The Paul Trap Simulator Experiment (PTSX) and the Neutralized Transport Experiment (NTX) Plasma Source

Two PPPL Beam Physics Experiments*

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PS&T Seminar

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** In collaboration with…

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LBNL: Simon Yu, Shmuel Eylon, Prabir Roy

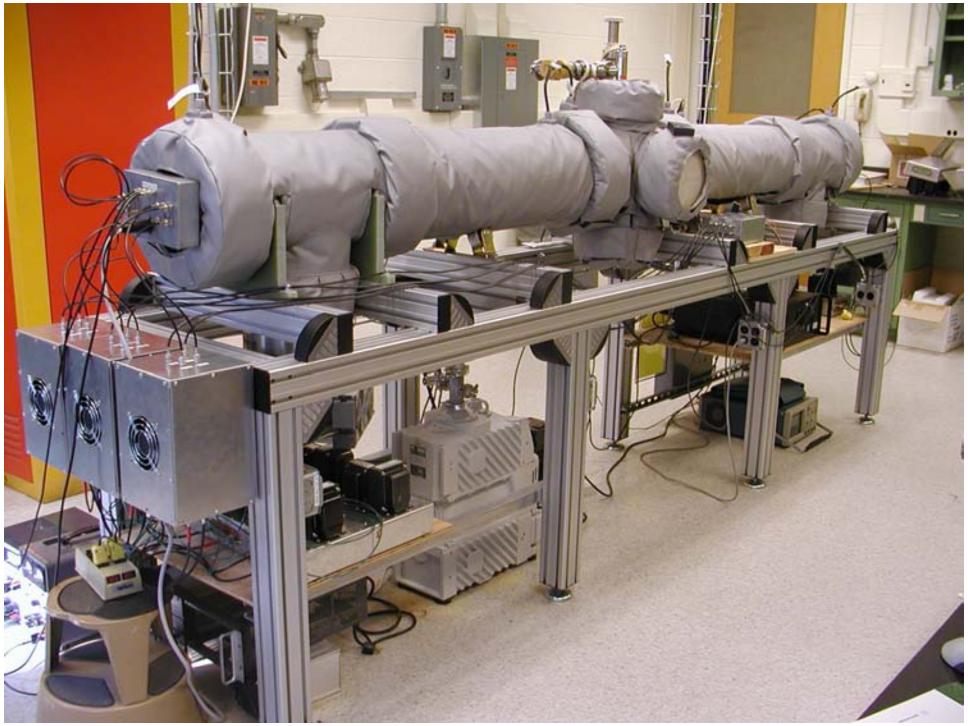
MRC: Dale Welch

PTSX Simulates Nonlinear Beam Dynamics in Magnetic Alternating-Gradient Systems

- Purpose: PTSX simulates, in a compact experiment, the nonlinear dynamics of intense beam propagation over large distances through magnetic alternating-gradient transport systems.
- Applications: Accelerator systems for high energy and nuclear physics applications, heavy ion fusion, spallation neutron sources, and nuclear waste transmutation.

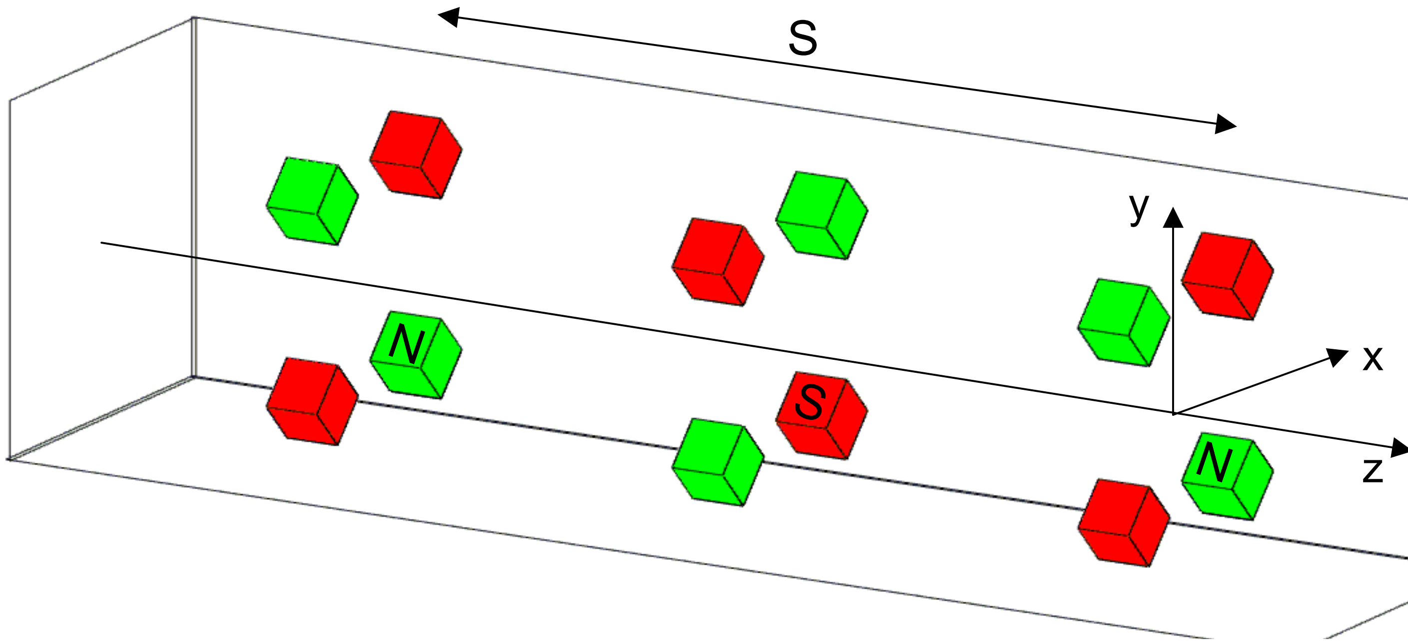
•Physics issues:

- •Beam mismatch and envelope instabilities;
- •Collective wave excitations;
- •Chaotic particle dynamics and production of halo particles;
- •Mechanisms for emittance growth;
- •Compression techniques; and
- •Effects of distribution function on stability properties.



Davidson, Qin and Shvets, Phys. Plasmas **7**, 1020 (2000); Okamoto and Tanaka, Nucl. Instrum. Methods A **437**, 178 (1999).
Gilson, Davidson, Efthimion and Majeski, Phys. Rev. Lett. **92**, 155002 (2004).

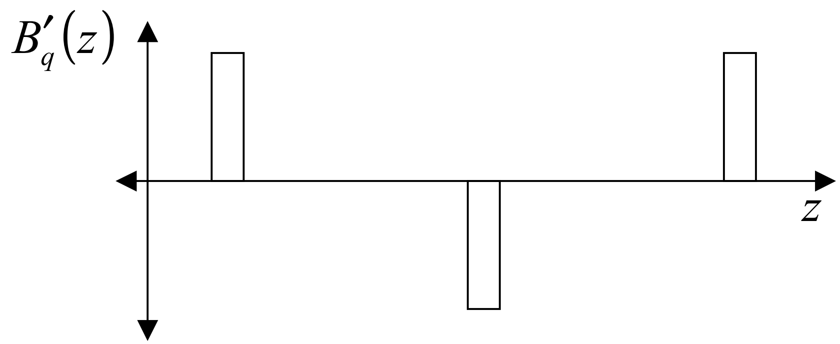
Magnetic Alternating-Gradient Transport Systems



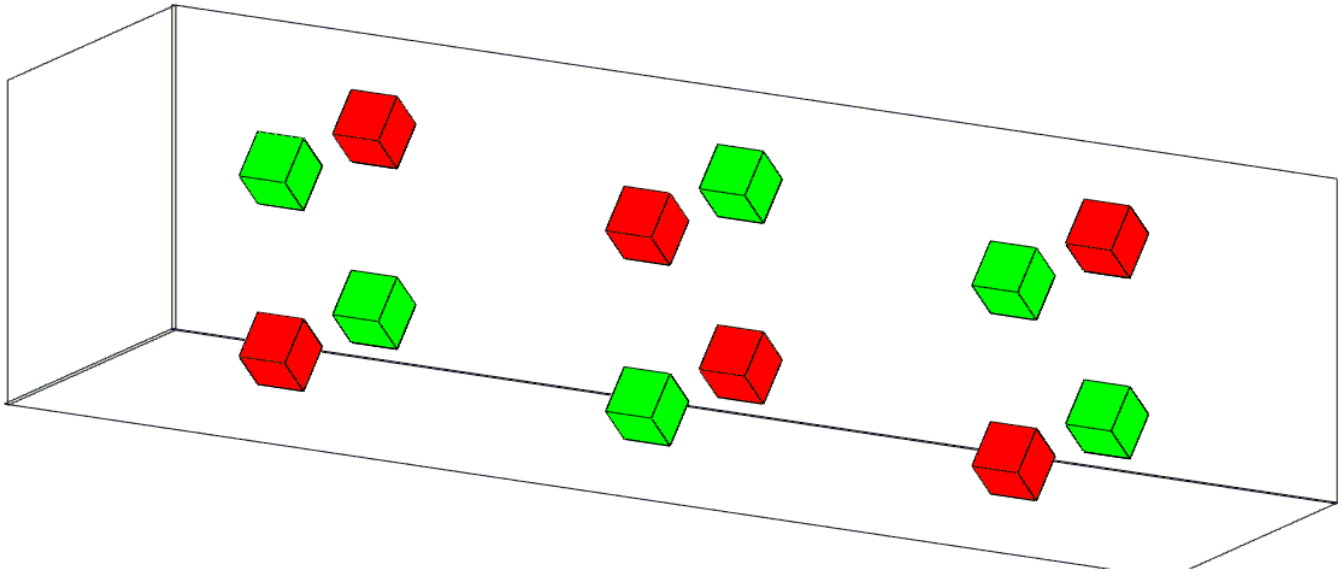
$$\boldsymbol{B}_q^{foc}(\boldsymbol{x}) = B_q'(z)\left(y\hat{\boldsymbol{e}}_x + x\hat{\boldsymbol{e}}_y\right)$$

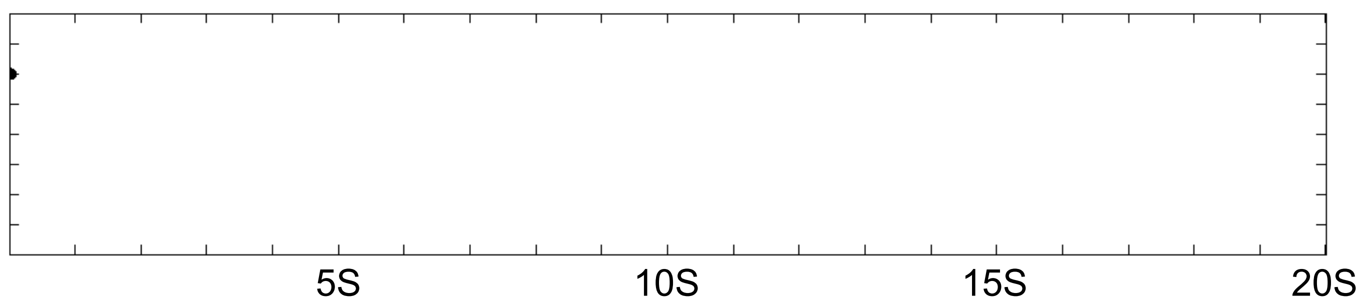
$$\boldsymbol{F}_{foc}(\boldsymbol{x}) = -\kappa_q(z)\left(x\hat{\boldsymbol{e}}_x - y\hat{\boldsymbol{e}}_y\right)$$

$$\kappa_q(z) \equiv \frac{Z_b e B_q'(z)}{\gamma_b m_b \beta_b c^2}$$

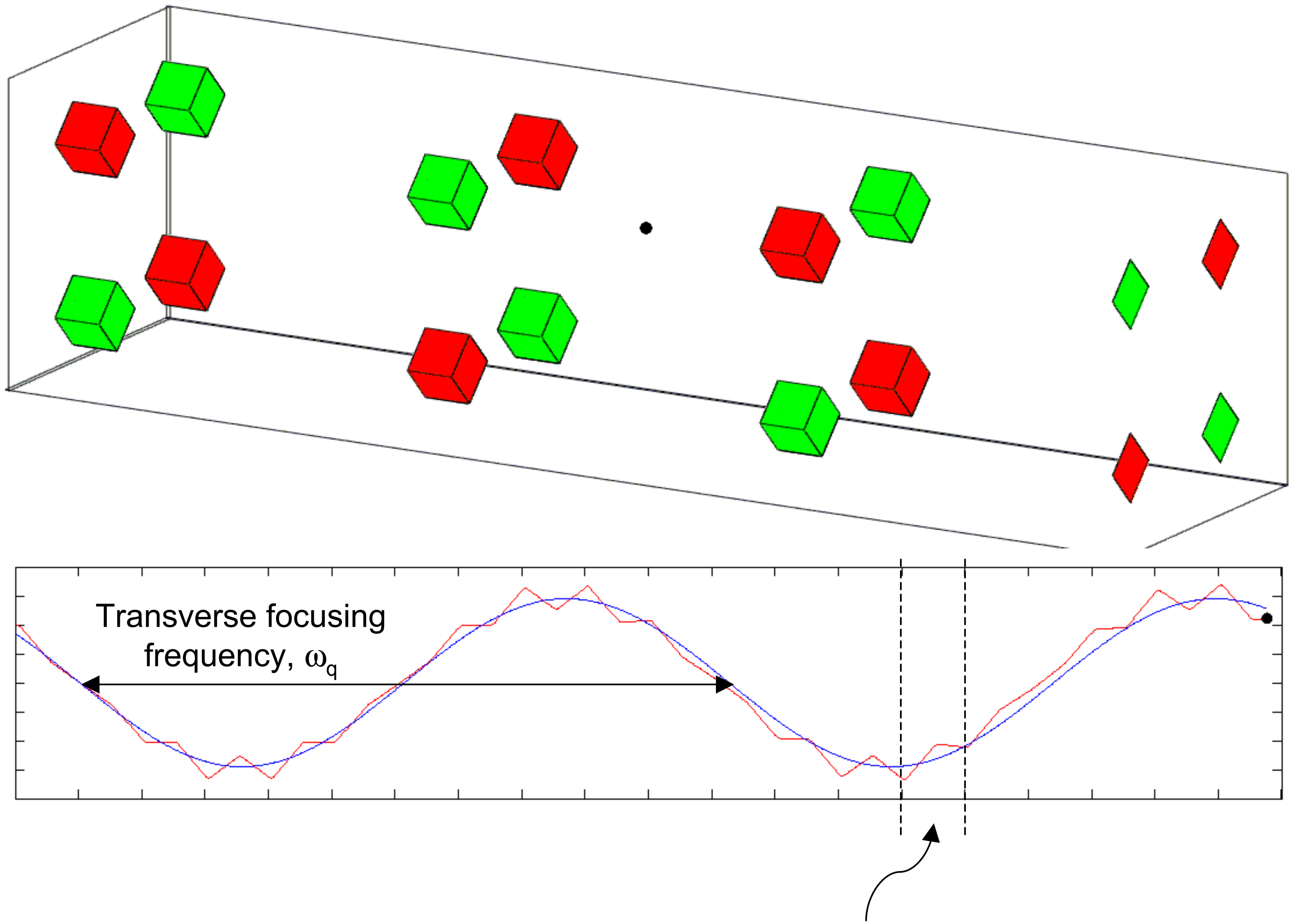


Particle Motion Consists of Rapid Micromotion and Slow Guiding-Center Oscillation



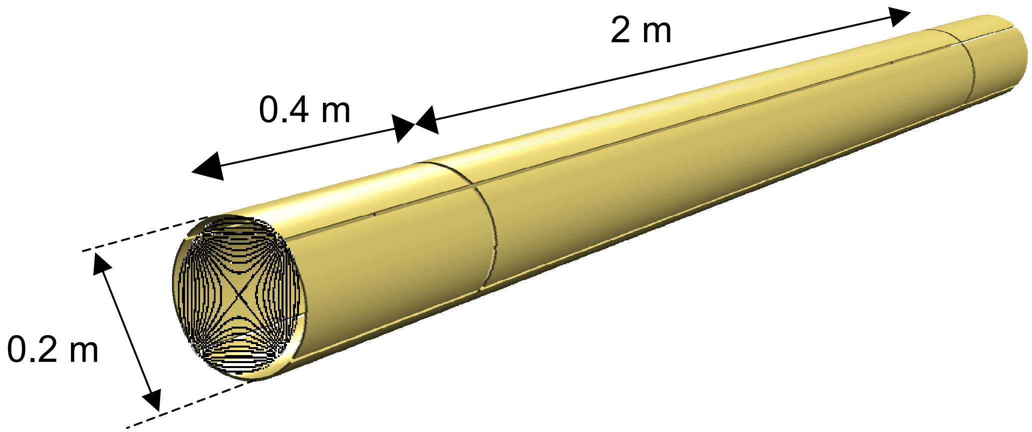


Transverse Focusing Frequency and Phase Advance Characterize the Motion



In one lattice period, S, the smooth trajectory's vacuum phase advance, σ_v, is 35 degrees.

PTSX Configuration – A Cylindrical Paul Trap



$$e_b\phi_{ap}(x,y,t)=\frac{1}{2}\kappa_q(t)(x^2-y^2)$$

$$\kappa_q(t)=\frac{8e_bV_0(t)}{m_b\pi\, r_w^2}$$

- The injection electrodes oscillate with the voltage $\pm V_0(t)$ during cesium ion injection.
- The 40 cm long electrodes at the far end of the trap are held at a constant voltage during injection to prevent ions from leaving the trap.
- The dump electrodes oscillate with the voltage $\pm V_0(t)$ during ion dumping.

Plasma column length	2 m	Maximum wall voltage	400 V
Wall electrode radius	10 cm	End electrode voltage	150 V
Plasma column radius	1 cm	Voltage oscillation frequency	100 kHz

Transverse Dynamics are the Same – Including Self-Field Effects

Dimensionless self-field potential $$\psi(x,y,s)=\frac{Z_b e}{\gamma_b m_b \beta_b^2 c^2}\left[\phi_{self}(x,y,s)-\beta_b A_{z\,self}(x,y,s)\right]$$

$\phi_{self}(x,y,s)$ is the space-charge potential, and $A_{z\,self}(x,y,s)\cong\beta_b\phi_{self}(x,y,s)$

Gauss' & Ampere's Laws:

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\psi=-\frac{2\pi K_b}{N_b}\int dx'dy'\,f_b$$

$$K_b=\frac{2N_b Z_b^2 e^2}{\gamma_b^3 m_b \beta_b^2 c^2}=const.$$

$$N_b=\int dx\,dy\,dx'dy'\,f_b\left(x,y,x',y',s\right)=const.$$

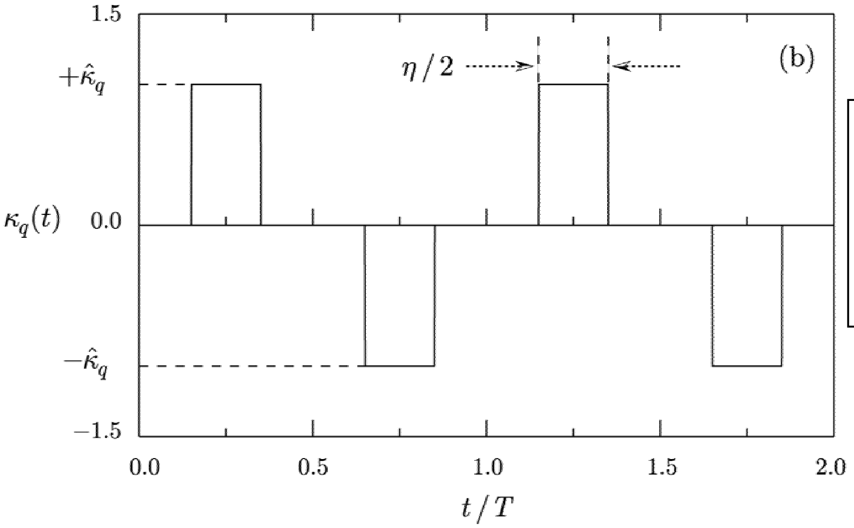
- Thin beam ($r_b \ll S$)
- The particle motion in the beam frame is assumed to be nonrelativistic.

→

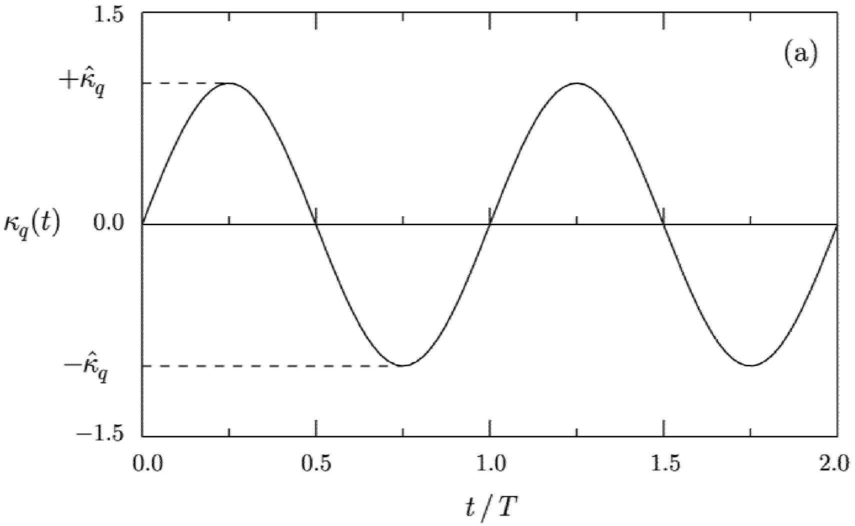
- Ions in PTSX have the same transverse equations of motion as ions in an alternating-gradient system ***in the beam frame***.

$$s=\beta_b ct \qquad '=\frac{d}{ds}$$

$V(t)$ Corresponds to $B_q{'}(s)$

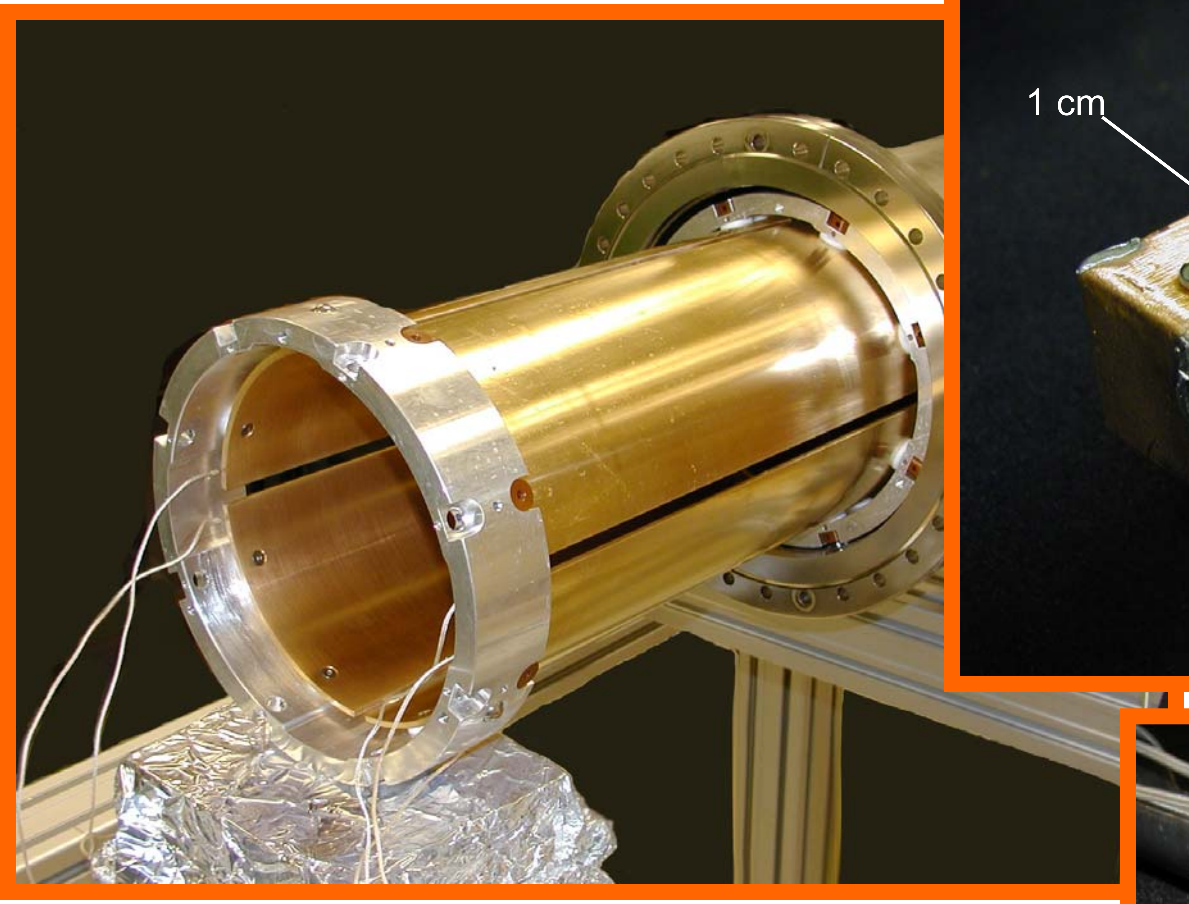


$$\kappa_q(t) = \hat{\kappa}_q \begin{cases} 1, & (0.25 - \eta/4) < t/T < (0.25 + \eta/4) \\ -1, & (0.75 - \eta/4) < t/T < (0.75 + \eta/4) \\ 0, & \text{otherwise} \end{cases}$$



$$\kappa_q(t) = \hat{\kappa}_q \sin\left(\frac{2\pi t}{T}\right)$$

PTSX Components – Electrodes, Ion Source, and Faraday cup



Constraints on Vacuum Phase Advance σ_v and Intensity Parameter *s* are the Same

PPPL PRINCETON PLASMA PHYSICS LABORATORY

The *average* (Smooth-focusing/Ponderomotive) transverse focusing frequency is given by

$$\omega_q = \frac{8 e_b V_{0\,\max}}{m_b \pi r_w^2 f}\xi$$

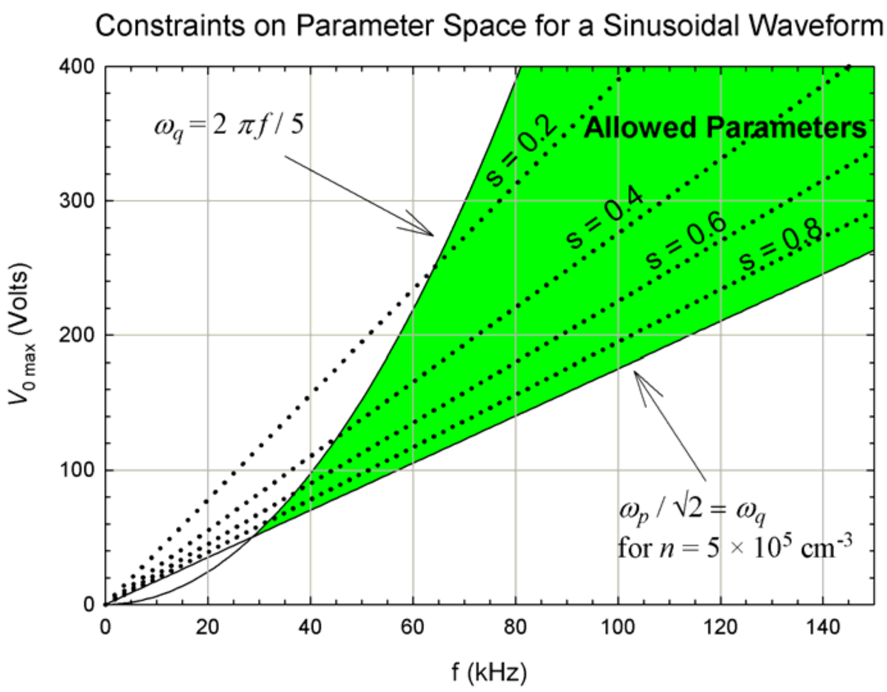
where $\xi = \frac{1}{2\sqrt{2}\pi}$ for a sinusoidal waveform

The vacuum phase advance must be small enough to avoid instabilities.

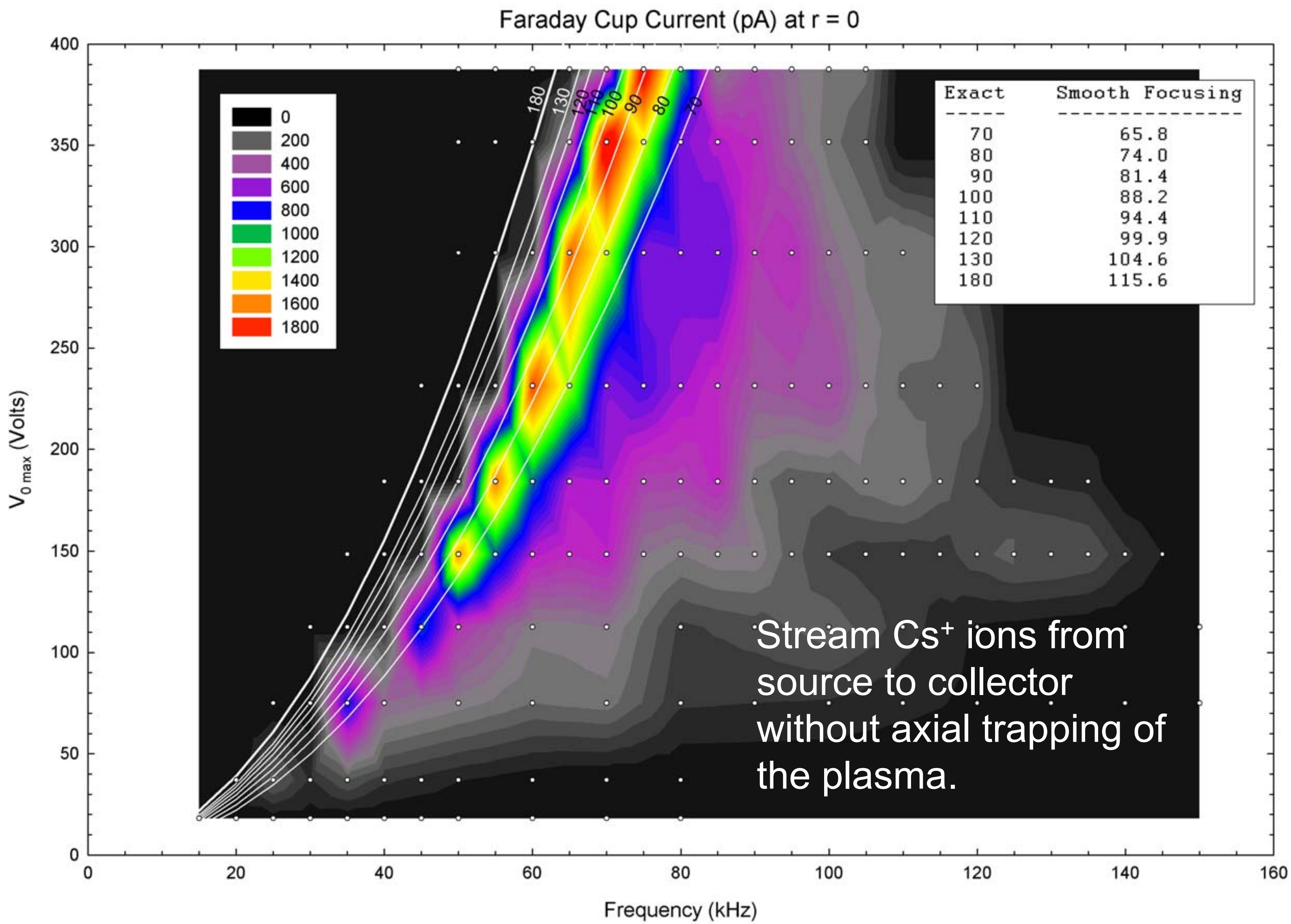
$$\sigma_v = \frac{\omega_q}{f} < \frac{2\pi}{5}$$

The confining force must be strong enough to confine the space-charge.

$$s \equiv \frac{\omega_p^2}{2\omega_q^2} < 1$$



Confinement is Lost if Phase Advance is Too Big



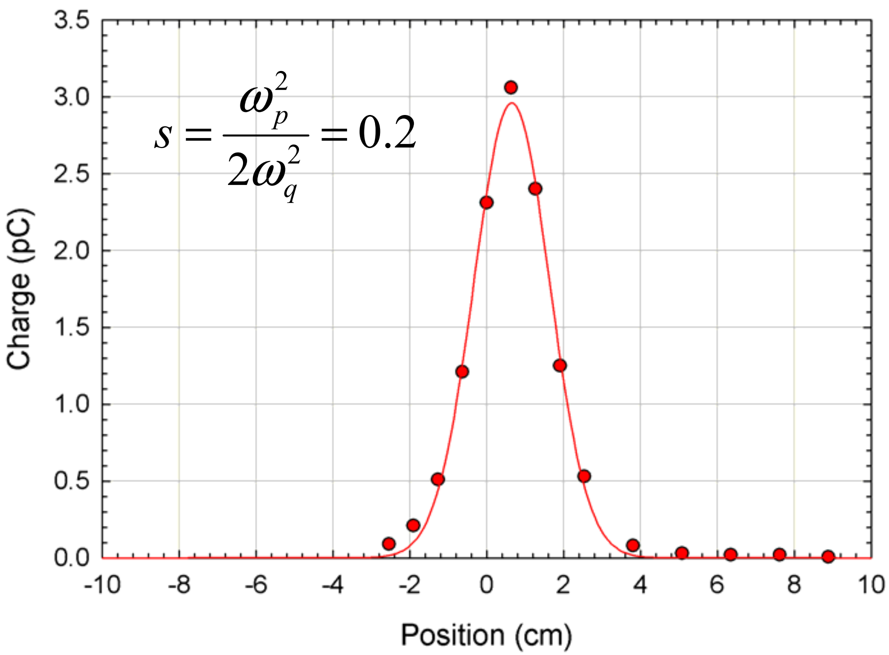
Radial Profiles of Trapped Plasmas are Gaussian – Consistent with Thermal Equilibrium

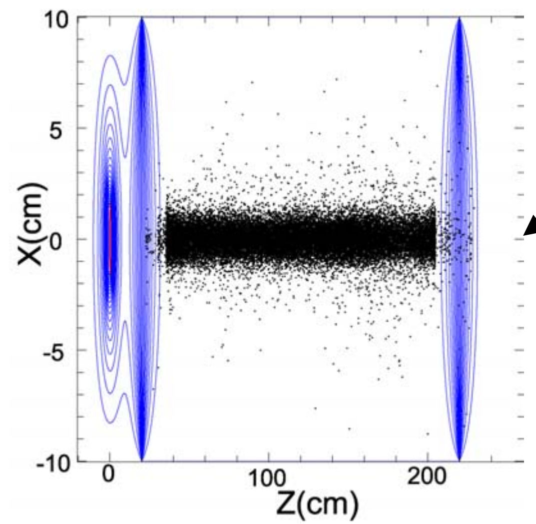
- I_b = 5 nA
- V_0 = 235 V
- f = 75 kHz
- t_{hold} = 1 ms
- $\sigma_v = 49^o$
- $\omega_q = 6.5 \times 10^4\ s^{-1}$

The charge $Q(r)$ is collected through the 1 cm aperture is averaged over 2000 plasma shots.

The density is calculated from

$$n(r) = \frac{Q(r)}{e\pi r_{aperture}^2 l_{plasma}}$$



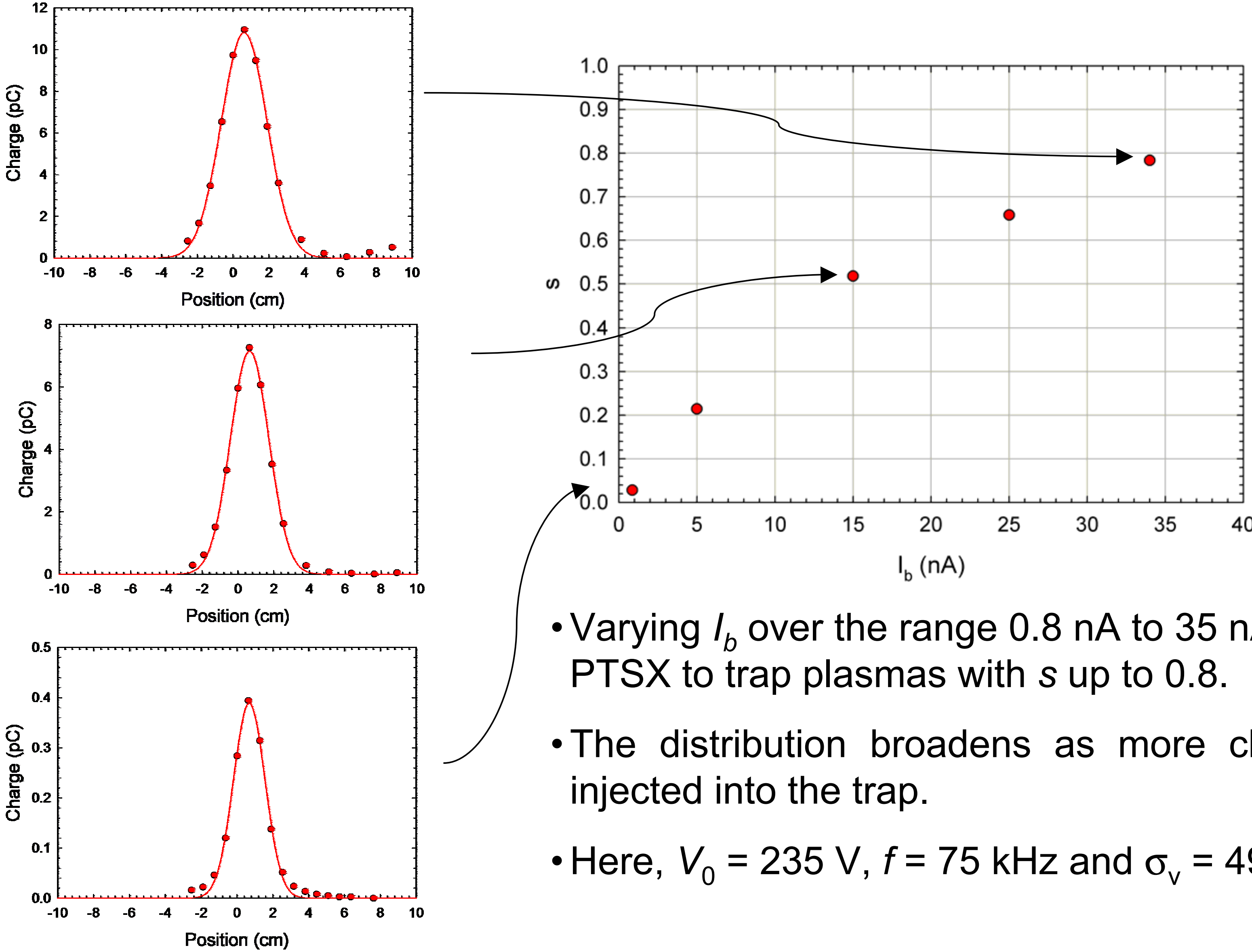


- $n(r_0) = 1.4 \times 10^5\ cm^{-3}$
- R_b = 1.4 cm
- s = 0.2

A Gaussian fit yields 3 parameters:

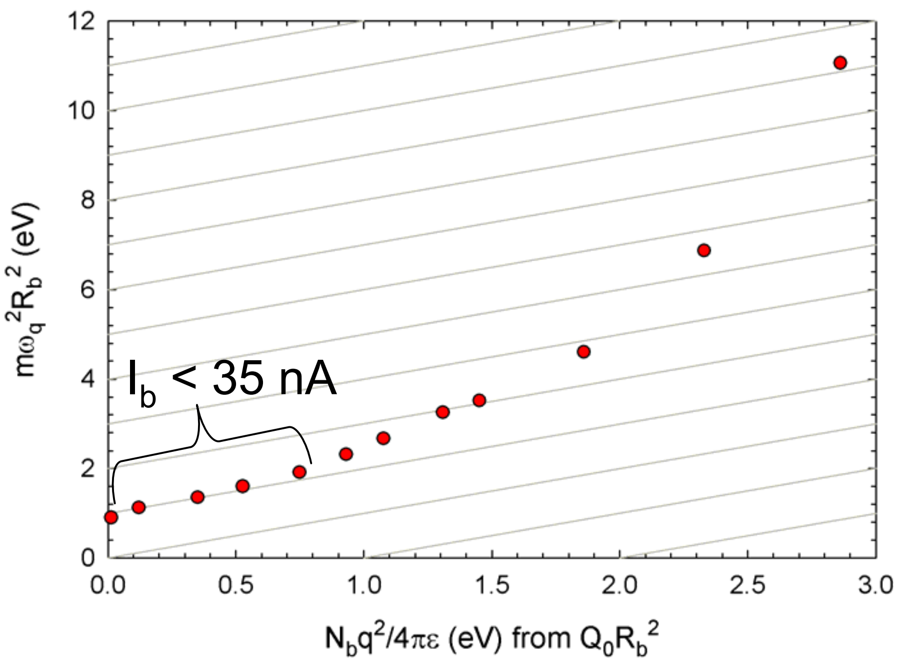
Q_0	amplitude
R_b	rms radius
r_0	offset

Accessible Values of $s = \omega_p^2/2\omega_q^2$ Range From 0 to 0.8



- Varying I_b over the range 0.8 nA to 35 nA allows PTSX to trap plasmas with s up to 0.8.
- The distribution broadens as more charge is injected into the trap.
- Here, V_0 = 235 V, f = 75 kHz and σ_v = 49°

Data Agrees with Force-Balance Model

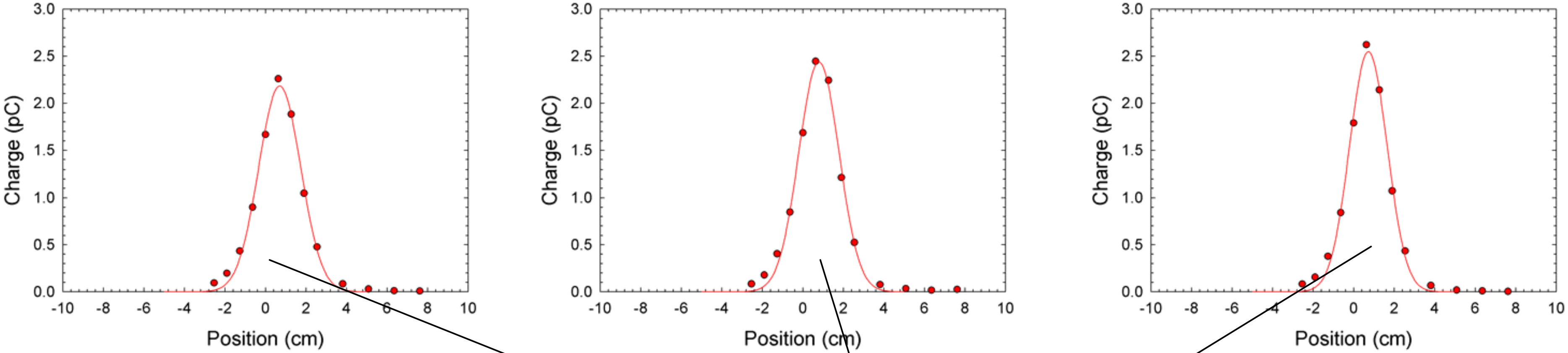


The mean-squared-radius is determined by balancing the confining force against the thermal pressure and the space-charge force. In thermal equilibrium,

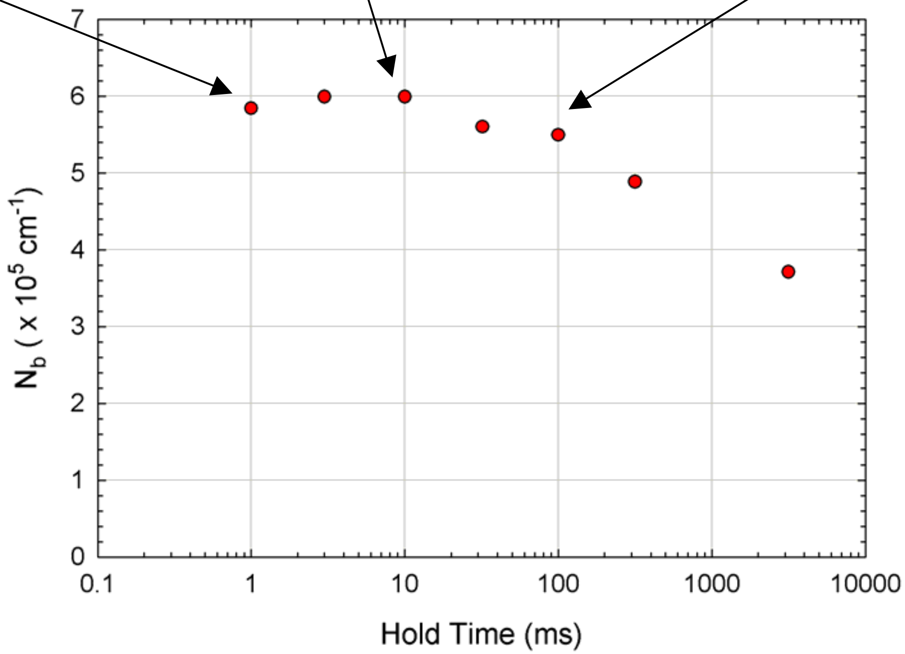
$$m\omega_q^2 R_b^2 = 2kT + \frac{N_b q^2}{4\pi\varepsilon_o}$$

At larger N_b, the increasing mismatch between the ion source and the trapped plasma likely leads to plasma heating. Note that kT = 0.5 eV as N_b approaches zero.

PTSX Simulates Equivalent Propagation Distances of 7.5 km

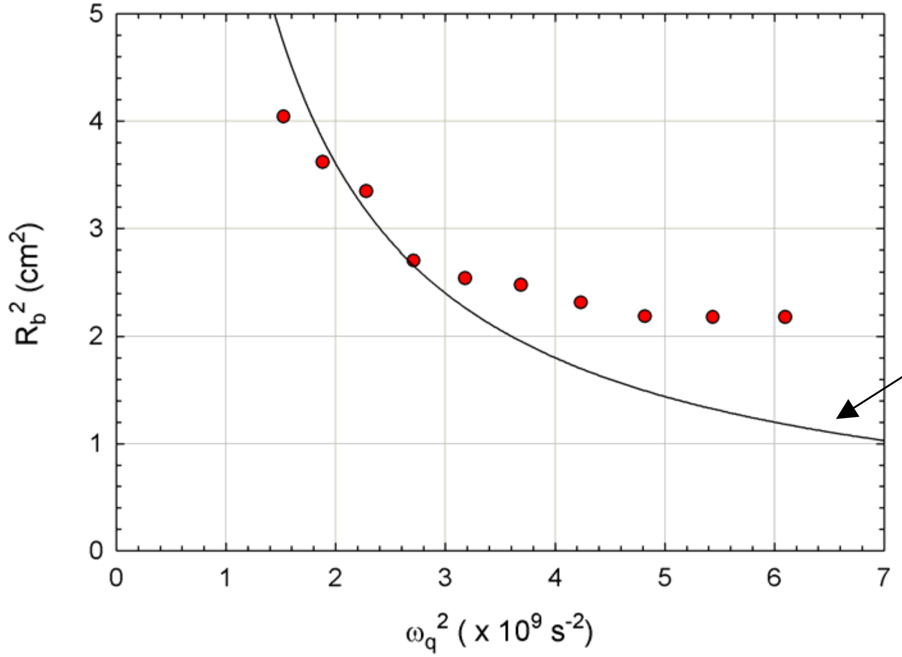


- At f = 75 kHz, a lifetime of 100 ms corresponds to **7,500 lattice periods**.
- If S is 1 m, the PTSX simulation experiment would correspond to a **7.5 km beamline**.



- $s = \omega_p^2/2\omega_q^2$ = 0.18.
- V_0 = 235 V
  f = 75 kHz
  σ_v = 49°

Dependence of R_b^2 on ω_q^2 Shows Moderate Agreement with Force Balance Model



$$R_b^2 = \frac{2(0.5\ \text{eV})}{(133\ \text{amu})\omega_q^2}$$

$$R_b^2 = \frac{2kT}{m\omega_q^2}$$ for an emittance-dominated beam.

- R_b^2 saturates at ~ 2 cm^2, possibly because of the finite size of the ion source.
- *V*/*f* is adjusted to vary ω_q while keeping V/f^2 fixed to maintain σ_v = 49°.

3D PIC Code Simulations – WARP-3D

- 3D particle-in-cell simulations by Edward Startsev using the WARP-3D code*
- $512 \times 48 \times 48$ grid
- 2.5×10^5 particles
- Timestep $\Delta t = 0.66\ \mu s$
- 64 processors at NERSC
- Simulate typical experimental parameters:
    - $I_b = 2.2$ nA
    - $V_0 = 235$ V, $f = 75$ kHz and $\sigma_v = 49^o$
    - $t_{inject} = 5$ ms, $t_{hold} = 1$ ms

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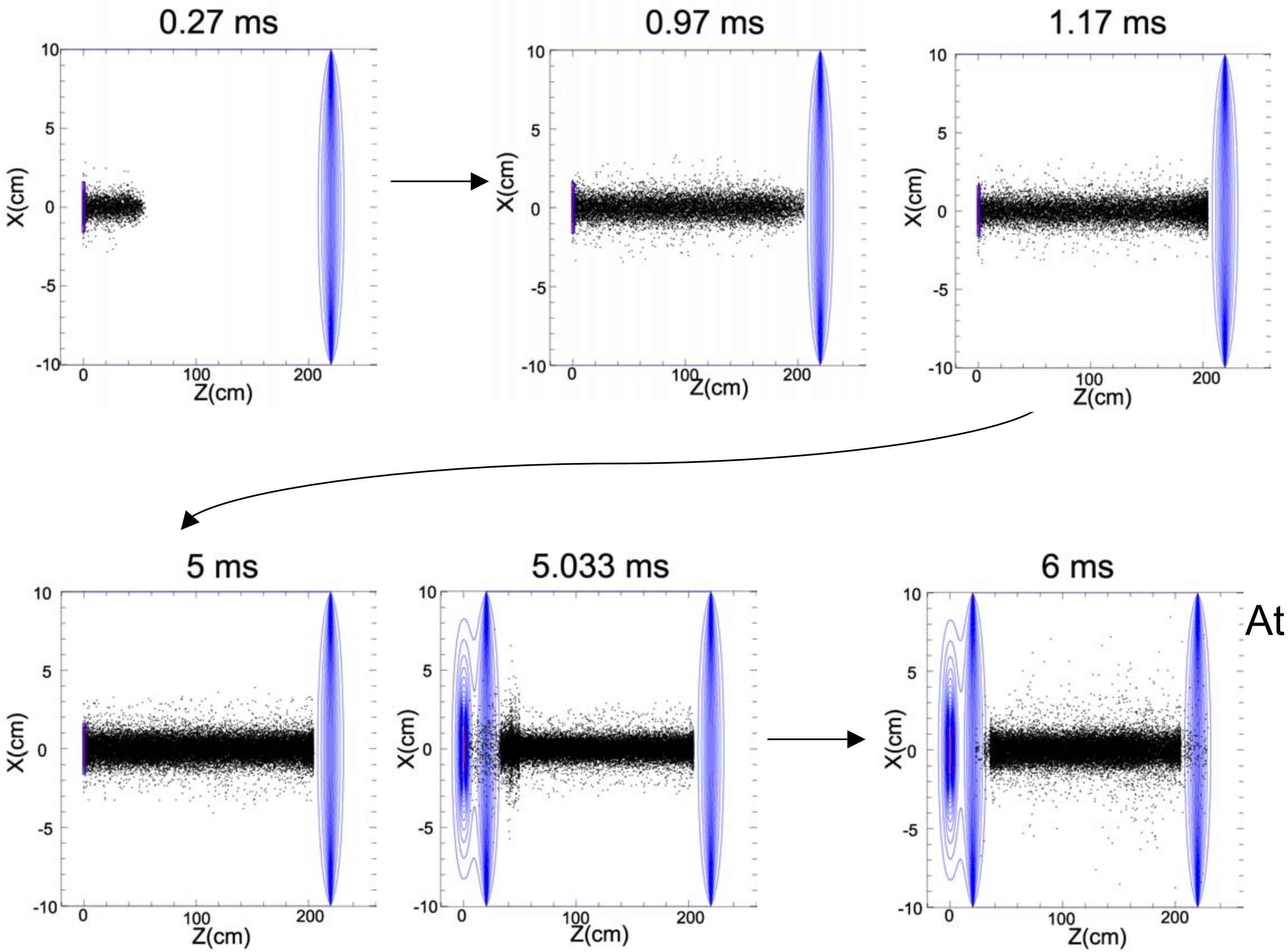
* Developed by Alex Friedman, Dave Grote and Irving Haber.

WARP Simulations Agree Well with PTSX Data



At t = 6 ms,

- $s = \omega_p^2/2\omega_q^2 = 0.1$
- kT = 0.5 eV
- R_b = 0.7 cm

PTSX is a Compact Experiment for Studying the Propagation of Beams Over Large Distances

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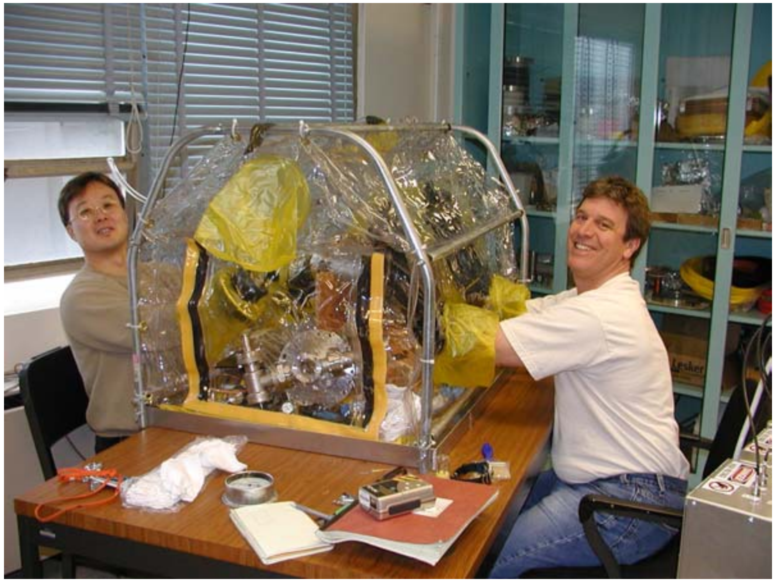
- PTSX is a versatile research facility in which to simulate collective processes and the transverse dynamics of intense charged particle beam propagation over large distances through an alternating-gradient magnetic quadrupole focusing system using a compact laboratory Paul trap.
- Future plans include exploring important physics issues such as:
  - Beam mismatch and envelope instabilities;
  - Collective wave excitations;
  - Chaotic particle dynamics and production of halo particles;
  - Mechanisms for emittance growth;
  - Compression techniques; and
  - Effects of distribution function on stability properties.

Barium Ion Source Development

- A barium ion source is being developed in order to implement laser-induced fluorescence (LIF) to characterize the transverse distribution function.

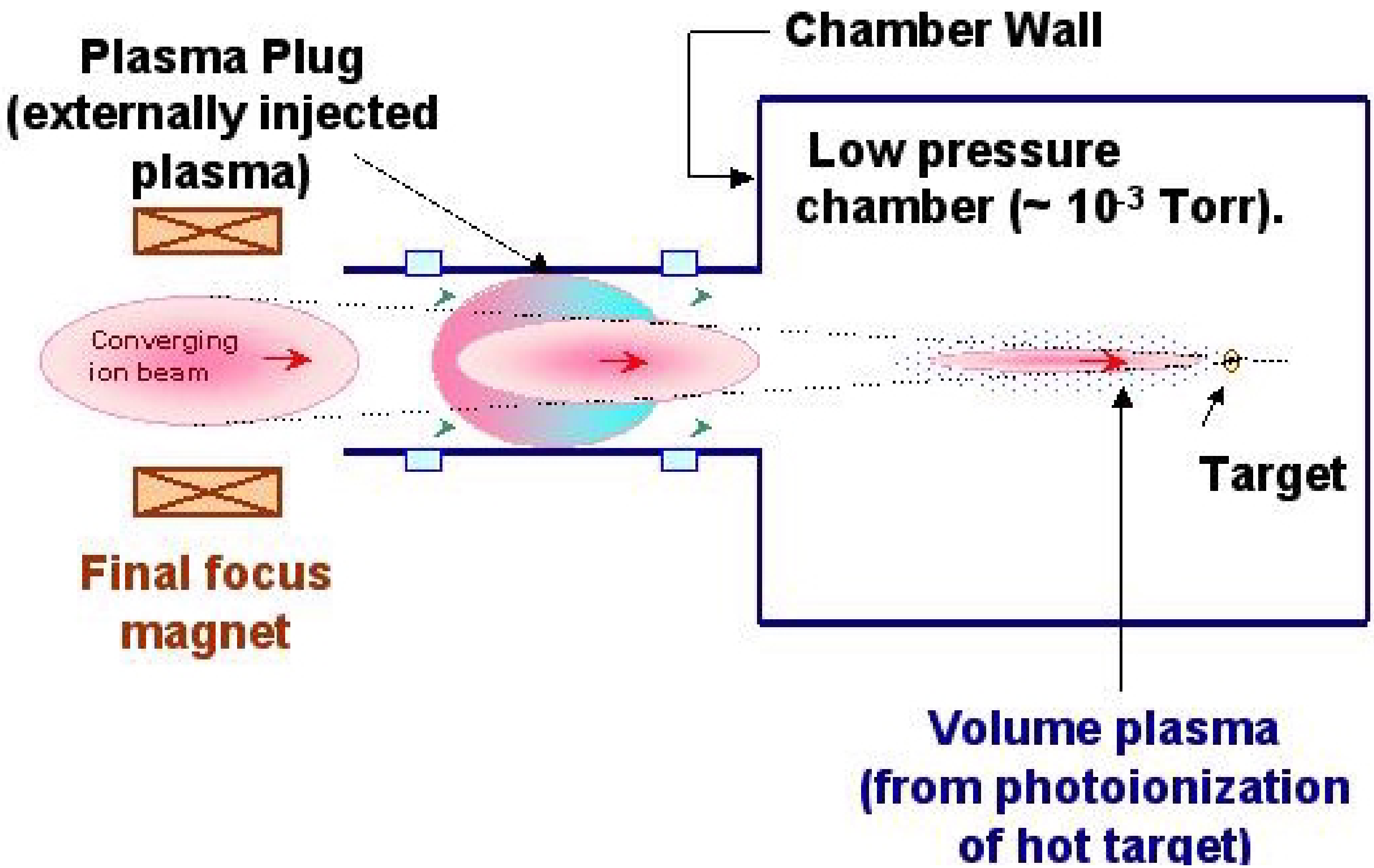


Graduate student Moses Chung and technician Andy Carpe load barium into the test chamber in an inert environment to prevent contamination.

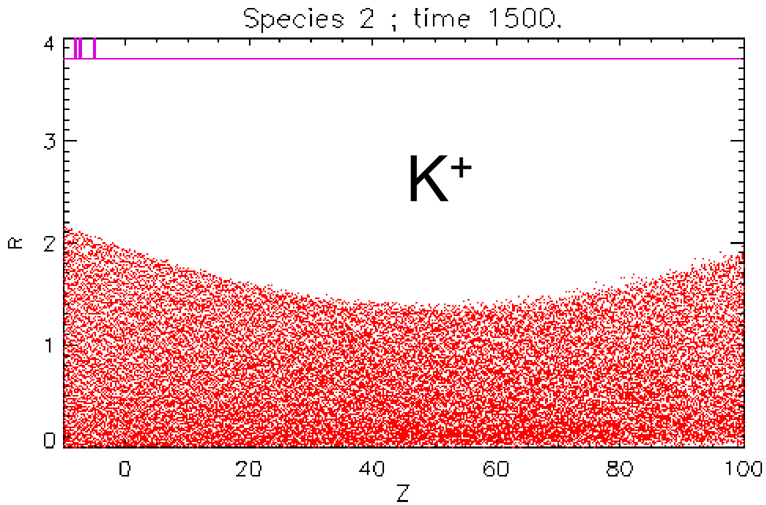
Graduate student Moses Chung monitors barium ion current from contact ionization of barium on a rhenium plate.

Neutralized Transport Experiment (NTX)

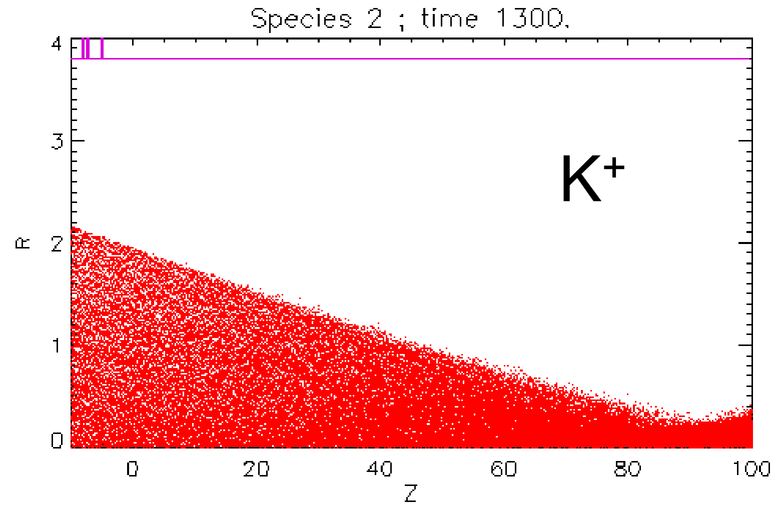
Beam Neutralization for Heavy Ion Fusion



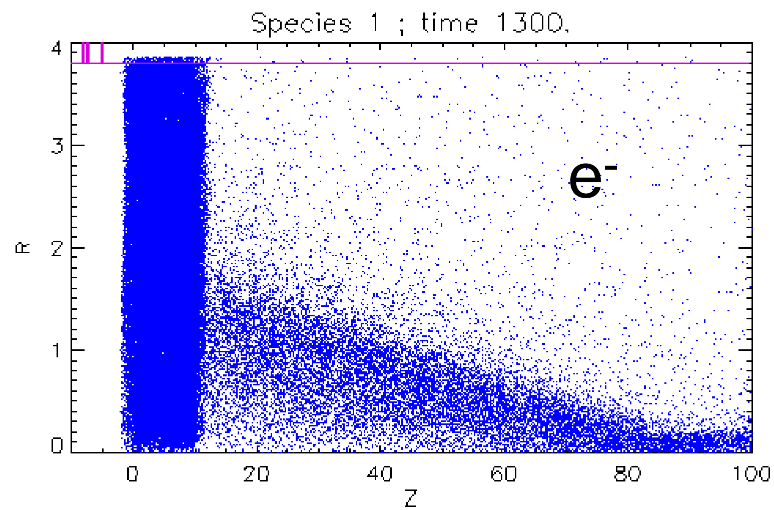
LSP Simulations of Beam Neutralization



No Neutralization

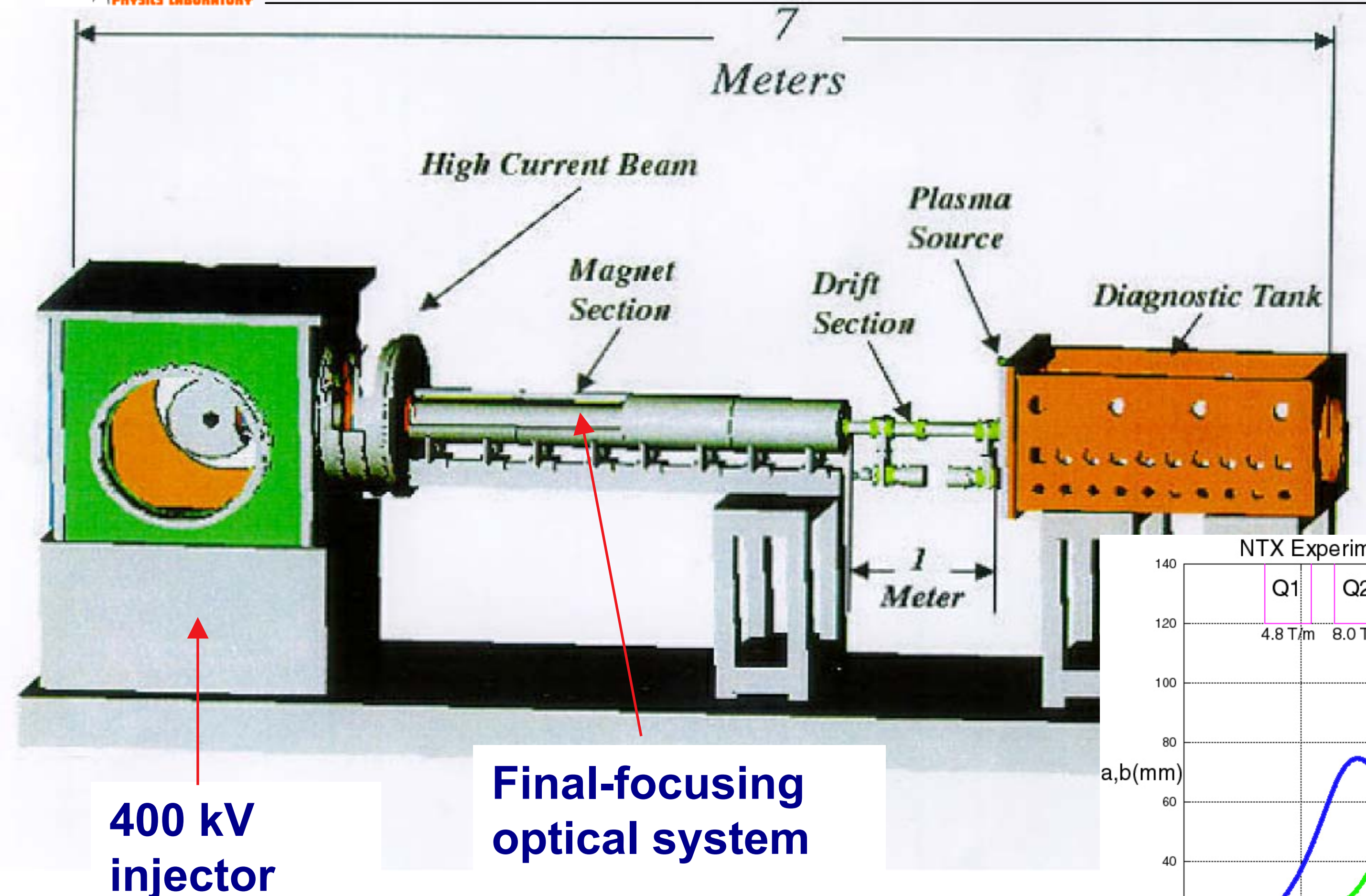


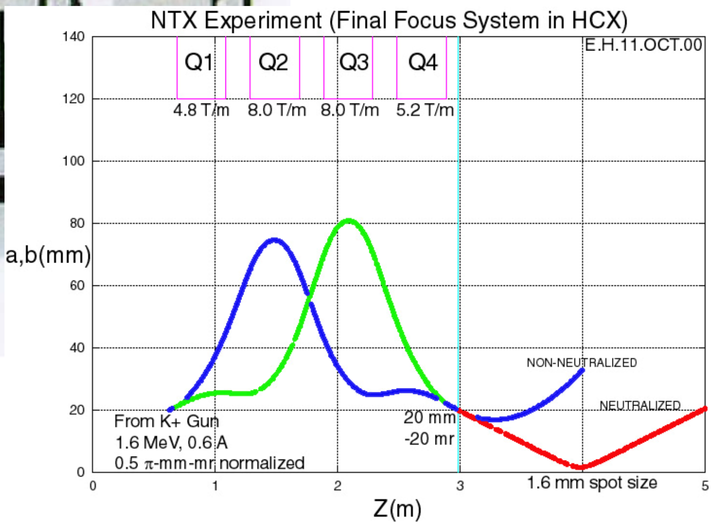
Neutralization with plug



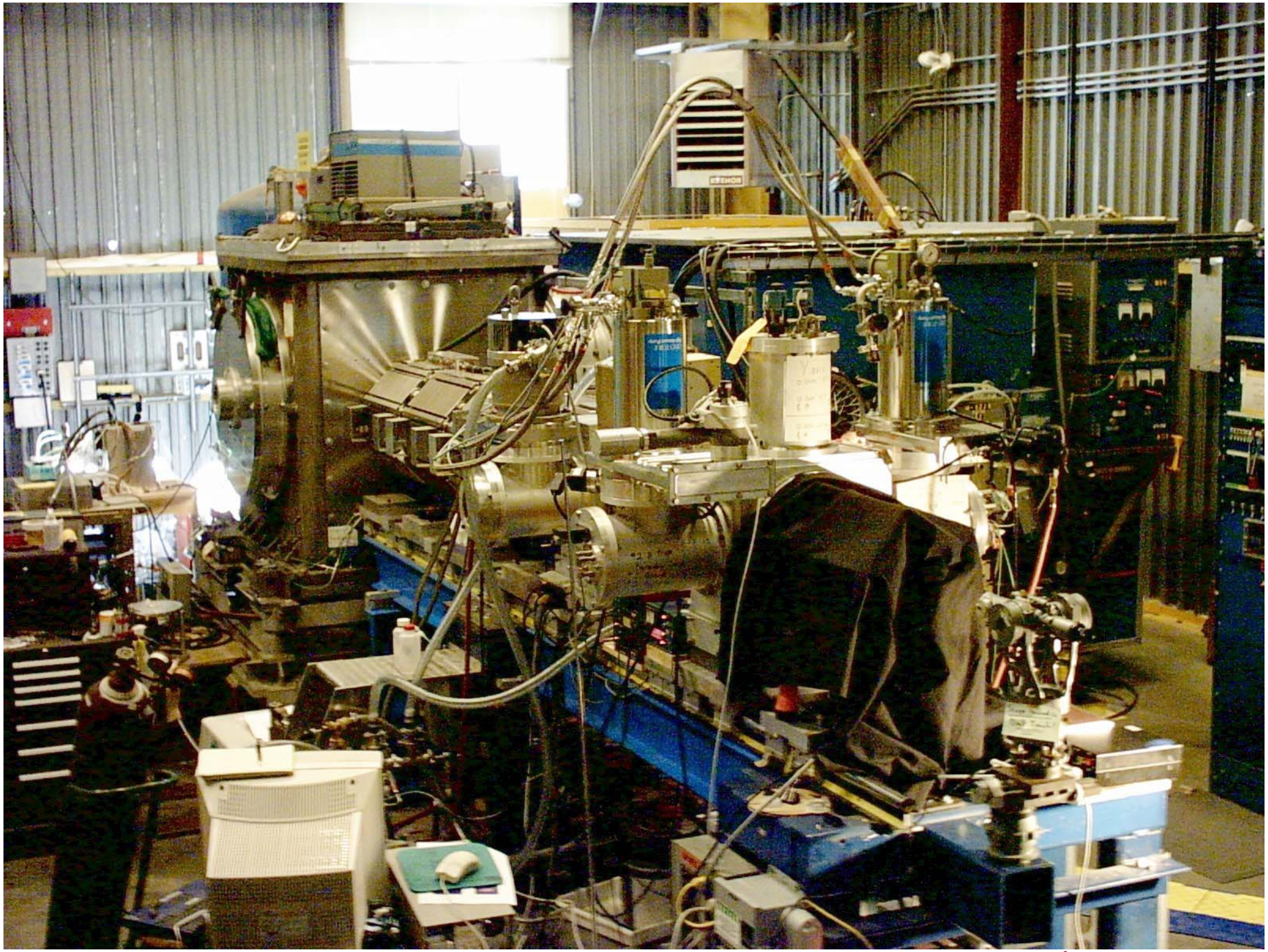
- Dale Welch - MRC
- 300 keV, 25 mA, 0.1 π-mm-mrad K^+ beam
- Plasma plug had 1.4×10^{12} electrons with electrical connection to wall

Neutralized Transport Experiment

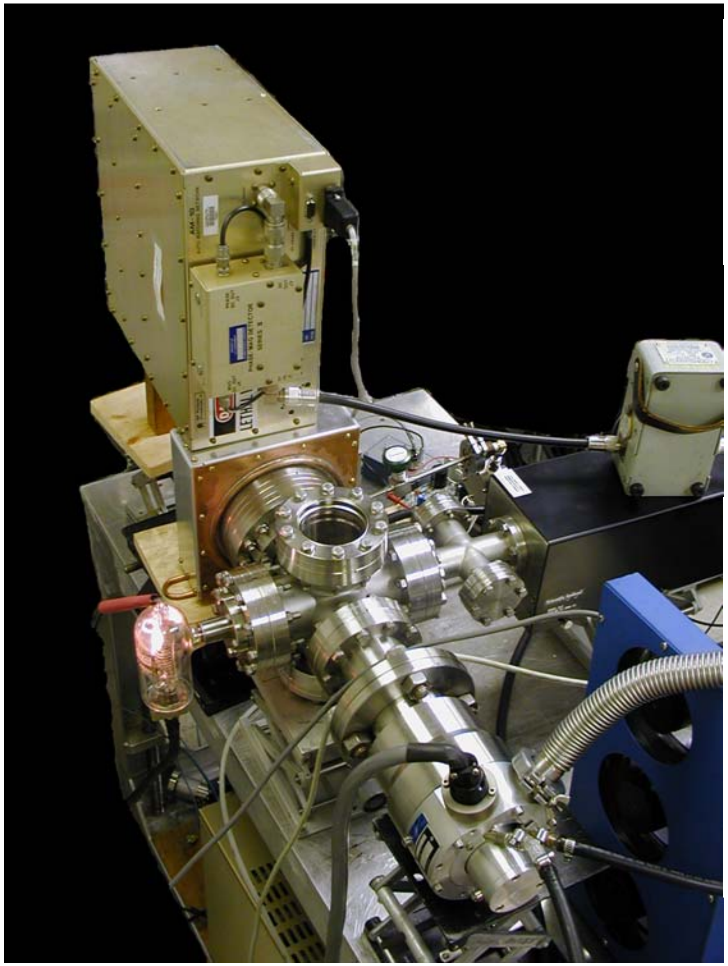


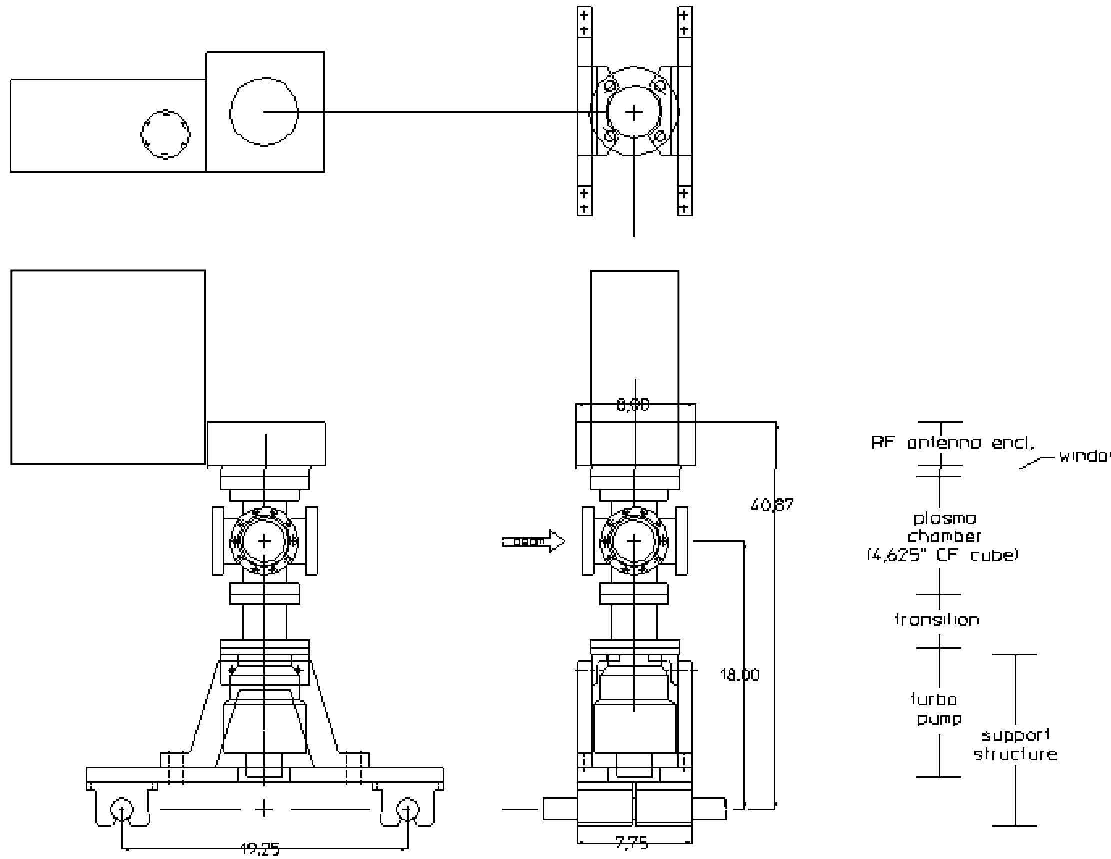


NTX Apparatus at LBNL

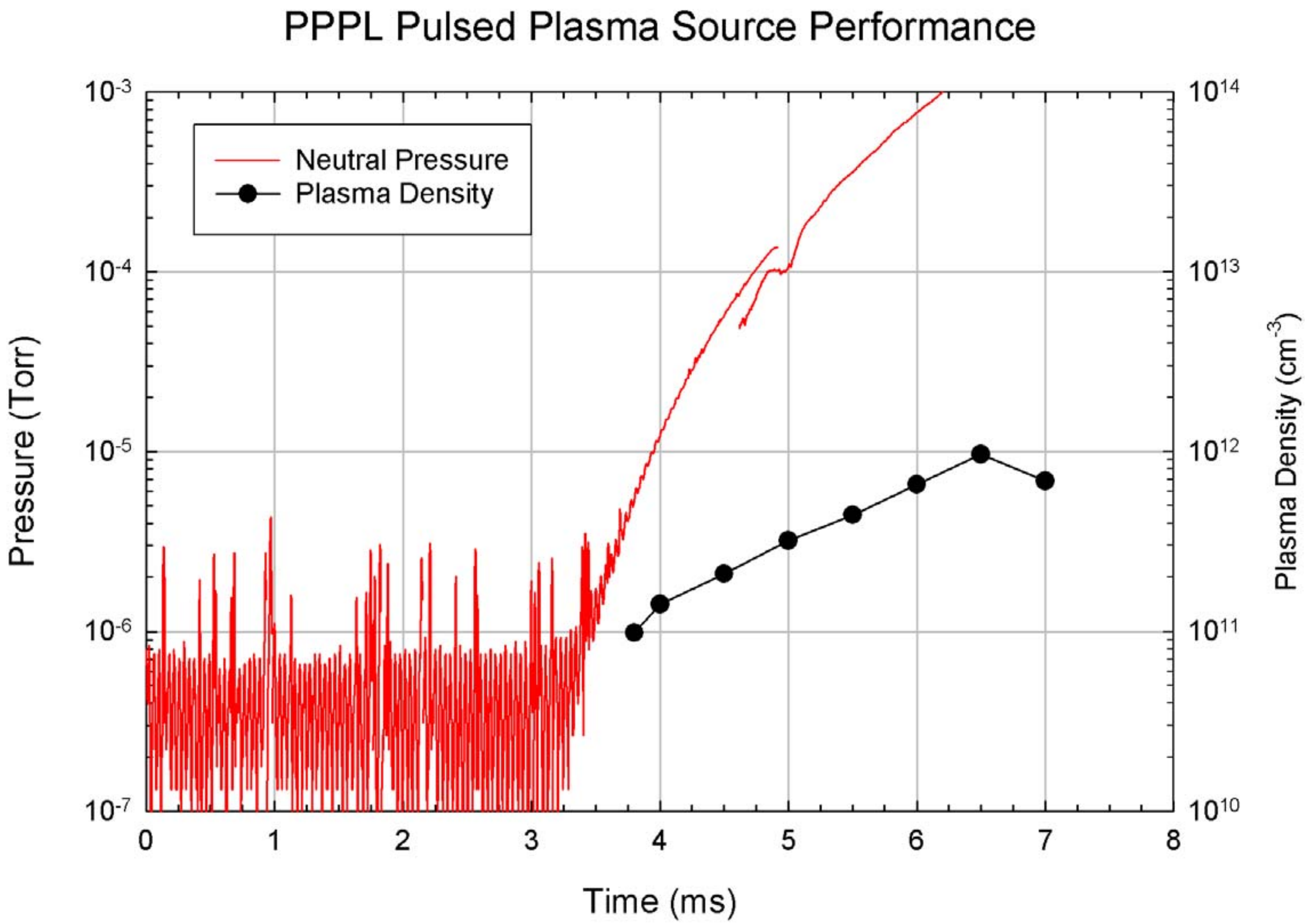


PPPL RF Plasma Source

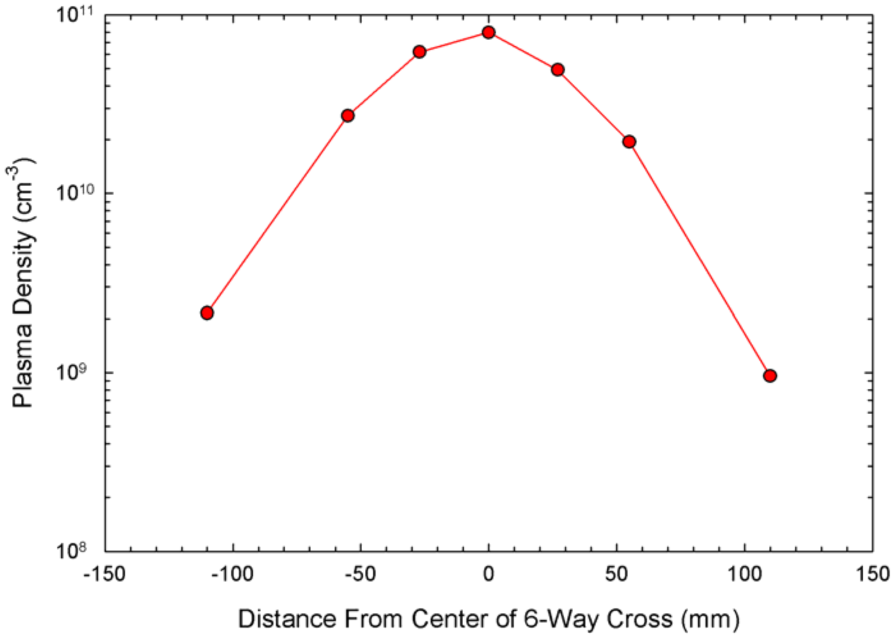


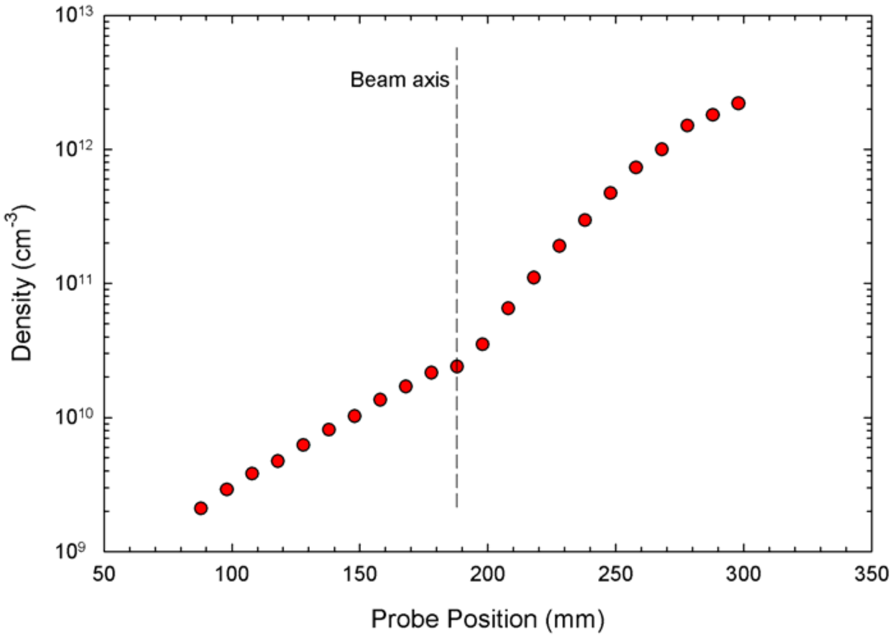


Characterization at PPPL



Density Profiles

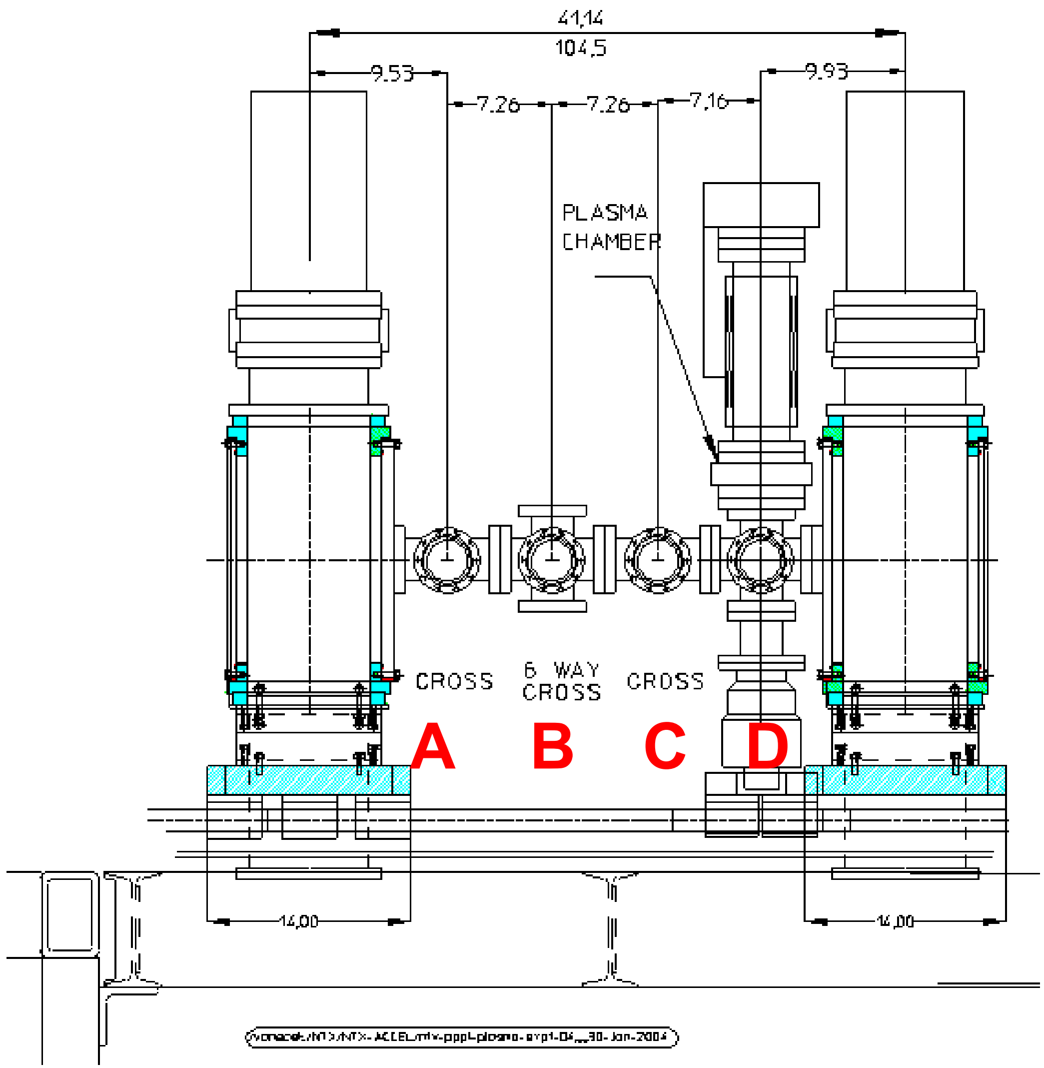




Plasma density is peaked in the plane transverse to the plasma source axis.

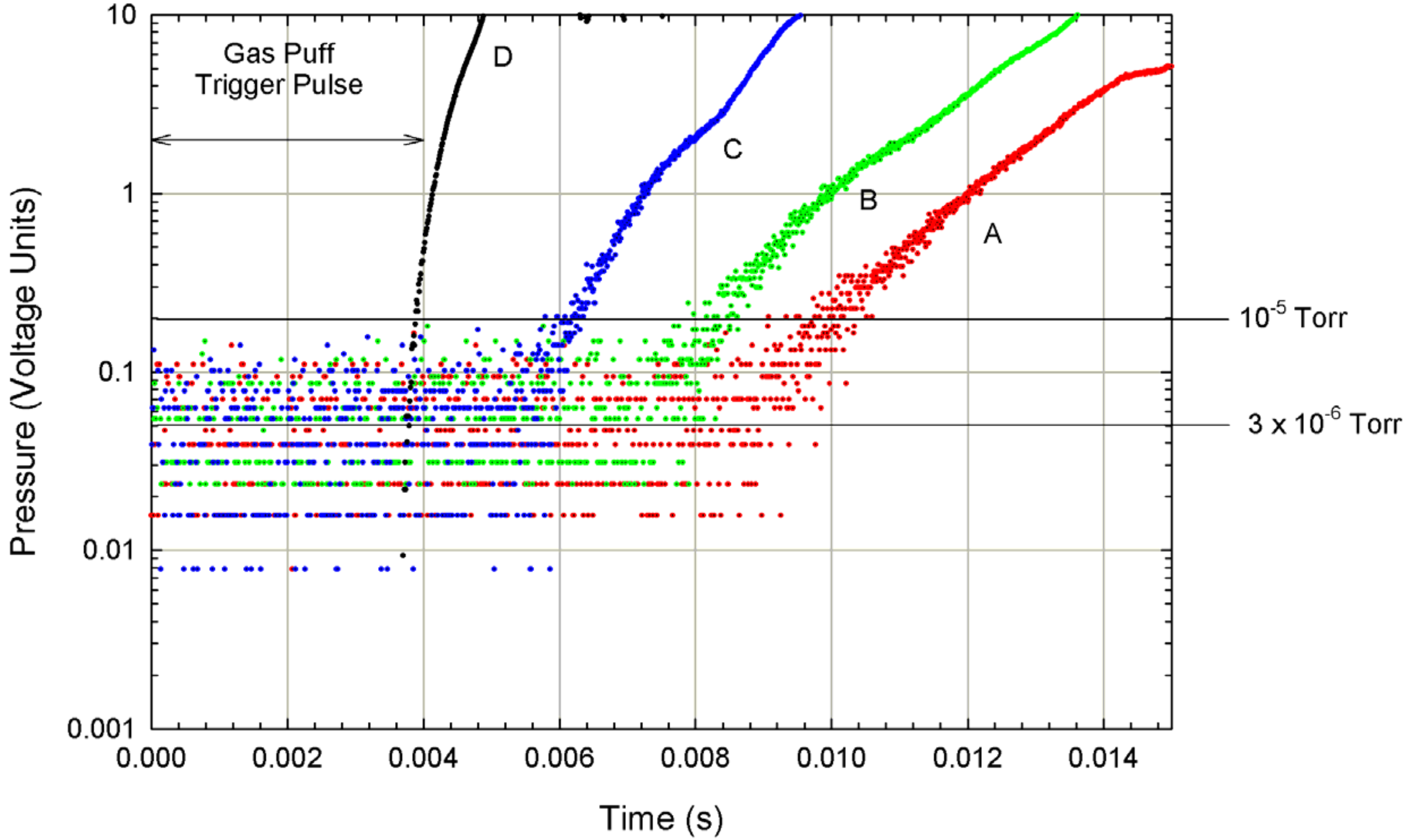
Plasma density drops off quickly moving away from the RF energy source.

Characterization in-situ

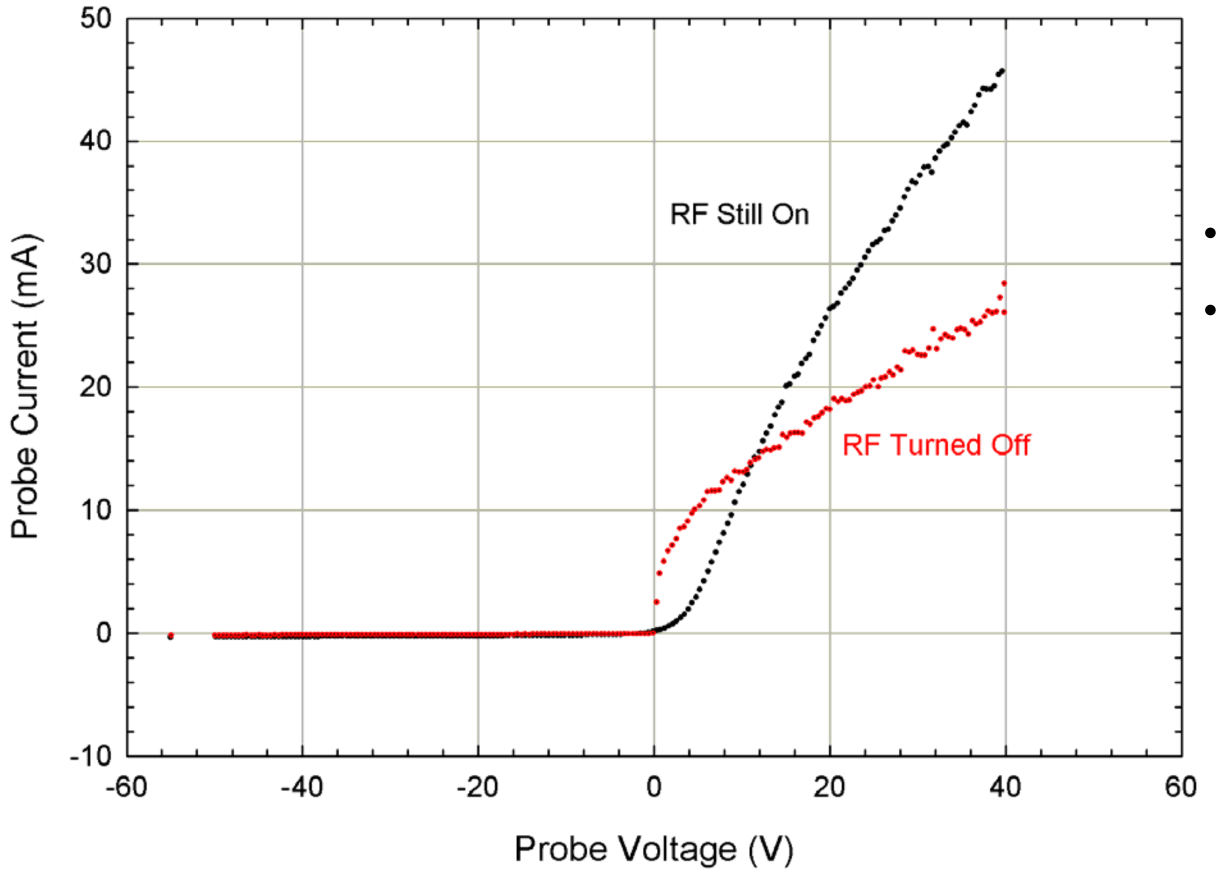


No Argon Upstream Until After Beam has Passed

50 psi Argon & 4 ms Gas Puff

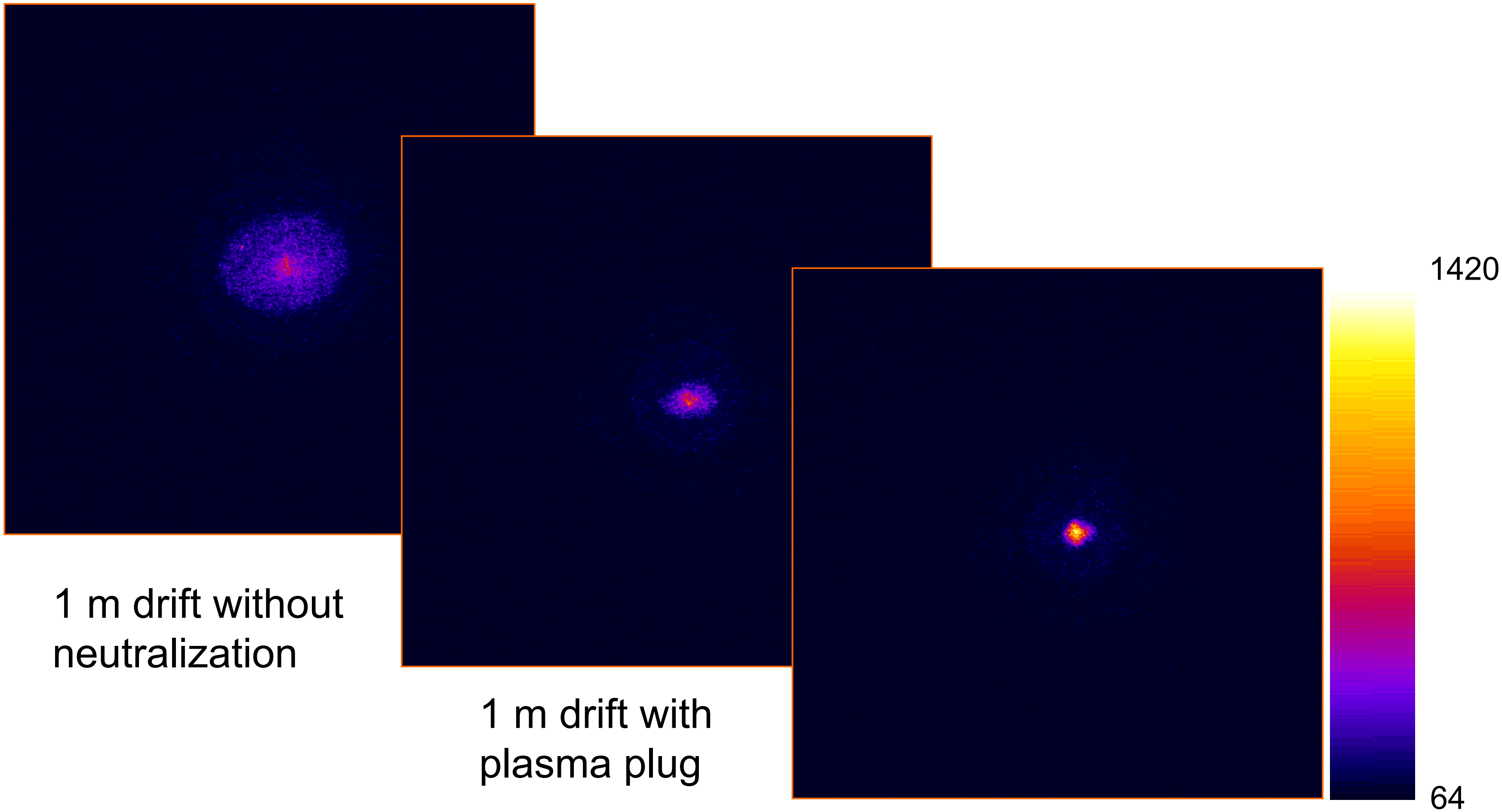


Langmuir Probe Measurements Show the Afterglow is Cooler



- $kT_{RF\ ON}$ ~ 3 eV
- $kT_{RF\ OFF}$ ~ 0.5 eV

Plasma Plug and Volumetric Plasma Give Smaller Spot Sizes



1 m drift without neutralization

1 m drift with plasma plug

1 m drift plasma plug and volumetric plasma

266 kV Beam

NTX Demonstrates Ability to Focus an Ion Beam to Small Spot Sizes

- PPPL RF argon plasma source meets requirements of instantaneous high plasma density and low neutral pressure.
- Plasmas allow focusing of beam down to 1mm.
- A 1 m long ferroelectric plasma source for enhanced control over axial density profile is in development.