Conditions for minimization of halo particle production during transverse compression of intense ion charge bunches in the Paul trap simulator experiment (PTSX)*

Erik P. Gilson
Princeton Plasma Physics Laboratory

16th International Symposium on
Heavy Ion Inertial Fusion
July 2006
Saint Malo, France

In collaboration with: Moses Chung, Ronald C. Davidson, Mikhail Dorf, Philip C. Efthimion, Richard Majeski, and Edward A. Startsev

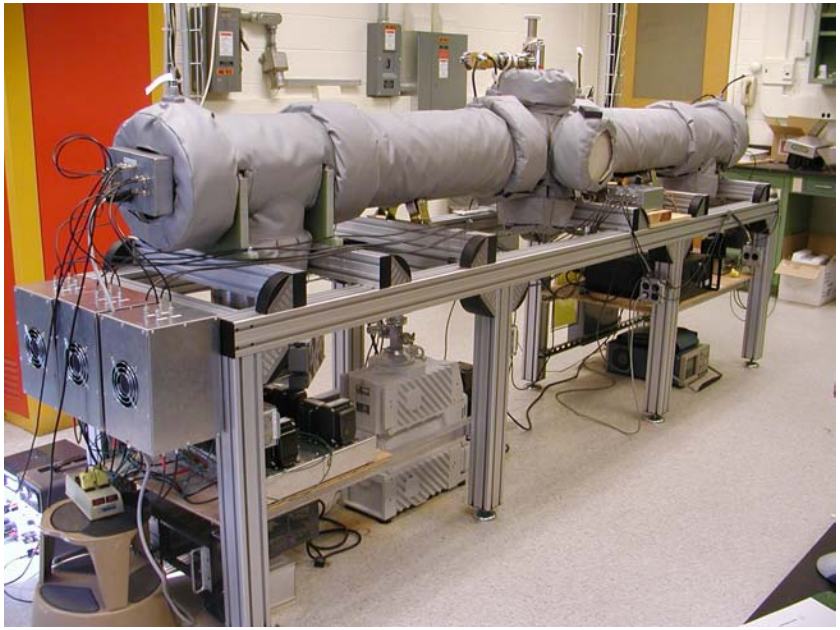
Thanks to: David P. Grote

*This work is supported by the U.S. Department of Energy.

PTSX Simulates Nonlinear Beam Dynamics in Magnetic Alternating-Gradient Systems

<u>Purpose</u>: Simulate the nonlinear transverse dynamics of intense beam propagation over large distances through magnetic alternating-gradient transport systems in *a compact experiment*.

<u>Applications</u>: Accelerator systems for high energy and nuclear physics applications, high energy density physics, heavy ion fusion, spallation neutron sources, and nuclear waste transmutation.

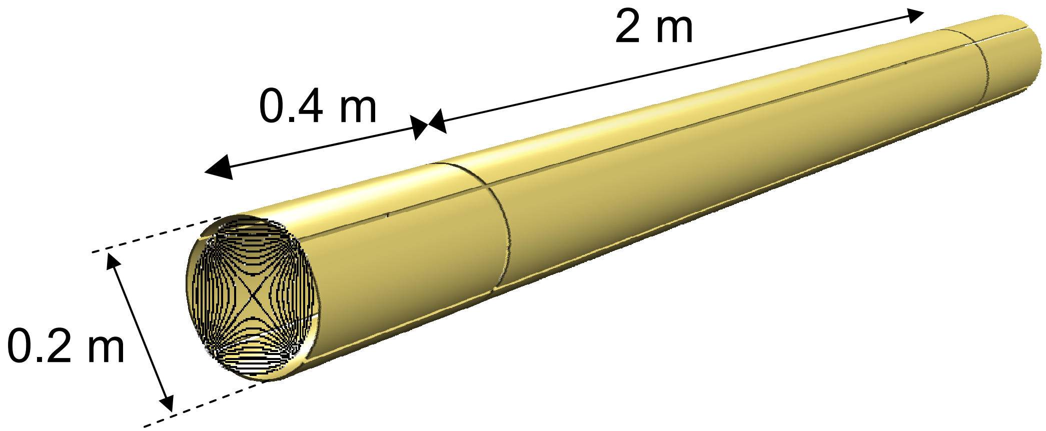


- Davidson, Qin and Shvets, Phys. Plasmas **7**, 1020 (2000)
- Okamoto and Tanaka, Nucl. Instrum. Methods A **437**, 178 (1999)
- Gilson, Davidson, Efthimion and Majeski, Phys. Rev. Lett. **92**, 155002 (2004)
- N. Kjærgaard, K. Mølhave, M. Drewsen, Phys. Rev. E **66**, 015401 (2002).
- M. Walter, et al., Phys. Plasmas **13**, 056703 (2006) – and **IRV HABER** AFTER LUNCH

Scientific Motivation

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

PTSX Configuration – A Cylindrical Paul Trap



$$e\phi_{ap}(x,y,t) = \frac{1}{2}\kappa_q'(t)(x^2 - y^2)$$

$$\kappa_q'(t) = \frac{8eV_0(t)}{m\pi r_w^2}$$

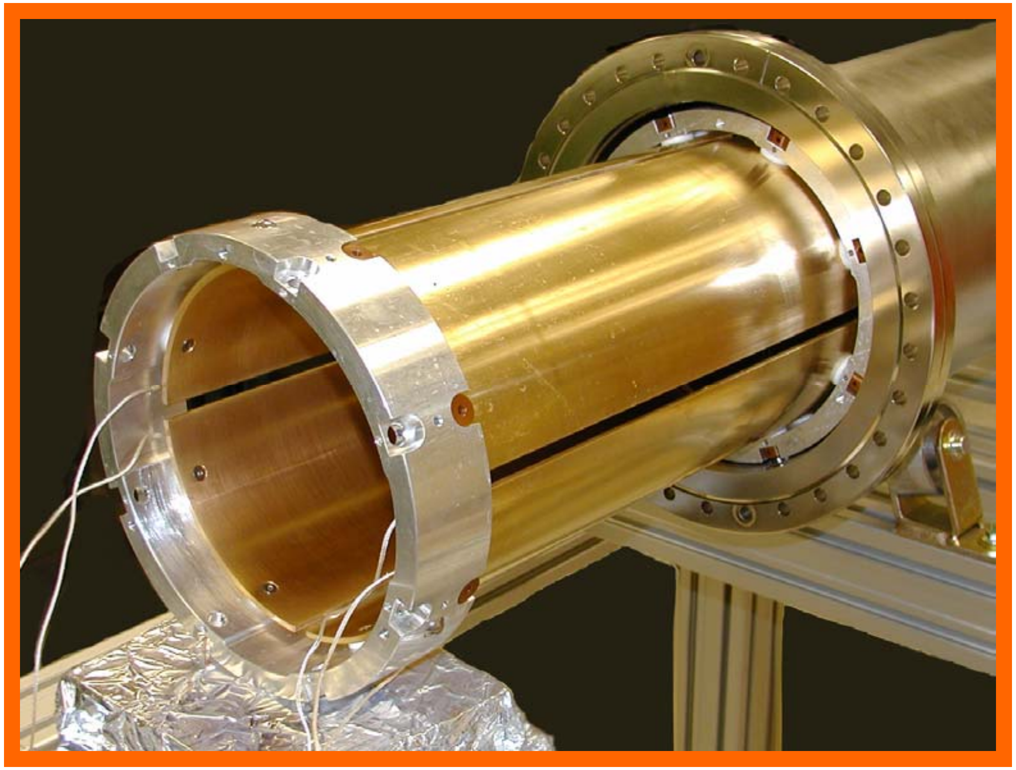
sinusoidal in this work

$$\omega_q = \frac{8eV_{0\,\max}}{m\pi r_w^2 f}\xi$$

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
Cesium ion mass	133 amu	Operating pressure	5×10^{-10} Torr
Ion source grid voltages	< 10 V		

Electrodes, Ion Source, and Collector

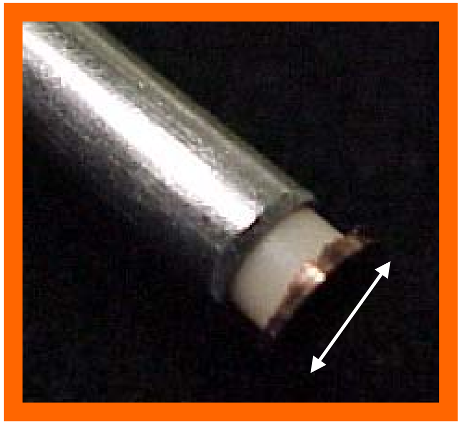
Broad flexibility in applying V(t) to electrodes with arbitrary function generator.



Increasing source current creates plasmas with intense space-charge.

1.25 in

Large dynamic range using sensitive electrometer.



5 mm

Measures average Q(r).

Transverse Dynamics are the Same Including Self-Field Effects

If…

- Long coasting beams
- Beam radius << lattice period
- Motion in beam frame is nonrelativistic

Then, when in the beam frame, both systems have…

- Quadrupolar external forces
- Self-forces governed by a Poisson-like equation
- Distributions evolve according to nonlinear Vlasov-Maxwell equation

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

Force Balance and Normalized Intensity *s*

If $p = n\,kT$, then the statement of local force balance on a fluid element can be integrated over a radial density distribution such as,

$$n(r) = n(0)\exp\left[-\frac{m\omega_q^2 r^2 + 2q\phi^s(r)}{2kT}\right]$$

to give the global force balance equation,

$$m\omega_q^2 R^2 = 2kT + \frac{Nq^2}{4\pi\varepsilon_o}$$

$$s \equiv \frac{\omega_p^2}{2\omega_q^2} < 1 \qquad \frac{\upsilon}{\upsilon_0} = (1-s)^{1/2}$$

for a flat-top radial density distribution

s	ν/ν_0
0.1	0.95
0.2	0.90
0.3	0.84
0.4	0.77
0.5	0.71
0.6	0.63
0.7	0.55
0.8	0.45
0.9	0.32
0.99	0.10
0.999	0.03

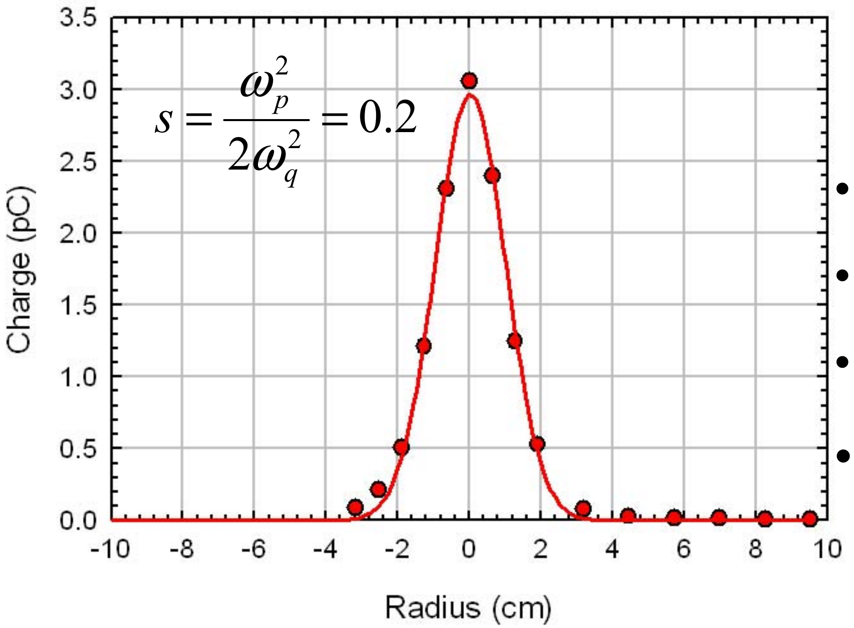
PTSX-accessible (s = 0.1 to 0.8)

Radial Profiles are Approximately Gaussian – Consistent with Thermal Equilibrium

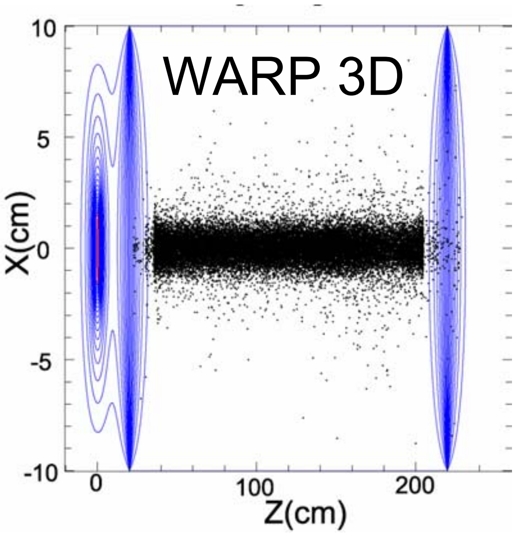
$$n(r) = n(0)\exp\left[-\frac{m\omega_q^2 r^2 + 2q\phi^s(r)}{2kT}\right]$$

- $V_{0\,max}$ = 235 V
- f = 75 kHz
- t_{hold} = 1 ms
- σ_v = 49°
- $\omega_q = 6.5 \times 10^4\ s^{-1}$

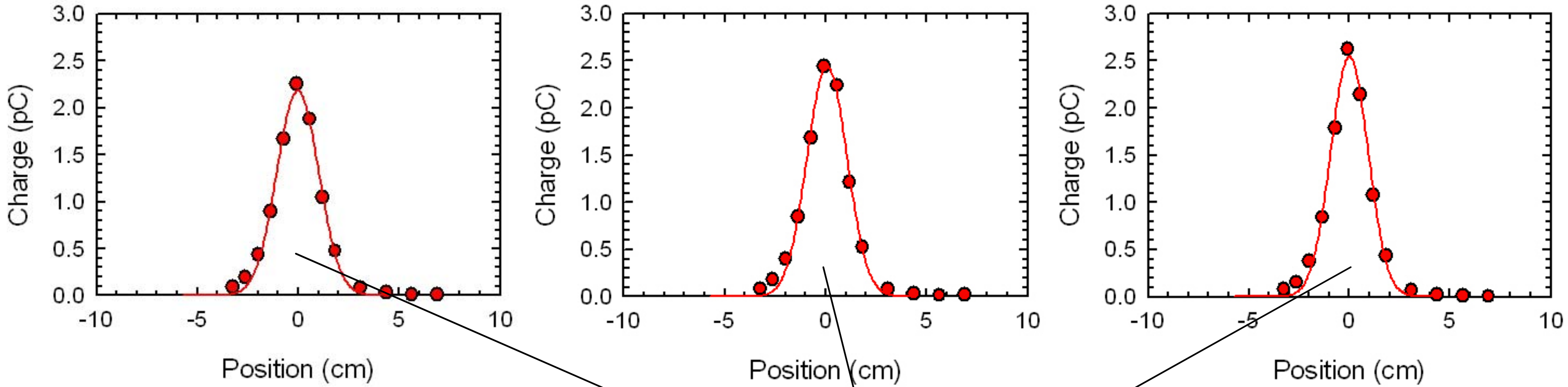
$$n(r) = \frac{Q(r)}{e\pi r_{aperture}^2 l_{plasma}}$$

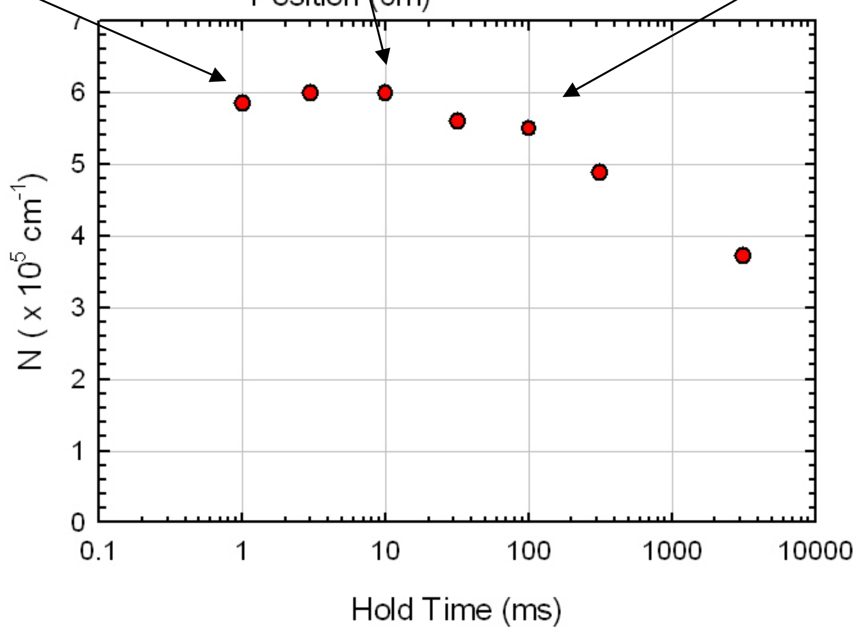


- $n(0) = 1.4\times10^5\ cm^{-3}$
- R = 1.4 cm
- s = 0.2
- v/v_0 = 0.9



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 lattice period is 1 m, the PTSX simulation experiment would correspond to a **7.5 km beamline**.

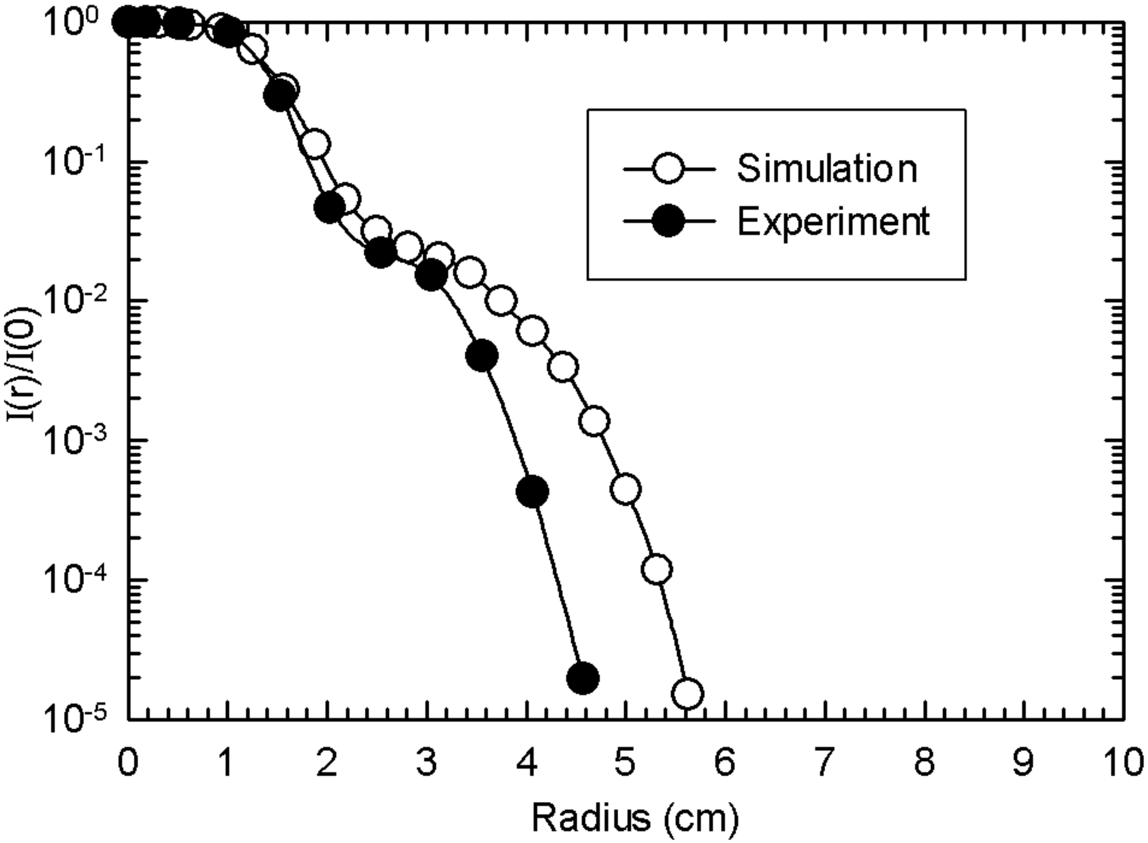
- $s = \omega_p^2/2\omega_q^2$ = 0.18.
- ν/ν_0 = 0.9
- $V_{0\ max}$ = 235 V
  f = 75 kHz
  σ_v = 49°

Mismatch Between Ion Source and Focusing Lattice Creates Halo Particles

PPPL PRINCETON PLASMA PHYSICS LABORATORY

HIF 06

Streaming-mode experiment

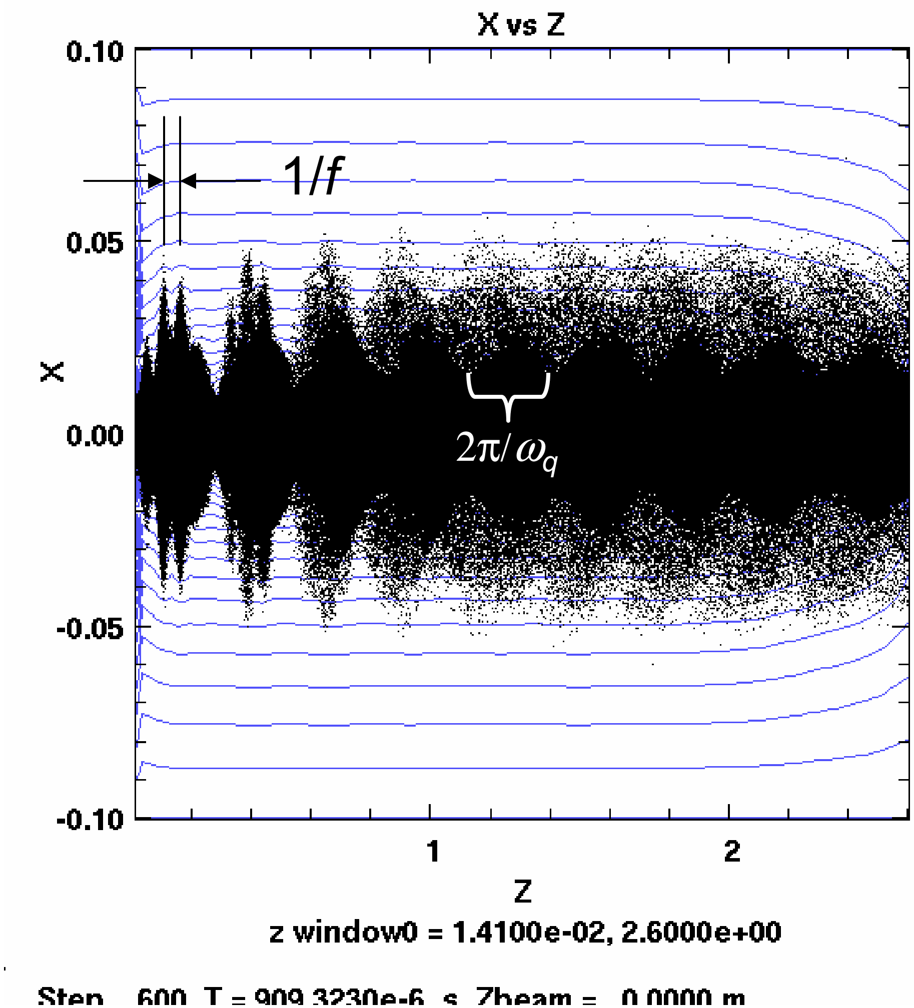


"Simulation" is a 3D WARP simulation that includes injection from the ion source.

- $s = \omega_p^2/2\omega_q^2 = 0.6$.
- $\nu/\nu_0 = 0.63$
- $V_{0\,max} = 235$ V
  $f = 75$ kHz
  $\sigma_v = 49^o$

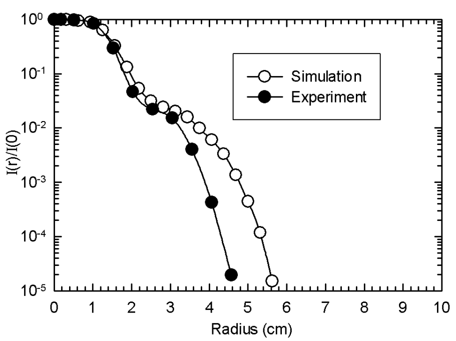
Qualitatively similar to C. K. Allen, *et al*., Phys. Rev. Lett. **89** (2002) 214802 on the Los Alamos low-energy demonstration accelerator (LEDA).

WARP Simulations Reveal the Evolution of the Halo Particles in PTSX



Oscillations can be seen at both f and the ω_q near $z = 0$.

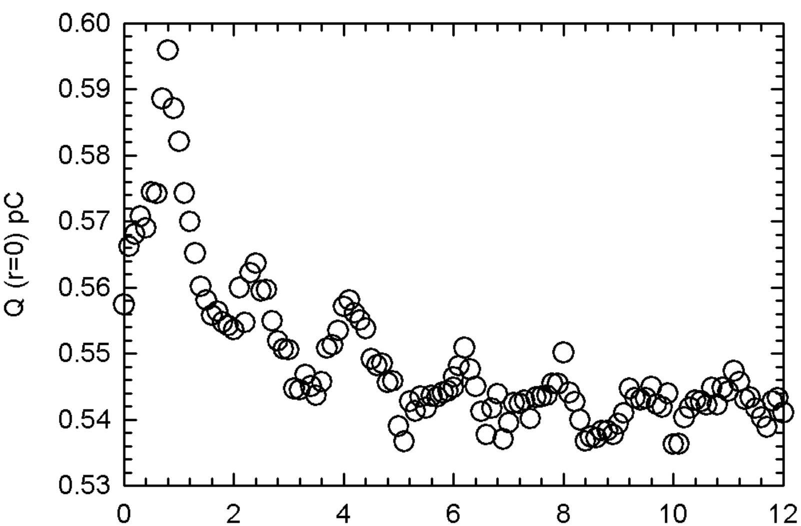
Downstream, the transverse profile relaxes to a core plus a broad, diffuse halo.



Go back to s ~ 0.2.

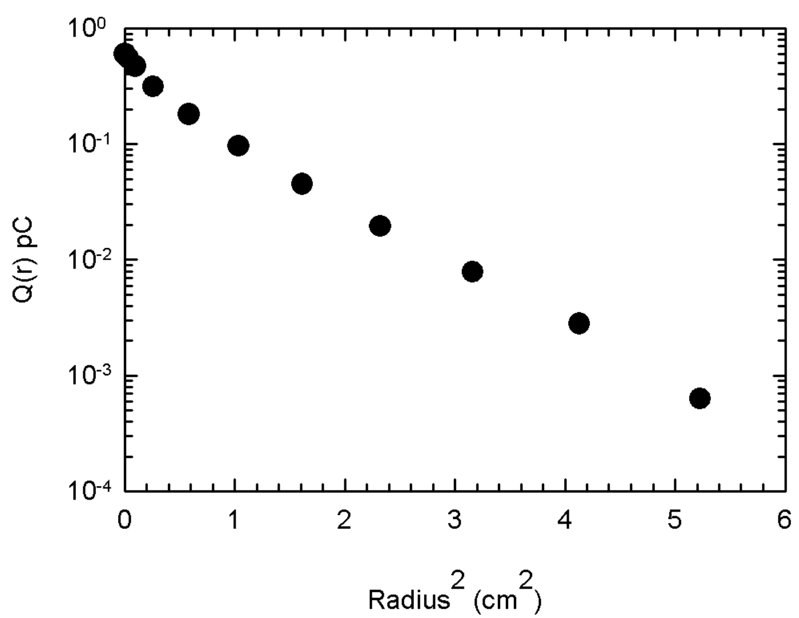
- $s = \omega_p^2/2\omega_q^2 = 0.6$.
- $v/v_0 = 0.63$
- $V_{0\,max} = 235$ V
  $f = 75$ kHz
  $\sigma_v = 49^o$

Oscillations From Residual Ion Source Mismatch Damp Away in PTSX



The injected plasma is still mismatched because a circular cross-section ion source is coupling to an oscillating quadrupole transport system.

Over 12 ms, the oscillations in the on-axis plasma density damp away…



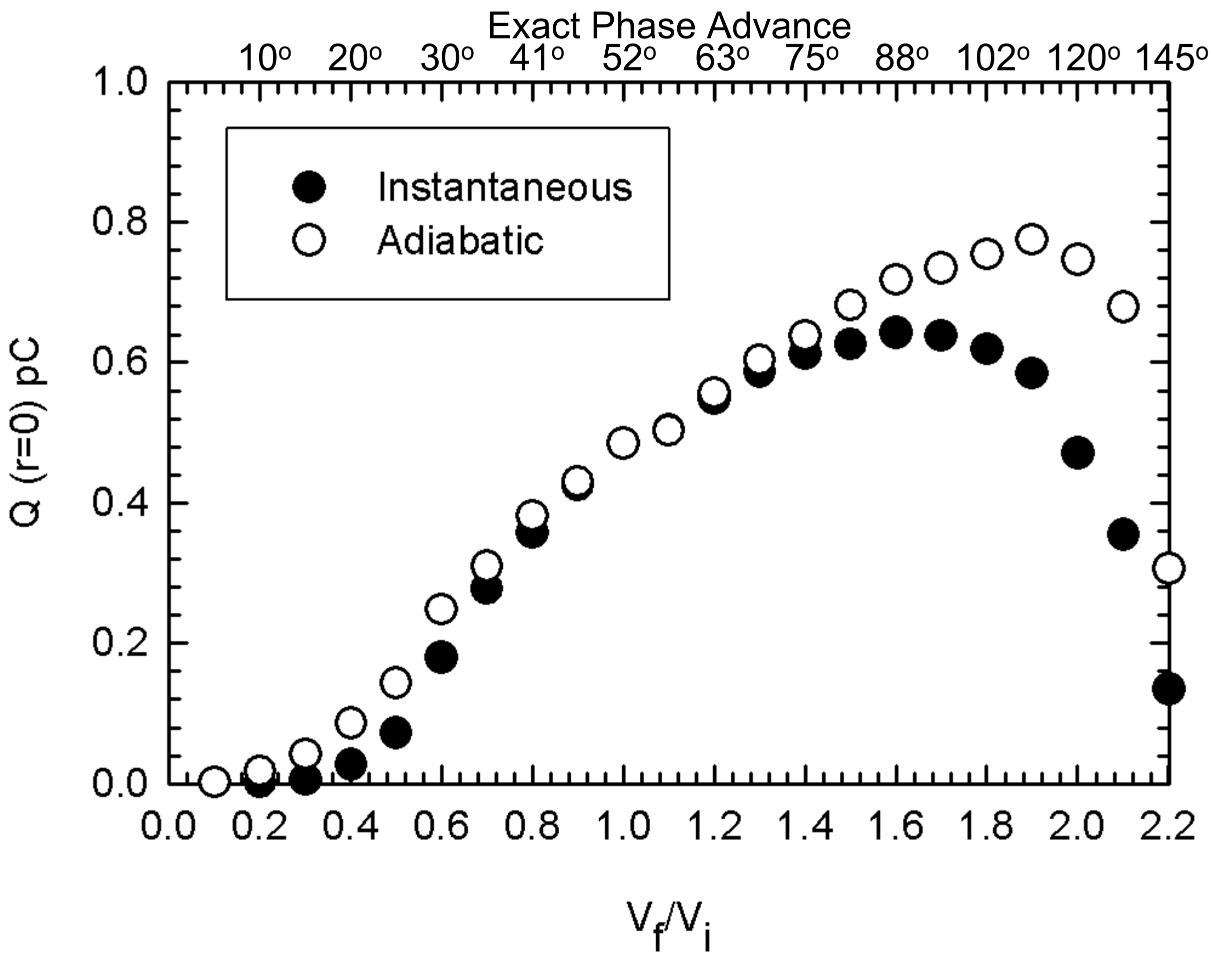
… and leave a plasma that is nearly Gaussian.

$kT = 0.12\text{eV}$

nearly the thermal temperature of the ion source.

- $s = \omega_p^2/2\omega_q^2 = 0.2.$
- $\nu/\nu_0 = 0.88$
- $V_{0\ max} = 150$ V
  $f = 60$ kHz
  $\sigma_v = 49^o$

Voltage Waveform Amplitude Changes: Adiabatic is Better Than Instantaneous

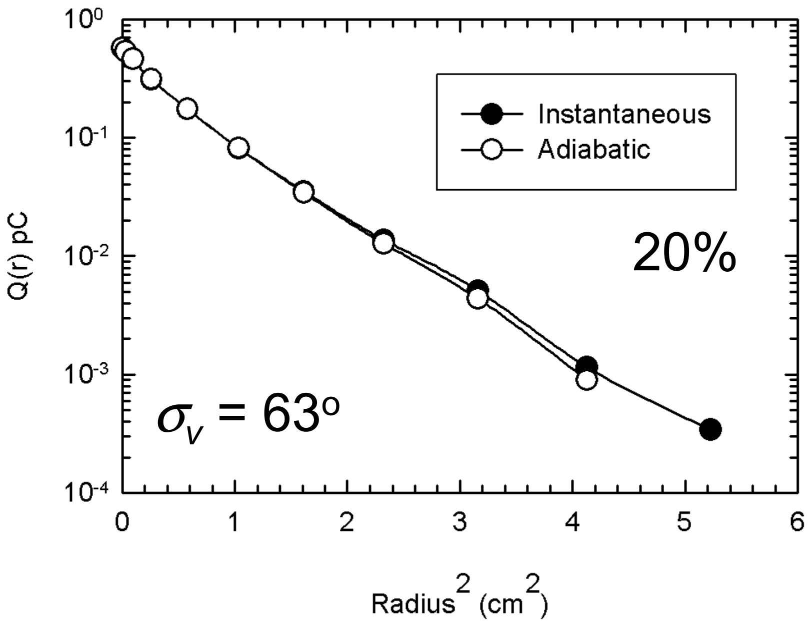


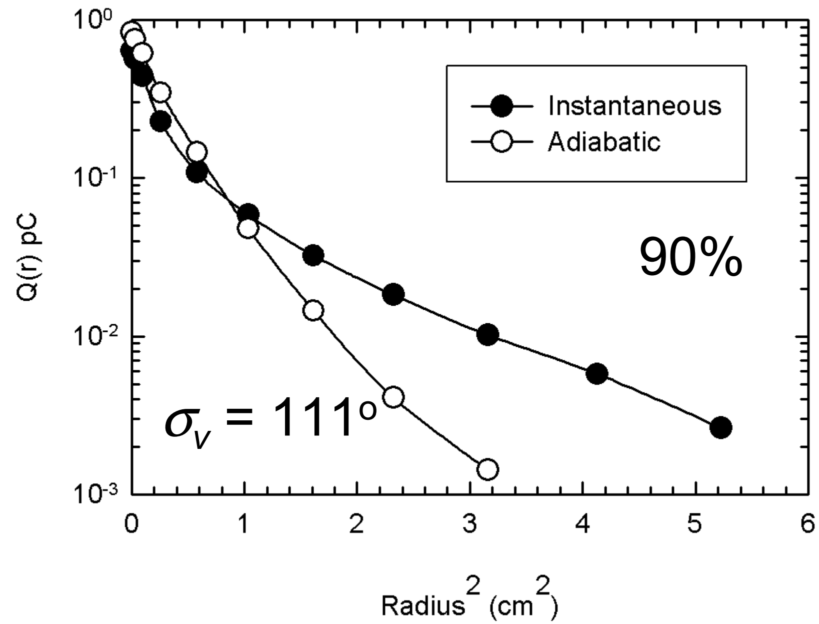
Adiabatic means 40 lattice periods for 90% of the hyperbolic tangent transition from V_i to V_f.

Changes of +/- 20% can be made instantaneously.

Changes of 90% must be made adiabatically to optimize compression and minimize halo particle production.

20% and 90% Changes in Amplitude: Instantaneous and Adiabatic



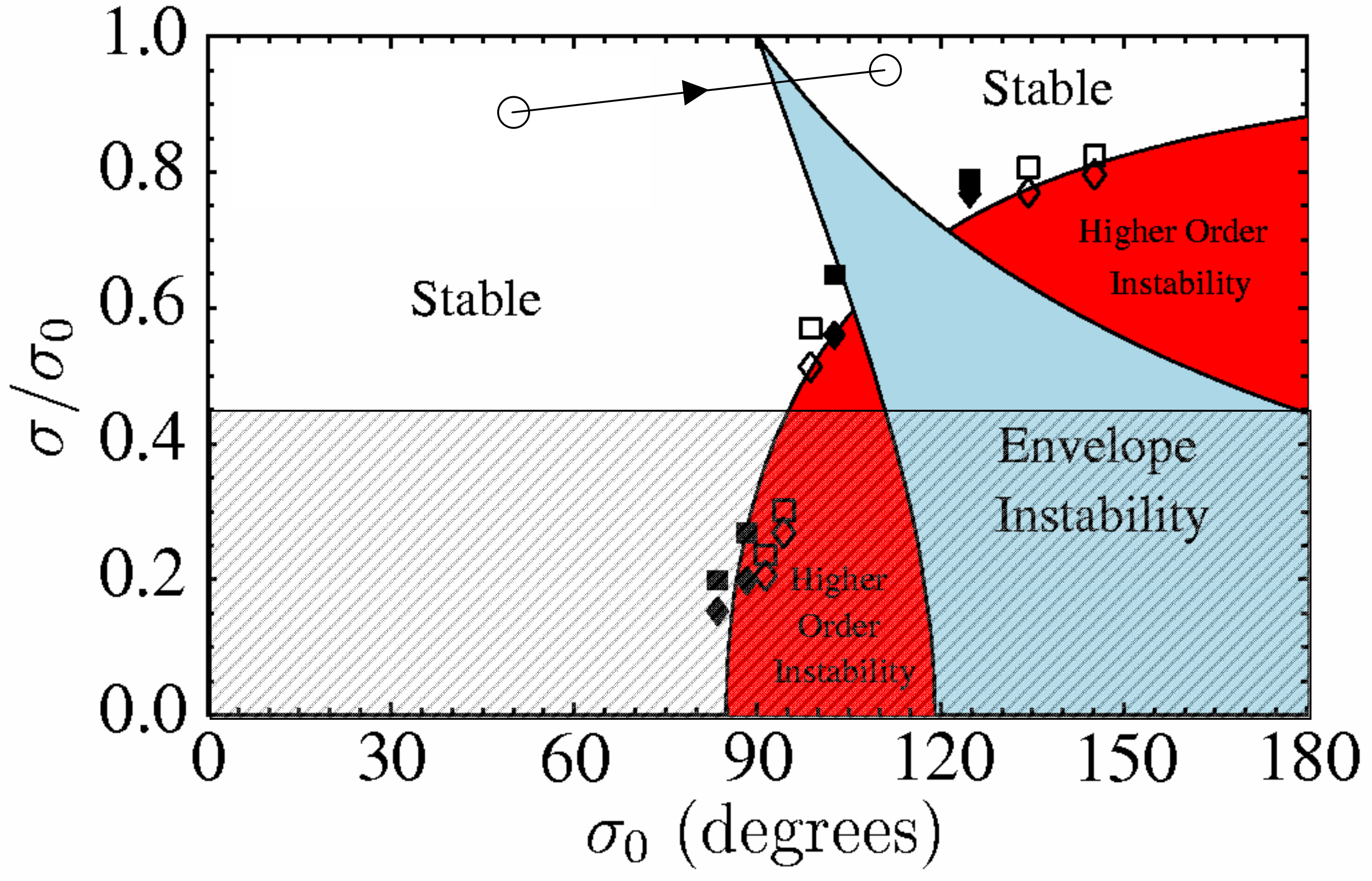


R_b = 0.79 cm
kT = 0.16 eV
s = 0.18
$\Delta\varepsilon$ = 10%

Adiabatic	Instantaneous
R_b = 0.63 cm	R_b = 0.93 cm
kT = 0.26 eV	kT = 0.58 eV
s = 0.10	s = 0.08
$\Delta\varepsilon$ = 10%	$\Delta\varepsilon$ = 240%

- $s = \omega_p^2/2\omega_q^2 = 0.20$
- $\nu/\nu_0 = 0.88$
- $V_{0\,max}$ = 150 V
- f = 60 kHz
- $\sigma_v = 49^o$

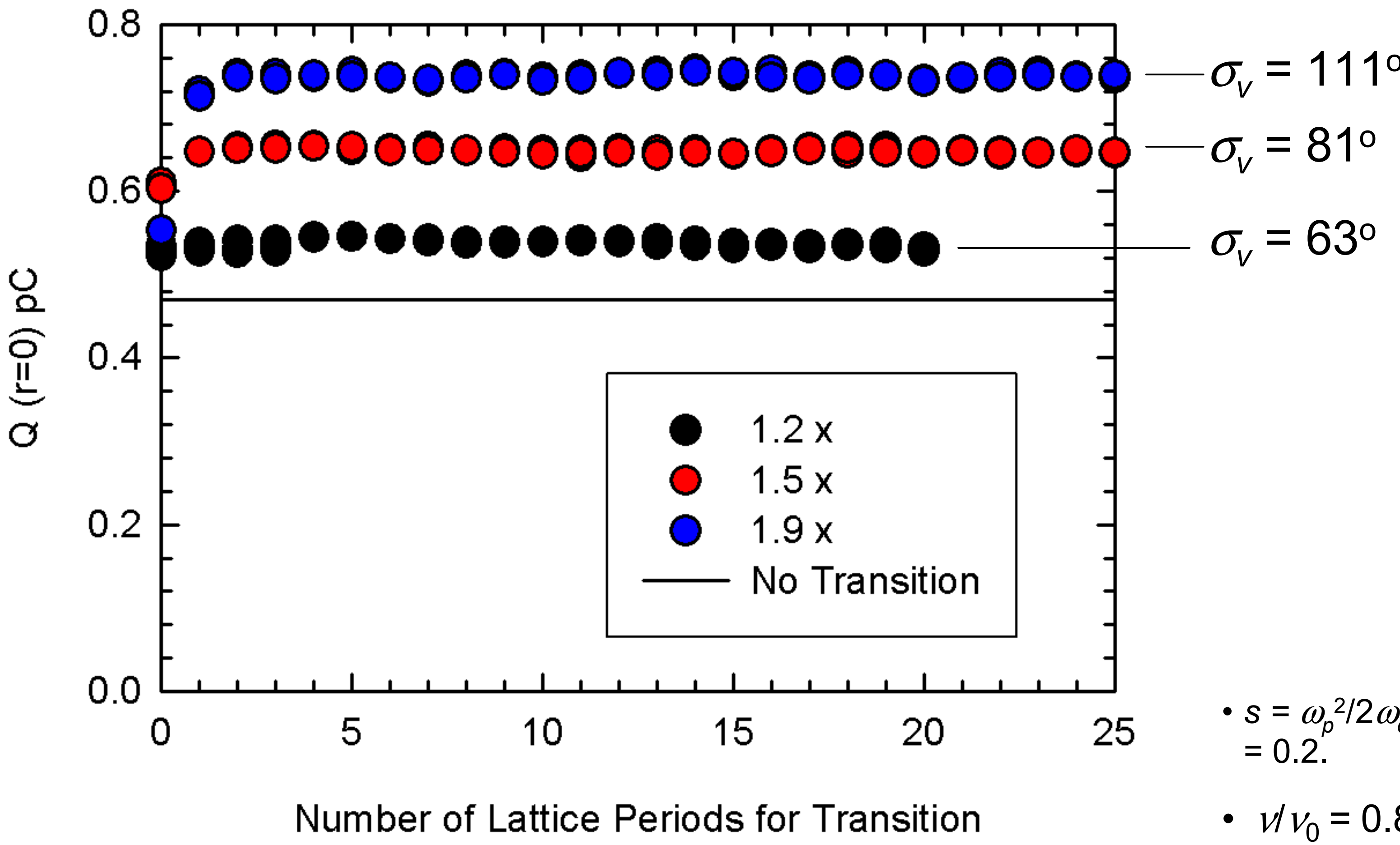
The Plasma Spends a Short Time in a Region of Parameter Space Where There is an Envelope Instability



[M.G. Tiefenback, Ph.D Thesis, UC Berkeley (1986)]

Steve Lund: Wednesday morning.

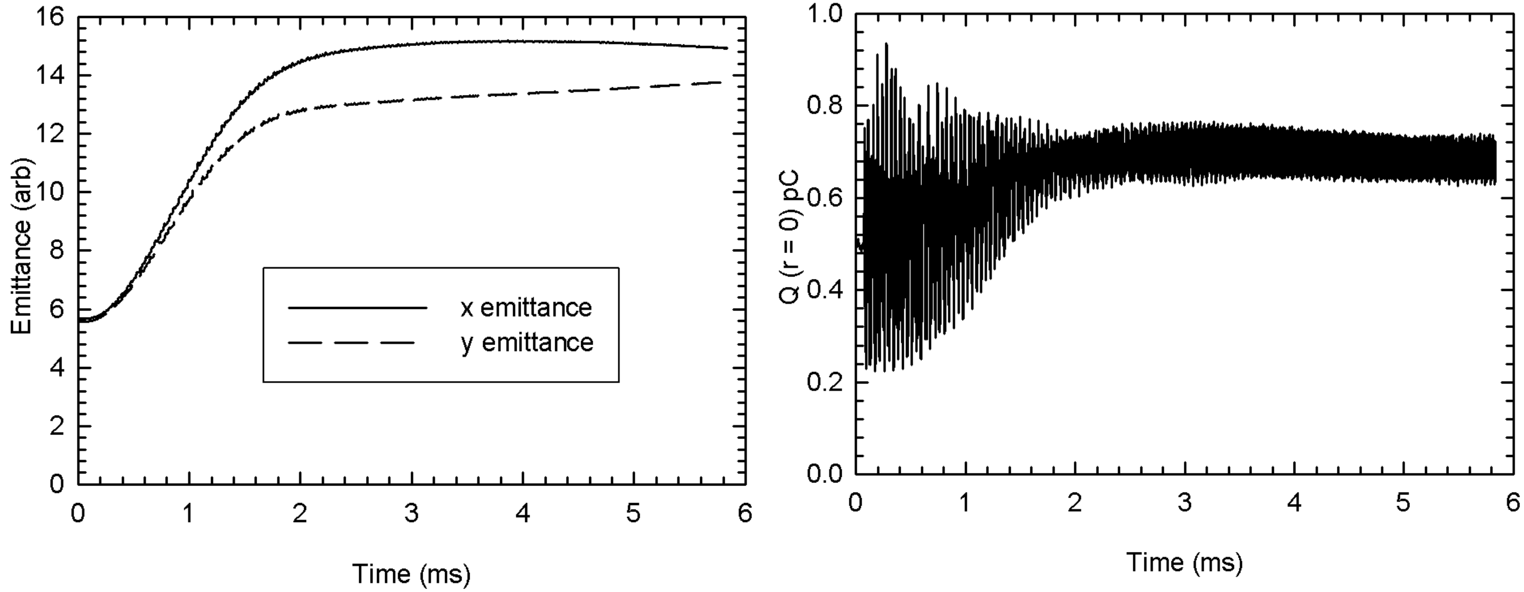
In PTSX Experiments Only Four Lattice Periods are Needed to "Adiabatically" Increase the Voltage By Up To 90%



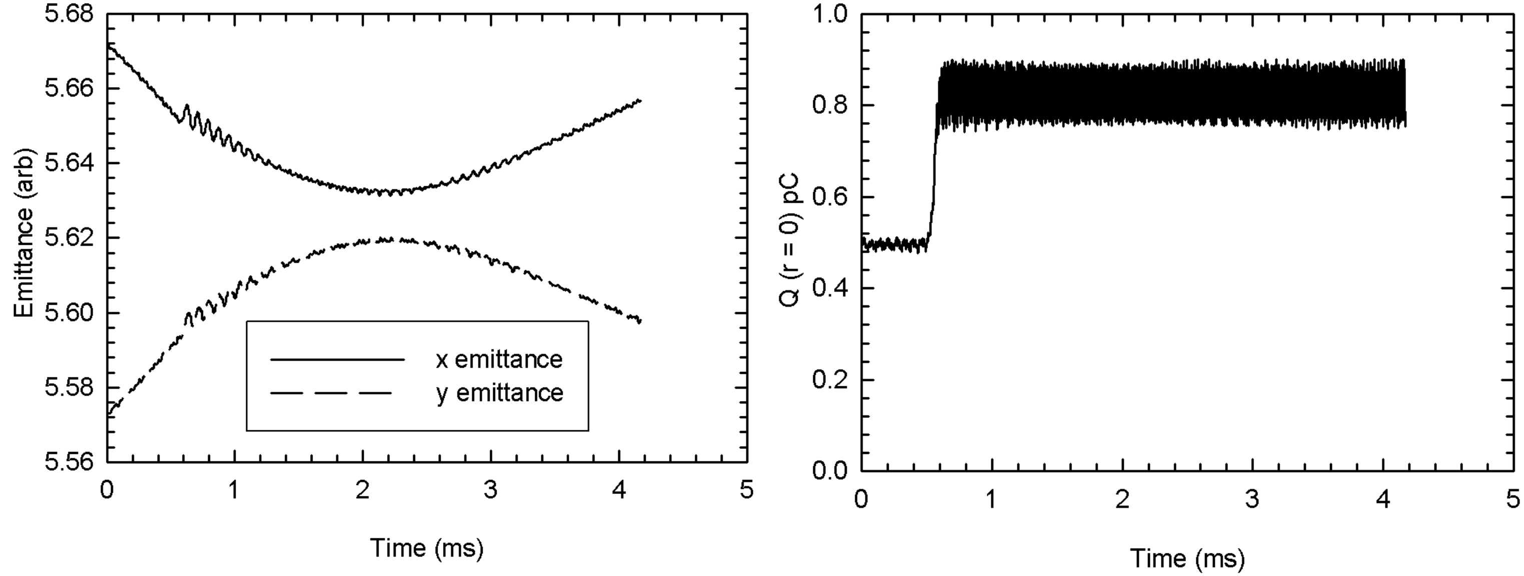
- $s = \omega_p^2/2\omega_q^2 = 0.2$.
- $\nu/\nu_0 = 0.88$
- $V_{0\,max} = 150$ V
  $f = 60$ kHz
  $\sigma_v = 49^o$

2D WARP Simulations Also Demonstrate Adiabatic Transitions in Only Four Lattice Periods

Instantaneous Change.



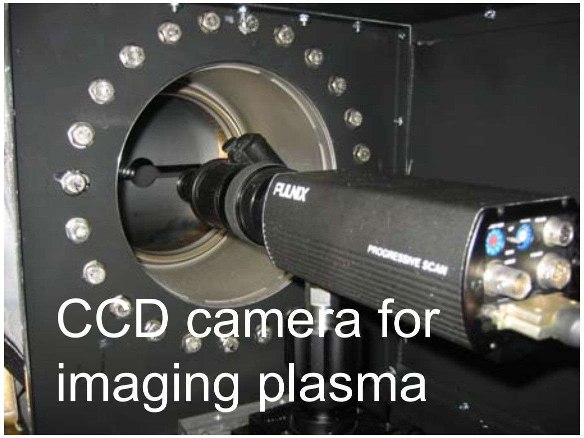
Change Over Four Lattice Periods.

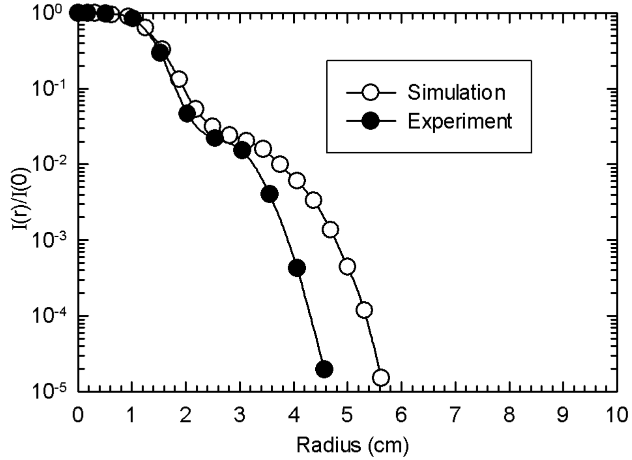


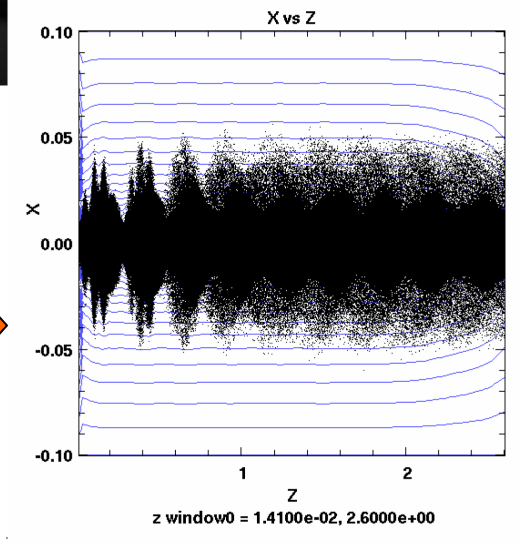
Laser-Induced Fluorescence (LIF) System Ready For Use This Summer

- Nondestructive
- Image entire transverse profile at once
- Time resolution
- Velocity measurement

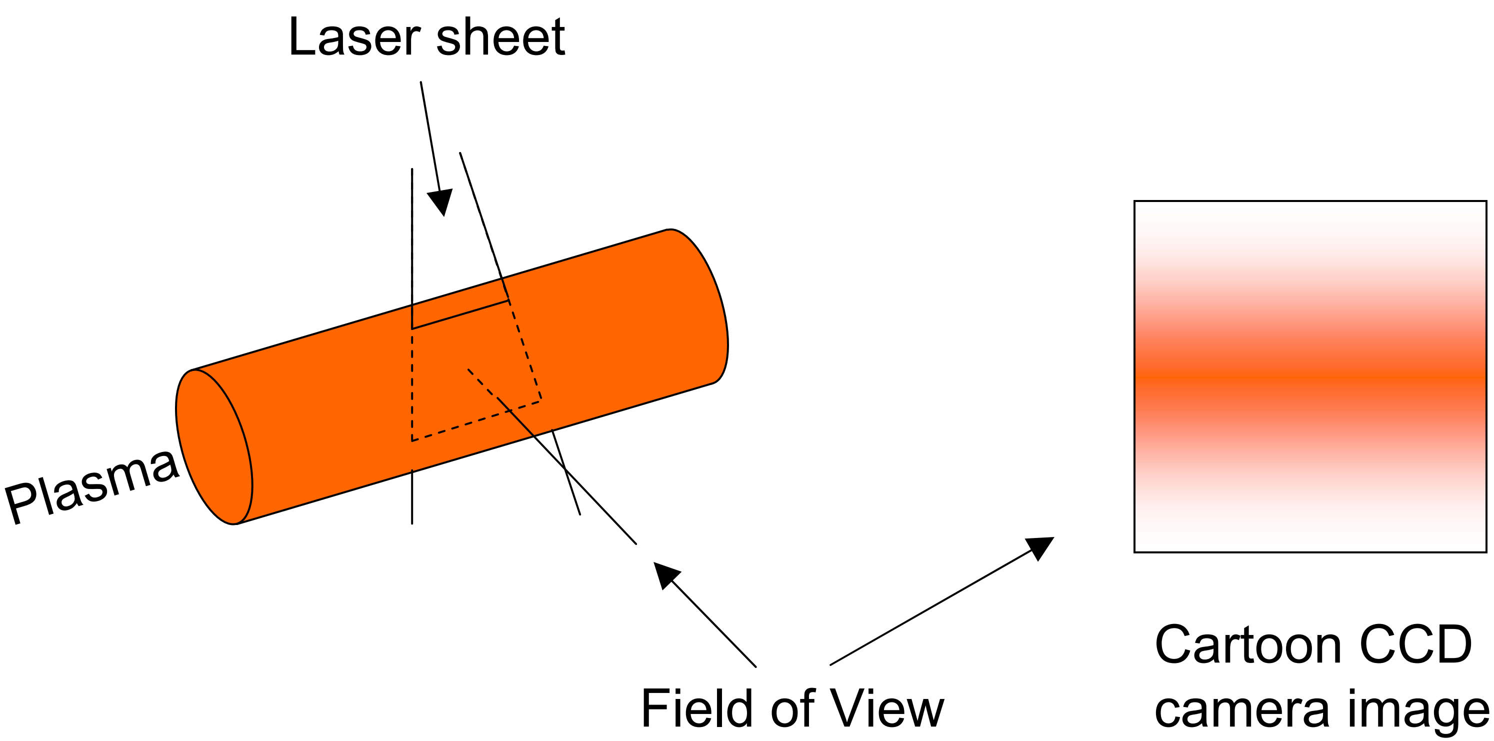

Barium ion source will replace Cesium ion source.


CCD camera for imaging plasma





Laser-Induced Fluorescence (LIF) System Geometry



Near-Term Plans

- Smooth frequency changes.
- Simultaneous smooth changes in Voltage and frequency
- Complete experimental investigations of halo particle excitation and emittance growth mechanisms at moderate charge bunch intensity using LIF.

PTSX Simulates the Transverse Dynamics of Intense Beam Propagation Over Large Distances Through Magnetic Alternating-Gradient Transport Systems

- PTSX is a compact and flexible laboratory experiment.
- PTSX can trap plasmas with normalized intensity *s* up to 0.8.
- Confinement times can correspond to up to 7,500 lattice periods.
- Halo particle production that is seen in streaming-mode experiments is due to the mismatch between the ion source and the transverse focusing lattice.
- Adiabatic increases in the voltage waveform amplitude can be applied over only four lattice periods when making changes of up to 90%. Instantaneous changes cause significant emittance growth and lead to halo particle production.