Recent Results from the S-POD Trap Systems on the Stability of Intense Hadron Beams

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.

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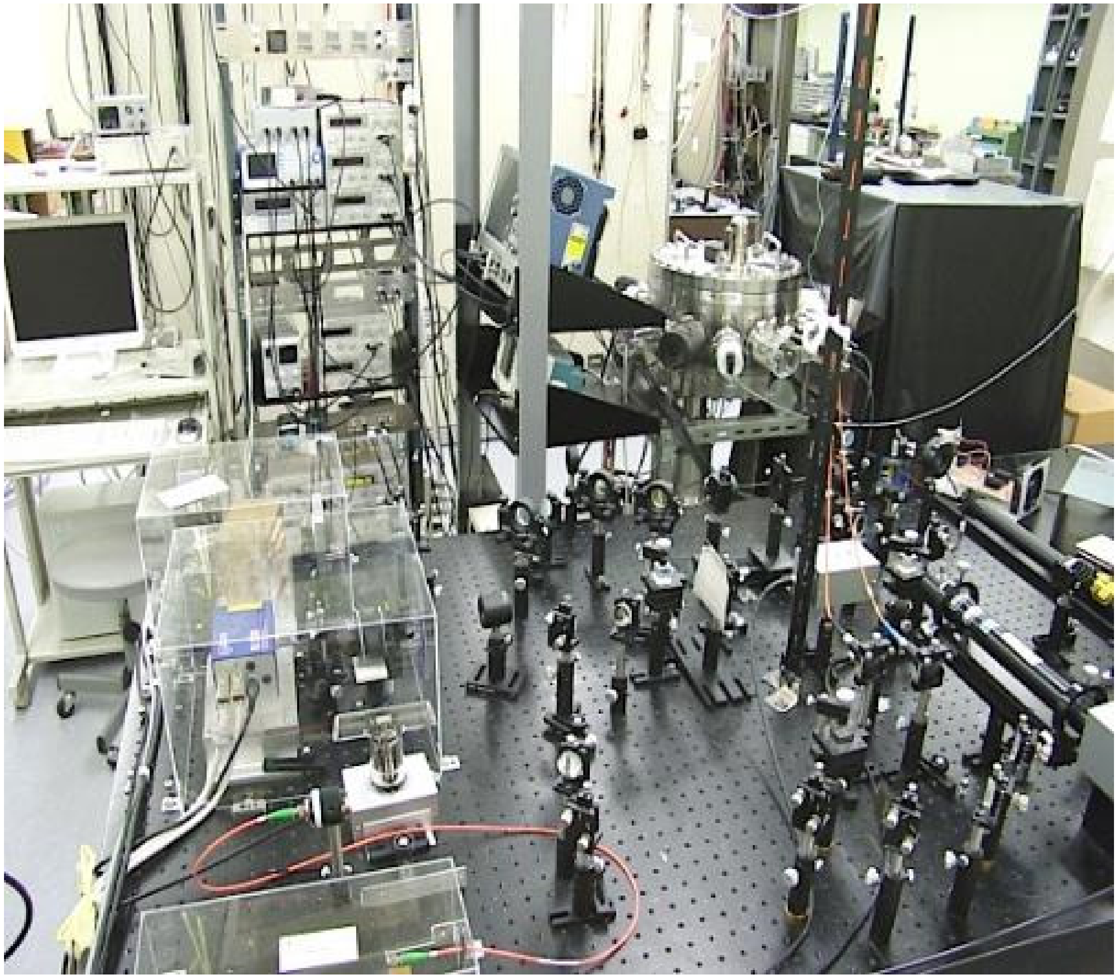

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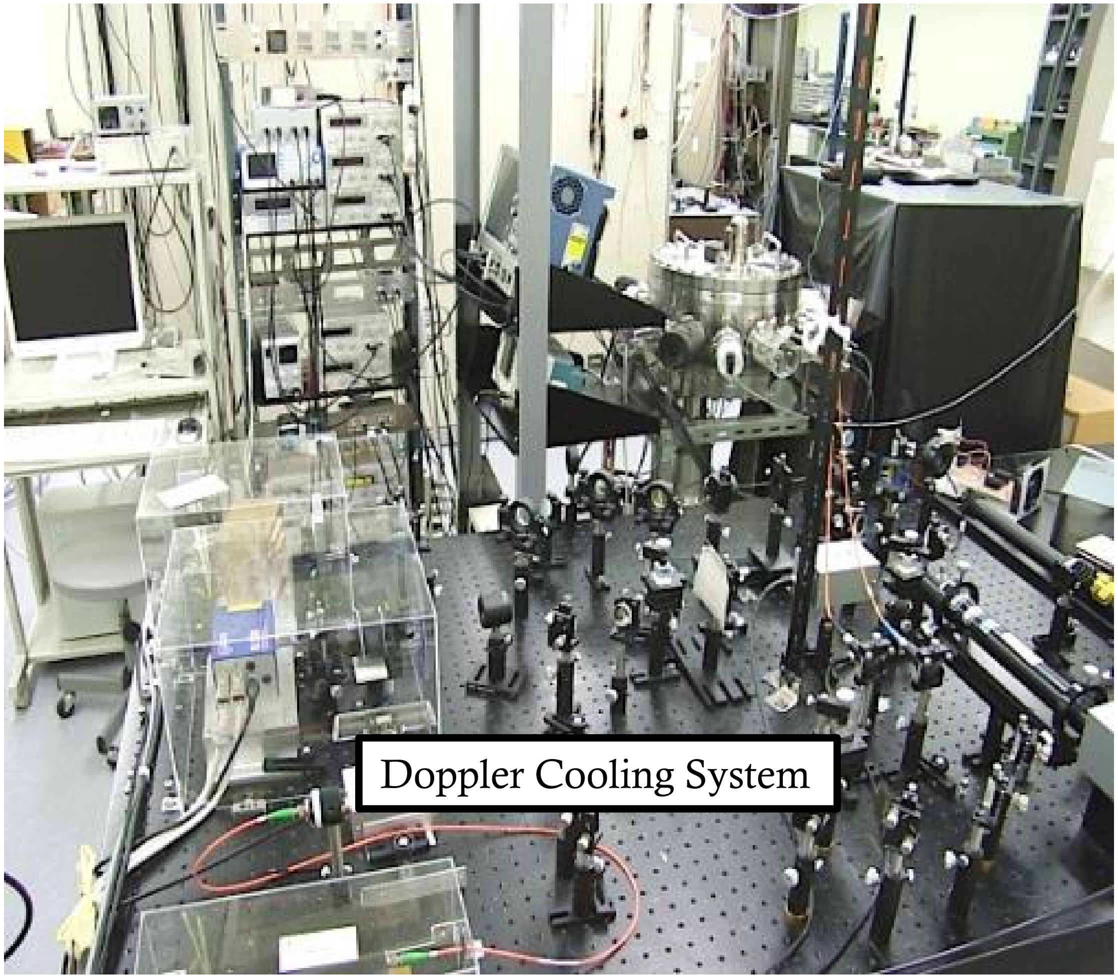

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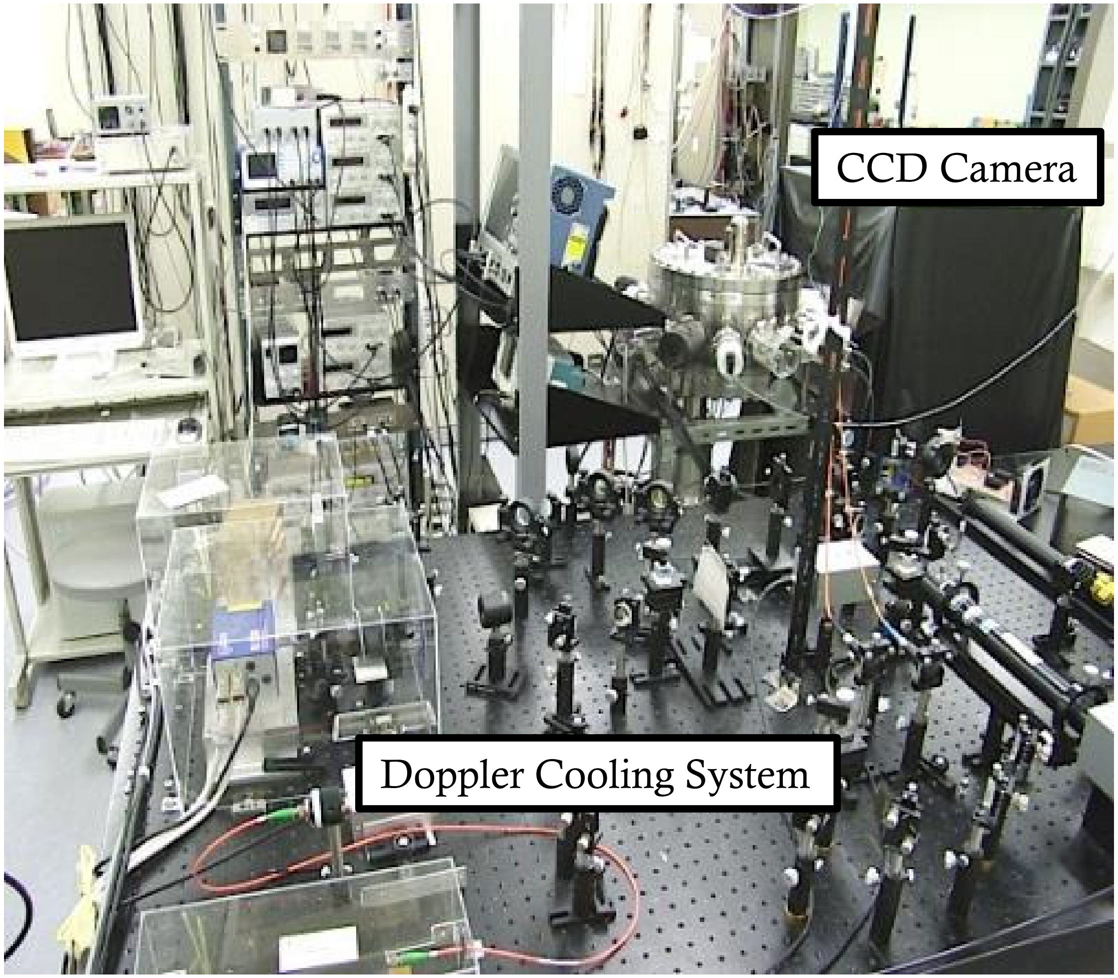

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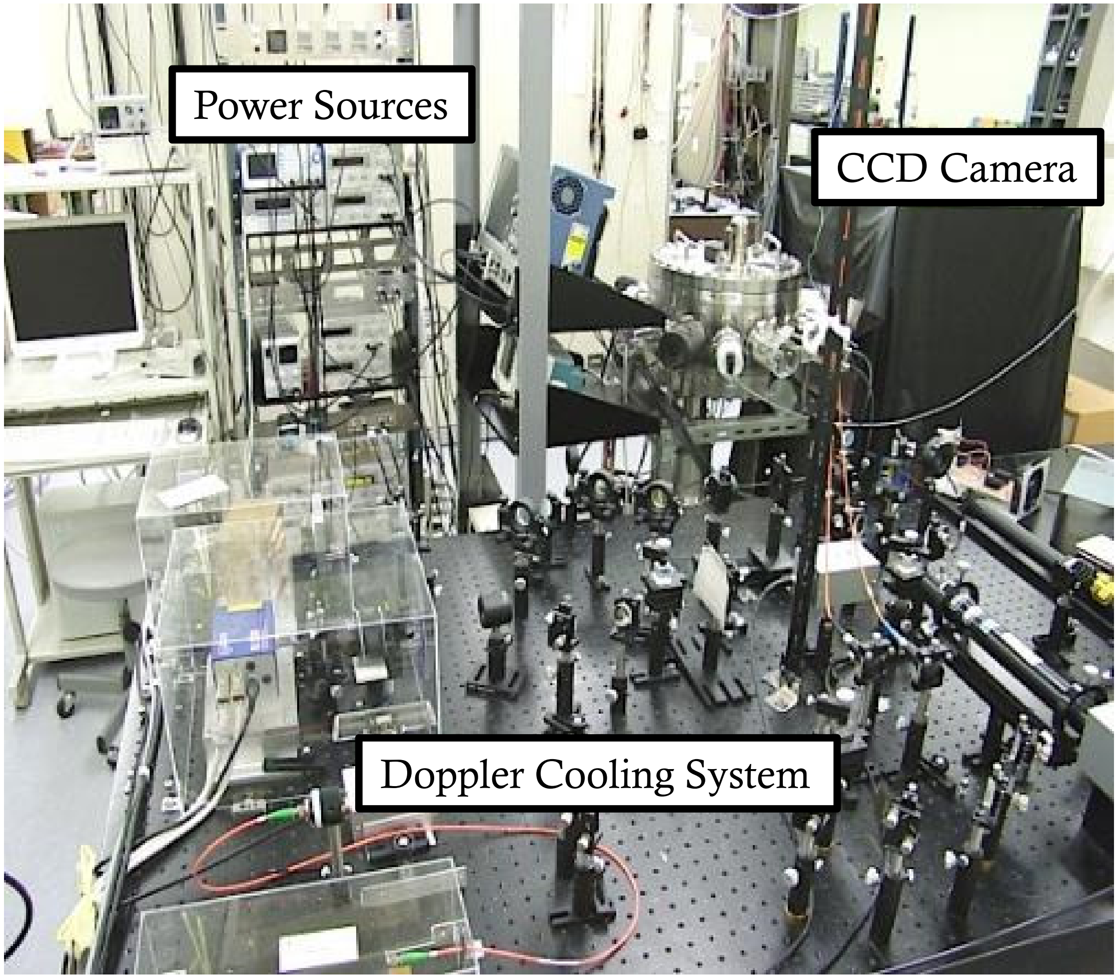

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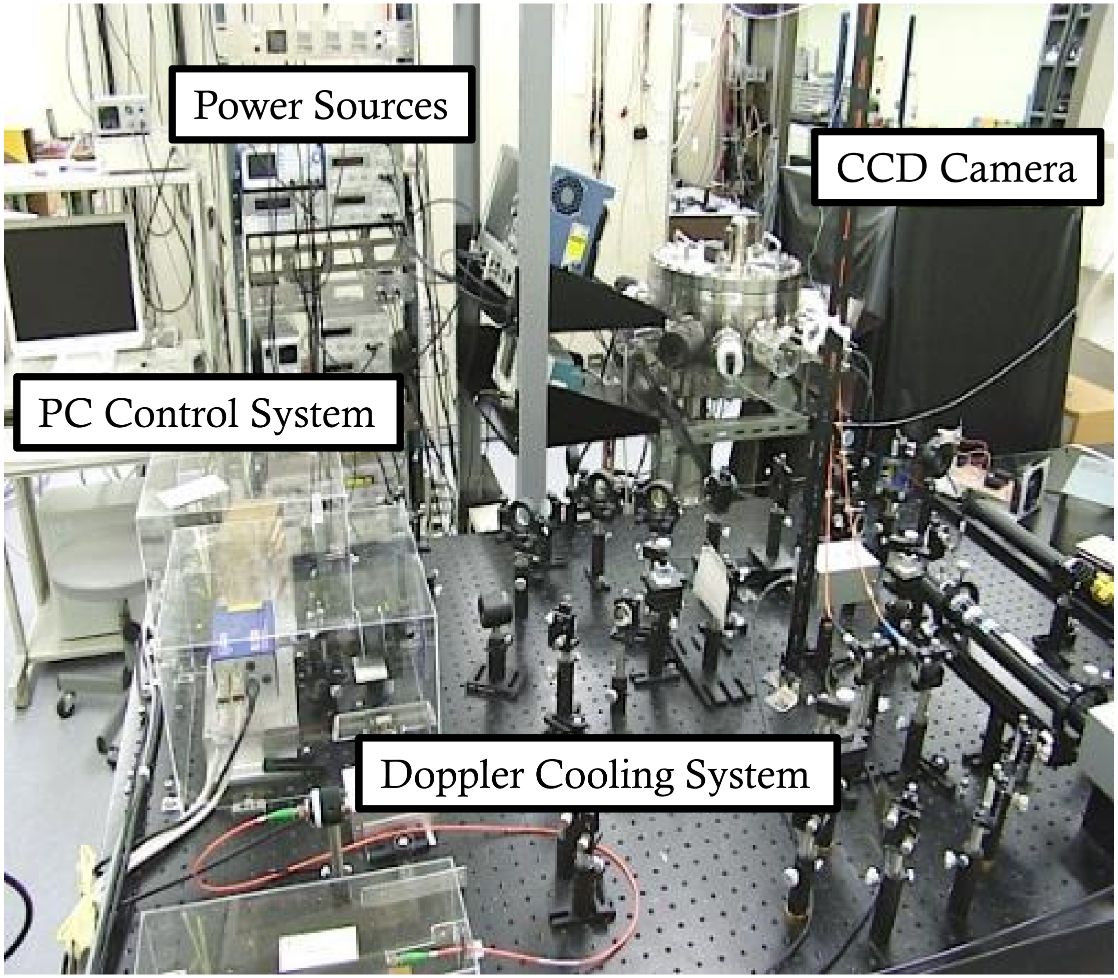

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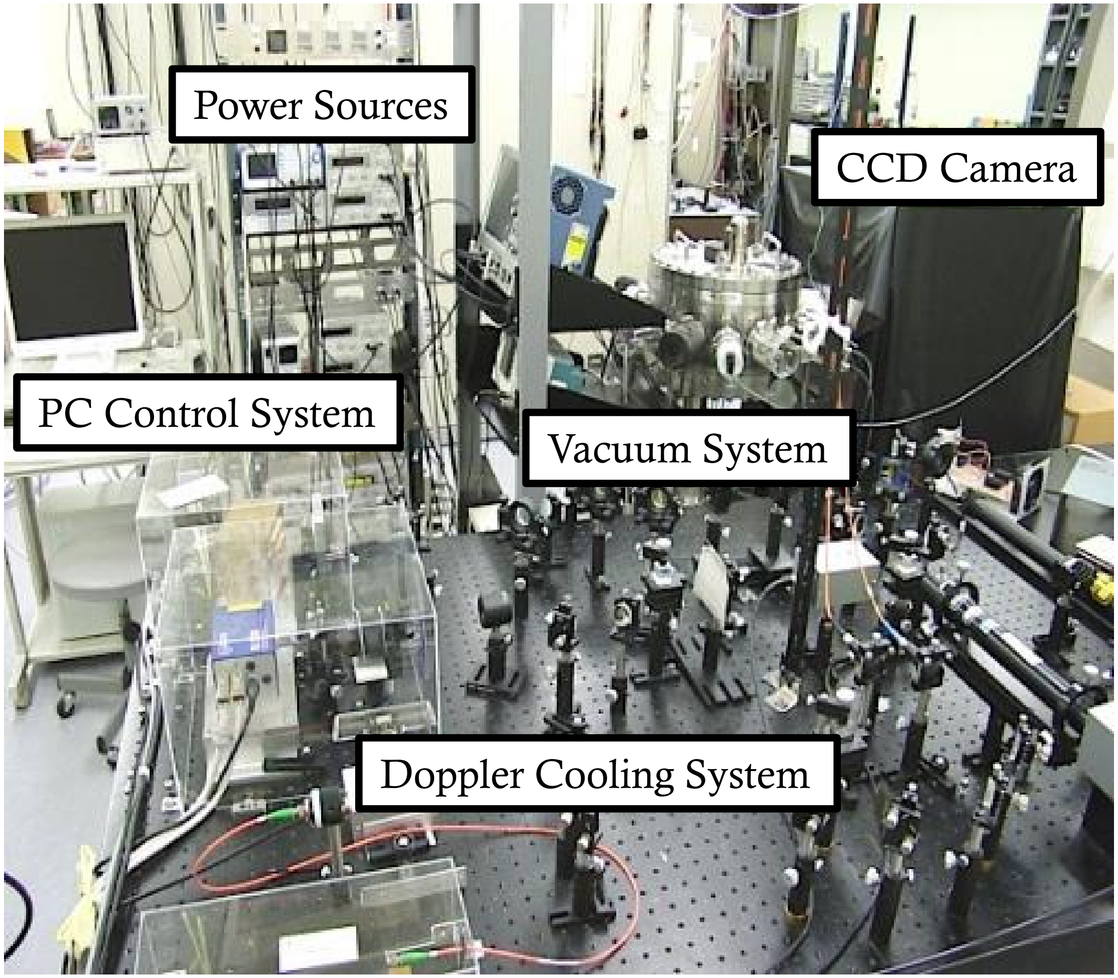

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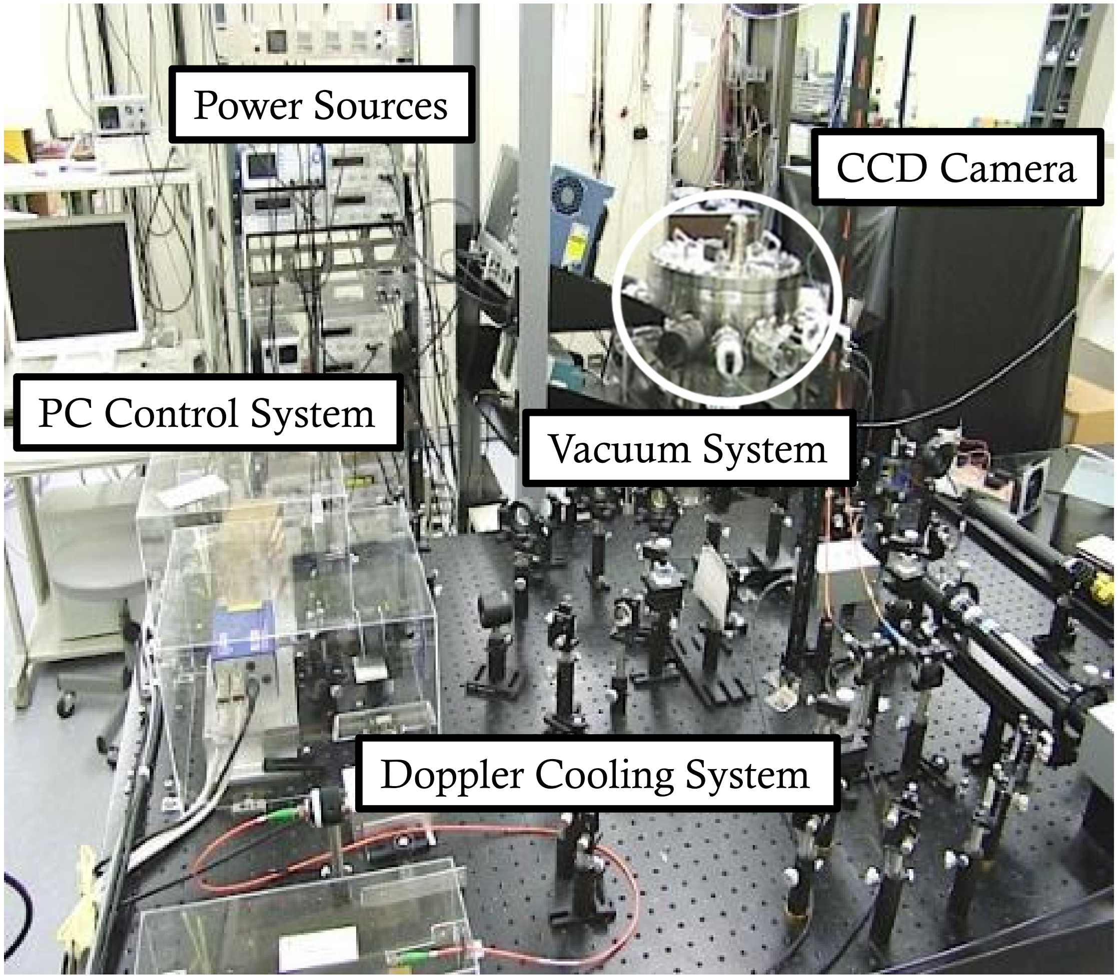

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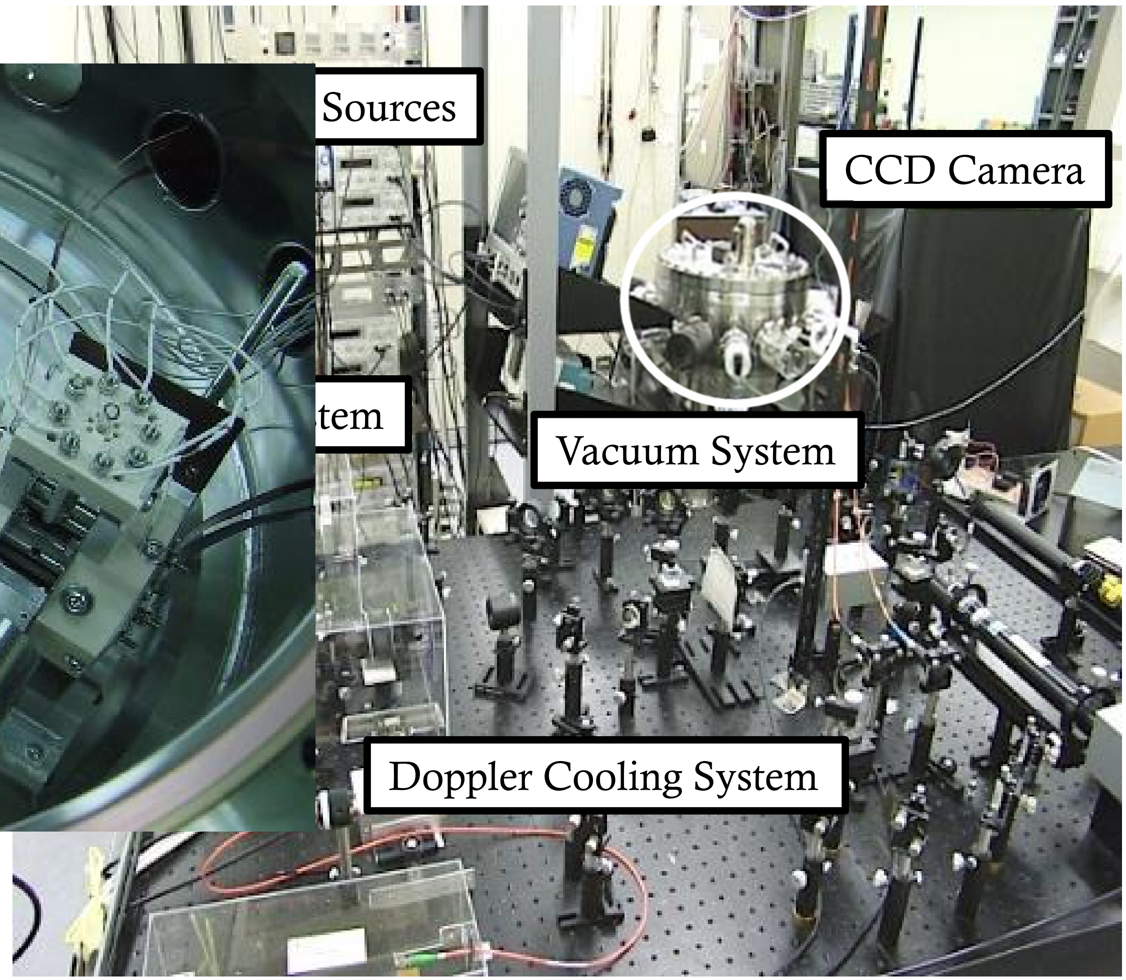

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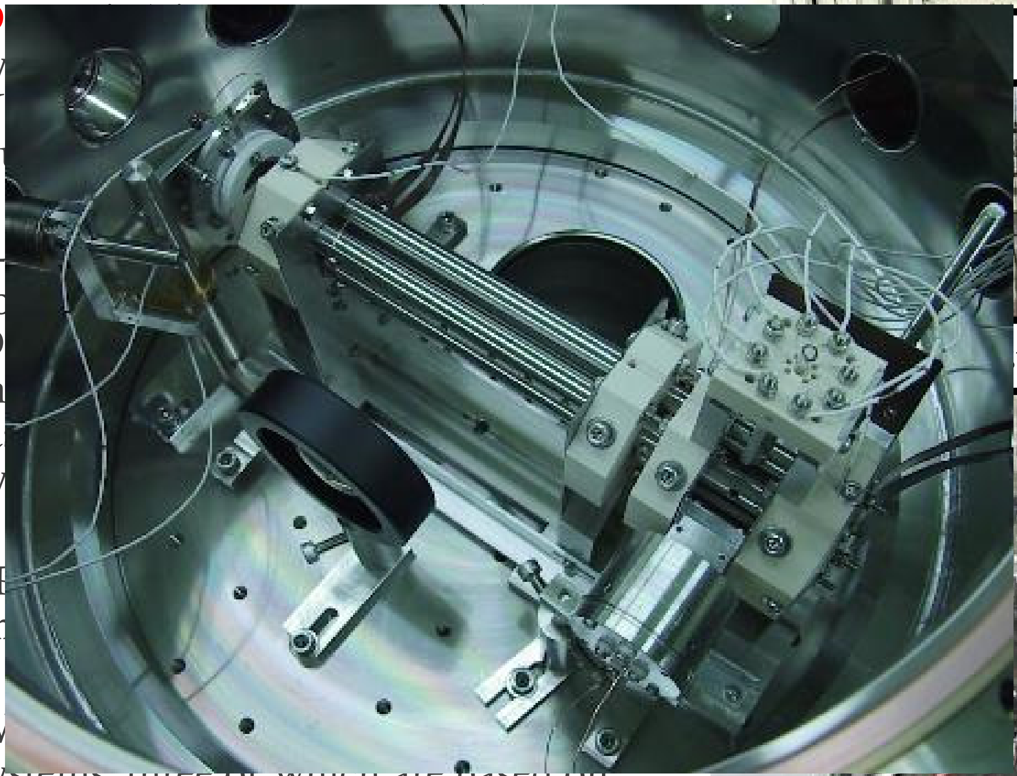

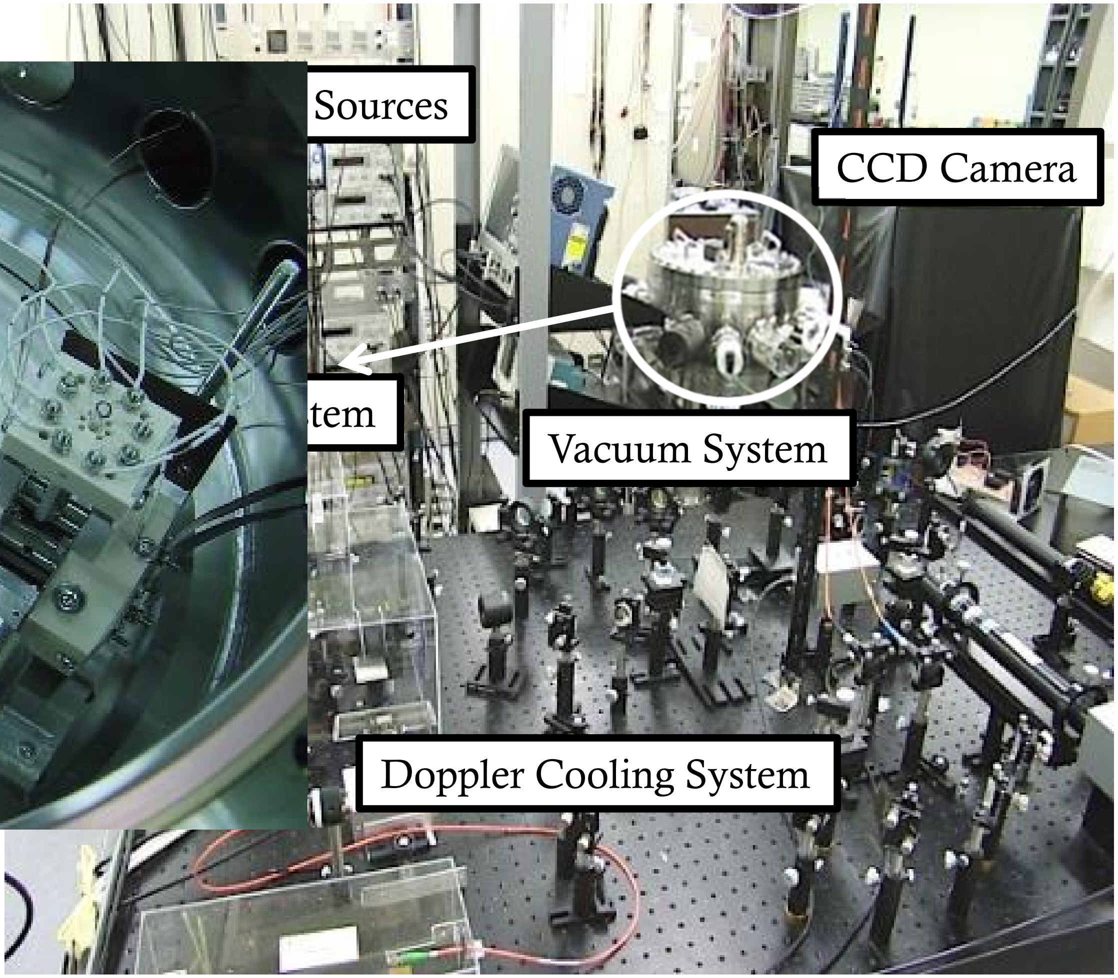

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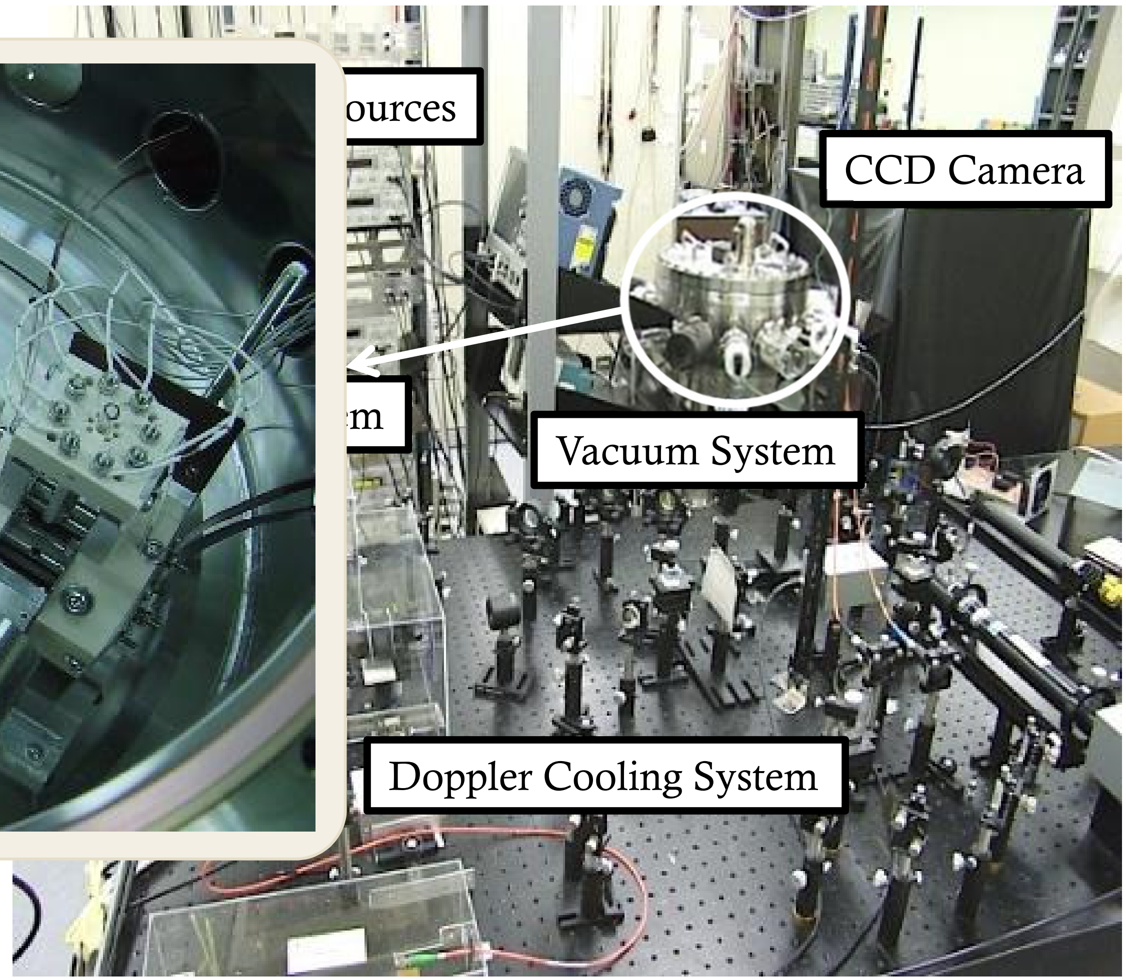

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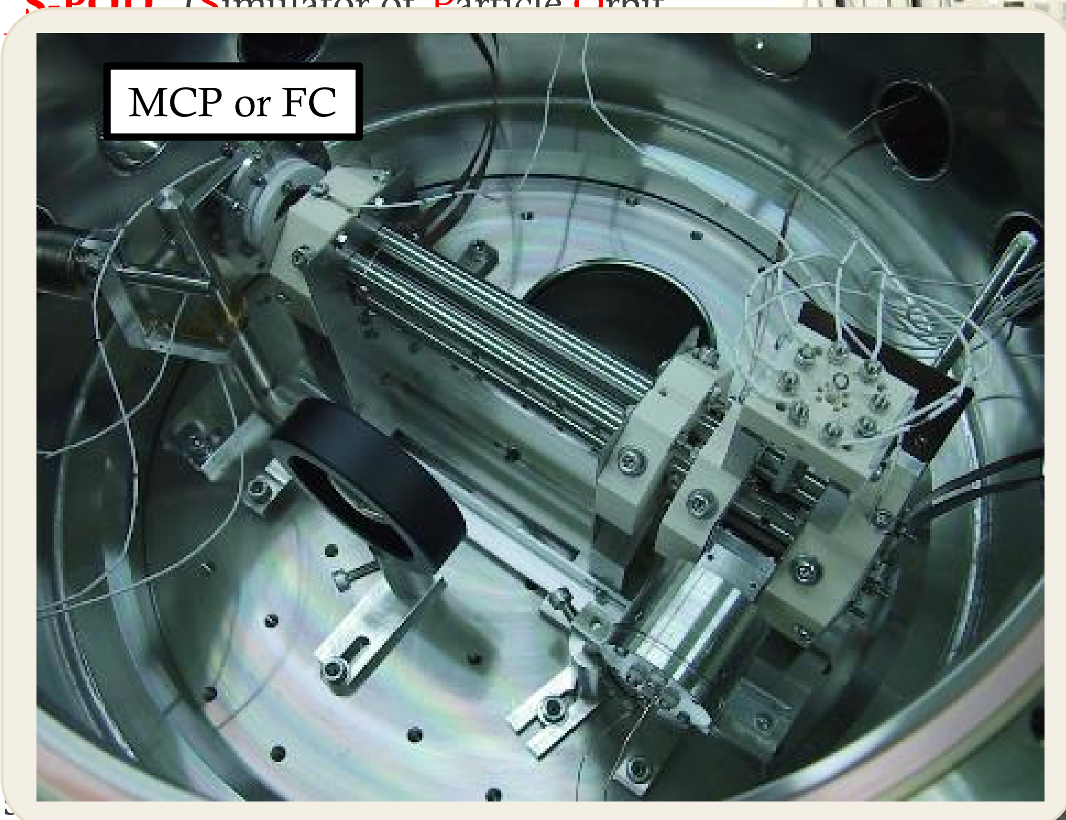

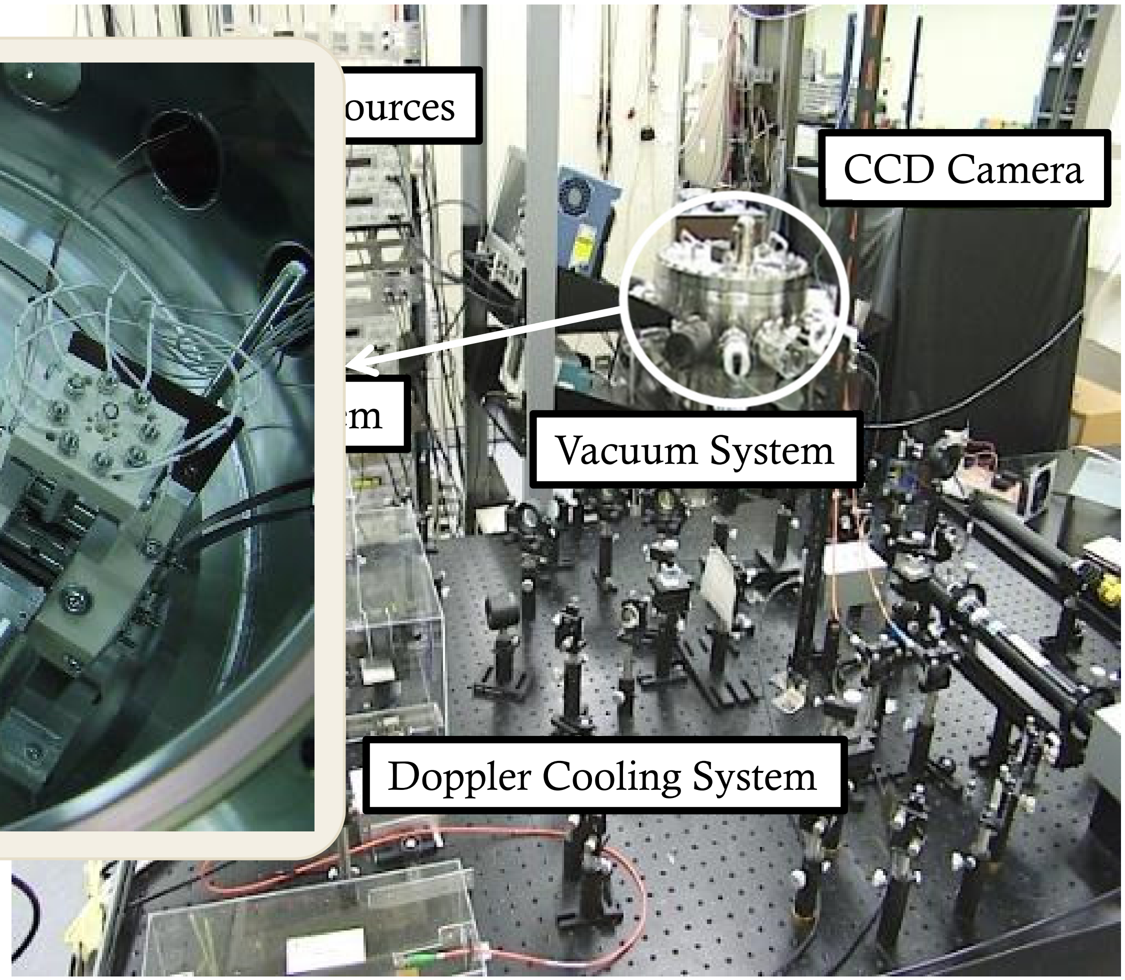

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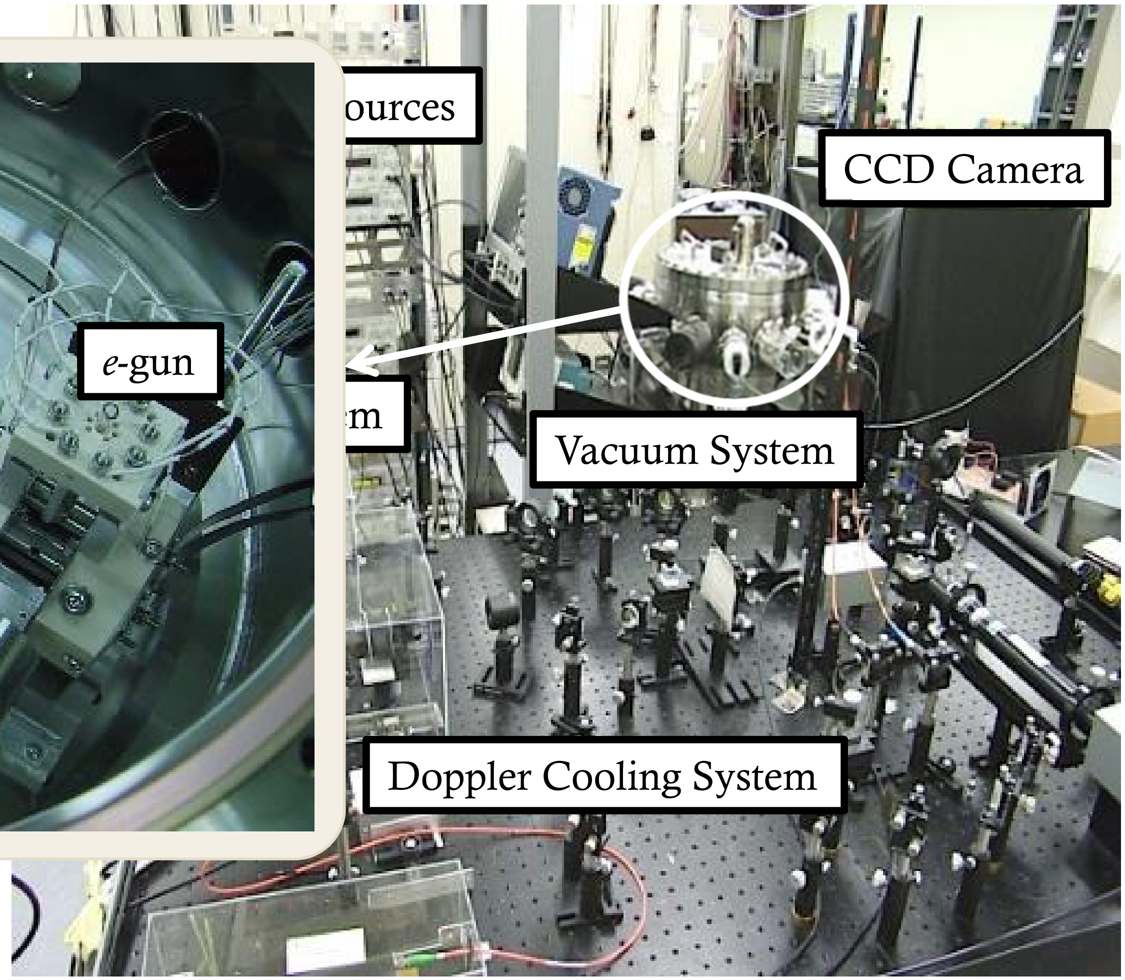

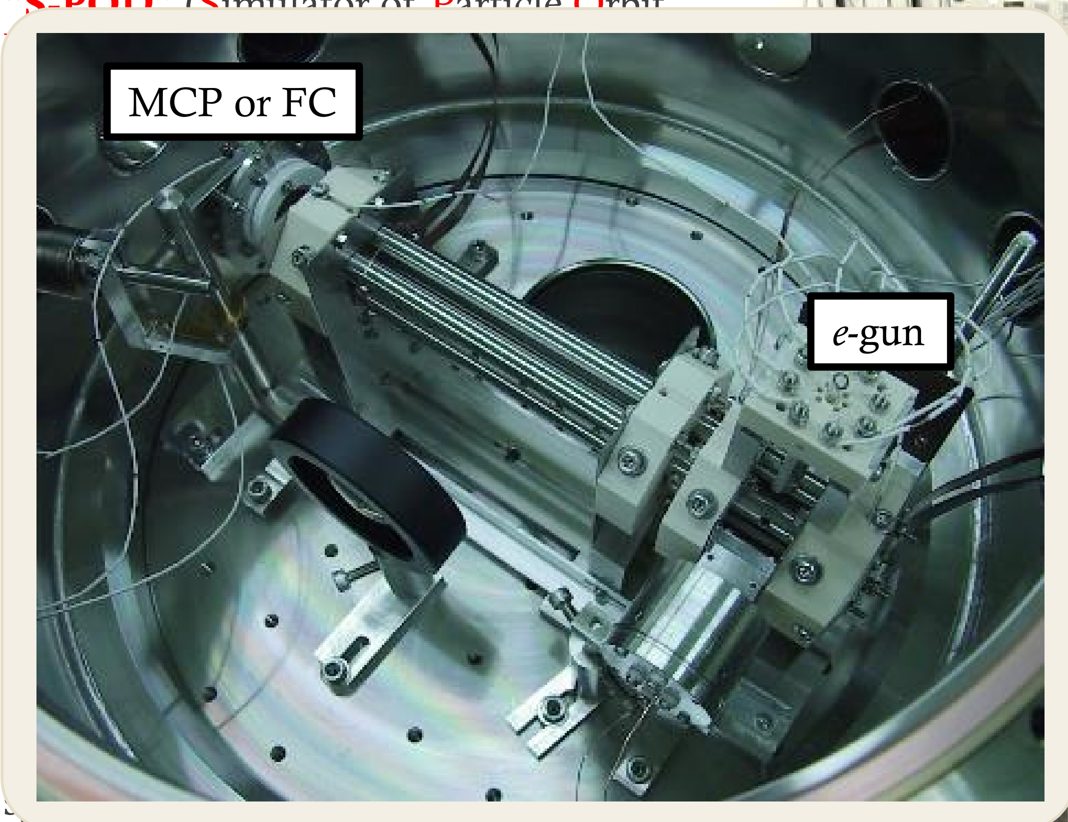

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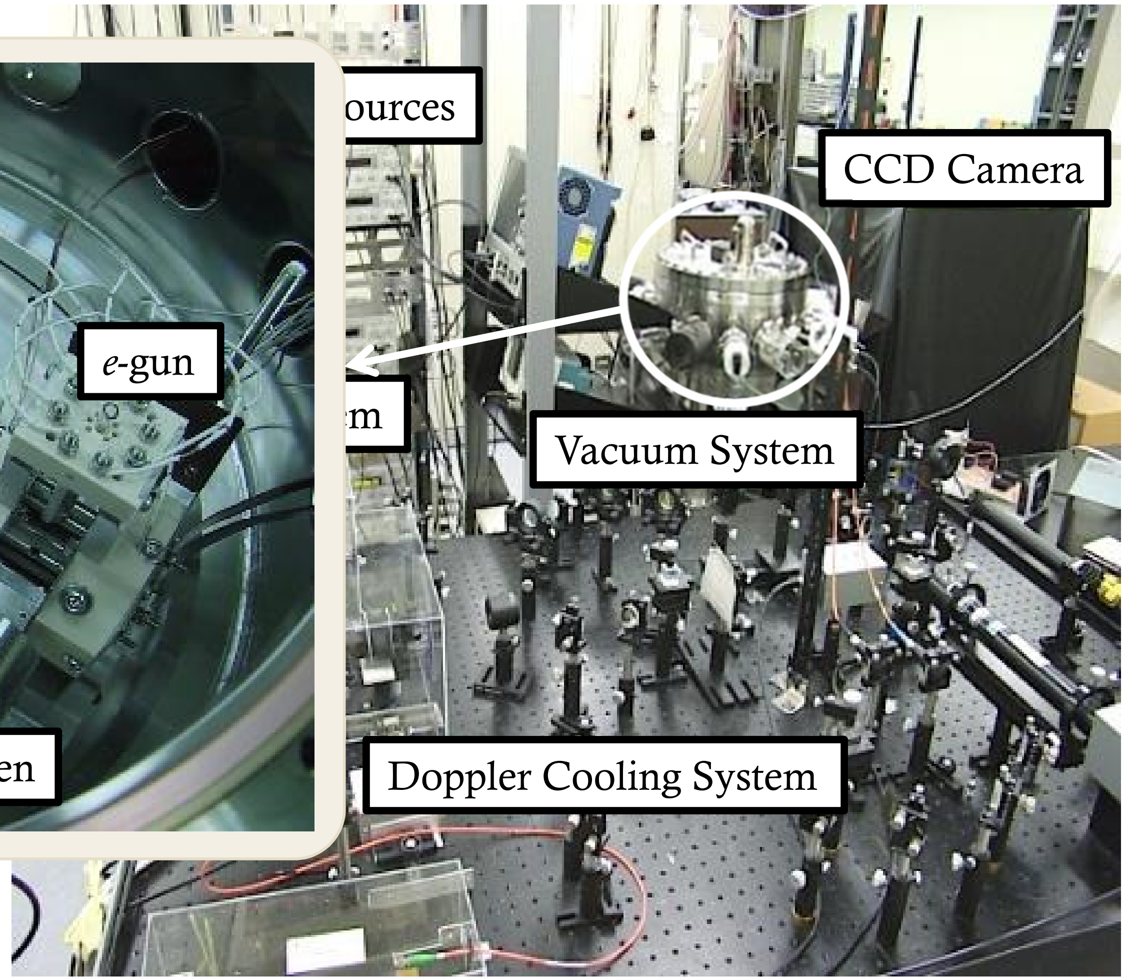

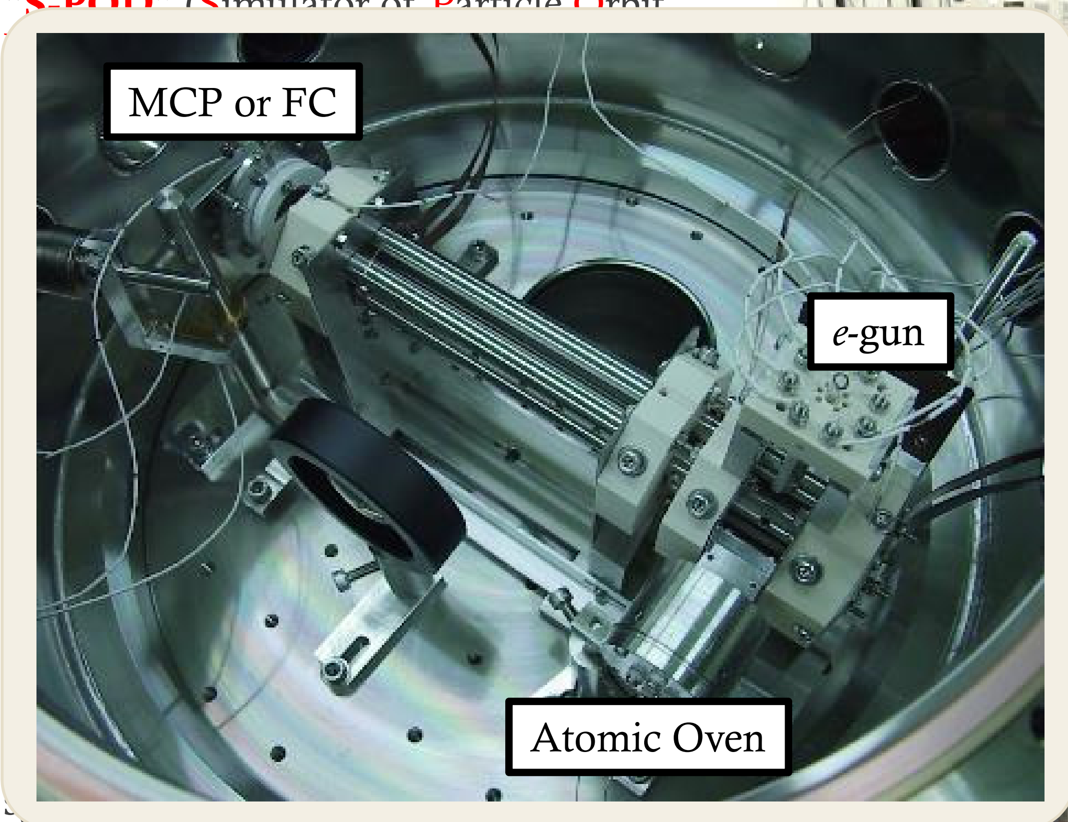

Paul traps and the other two on Penning traps.

How it works…

S-POD experiment is based on an 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:

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

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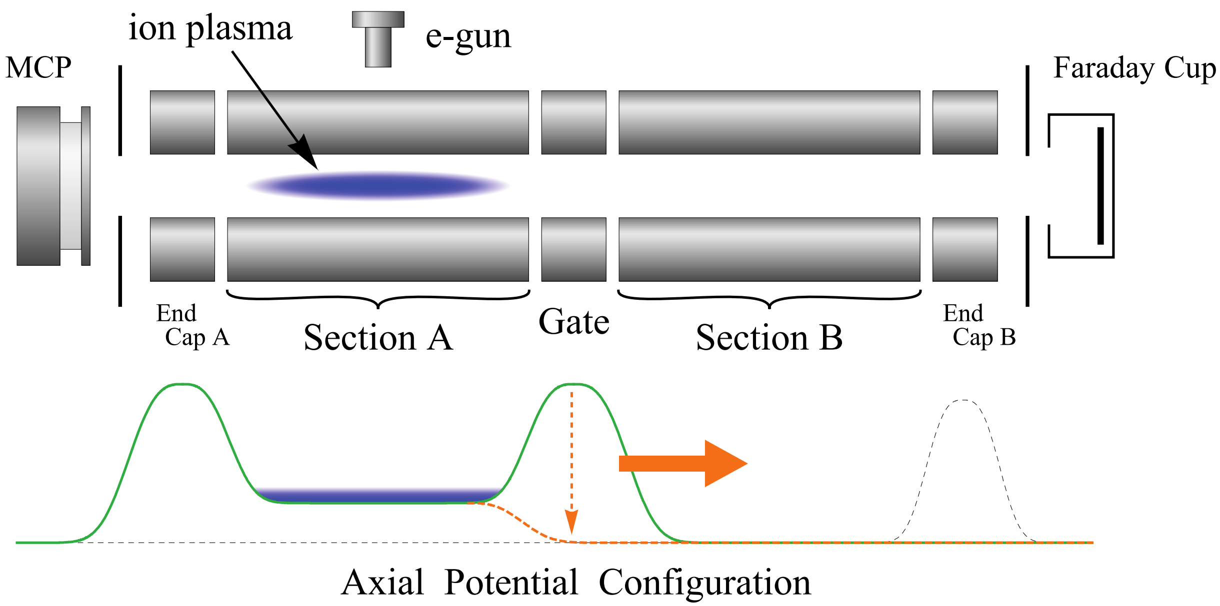


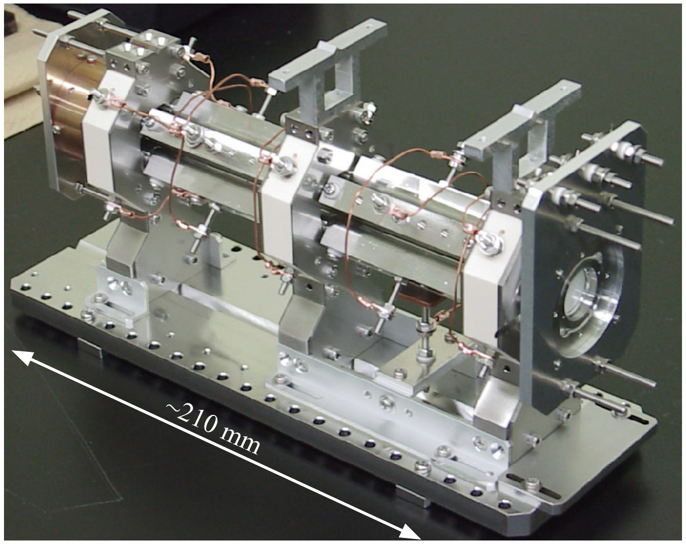
* Operating frequency : 1 MHz

* 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

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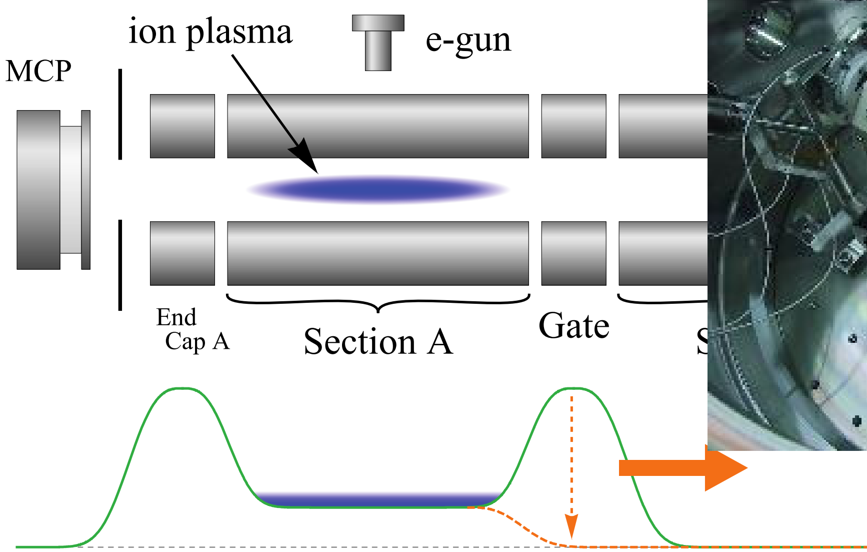

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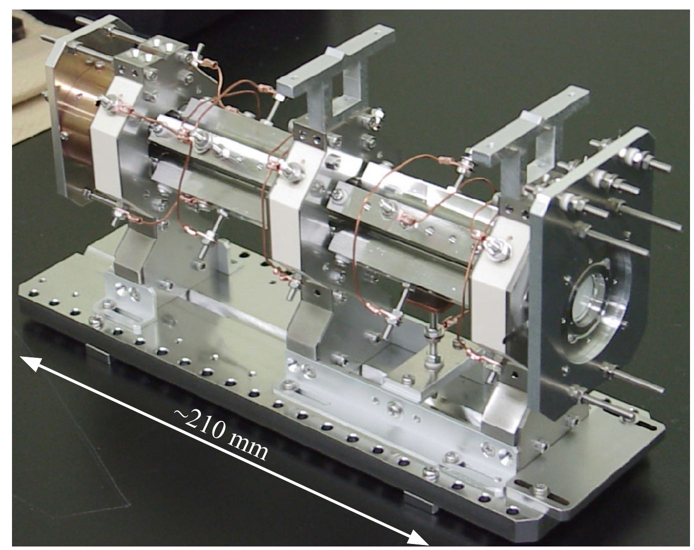

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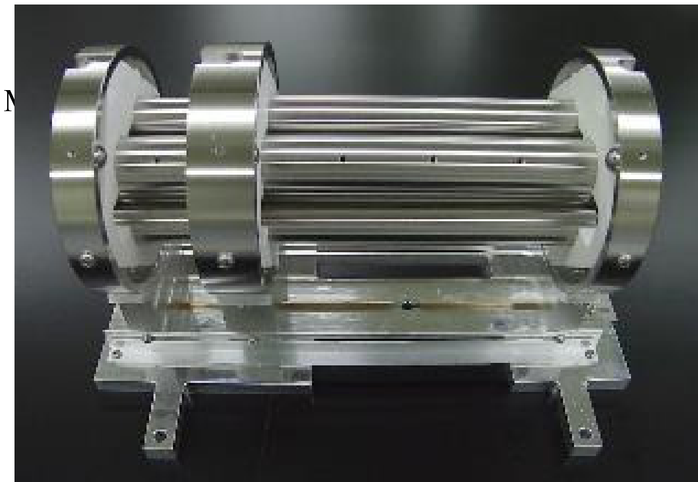

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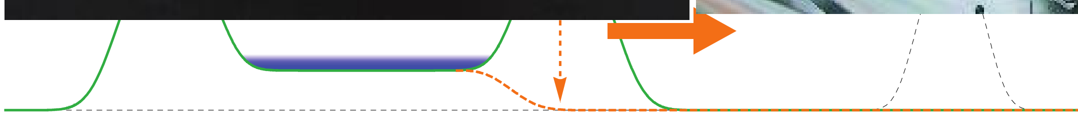

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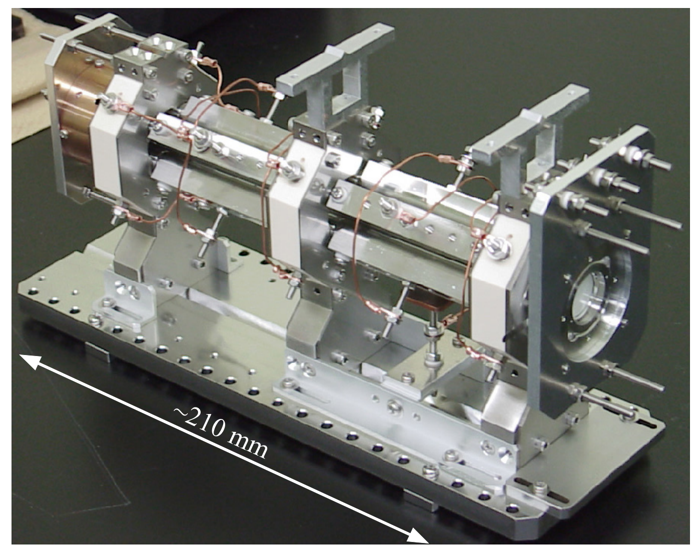

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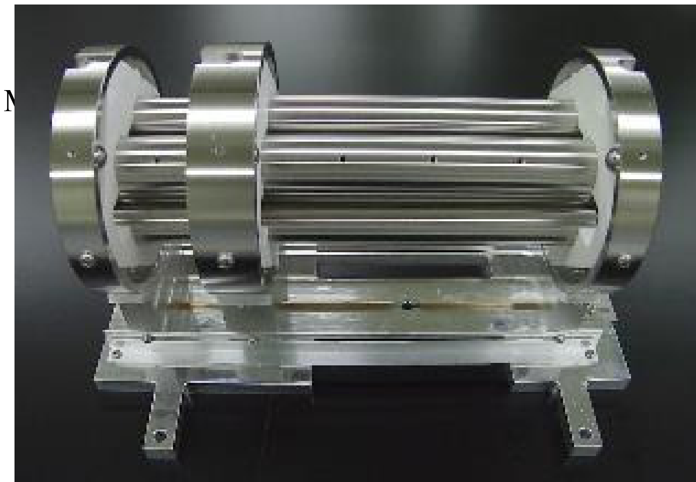

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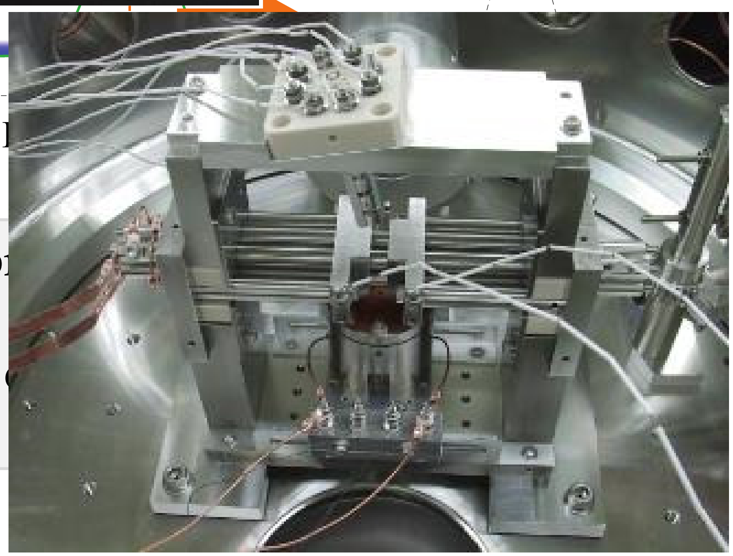

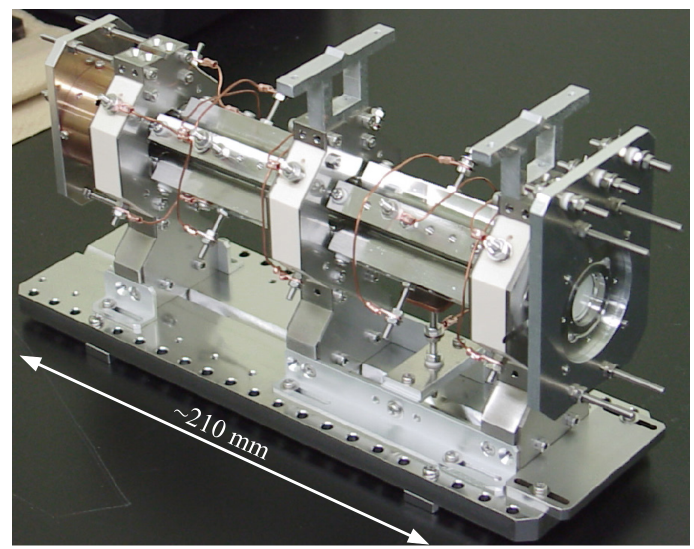

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Longitudinal

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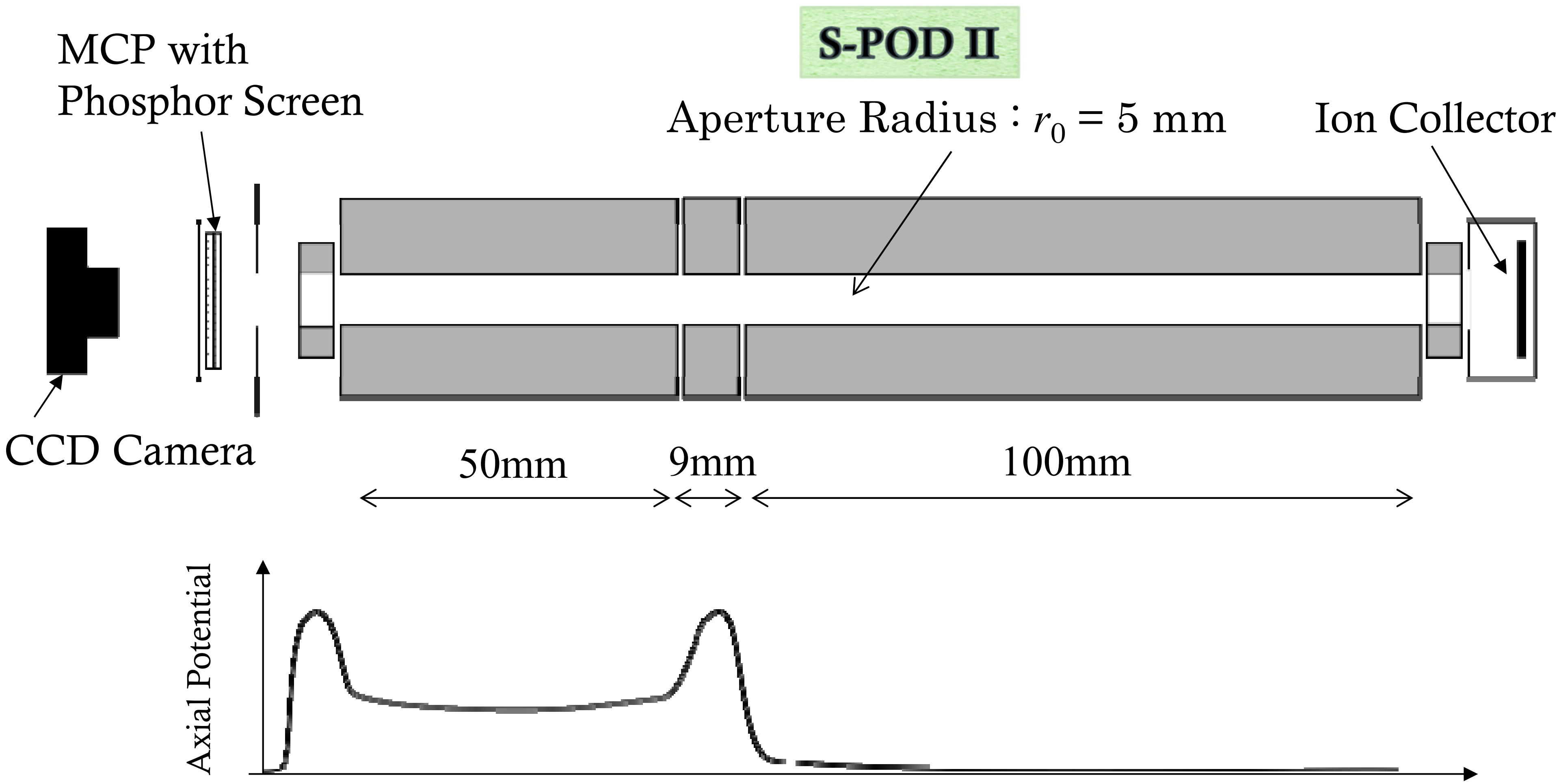

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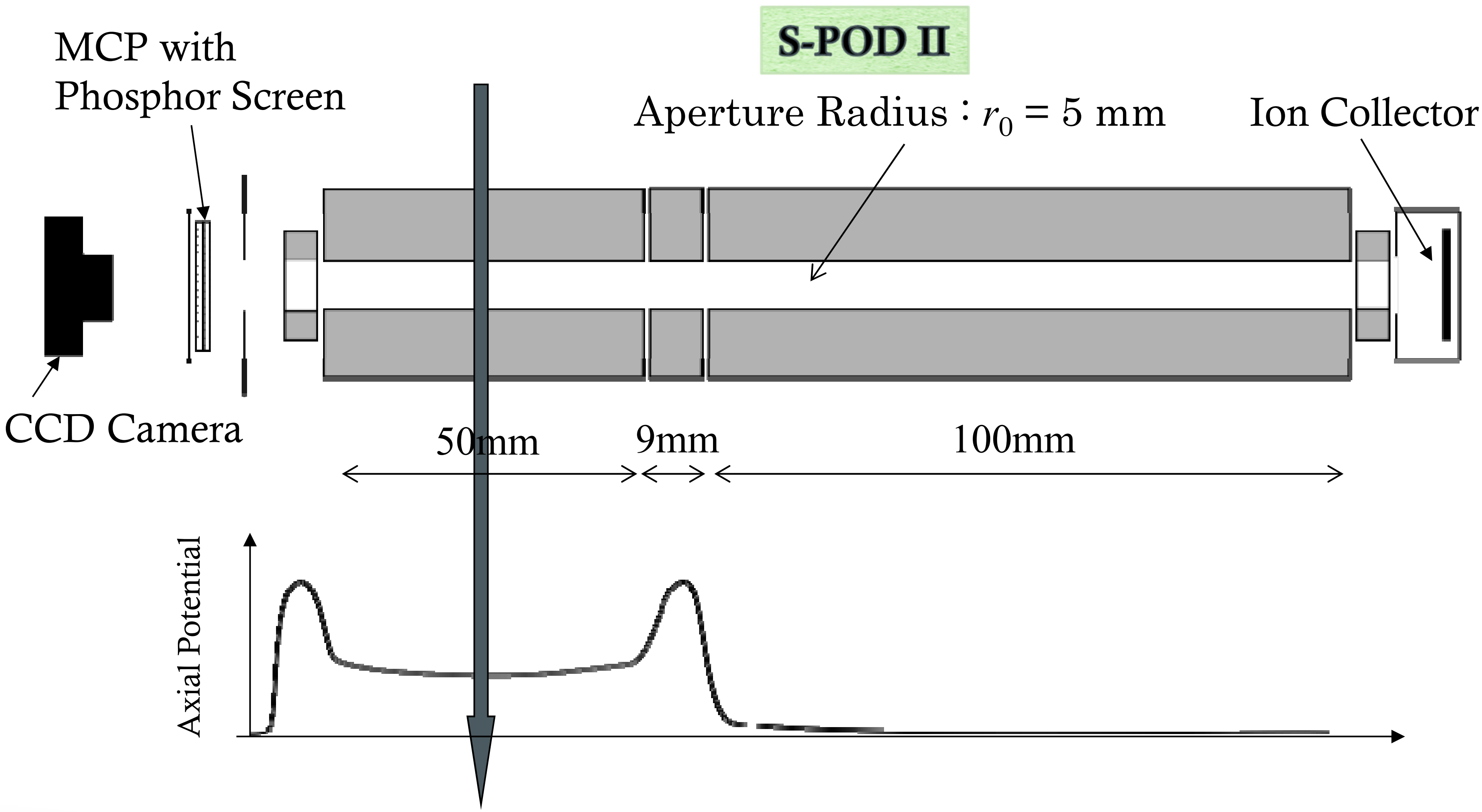

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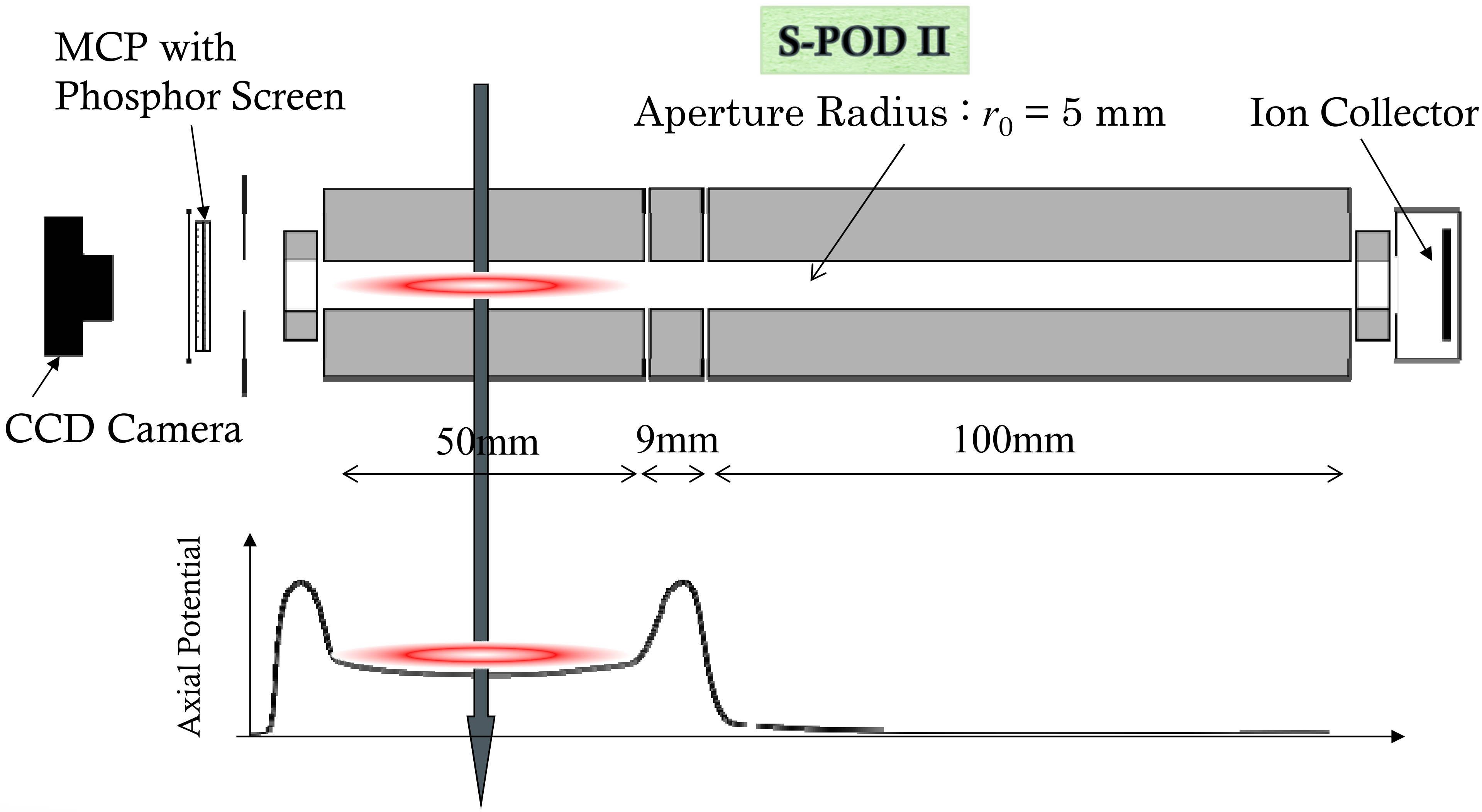

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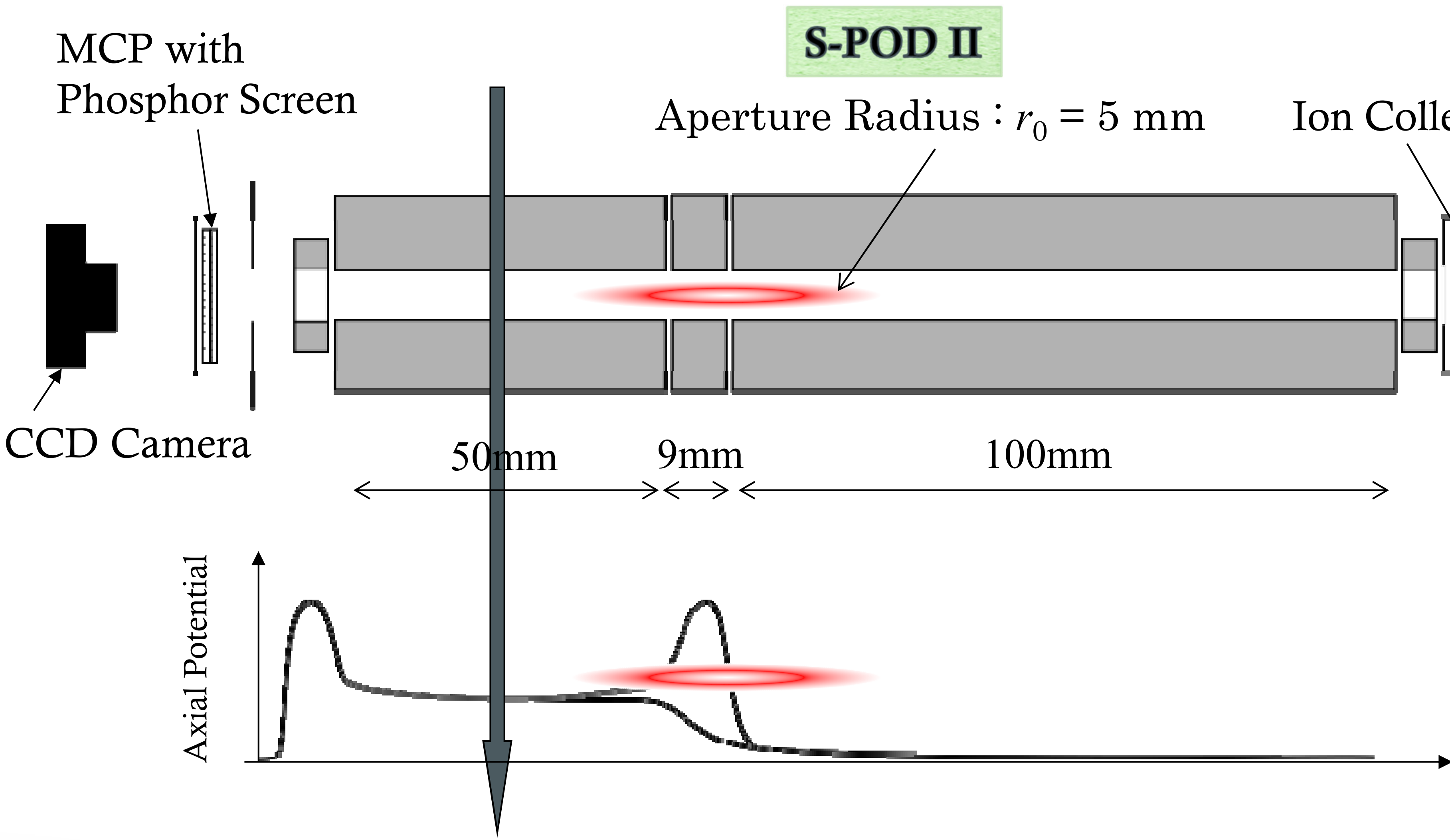

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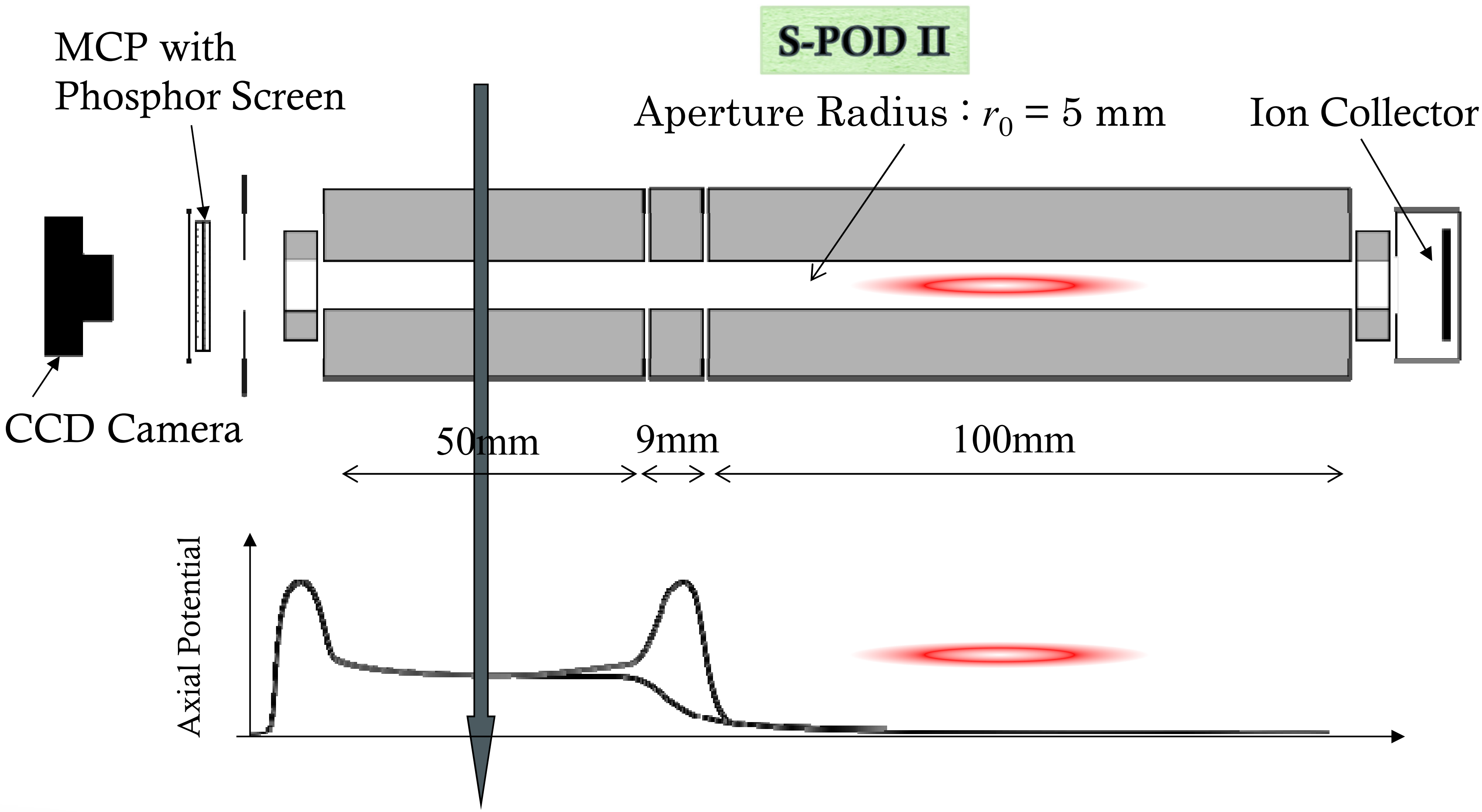

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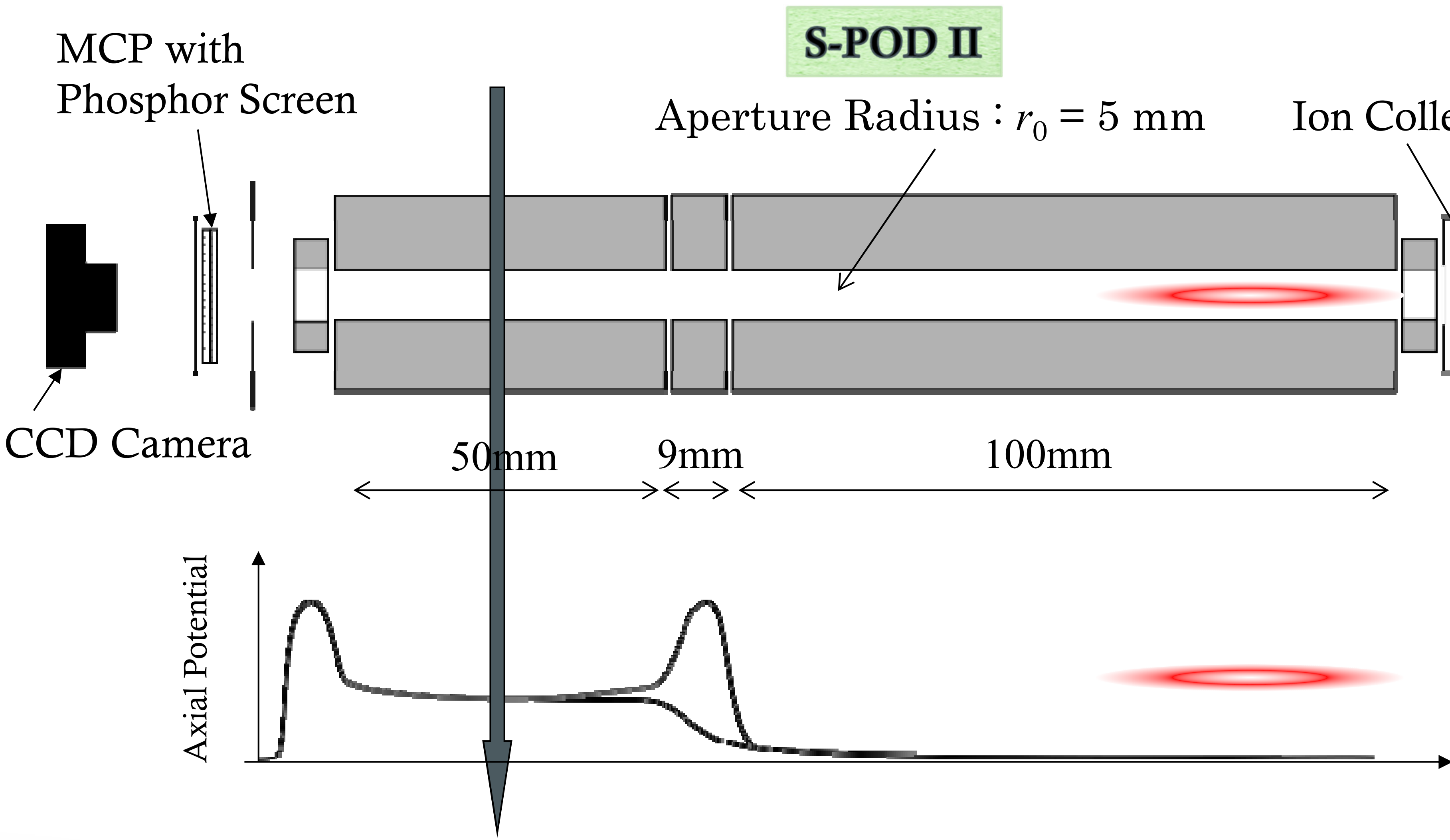
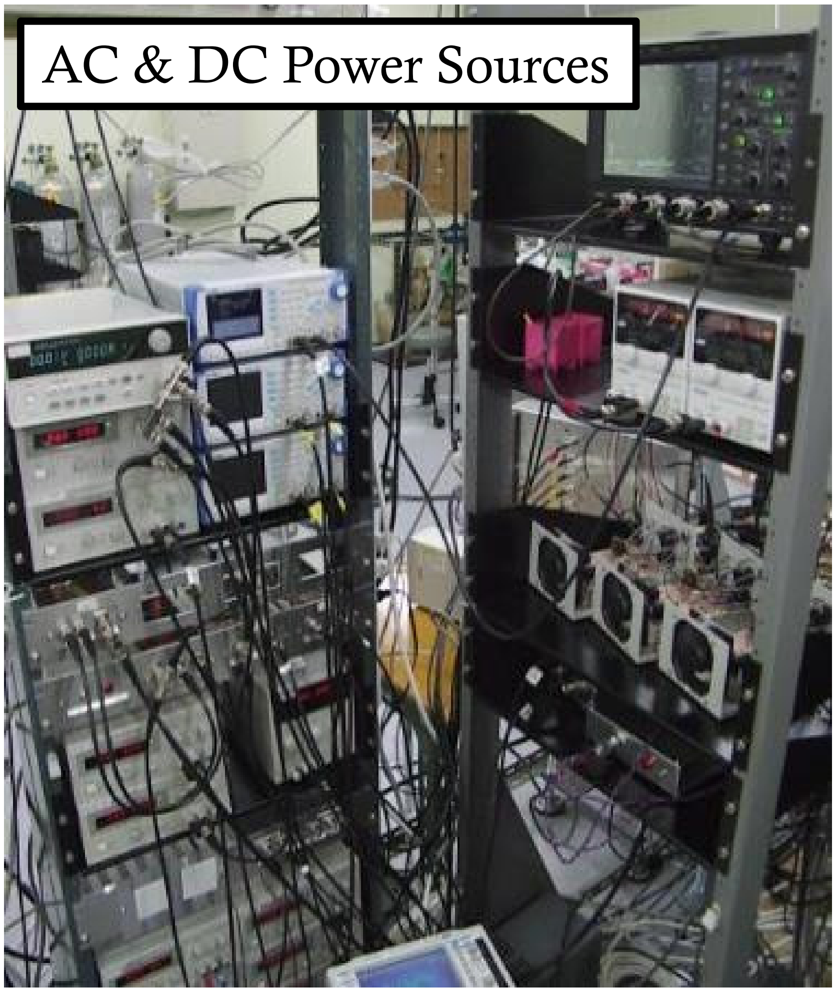
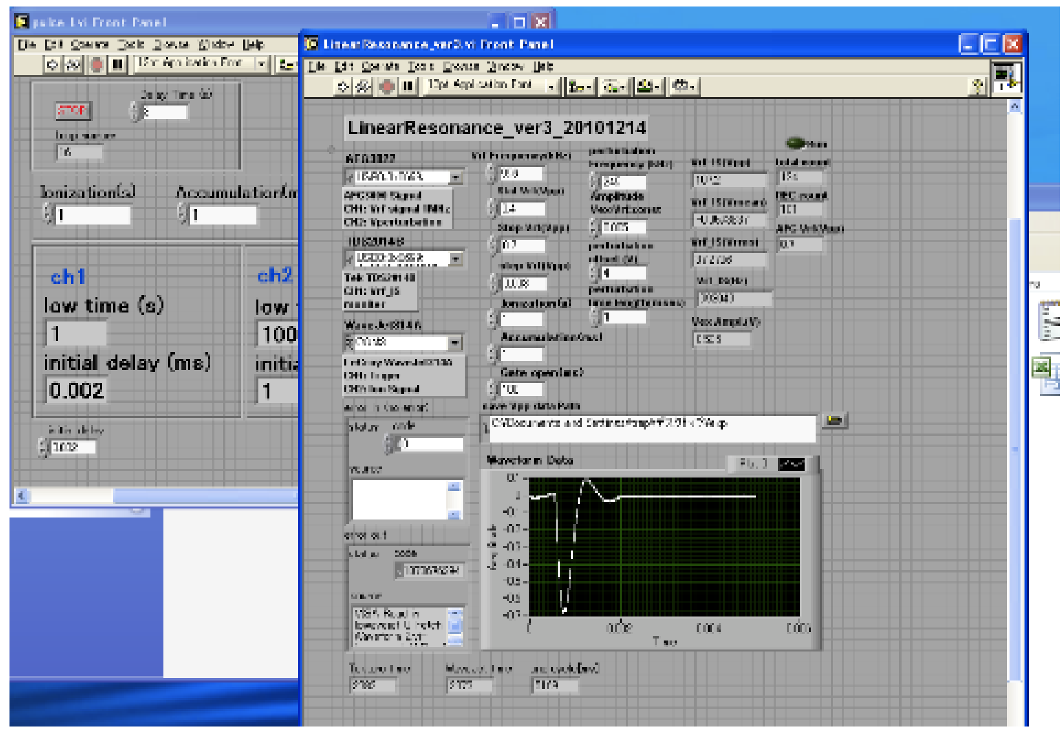


Control System

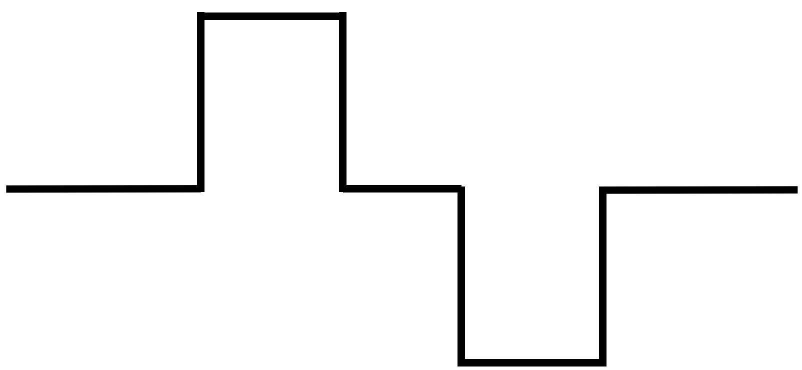


All experimental procedures are automated.



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

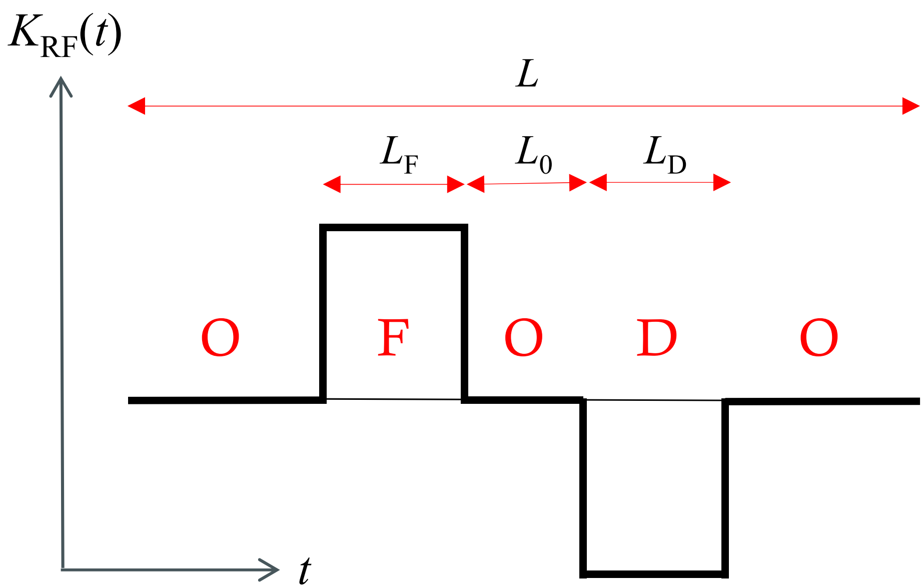
Doublet Focusing



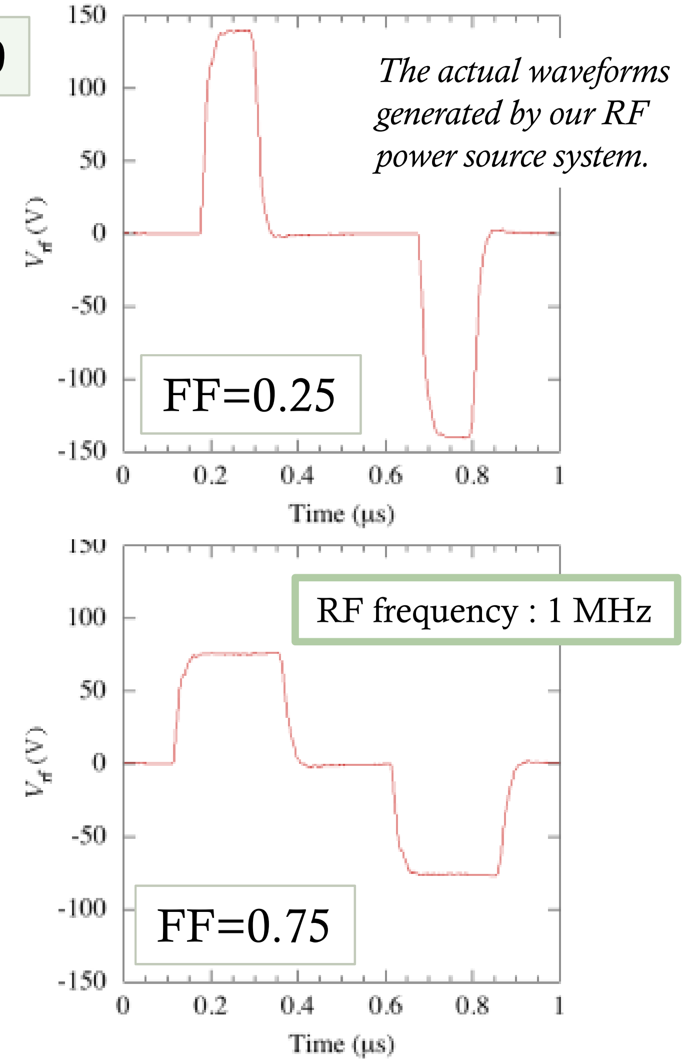
From S-POD II

Doublet Geometry

RF Waveform for Doublet



DR=1.0



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

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

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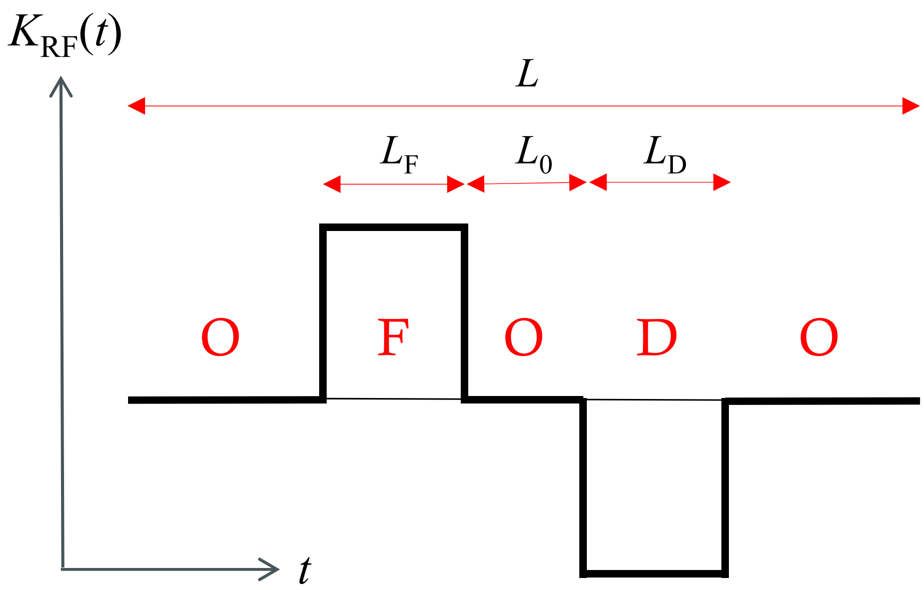

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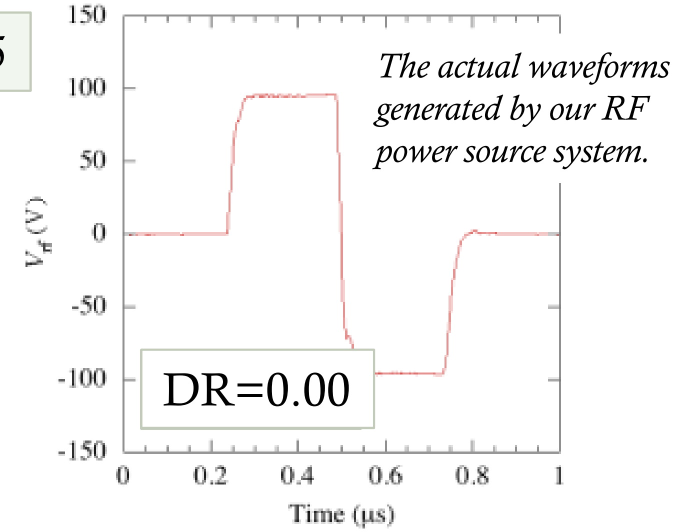
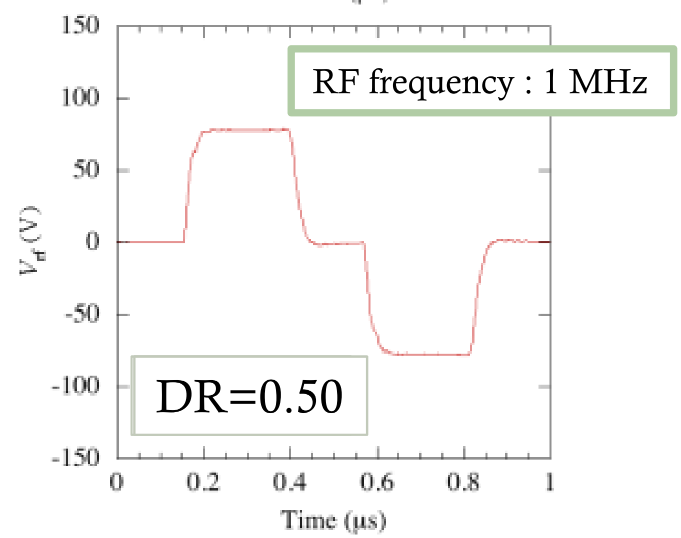




FODO : *intensity dependence*

FF = 0.5 DR = 1.0

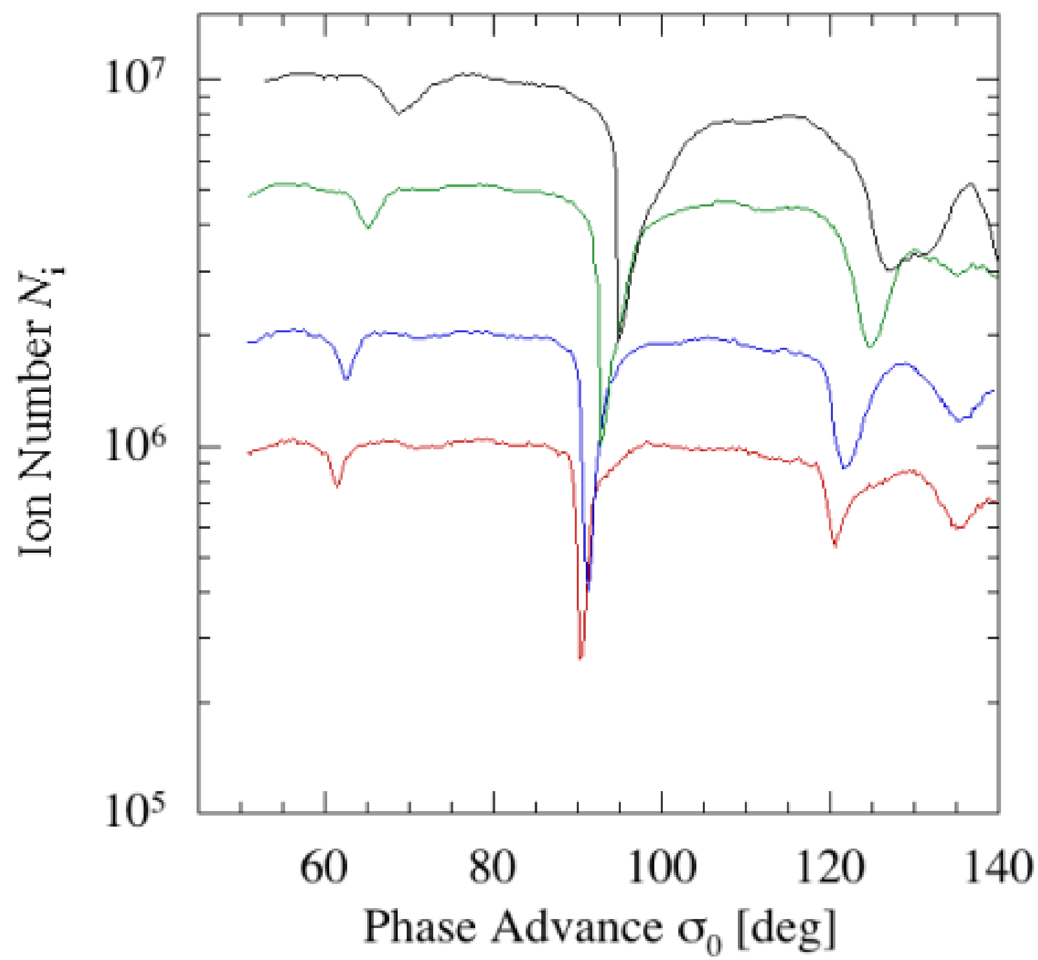
Phase Advance : $\sigma_{0x} = \sigma_{0y}\ (\equiv \sigma_0)$

(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) .]

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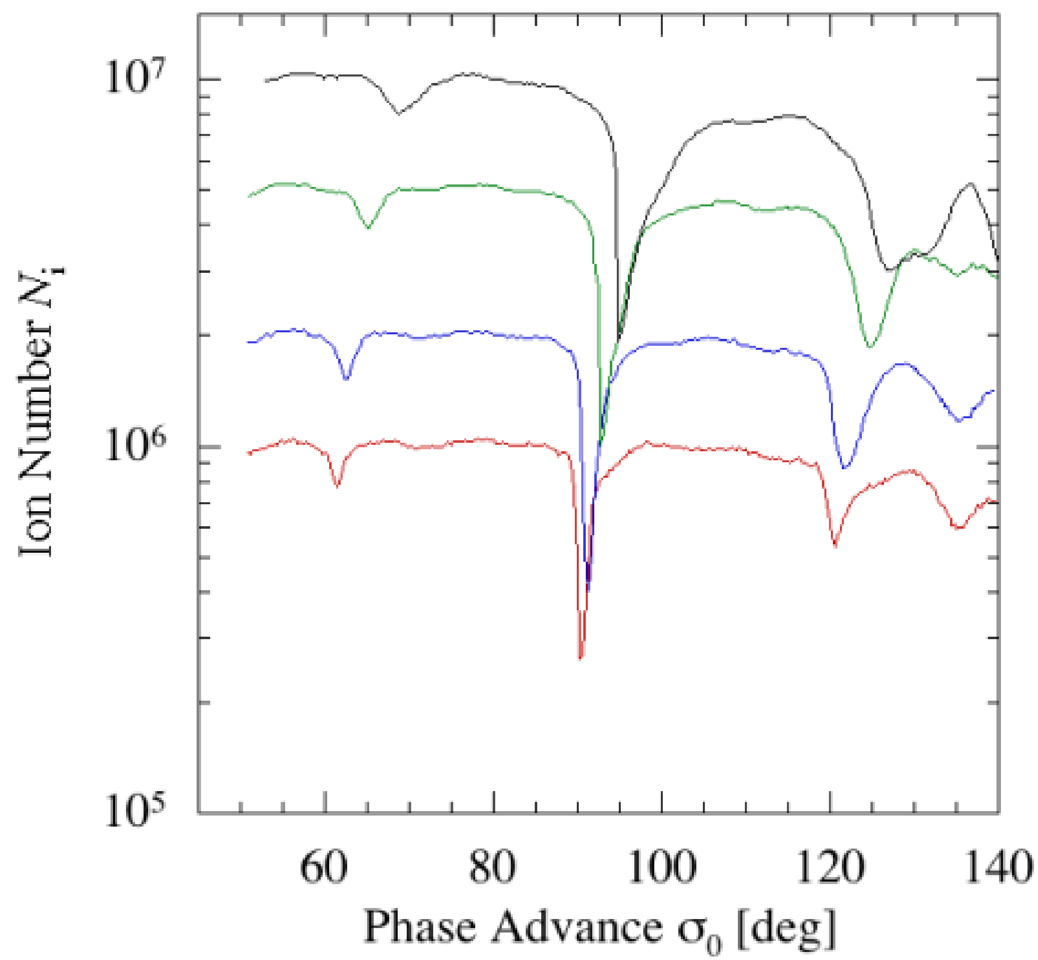
Space-charge-induced tune shift



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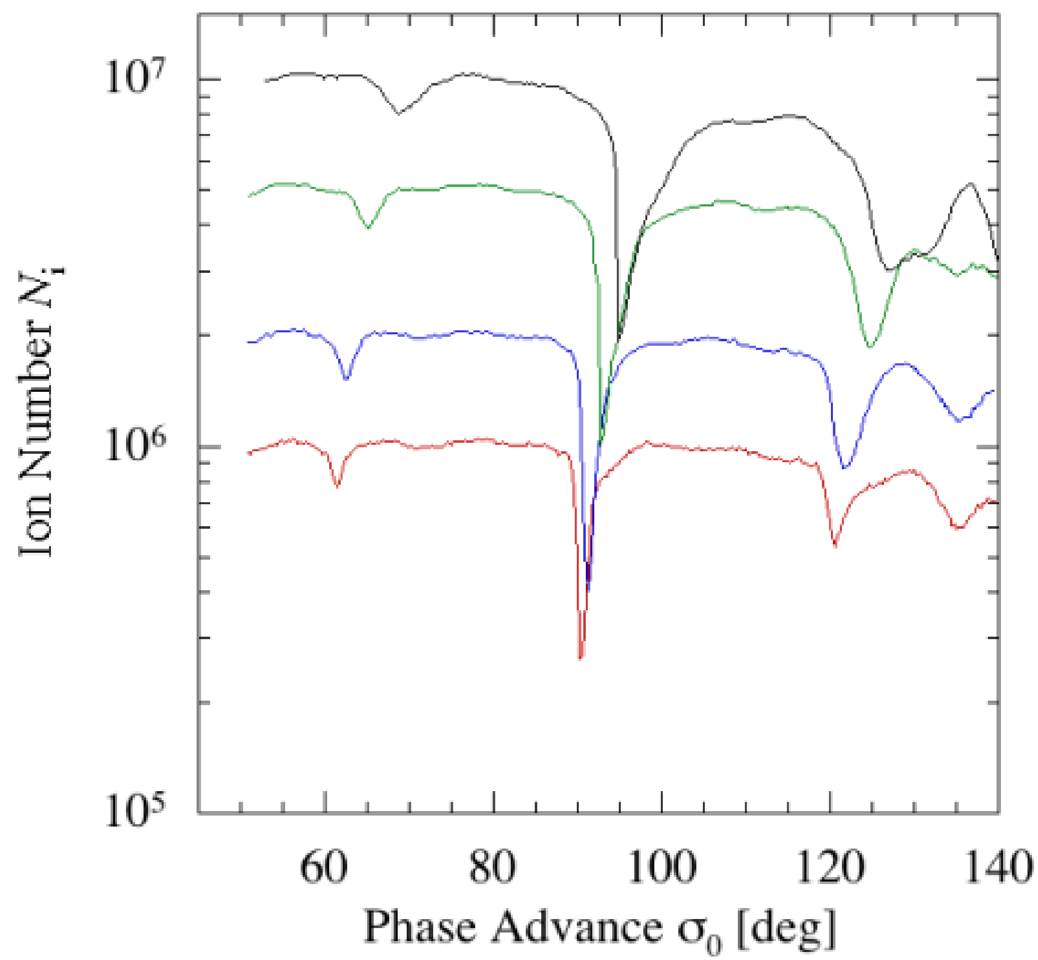
Constant factor < 1



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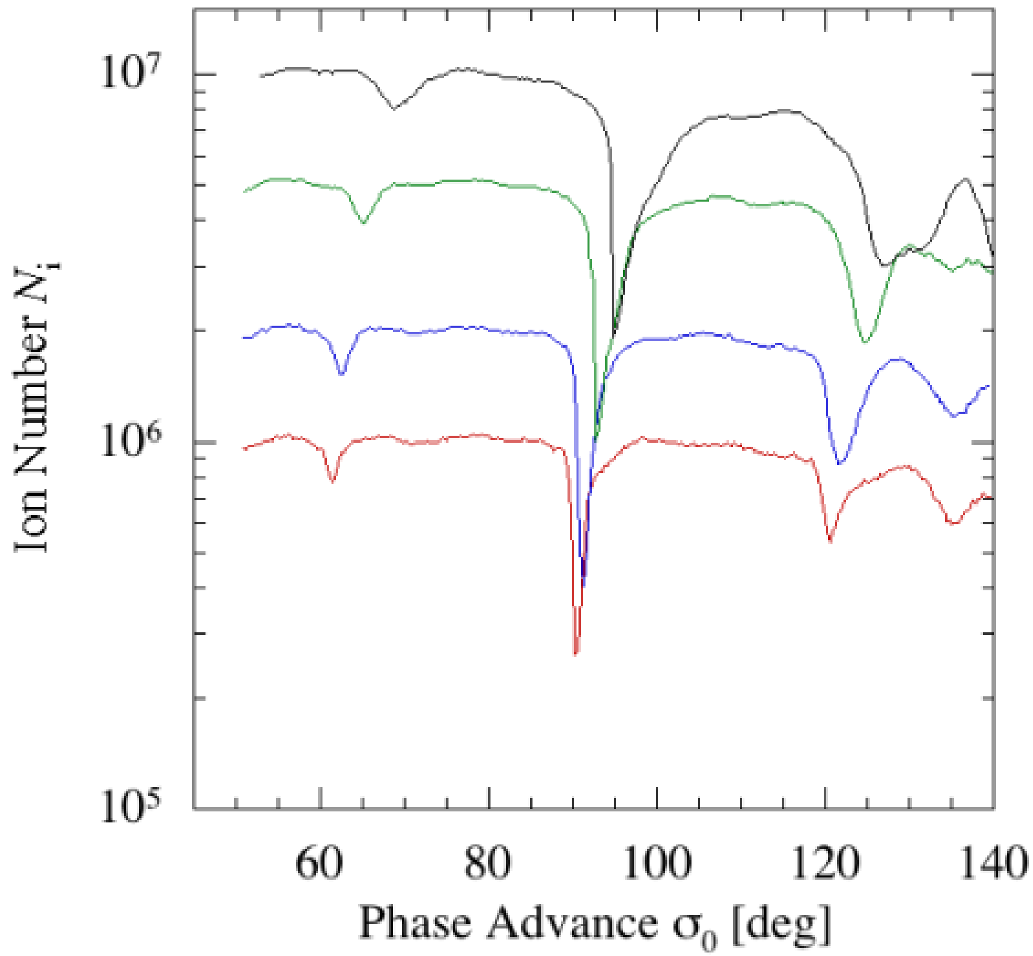
Coherent Resonance Condition

(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 : $\sigma_{0x} = \sigma_{0y}\ (\equiv \sigma_0)$

(symmetric transverse focusing)

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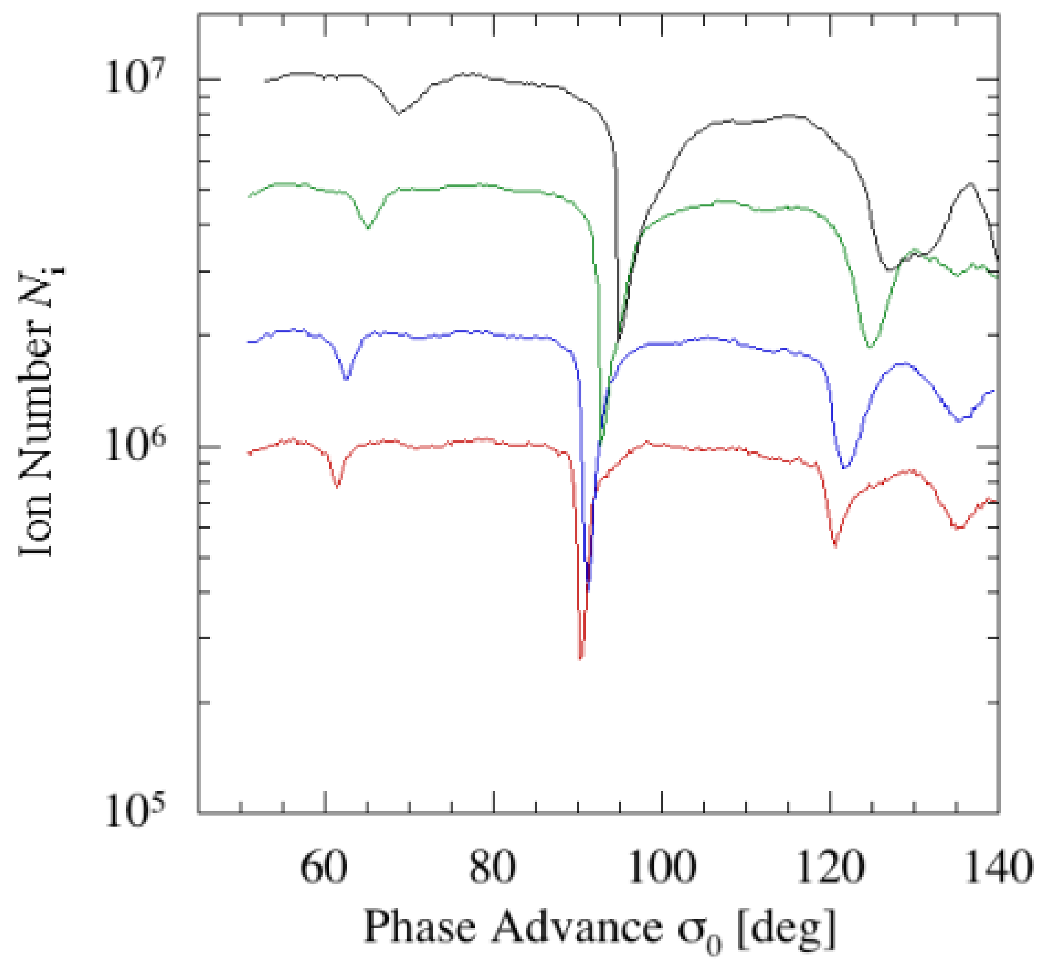
$m = 2$: quadrupole

$m = 3$: sextupole

.....

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



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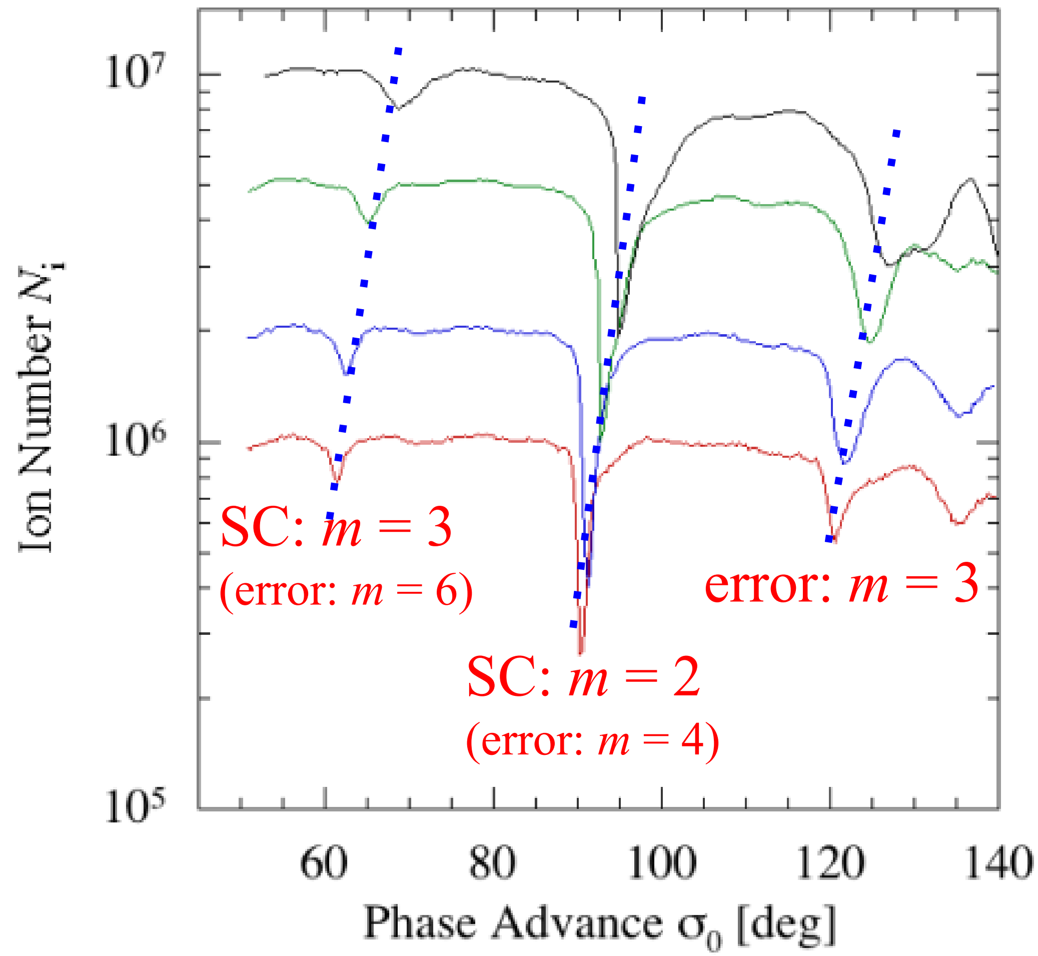
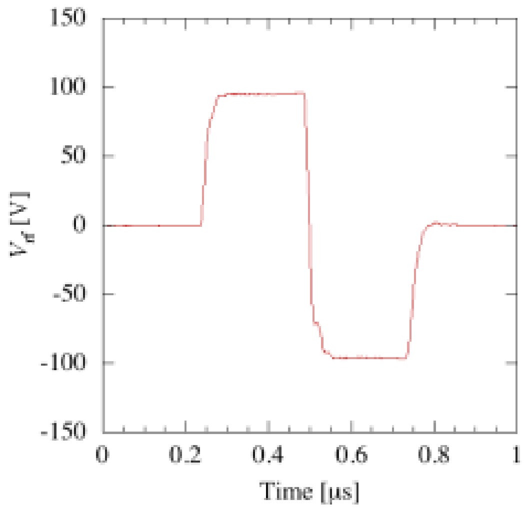


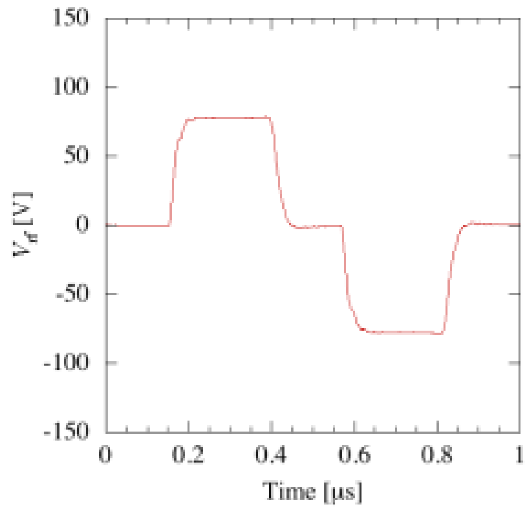
Doublet : *geometry dependence*

FF = 0.5

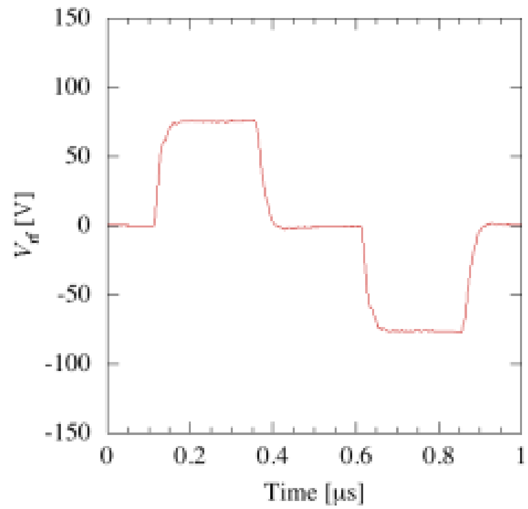
DR = 0



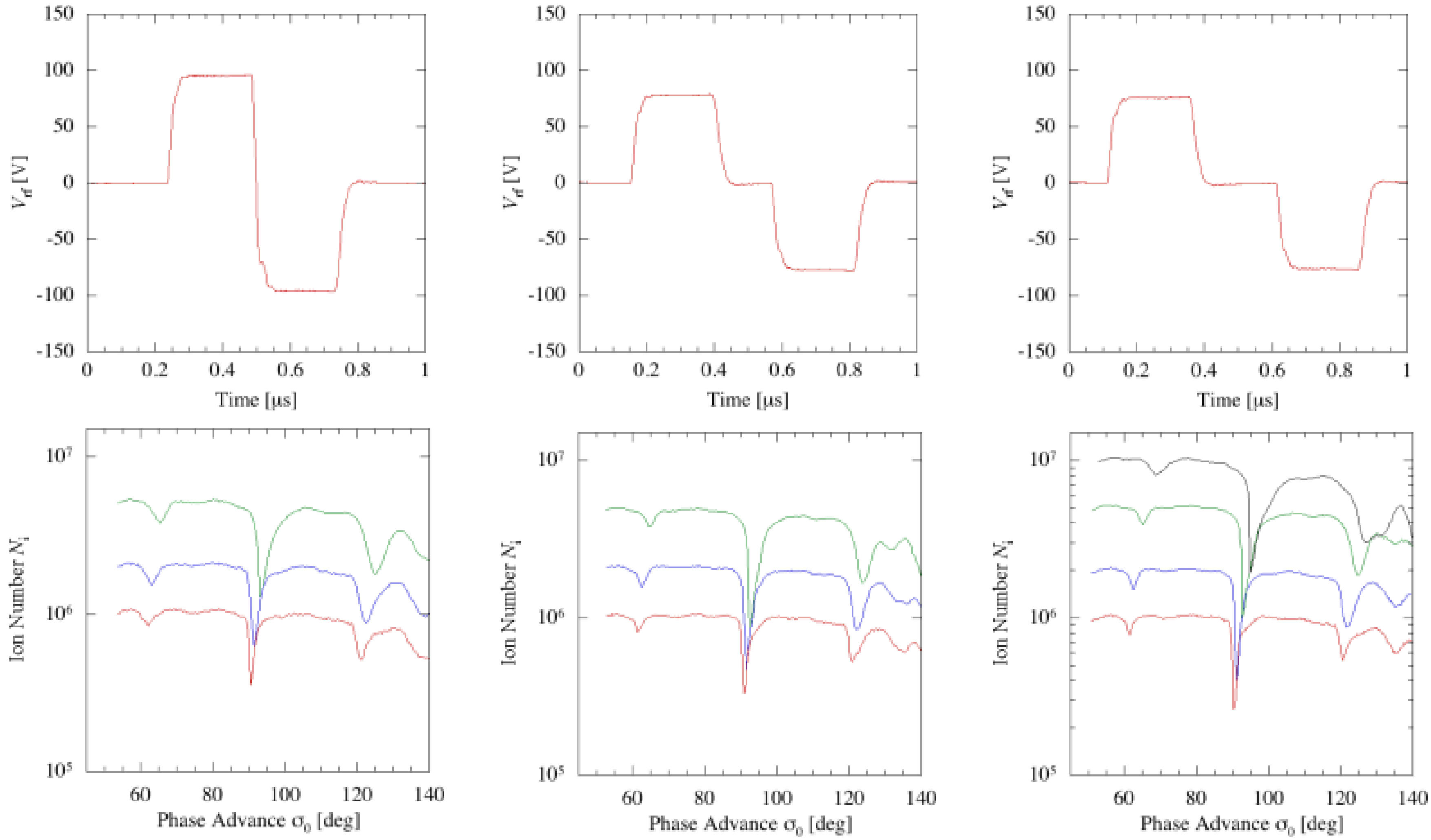
DR = 0.5



DR = 1.0



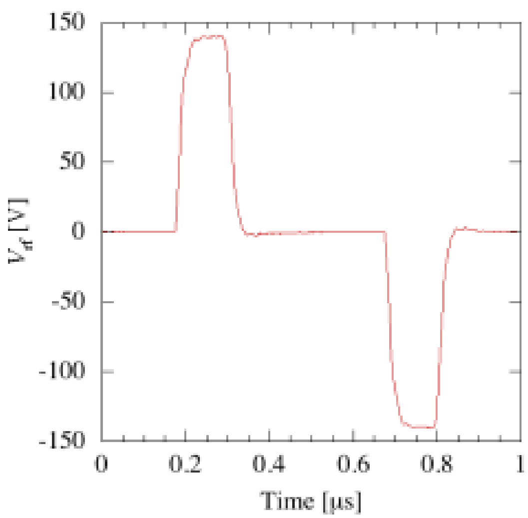
Doublet : *geometry dependence*



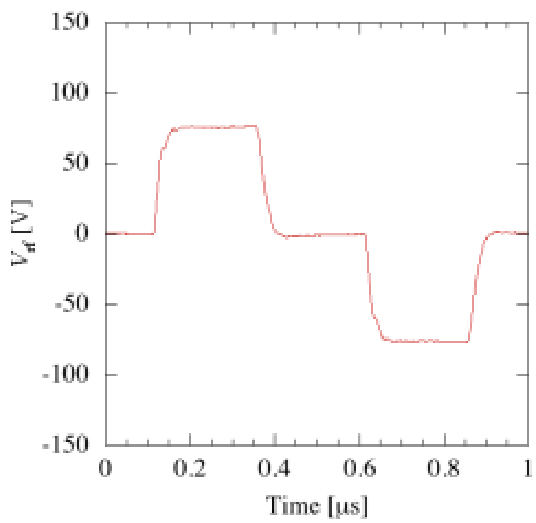
Doublet : *geometry dependence*

DR = 1.0

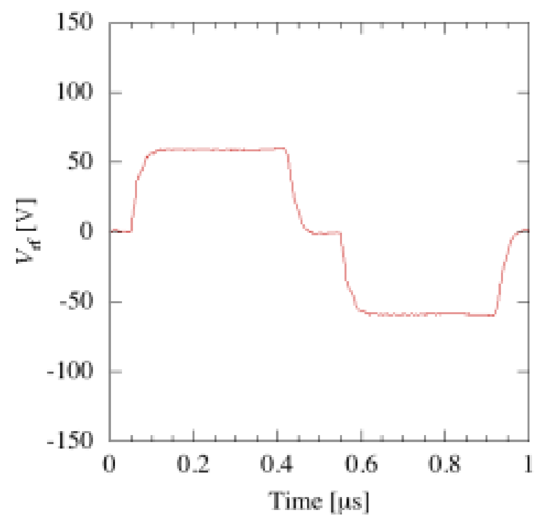
FF = 0.25



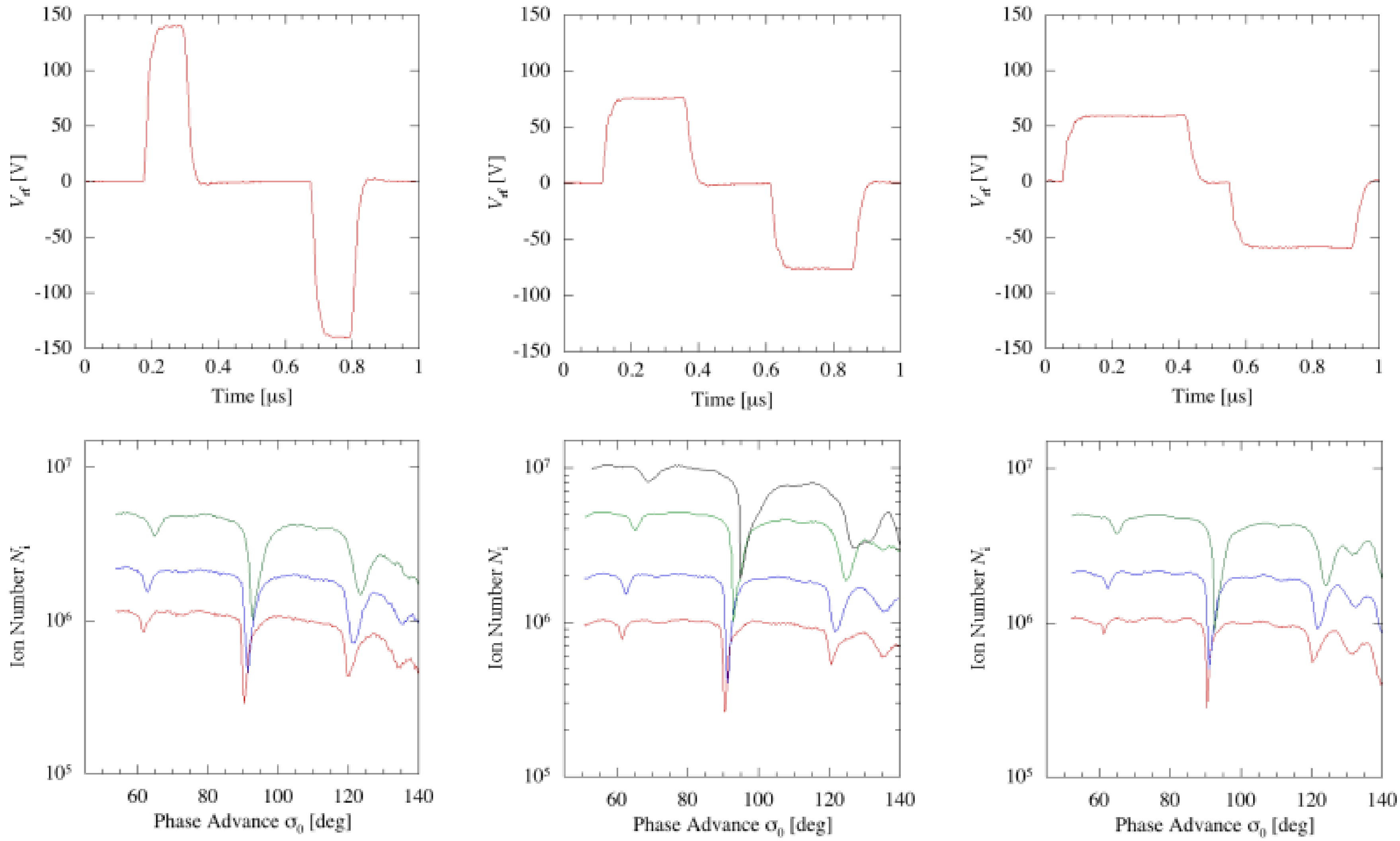
FF = 0.5



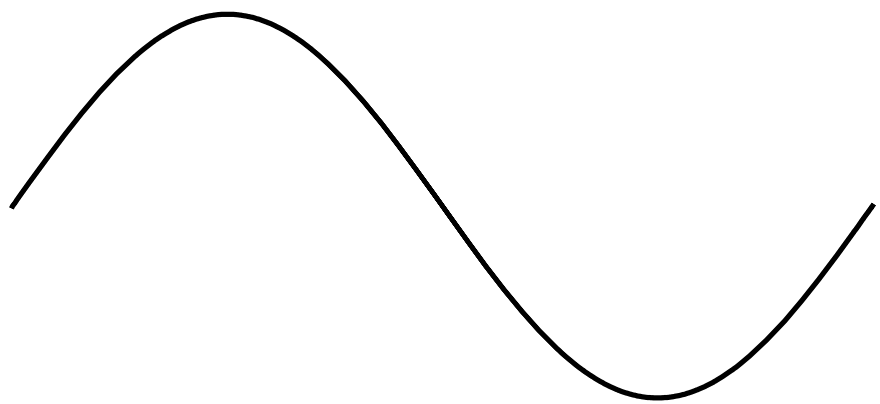
FF = 0.75



Doublet : *geometry dependence*

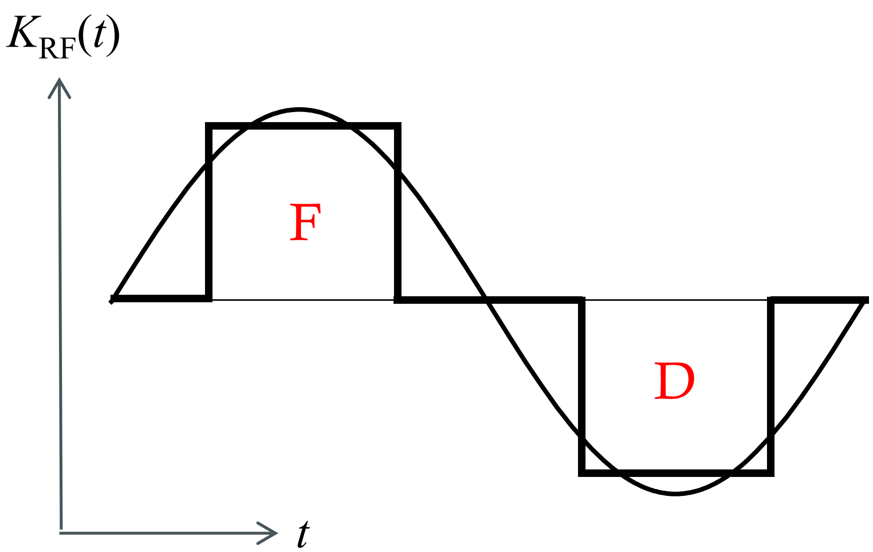


Sinusoidal Focusing



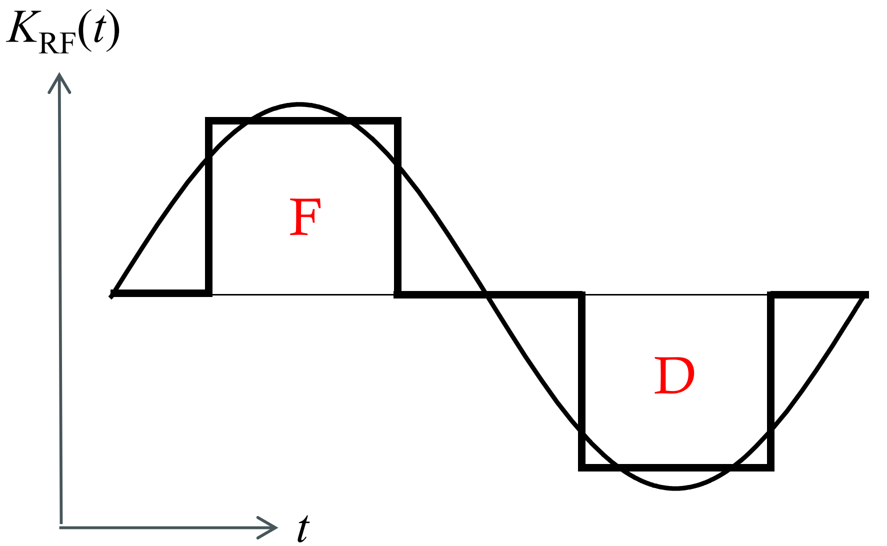
From S-POD III

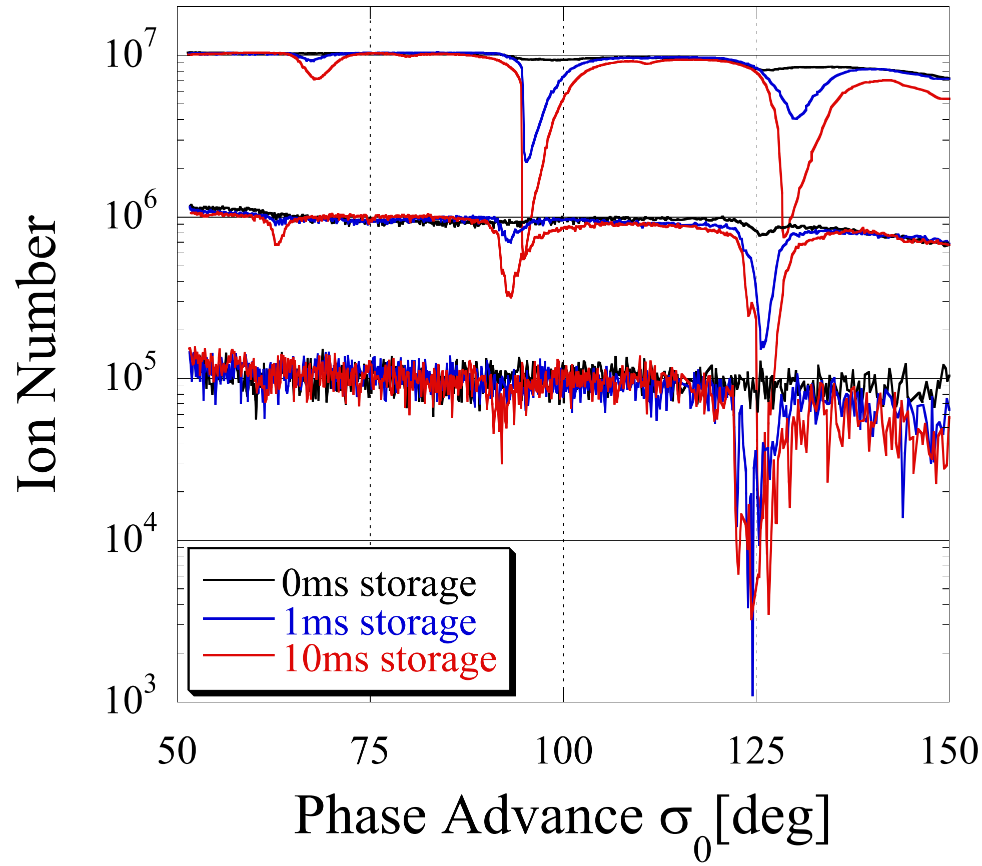
Stop Bands



- We reasonably expect the stop band distribution similar to that of doublet (because sinusoidal focusing is obviously close to FODO focusing).
- In fact, the 2D Vlasov theory predicts almost identical stop band distributions for FODO and sinusoidal focusing.

Stop Bands





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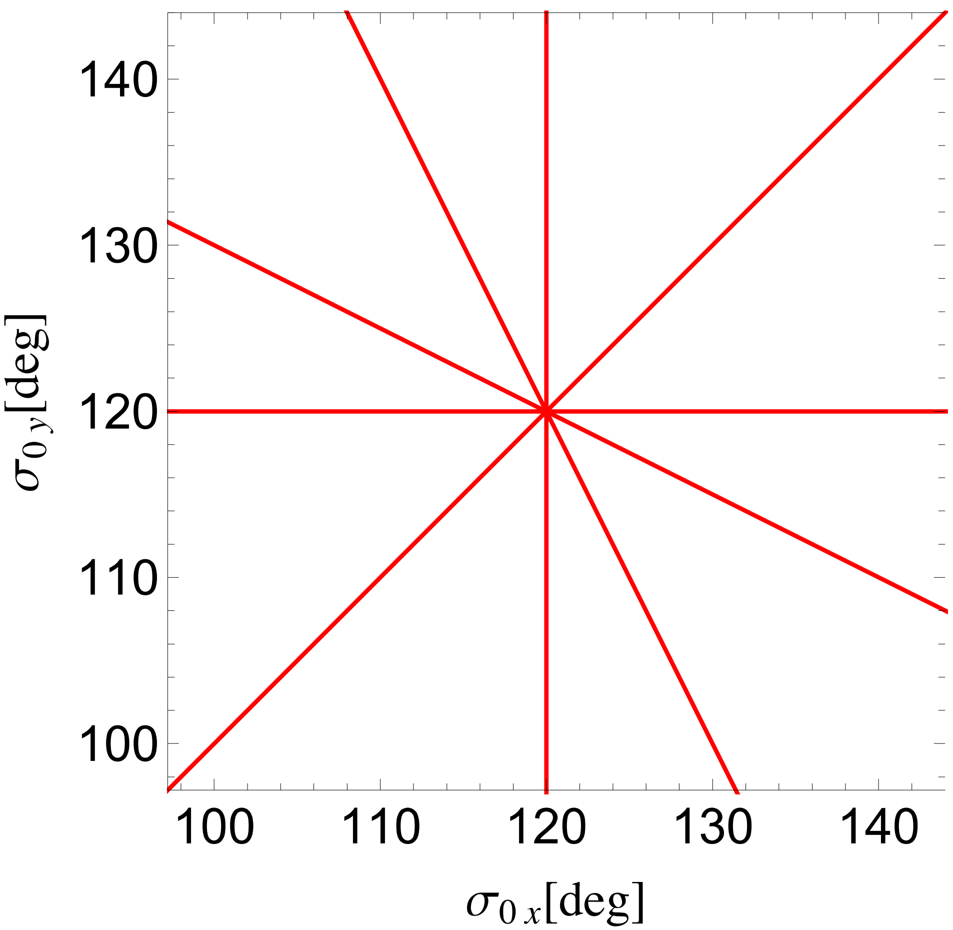
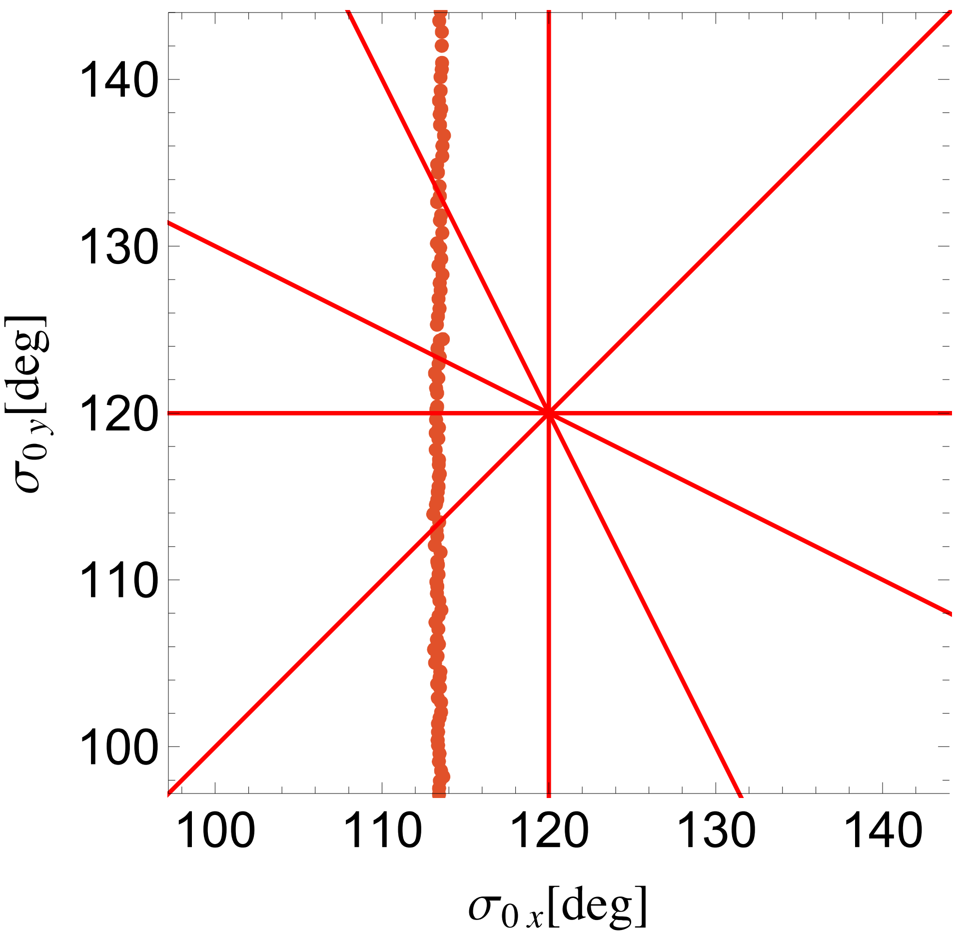
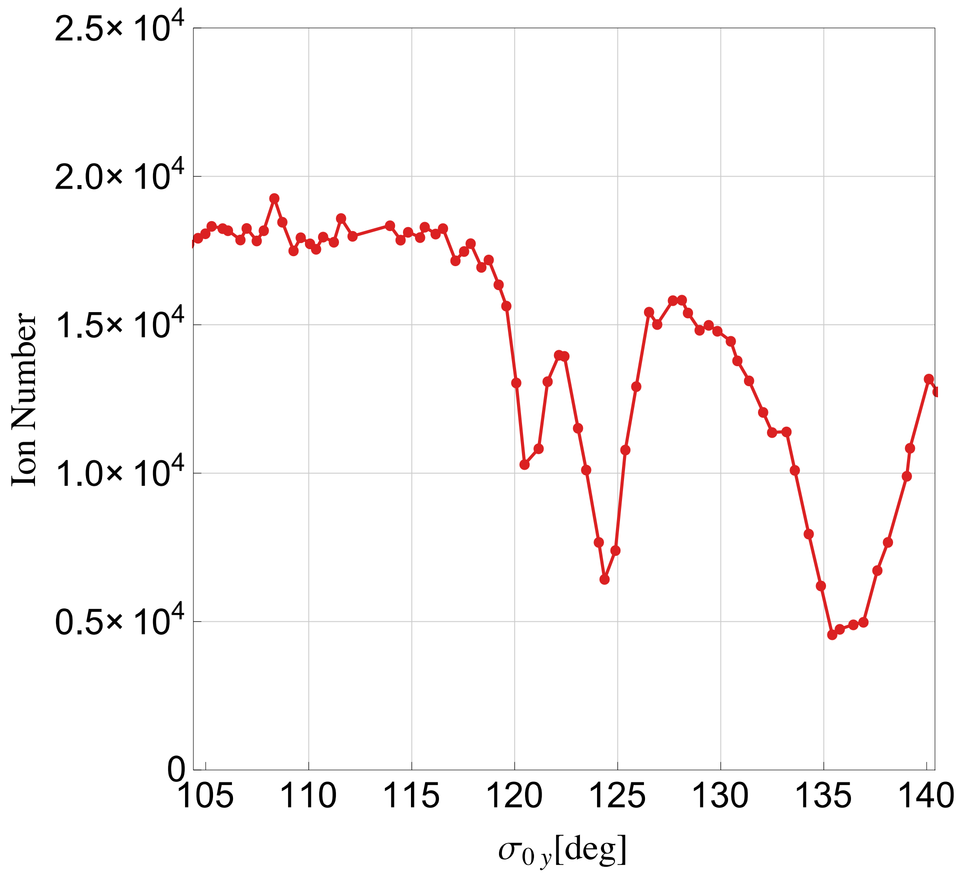
Coupling Resonance

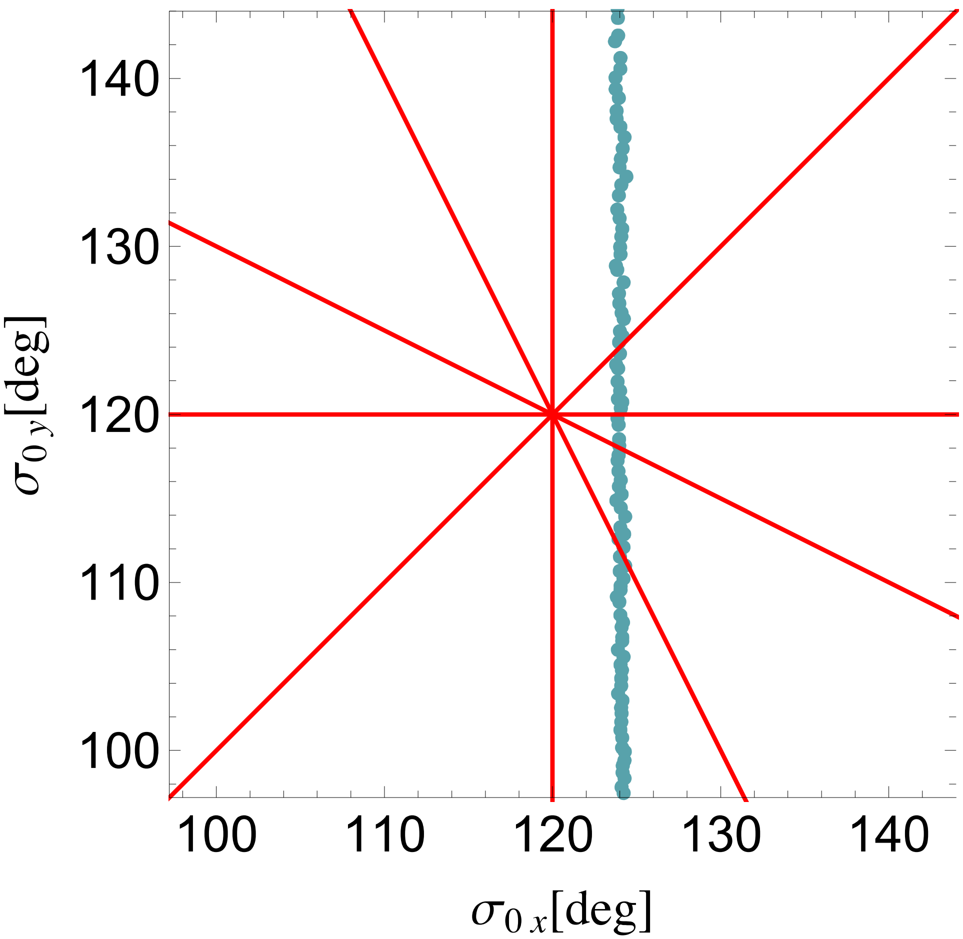


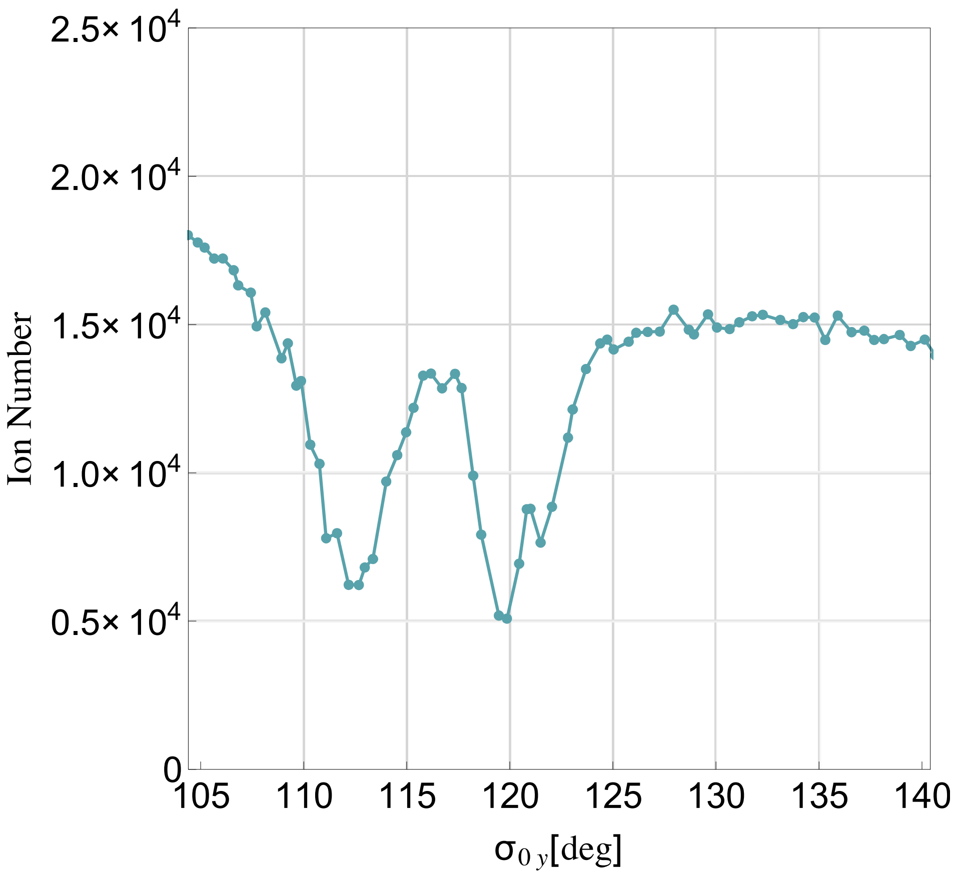
Coupling Resonance



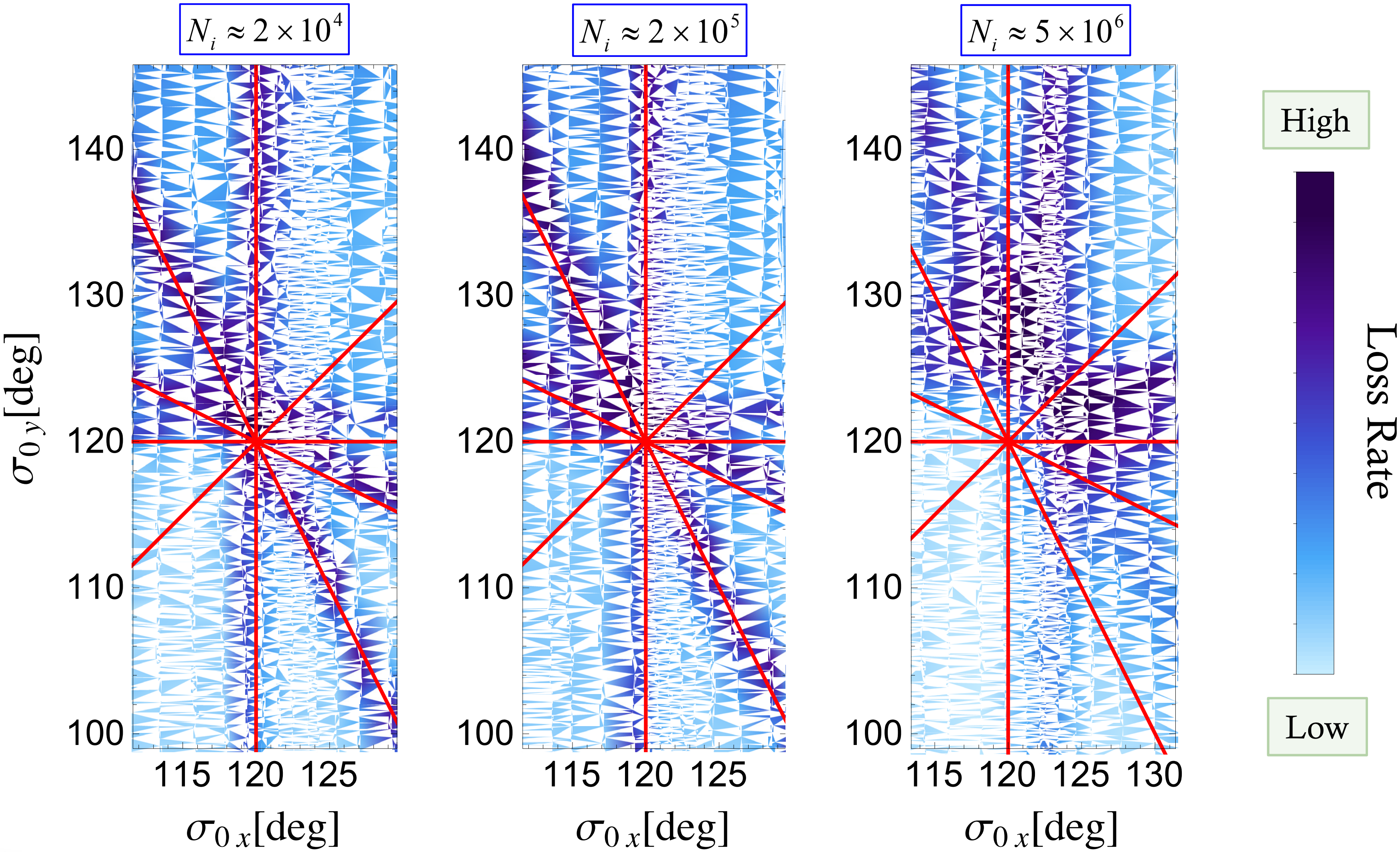


Coupling Resonance

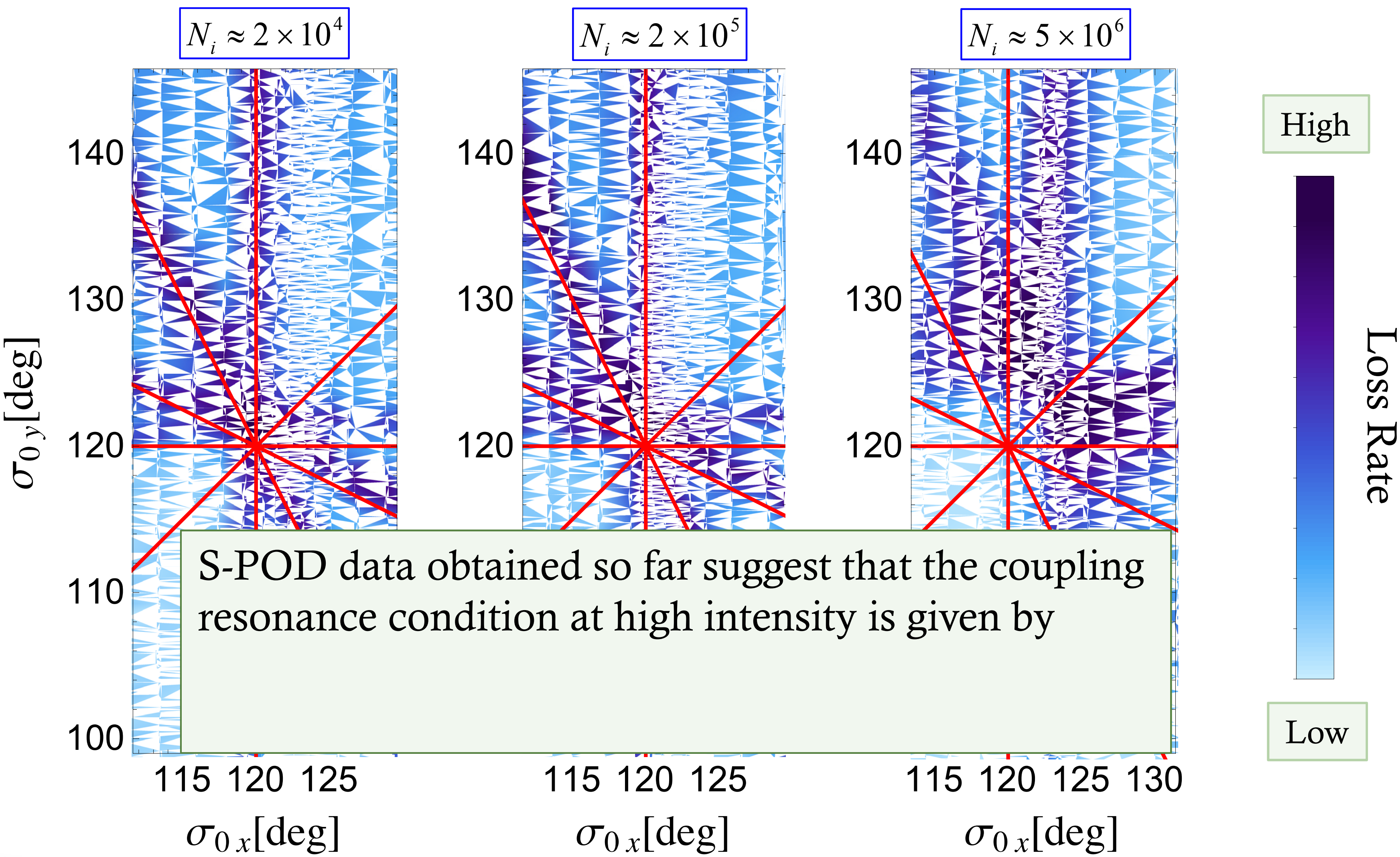




Tune Diagram

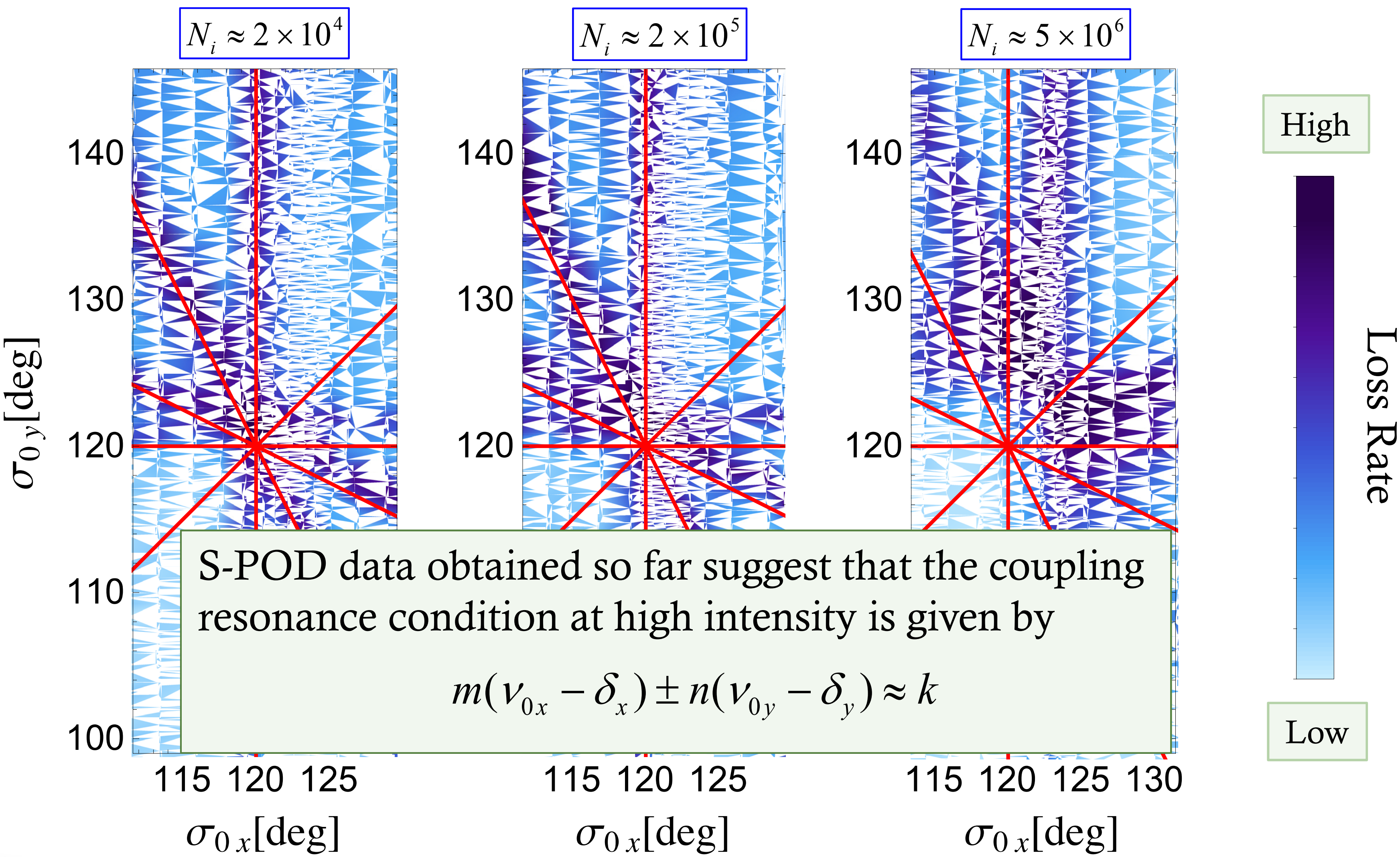


Tune Diagram



S-POD data obtained so far suggest that the coupling resonance condition at high intensity is given by

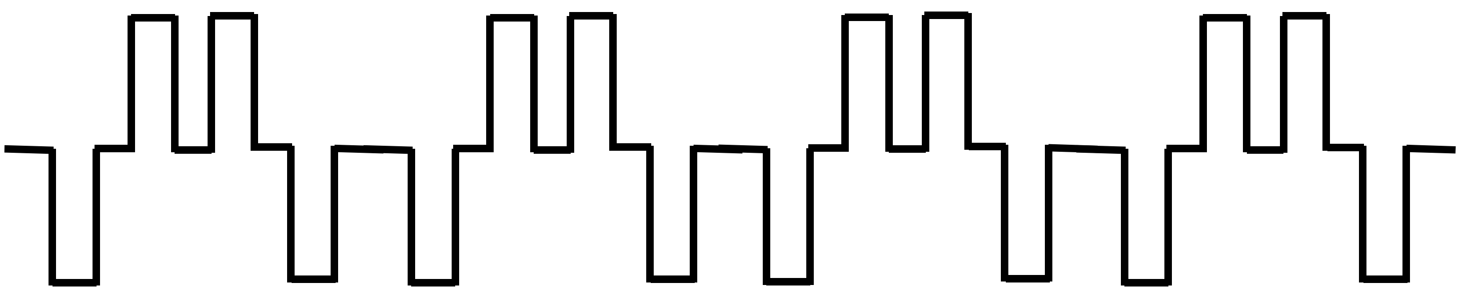
Tune Diagram



S-POD data obtained so far suggest that the coupling resonance condition at high intensity is given by

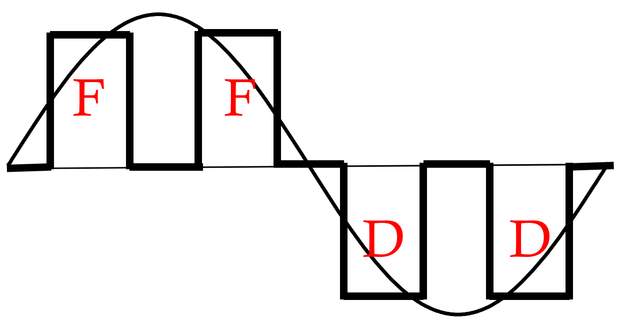
$$m(\nu_{0x}-\delta_x)\pm n(\nu_{0y}-\delta_y)\approx k$$

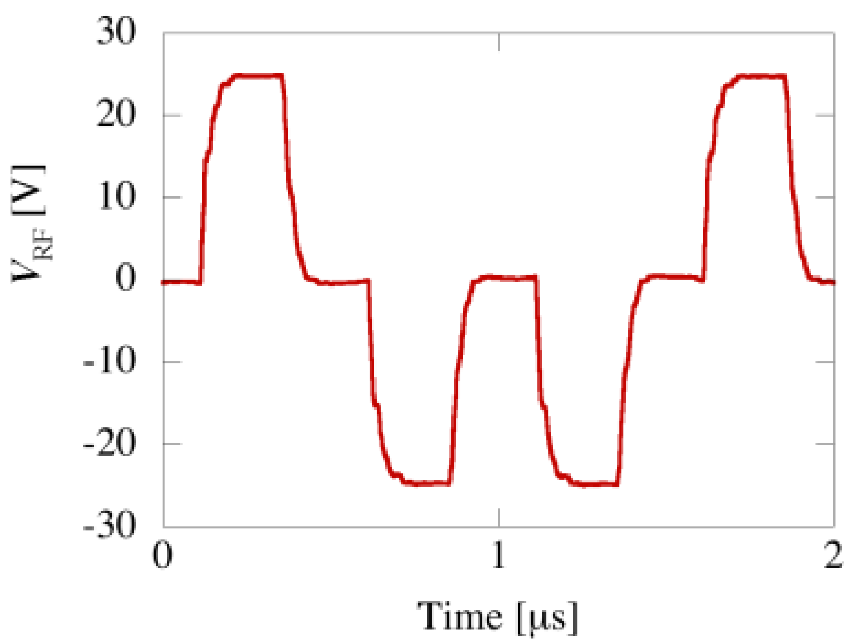
FDDF Sequence



From S-POD II

FDDF Lattice





- A popular lattice employed, e.g., for GSI UNILAC, CERN PS, etc.
- The resonance characteristics should be similar to those of doublet and sinusoidal focusing.

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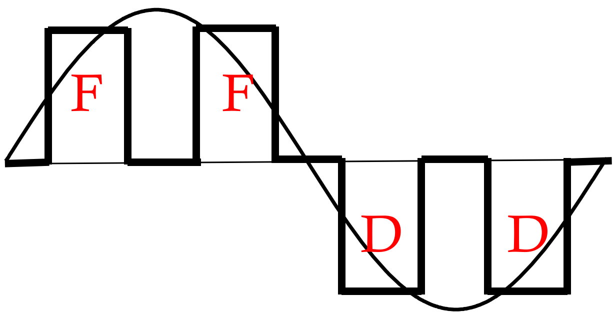

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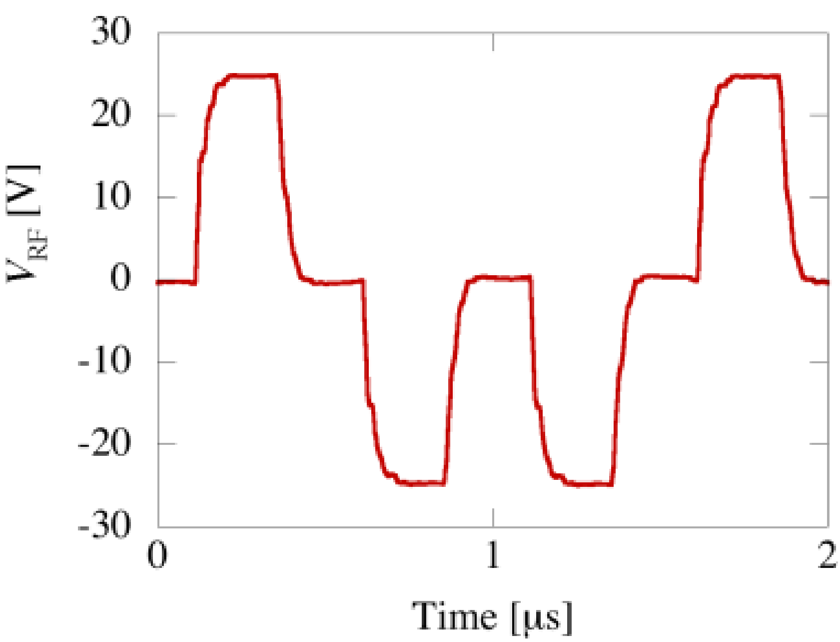
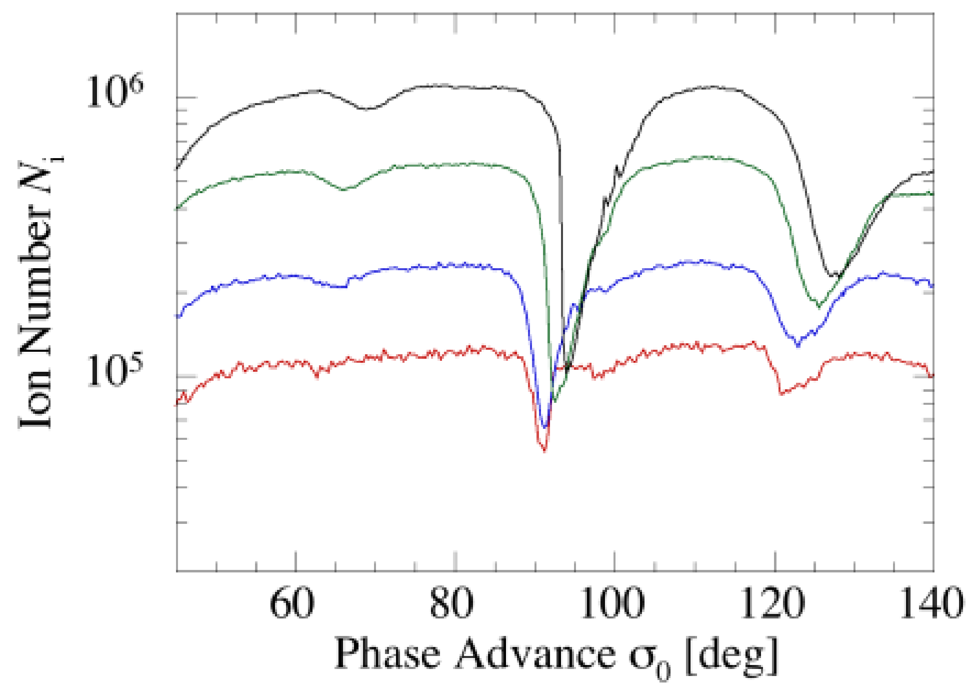
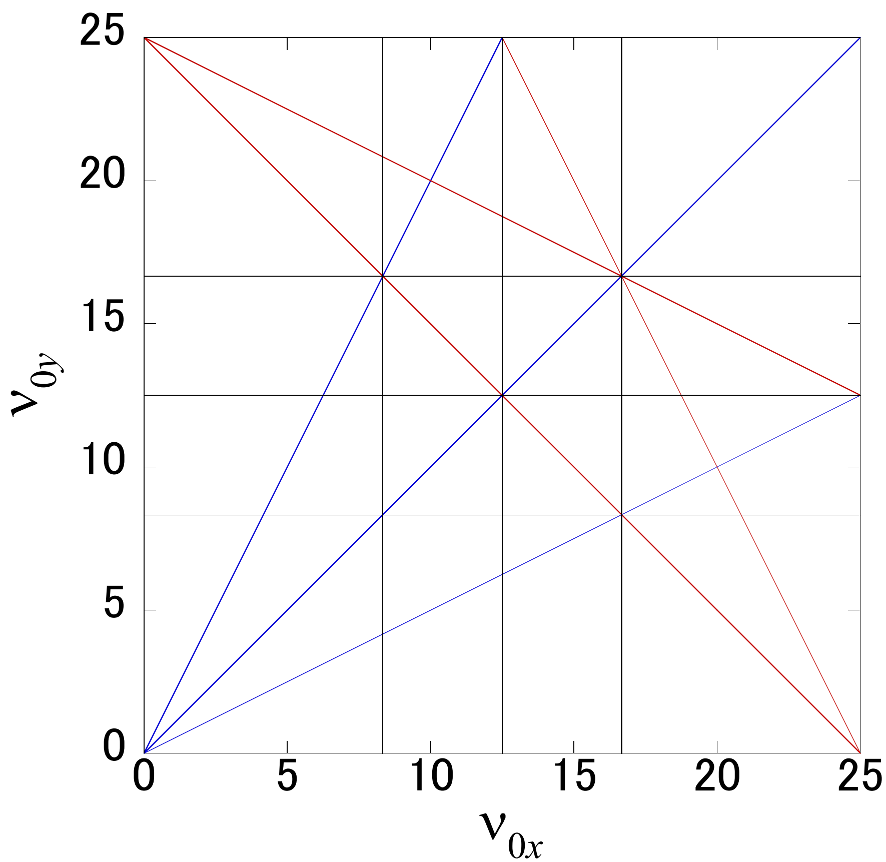




50 x FDDF (symmetric focusing)

Imagine a storage ring composed of 50 identical FDDF cells.



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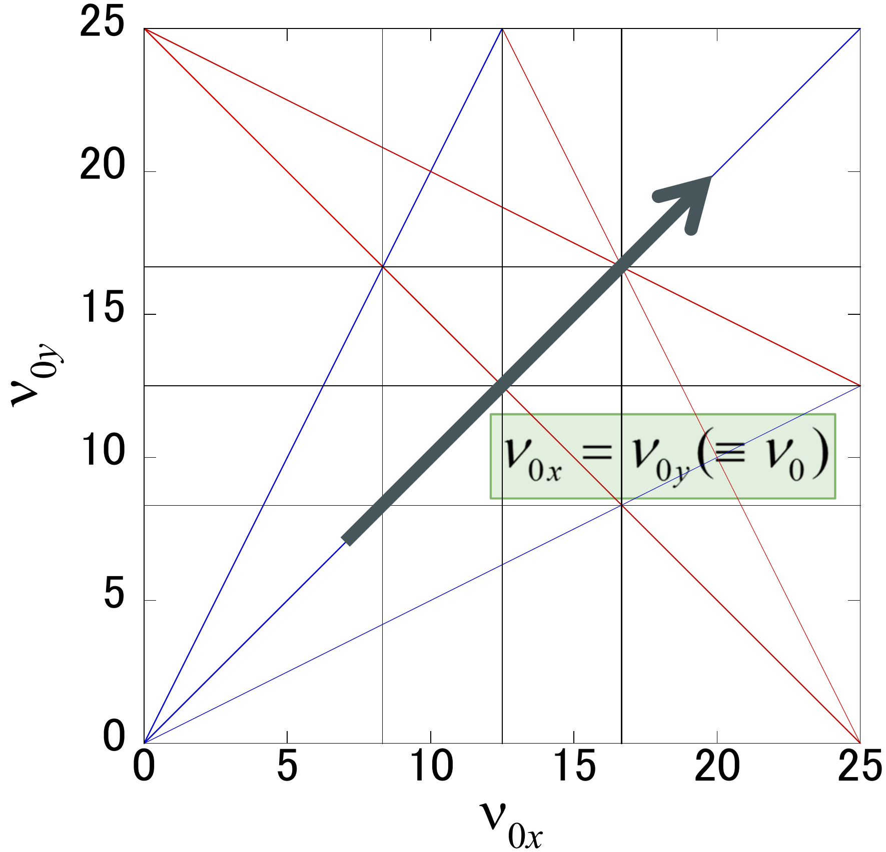

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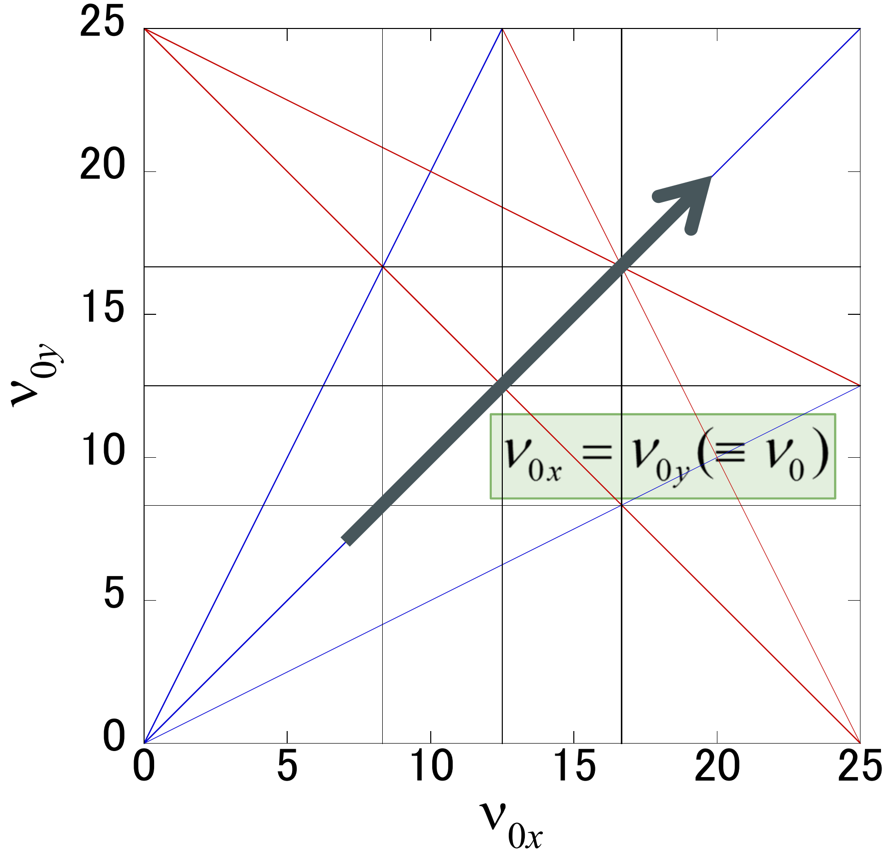

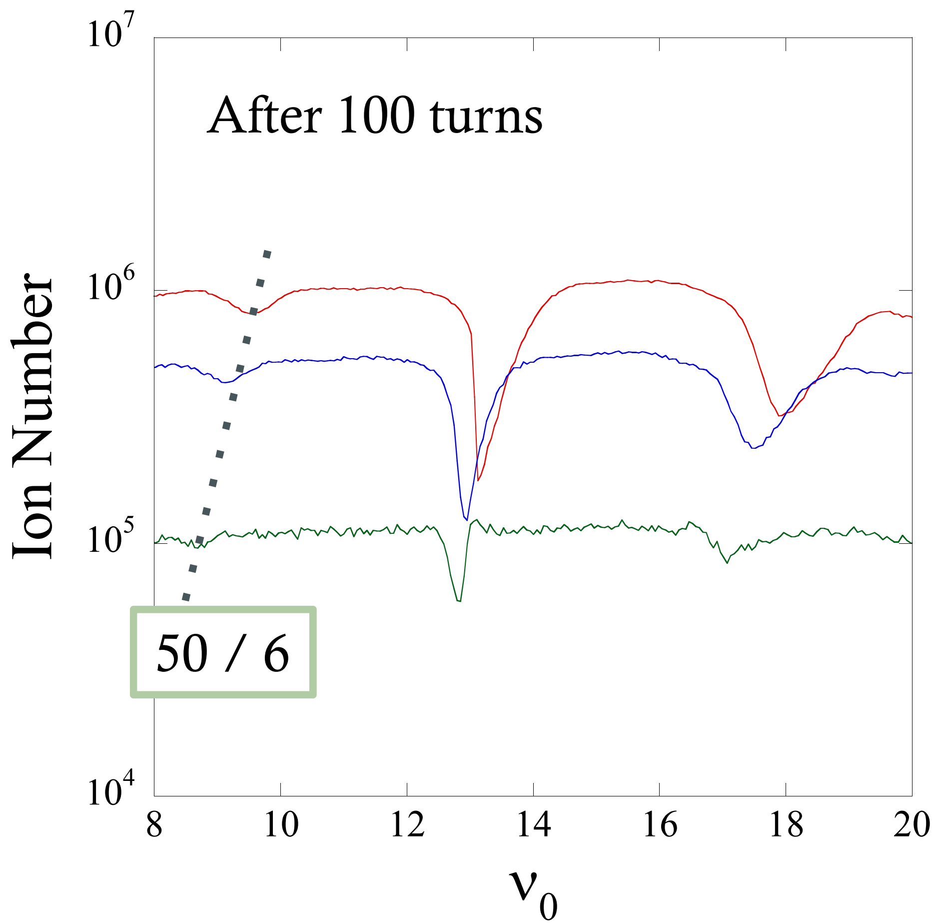

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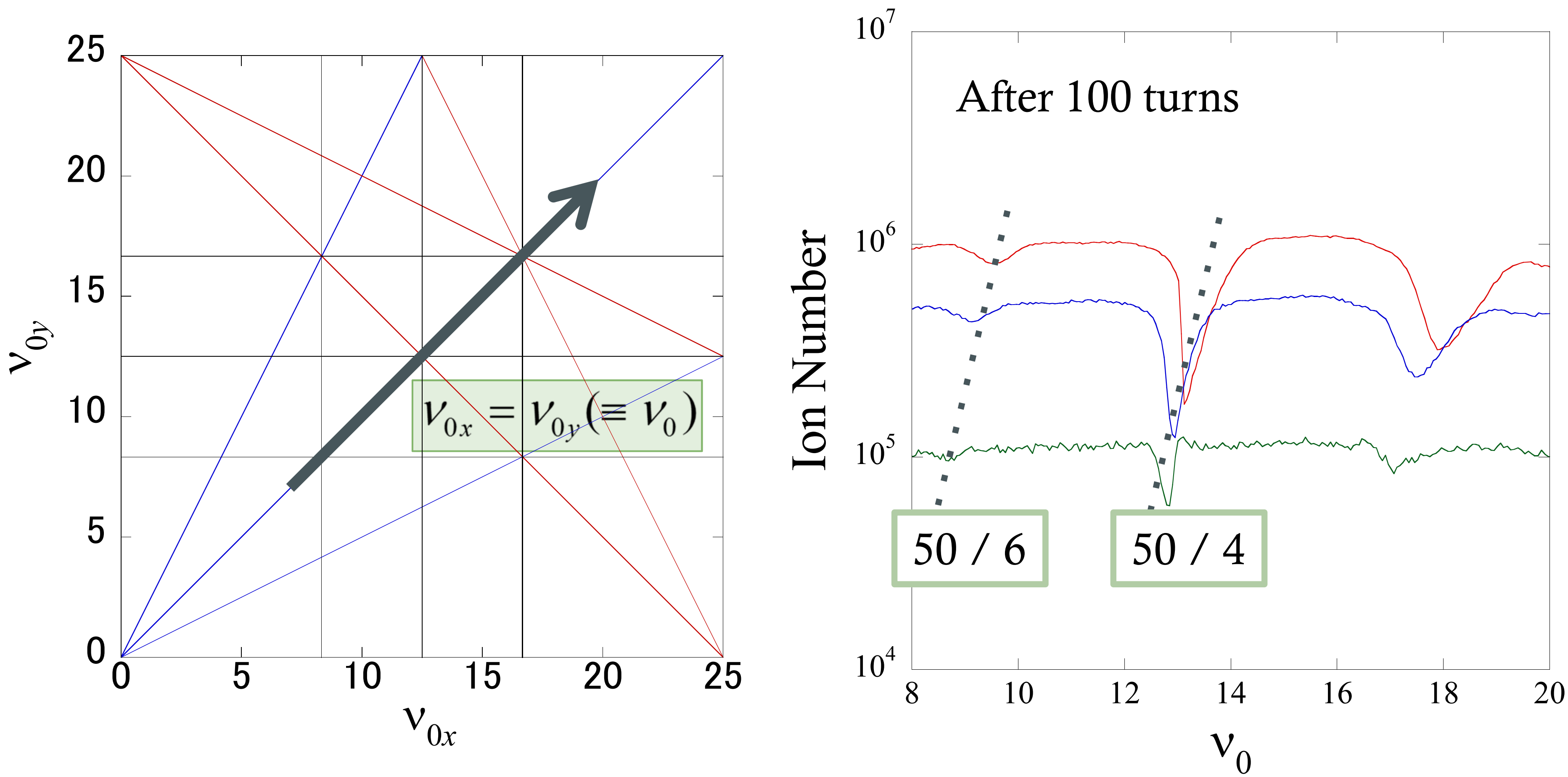

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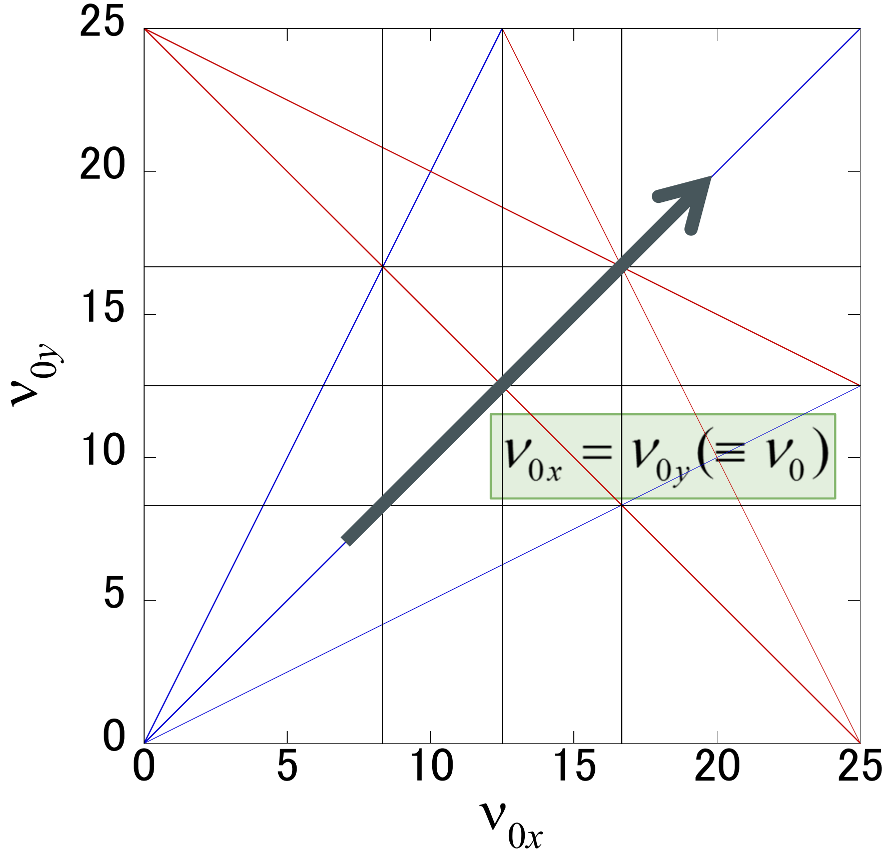
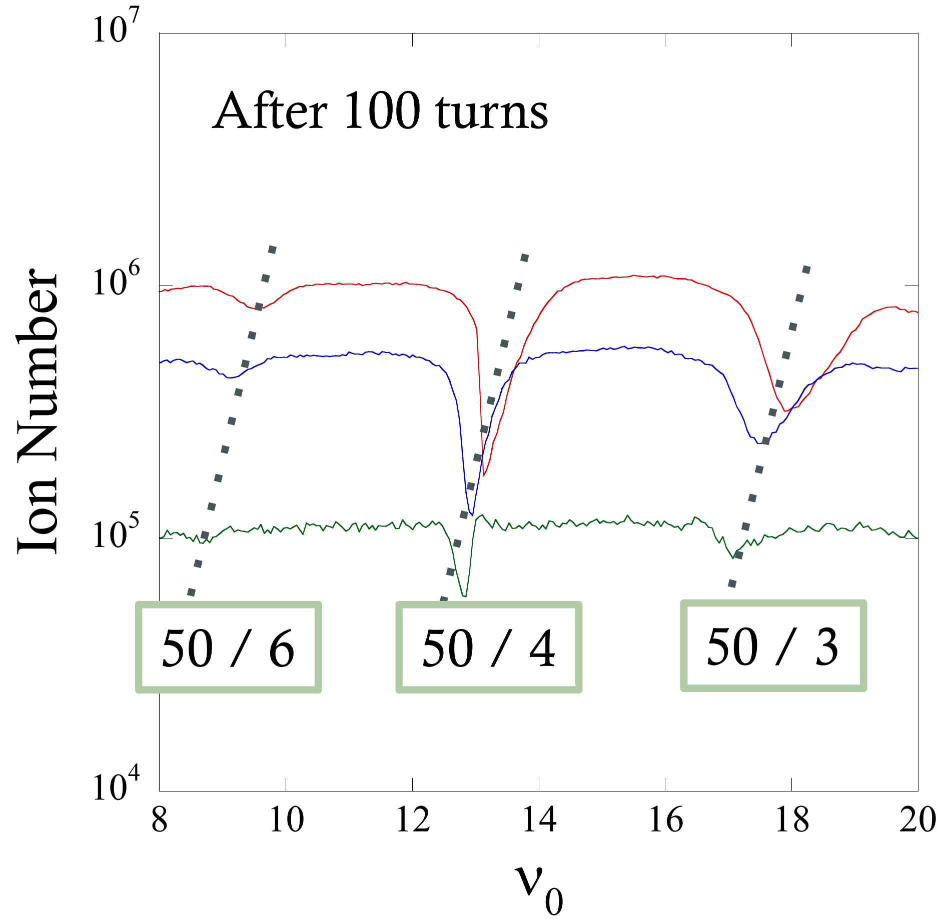
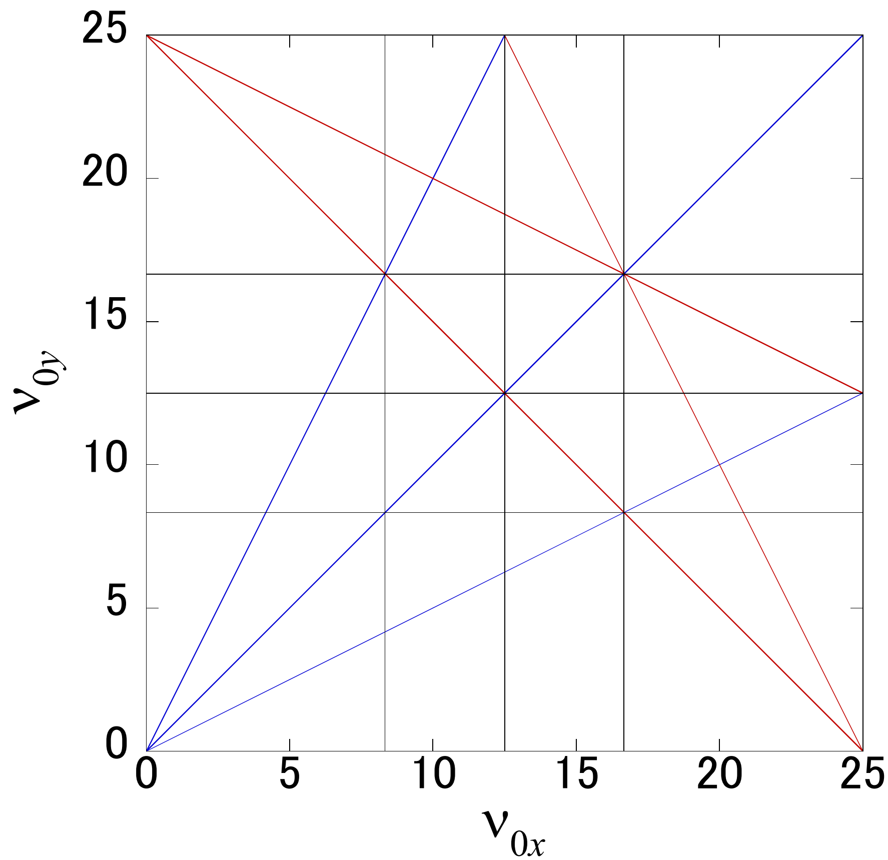
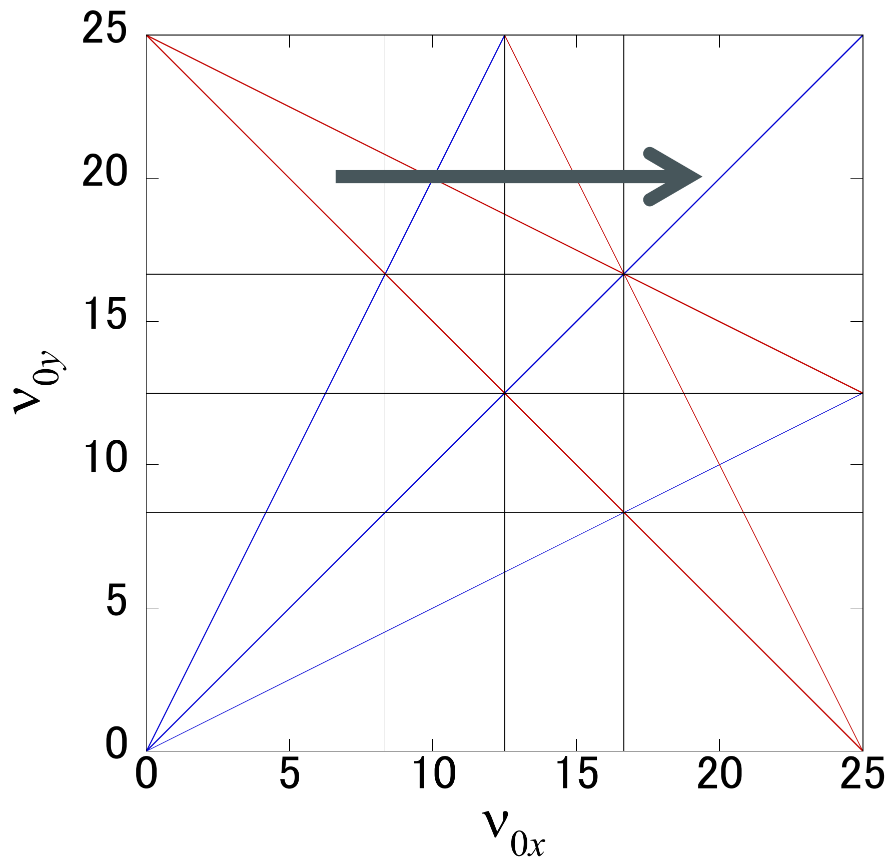


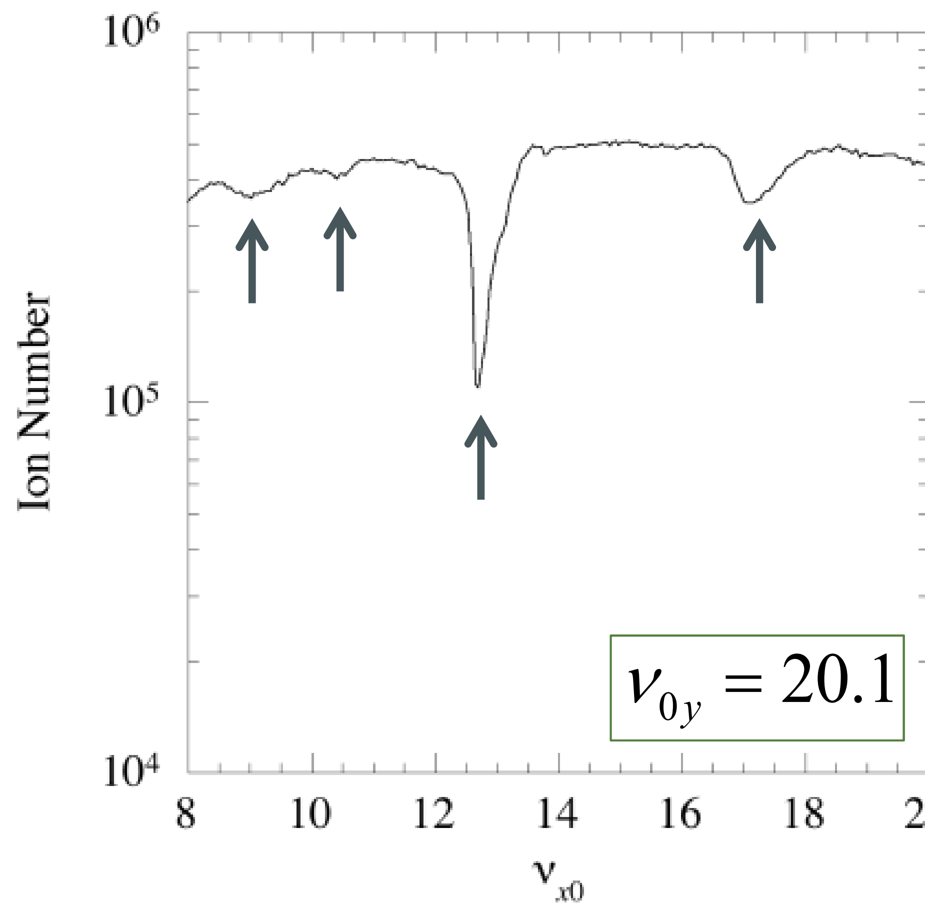


50 x FDDF (asymmetric focusing)

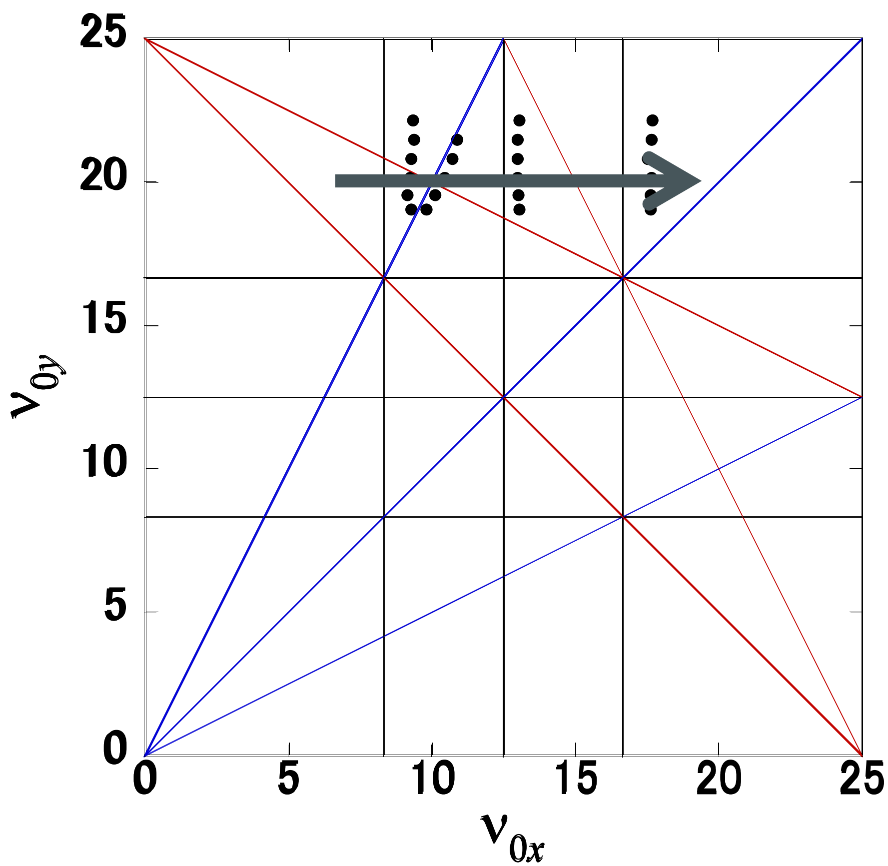


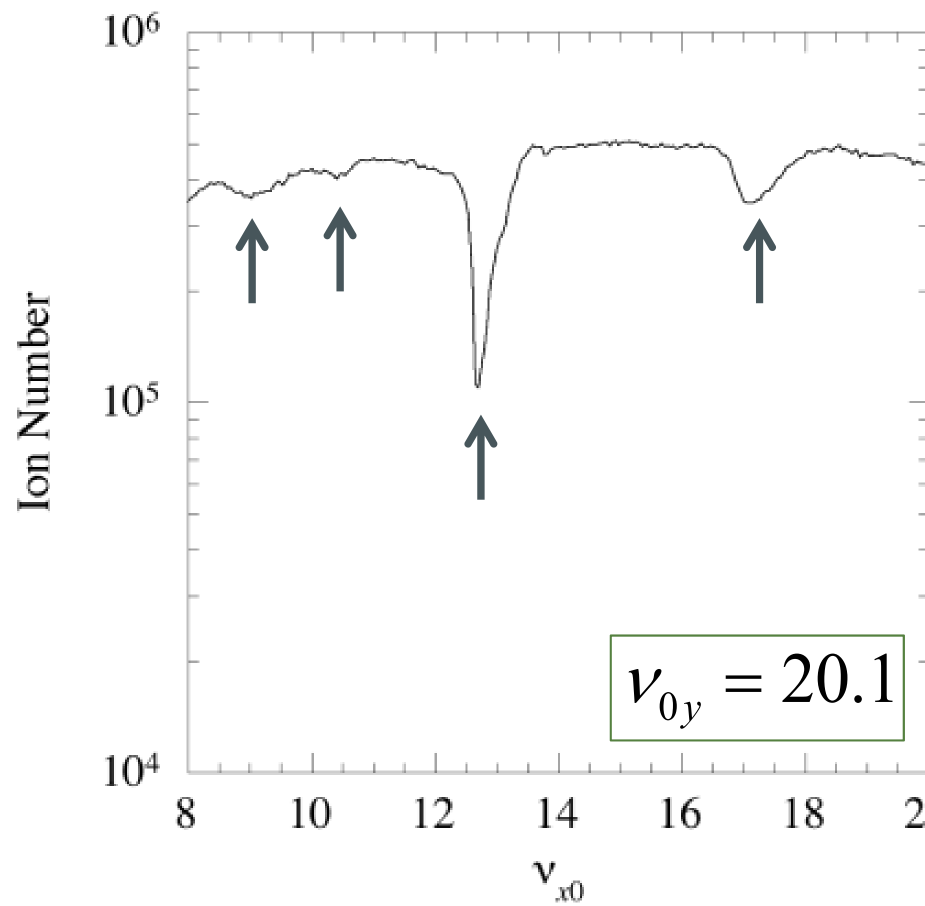
50 x FDDF (asymmetric focusing)





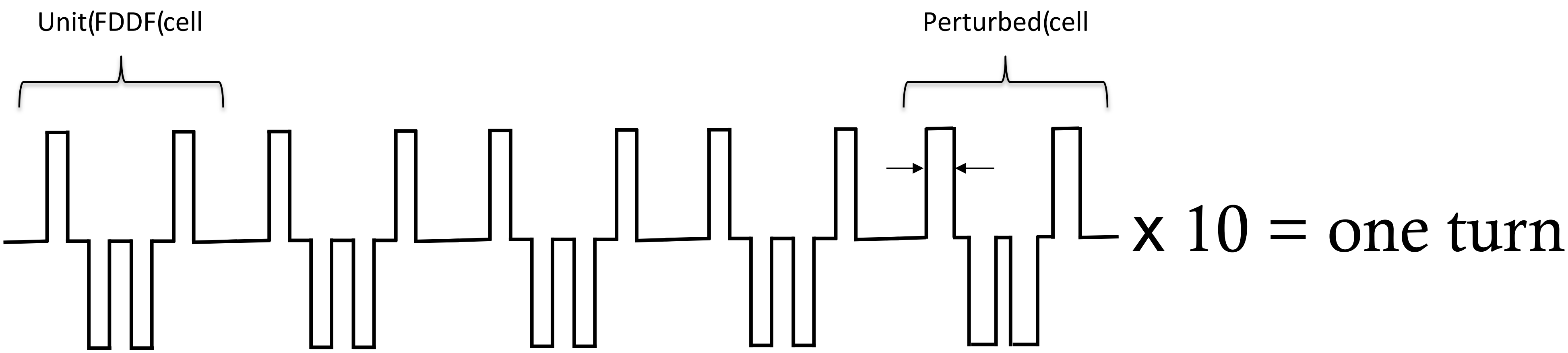
50 x FDDF (asymmetric focusing)





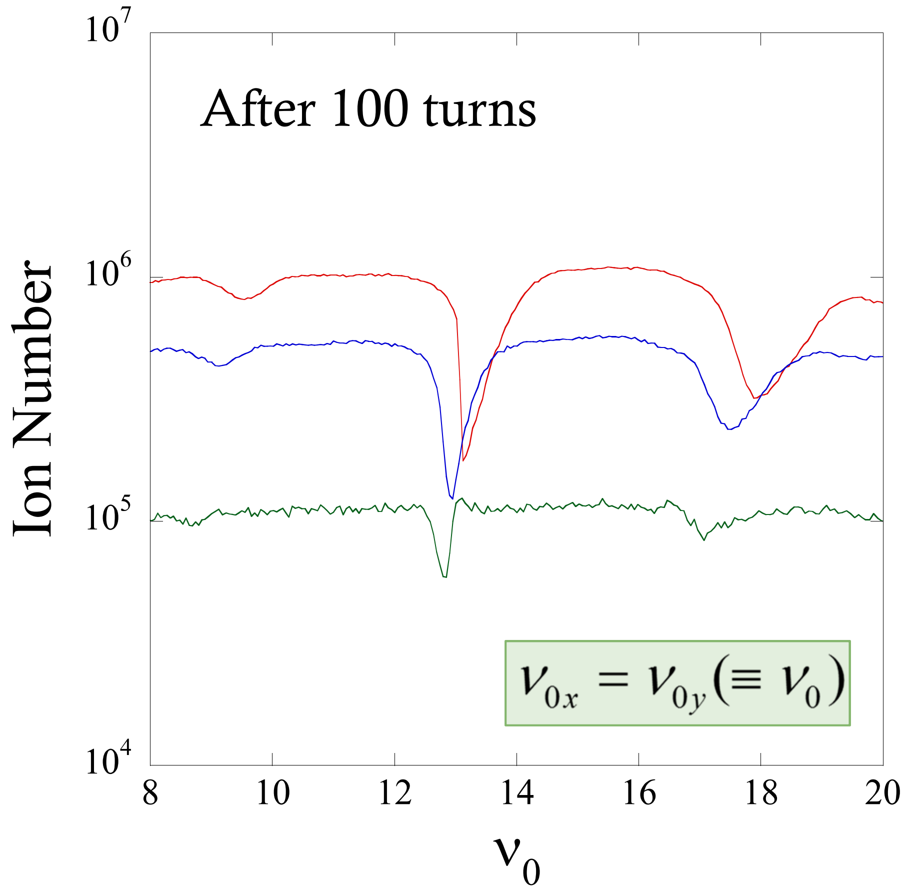
50 x FDDF (with 10-fold symmetry)

We now slightly modify the FDDF waveform at every five cells to reduce the lattice symmetry. Imagine a 10-fold symmetric ring where each lattice superperiod contains five FDDF cells.



50 x FDDF (with 10-fold symmetry)

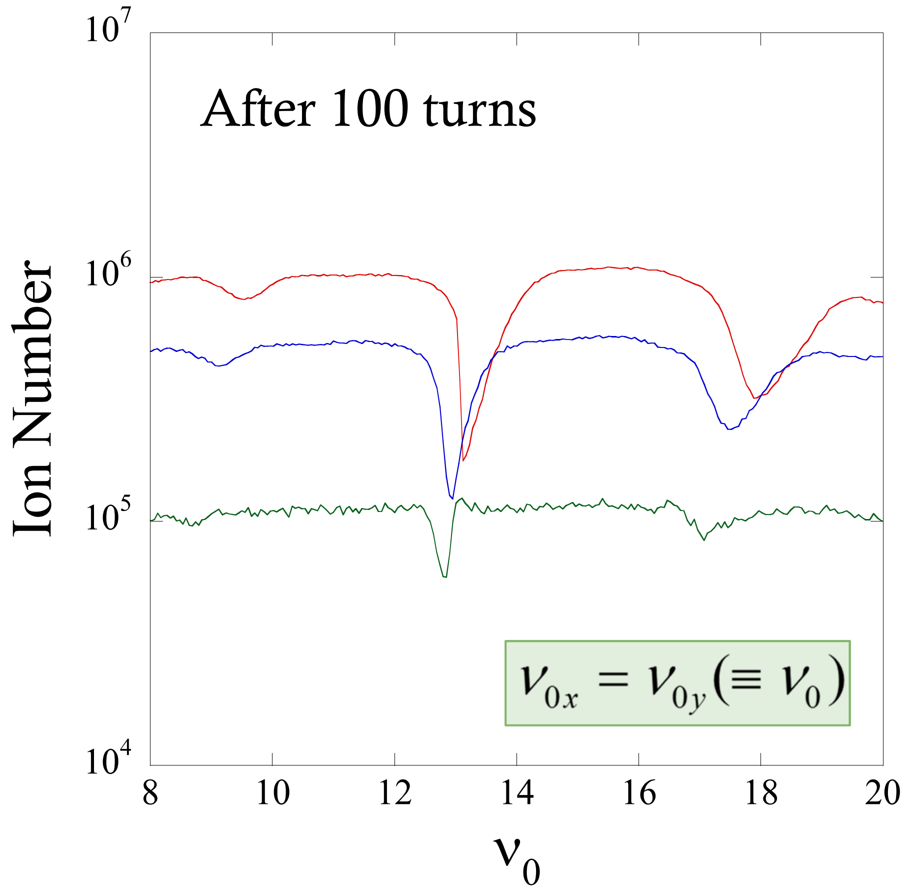
50-fold symmetric case

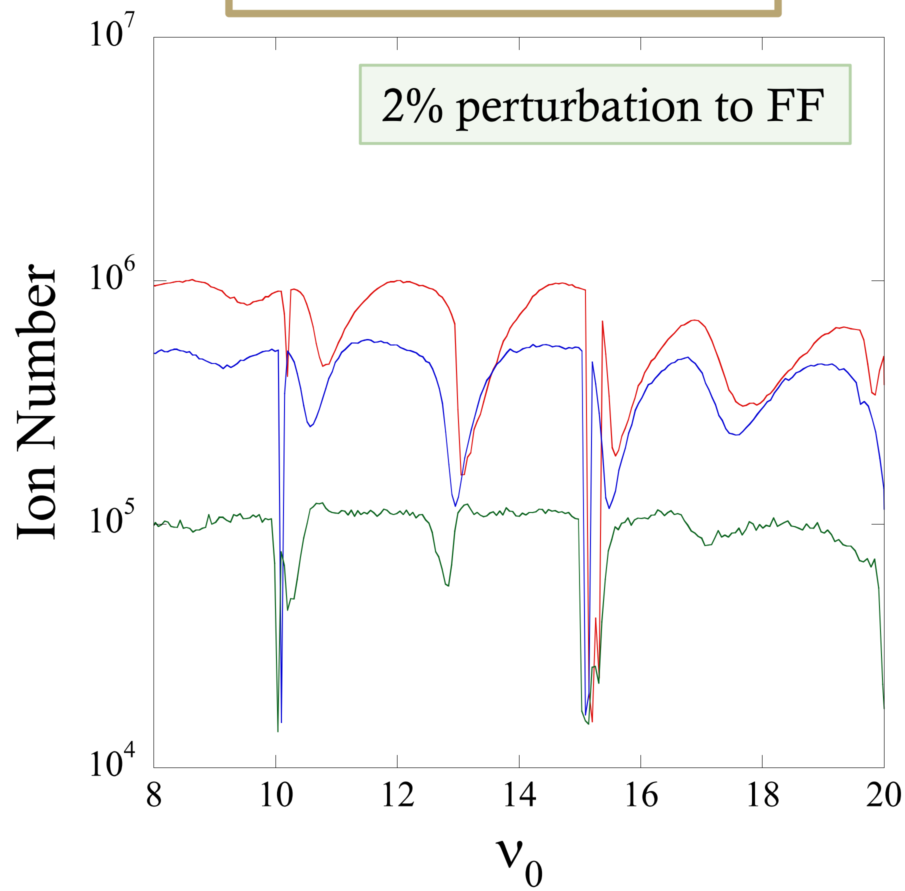


50 x FDDF (with 10-fold symmetry)

50-fold symmetric case

10-fold symmetric perturbation introduced !

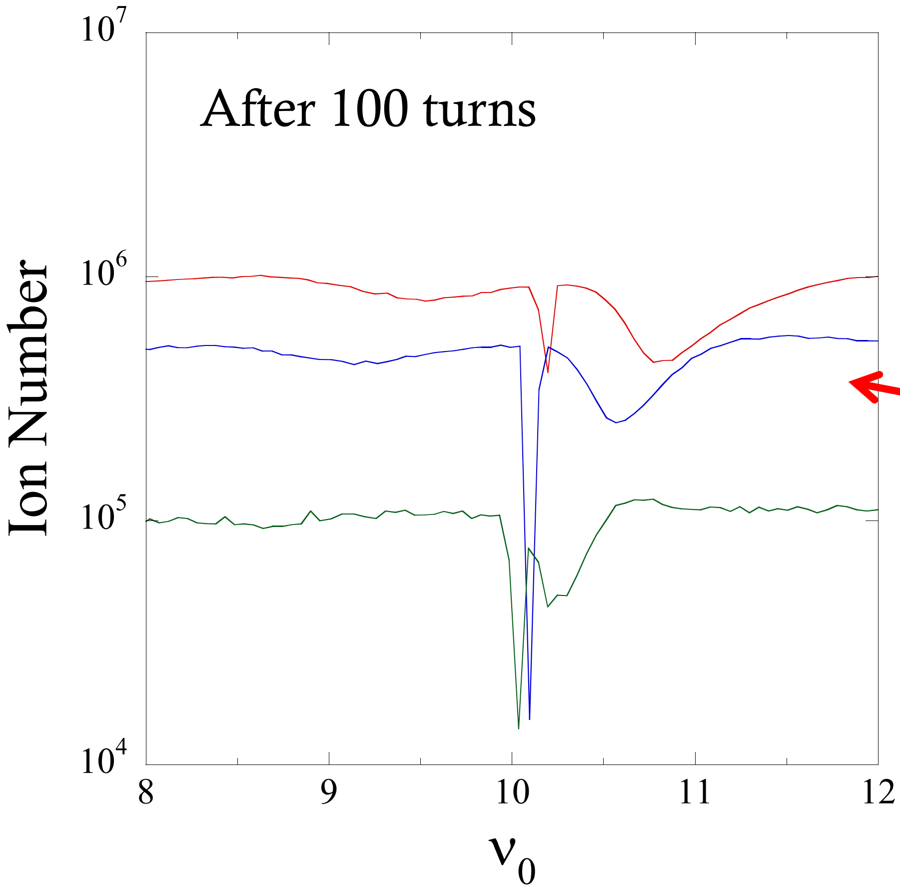


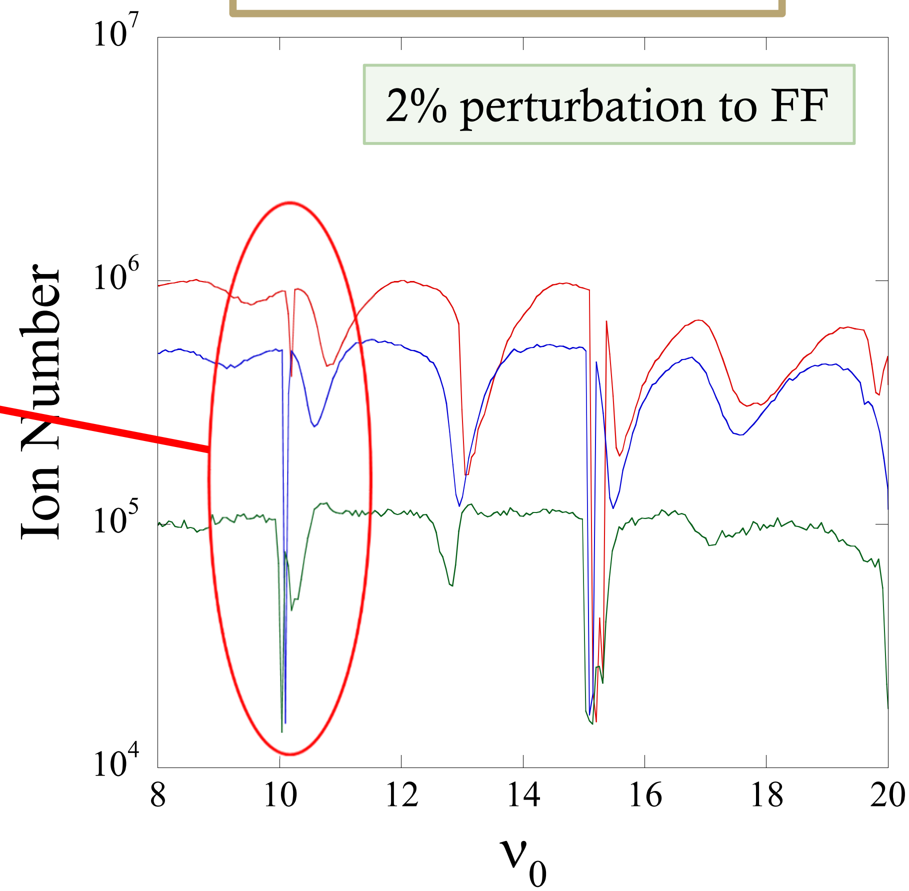


50 x FDDF (with 10-fold symmetry)

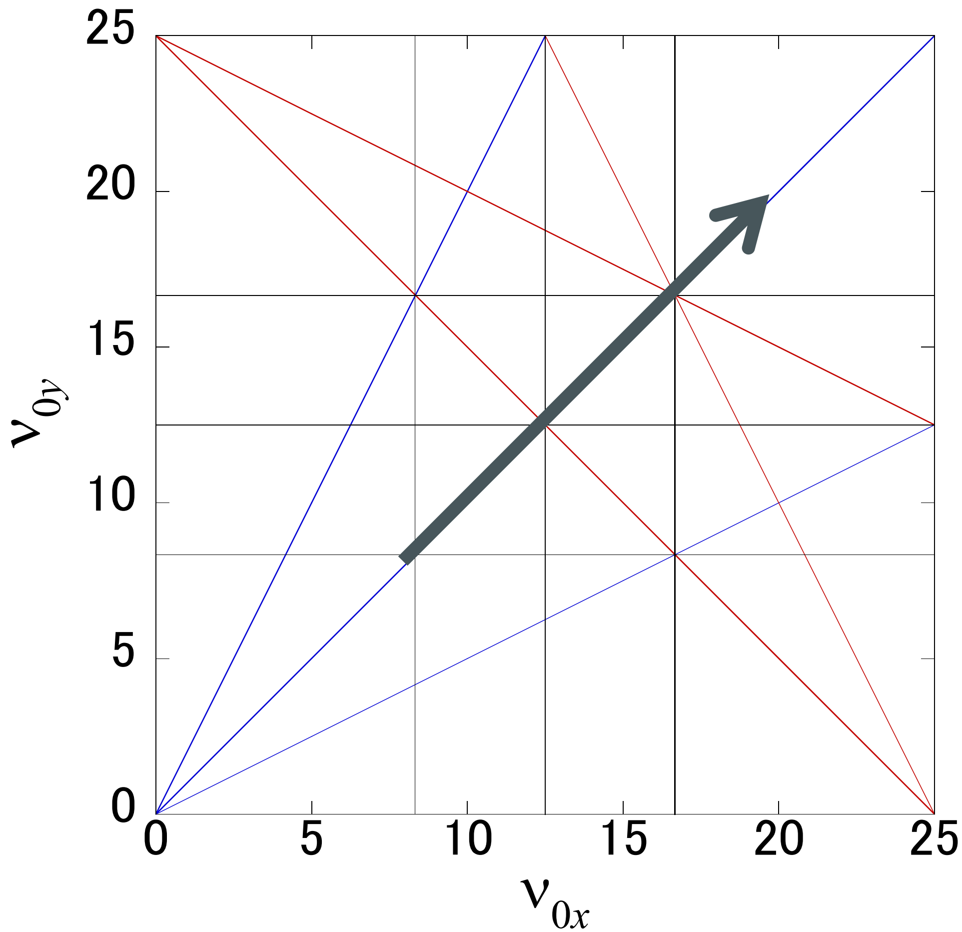
50-fold symmetric case

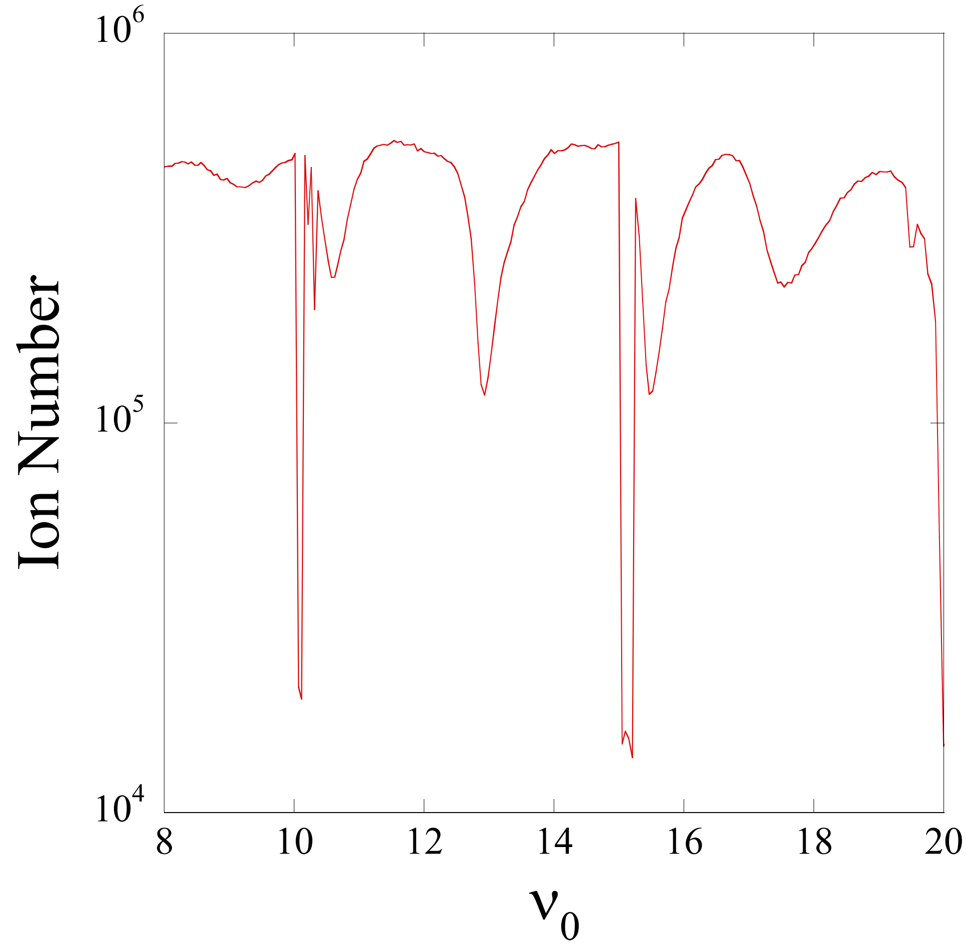
10-fold symmetric perturbation introduced !



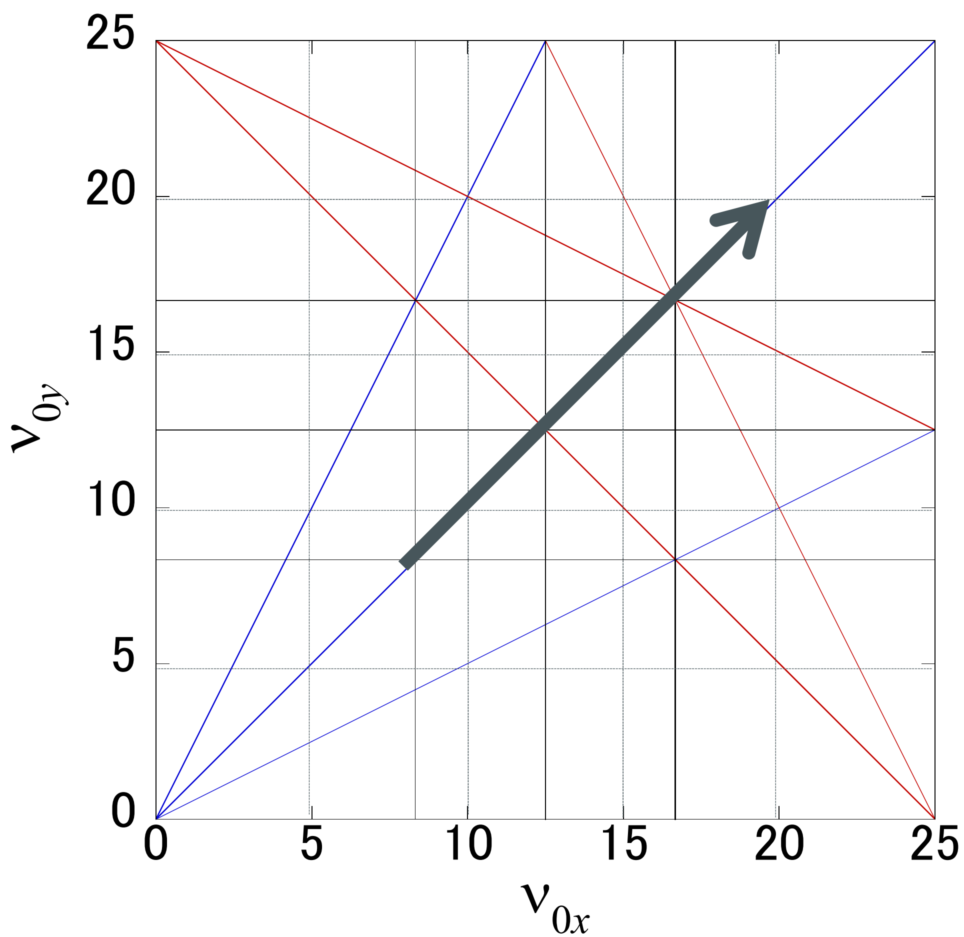


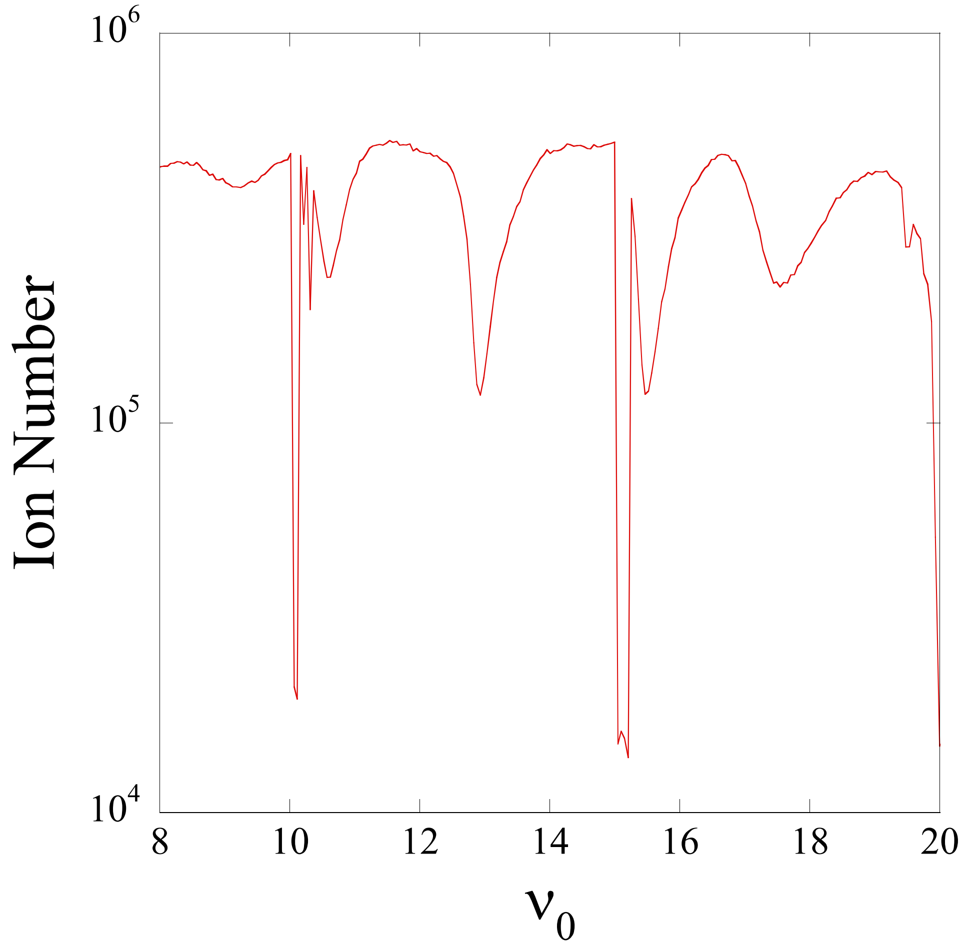
Asymmetric Focusing



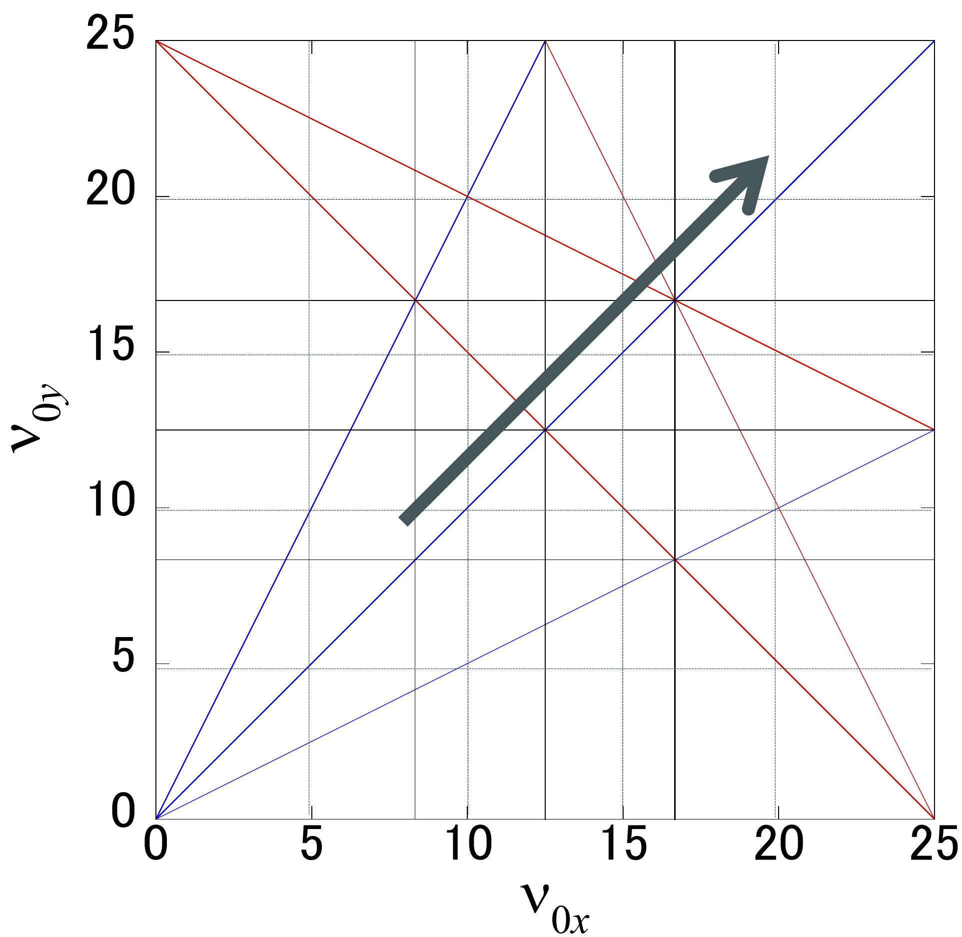


Asymmetric Focusing

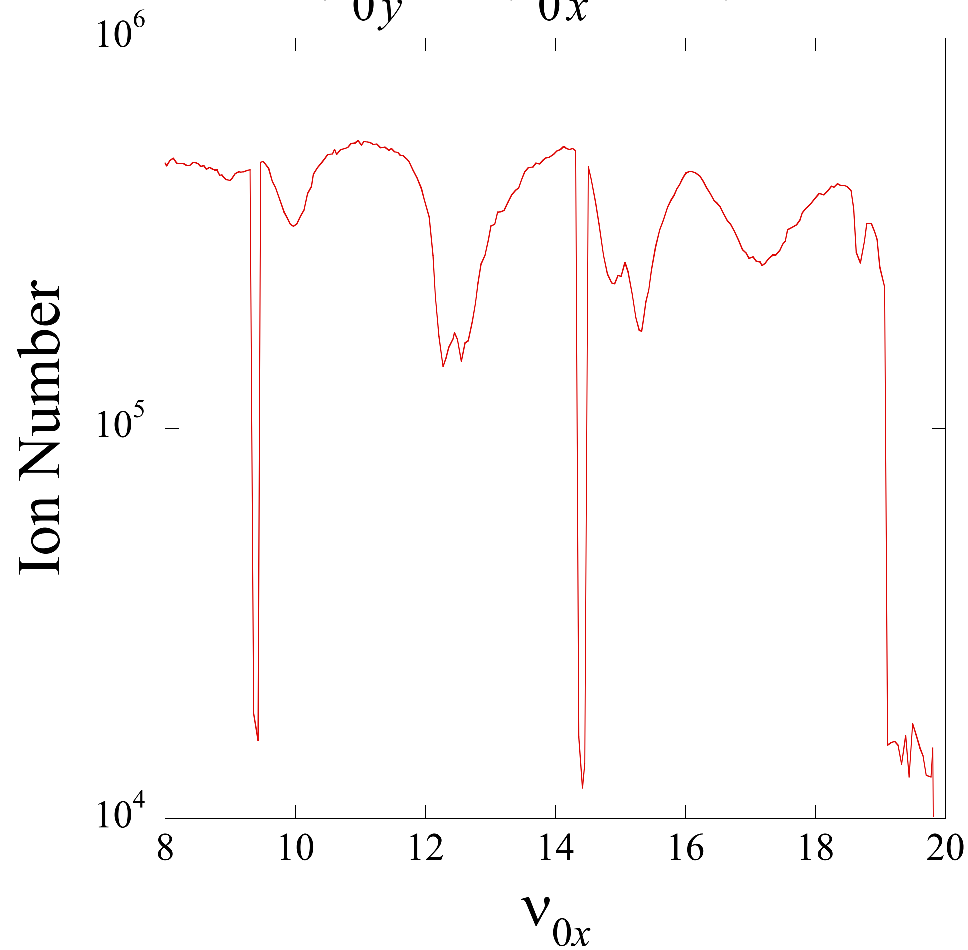




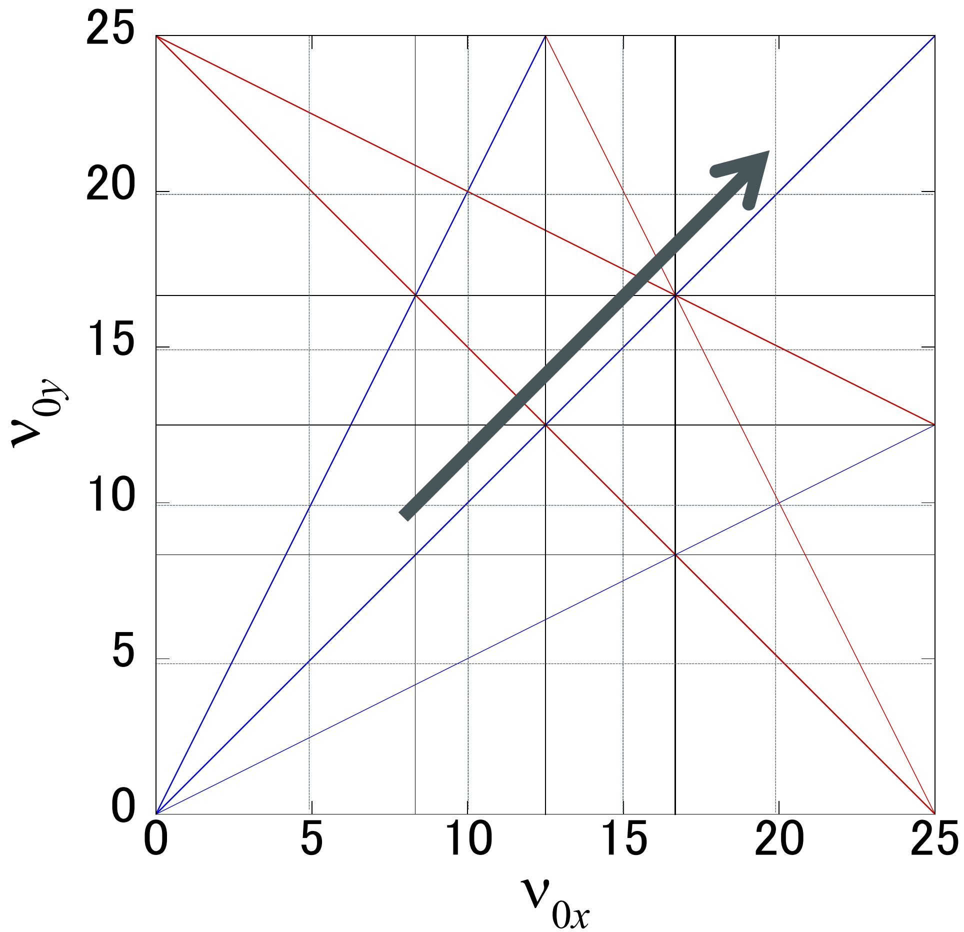
Asymmetric Focusing



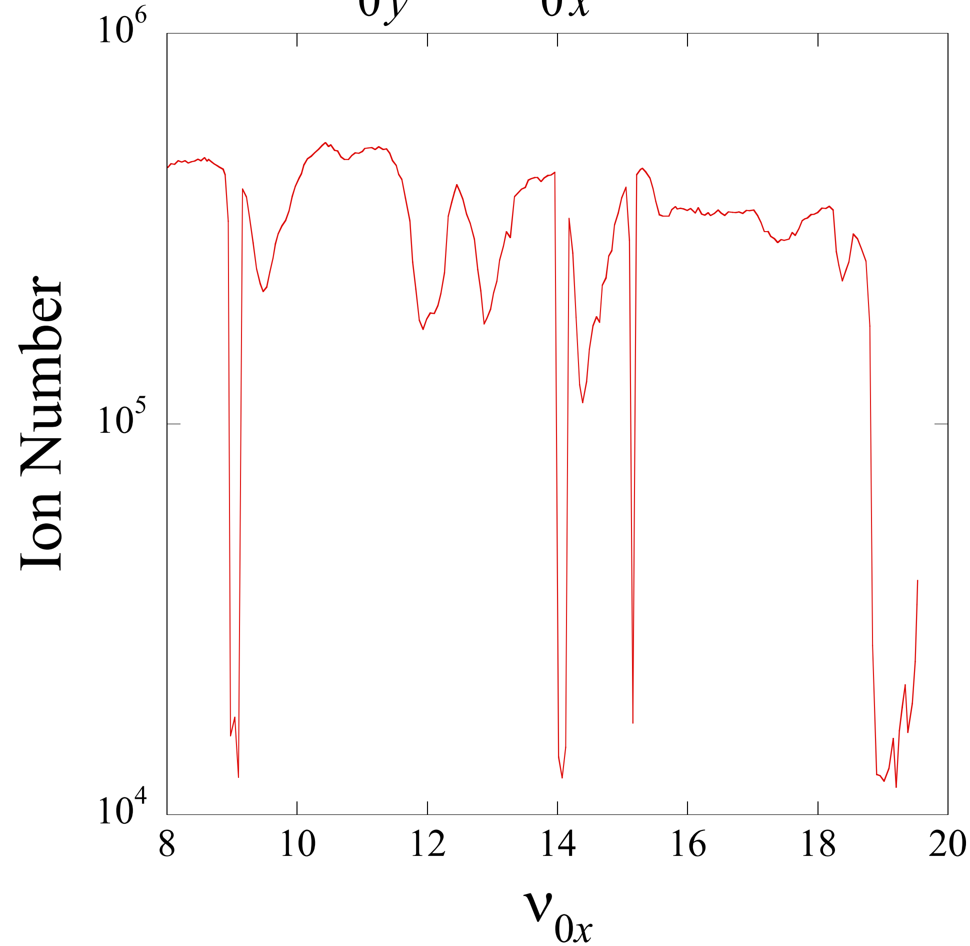
$$\nu_{0y} = \nu_{0x} + 0.01$$



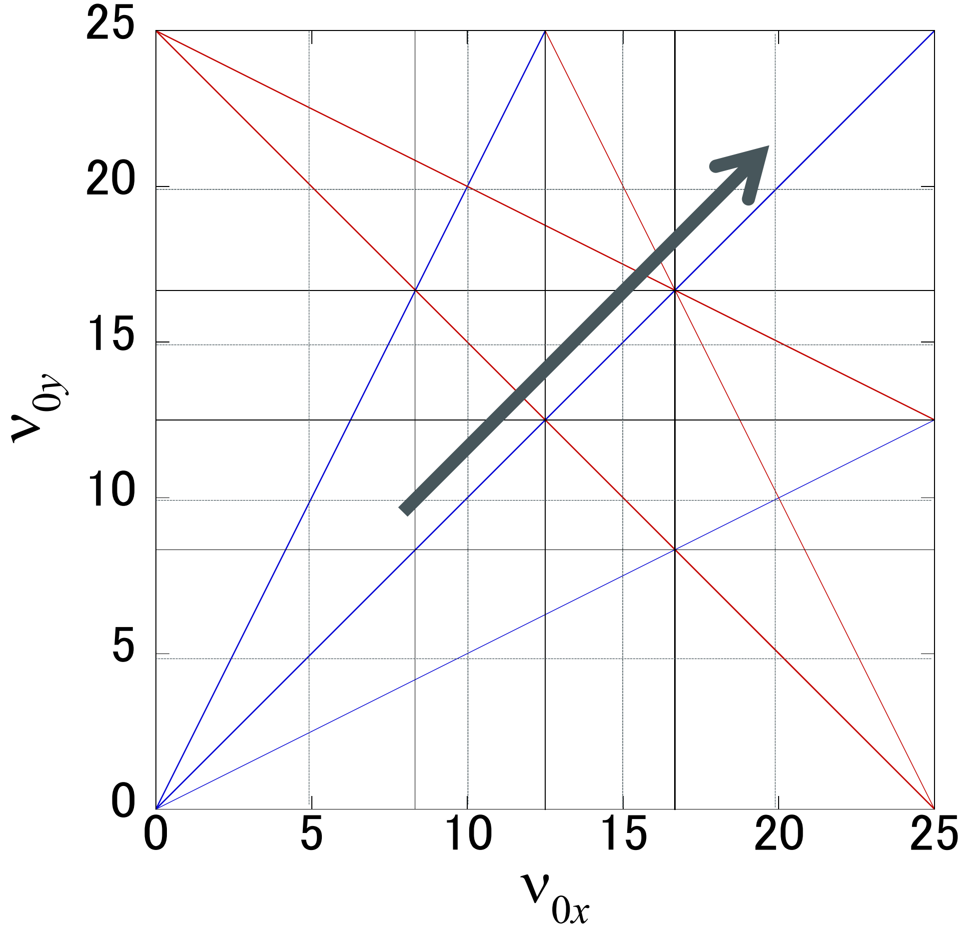
Asymmetric Focusing

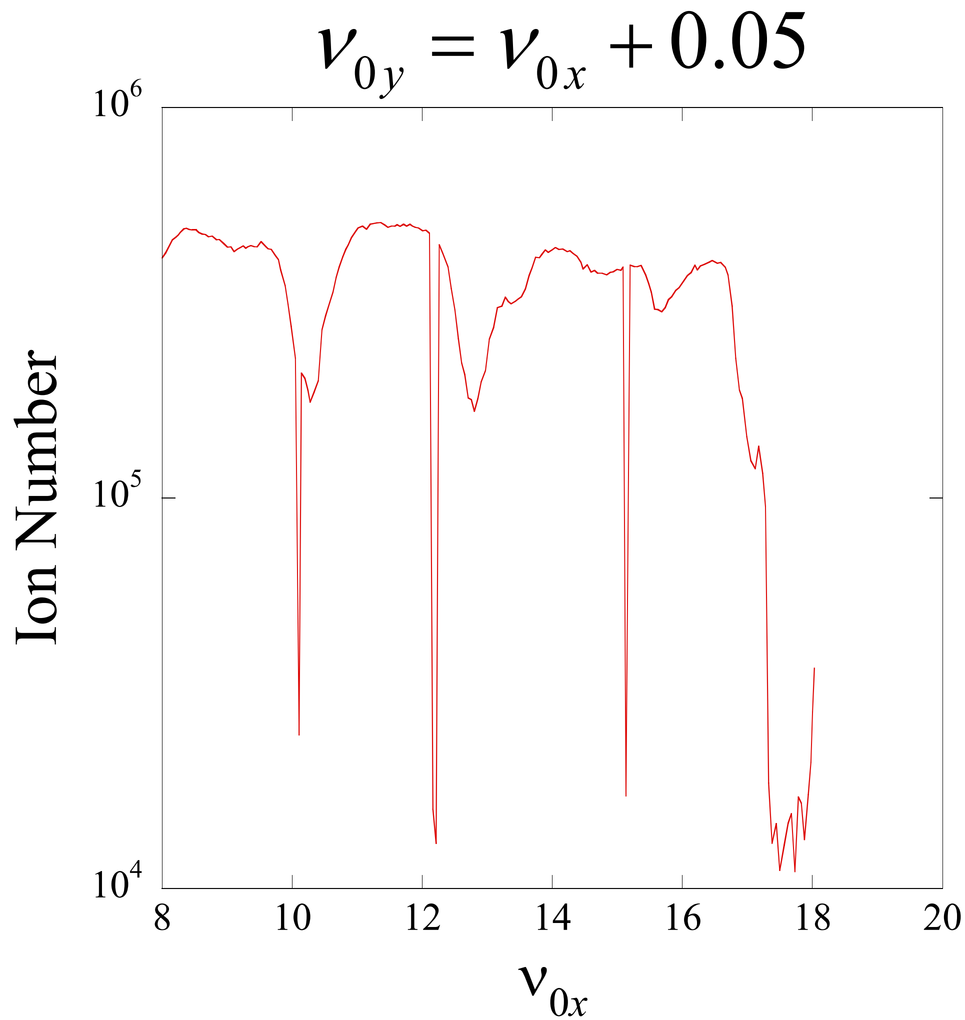


$$\nu_{0y} = \nu_{0x} + 0.02$$



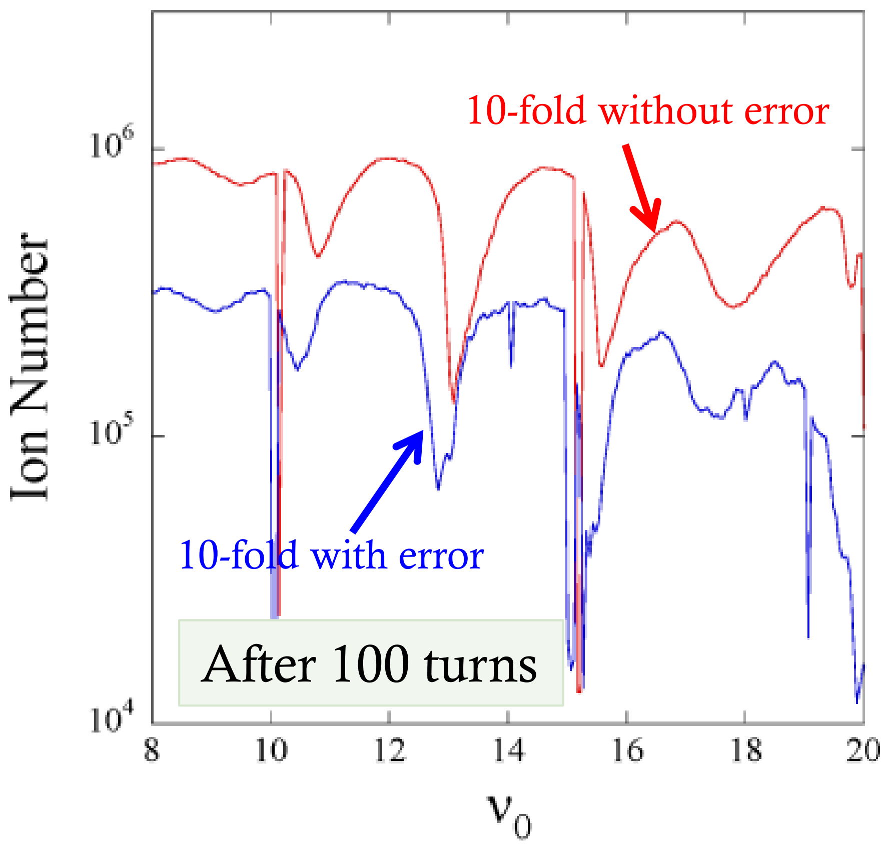
Asymmetric Focusing





50 x FDDF (with error fields)

Pattern I : A-A-A-A-B (1^{st} to 49^{th} cell)
A-A-A-A-C (50^{th} cell)



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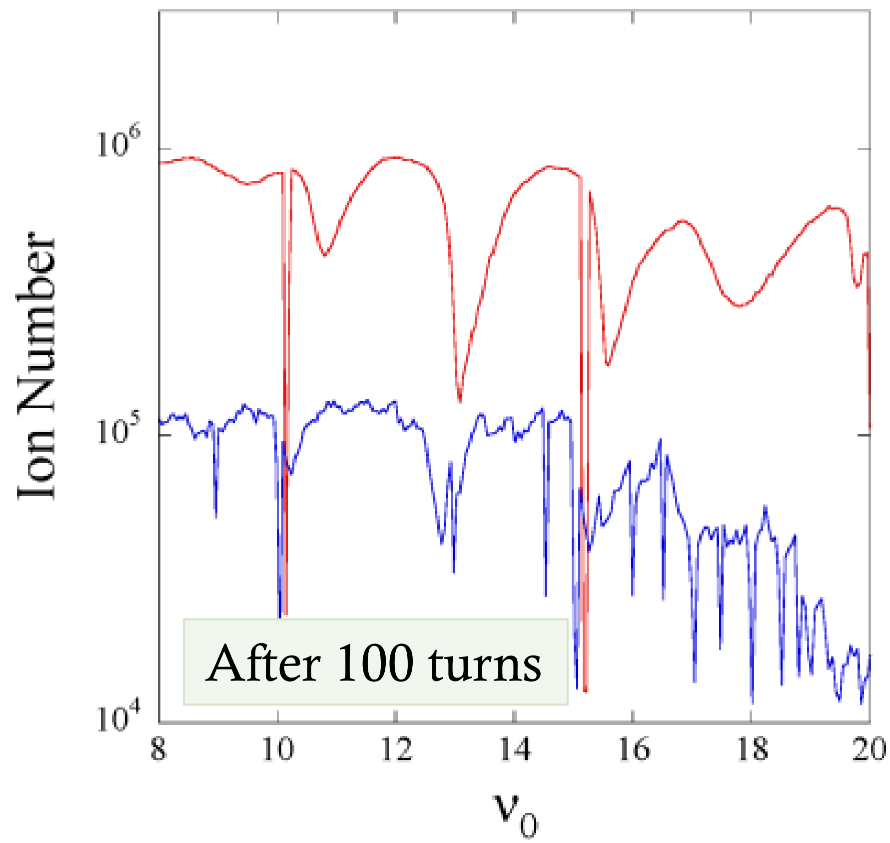
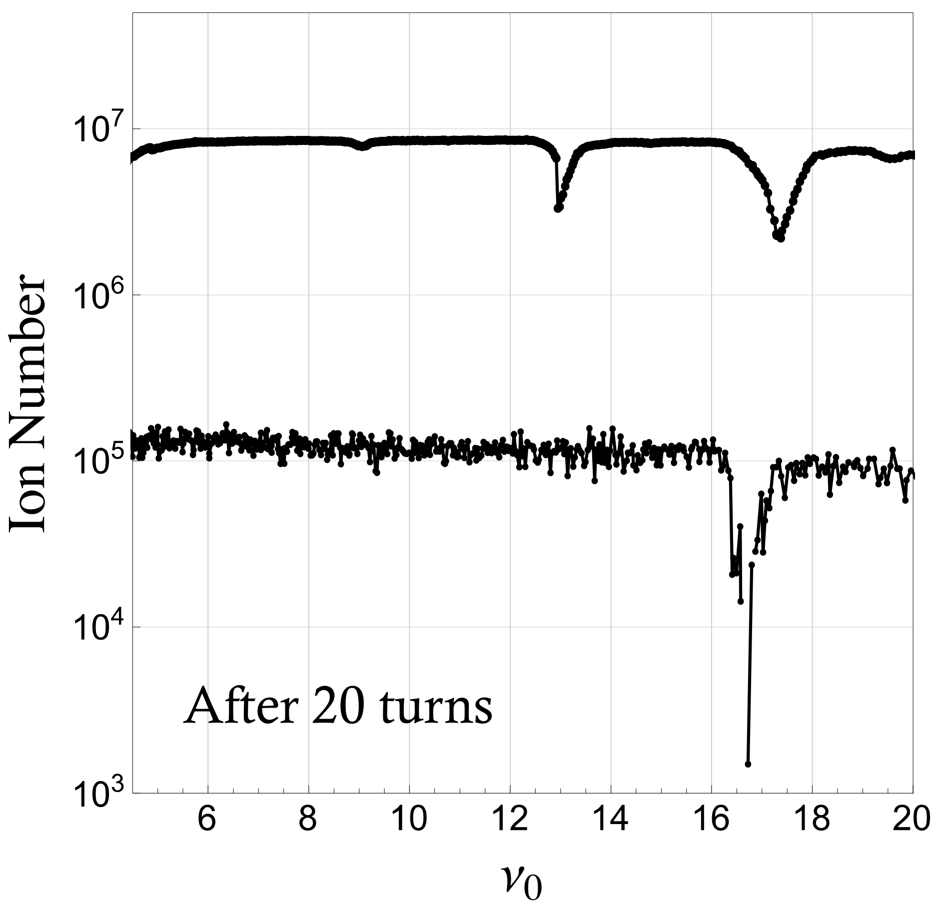


Note : the perturbation has been applied during the plasma production process.

50 x Sinwave (with 10-fold symmetry)

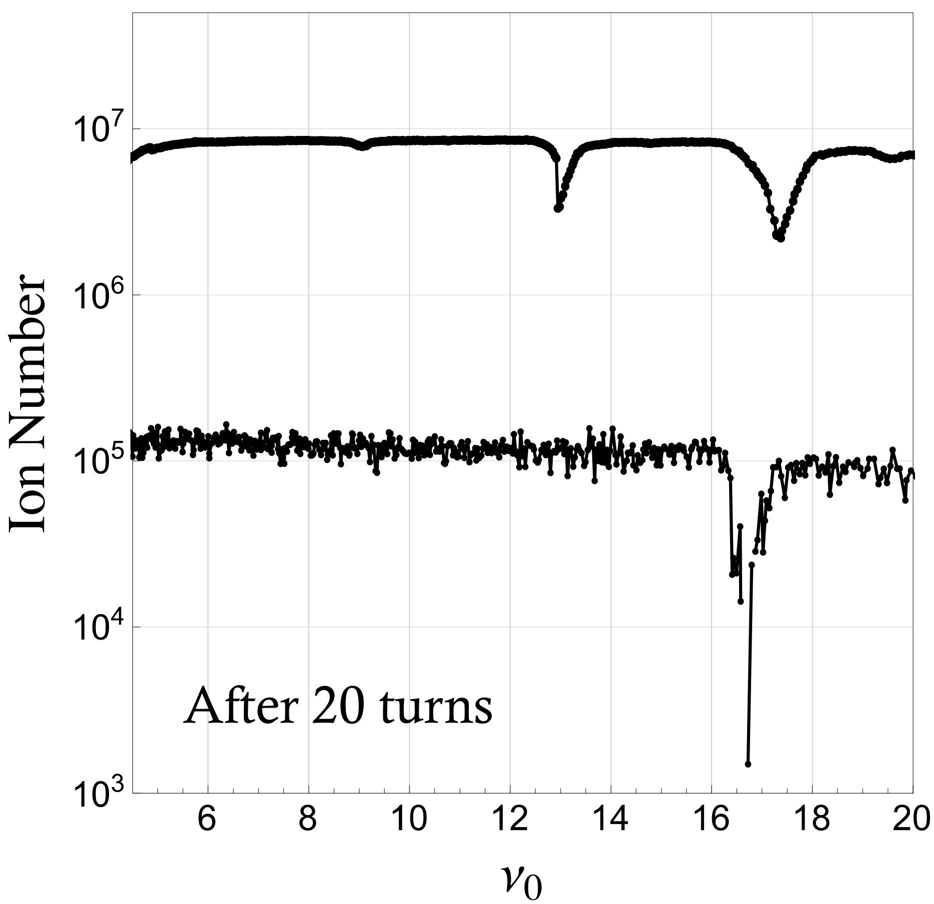
50-fold symmetric case

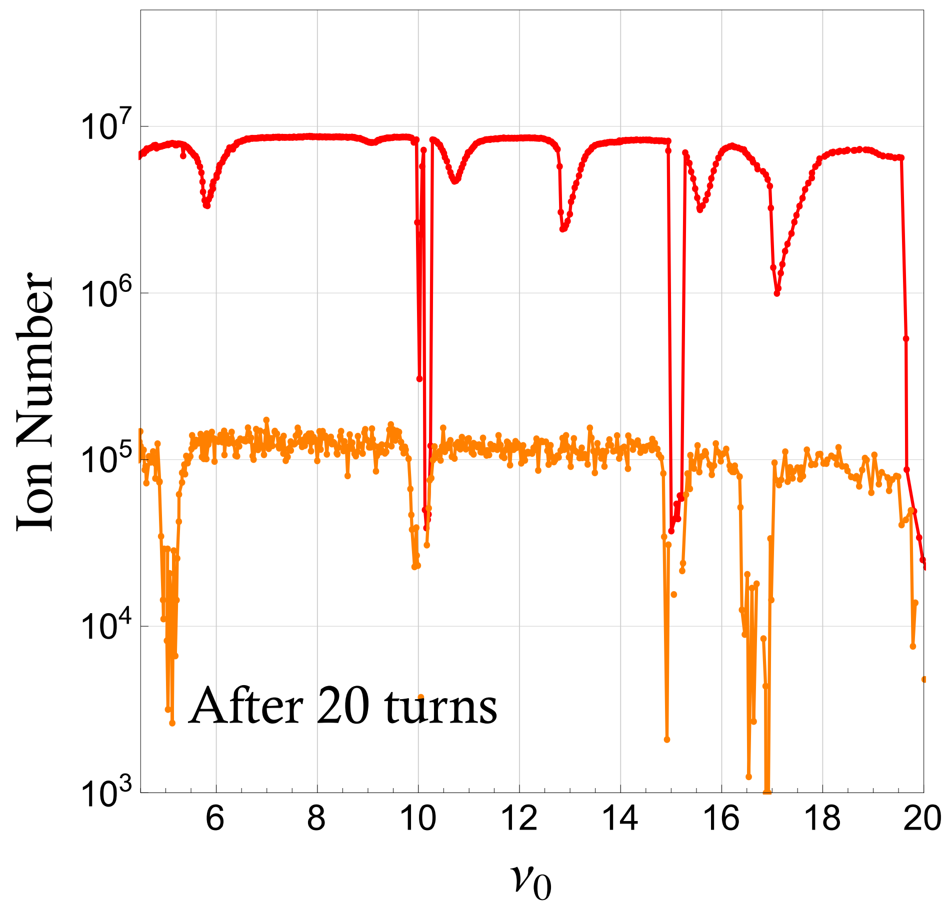


50 x Sinwave (with 10-fold symmetry)

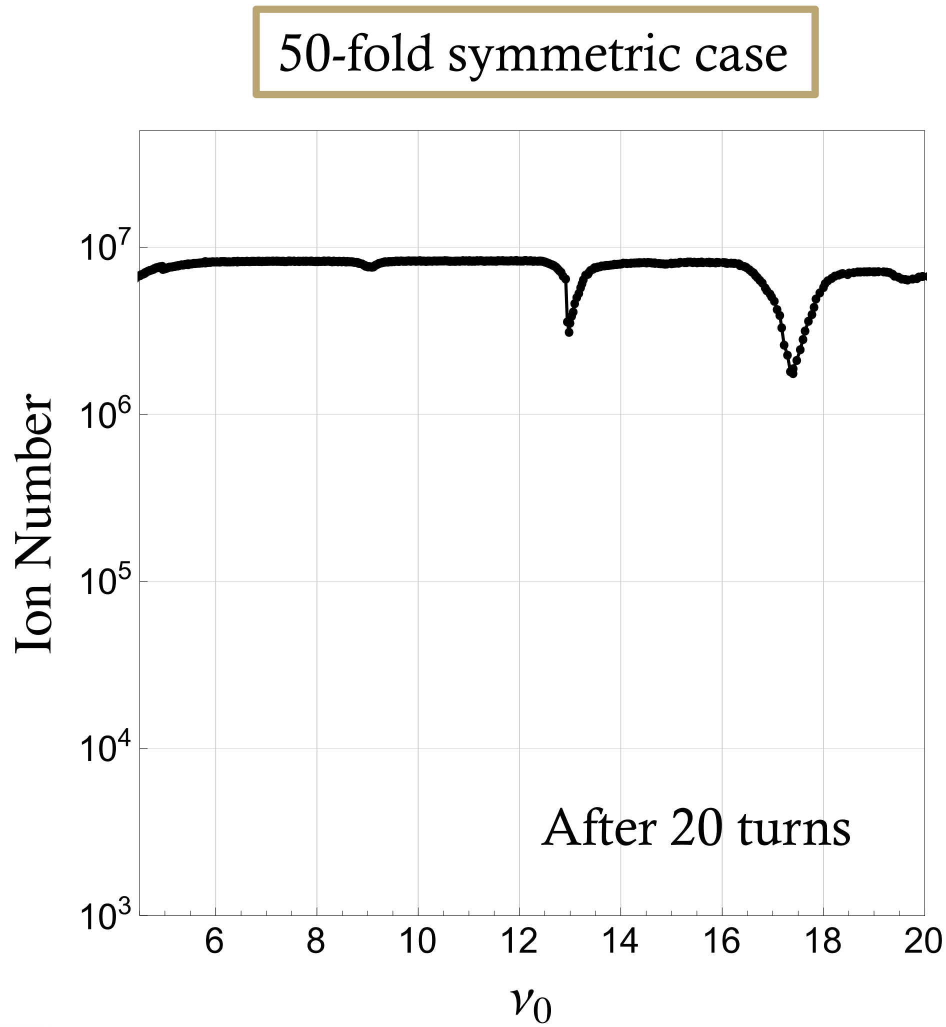
50-fold symmetric case

10-fold symmetric perturbation introduced !



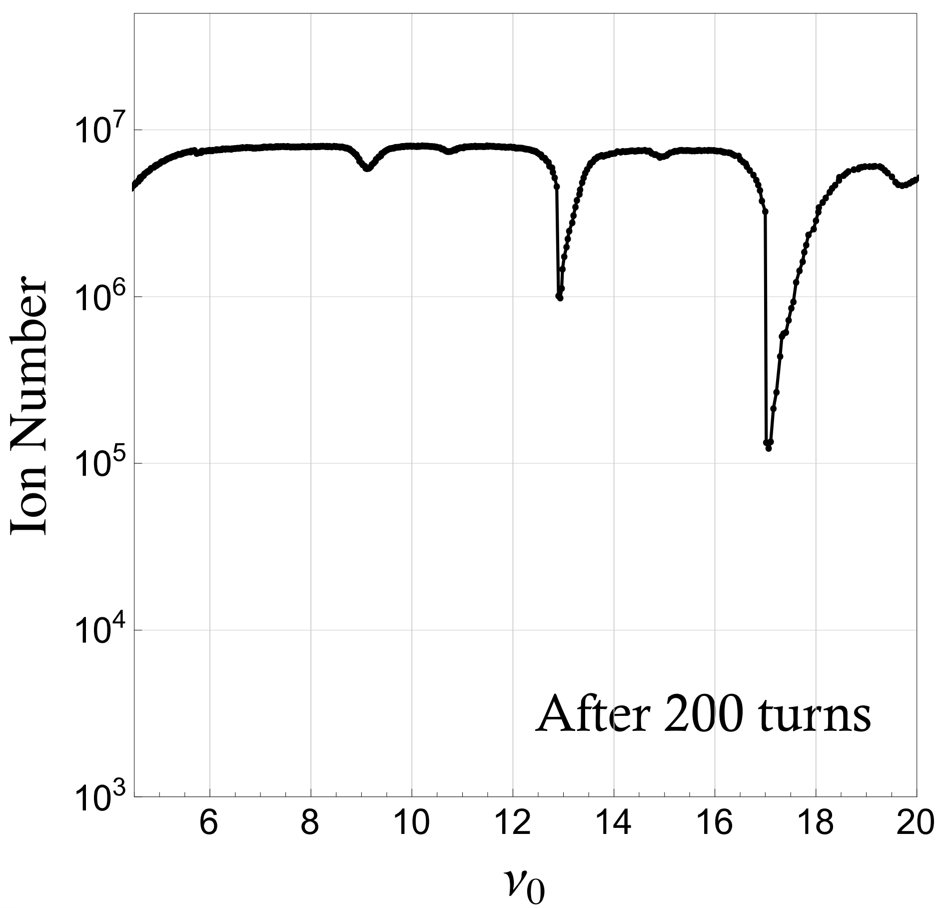


50 x Sinwave (with error fields)



50 x Sinwave (with error fields)

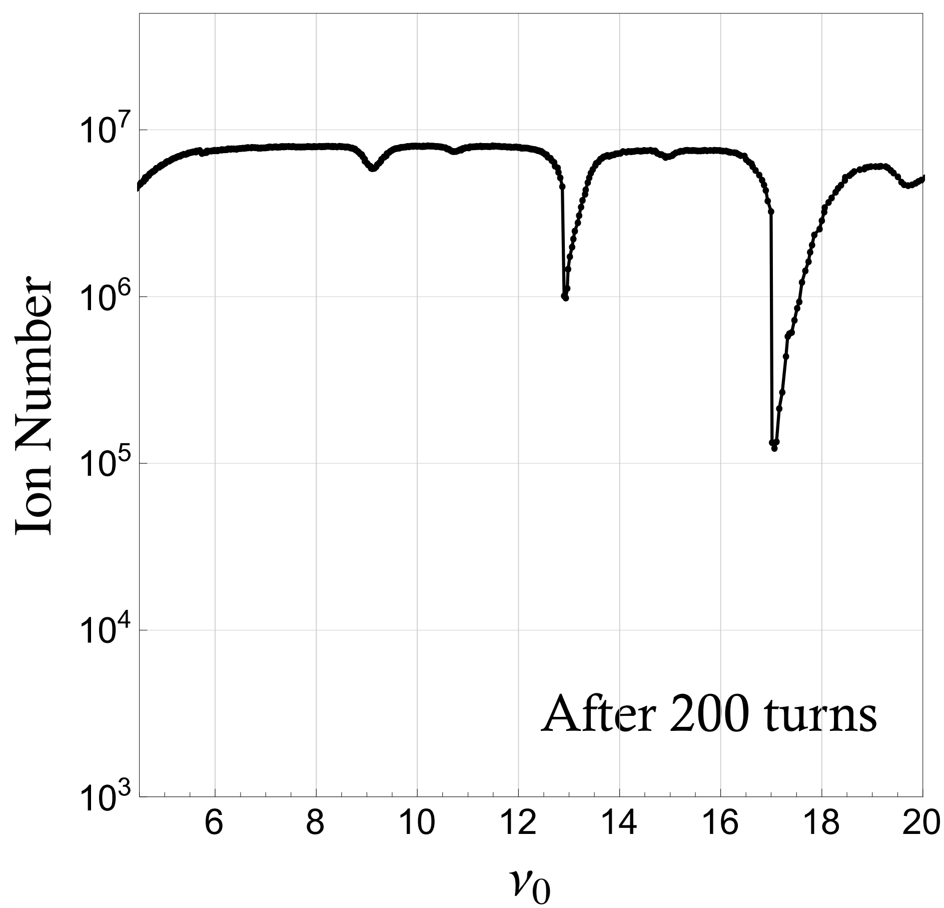
50-fold symmetric case



50 x Sinwave (with error fields)

50-fold symmetric case

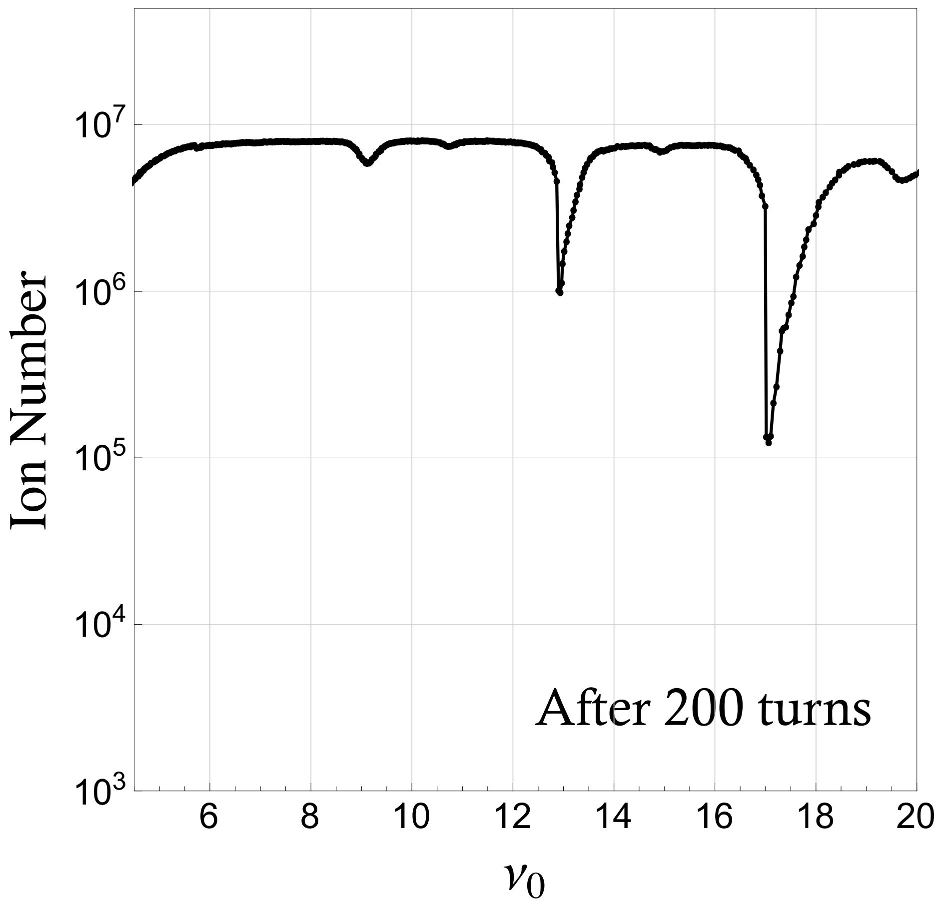
A perturbation pulse added in every 50 sinusoidal periods !

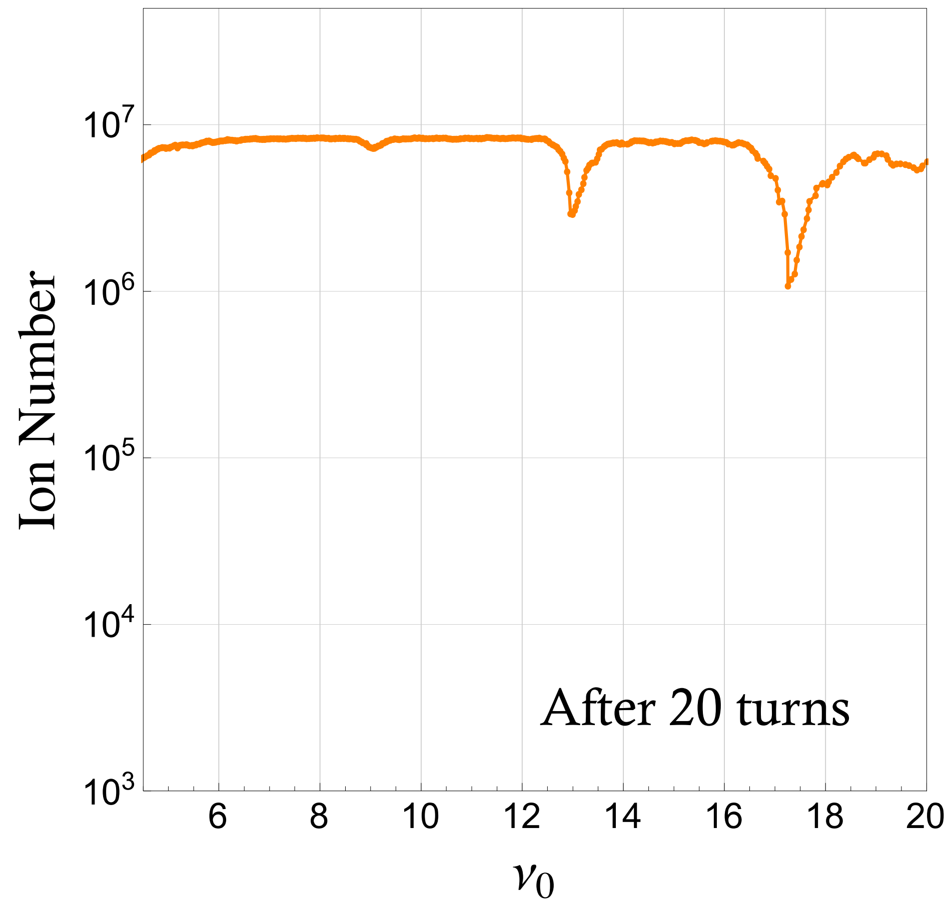


50 x Sinwave (with error fields)

50-fold symmetric case

A perturbation pulse added in every 50 sinusoidal periods !





50 x Sinwave (with error fields)

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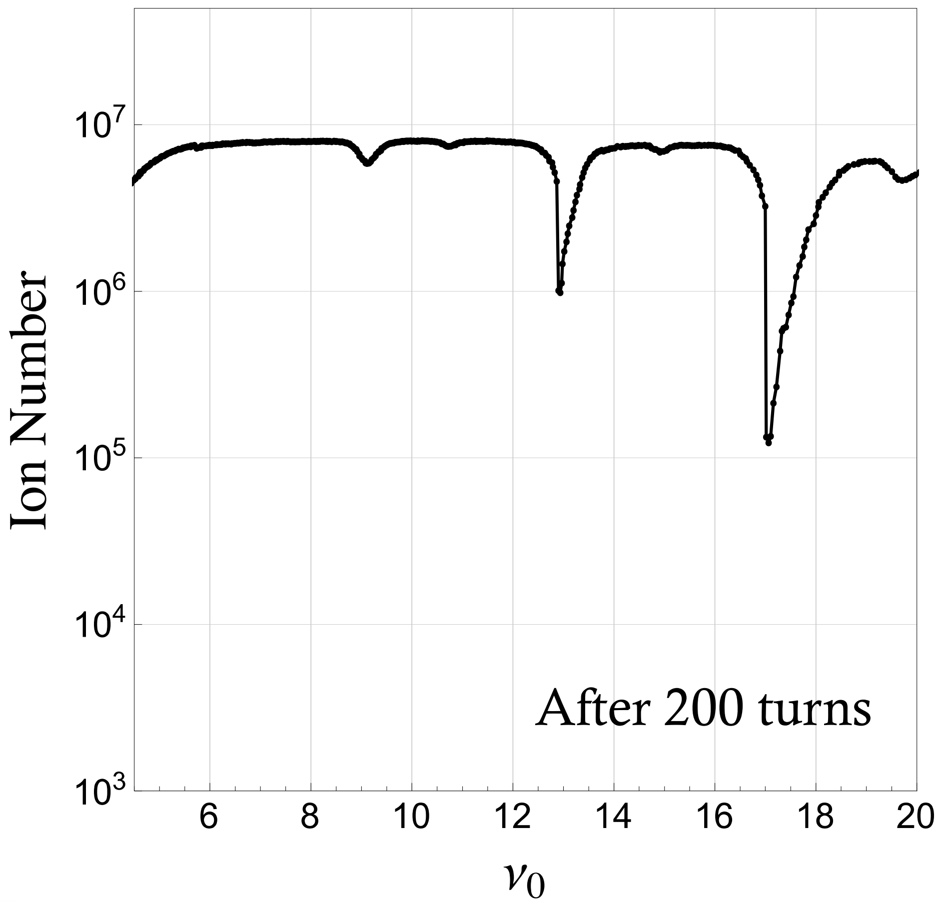
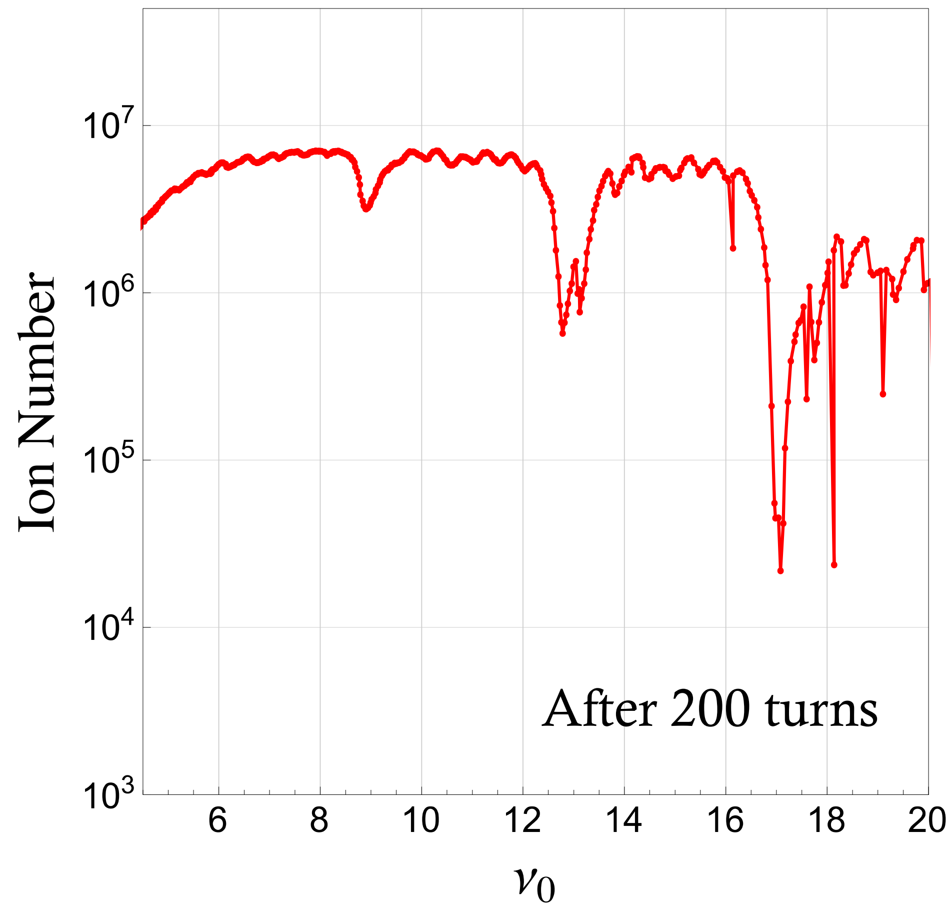
A perturbation pulse added in every 50 sinusoidal periods !

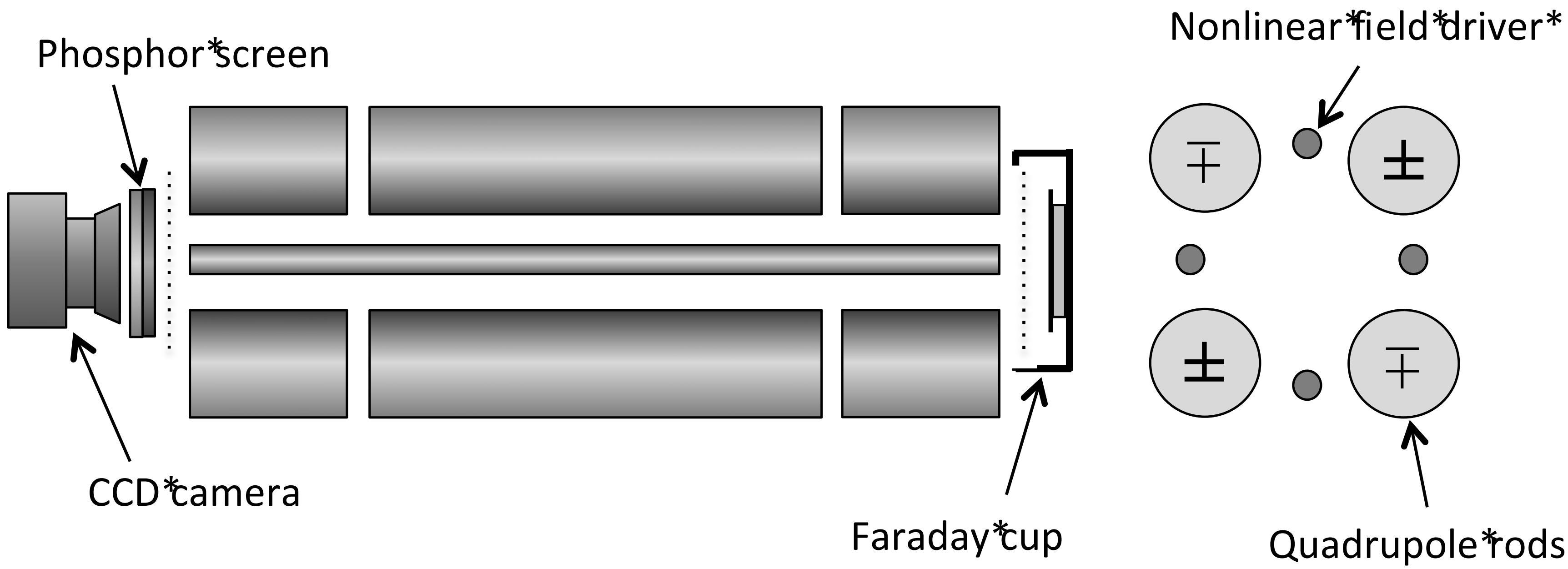




Nonlinear Multipole Trap

- In a regular LPT, nonlinear field components come mainly from misalignments (and non-hyperbolic surface) of the quadrupole rods, which means that we cannot control the strength and time structure of those nonlinear components independently of the linear focusing field.

- We are planning to construct a unique LPT with additional electrodes that produce controllable nonlinear driving fields.



Summary

- Non-neutral plasma traps are useful in exploring a wide range of beam dynamics.
- Three independent S-POD systems based on compact linear Paul traps have been developed at Hiroshima University and employed for various beam physics experiments.
- We have experimentally explored linear and nonlinear resonance instabilities in several standard AG transport channels (sinusoidal, doublet, triplet, FDDF).
- We have confirmed particle losses due to nonlinear coupling resonances, the effect of lattice symmetry breaking, the space-charge-induced shifts of stop bands, etc.
- 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.)