

INFLUENCE OF SPACE CHARGE EFFECTS ON LANDAU DAMPING IN HIGH-INTENSITY HADRON SYNCHROTRONS



Poster overview | CSNS-RCS | Hofmann-Pedersen model, tracking program, and PIC simulation

Jingtong Du · Institute of High Energy Physics, CAS

Core results

Research question

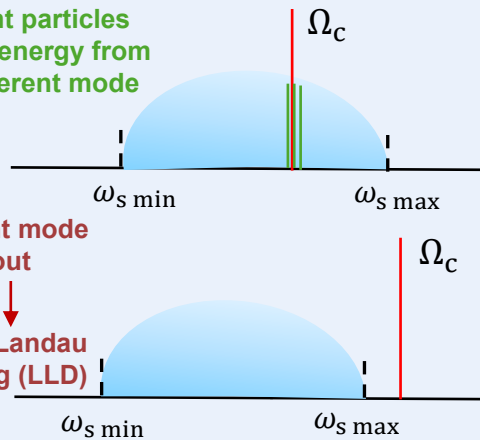
How does longitudinal space charge influence Landau damping?

Physical picture

resonant particles absorb energy from the coherent mode

coherent mode moves out

loss of Landau damping (LLD)



How the work is built

1

Hofmann-Pedersen model

- Synchrotron frequencies for **sinusoidal rf cavity**
- Coherent dipole frequency from a rigid model

2

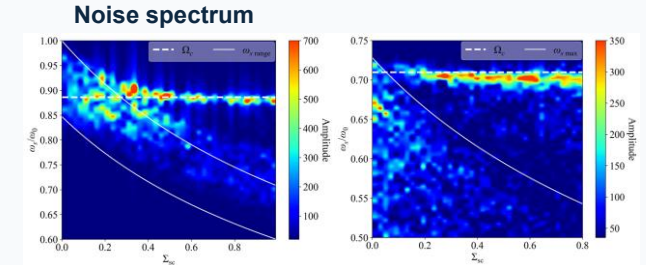
Tracking program and Benchmark

- **FFT-based** longitudinal space-charge solver
- Matched beam dynamics

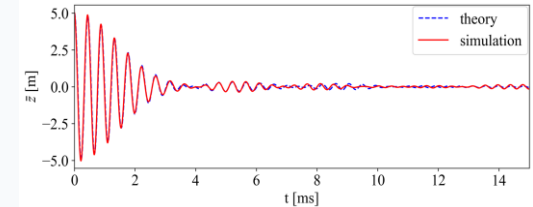
3

PIC simulation

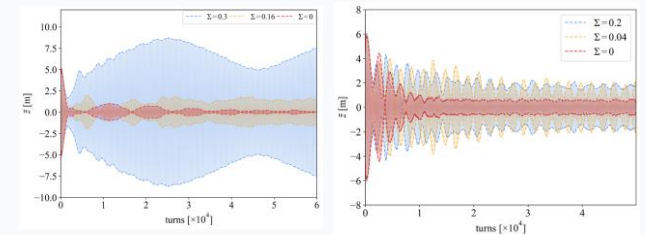
- Noise spectrum from centroid-motion extraction
- Apply an **initial offset** and **rf phase modulation**



Decoherence baseline



Threshold validation

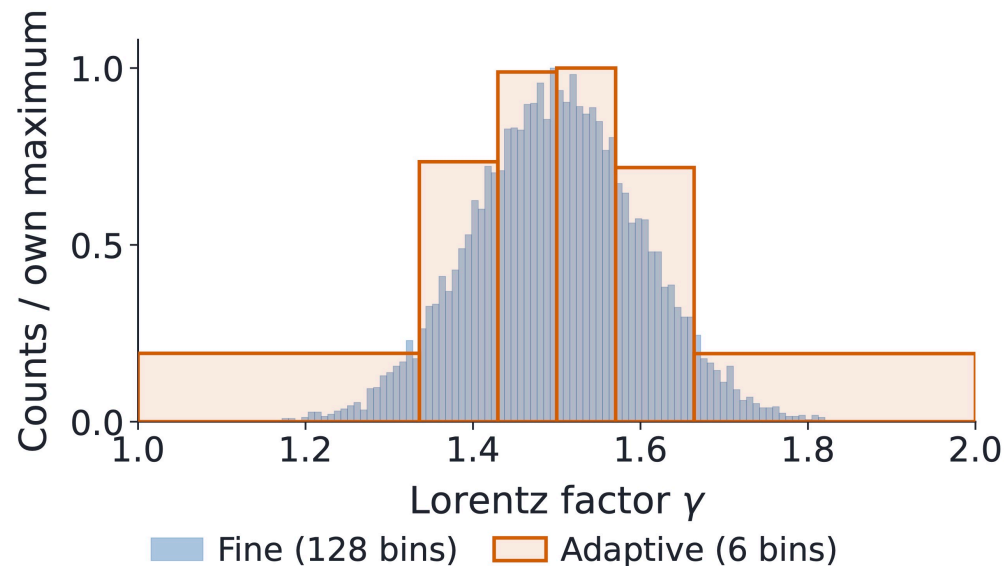


Takeaway: Space charge modifies the incoherent frequency spectrum, thereby affecting the Landau-damping threshold.

Matched accuracy with up to 60% less solver runtime

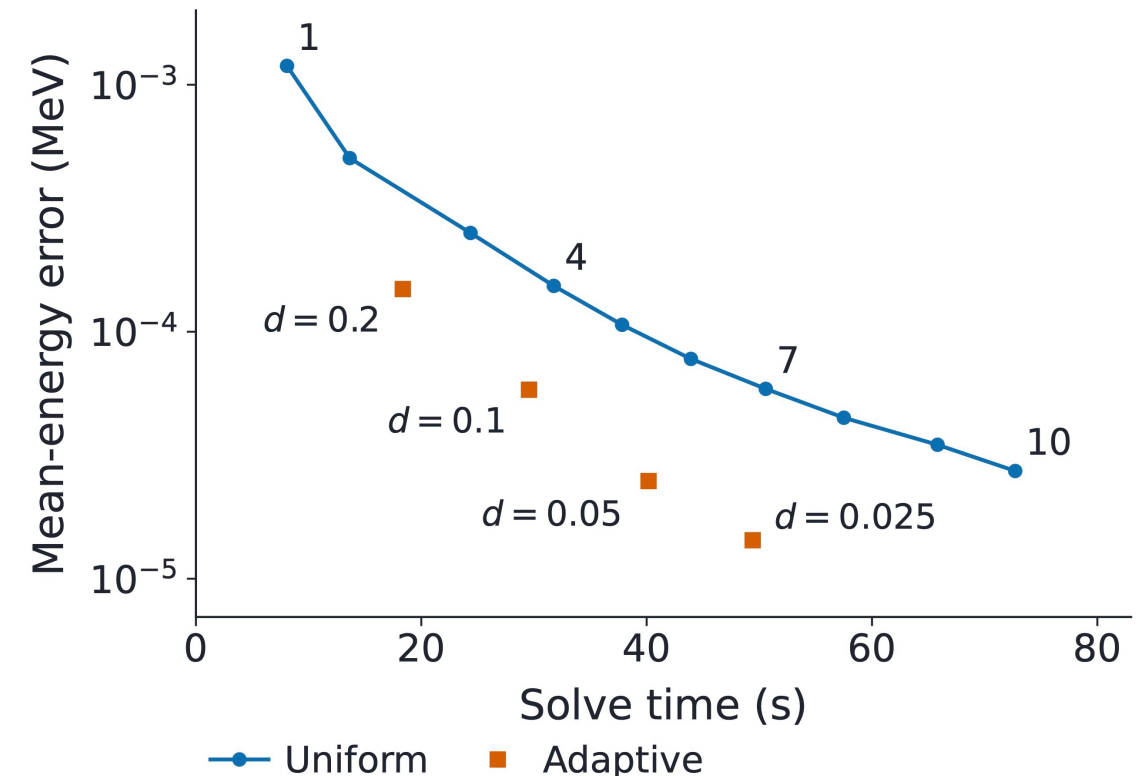
In realistic gun simulations with relativistically significant energy spread

Energy binning balances
modelling error and solver cost



- Merge adjacent bins in sparse tails of a fine γ histogram.
- A cost function guides dynamic programming.

AWAGun

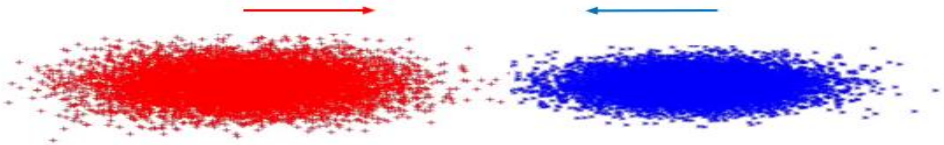


Visit my poster for the binning algorithm and GPU scaling

Beam-Beam Simulation Models and Numerical Noises for Flat-Beam Collisions in the Electron-Ion Collider

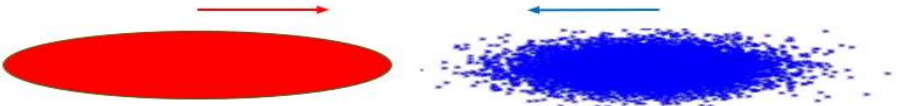
Abstract #12
Yum Luo, BNL

- Strong-strong simulation model

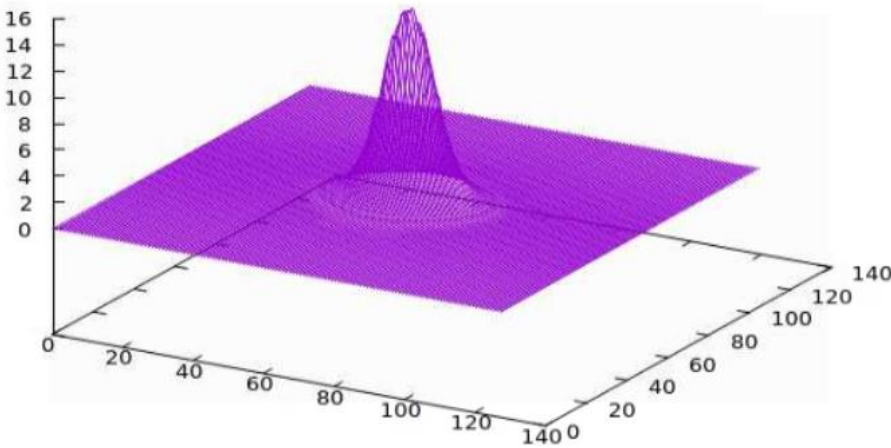


Both bunches are represented by ~ a million macro-particles. Subject to numerical noises.

- Weak-Strong simulation model

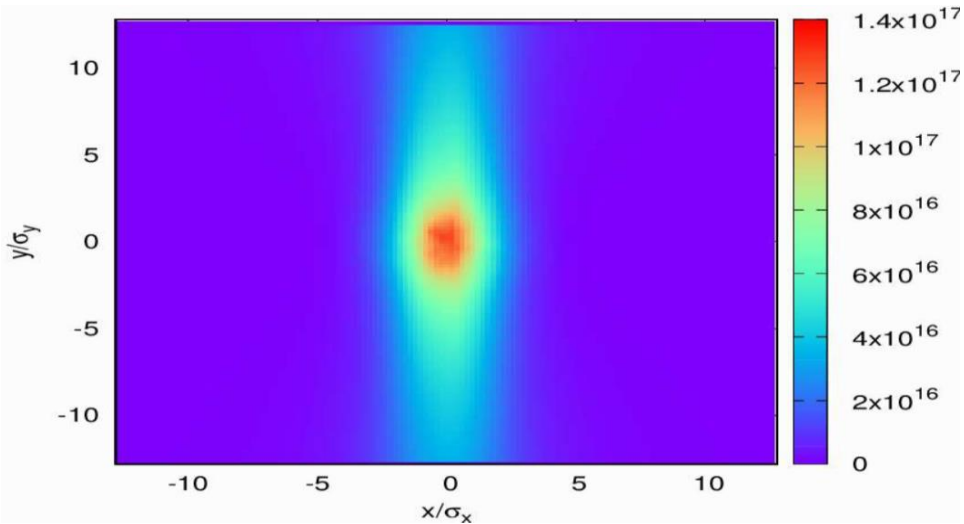
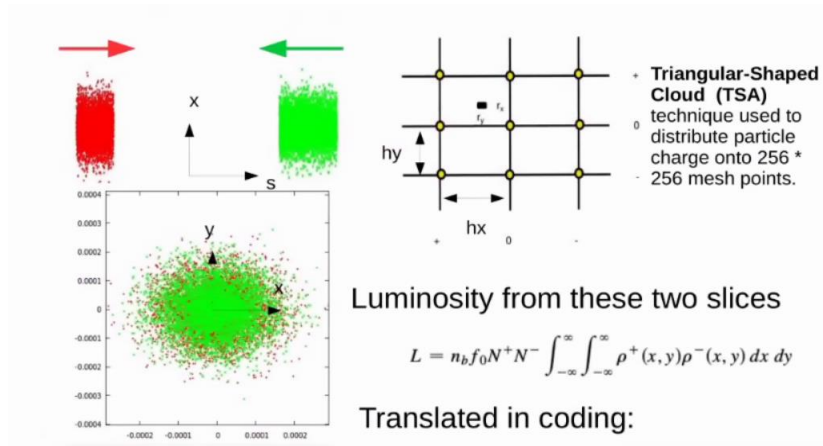


Strong bunch is rigid while weak bunch is represented by macro-particles. Not consistent.



Charge density variation on grids

Particle-In-Cell (PIC) Poisson solver



Space charge kick variation on grids

Mismatch is inherent

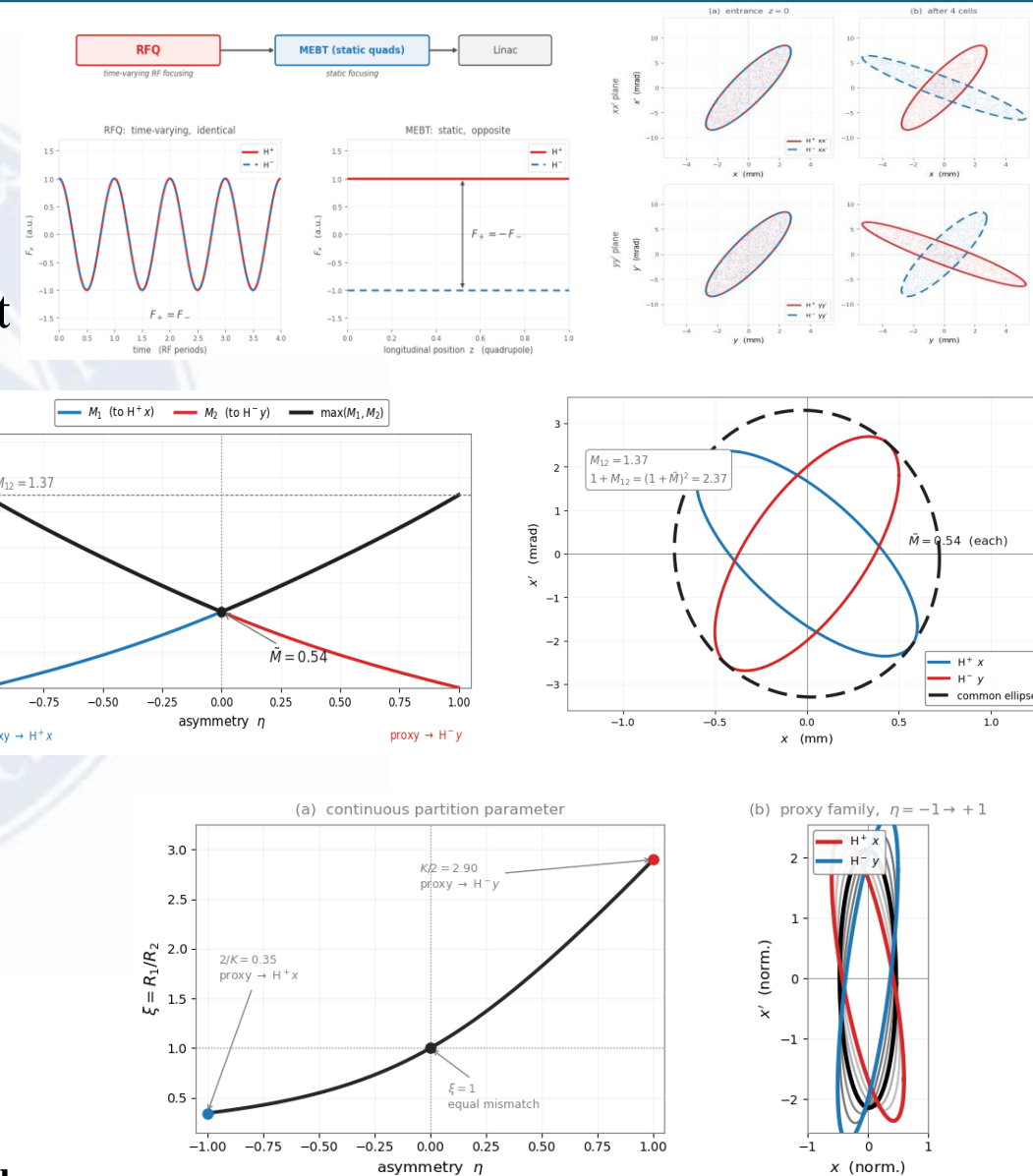
- One linac, two beams: power doubled, ions neutralize.
- RFQ: same force. MEBT: opposite forces.
- Identical at the RFQ exit but not round: one MEBT setting cannot match both.

Single-particle analytic solution (no space charge)

- Smallest ellipse enclosing both beams, found analytically.
- Mismatch split equally; neither beam is favored.
- Minimize the maximum mismatch.

Space-charge correction

- With space charge, the partition needs a correction.
- One continuous parameter shifts the reference ellipse.
- It acts as a compensation parameter for the space-charge force.



Differentiable Self-Consistent Space-Charge Mapping Using Differential Algebra and a Truncated Green's Function Solver

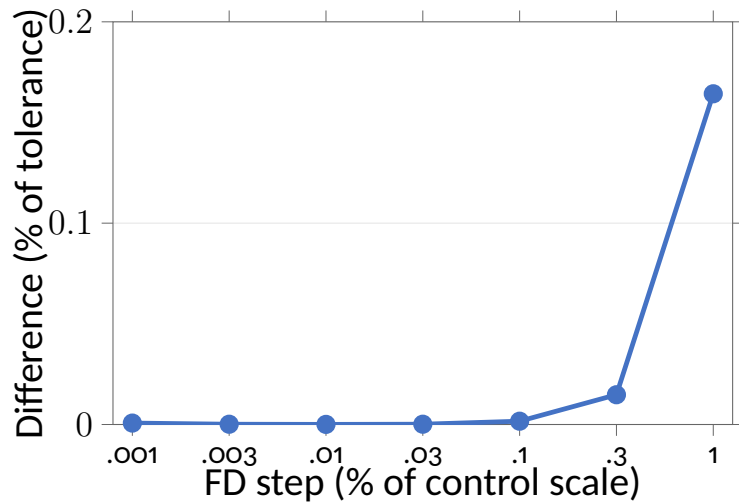
Track the beam and its response together.

$$\text{TGF: } \widehat{G}_R(k) = [1 - \cos(kR)]/k^2, \quad \widehat{G}_R(0) = R^2/2; \quad \widehat{\phi}_j = \widehat{G}_R \widehat{\rho}_j / \varepsilon_0$$

$k = |\mathbf{k}|$; R covers required source-target separations; j labels a DA coefficient.

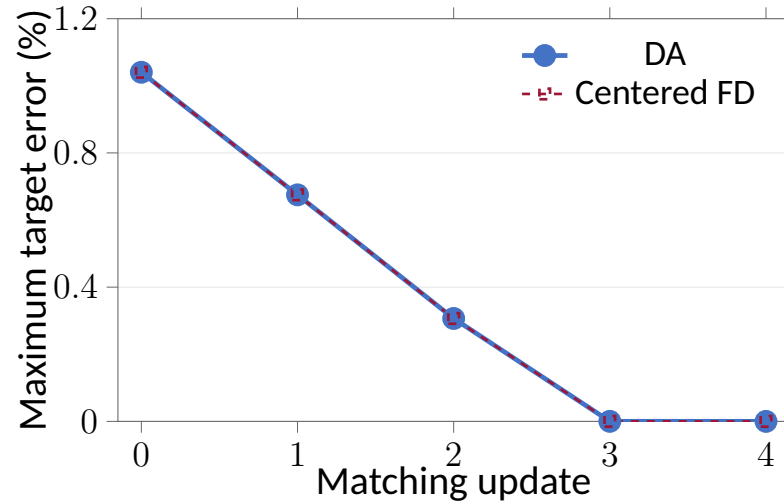
10 MeV protons • 10 pC • 0.20 m FODO • 64 particles • 0.75 mm Gaussian clouds

Derivative agreement



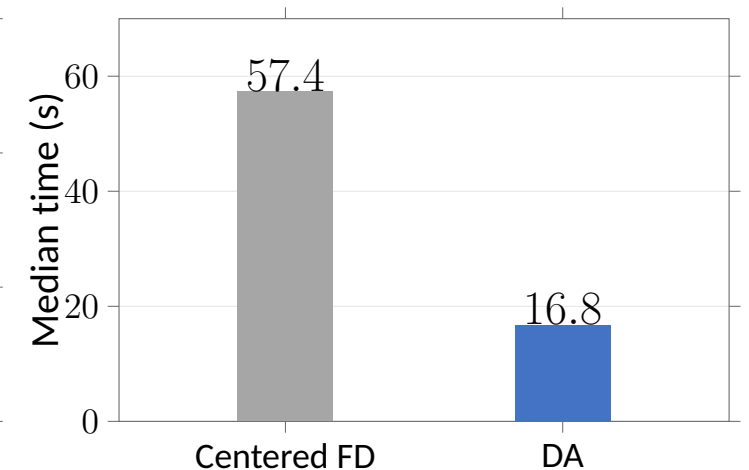
All seven steps pass

Beam-size matching



4 updates to the targets

Response runtime



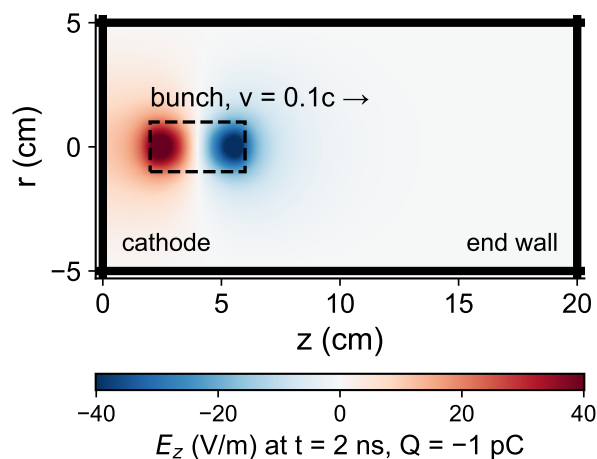
3 controls • 1 CPU thread

Validated at 0.75 mm cloud width. Smaller clouds and new particle ensembles remain open.

Electromagnetic Space-Charge Fields in a Cylindrical RF Cavity with an Axial Aperture

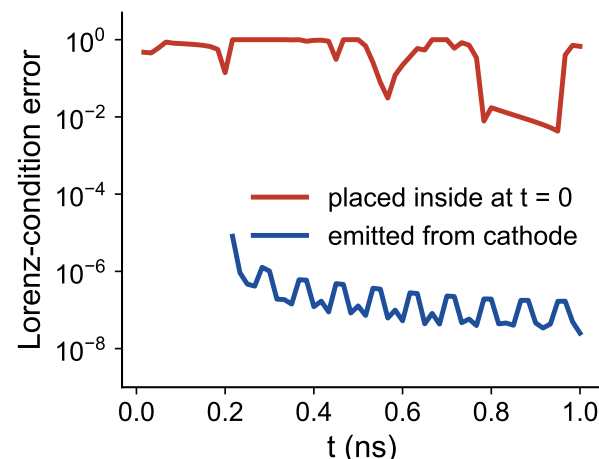
Cathode emission makes eigenmode fields Maxwell-consistent

1 Bunch leaves the cathode



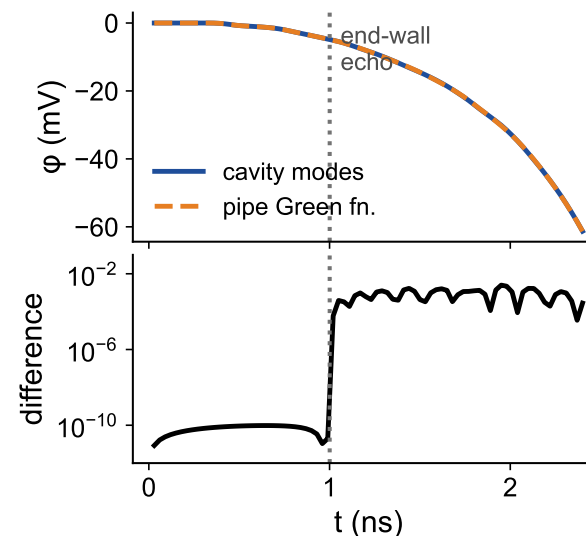
Cavity eigenmodes: every wall condition exact; $\mathbf{E}$ and $\mathbf{B}$ as formulas.

2 Start from the cathode



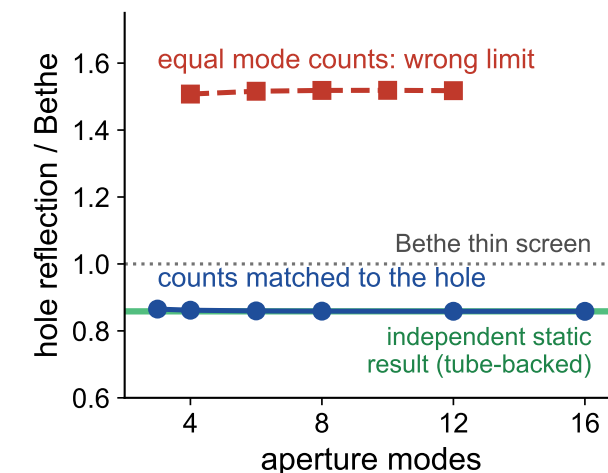
A bunch placed inside breaks the Lorenz condition for good; an emitted one does not.

3 Independent check



Matches the cathode-pipe Green function to $\sim 10^{-10}$ in ϕ until the end-wall echo.

4 The aperture



Matched mode counts give the tube-backed hole, $0.572 b^3$; equal counts do not.

Prescribed trajectories, no rf field yet. Next: rf-driven bunch and a full-wave comparison.

Fast Frozen Indirect Space Charge Modelling

Robert Simpson — Department of Physics, University of Oxford

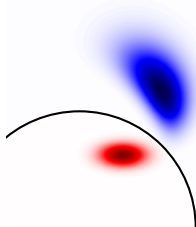
Indirect Space Charge

- ▶ Field produced by mirror currents in conductive surroundings
- ▶ Can drive instability-causing resonances

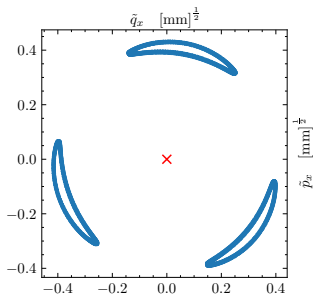
Frozen Modelling

- ▶ Faster computation*
- ▶ Fewer particles *
- ▶ Symplectic

*Compared to collective/PIC modelling



ISIS RCS Model



$3Q_x = 13$ resonance
Poincaré plot



UNIVERSITY OF
OXFORD



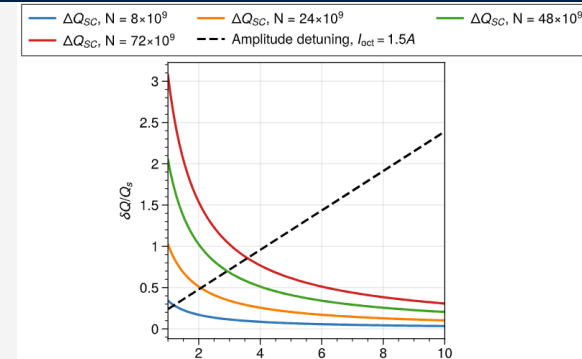
Science and
Technology
Facilities Council

ISIS Neutron and
Muon Source

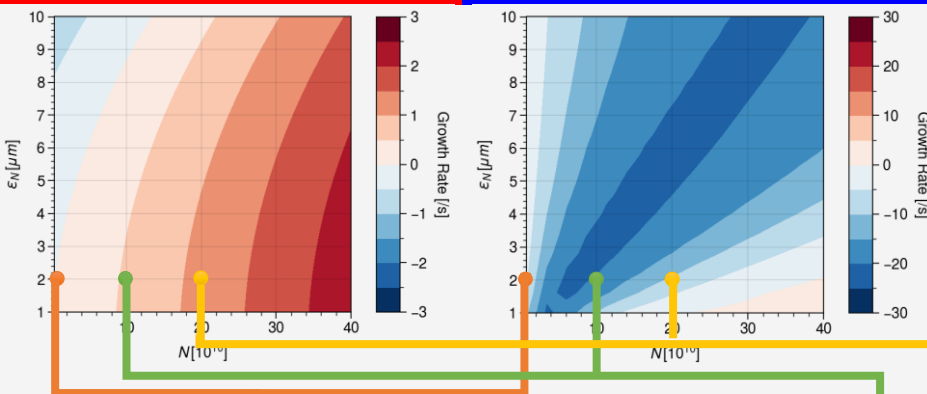
Landau Damping with Space Charge in the LHC

Idea:

- During early LHC commissioning, LHC was operated without Landau octupoles: injection was stable, but an instability occurred during ramp. The reason for this was never fully ascertained.
 - Two possible explanations: **residual nonlinearities** or **space charge contribution**
- For intense beams at small transverse emittance, tune shift from SC can be larger than from external nonlinearities

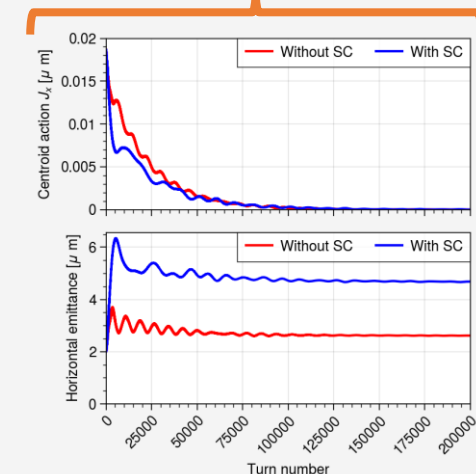


Without space charge With space charge



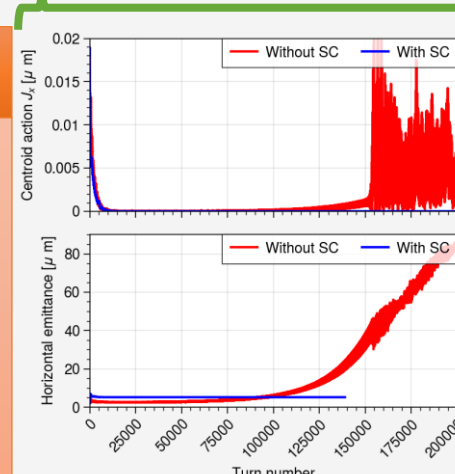
Tune shift measurements at injection were used to estimate residual detuning:

- Coefficients combined with formulae from Burov and growth rate simulations to estimate overall stability of LHC at injection without space charge as a function of **intensity** and **emittance**
- Effect of space charge was incorporated following formulae of Macridin et al



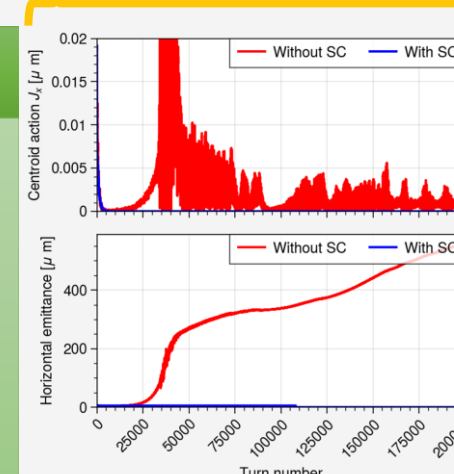
$$N_B = 8 \times 10^9$$

No instability:
Intensity too low to overcome Landau damping from residual nonlinearities



$$N_B = 1 \times 10^{11}$$

No SC: Slowly growing instability
SC applied: damped instability

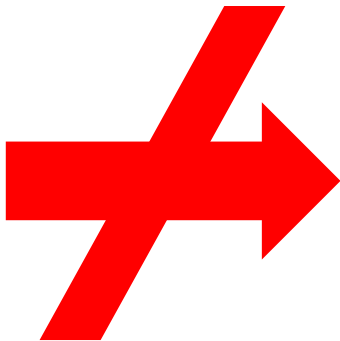
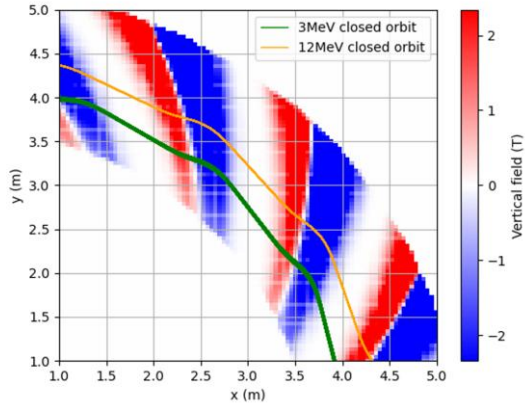


$$N_B = 1 \times 10^{11}$$

No SC: rapid instability growth (order 20k turns)
SC applied: fully damped instability

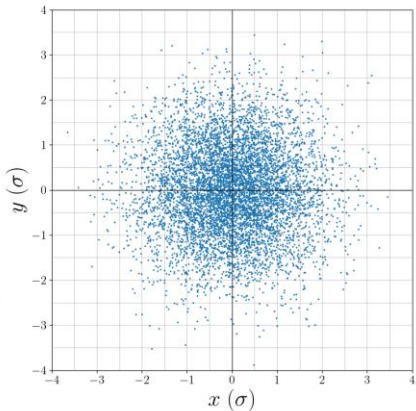
Typically, particles are tracked through a 3D field map.

In an FFA, the position of the closed orbit is non-trivial..



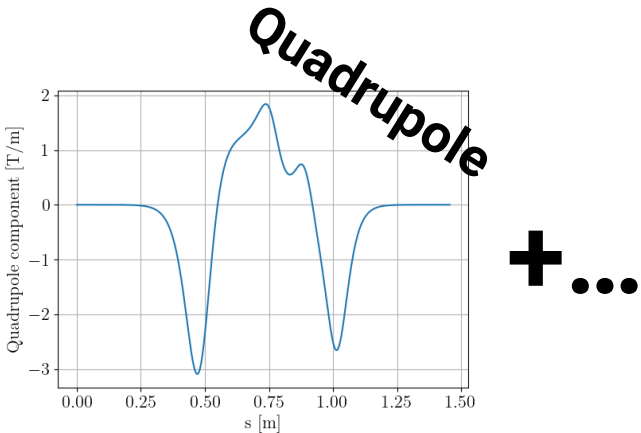
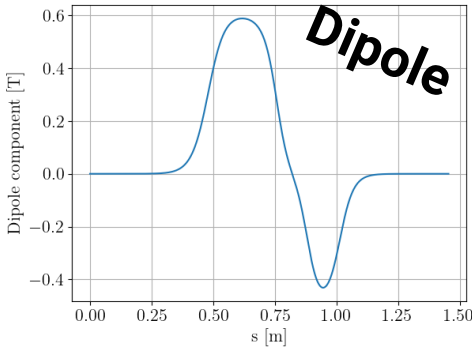
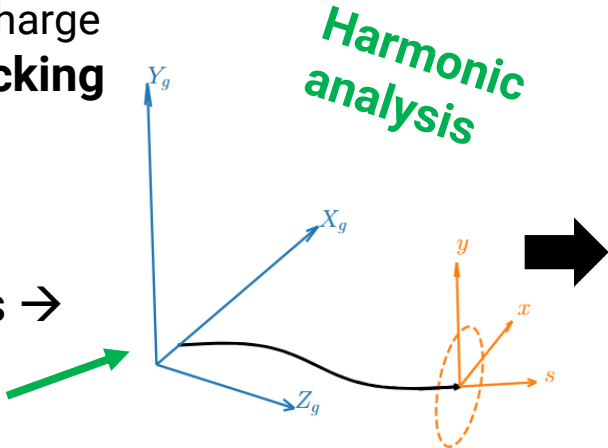
We want to combine FFA tracking a “2.5D” space-charge solver.

The solver requires a coordinate system centred on the beam.



To work with a conventional space-charge solver → we need the particle tracking to happen in the beam’s local coordinate system.

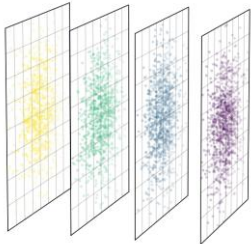
3D field map to local coordinates →
Decompose the field into its multipole components



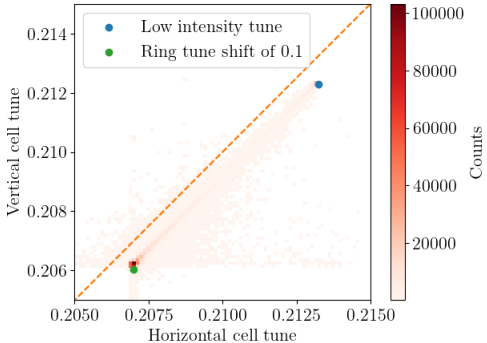
Motion in the FFA calculated with a Taylor map (MAD-NG)



PyPIC 2.5D space-charge solver



Simulation of a KV distribution in an FFA

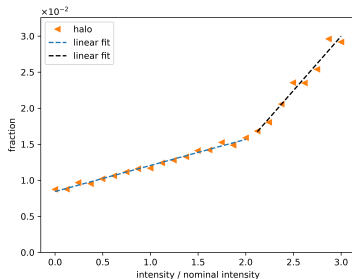
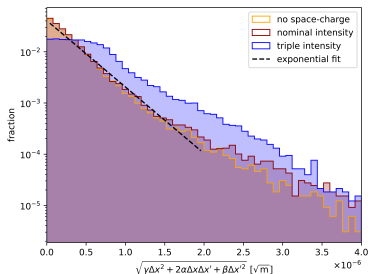
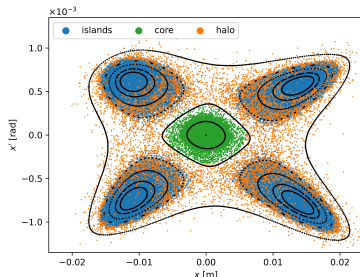


Simulation of adiabatic trapping with space-charge effects

Pancaldi, Bazzani, Capoani, Giovannozzi, Londrillo

Poster # 54

- ▶ Multi-Turn Extraction: used at the CERN Proton-Synchrotron to **adiabatically** split beams
- ▶ Experimental measurements: possibly non-negligible space-charge effects
- ▶ We simulate an adiabatically split beam with **self-consistent** space-charge forces
- ▶ Adiabaticity $\rightarrow$ **long** sim. times $\rightarrow$ GPU-accelerated code



Simulations of Landau Damping on the ISIS RCS

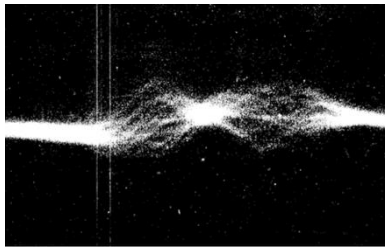
Simulate head-tail modes to measure their landau damping

Fit the decay of the head-tail signal over turns.

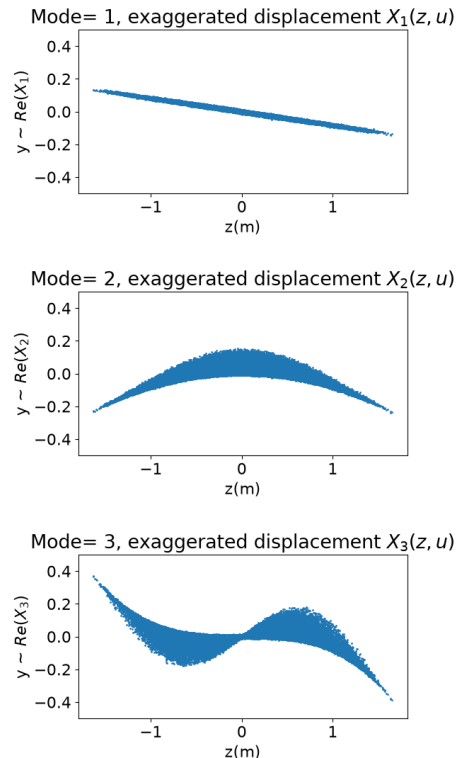
Perform intensity scan for different space charge regimes

ISIS RCS experiences head-tail instabilities.

1

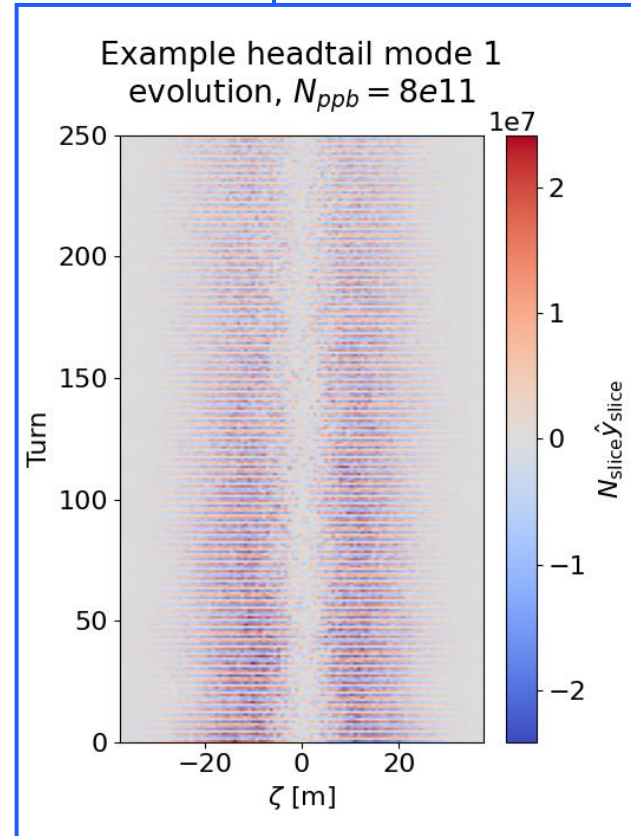


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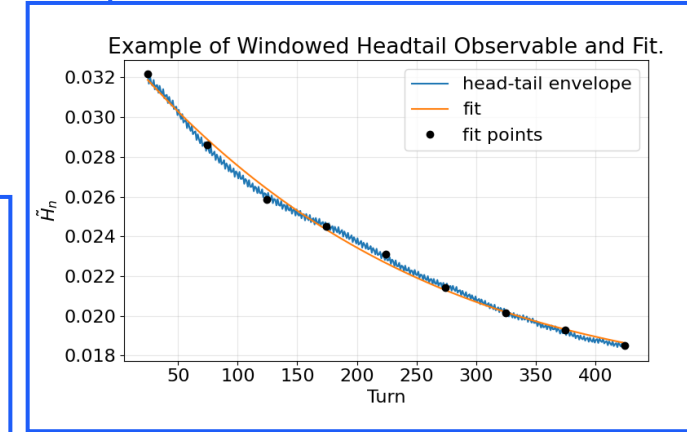


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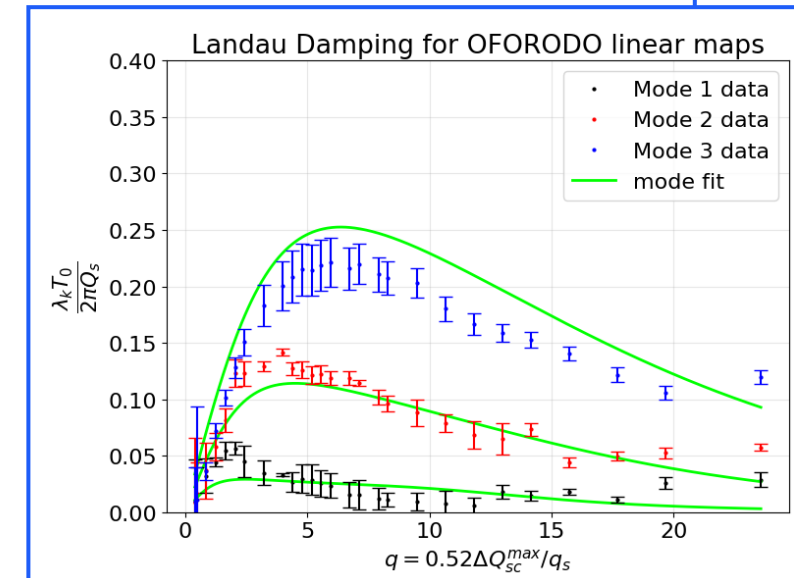
Track bunch turn-by-turn with Xsuite.



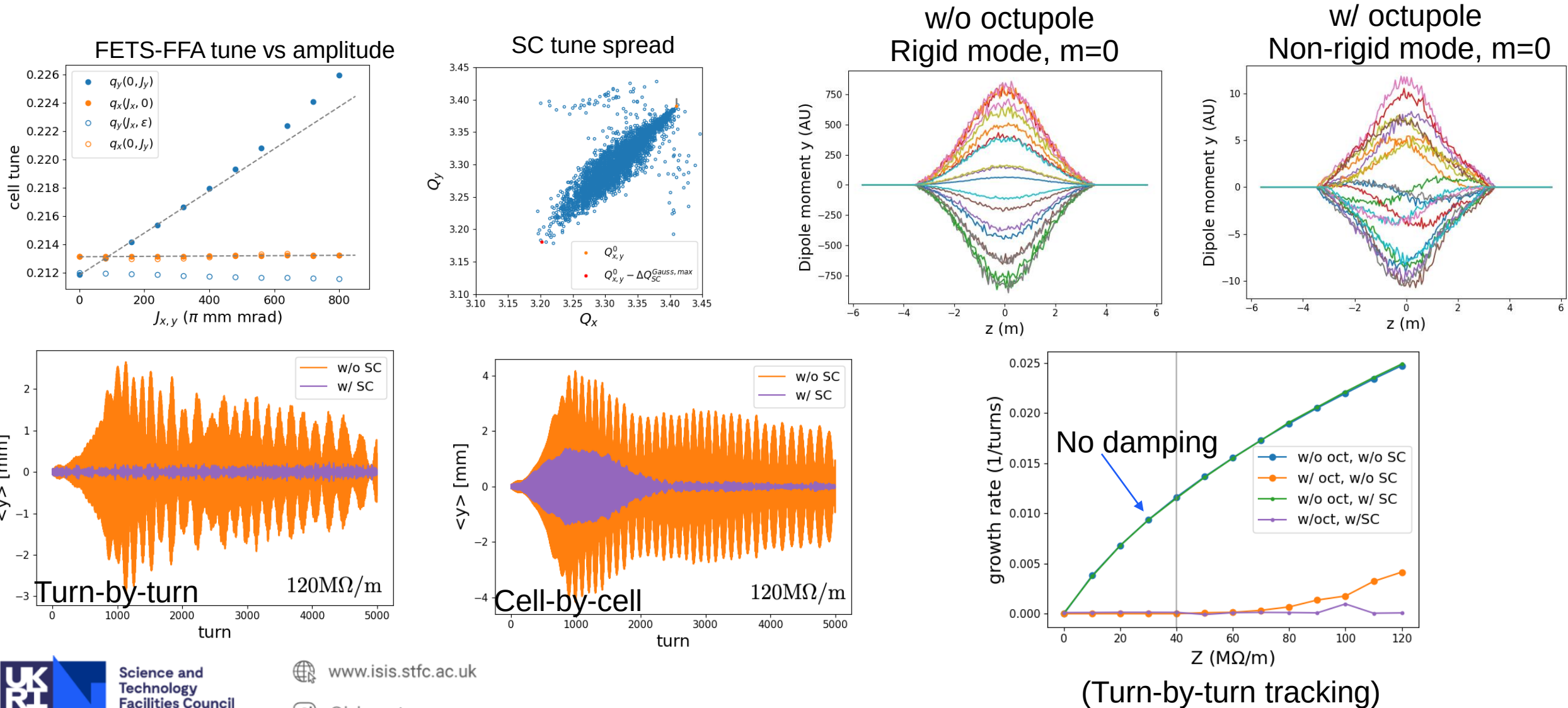
4



5

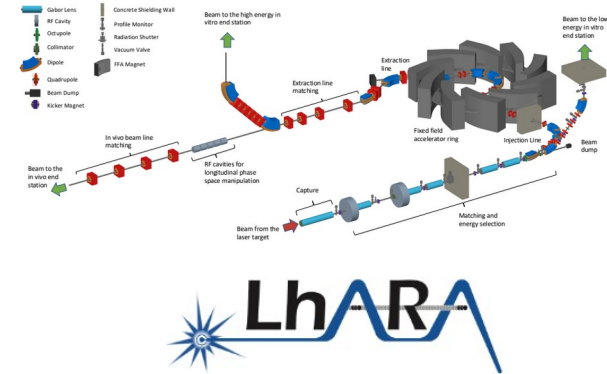


Landau damping from octupolar tune spread and space charge in scaling FFAs



First beam-tracking study of LhARA FFA with space charge effects

- **LhARA project** : interdisciplinary collaboration aiming to build a facility for radiobiological studies using proton and ion beam irradiation
- **Fixed Field alternating gradient (FFA) accelerator** : protons from 15 MeV to 127 MeV
- **Beam tracking with space charge (RF-Track code)** : from beamline entrance up to 50 turns in the FFA
- **LhARA FFA** : initial study reveals stable beam size over 50 turns



M. Mannie-Corbisier¹ | J. Pasternak² | N. Pauly¹ | W. Shields³

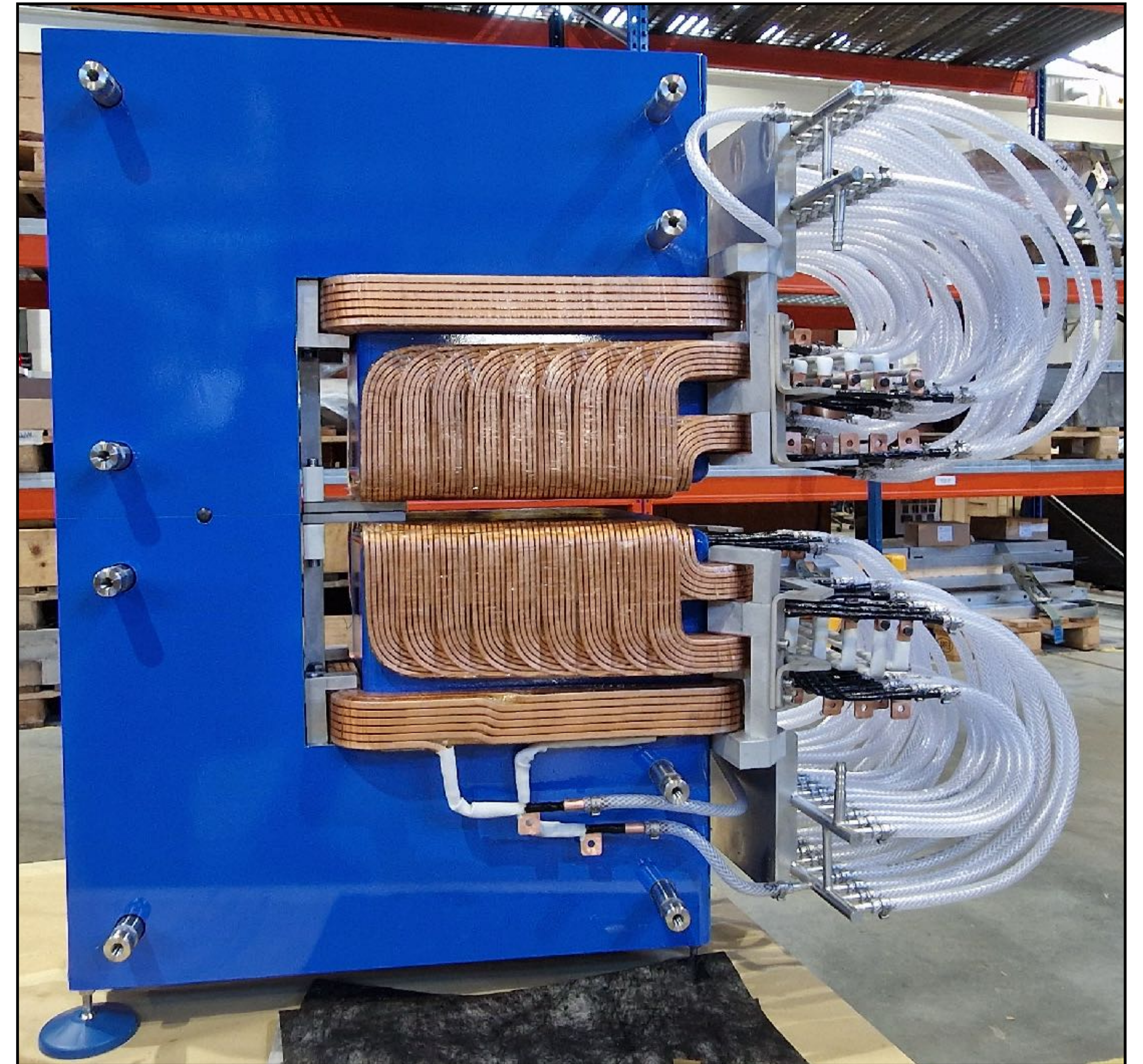
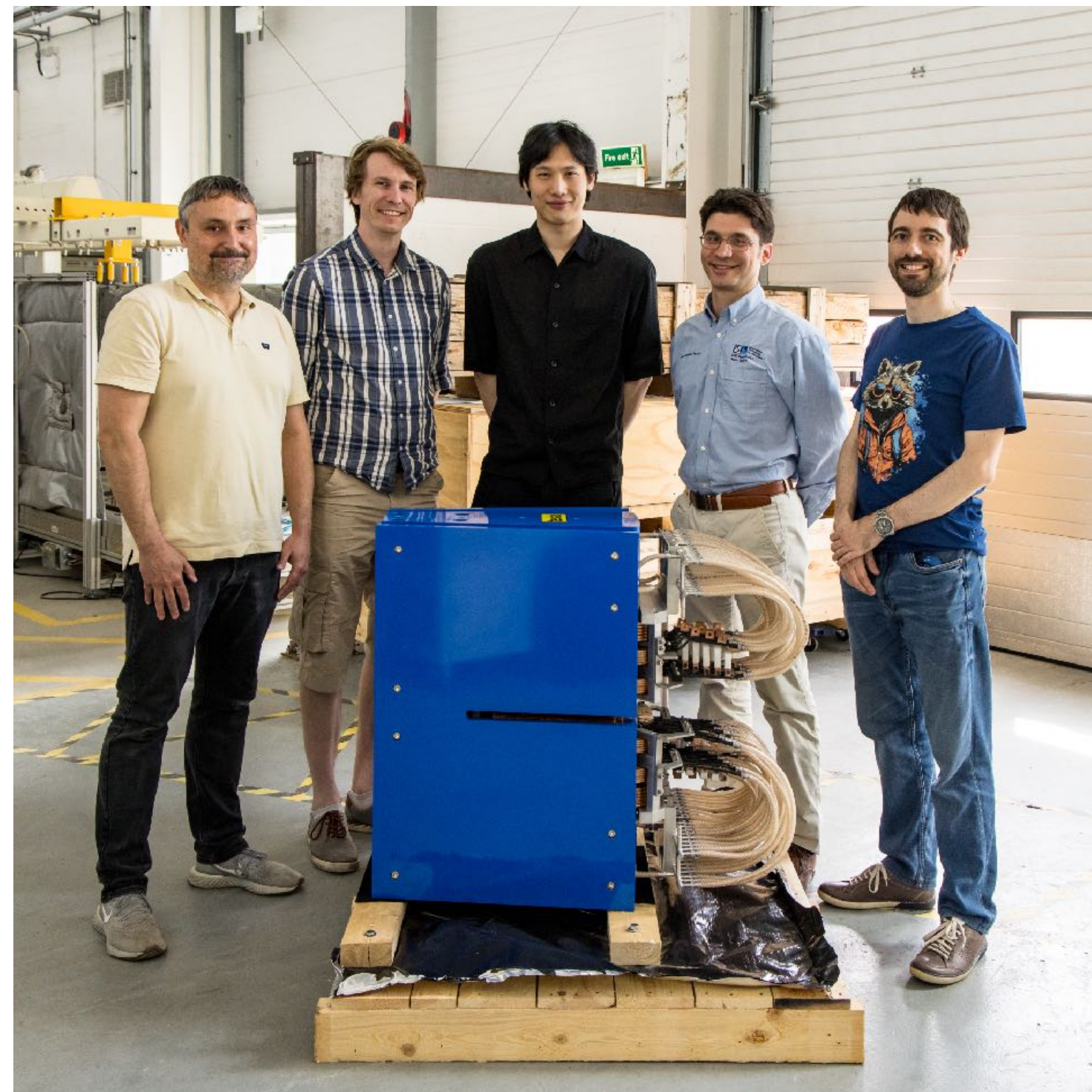
¹ Université libre de Bruxelles, Belgium ² Imperial College London, United Kingdom

³ Royal Holloway University of London, United Kingdom

30/09/26
Space charge 2026
Oxford

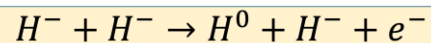
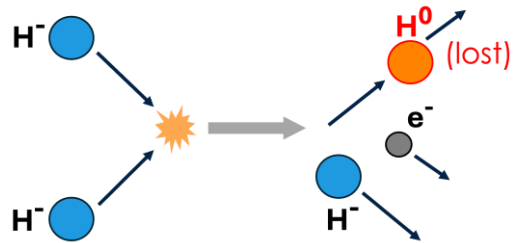
FFA Magnet prototype for high power pulsed proton driver

- FFA natural candidate for high power pulsed operation
- Necessity to use trim coils in the main magnets to adjust field gradient as a function of beam intensity.
→ Field gradient created by saddled (to keep magnet compact) trim coils around flat pole.
- Prototype magnet manufactured with measurement planned to investigate field quality and local correction schemes



A new way to calculate Intra-Beam Stripping (IBSt) losses

1 The Problem



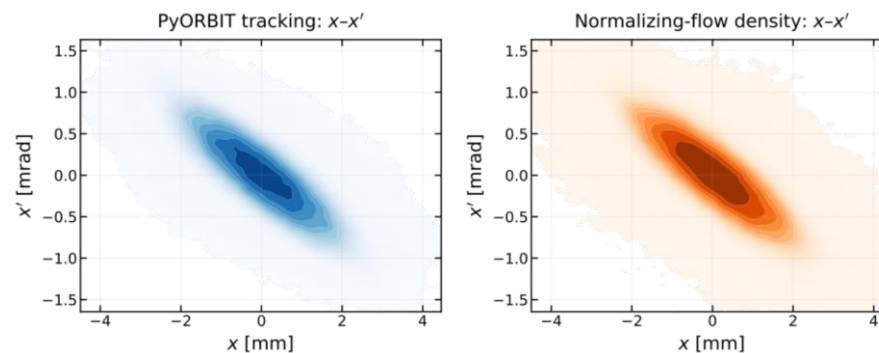
IBSt calculations require evaluating a high-dimensional integral.

$$\frac{dN}{dt_{rest}} = \frac{N^2}{2} \int |u| \sigma_H(|u|) f(v_1, r_1) f(v_2, r_2) \delta(r_1 - r_2) d\Gamma_1 d\Gamma_2$$

2 Challenges with Monte Carlo Integration

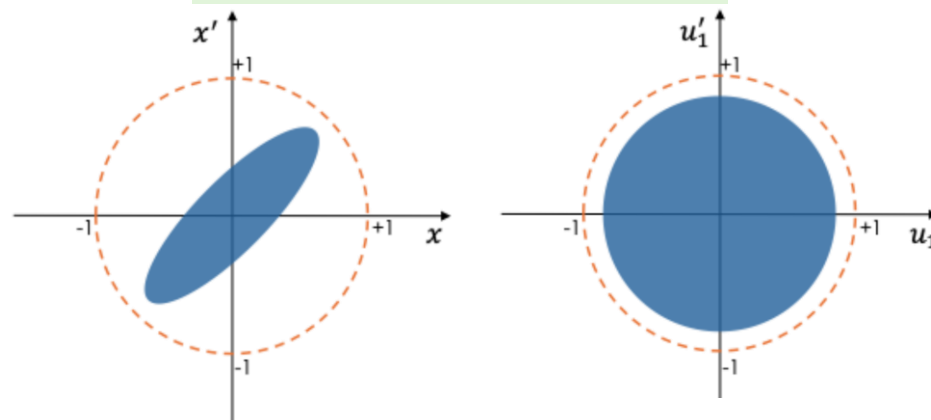
1) Representing the beam distribution

Normalizing Flow

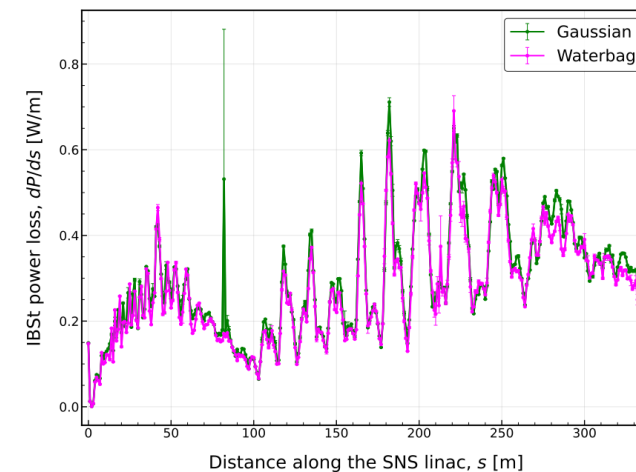
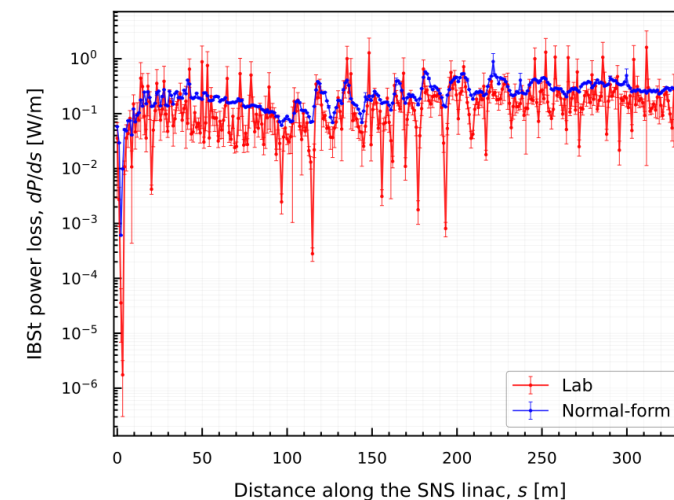


2) Efficient Monte Carlo sampling

Normal-Form Coordinates



3 IBSt loss prediction along the SNS linac



4D Beam Matching, Phase Smoothing, and Resonant Energy Exchange in a 1 Ampere Deuteron LINAC

Lucas Zaïdat ¹, Hiroki Okuno ², ¹École Polytechnique, ²RIKEN Nishina Center

The 1A Space-Charge Challenge

At 1A, extreme space-charge forces destroy longitudinal bunching and create a massive transverse halo.

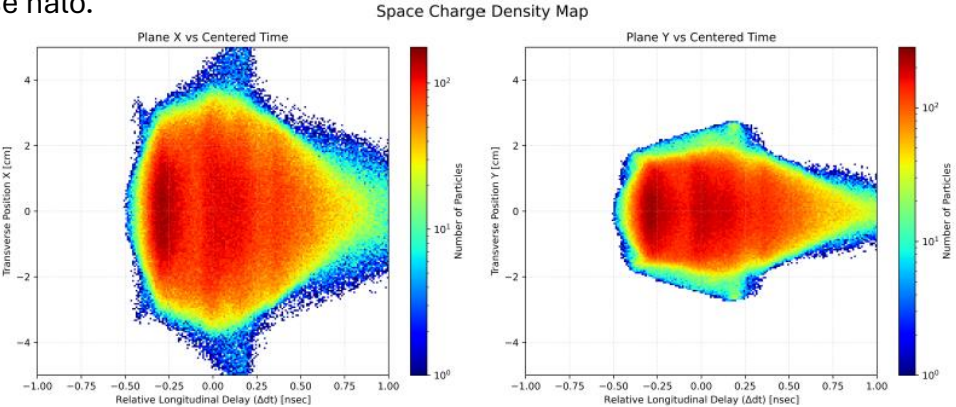


Figure : 2D Density map with the previous design. 0A lattice + $1/\beta^2\gamma^3$

The Solution : Phase Smoothing

Nelder-Mead 4D Twiss optimization coupled with a tailored parabolic RF phase profile $\phi_s(z)$

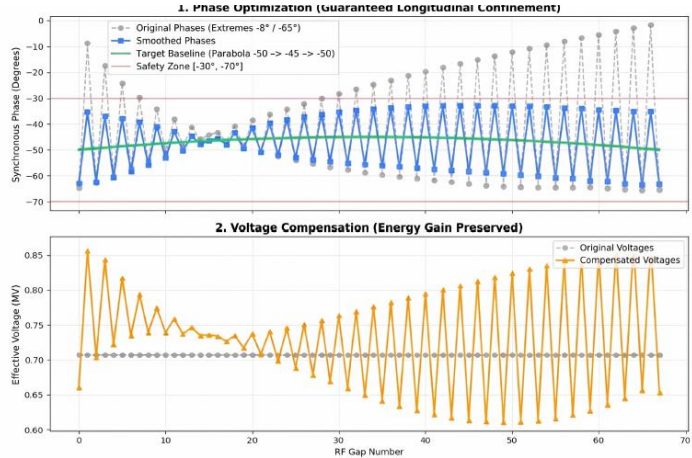


Figure : Graph of the phases and voltage profiles

Results : Halo Supression

Non-adiabatic transitions mitigated. Longitudinal bunching restored and halo safely confined

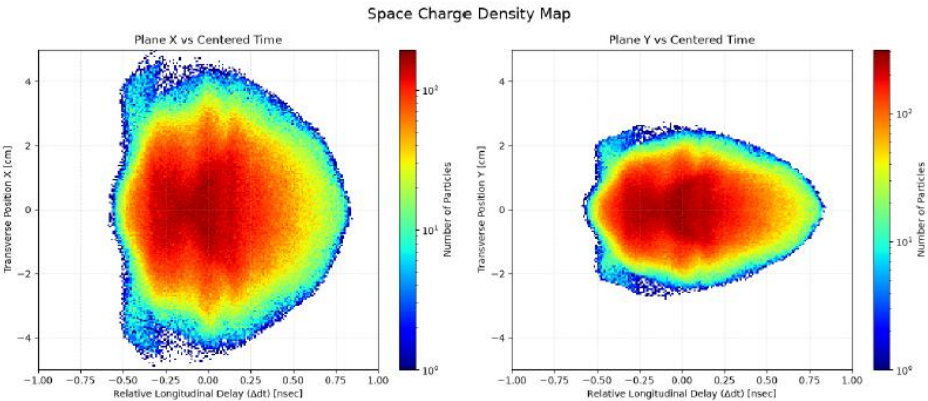


Figure : 2D Density map with the new design

Resonance Limits

Emittance exchange driven by structural resonances ($\sigma_t = \sigma_l$). Points towards future magnetic tapering and solenoid confinement.

Desiable tune evolution

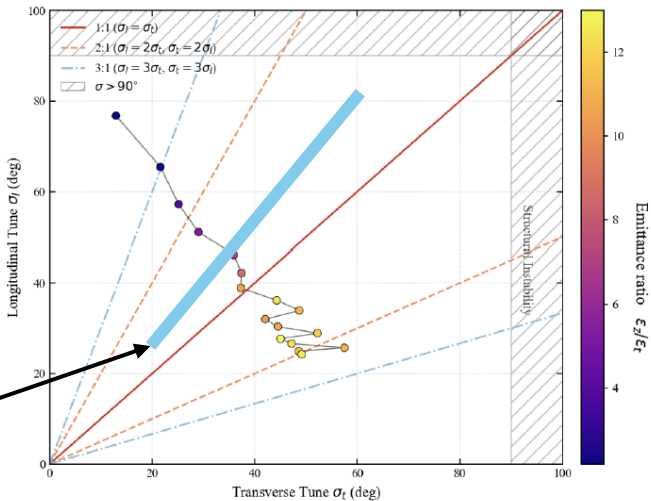


Figure : Tune stability diagram