INTENSITY EFFECTS IN THE FORMATION OF STABLE ISLANDS IN PHASE SPACE DURING THE MULTI-TURN EXTRACTION PROCESS AT THE CERN PS

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5 July 2016

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- Introduction
- Space charge model
- Boundary condition
- Toward quantitative comparison
- Summary

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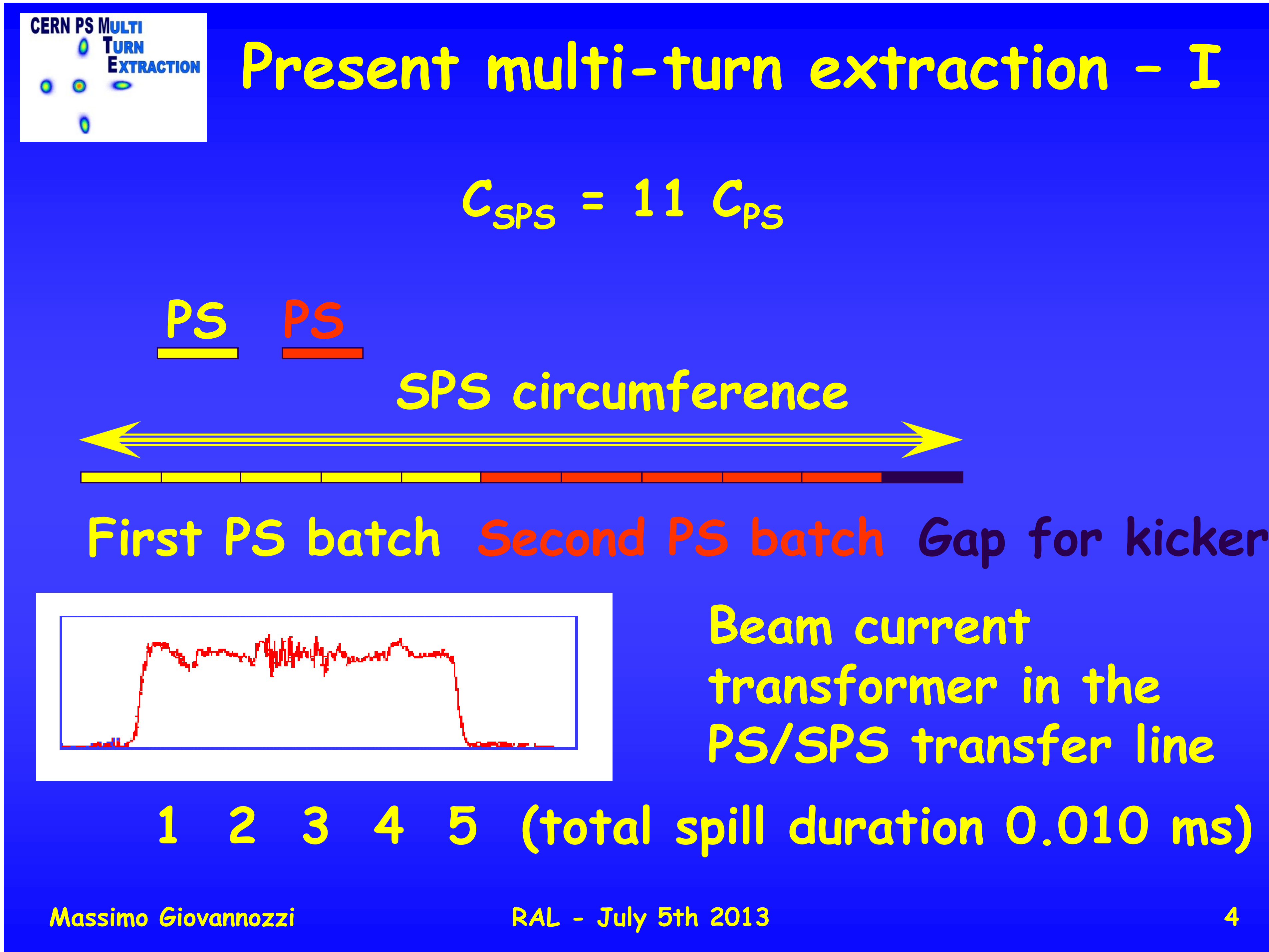
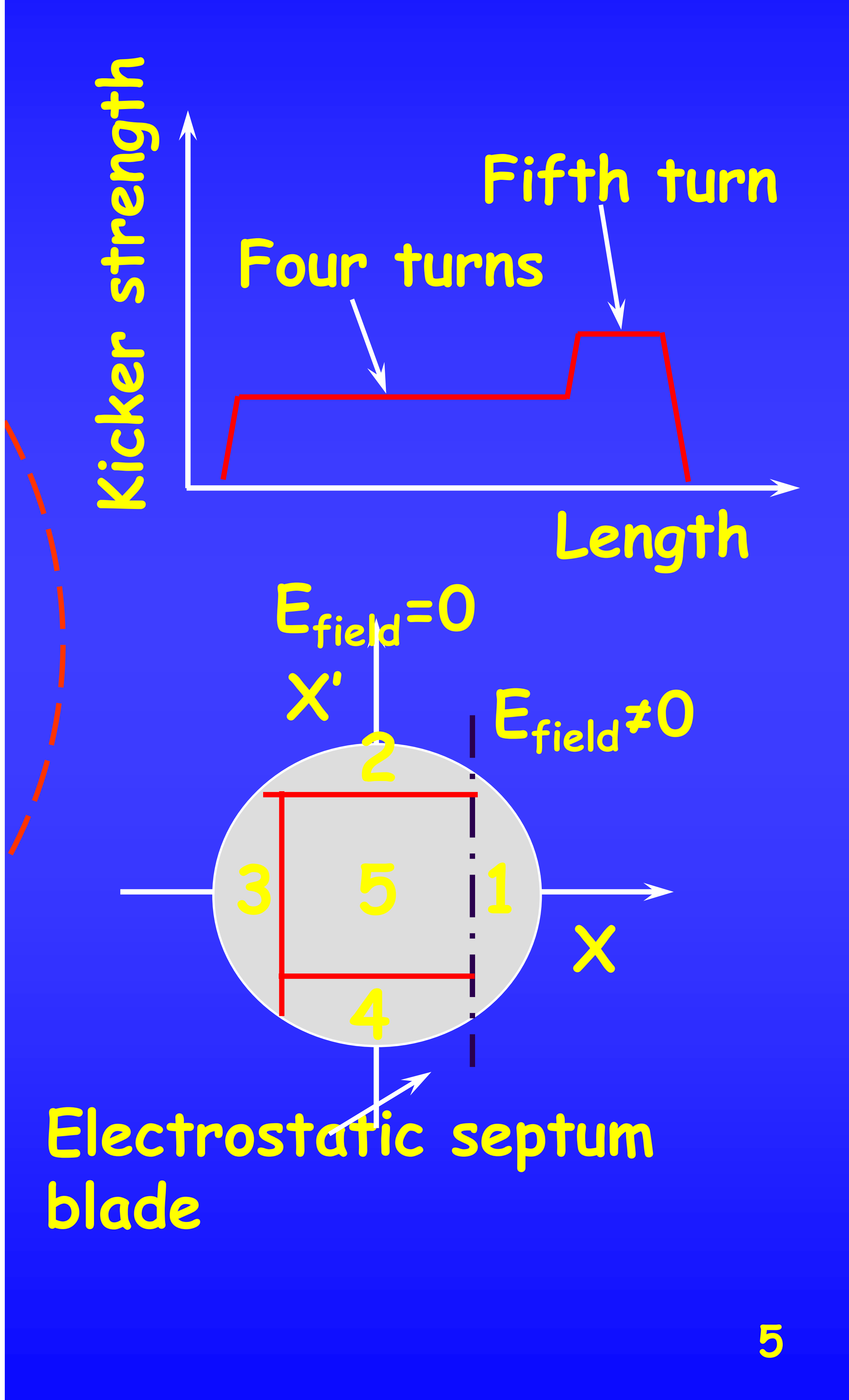
What is MTE?


CERN PS MULTI TURN EXTRACTION
Present multi-turn extraction - I
$C_{SPS} = 11\ C_{PS}$
PS
PS
SPS circumference
First PS batch
Second PS batch
Gap for kicker
Beam current transformer in the PS/SPS transfer line
1 2 3 4 5 (total spill duration 0.010 ms)
Massimo Giovannozzi
RAL - July 5th 2013
4

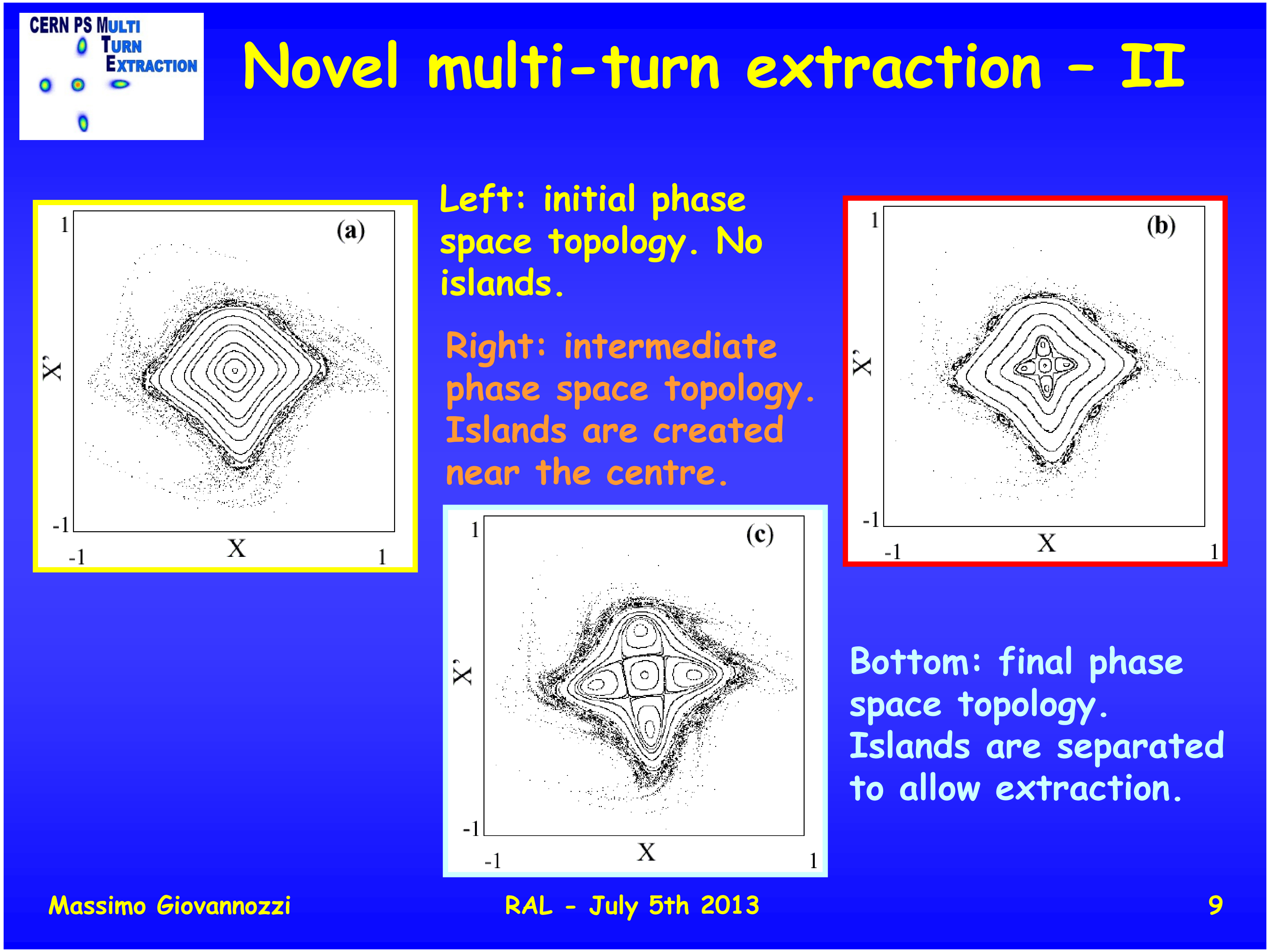
What is MTE?



Kicker strength
Fifth turn
Four turns
Length
$E_{field}=0$
X'
$E_{field}\neq0$
2
3
5
1
4
X
Electrostatic septum blade
5

extraction – I
e
tch
Gap for kicker
n current
sformer in the
SPS transfer line
uration 0.010 ms)
4

What is MTE?


CERN PS MULTI TURN EXTRACTION
Novel multi-turn extraction – II
Left: initial phase space topology. No islands.
Right: intermediate phase space topology. Islands are created near the centre.
Bottom: final phase space topology. Islands are separated to allow extraction.
(a)
(b)
(c)
X
X'
1
-1
Massimo Giovannozzi
RAL - July 5th 2013
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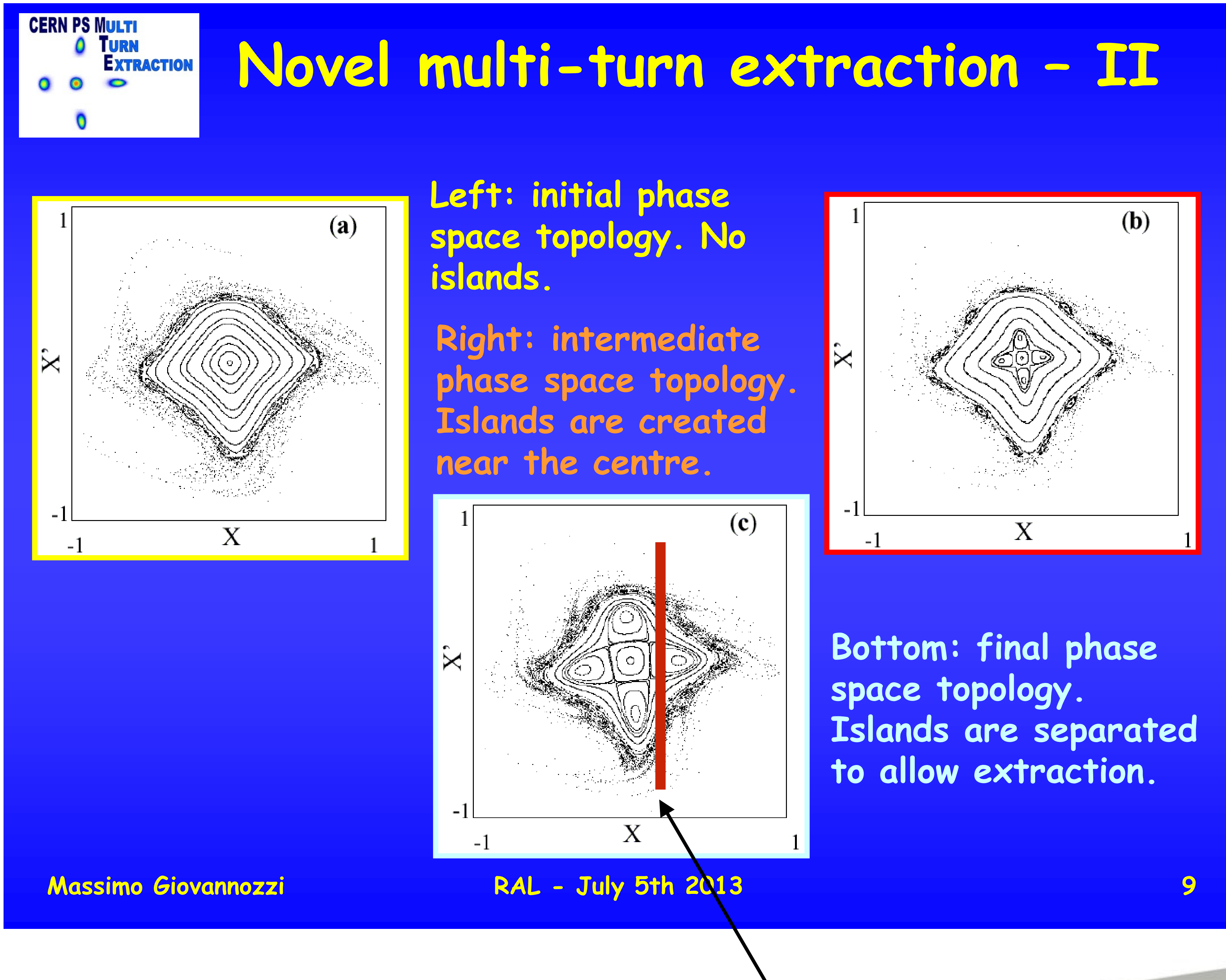
What is MTE?



septum

Creating beamlets

Two ingredients to create beamlets (resonance islands)

M. Giovannozzi

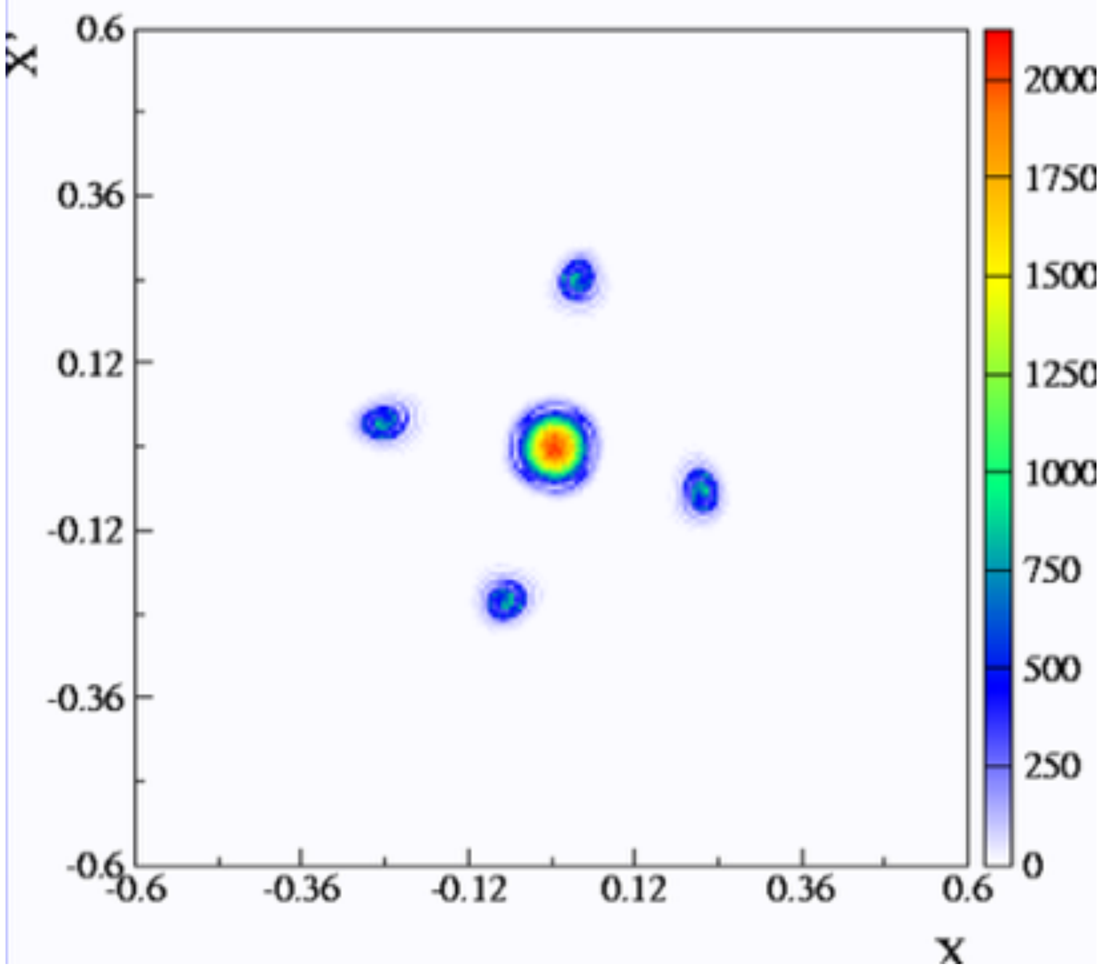
- Nonzero harmonic contents of multipole

  e.g. Octupole with 25th harmonics excites 4Qx=25.

  Determine the size of islands.

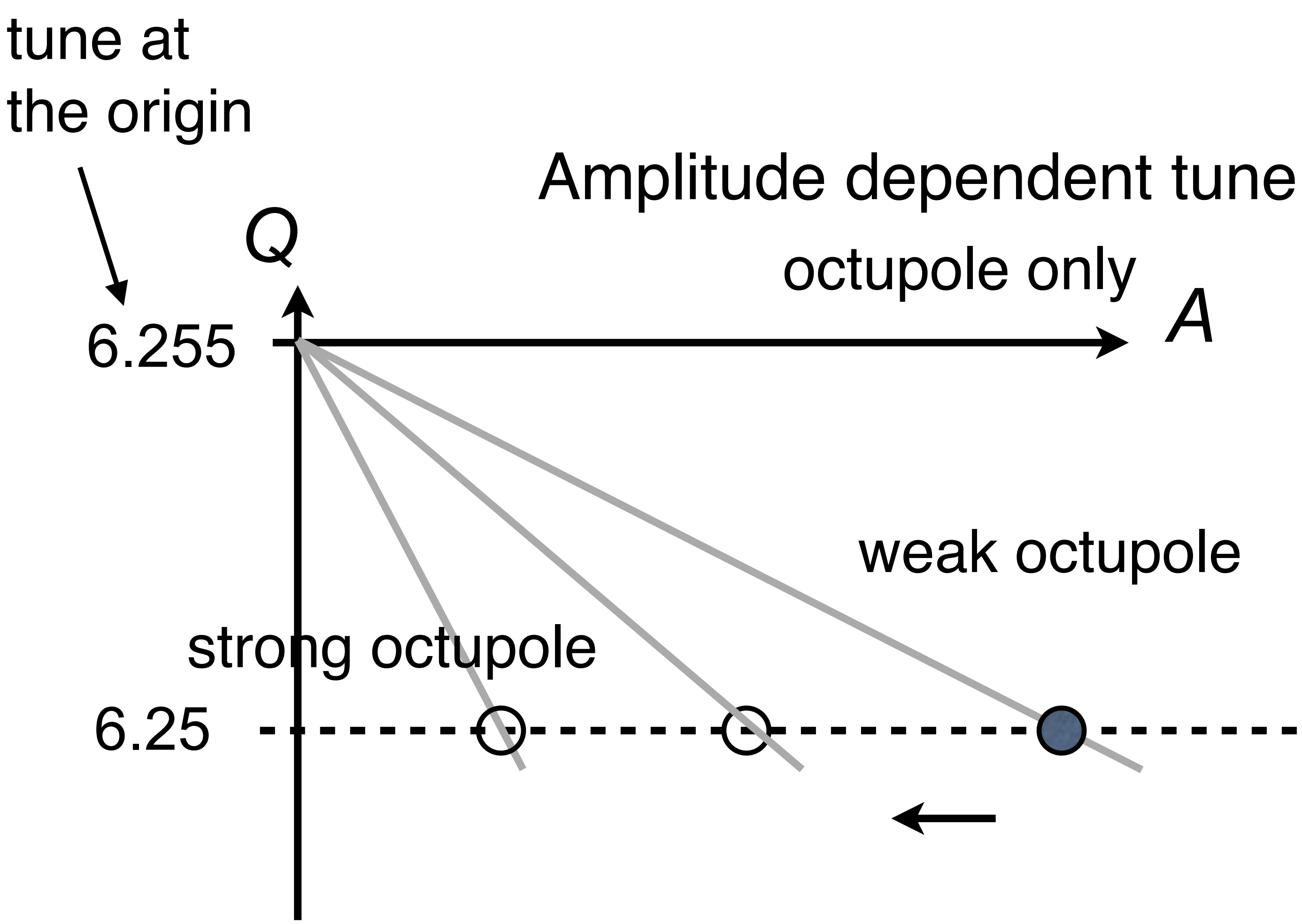
- Amplitude dependent tune shift

  Determine the position of islands.



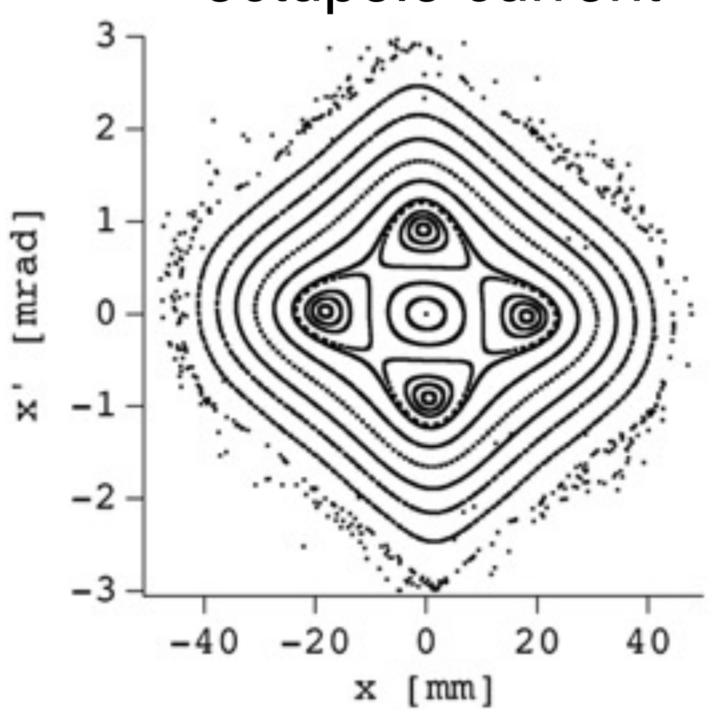
N.B. In the CERN experiment, sextupole as well as octupole are used to adjust x-y coupling and the islands size and position.

Position vs strength of nonlinearity

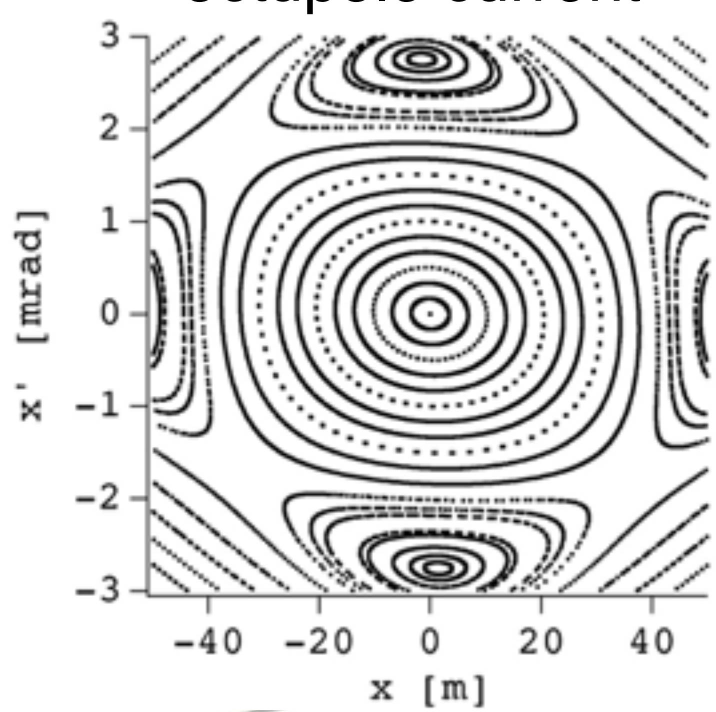


Fixed point should move inward when octupole strength increases.

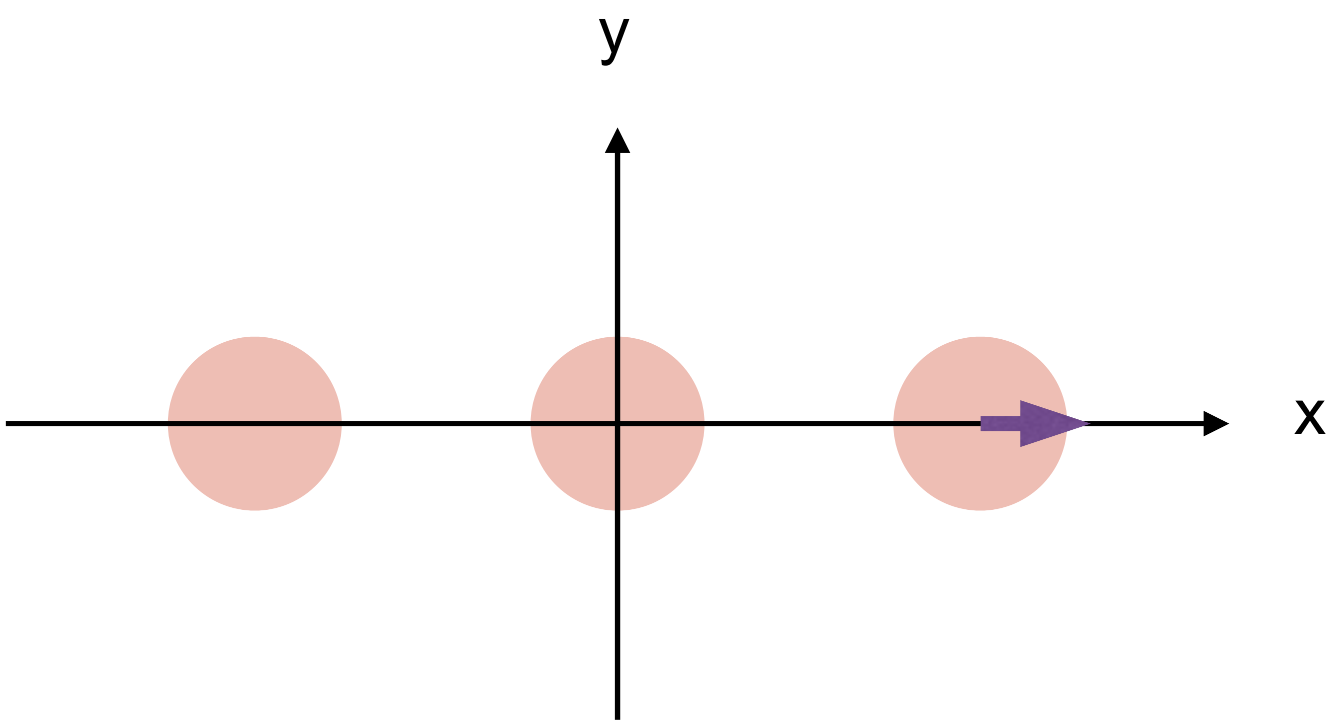
octupole current = -20 A



octupole current = -1 A



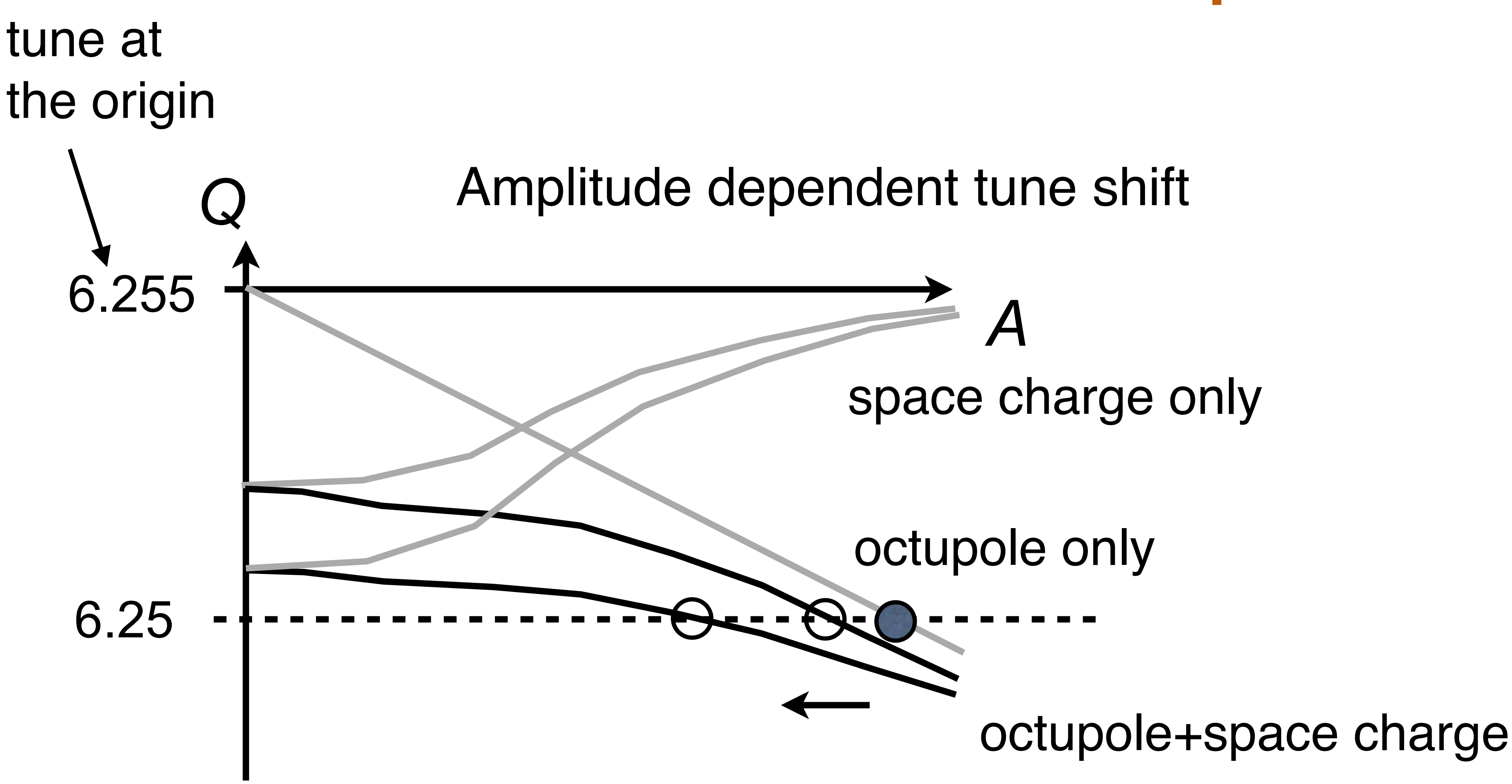
Space charge
repulsive force



$$F_d = (1 - \beta^2)\frac{3e\lambda}{4\pi\epsilon_0}\frac{1}{x}$$

Repulsive coulomb interaction weakens restoring force and cause negative tune shift

Position vs strength of nonlinearity and space charge



Negative tune shift due to space charge is added to tune shift due to octupole.

Fixed point should move <u>inward</u> when intensity increases.

However, experimental observation is

Gilardoni, Giovannozzi and Hernalsteens,
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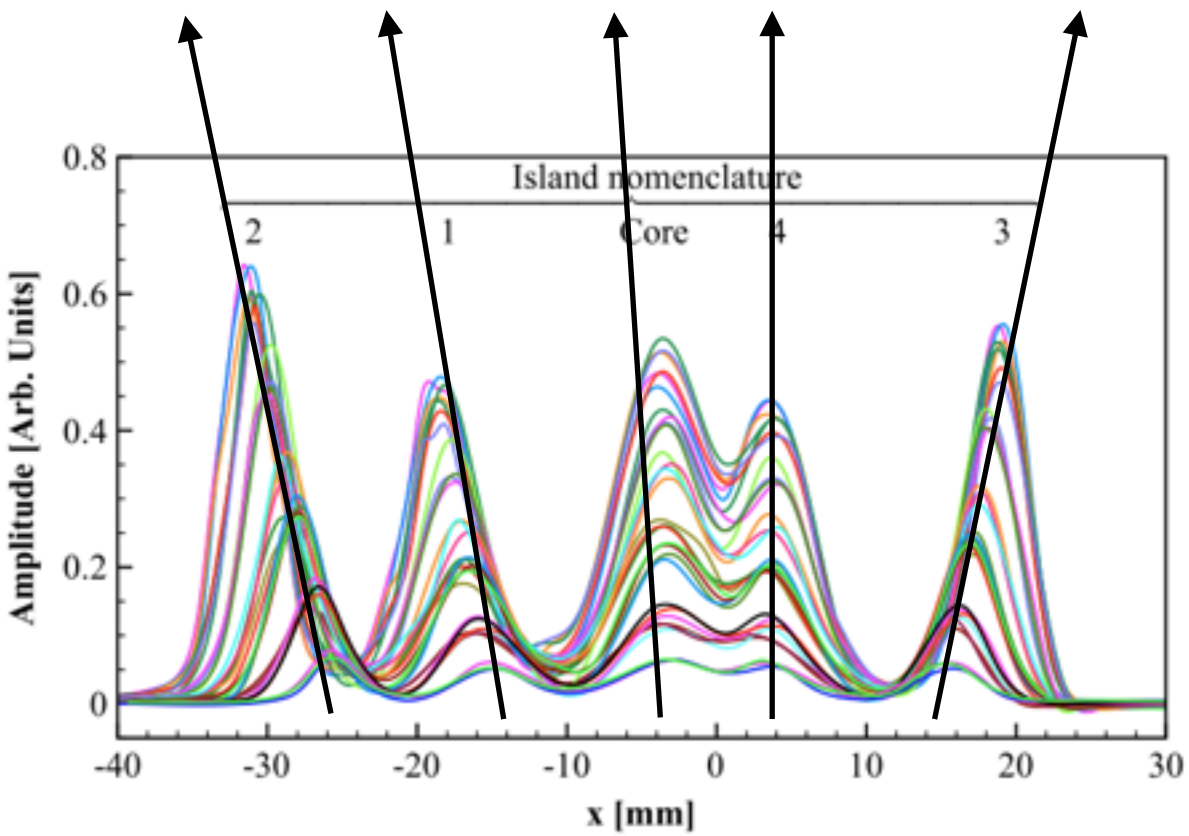

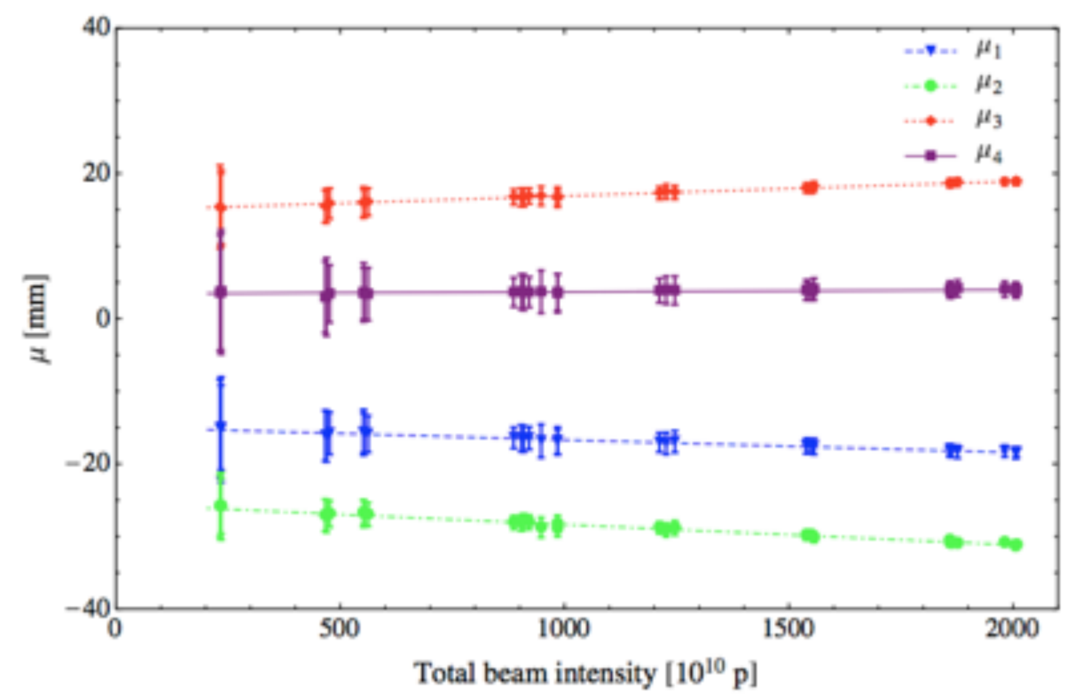

Beamlets move outward with beam current.

Why the beamlets move the opposite direction to our simple model ?

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Simple space charge model

semi-frozen space charge

- Particle in Cell (PIC) simulation for multiple beamlets is hard and time consuming.
- Beamlets are well separated (at least in phase space).
- Space charge interaction is basically between the beamlet centre.
- There is no beam loss.

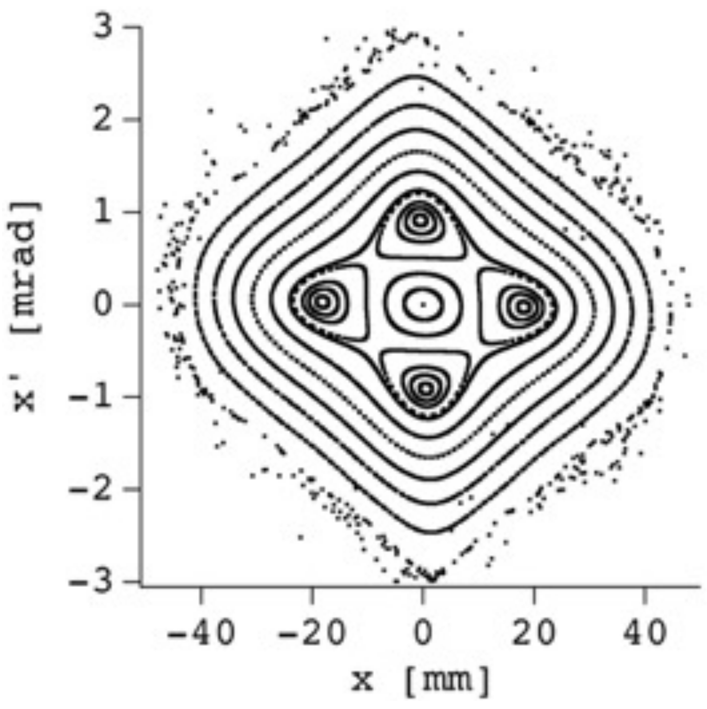
Fix the charge distribution. → Frozen space charge model.

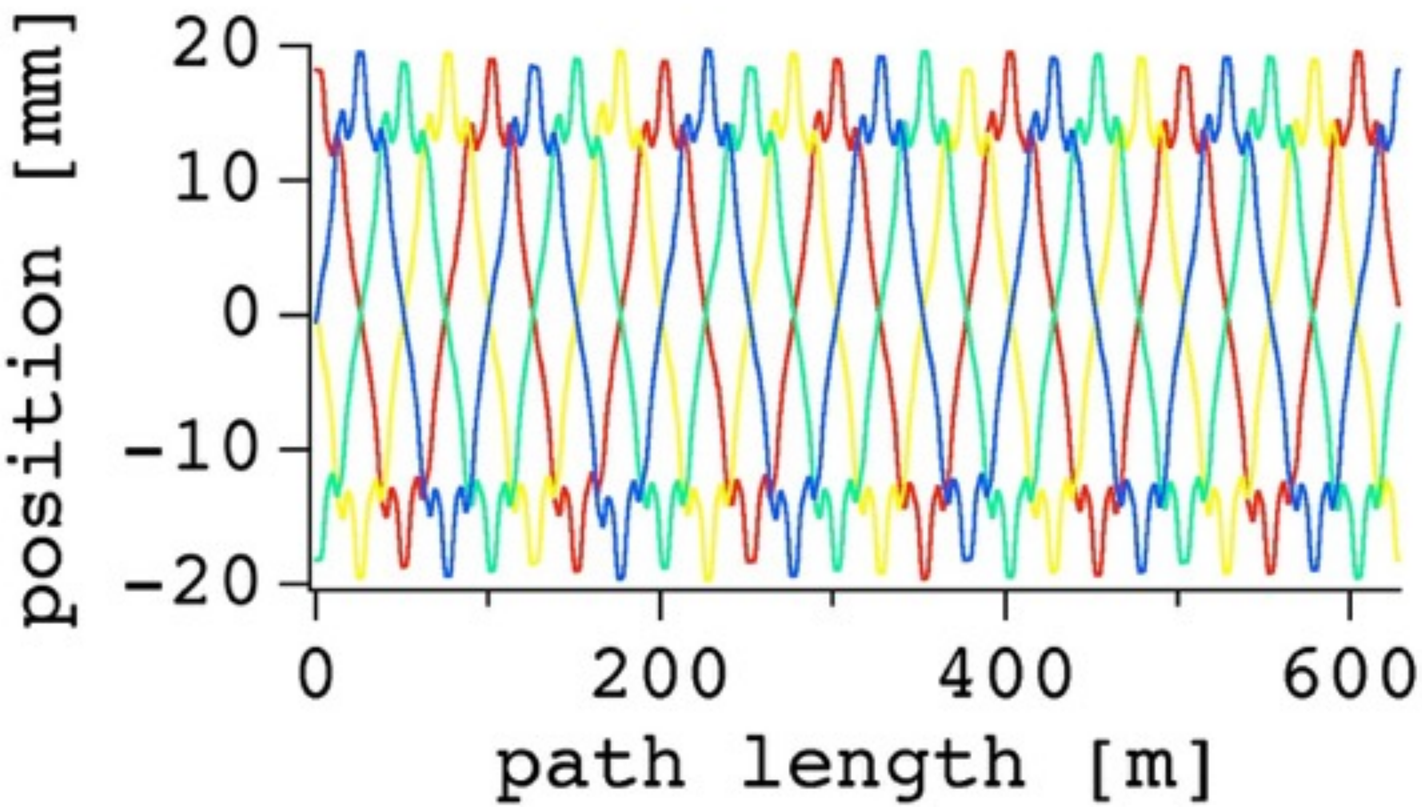
Calculate beamlet position iteratively. → Self-consistent model.

Simple space charge model

beamlets position

Trajectory of four beamlets oscillate around the ring, and can be calculated as one of closed orbits coming back to the same point after 4 turns. This gives the position of fixed points around the ring.





Simple space charge model

iteration

Distribute space charge potential along closed orbit.

Calculate closed orbit including space charge potential.

Check if the closed orbit changes.

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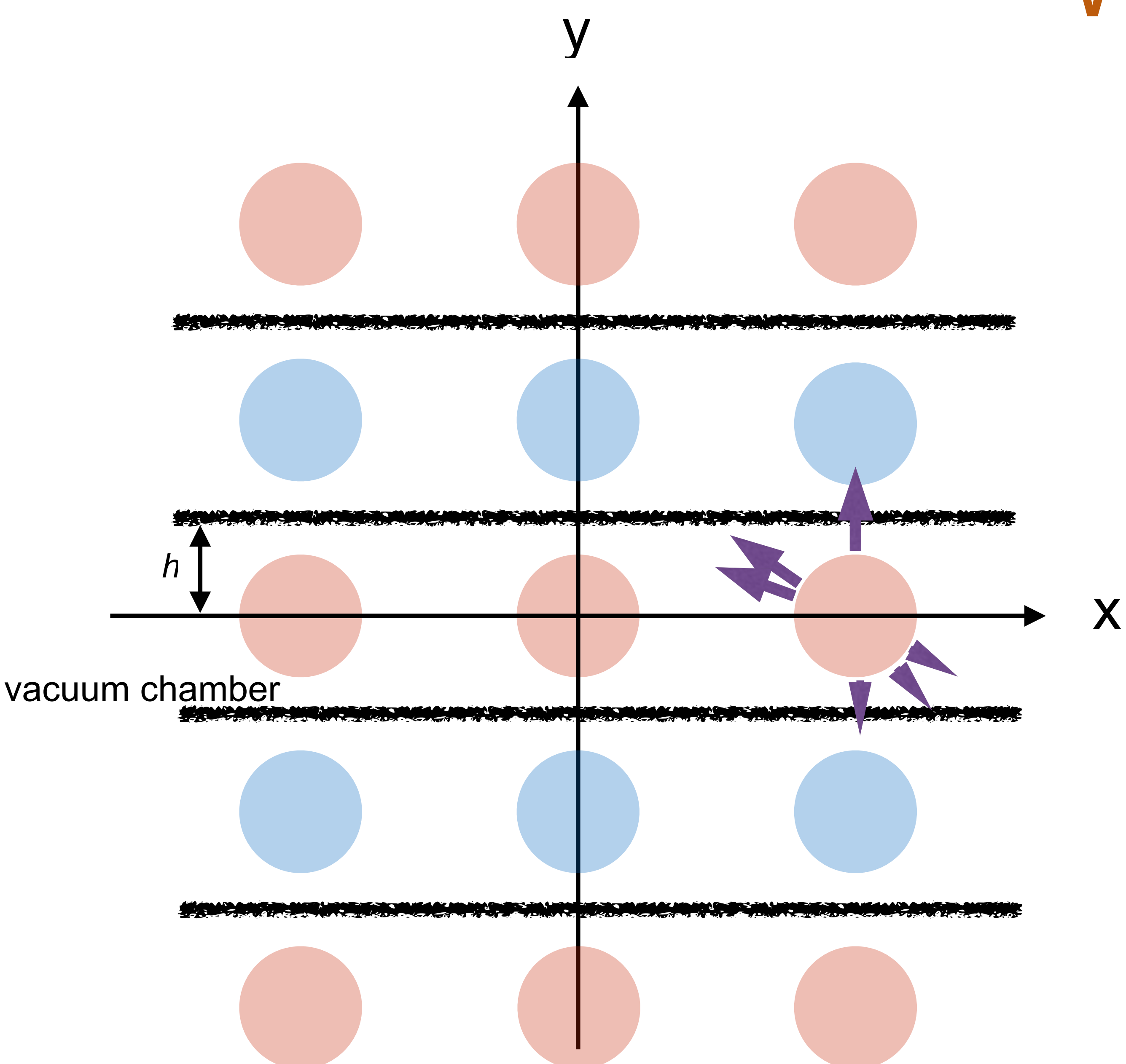
With boundary condition

image charge



Parallel plates model.

Image charge on the vacuum chamber. The net force always strengthens restoring force in horizontal.

$$F_{ie} = -\frac{e\lambda}{\pi\epsilon_0}[\frac{x}{(2h)^2+x^2} + \frac{2x}{(2h)^2+(2x)^2} - \frac{x}{(4h)^2+x^2} - \frac{2x}{(4h)^2+(2x)^2} + ...]$$

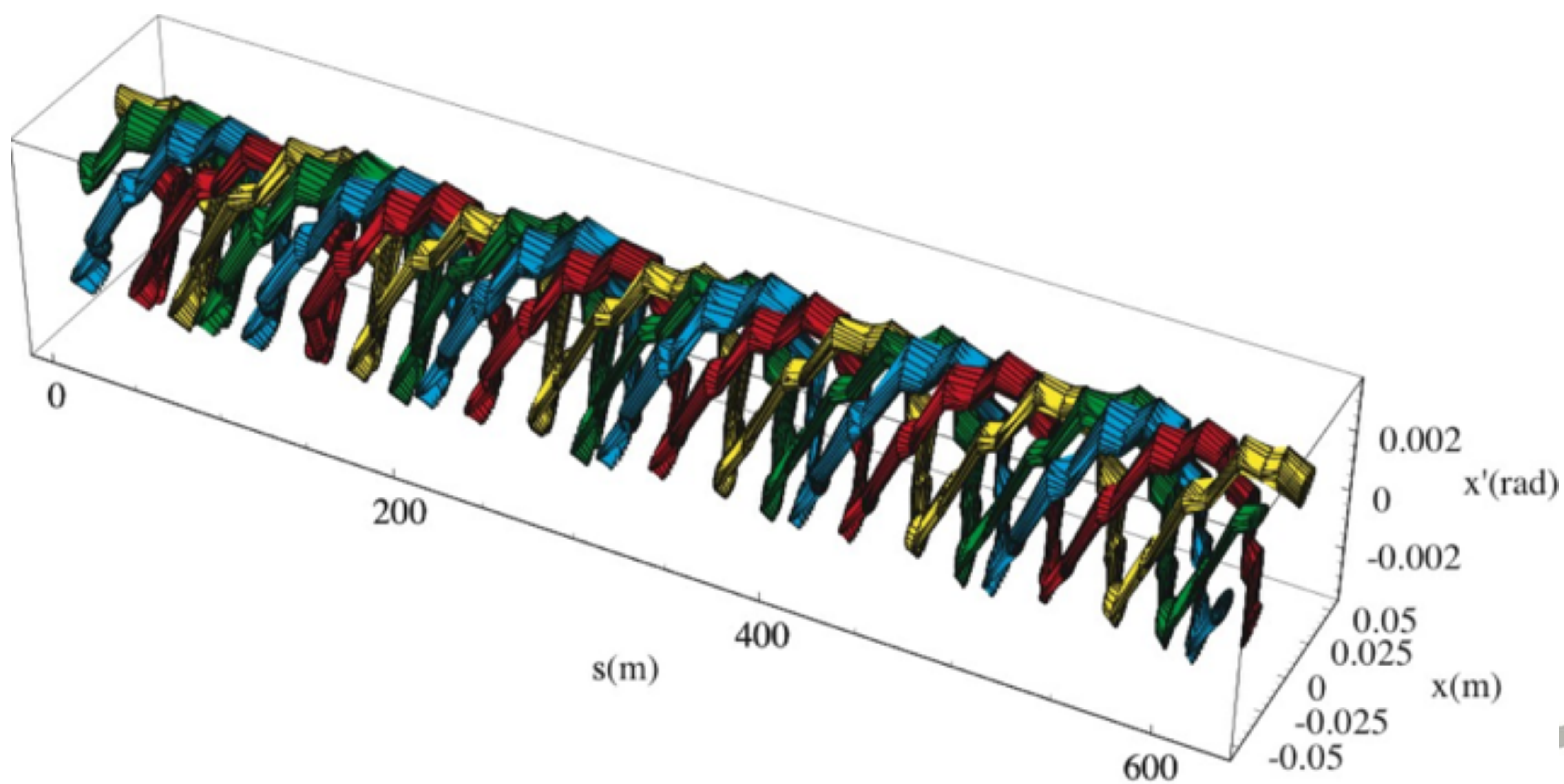
1st layer 2nd layer

With boundary condition
DC magnetic field

Beamlets orbits oscillate around the ring, but fix in time.

There is no AC magnetic fields.

Therefore magnetic field penetrates vacuum chamber.



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With boundary condition
PS lattice

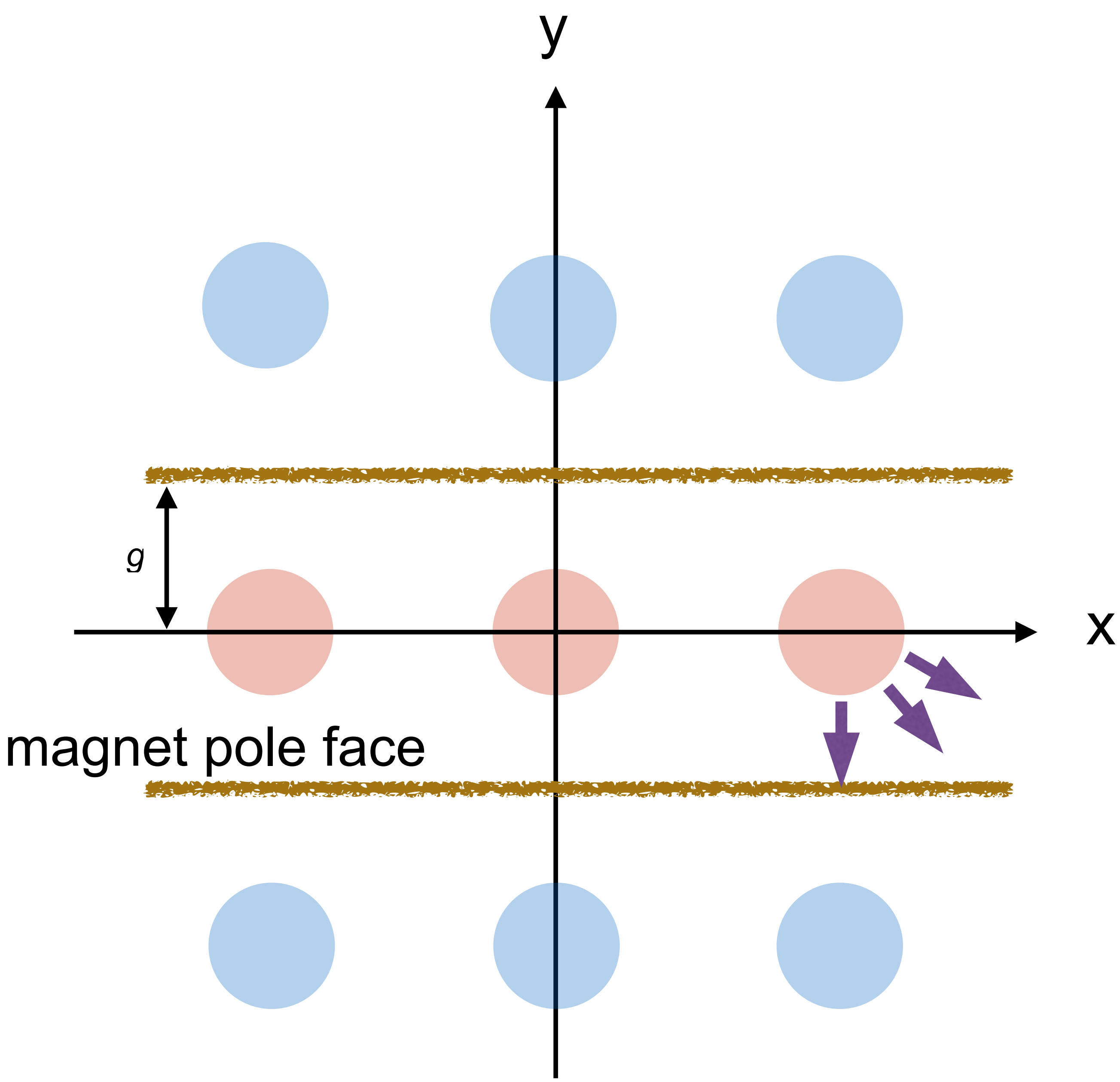
Filling factor of magnet is 80% of the circumference.

Image current are not negligible.

CERN PS magnet

With boundary condition

image current



Parallel plates model.

Image current on the magnet pole. This weakens restoring force and causes negative tune shift.

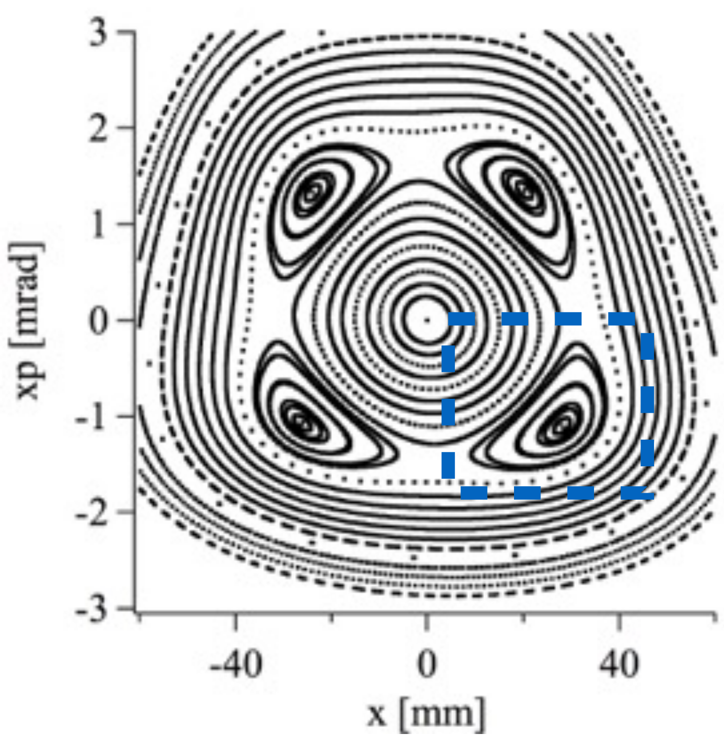
$$F_{im} = \beta^2 \frac{e\lambda}{\pi\epsilon_0}\left[\frac{x}{(2g)^2+x^2} + \frac{2x}{(2g)^2+(2x)^2} - \frac{x}{(4g)^2+x^2} - \frac{2x}{(4g)^2+(2x)^2} + \ldots\right]$$

1st layer 2nd layer

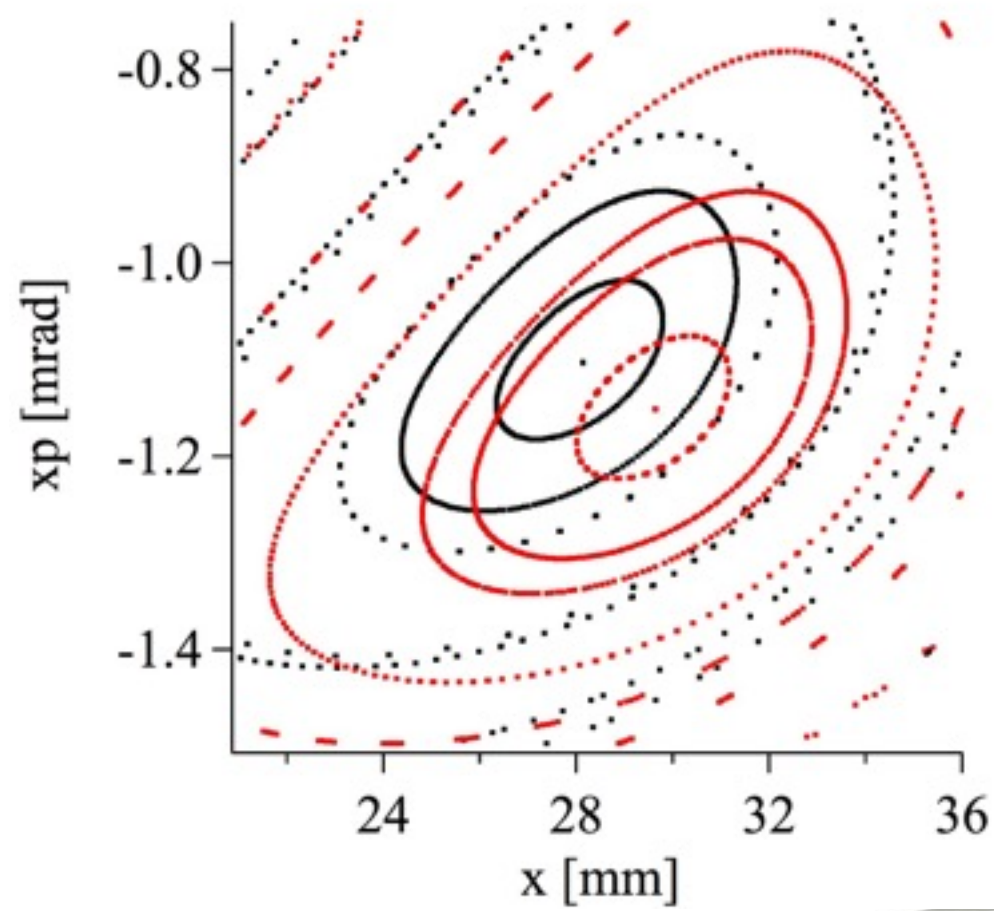
With boundary condition

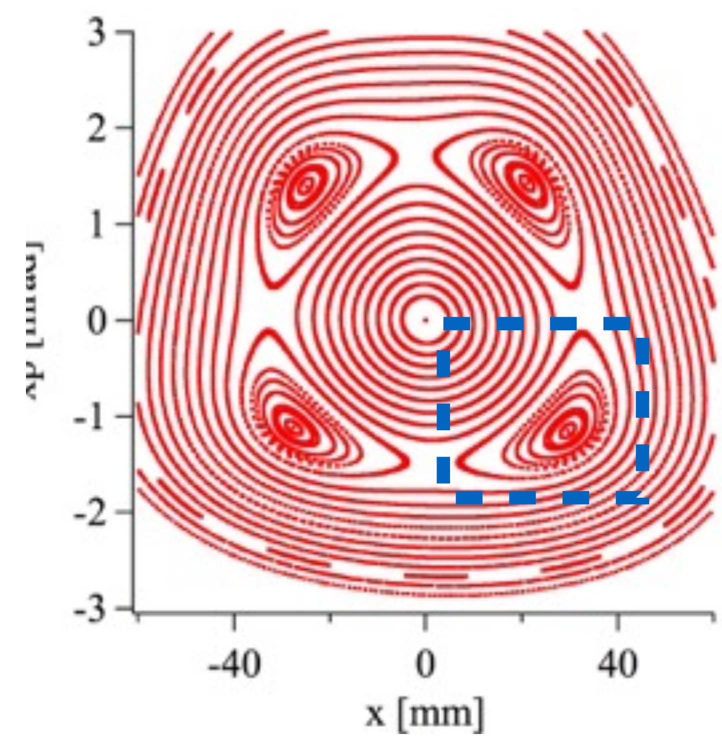
intensity dependence

All contributions from direct (-Q), image charge on vacuum chamber (+Q) and image current on magnet pole (-Q) combined moves the beamlets outward.



$0x10^{13}$





$3.27x10^{13}$

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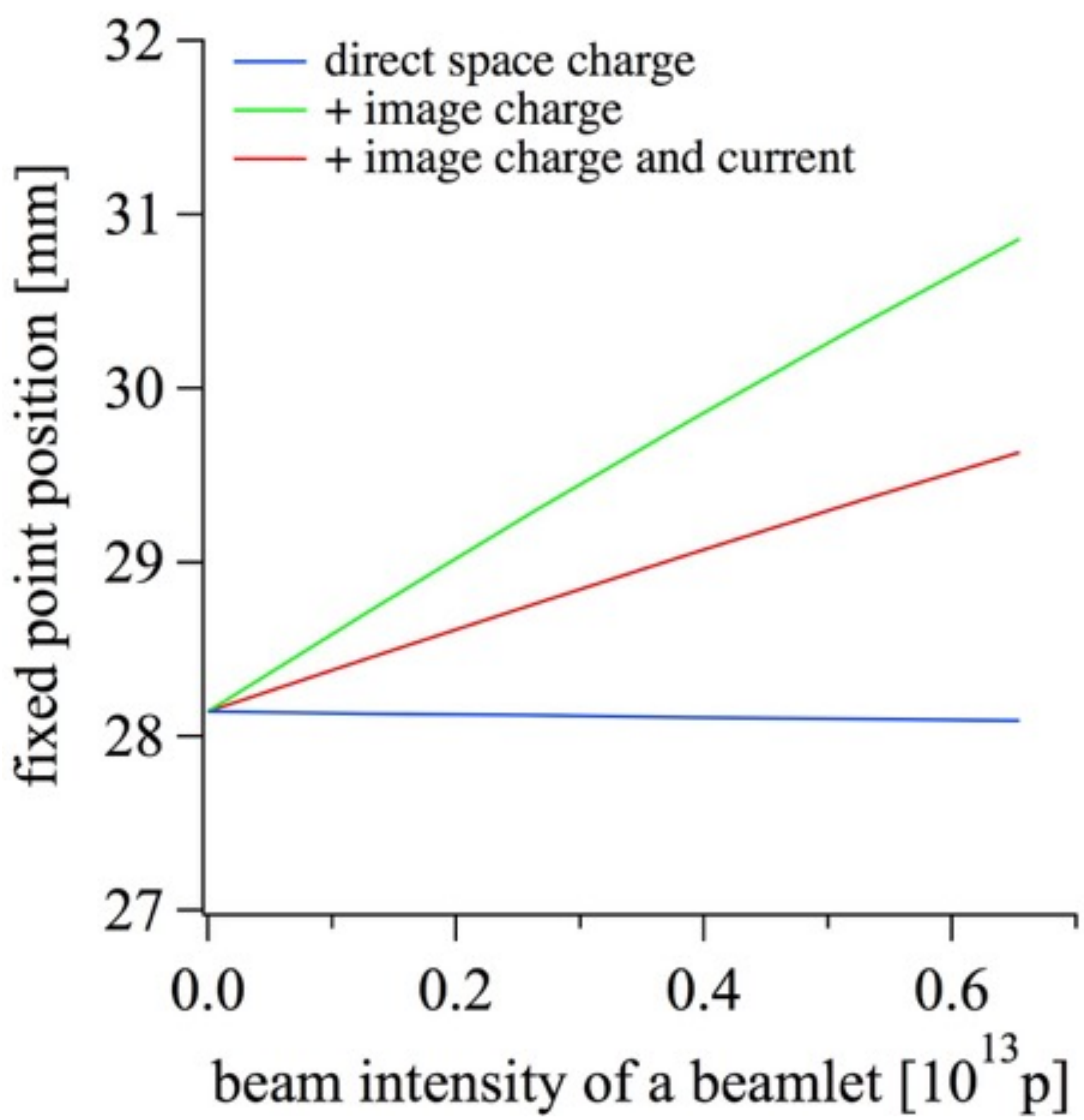
With boundary condition
intensity dependence

Direct space charge and image current push beamlets inward.

Image charge push beamlets outward.



Shift is almost linear with beam intensity.

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With boundary condition

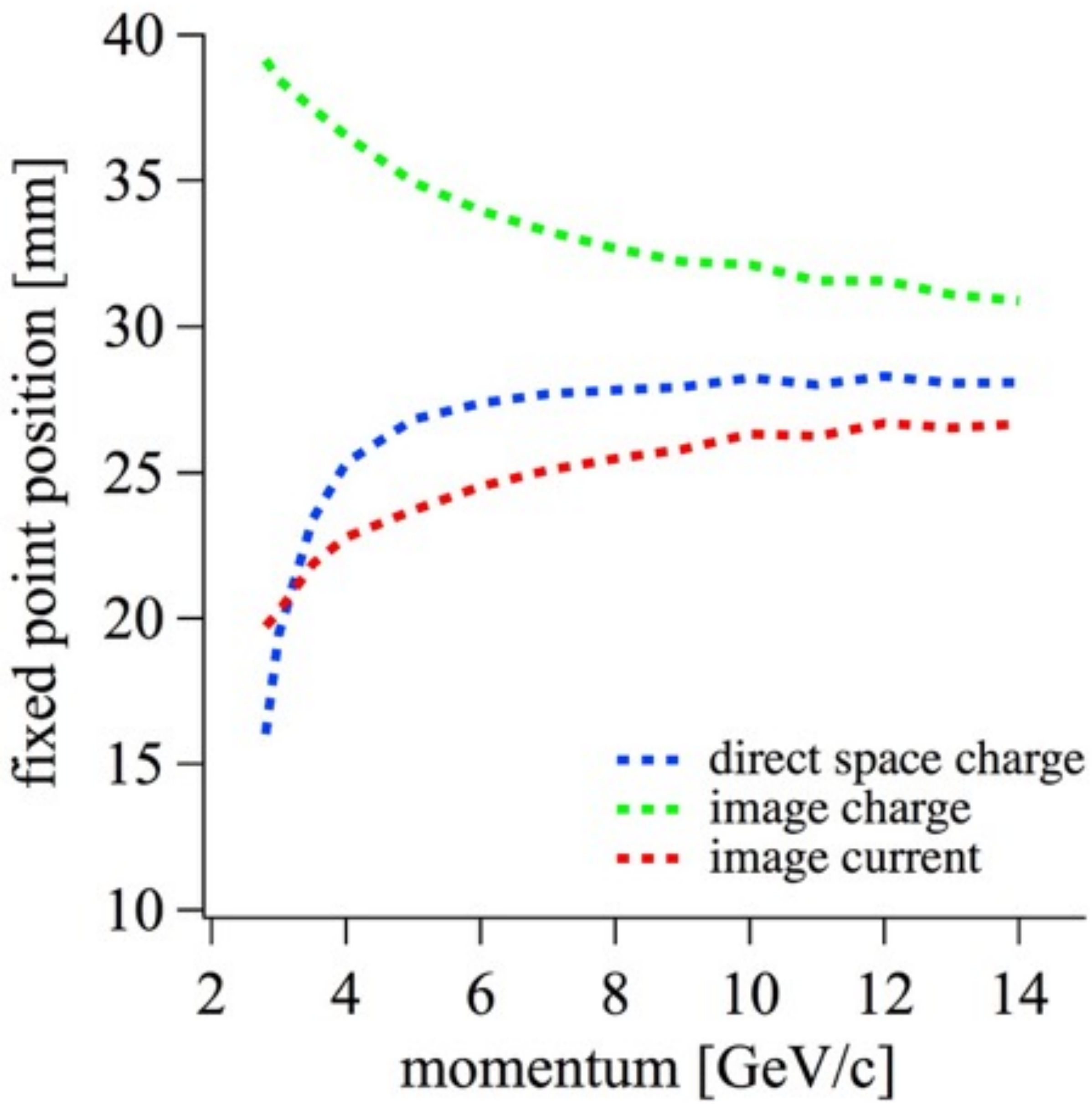
momentum dependence

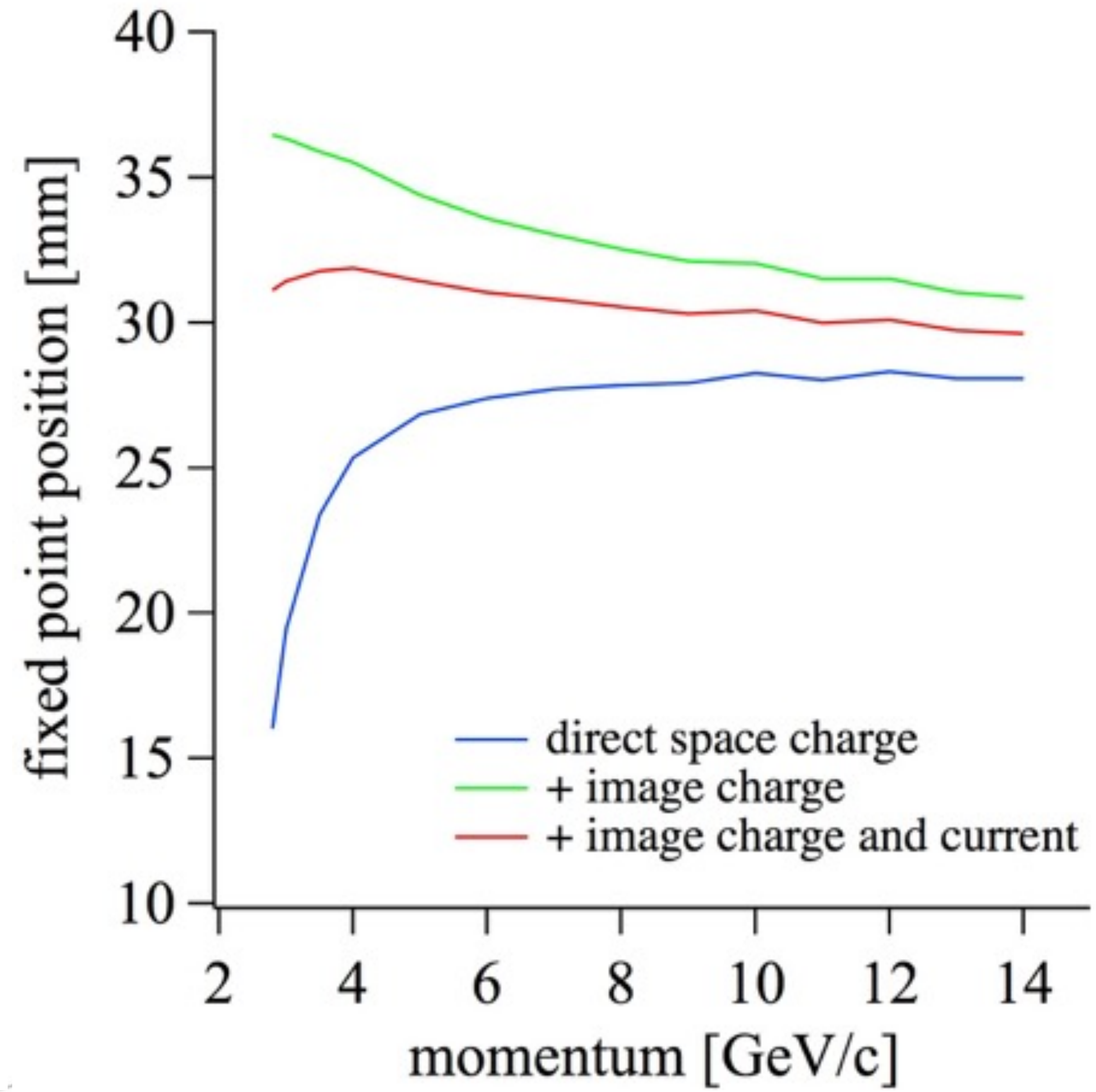
Direct space charge and image current push beamlets inward.

- Direct space charge is dominant at lower momentum.

Image charge push beamlets outward.

- Image charge is dominant at higher momentum.





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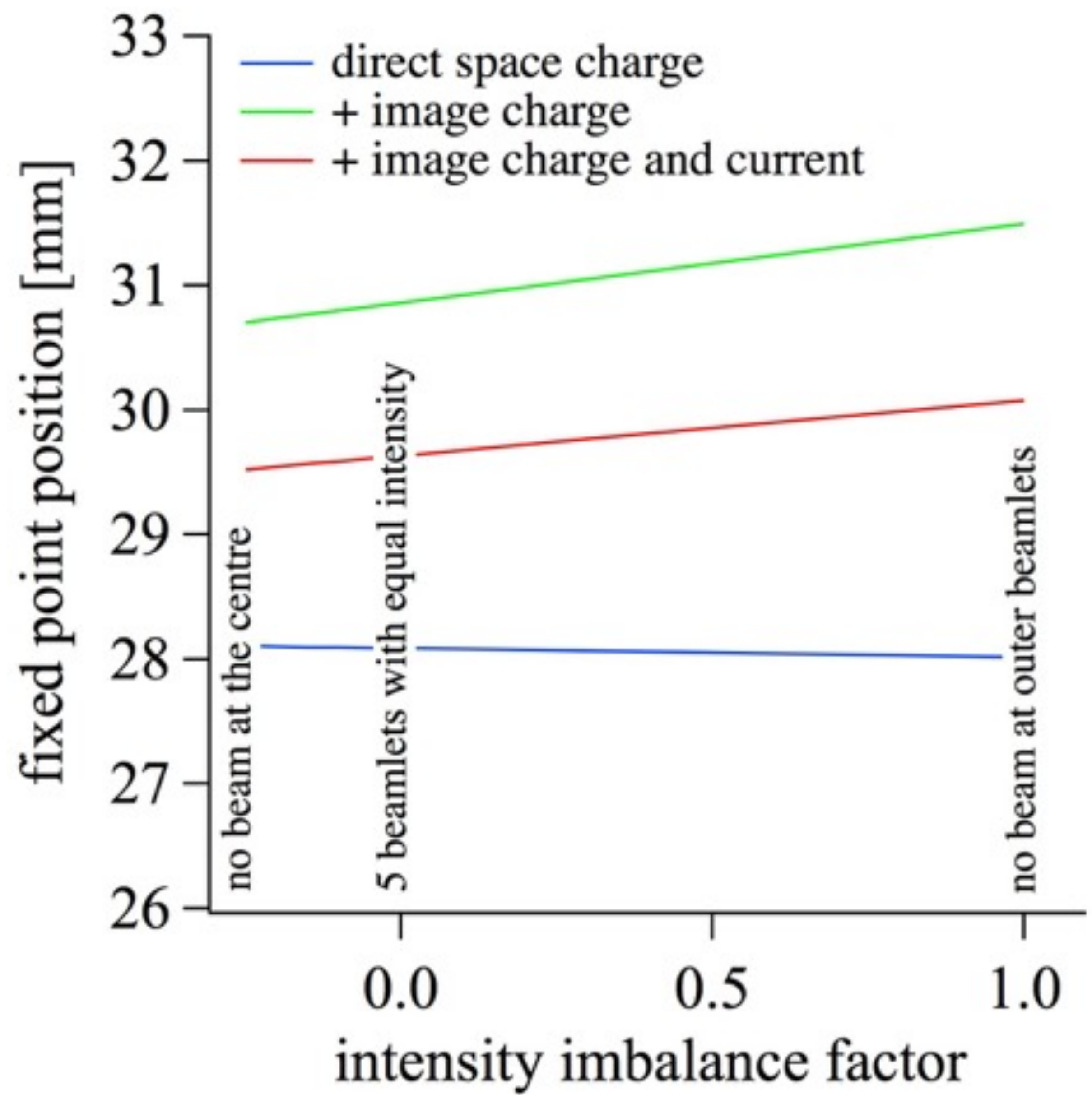
Unequal intensity

Unequal beam intensity change fixed points position but the dependency is rather small.



$$I_{core} = (1 + 4f) \times I_{core,eq}$$
$$I_{outer} = (1 + 4f) \times I_{outer,eq}$$

Intensity imbalance factor: *f*

f=-0.25: no beam in core beamlet

f=+1.0: no beam in outer beamlet

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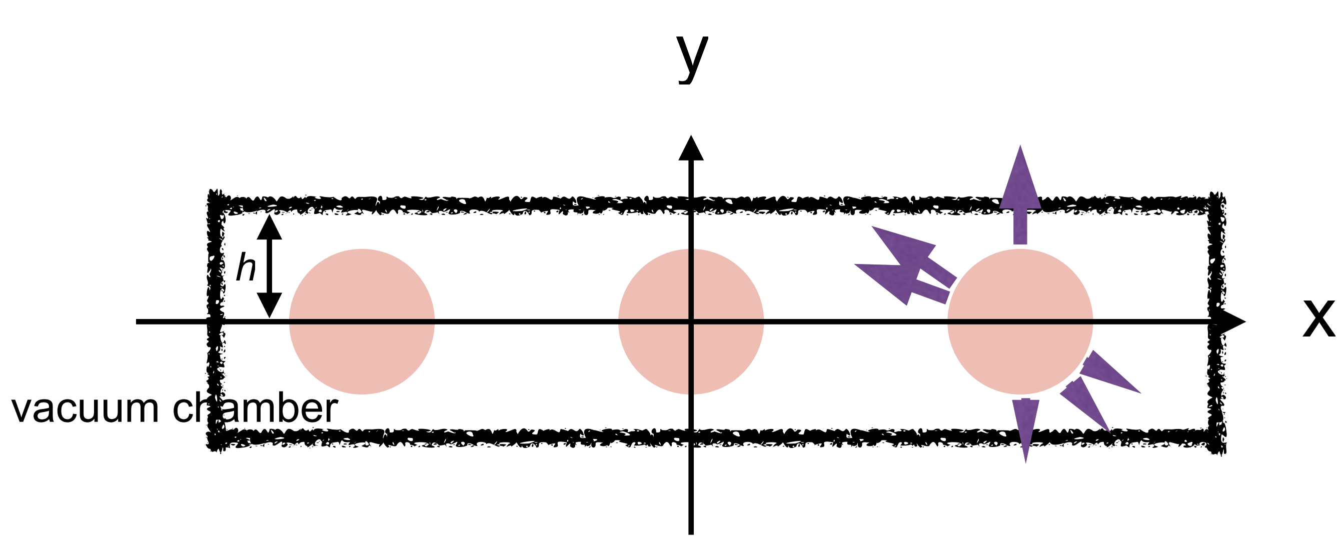
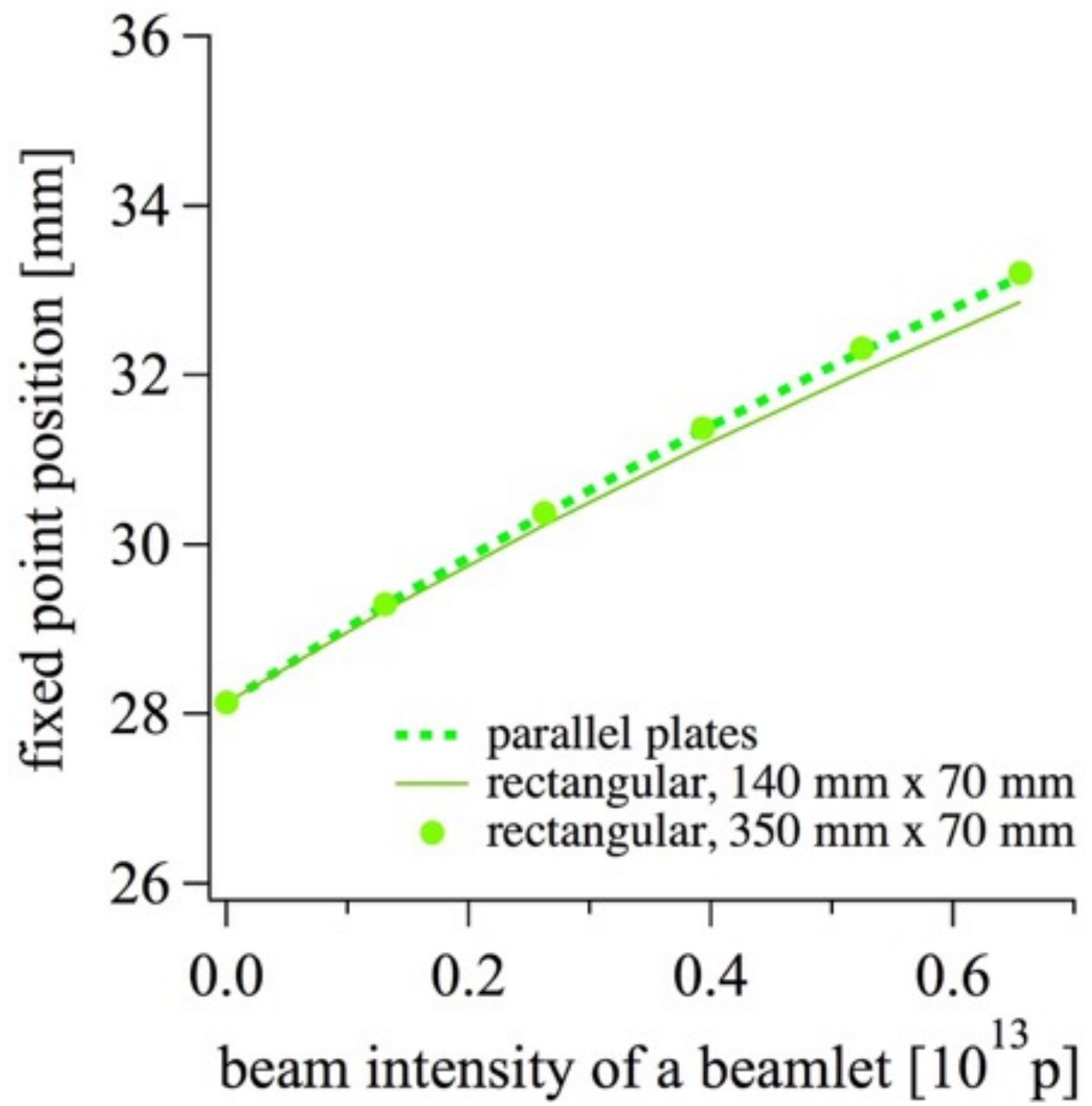
Rectangular boundary

As long as the beam stays away from vertical wall, existence of vertical wall does not change the dependence much.



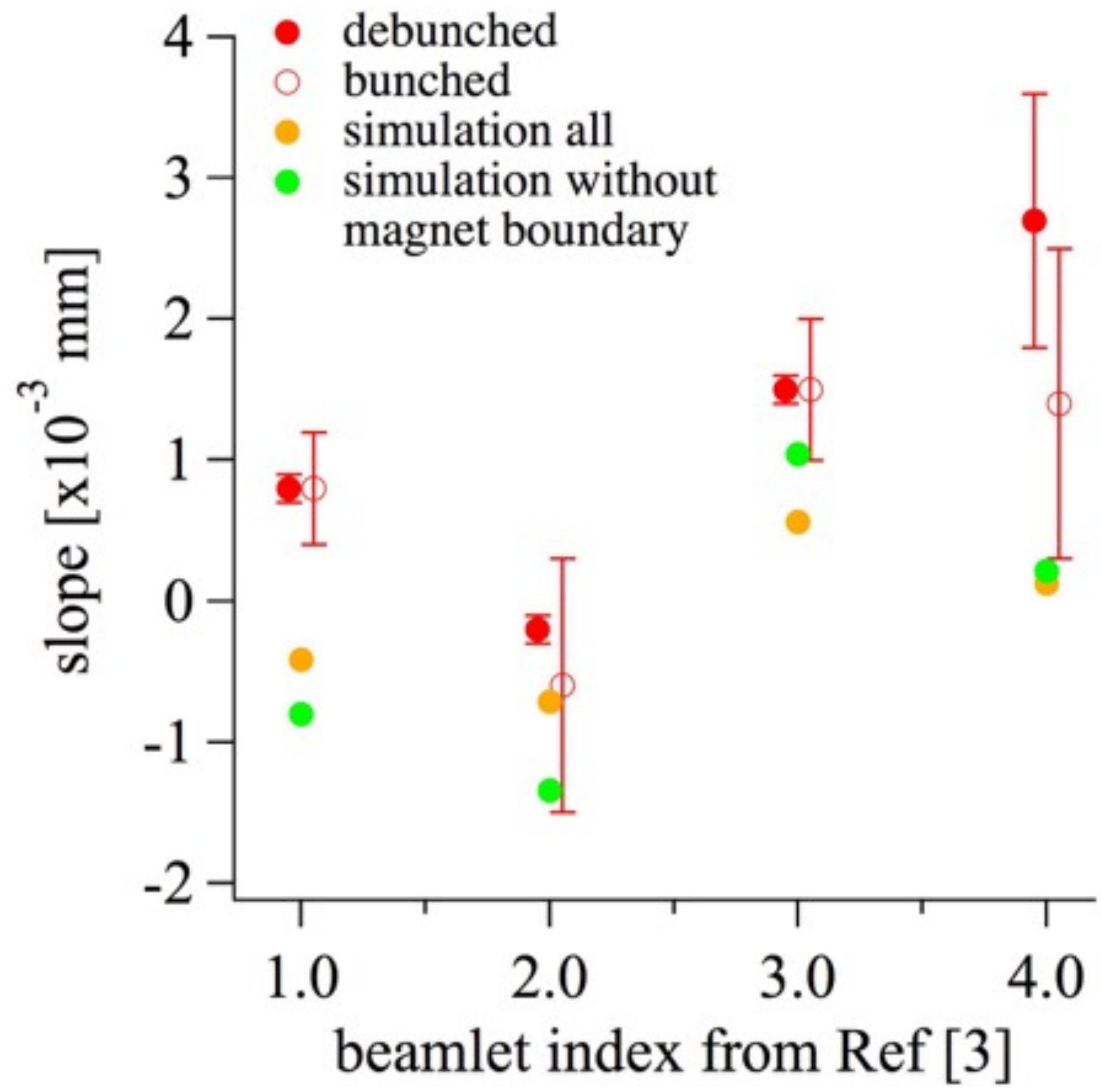


Comparison with experiment

The best estimate by simulation.

Quantitatively there is still some discrepancy.

N.B. Almost no different results between debuted and bunched beams suggest image charge and current are the dominant effect.



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Summary

- Intensity-dependent effects for the MTE was simulated.
- Simulation results agree with experiment at least qualitatively on the position shift with the image effects.

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Thank you for your attention.