# Non-neutral Plasma Traps for Accelerator-free Experiments on Space-charge-dominated Beam Dynamics

Hiromi Okamoto (Hiroshima Univ.)

and the members of the HU Beam Physics Group

# Motivations

Recent worldwide interest in intense or low-emittance beams

(Neutron sources and other high-power machines; Progress in various beam cooling techniques)

Necessity of understanding "**space-charge effects**"

(Important to clarify the fundamental mechanisms and parameter-dependence of SCEs.)

BUT

*Many limitations both experimentally and theoretically …*

- Parameters (tune, beam density, lattice, etc.) are not so flexible in real machines.
- High precision measurements are always troublesome (because any beams are travelling at relativistic speed in the lab frame).
- Too much beam losses are not acceptable in practice (to avoid machine damages).
- The basic equations are too complex to allow rigorous analytic calculations.
- Trustable 3D numerical simulations are very time-consuming.

*Alternative methods and/or tools should be developed for detailed SCE studies.*

# Principle

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 $$\frac{\partial f}{\partial t} + [f, H] = 0$$

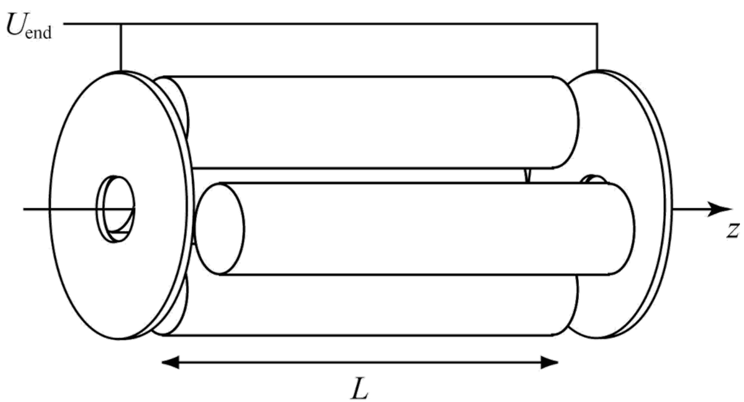
*Two systems are physically equivalent if governed by similar Hamiltonians.*

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

First proposal : H. Okamoto and H. Tanaka, NIM A **437** (1999) p.178.

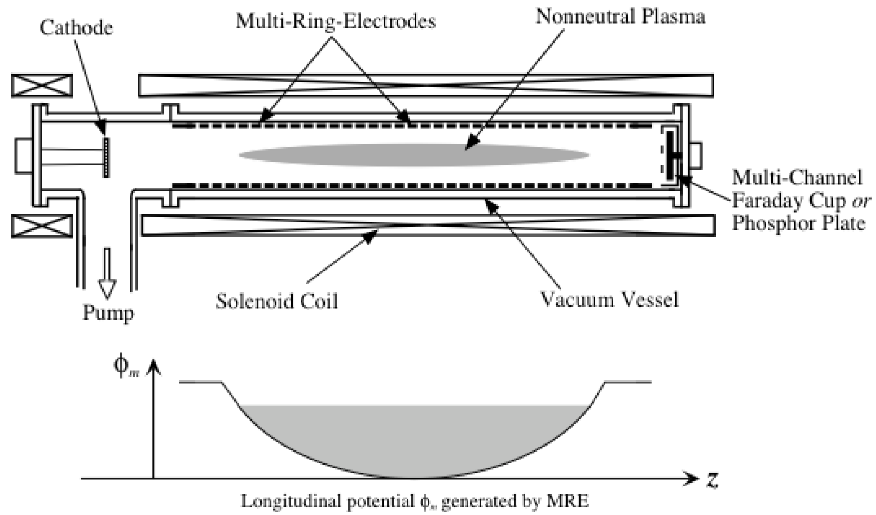
# Typical Non-neutral Plasma Traps

- Linear Paul Trap




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

- Multi-Ring-Electrode Trap




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

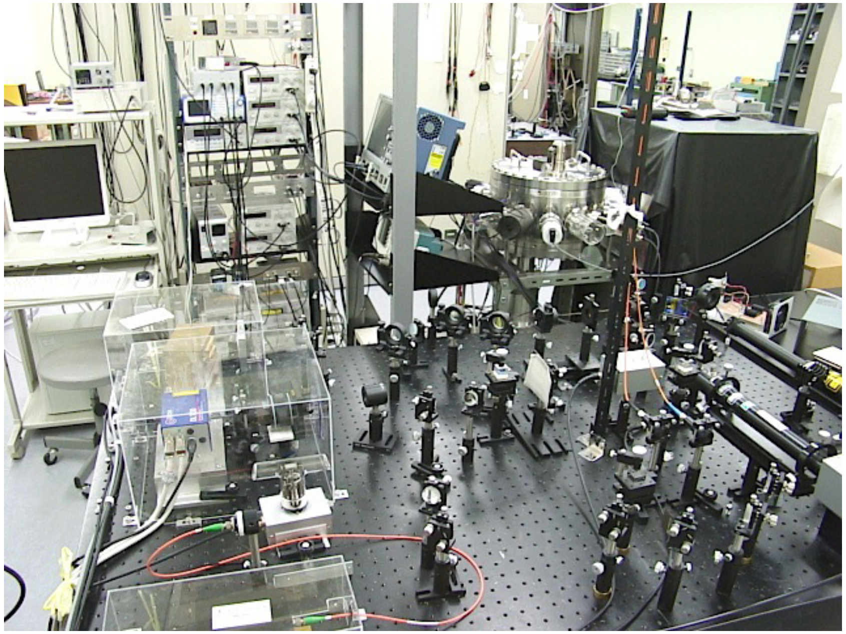
# Why traps ?

- 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

# Trap Systems at Hiroshima

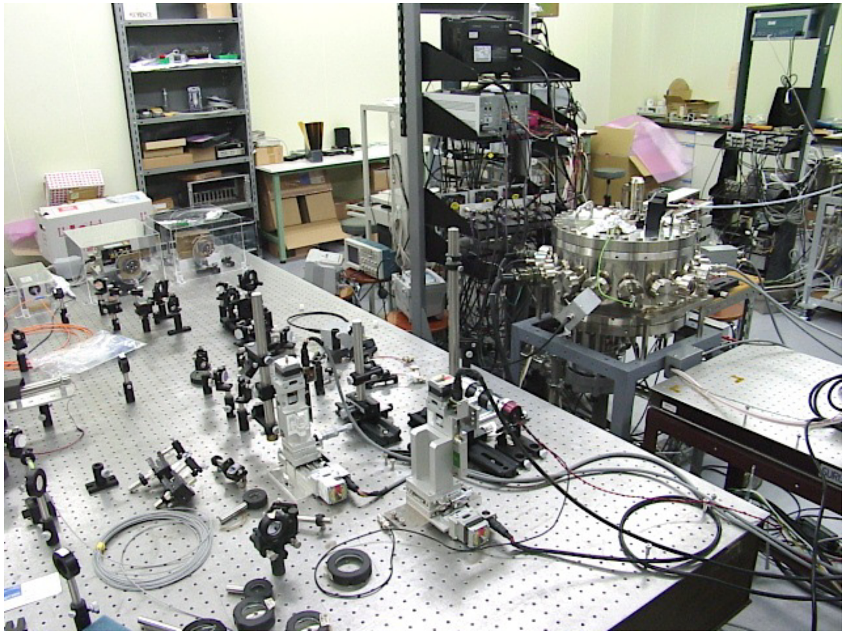
S-PODs (Simulator for Particle Orbit Dynamics)

## Paul trap I



- Nano-ion-beam production
- Coulomb crystal stability, etc.

## Paul trap II

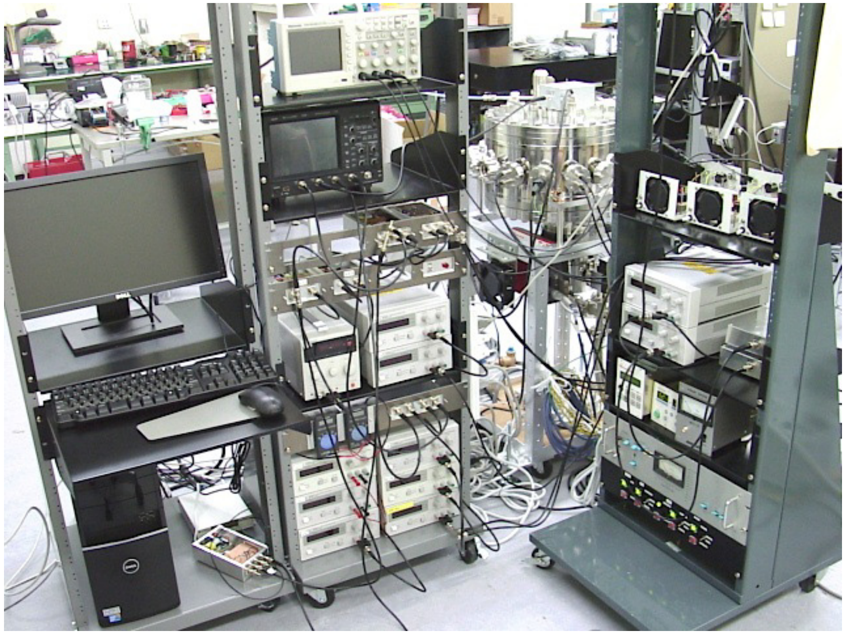


- Coherent resonances
- Lattice-dependent effects

# Trap Systems at Hiroshima (cont.)

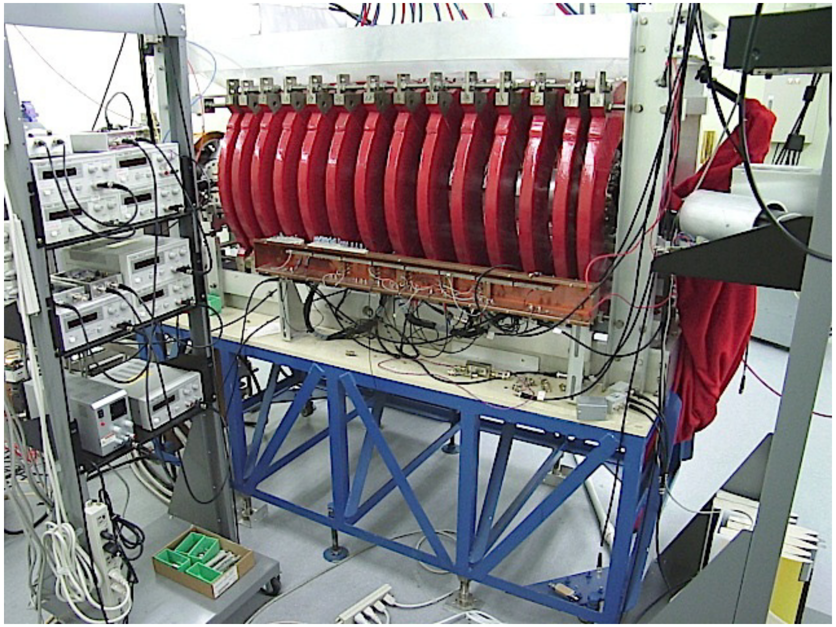
S-PODs (Simulator for Particle Orbit Dynamics)

## Paul trap III *(under test)*



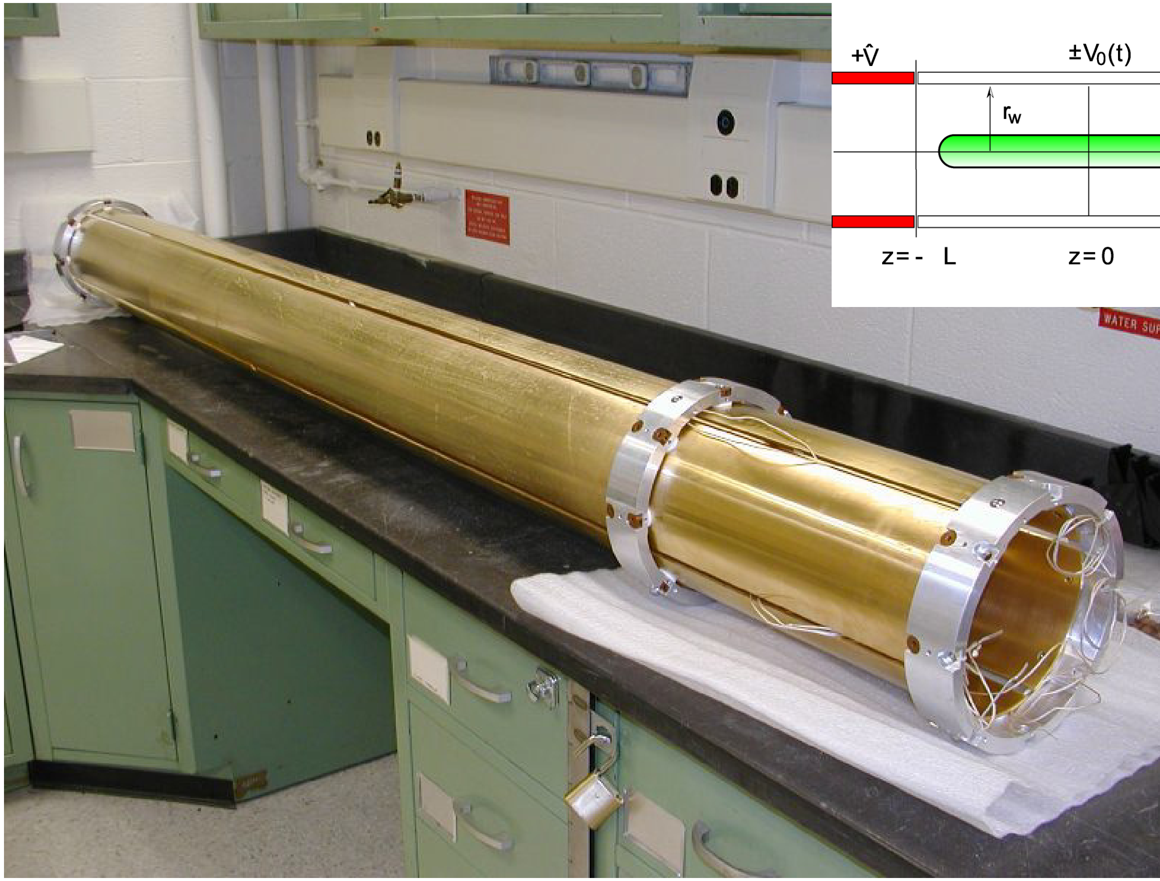
- Resonance crossing, etc.

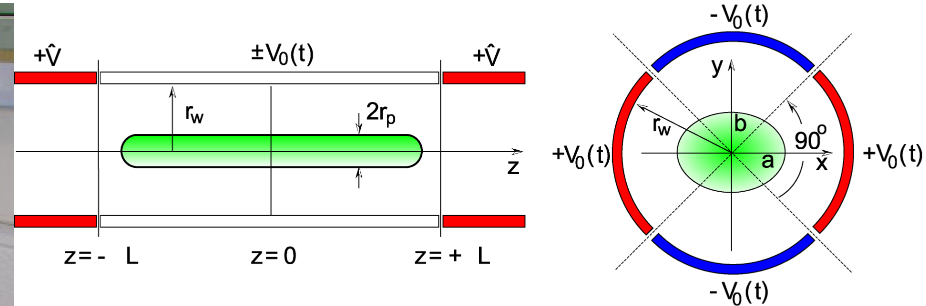
## MRE trap



- Halo formation, etc.

# Trap System at Princeton



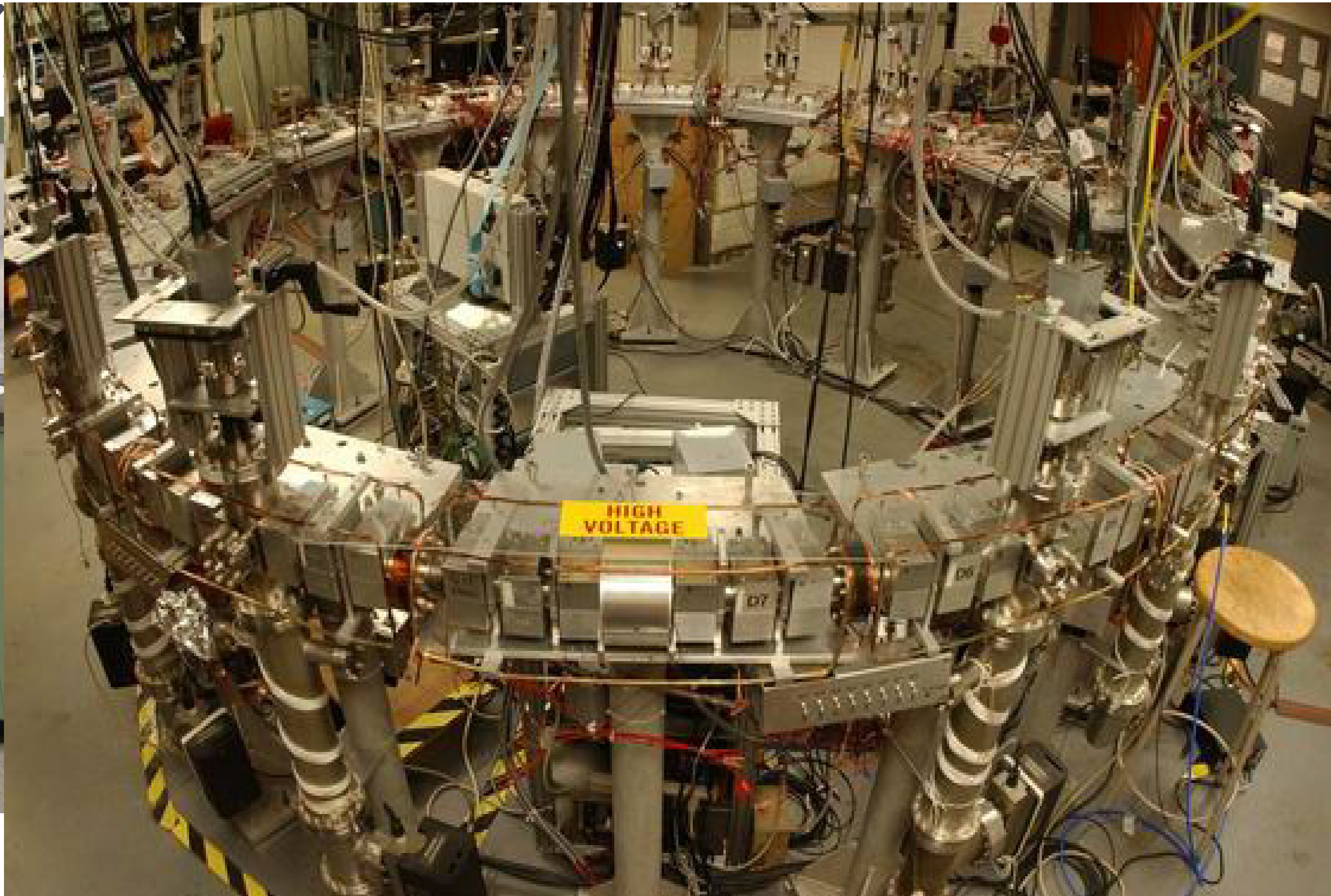




Cylindrical Paul Trap

- Axial length ~ 280 cm
- 20 cm in diameter
- RF frequency less than 100 kHz
- Maximum RF amplitude ~ 400 V
- End electrode voltage < 150 V

(From PPPL homepage)

Ref.: R. C. Davidson, H. Qin, G Shvets, Phys. Plasmas 7, 1020 (2000).
E. P. Gilson et al., Phys. Rev. Lett. 92, 155002 (2004).



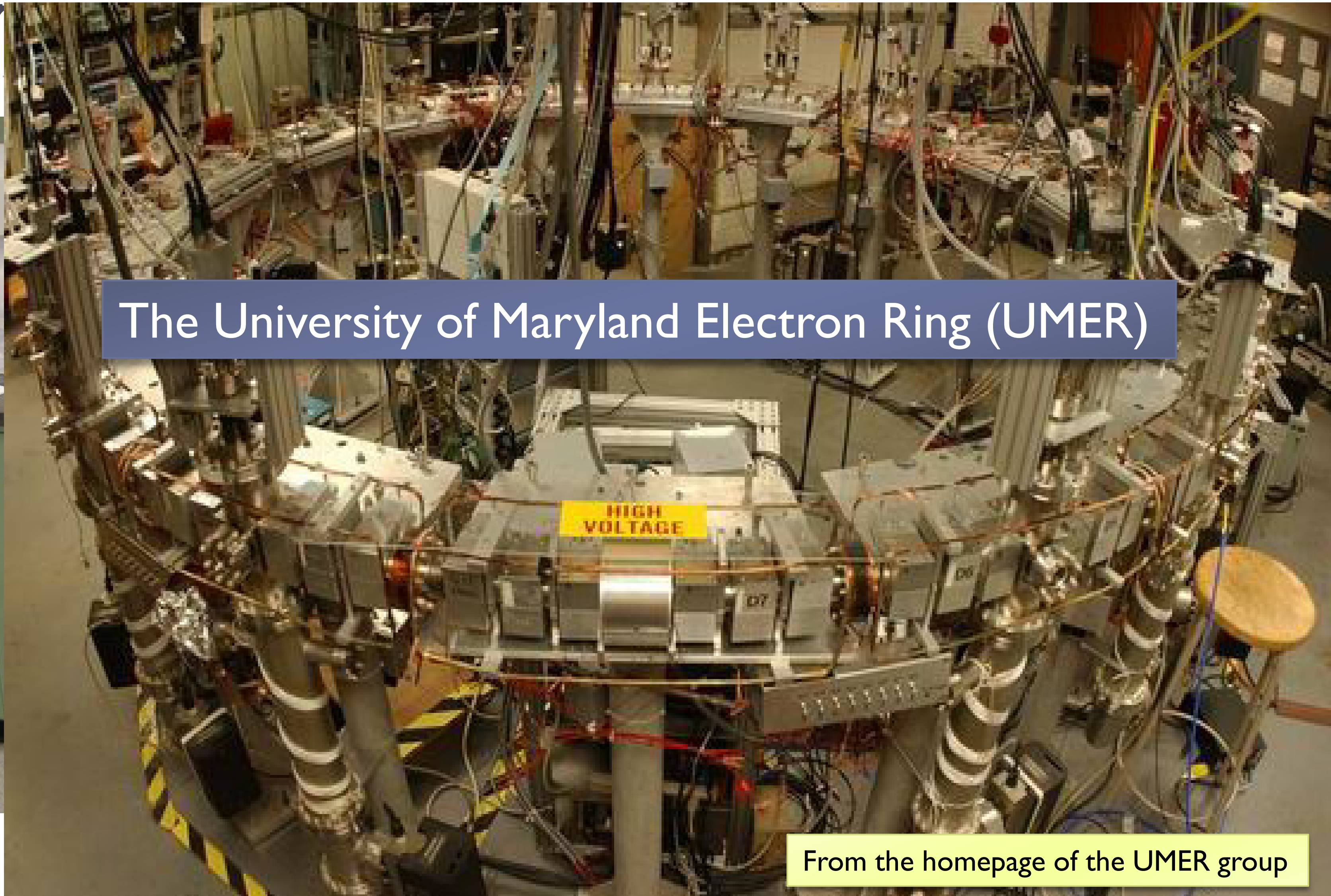

kHz

00

V

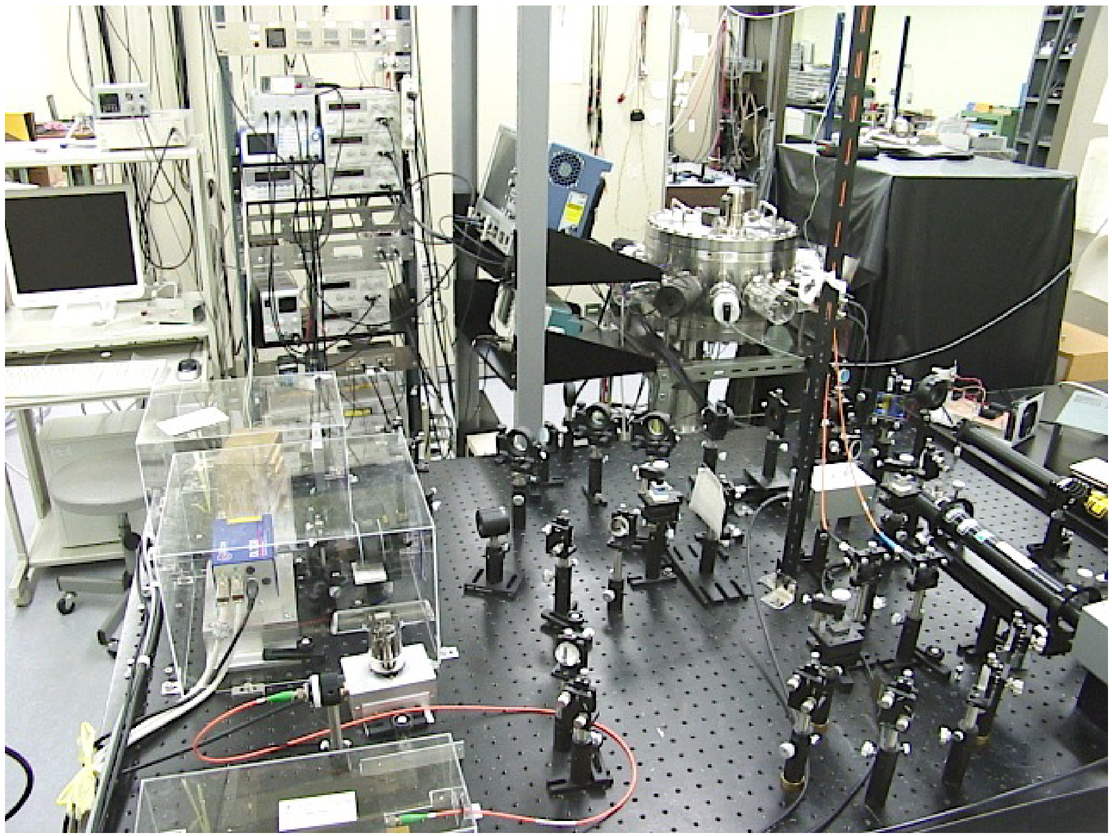
ge)

# The University of Maryland Electron Ring (UMER)




From the homepage of the UMER group

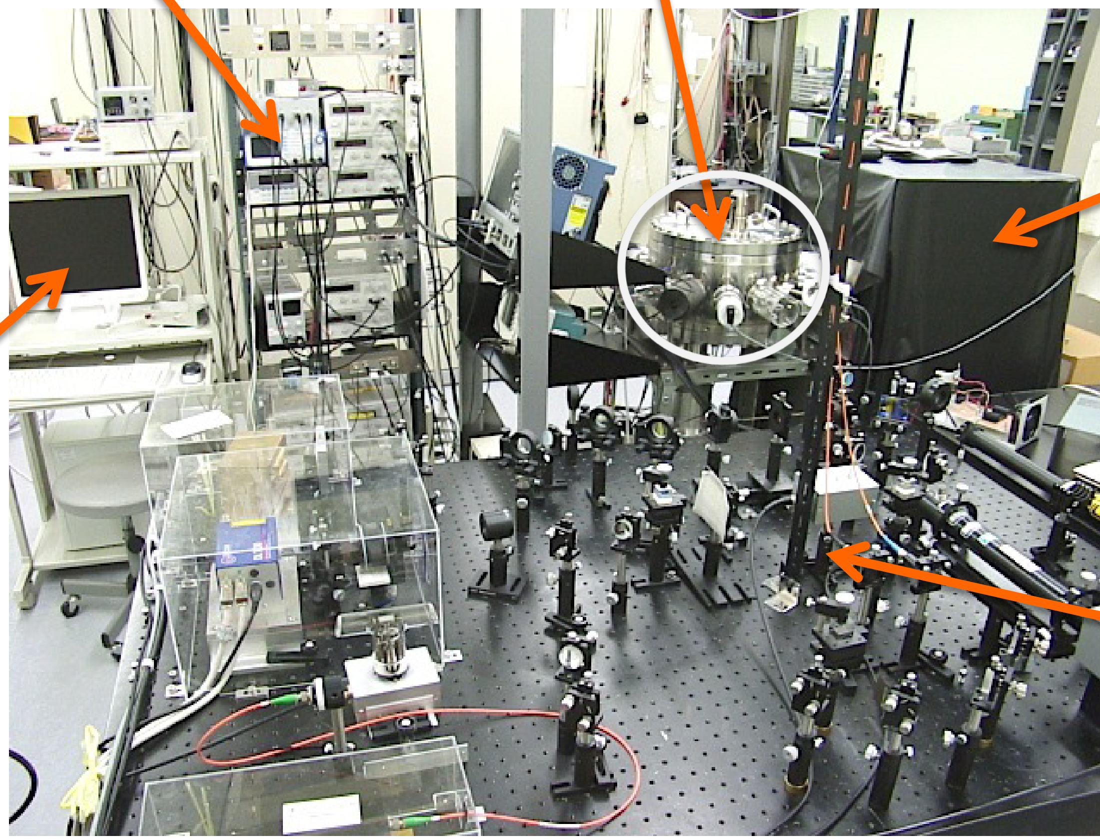
# S-POD Components



# S-POD Components

AC & DC Power Sources

Vacuum System



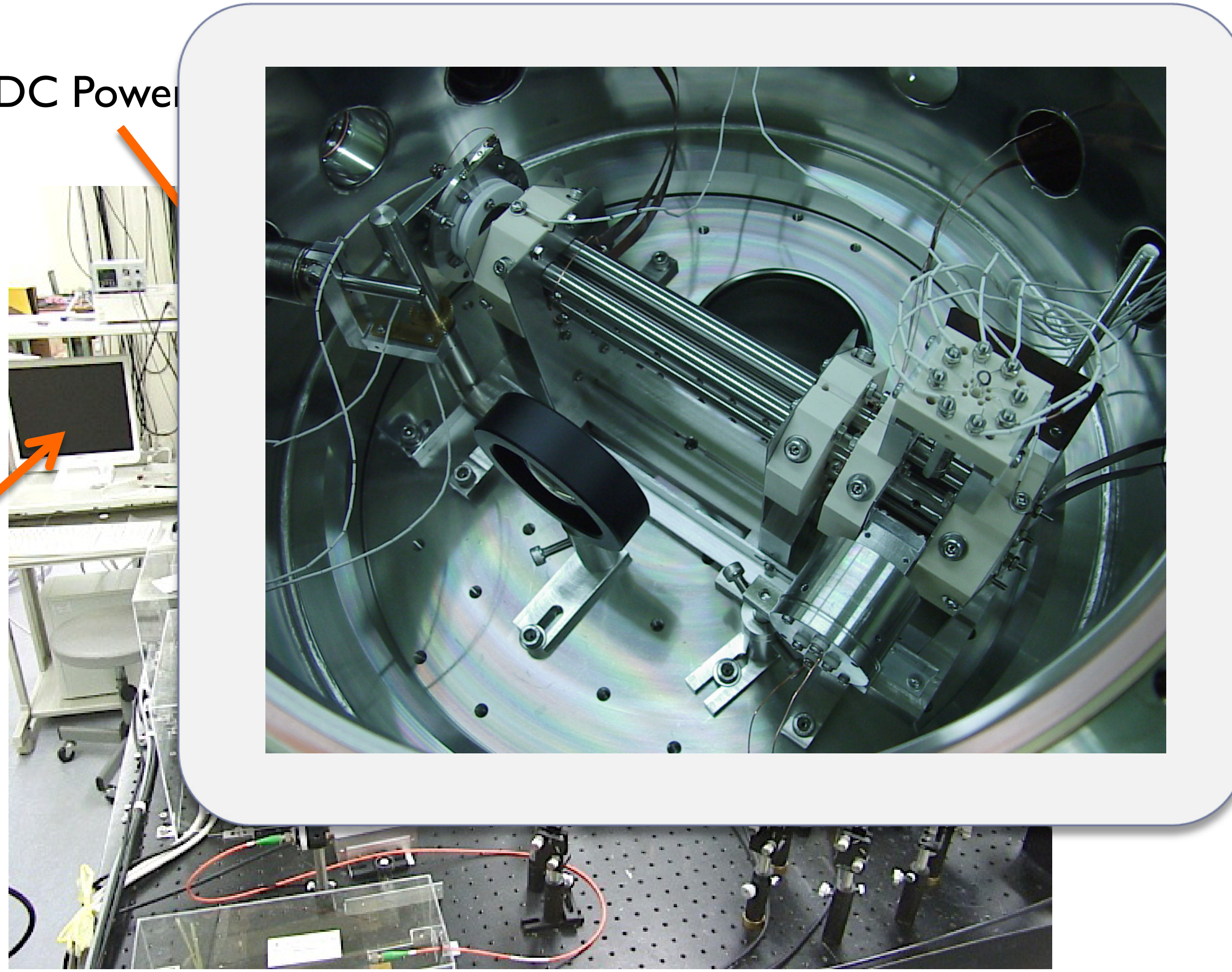
CCD Camera

PC Control System

Laser System

# S-POD Components

AC & DC Powe



amera

PC Control System

ystem

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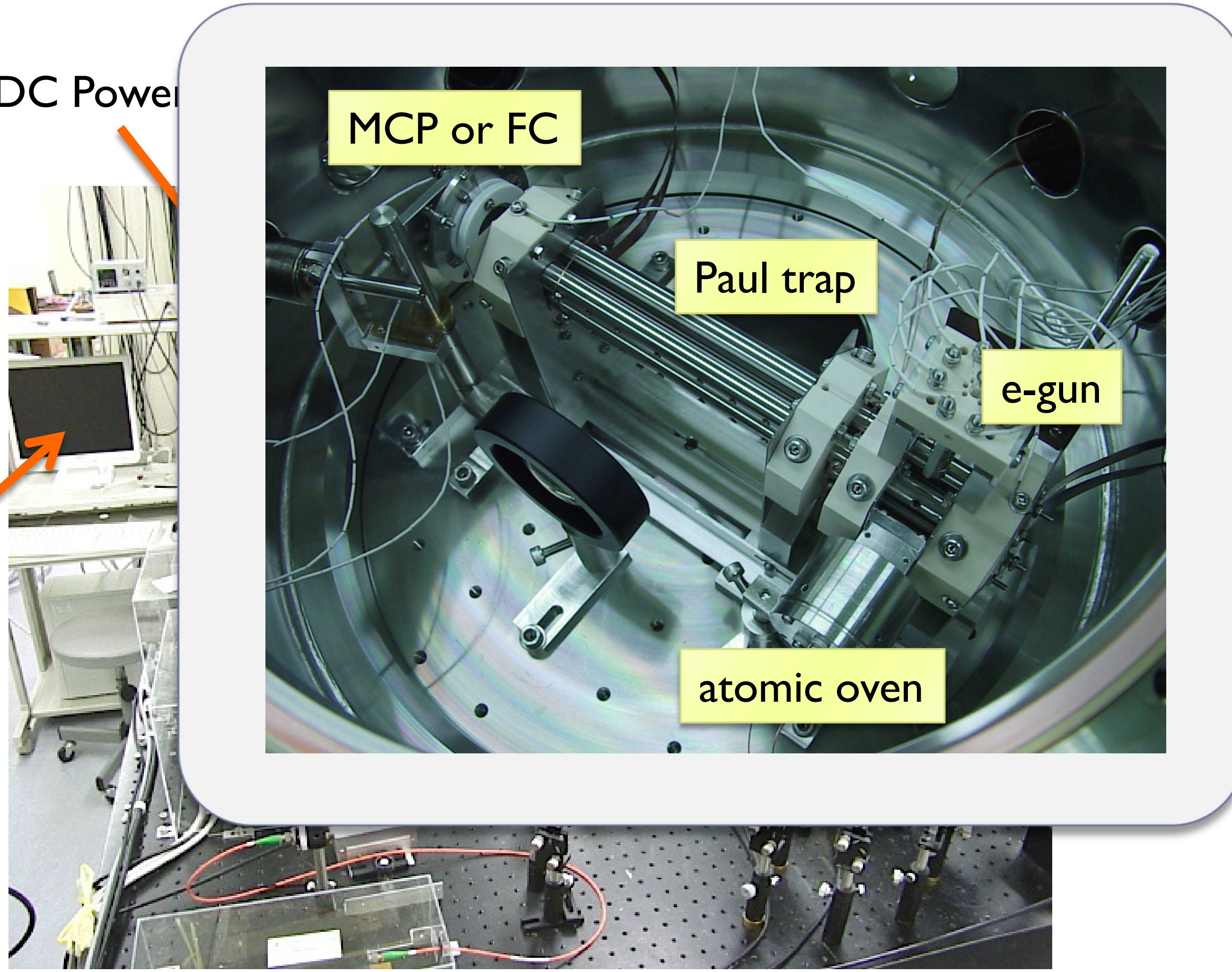
AC & DC Powe

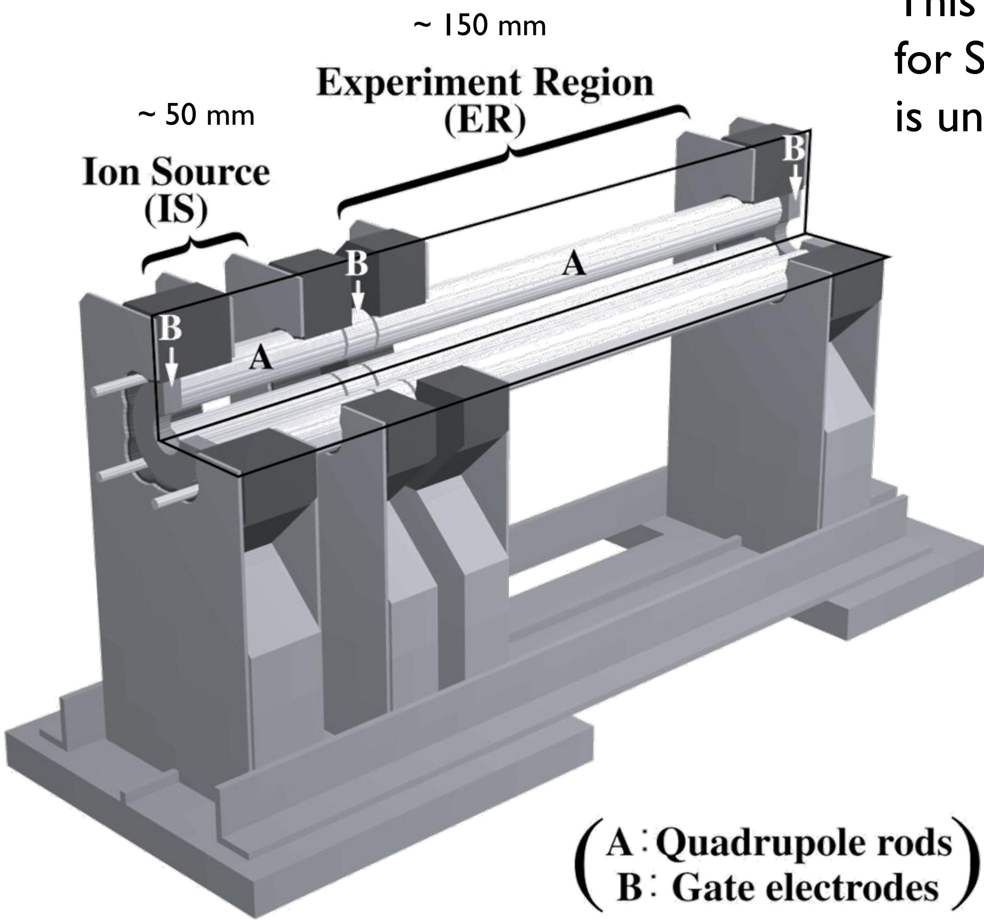
PC Control System

amera

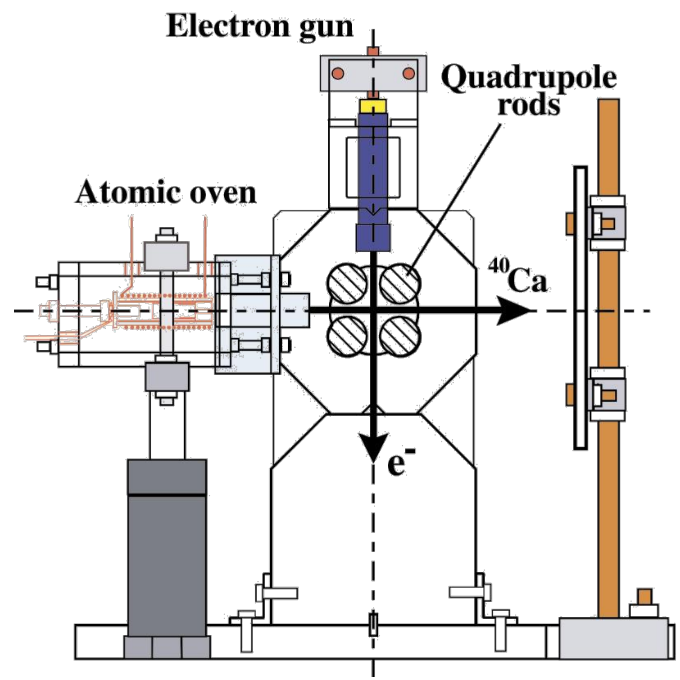
ystem



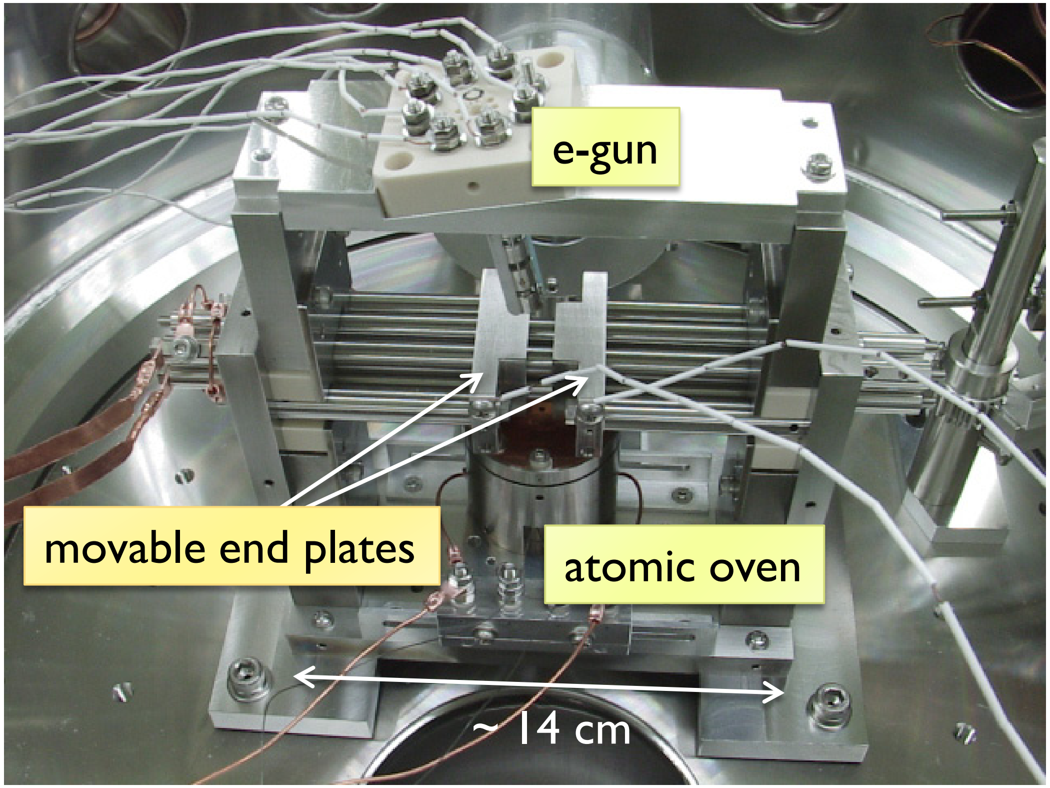
# Multi-sectioned Linear Paul Trap

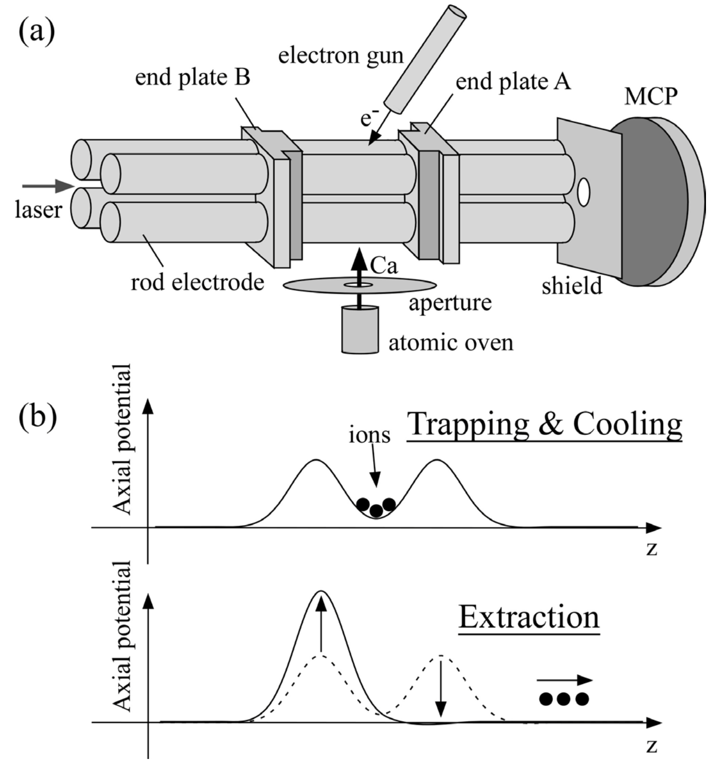



This type of Paul trap is currently used for S-POD No.2 and No.3. (A new trap is under construction for S-POD III.)



# Paul Trap for S-POD I



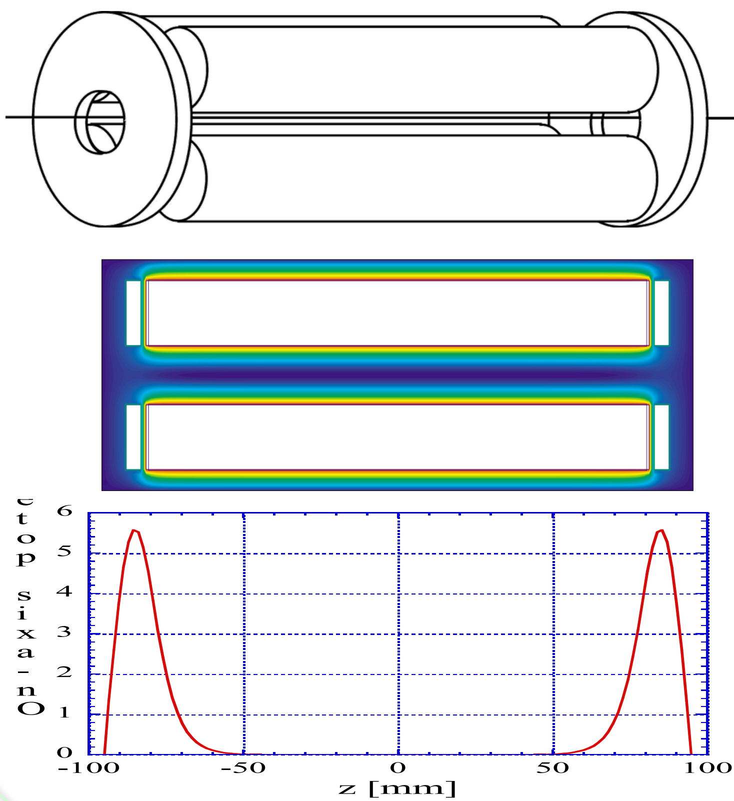




S-POD No.1 is currently employed for experimental studies of nano-ion-beam source and Coulomb crystal stability.

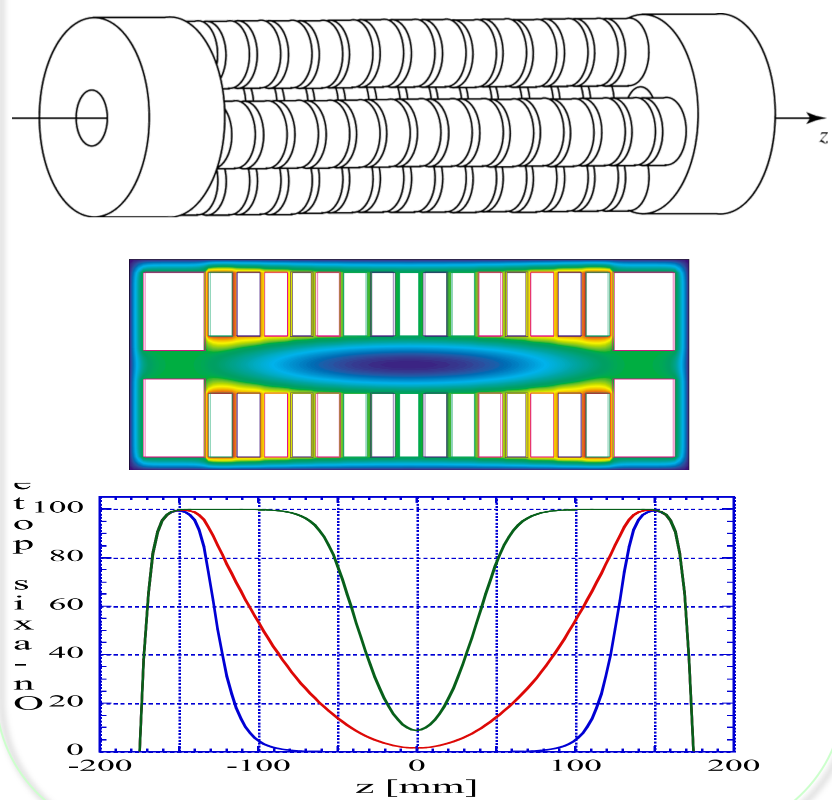
J. Phys. Soc. Jpn. **79**, 124502 (2010)

# Aspect Ratio Control

## ~For coasting beams~




## ~For bunched beams~



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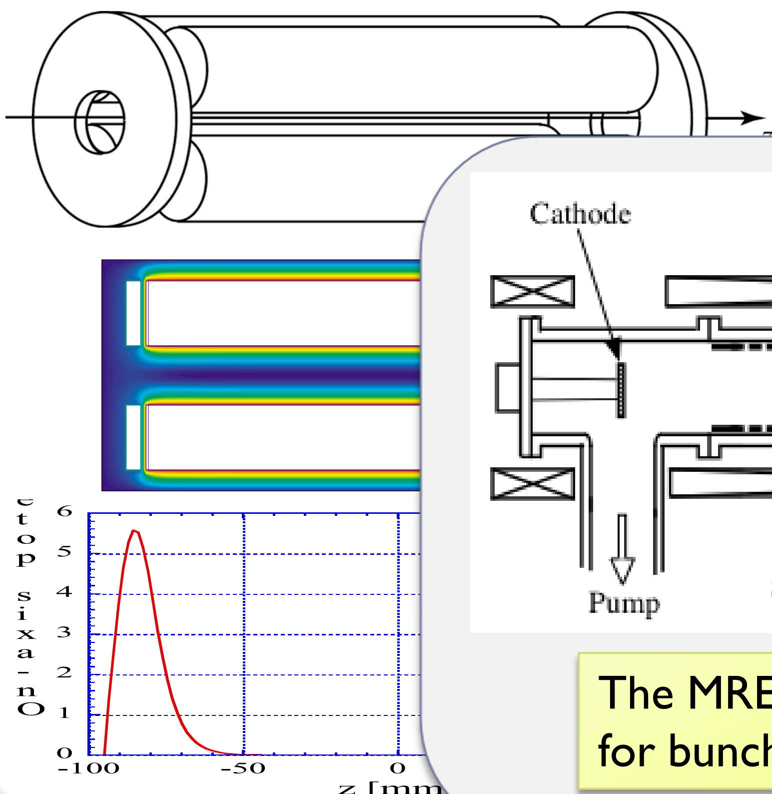


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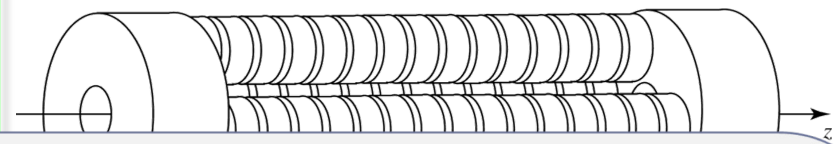
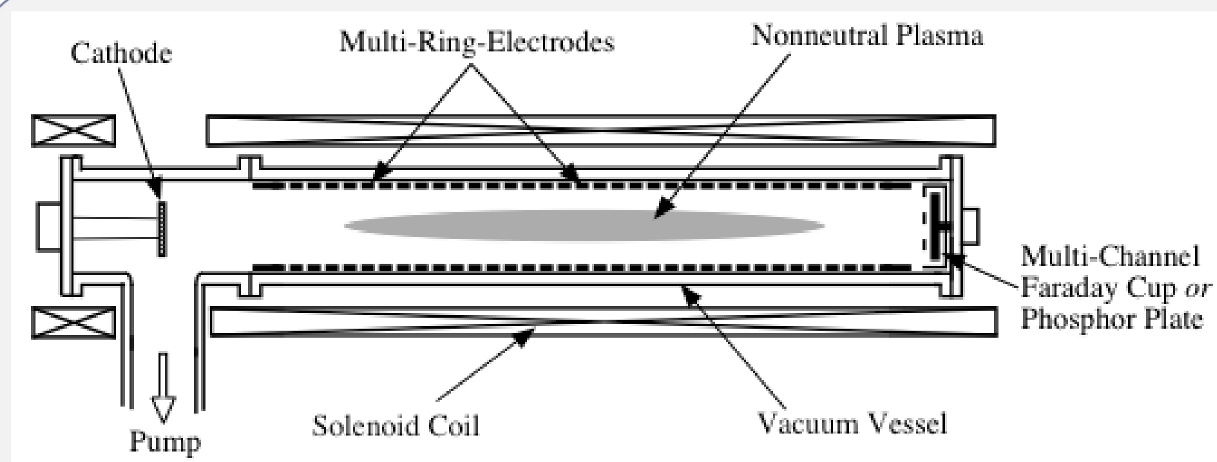
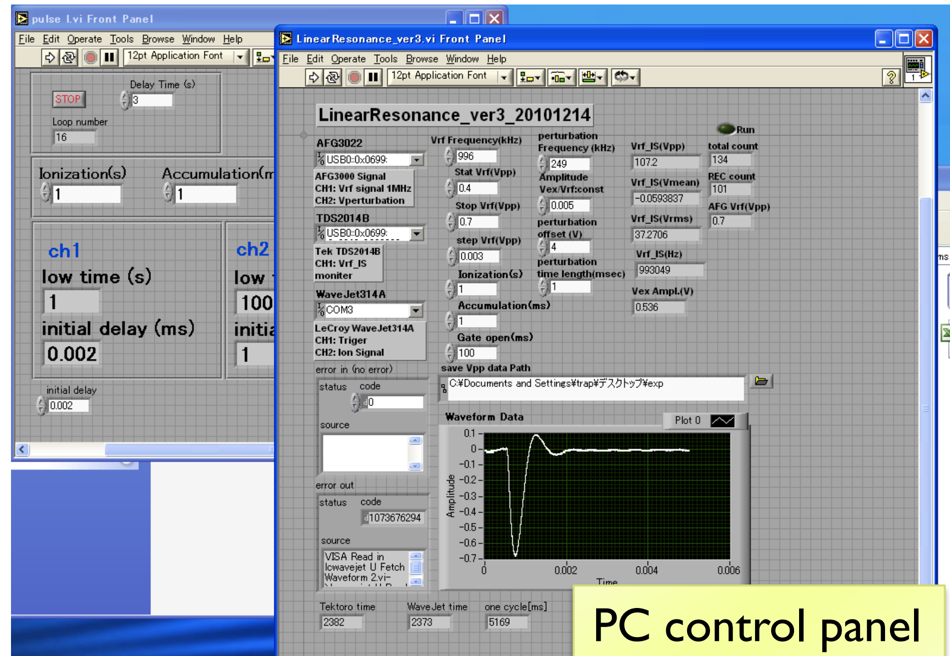





The MRE trap has many axially aligned electrodes for bunch-shape control.

# 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.)

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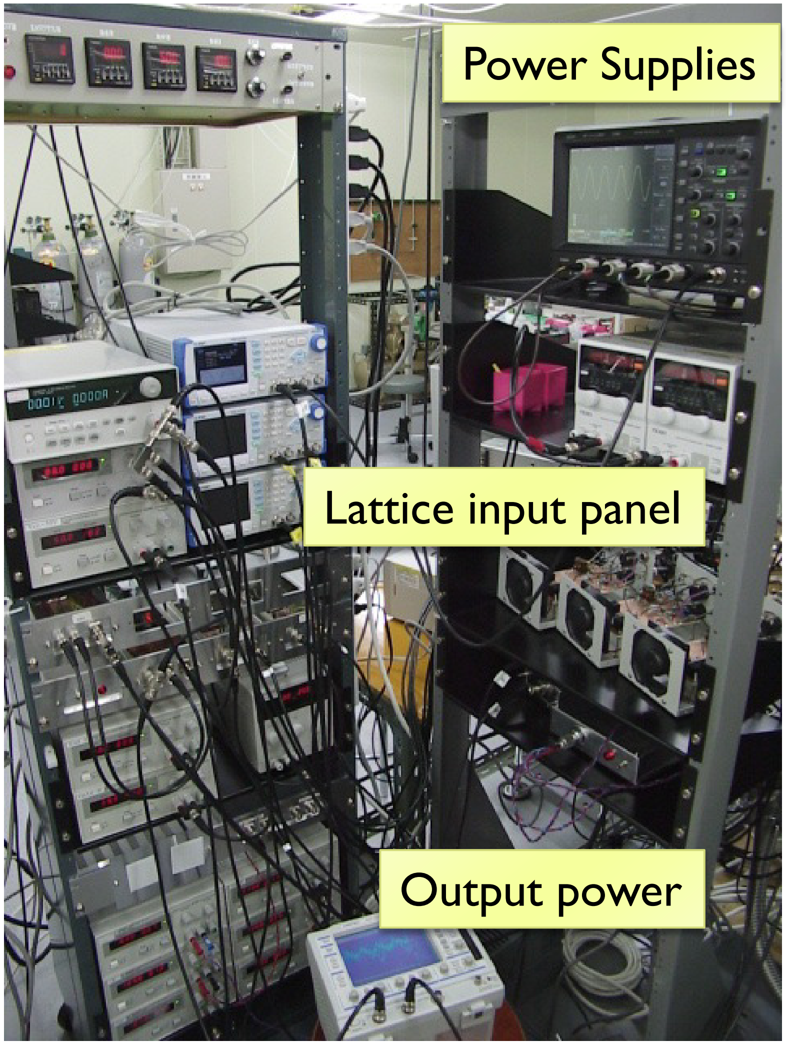


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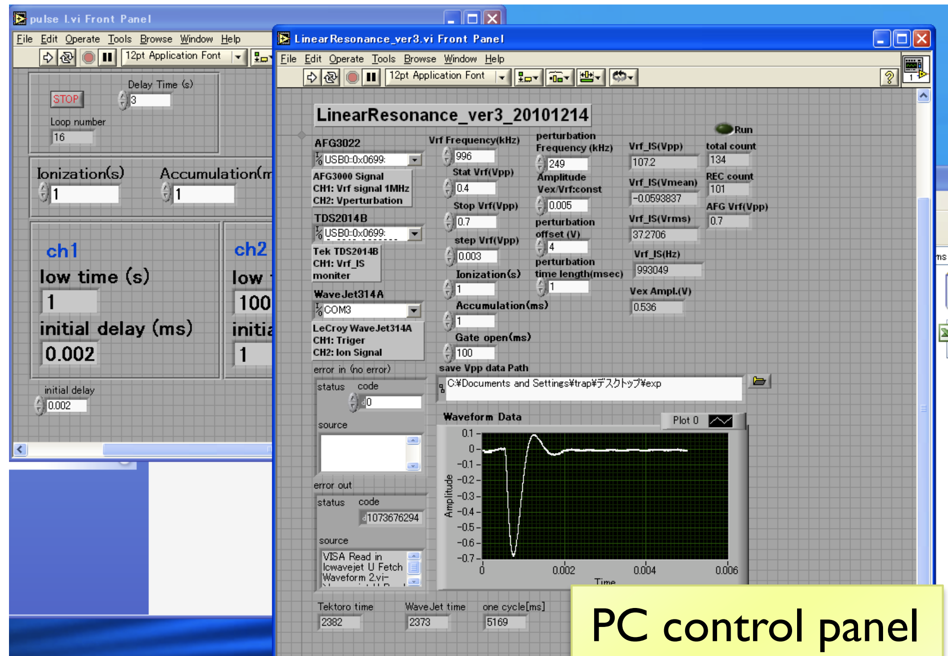


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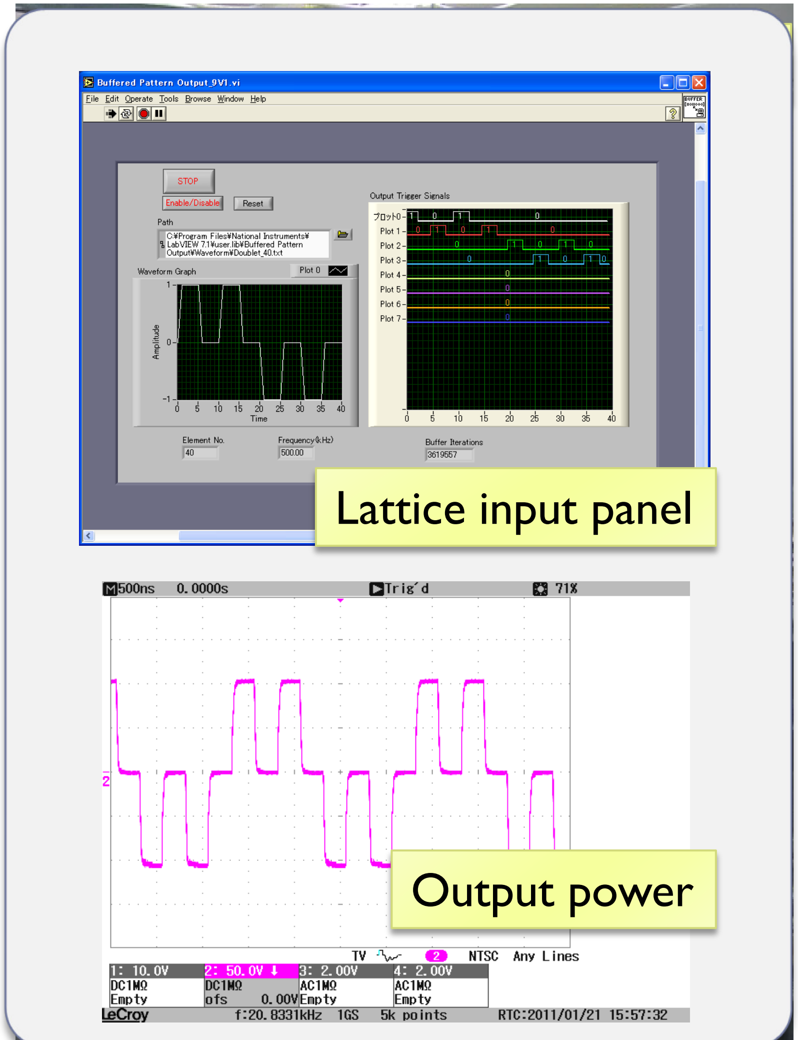


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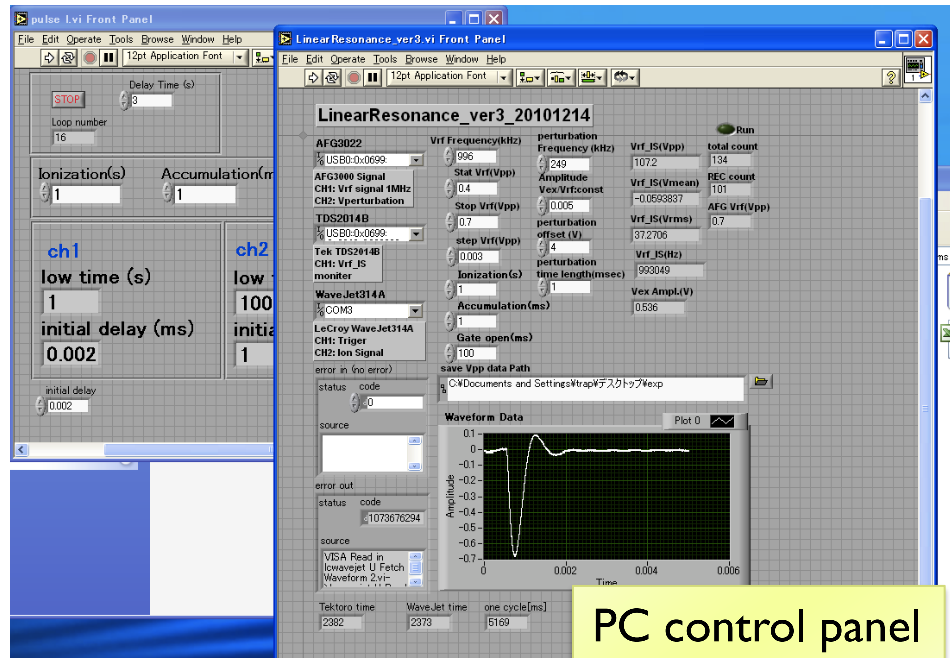


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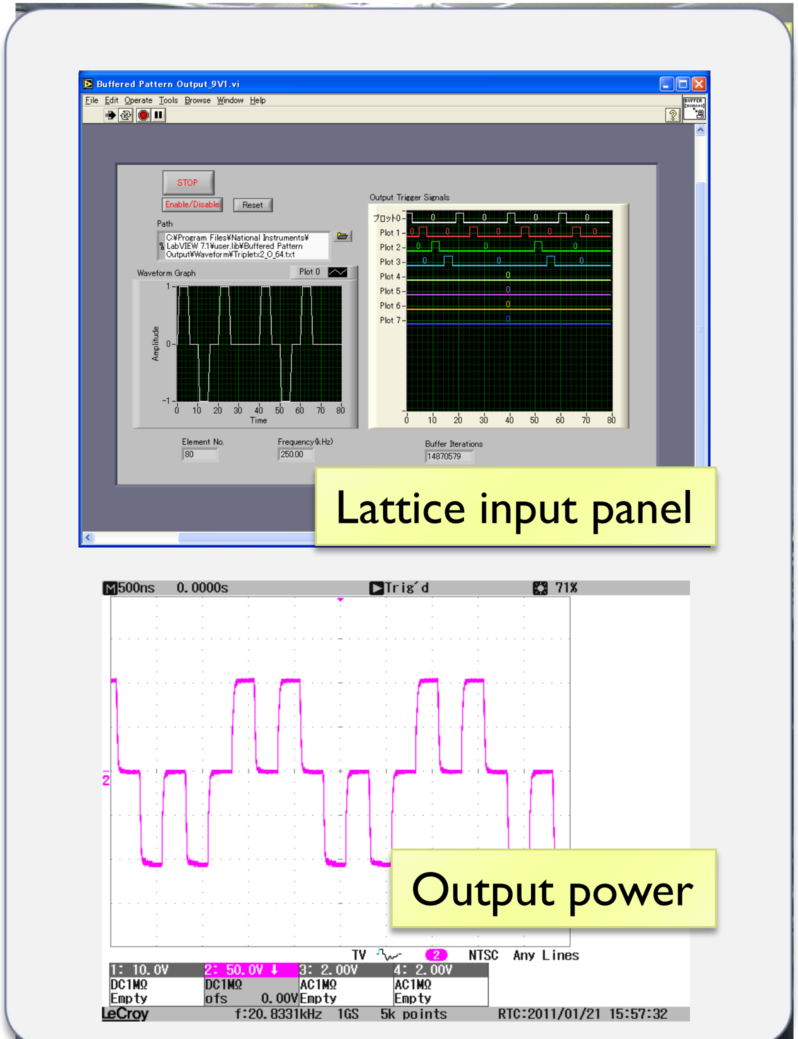


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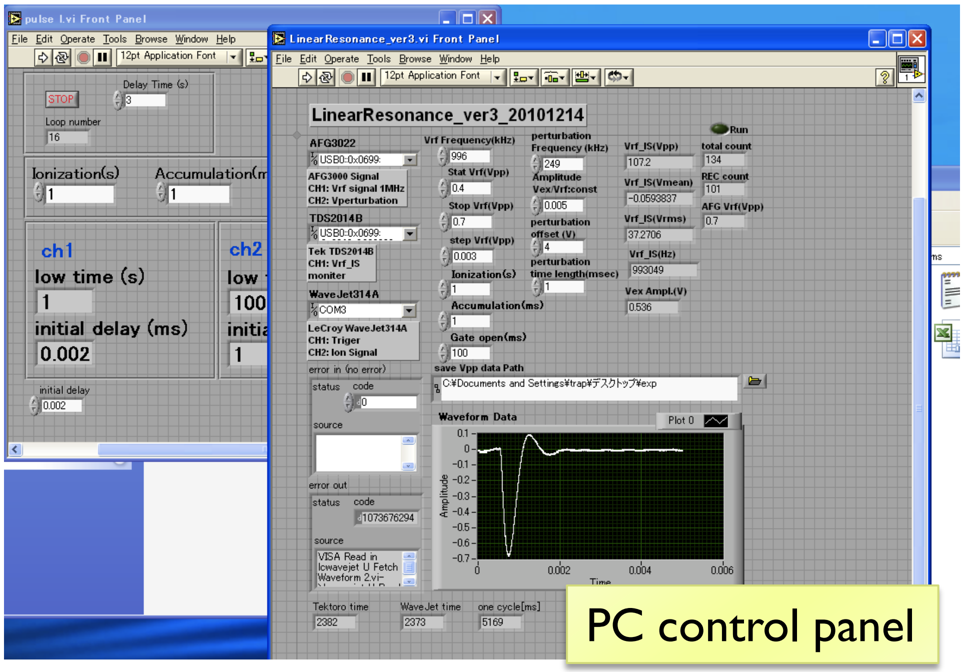


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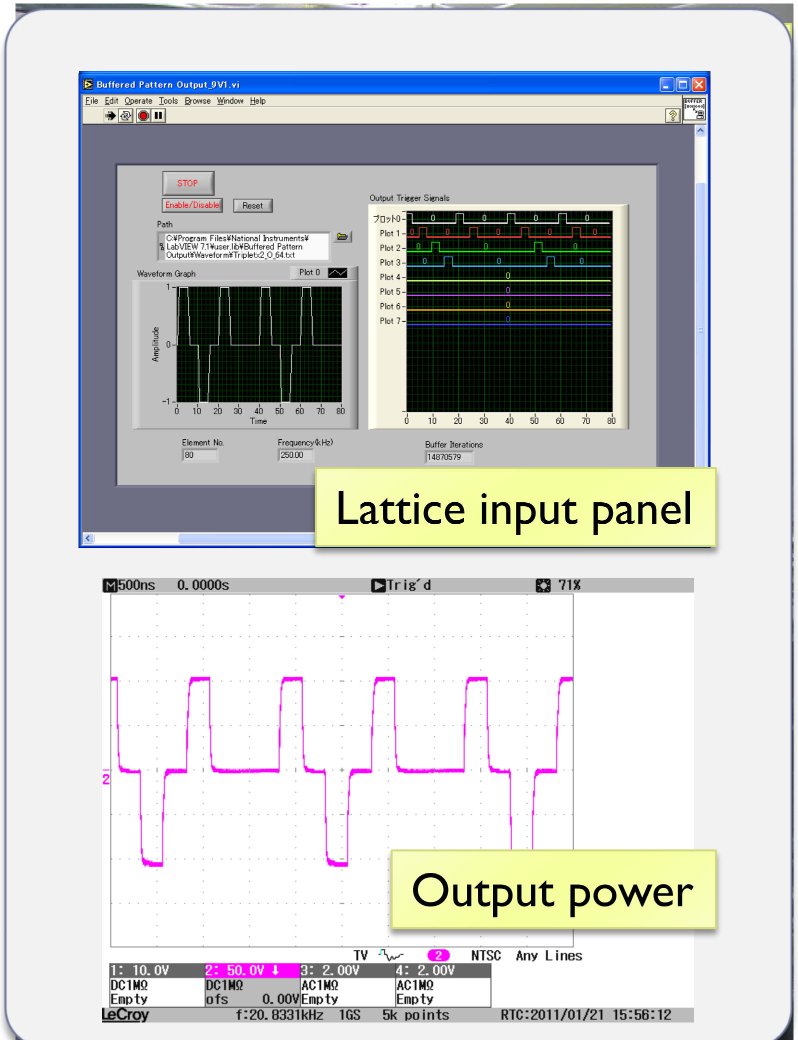


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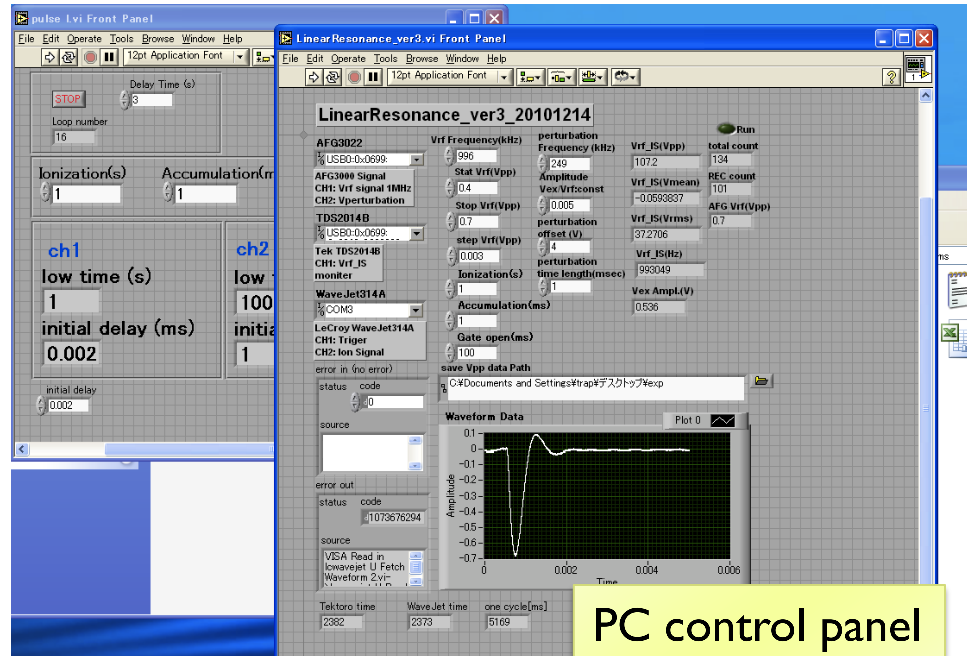


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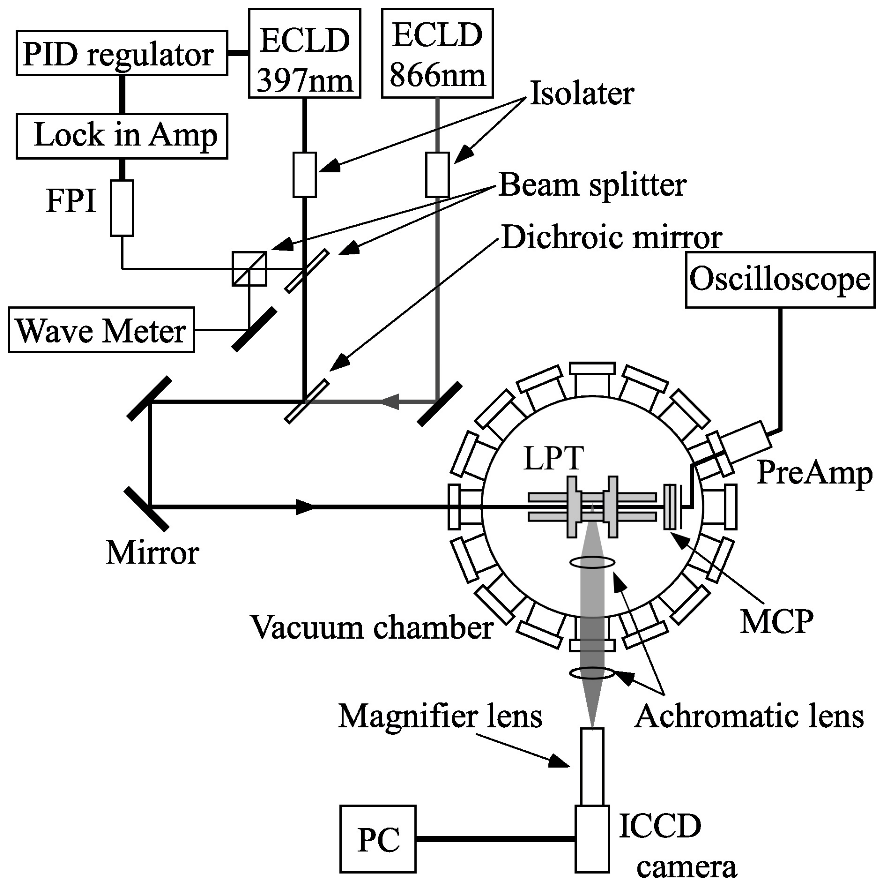
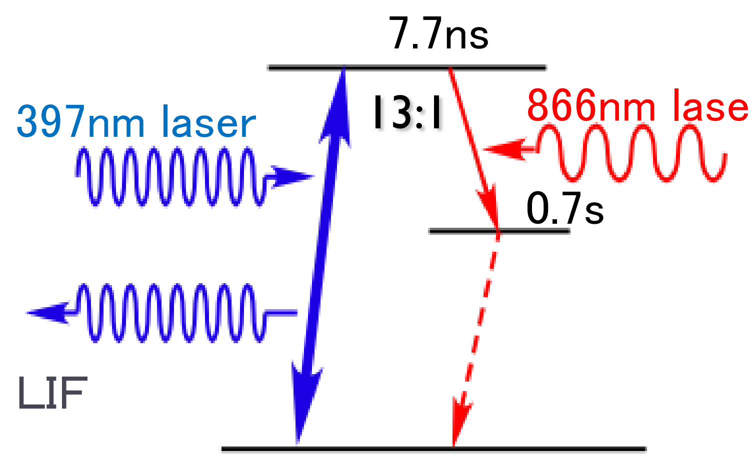
# Laser Cooling System (for $^{40}Ca^{+}$)




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.

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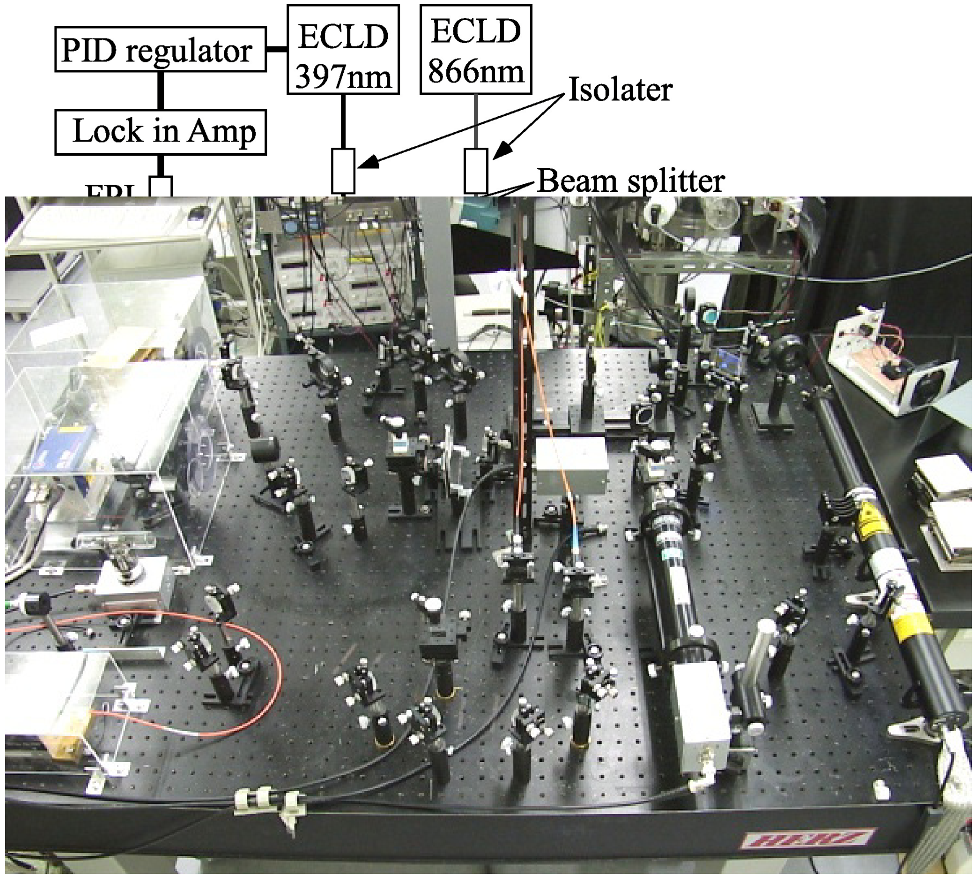


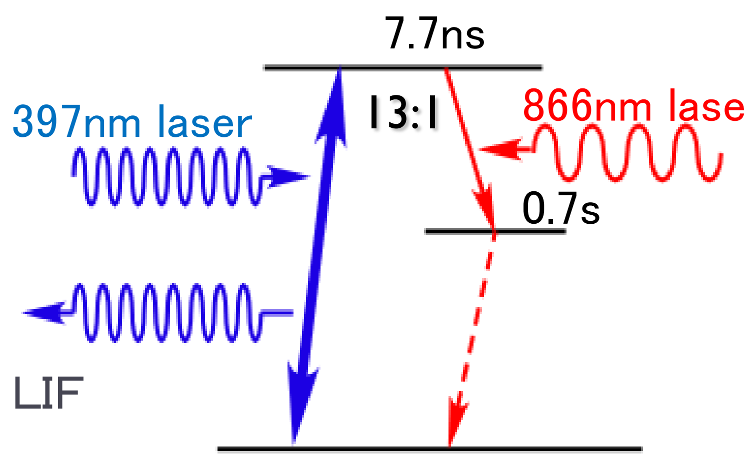


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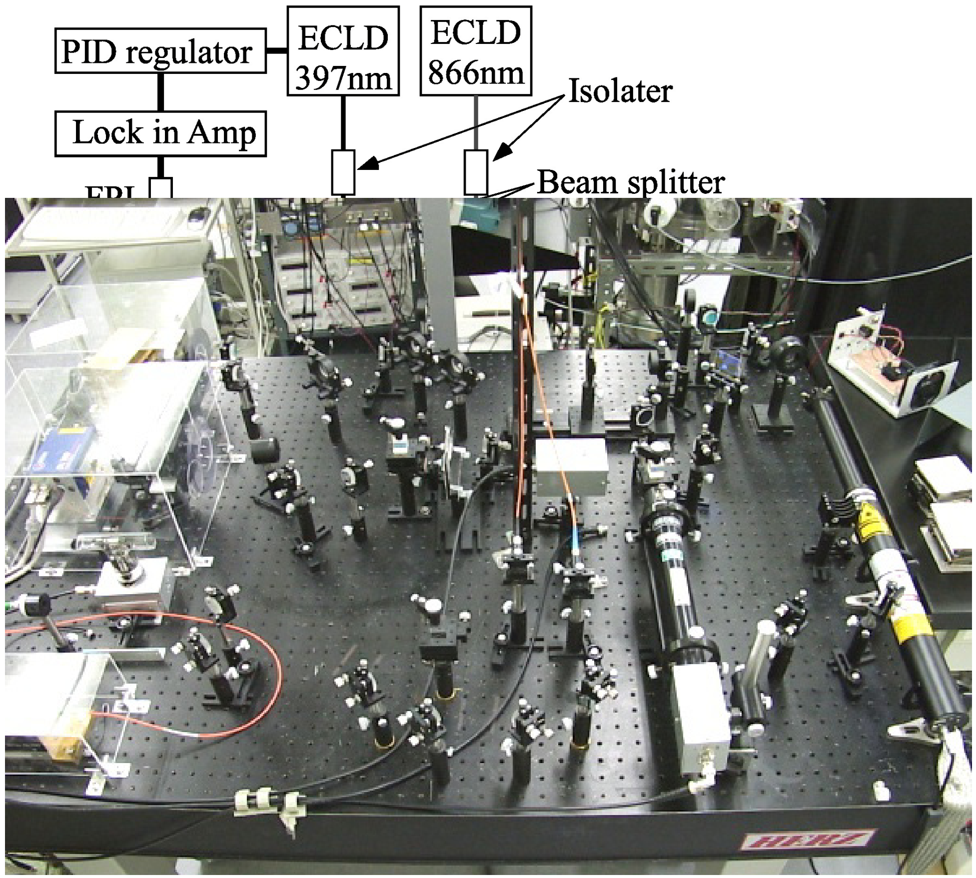


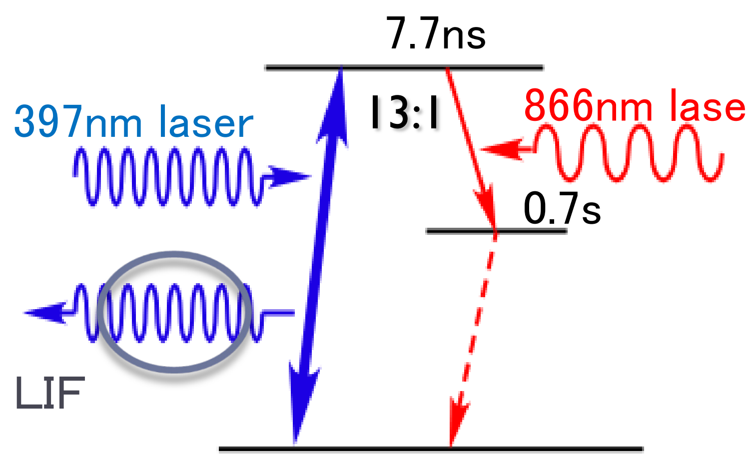


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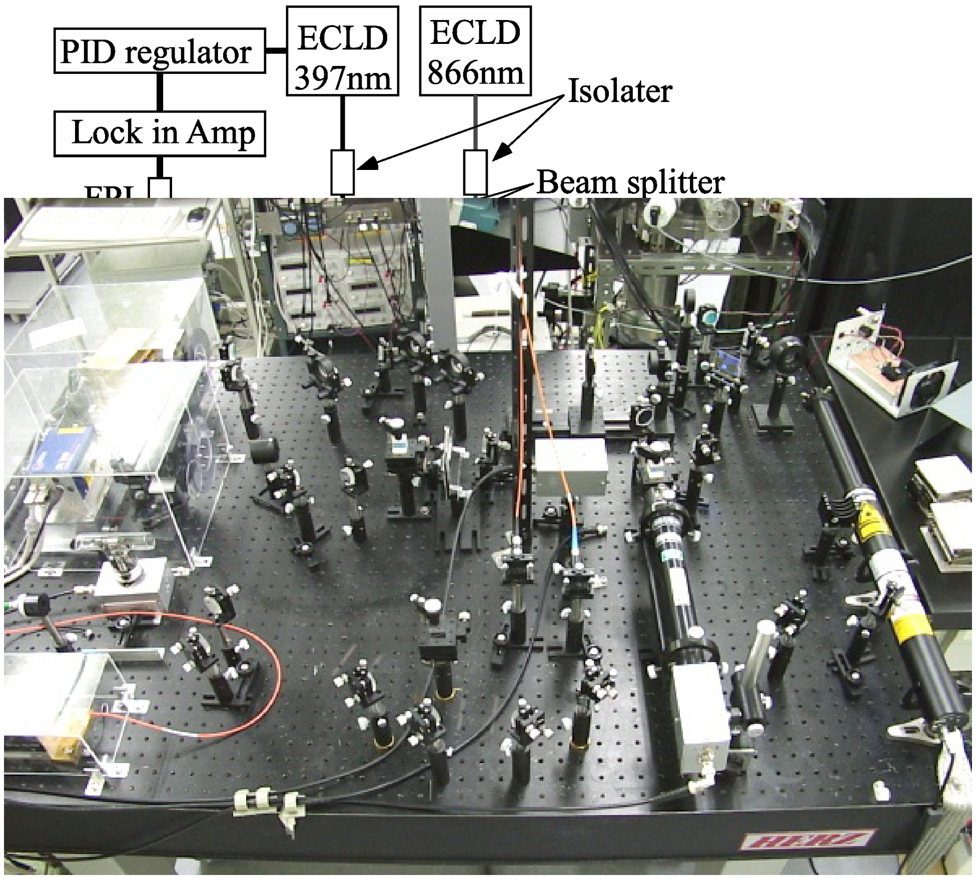
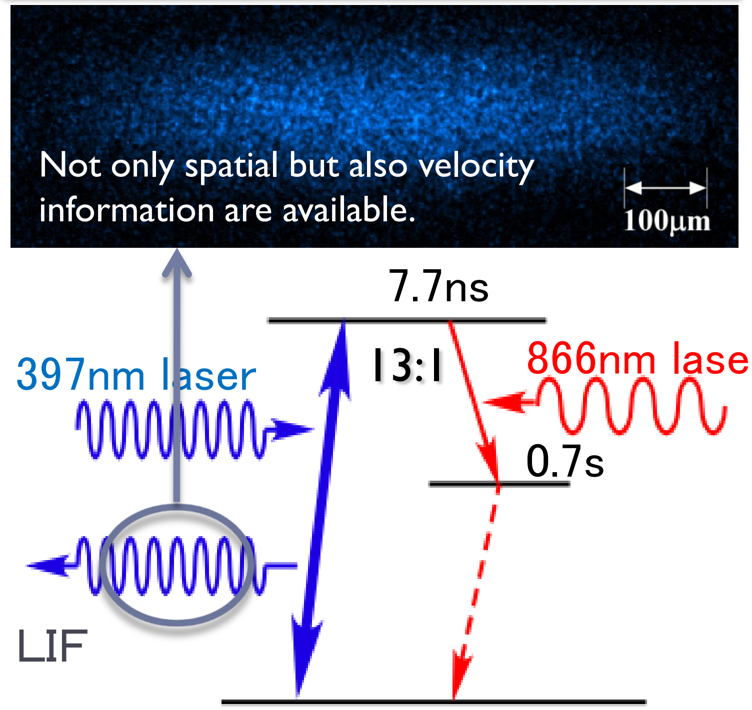



Laser-Induced-Fluorescence (LIF) signals

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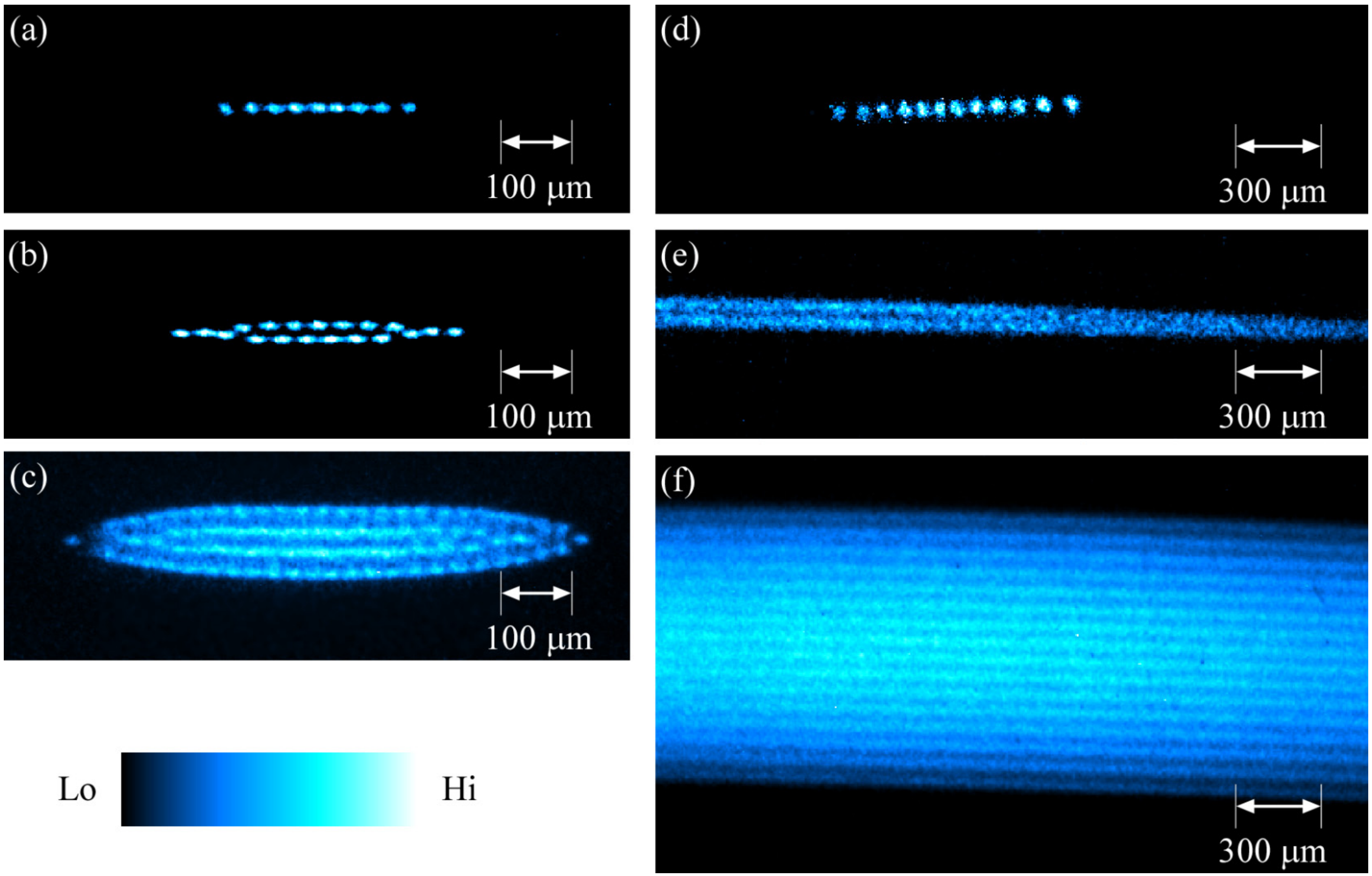
The tune shift (in other words, tune depression) can be controlled over the full range by means of the Doppler laser cooling technique.

# Ultralow Emittance Limit (*Coulomb Crystals*)

**S-POD I**

End-plate spacing = 6 mm    End-plate spacing = 60 mm



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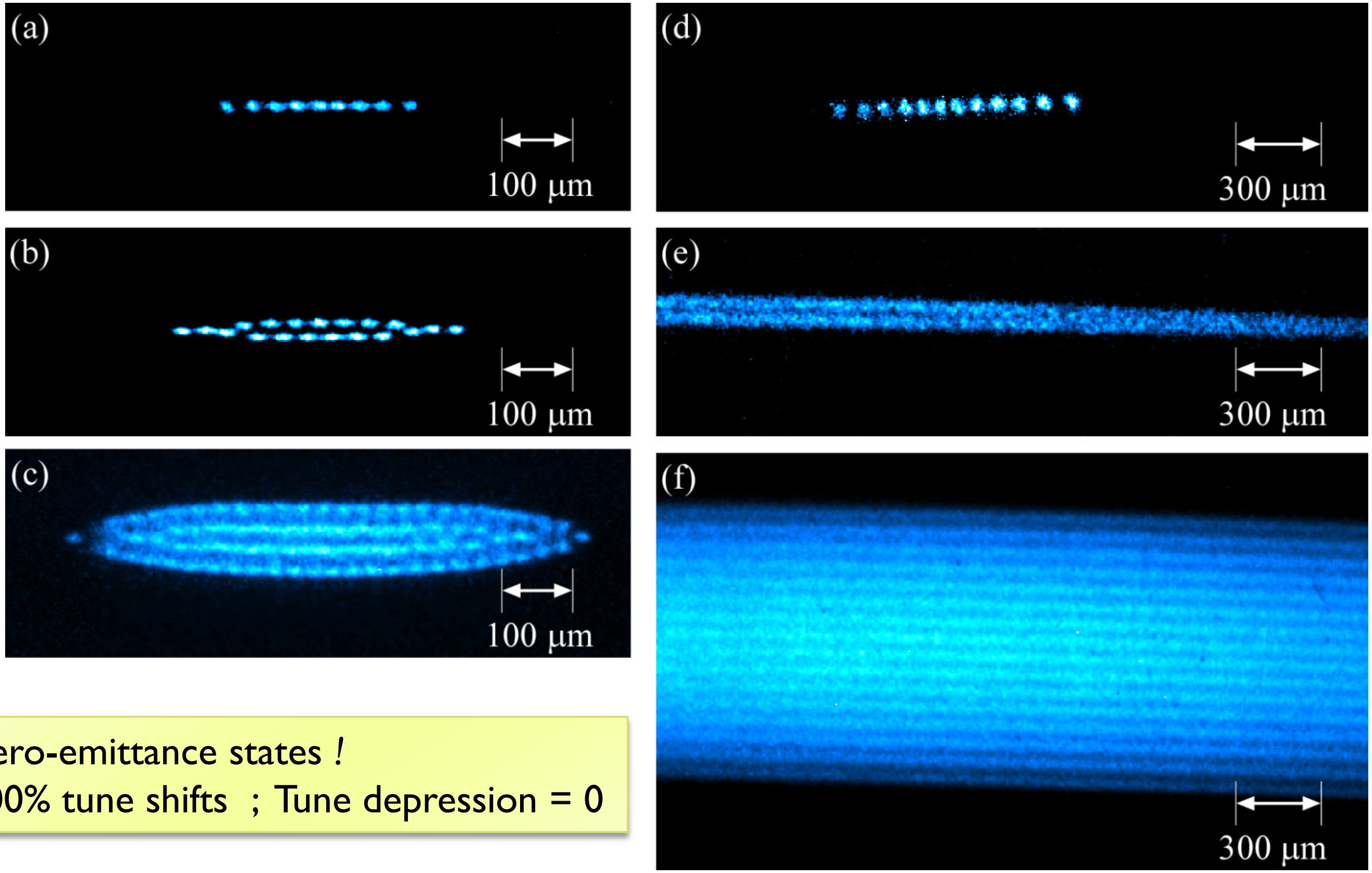
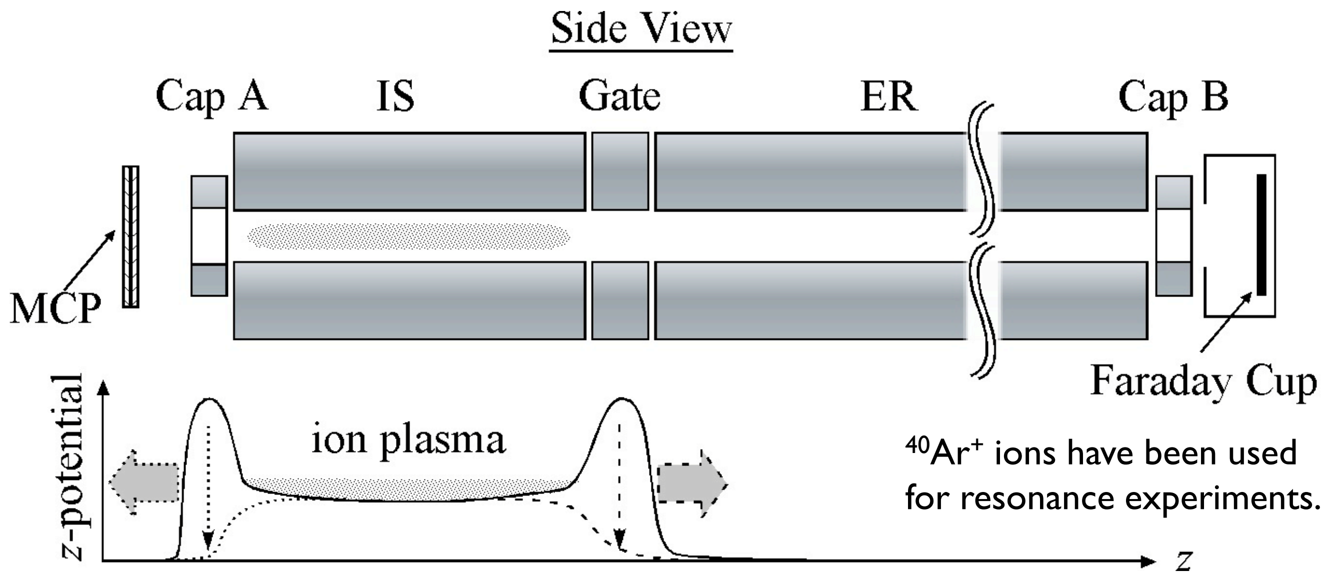



Zero-emittance states !
100% tune shifts ; Tune depression = 0

# Coherent Resonance Experiment

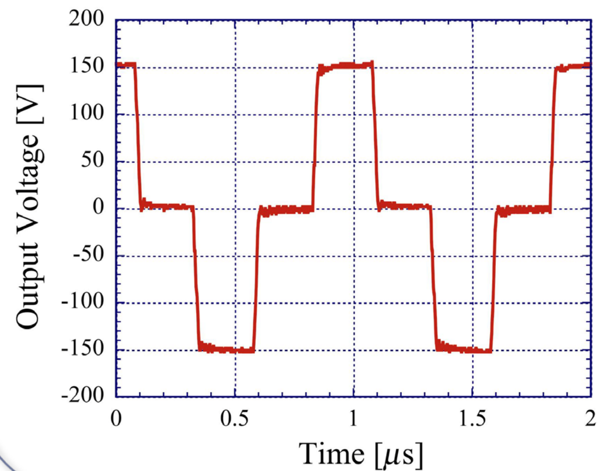



$^{40}Ar^{+}$ ions have been used for resonance experiments.

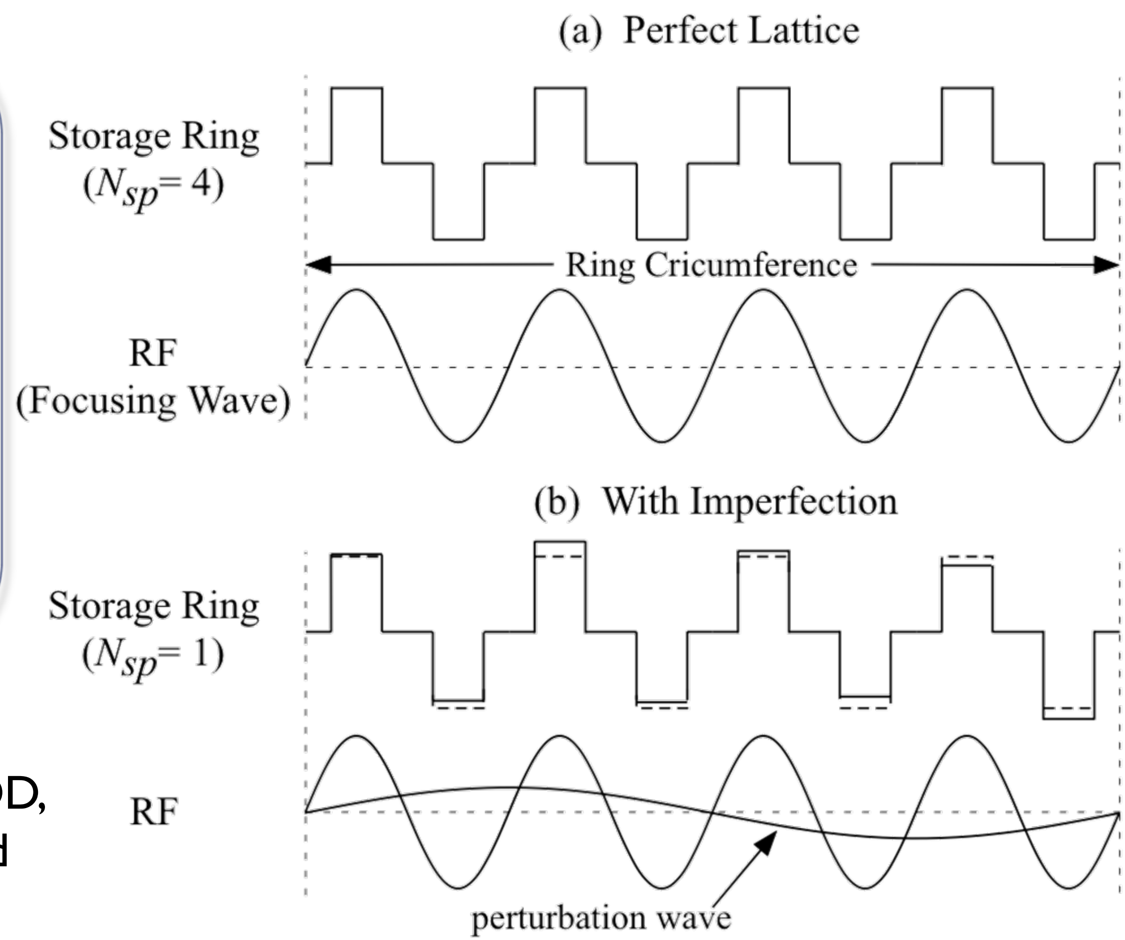
- Add specific DC bias voltages to Cap A and Gate.
- Ionize neutral Ar gas in the IS region (typically for 1 second).
- After a short storage (typically for 1 msec to 10 msec), switch off the bias on Gate (or Cap A).
- Measure the ion number with the Faraday cup (or MCP).
- Transfer the data to a personal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

# Driving Force Example

An example of the rf voltage generated by the S-POD power supply system.




A wide variety of lattice structures can very easily be emulated in S-POD, but we have so far mostly employed the simplest sinusoidal waveform.



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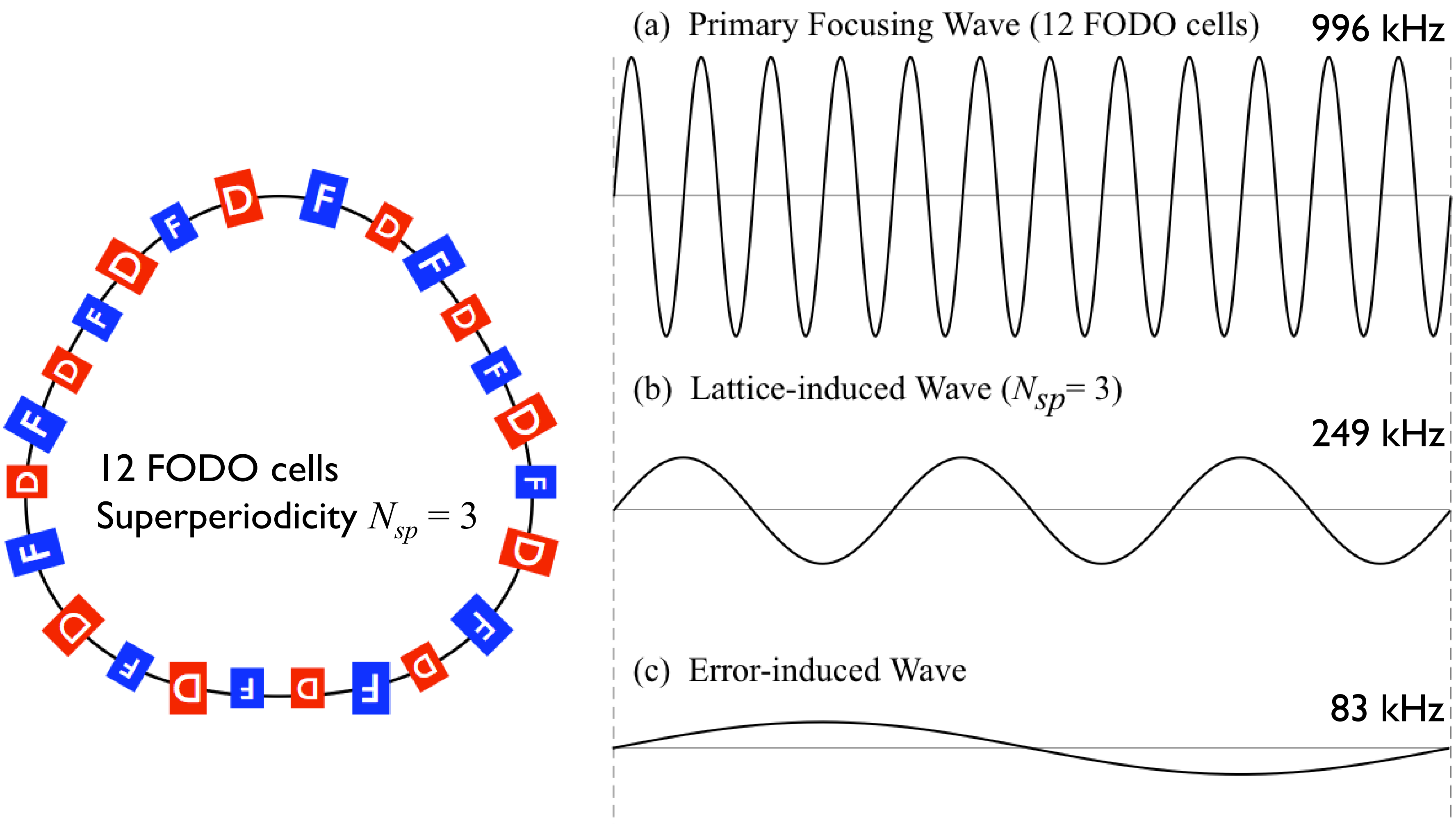
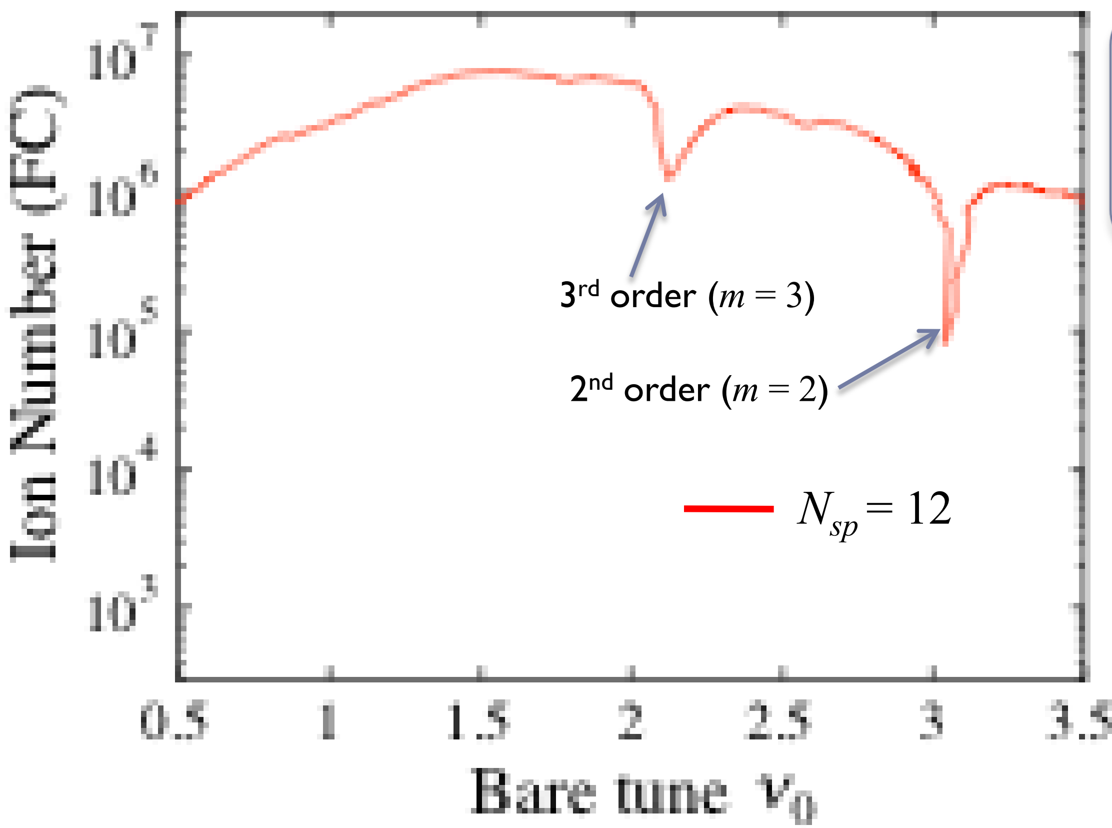


# Stop Band Measurements




**Coherent Resonance Condition**

$$(\nu_0 - C_m \Delta \nu) \approx N_{sp} \frac{n}{2m}$$

Nucl. Instrum. Meth. A **482**, 51 (2002)

$$(\nu_0 - C_m \Delta \nu) \approx 12 \times \frac{n}{2m}$$

Phys. Rev. STAB **13**, 044201 (2010)

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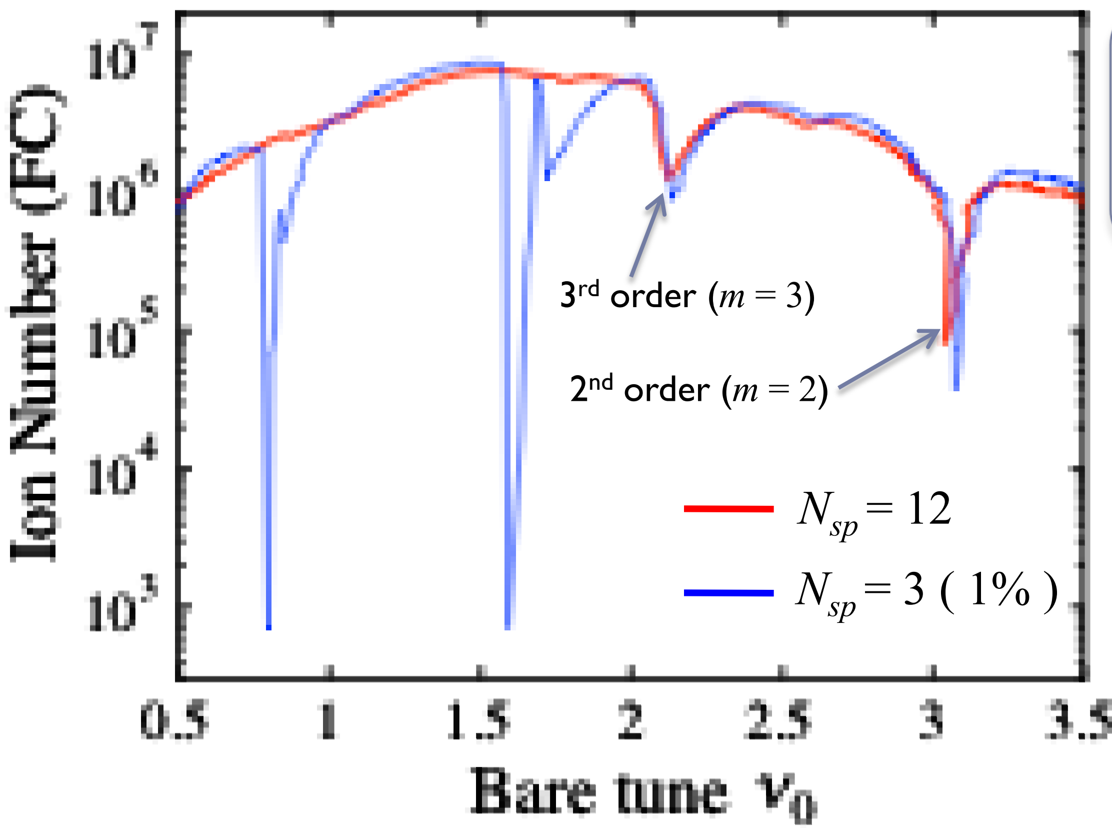


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$$(\nu_0 - C_m \Delta\nu) \approx 12 \times \frac{n}{2m} \quad \Rightarrow \quad (\nu_0 - C_m \Delta\nu) \approx 3 \times \frac{n}{2m}$$

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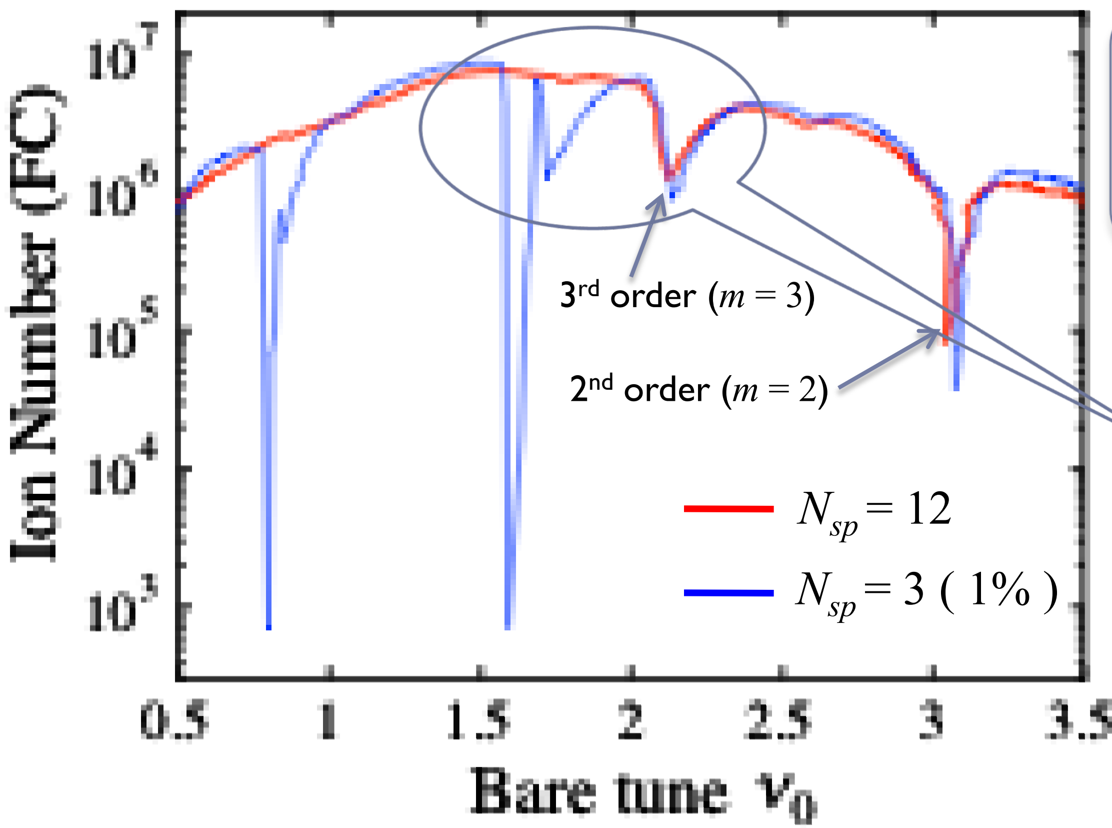


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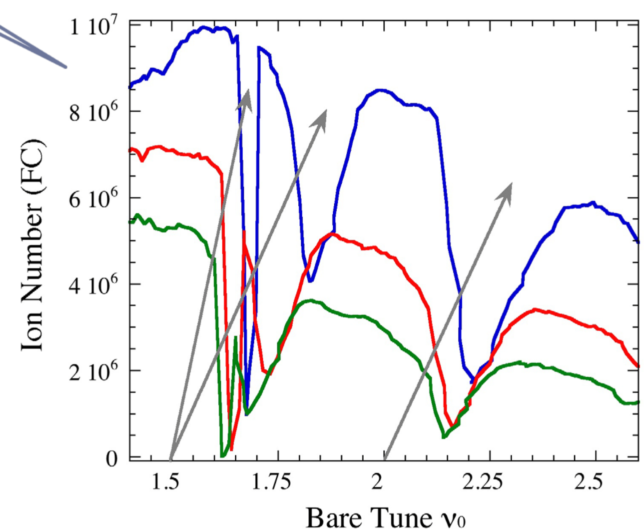


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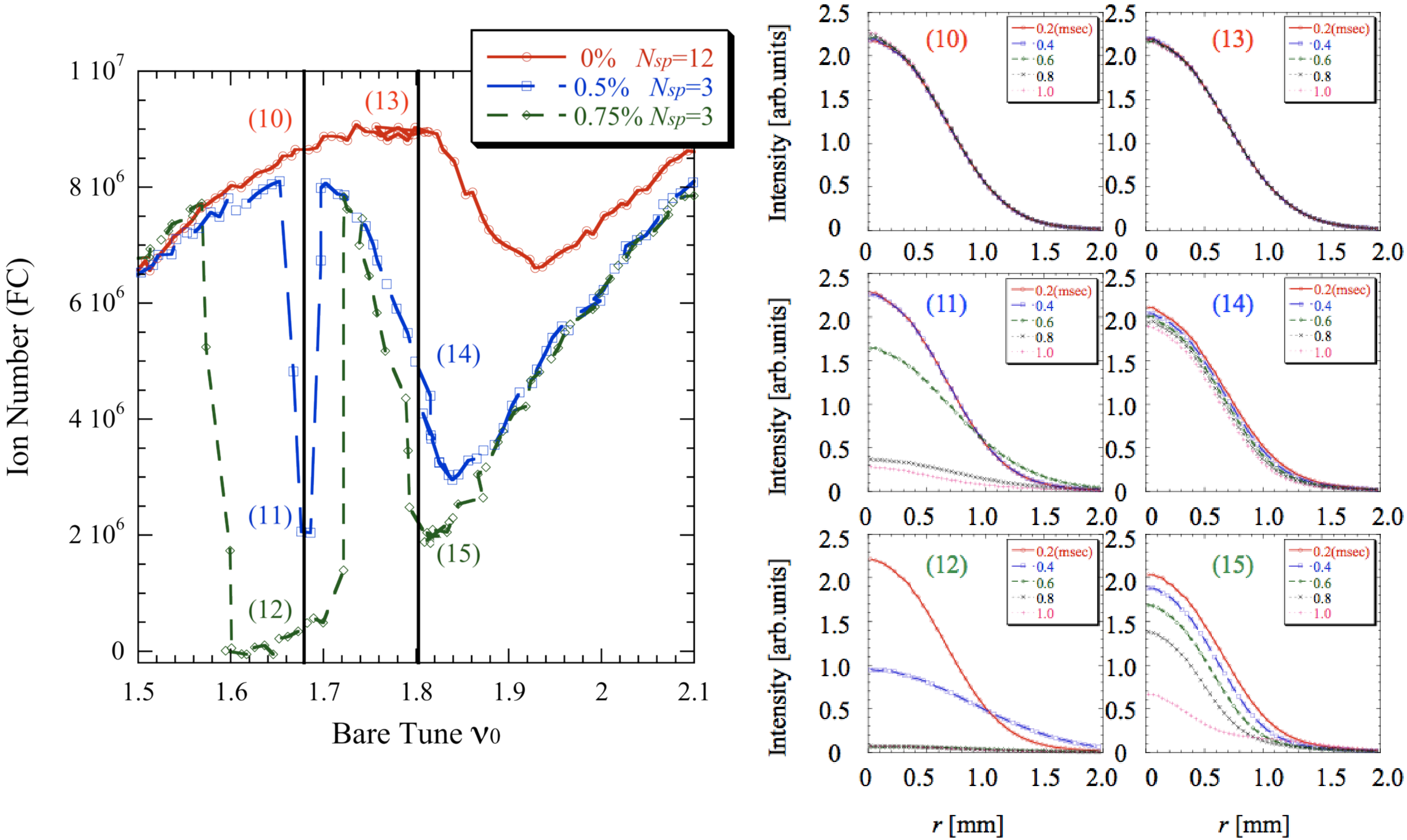
# Plasma Profiles



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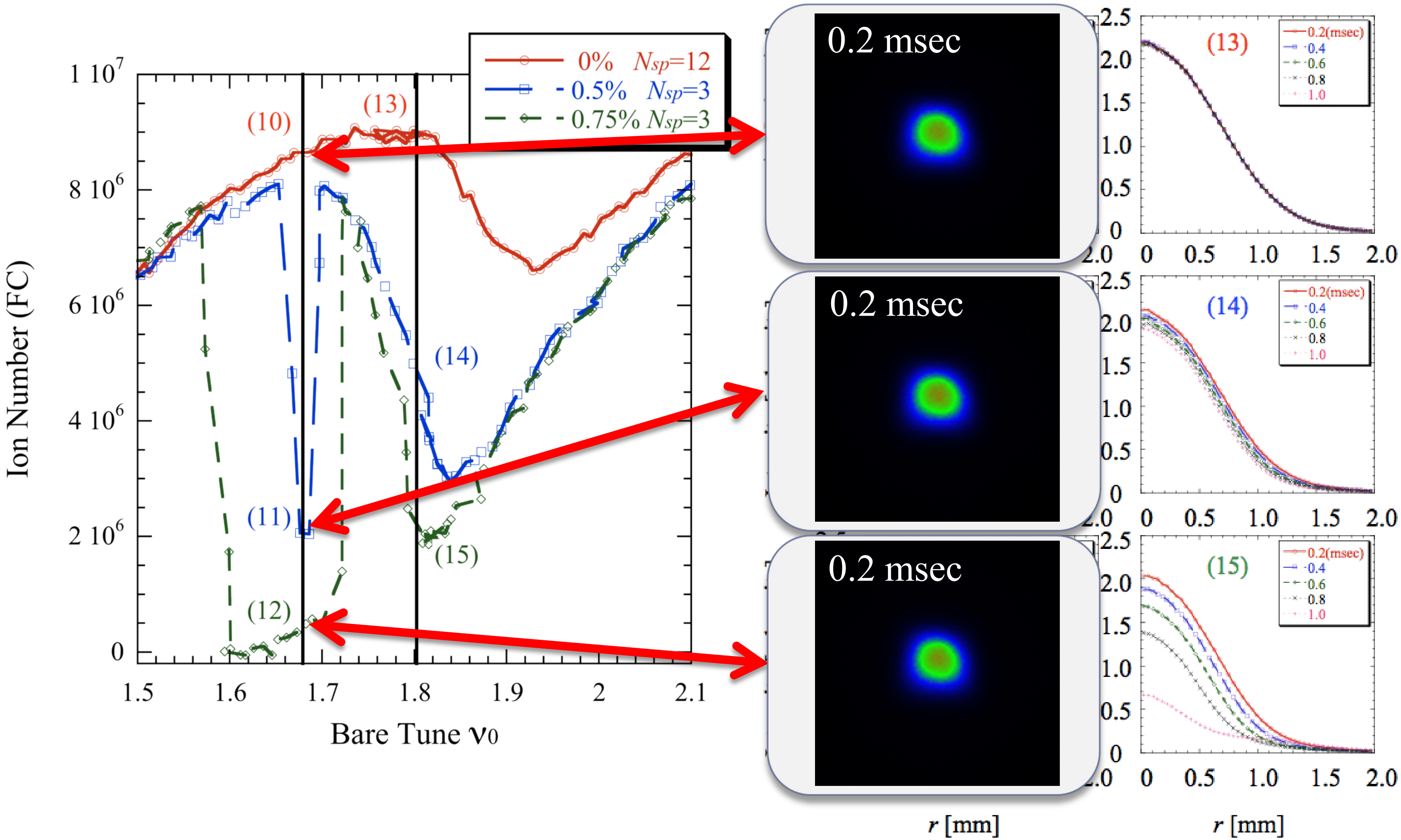

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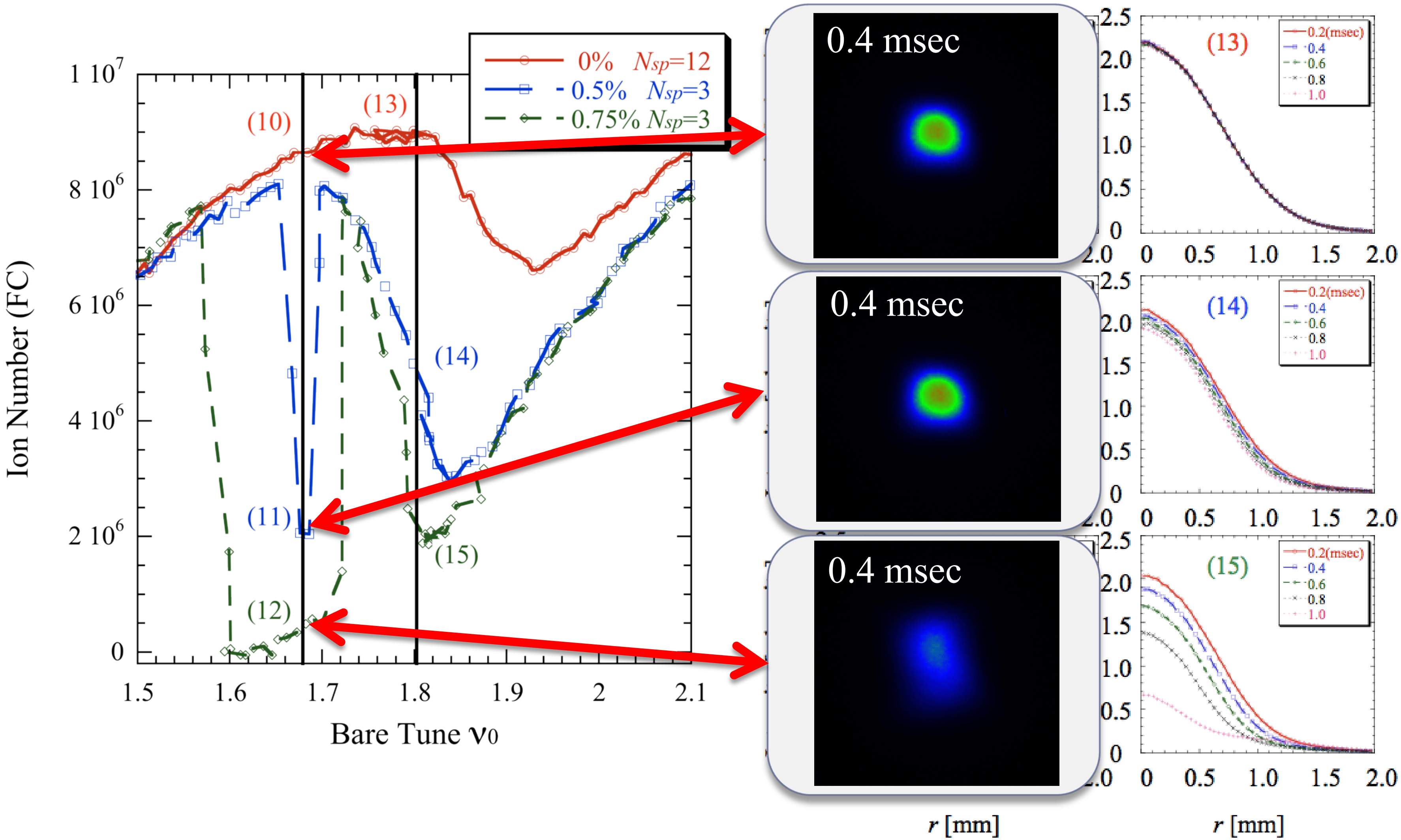
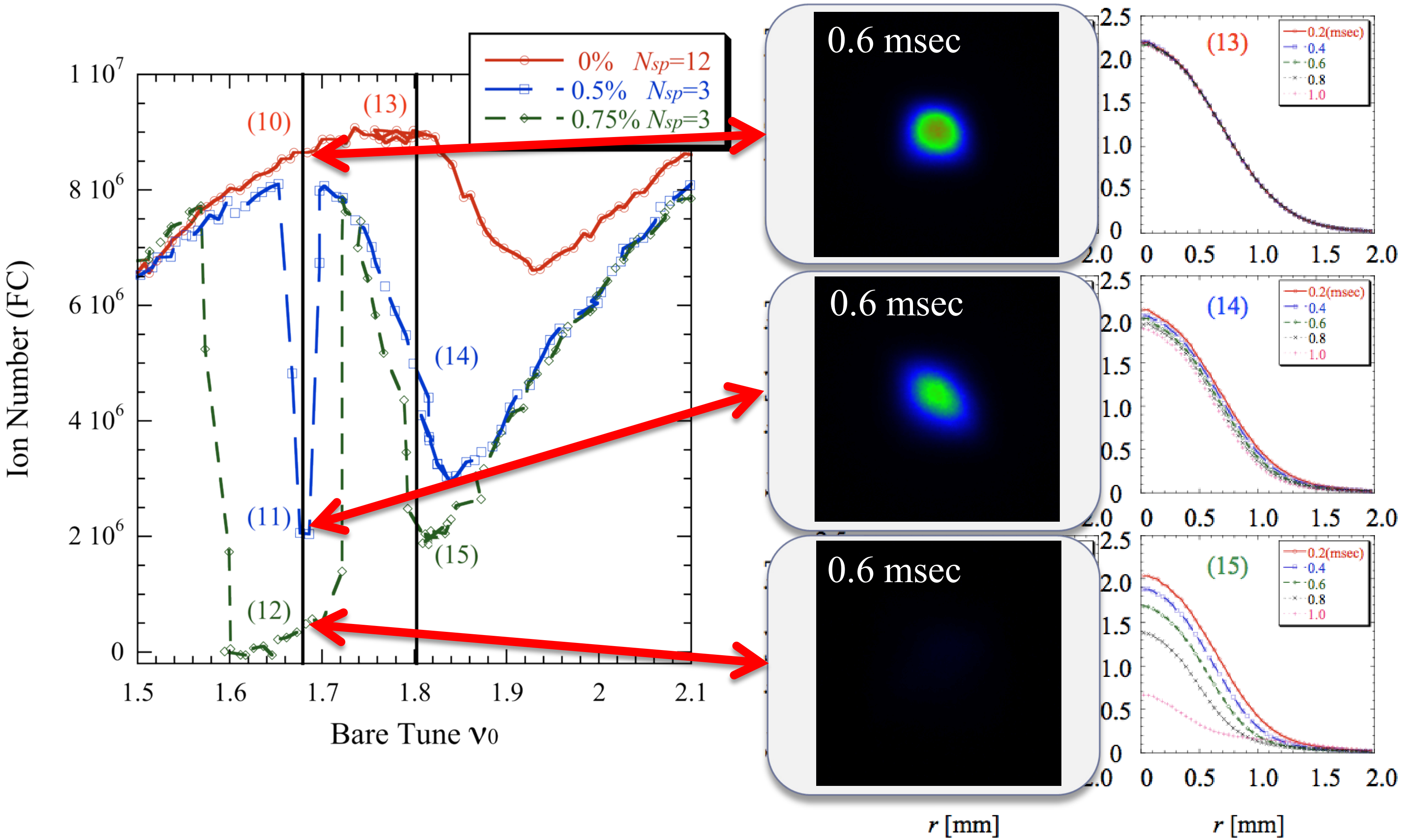


# Plasma Profiles



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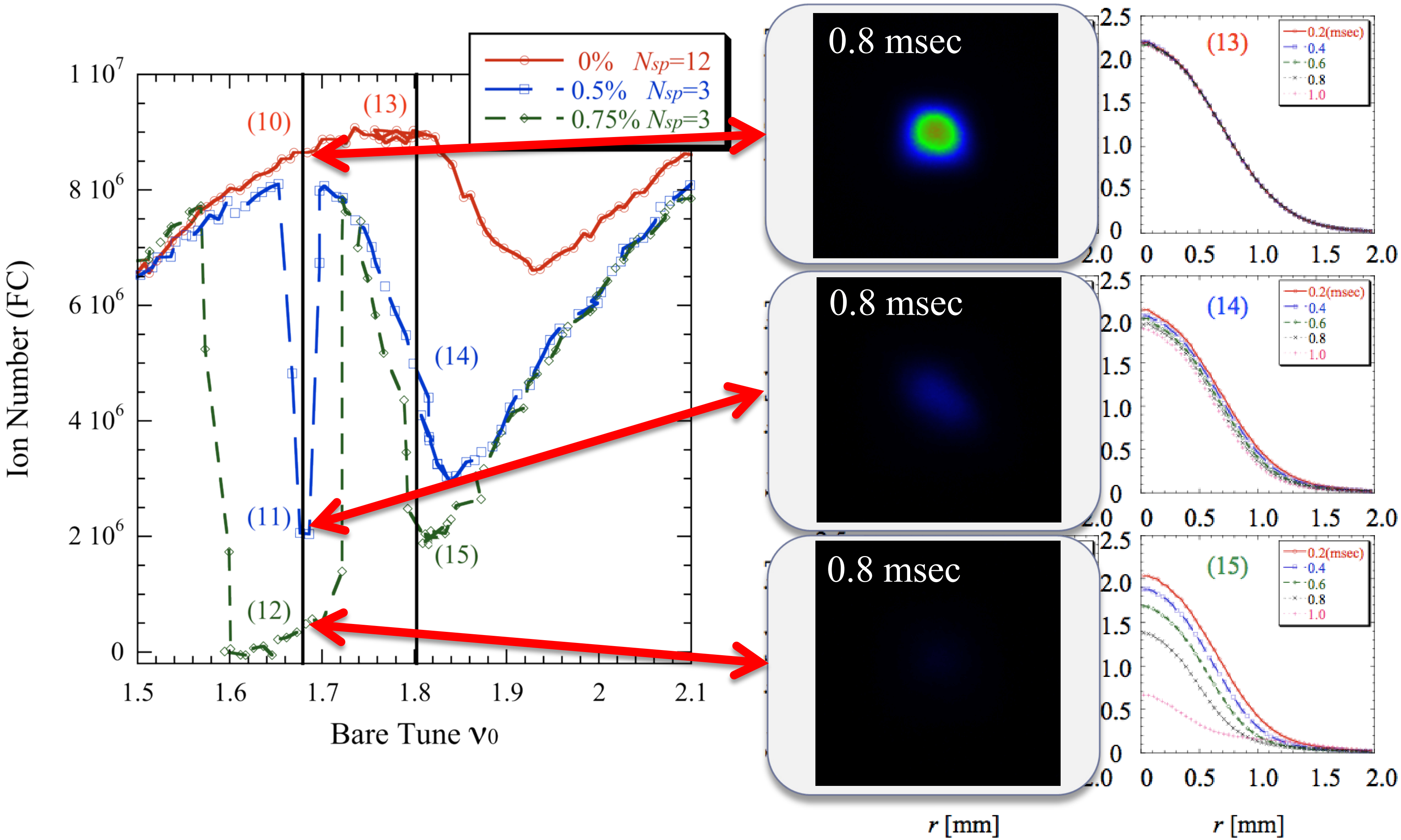

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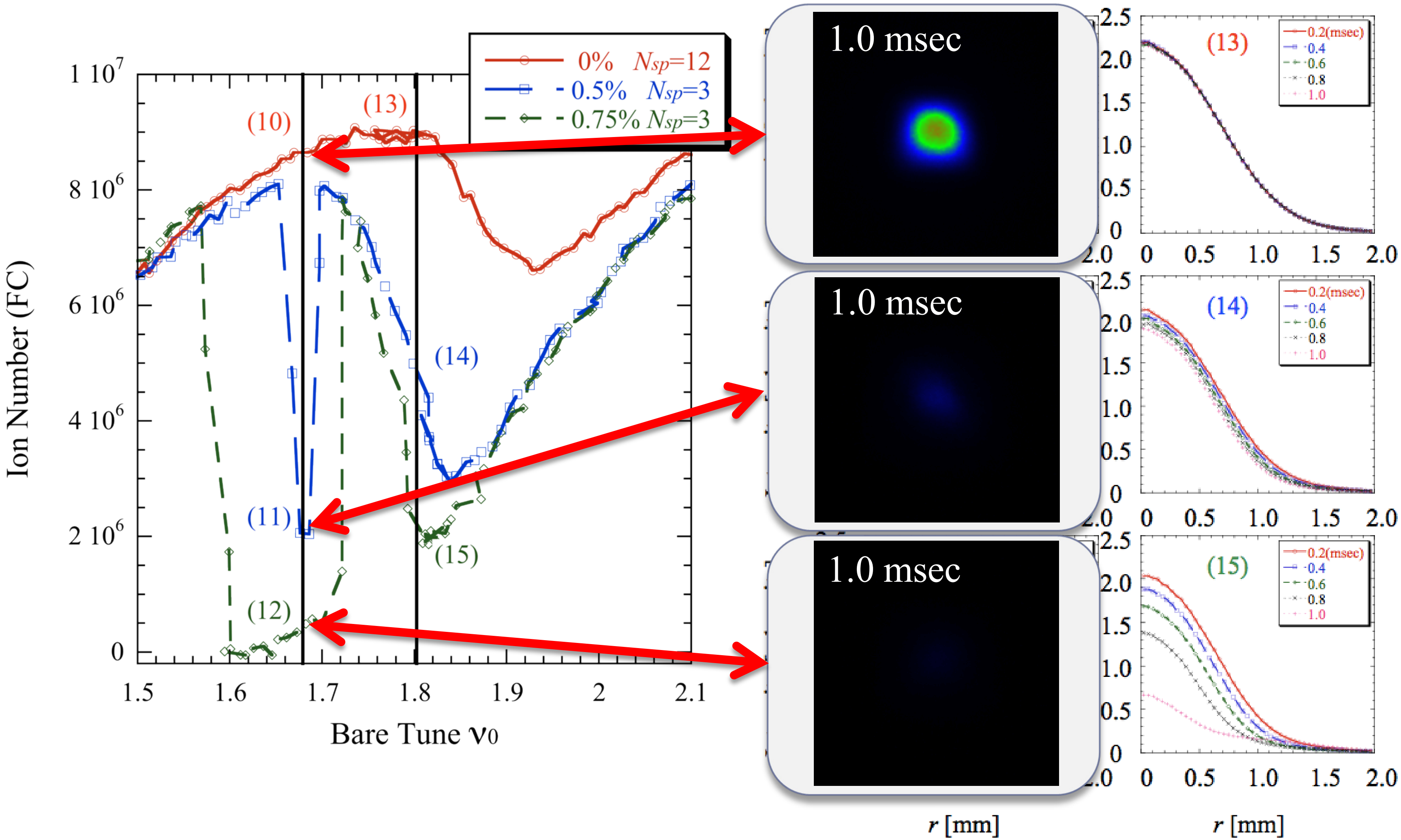
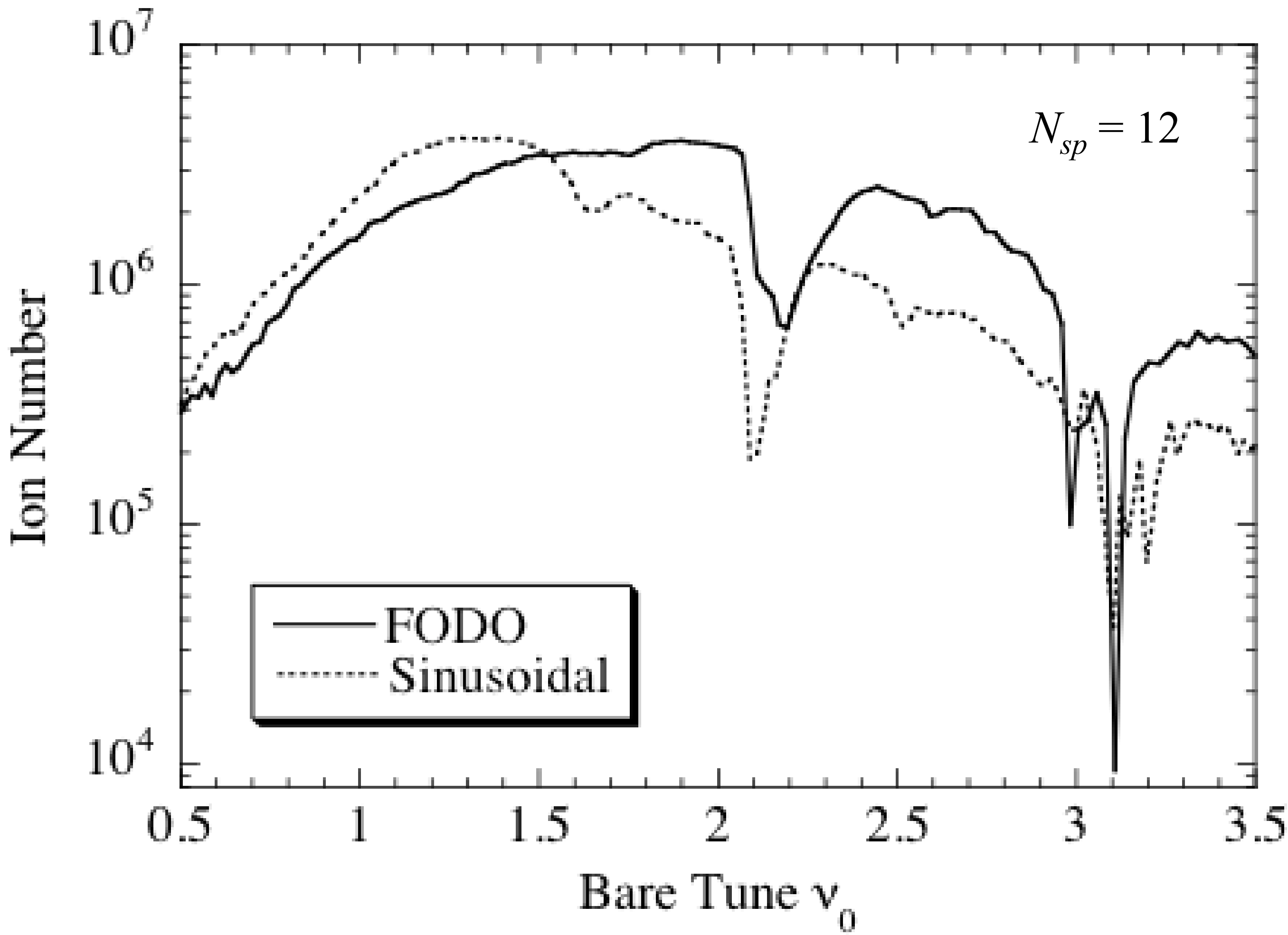


# Stop Bands in FODO (Preliminary)



# Resonance Crossing

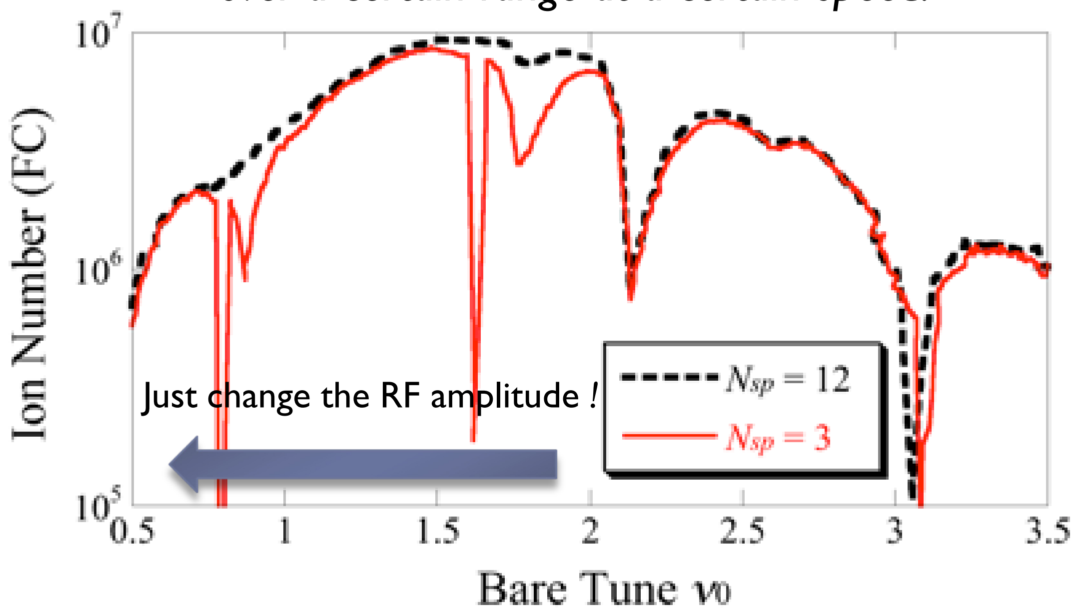
What happens if the operating point of an accelerator crosses a resonance stop band(s) ??

Resonance crossing can actually take place
in non-scaling FFAGs, advanced cooler storage rings, etc.

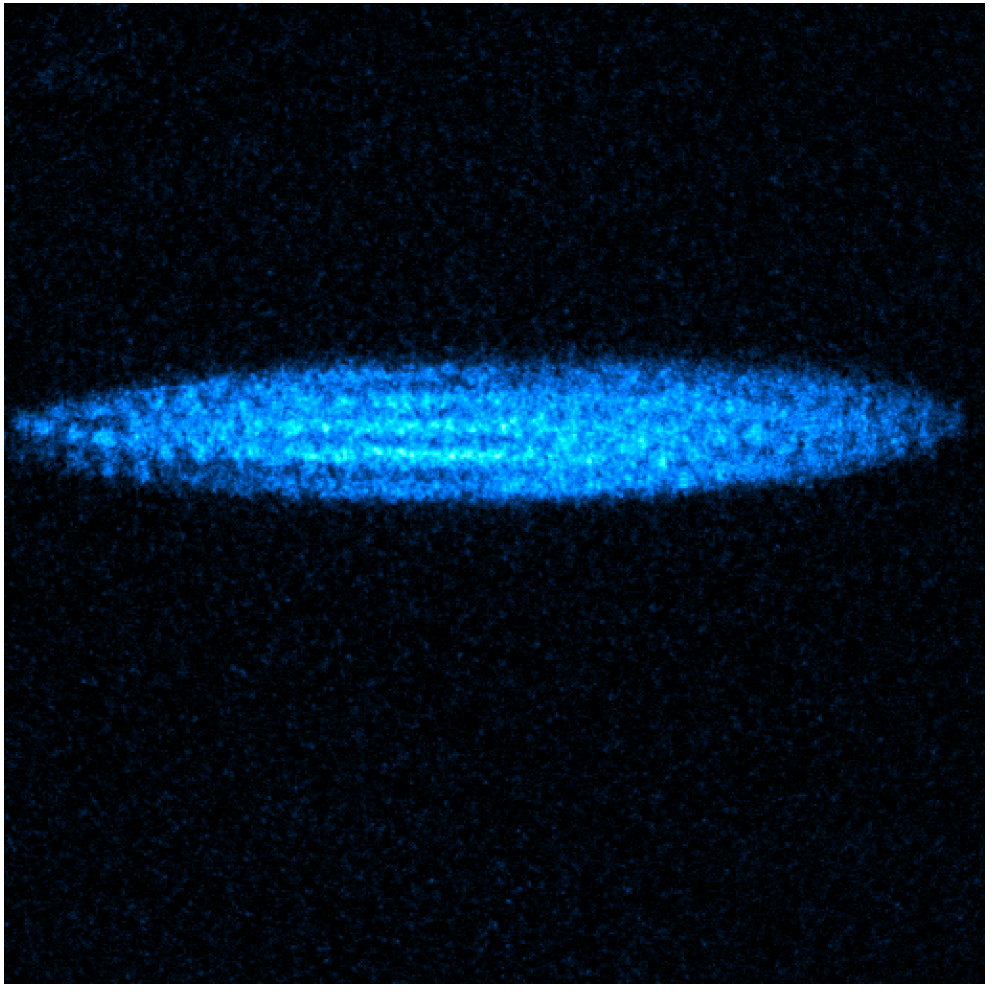
**S-POD experiments for resonance crossing**

Easily adjustable parameters :
 * *lattice periodicity,*
 * *crossing speed & direction,*
 * *tune variation range,*
 * *degree of lattice symmetry breakdown and/or error strength,*
 * *beam intensity,*
 * *with or without cooling, …*

*Move the S-POD operating point over a certain range at a certain speed.*



# Crystalline Beam Stability



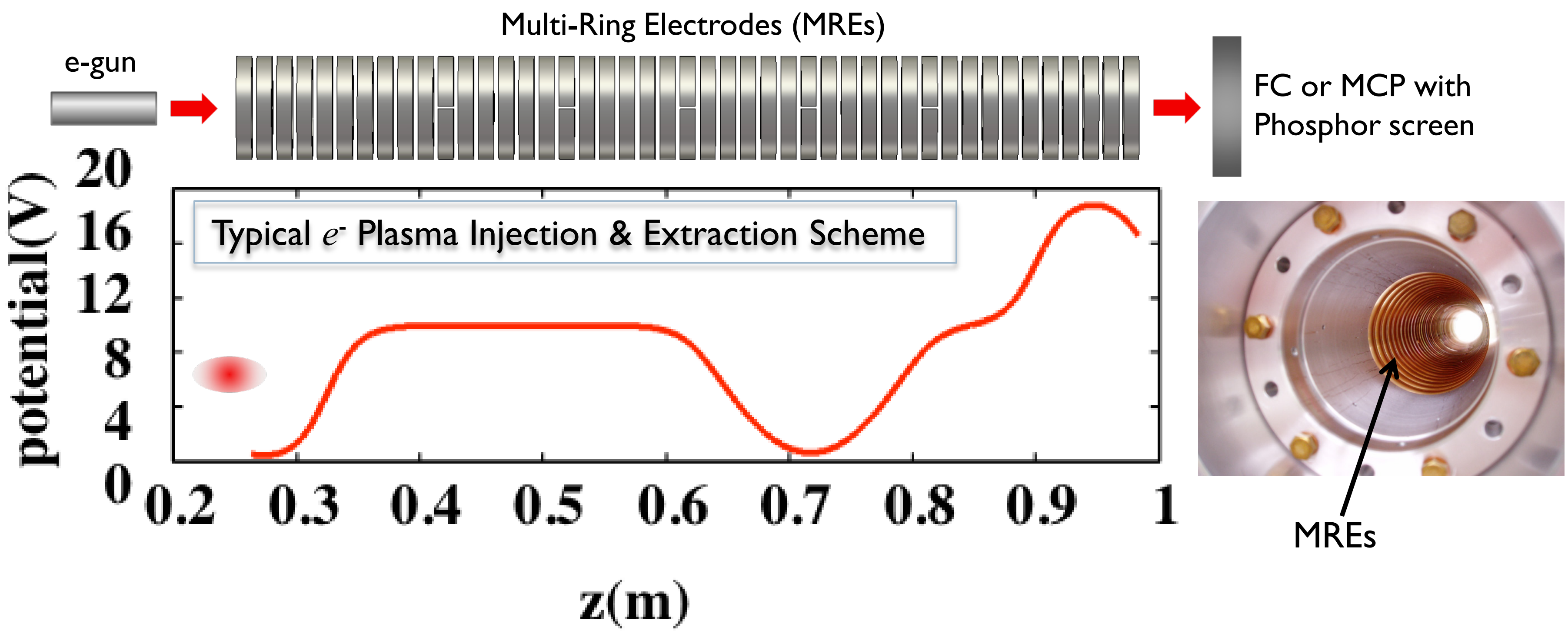
# Halo Formation by Sudden External Disturbance

Hamiltonian in a rotating frame

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

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

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



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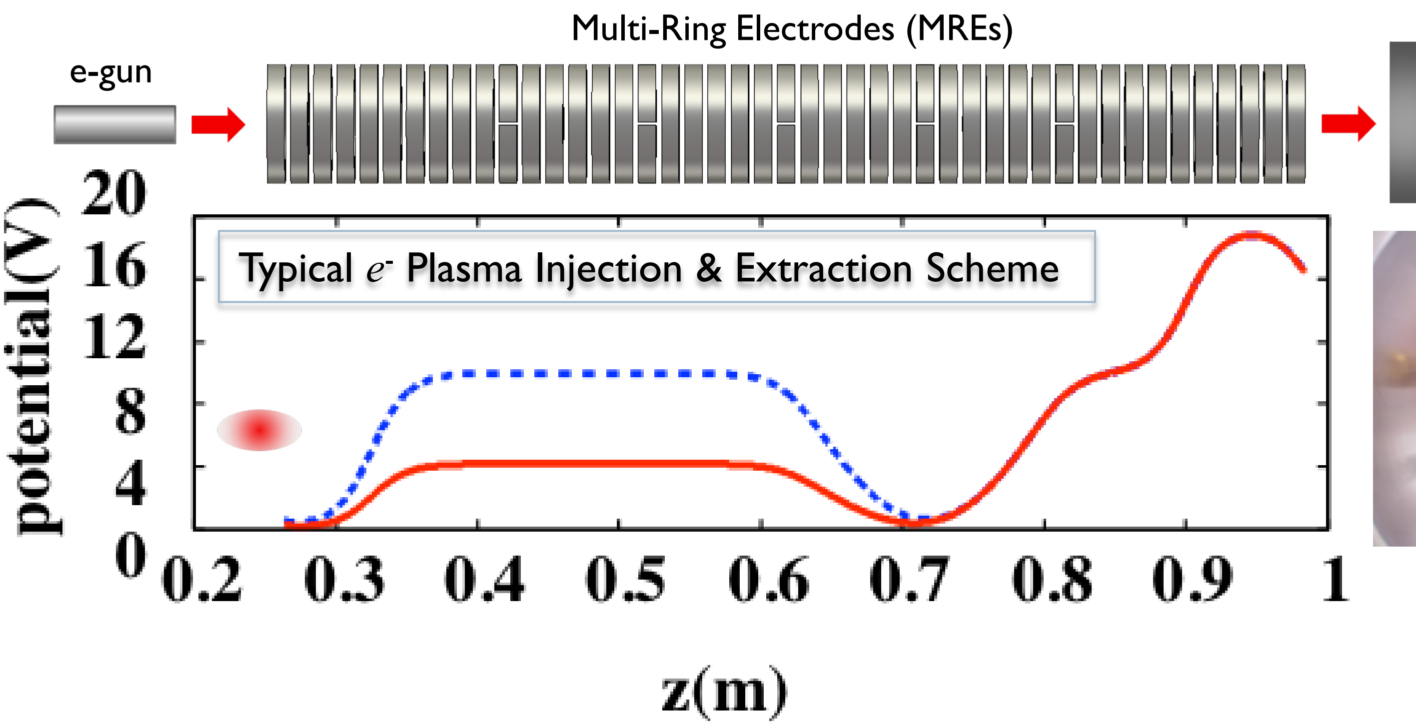


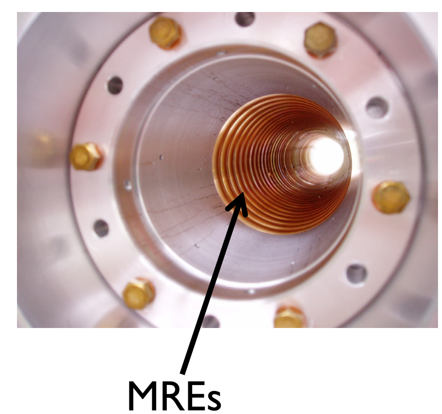

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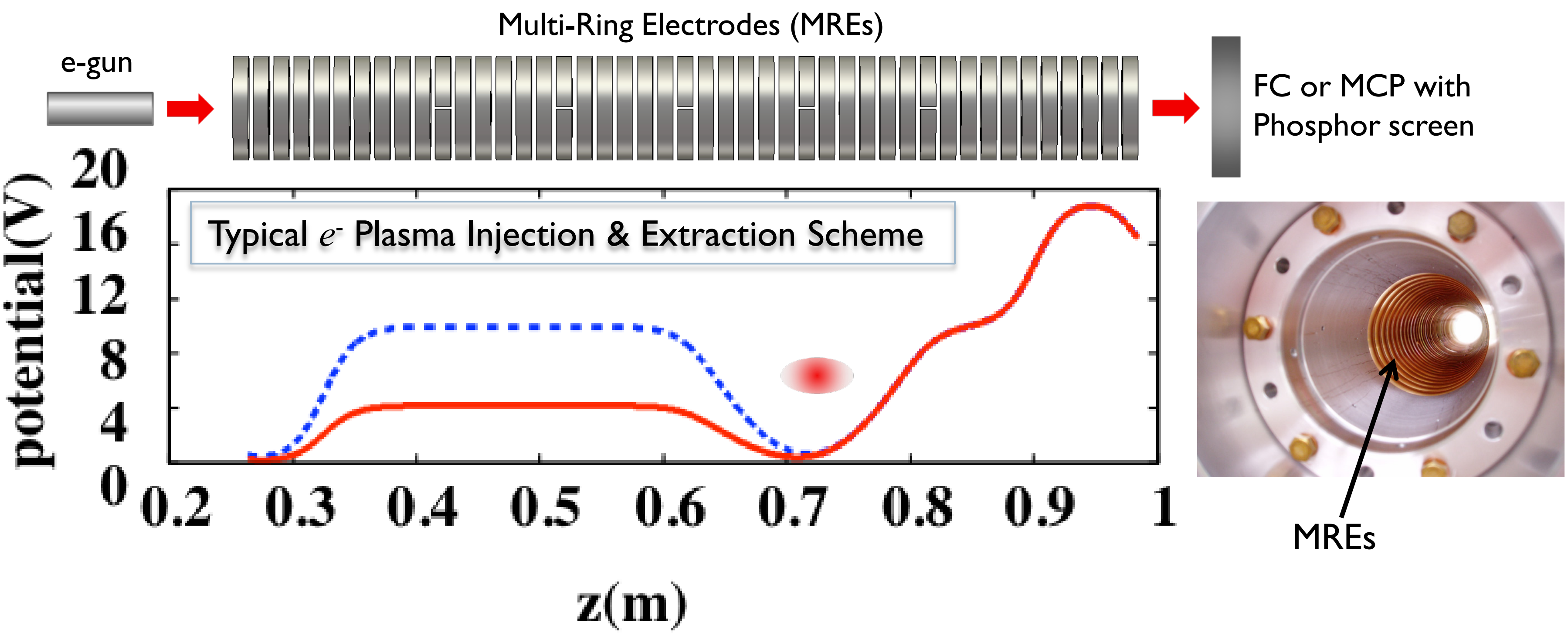

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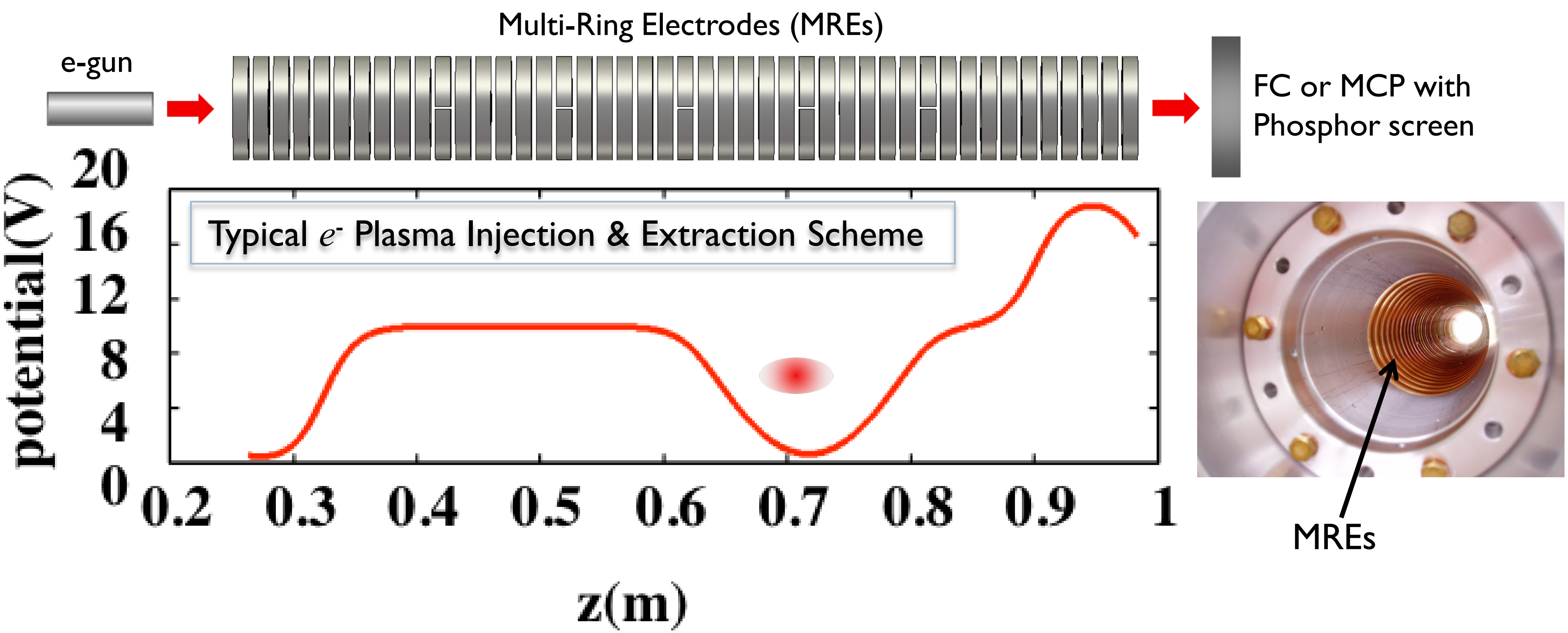

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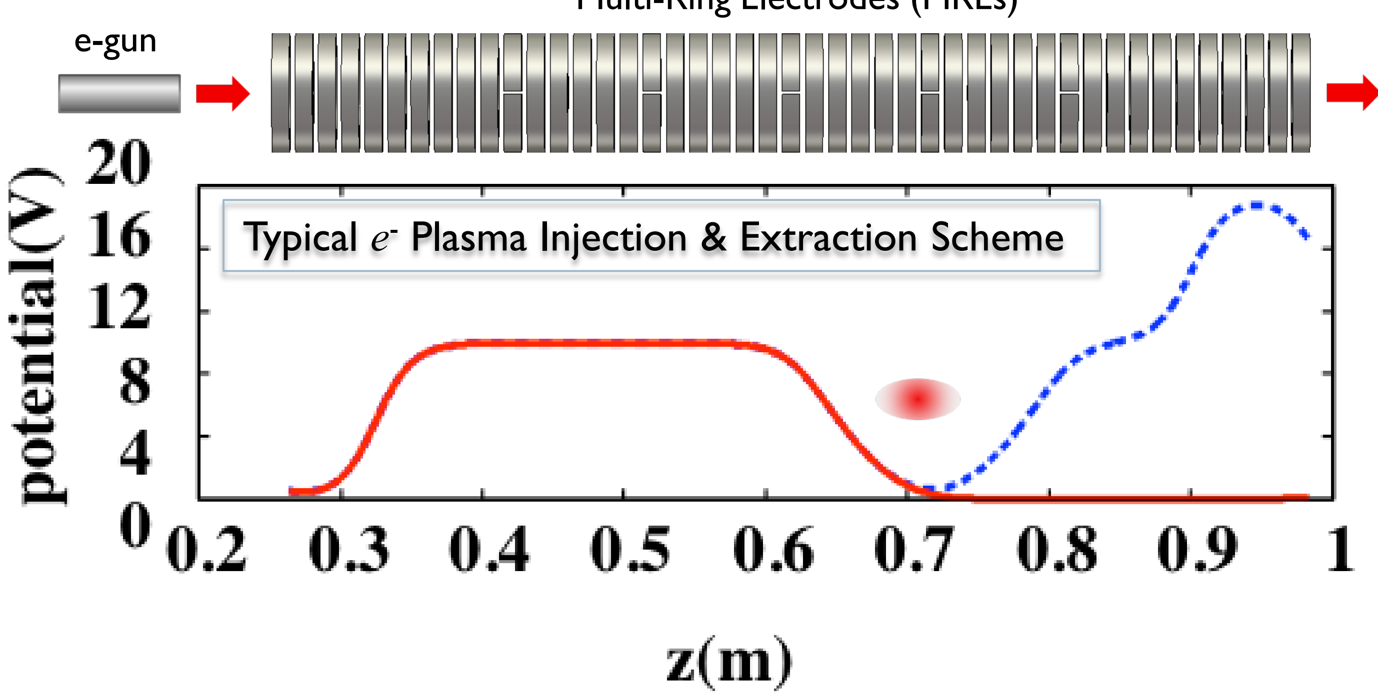


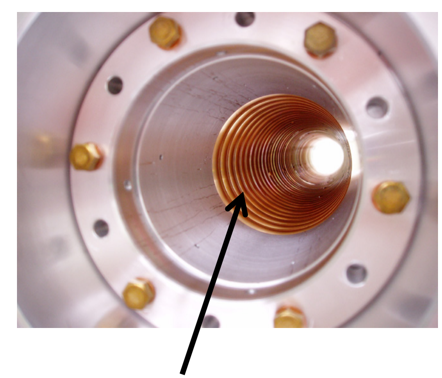

MREs

# Halo Formation by Sudden External Disturbance

Hamiltonian in a rotating frame

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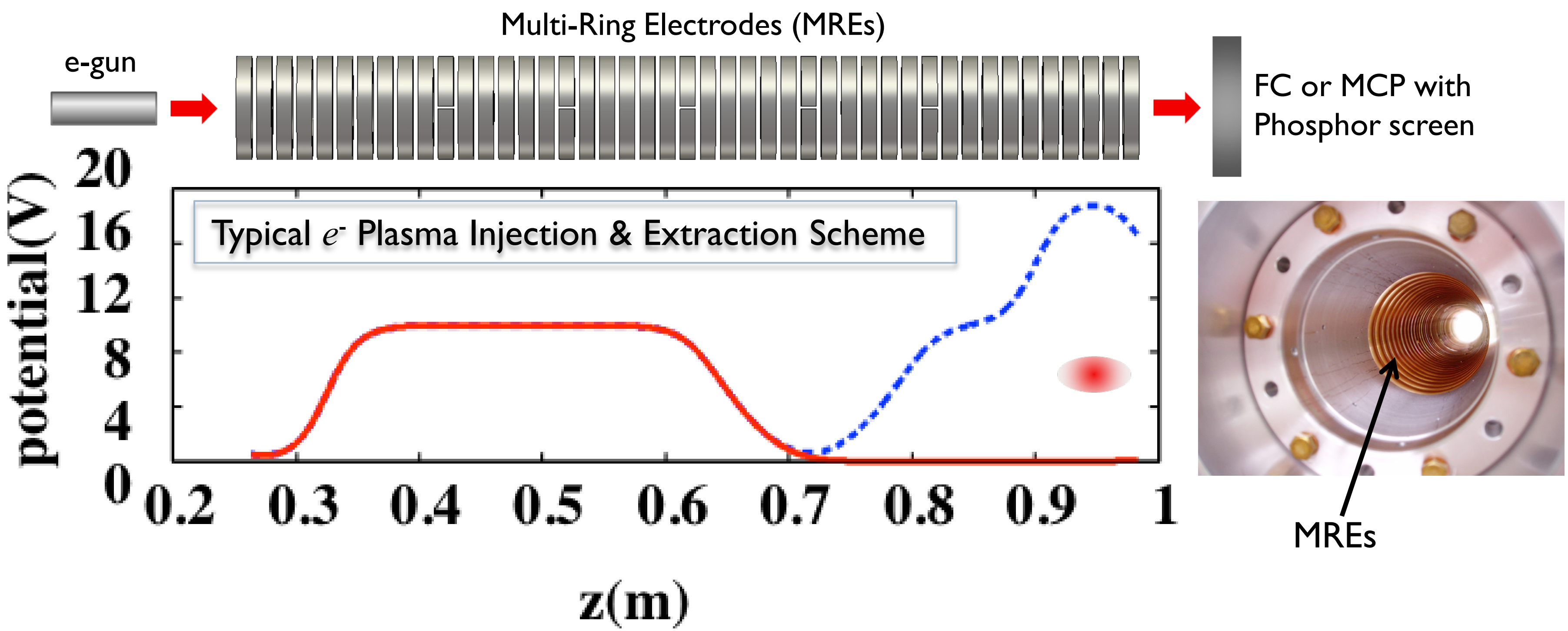


# Halo Measurements (Preliminary)

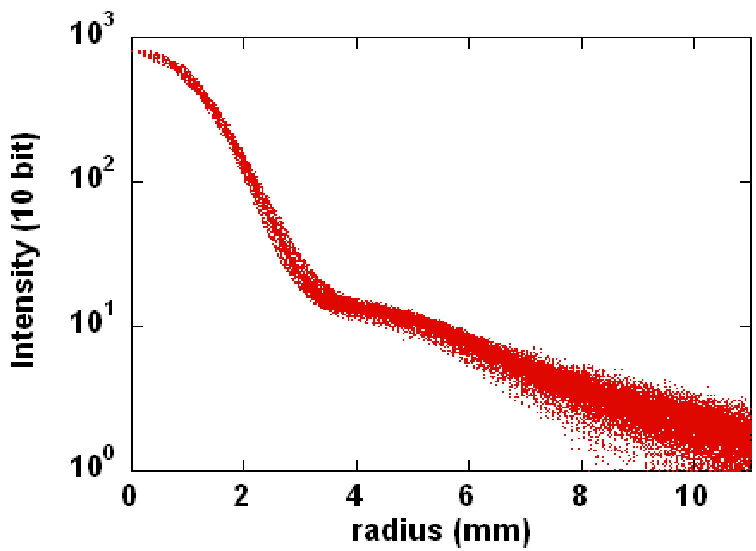
Axial magnetic field : 62.5 Gauss
Axial potential depth : (40 – 60) V
Cyclotron ang. freq. : 1.1 GHz
Brillouin density limit : 1.9 x $10^8$ $cm^{-3}$

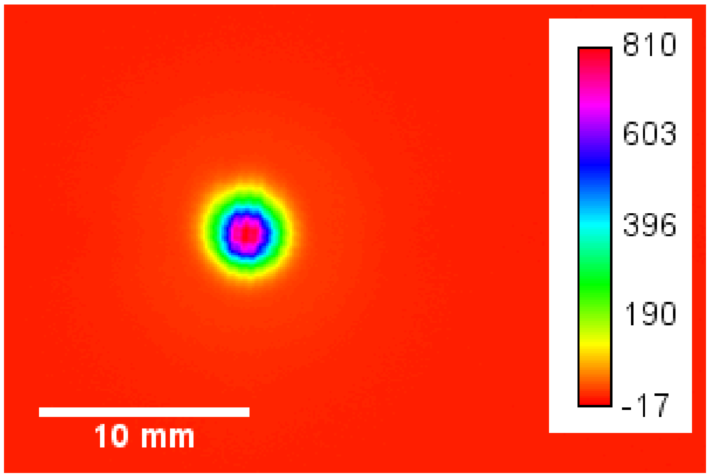
$$H = \frac{\mathbf{p}^2}{2} + \frac{1}{2}(k_\perp^2 - k_P^2)r^2 + k_P^2 z^2 + \frac{e}{mc^2}\phi_{sc}$$

The ratio $k_\perp / k_P$ 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.)

NO DISTURBANCE : z-potential depth (40 V)



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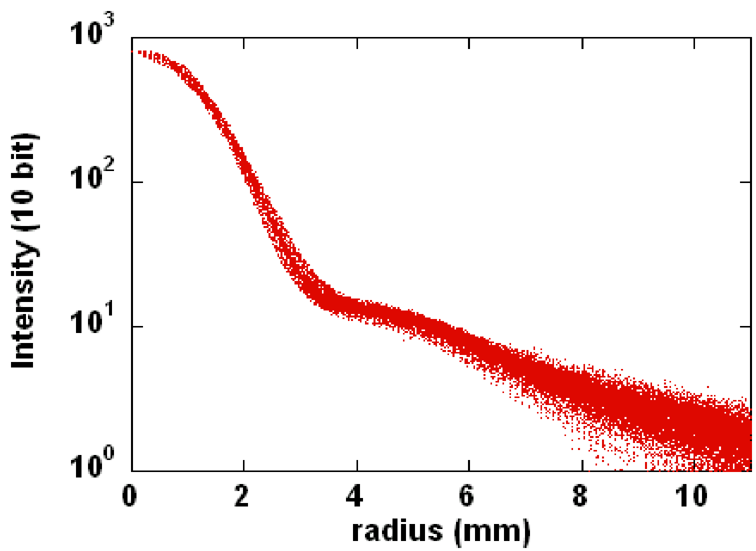
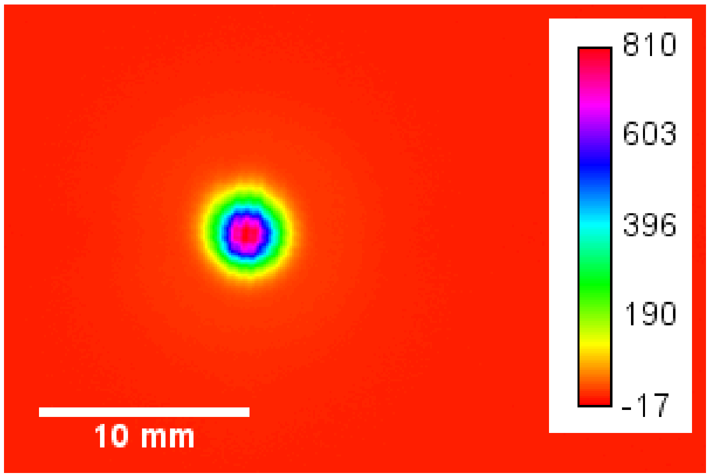
DISTURBED : z-potential depth (40 V → 50V)



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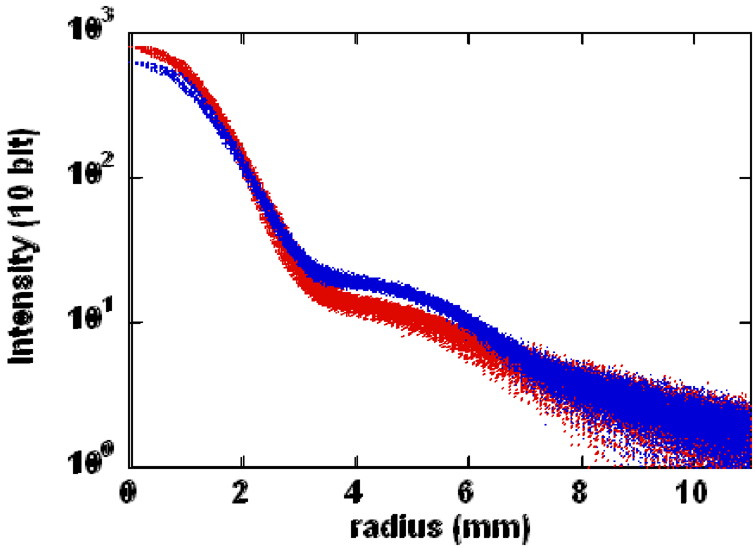


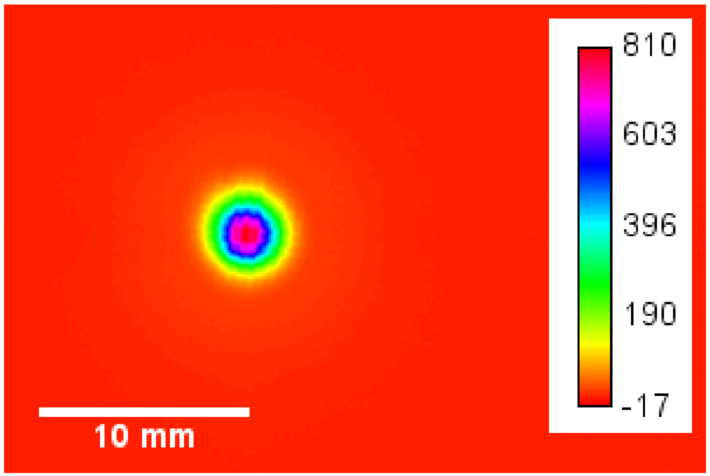

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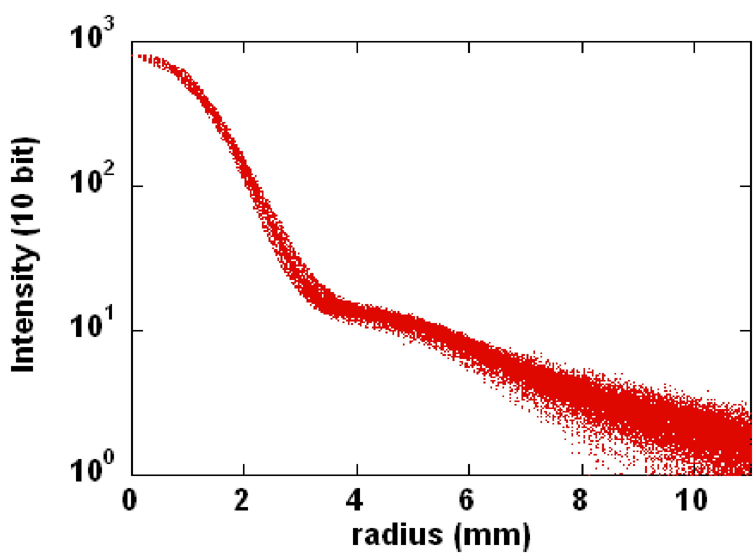


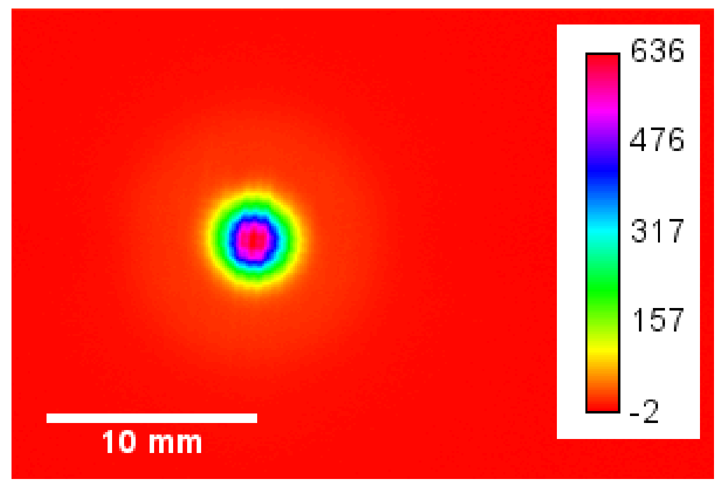

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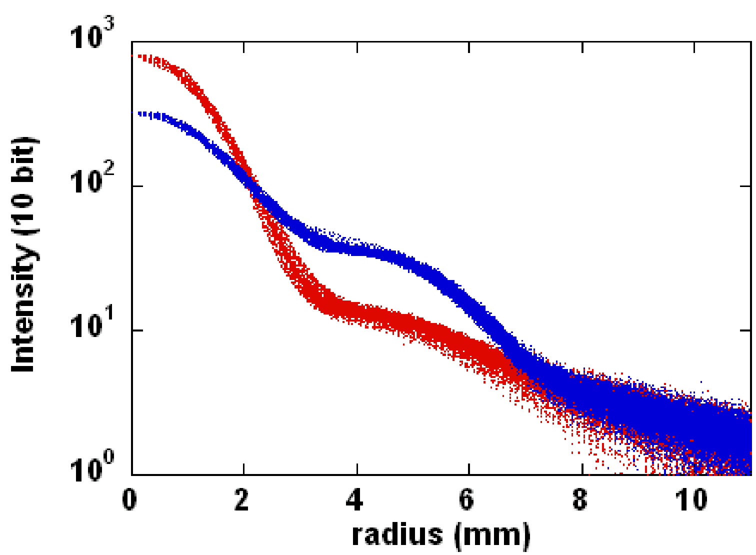


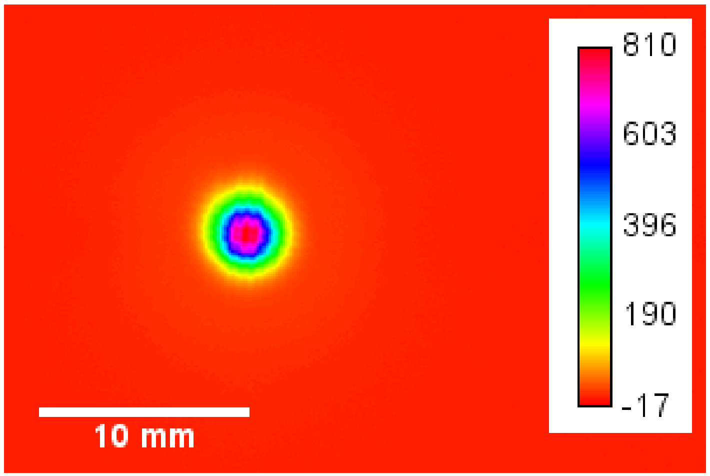

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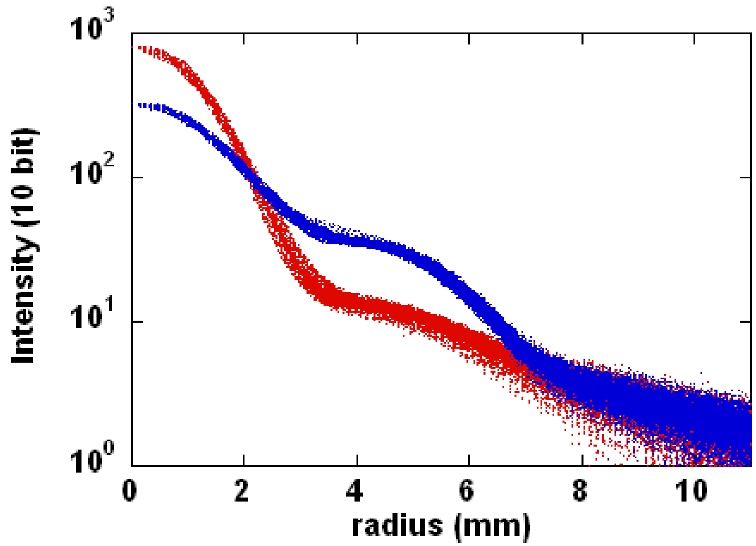


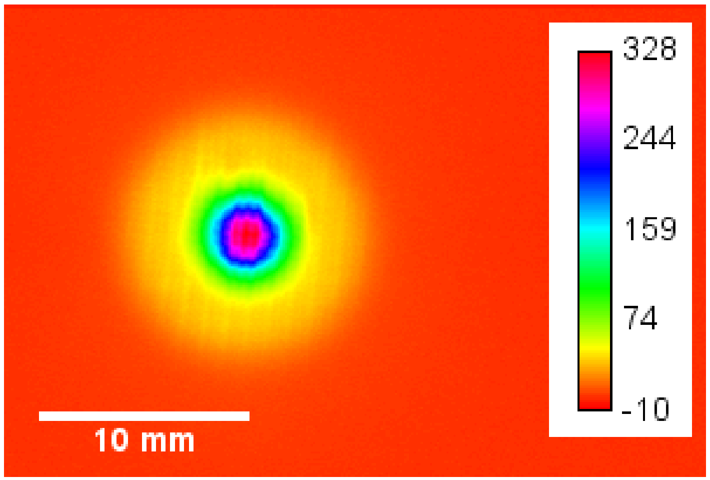

# Concluding Remarks

*S-POD offers a new experimental means with which we can systematically explore the collective nature of particle beams over a wide range.*

- Ongoing experimental subjects include :
  - Resonance-induced instabilities (lattice-induced effects, stop-band crossing)
  - Mismatch-induced effects (halo formation)
  - Ultralow-emittance Coulomb systems (crystalline-beam stability, nanobeam production)
- Other subjects that will be studied in the near future include :
  - Short bunch experiments, Synchro-betatron coupling effects, Resonance-induced halo formation,
  - Heating from Coulomb collisions, … etc.

*We need more experiences to perfectly establish this new approach.*

- Matters Under Consideration
  - Systematic numerical simulations
  - Fine tune-depression control by the laser system & LIF diagnostics development
  - Further increase of confinable particle numbers (plasma stacking)
  - Improvements of S-POD components (rf power generators, ionization system, etc.)

# Acknowlegements


**Past and Present Contributors to the S-POD Project**

- Hiroshima University

  Hiroyuki Higaki, Kiyokazu Ito

  (Students)

  Shuhei Fujimoto, Masaharu Fujioka, Kyohei Fukata, Haruki Hitomi, Keiichi Homma, Masao Kano, Yasuhiko Mizuno, Kenji Nakayama, Shunsuke Ohtsubo, Kota Okabe, Shunsuke Sakao, Hiroshi Sugimoto, Hiroki Takeuchi, Kazuhisa Tanaka, Ryota Takai, Genki Uchimura

- Osaka University

  Kenji Toyoda

- LBNL & LLNL

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Hiroyuki I

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Shuhei Fu                                                                                                  omma,
Masao Ka                                                                                                  abe,
Shunsuke                                                                                                  akai,
Genki Uc

- Osaka U

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- LBNL & LLNL

Steven M. Lund, Andrew M. Sessler, Jean-Luc Vay, David Grote

S-POD facilities are open to anybody who has interest in using them for beam-physics purposes.

Everybody is welcome if he/she wants to try any new experiments with S-PODs in Hiroshima.

Thank you for attention !