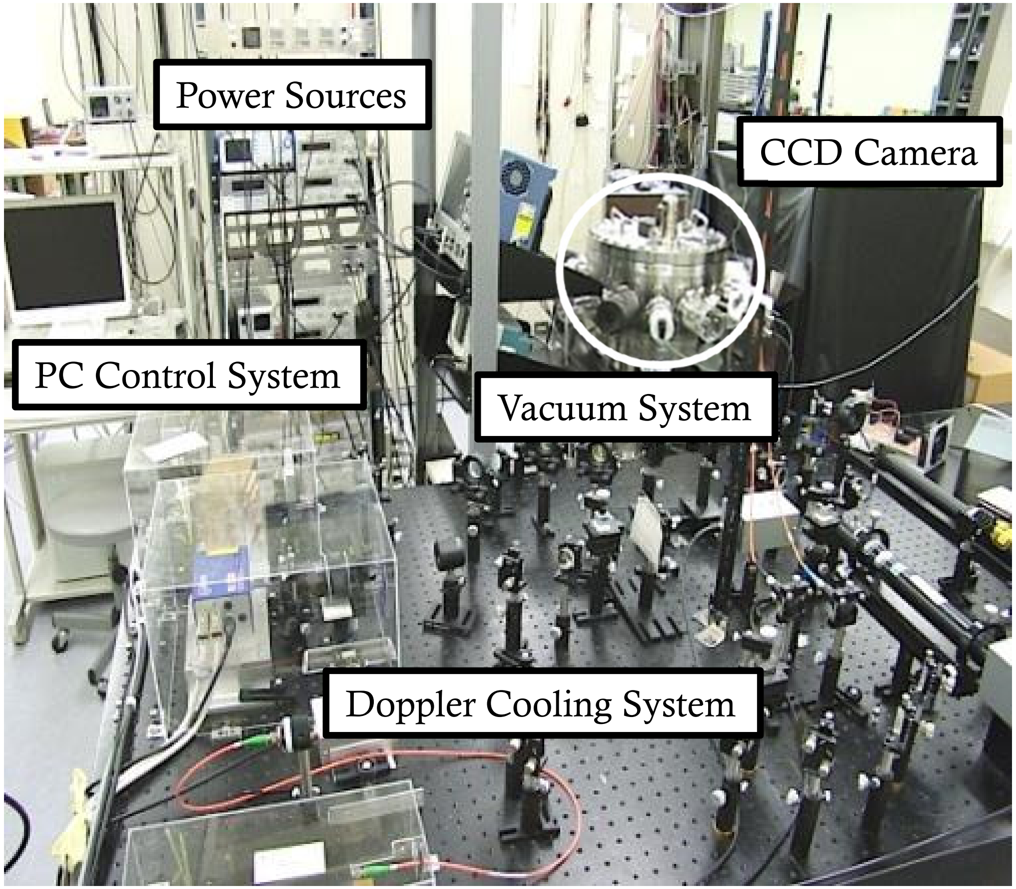
Beam Dynamics Studies with Non-neutral Plasma Traps

Hiromi Okamoto
(AdSM, Hiroshima University)

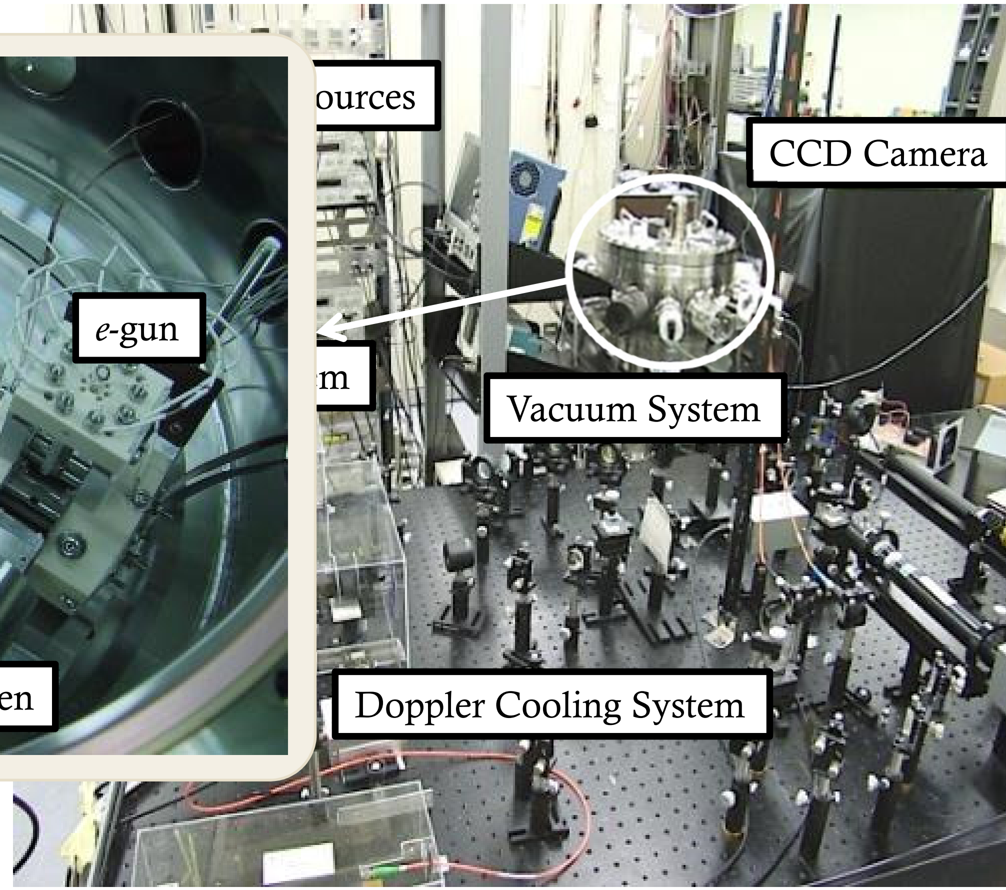
S-POD

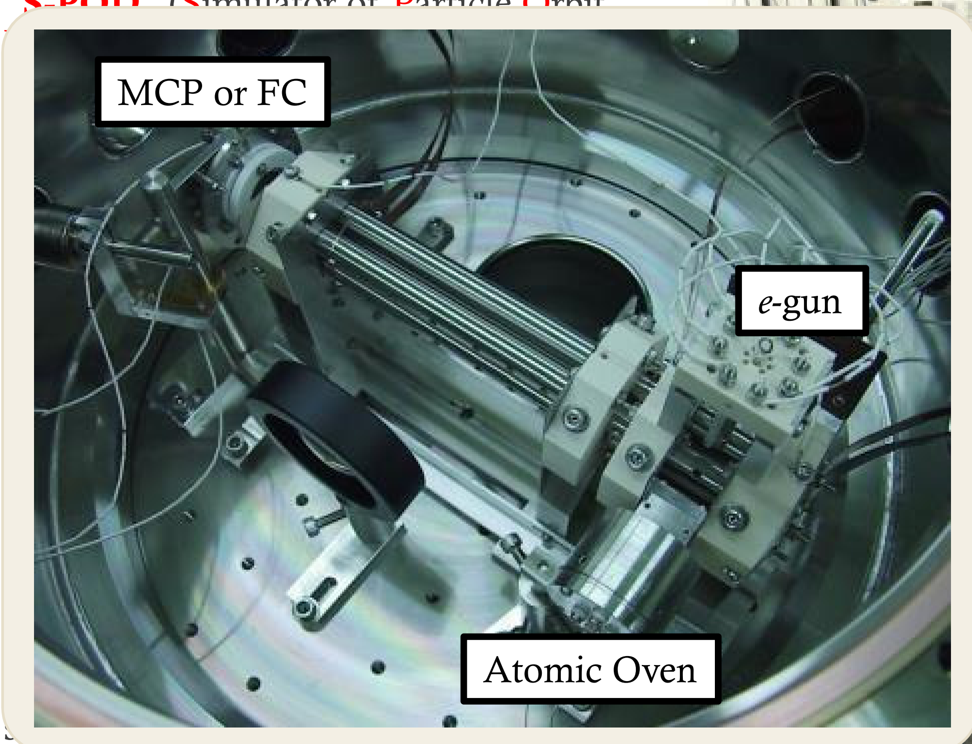
- "**S-POD**" (Simulator of Particle Orbit Dynamics) is a non-neutral plasma trap system developed at Hiroshima University for various beam dynamics studies.
- S-POD is composed mainly of a compact ion or electron trap, AC and DC power supplies, vacuum pumps, monitors (MCP, FC, CCD), a Doppler laser cooler, and a computer control system.
- "Paul ion trap" or "Penning trap" can be employed for S-POD.
- We have five independent S-POD systems, three of which are based on Paul traps and the other two on Penning traps.



S-POD

- “S-POD” (Simulator of Particle Orbit





Paul traps and the other two on Penning traps.

How it works…

S-POD experiment is based on the isomorphism between the beam dynamics in periodic AG focusing channels and the non-neutral plasma dynamics in trap systems.

The collective motion of an intense beam and that of a non-neutral plasma are both governed by the Vlasov-Poisson equations:

$$\frac{\partial f}{d\tau} + [f, H(\phi)] = 0 \qquad \nabla^2 \phi = -\frac{q}{\varepsilon_0} \int f \, d\mathbf{p}$$

The independent variable τ is either the path length s or time t.

How it works…

S-POD experiment is based on the isomorphism between the beam dynamics in periodic AG focusing channels and the non-neutral plasma dynamics in trap systems.

The collective motion of an intense beam and that of a non-neutral plasma are both governed by the Vlasov-Poisson equations:

$$\frac{\partial f}{d\tau} + [f, H(\phi)] = 0 \qquad \nabla^2 \phi = -\frac{q}{\varepsilon_0} \int f \, d\mathbf{p}$$

The independent variable τ is either the path length s or time t.

$$H_{\text{beam}} = \frac{p_x^2 + p_y^2}{2} + \frac{1}{2}[K_x(s)x^2 + K_y(s)y^2] + I_{\text{beam}}\phi$$

How it works…

S-POD experiment is based on the isomorphism between the beam dynamics in periodic AG focusing channels and the non-neutral plasma dynamics in trap systems.

The collective motion of an intense beam and that of a non-neutral plasma are both governed by the Vlasov-Poisson equations:

$$\frac{\partial f}{d\tau} + [f, H(\phi)] = 0 \qquad \nabla^2 \phi = -\frac{q}{\varepsilon_0}\int f\, d\mathbf{p}$$

The independent variable τ is either the path length s or time t.

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

How it works…

S-POD experiment is based on the isomorphism between the beam dynamics in periodic AG focusing channels and the non-neutral plasma dynamics in trap systems.

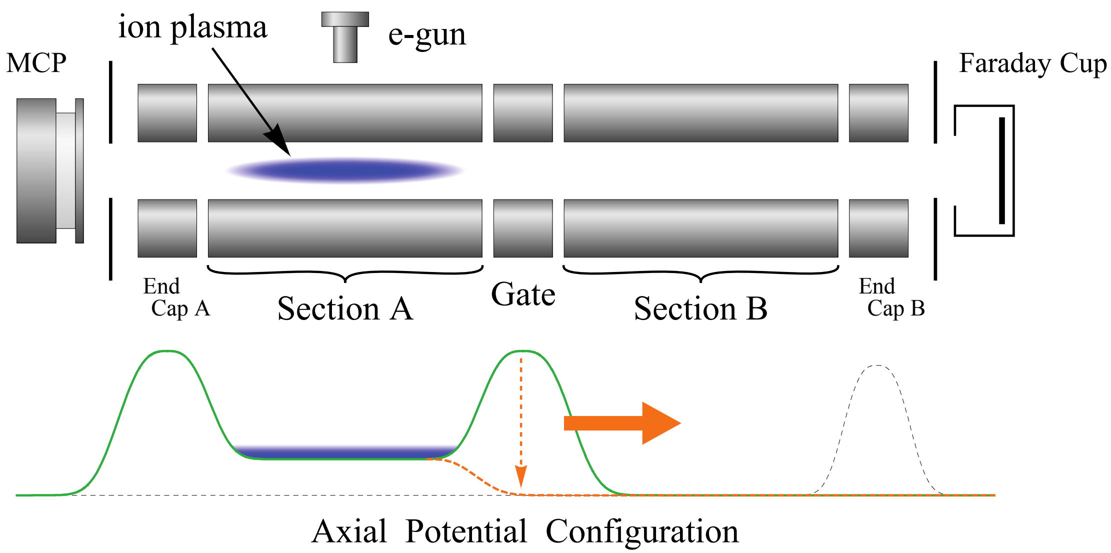
The collective motion of an intense beam and that of a non-neutral plasma are both governed by the Vlasov-Poisson equations:

$$\frac{\partial f}{d\tau} + [f, H(\phi)] = 0 \qquad \nabla^2 \phi = -\frac{q}{\varepsilon_0}\int f \, d\mathbf{p}$$

The independent variable τ is either the path length s or time t.

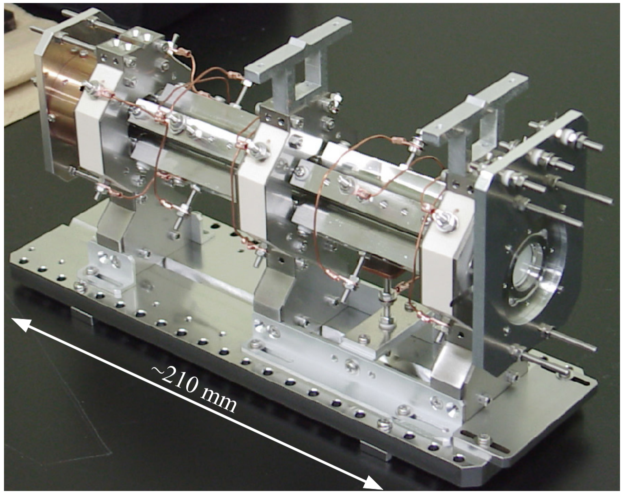
$$H_{\mathrm{beam}} = \frac{p_x^2 + p_y^2}{2} + \frac{1}{2}[K_x(s)x^2 + K_y(s)y^2] + I_{\mathrm{beam}}\phi \Leftrightarrow H_{\mathrm{plasma}} = \frac{p_x^2 + p_y^2}{2} + \frac{1}{2}K_{\mathrm{RF}}(t)(x^2 - y^2) + I_{\mathrm{plasma}}\phi$$

Linear Paul Traps

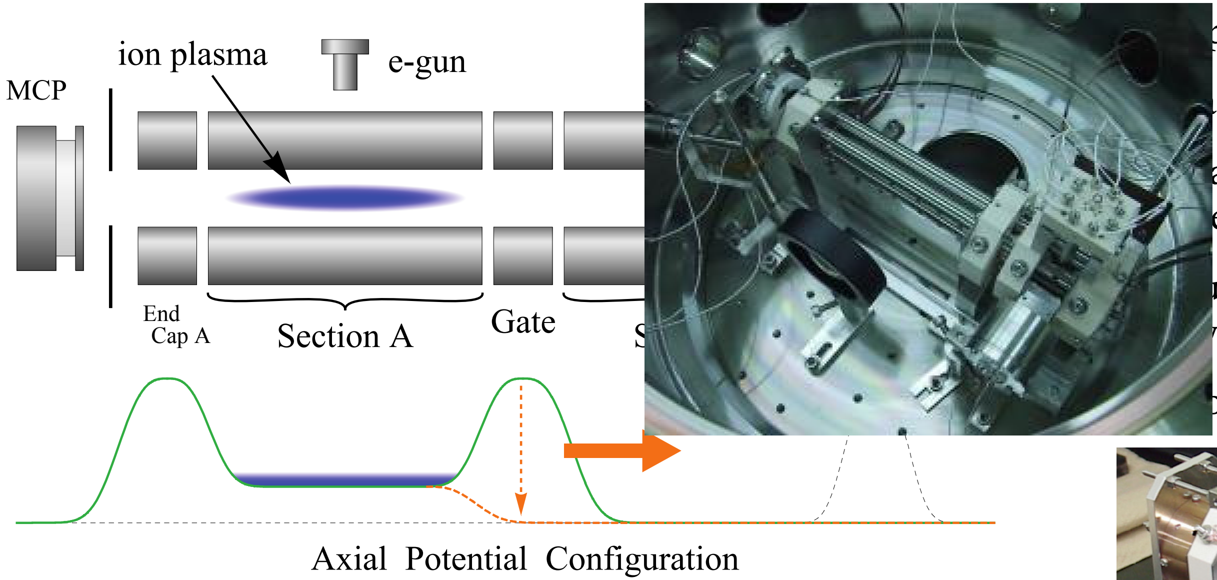


Transverse confinement :
rf quadrupole
Longitudinal confinement :
rf or electrostatic potential

* 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 !

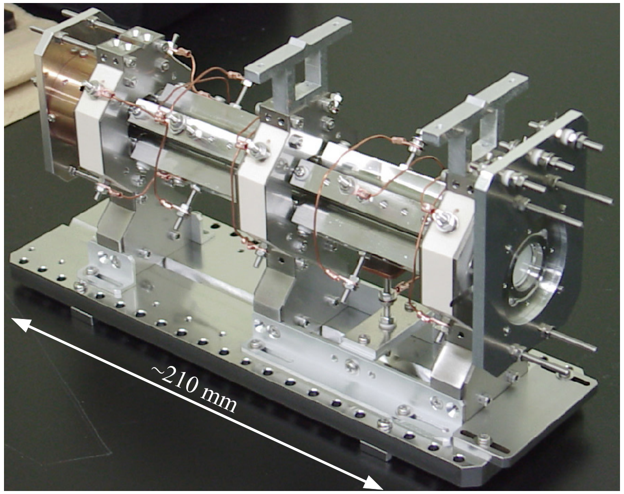


Linear Paul Traps

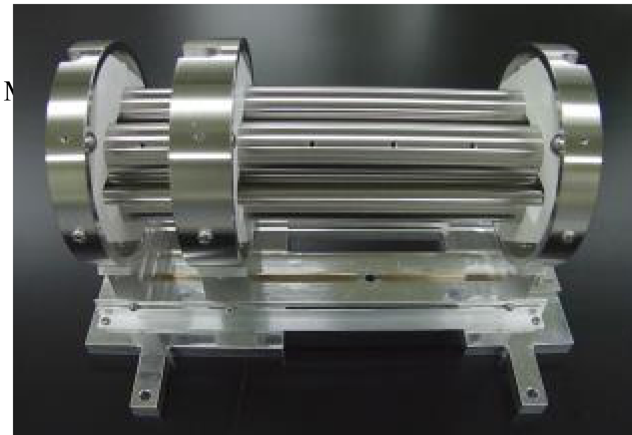


- perating frequency : 1 MHz
- rticle species : Ar^+, Ca^+, N^+, etc.
- asma lifetime : order of seconds
  ependent on plasma conditions)
- ne depression : > 0.8
  ithout cooling)
- st : a few thousand USD !

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



Linear Paul Traps



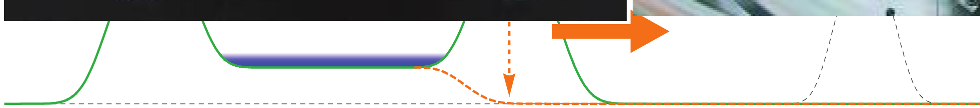
perating frequency : 1 MHz

rticle species : Ar^+, Ca^+, N^+, etc.

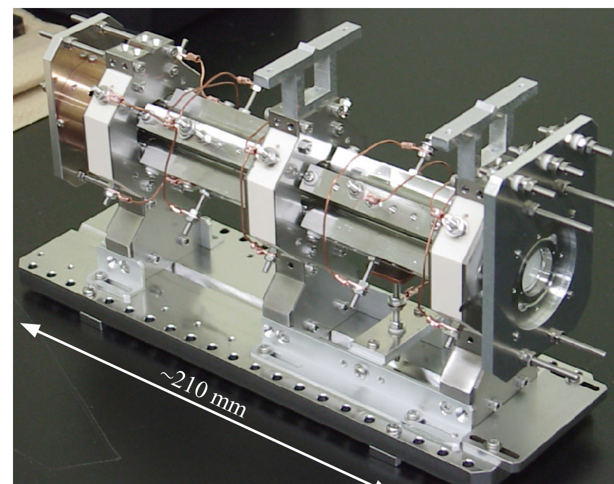
asma lifetime : order of seconds
ependent on plasma conditions)

ine depression : > 0.8
vithout cooling)

ost : a few thousand USD !

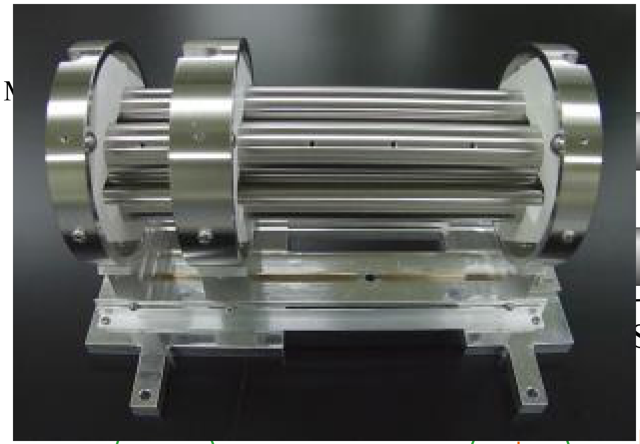


Axial Potential Configuration



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

Linear Paul Traps



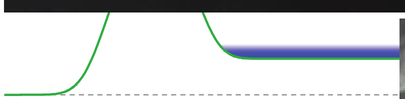
perating frequency : 1 MHz

rticle species : Ar^+, Ca^+, N^+, etc.

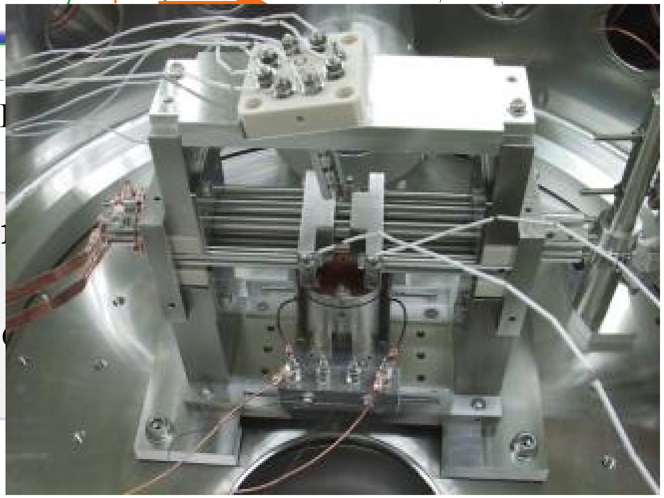
asma lifetime : order of seconds
ependent on plasma conditions)

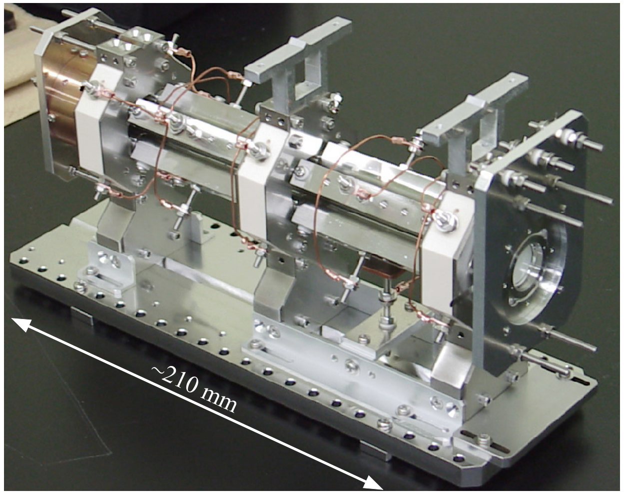
une depression : > 0.8
vithout cooling)

ost : a few thousand USD !



Axial



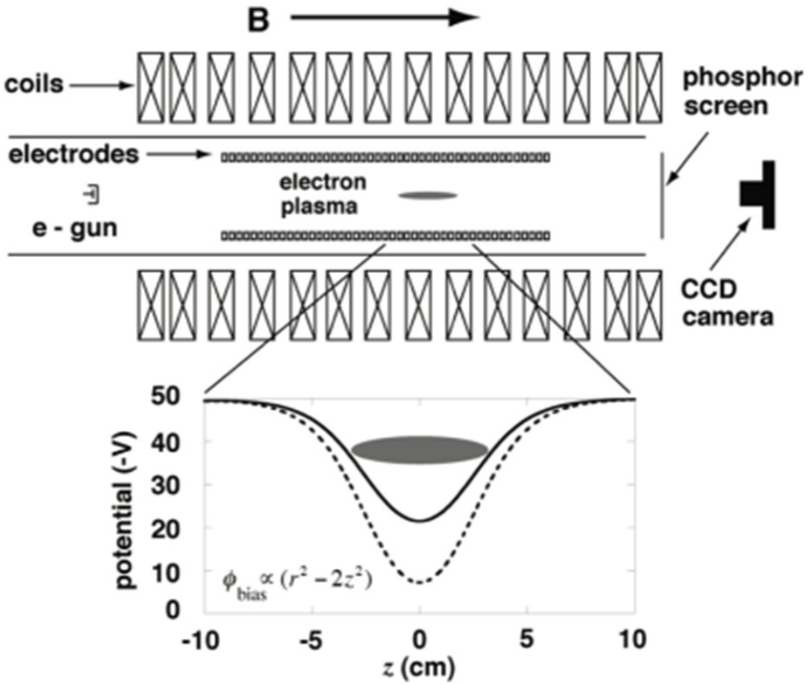


Transverse co

Longitudinal

Penning Traps

- Penning Trap with Multi-Ring Electrodes



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

* Particle species : e^-

* Field strength : < 1 kG

Why plasma traps…?

The S-POD trap system is just a toy model, so it does not perfectly reproduce the dynamic behavior of charged-particle beams. However, the concept of trap experiment has some obvious advantages:

- Compactness
- Low cost
- Flexibility
- Easy measurement
- No radioactivation

Why plasma traps…?

The S-POD trap system is just a toy model, so it does not perfectly reproduce the dynamic behavior of charged-particle beams. However, the concept of trap experiment has some obvious advantages:

- Compactness ⟵ *Tabletop size*
- Low cost
- Flexibility
- Easy measurement
- No radioactivation

Why plasma traps…?

The S-POD trap system is just a toy model, so it does not perfectly reproduce the dynamic behavior of charged-particle beams. However, the concept of trap experiment has some obvious advantages:

- Compactness ⟵ *Tabletop size*
- Low cost ⟵ *No question about this !*
- Flexibility
- Easy measurement
- No radioactivation

Why plasma traps…?

The S-POD trap system is just a toy model, so it does not perfectly reproduce the dynamic behavior of charged-particle beams. However, the concept of trap experiment has some obvious advantages:

- Compactness ⟵ *Tabletop size*
- Low cost ⟵ *No question about this !*
- Flexibility ⟵ *Very wide parameter ranges and lattice choices*
- Easy measurement
- No radioactivation

Why plasma traps…?

The S-POD trap system is just a toy model, so it does not perfectly reproduce the dynamic behavior of charged-particle beams. However, the concept of trap experiment has some obvious advantages:

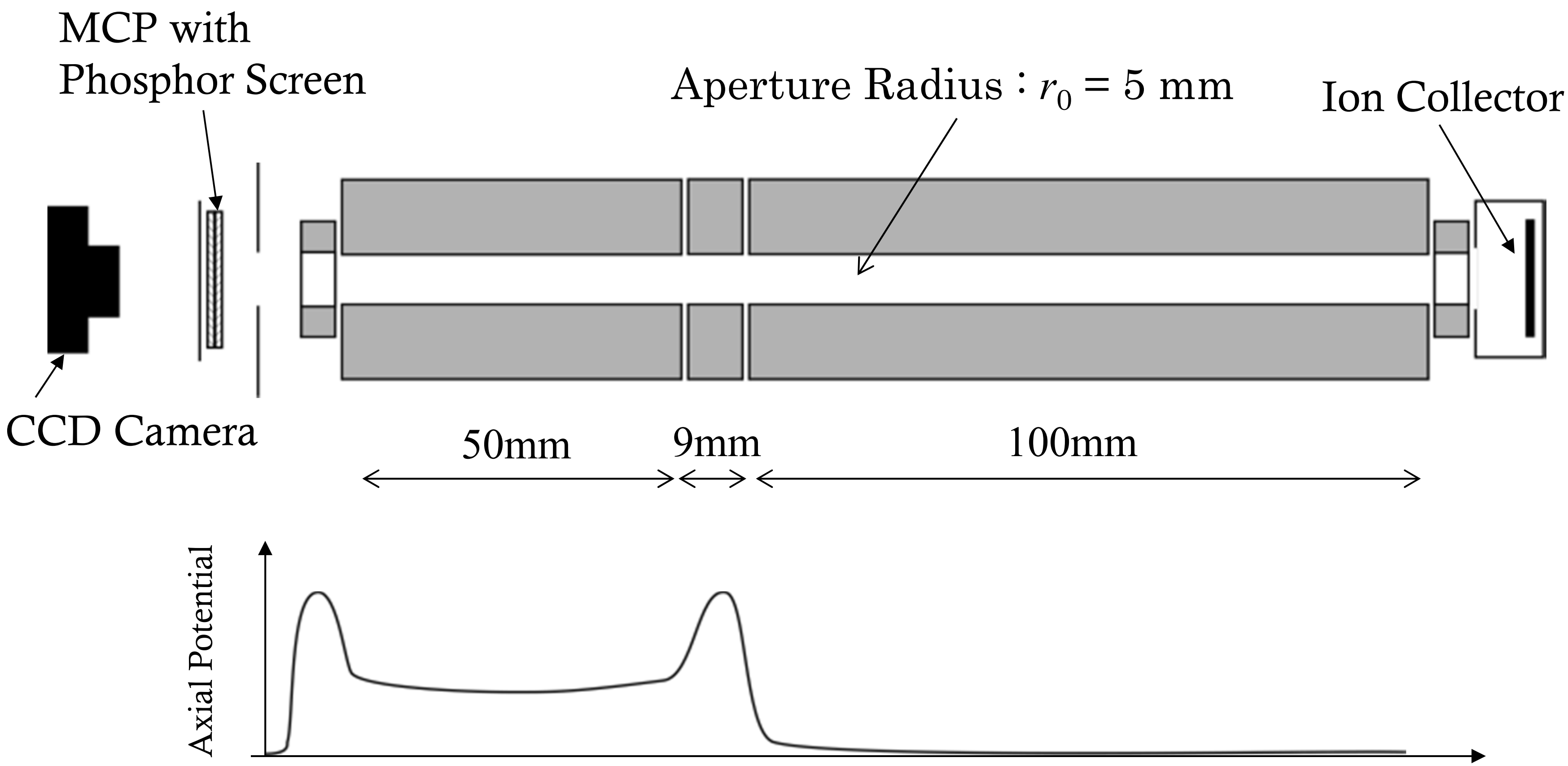
- Compactness ⟵ *Tabletop size*
- Low cost ⟵ *No question about this !*
- Flexibility ⟵ *Very wide parameter ranges and lattice choices*
- Easy measurement ⟵ *Everything is in the lab frame.*
- No radioactivation

Why plasma traps…?

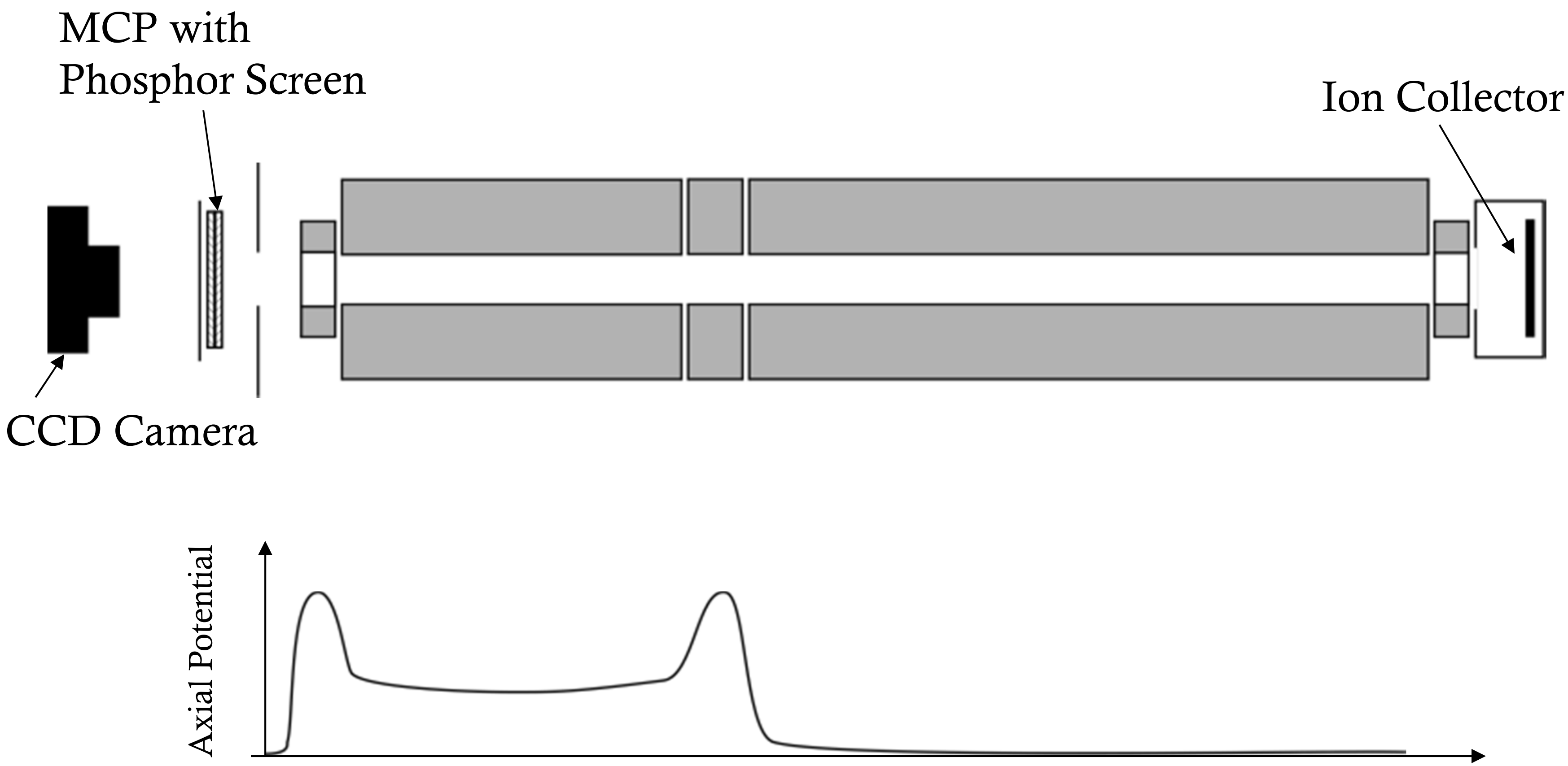
The S-POD trap system is just a toy model, so it does not perfectly reproduce the dynamic behavior of charged-particle beams. However, the concept of trap experiment has some obvious advantages:

- Compactness ⟵ *Tabletop size*
- Low cost ⟵ *No question about this !*
- Flexibility ⟵ *Very wide parameter ranges and lattice choices*
- Easy measurement ⟵ *Everything is in the lab frame.*
- No radioactivation ⟵ *Absolutely no problem with particle losses*

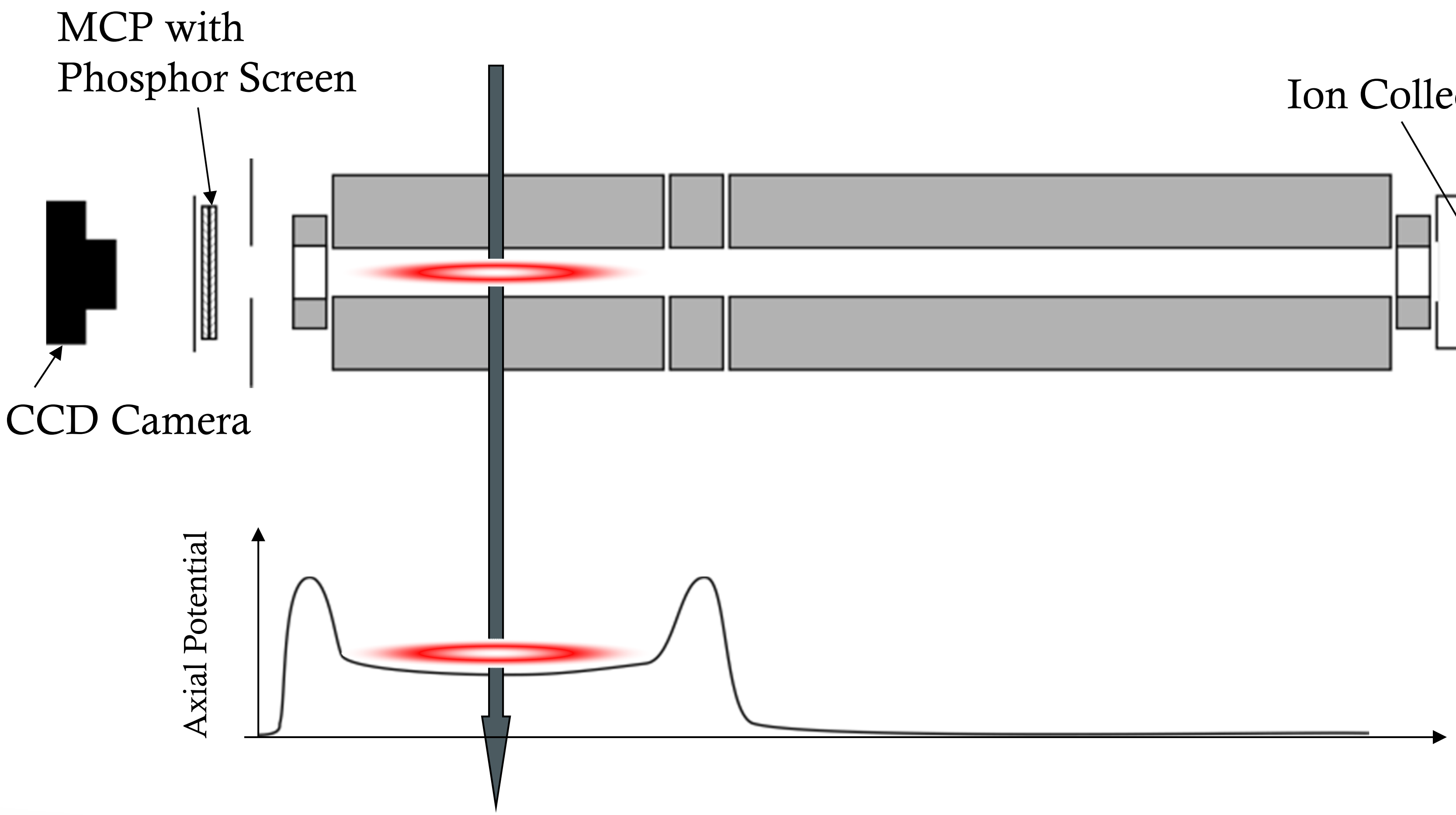
Typical Experiment Process



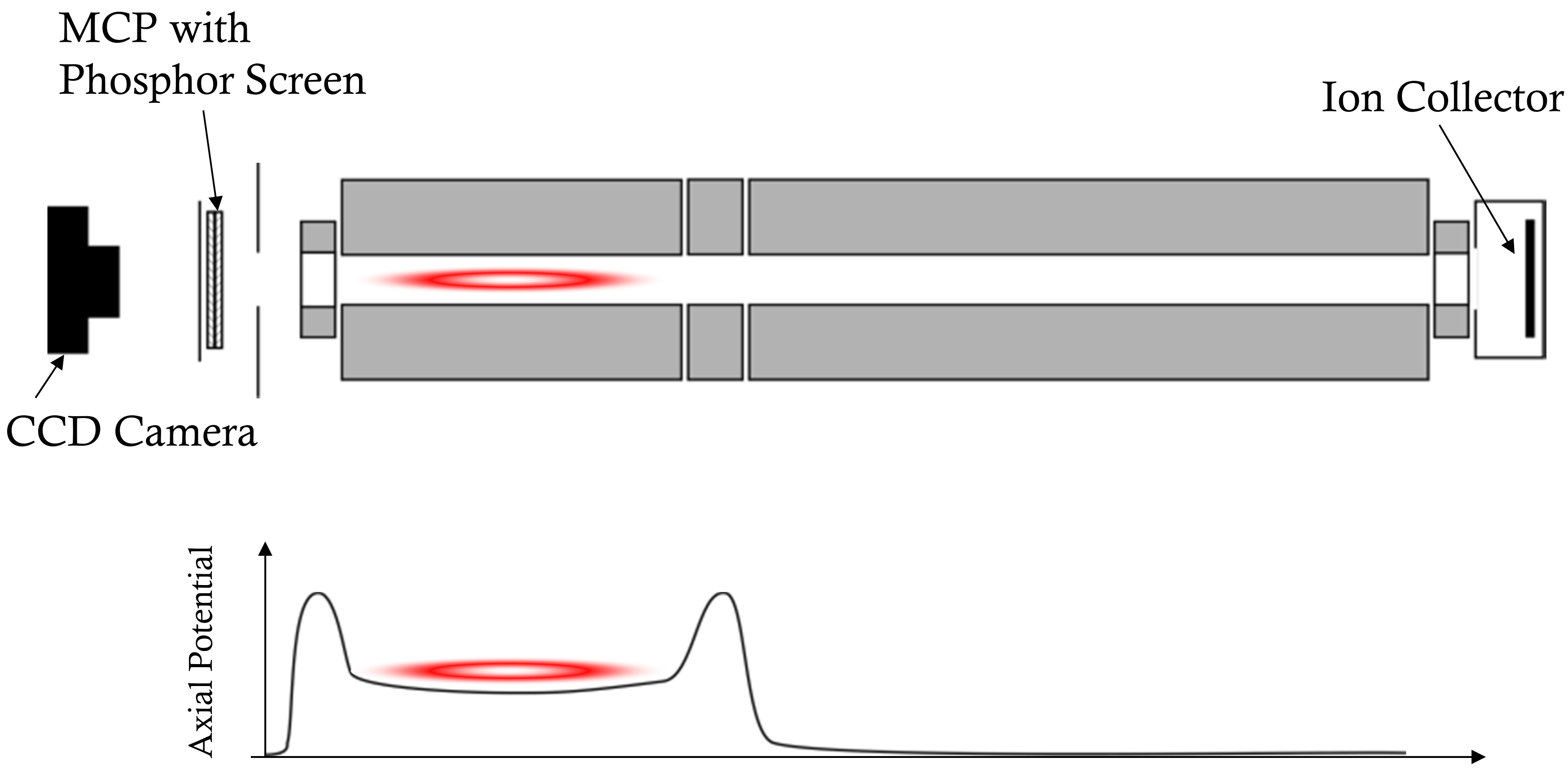
Typical Experiment Process



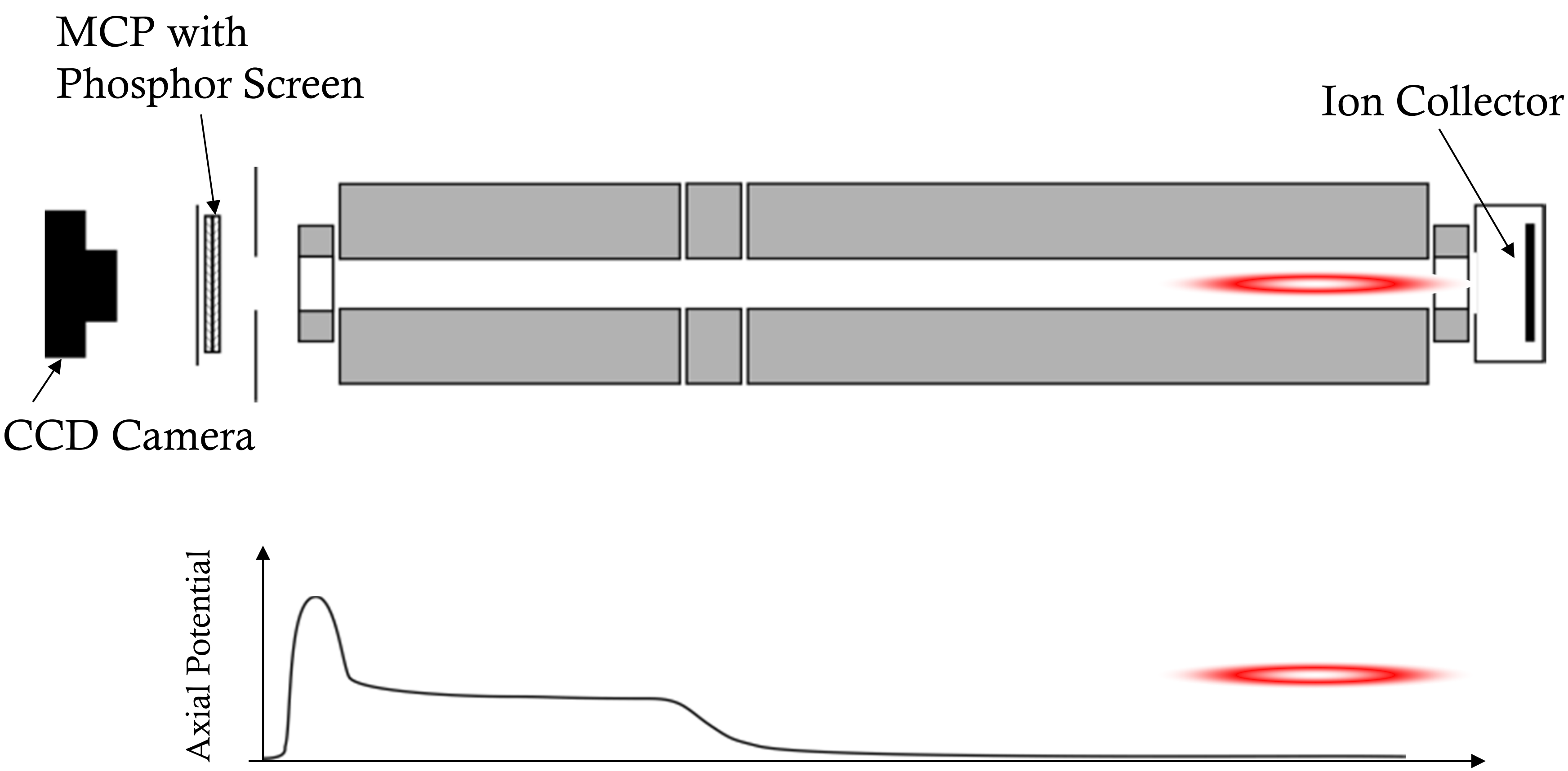
Typical Experiment Process



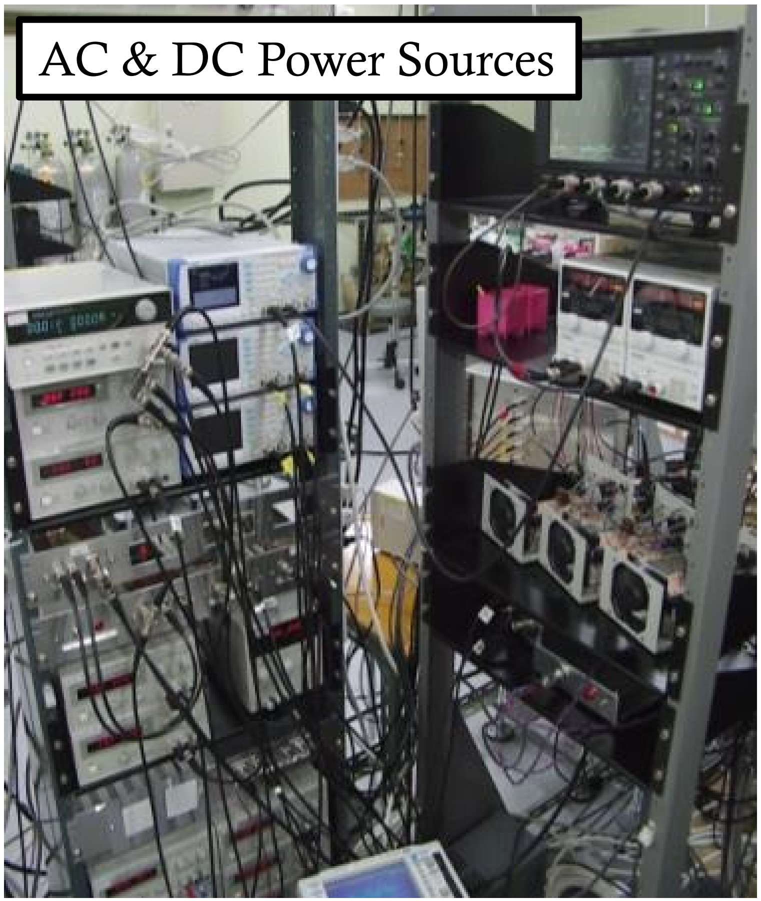
Typical Experiment Process



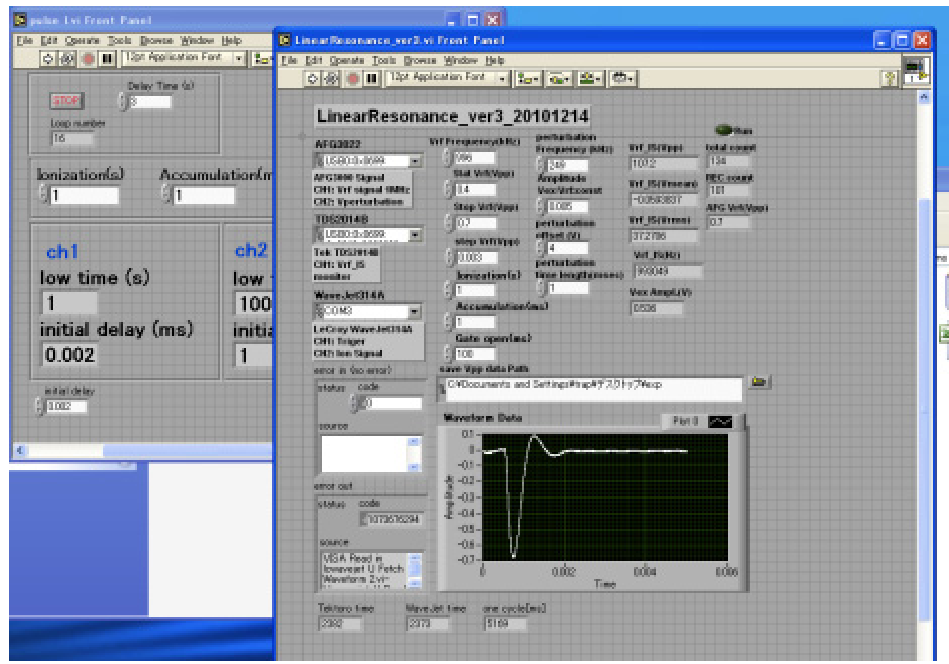
Typical Experiment Process



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.)

Experiment Plans

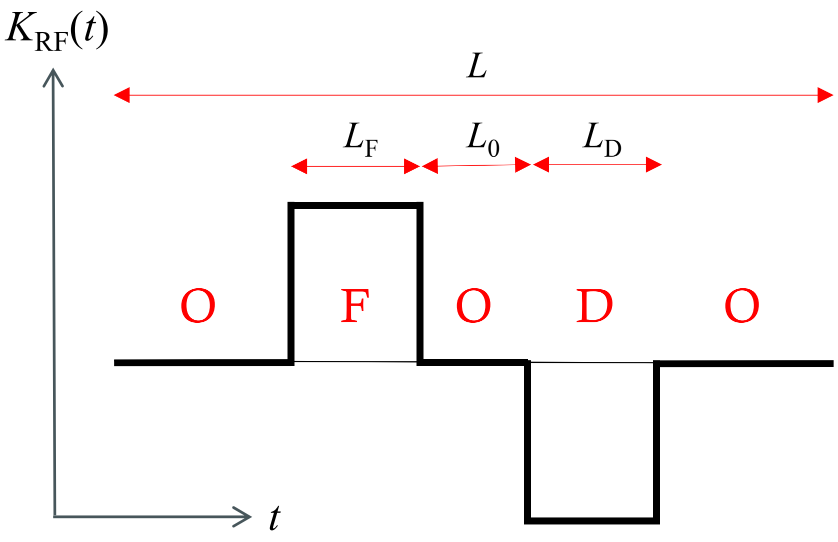
- Ongoing and Past
  - Linear and nonlinear stop-band measurements
  - Resonance crossing
  - Halo formation
  - Cooling experiments
- Near Future
  - Stop-band measurements with complex AG waveforms
  - Long-term stability of intense hadron beams
  - Plasma stacking experiments
  - Long and short bunch experiments, synchrotron resonances, controlled nonlinear resonance experiments, etc.

Stop Band Measurement

Intensity Dependence, Lattice-Structure Dependence, Error-Field Dependence, … etc.

Doublet Geometry

RF Waveform for Doublet

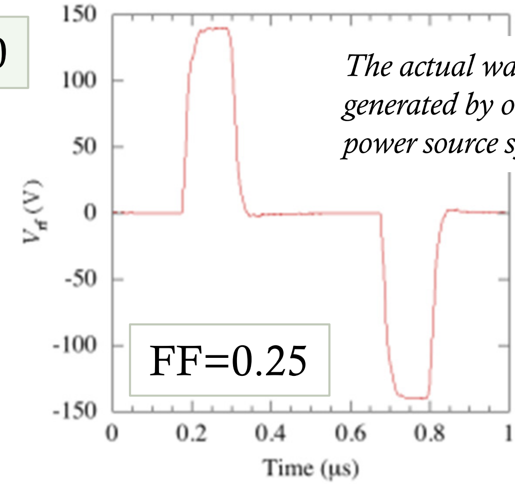


Filling Factor : $FF = \dfrac{L_F + L_D}{L}$

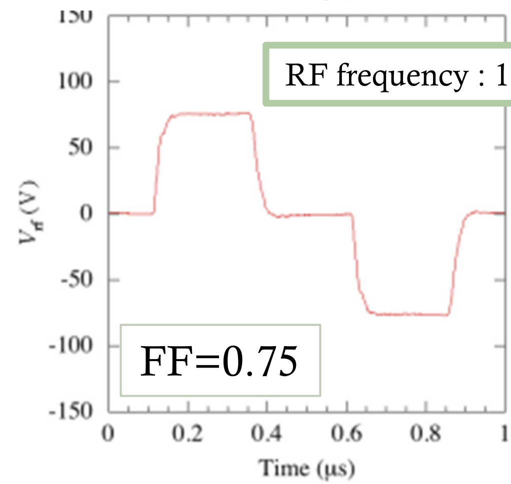
Drift Ratio : $DR = \dfrac{L_0}{L(1 - FF) - L_0}$

DR=1.0

The actual waveforms generated by our RF power source system.

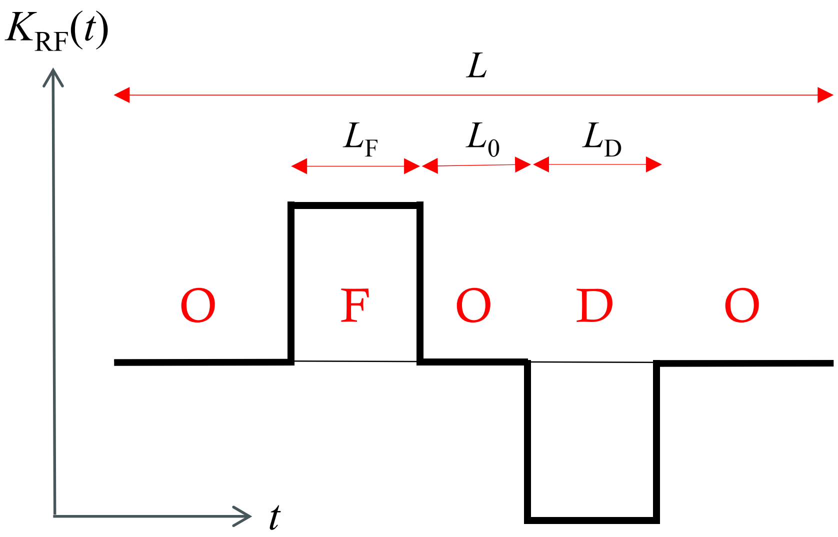


RF frequency : 1 MHz



Doublet Geometry

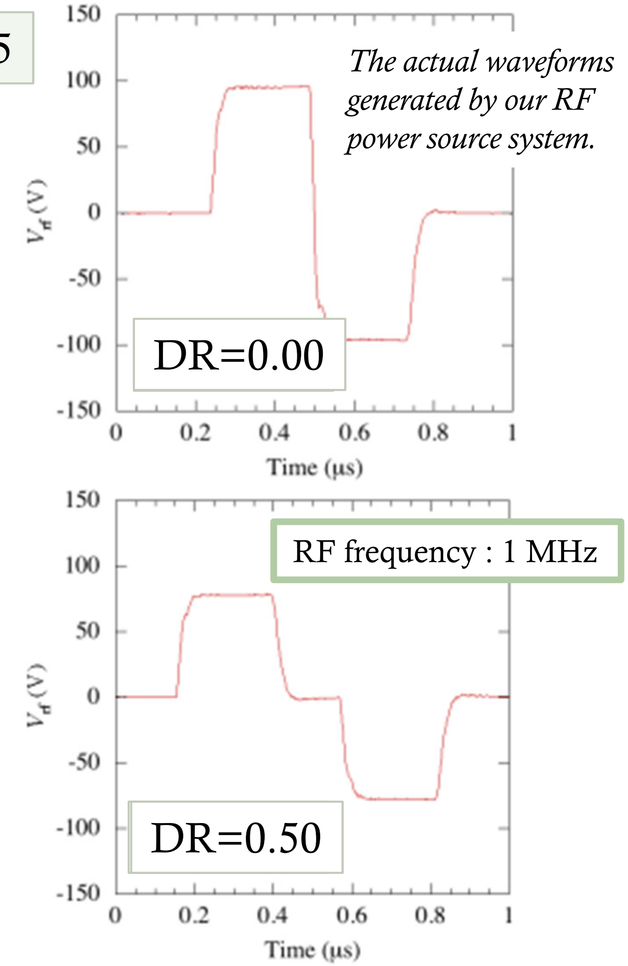
RF Waveform for Doublet



Filling Factor : $$FF = \frac{L_F + L_D}{L}$$

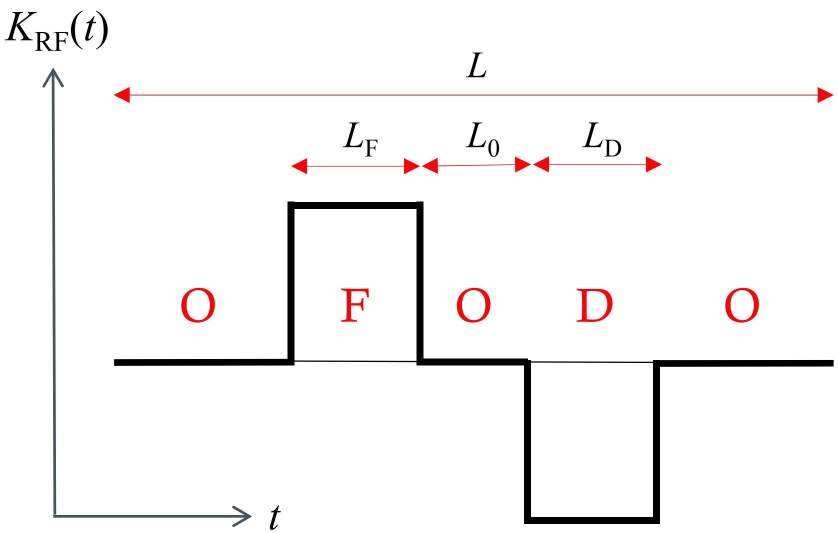
Drift Ratio : $$DR = \frac{L_0}{L(1 - FF) - L_0}$$

FF=0.5

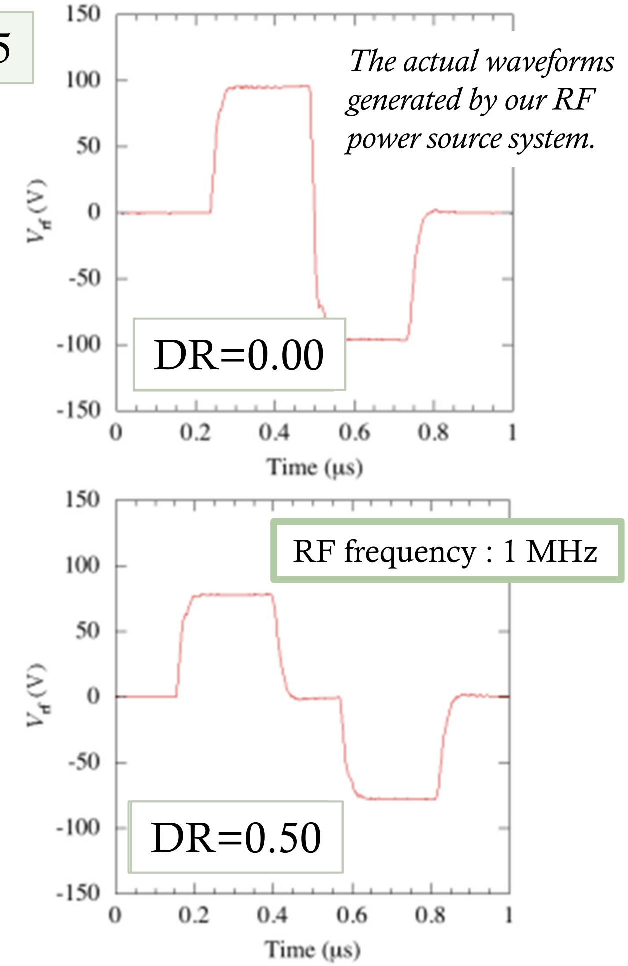


Doublet Geometry

RF Waveform for Doublet



FF=0.5



The examples shown here are *symmetric* doublet waveforms, namely, $L_F = L_D$.

It is possible to generate *asymmetric* RF waveforms to make the two transverse tunes unequal.

FODO : *intensity dependence*

FF = 0.5 DR = 1.0

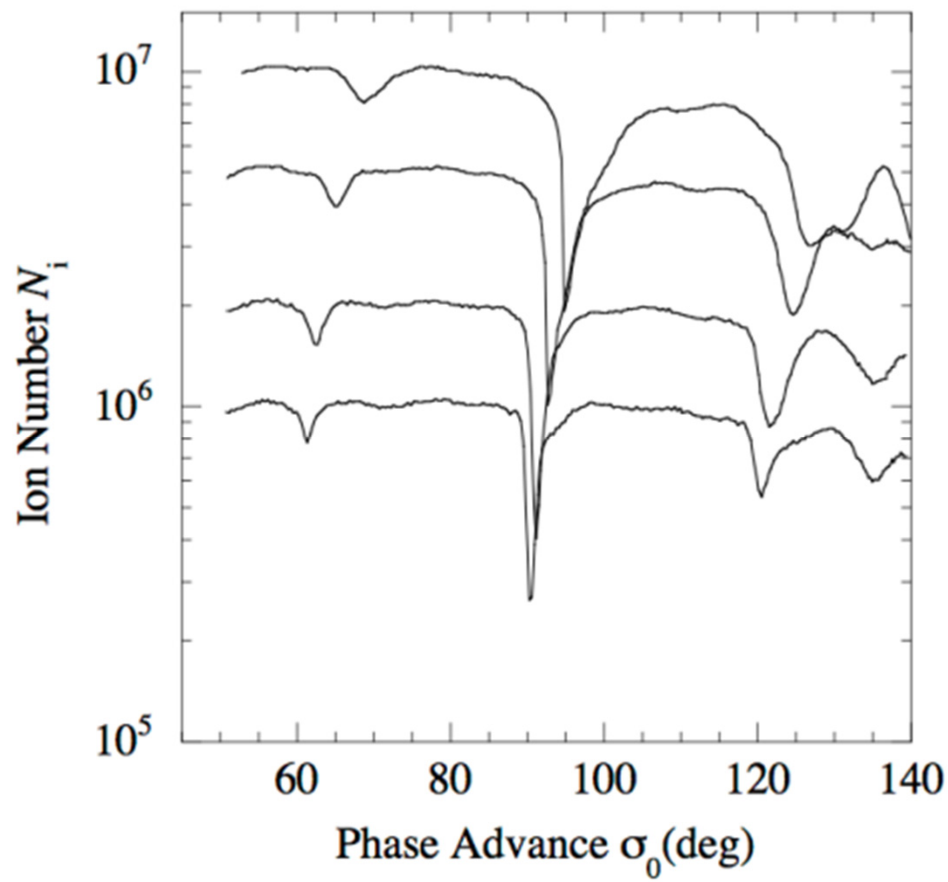
Phase Advance : $\sigma_x = \sigma_y \ (\equiv \sigma_0)$

(symmetric transverse focusing)

Coherent Resonance Condition

(1D model prediction)

$$\sigma_0 - C_m \Delta\sigma \approx 2\pi \times \left(\frac{n}{2m}\right)$$



[H. Okamoto and K. Yokoya, NIM A **482**, 51 (2002) .]

FODO : *intensity dependence*

FF = 0.5 DR = 1.0

Phase Advance : $\sigma_x = \sigma_y \ (\equiv \sigma_0)$

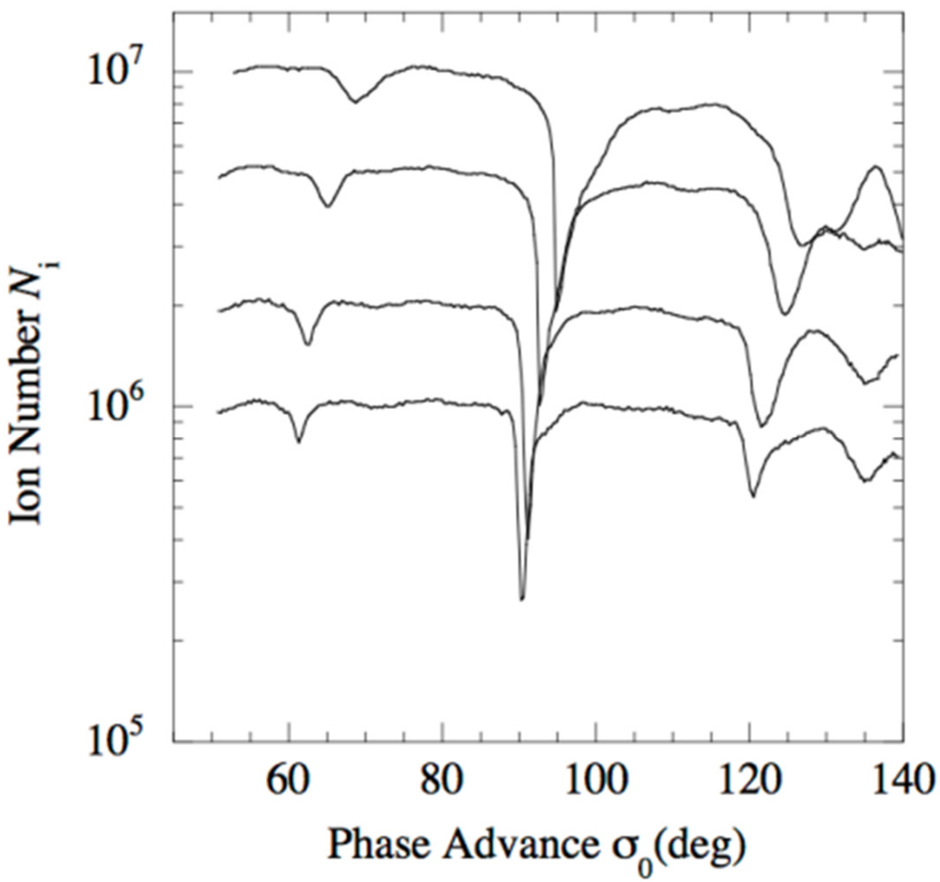
(symmetric transverse focusing)

Coherent Resonance Condition

(1D model prediction)

$$\sigma_0 - C_m \Delta\sigma \approx 2\pi \times \left(\frac{n}{2m}\right)$$

Space-charge-induced tune shift



[H. Okamoto and K. Yokoya, NIM A **482**, 51 (2002) .]

FODO : *intensity dependence*

FF = 0.5 DR = 1.0

Phase Advance : $\sigma_x = \sigma_y \ (\equiv \sigma_0)$

(symmetric transverse focusing)

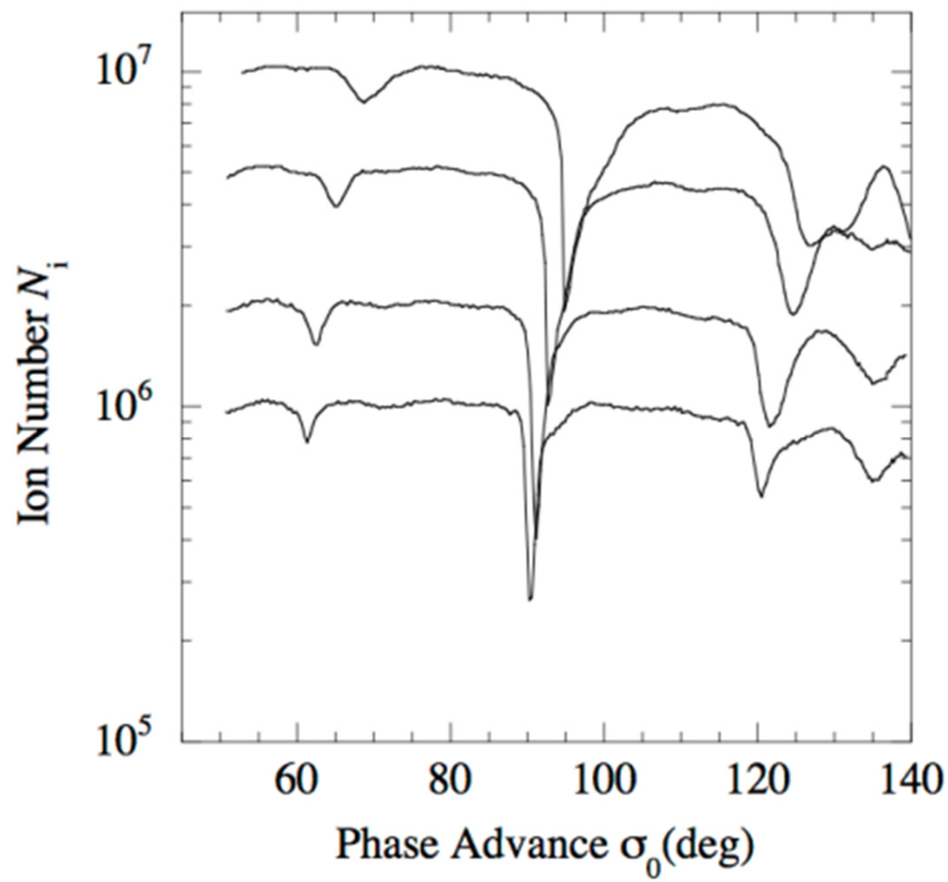
⇩

Coherent Resonance Condition

(1D model prediction)

$$\sigma_0 - C_m \Delta\sigma \approx 2\pi \times \left(\frac{n}{2m} \right)$$

Constant factor < 1



[H. Okamoto and K. Yokoya, NIM A **482**, 51 (2002) .]

FODO : *intensity dependence*

FF = 0.5 DR = 1.0

Phase Advance : $\sigma_x = \sigma_y \ (\equiv \sigma_0)$

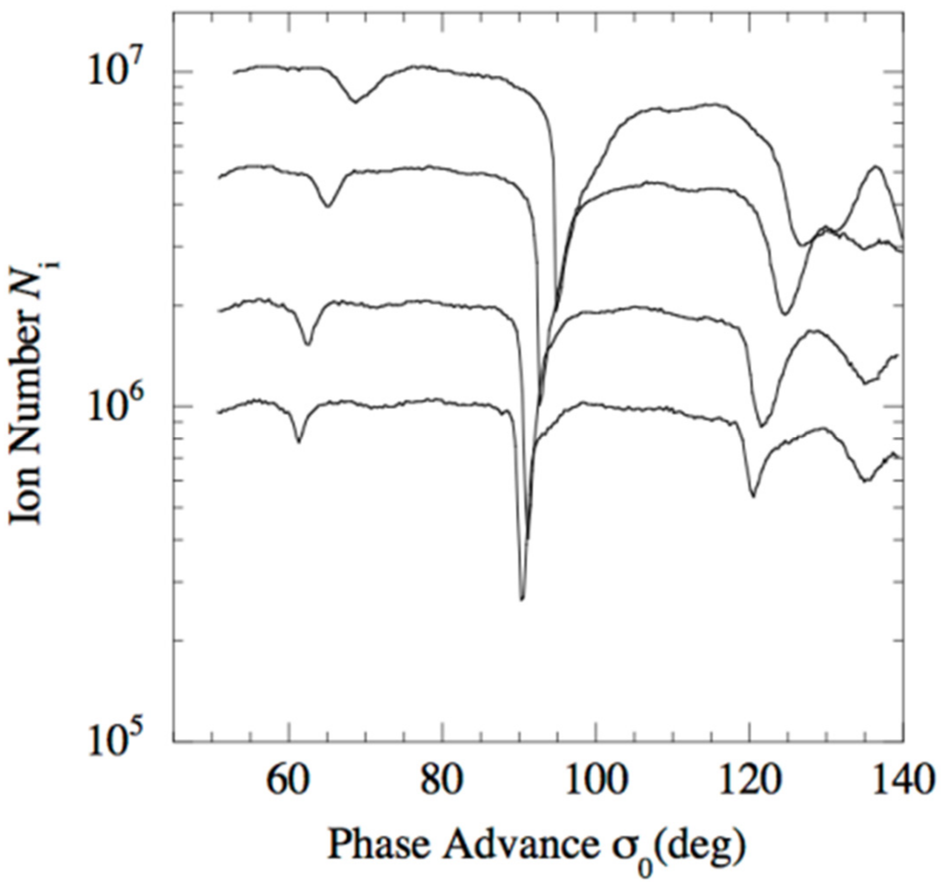
(symmetric transverse focusing)

Coherent Resonance Condition

(1D model prediction)

$$\sigma_0 - C_m \Delta\sigma \approx 2\pi \times \left(\frac{n}{2m}\right)$$

Collective mode number



[H. Okamoto and K. Yokoya, NIM A **482**, 51 (2002) .]

FODO : *intensity dependence*

FF = 0.5 DR = 1.0

Phase Advance : $\sigma_x = \sigma_y\ (\equiv \sigma_0)$

(symmetric transverse focusing)

Coherent Resonance Condition

(1D model prediction)

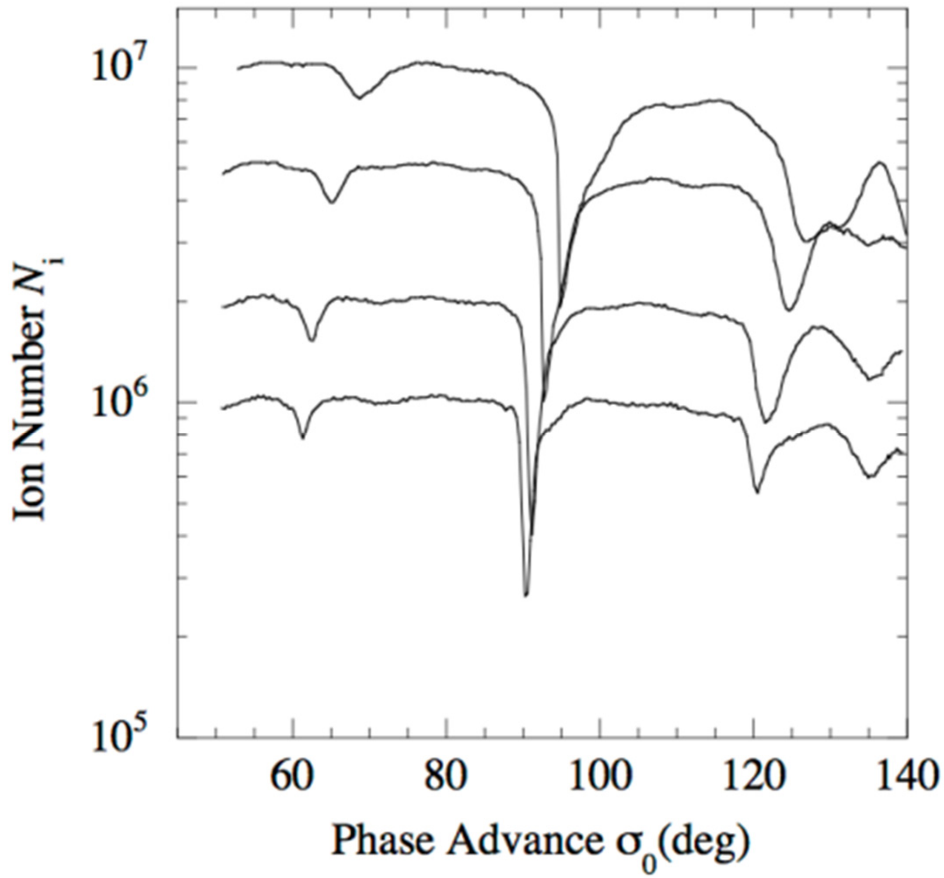
$$\sigma_0 - C_m \Delta\sigma \approx 2\pi \times \left(\frac{n}{2m}\right)$$

$m = 2$: quadrupole

$m = 3$: sextupole

…..

[H. Okamoto and K. Yokoya, NIM A **482**, 51 (2002) .]



FODO : *intensity dependence*

FF = 0.5 DR = 1.0

Phase Advance : $\sigma_x = \sigma_y \; (\equiv \sigma_0)$

(symmetric transverse focusing)

Coherent Resonance Condition

(1D model prediction)

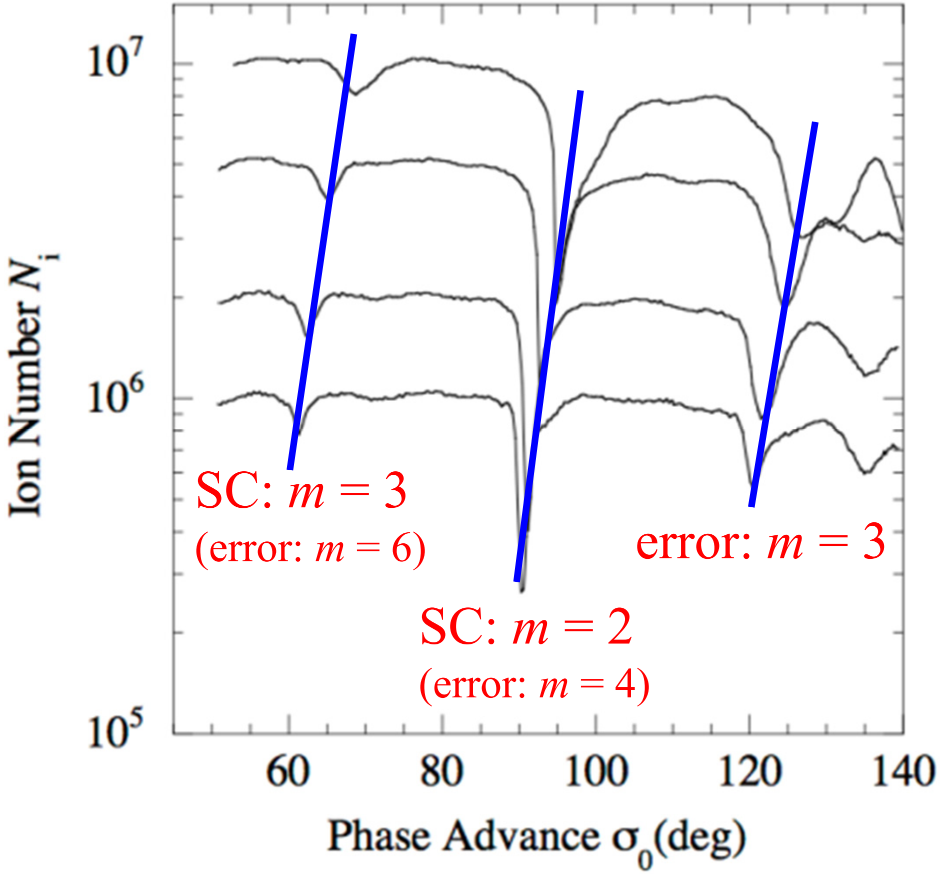
$$\sigma_0 - C_m \Delta\sigma \approx 2\pi \times \left(\frac{n}{2m}\right)$$

$m = 2$: quadrupole

$m = 3$: sextupole

.....

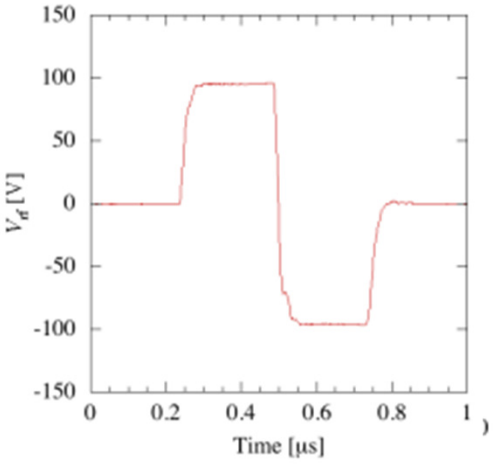
[H. Okamoto and K. Yokoya, NIM A **482**, 51 (2002) .]



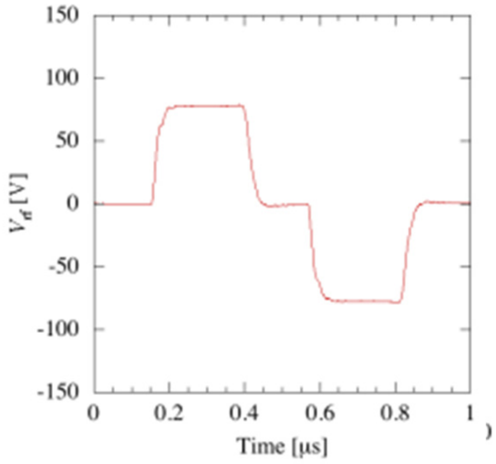
Doublet : *geometry dependence*

FF = 0.5

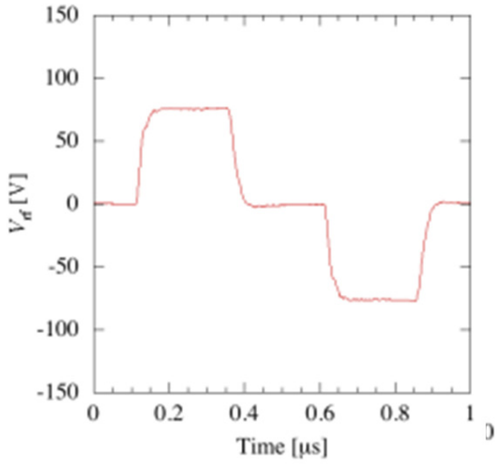
DR = 0



DR = 0.5



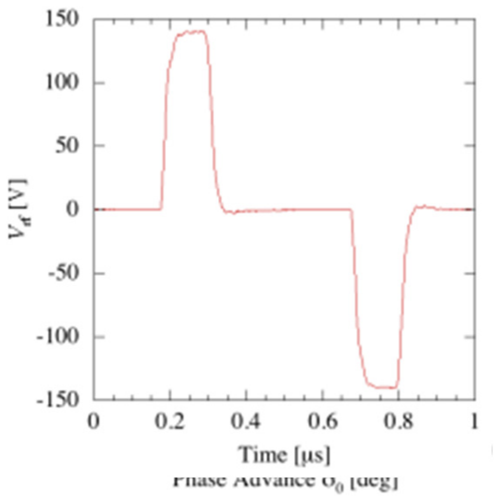
DR = 1.0



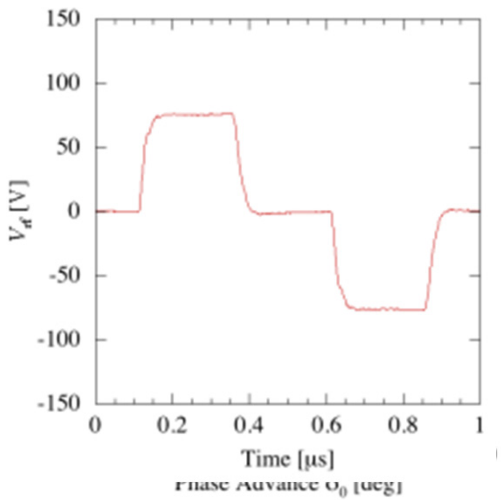
Doublet : *geometry dependence*

DR = 1.0

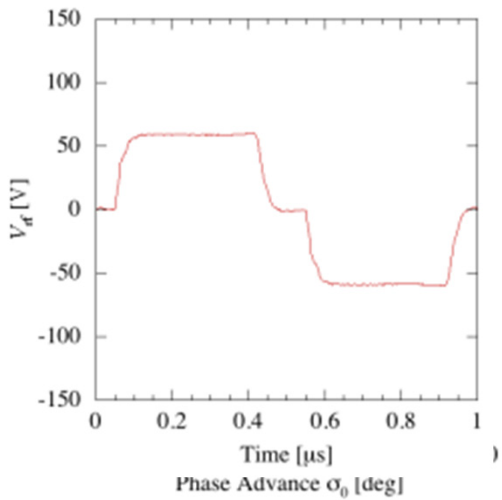
FF = 0.25



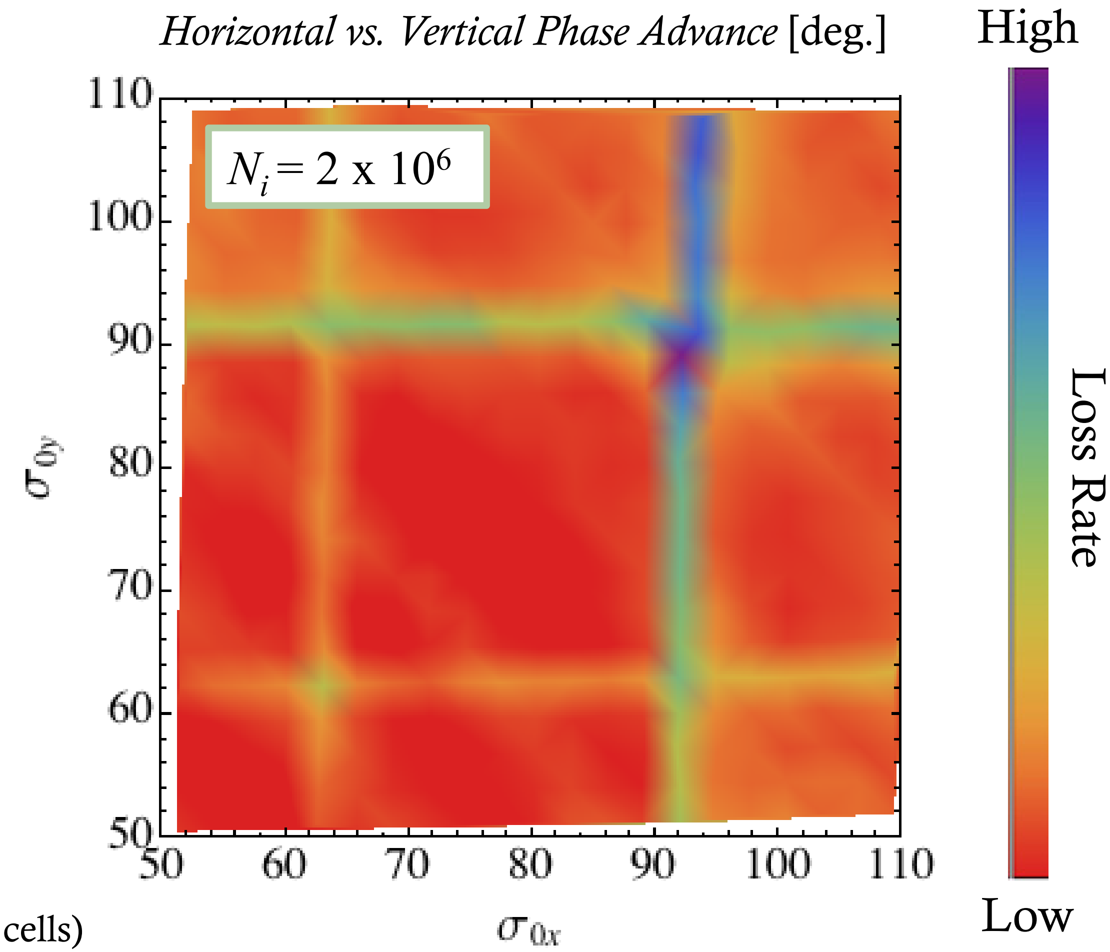
FF = 0.5



FF = 0.75

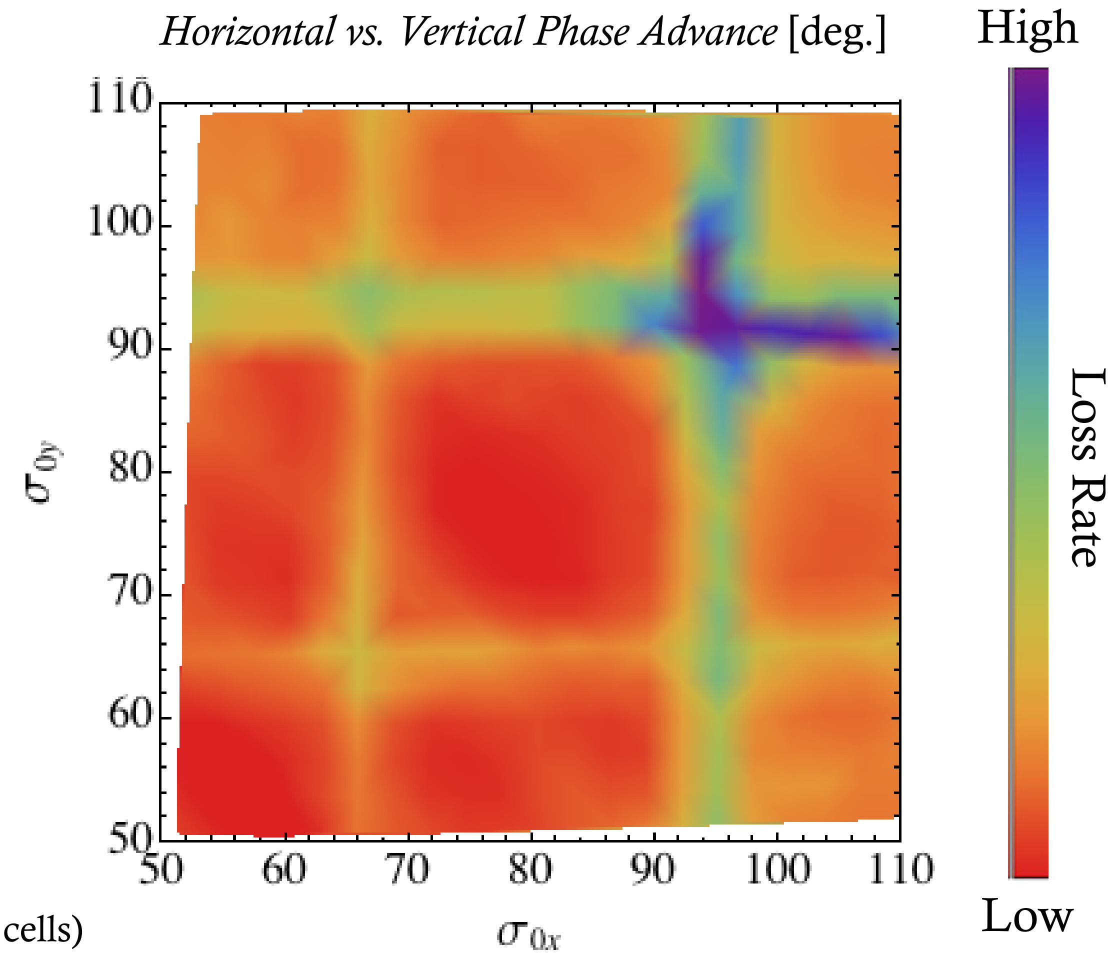


Tune Diagram of Doublet



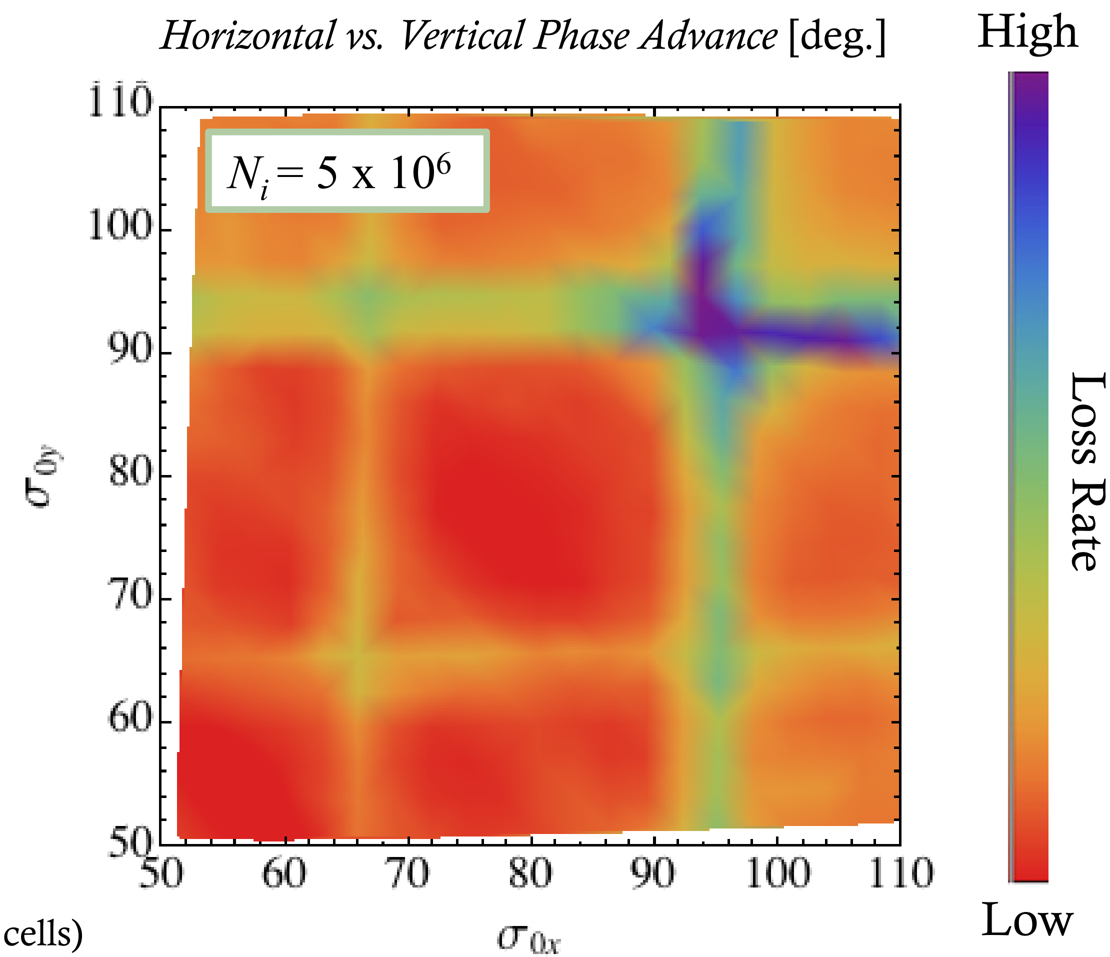
Storage Time : 10 ms (10,000 doublet cells)

Tune Diagram of Doublet



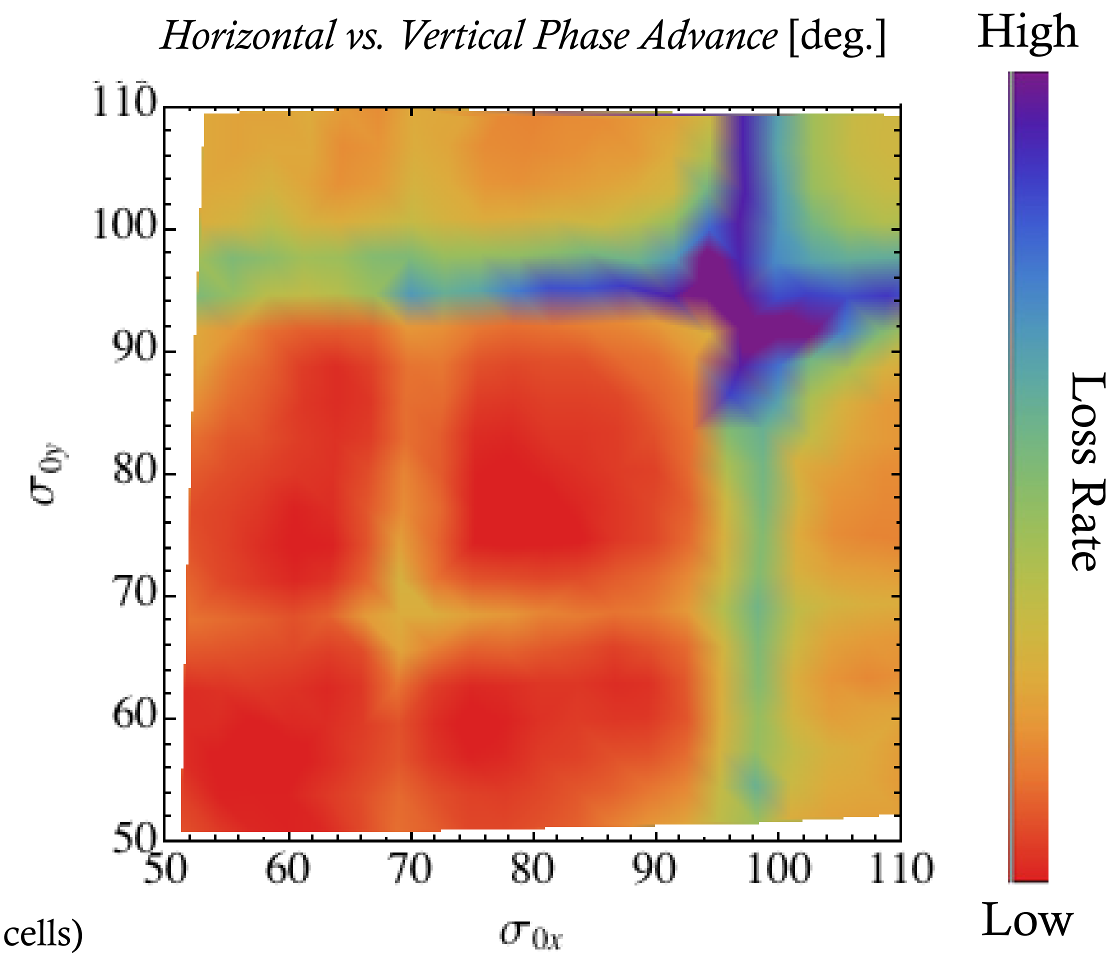
Storage Time : 10 ms (10,000 doublet cells)

Tune Diagram of Doublet



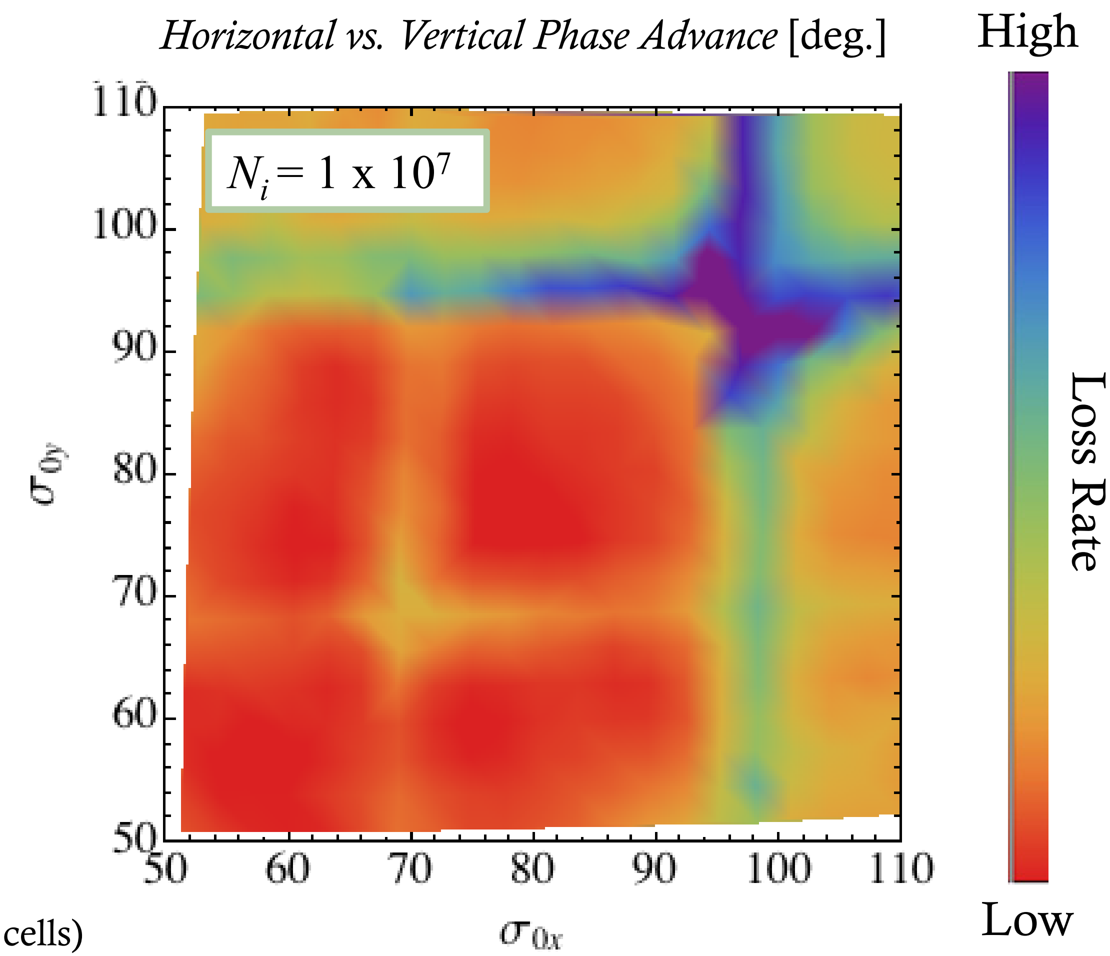
Storage Time : 10 ms (10,000 doublet cells)

Tune Diagram of Doublet



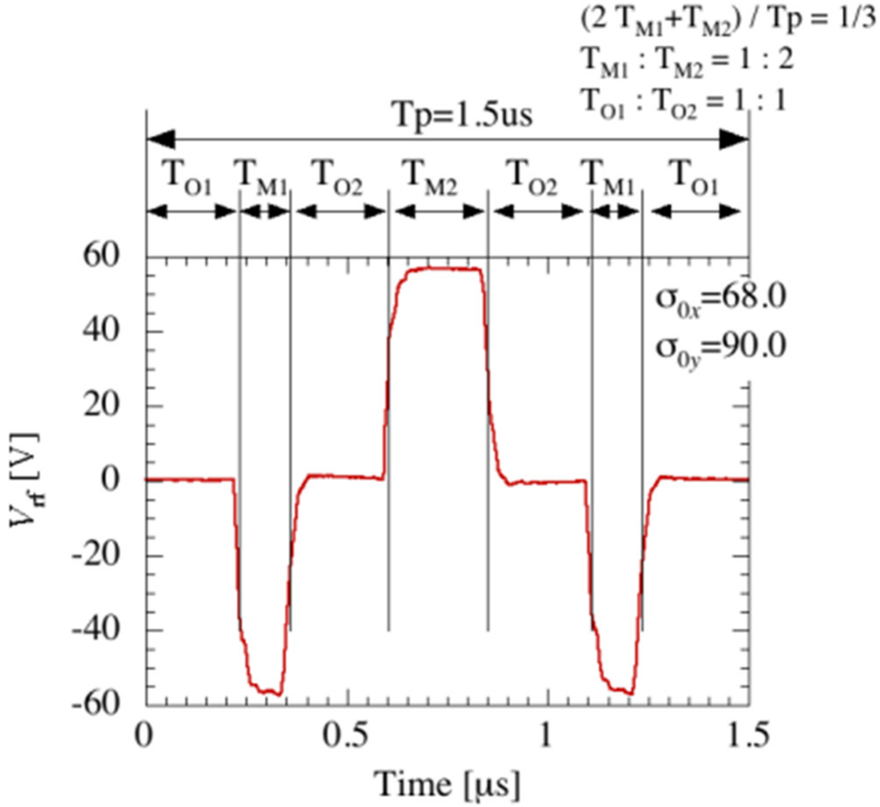
Storage Time : 10 ms (10,000 doublet cells)

Tune Diagram of Doublet

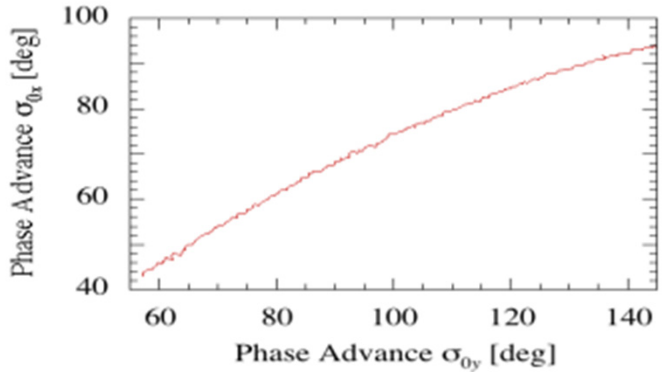


Storage Time : 10 ms (10,000 doublet cells)

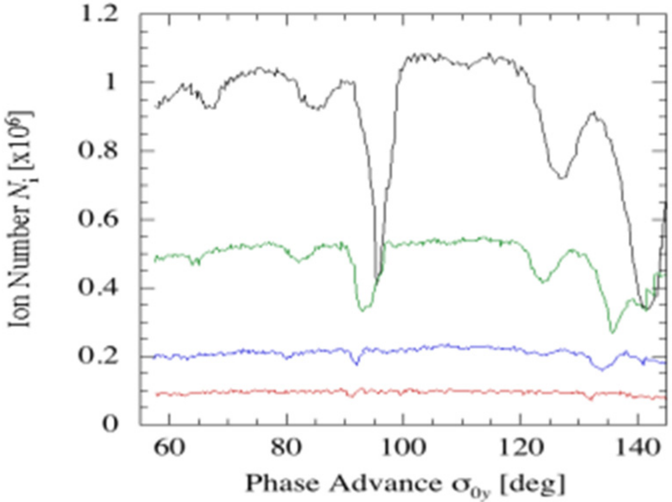
Triplet



(2 T_{M1}+T_{M2}) / Tp = 1/3
T_{M1} : T_{M2} = 1 : 2
T_{O1} : T_{O2} = 1 : 1
Tp=1.5us
T_{O1} T_{M1} T_{O2} T_{M2} T_{O2} T_{M1} T_{O1}
σ_{0x}=68.0
σ_{0y}=90.0
V_{rf} [V]
Time [μs]



Phase Advance σ_{0x} [deg]
Phase Advance σ_{0y} [deg]

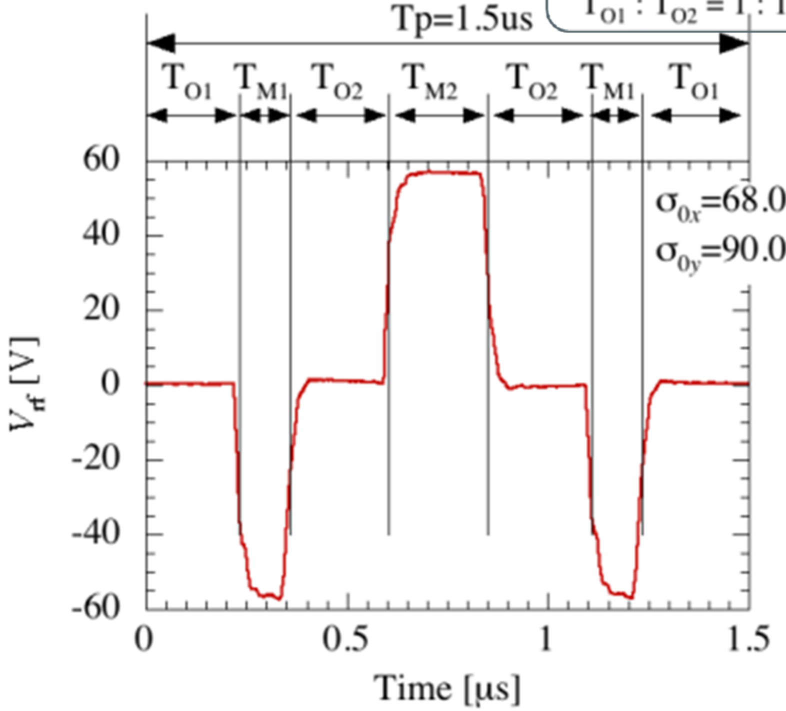


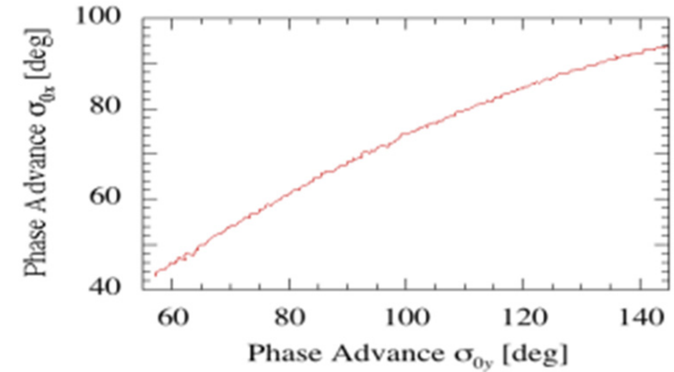
Ion Number N_i [x10^6]
Phase Advance σ_{0y} [deg]

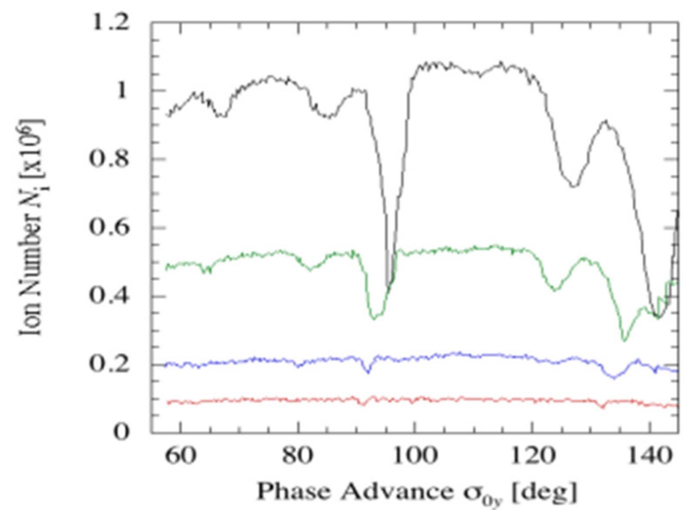
Triplet

We changed the pulse heights, keeping these ratios !

$(2\,T_{M1}+T_{M2})\,/\,Tp = 1/3$
$T_{M1} : T_{M2} = 1 : 2$
$T_{O1} : T_{O2} = 1 : 1$







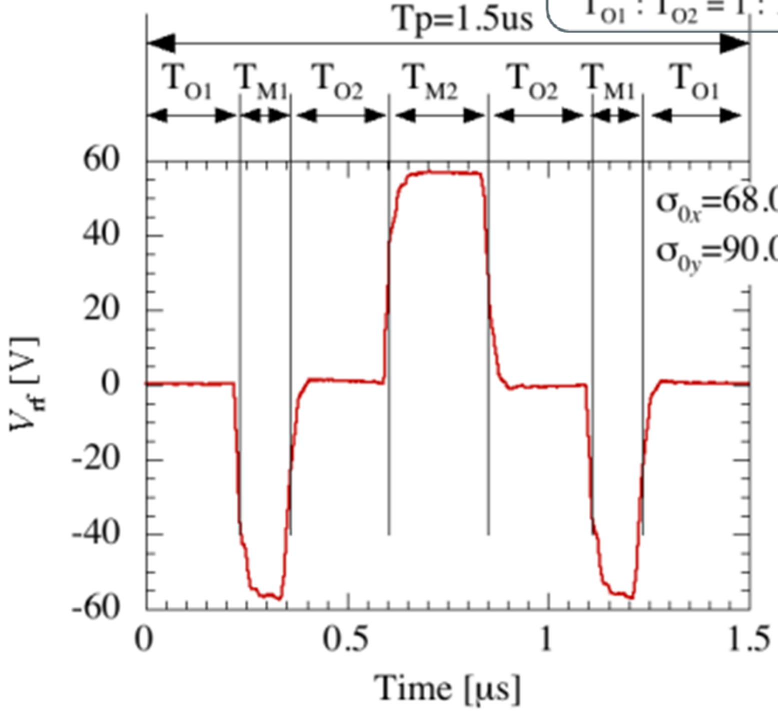
Triplet

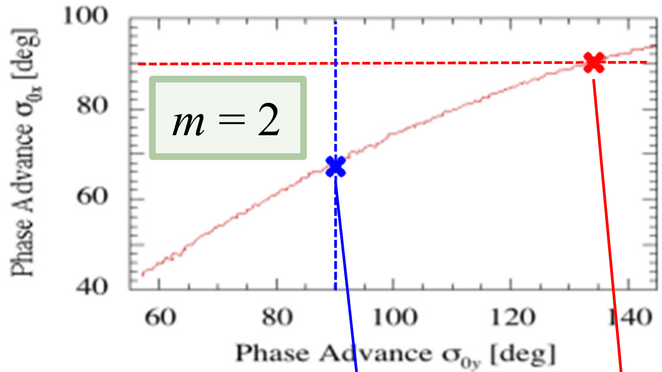
We changed the pulse heights, keeping these ratios !

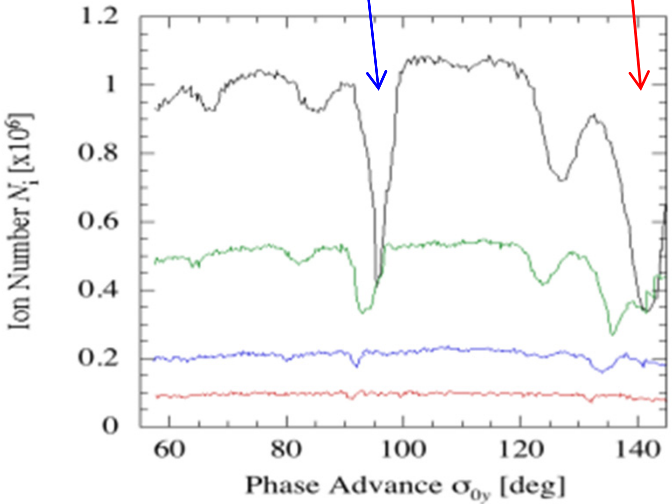
$(2\,T_{M1}+T_{M2}) / Tp = 1/3$

$T_{M1} : T_{M2} = 1 : 2$

$T_{O1} : T_{O2} = 1 : 1$







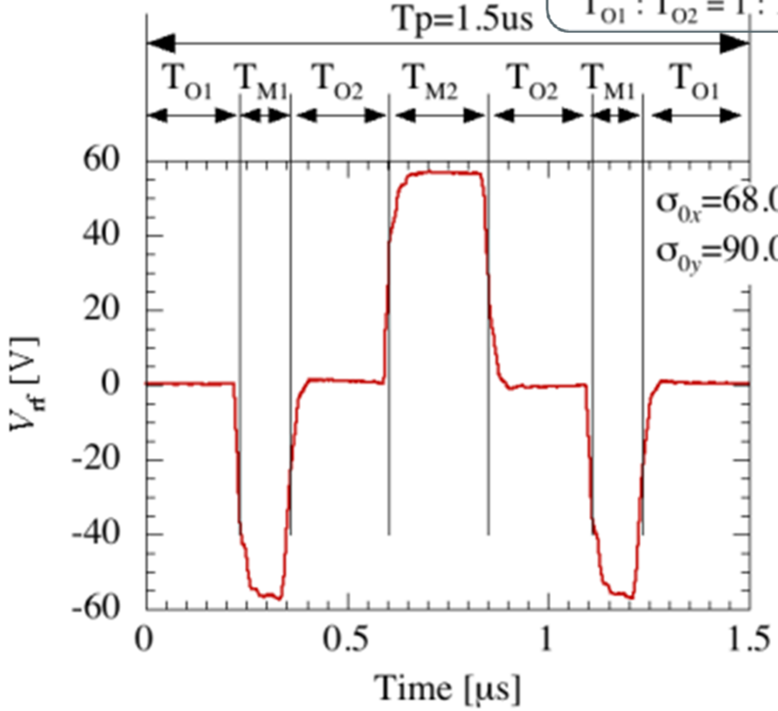
Triplet

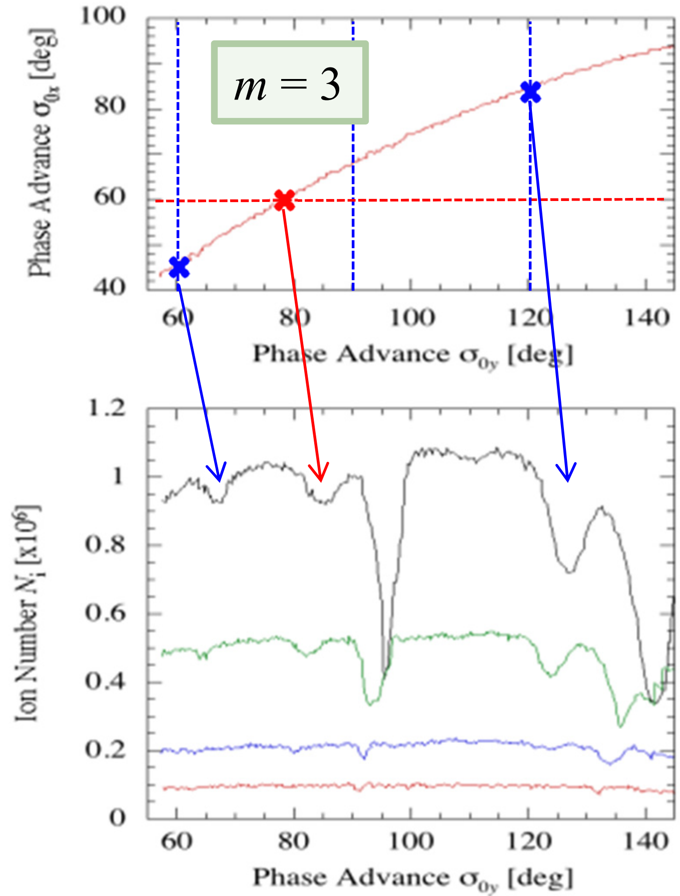
We changed the pulse heights, keeping these ratios !

$(2\,T_{M1}+T_{M2})\,/\,T_p = 1/3$

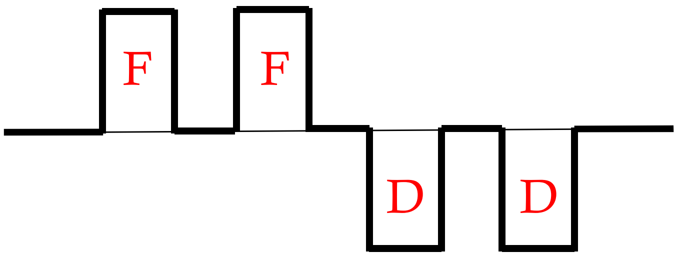
$T_{M1} : T_{M2} = 1 : 2$

$T_{O1} : T_{O2} = 1 : 1$

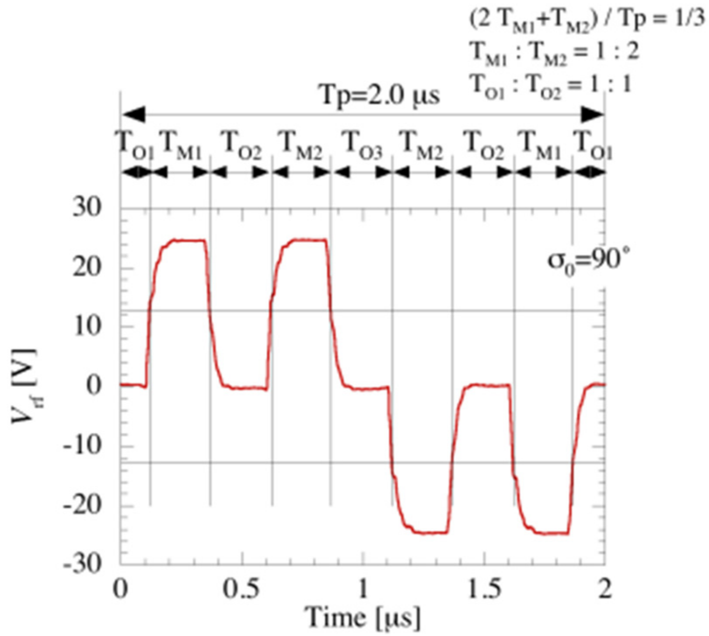


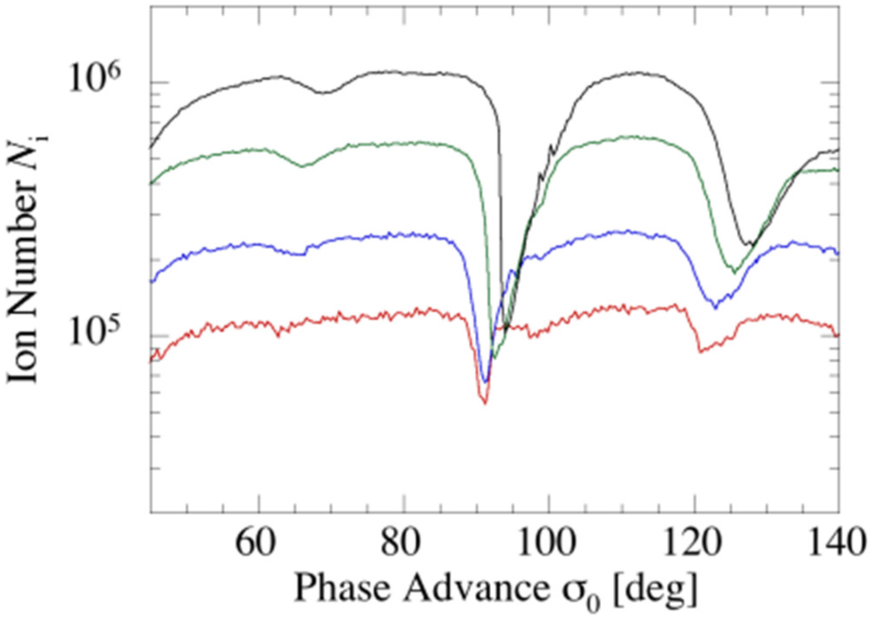


FFDD Lattice



- Another popular lattice (used, e.g., for GSI UNILAC, CERN PS)
- The resonance characteristics should probably be similar to doublets'.





Resonance Crossing

Integer and Other Higher-Order Resonance Crossing, Single or Multiple Resonance Crossing, Nonlinear Effects, … etc.

Non-scaling FFAG

- Considering what generally happens in ns-FFAGs, we have done downward resonance crossing experiments with different beam intensities, different crossing speeds, different dipole errors, etc.

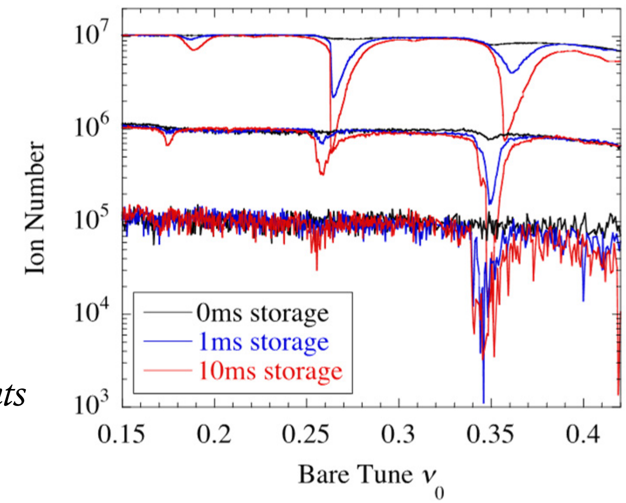
See, e.g., H. Takeuchi *et al*., PRST-AB **15**, 074201 (2012).

- Recently, we have been studying various effects of ***integer*** resonance crossing excited by dipole errors.

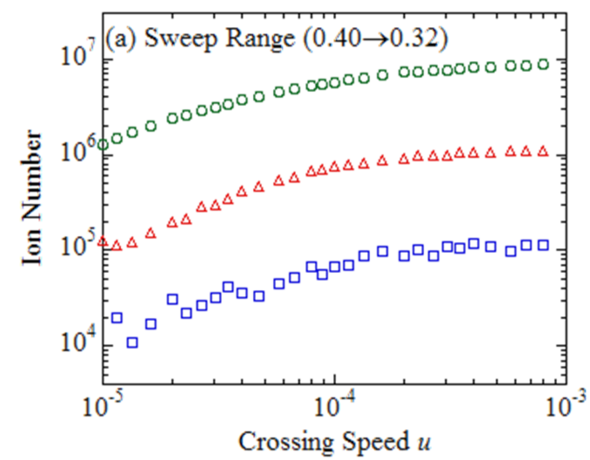
→ Collaboration with ASTeC, STFC in England
(S. Sheehy, D. Kelliher, S. Machida, and C. Prior)

See, e.g., D. Kelliher *et al*., TUPRI009 (poster), this conference.

Resonance Crossing



The three major stop bands found in previous experiments are crossed at various speeds and at various intensities.

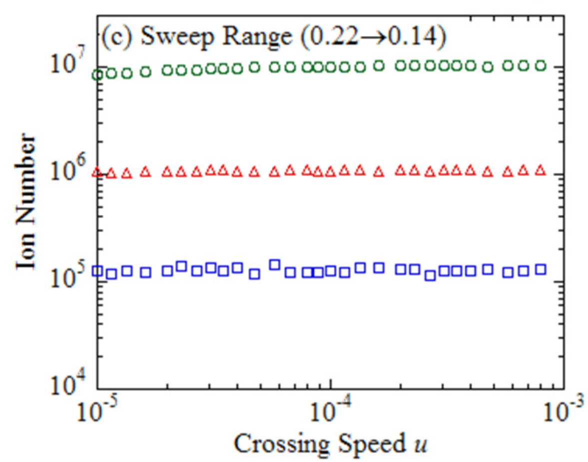


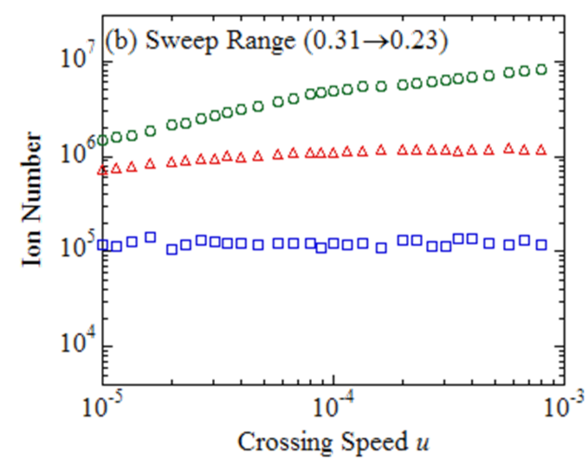
Crossing Speed

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

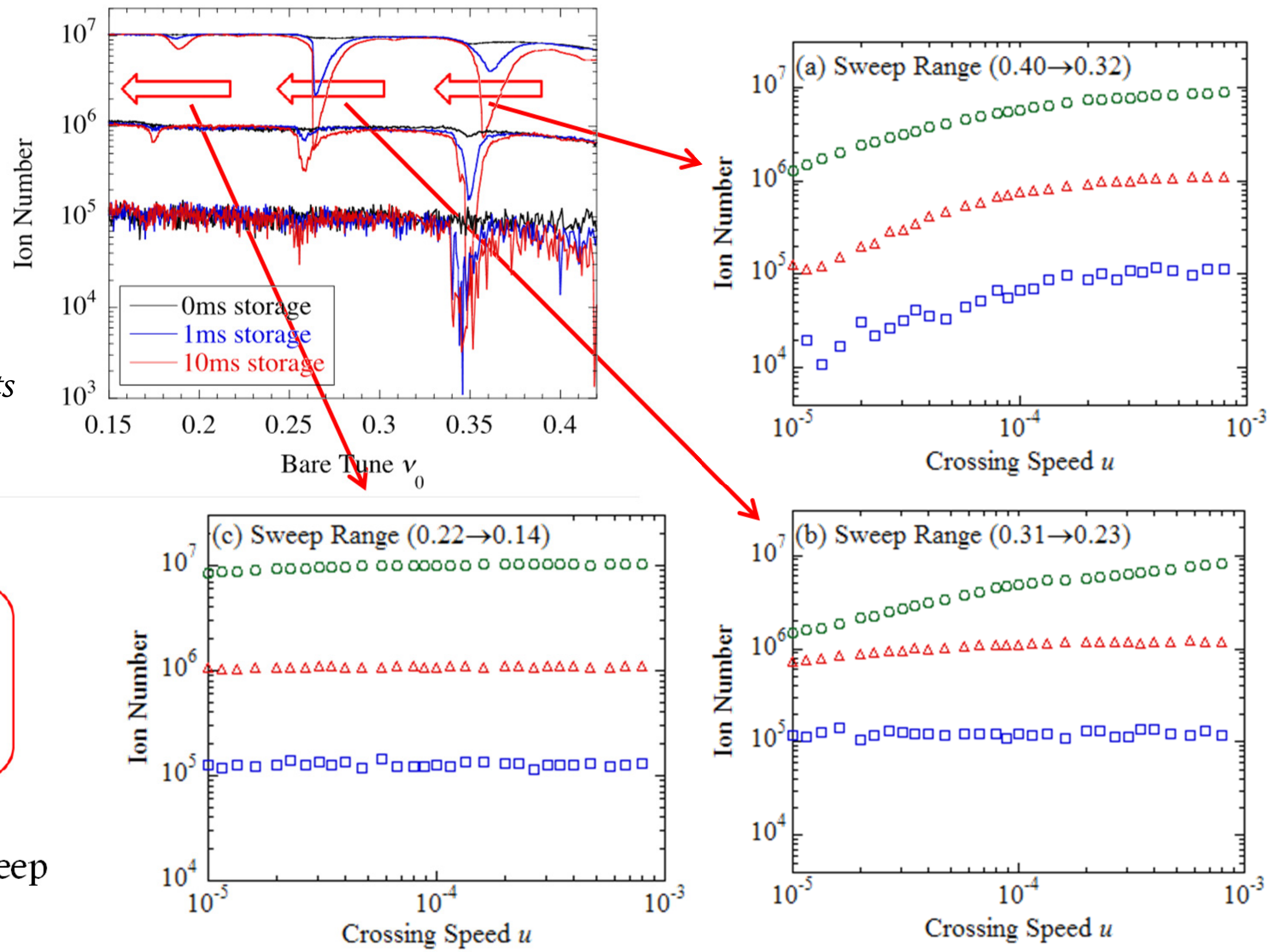
δ : tune-sweep width

n_{rf} : rf period for tune sweep





Resonance Crossing



The three major stop bands found in previous experiments are crossed at various speeds and at various intensities.

Crossing Speed

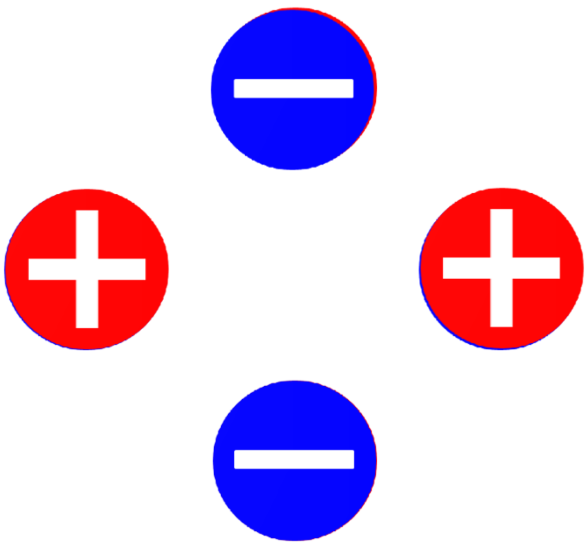
$$u \equiv \delta / n_{\mathrm{rf}}$$

δ : tune-sweep width

n_{rf} : rf period for tune sweep

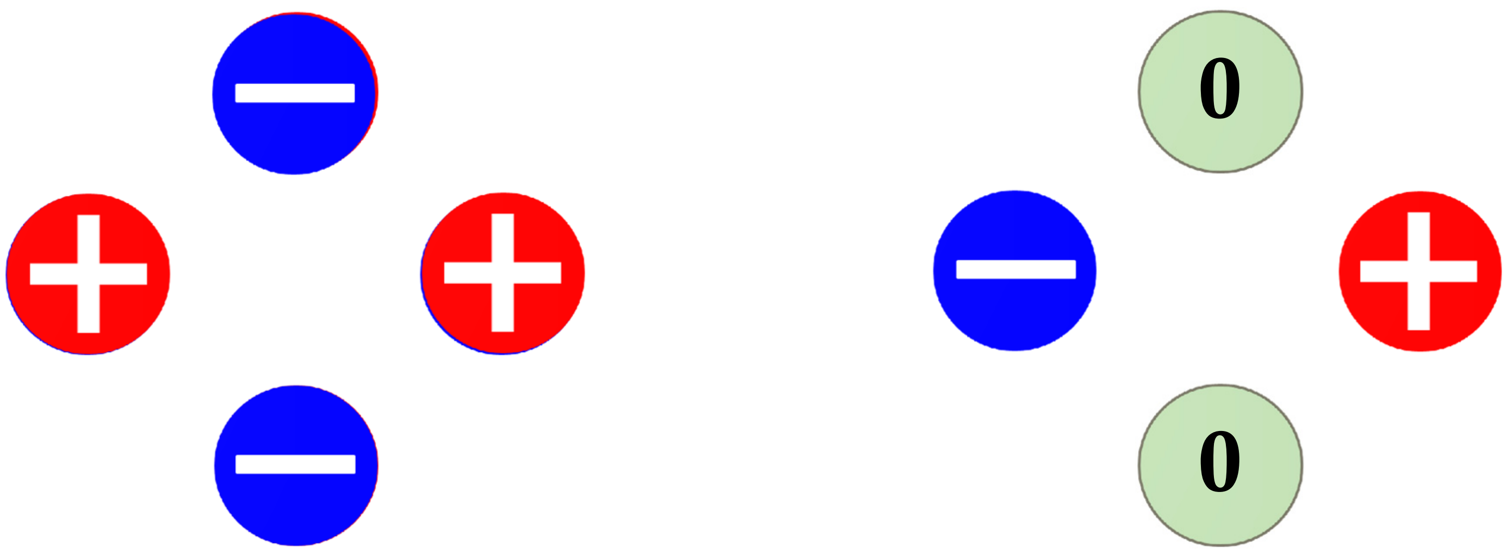
Dipole Perturbation

- In regular Paul traps, we generally have no integer resonance because of the symmetry of the plasma confinement field.



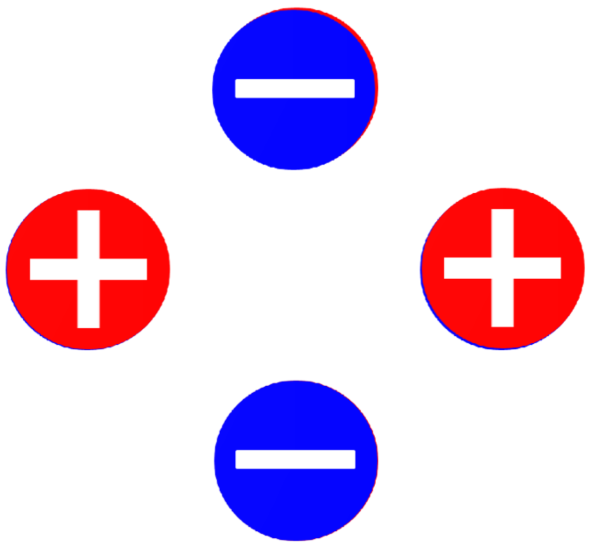
Dipole Perturbation

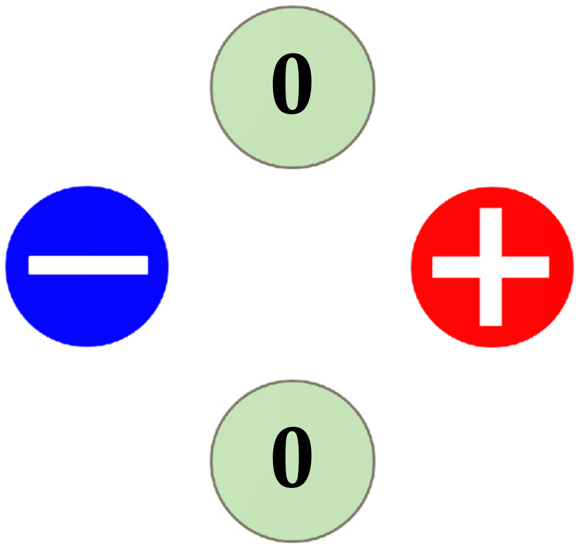
- In regular Paul traps, we generally have no integer resonance because of the symmetry of the plasma confinement field.



Dipole Perturbation

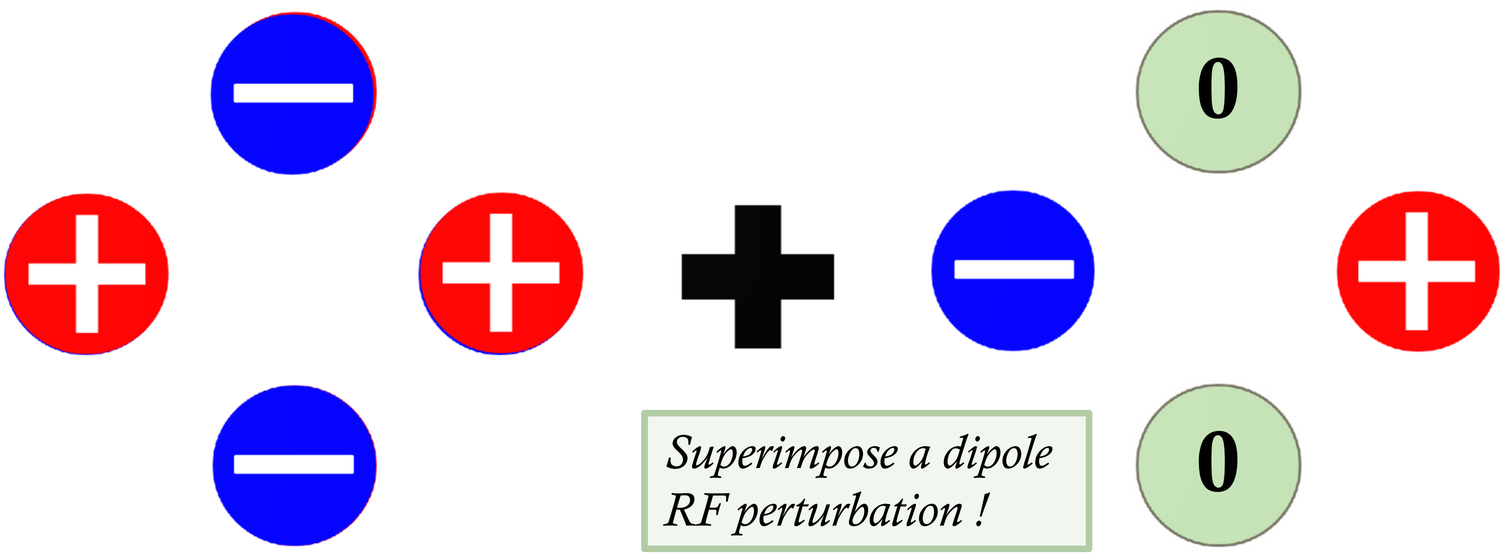
- But it is possible to excite integer resonances by intentionally applying a dipole RF perturbation to a pair of the electrodes.





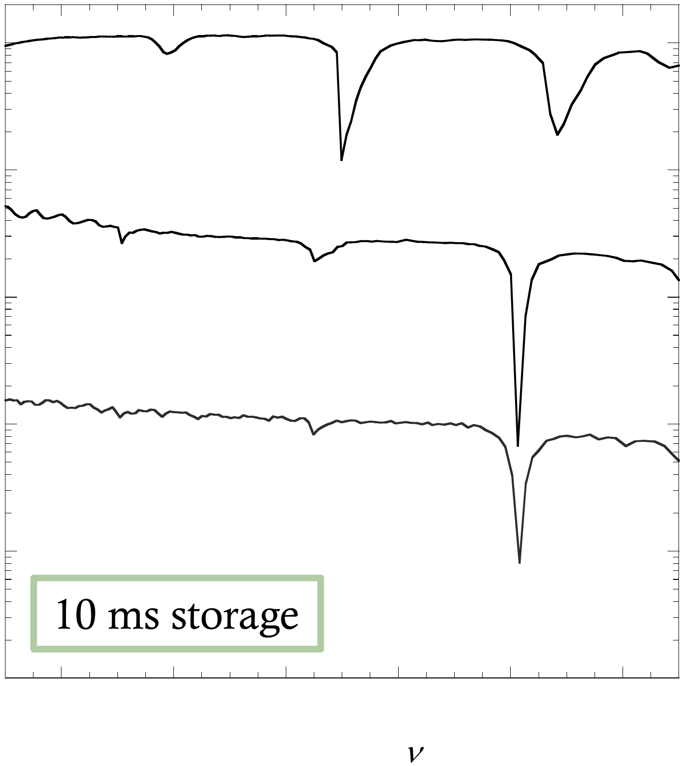
Dipole Perturbation

- But it is possible to excite integer resonances by intentionally applying a dipole RF perturbation to a pair of the electrodes.



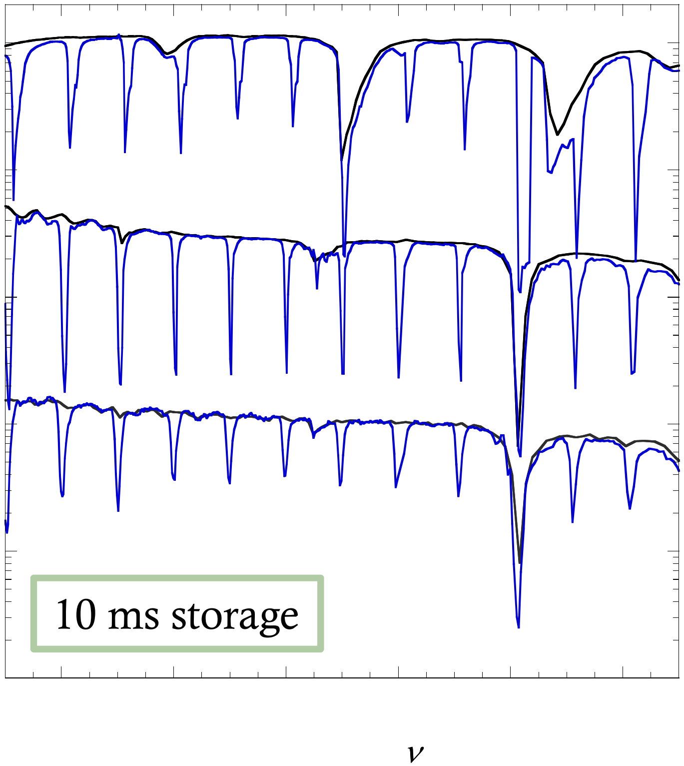
Integer Resonance Excitation

42-fold symmetric ring (EMMA)



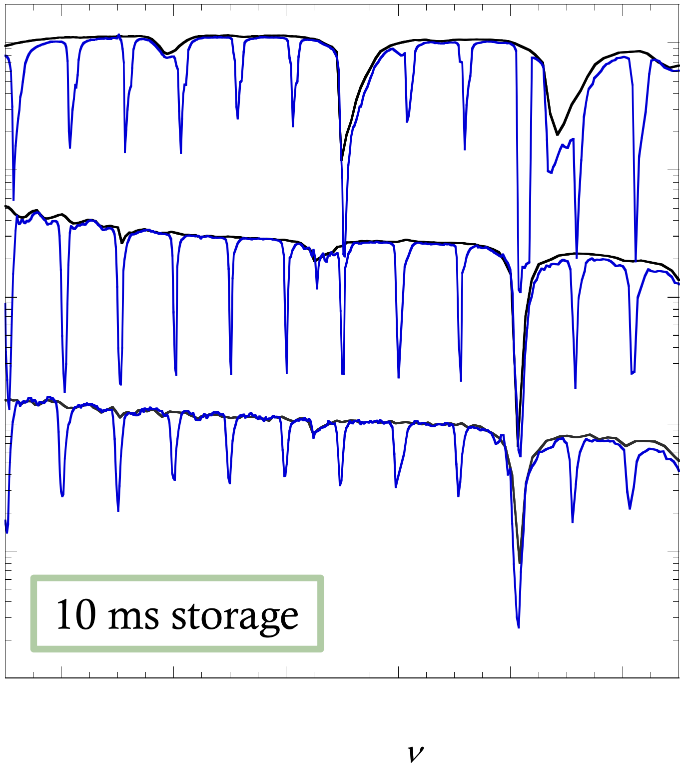
Integer Resonance Excitation

42-fold symmetric ring (EMMA)



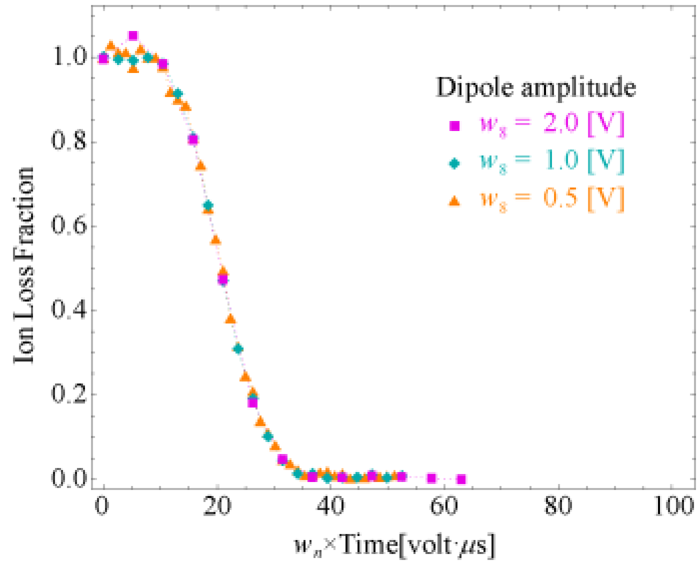
Integer Resonance Excitation

42-fold symmetric ring (EMMA)

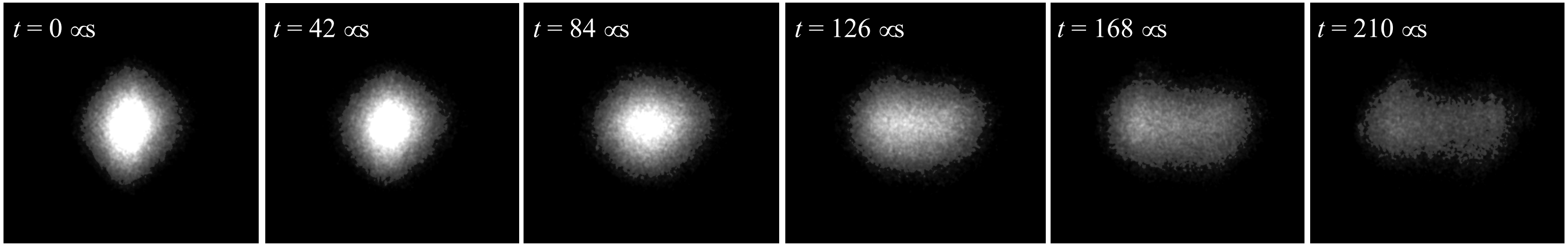


Dipole pulse width : 1 micro-sec
pulse height : 0.5 V

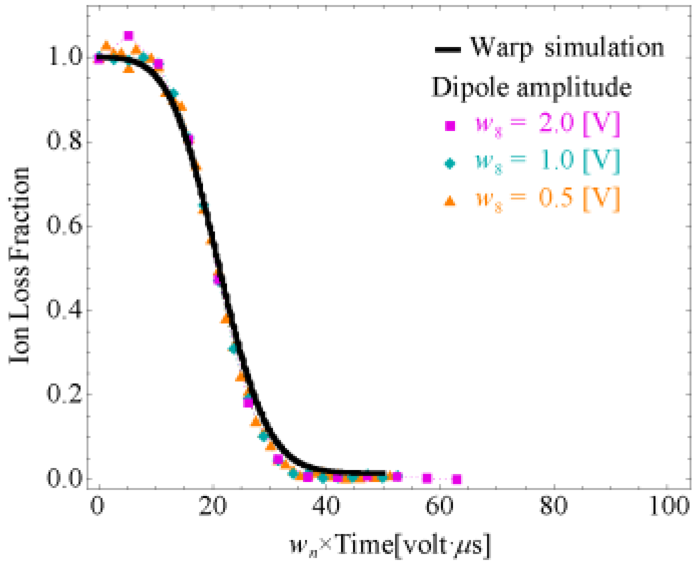
On-Resonance Experiment



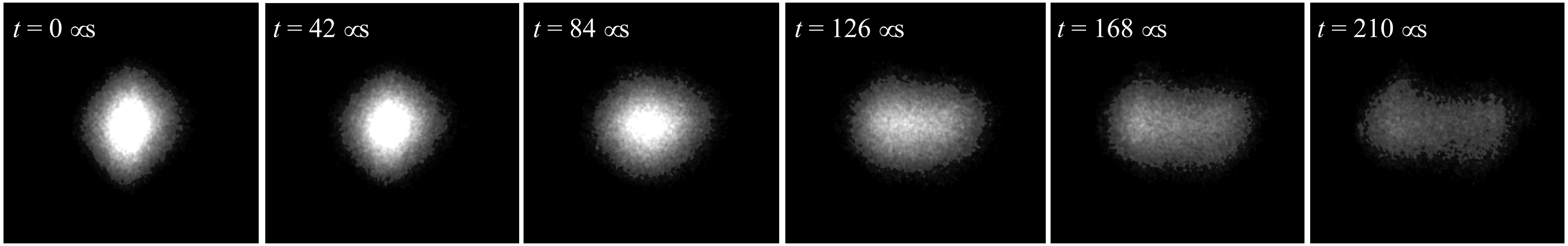
CCD images of the transverse plasma profile on the phosphor screen (w_8 = 0.1 V)



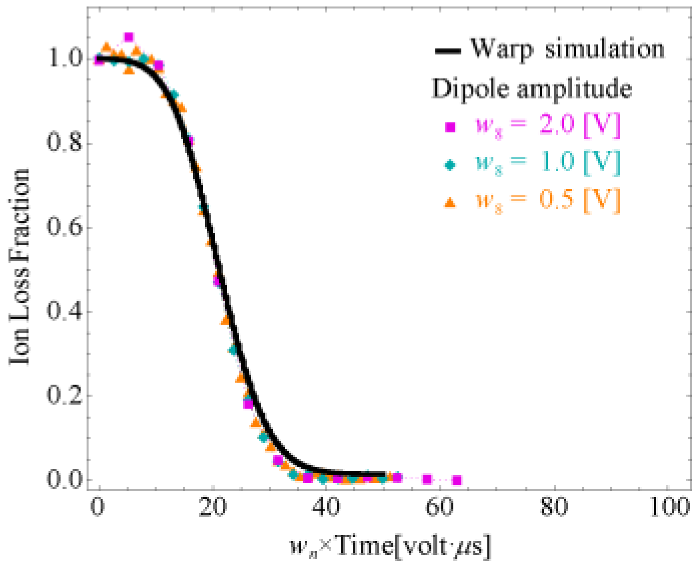
On-Resonance Experiment

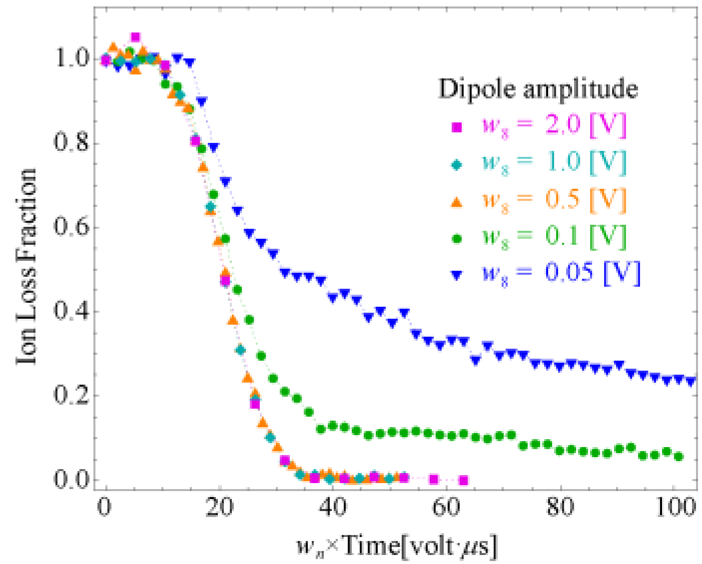


CCD images of the transverse plasma profile on the phosphor screen (w_8 = 0.1 V)

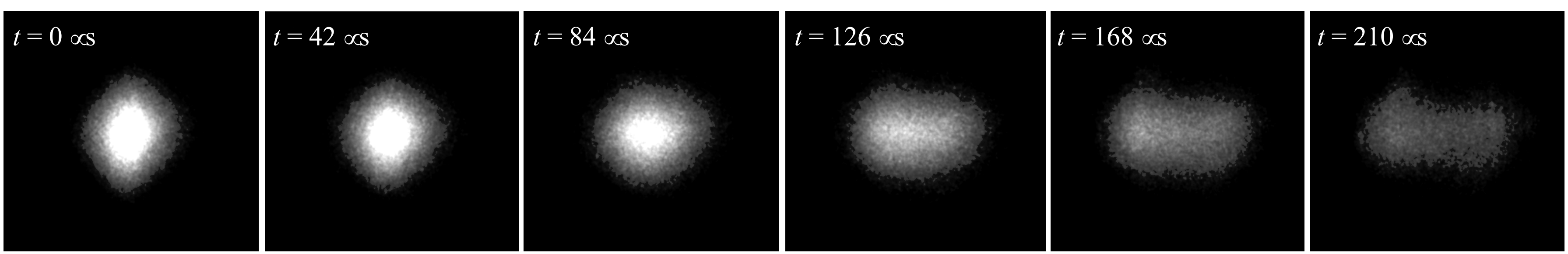


On-Resonance Experiment

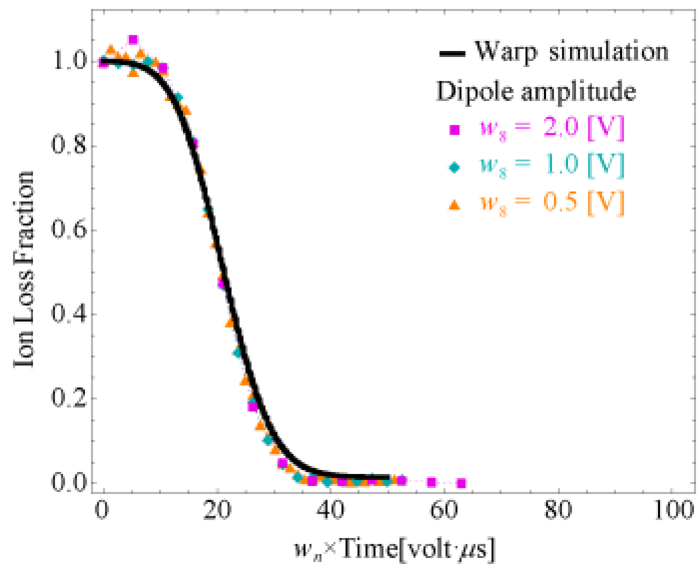


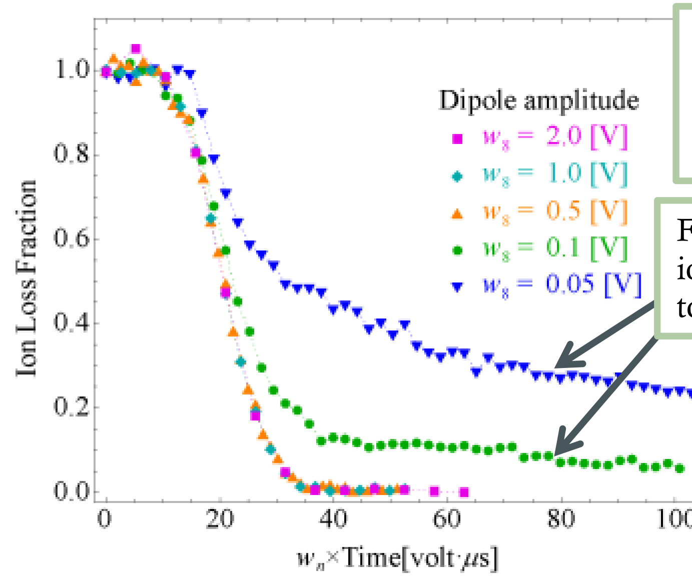


CCD images of the transverse plasma profile on the phosphor screen (w_8 = 0.1 V)



On-Resonance Experiment

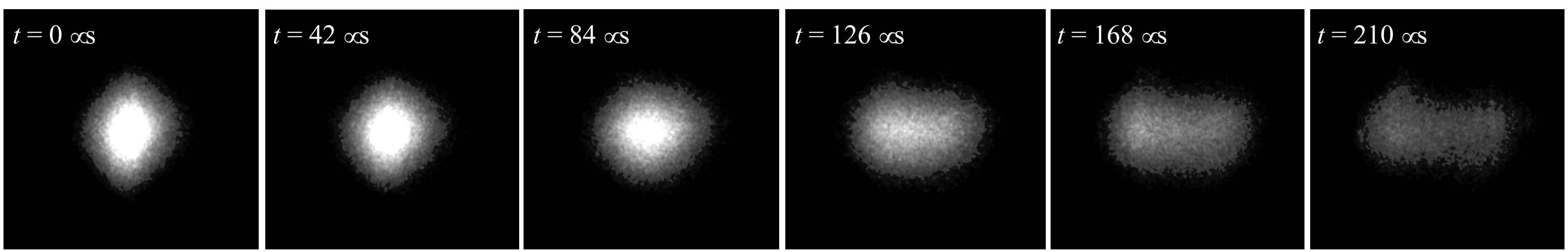




Probably due to the amplitude-dependent tune shift caused by field nonlinearity.

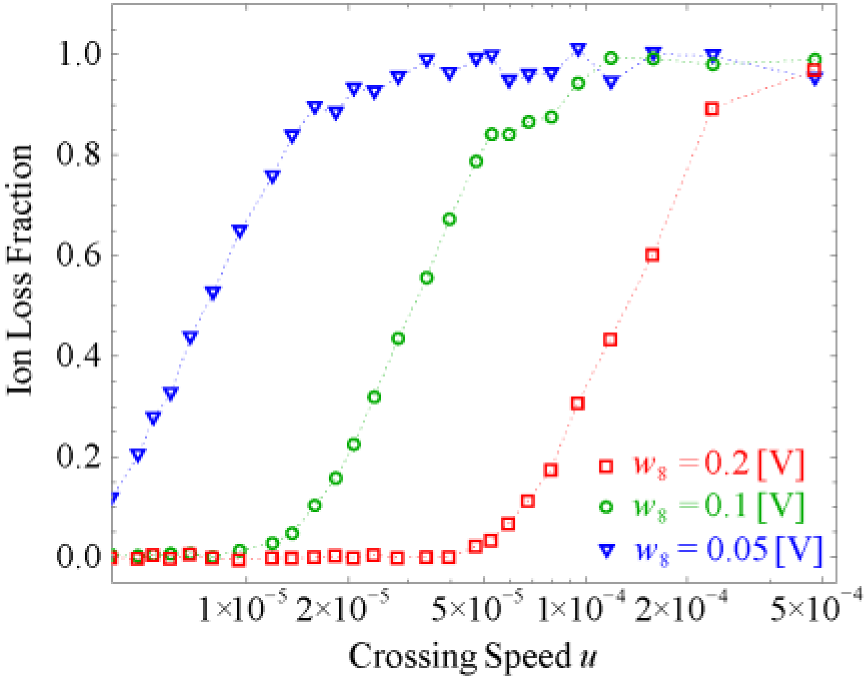
For weak perturbation, ion losses are lightened to some degree !

CCD images of the transverse plasma profile on the phosphor screen (w_8 = 0.1 V)



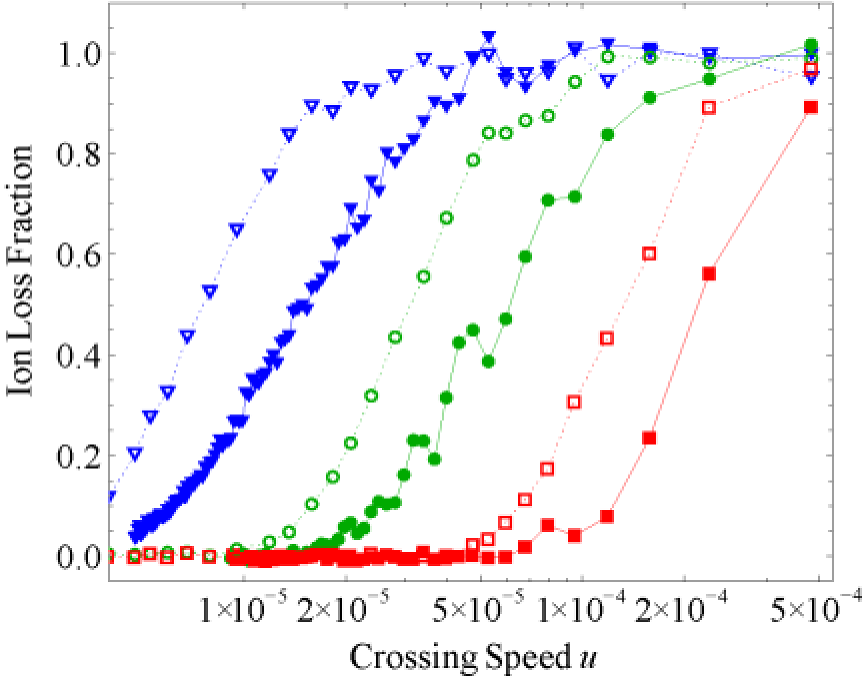
Integer Resonance Crossing

Single Resonance Crossing



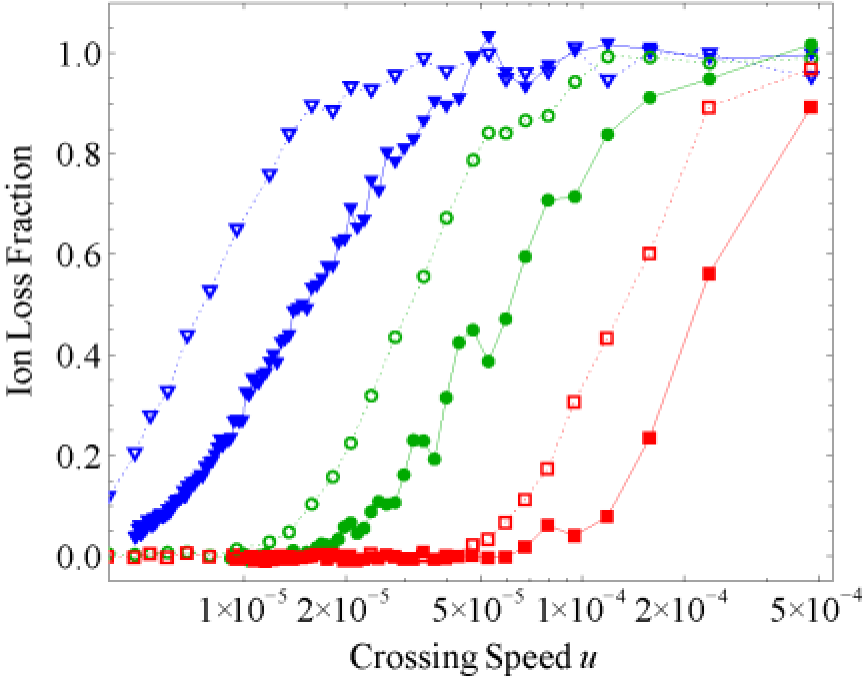
Integer Resonance Crossing

Single Resonance Crossing

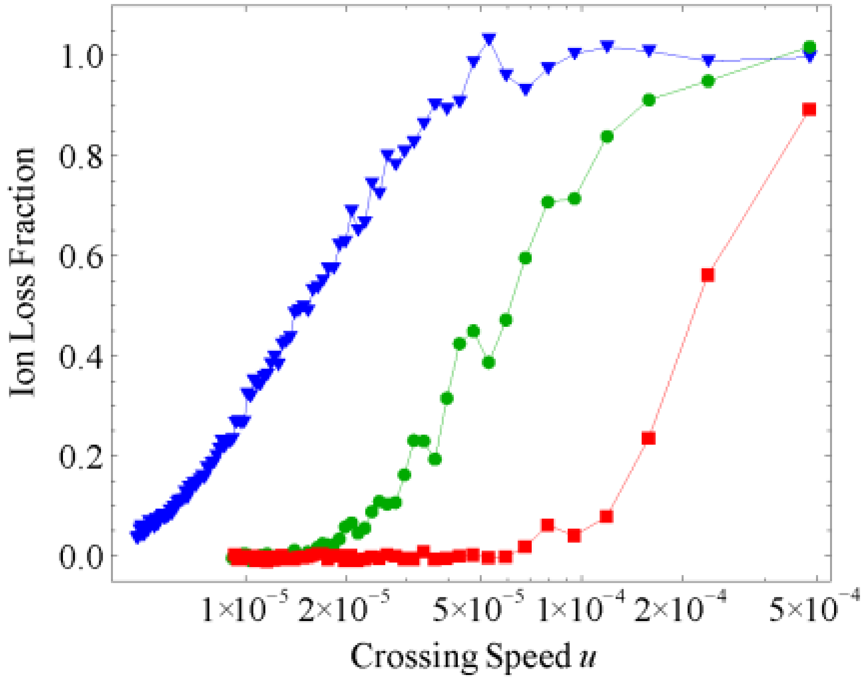


Integer Resonance Crossing

Single Resonance Crossing

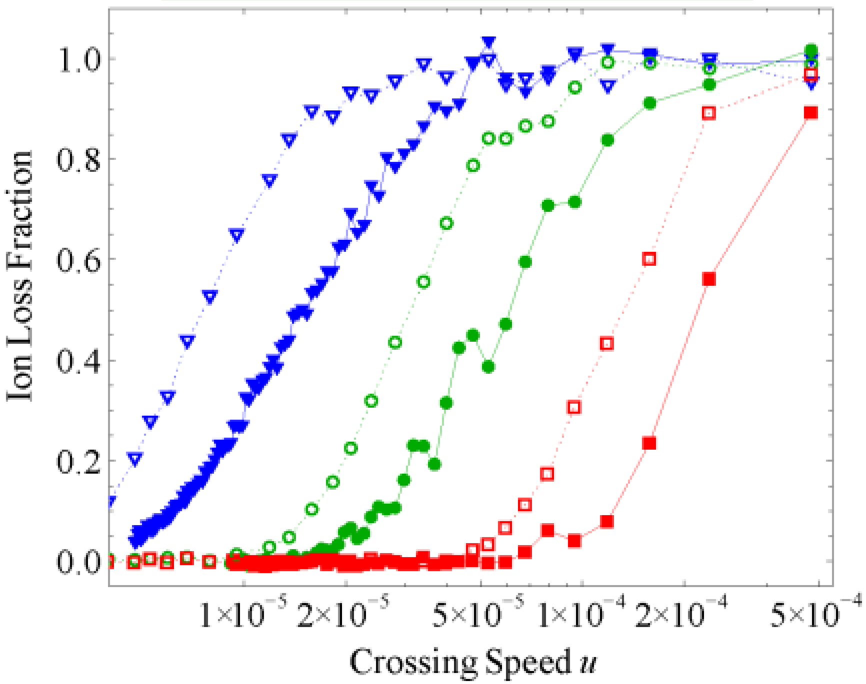


Double Resonance Crossing

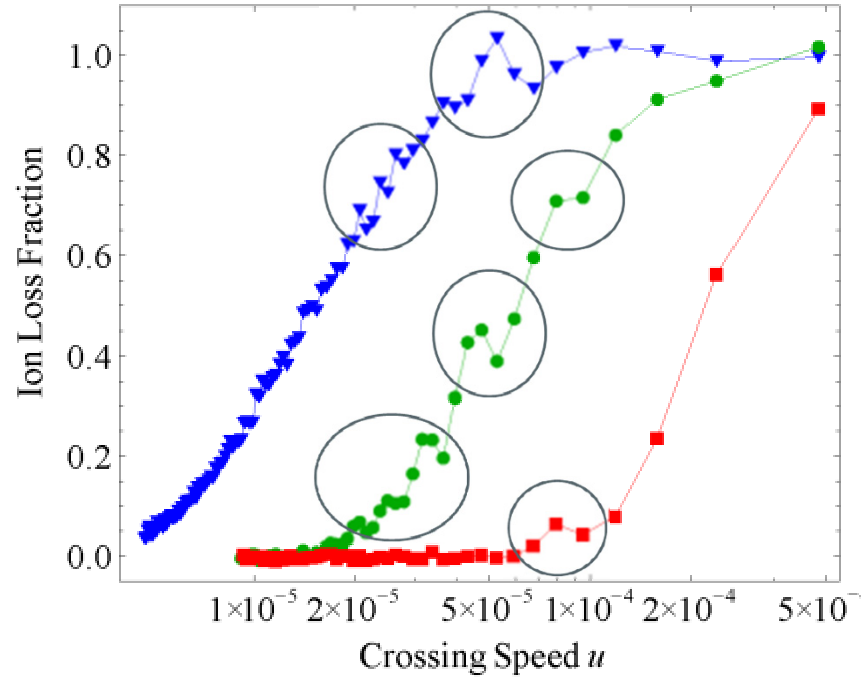


Integer Resonance Crossing

Single Resonance Crossing



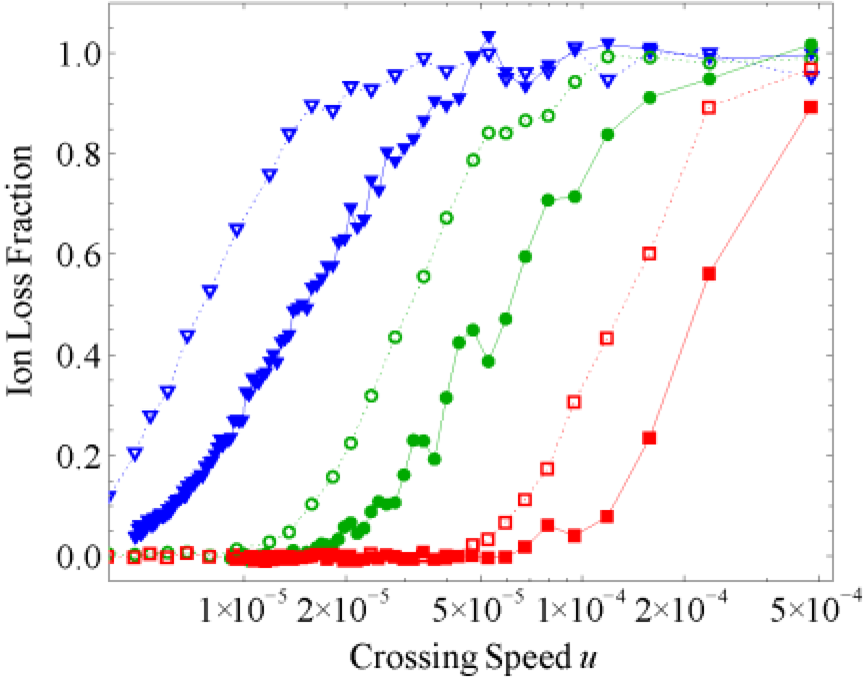
Double Resonance Crossing



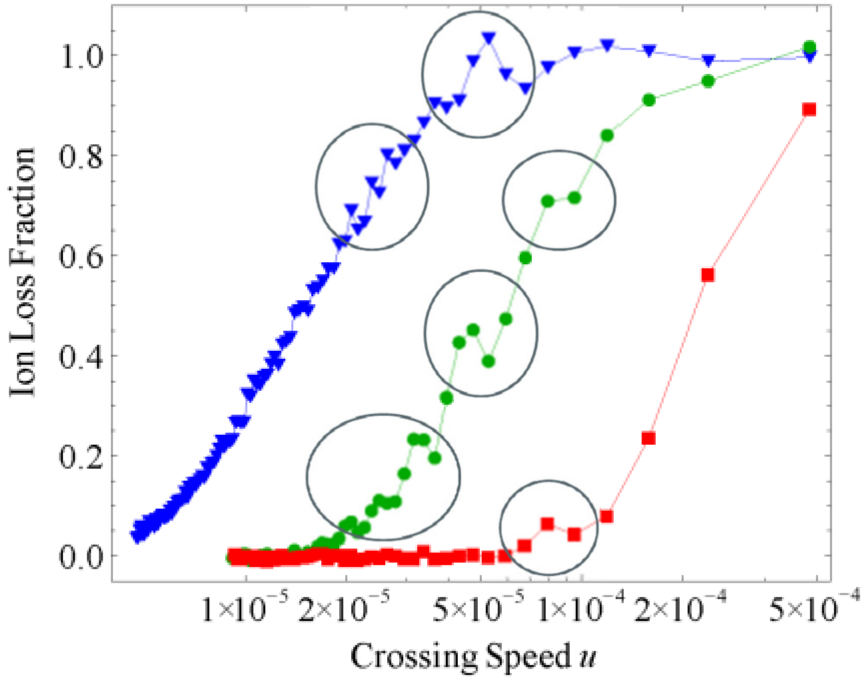
Integer Resonance Crossing

We notice weak oscillatory behavior of the loss curves in the cases of ***double*** resonance crossing.

Single Resonance Crossing



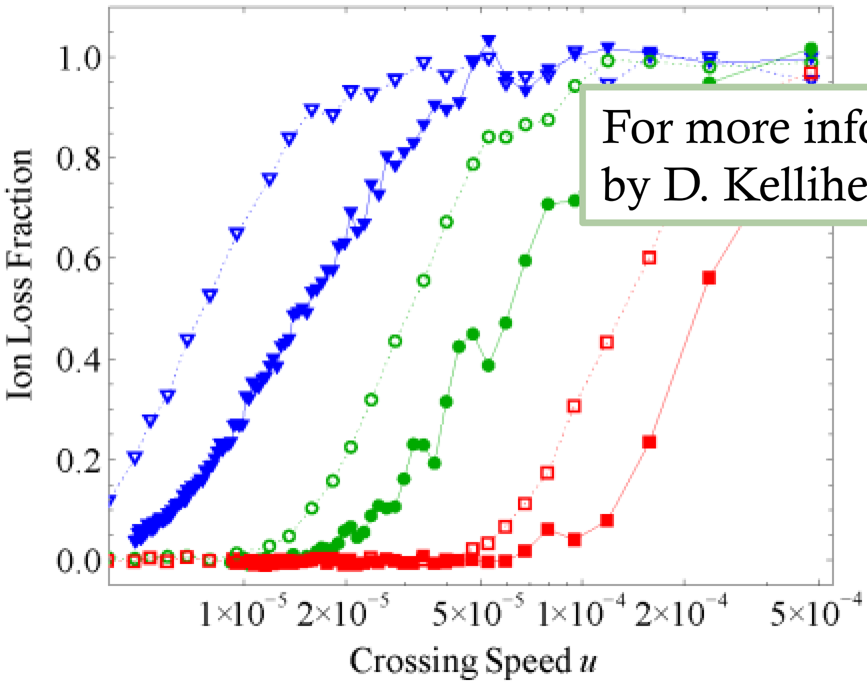
Double Resonance Crossing



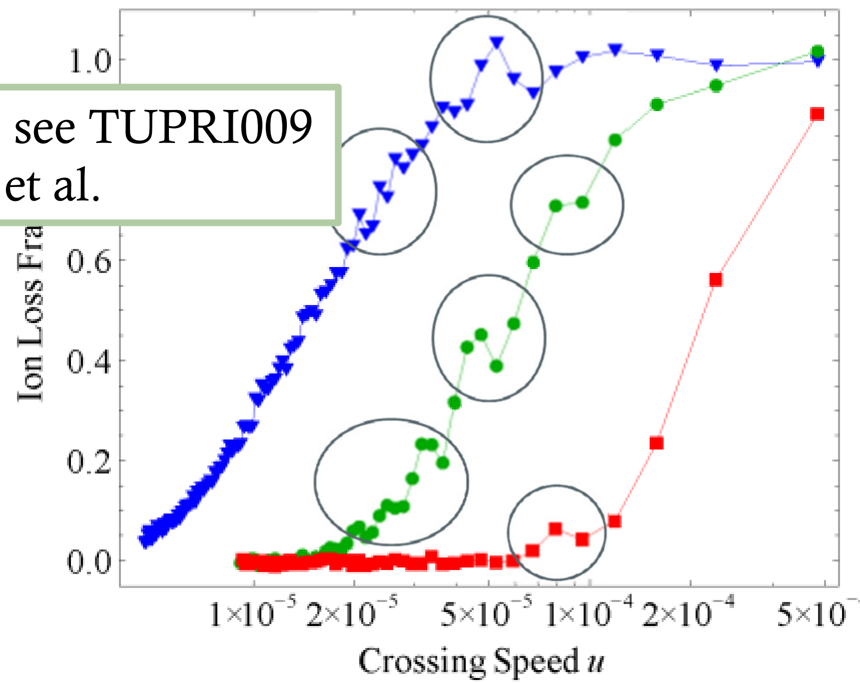
Integer Resonance Crossing

We notice weak oscillatory behavior of the loss curves in the cases of ***double*** resonance crossing.

Single Resonance Crossing



Double Resonance Crossing



For more info, see TUPRI009 by D. Kelliher et al.

Cooling Experiment

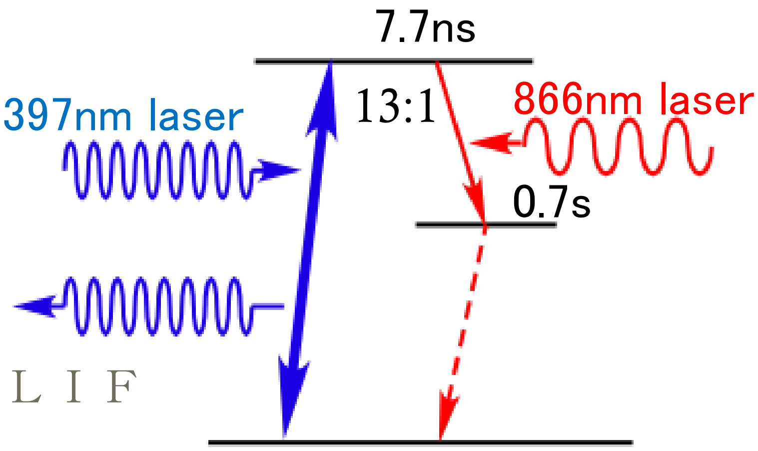
--- Preparation for future advanced experiments ---

Full-Range Density Control, Non-Destructive High-Precision Diagnostics, Ultralow-Intensity Ion Source, Crystalline Beams, … etc.

Ultimate Control of Tune Depression

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

Space-charge limit (where **tune depression = 0**)
can be reached experimentally !



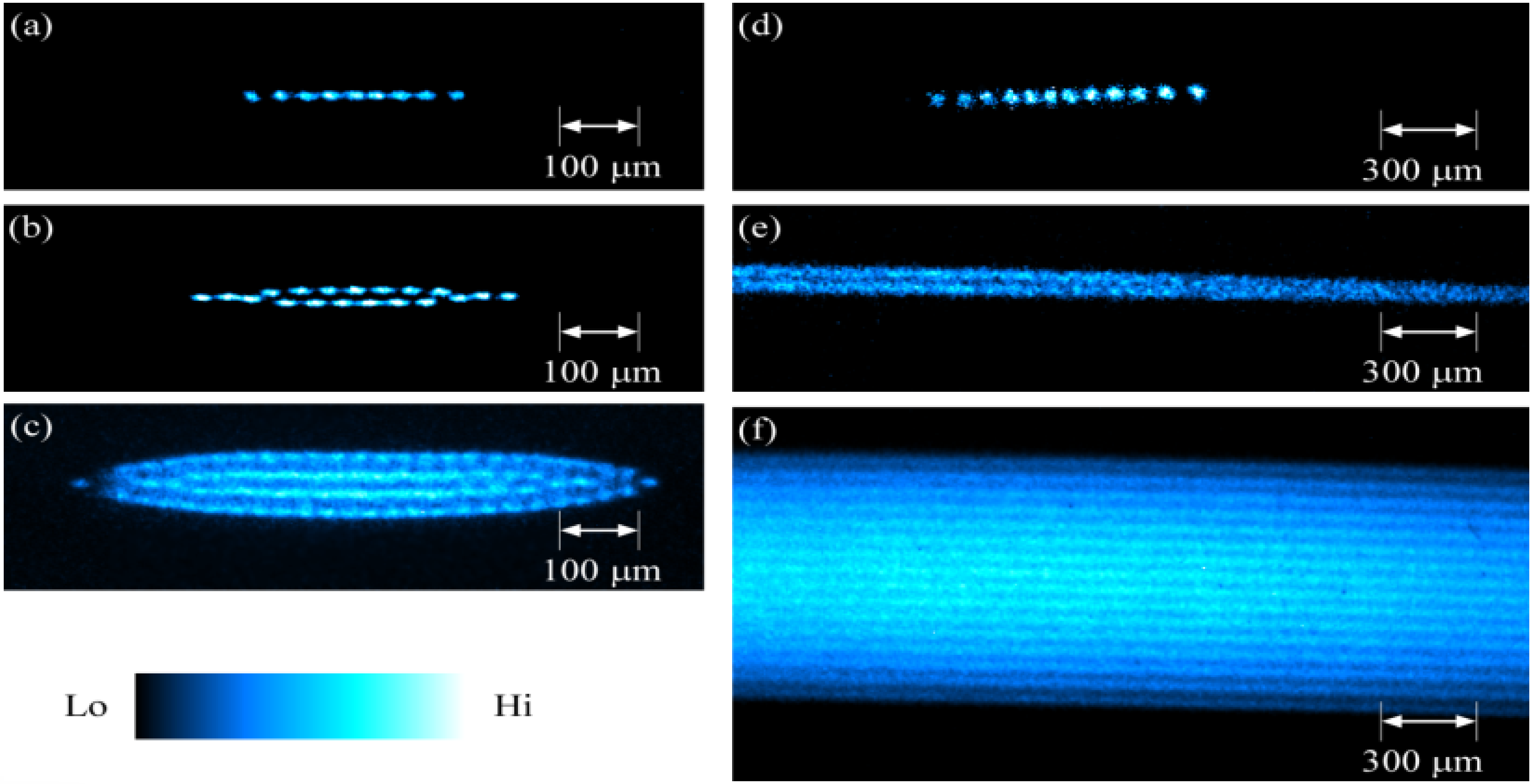
Cooling transition of $^{40}Ca^{+}$

Ultimate Control of Tune Depression

S-POD I

End-plate spacing = 6 mm

End-plate spacing = 60 mm



Plasma Stacking

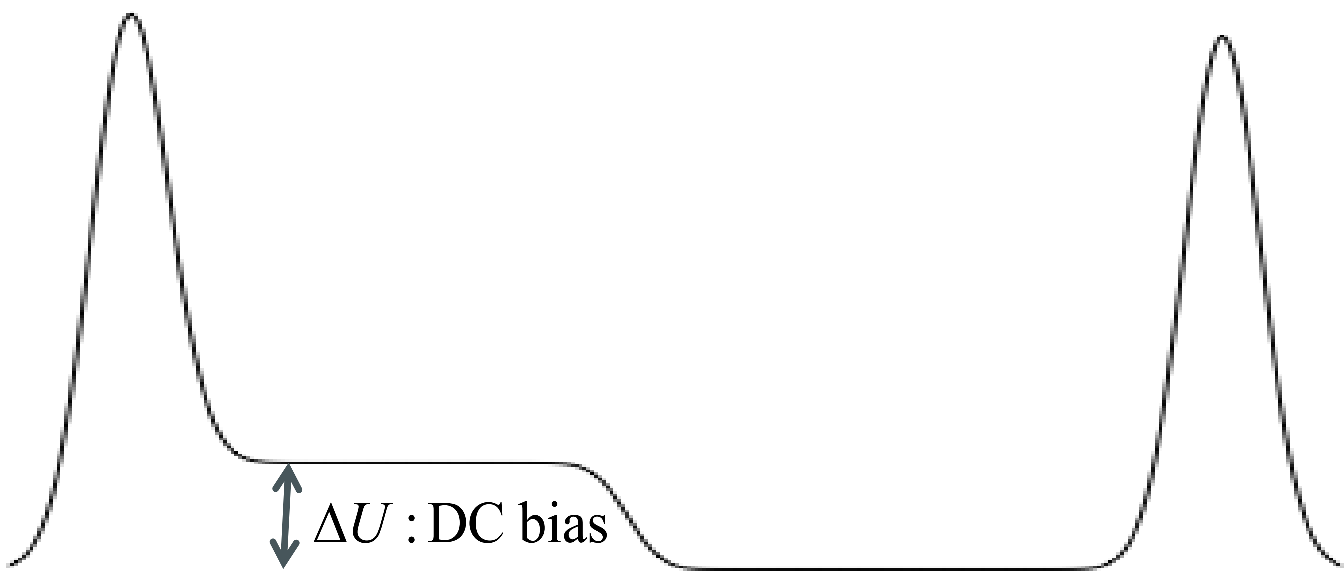
The use of $^{40}Ca^+$ ions instead of $^{40}Ar^+$ considerably widens the range of possible S-POD experiments.

- $^{40}Ca^+$ ions are laser-coolable : *the ultimate control of tune depression, a longer plasma life time , …*
- LIF (Laser-Induced Fluorescence) signals are available : *high-precision, real-time CCD measurements, …*
- But we must turn on the atomic oven to produce $^{40}Ca^+$ plasmas.

To increase a number of $^{40}Ca^+$ ions for future experiments, we are now trying to establish a **plasma stacking scheme**.

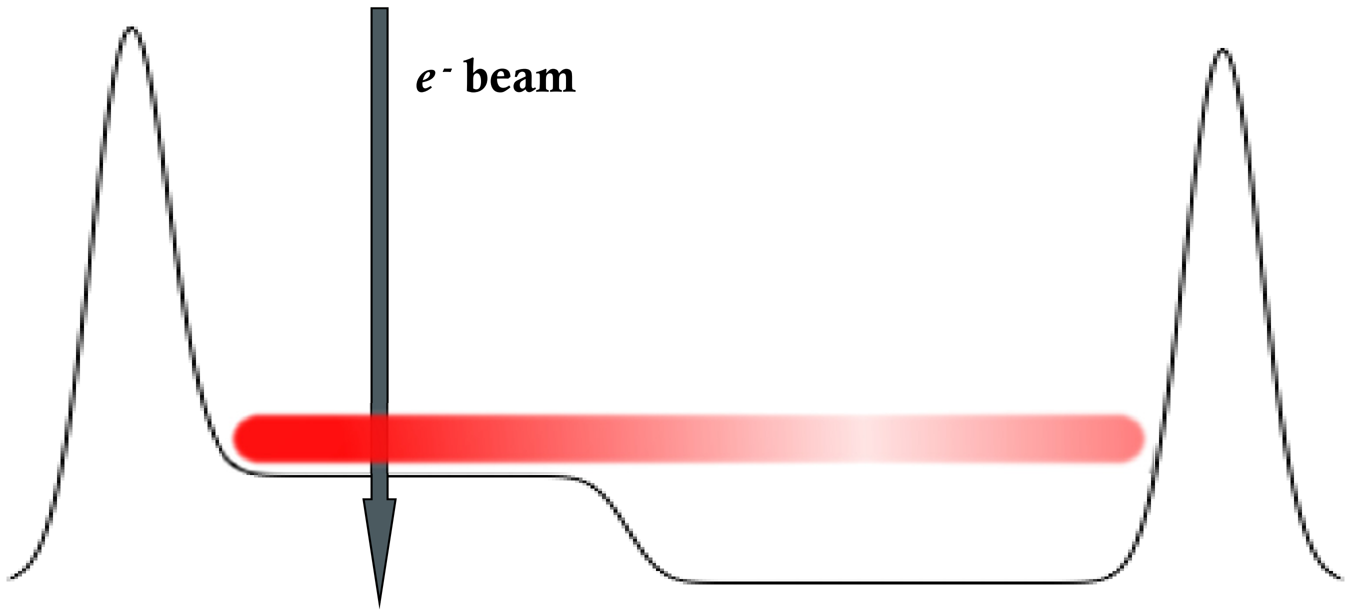
Plasma Stacking

To increase a number of $^{40}Ca^+$ ions for future experiments, we are now trying to establish a **plasma stacking scheme**.



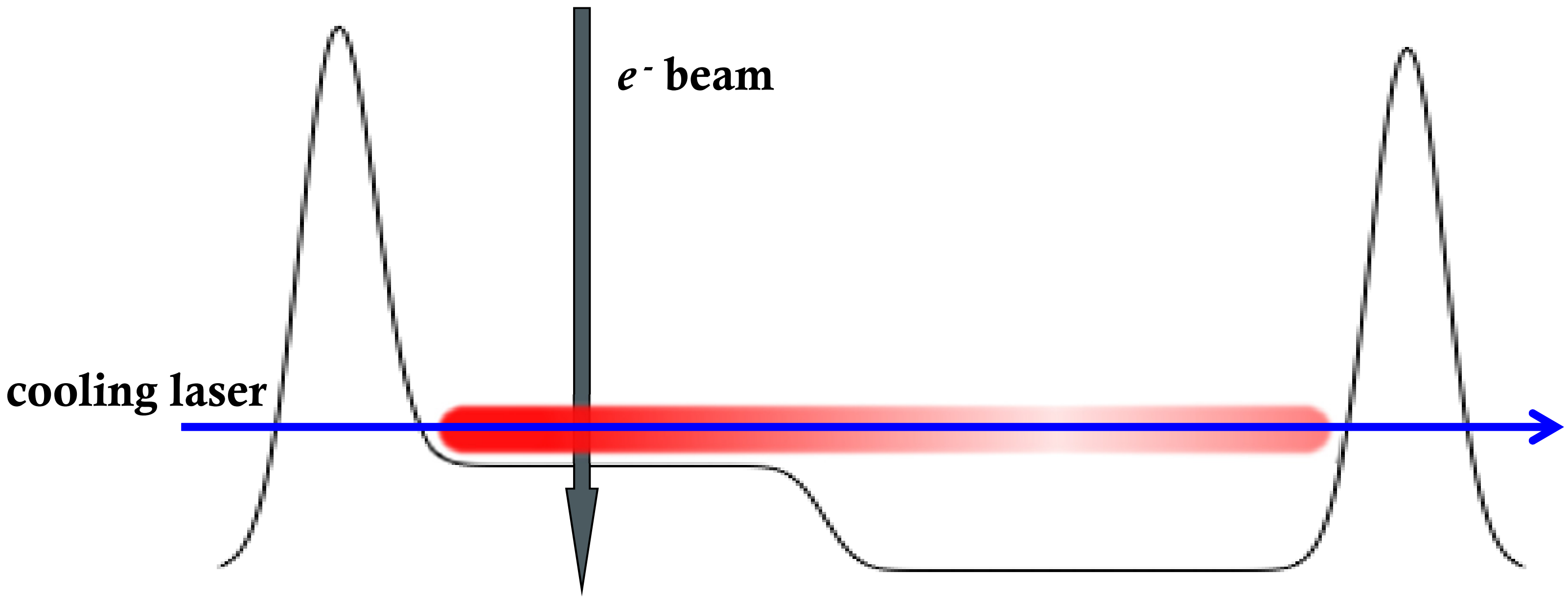
Plasma Stacking

To increase a number of $^{40}Ca^{+}$ ions for future experiments, we are now trying to establish a **plasma stacking scheme**.



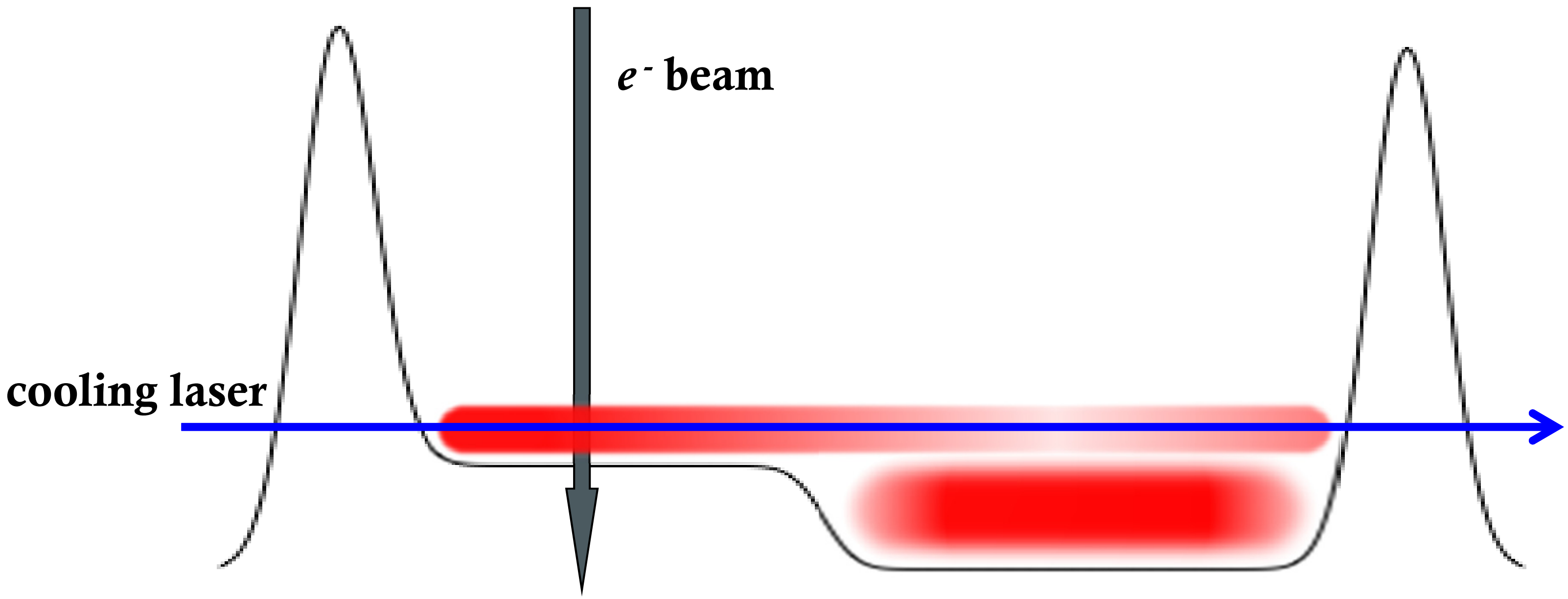
Plasma Stacking

To increase a number of $^{40}Ca^{+}$ ions for future experiments, we are now trying to establish a **plasma stacking scheme**.



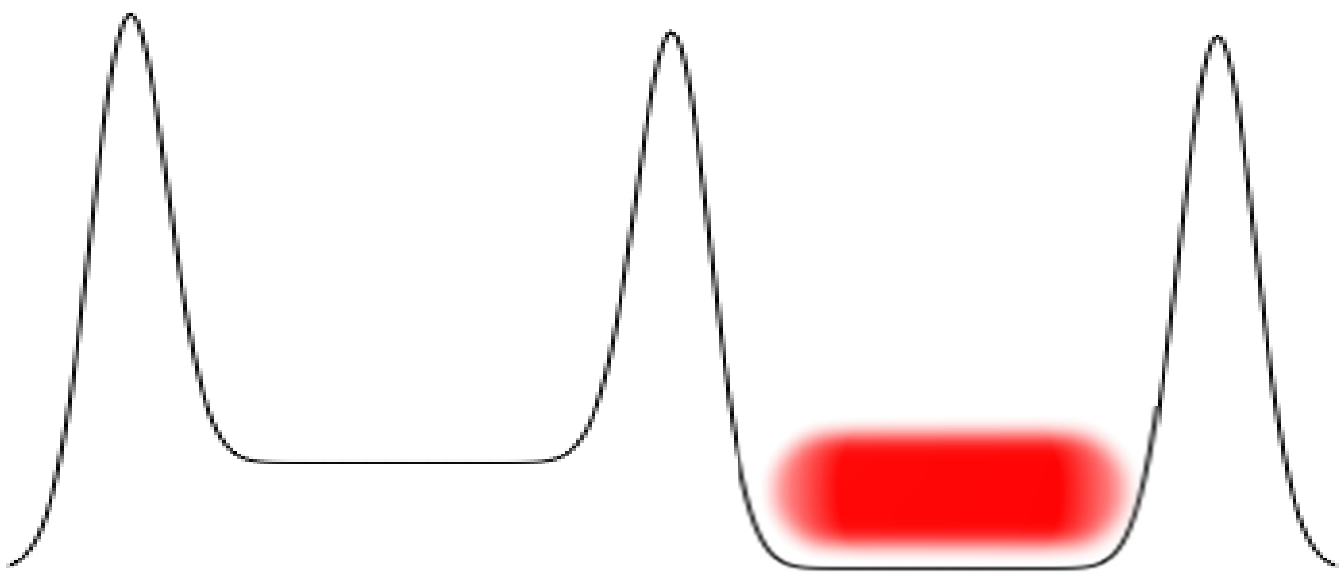
Plasma Stacking

To increase a number of $^{40}Ca^{+}$ ions for future experiments, we are now trying to establish a **plasma stacking scheme**.



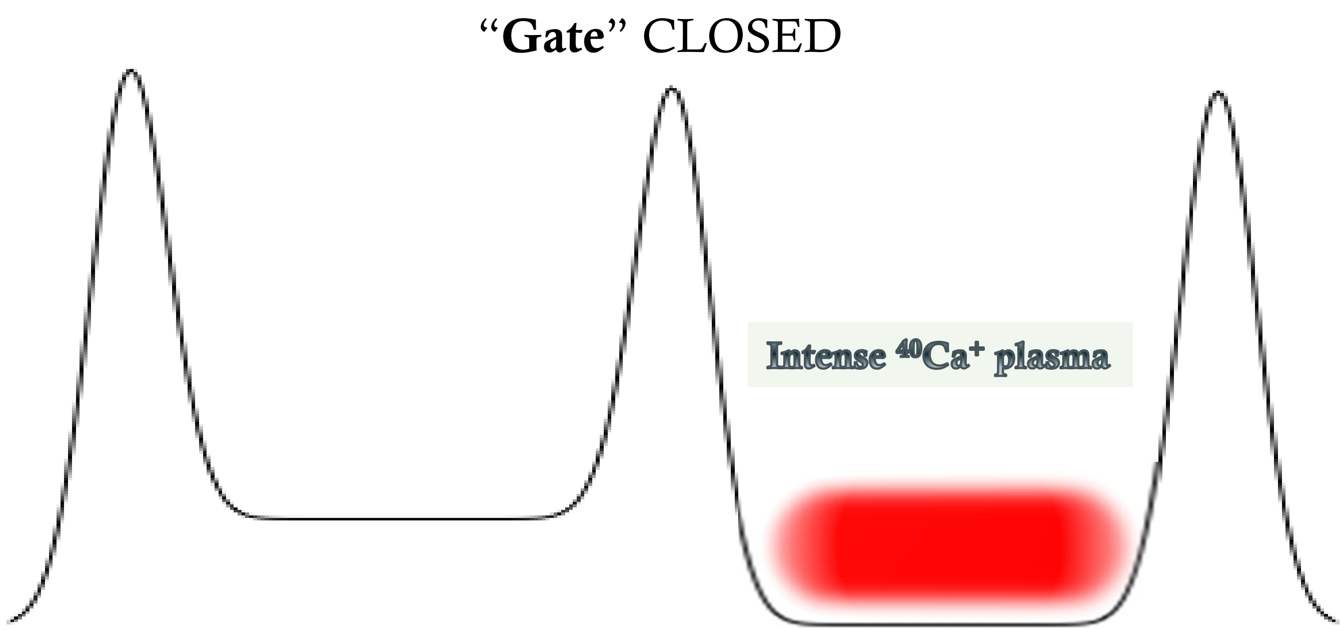
Plasma Stacking

To increase a number of $^{40}Ca^{+}$ ions for future experiments, we are now trying to establish a **plasma stacking scheme**.



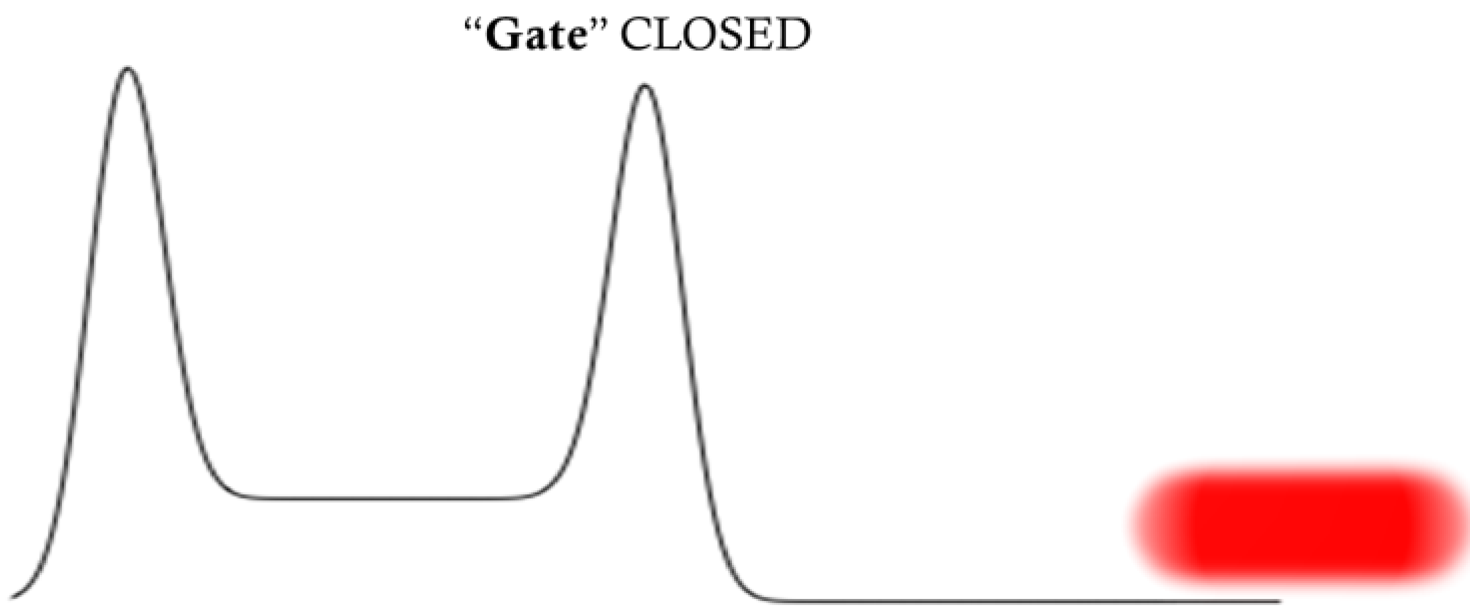
Plasma Stacking

To increase a number of $^{40}Ca^{+}$ ions for future experiments, we are now trying to establish a **plasma stacking scheme**.



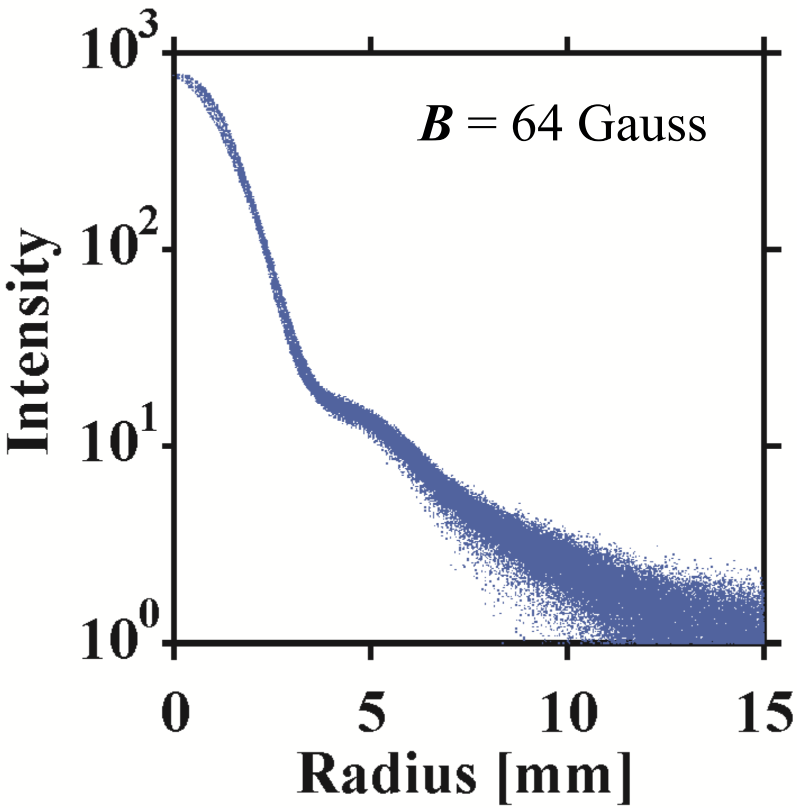
Plasma Stacking

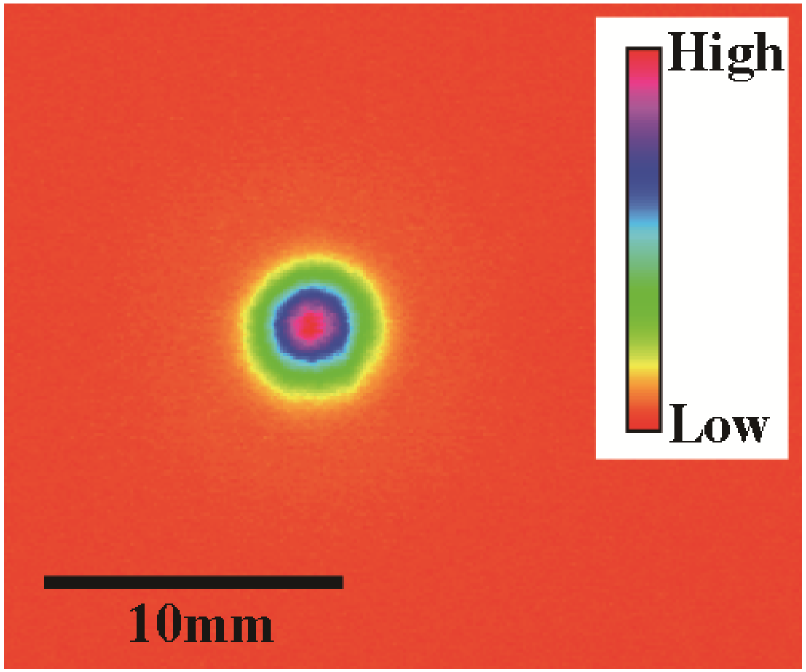
To increase a number of $^{40}Ca^+$ ions for future experiments, we are now trying to establish a **plasma stacking scheme**.



Example

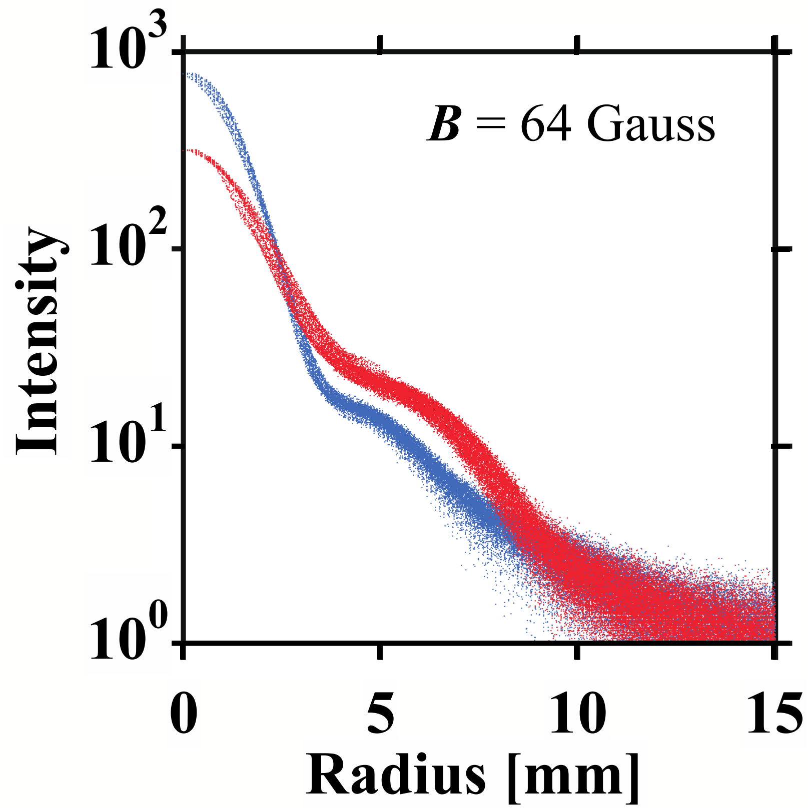
INITIAL

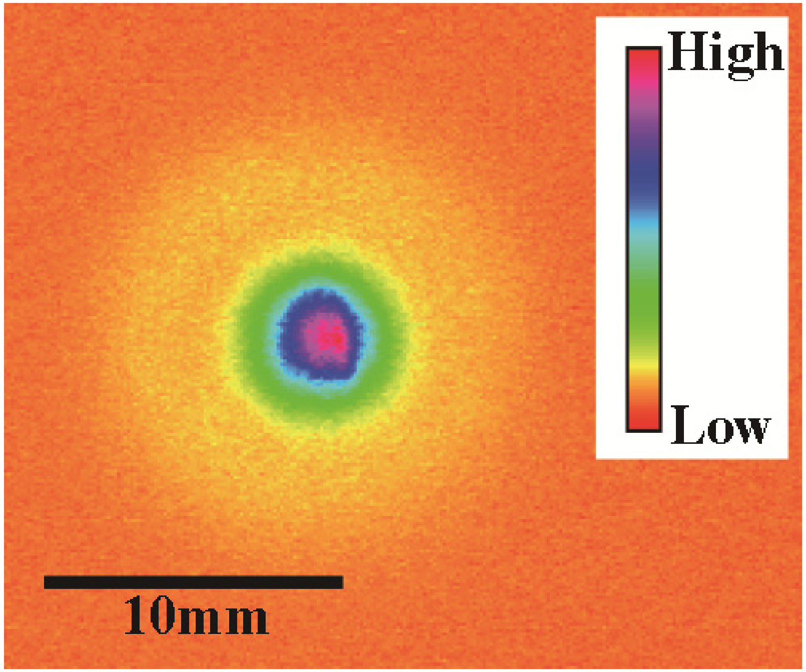




Example

AFTER 7 ms





Summary

- Non-neutral plasma traps are useful in exploring a wide range of beam dynamics.
- Several S-POD systems (based on Paul traps & Penning traps) have been developed at Hiroshima University and applied for various beam physics experiments.
- We have experimentally identified resonance stop bands in several standard AG transport channels (doublet, triplet, FFDD) and confirmed their parameter dependence.
- Beam losses due to integer and other higher-order resonance crossing have been investigated systematically.
- The Doppler cooling technique is being applied in order to widen the range of possible S-POD experiments.
- Halo formation experiments with a Penning trap is in progress.
- More S-POD experiments are in preparation or under consideration (e.g., long-term stability of intense beams, stop band measurements with controlled nonlinearity, the effect of synchrotron motion, dynamics of ultralow-emittance hadron beams, etc.)