Paul Trap – beam simulator tool for study of long-distance transport of intense particle beams in accelerators*

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PPPL Beam Dynamics Group (1/2)

Objectives

Develop advanced analytical and numerical models describing the nonlinear dynamics and collective processes in intense nonneutral beams in periodic focusing accelerators and transport systems, with emphasis on:

  - Heavy ion fusion.
  - High energy and nuclear physics applications.

- Experimental and theoretical studies of heavy ion beam propagation on and beam-plasma interactions in the target chamber.
- Basic experimental and theoretical investigations of nonneutral plasmas confined in Malmberg-Penning traps and a Paul traps.

Personnel

PPPL Staff: R. C. Davidson, P. Efthimion, E. Gilson, L. Grisham, I. Kaganovich, R. Majeski, W. W. Lee, H. Qin, E. Startsev.

PPPL Beam Dynamics Group (2/2)

Technical focus of experimental activities:

Develop advanced beam and plasma diagnostics, and advanced plasma sources for intense charge bunch neutralization in neutralized drift compression experiments on NDCX-II.

Make use of Princeton 100kV Test Stand to develop and test advanced high density plasma sources for beam neutralization at very high beam intensities.

Technical focus of intense beam theory and modeling activities:

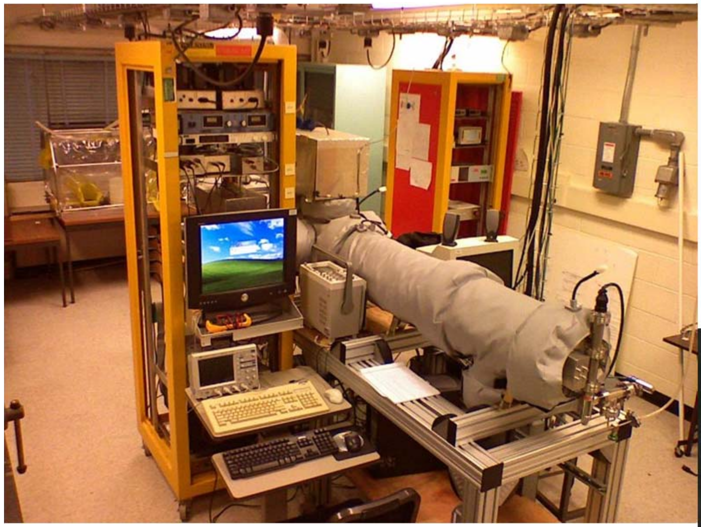
Advanced analytical and numerical modeling of intense beam propagation, nonlinear dynamics, beam-plasma interactions, and pulse compression.

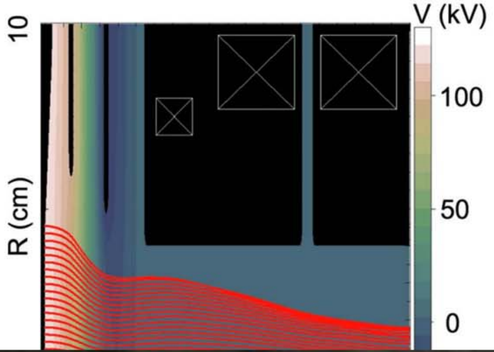
Mitigation and control of collective interactions and instabilities; optimization of beam quality and brightness; identify techniques for halo particle production and control.

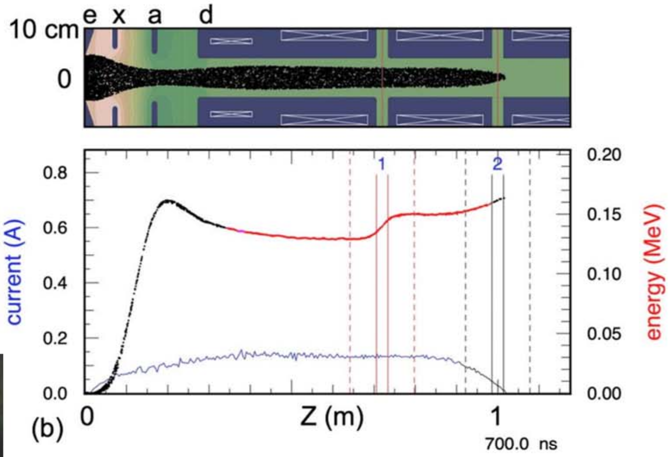
Beam pulse compression and focusing in neutralizing background plasma.

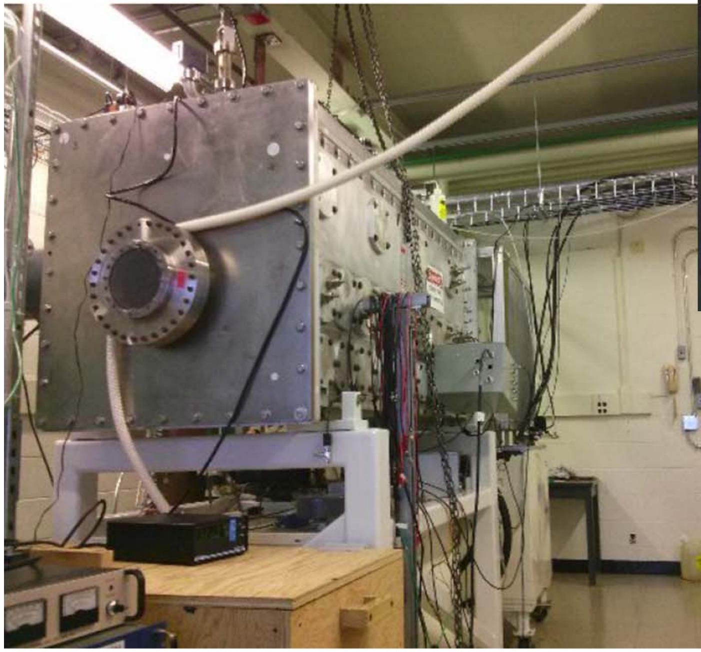
Atomic physics; develop improved charge-changing cross section models.

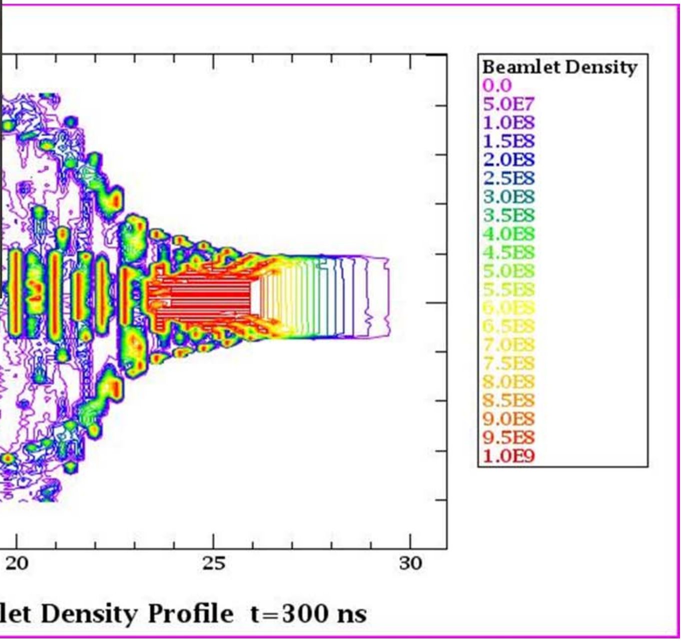
Facilities and Simulation Capabilities











Beamlet Density Profile t=300 ns

Paul Trap Simulator Experiment (PTSX) Overview

Developing an improved understanding of intense beam propagation in high energy accelerators is essential for high energy and nuclear physics applications, heavy ion fusion, spallation neutron sources, and high energy density physics.

Critical issues for accelerators:

- Long time, long distance propagation of intense beam bunches.
- Stability against lattice noise.
- Stability against coherent periodic perturbations.
- Beam mismatch and envelope instabilities.
- Chaotic particle dynamics and production of halo particles.
- Emittance growth.

Paul traps help to address these critical issues in a cost-effective manner by simulating the transverse dynamics of intense charge bunches in an accelerator. The simulation is possible because the transverse dynamics are equivalent since the configurations are Lorentz transformations of one another.

H. Okamoto and H. Tanaka, Nucl. Instr. and Meth. in Phys. Res. A **437**, 178 (1999).
R. C. Davidson, H. Qin, and G. Shvets, Phys. Plasmas **7**, 1020 (2000).
N. Kjærgaard and M. Drewsen, Phys. Plasmas **8**, 1371 (2001).

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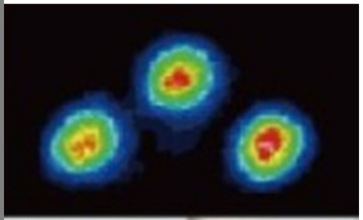
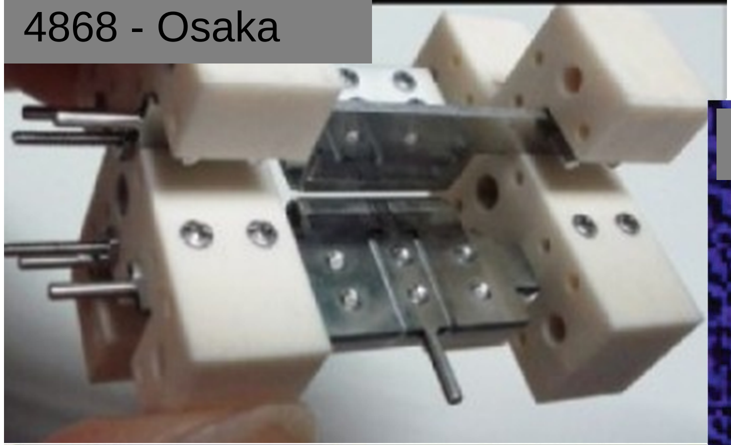
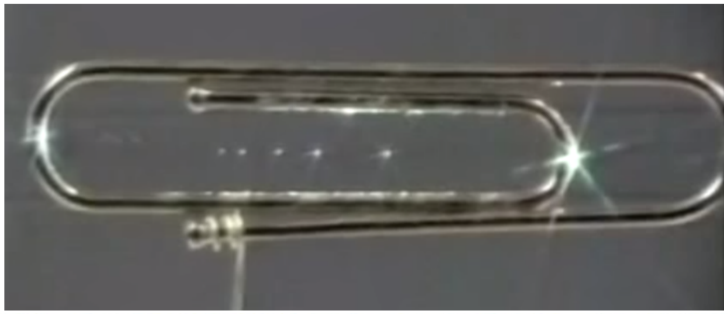
Paul Traps Use Temporally Periodic Quadrupole Electric Fields to Confine Particles

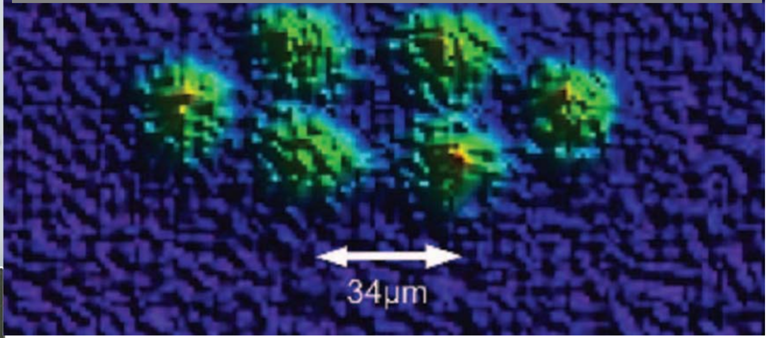
Nature Communications, 2014; 5 DOI 10.1038/ncomms4868 - Osaka

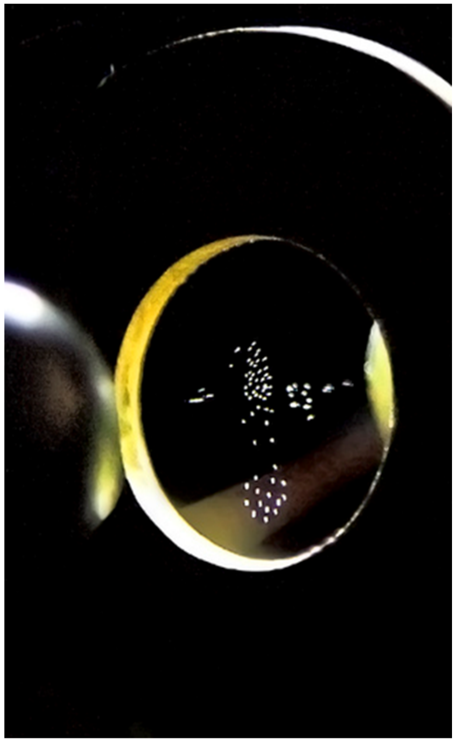


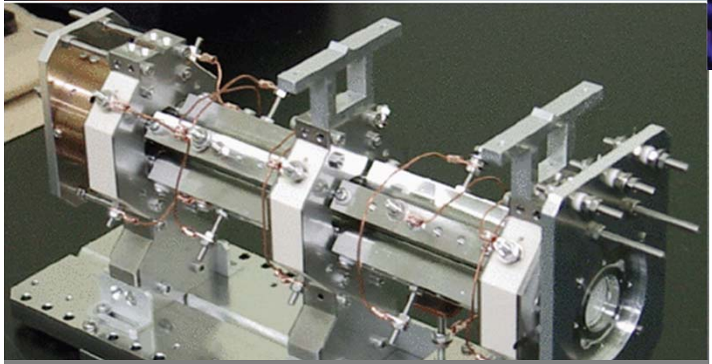




M. Schwarz et al., RSI **83**, 083115 (2012).







Phys. Rev. ST Accel. Beams **15**, 074201 (2012)
H. Takeuchi, K. Fukushima, K. Ito, K. Moriya, H. Okamoto, and H. Sugimoto

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

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

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

The oscillating electric field with a spatial gradient gives rise to a ponderomotive force that confines the particles.

The Alternating Gradient Transport System and PTSX are Analogous

$\mathbf{B}_q^{foc}(\mathbf{x}) = B_q'(z)\left(y\hat{\mathbf{e}}_x + x\hat{\mathbf{e}}_y\right)$ $\mathbf{F}_{foc}(\mathbf{x}) = -\kappa_q(z)\left(x\hat{\mathbf{e}}_x - y\hat{\mathbf{e}}_y\right)$ $\kappa_q(z) = \dfrac{ZeB_q'(z)}{\gamma m\beta c^2}$	Quadrupolar Focusing	$e\phi_{ap}(x,y,t) = \dfrac{1}{2} m\kappa_q'(t)(x^2 - y^2)$ $\kappa_q'(t) = \dfrac{8eV_0(t)}{m\pi\, r_w^2}$
$\psi = \dfrac{Ze}{\gamma m\beta^2 c^2}\left[\phi(x,y,s) - \beta\, A_z(x,y,s)\right]$	Self-Forces	usual $\phi_{self}(x,y,t)$
$\left(\dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial y^2}\right)\psi = -\dfrac{2\pi K}{N}\int dx'dy'\, f_b$	Field Equations	Poisson's Equation

Vlasov Equation

$$\left\{\frac{\partial}{\partial s} + x'\frac{\partial}{\partial x} + y'\frac{\partial}{\partial y} - \left(\kappa_q(s)x + \frac{\partial\psi}{\partial x}\right)\frac{\partial}{\partial x'} - \left(-\kappa_q(s)y + \frac{\partial\psi}{\partial y}\right)\frac{\partial}{\partial y'}\right\} f_b = 0$$

The PTSX team over the years includes primarily: M. Chung, R. C. Davidson, E. P. Gilson, I. D. Kaganovich, R. Majeski, H. Qin, E. A. Startsev, and H. Wang.

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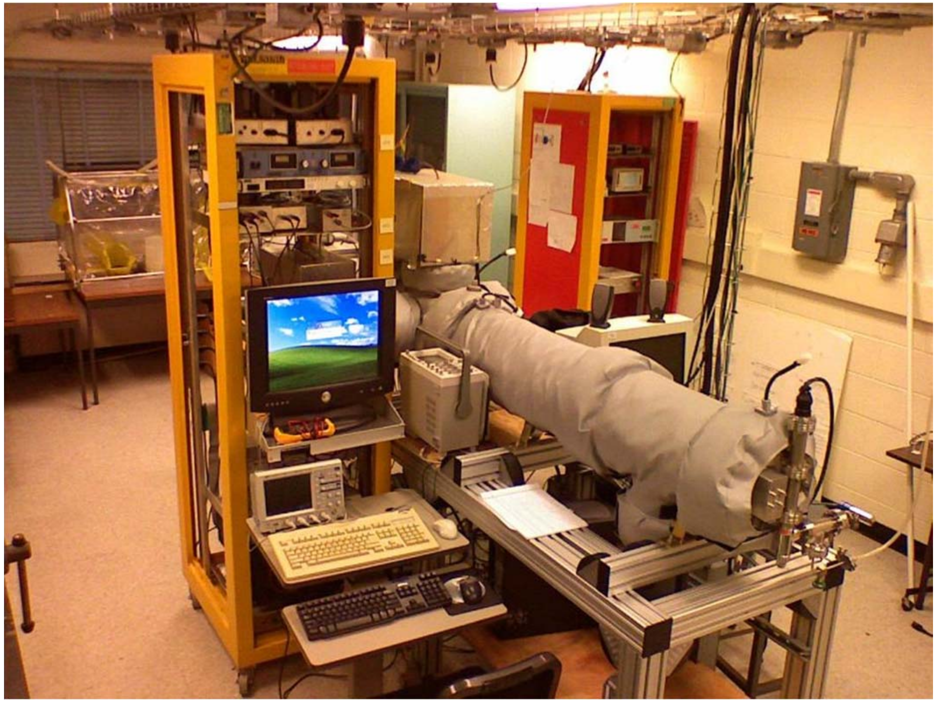
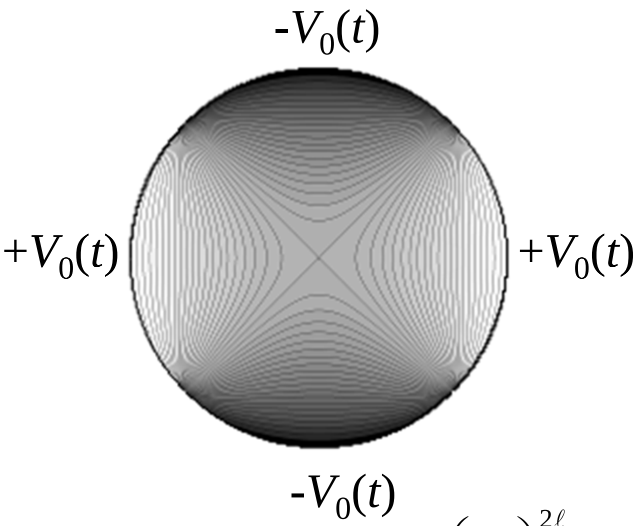
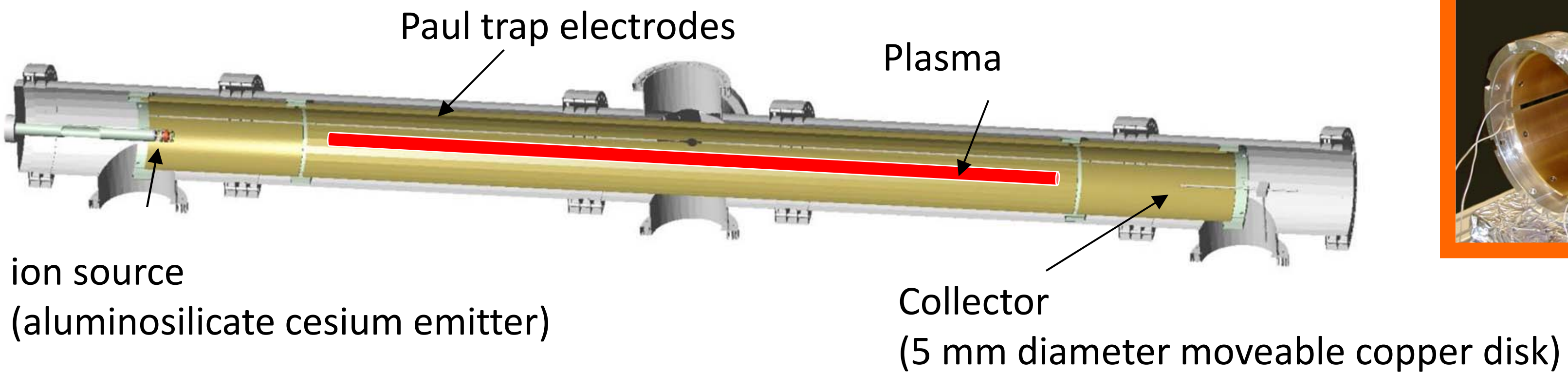
PTSX is a Cylindrical Paul Trap so that the Boundary Condition is the Same as in an Accelerator Pipe

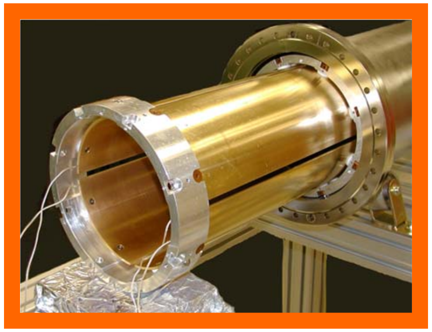




$$\phi_{ap}(x,y,t)=\frac{4V_0(t)}{\pi}\sum_{\ell=1}^{\infty}\frac{\sin(\ell\pi/2)}{\ell}\left(\frac{r}{r_w}\right)^{2\ell}\cos(2\ell\theta)$$

The quadrupole field is produced by quartering the pipe and applying voltages with opposite sign on neighboring electrodes. DC voltages on the ends provide axial confinement.





PTSX Studies Accelerator-Relevant Charge Bunches with Moderate Intensity that Travel for Thousands of Lattice Periods

Plasma length	2 m	Wall voltage	140 V
Wall radius	10 cm	End electrode voltage	20 V
Plasma radius	~ 1 cm	Frequency	60 kHz
Cesium ion mass	133 amu	Pressure	5 x 10^{-10} Torr
Ion source grid voltages	< 10 V	Trapping time	100 ms

Experimental data include:

On-axis charge: $Q = 515$ fC

On-axis number density: $n = 10^5\ \text{cm}^{-3}$

Line charge: $N_b = 2.0\ 10^7\ \text{m}^{-1}$

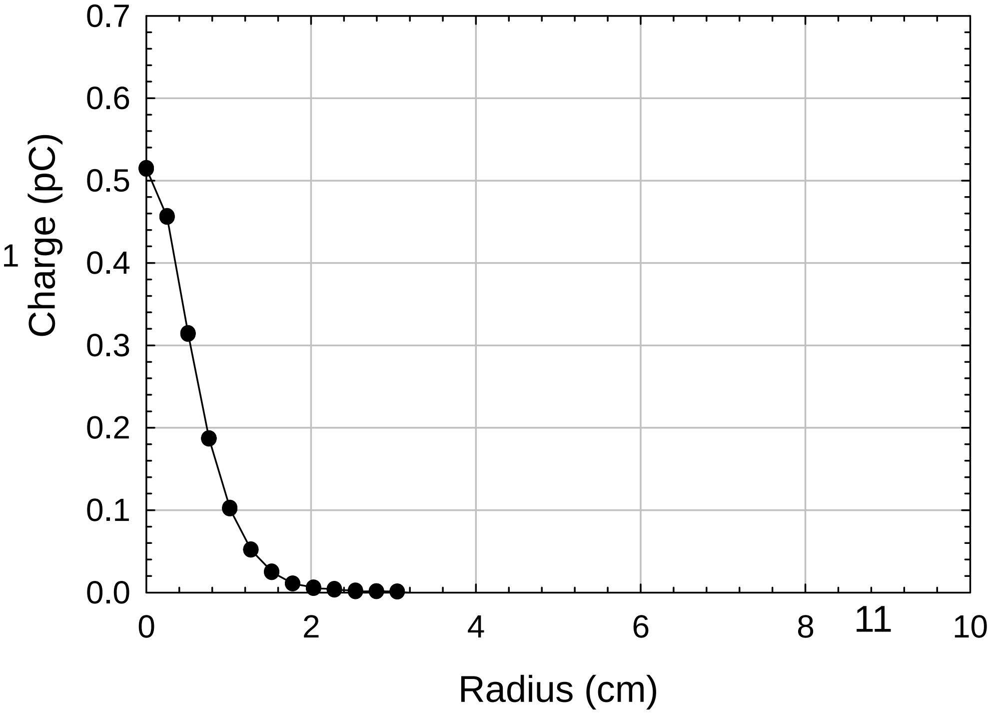
RMS radius: $R_b = 0.9$ cm

Effective temperature: $kT = 0.15$ eV

Normalized intensity: $s = 0.22$

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

Phys. Rev. Lett. **92**, 155002 (2004).



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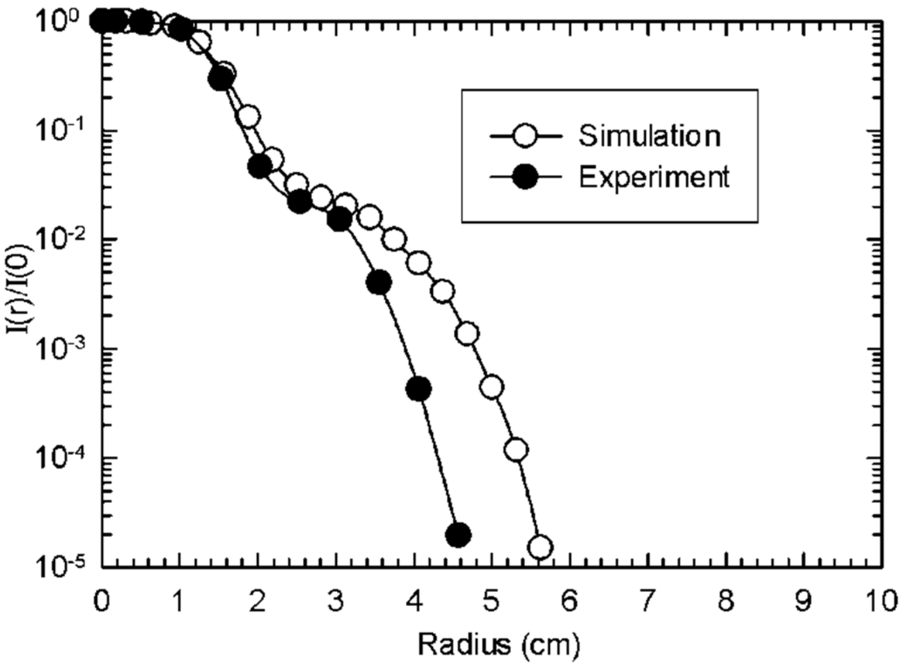
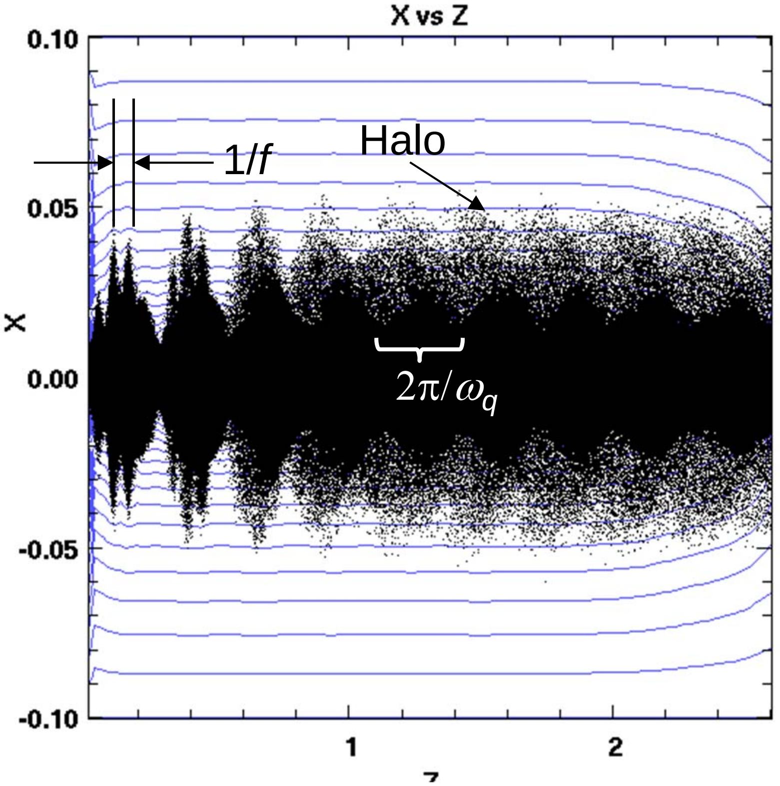
Experiments Demonstrated Halo Particle Generation from Mismatch of Over-Intense Beams into the Transport System

PTSX data and Warp particle-in-cell simulations of a steady state, flowing charge cloud show large mismatch oscillations and the growth of a population of halo particles when the injected ion number density is too large.



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



Phys. Rev. ST Accel. Beams **10**, 014202 (2007).

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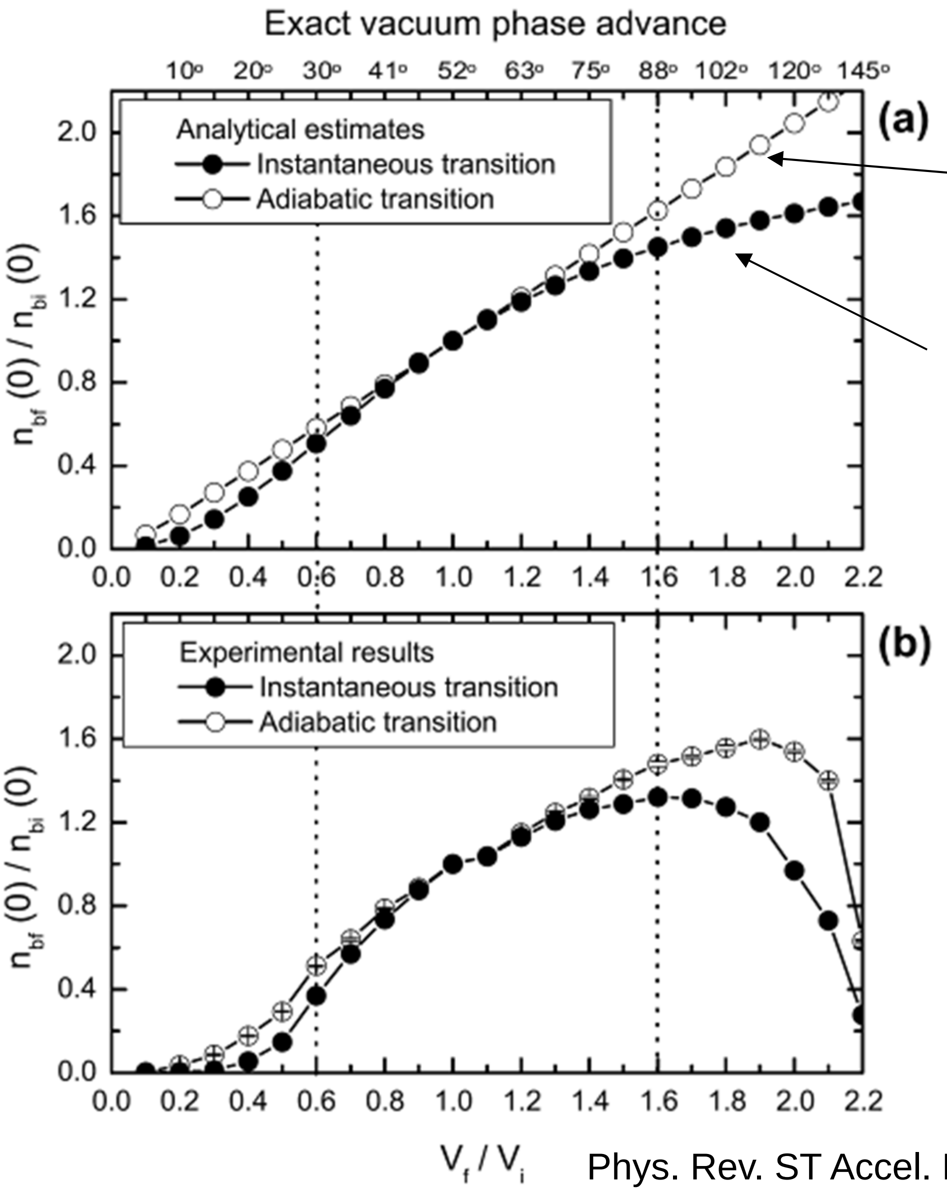
Experimental Study of Beam Compression

Plots show change in density after beam compression when the strength of focusing is changed.

Instantaneous changes lead to emittance growth and reduced comrpession.



Constant emittance

Constant energy

Phys. Rev. ST Accel. Beams **10**, 064202 (2007).

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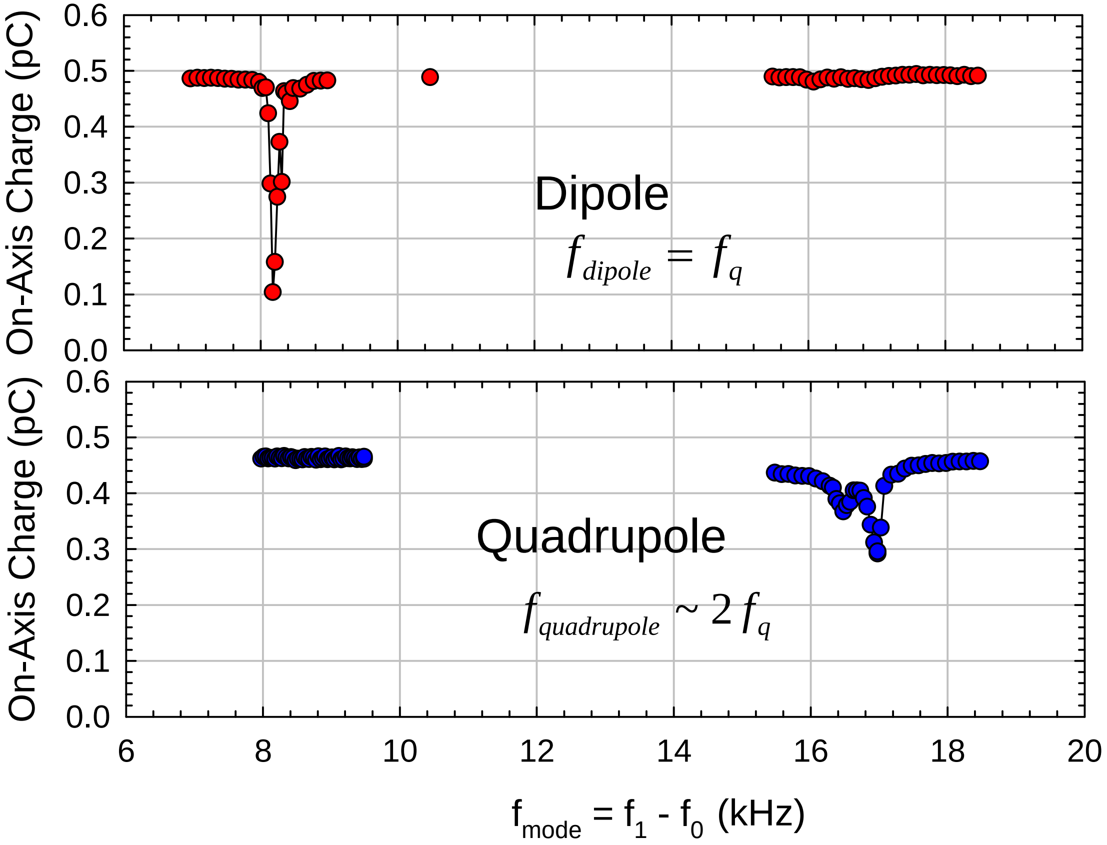
Both the Dipole Mode and the Quadrupole Mode Can be Excited as Expected

$$V(t) = V_0 \sin(2\pi f_0 t) + \delta V \sin(2\pi f_1 t)$$



$\delta V/V_0 = 0.01$
Electrode voltage: $V_0 = 140$ V
Electrode frequency: $f_0 = 60$ kHz
$f_q \sim 8$ kHz

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

$$f_q = \frac{\omega_q}{2\pi}$$

Both the frequency and the spatial structure of the perturbation must be appropriate to excite the mode. Driving all four PTSX wall electrodes with properly phased V(t) excites the quadrupole mode, while driving a single PTSX wall electrode excites the dipole mode.

Physics of Plasmas **20**, 055706 (2013).

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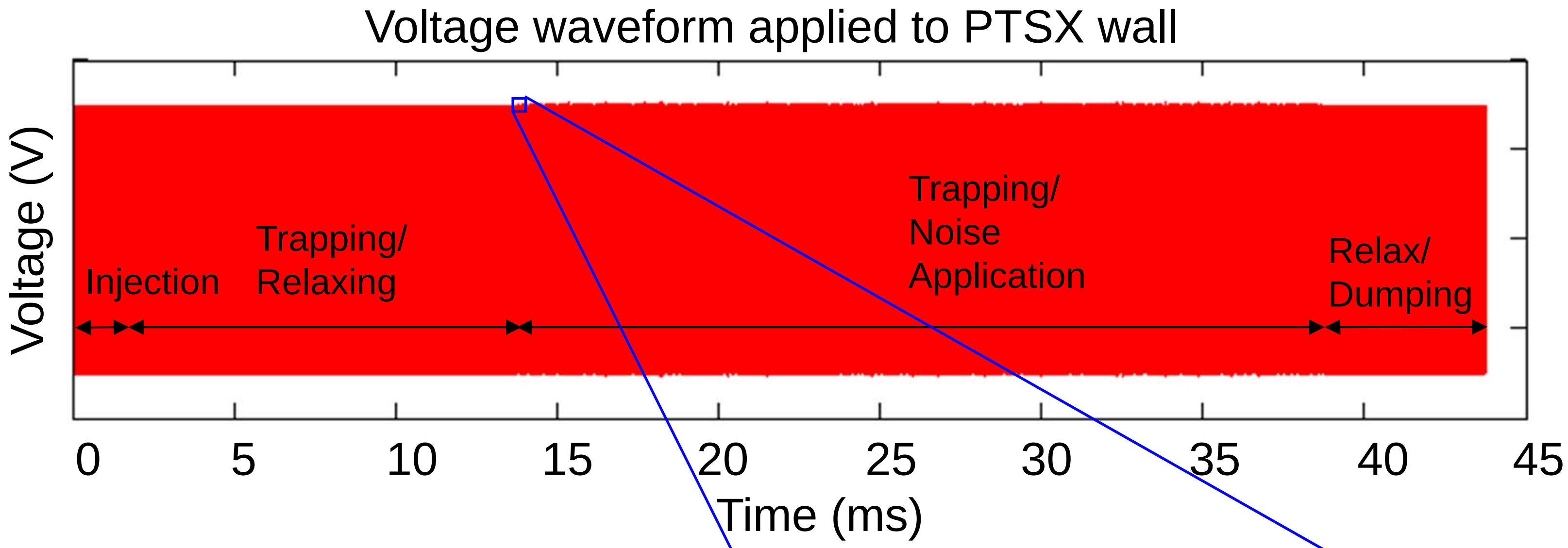
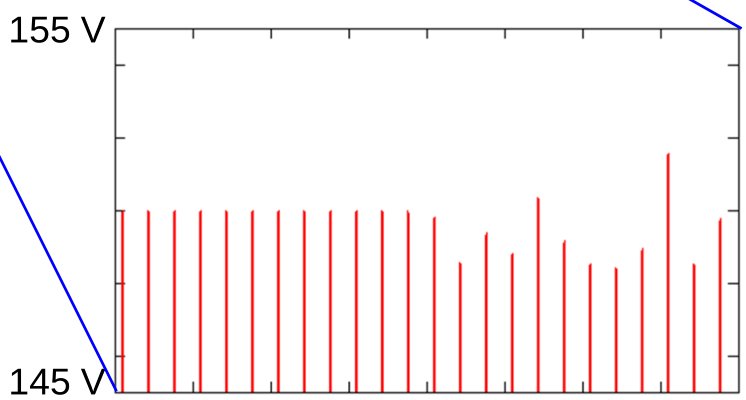
We Applied 1.5% Amplitude Noise to the Lattice to Study the Effect on Emittance Growth



Vary the amplitude of each half-period by an amount chosen from a uniform distribution.

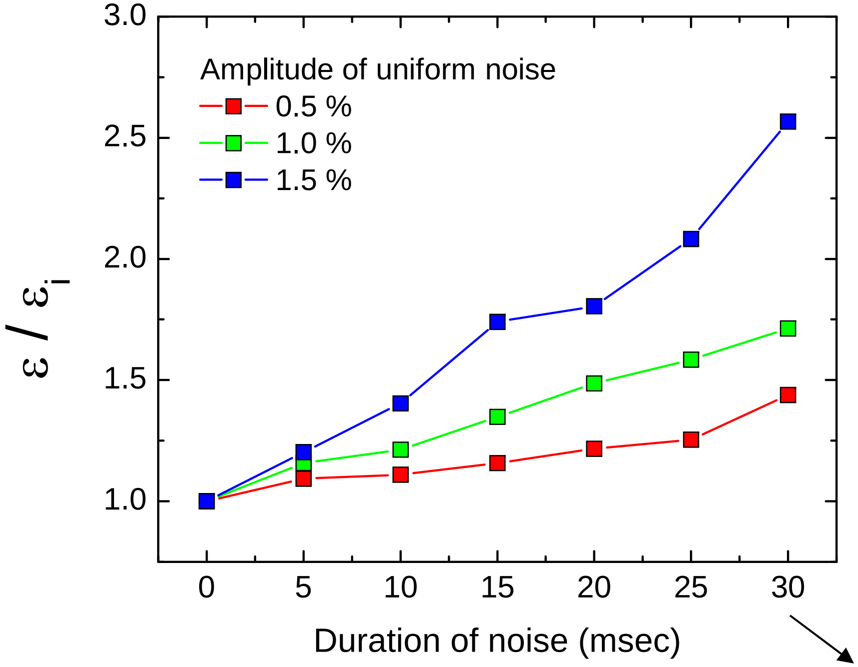


Even 0.5% Amplitude Noise Drives Significant Emittance Growth

- Continuous emittance growth ~ linear with the noise duration

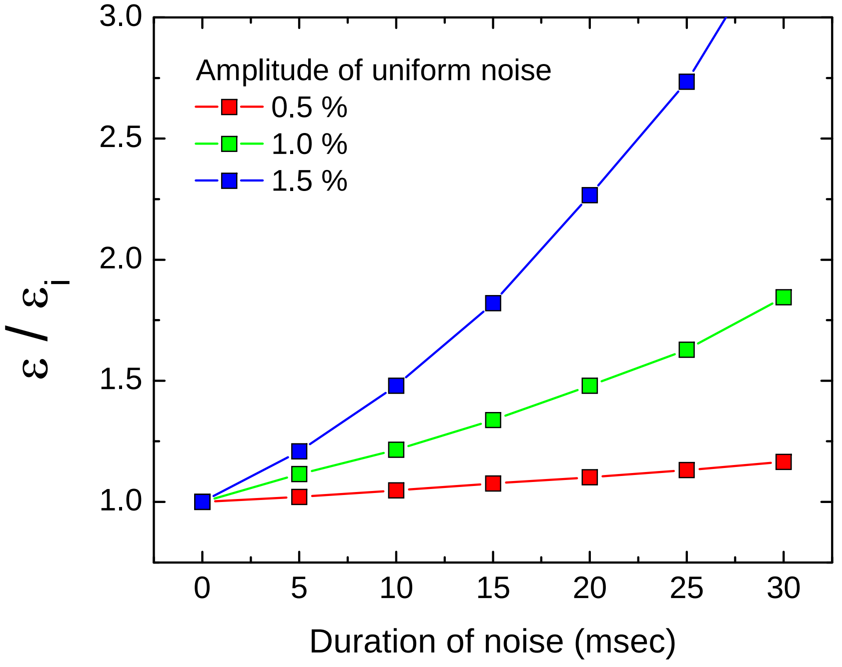
$$\frac{\varepsilon}{\varepsilon_i} = \frac{R_b\sqrt{T_\perp}}{R_{bi}\sqrt{T_{\perp i}}}, \quad m\omega_q^2 R_b^2 = 2k_B T_\perp + \frac{N_b q^2}{4\pi\varepsilon_o}$$

Experiments



1800 lattice periods

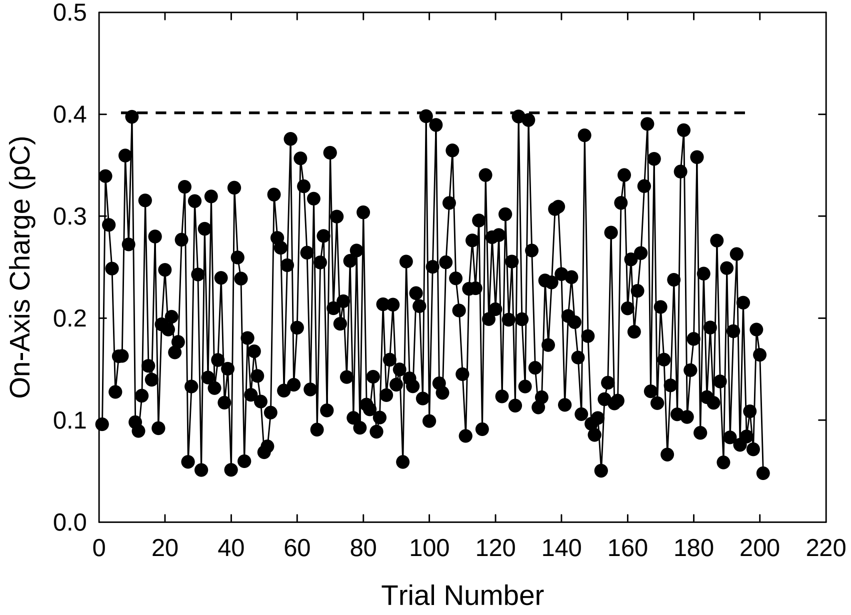
WARP 2D PIC Simulations



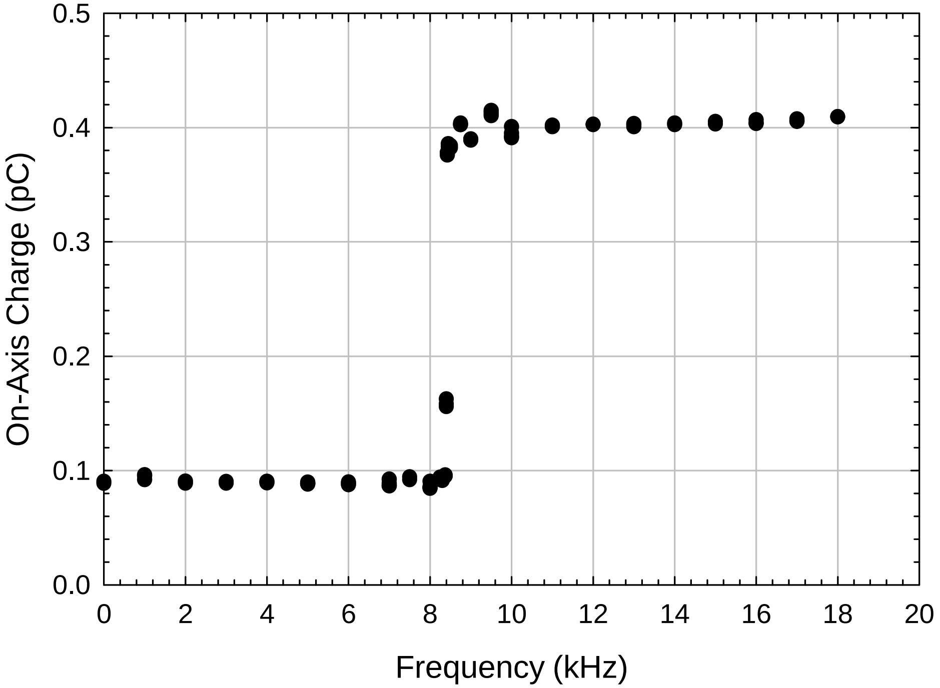
Phys. Rev. ST Accel. Beams **12,** 054203 (2009).

The Component of the Noise at the Resonant Mode Frequency Leads to Emittance Growth and Beam Loss

200 “Noisy” Accelerators Were Created – Some Had a Large Frequency Component at the Mode Frequency – Some Didn’t



When the filter eliminates the dipole mode frequency, the deleterious effect is removed.



Physics of Plasmas **20**, 055706 (2013).

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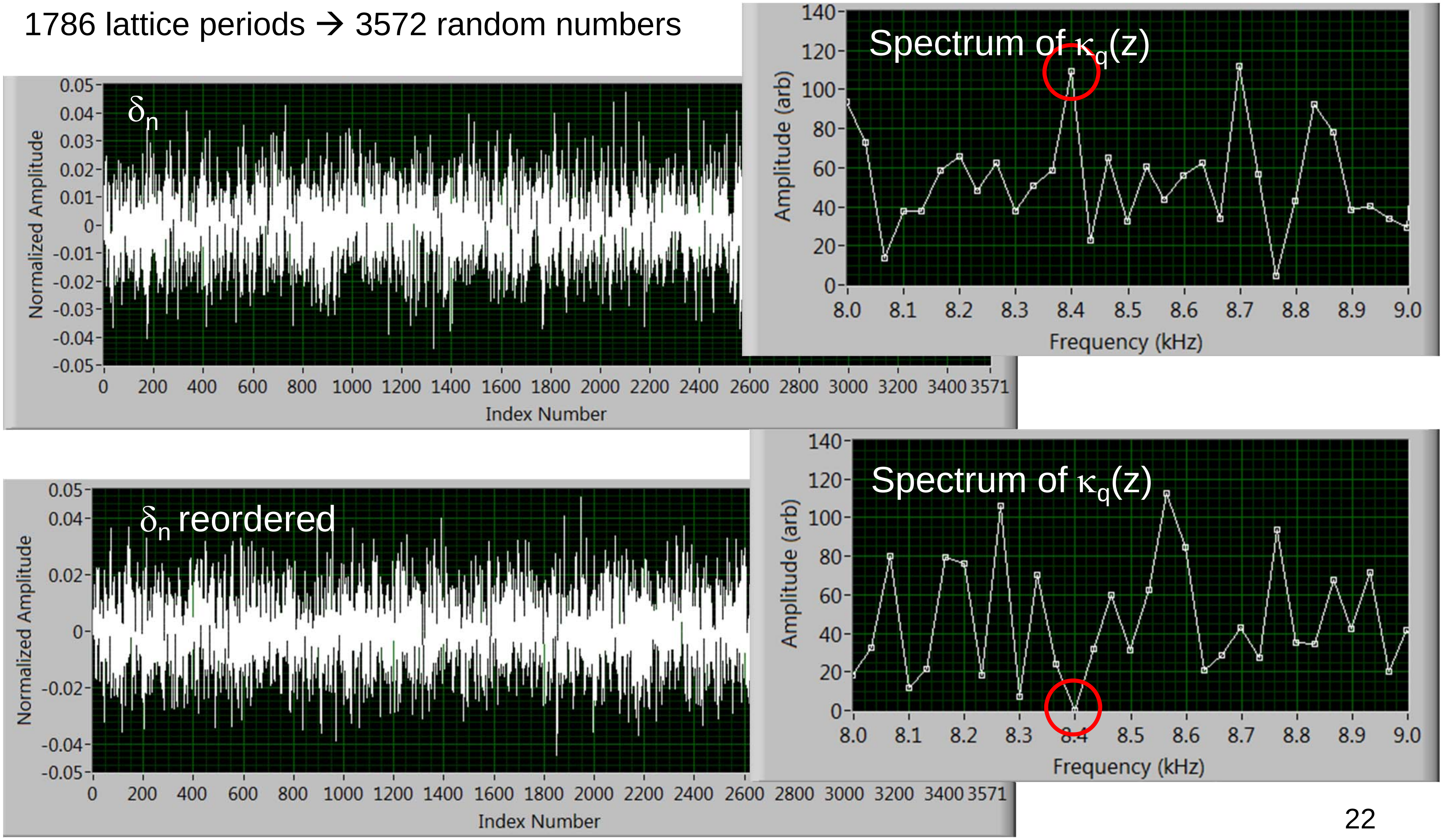
The Lattice Can Be Reordered to Remove the Component at the Mode Frequency

1786 lattice periods → 3572 random numbers



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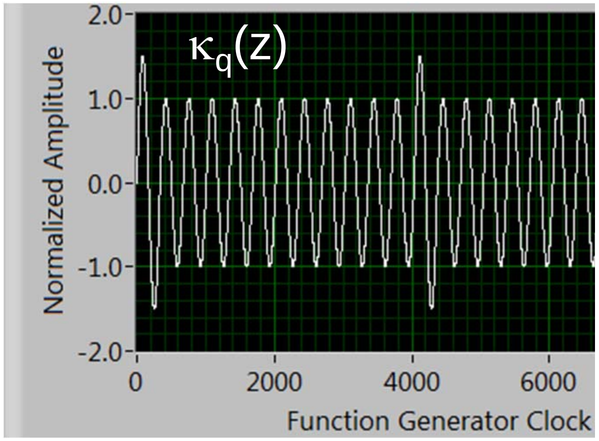
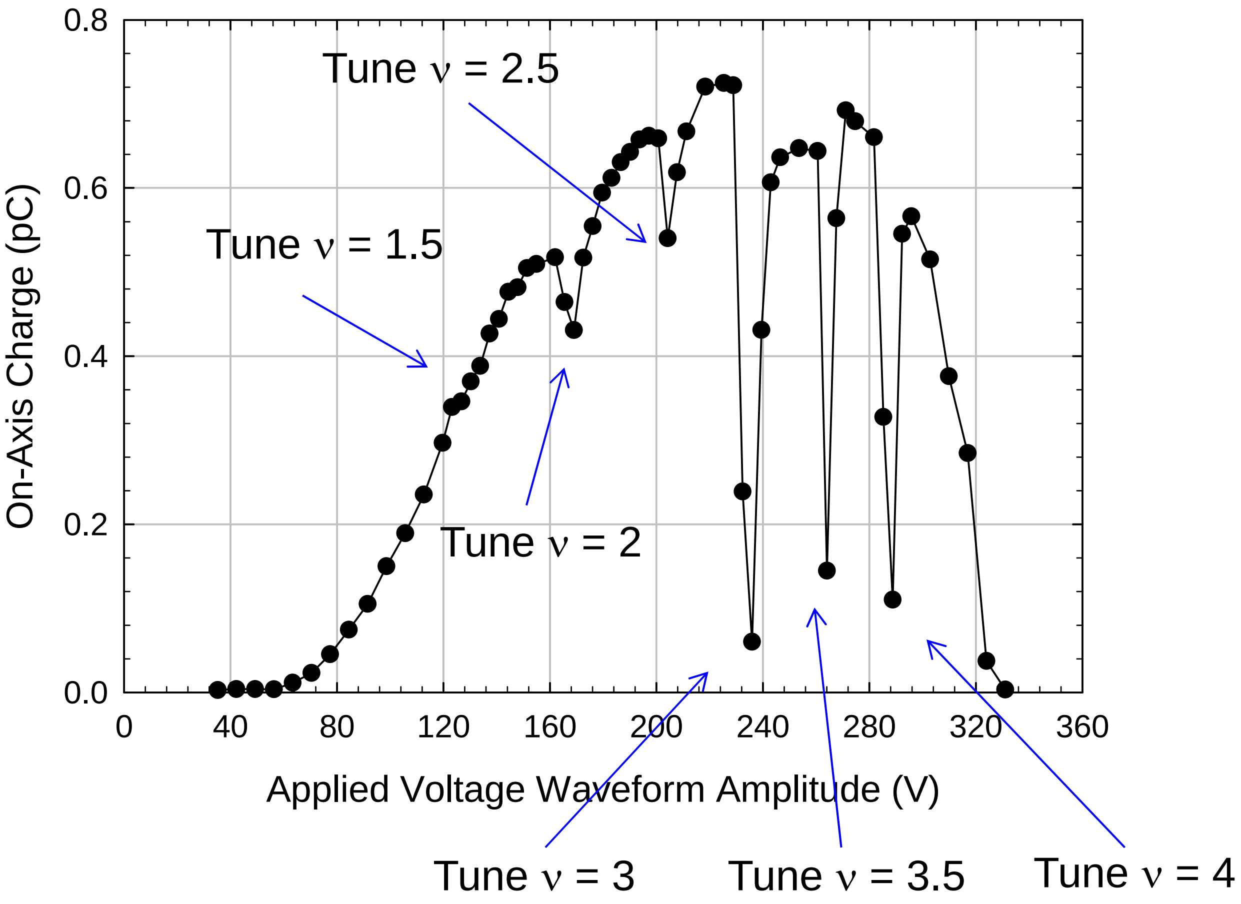
Half-Integer-Tune Quadrupole Mode Resonances are Seen in “Ring” Experiments

N = 12




Tune ν = 2.5

Tune ν = 1.5

Tune ν = 2

Tune ν = 3

Tune ν = 3.5

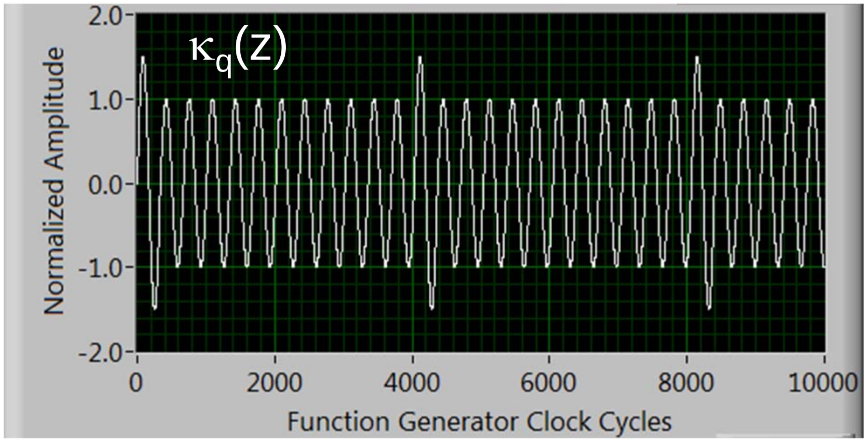
Tune ν = 4

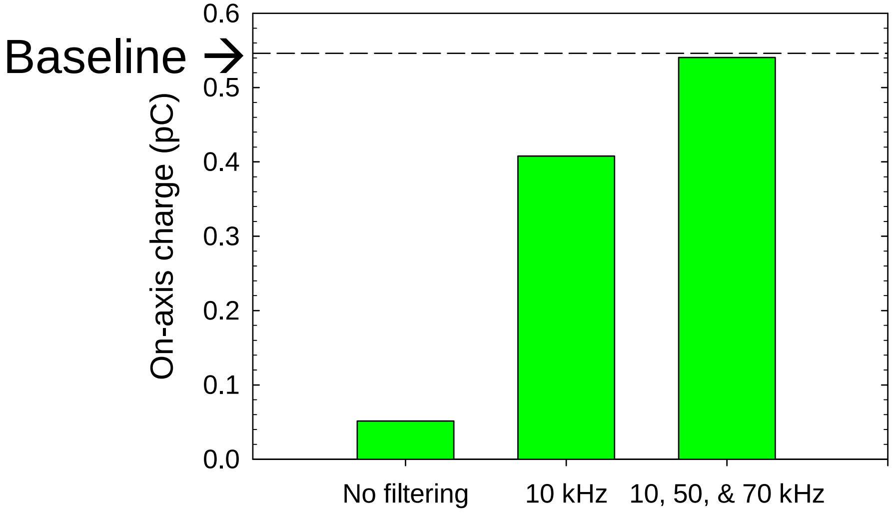
See also:
Ohtsubo et al., “Experimental Study of Coherent Betatron Resonances with a Paul Trap”, Phys. Rev. ST Accel. Beams, **13**, 044201 (2010).

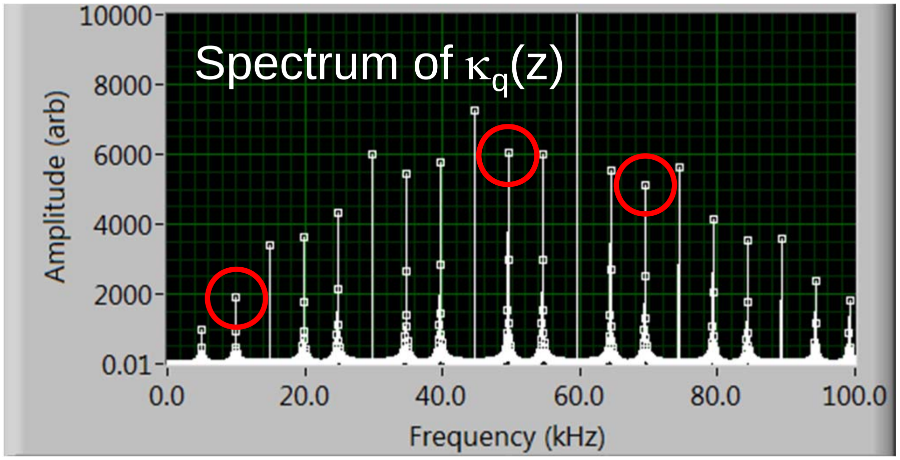
Resonant Loss Effects are Eliminated When Frequency Components that Drive the Mode are Removed

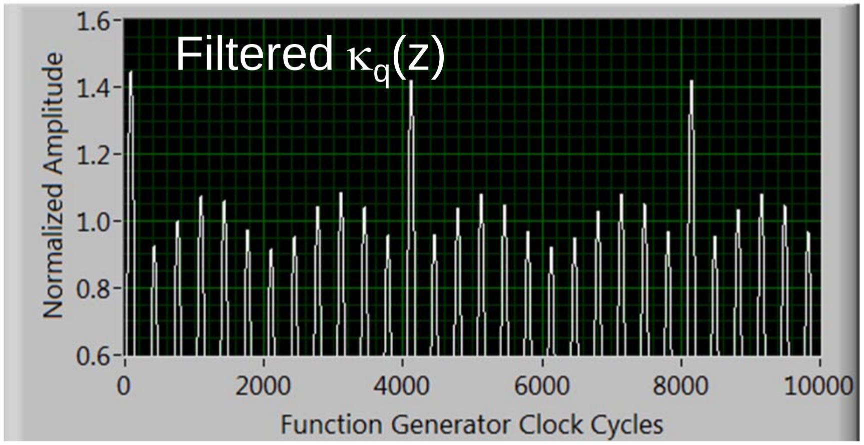
Ring Periodicity N = 12

2% amplitude dipole, σ_v = 60°, tune = 2









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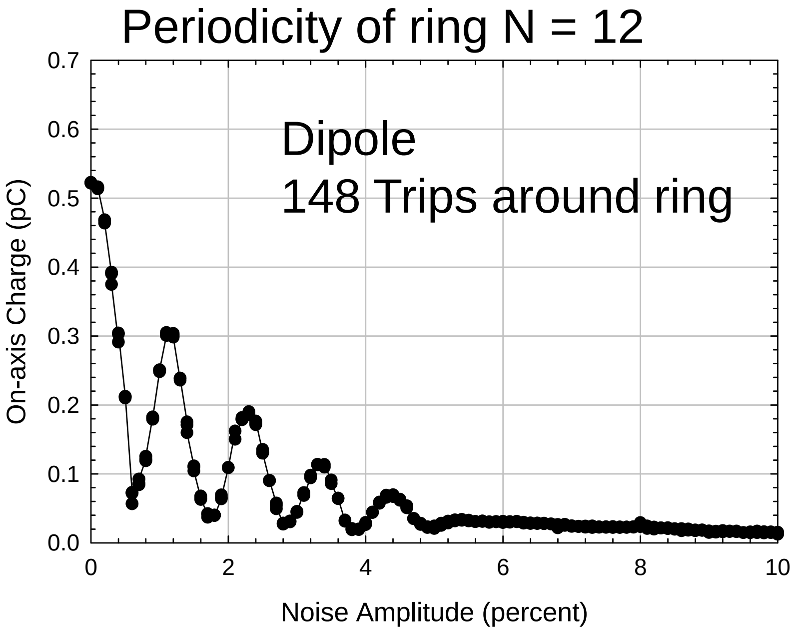
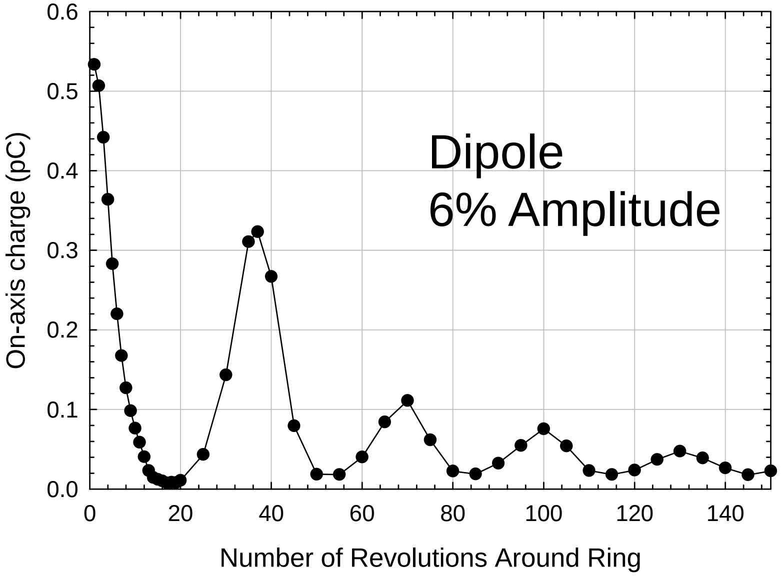
Modes are Driven to Large Amplitude Where Nonlinear Fields are Felt by the Charge Bunch

Driving a nonlinear oscillator at the linear mode frequency causes the mode amplitude to periodically increase and decrease.

The phase of the mode oscillation at the end of the drive determines how much emittance growth there is.





Scaling of Locations of “Valleys” Shows That the Nonlinearity is Coming From the 12-pole Contribution to the Lattice

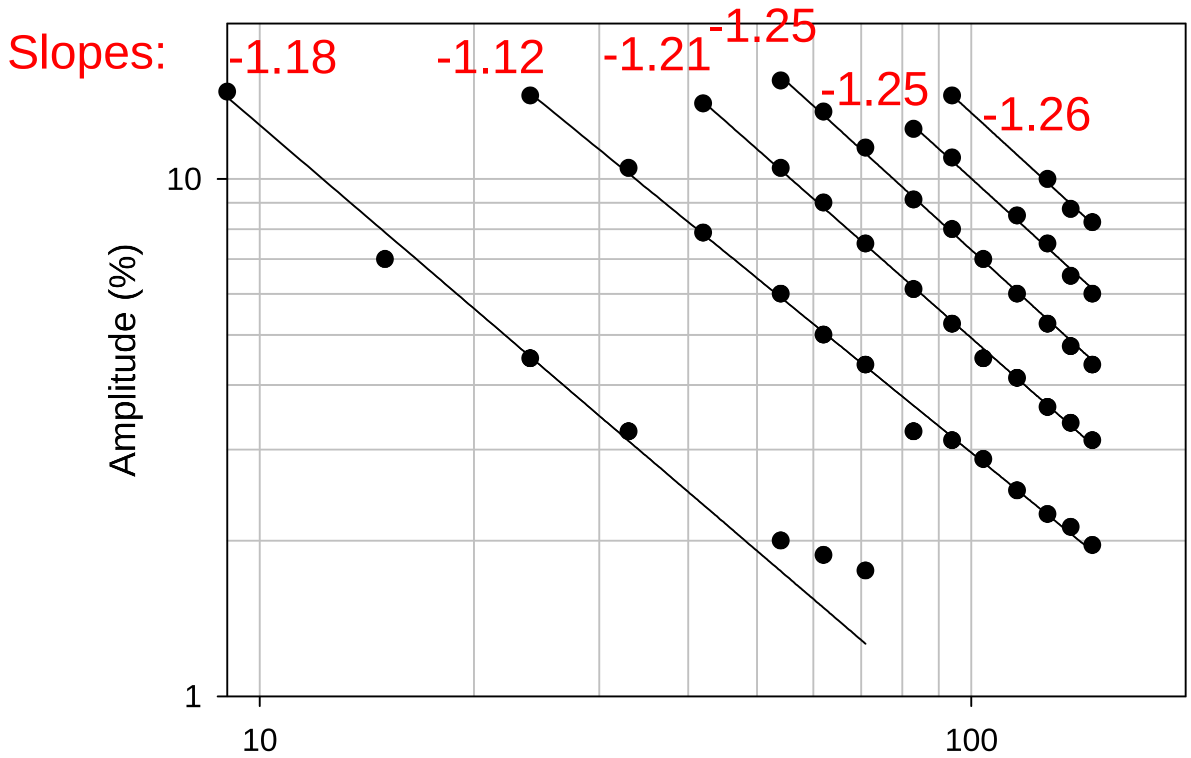
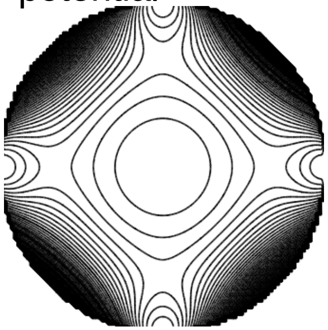


Image charge effect would have r^4 term and -3/2 scaling instead.

Ponderomotive potential



$$V(r,\theta,t) \sim A\sin(2\pi f_0 t)\left[\left(\frac{r}{r_w^2}\right)^2 \cos(2\theta)-\frac{1}{3}\left(\frac{r}{r_w^2}\right)^6 \cos(6\theta)+\ldots\right]$$

The r^n term gives scaling as -(n-1)/(n-2)

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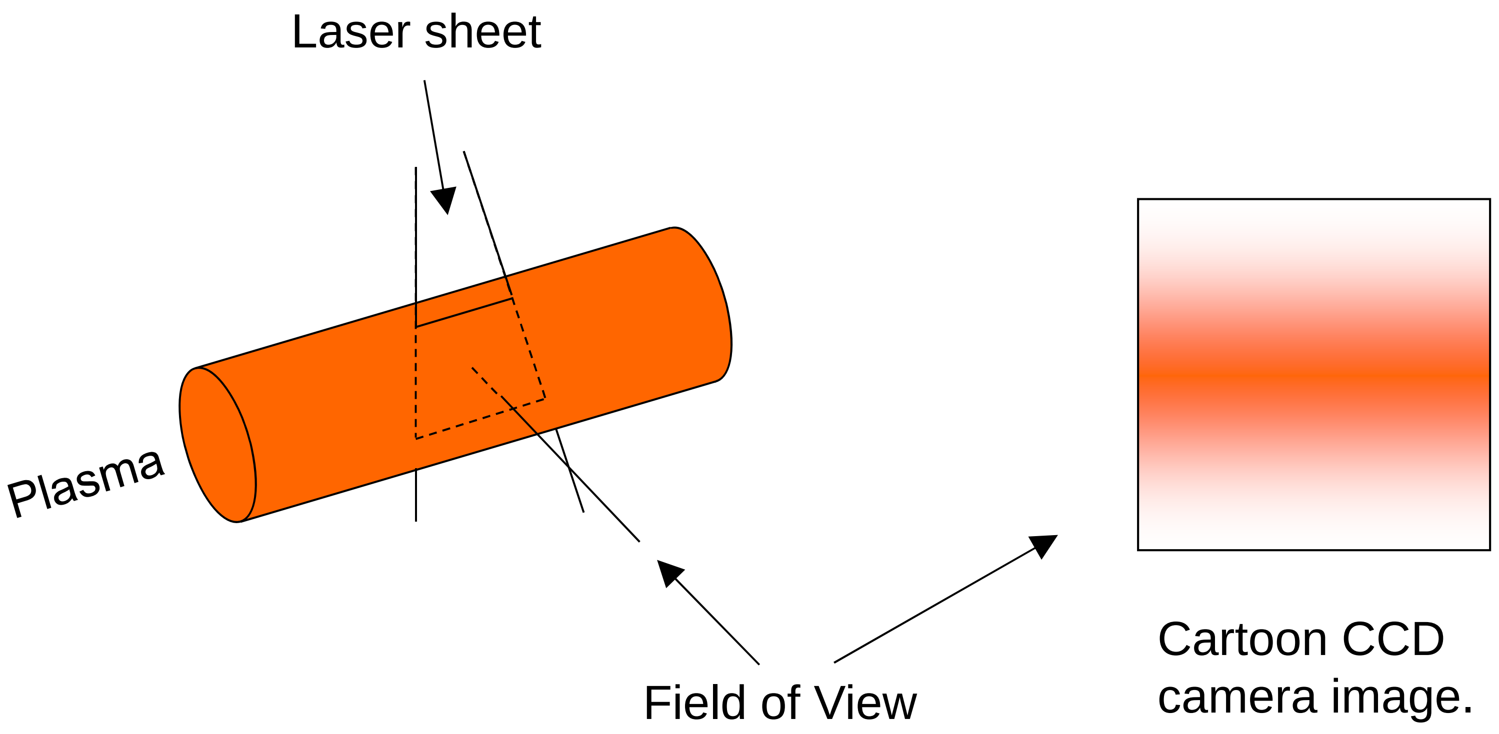
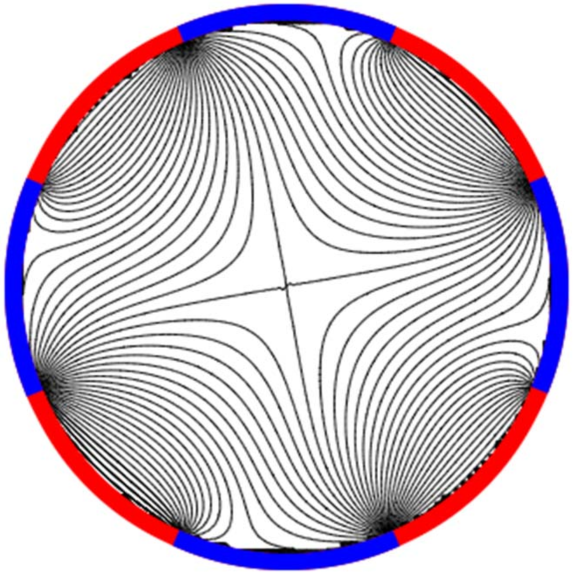
An Upgraded PTSX Would Include a Modified Ion Source, More Compact Electrodes, and a Laser-Induced Fluorescence (LIF) System

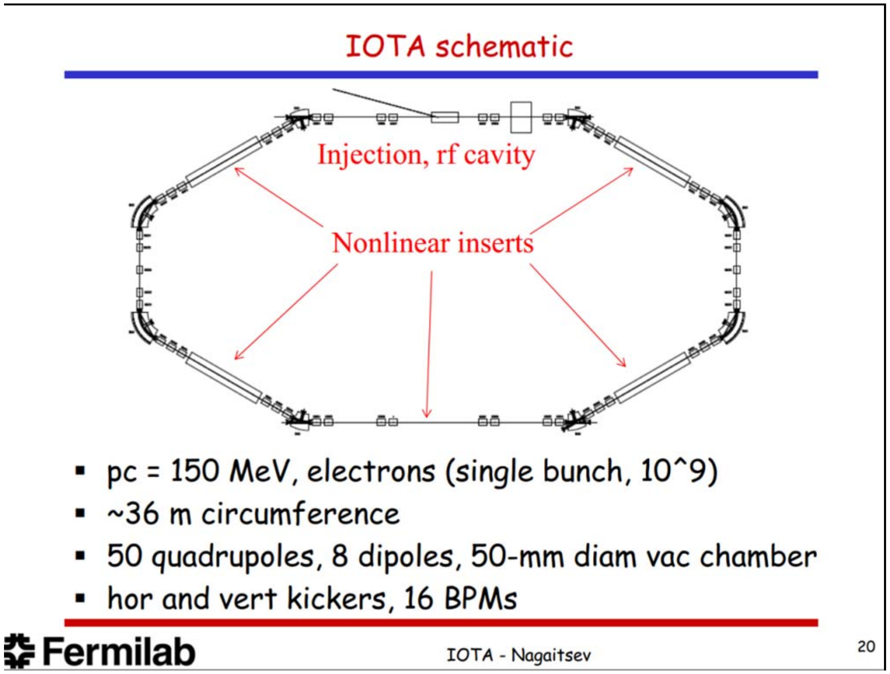
- A larger-radius ion source with matching into the time-dependent lattice would enable larger space-charge and lower-emittance studies.
- More compact electrodes would increase the strength of the confining lattice.
- A laser-induced-fluorescence diagnostic system would allow time-resolved measurements of the transverse phase-space distribution.



Future Research Directions Would Include Studies with Increased Space Charge, Understanding Higher-Order Confining Fields, and Rotating (Coupled x-y) Configurations

- Increasing the space charge in PTSX allows further studies of nonlinear effects.
- Making 8, or even 24, electrodes allows PTSX to study: higher-order (hexapole, octupole, etc.) optics, confinement, and errors; and coupled x-y configurations that may have better confinement properties.





IOTA schematic

- pc = 150 MeV, electrons (single bunch, 10^9)
- ~36 m circumference
- 50 quadrupoles, 8 dipoles, 50-mm diam vac chamber
- hor and vert kickers, 16 BPMs

Fermilab IOTA - Nagaitsev 20

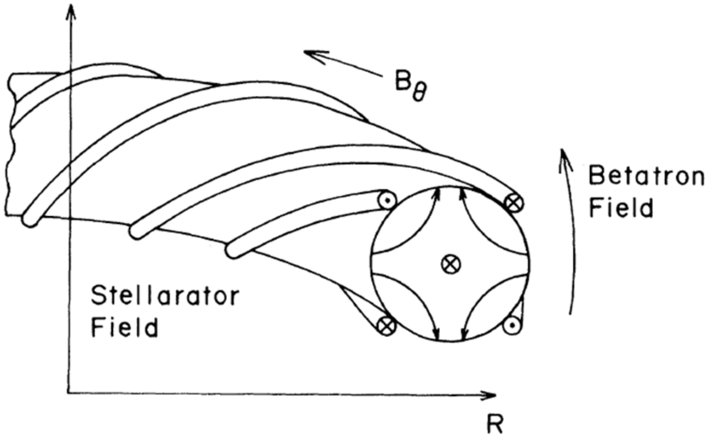


FIG. 1. Stellatron configuration.

C. W. Roberson, PRL, 1983.

Summary

- The Paul Trap Simulator Experiment (PTSX) is a compact linear Paul trap that simulates the transverse dynamics of intense beam propagation in magnetic alternating-gradient accelerator transport systems.

- PTSX confines single-component nonneutral plasmas for several hundred milliseconds, corresponding to several thousand lattice periods. This long equivalent propagation distance, together with moderate space-charge intensity s ~ 0.2, makes PTSX experiments accelerator-relevant.

- Emittance growth and halo particle generation due to beam mismatch have been observed and agree with particle-in-cell simulations and experiments on the Low Energy Demonstration Accelerator at Los Alamos National Laboratory.

- Transverse beam compression can be achieved by gradually increasing the strength of the confinement system – either by increasing the waveform amplitude, or by decreasing the waveform frequency.

Summary

- Transverse dipole and quadrupole modes can be excited by perturbing the charge bunch with the corresponding frequency and spatial pattern.

- Periodic coherent perturbations in a ring machine, such as from an injection/extraction section of the ring, can resonate with beam modes and cause particle loss. Filtering the applied waveform to remove frequency components at the mode frequencies eliminates the deleterious effects.

- Similarly, random noise, such as from magnet misalignments, causes particle loss if there is a large frequency component at a collective mode frequency.

- Devices like PTSX can be used to further study the propagation of intense charged-particle beams, including the use of so-called nonlinear beam focusing elements such as hexapole and octopole magnets.