Plasma Focusing:
Opportunities and Challenges

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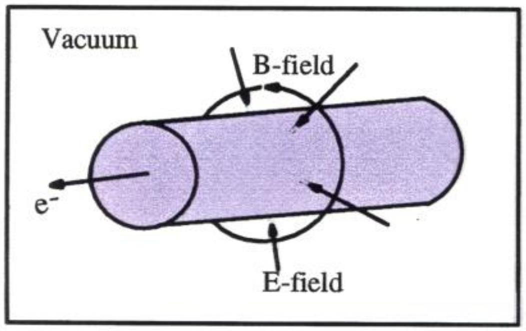
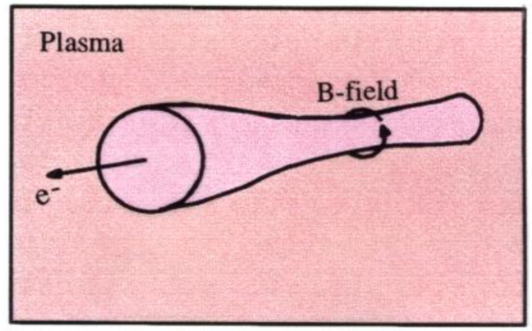
Outline

- Introduction: Overview and Motivation
- Experimental Results
- Challenges
  - Emittance preservation
  - Collider application: detector background
- Summary

Plasma lens focusing for linear colliders

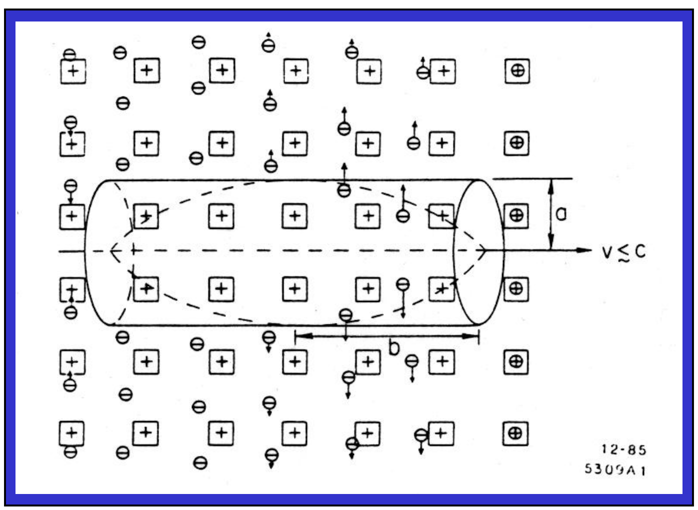
[Pisin Chen, Part. Accel., **20,** 171 (1987)]





In vacuum, there is no net Lorentz force on the beam

In a plasma, E-field is neutralized; B-field pinches the beam.



An electron beam traversing a plasma

The plasma electron density relative to the beam electron density will determine the location of the return current.

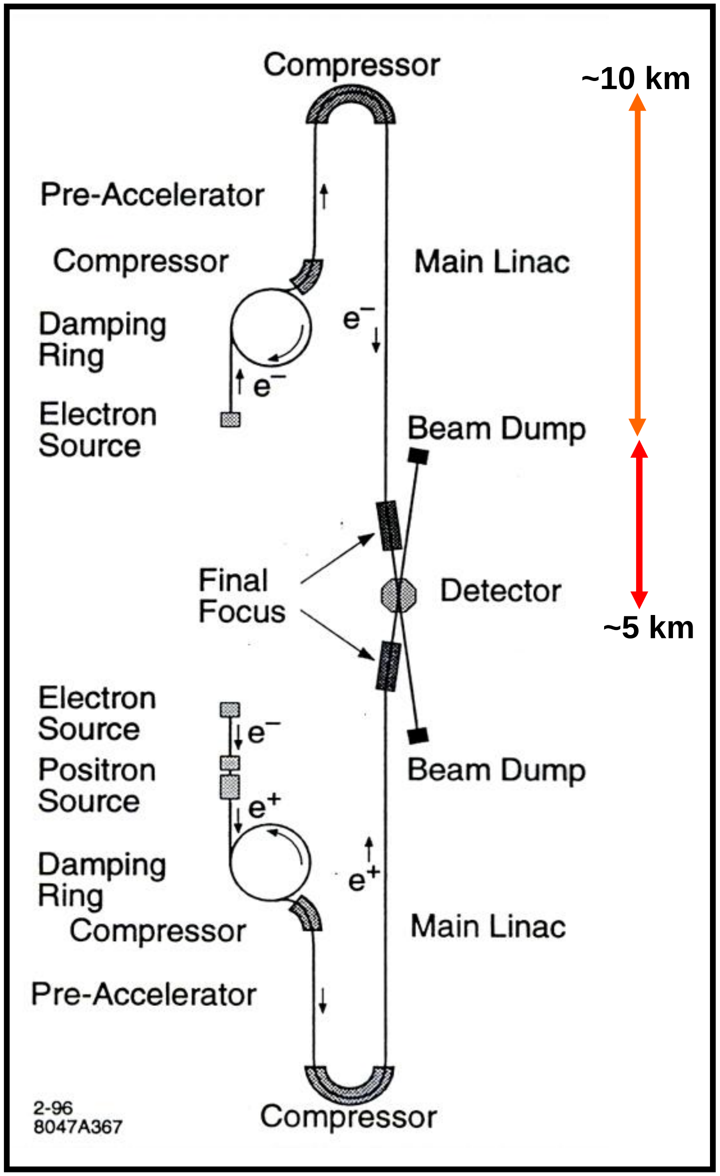
Review: Plasma Focusing

[P. Chen, in Handbook of Acc. Phys. and Eng., p484]

Regimes:	*Focusing mechanism*	*Focusing Strength*	*Beam Optics*
Underdense ($n_p < n_b$) SLAC-E157 and E164x [e.g., P. Muggli *et al* PRL2008] UCLA/FNPL, [Thompson *et al* PAC07]	e^-: total rarefaction, ions provide nearly linear focusing. e^+: excess plasma electrons and current pull positrons inward	$K_{e^-} \approx \frac{2\pi \cdot r_e}{\gamma} \cdot n_p$ $K_{e^+} \approx \frac{8 \cdot r_e}{\gamma} \cdot n_p$	-Thick lens considered. $\beta(s) = \frac{\beta_0}{2} + \frac{1}{2K\beta_0^*} + \frac{s_0}{\sqrt{K}\beta_0^*}\sin\left[2\sqrt{K}(s-s_0)\right] + \left(\frac{\beta_0}{2} - \frac{1}{2K\beta_0^*} - \frac{s_0}{\sqrt{K}\beta_0^*}\right)\cos\left[2\sqrt{K}(s-s_0)\right]$ -Maximum reduction: $\frac{\beta^*}{\beta_0^*} = \frac{1}{1+K\beta_0^*(\beta_0-\beta_1)}$
Overdense $n_p > n_b$, $k_p \cdot \sigma_r << 1$ SLAC E-150 [J.Ng *et al,* PRL 2001]	-Plasma fully neutralize space charge of the beam while the return current runs outside of the beam volume -Beam's magnetic field leads to self-focusing	$K \approx \frac{2\pi \cdot r_e}{\gamma} \cdot n_b$	- Thin lens considered. - Aberration power: $P = \left[1 + (\frac{\beta_0}{f} \cdot \delta)^2\right]^{1/2}, f = 2/K \cdot l$ -Courant-Snyder parameters: $\alpha = \alpha_0/P, \beta = \beta_0/P, \varepsilon = \varepsilon_0 \cdot P$ -Reduction in spot size: $\frac{\beta^*\varepsilon}{\beta_0\varepsilon_0} = \frac{P^2}{P^2 + (\alpha_0 + \beta_0/f)^2}$
Superdense $n_p >> n_b$ $k_p \cdot \sigma_r >> 1$	Return current penetrates beam volume; both beam fields (magnetic and electric) largely cancelled; self-focusing diminishes.	$K \approx \frac{2\pi \cdot r_e}{\gamma} \cdot \frac{n_b}{1+(k_p \cdot \sigma_r)^2}$	

Why a Plasma Lens ?

- Linear collider luminosity ~$1/\sigma_x \sigma_y$.
- Plasma lens is super strong:
  of order 1000 Tesla / cm;
  about **1000 times** stronger than
  conventional quadrupoles.
- Plasma lens is an integral part of a plasma accelerator.
- Potential reduction of complexity and **length** of FFS in linear collider.
- Plasma lens focuses **electrons** as well as **positrons**



Early Experiments

- **ANL - J.Rosenzweig,et al.,(1989)**
  - **Thick plasma lens 35 cm long with n~1-7 x 10^{13} cm^{-3}**
  - **21 MeV electron beam with n ~ 2.5-4 x 10^{10} cm^{-3}**
  - **Beam size reduced from σ = 1.4 mm to σ = 0.9 mm**

- **Tokyo university - H. Nakanishi, et al., (1990)**
  - **Thin plasma lens with density n~1.4 x 10^{11} cm^{-3}**
  - **18 MeV electron beam with n ~ 1.2 x 10^{10} cm^{-3}**
  - **Theory for thin plasma lens is confirmed**

- **UCLA - G. Hairapetian, et al., (1993)**
  - **Thin plasma lens with n ~ 4 x 10^{12} cm^{-3}**

- **LBNL - W. Leemans, et al., (1996)**

These experiments confirmed the plasma lens concept, but operated at low energies with electron beams only, and low plasma densities: ~ 10^{-6} to that for SLC/NLC

SLAC E150 : Plasma Focusing of Positrons

- Study plasma focusing for high-energy,
  high-density electron and positron particle beams
  in the regime relevant to high energy colliders

- Better understanding of beam-plasma interactions
  and benchmarking of computer codes
  for future plasma lens designs

- Develop compact, simple and economical
  plasma lens designs suitable for high-energy
  collider applications

SLAC E150 Collaboration

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Parameters of the E150 Experiment

Final Focus Test Beam Facility (FFTB) beam parameters (e- and e+)

- **bunch charge:** 1.5×10^{10} (electrons or positrons) per pulse
- **beam size:** 5-11 μm in X, 3-5 μm in Y
- **bunch length:** 600 μm
- **beam energy:** 28.5 GeV
- **norm. emittance:** 5×10^{-5} m rad in X
  0.5×10^{-5} m rad in Y

→ **beam density:** $\sim 7 \times 10^{16}$ /cm^3

Gas Jet

- **gas:** N_2 or H_2, neutral density $\sim 3 \times 10^{18}$ /cm^3
- **nozzle size:** 3 mm
- **gas pressure:** 250-1000 lb per square inch

Plasma Production

- **beam-induced ionization:** ~7% efficiency
- **laser-induced ionization:** ~50% efficiency
- **laser pulse:** λ=1.06μm, E~1J, τ ~ 10 ns FWHM
- **plasma characterization:** optical interferometry

Schematic Layout of the Experiment

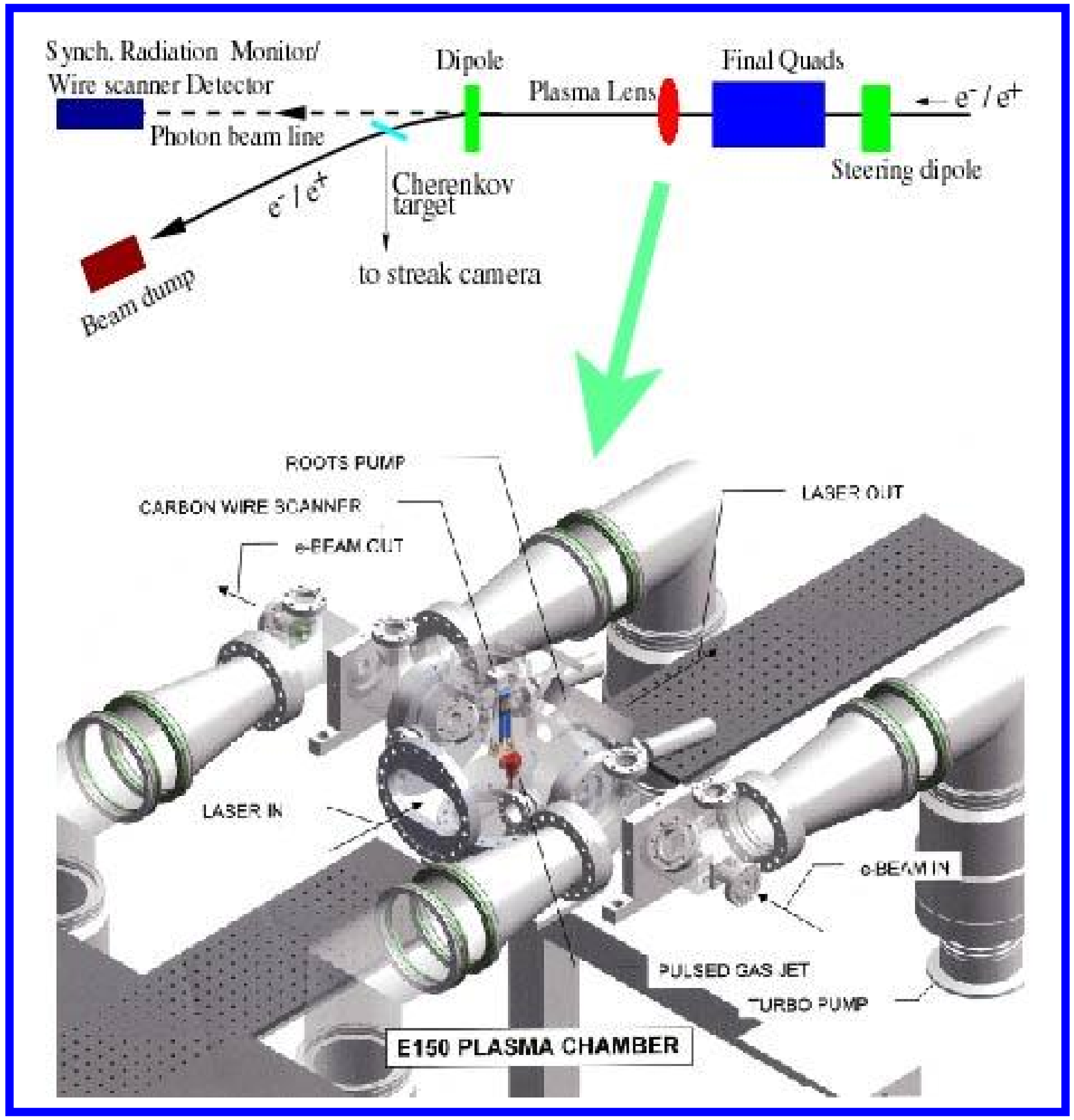
Plasma Lens Experiment at the Stanford Linear Accelerator Center

SLAC E-150 Plasma Lens Collaboration

FNAL, Hiroshima, KEK, LLNL, SLAC, Tennessee, UCLA

The Final Focus Test Beam Line

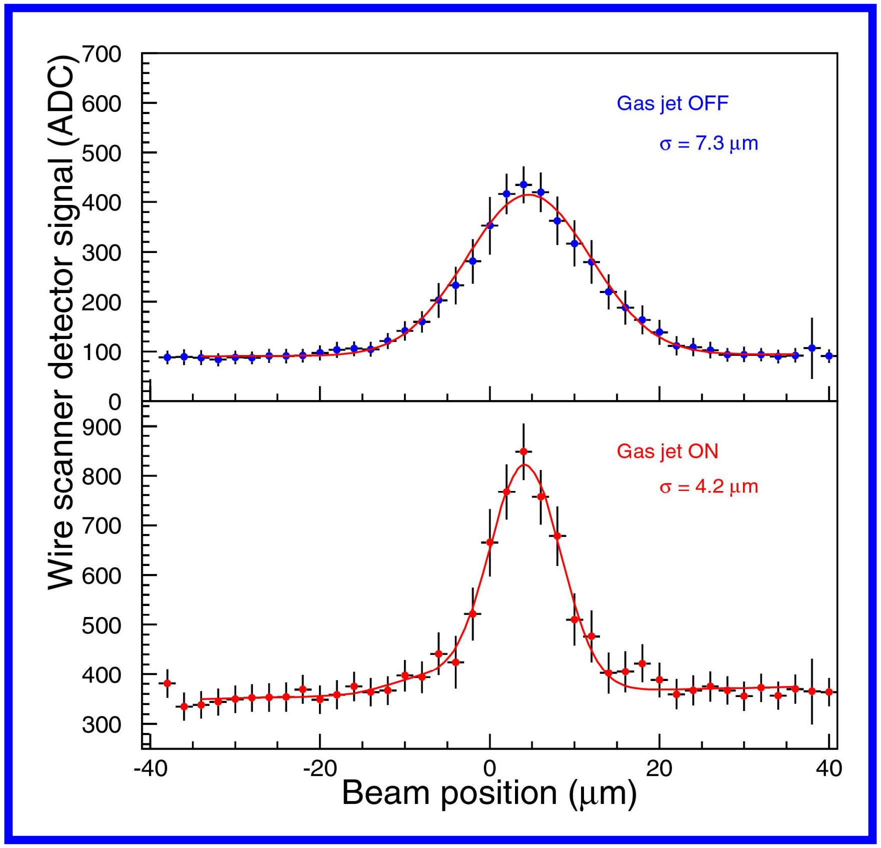
3D drawing of the plasma chamber



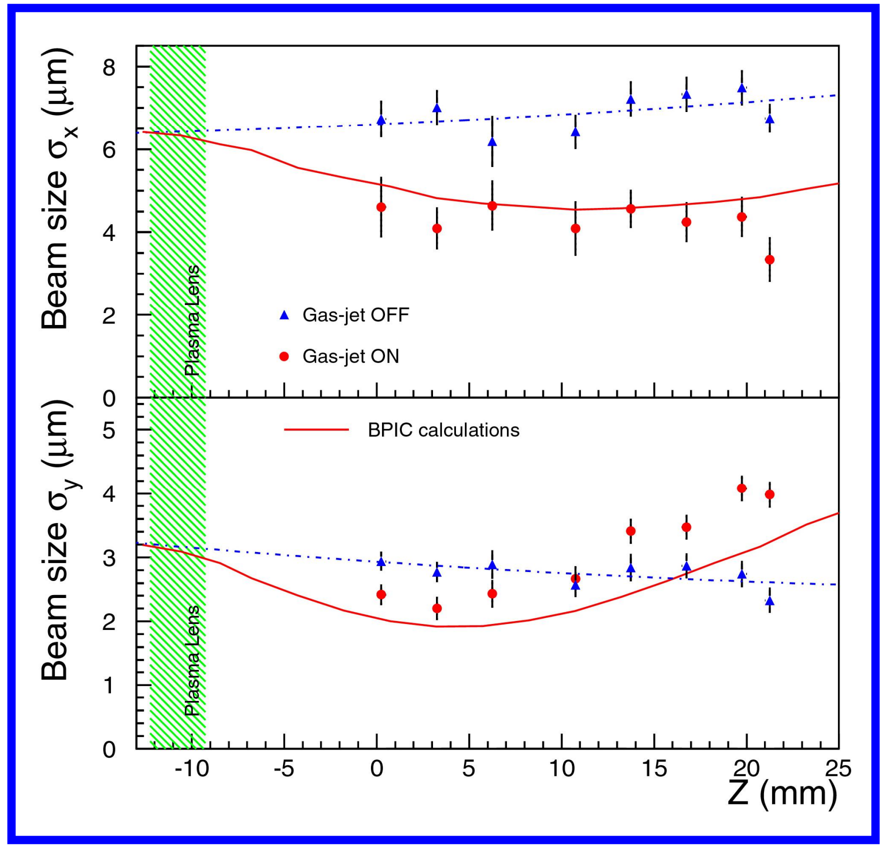
Beam Self-ionization Plasma Focusing

[J.S.T. Ng *et al.*, PRL 2001]

29 GeV electron beams



Transverse beam profile

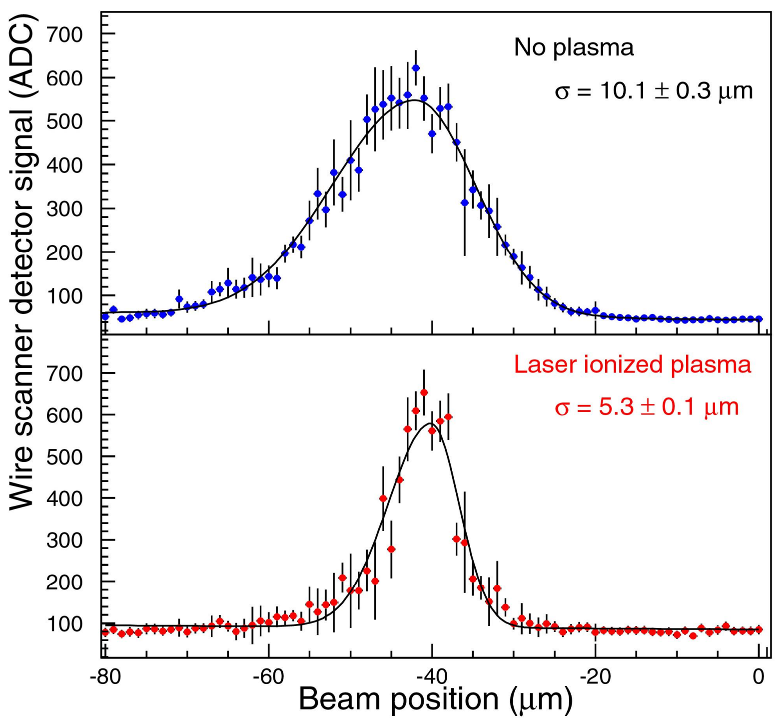


Beam envelope

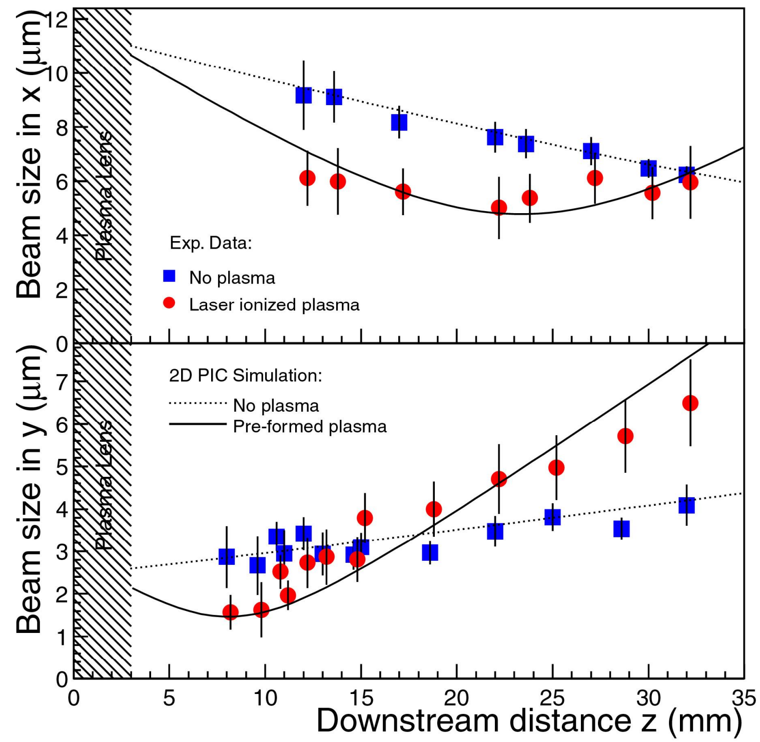
Laser Ionization Plasma Focusing

[J.S.T. Ng *et al.*, PRL 2001]

29 GeV positron beams



Transverse beam profile



Beam envelope

SLAC E157, E162, E164X: Plasma Acceleration and Focusing

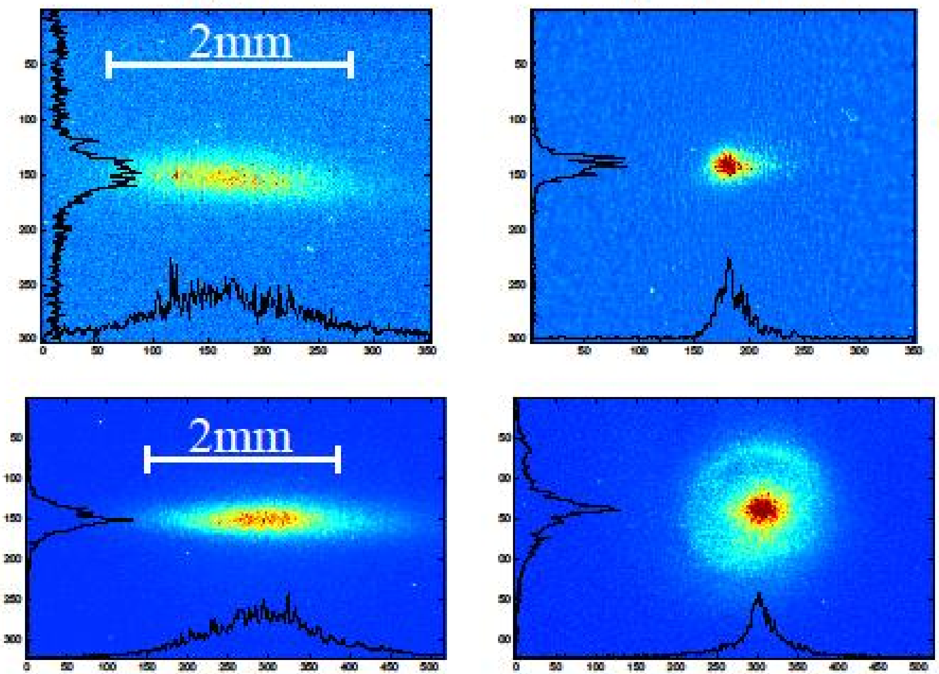
[P. Muggli, 2003]

FOCUSING OF e^-/e^+

- OTR images ≈1m from plasma exit ($\varepsilon_x \neq \varepsilon_y$)

$n_e=0$ | $n_e \approx 10^{14}$ cm^{-3}

e^- / e^+



- Ideal Plasma Lens in Blow-Out Regime
- Plasma Lens with Aberrations

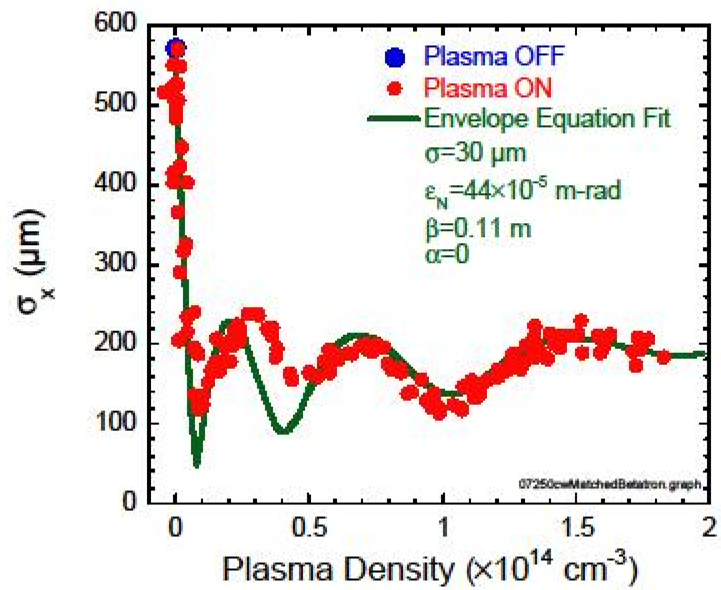
P. Muggli, SLAC-DoE, 04/10/03

E164X: Plasma focusing as a function of plasma density

[P. Muggli *et al*, PRL 2004]

CHANNELING OF e⁻

OTR Images ≈1m downstream from plasma



Envelope equation:

$$\frac{\partial^2\sigma}{\partial z^2}+\left(K^2-\frac{\varepsilon^2}{\sigma^3}\right)\sigma^2=0$$

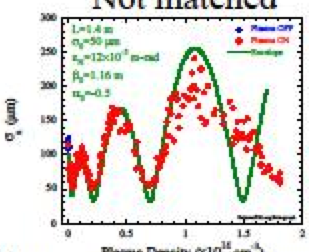
In an ion channel:

$$K=\frac{\omega_{pe}}{\sqrt{2\gamma c}}\propto(n_e)^{1/2}$$

Beam-plasma matching:

$$K^2=\frac{n_e e^2}{\varepsilon_0 m_e 2\gamma c^2}=\frac{\varepsilon^2}{\sigma^4}$$

Not matched



- $n_{e,\,matched}$ =2.5×10¹⁴ cm⁻³
- σ insensitive to n_e at matching, stabilize hose instability
- Channeling of the beam over 1.4 m or >12β_0

P. Muggli, SLAC-DoE, 04/10/03

E164X: Halo Formation and Emittance Growth

[P. Muggli *et al*, PRL 2008]

Observed halo formation: e^+ beam

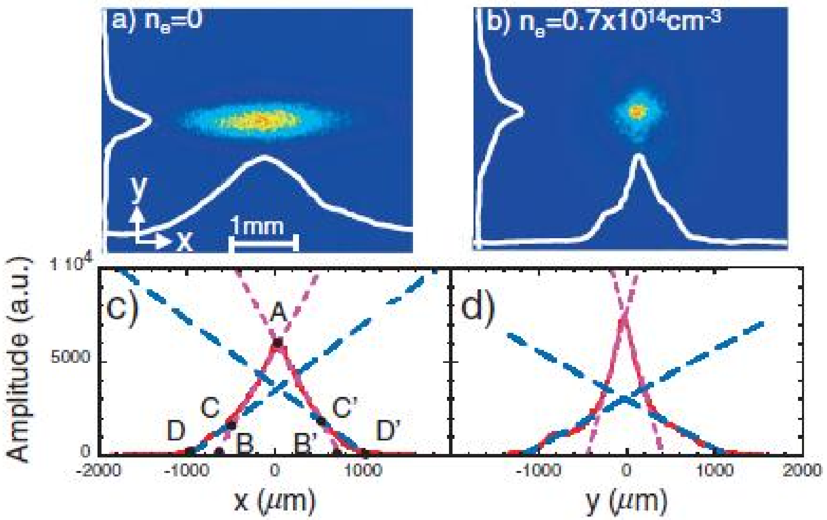


FIG. 1 (color). Experimental images of the beam at the downstream OTR location for (a) $n_e = 0$ and (b) $n_e \approx 0.7 \times 10^{14}\ \mathrm{cm}^{-3}$. Examples of the experimental beam profiles ($n_e > 0$), as well as the triangle fits used for the calculation of the beam transverse sizes (FWHM of ABB' triangle), and charge fractions in the core (area of ABB' triangle) and halo (area $CBD + C'B'D' = 2CBD$) in the (c) x plane and (d) y plane.

Use simulation (QuickPIC) to quantify emittance growth.

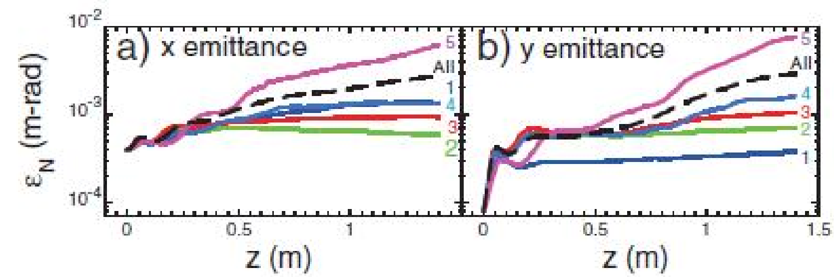


FIG. 4 (color). Emittance of the whole beam (dashed black line, labeled "All") and of five z slices containing 20% each of the total beam charge, in the (a) x and (b) y plane as obtained from simulations. The lines are labeled with their slice number, starting from the bunch front. The focused beam size at the plasma entrance is 25 μm (round); the incoming invariant emittances are $\epsilon_{Nx} \approx 390 \times 10^{-6}$ m rad and $\epsilon_{Ny} \approx 80 \times 10^{-6}$ m rad, and $n_e = 2 \times 10^{14}\ \mathrm{cm}^{-3}$.

Mitigate using a hollow channel plasma?

UCLA/FNPL Experiment: Underdense Plasma Focusing

[M.C. Thompson *et al*., PAC 07]

Beam:15 MeV, 19 nC, e^- beam
Plasma Lens: 20 mm, n_p ~ 5E12 cm^{-3}

Angular spread from lens aberration:
$\varepsilon_{n,x,eff}$ ~ 110 μm vs. $\varepsilon_{n,x,0}$ ~ 87 μm

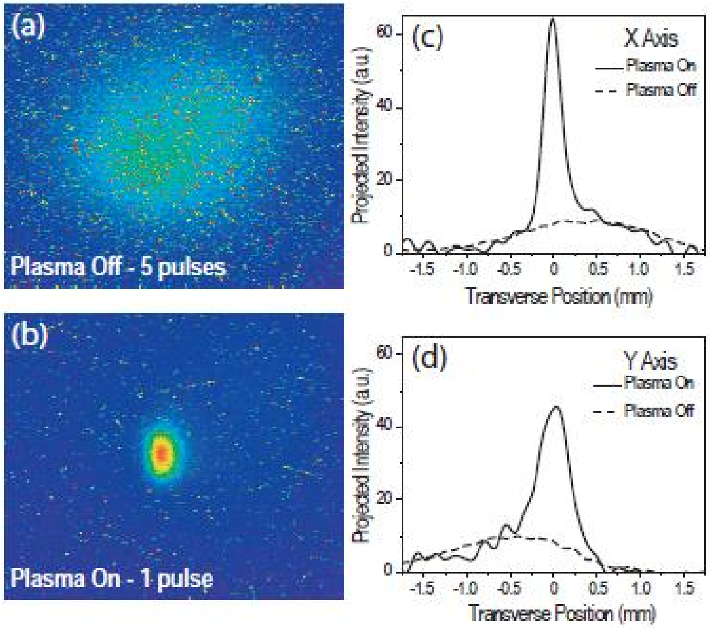


Figure 2: Images of the unfocused (a) and focused (b) electron beam OTR displayed with the same scaled to intensity color map. In order to provide sufficient contrast, the unfocused image (a) is the integration of 5 beam pulses. The projected intensity of the focused and unfocused beams (normalized to 1 pulse) in the x axis (c) and y axis (d) is also shown.

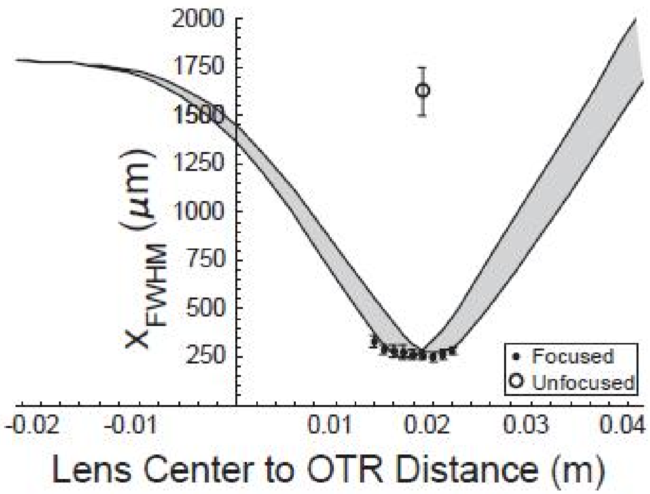


Figure 3: Measurements of underdense plasma lens focusing of a round beam in the x axis shown with solutions to the envelope equation (solid lines and shaded region). The shaded region indicate the shift in focal length caused by the variation in plasma lens parameters.

Strong focusing with lower aberration than overdense lens.

Collider Application: Detector Background

- The plasma lens is placed deep inside the particle detector near the IP
- Background estimates strongly dependent on detector configuration and machine parameters
- Simulation studies indicate background predominantly due to photons

Background Study for NLC-Type Detector

[A. Weidemann et al., SLAC-PUB-9207, 2002]

Table 1: Summary of background sources from a plasma lens in NLC for a single beam crossing. The cross sections σ_{tot} are integrated as in Eq. (11) and (5); energy cuts (of $4-100keV$, $> 100keV$) were imposed in the calculation of particle numbers in the last two columns; see Section 5.

Background source	σ_{tot} (cm^{-2}) $\lvert\cos\theta\rvert \leq 0.99$	Vertex detector	Drift chamber
Bhabha and Møller e^+, e^-	0	0	0
Elastic *ep*: e	0.103×10^{-45}	negligible	negligible
p	0.613×10^{-39}	negligible	negligible
Inelastic *ep*: e	0.132×10^{-33}	negligible	negligible
charged hadrons	0.396×10^{-29}	0.021	0.021
Inelastic γp: charged hadrons	0.372×10^{-28}	0.139	0.139
Compton γ's from quadrupole	0.18×10^{-24}	270	380
Compton γ's from plasma focusing	0.23×10^{-24}	290	580
Compton γ's from bremsstrahlung	0.19×10^{-23}	970	480
Compton γ's from beamstrahlung	0.52×10^{-25}	70	130

- NLC beam parameters
- Plasma lens: overdense $n_p = 2 \times 10^{18}$ cm^{-3}, 3mm thick

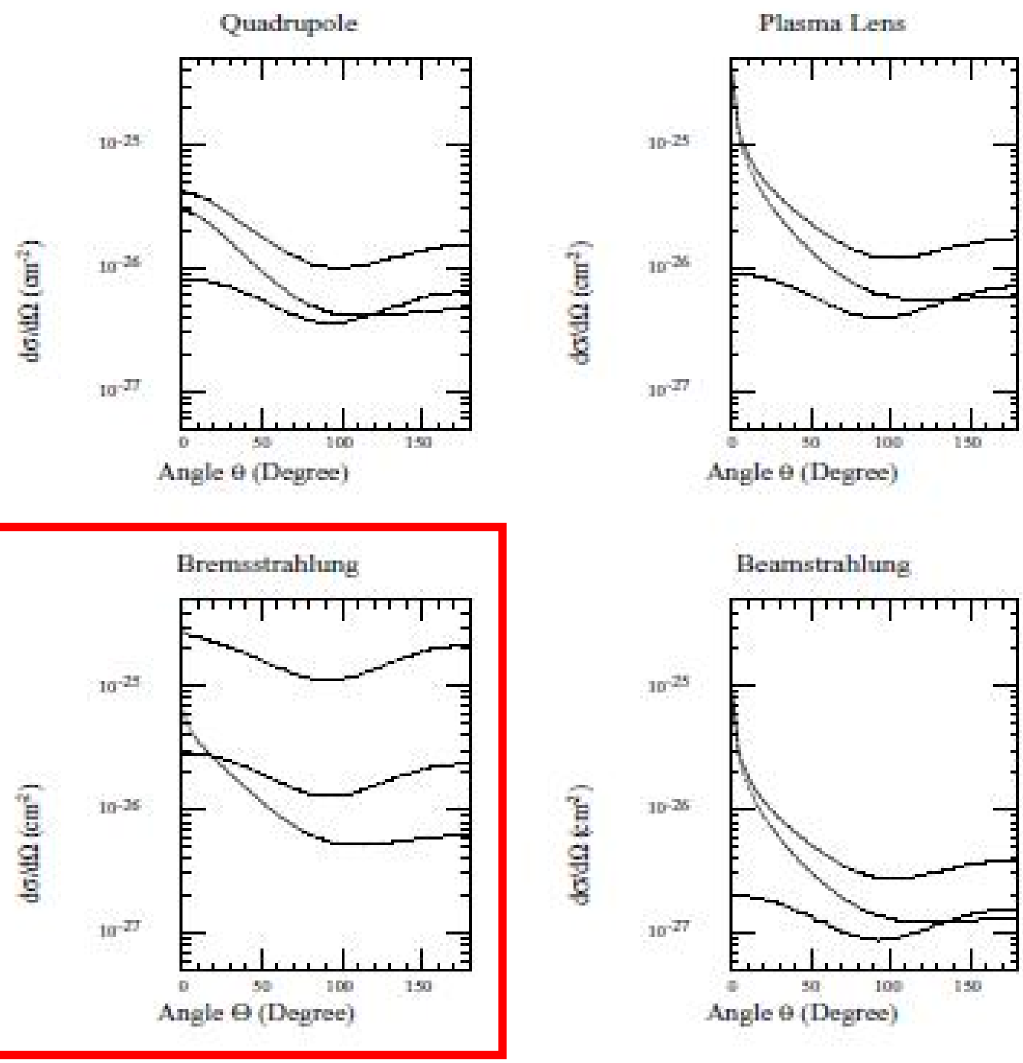


Fig. 3. Angular distributions of the Compton cross sections from the four sources of photons: quadrupole focusing, plasma-lens focusing. bremsstrahlung in plasma,beamstrahlung. The topmost solid lines are integrated over the whole energy range, the next lower ones for the energy range between 4 keV and 100 keV (relevant for the vertex detector), and the lines lowest (at right-hand side of plot) are for photons of energy greater than 100 keV (relevant for the drift chamber).

Plasma-induced Detector Background: Further Studies Needed

- Important issue for collider application
- So far only one serious study has been carried out (some time ago)
- Must include simulation of detector
- What about underdense plasma lens?

Summary and Outlook

- Strong plasma focusing of e^- and e^+ has been demonstrated for collider parameters; underdense plasma lens advantageous.
- Further experiments needed to study emittance preservation/growth mitigation: FACET, NLCTA, …
- Plasma-induced detector background requires further study