Plasma Trap Simulations of Beam Propagation over Long Paths

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Acknowlegements

Past and Present Contributors to the S-POD Project

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Background

Stable Transport
of High-Power or Low-Emittance Hadron Beams

↕

Detailed Information on **"Space-Charge Effects"**

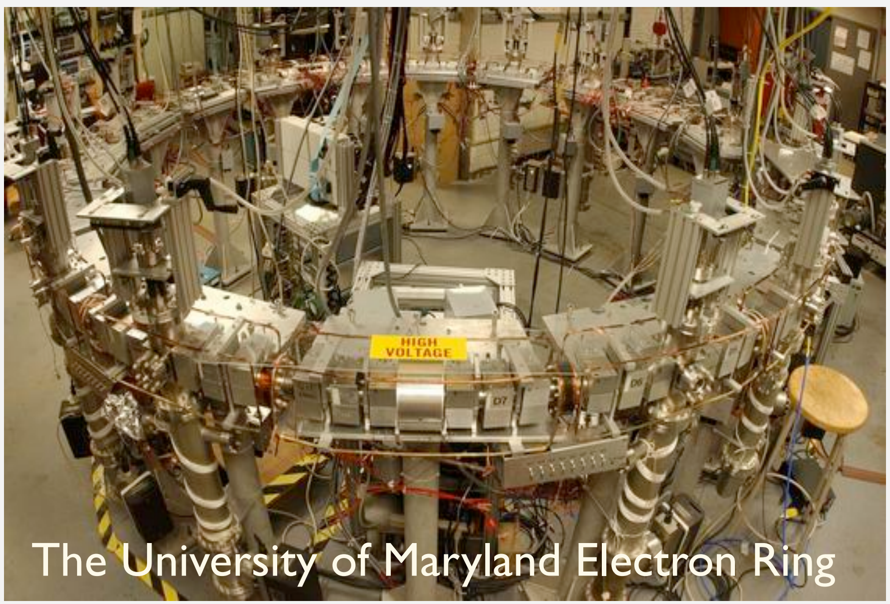
Numerical Simulations

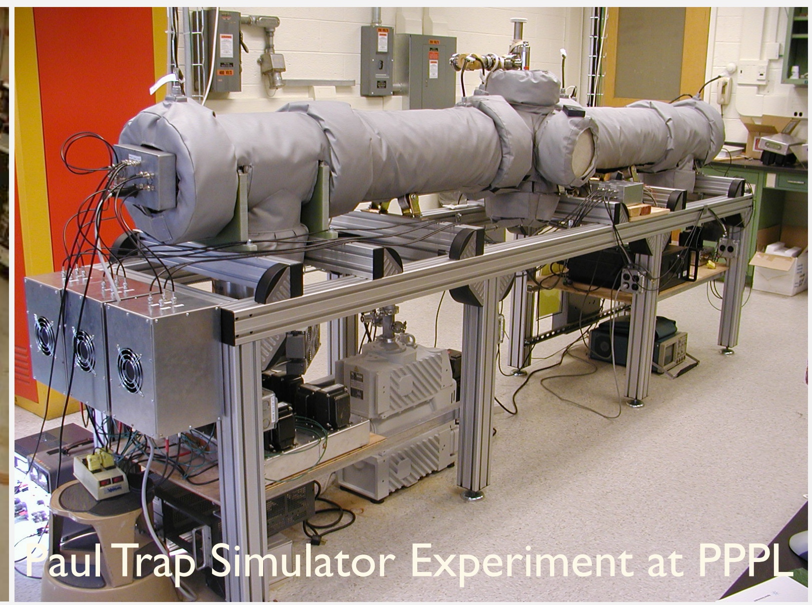
At present, probably the most popular approach
toward various space-charge effects
BUT
Often very time-consuming…

Plasma Trap Experiment

Use a compact, low-cost model that provides
a dynamical system equivalent to charged-particle beams *!*

Other compact experimental facilities based on the same concept





Principle

Charged-particle beams in an AG focusing channel	⟷	Non-neutral plasmas in a trap system
$H_{beam} = \frac{1}{2}(p_x^2 + p_y^2) + \frac{1}{2}K_Q(x^2 \; ! \; y^2) + \frac{q}{m \; ^3(\#c)^2}$		$H_{plasma} = \frac{1}{2}(p_x^2 + p_y^2) + \frac{1}{2}K_{RF}(x^2 - y^2) + \frac{q}{mc^2}\phi$

Both interacting many-body systems obey the following equations:

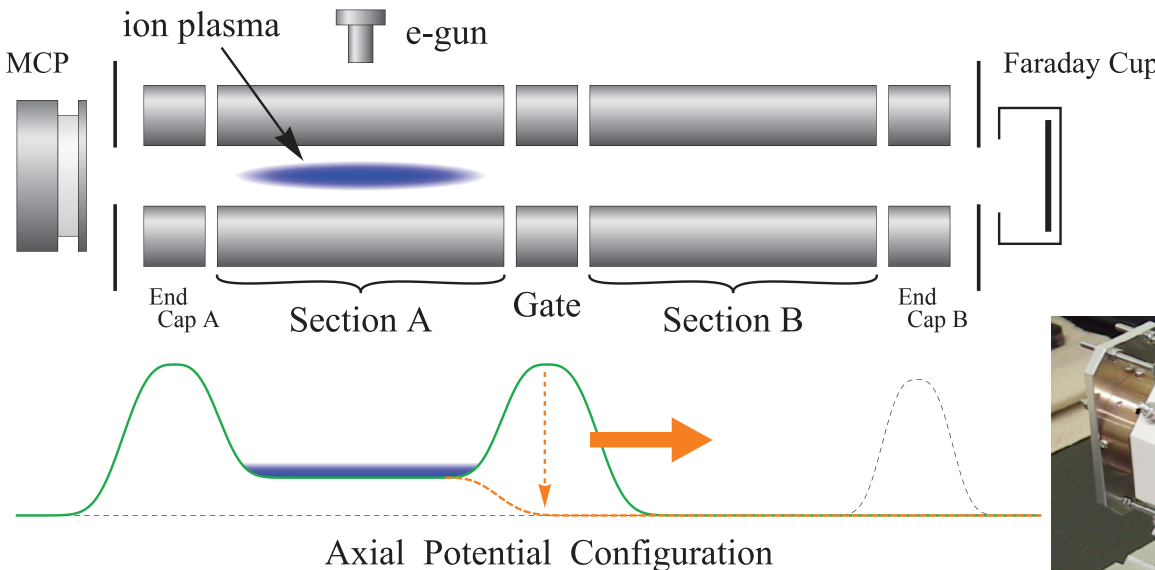
- Poisson equation $\quad ! \quad = \# \frac{q}{\;}_{0} \, \%\!\!\int f(\mathbf{r},\mathbf{p};t)d^3\mathbf{p}$
- Vlasov equation $\quad \frac{!f}{!t} + [f, H] = 0$

Two systems are physically equivalent if governed by similar Hamiltonians.

Use this simple fact to study various collective effects in space-charge-dominated beams !

RF Ion Trap

- Linear Paul Trap

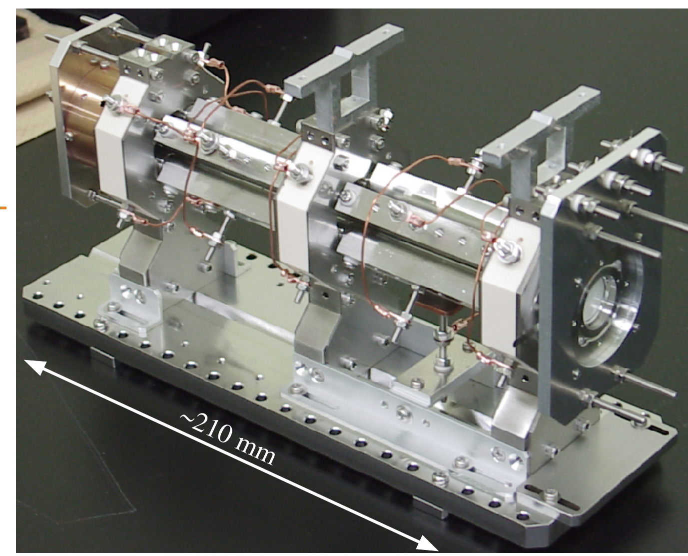


Transverse confinement :

rf quadrupole

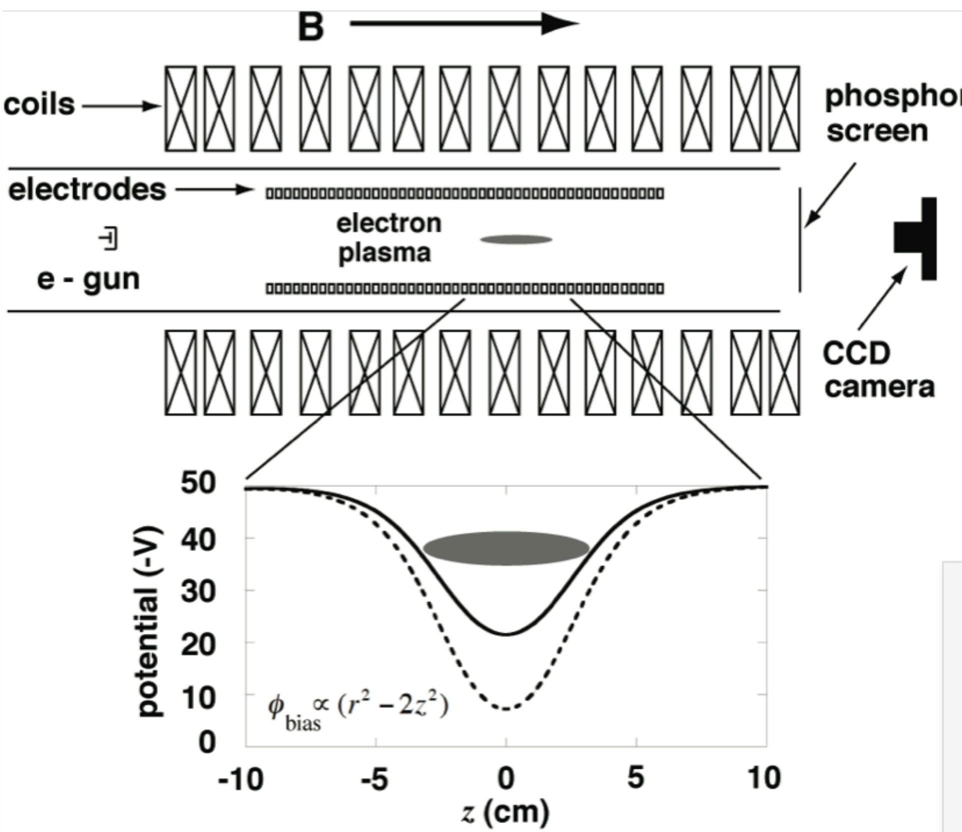
Longitudinal confinement :

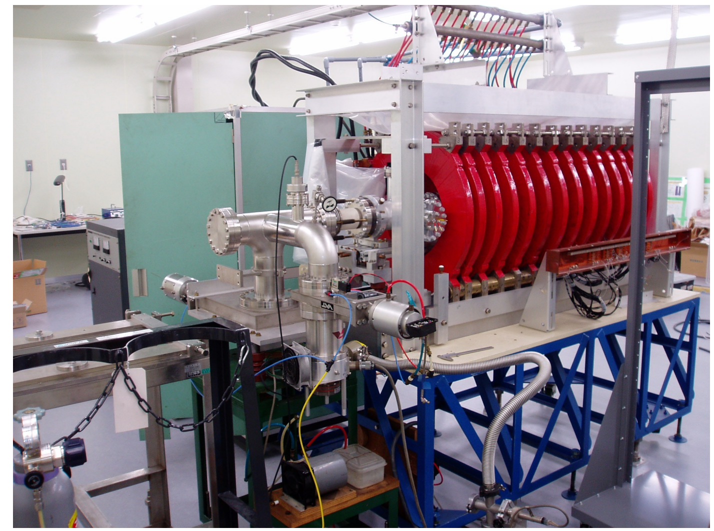
rf or electrostatic potential



Magnetic Trap

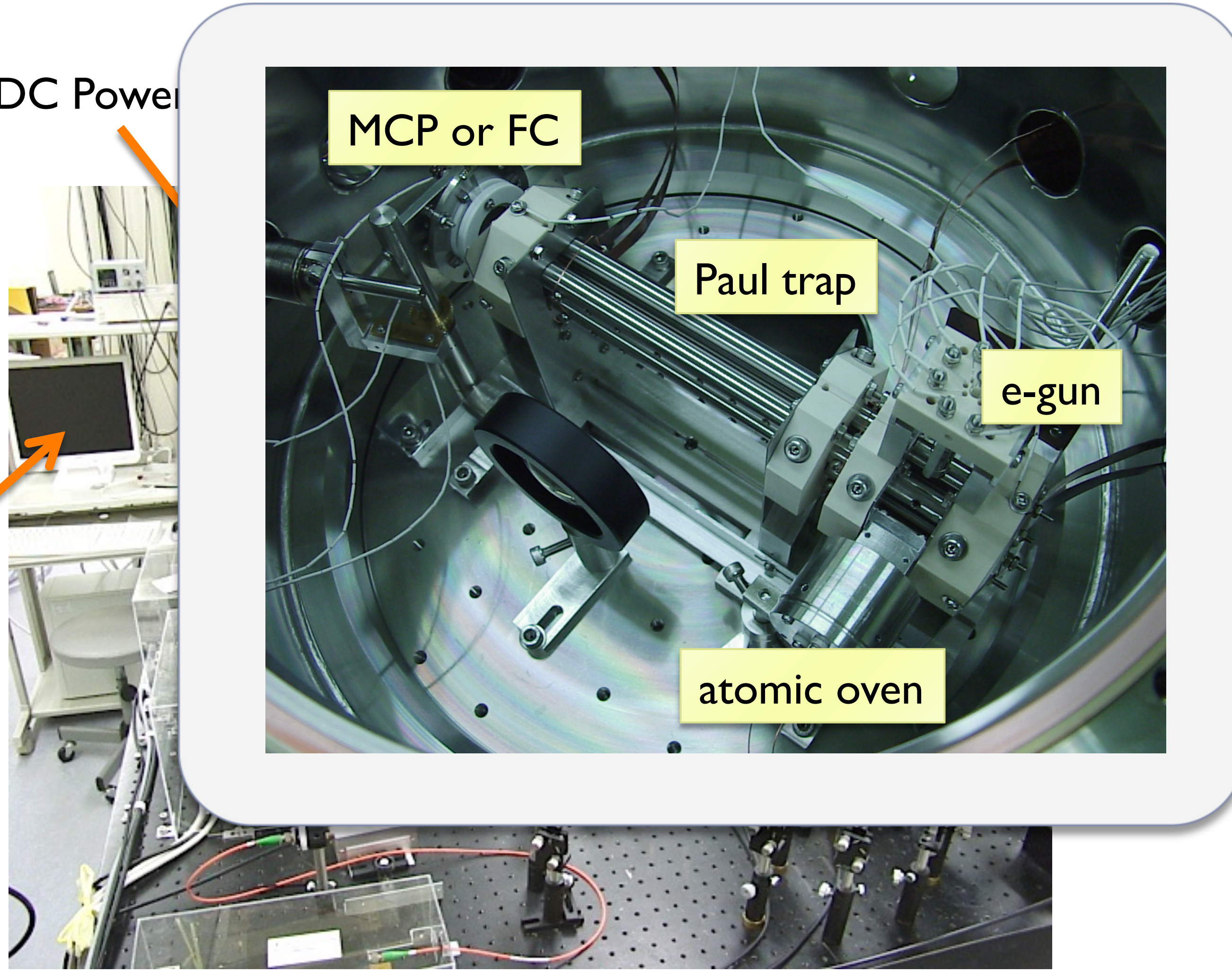
- Penning Trap with Multi-Ring Electrodes



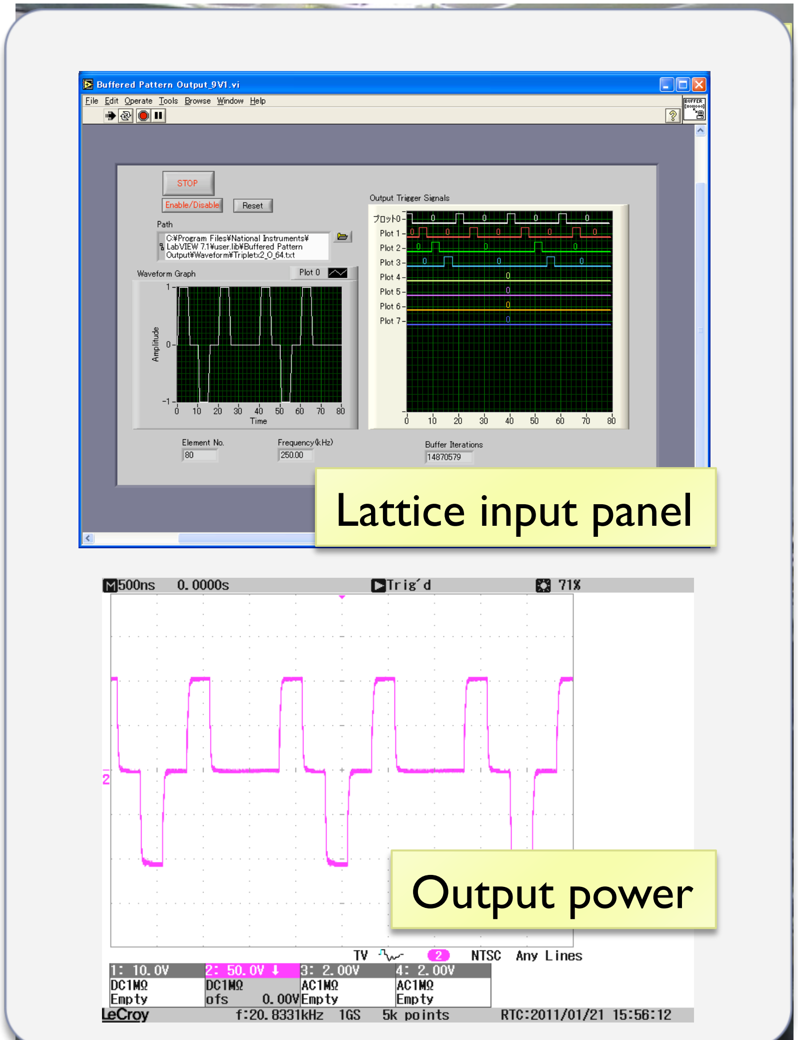


Transverse confinement :
axial magnetic field
Longitudinal confinement :
electrostatic potential
(+ magnetic mirror)

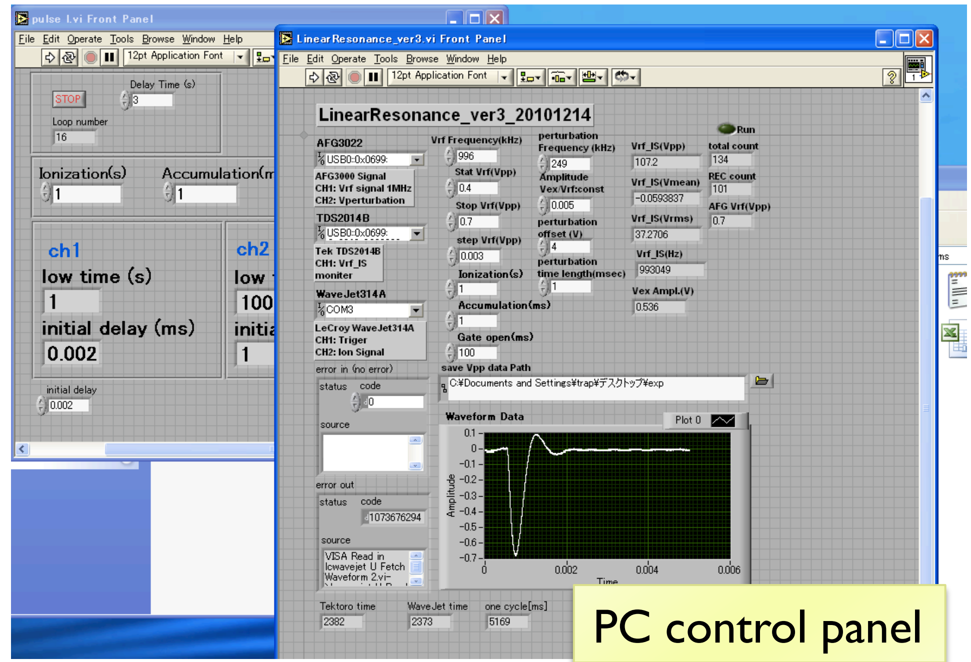
S-POD Components



Control System

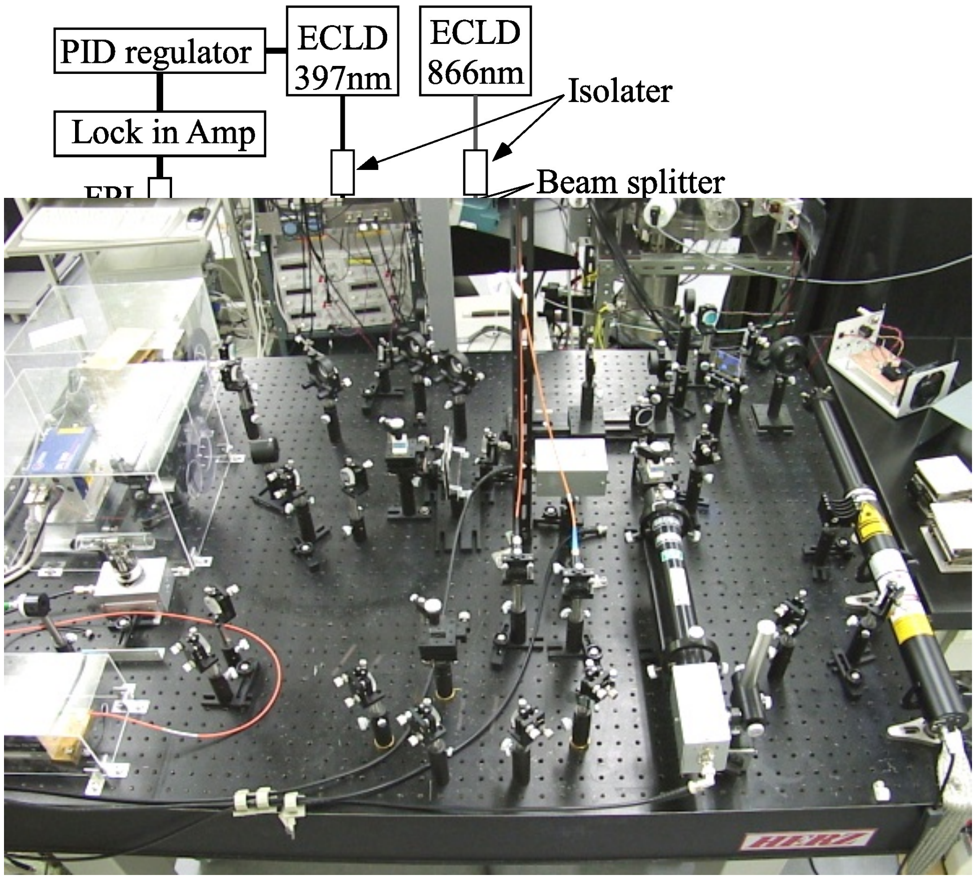


All experimental procedures are automated.

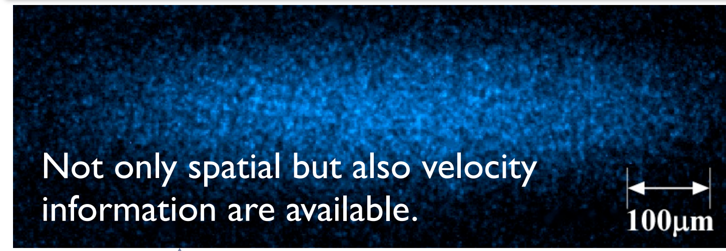


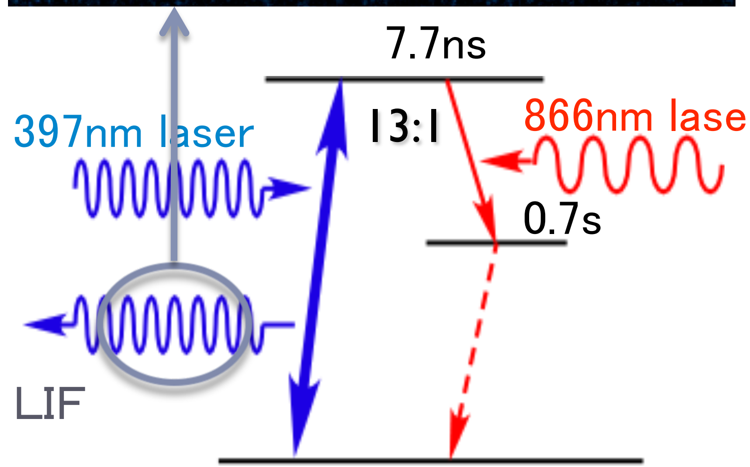
INPUT PARAMETERS
(initial tune, final tune, plasma storage time,
number of measurement points,
ionization time, end plate voltages, etc.)

Laser Cooling System (for $^{40}Ca^{+}$)



Laser-Induced-Fluorescence (LIF) signals





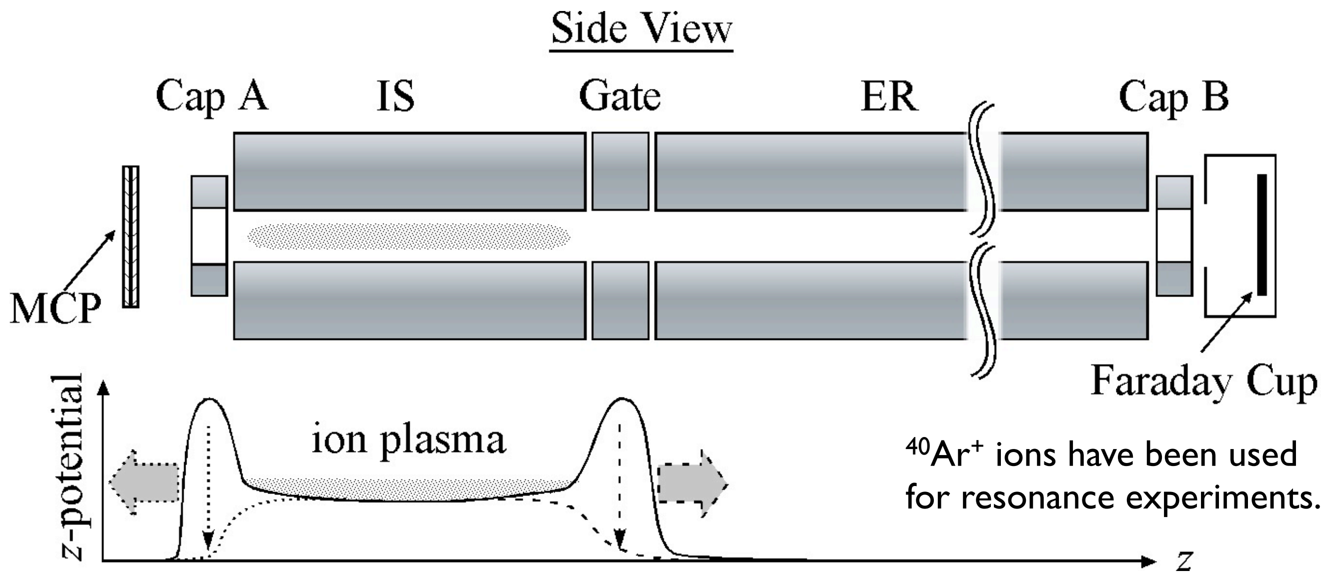
Cooling transition of $^{40}Ca^{+}$

The tune shift (in other words, tune depression) can be controlled over the full range by means of the Doppler laser cooling technique.

Typical S-POD Experiments

- Collective resonance excitation (Ar^+)
- Lattice dependence of stop bands (Ar^+)
- Resonance crossing (Ar^+)
- Halo formation (e^-)
- Ultralow-emittance beam stability (Ca^+)

Basic Measurement Cycle



$^{40}Ar^{+}$ ions have been used for resonance experiments.

- Add specific DC bias voltages to Cap A and Gate.
- Ionize neutral Ar gas in the IS region (typically for 1 second).
- After a short storage (typically for 1 msec to 10 msec), switch off the bias on Gate (or Cap A).
- Measure the ion number with the Faraday cup (or MCP).
- Transfer the data to a personal computer and save it.
- Change slightly the amplitude of the rf voltage on the quadrupole electrodes.

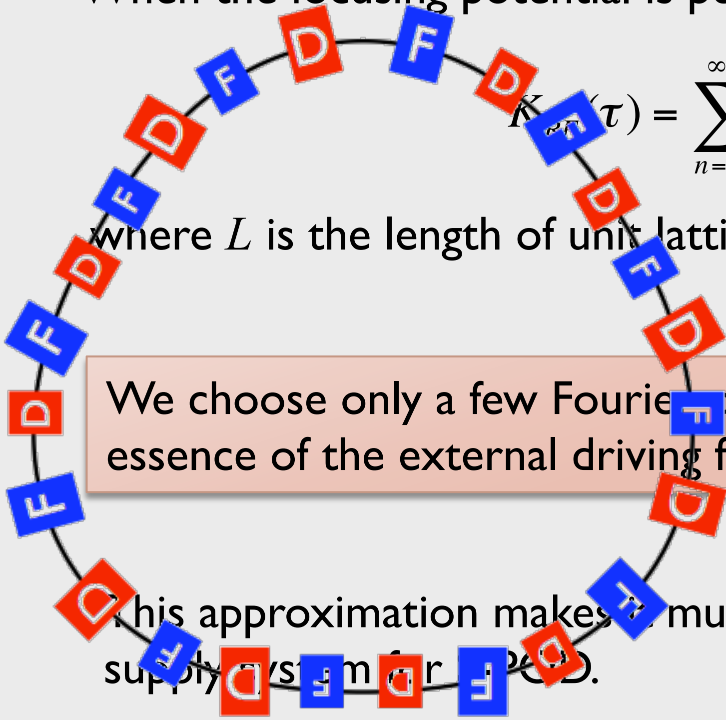
Driving Force

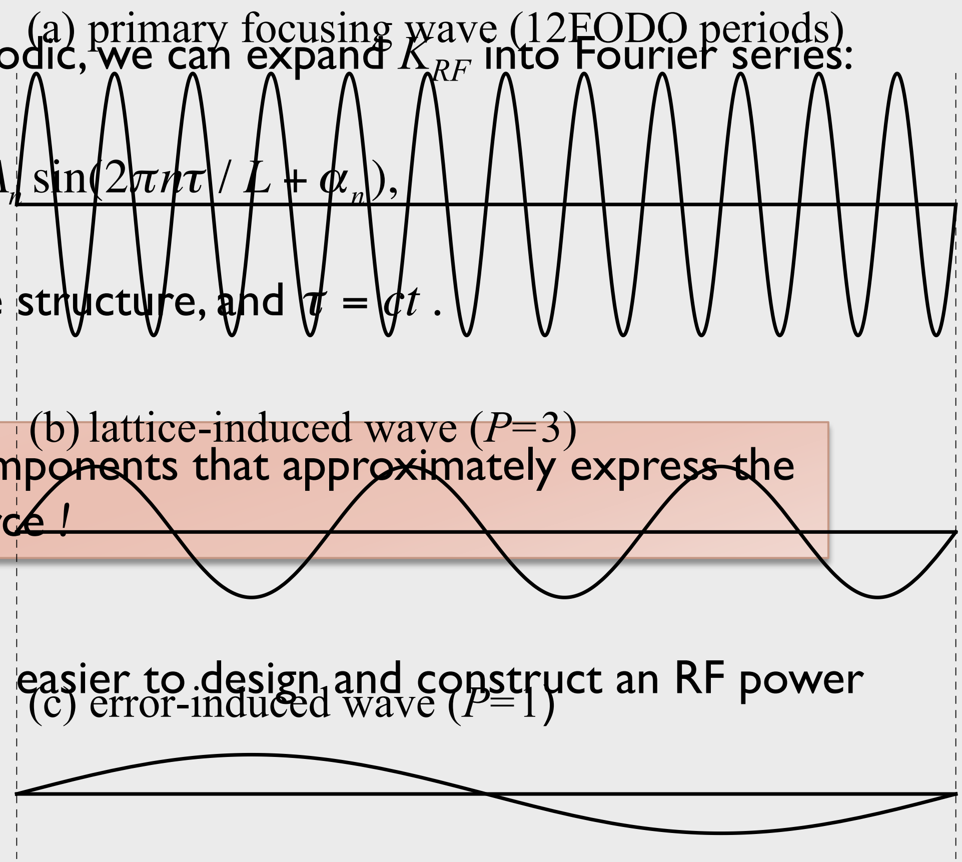
Sinusoidal Wave Model

When the focusing potential is periodic, we can expand K_{RF} into Fourier series:

$$K_{RF}(\tau) = \sum_{n=1}^{\infty} A_n \sin(2\pi n\tau / L + \alpha_n),$$

where L is the length of unit lattice structure, and $\tau = ct$.





We choose only a few Fourier components that approximately express the essence of the external driving force !

This approximation makes it much easier to design and construct an RF power supply system for PCD.

Stop Bands in Doublets

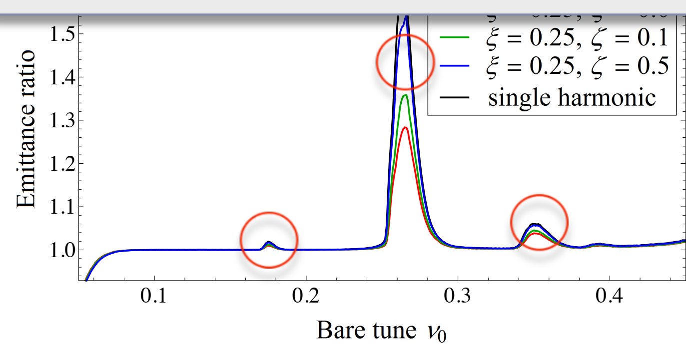
- WARP
- S-POD

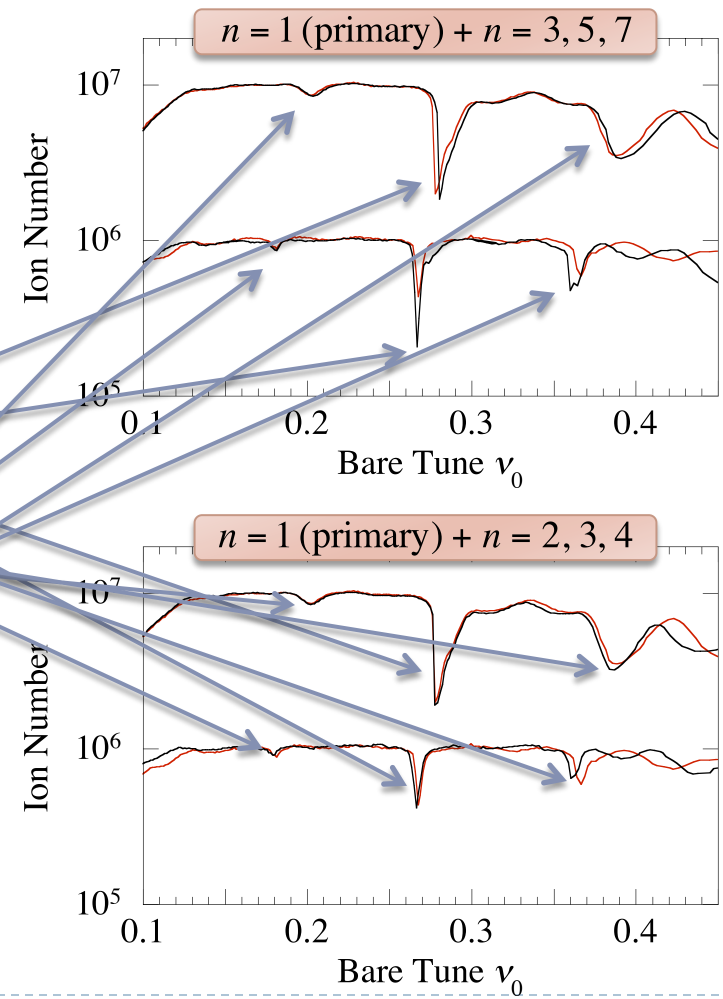
Collective Resonance Condition

$$\nu_0 - C_m \Delta\nu \approx P \cdot \frac{k}{2m}$$

For $P = 1$,

- Linear $(m = 2)$: $\nu_0 - C_2 \Delta\nu \approx \frac{1}{4}$
- Third-order $(m = 3)$: $\nu_0 - C_3 \Delta\nu \approx \frac{1}{6}, \frac{2}{6}$

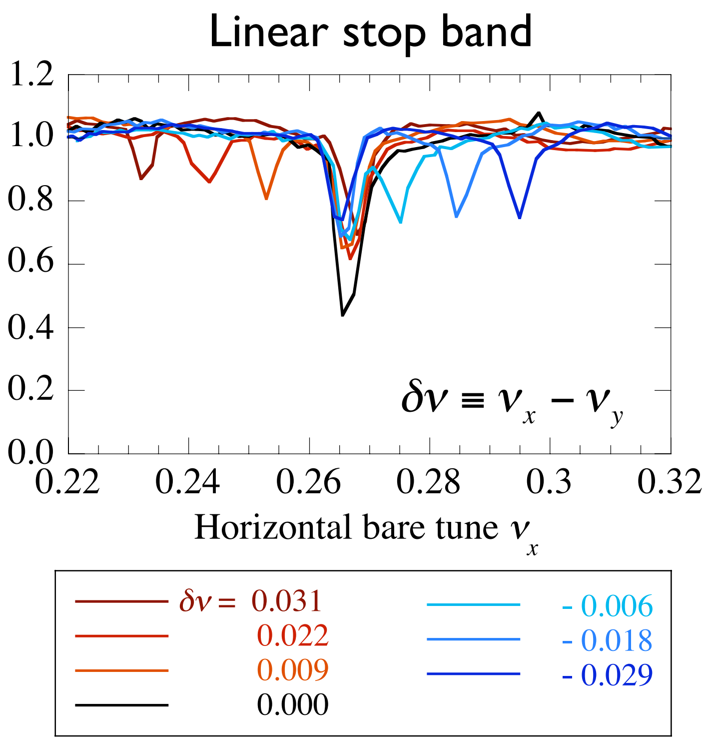


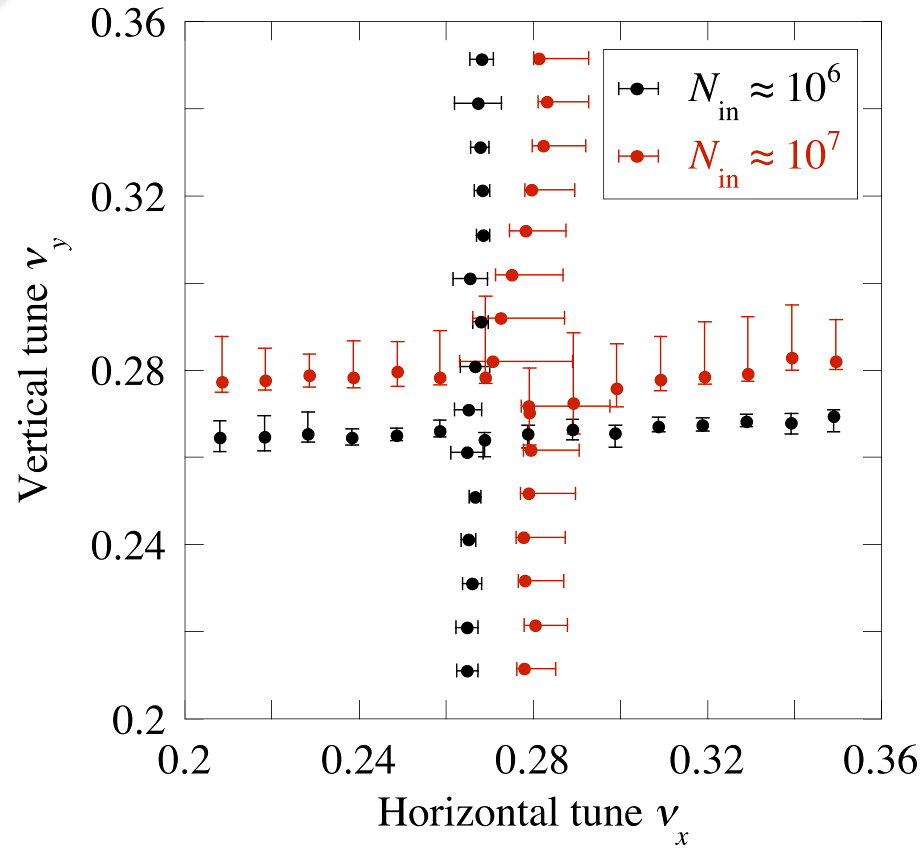


Stop-Band Splitting

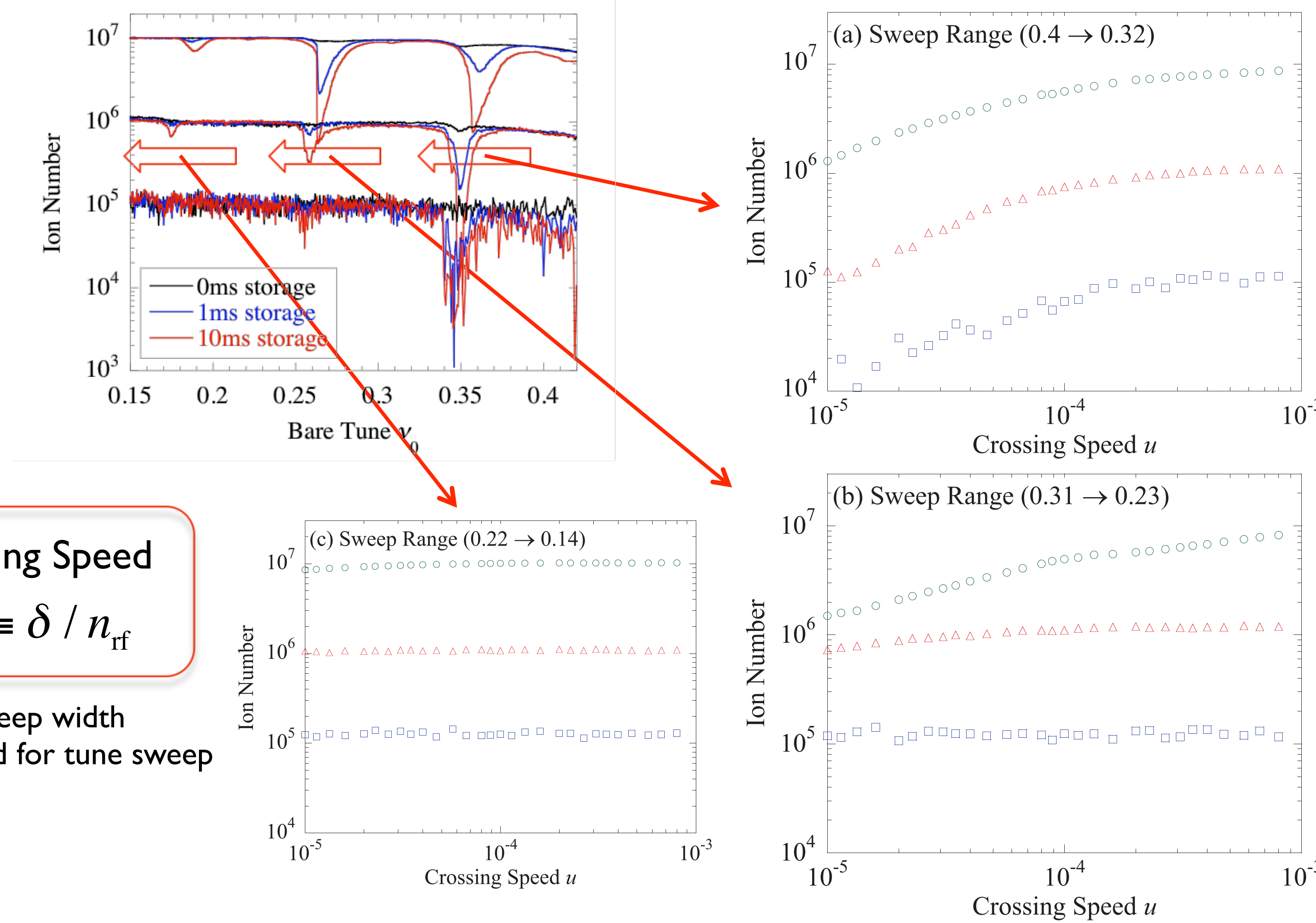
When $\nu_x \neq \nu_y$, all stop bands split !

Tune Diagram





Resonance Crossing

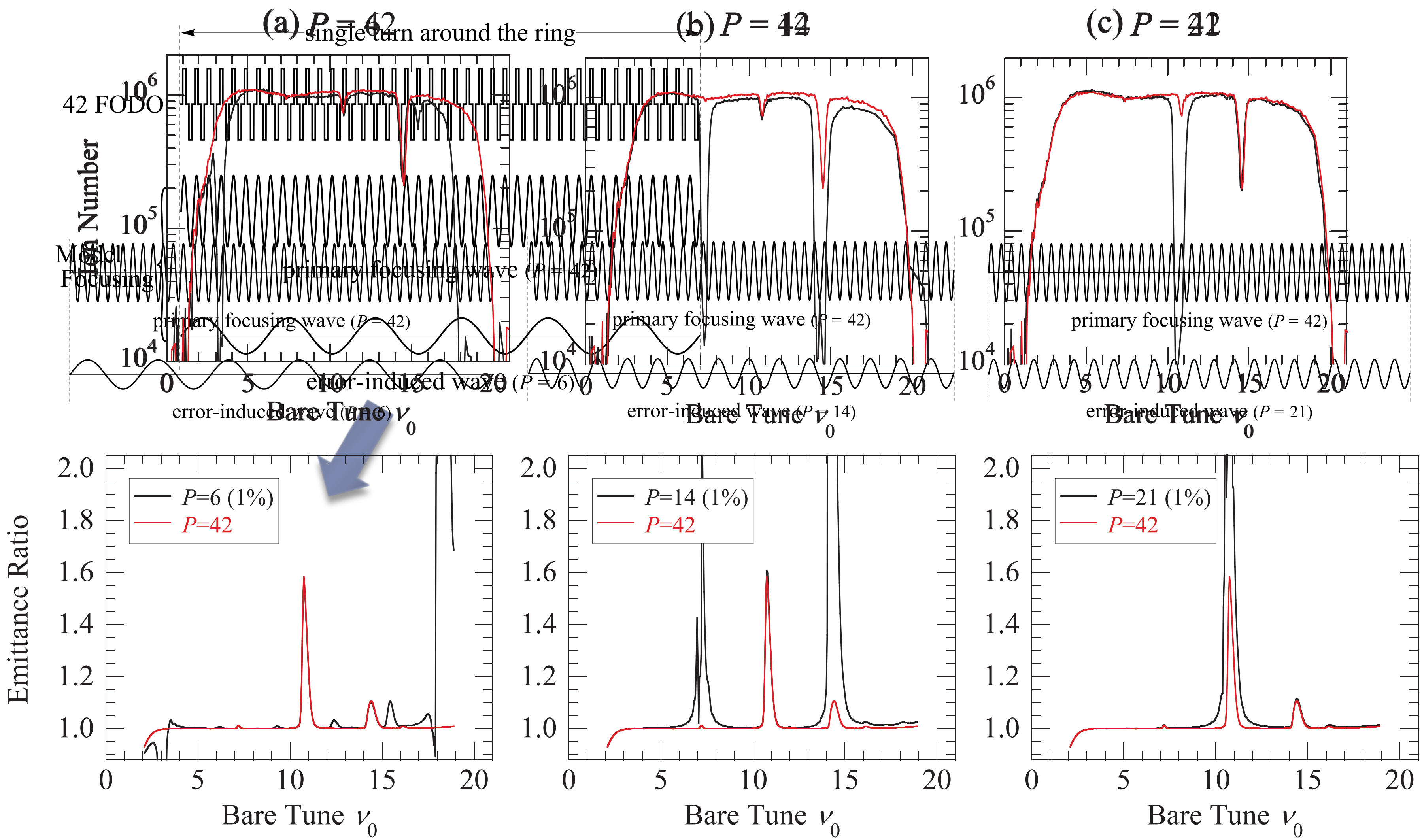


Crossing Speed

$$u \equiv \delta / n_{rf}$$

δ : tune-sweep width
n_{rf} : rf period for tune sweep

Effect of Lattice Superperiodicity

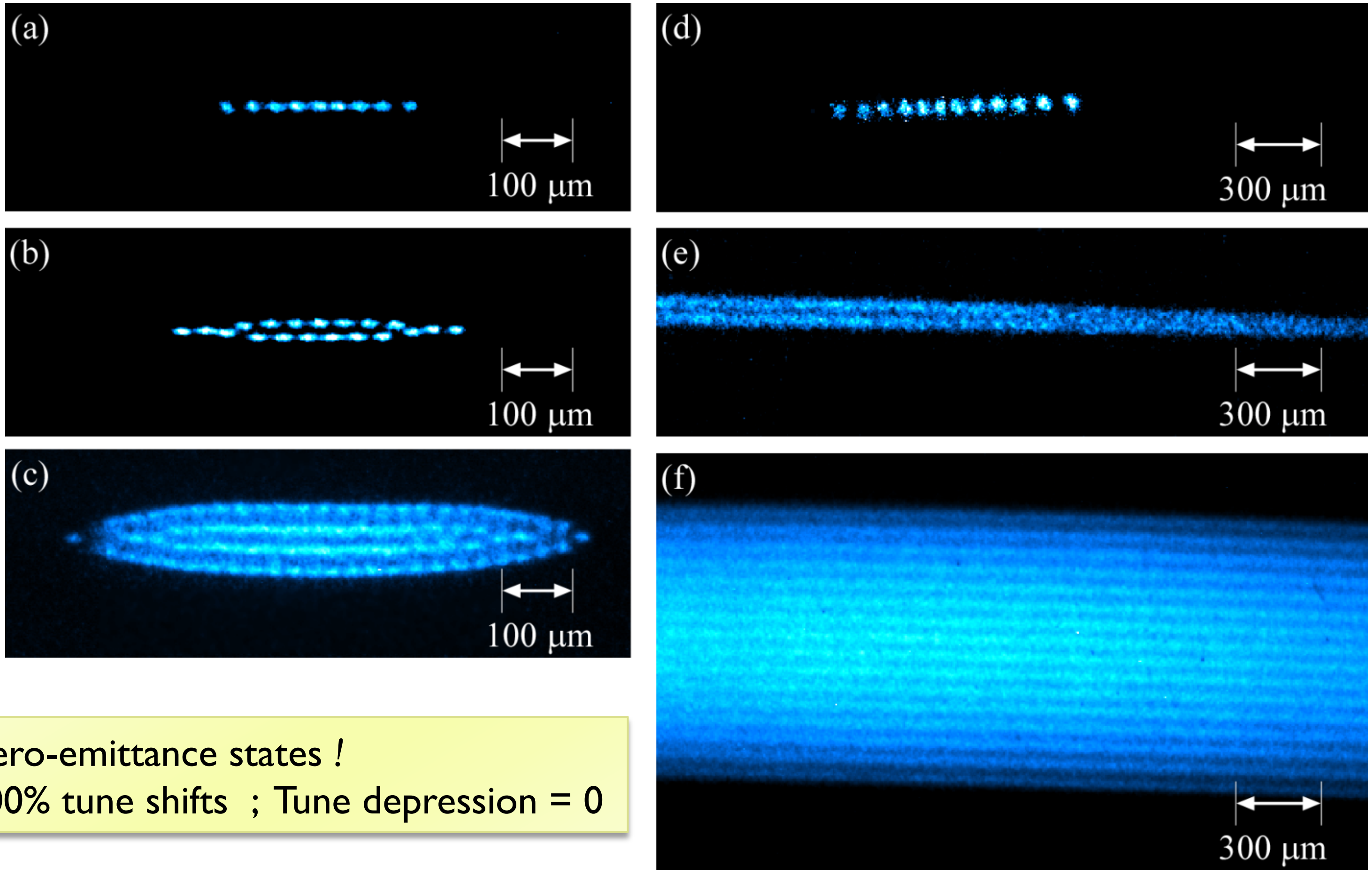


Ultralow Emittance Limit (*Coulomb Crystals*)

S-POD I

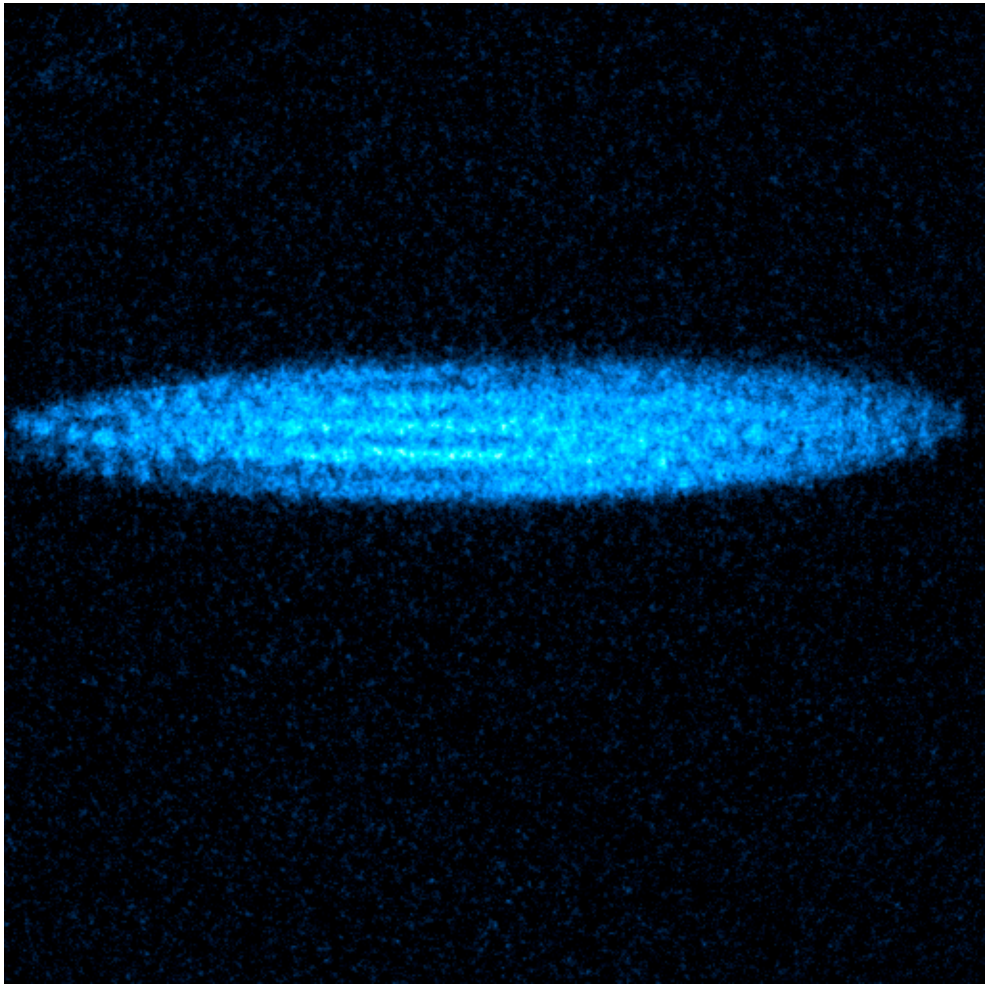
End-plate spacing = 6 mm

End-plate spacing = 60 mm



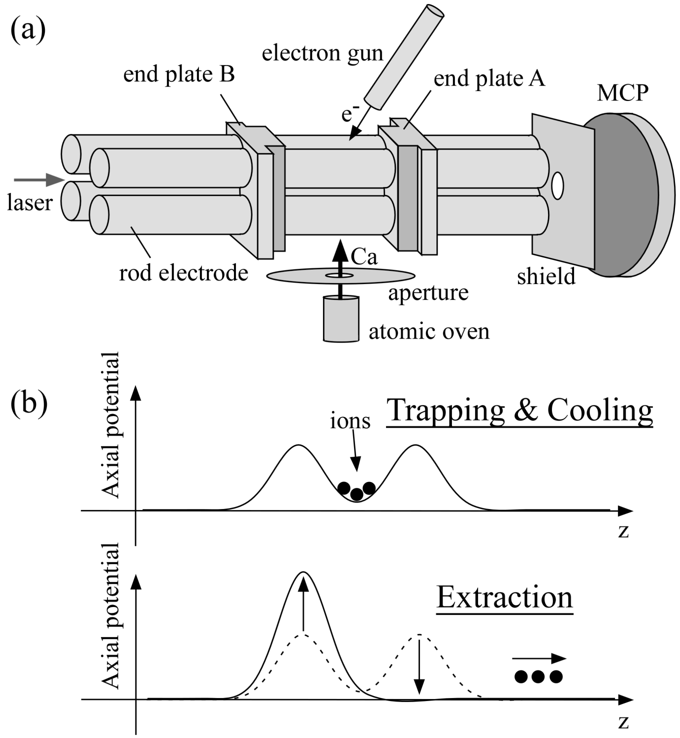
Zero-emittance states !
100% tune shifts ; Tune depression = 0

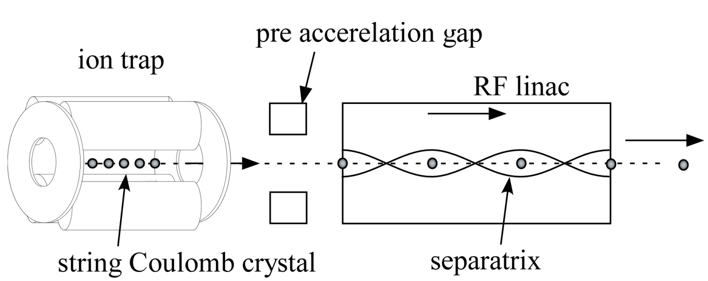
Crystalline Beam Stability

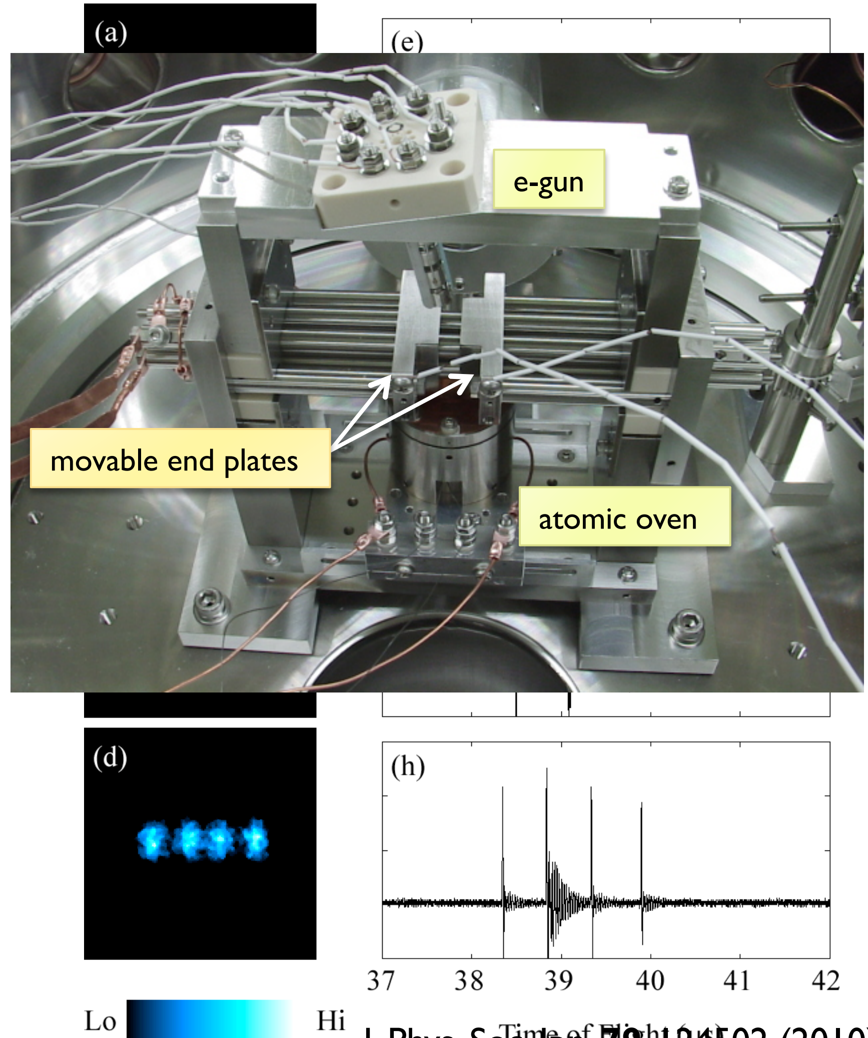


Select box to open film animation

Ion Machine Gun







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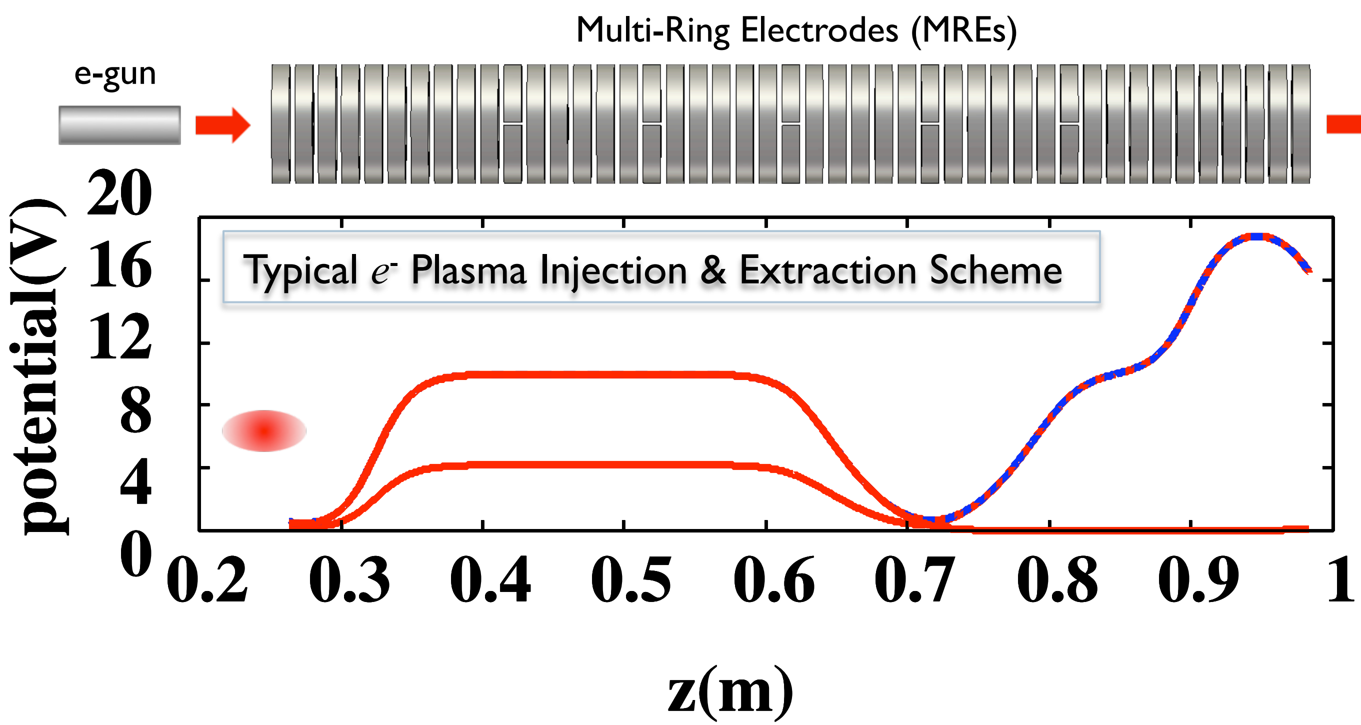
Halo Formation by Sudden External Disturbance

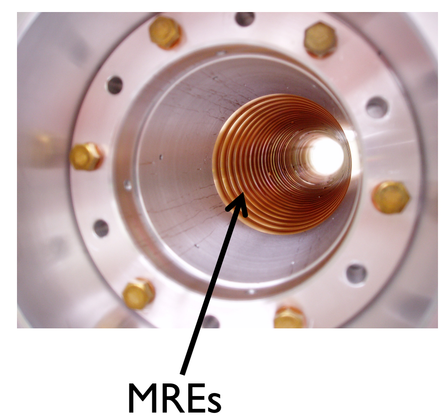
Hamiltonian in a rotating frame

$$H = \frac{\mathbf{p}^2}{2} + \frac{1}{2}\left(\frac{\omega_c}{c}\right)^2 r^2 + \frac{e}{mc^2}(\phi_{\mathrm{MRE}} + \phi_{sc})$$

$$\phi_{\mathrm{MRE}} \approx aV_0\left(z^2 - \frac{r^2}{2}\right)$$

We give an axially symmetric perturbation to the plasma by suddenly changing the DC voltage V_0 on the MREs.





Halo Measurements (Preliminary)

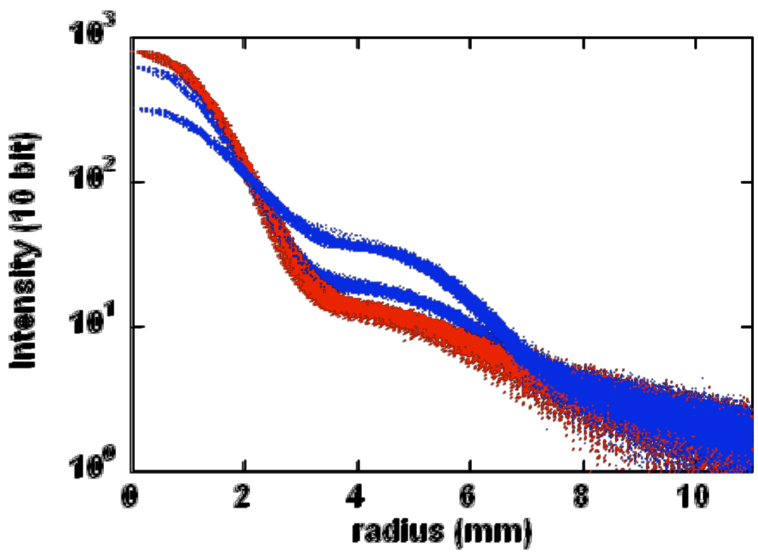
Axial magnetic field : 62.5 Gauss
Axial potential depth : (40 – 60) V
Cyclotron ang. freq. : 1.1 GHz
Brillouin density limit : 1.9 x 10^8 cm^{-3}

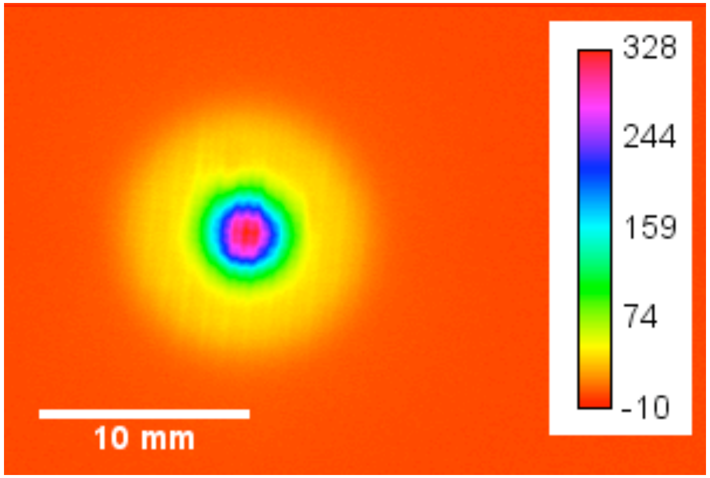
$$H = \frac{\mathbf{p}^2}{2} + \frac{1}{2}(k_\perp^2 - k_\parallel^2)r^2 + k_\parallel^2 z^2 + \frac{e}{mc^2}\phi_{sc}$$

The ratio $k_\perp / k_\parallel$ is less than 0.1 under the present experimental conditions.

Total number of electrons ~ 10^8 resulting in the *local* tune depression ~ 0.5 (max.)

DISTURBED : *z*-potential depth (40 V → 60V)





Summary

- Compact non-neutral plasma traps can be employed to experimentally simulate the collective beam behavior in AG focusing channels.
- The S-POD systems are now in operation at Hiroshima University.
- Detailed, systematic information on various resonance-related issues and beam-halo formation are being produced from S-POD.

> We believe that the present approach can be an alternative means or one of very useful options for us to study space-charge effects in high-intensity hadron accelerators.

- For more advanced, future experiments, we need
  - Further improvement of RF and DC power sources,
  - Fast multi-particle simulations,
  - Development of handy phase-space monitors,
  - More precise control of initial plasma conditions … etc.