Plasma Traps for Space-Charge Studies : Status and Perspectives

Hiromi Okamoto (Hiroshima Univ.)

Acknowlegements

Past and Present Contributors to the S-POD Project

- Hiroshima University

  Hiroyuki Higaki, Kiyokazu Ito

  (Students)

  M. Endo, S. Fujimoto, M. Fujioka, K. Fukata, K. Fukushima, H. Hitomi, K. Homma, M. Kano, Y. Mizuno, K. Moriya, K. Nakayama, S. Ohtsubo, K. Okabe, S. Sakao, H. Sugimoto, H. Takeuchi, K. Tanaka, R. Takai, G. Uchimura, S. Yamaguchi
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Purpose

Systematic experimental studies of various space-charge effects in high-intensity and high-brightness hadron beams

Use of **non-neutral plasmas**
physically equivalent to charged-particle beams in periodic AG channels

- At Hiroshima University, compact non-neutral plasma trap systems have been developed solely for beam physics purposes.
- The tabletop experimental tool for space-charge studies are called

S-POD (Simulator for Particle Orbit Dynamics).

- Three Paul ion traps and a Penning electron trap are now employed to explore the collective behaviors of intense hadron beams systematically.

Principle of S-POD Experiments

Charged-particle beams in an AG focusing channel

$$H_{beam} = \frac{1}{2}(p_x^2 + p_y^2) + \frac{1}{2}K_Q(x^2 - y^2) + \frac{q}{m\gamma^3(\beta c)^2}\phi$$

Non-neutral plasmas in a trap system

$$H_{plasma} = \frac{1}{2}(p_x^2 + p_y^2) + \frac{1}{2}K_{RF}(x^2 - y^2) + \frac{q}{mc^2}\phi$$

Both interacting many-body systems obey the following equations:

- Poisson equation $$\Delta\phi = -\frac{q}{\varepsilon_0}\int f(\mathbf{r},\mathbf{p};t)d^3\mathbf{p}$$
- Vlasov equation $$\frac{\partial f}{\partial t} + [f, H] = 0$$

Two systems are physically equivalent if governed by similar Hamiltonians.

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

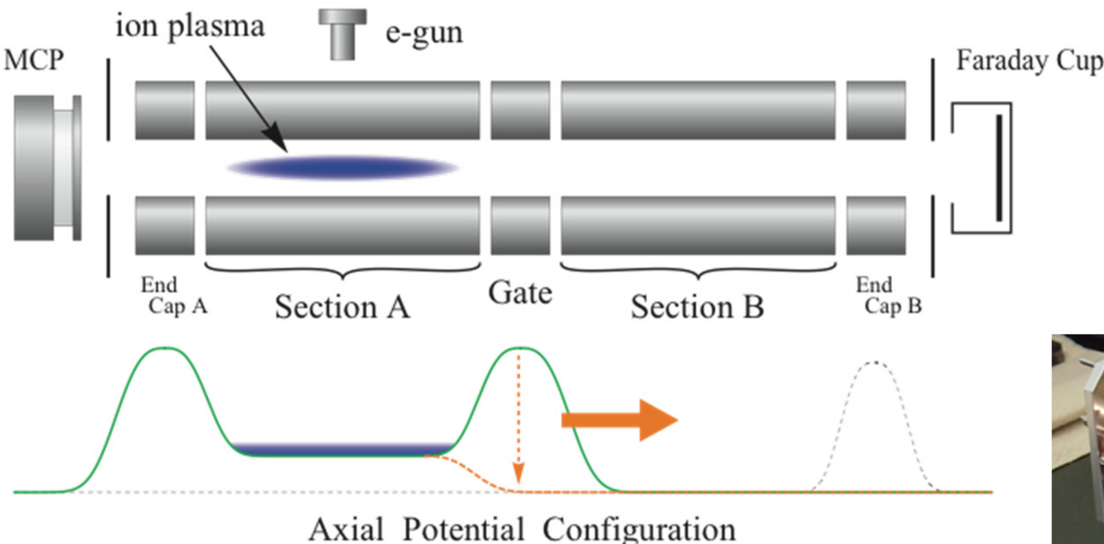
Why Traps ?

- Very compact
  - ➡ Table-top size (Our Paul traps are shorter than ~20 cm in axial length.)
- Low cost
  - ➡ We have several traps of different designs, each of which costs a few k$.
- Extremely wide parameter range
  - ➡ Easy control of tunes and tune depression (and even lattice structures)
- High resolution & precision measurements
  - ➡ MCPs, Faraday cups, and laser-induced fluorescence (LIF) diagnostics
- No radio-activation
  - ➡ No machine damage from any large particle losses

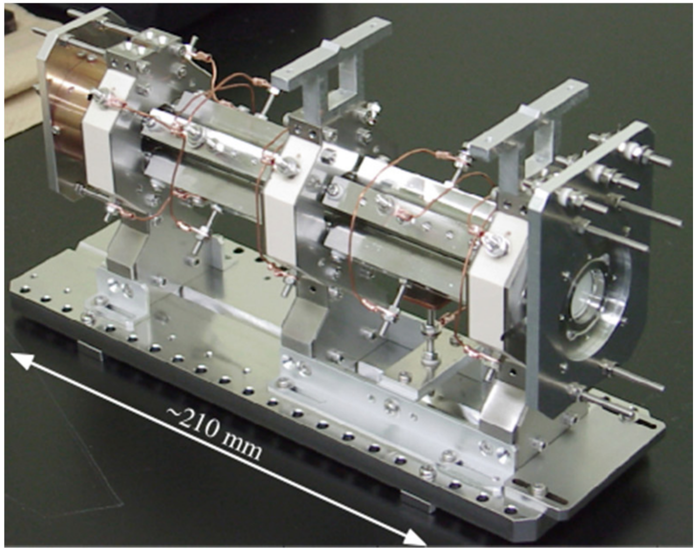
Present Status

RF Ion Trap

- Linear Paul Trap



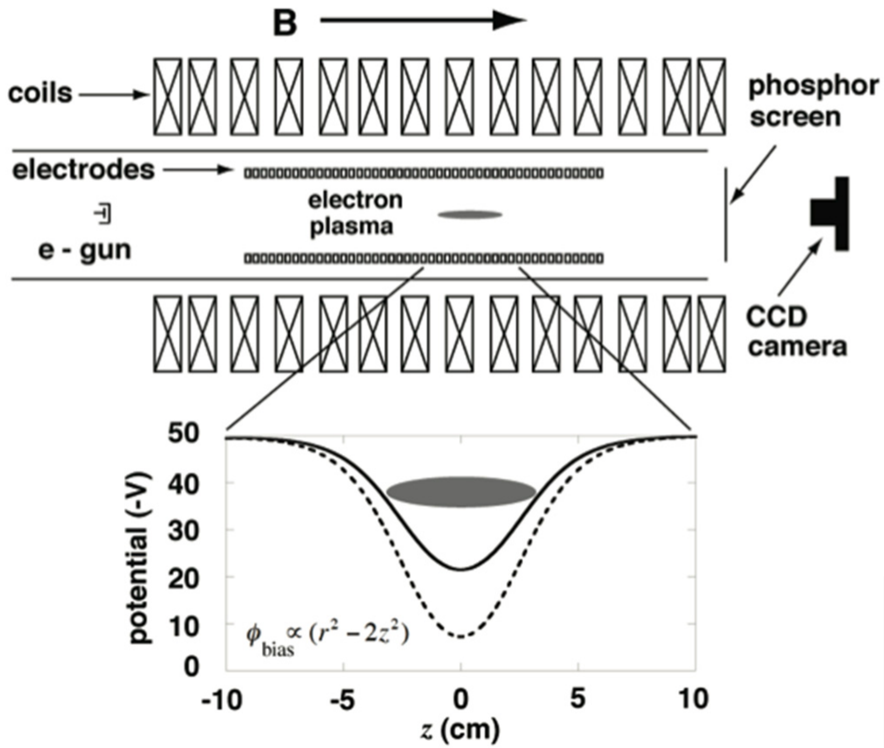
* Operating frequency : 1 MHz
* Particle species : Ar^+, Ca^+, N^+, etc.
* Plasma lifetime : order of seconds (dependent on plasma conditions)
* Tune depression : < 0.8 (without cooling)
* Cost : a few thousand USD !

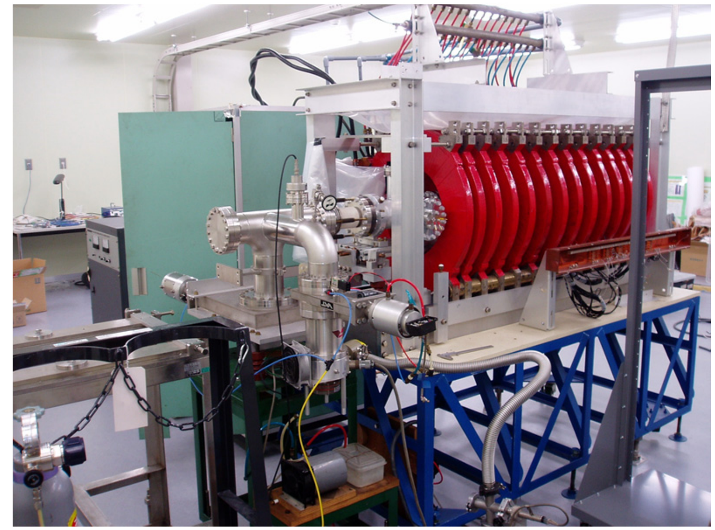


Transverse confinement :
rf quadrupole
Longitudinal confinement :
rf or electrostatic potential

Magnetic Trap

- Penning Trap with Multi-Ring Electrodes



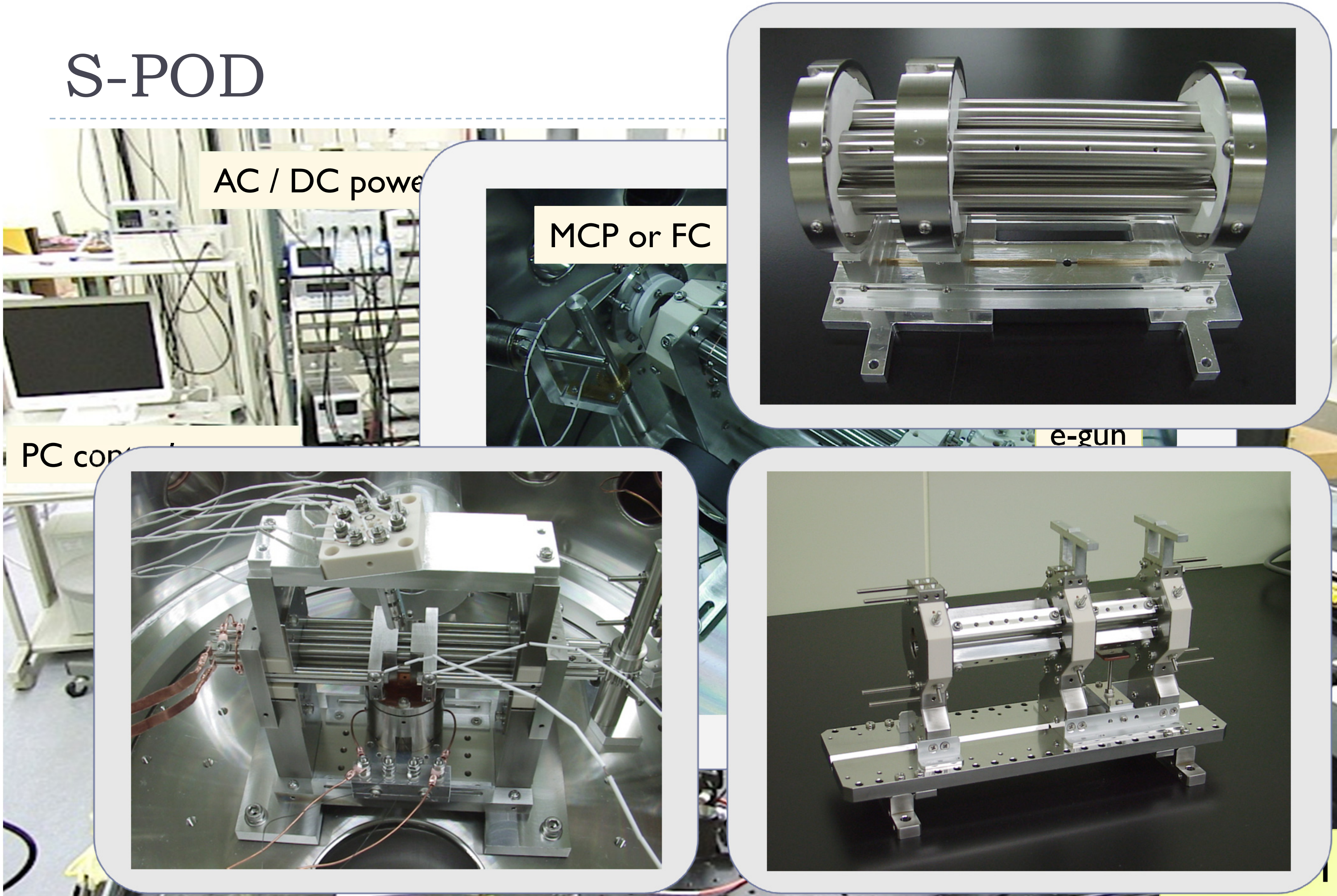


* Particle species : e^-

* Field strength : < 500 G

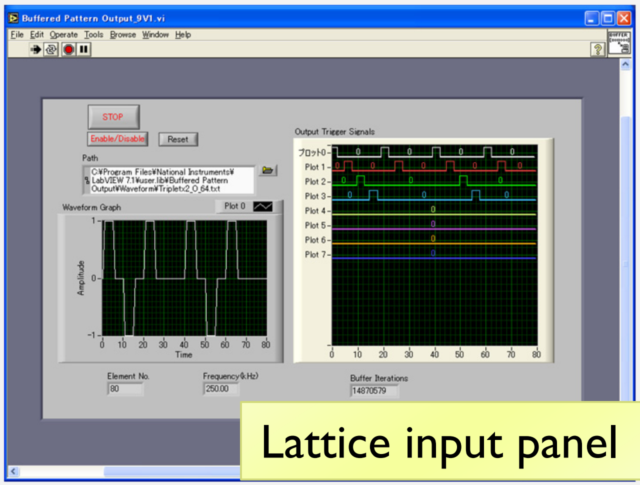
Transverse confinement :
axial magnetic field
Longitudinal confinement :
electrostatic potential
(+ magnetic mirror)

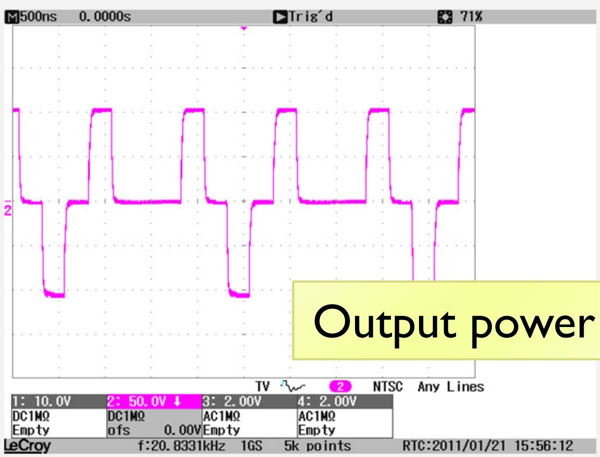
S-POD



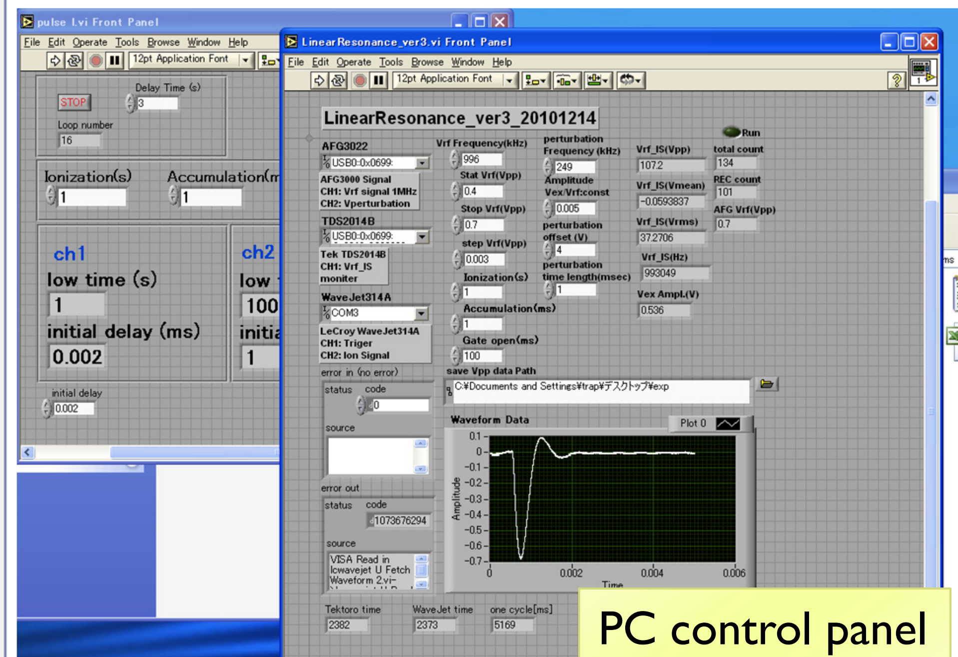
- Resonance crossing

Control System


Lattice input panel


Output power

All experimental procedures are automated.


PC control panel

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

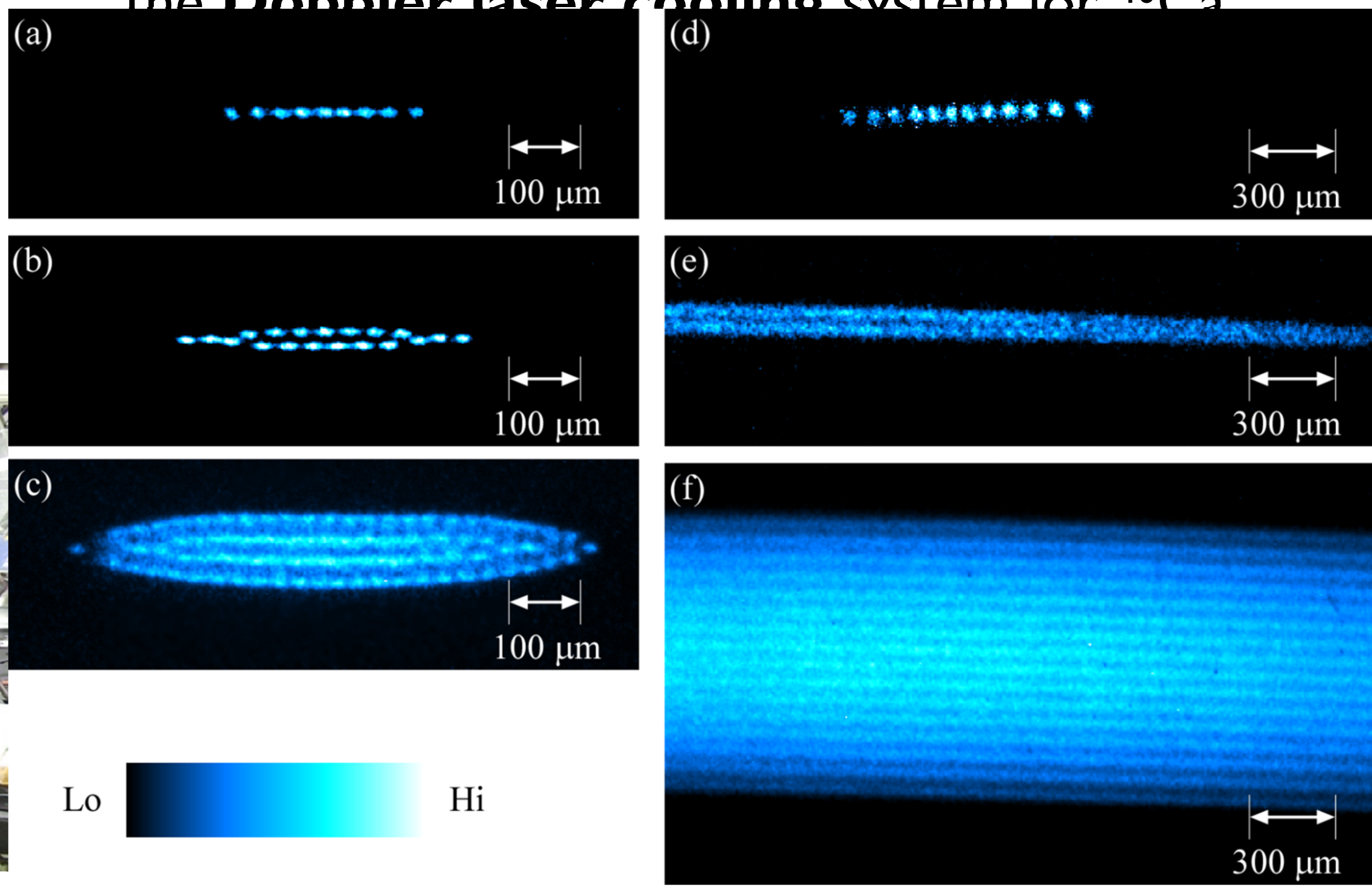
Ultimate Control of Tune Depression

S-POD I and II are equipped with the Doppler laser cooling system for $^{40}Ca^{+}$

S-POD I

End-plate spacing = 6 mm

End-plate spacing = 60 mm



Recent S-POD Experiments

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

Stop Bands in Doublets

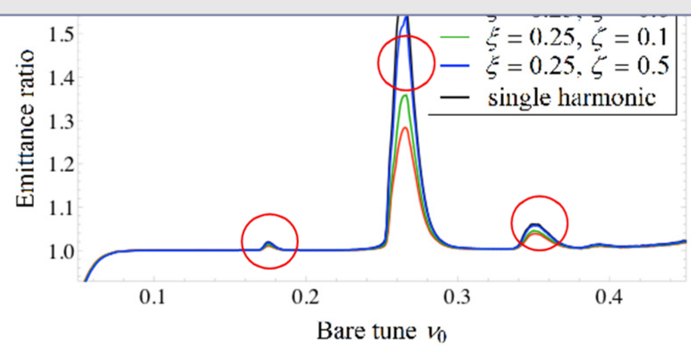
- WARP
- S-POD

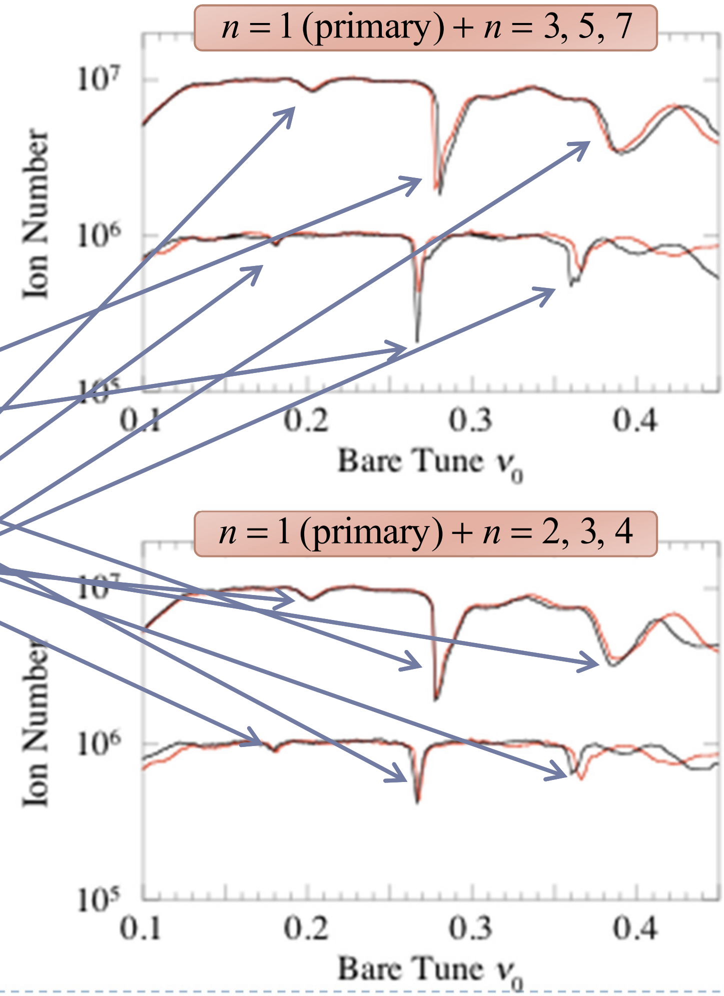
Collective Resonance Condition

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

For $P = 1$,

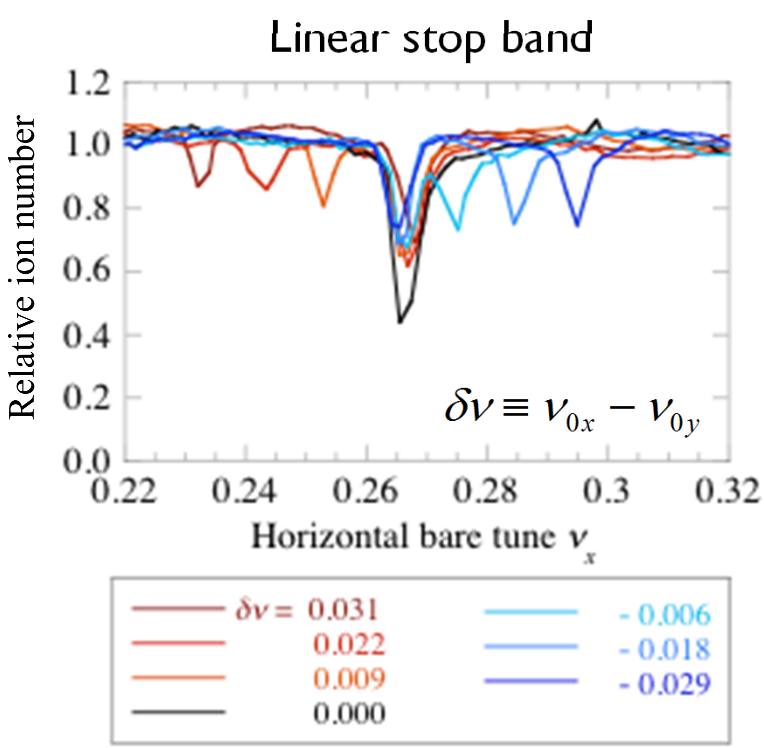
- Linear $(m = 2)$: $\nu_0 - C_2 \Delta\nu \approx \frac{1}{4}$
- Third-order $(m = 3)$: $\nu_0 - C_3 \Delta\nu \approx \frac{1}{6}, \frac{2}{6}$



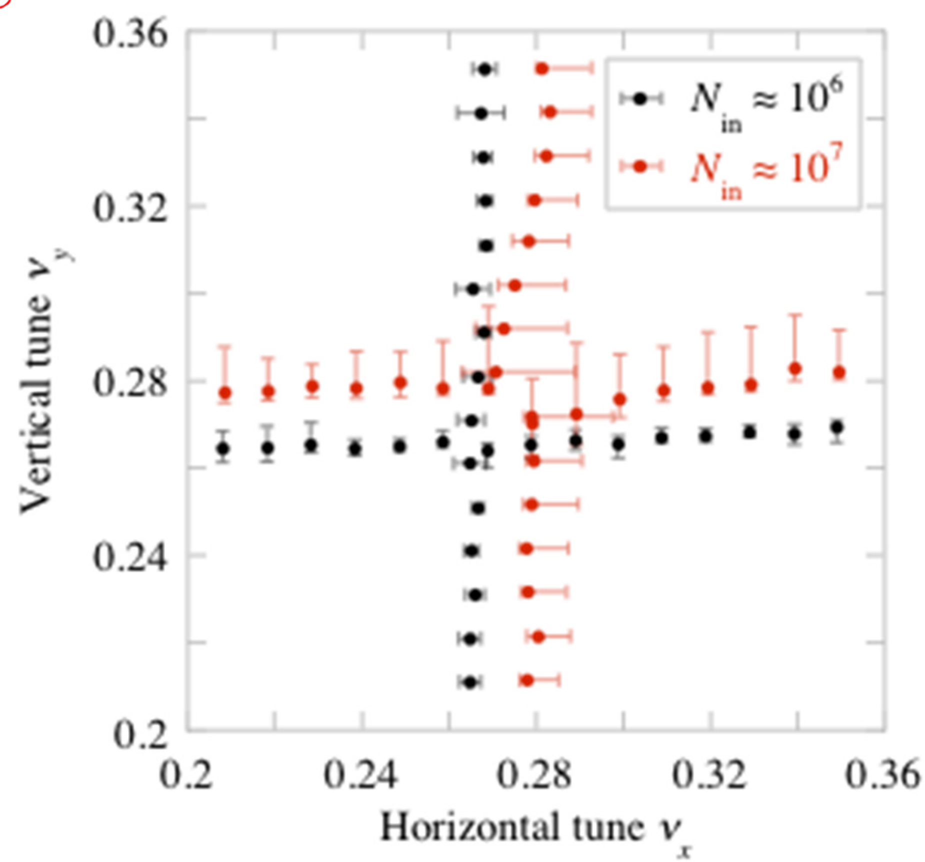


Stop-Band Splitting : S-POD Experiments

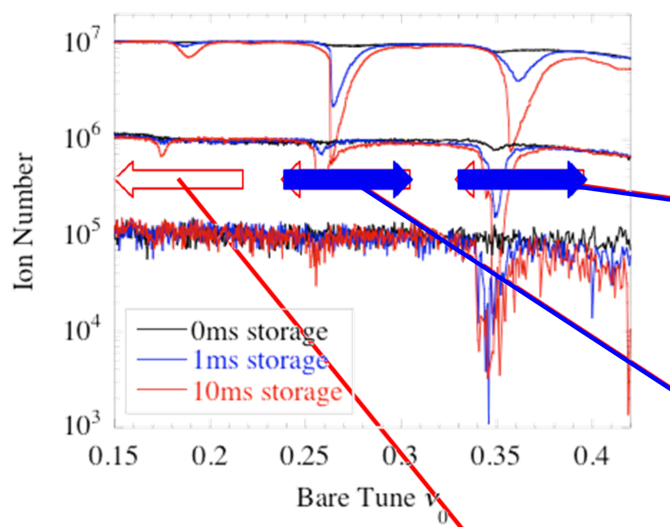
When $\nu_{0x} \neq \nu_{0y}$, all stop bands split !

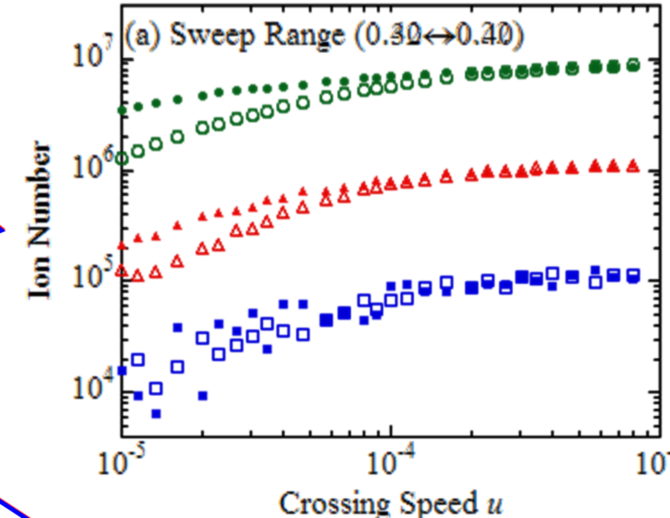


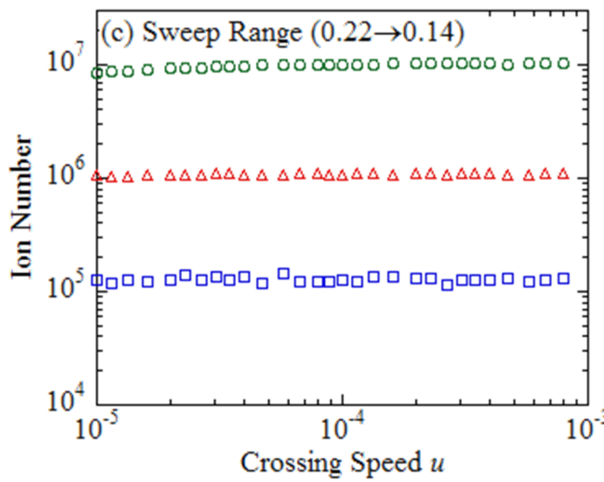
Tune Diagram

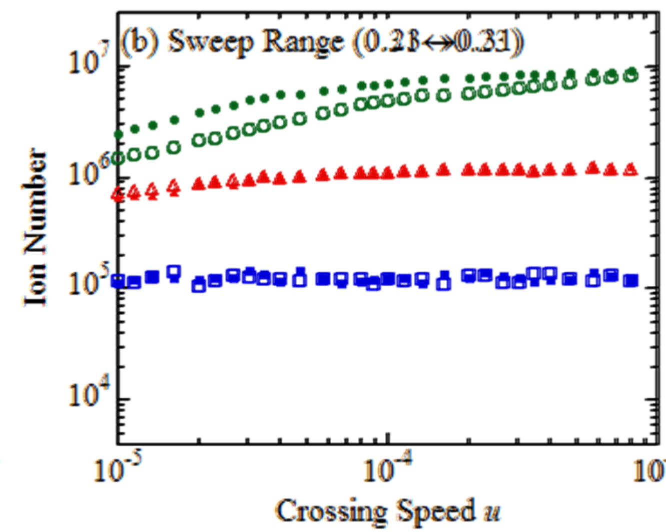


Resonance Crossing : S-POD Experiments









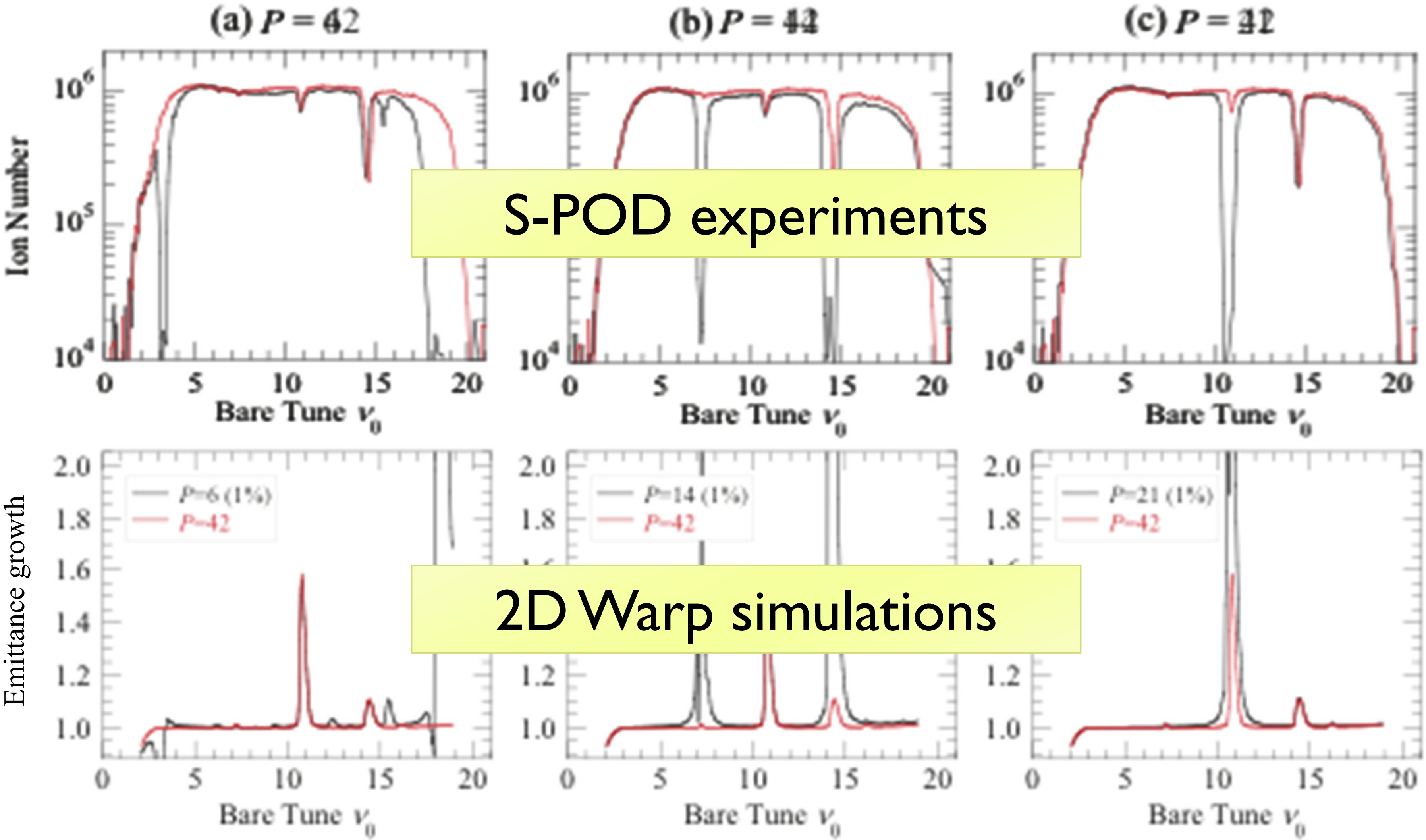
Crossing Speed

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

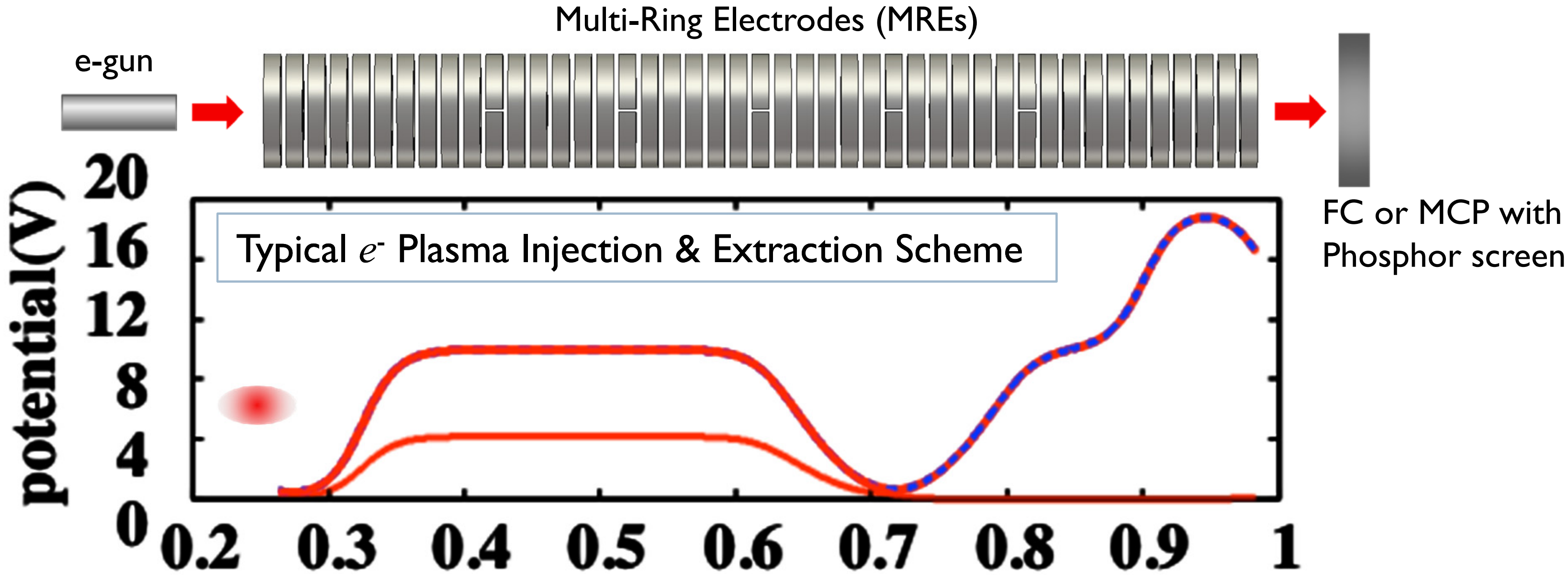
δ : tune-sweep width

n_{rf} : rf period for tune sweep

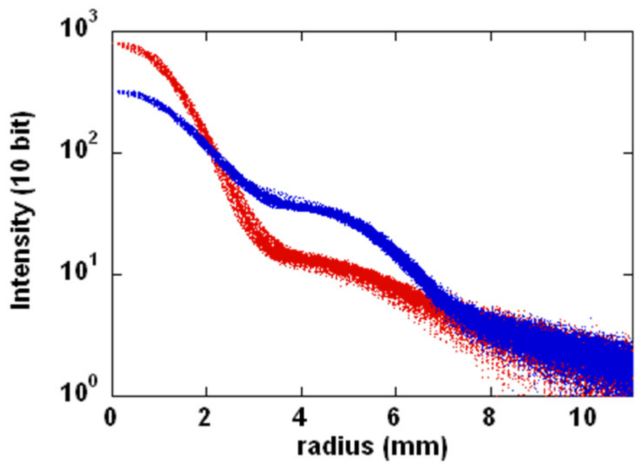
Effect of Lattice Superperiodicity

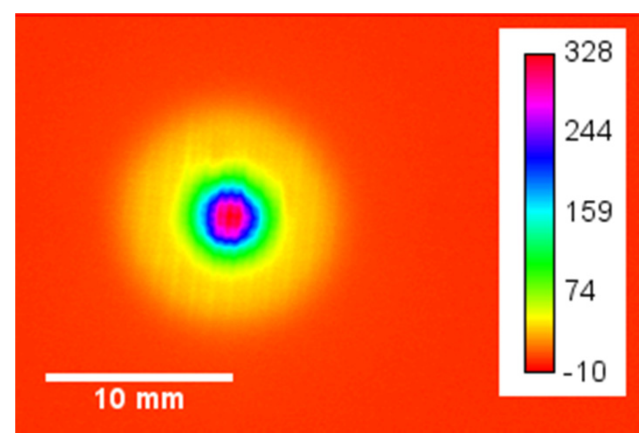


Halo Formation by Sudden External Disturbance



NO DISTURBED
V_z (40 V → 60V)





Summary and Near-Future Plans

Present Status

What we have now are :

- Three electric S-PODs based on Paul traps
- One magnetic S-POD based on a Penning trap

• 20% space-charge-induced tune shift available without any particular plasma cooling
• Ar^+ or Ca^+ ion plasmas for the Paul traps & pure electron plasmas for the Penning trap

What we can do now are :

- Collective resonance excitation
- Arbitrary lattice emulation (but mostly the sinusoidal-wave model employed so far)
- Forward and backward resonance crossing
- Mismatch-driven halo formation
- Coulomb crystal generation

Possible Near-Future Plans

- Construction of ***a new Penning trap***
- ***Dipole resonance*** excitation
- More experiments on ***longitudinal dynamics***
  - Synchrotron resonances
  - Synchro-betatron resonances
  - Longitudinal bunch compression
- Space-charge effects on ***bunch aspect ratio*** and ***exact lattice structures***
- Detailed study of ***halo formation***

Experiment proposals, suggestions, and comments very welcomed !

- Full-range control of tune depression (from 0 to 1)
- Plasma stacking scheme
- RF power generator improvement
- New cold ion-beam source
- Fast pulse magnetic-field generator
- New diagnostic system development
  - Compact emittance monitors
  - Laser-induced fluorescence diagnostics

Technical Issues