Plasma Tools for Antimatter Physics*

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Acknowledgements:

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Antimatter Basics

- All known particles have an antiparticle
  - Equal mass, but opposite charge (q = -q)
  - Example: Antiprotons, positrons (antielectrons)
- Created during high energy processes when $E > mc^2$
  - Radioactive decay
  - High energy accelerators
- Annihilates with it's matter counter part

Positron Applications

- Positron beams to probe surfaces
- Creation of antihydrogen at CERN to test CPT symmetry
- Positron atomic physics

Future…

- Bose-Einstein condensed positronium
- Gamma ray laser
- Plasma diagnostics (test particle)

Current Limitation: Positron Sources

- Low energy positron sources are weak, I ~ pA

Solution: Positron Trapping

- Collect large numbers of positrons in charge particle traps

Outline

- High Field positron trap
- Beams
  - Extraction method
  - Predictions and results
- Attractive features
  - Cold beams
  - Narrow beams
  - Multiple beams
- Electrostatic beams

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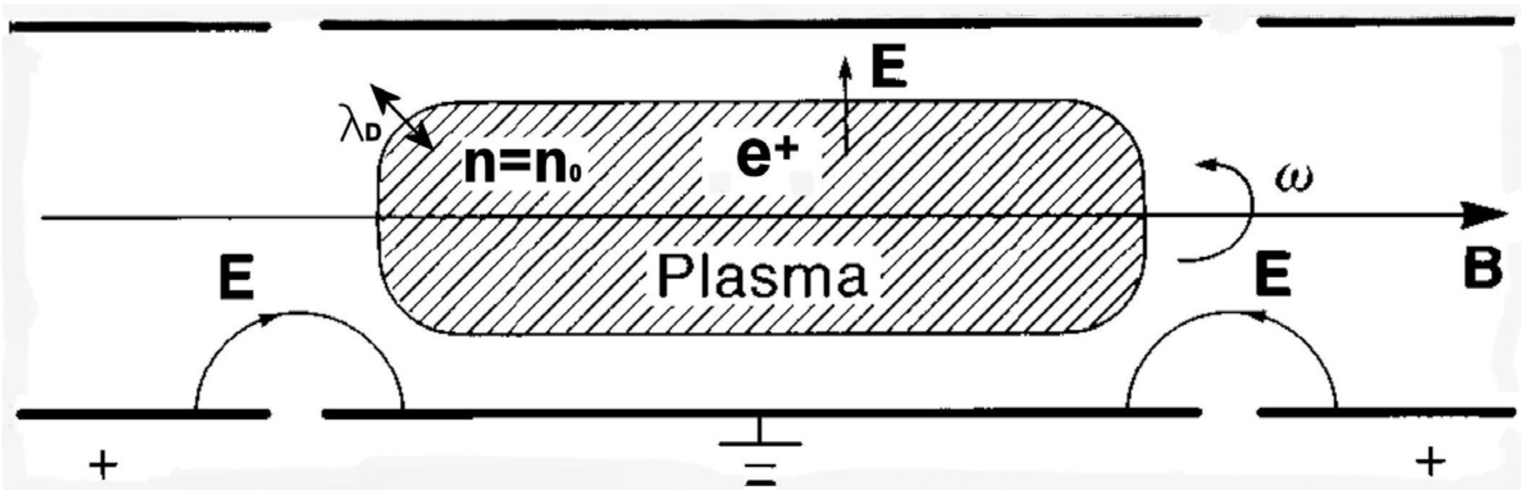
Penning-Malmberg Trap



-Uniform density (n_0) rigid rotor (E × B drift)

$$f_E \propto n_0$$

-Confined in state of thermal equilibrium

-Infinite confinement times

-Thermal equilibrium with walls

(Dubin, Rev. of Mod. Phys. '99)

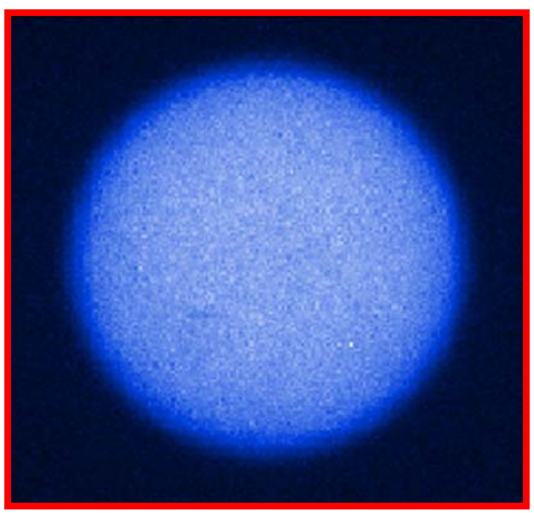
High Field Trap

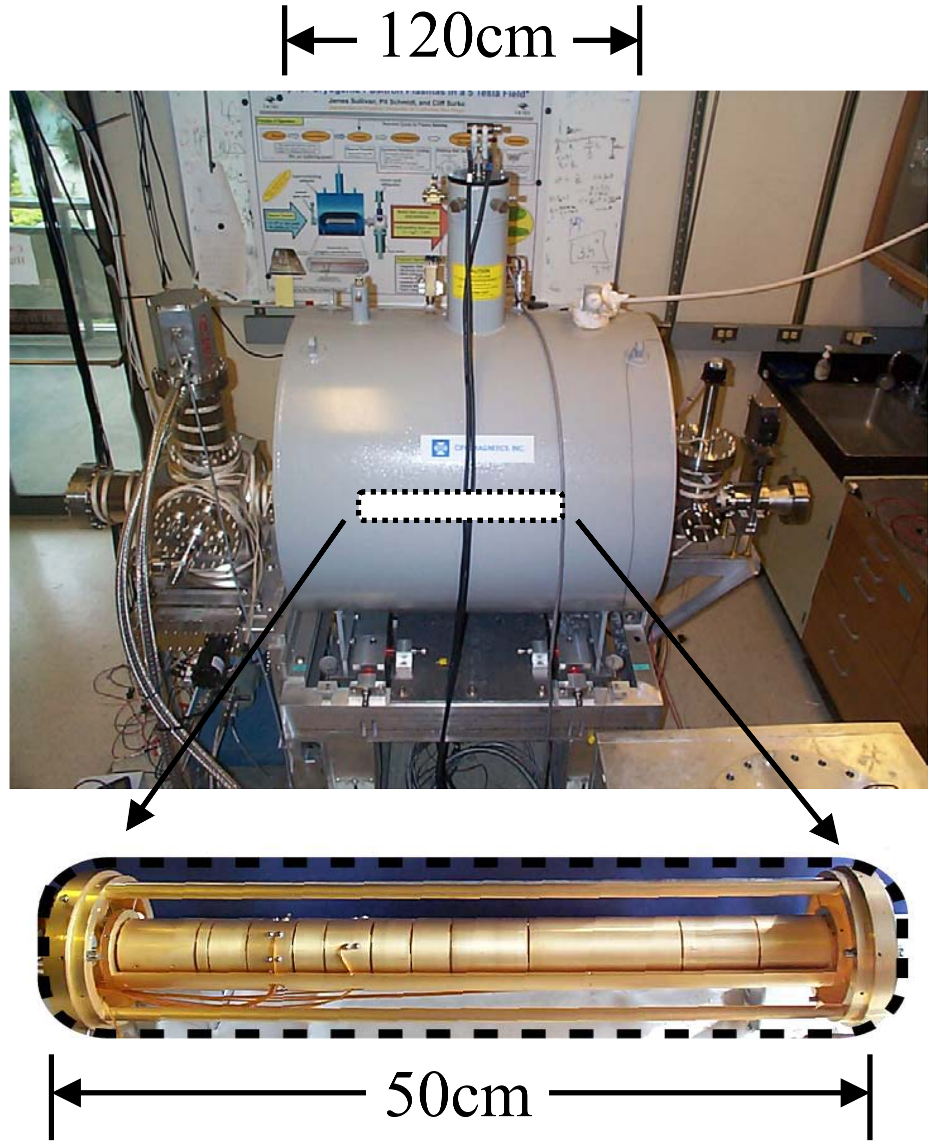
-B = 5 T

-T_{elec}~ 10 ⇔ 300 K

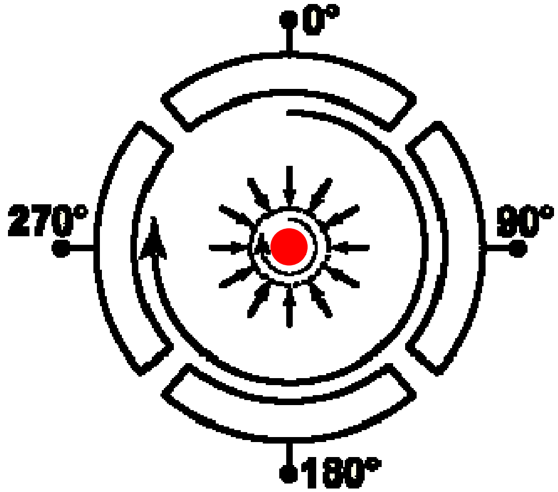
-Screen & Camera

-“Rotating Wall”



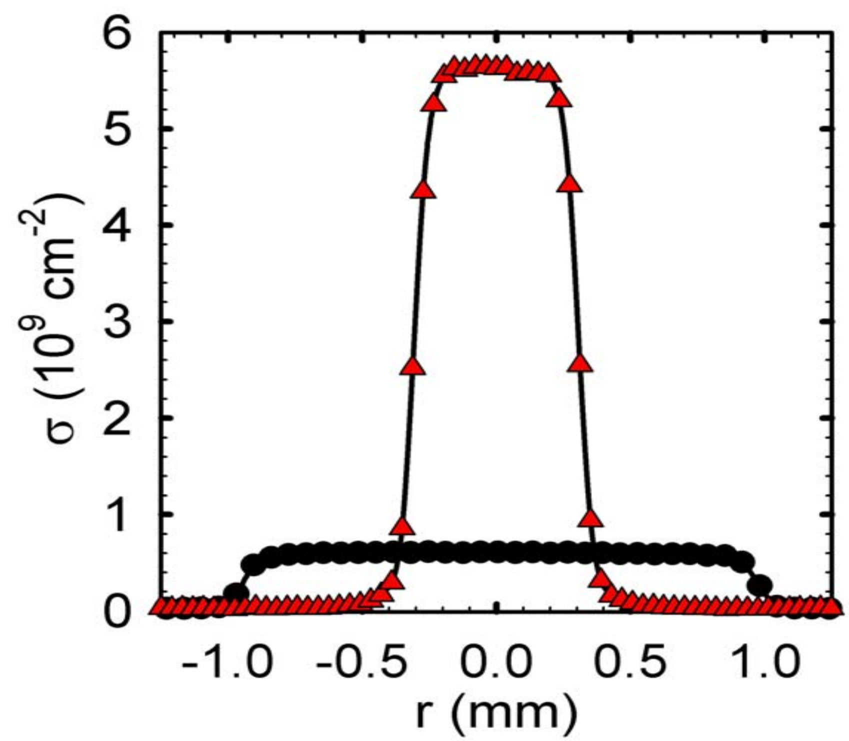


“Rotating Wall” Compression*



$f_{RW} > f_E$ compression
$f_{RW} < f_E$ expansion

$$V = V_{RW} \cos[(2\pi f_{RW})\, t + \theta]$$



“Strong Drive” regime

X.-P. Huang , et. al., *PRL* ‘97.
Danielson, et. al., *PRL* 05; 07; *Phys. Pl.* ‘06.

Trapping Parameters Achieved

- **$N \sim 10^{10}$**
- **$T < 20$ meV**
- **$n \sim 5 \times 10^{10}$ cm^{-3}**
- **$\tau \sim$ days**

High Quality Beams from Trap?

- Most positron applications require high quality beams (narrow, bright, and cold)
- Future applications hinge on beam quality

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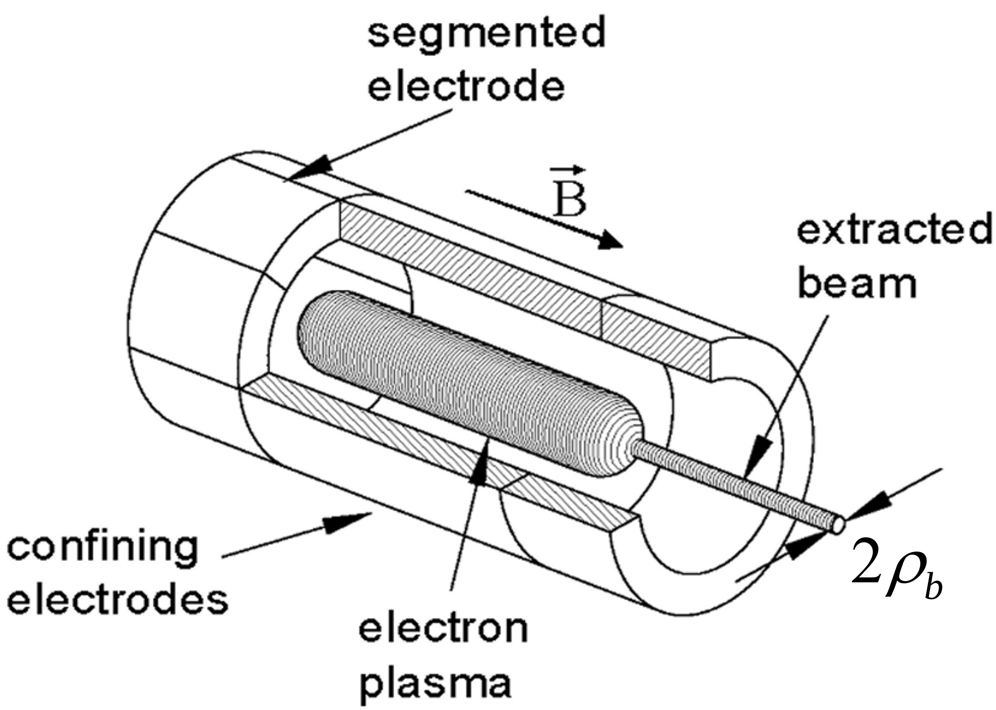
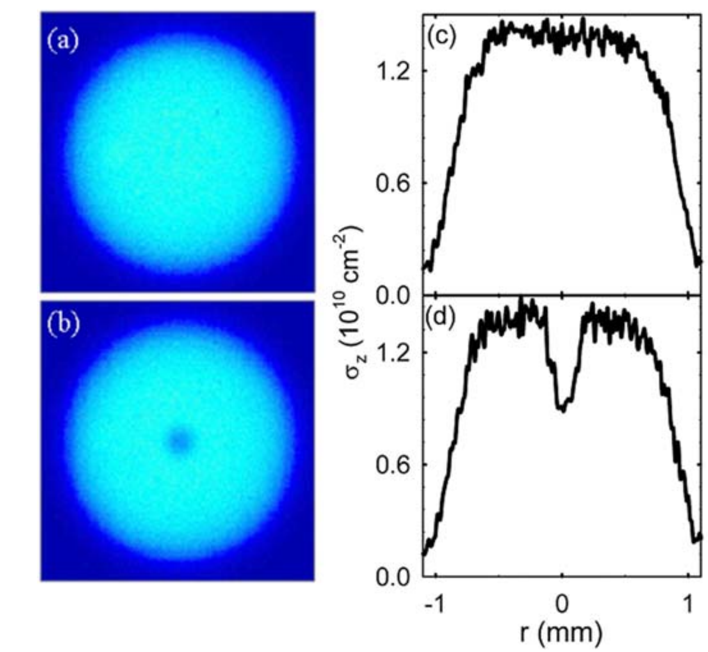
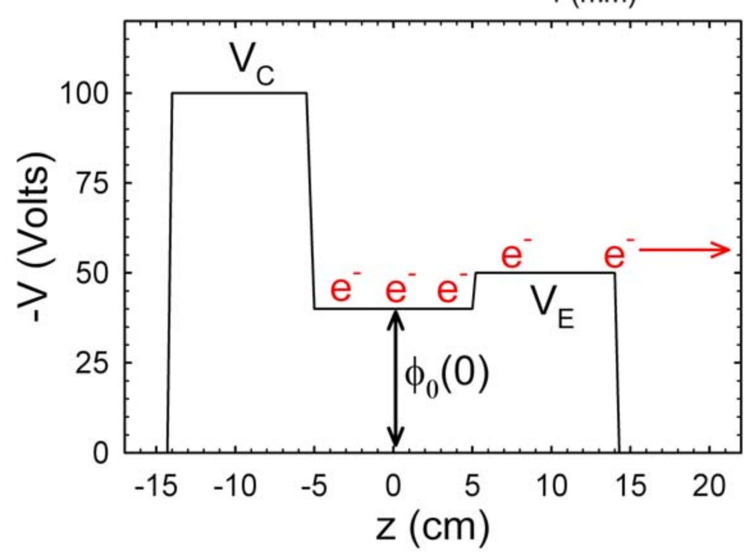
Extraction Method



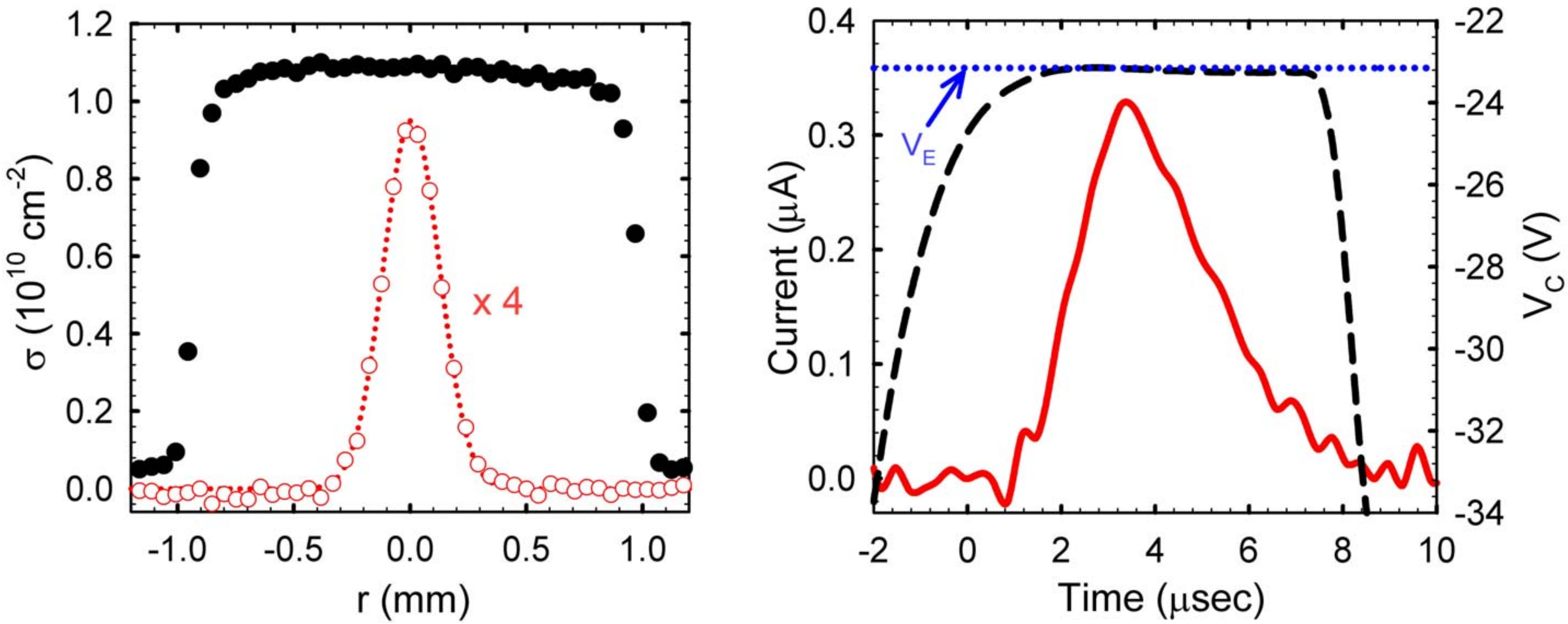
$$V_C \rightarrow V_E$$





Danielson, et. al., *Appl. Phys. Lett.*, 2007.
Weber, et. al., *Phys. Plasmas*, 2008.

Beam Measurements



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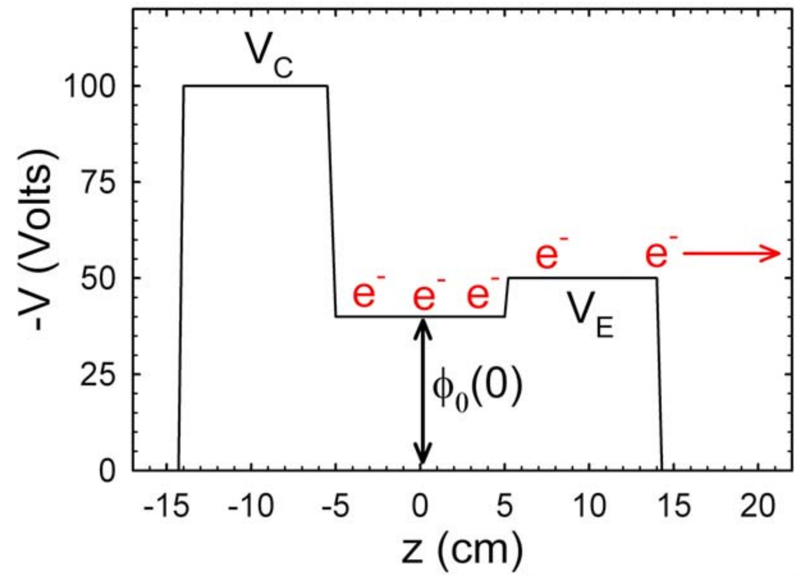
Beam Model

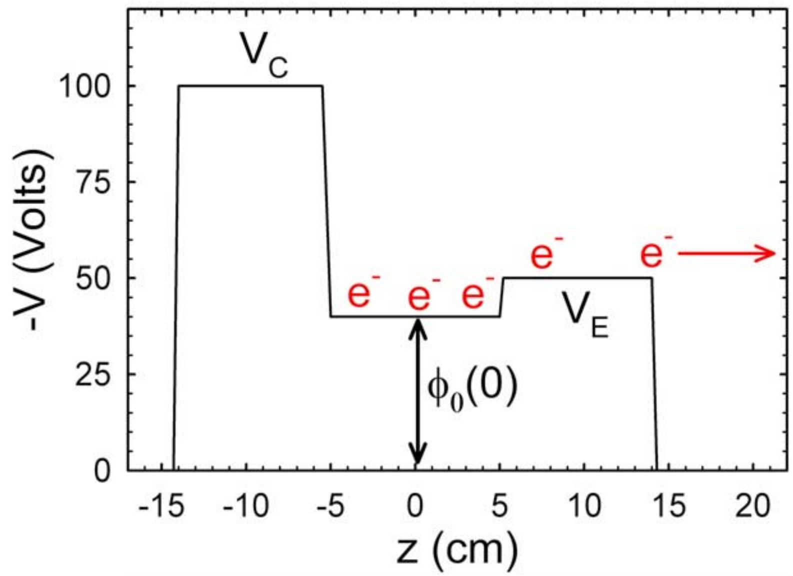
$$v_{z\,\min}(r) = \sqrt{-\frac{2e}{m_e}\left[V_E - \phi_o(r)\right]}$$

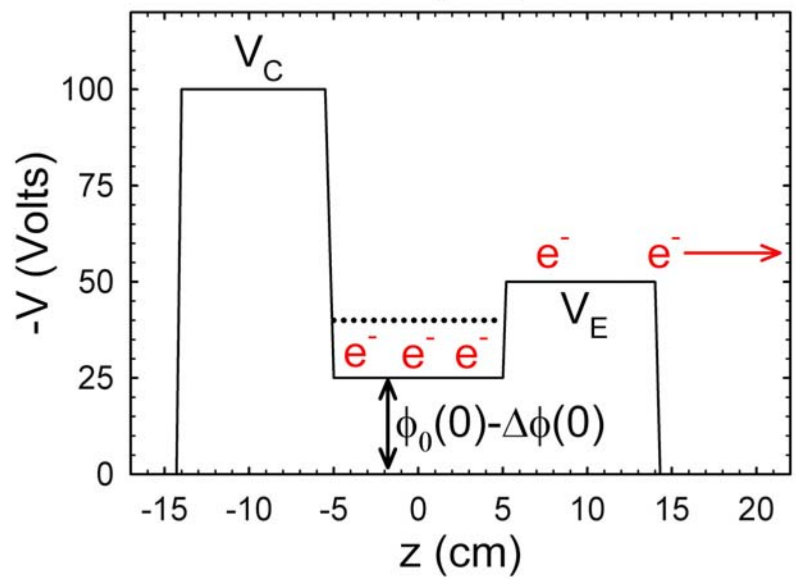


Beam Model

$$v_{z\min}(r) = \sqrt{-\frac{2e}{m_e}\left[V_E - \phi_o(r)\right]}$$

$$v_{z\min}(r) = \sqrt{-\frac{2e}{m_e}\left[V_E - \phi_o(r) + \Delta\phi(r)\right]}$$





Beam Profile Theory

$$\sigma_b(r) = \int_{v_z > v_{z\min}(r)} f_p d^3\vec{v}\, d\theta dz \approx \sigma_0 \exp\left[-\left(\frac{r}{2\lambda_D}\right)^2 + \frac{e\Delta\phi(r)}{T} \right]$$

Gaussian beam $\longrightarrow$ $\Delta\phi(r) \approx \Delta\phi(0) + \dfrac{eN_b}{L_P}\dfrac{r^2}{\rho_b^2}$

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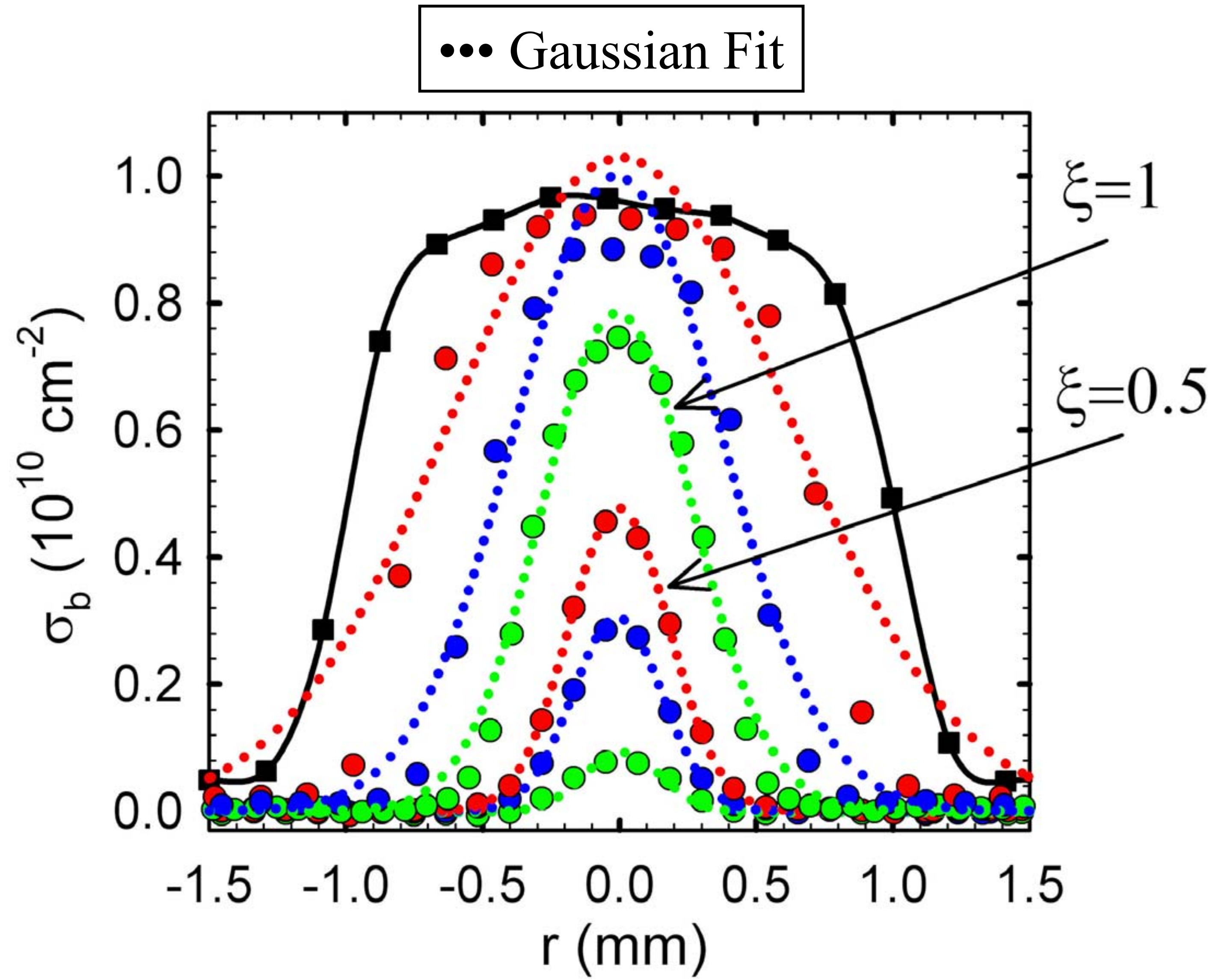
Gaussian beam $\longrightarrow$ $\Delta\phi(r) \approx \Delta\phi(0) + \frac{eN_b}{L_P}\frac{r^2}{\rho_b^2}$

Beam profile: $\sigma_b(r) = \sigma_{bo} \exp\left[-\left(\frac{r}{\rho_b} \right)^2 \right]$

Beam width: $\rho_b = 2\lambda_D (1+\xi)^{1/2}$

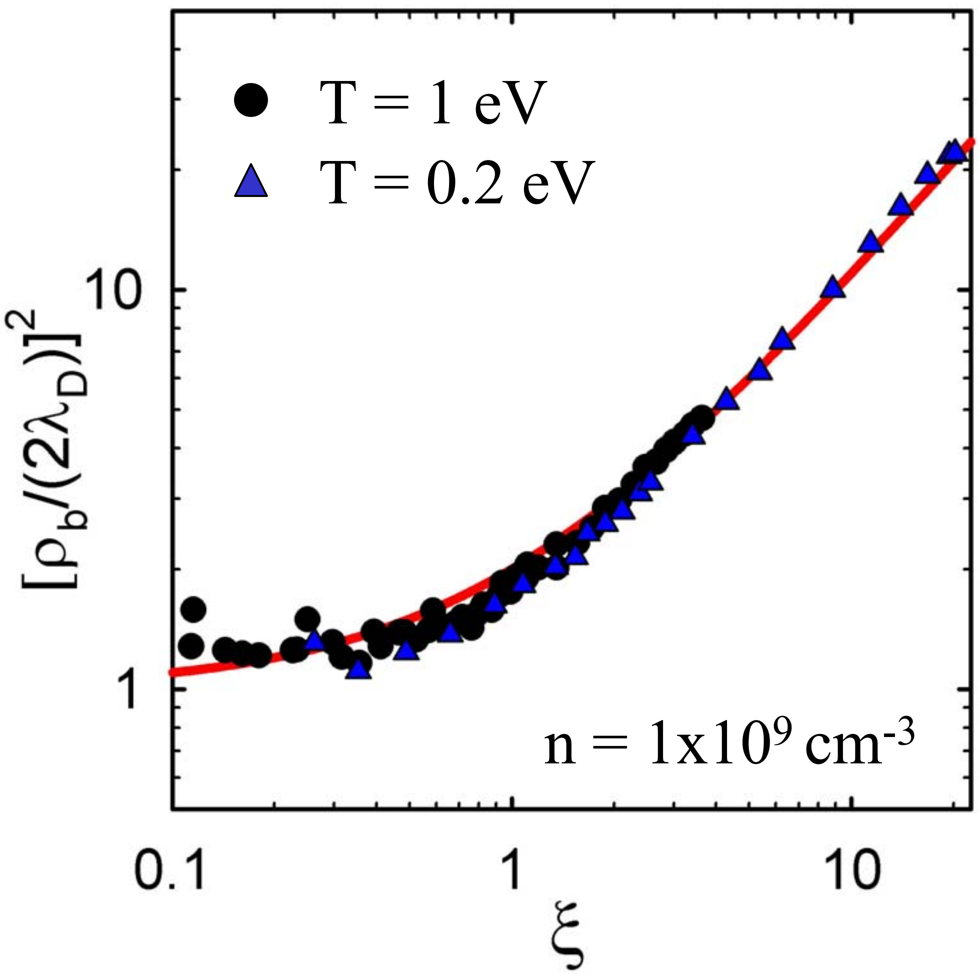
Beam parameter: $\xi = \frac{e^2 N_b}{TL_P} = \left. \frac{e\Delta\phi(r)}{T} \right|_0^{\rho_b}$

Test Predictions



Beam Widths

$$\rho_b = 2\lambda_D(1+\xi)^{1/2}$$



$$\xi = \frac{e^2 N_b}{T L_P}$$

Beam Number Equation: $N_b(V_E)$

$$N_b = \int_{v_z > v_{z\min}(r)} f_p \, d^3\vec{v} \, d^3\vec{r}$$

$$v_{z\min}(r) = \sqrt{-\frac{2e}{m_e}\left[V_E - \phi_o(r) + \Delta\phi(r)\right]}$$

$$\Delta\phi(r) \approx -\frac{eN_b}{L_P}\left[\gamma + 2\log\left(\frac{R_W}{\rho_b}\right) + \Gamma\left(\frac{R_W^2}{\rho_b^2}\right) - \frac{r^2}{\rho_b^2}\right]$$

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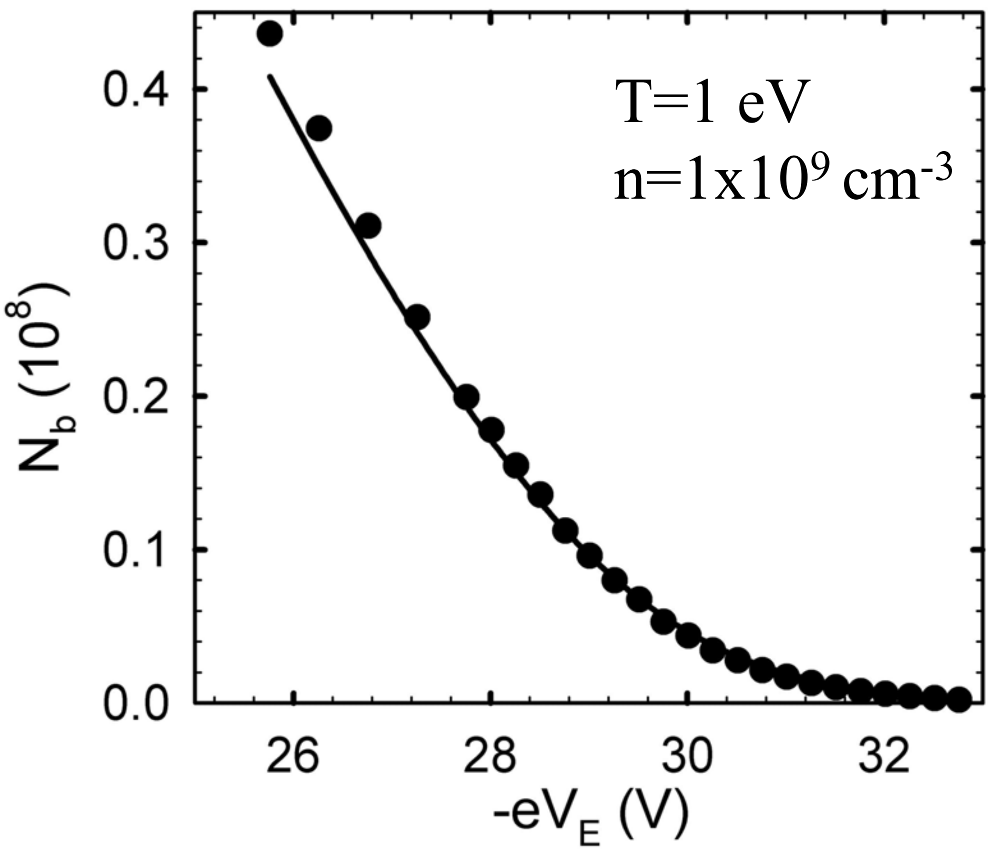
⬇

$$\boxed{N_b = A(V_E, \text{plasma parameters})}$$

Test Predictions

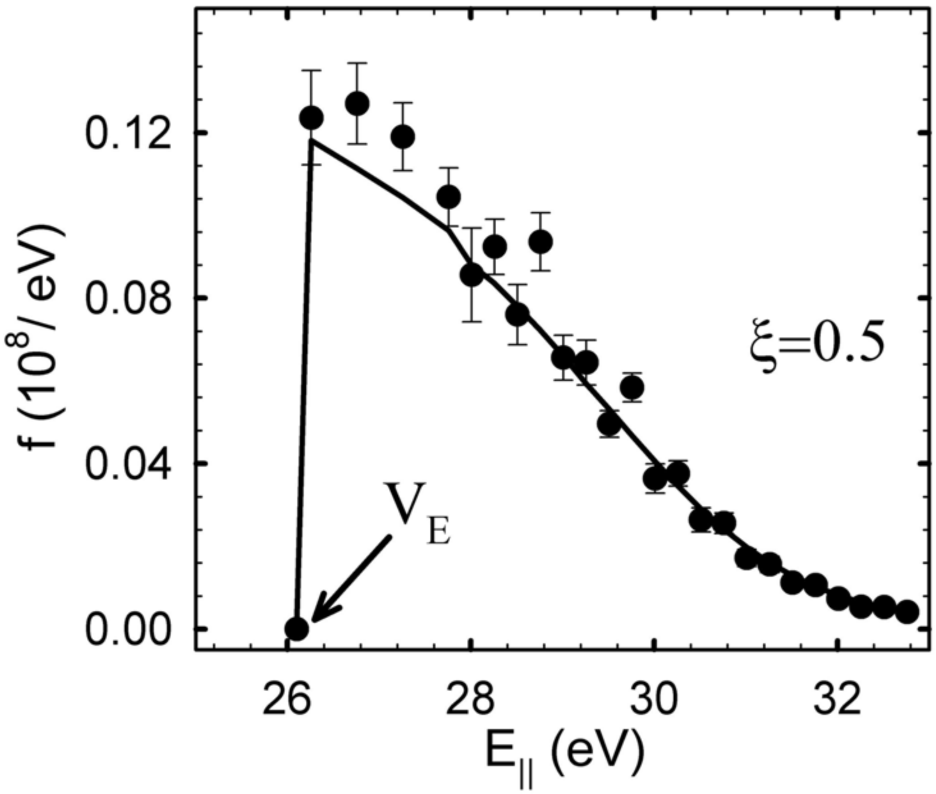


Only fitted parameter is $\varphi_0(0)$

Weber, et. al., *Phys. Plasmas*, 2009.

Energy Distribution Function

$$f(E_{\|}, E_{\perp}) \propto e^{-E_{\perp}/T} \left.\frac{dN_b}{dV_E}\right|_{V_E = E_{\|}}$$



NOT a thermal beam (i.e., Non-Maxwellian)

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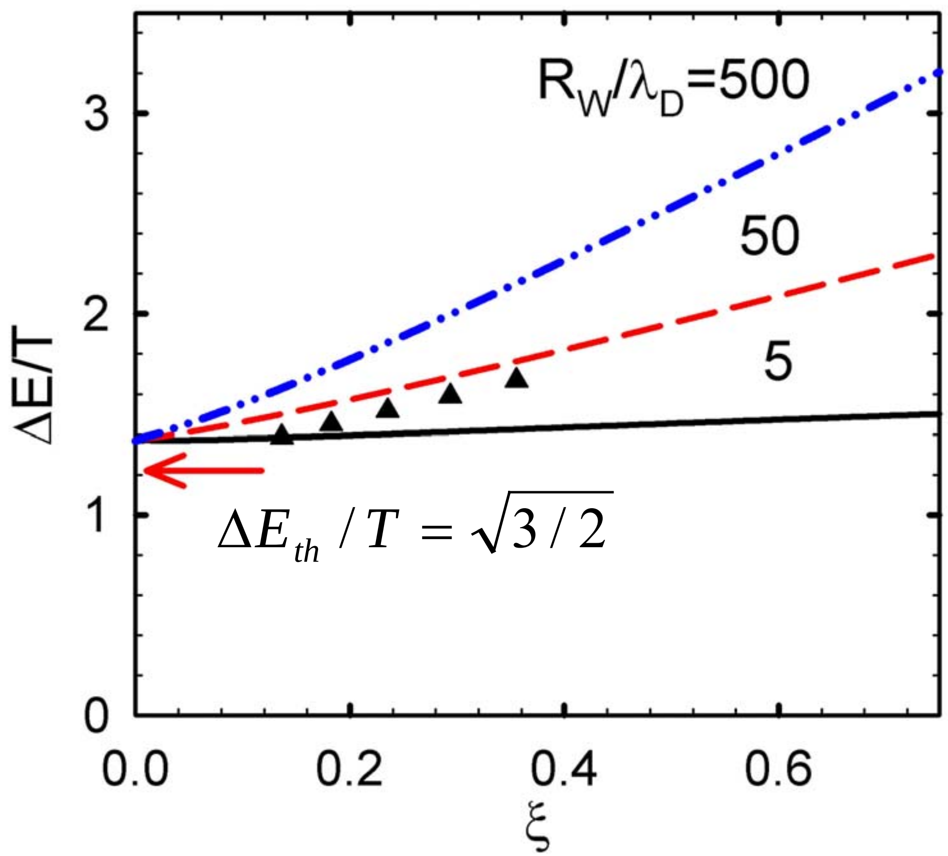
Energy Spread Trends



Low energy spreads ~ 4 K achievable!

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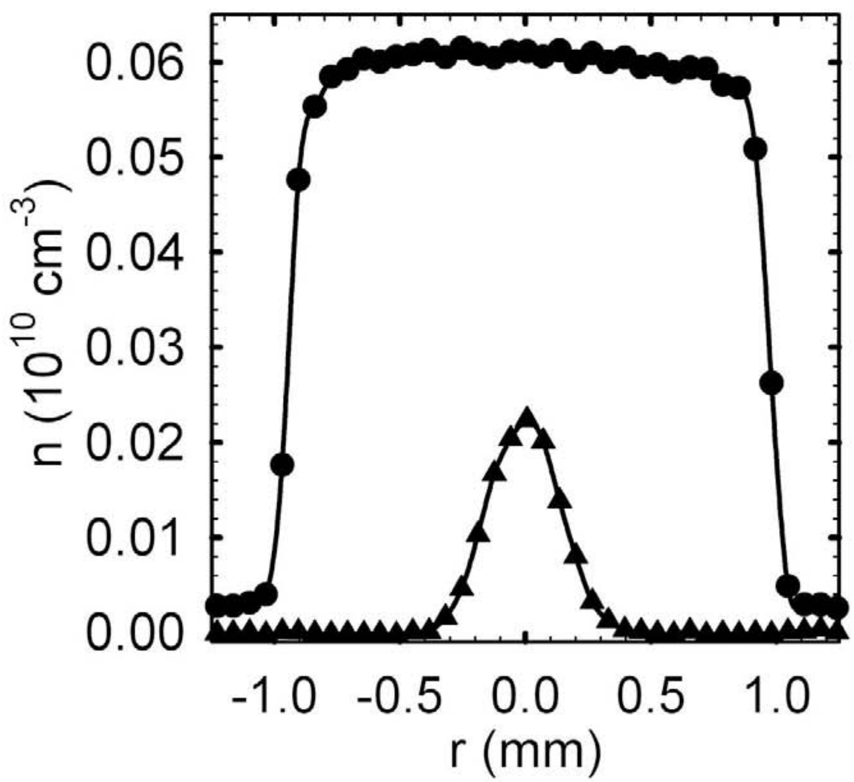
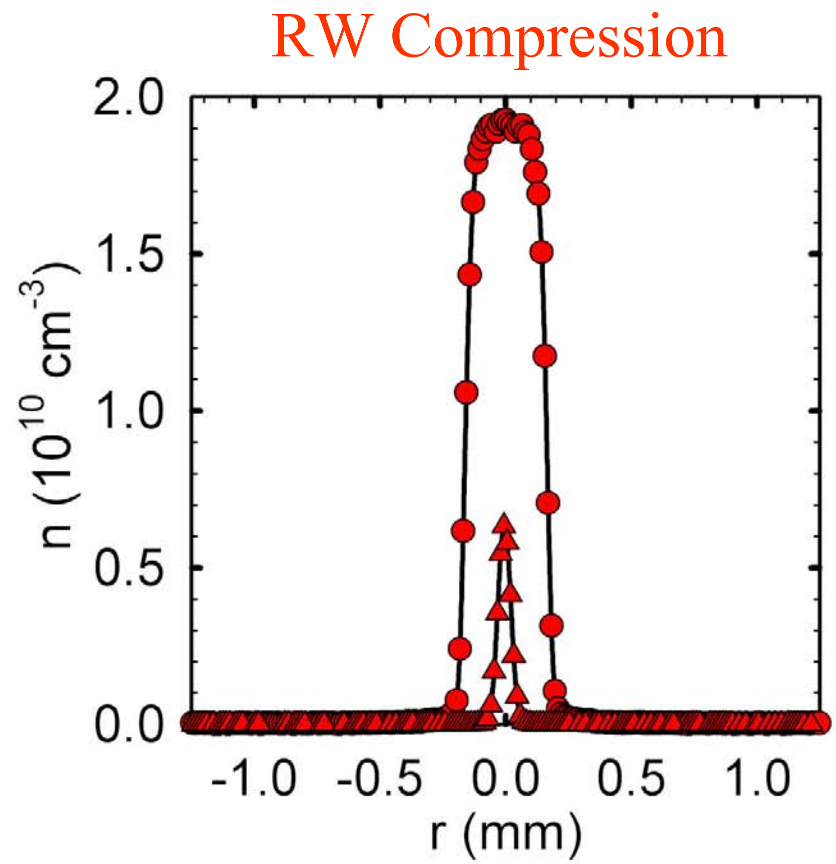
Narrow Beams

$$\xi = 0.5$$





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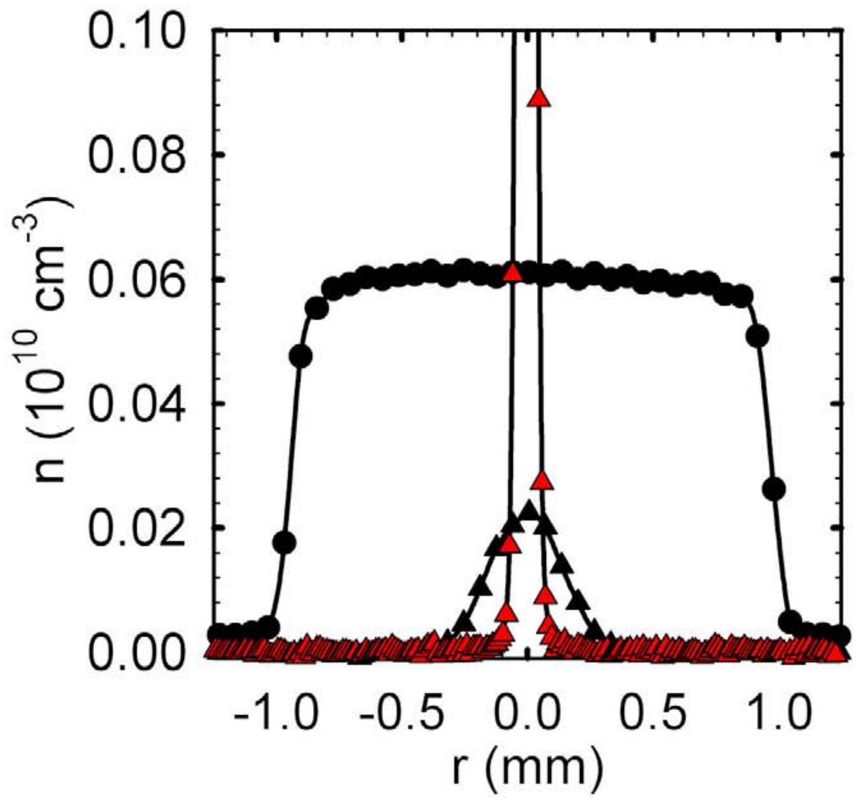

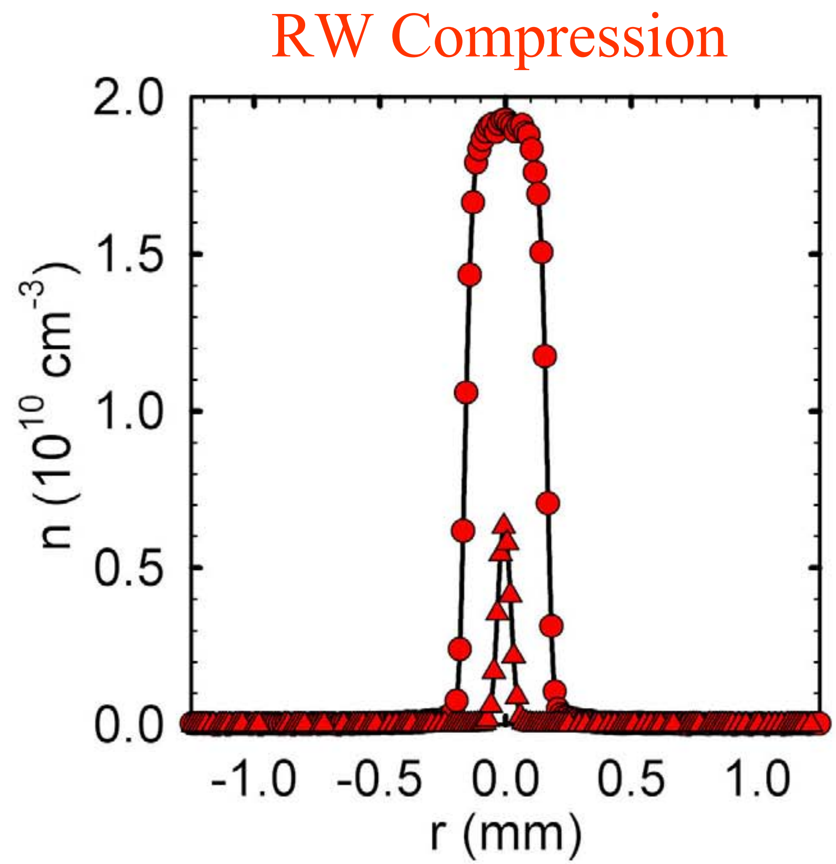

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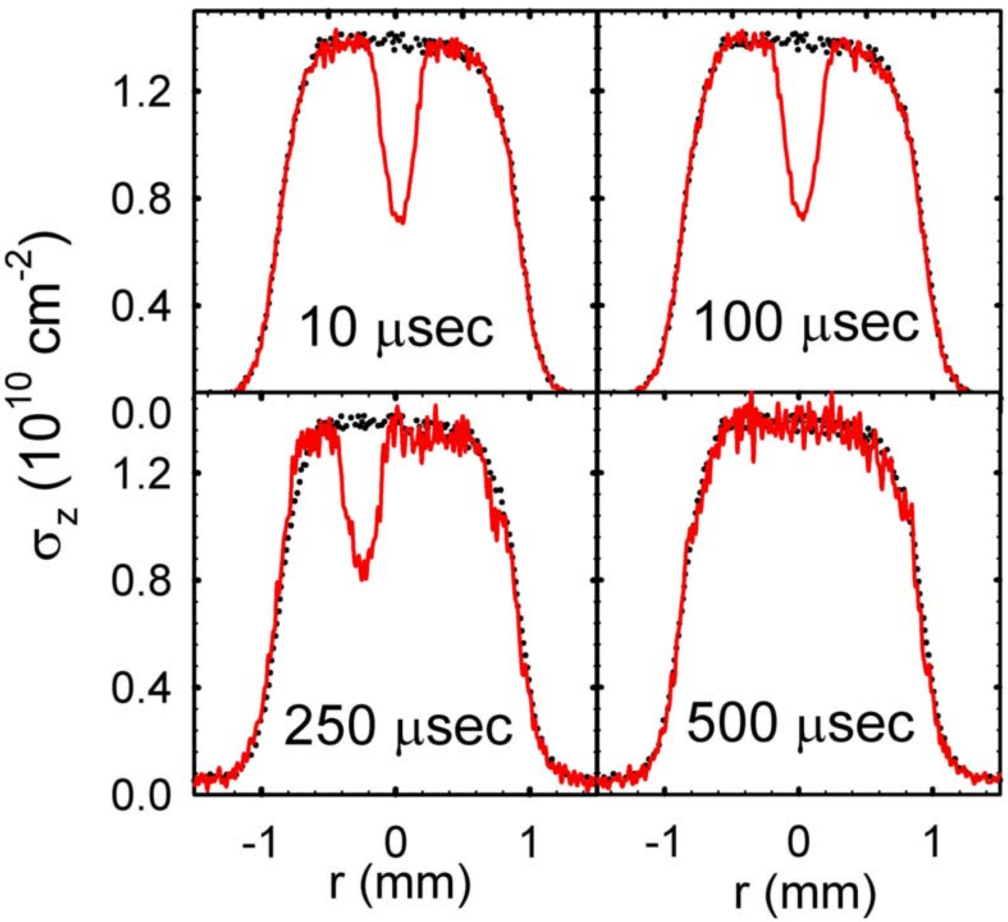
Multiple Beams: Plasma Recovery

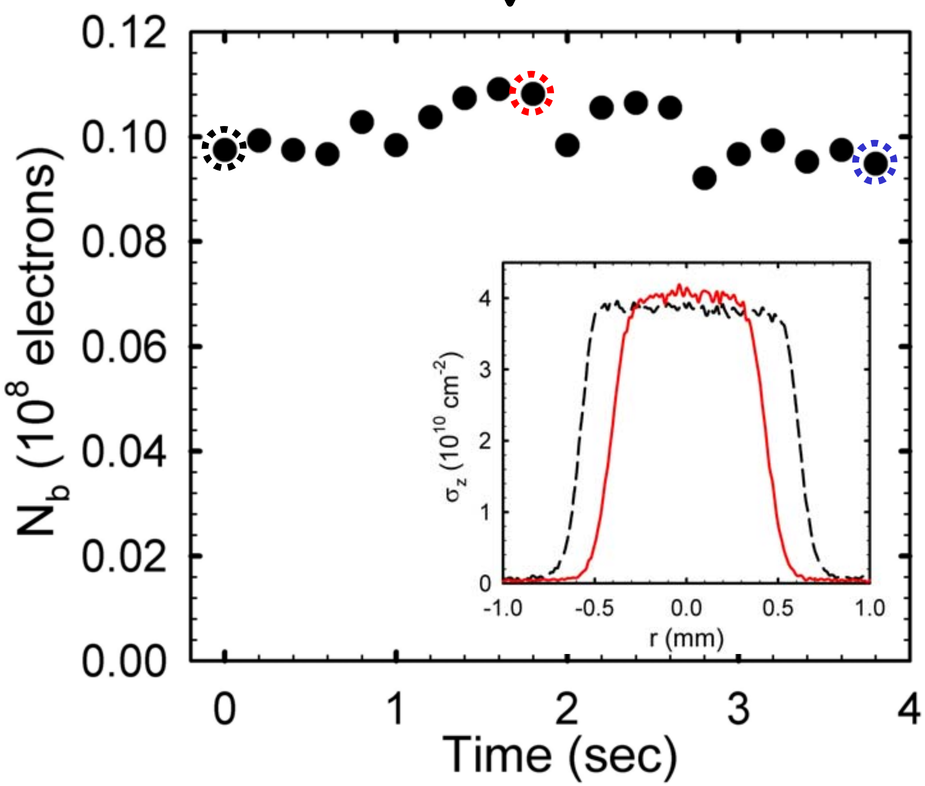


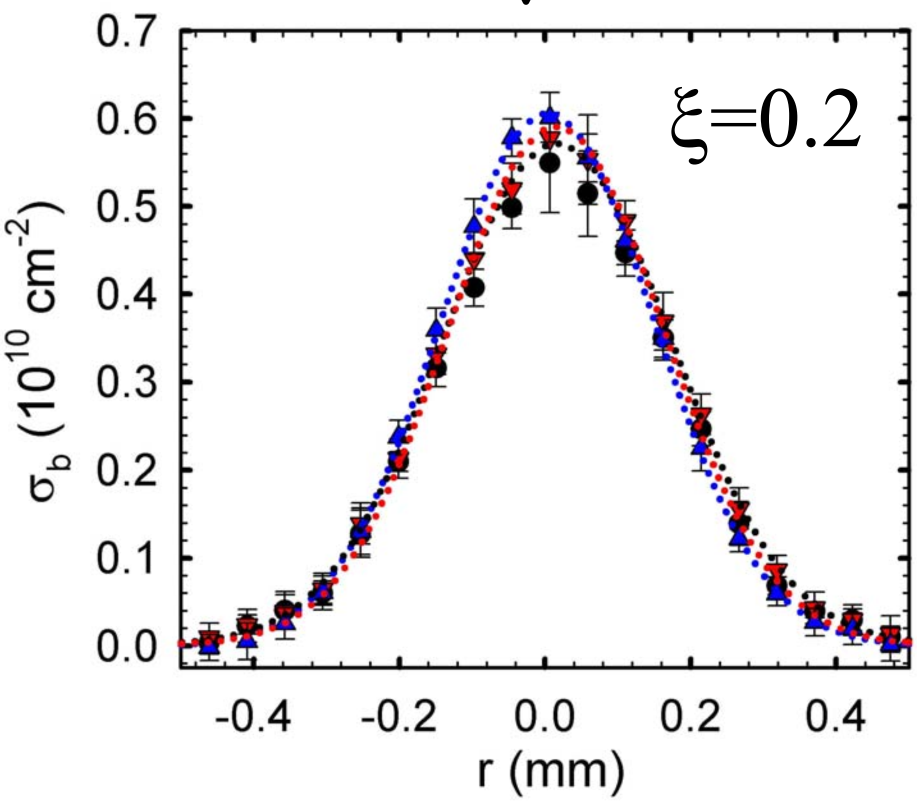
Multiple Beams Results

> 50% of plasma extracted

1st, 10th, and 20th beams with RW on

$$\frac{\Delta N_b}{N_b} < 5\%$$





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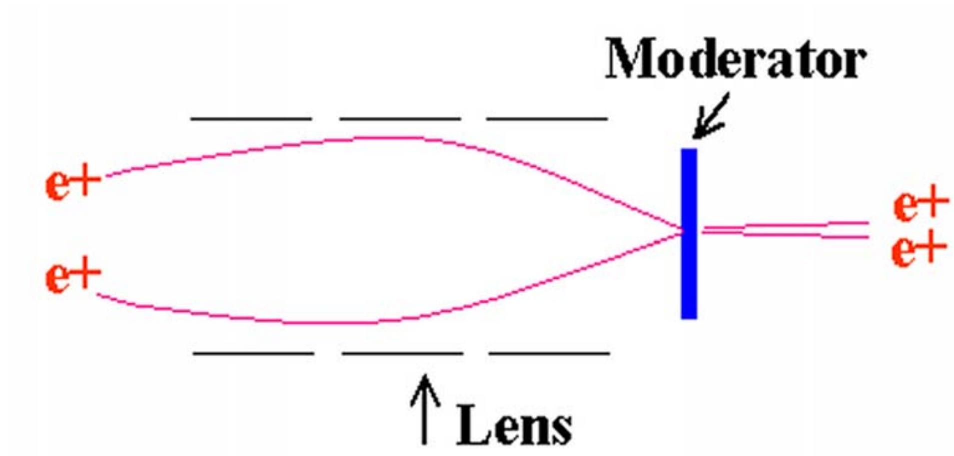
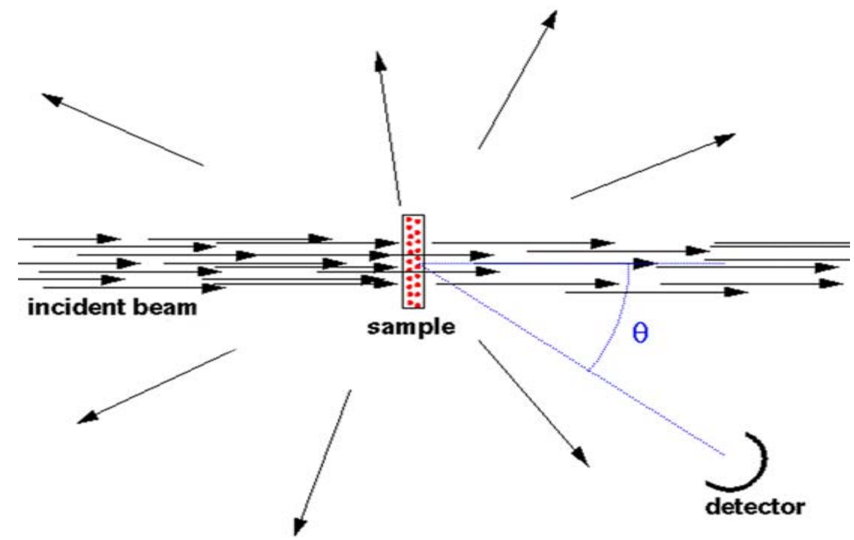
Electrostatic Beam

- Beam in B=0 region
- Applications include:
  - Microbeams through electrostatic focus and re-moderation
  - Atomic physics scattering experiments
- Require extraction from the 5 T field

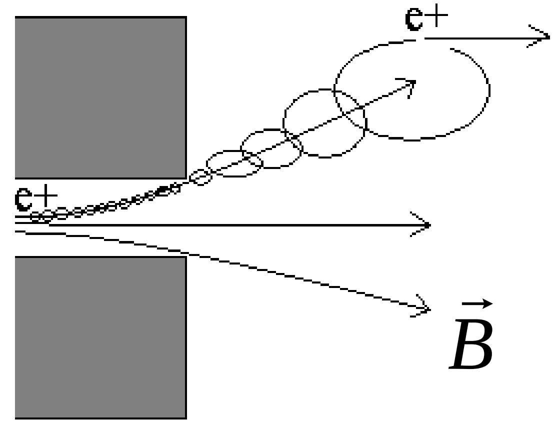




Single particle motion

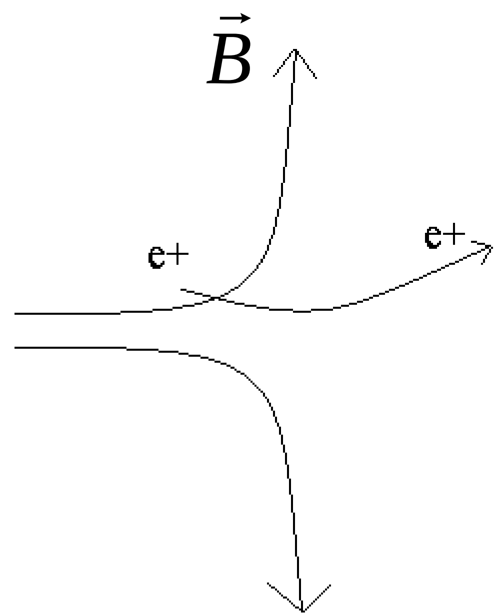
•For slow extraction, particles stayed "glued" to field lines and maintain adiabatic invariant

$$\frac{E_{\perp}}{B} = const.$$

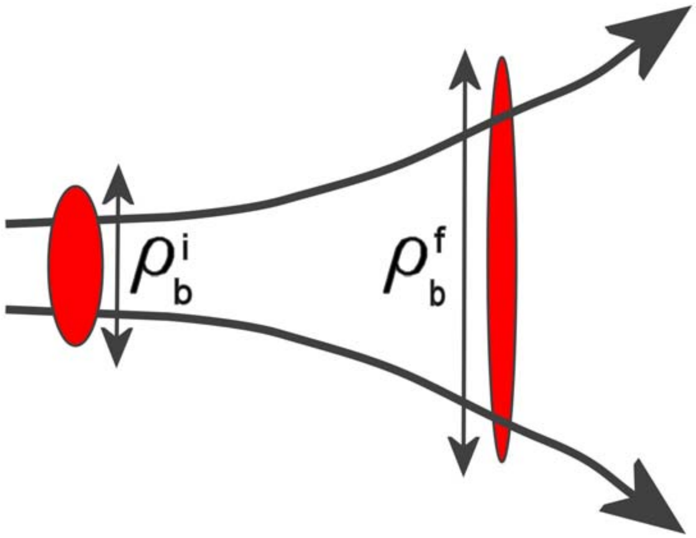


•Fast extraction, particles leave field lines and conserve canonical angular momentum with θ "kick"

$$L_z = const. = rp_\theta + qrA_\theta$$

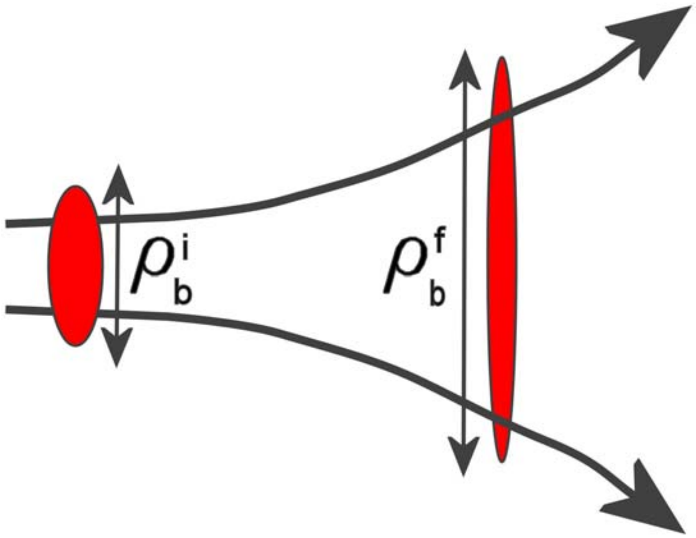


Slow Extraction



$$\rho_{bf} = \rho_{bi}\sqrt{\frac{B_i}{B_f}}$$

Slow Extraction



$$\rho_{bf} = \rho_{bi}\sqrt{\frac{B_i}{B_f}}$$

as $B_f \to 0$ ⇒

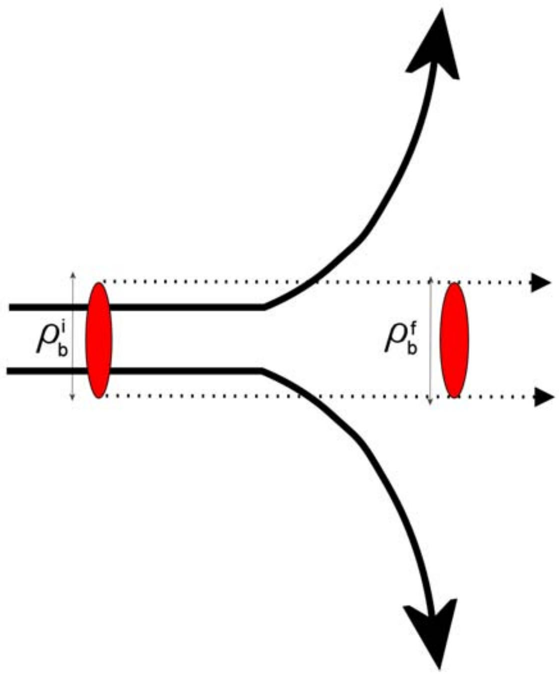
$$\rho_{bf} \to \infty$$

$$\Delta E_{\parallel} = \sqrt{3/2T}$$

$$\Delta E_{\perp} = 0$$

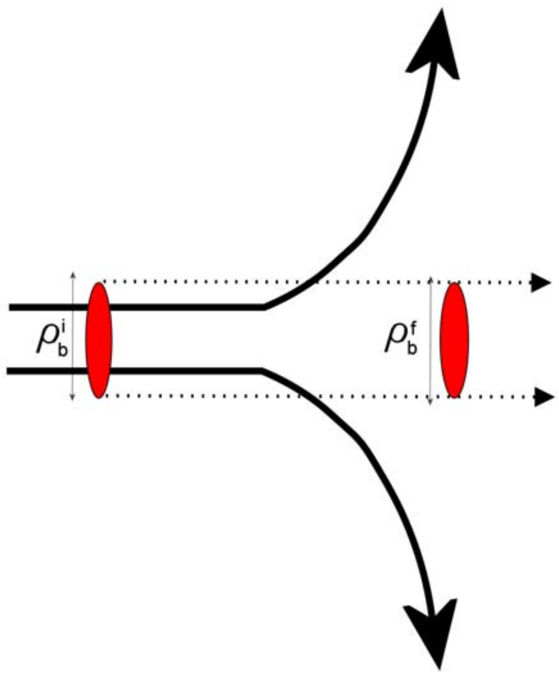
$$\Delta E = \sqrt{3/2T}$$

Fast Extraction



$$\rho_{bf} = \rho_{bi}$$

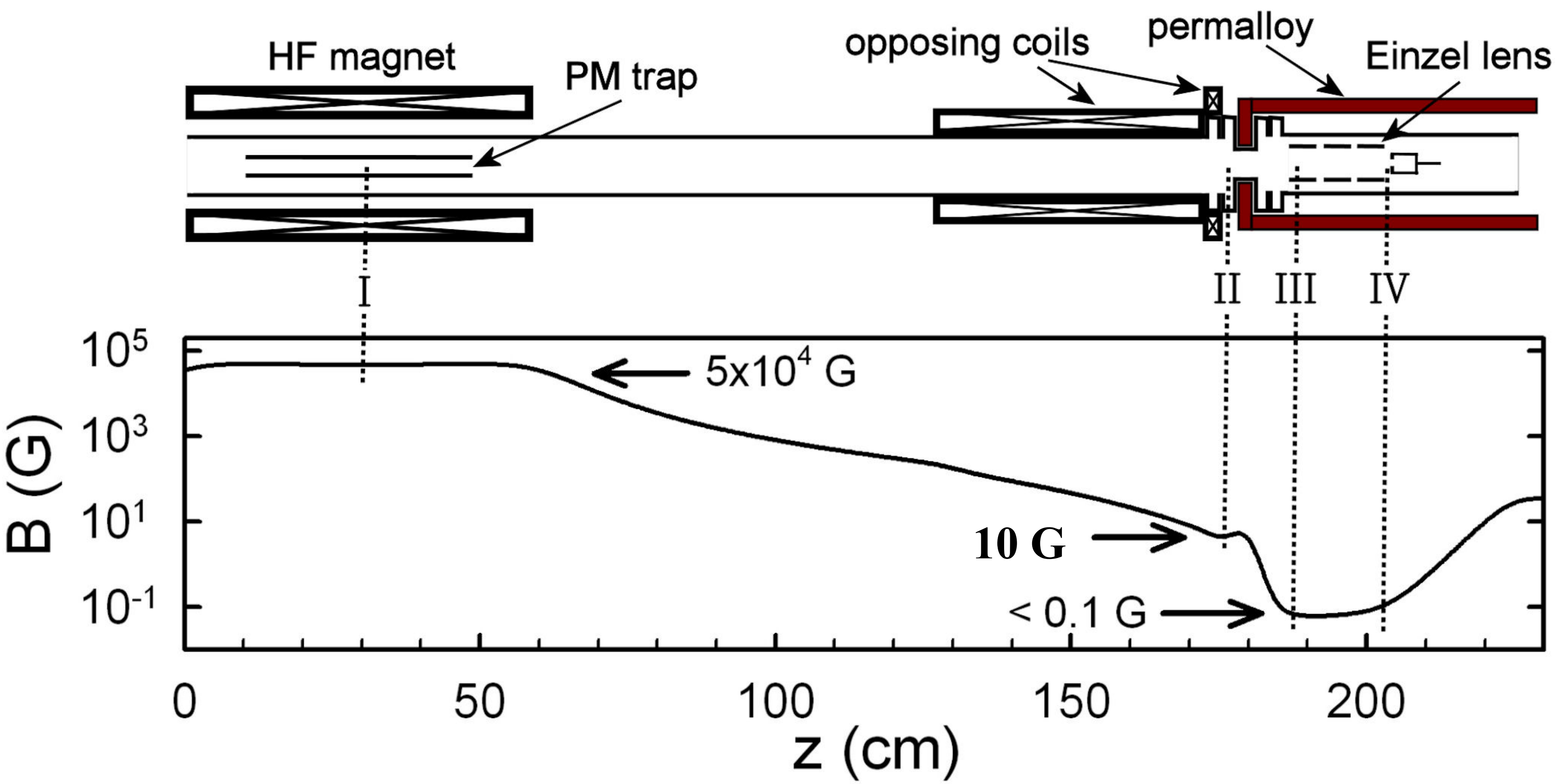
Fast Extraction



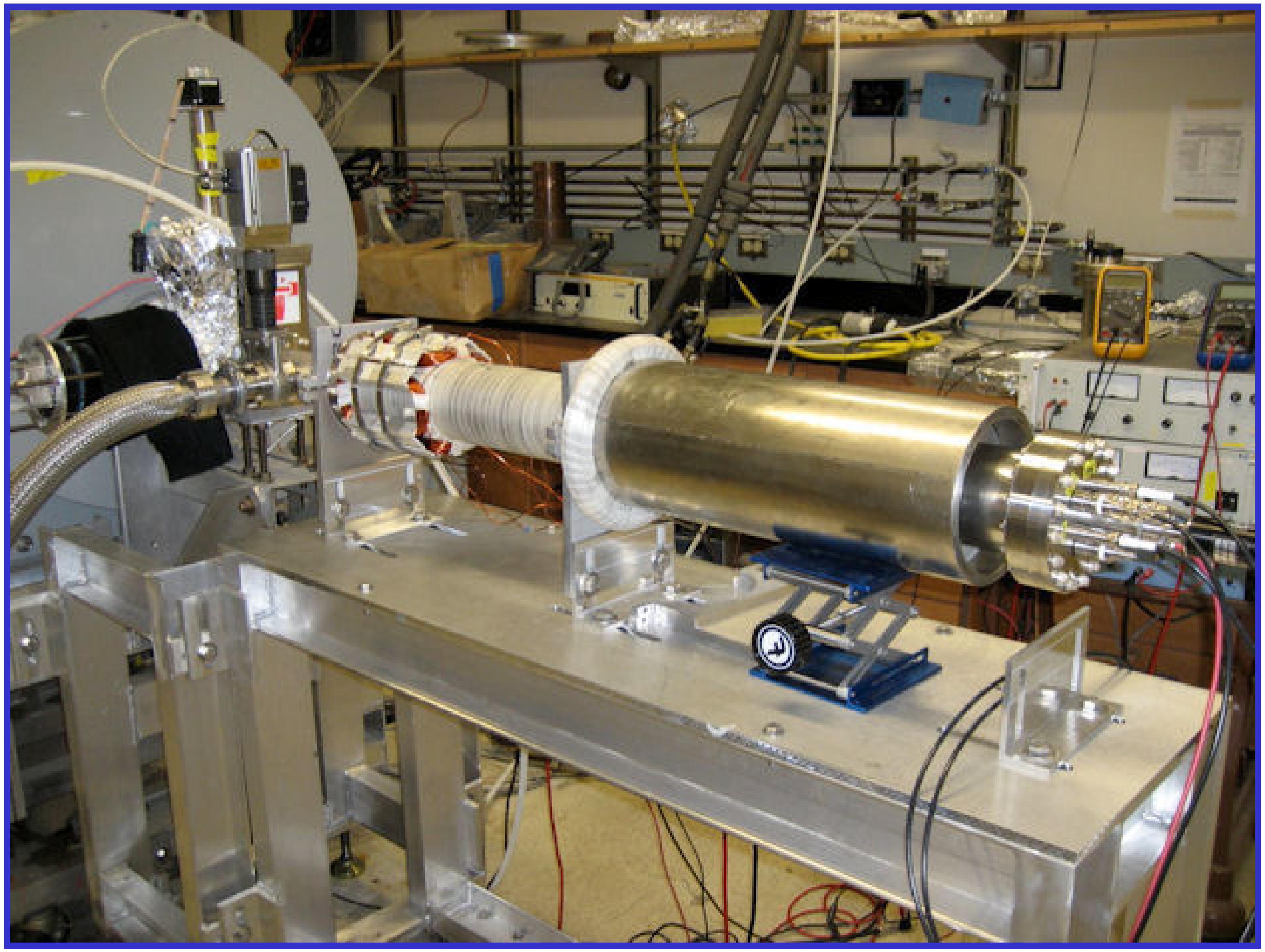
$$\rho_{bf} = \rho_{bi}$$

$$\Delta E_\perp \propto B^2 \rho_b^2 \qquad \Delta E_{||} \propto B^2 \rho_b^2 \qquad \Delta E = \sqrt{3/2T}$$

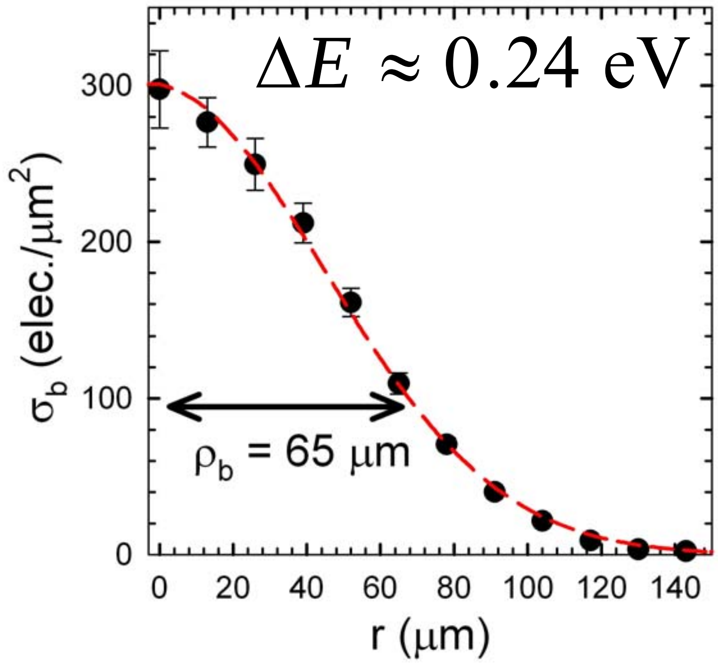
New Experiment



The Beam Line



A First Experiment



Stage	I	II	III	IV
B (G)	4.8×10^4	10	0	0
$\Delta E_{\parallel}$ (eV)	0.22	0.24	0.51	4.66
$\Delta E_{\perp}$ (eV)	0.1	2.1×10^{-5}	0.45	4.65
ΔE (eV)	0.24	0.24	0.24	6.58
ρ_b (cm)	6.5×10^{-3}	0.45	0.45	0.14
ϵ (cm$\sqrt{\text{eV}}$)	2.1×10^{-3}	2.1×10^{-3}	0.3	0.3

Advantages of Trap Based Positron Beams

- High brightness and low emittance
  - Rotating Wall
  - Cyclotron cooling to T_W
- Reproducible
- Efficiently use most trapped positrons
- Electrostatic beams

Conclusions

- Positrons have many exciting applications but require bright, energy resolved sources
- Penning-Malmberg trap has a great potential as a future positron source
- Demonstrated ability to confine large numbers, and extract tailored, high quality beams
- Electrostatic beam has been demonstrated
- *Exciting new tools to drive positron research!*

References:

T. R. Weber, J. R. Danielson, and C. M. Surko, *Phys. Plasmas* **16**, 057105 (2009).
T. R. Weber, J. R. Danielson, and C. M. Surko, *Phys. Plasmas* **15**, 012106 (2008).
J. R. Danielson, T. R. Weber, and C. M. Surko, *Appl. Phys. Lett.* **90**, 081503 (2007).

http://positrons.ucsd.edu