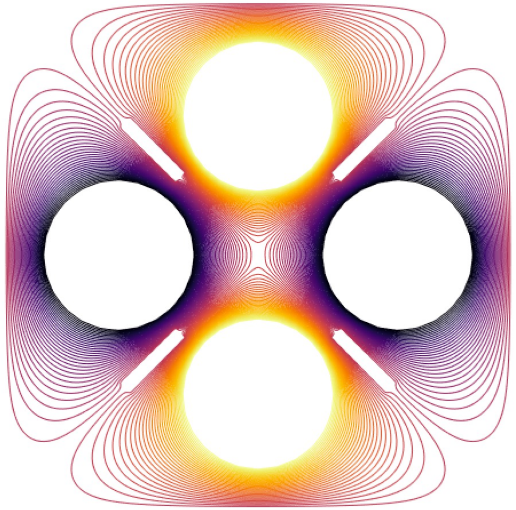
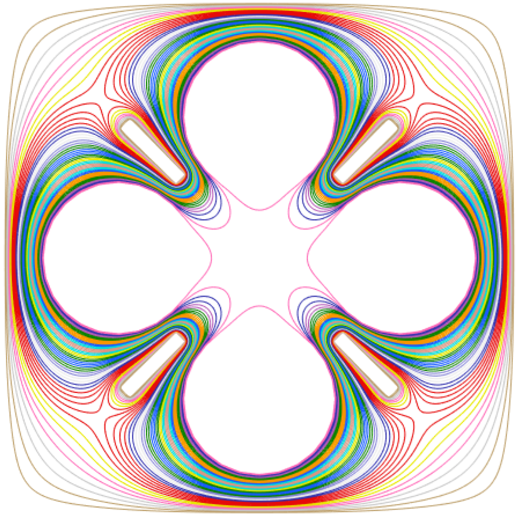
Simulating the mitigation of space charge effects with Quasi-Integrable Optics using a Paul Trap



Jake Flowerdew

Space Charge Workshop 2022

Knoxville, Tn



John Adams Institute for Accelerator Science

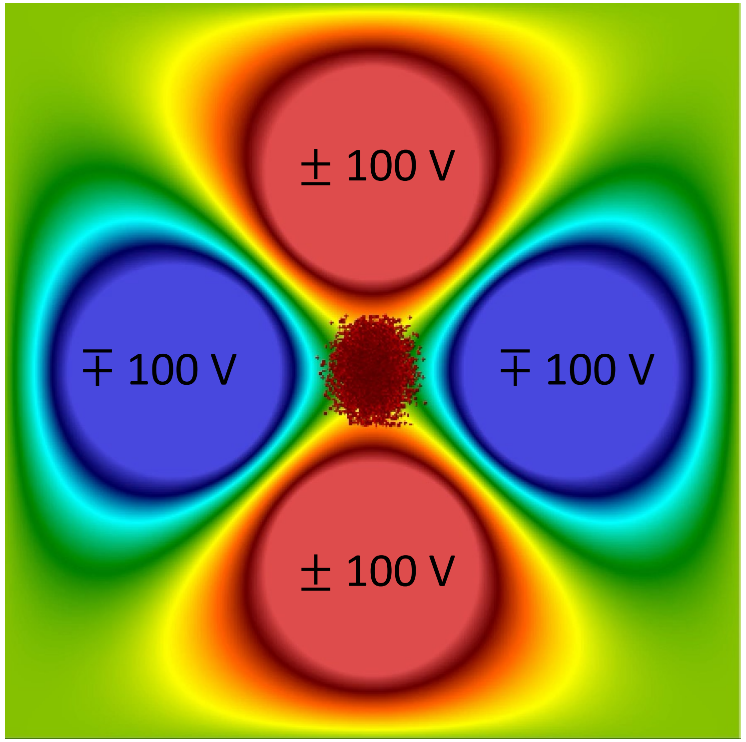
UNIVERSITY OF OXFORD

Outline

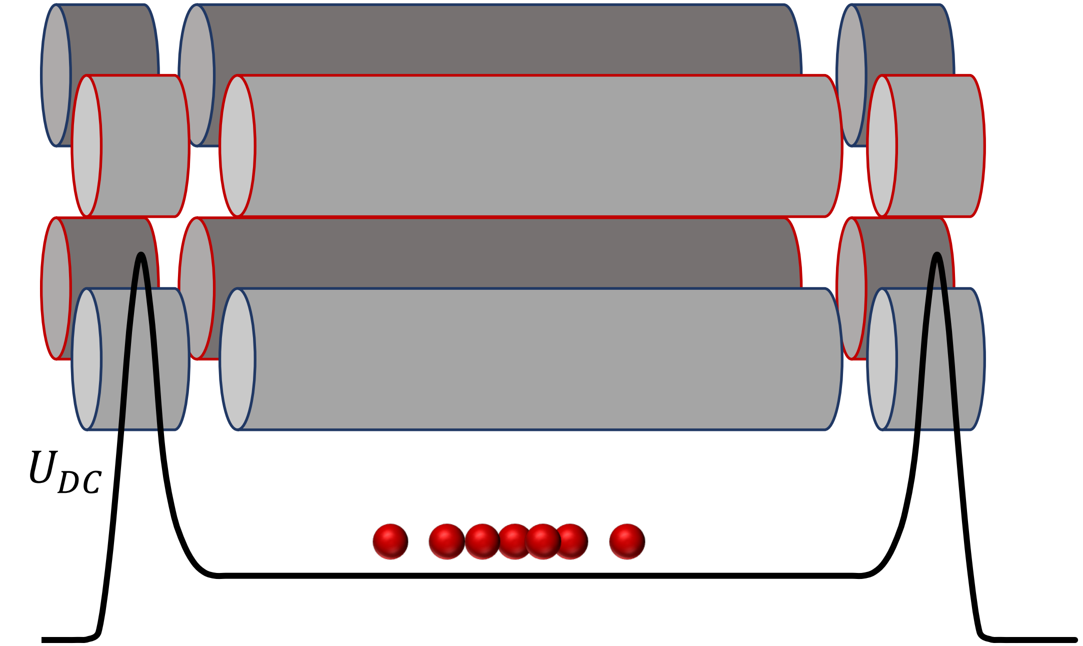
- Operation of a Paul trap
- Motivation to study accelerator physics in a Paul trap
- Quasi-Integrable Optics (QIO): Motivation to construct a nonlinear Paul trap
- Simulation results: Testing QIO with the Intense Beams Experiment (IBEX)
- Nonlinear upgrade to IBEX

Using Paul Traps to study Accelerator physics

Transverse confinement



Longitudinal confinement



$$H_{\mathrm{paul}} = \frac{(p_x^2 + p_y^2)}{2} + \frac{1}{2}K_{\mathrm{p}}(\tau)(x^2 - y^2) + \frac{q}{mc^2}(\phi_{\mathrm{sc}}) \qquad K_{\mathrm{p}}(\tau) = \frac{2qV_Q(\tau)}{mc^2 r_0^2}$$

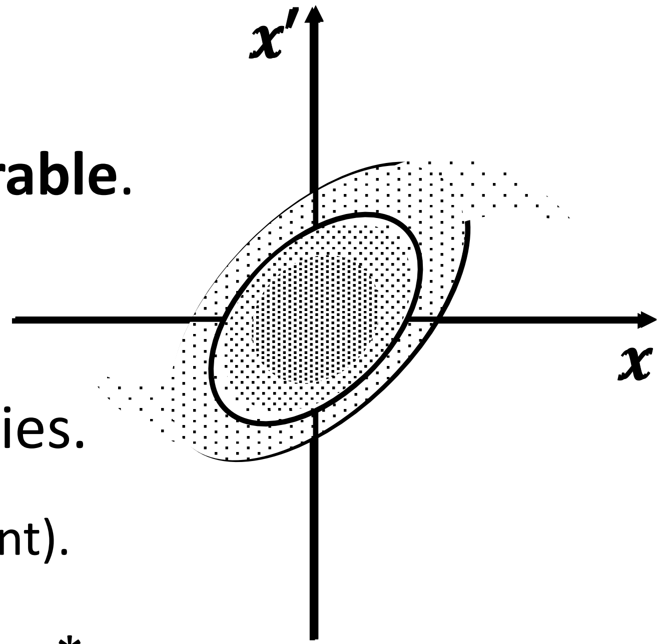
Why study accelerator physics in a Paul trap?

- **Fast measurement times** ($1\ s \sim 1{,}000{,}000$ periodic cells).
- **Large parameter space:**
  - Can easily create various different lattice types.
  - Can easily change the intensity ($\Delta Q{\sim}10^{-5} - 0.1$).

- **Low energy** ions – will not damage components when lost.
- **Dispersion-** and **chromaticity- free** environment.
- **Cost effective** when compared to building an accelerator.

Quasi-Integrable Optics

Bounded & regular particle motion
Reduced dynamic aperture
Emittance growth



- In an ideal accelerator (linear components) the motion is **integrable**.
- Linear accelerators are susceptible to resonances.
- Use nonlinear components (i.e. octupoles) to dampen instabilities.
  - However, now the system is **non-integrable** (no longer time-independent).
- Can make a quasi-integrable system with correct octupole scaling*:

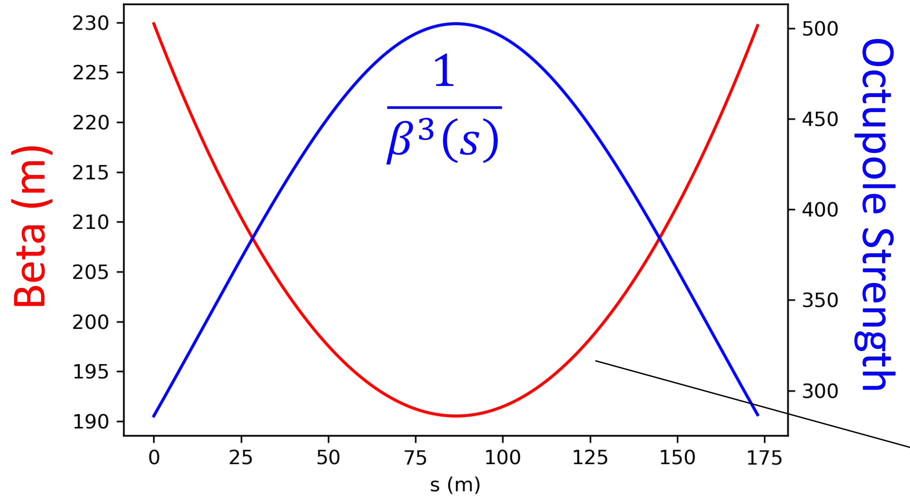
$$H_N = \frac{p_{xN}^2 + p_{yN}^2}{2} + \frac{x_N^2 + y_N^2}{2} + U(x_N, y_N),$$

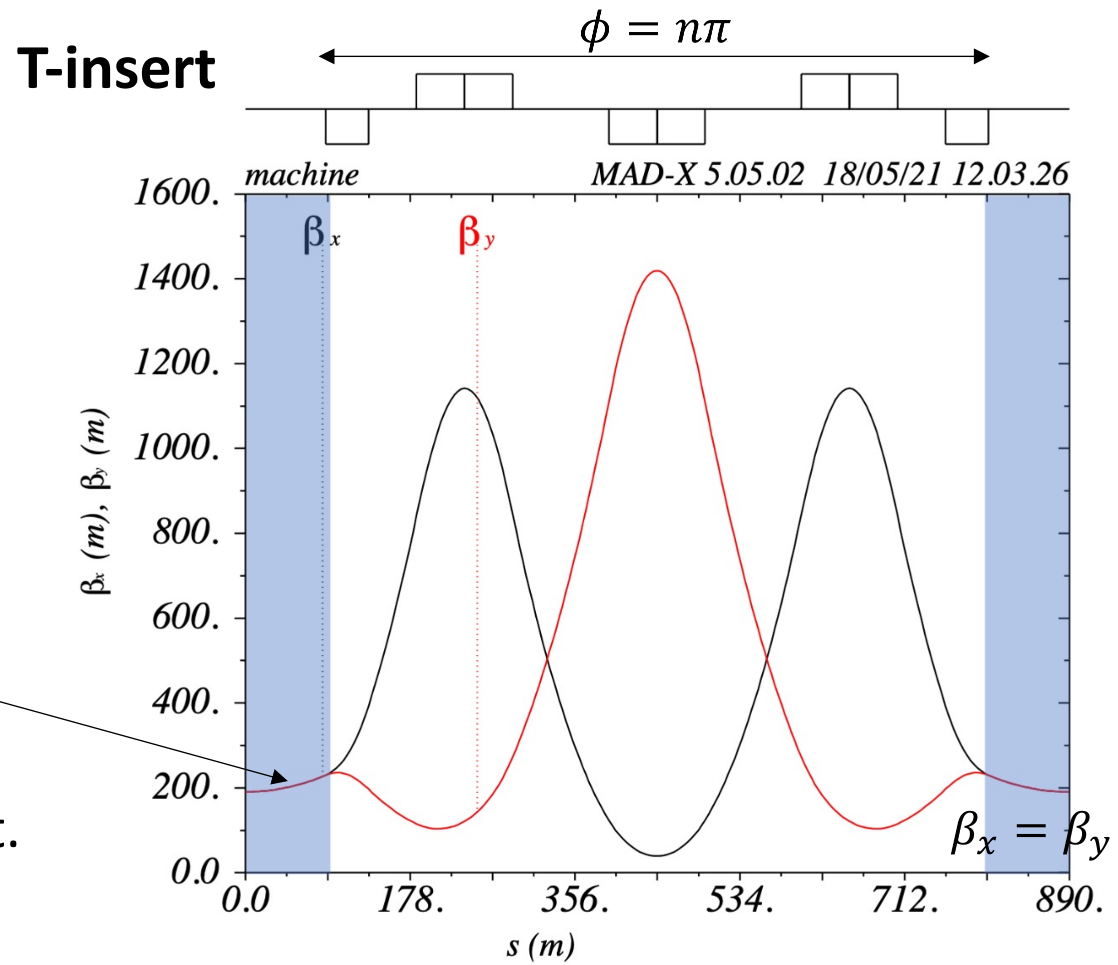
$$U\left(x_N, y_N\right) = k_4 \left(\frac{x_N^4}{4} + \frac{y_N^4}{4} - \frac{3x_N^2 y_N^2}{2} \right)$$

*V. Danilov and S. Nagaitsev (2010)

T-insert lattice for QIO

$$V(x,y,s) = \frac{k}{\beta(s)^3}\left(\frac{x^4}{4} + \frac{y^4}{4} - \frac{3x^2y^2}{2}\right)$$

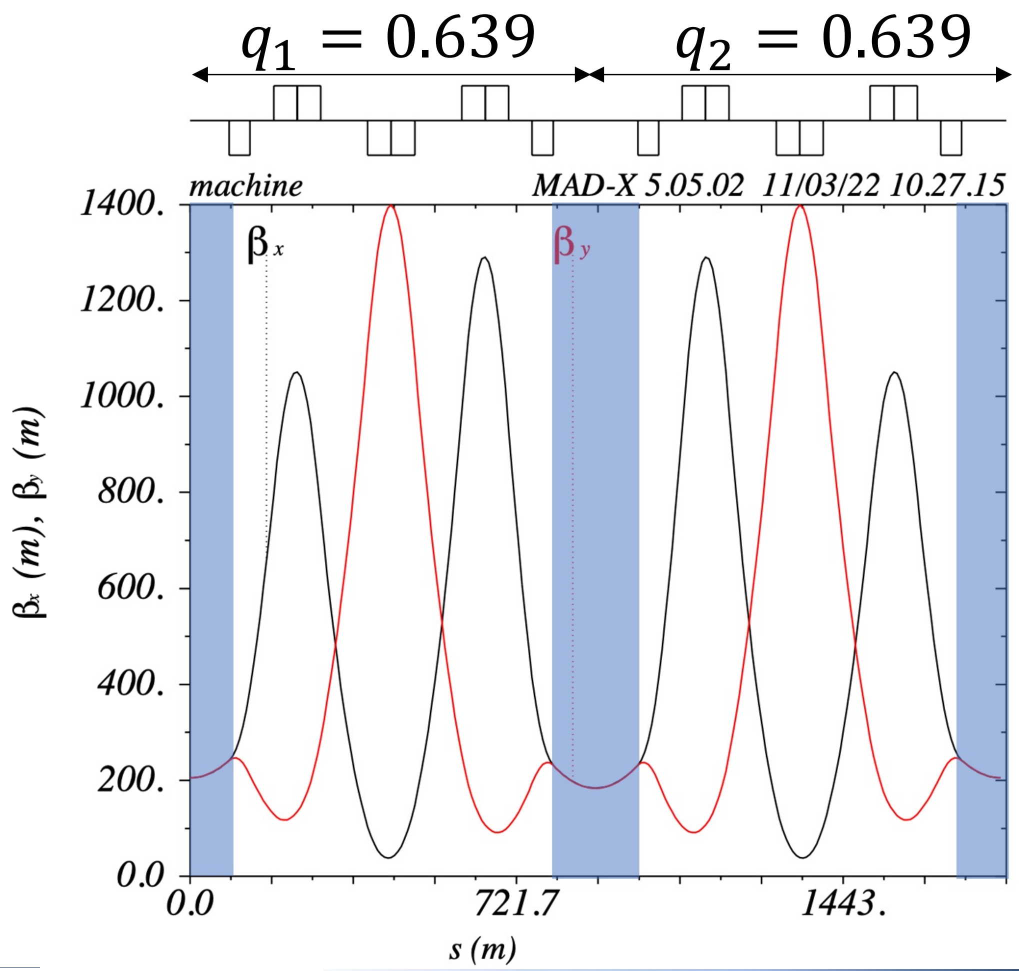


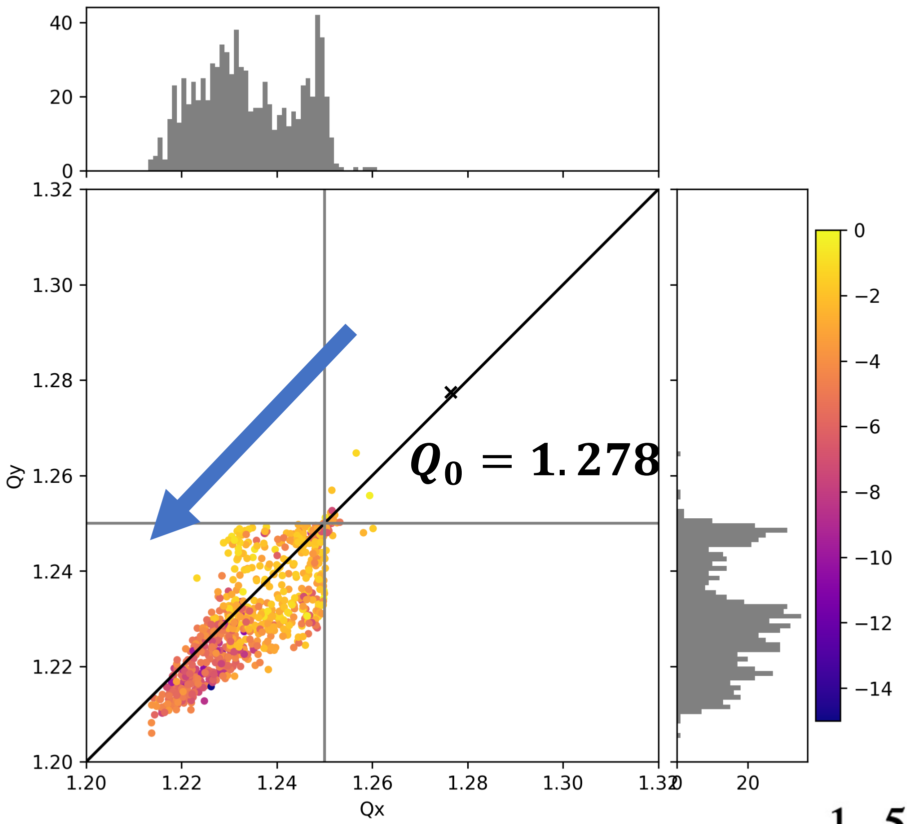


- Requires $n\pi$ phase advance and $\beta_x = \beta_y$ in drift.
- $1/\beta^3(s)$ octupole scaling makes H time-independent.

➢ (Quasi-) Integrable lattice which is robust to small perturbations.

T-insert to excite coherent resonance

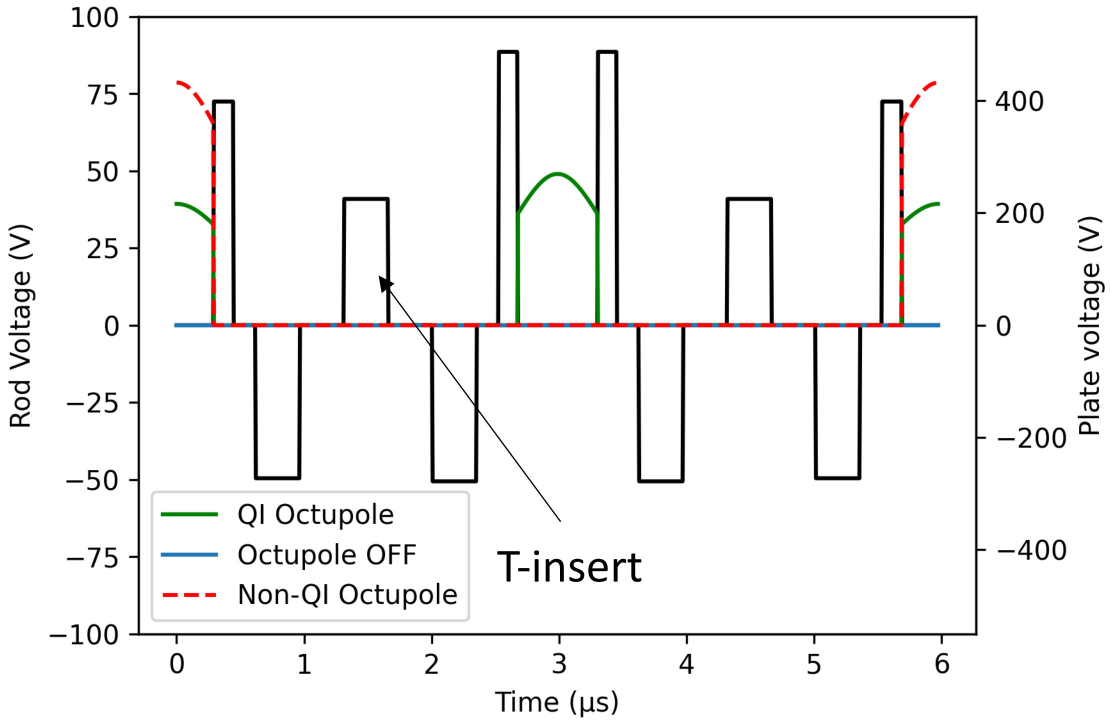


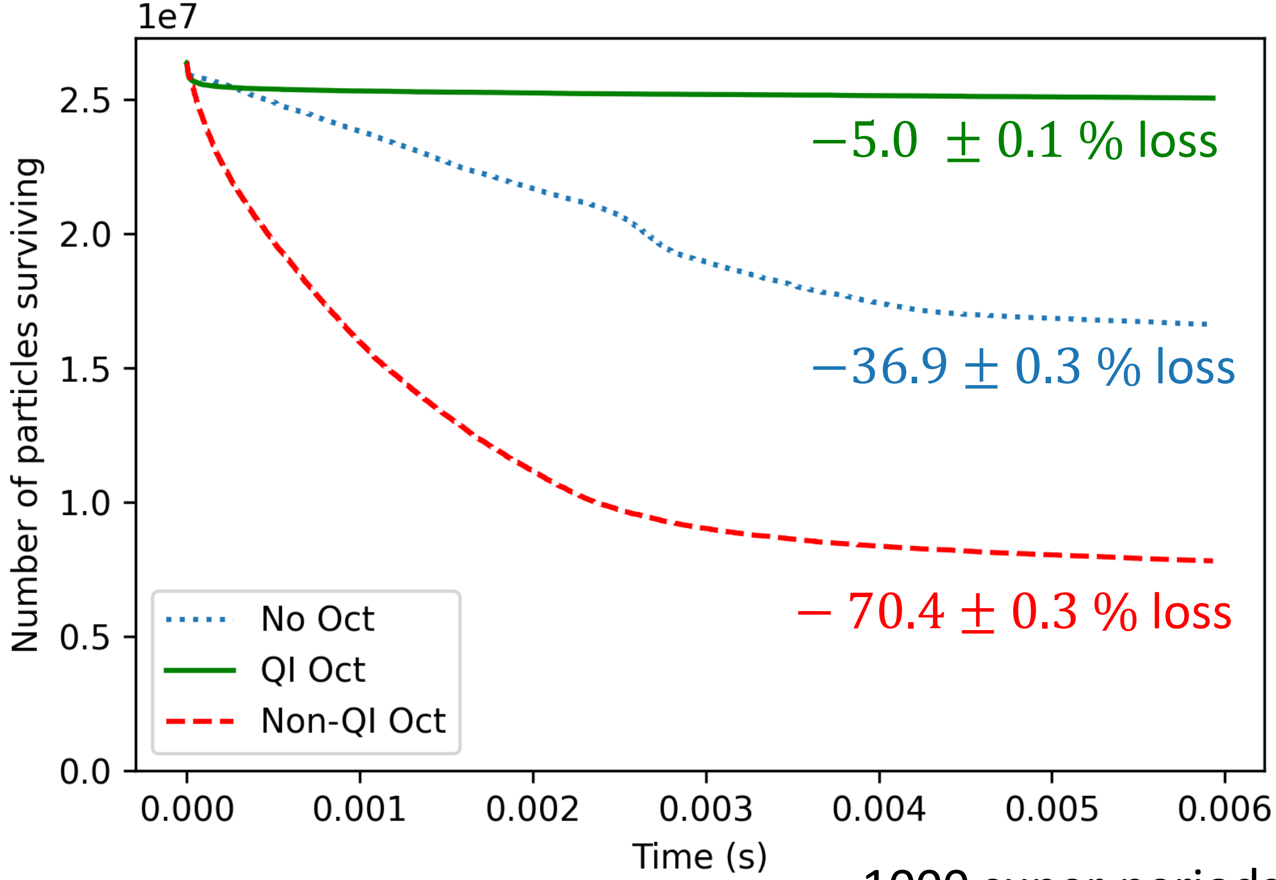


$$Q_0 + C_2 \Delta Q_{rms} = \frac{1}{2}\left(\frac{5}{2}\right)$$

VSim Numerical simulations results

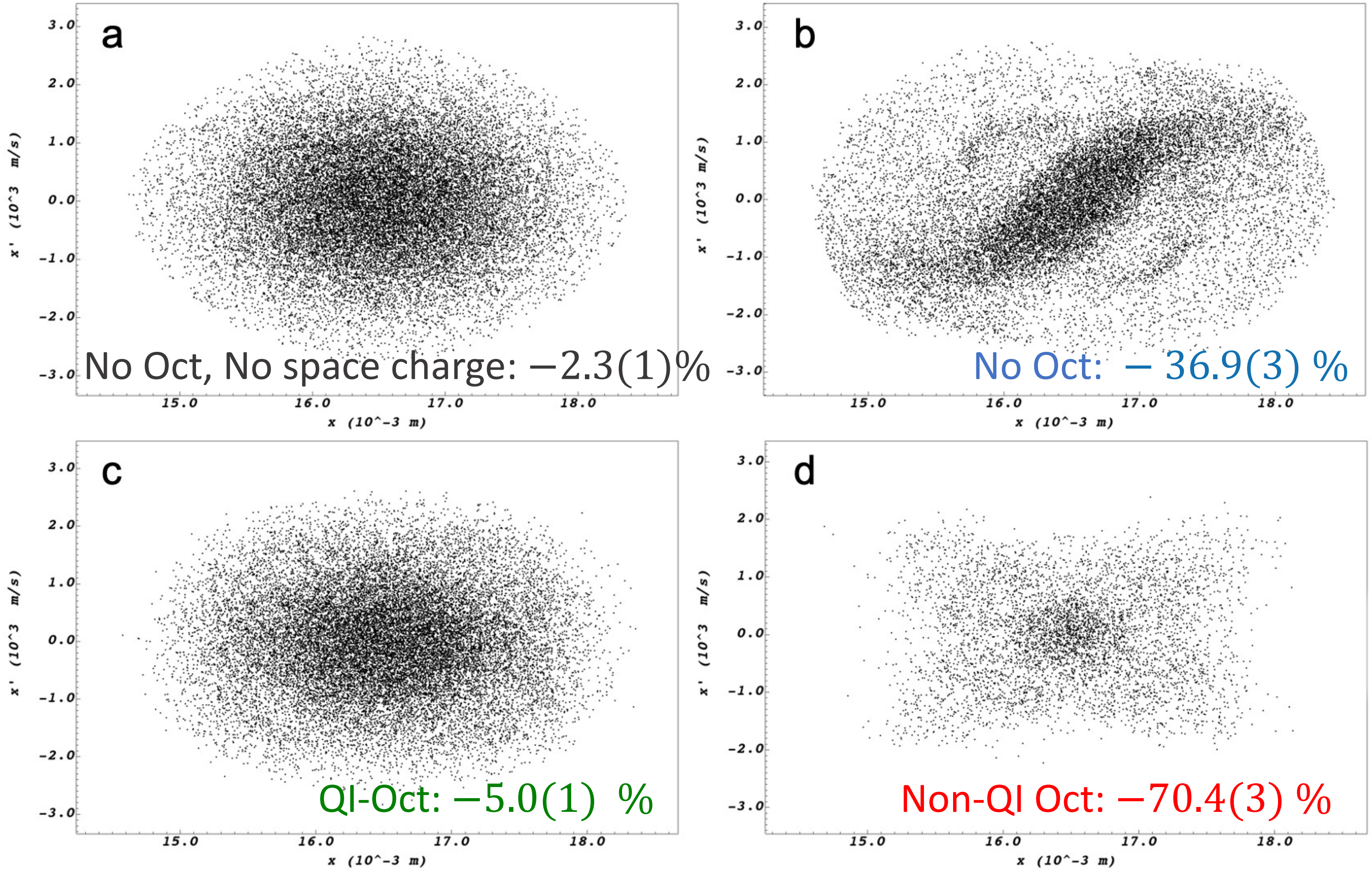
$Q_0 = 1.278, \quad \Delta Q_{rms} = 0.036$





1000 super-periods

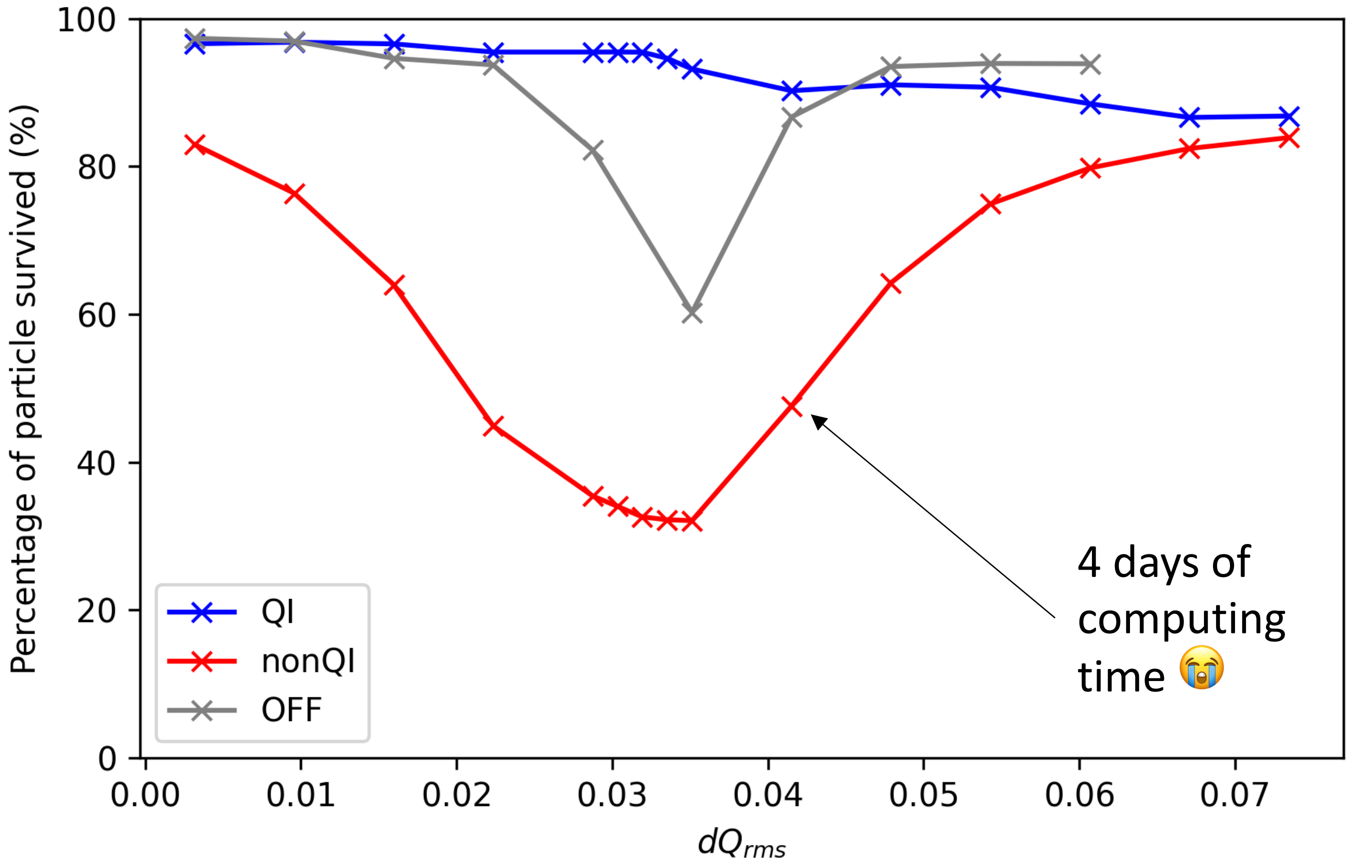
QI lattice dampens 2nd order coherent resonance

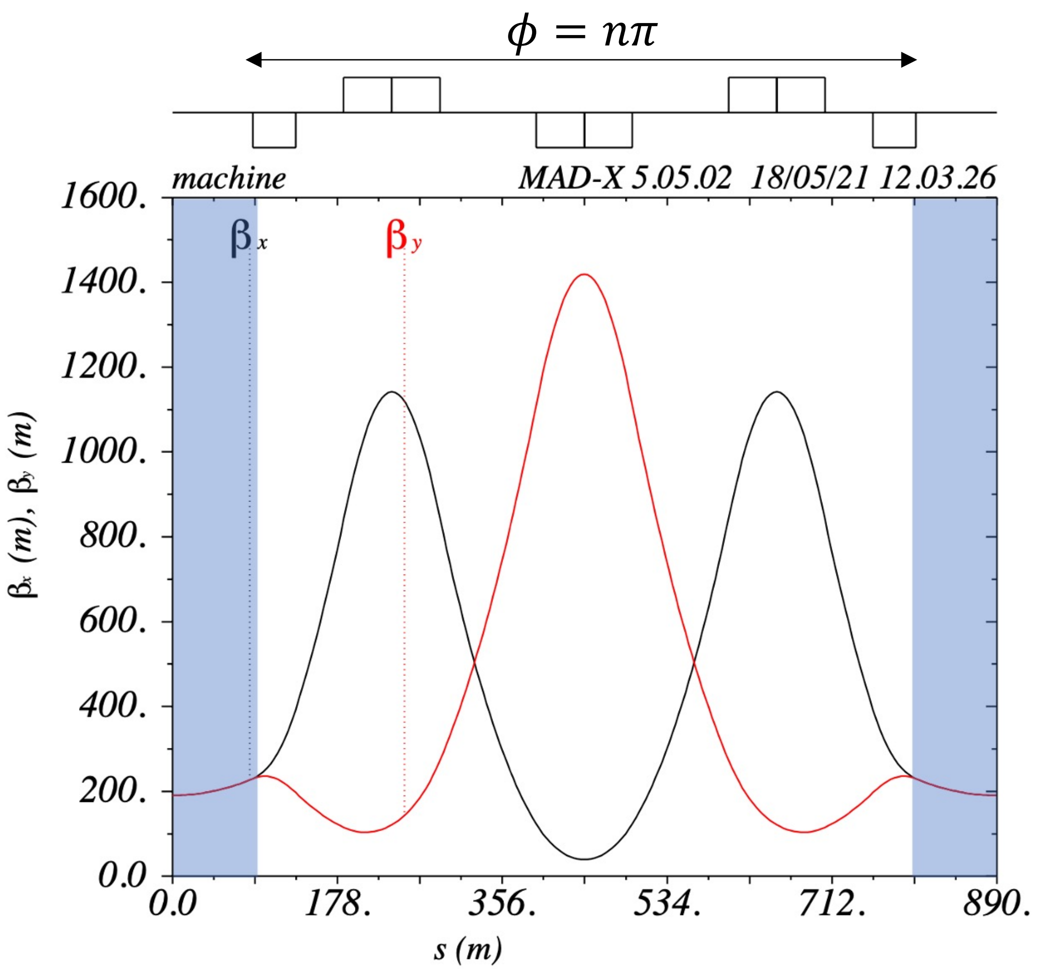


$$Q_0 + C_2 \Delta Q_{rms} = \frac{1}{2}\left(\frac{5}{2}\right)$$

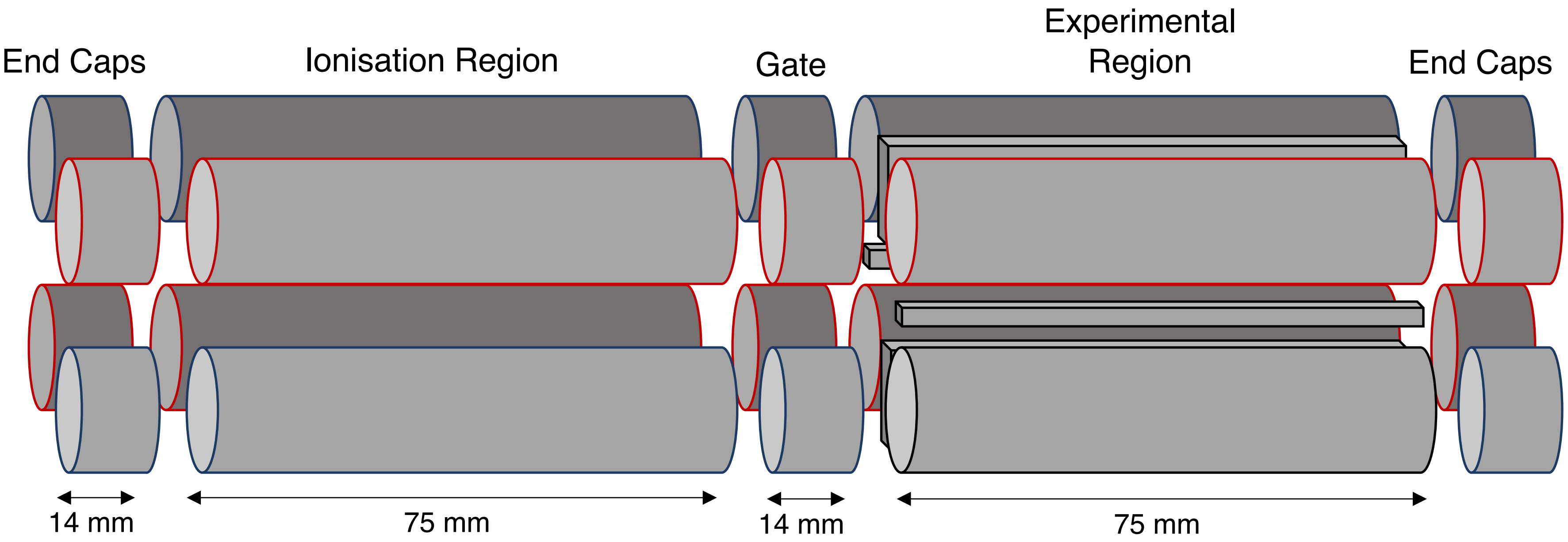
$$Q_0 + \Delta Q_{rms} = \frac{5}{4}$$

Intensity scan (simulation)

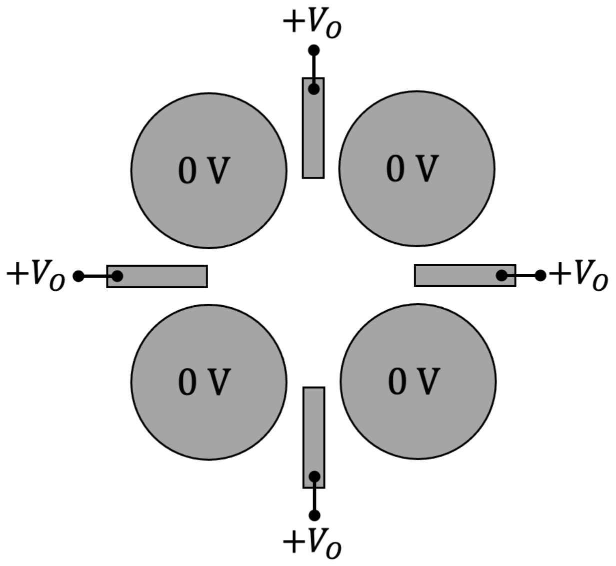




Nonlinear upgrade to IBEX

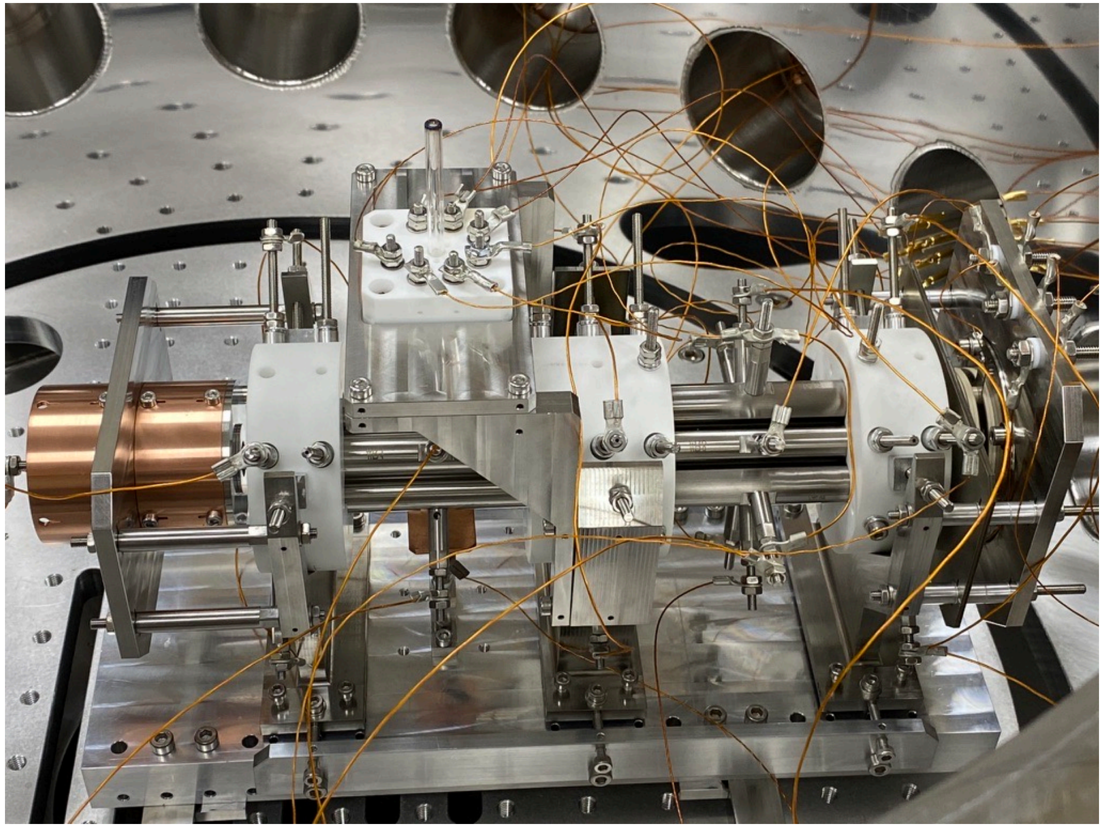


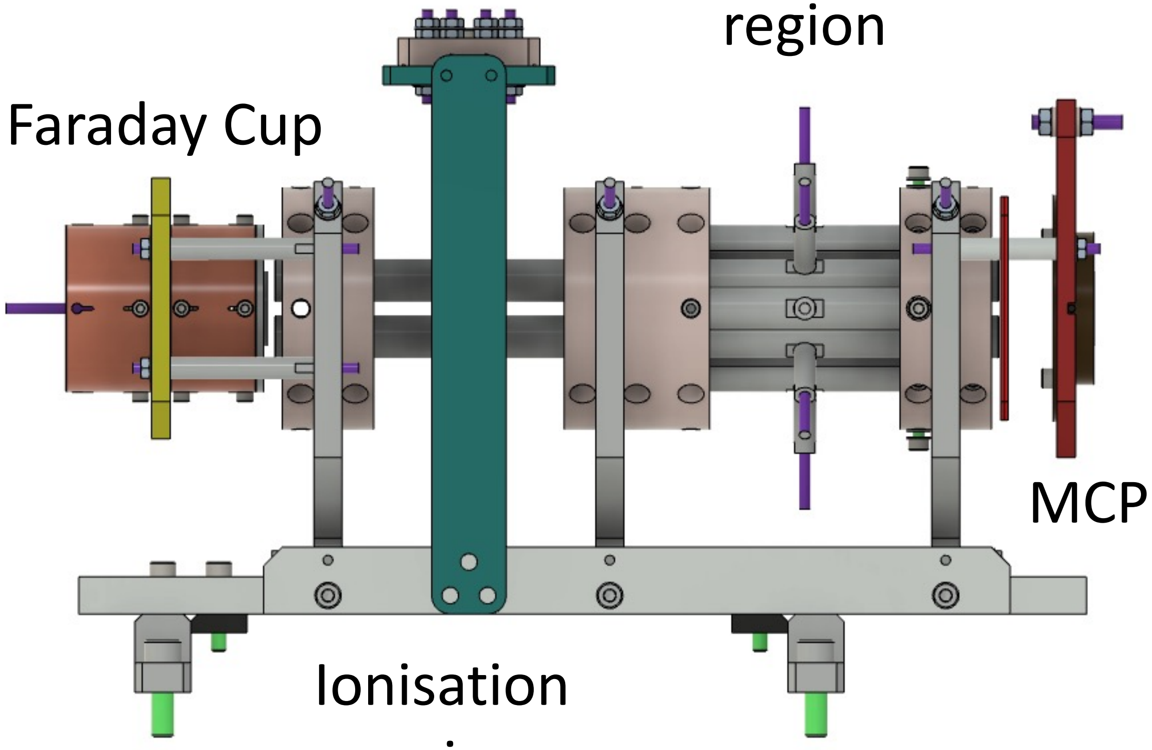
Octupole field



FUKUSHIMA, K., & OKAMOTO, H. (2015). Design Study of a Multipole Ion Trap for Beam Physics Applications. *Plasma and Fusion Research*, *10*(0), 1401081–1401081.

IBEX 2.0!




Electron gun
Experimental region
Faraday Cup
MCP
Ionisation region

Bridging the gap in space charge dynamics

Summarize the content of this presentation:
IBEX is a tool to test new lattice designs with space charge. In this work I presented a possible way to test the mitigation of a coherent space charge resonance with a QIO lattice in a Paul trap.

From your perspective, where is the gap regarding space charge effects?
Validating and improving upon numerical simulations of space charge.

What is needed to bridge this gap?
Experimental validation of space charge effects and techniques for mitigation.

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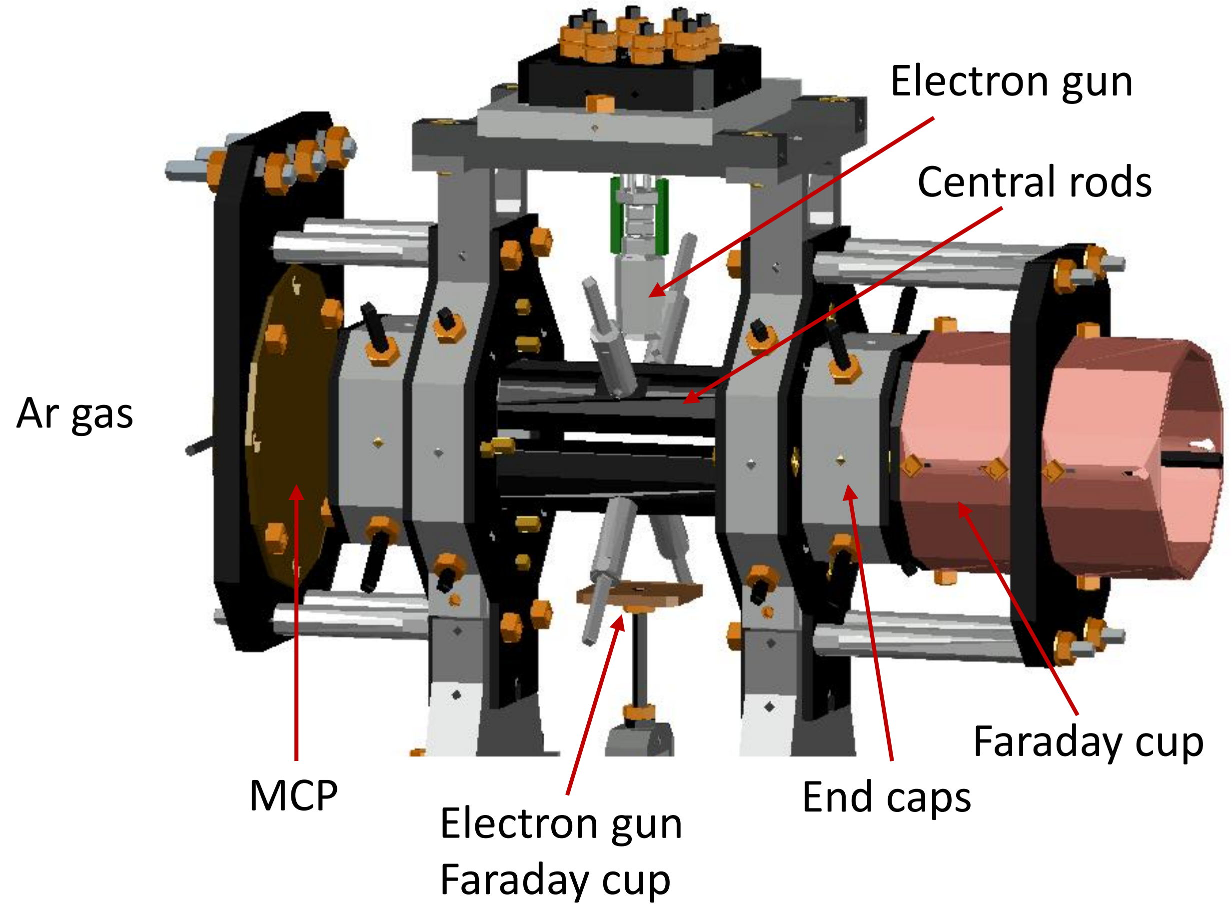
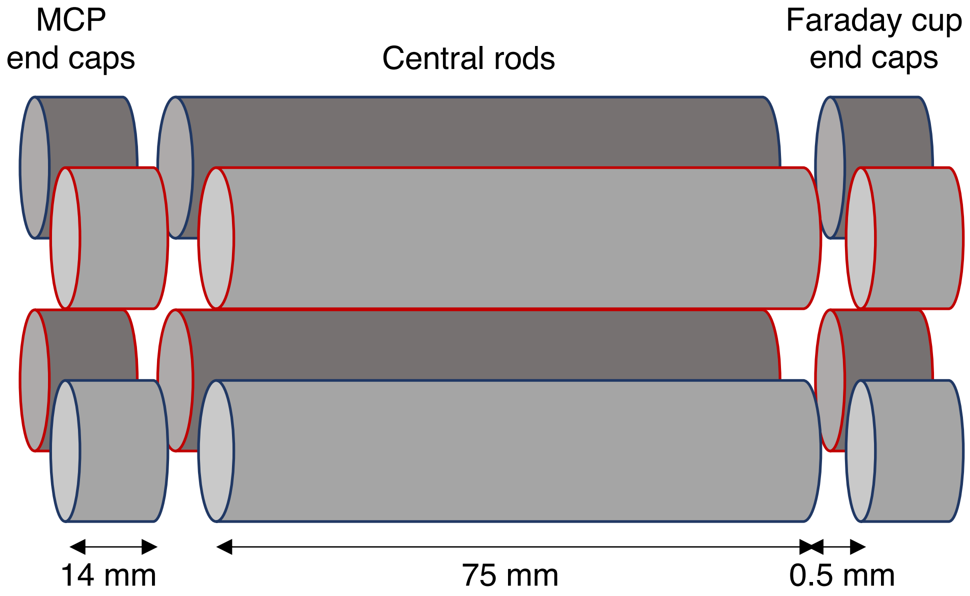
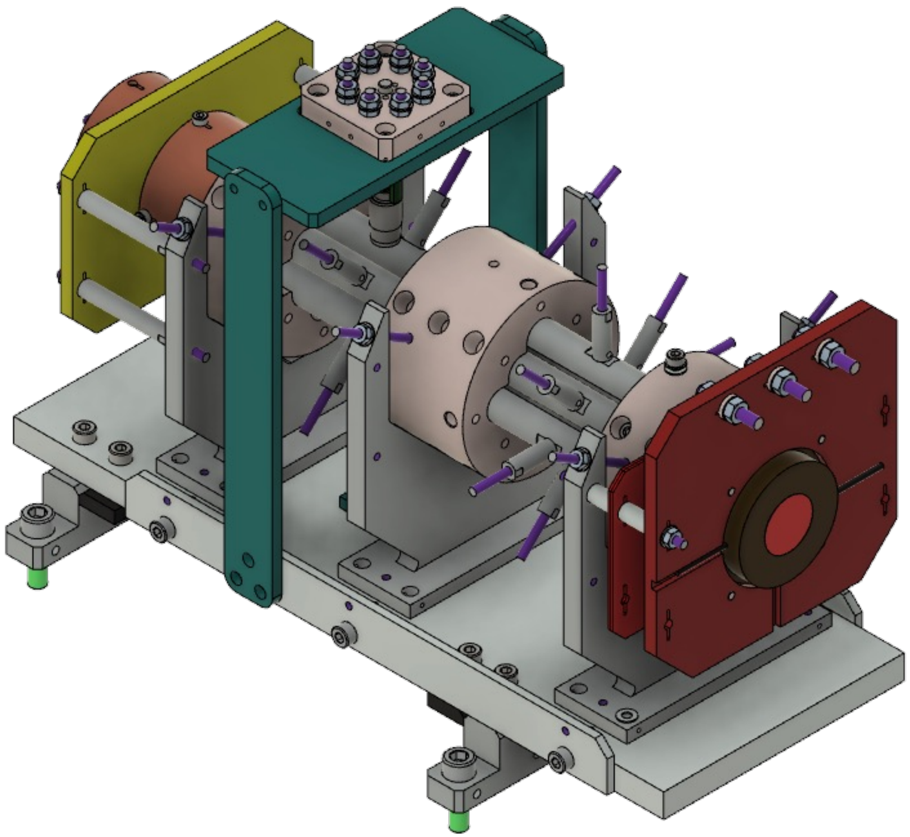
Back up slides

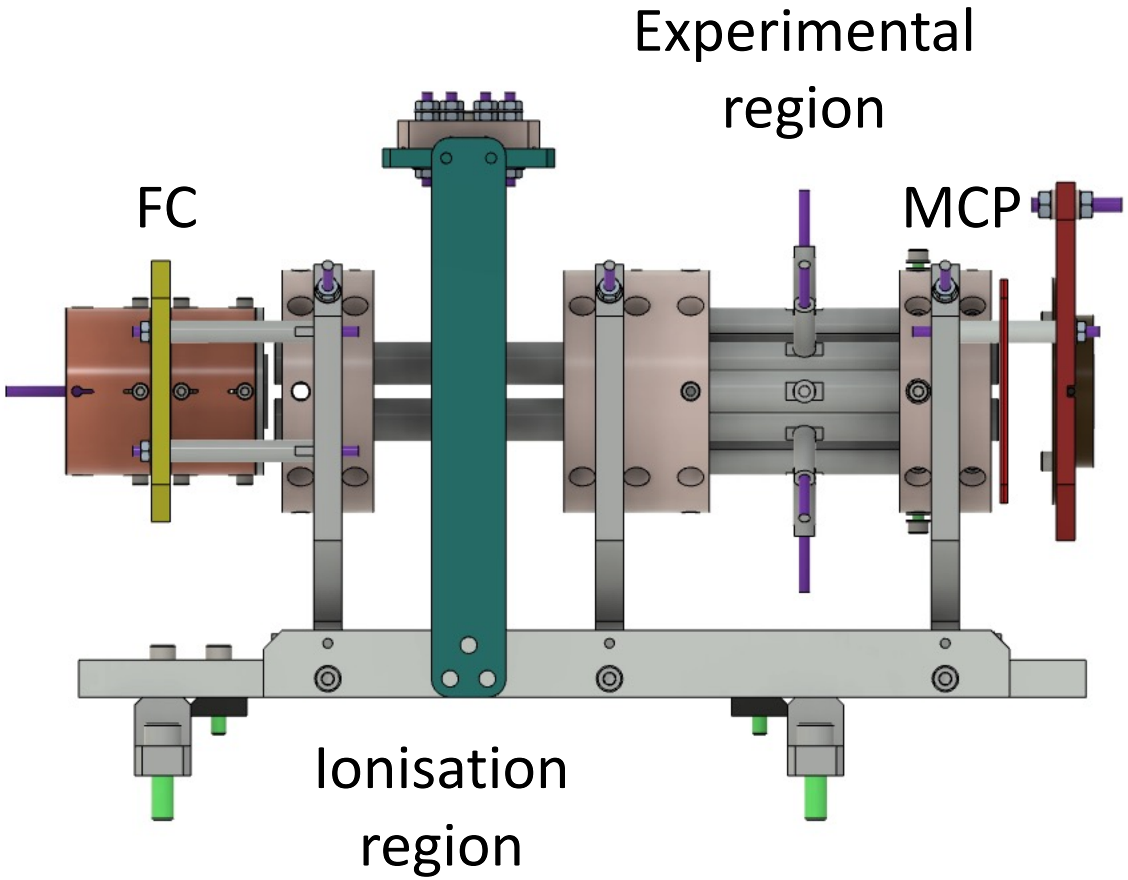
IBEX: Current Trap



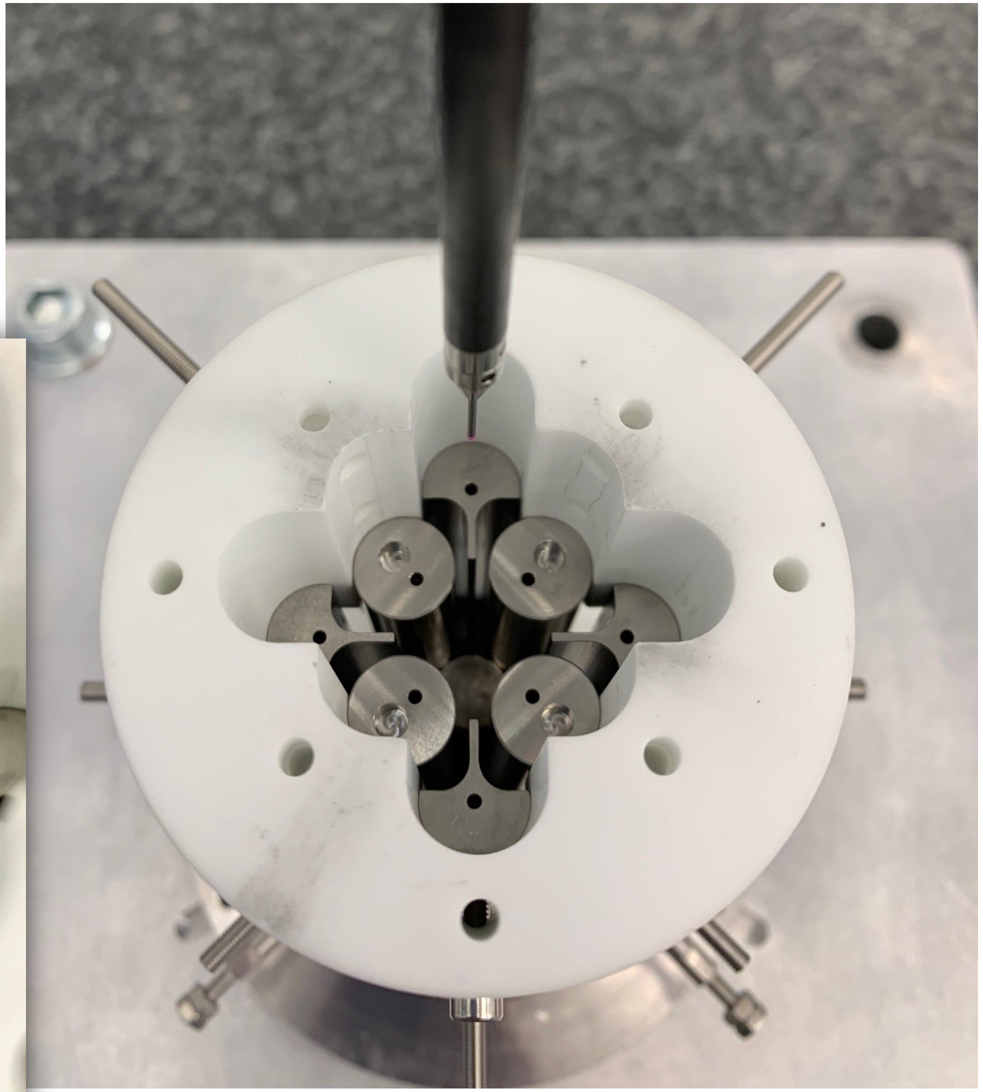


Nonlinear upgrade to IBEX



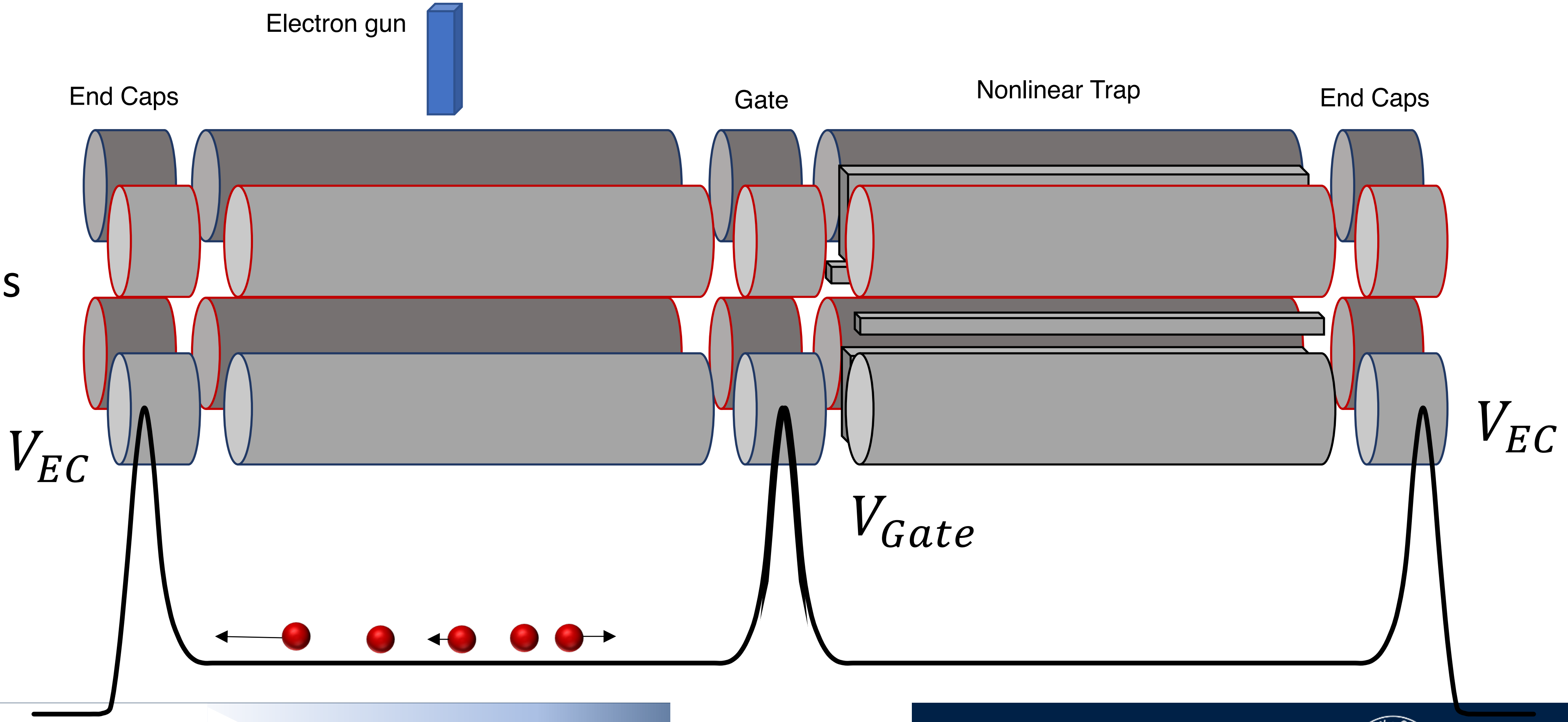


CMM measurements



Trap operation

Ar gas



Octupole perturbation