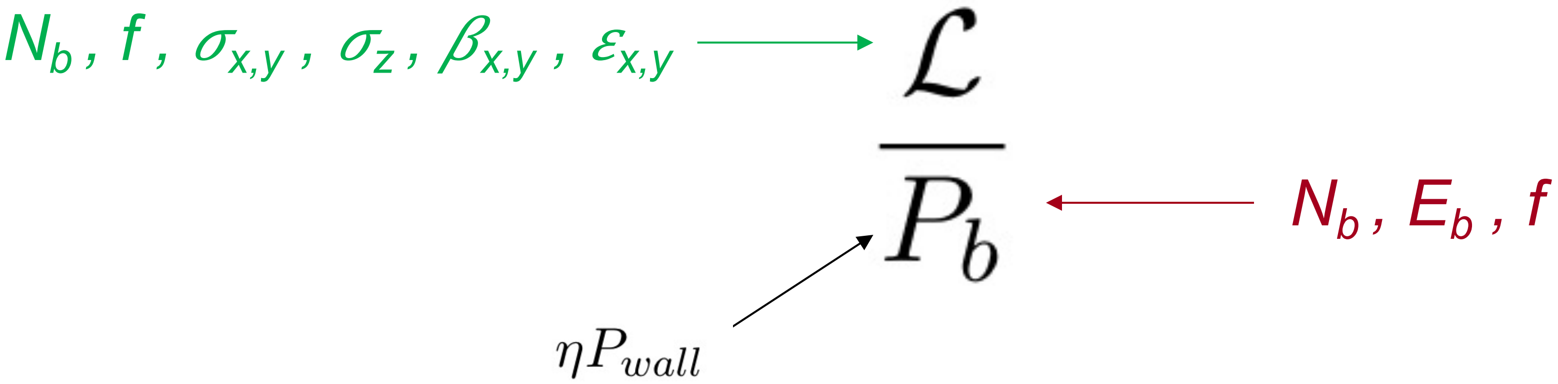
$$N_b\,,\ f\,,\ \sigma_{x,y}\,,\ \sigma_z\,,\ \beta_{x,y}\,,\ \varepsilon_{x,y} \longrightarrow \mathcal{L}$$

$$\frac{\mathcal{L}}{P_b}$$

$$P_b \longleftarrow N_b\,,\ E_b\,,\ f$$

The figure of merit for a linear collider is “Luminosity per beam power”.

Figure of Merit



$N_b\,,\ f\,,\ \sigma_{x,y}\,,\ \sigma_z\,,\ \beta_{x,y}\,,\ \varepsilon_{x,y}$

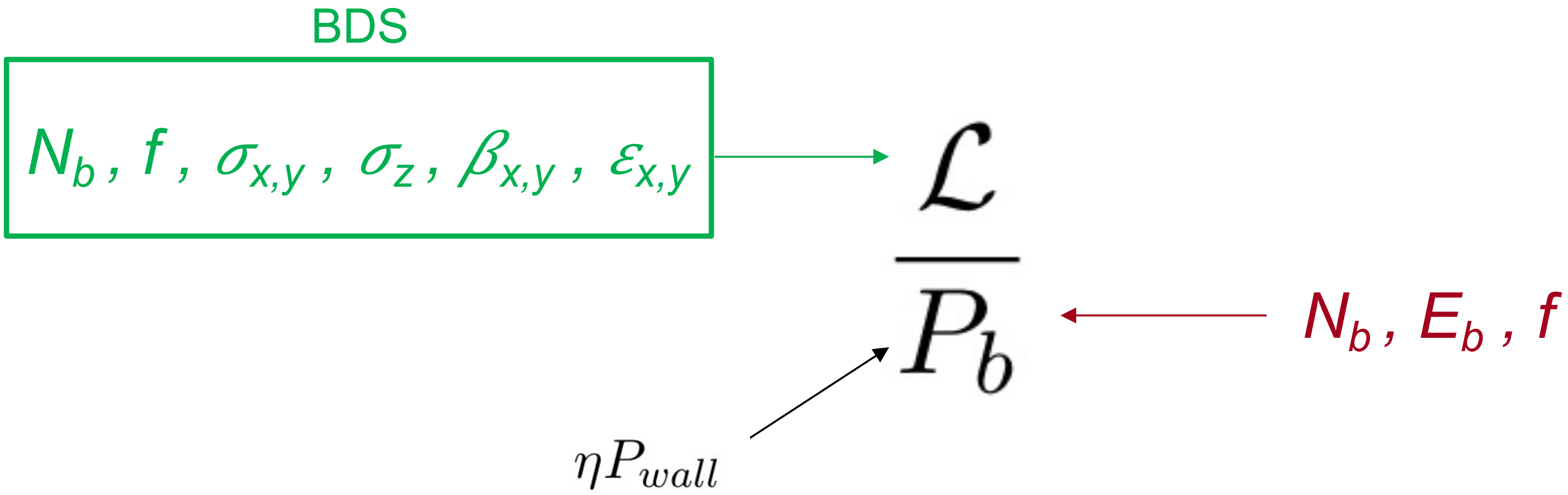
$$\frac{\mathcal{L}}{P_b}$$

$N_b\,,\ E_b\,,\ f$

ηP_{wall}

The figure of merit for a linear collider is “Luminosity per beam power”.

Figure of Merit



BDS

$N_b, f, \sigma_{x,y}, \sigma_z, \beta_{x,y}, \varepsilon_{x,y}$

$$\frac{\mathcal{L}}{P_b}$$

N_b, E_b, f

ηP_{wall}

The figure of merit for a linear collider is “Luminosity per beam power”.

Evaluating New Ideas

- The Linear Collider community (NLC, ILC, CLIC) has already put considerable time and effort into the design and optimization of BDS for LCs.
  - It is critical that the Advanced Accelerator community understands the previous work in the pursuit of new ideas:
    - Final-focus systems in linear colliders, T. Raubenheimer and F. Zimmerman, *RMP* 72, 95, (2000).
    - Novel Final Focus Design for Future Linear Colliders, P. Raimnodi and A. Seryi, *PRL* 86, 3779, (2001).
    - ILC Technical Design Report, *arXiv* 0712.2316

- New ideas may come in the form of new technology (*e.g.* plasma lens), new physics (*e.g.* short-bunch collisions), or new design choices.

“Traditional” BDS

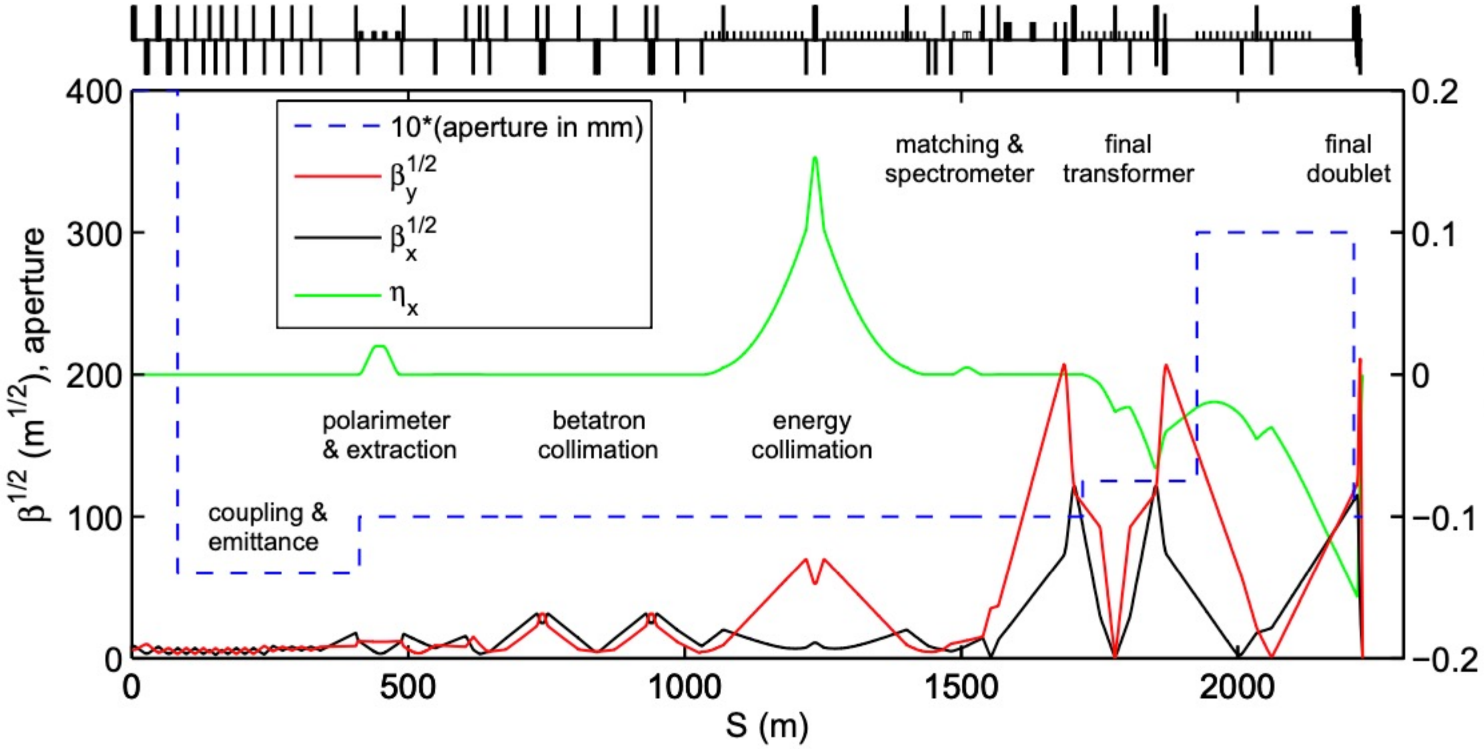
The traditional BDS is composed of:

- Tune-up and diagnostic sections including:
  - Emittance (laser wire)
  - Polarimetry
  - Energy measurement
- Collimation system
  - Design requirement for ILC is ZERO particles lost in final few hundred meters
- Machine protection
- Final focus with local chromaticity correction

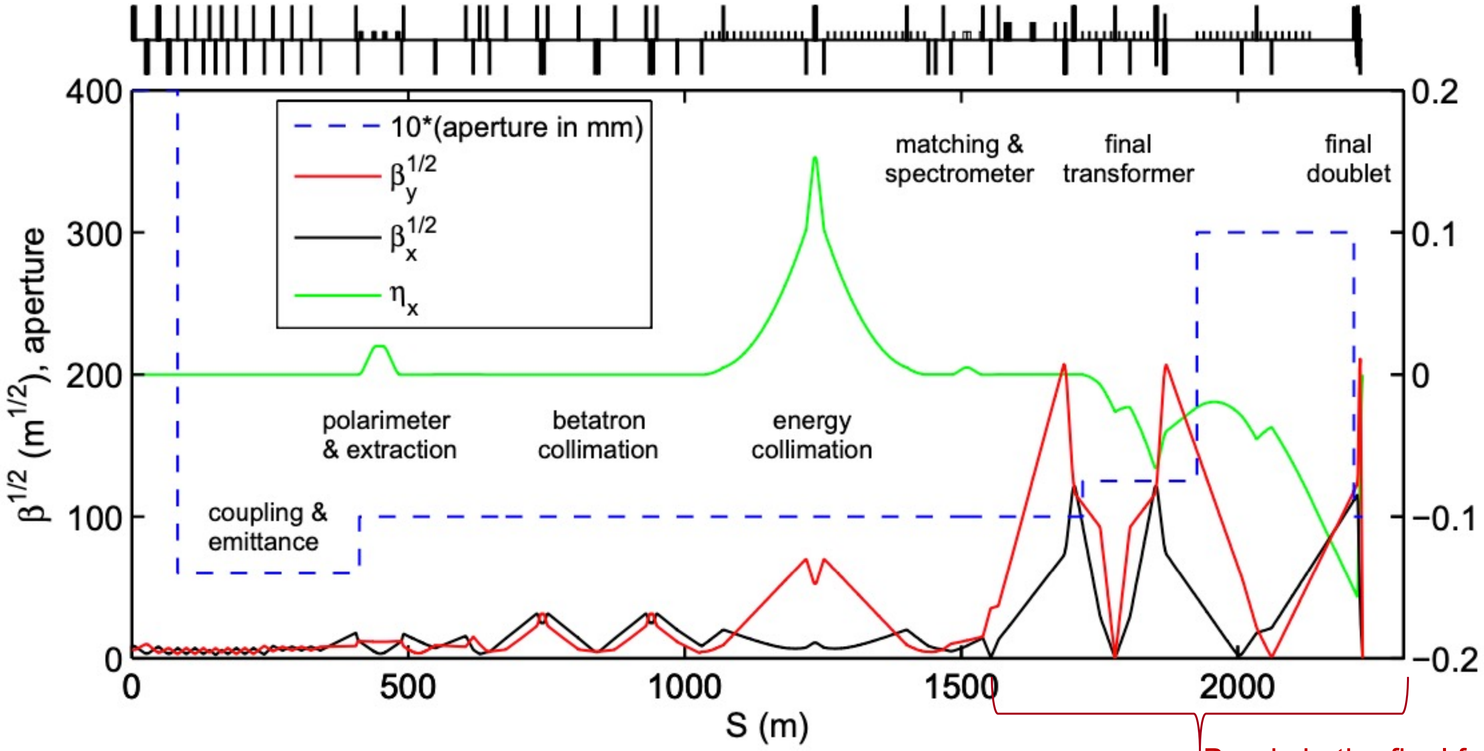
The cost and size of the BDS represents about 1/3 of the machine.

ILC BDS

ILC TDR: https://arxiv.org/abs/0712.2361



What drives the length of the BDS?



Bends in the final focus system are required for chromatic correction.

Questions to be explored in White Paper

- Can we beat scaling laws for "traditional" BDS systems?
  - Shorter BDS using novel diagnostic and collimation systems?
  - Do Machine-Detector Interface requirements change if we pursue an energy frontier machine (*i.e.* no longer focus on precision measurements)?
- Should we consider BDS for both symmetric and flat beams?
  - Symmetric beams are more natural for plasma accelerators.
- What are the benefits/drawbacks of plasma lens systems?
  - What are the implications of using plasma lenses near the IP?
- What are the implications of using ultra-short bunches?

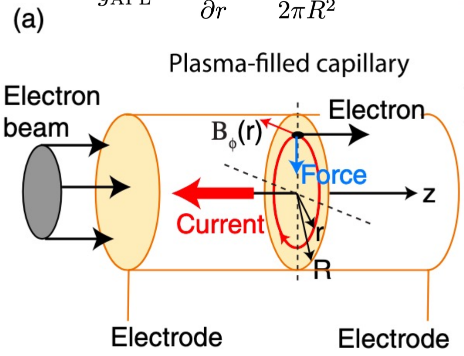
Plasma Lens Solutions

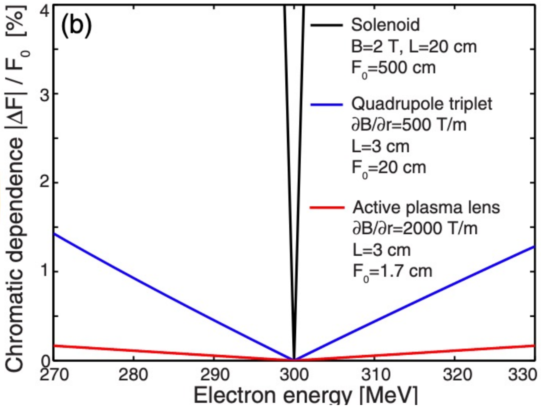
Plasma lens systems offer two main advantages:

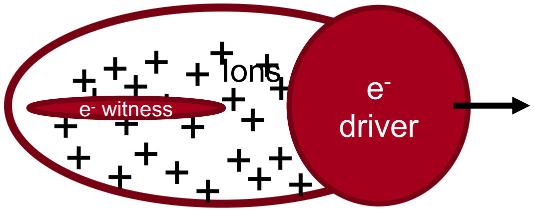
1. Focusing gradients are orders of magnitude larger than what can be achieved with traditional systems.
2. Axisymmetric focusing strongly reduces chromatic effects.

$$g_{\mathrm{APL}} = \frac{\partial B_\phi}{\partial r} = \frac{\mu_0 I}{2\pi R^2}$$

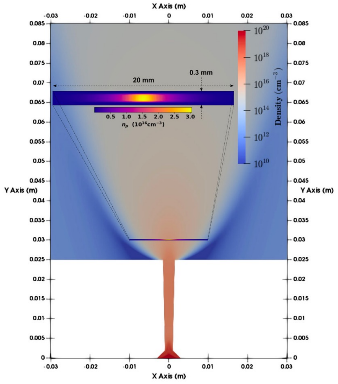
J. van Tilborg et. al., PRL115,184802 (2015)





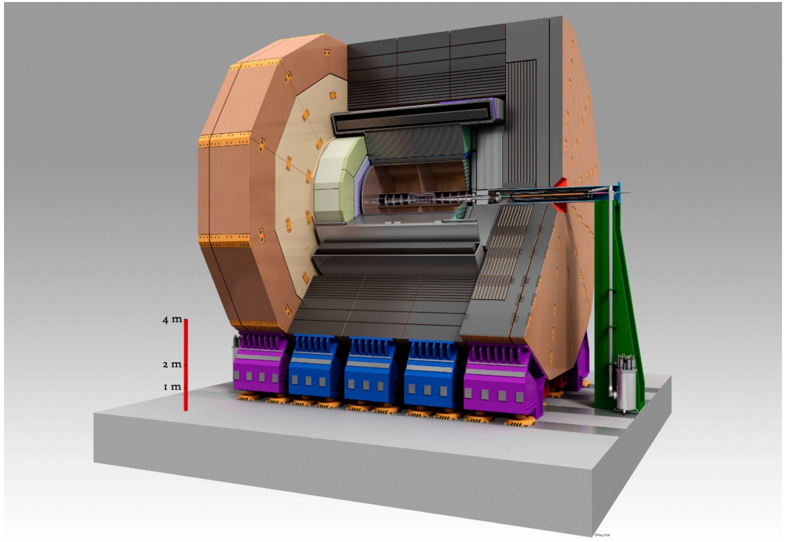


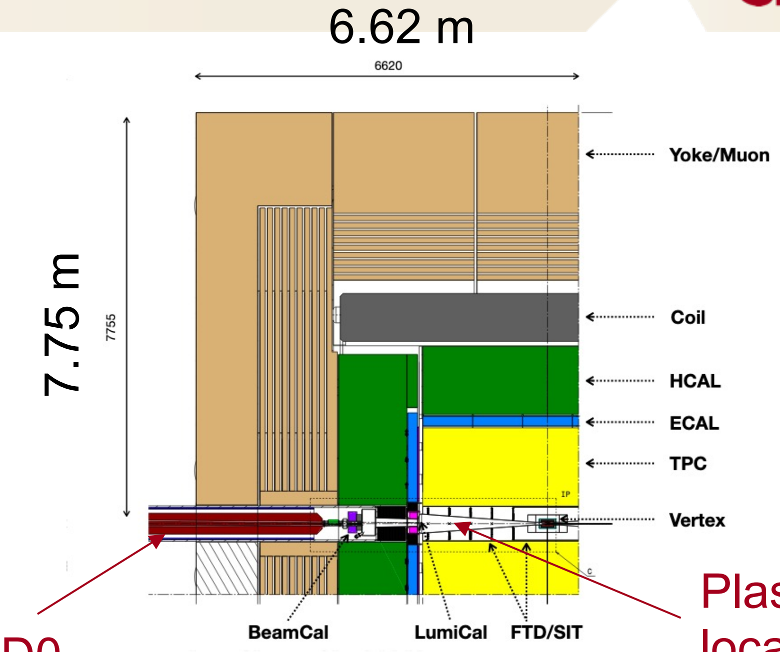
$$g_{\mathrm{PPL}} = 30\ n_0[10^{18}\ \mathrm{cm}^{-3}]\ \mathrm{MT/m}$$



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

Machine-Detector Interface





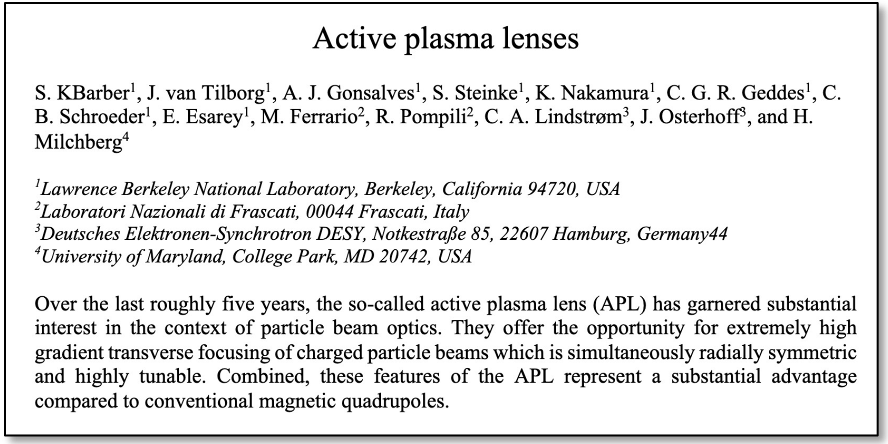
QD0

Plasma lens location?

Do plasma lenses need to be *in* the detector to be effective?

Snowmass LoIs on Plasma Lenses

Active Plasma Lenses



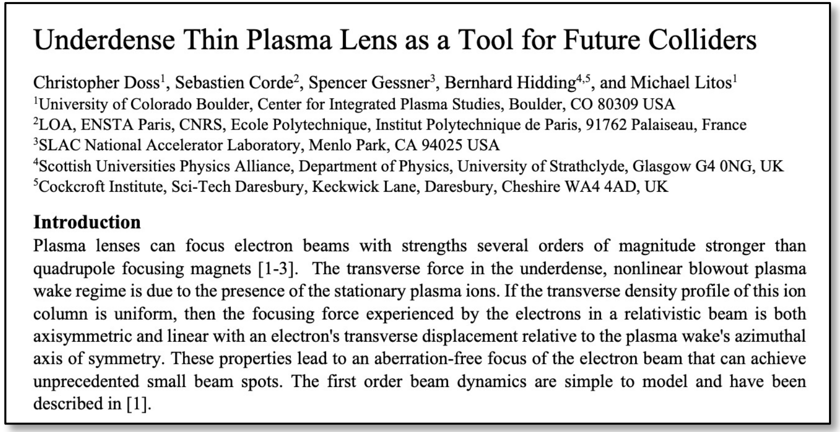
Active plasma lenses

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]

[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[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.

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]
[1]University of Colorado Boulder, Center for Integrated Plasma Studies, Boulder, CO 80309 USA
[2]LOA, ENSTA Paris, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, 91762 Palaiseau, France
[3]SLAC National Accelerator Laboratory, Menlo Park, CA 94025 USA
[4]Scottish Universities Physics Alliance, Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK
[5]Cockcroft Institute, Sci-Tech Daresbury, Keckwick Lane, Daresbury, Cheshire WA4 4AD, UK

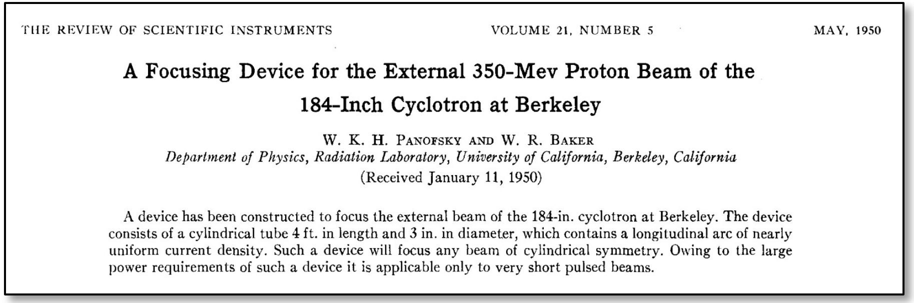
Introduction

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].

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

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

Plasma Lens History



THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 21, NUMBER 5 MAY, 1950

A Focusing Device for the External 350-Mev Proton Beam of the 184-Inch Cyclotron at Berkeley

W. K. H. PANOFSKY AND W. R. BAKER
Department of Physics, Radiation Laboratory, University of California, Berkeley, California
(Received January 11, 1950)

A device has been constructed to focus the external beam of the 184-in. cyclotron at Berkeley. The device consists of a cylindrical tube 4 ft. in length and 3 in. in diameter, which contains a longitudinal arc of nearly uniform current density. Such a device will focus any beam of cylindrical symmetry. Owing to the large power requirements of such a device it is applicable only to very short pulsed beams.

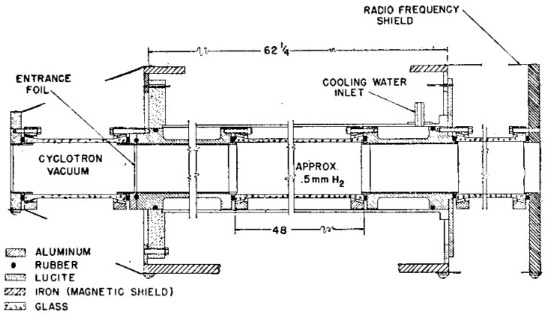
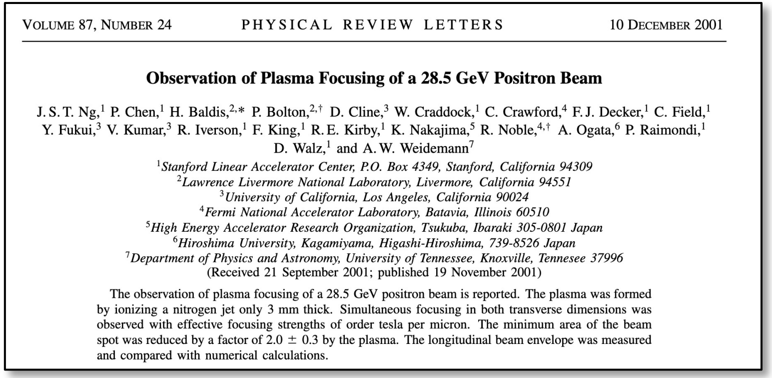


FIG. 2. Cross section of magnetic arc lens.



VOLUME 87, NUMBER 24 PHYSICAL REVIEW LETTERS 10 DECEMBER 2001

Observation of Plasma Focusing of a 28.5 GeV Positron Beam

J. S. T. Ng,[1] P. Chen,[1] H. Baldis,[2,*] P. Bolton,[2,†] D. Cline,[3] W. Craddock,[1] C. Crawford,[4] F. J. Decker,[1] C. Field,[1] Y. Fukui,[3] V. Kumar,[3] R. Iverson,[1] F. King,[1] R. E. Kirby,[1] K. Nakajima,[5] R. Noble,[4,†] A. Ogata,[6] P. Raimondi,[1] D. Walz,[1] and A. W. Weidemann[7]

[1]*Stanford Linear Accelerator Center, P.O. Box 4349, Stanford, California 94309*
[2]*Lawrence Livermore National Laboratory, Livermore, California 94551*
[3]*University of California, Los Angeles, California 90024*
[4]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[5]*High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801 Japan*
[6]*Hiroshima University, Kagamiyama, Higashi-Hiroshima, 739-8526 Japan*
[7]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996*
(Received 21 September 2001; published 19 November 2001)

The observation of plasma focusing of a 28.5 GeV positron beam is reported. The plasma was formed by ionizing a nitrogen jet only 3 mm thick. Simultaneous focusing in both transverse dimensions was observed with effective focusing strengths of order tesla per micron. The minimum area of the beam spot was reduced by a factor of 2.0 ± 0.3 by the plasma. The longitudinal beam envelope was measured and compared with numerical calculations.

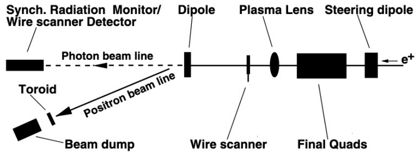


FIG. 1. Schematic layout of the SLAC Plasma Lens experiment at the FFTB. "Final Quads" are conventional focusing quadrupole magnets. The positron beam is deflected towards the dump by the magnetic dipole.

SLAC has a proud history on the topic of plasma lenses.

Short Bunches for Increased Luminosity

Advanced Accelerator technologies naturally employ short bunches. We “win’ twice by using short bunches.

First, short bunches suppress beamstrahlung, increasing both luminosity and luminosity in 1%.

Second, shorter bunches allow for smaller betafunctions due to hourglass effect.

$$\mathcal{L} = \frac{0.30 H_{\mathrm{D}}}{4\pi\alpha^2}\sqrt{\frac{\gamma}{r_{\mathrm{e}}\boxed{\sigma_z}}}\frac{n_\gamma^{3/2}}{\sigma_y}\frac{\eta P_{\mathrm{AC}}}{\mathcal{E}_{\mathrm{b}}}$$

Beamstrahlung considerations in laser-plasma accelerator-based linear colliders.
C. B. Schroeder, et. al. PRAB 15, 051301

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Beamstrahlung considerations in laser-plasma accelerator-based linear colliders.
C. B. Schroeder, et. al. PRAB 15, 051301

By going to the shortest possible bunches, we may open a new paradigm for collider physics.

V. Yakimenko, et.al. PRL 122, 190404 (2019)

Collider with extremely short bunches

Why: *Beamstrahlung is mitigated (not enough time to emit photon) => can collide round beams => Orders of magnitude reduction in required beam power for the same luminosity in LC*

R. Blankenbecler, S. Drell, PRD 36, 277 (1987)

New unexplored physics

Fully non-perturbative QED regime

V. I. Ritus, Ann. Phys. 69, 555{582 (1972).
AA Mironov, S Meuren, AM Fedotov, PRD 102 (5), (2020)

QED cascades - astrophysical phenomena in Laboratory

Bell & Kirk, PRL 101, 200403 (2008)
K.Qu, S. Meuren, and N. J. Fisch PRL 127, 095001 (2021)

Fully coupled, analogous to spontaneous chiral symmetry breaking

D. K. Sinclair and J. B. Kogut, arXiv:2111.01990v1 (2021)

How: *Adiabatic CSR compensation in multistage bunch compressor*

To be published

Where we are:

Theory of 2D/3D CSR is sufficiently advanced and implemented in simulation codes

Y Cai, PRAB 24 (6), (2020)
G Stupakov, J Tang, PRAB 24 (9), (2021)

Strawman designs for demonstrator facility at 30 GeV and collider at 250GeV

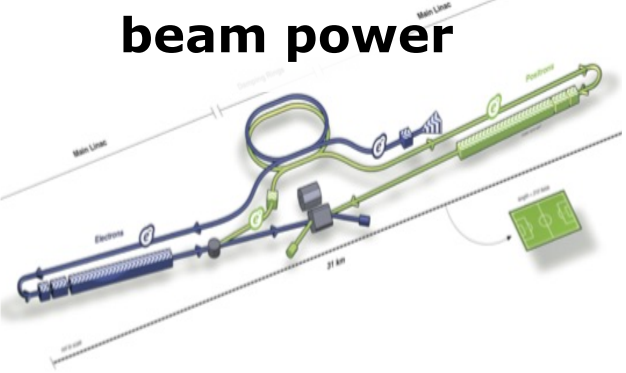
G.White, V.Yakimenko, arXiv:1811.11782 (2019)

What is needed:

Sustained efforts towards improving design and understanding tolerances/tuning algorithms.

Demonstration facility

HEP collider with low beam power



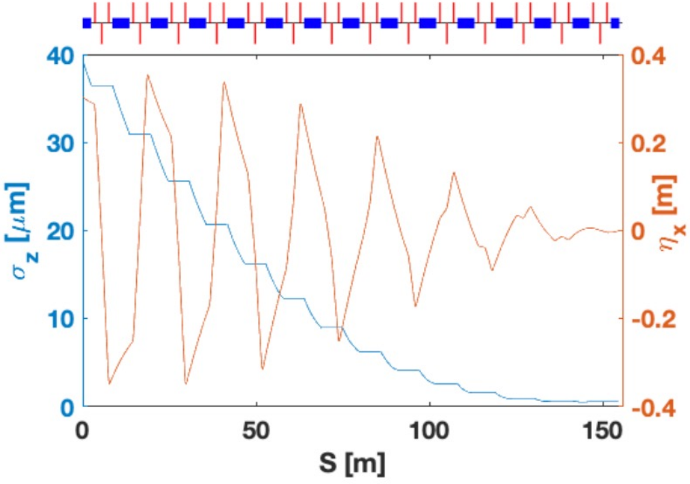
Short bunches -> beamstrahlung suppressed -> round beams at IP -> ≳100x reduction in beam & wall power / backgrounds / activation / cost

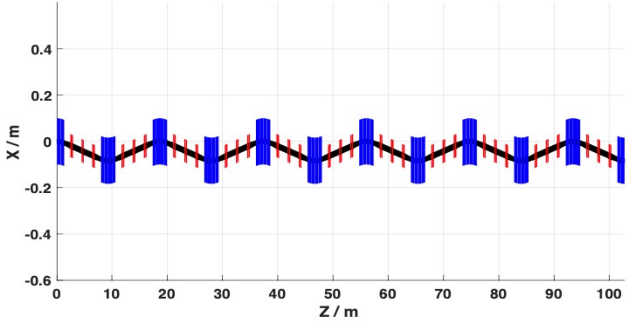
$$\sigma_z \sim 1\mu m@1TeV$$

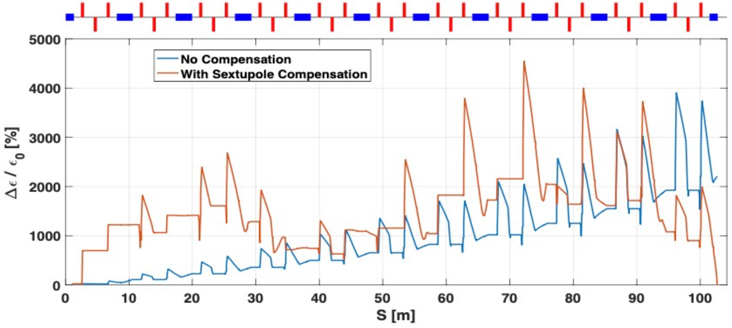
R. Blankenbecler, S. Drell, PRD 36, 277 (1987)

Wiggler-Compressor Concept at 30 GeV

$L_{bend} = 2.5\text{m}, \rho = 667\text{ m}, B_0 = 0.15\text{ T}, \delta_E/E = 0.25\%, R56 = 18\text{mm}$



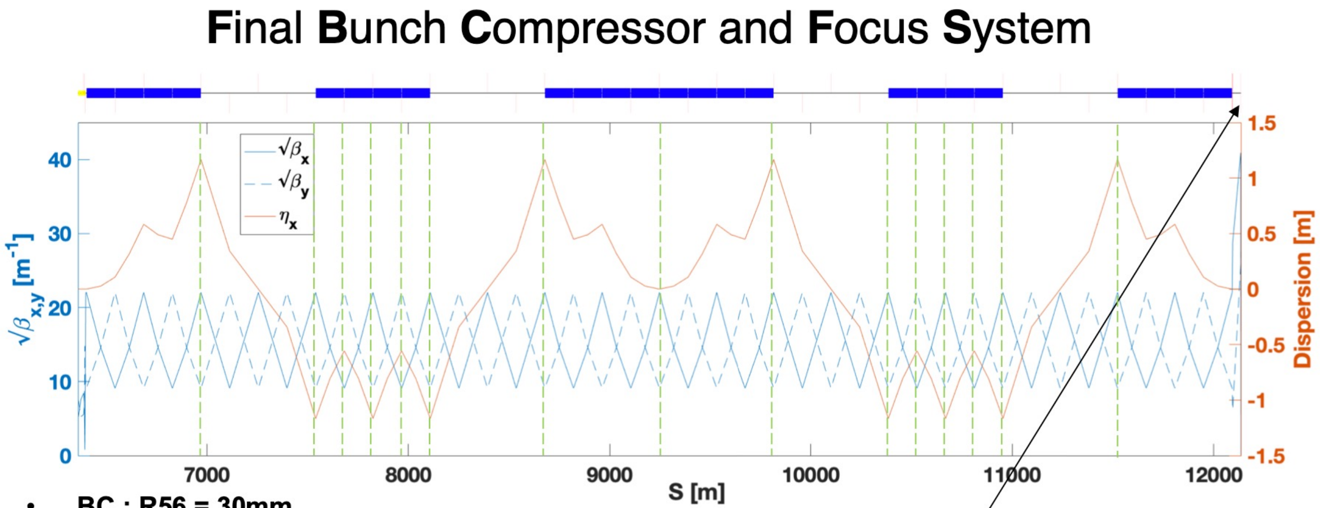




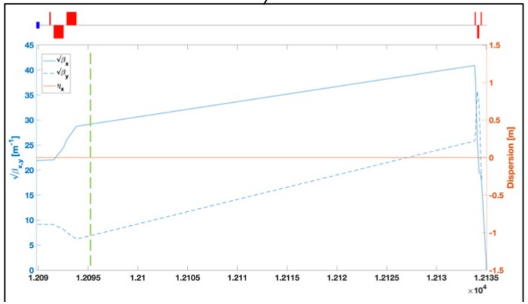
- 14X dogleg cells, triplet focusing lattice
- ISR emittance growth <10%

G. White, FACET-III Presentation

Final Focus-Compressor Concept


Final Bunch Compressor and Focus System

- **BC : R56 = 30mm**
  - 10 x 90^0 FODO cells x 2
  - 2nd order achromatic
  - large T566 & U5666
    - 16 sextupoles & octupoles
- **FFS:** doublet + triplet (β^* = 0.8 mm)
  - V. compact: L^*=0.5m, L_B=10cm



125 GeV CM
Collider concept for Higgs Production

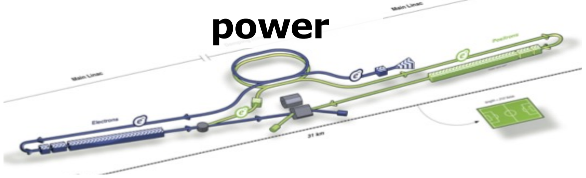
G. White, FACET-III Presentation

V. Yakimenko

Short Bunches to Enable New Physics

SLAC

HEP collider with low beam power



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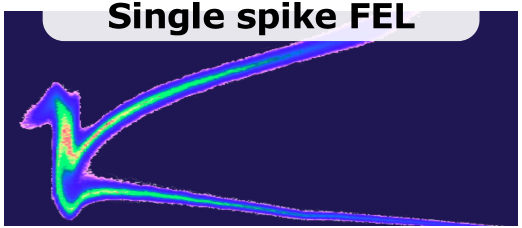
$\sigma_z \sim 1\mu m@1TeV$

R. Blankenbecler, S. Drell, PRD 36, 277 (1987)

Single spike FEL

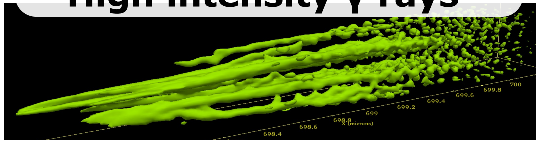


X-ray pulse has single spike when radiation emitted by the electrons in beam tail, travels to beam head in time shorter than few gain times

$\sigma_z \sim 0.1\mu m@10GeV$

R. Bonifacio et al. PRL 73, 70 (1994)

High intensity γ rays

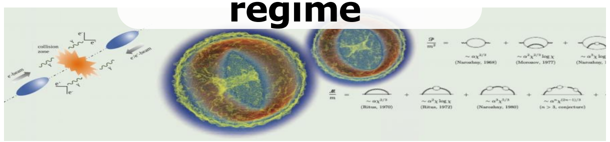


- Counter-streaming beam and plasma electrons result in instability and form self-generated beam filaments and EM fields.
- Trajectories of the beam electrons are bent in these fields and synchrotron radiation is emitted

$\sigma_z \sim 0.5\mu m@10GeV$

A. Benedetti et al. Nature Photon. 12, 319 (2018)

Fully non-perturbative QED regime



Key challenge: radiative energy loss in field transition (if $\chi \gtrsim 1$) prevents reaching $\chi \gg 1$, Radiation probability:

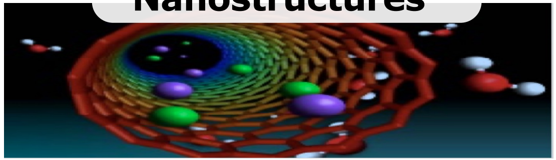
$\alpha\chi^{2/3} \gtrsim 1$

$$W \sim \alpha\chi^{2/3}\frac{\sigma_z/\gamma}{\lambda_c} < 1$$

$\sigma_z \sim 0.1\mu m@100GeV$

V. Yakimenko, et.al. PRL 122, 190404 (2019)

TV/m in Crystals and Nanostructures



Acceleration in solid-state plasma of crystals or nanostructures has promise of ultra-high accelerating gradients 1-10 TeV/m, continuous focusing and small emittances

$\sigma_z \sim 0.3\mu m@10GeV$

T. Tajima, et.al. PRL 59,1440 (1987)

Beam Physics Advancement

The research problems associated with generation and acceleration of extremely short and intense beams are fundamental and difficult, requiring sustained in-depth efforts and acceptance of greater uncertainty of the outcome.

Conclusion

- We can use novel technology and physics concepts to reshape the idea of a linear collider.

Or

- We can use conventional technology, but apply different design choices to reduce the scale and cost of the LC.

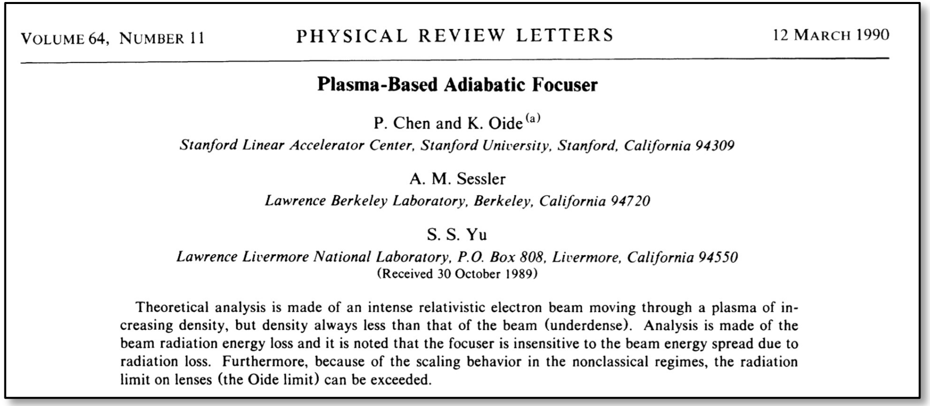
We plan to explore both possibilities for Snowmass White Papers.

Backup

Beating the Oide Limit

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

This solutions requires that the beam be made 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)]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

A. M. Sessler
Lawrence Berkeley Laboratory, Berkeley, California 94720

S. S. Yu
Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550

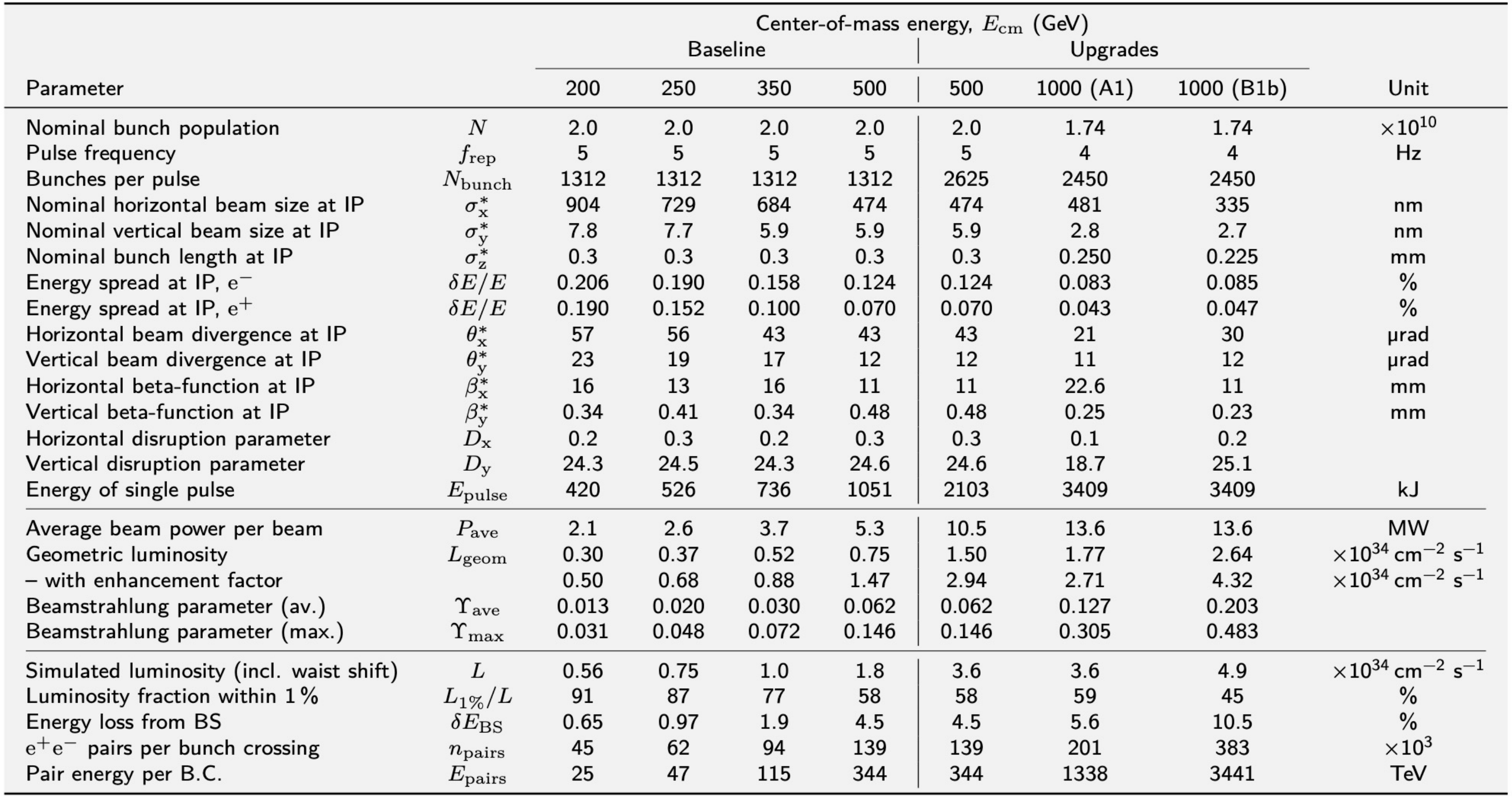
(Received 30 October 1989)

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.

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

ILC BDS

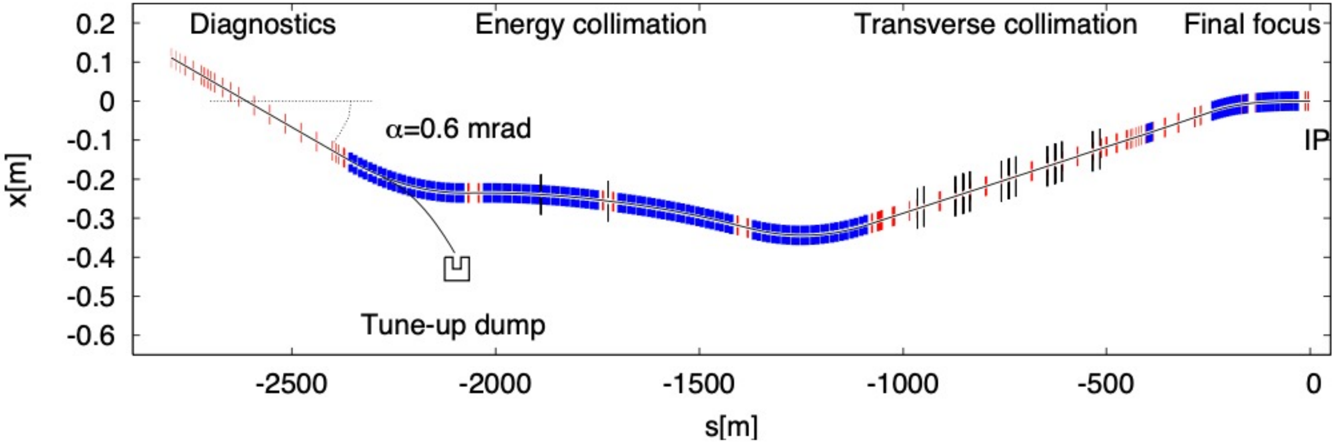
ILC TDR: https://arxiv.org/abs/0712.2361



		Center-of-mass energy, E_{cm} (GeV)							
		Baseline				Upgrades			
Parameter		200	250	350	500	500	1000 (A1)	1000 (B1b)	Unit
Nominal bunch population	N	2.0	2.0	2.0	2.0	2.0	1.74	1.74	$\times10^{10}$
Pulse frequency	f_{rep}	5	5	5	5	5	4	4	Hz
Bunches per pulse	N_{bunch}	1312	1312	1312	1312	2625	2450	2450	
Nominal horizontal beam size at IP	σ_{x}^*	904	729	684	474	474	481	335	nm
Nominal vertical beam size at IP	σ_{y}^*	7.8	7.7	5.9	5.9	5.9	2.8	2.7	nm
Nominal bunch length at IP	σ_{z}^*	0.3	0.3	0.3	0.3	0.3	0.250	0.225	mm
Energy spread at IP, e^-	$\delta E/E$	0.206	0.190	0.158	0.124	0.124	0.083	0.085	%
Energy spread at IP, e^+	$\delta E/E$	0.190	0.152	0.100	0.070	0.070	0.043	0.047	%
Horizontal beam divergence at IP	θ_{x}^*	57	56	43	43	43	21	30	μrad
Vertical beam divergence at IP	θ_{y}^*	23	19	17	12	12	11	12	μrad
Horizontal beta-function at IP	β_{x}^*	16	13	16	11	11	22.6	11	mm
Vertical beta-function at IP	β_{y}^*	0.34	0.41	0.34	0.48	0.48	0.25	0.23	mm
Horizontal disruption parameter	D_{x}	0.2	0.3	0.2	0.3	0.3	0.1	0.2	
Vertical disruption parameter	D_{y}	24.3	24.5	24.3	24.6	24.6	18.7	25.1	
Energy of single pulse	E_{pulse}	420	526	736	1051	2103	3409	3409	kJ
Average beam power per beam	P_{ave}	2.1	2.6	3.7	5.3	10.5	13.6	13.6	MW
Geometric luminosity	L_{geom}	0.30	0.37	0.52	0.75	1.50	1.77	2.64	$\times10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
– with enhancement factor		0.50	0.68	0.88	1.47	2.94	2.71	4.32	$\times10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Beamstrahlung parameter (av.)	Υ_{ave}	0.013	0.020	0.030	0.062	0.062	0.127	0.203	
Beamstrahlung parameter (max.)	Υ_{max}	0.031	0.048	0.072	0.146	0.146	0.305	0.483	
Simulated luminosity (incl. waist shift)	L	0.56	0.75	1.0	1.8	3.6	3.6	4.9	$\times10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Luminosity fraction within 1 %	$L_{1\%}/L$	91	87	77	58	58	59	45	%
Energy loss from BS	δE_{BS}	0.65	0.97	1.9	4.5	4.5	5.6	10.5	%
$\mathrm{e}^+\mathrm{e}^-$ pairs per bunch crossing	n_{pairs}	45	62	94	139	139	201	383	$\times10^3$
Pair energy per B.C.	E_{pairs}	25	47	115	344	344	1338	3441	TeV

CLIC BDS

CLIC CDR: https://project-clic-cdr.web.cern.ch/CDR_Volume1.pdf



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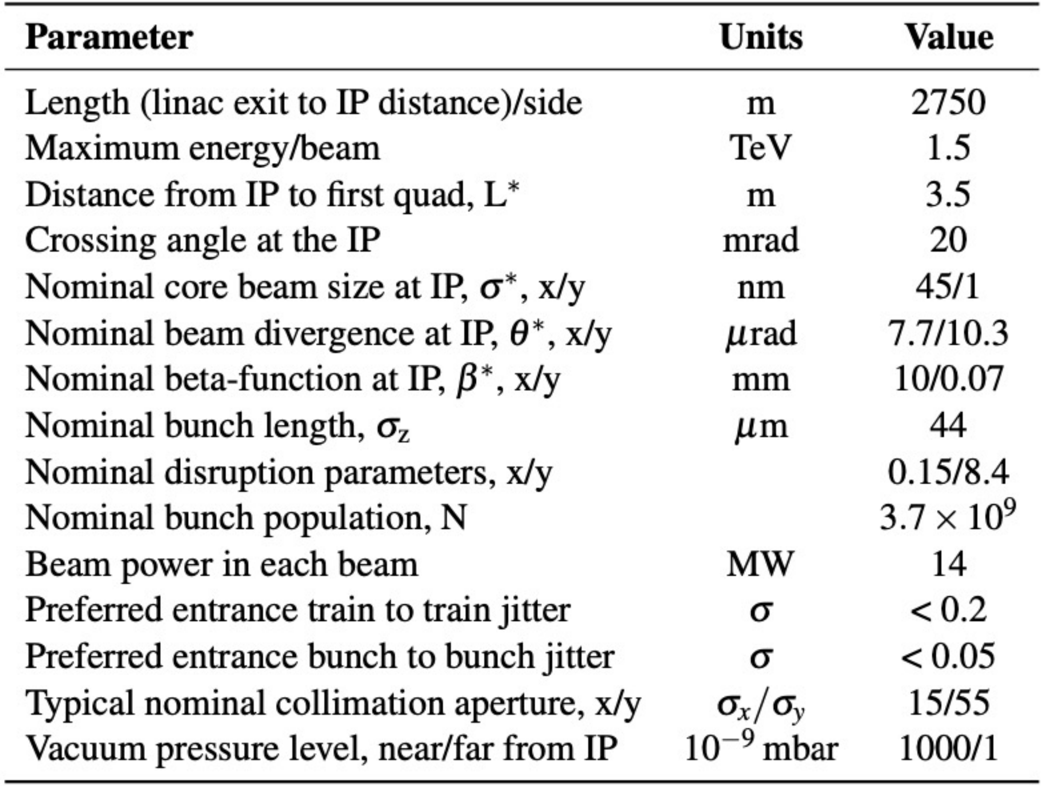

Parameter	Units	Value
Length (linac exit to IP distance)/side	m	2750
Maximum energy/beam	TeV	1.5
Distance from IP to first quad, L^*	m	3.5
Crossing angle at the IP	mrad	20
Nominal core beam size at IP, σ^*, x/y	nm	45/1
Nominal beam divergence at IP, θ^*, x/y	μrad	7.7/10.3
Nominal beta-function at IP, β^*, x/y	mm	10/0.07
Nominal bunch length, σ_z	μm	44
Nominal disruption parameters, x/y		0.15/8.4
Nominal bunch population, N		3.7×10^9
Beam power in each beam	MW	14
Preferred entrance train to train jitter	σ	< 0.2
Preferred entrance bunch to bunch jitter	σ	< 0.05
Typical nominal collimation aperture, x/y	σ_x/σ_y	15/55
Vacuum pressure level, near/far from IP	10^{-9} mbar	1000/1