Supported by Office of Science

Recent Experimental Results from Princeton Paul Trap Simulator Experiment (PTSX)

Moses Chung

In collaboration with

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Dick Majeski, Hong Qin, Ed Startsev, Mikhail Dorf, and Andy Carpe

Symposium on Recent Advances in Plasma Physics

Princeton University, June 11th , 2007

PTSX Produces a Quite Different Kind of Plasma

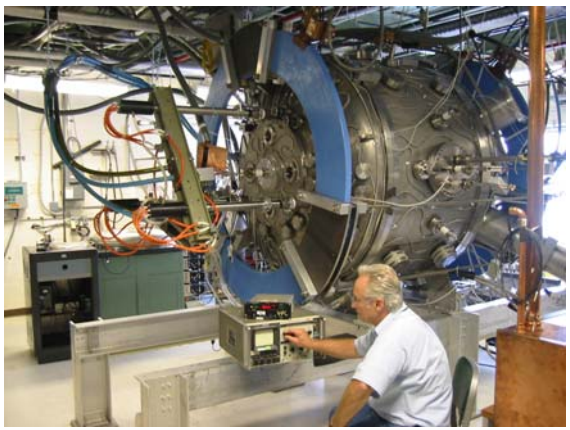
NSTX

$$n_i \sim n_e = 0.1 - 1 \times 10^{14}\ \mathrm{cm}^{-3}$$

$$T_i \sim T_e = 1 - 4\ \mathrm{keV}$$

$$B = 0.6\ \mathrm{T}$$

MRX

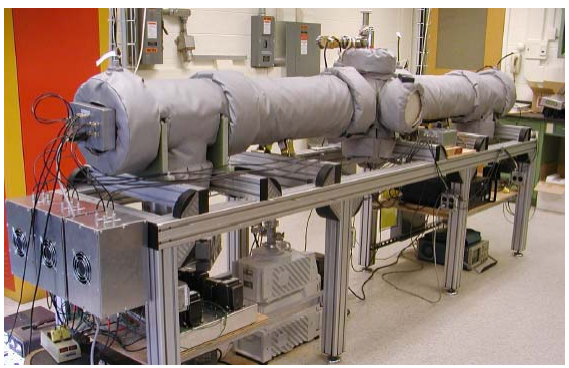


$$n_i \sim n_e = 0.1 - 1 \times 10^{14}\ \mathrm{cm}^{-3}$$

$$T_i \sim T_e = 5 - 20\ \mathrm{eV}$$

$$B = 0.1 - 0.5\ \mathrm{kG}$$

PTSX

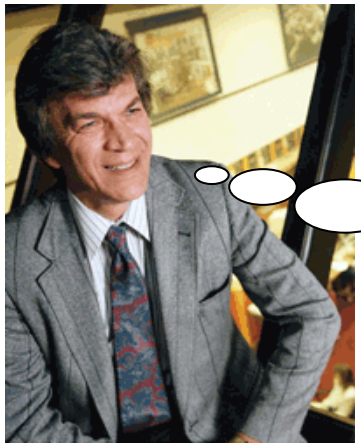


$$n_i \sim 10^5\ \mathrm{cm}^{-3},\ n_e = 0$$

$$T_i = 0.1 - 0.5\ \mathrm{eV}$$

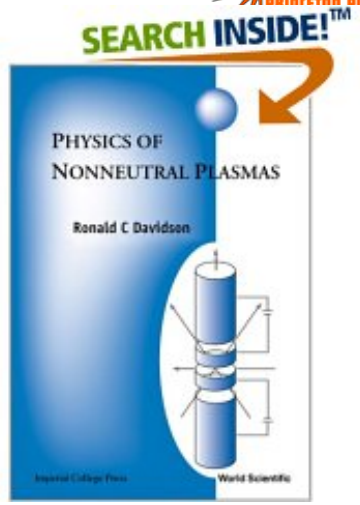
$$B = 0$$

Is It Really a Plasma? Yes, I think So

Because, Ron  **says it is a plasma**

Moses, it is a nonneutral plasma.

See my book.



Criteria for plasmas	**For PTSX plasma**
1. $\lambda_D << L$	1*. $\lambda_D \sim 0.88$ cm, $R_b \sim 0.85$ cm
2. $N_D >>> 1$	2. $N_D \sim 2.6 \times 10^5 >>> 1$
3. $\omega_p \tau > 1$	3. $\omega_p \sim 34$ kHz, $\tau > 1$ sec

* For $\lambda_D << R_b$, space-charge-dominated; for $\lambda_D >> R_b$, emittance-dominated

PTSX Simulates Intense Beam Propagation in a Compact Laboratory Setup

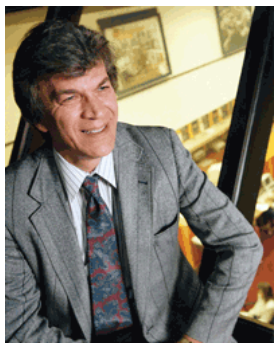
Theoretical Background

PHYSICS OF PLASMAS VOLUME 7, NUMBER 3 MARCH 2000

A Paul trap configuration to simulate intense non-neutral beam propagation over large distances through a periodic focusing quadrupole magnetic field

Ronald C. Davidson, Hong Qin, and Gennady Shvets
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543

(Received 9 September 1999; accepted 17 November 1999)



Experimental Realization

VOLUME 92, NUMBER 15 PHYSICAL REVIEW LETTERS week ending 16 APRIL 2004

Paul Trap Simulator Experiment to Model Intense-Beam Propagation in Alternating-Gradient Transport Systems

Erik P. Gilson,* Ronald C. Davidson, Philip C. Efthimion, and Richard Majeski
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543, USA

(Received 15 December 2003; published 16 April 2004)

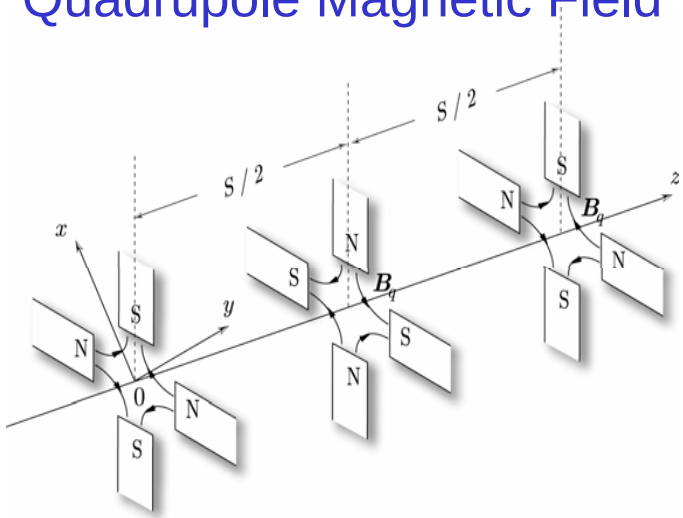
Purpose: Simulate the nonlinear transverse dynamics of intense beam propagation over large distances through magnetic alternating-gradient transport systems in *a compact experiment*.

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

An Intense Beam is a Nonneutral Plasma in the Beam Frame

$$s \text{ (space)} \rightarrow t \text{ (time)}$$

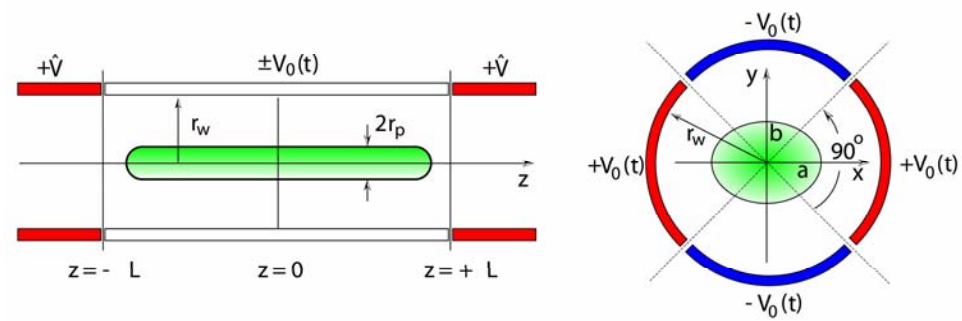
Intense Beam Propagating in Periodic Focusing Quadrupole Magnetic Field



$$H_\perp(x,y,x',y',s)$$
$$=\frac{1}{2}(x'^2+y'^2)+\frac{1}{2}\kappa_q(s)(x^2-y^2)+\underline{\psi(x,y,s)}$$

Self-field potential

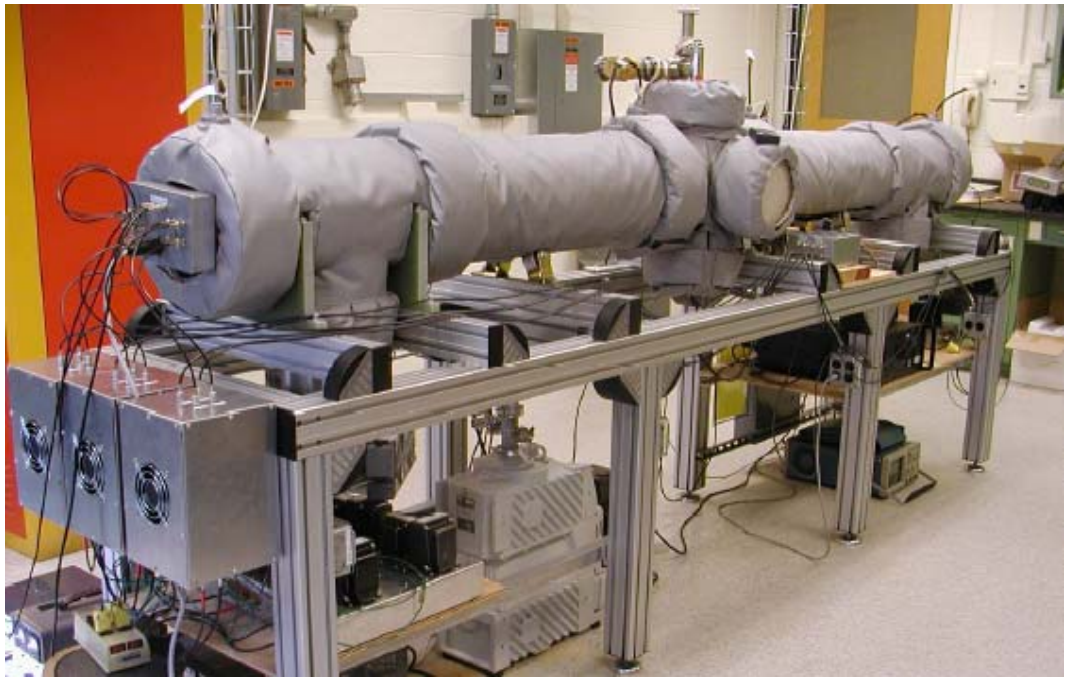
Nonneutral Plasma Trapped in Time Varying Quadrupole Electric Field



$$H_\perp(x,y,\dot{x},\dot{y},t)$$
$$=\frac{1}{2}m_b(\dot{x}^2+\dot{y}^2)+\frac{1}{2}m_b\kappa_q(t)(x^2-y^2)+e_b\underline{\phi^s(x,y,t)}$$

Self-field potential

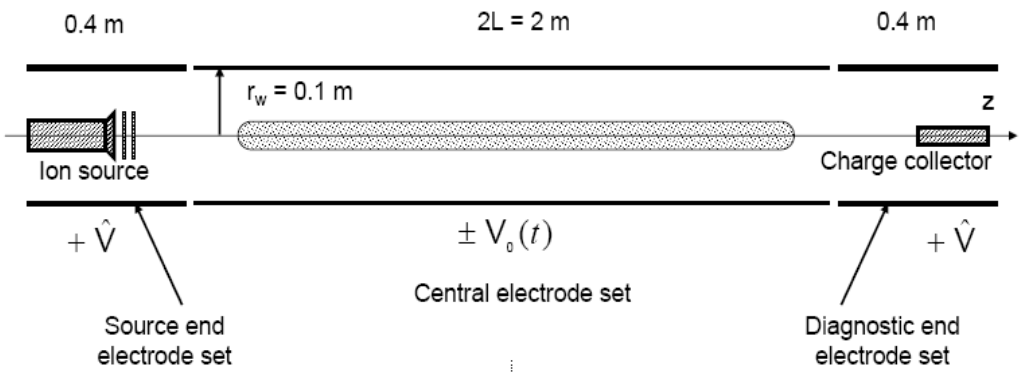
Paul Trap Simulator Experiment (PTSX) Apparatus



- Pressure 10^{-10} ~10^{-8} Torr
- Trap Time 1~100 ms
- Density 10^{5} ~10^{6} cm^{-3}
- End Electrodes (DC)

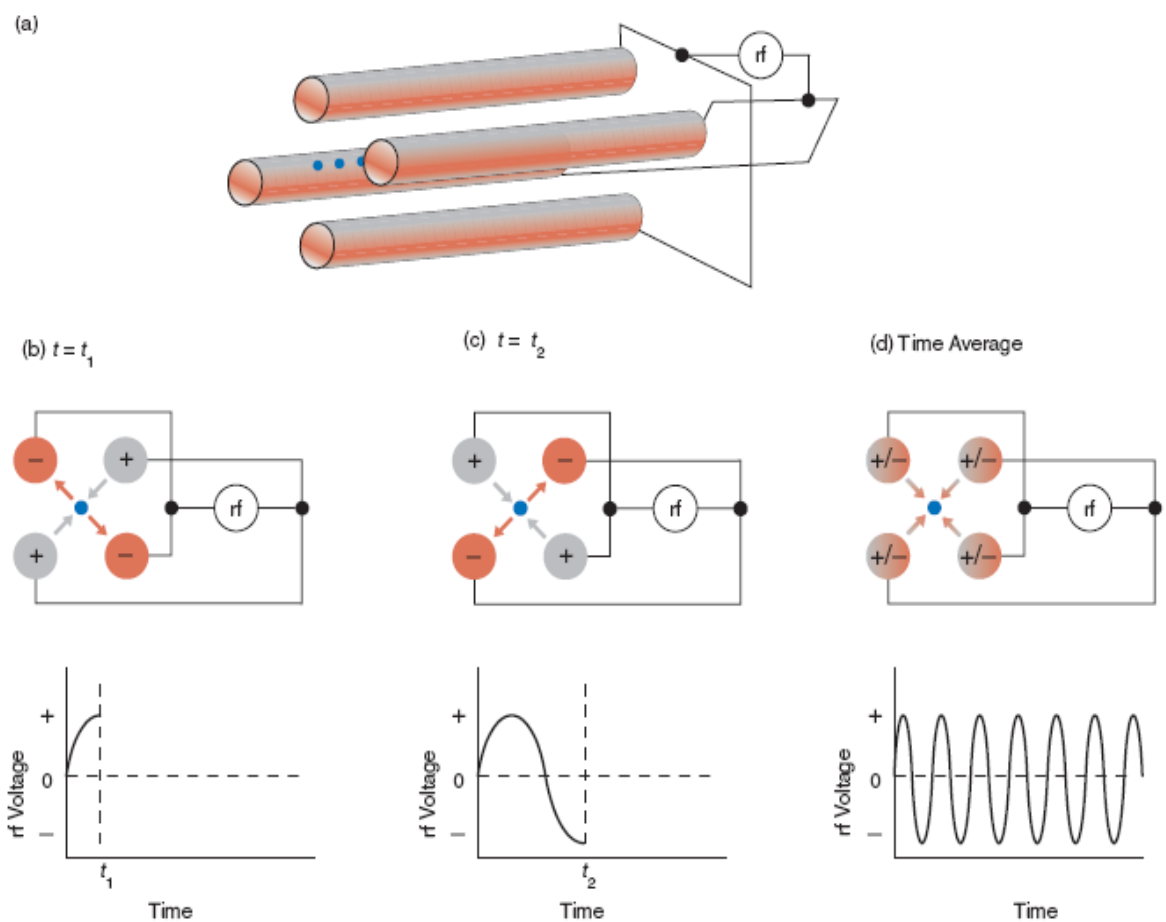
  36 ~ 150 V
- Central Electrodes (AC)

  f < 100 kHz , V_{0max} < 400 V

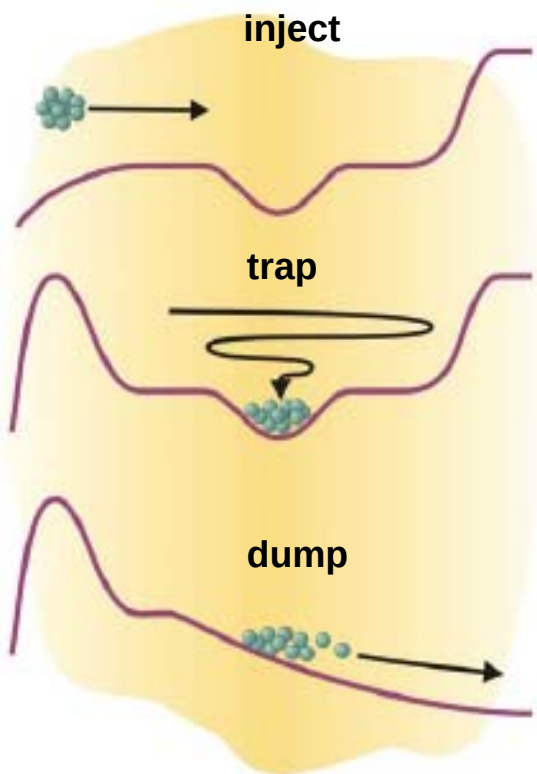


How Paul Trap Confines Plasma?

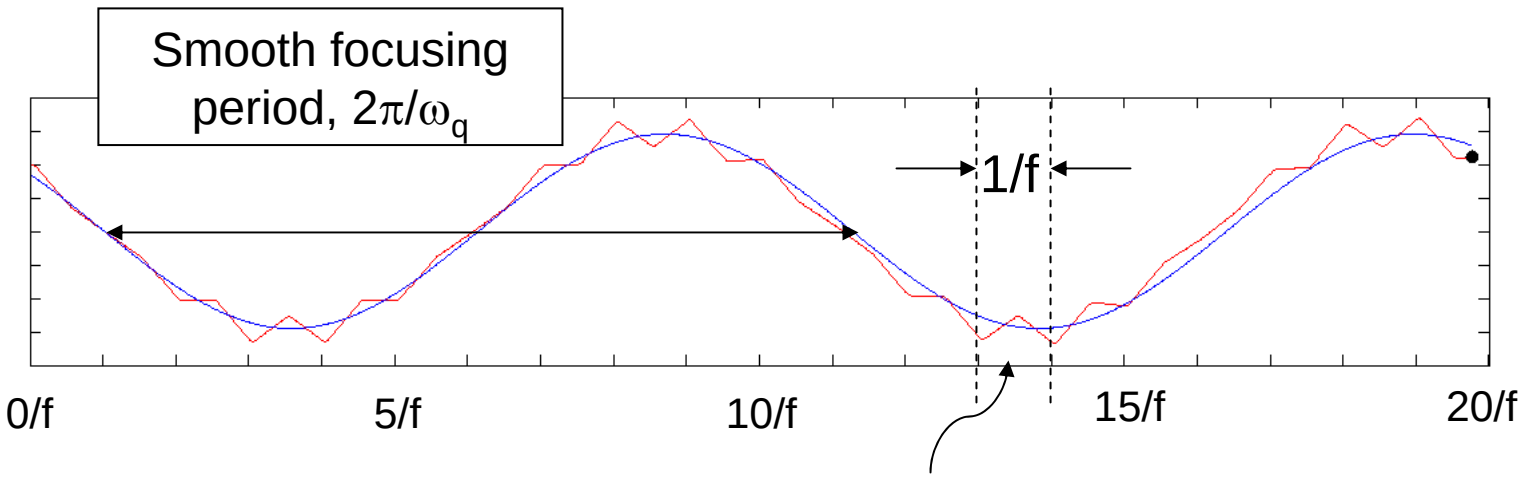
Radial direction: Ponderomotive force



Axial direction: DC potential well



Smooth Focusing Frequency, Vacuum Phase Advance, and Normalized Intensity Parameter Characterize the System



The smooth trajectory's phase advance during 1 applied focusing period $\sigma_v^{sf} = \frac{\omega_q}{f} < \sigma_{v\max}$ to avoid instabilities.

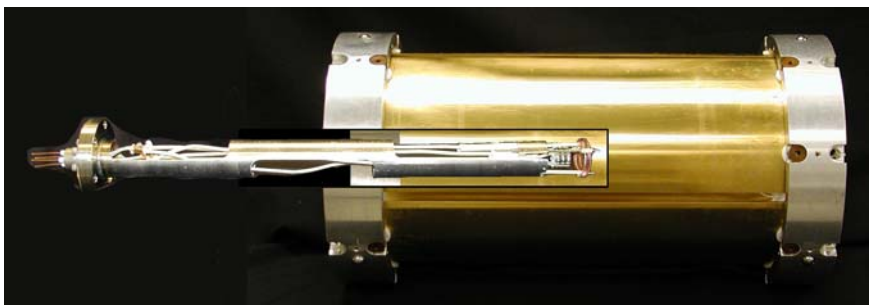
Normalized intensity parameter $s \equiv \frac{\omega_p^2}{2\omega_q^2} < 1$ to confine the space-charge.

s ~ 0.2 for Spallation Neutron Source.

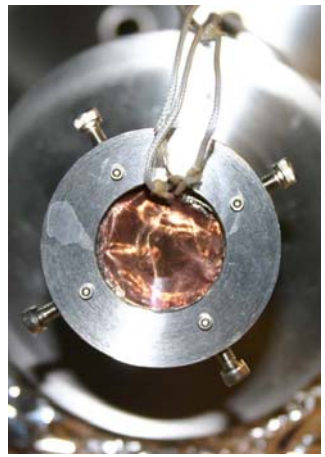
Ion Sources

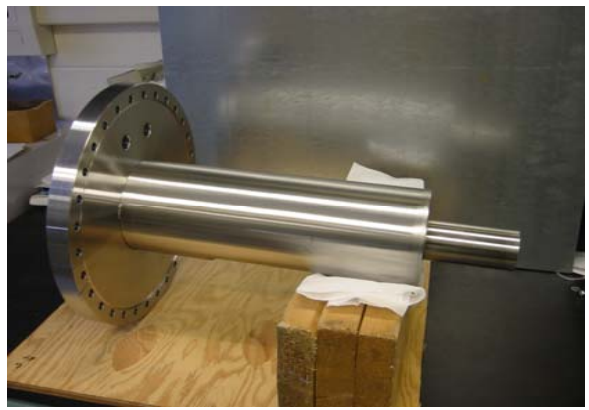
For LIF diagnostic

Cesium Ion Source



Barium Ion Source

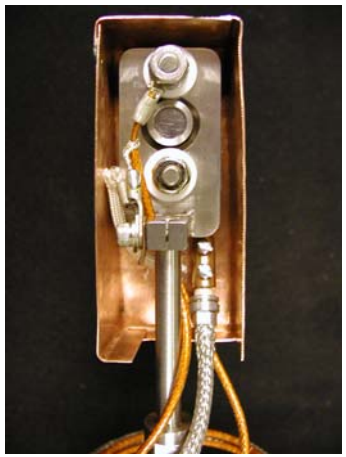


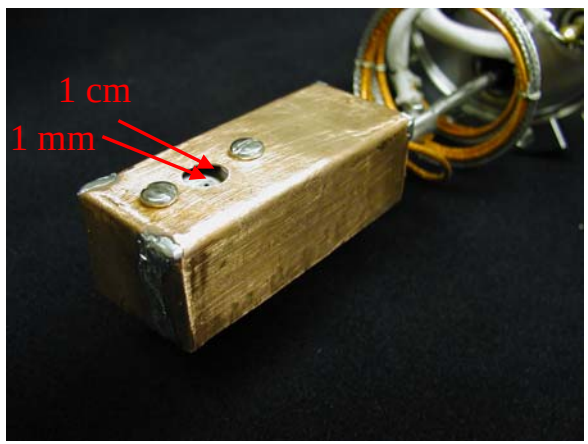


Diagnostic 1: Faraday cup

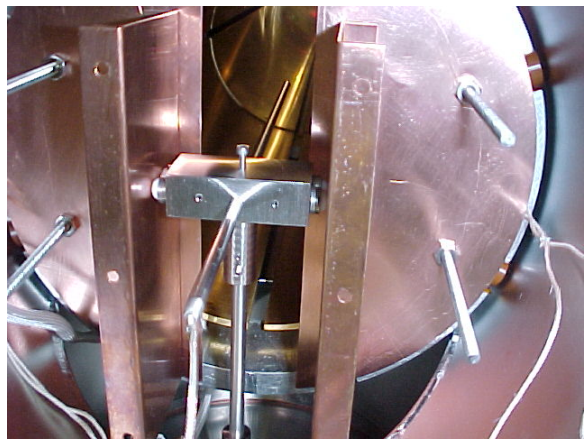
To assure boundary condition

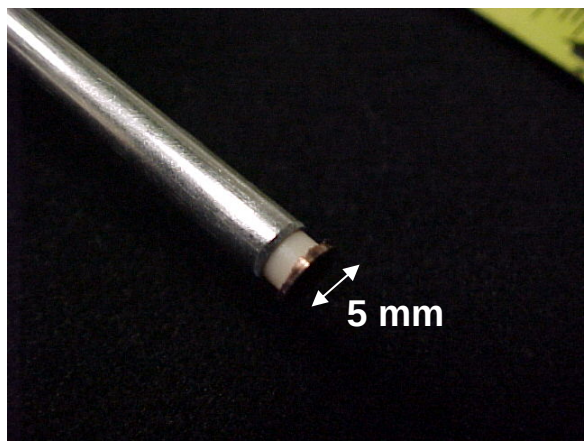
First Faraday Cup





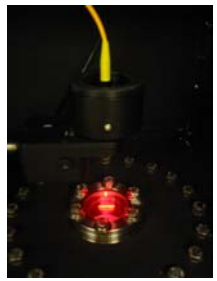
Second Faraday Cup

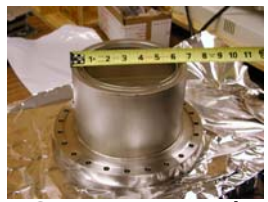




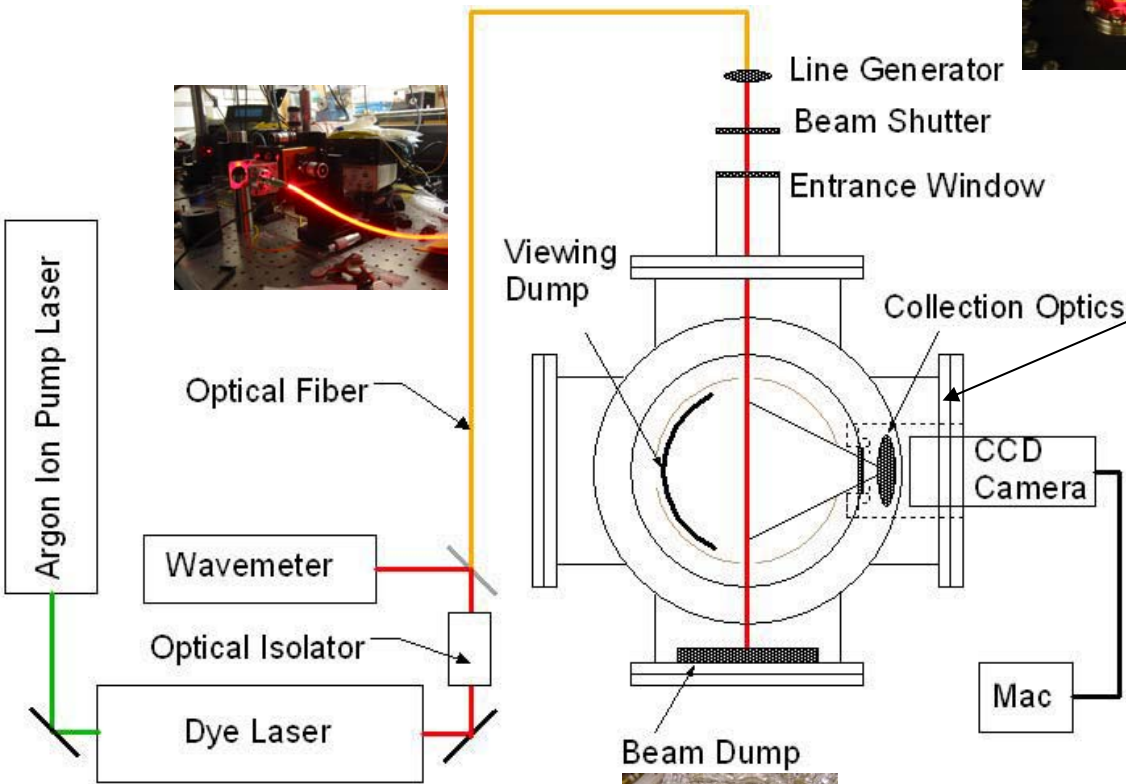
Diagnostic 2: Laser-induced Fluorescence (LIF) Diagnostic

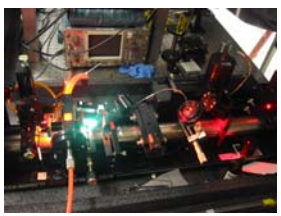
To do in-situ measurement of radial ion density profile

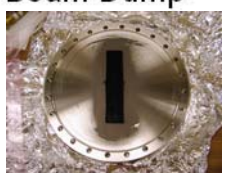




Custom-made Reentrant Flange

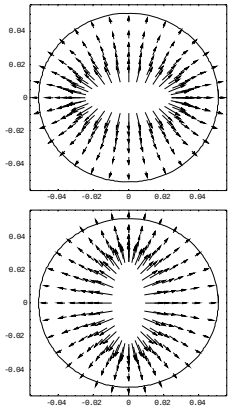


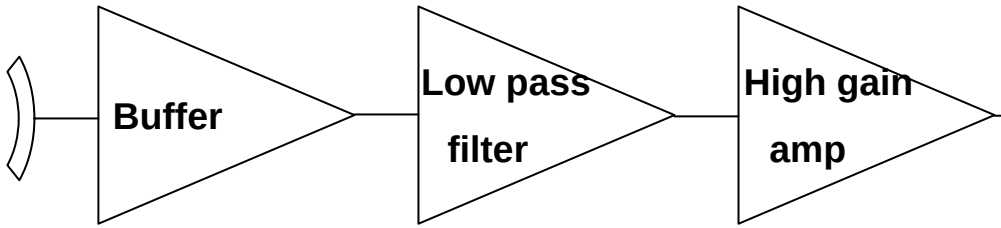




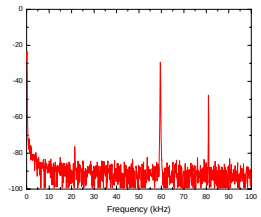
Diagnostic 3: Capacitive Pick-ups

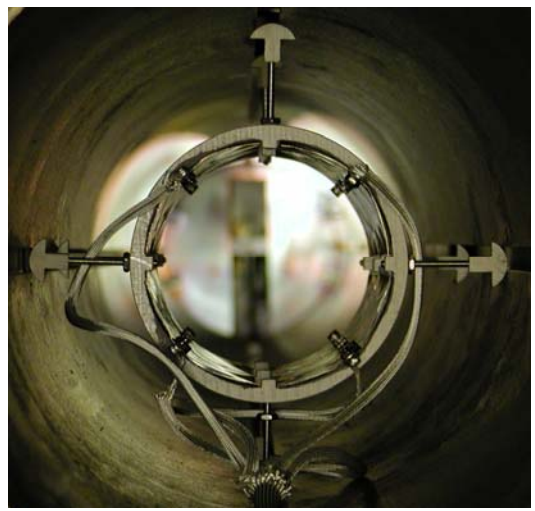
To detect collective oscillation (Quadrupole mode)





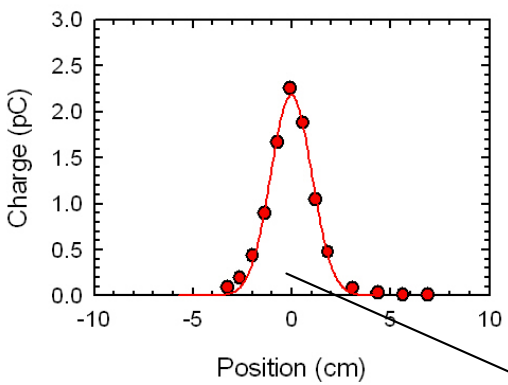
FFT

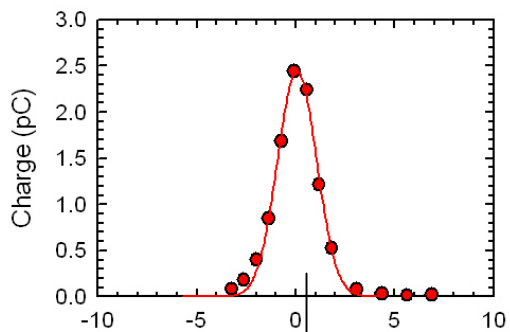


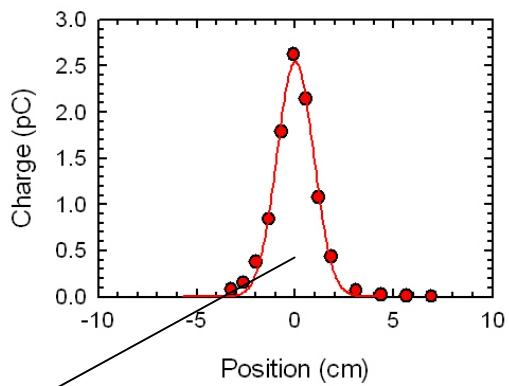


Experimental Simulation of Beam Propagation Over Large Distances

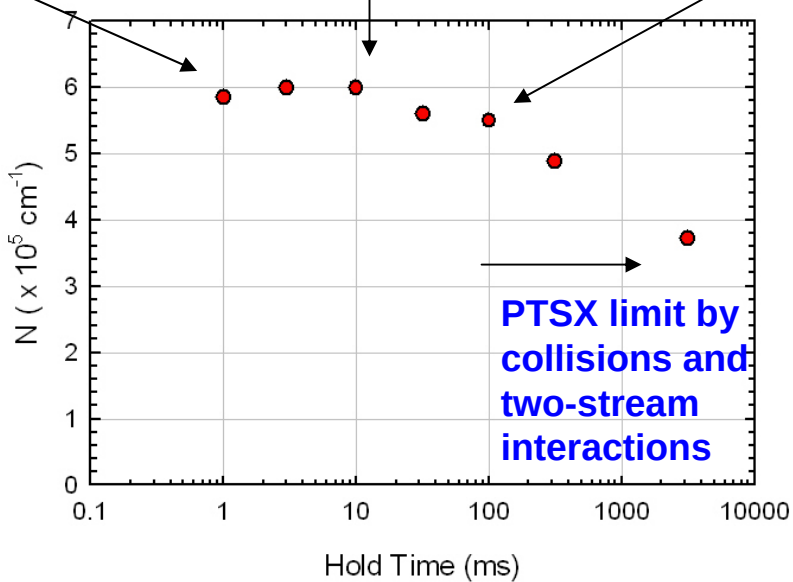
Identifying operating regimes for stable beam propagation over large distances, including a minimum beam degradation of beam quality and luminosity, is important for future accelerator application (e.g. ILC main linac ~ 11 km)







- 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**.



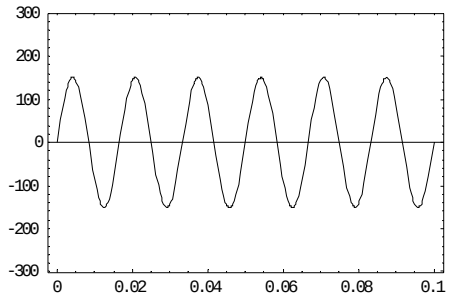
- $s = \omega_p^2/2\omega_q^2 = 0.18$.
- $V_{0\,max}$ = 235 V f = 75 kHz σ_v = 49°

Experimental Verification of Smooth Focusing Approximation

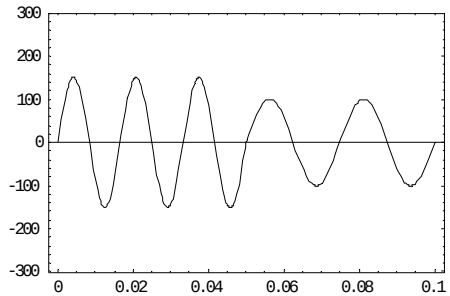
For sufficiently small vacuum phase advance, average effects of a periodic focusing quadrupole fields on beam's equilibrium, stability, and transport properties can be effectively described by an equivalent uniform focusing field

Different waveforms for the quadrupole focusing coefficient with same smooth focusing frequency $\omega_q = 52.2\,\text{kHz}$

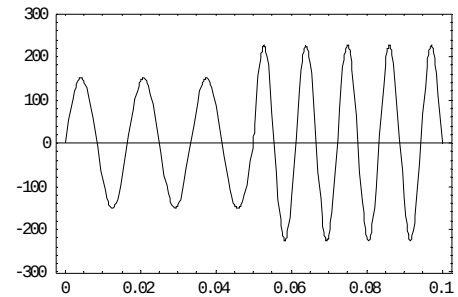
$\kappa_q(t)$



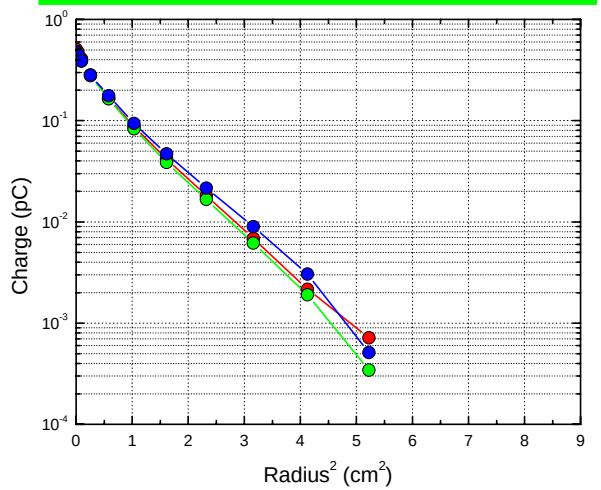
$f = 60\,\text{kHz},\ V_{0\max} = 150.4\,\text{V},\ \sigma_v^{sf} = 49.8°$



$f = 40\,\text{kHz},\ V_{0\max} = 100.3\,\text{V},\ \sigma_v^{sf} = 74.7°$



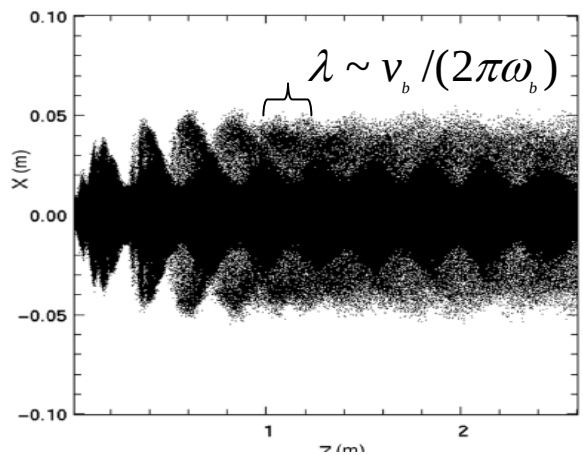
$f = 90\,\text{kHz},\ V_{0\max} = 225.6\,\text{V},\ \sigma_v^{sf} = 33.2°$

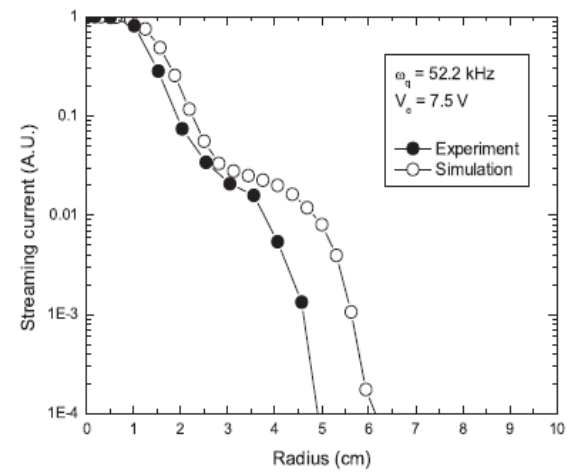


Experimental Observation of Initial Beam Mismatch

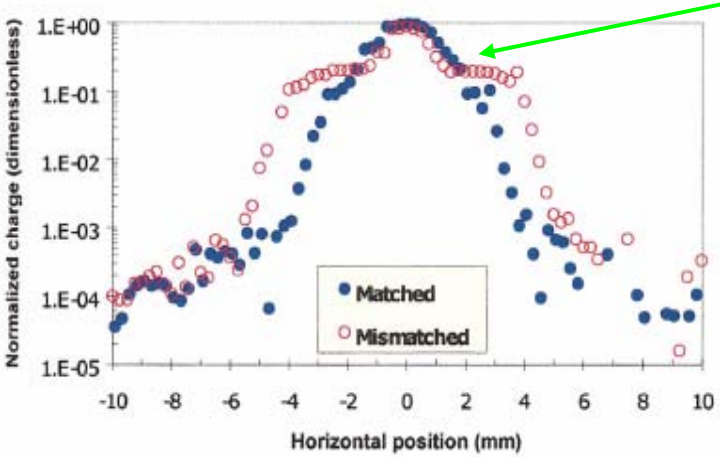
When initial injected beam radius is not equal to the final equilibrium radius in the focusing channel, there are oscillations in beam envelope

Good agreement with 3D WARP simulation



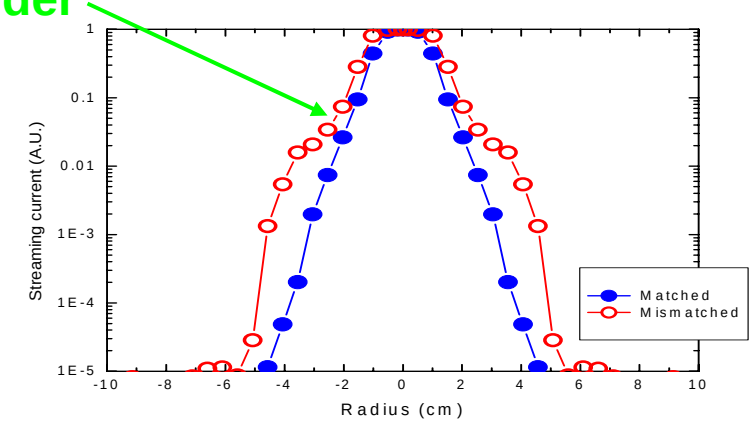


In the real accelerator (LEDA, LANL)



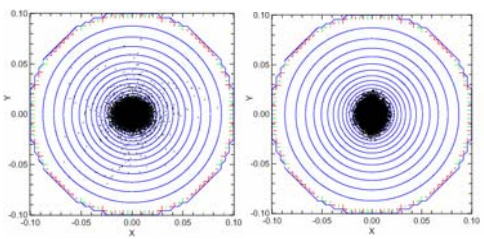
shoulder

In the PTSX (PPPL)

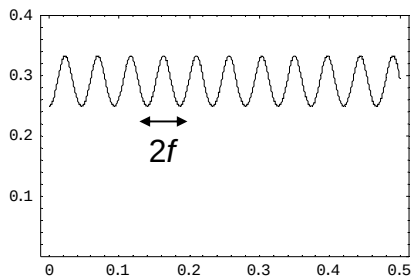


Experimental Observation of Fast Pulsation of Beam Envelope

When a beam propagates through the periodic focusing quadrupole field, there is fast pulsation of beam envelope with same periodicity of focusing channel



Pulsation of beam envelope with f (3D WARP simulation)

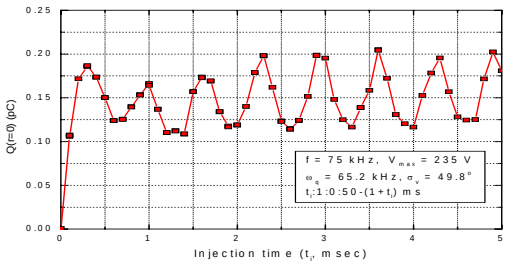


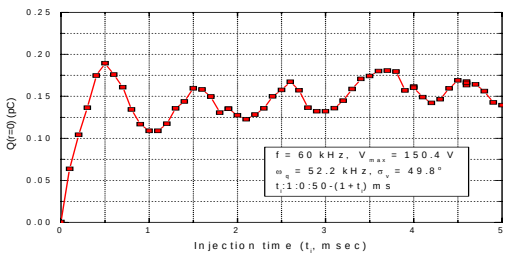
Oscillation of on-axis density with 2f

Kick a portion of beam out of the trap using DC potential with a time interval of 0.1 ms (f=10 kHz)

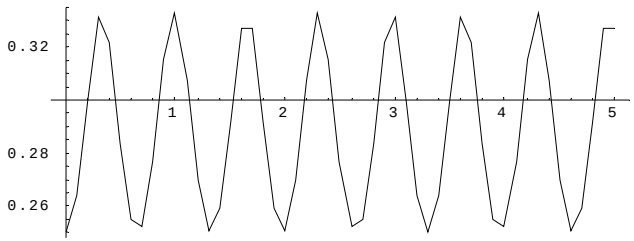
Unique aliasing pattern in on-axis density collected

Experiments

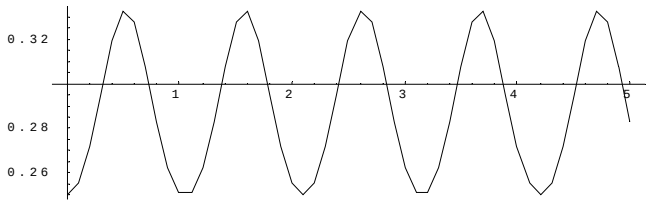




Theory



f = 75.7576 kHz

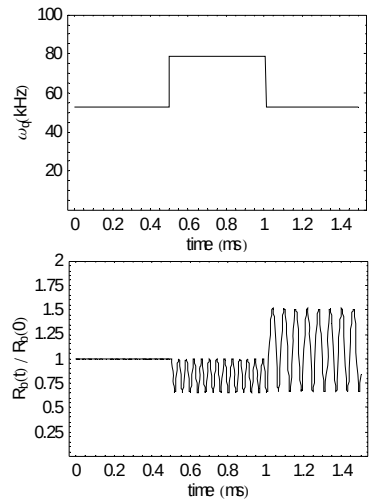


f = 59.5238 kHz

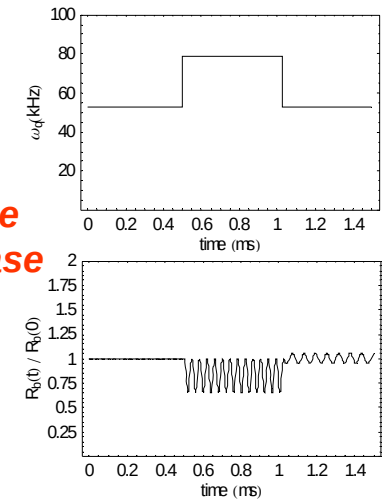
Experimental Observation of Collective Oscillation of Beam Envelope

When a beam is perturbed by temporarily changing the amplitude of focusing field, beam envelope starts to oscillate. The degree of resultant beam mismatch depends on when the amplitude is restored

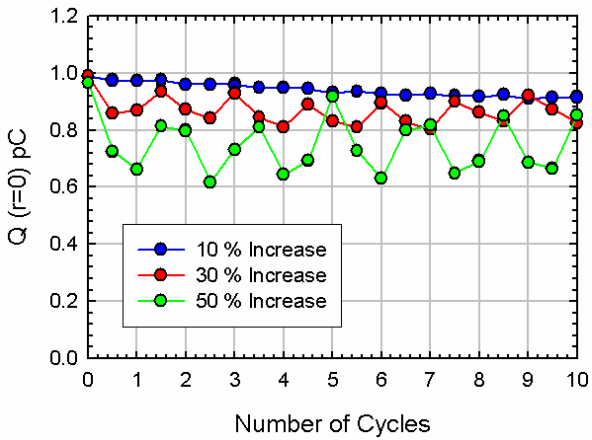
Focusing amplitude restores in wrong phase



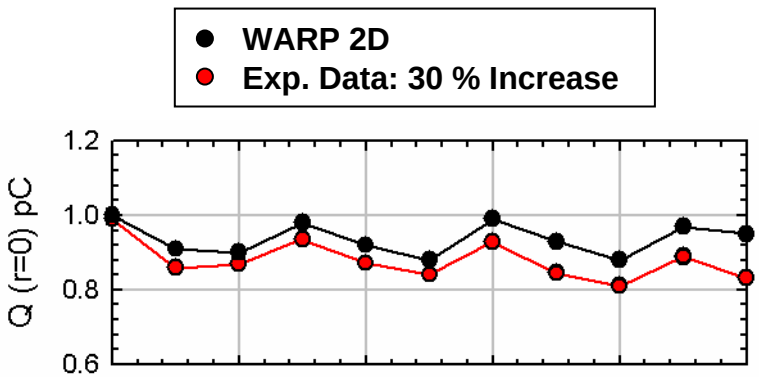
Focusing amplitude restores in right phase



Experiments



Good agreement with WARP 2D simulation

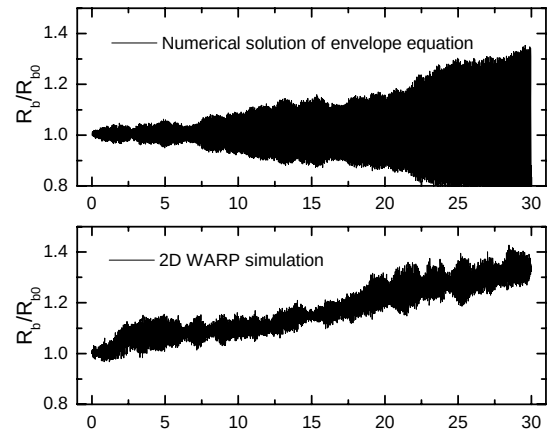


Experimental Verification of Random Error Induced Beam Degradation

In real accelerators, there are always unavoidable errors on components. Random errors act as a continuous supply of free energy, which results in irregular mismatch oscillation of the beam envelope, halo formation, and emittance growth

Error limits in quadrupole focusing gradient for components in SNS

Components	Limit on error
MEBT	1.732 %
DTL	0.5 %
CCDTL & CCL	0.25 %

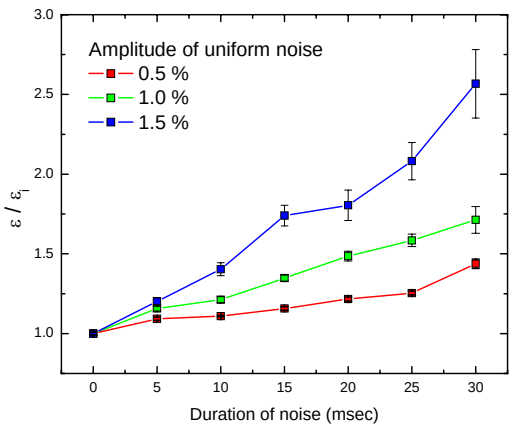


W/O emittance growth

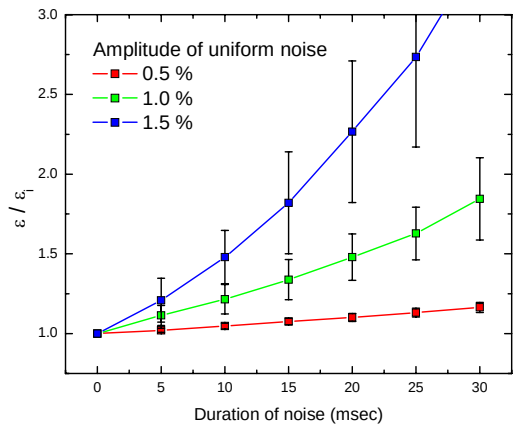
Same random error set with different physical model

W/ emittance growth

Experiments



Simulations

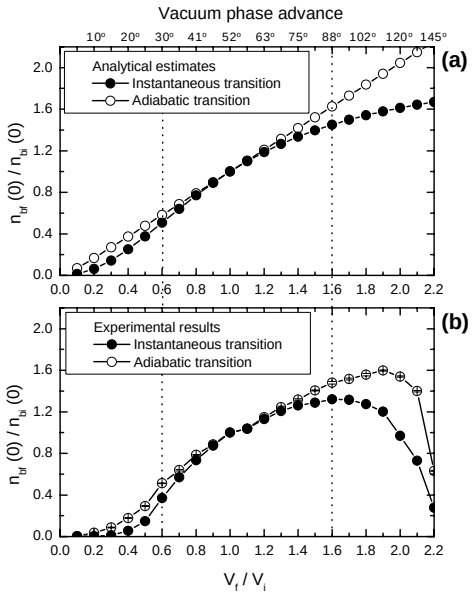


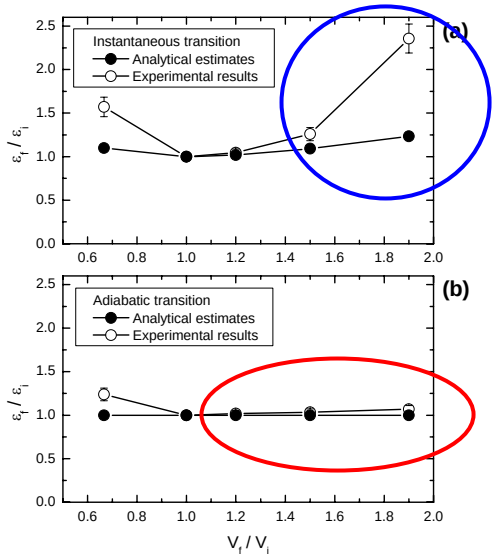
Experimental Studies of Transverse Beam Bunch Compression

Applications of present- and next- generation accelerators require transverse compression of the charge bunch to a small spot size at the target location

Theory

Experiment

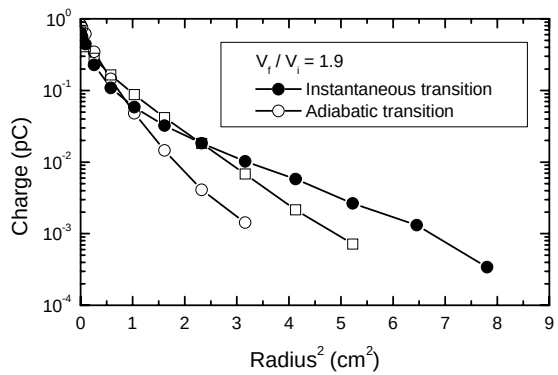




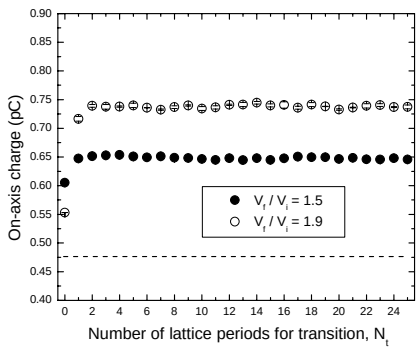
When beam is compressed abruptly, experiment shows huge increase in emittance due to the formation of halo, which is not predicted from theory.

When beam is compressed slowly, both theory and experiment shows the emittance is conserved

What about radial profiles?



How slow is slow?

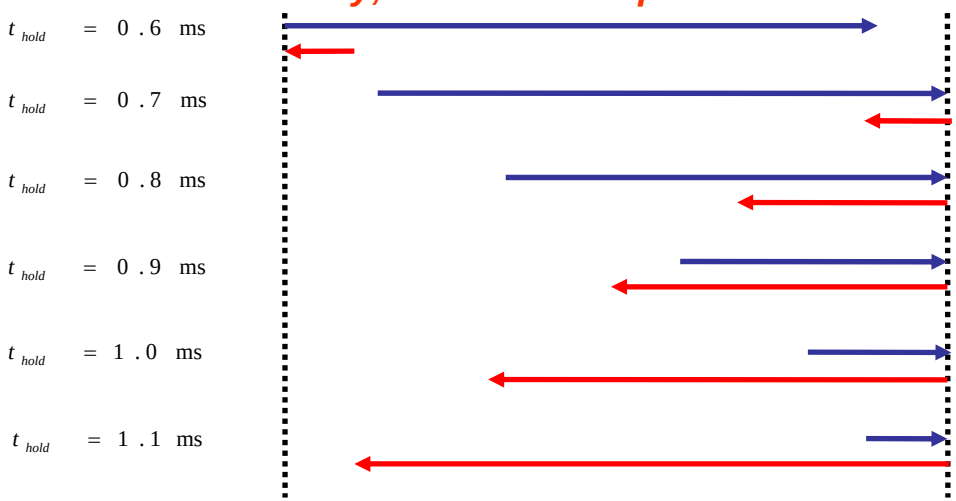


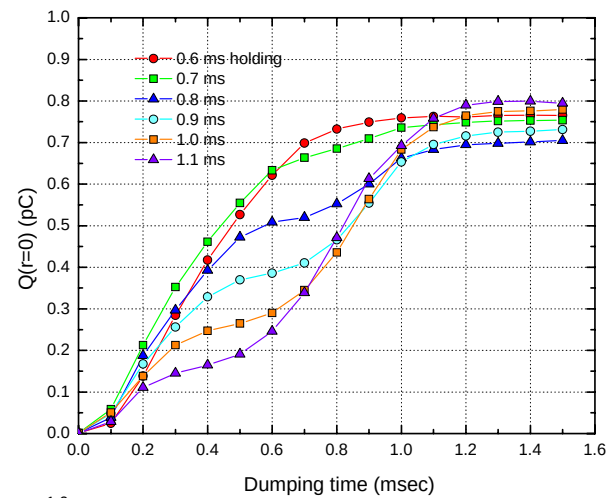
About 4 lattice periods are enough

Experimental Observation of Longitudinal Debunching of the Beam

Due to the space charge force and two stream interactions, initially bunched beam becomes debunched and uniform

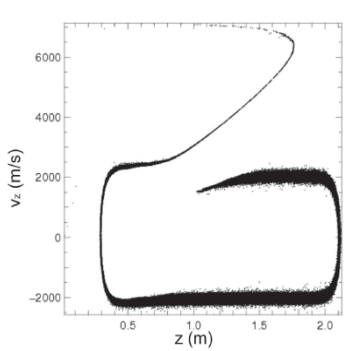
Initially, half of the trap is filled with beam

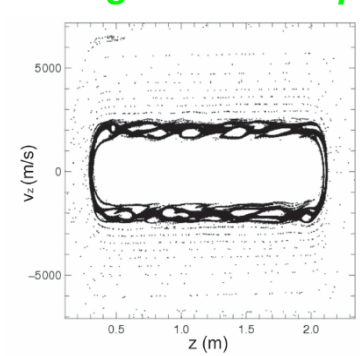


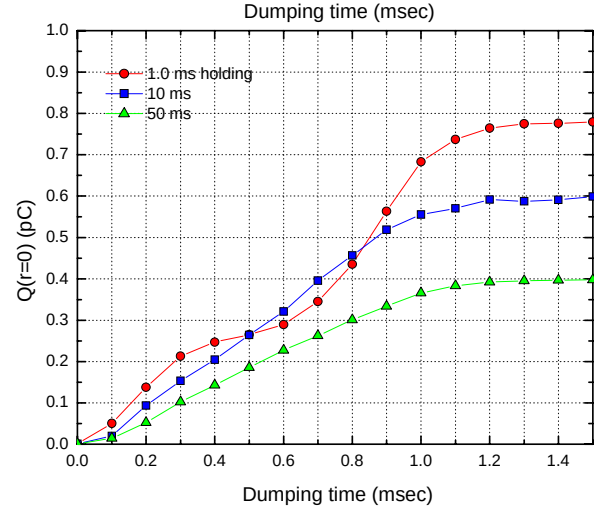


Beam is initially bunched

Two stream interactions mix the multi streaming beams and increase the longitudinal temperature







Beam is debunched and fill up the trap uniformly

I'd like to thank my colleagues

+ Mikhail Dorf