

Experimental and Simulation Studies of Non-linear Resonances in the ISIS Synchrotron

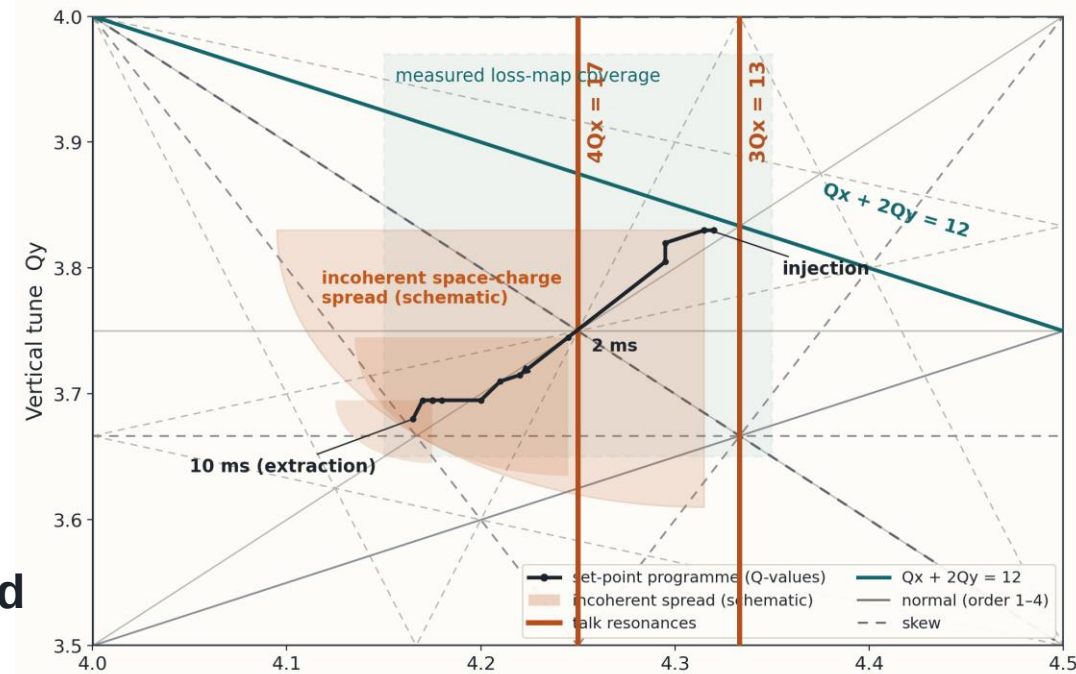
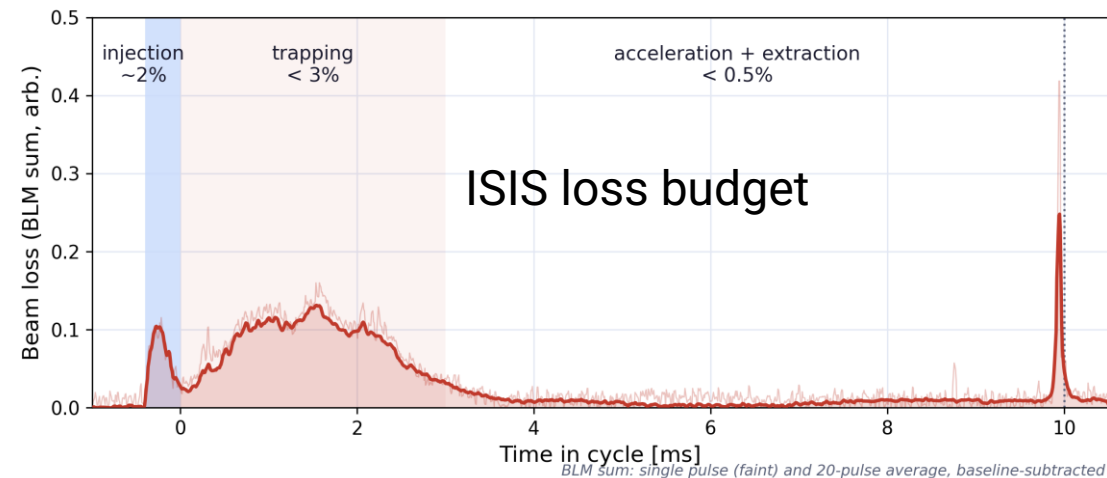
Esmaeil Ahmadi
Chris Warsop
Hayley Cavanagh

ISIS Neutron and Muon Source · STFC Rutherford Appleton Laboratory

Session A-4 · Beam Loss and Halo Dynamics · Oxford · 2 October 2026

THE ISIS TUNE FOOTPRINT SAMPLES NON-LINEAR RESONANCES

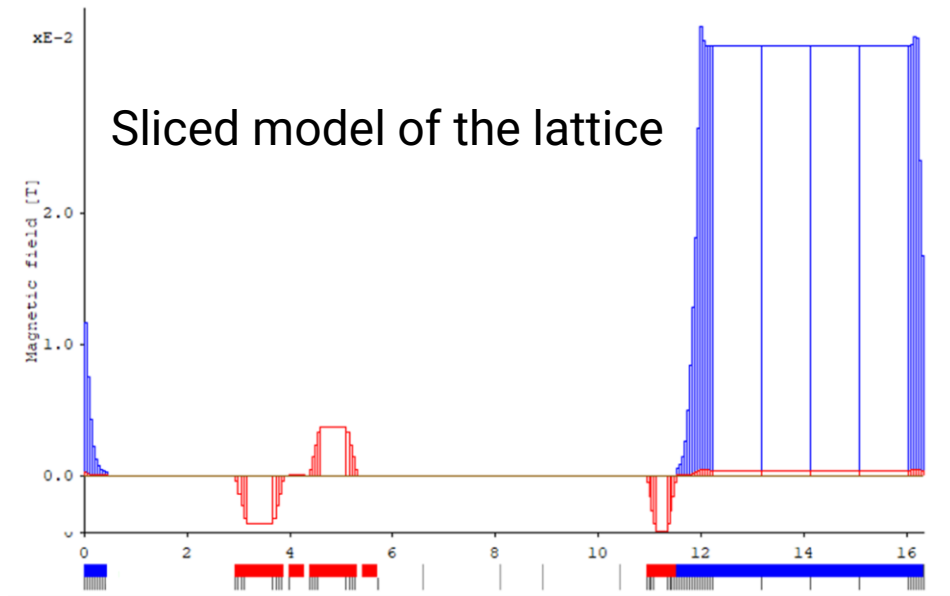
- The incoherent tune spread at injection is 0.4 to 0.5 — the footprint simply cannot avoid all the low-order lines
- ISIS operation is not about avoiding these resonances — it's about choosing where the footprint sits and how fast particles sweep across the lines
- **Measurement-based setup on benchmarked models** — we are measuring the machine in more detail than ever. Better models give a better basis for operations, improved understanding, and push the high-intensity limit



Measurement meets the model?

At ISIS the dipole bending radius is small and the aperture large – so fringe fields are strong.

How do we model the machine's nonlinearity?

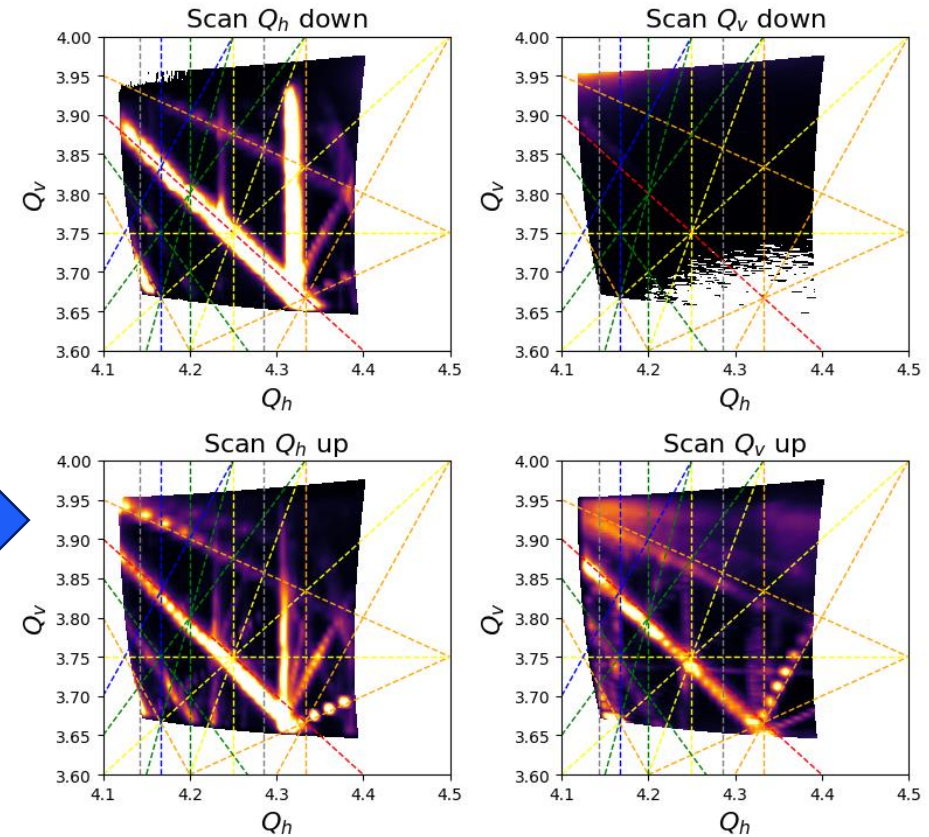


Does the model reproduce the measurements?



MEASUREMENTS

Beam loss during dynamic tune scans



Dynamic tune scan:

- A fingerprint of the machine's error content
- Up/down crossing asymmetry
- Stop band width

Ramp the tune, record everything, simulate the same ramp (Coasting beam, low intensity)

1

Ramp the tune

Dynamic Q_h and Q_v ramps across the resonance, from below and from above; fiducial-corrected tunes

2

Record the loss

Ring-summed beam-loss monitors plus the intensity monitor, through the crossing

3

Watch the halo

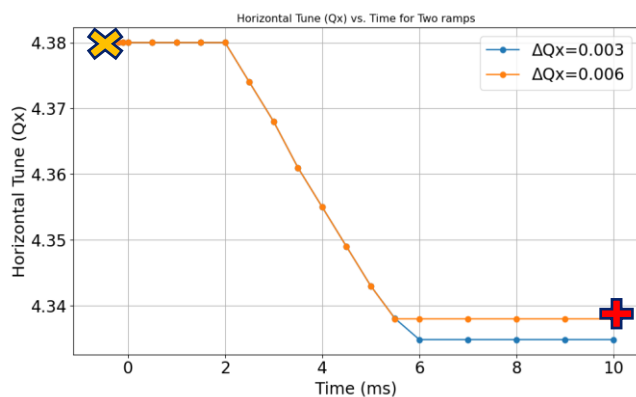
R6HPM1 / R6VPM2 profile monitors: tails and halo forming as the beam crosses

4

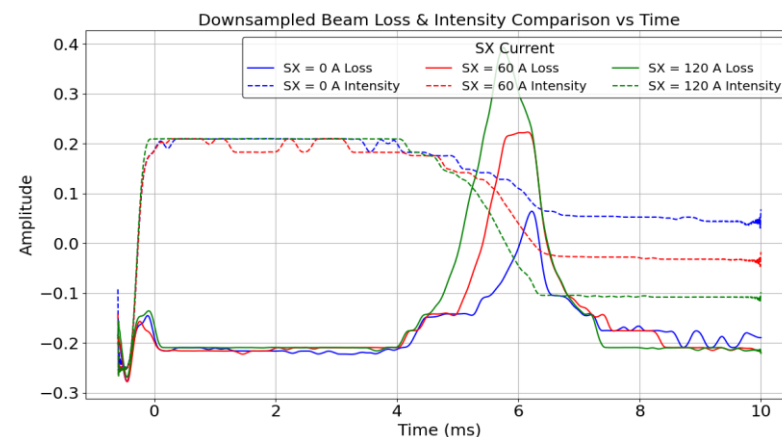
Simulate the ramp

The identical dynamic tune ramp in Xsuite (two trim families) — not a static tune grid

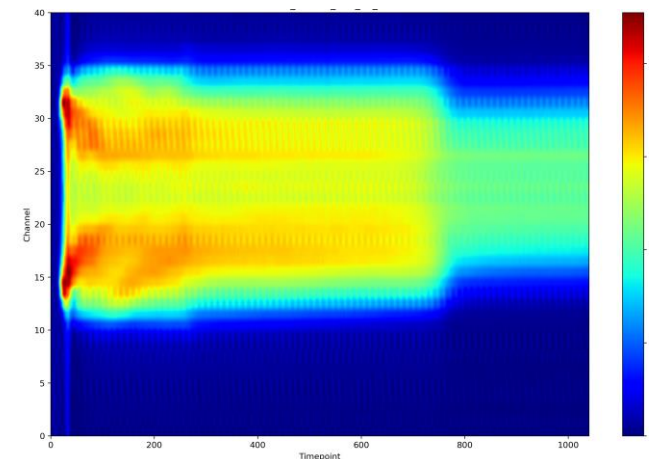
Q ramp



Beam loss while approaching the resonance

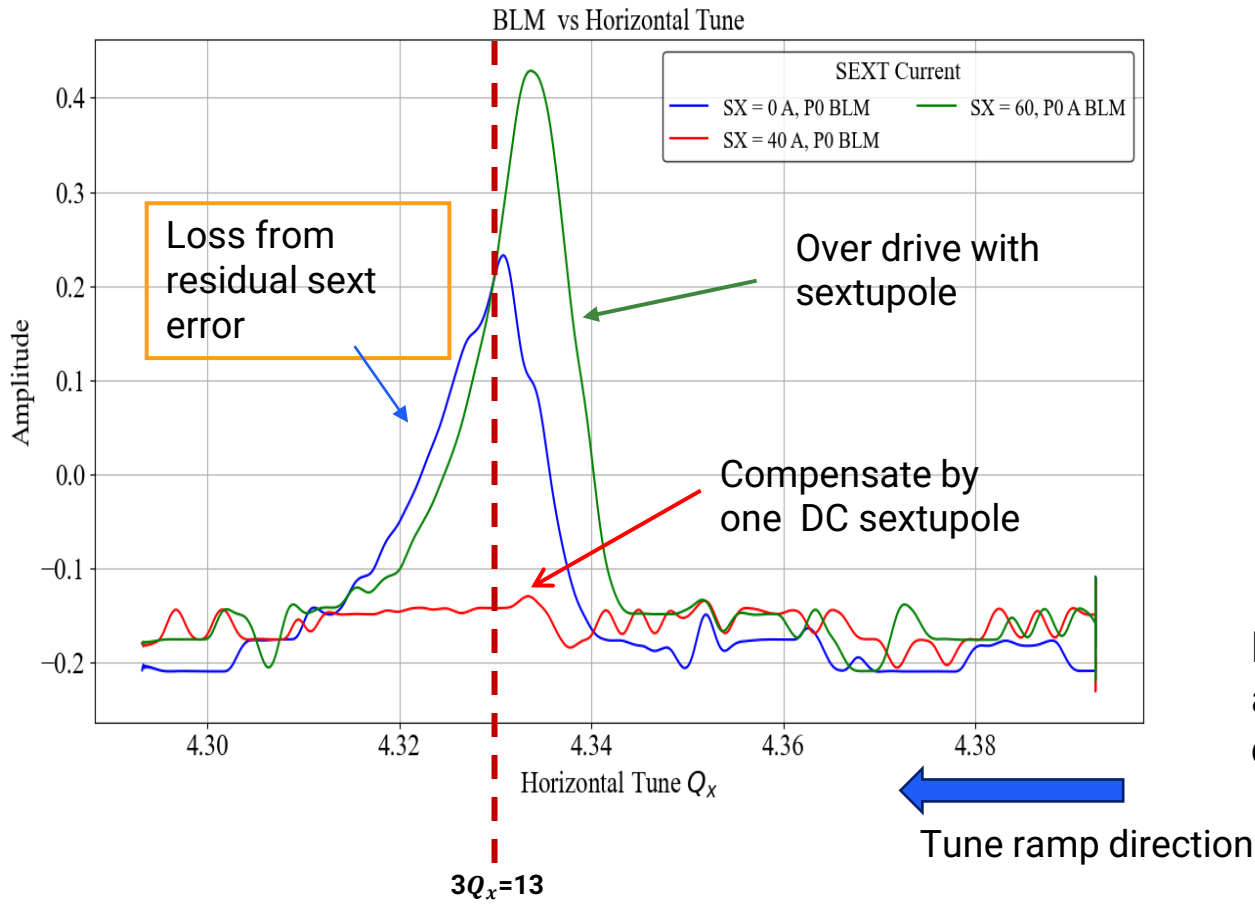


Beam Profile (RGI)

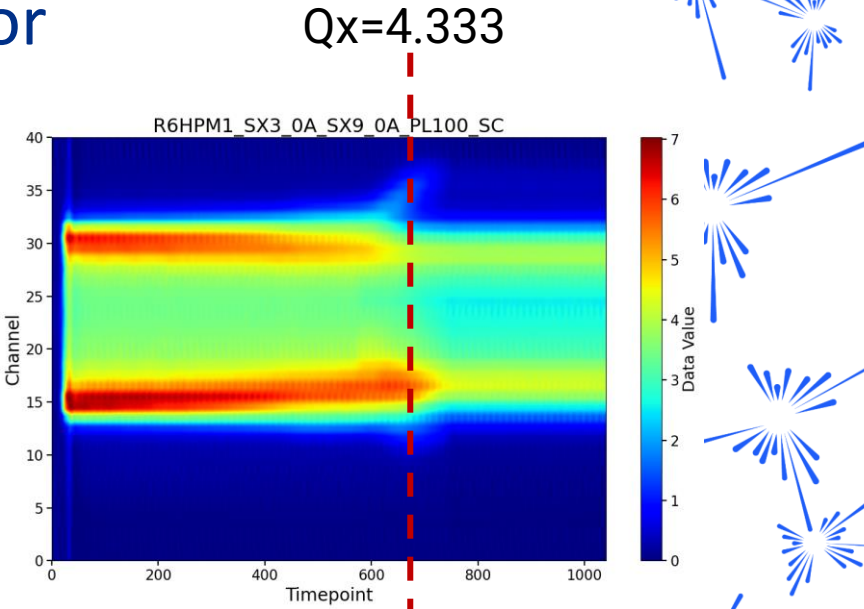


Sextupole compensation of the residual $3Q_x = 13$ error

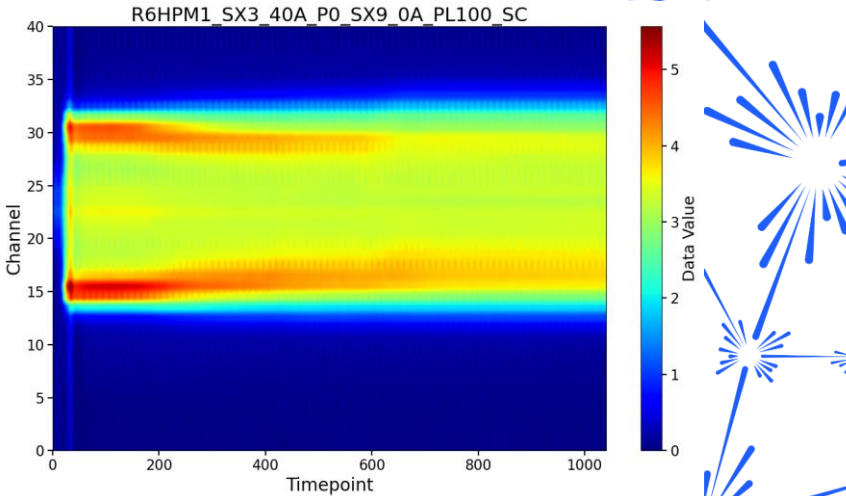
Beam loss vs Q_x along the ramp



Beam profile with residual Sextupole exciting $3Q_x=13$



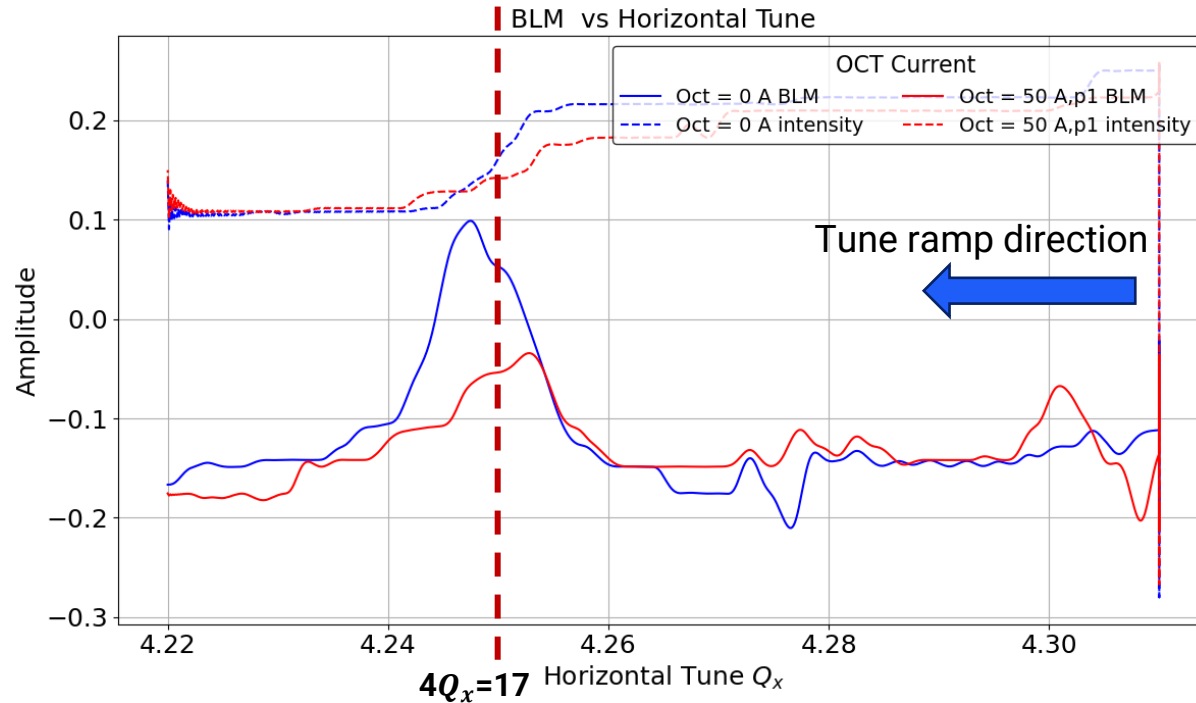
Beam profile after sextupole compensation



Nonlinear model calibration

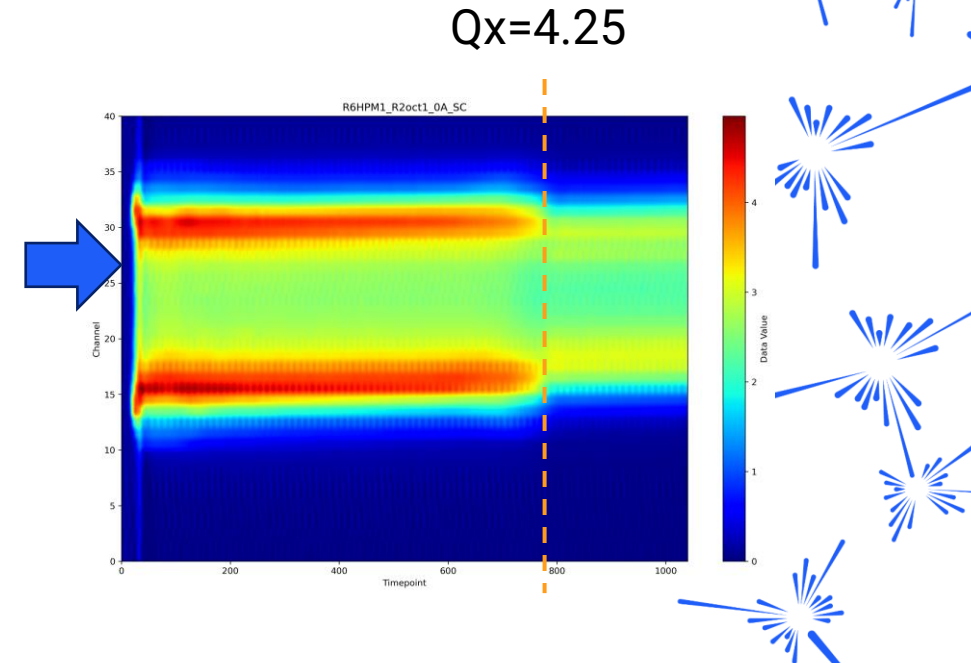
Octupole compensation of the residual $4Q_x = 17$ resonance

BLM and intensity vs Q_x across the $4Q_x = 17$ crossing

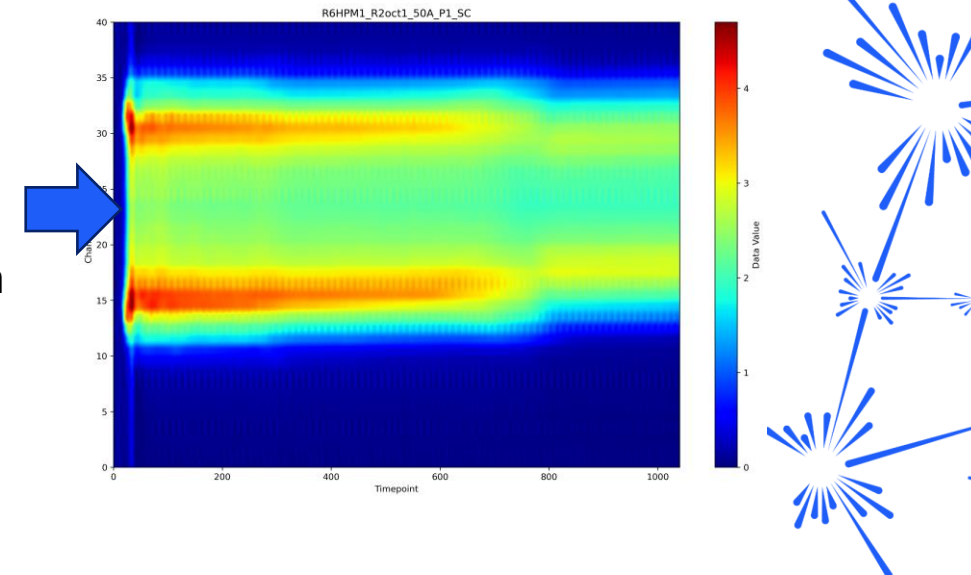


- A single DC octupole at 50 A partially compensates the crossing — $k_3L = 1.10 \text{ m}^{-3}$ at the null ($0.15701 \cdot I \cdot L_{\text{eff}} / B\rho$, $L_{\text{eff}} = 0.1719 \text{ m}$)

Beam profile with residual octupole



Beam profile after octupole compensation



Compensation theory: one phasor per resonance

Sextupole-driven third-order resonance:

$$G_3^{(13)} \propto \sum_j (k_2 L)_j \beta_{x,j}^{3/2} e^{i(3\phi_{x,j} - 13\theta_j)}$$

For: $3Q_x = 13$

Octupole-driven fourth-order resonance:

$$G_4^{(17)} \propto \sum_j (k_3 L)_j \beta_{x,j}^2 e^{i(4\phi_{x,j} - 17\theta_j)}$$

Residual machine error as a phasor:

$$G^{\text{machine}} = |G^{\text{machine}}| e^{i\psi_{\text{machine}}}$$

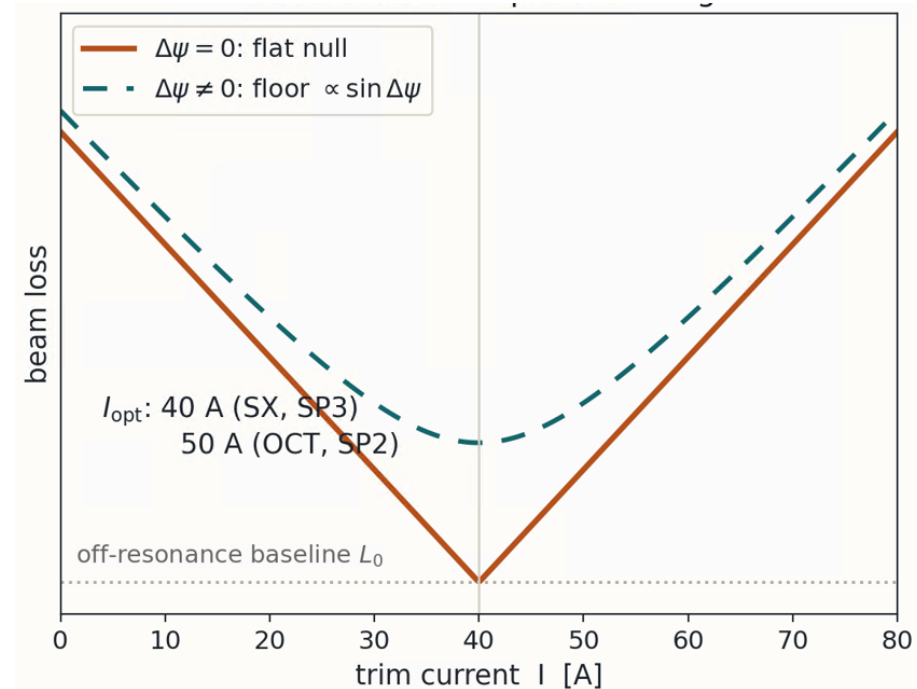
The trim magnet also generates its own resonance-driving term:

$$G^{\text{trim}} = A I e^{i\psi_{\text{trim}}}$$

Null condition:

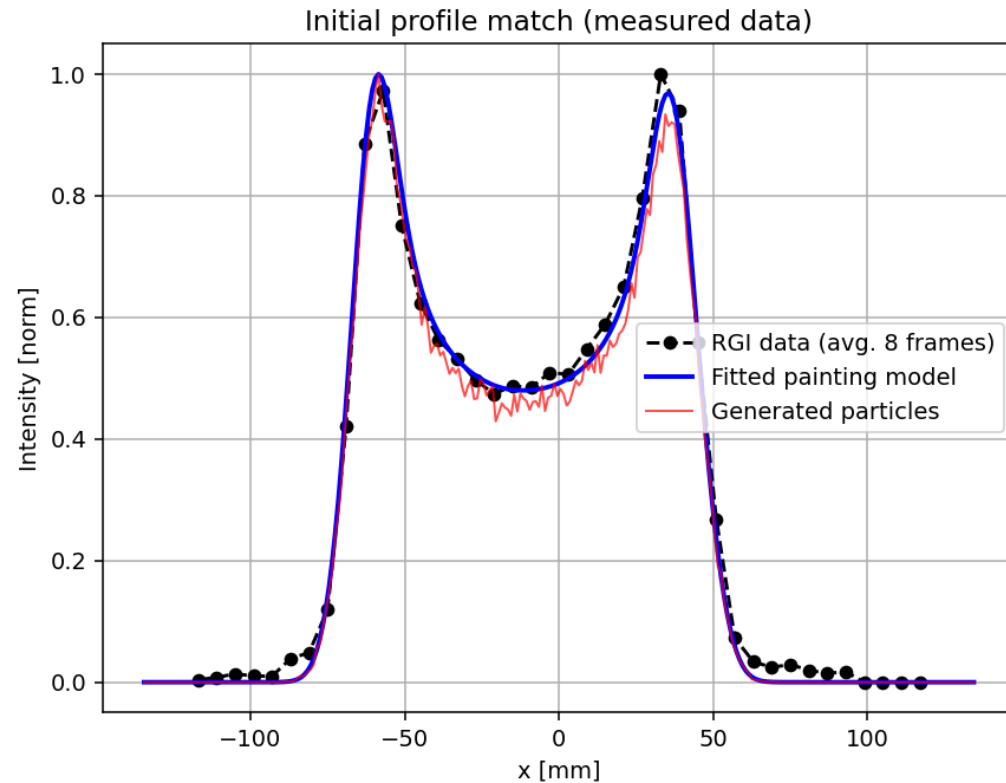
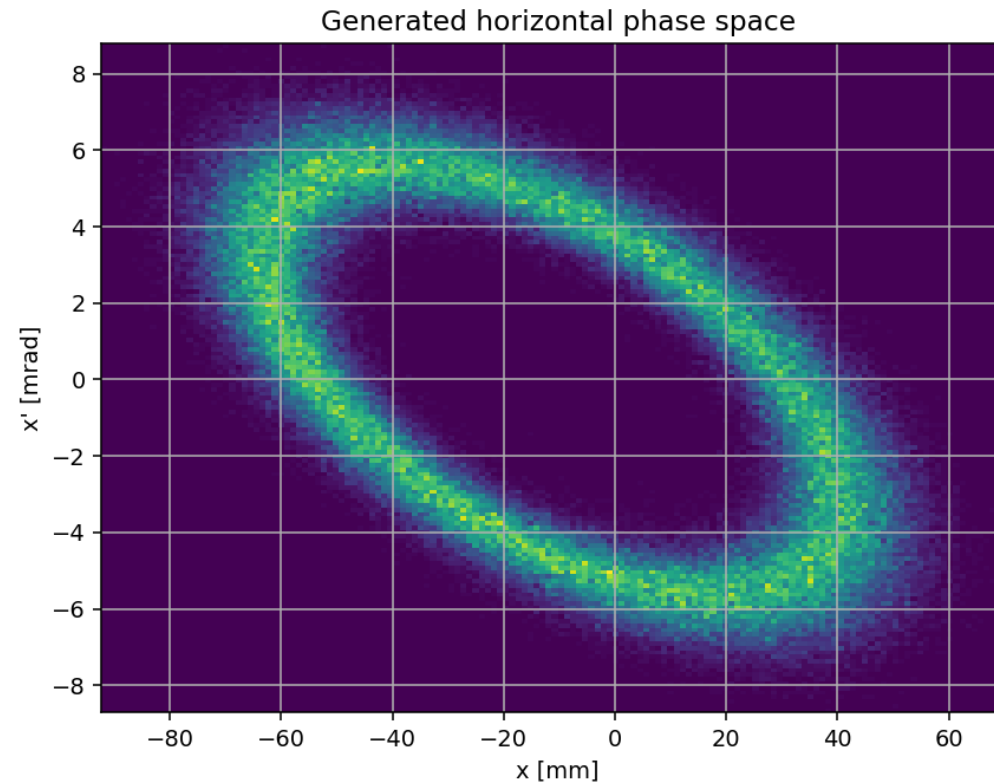
$$G^{\text{total}} = G^{\text{machine}} + G^{\text{trim}} \approx 0$$

- **Why one magnet is enough:** 13 and 17 are not multiples of $P = 10$, so symmetric magnet families cancel at these harmonics — the residual is symmetry-breaking, and a single symmetry-breaking trim can null it



Modelling nonlinearity near resonance $3Q_x=13$

Initial distribution from fitting profile monitor data

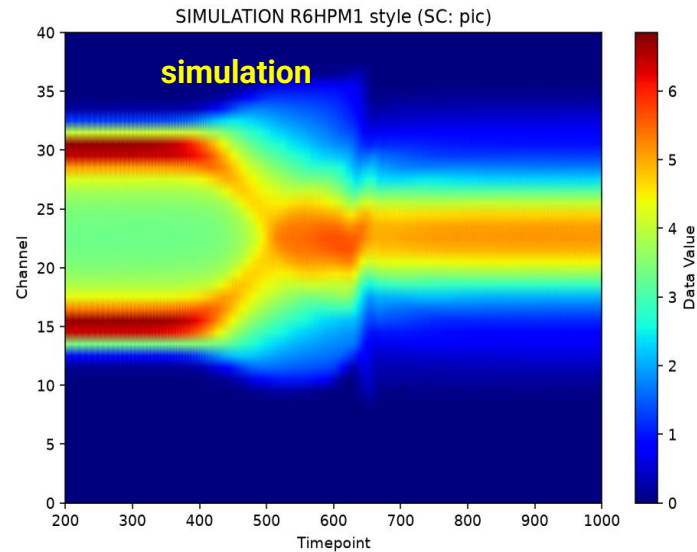
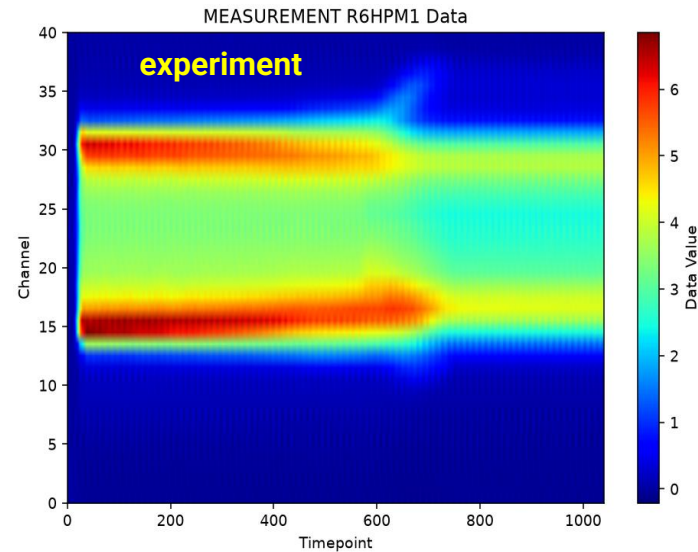
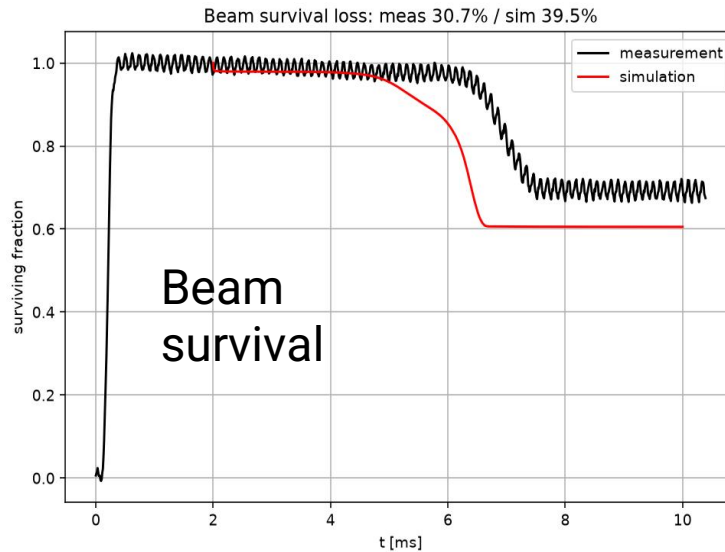
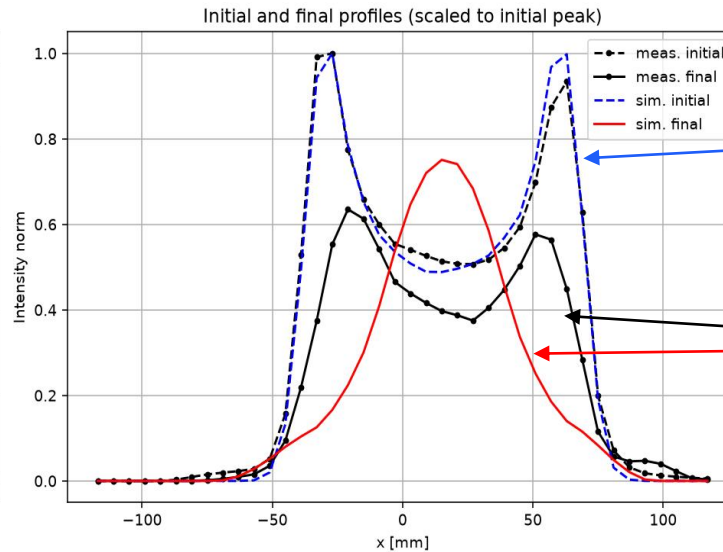


The initial coasting beam is a hollow beam.



Modelling nonlinearity near resonance $3Q_x=13$

Profile:



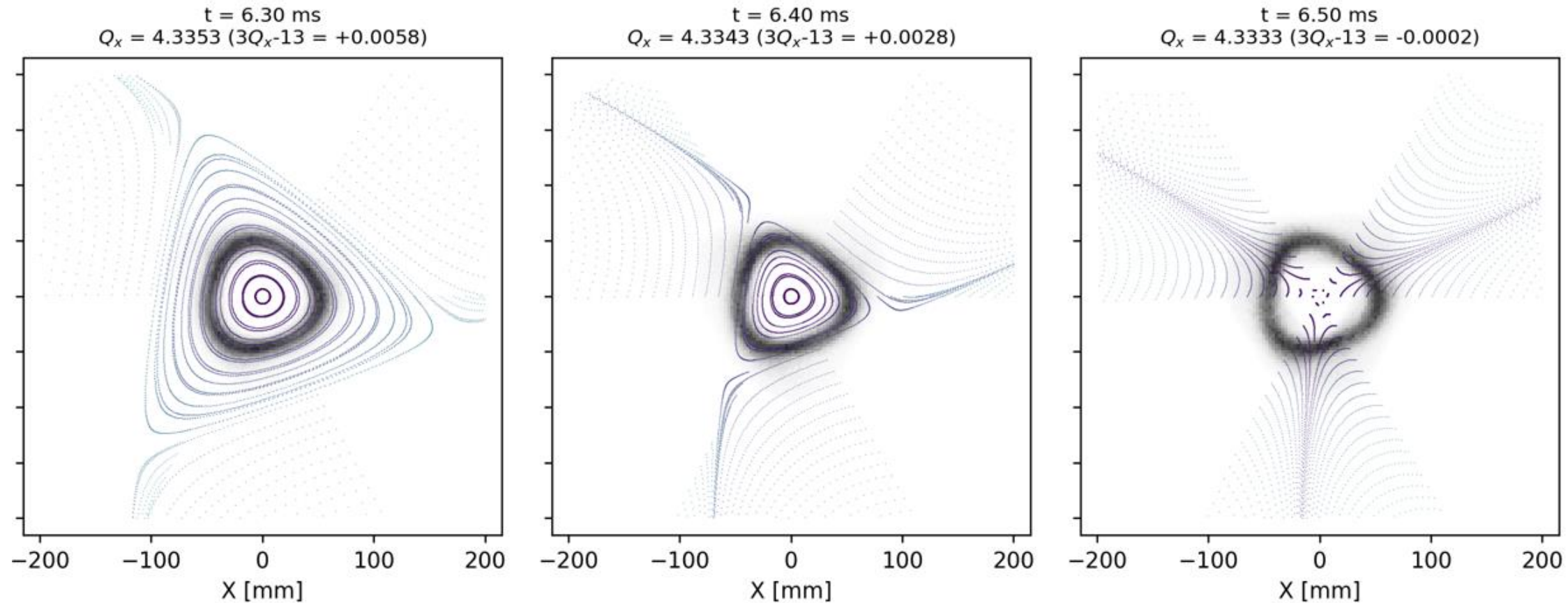
- Only the compensating sextupole is included in the model.
- Intensity ($N=8.5e11$ pp) effect included via PIC calculation

Initial distribution

Final distribution (Experiment and model)

Modelling nonlinearity near resonance $3Q_x=13$

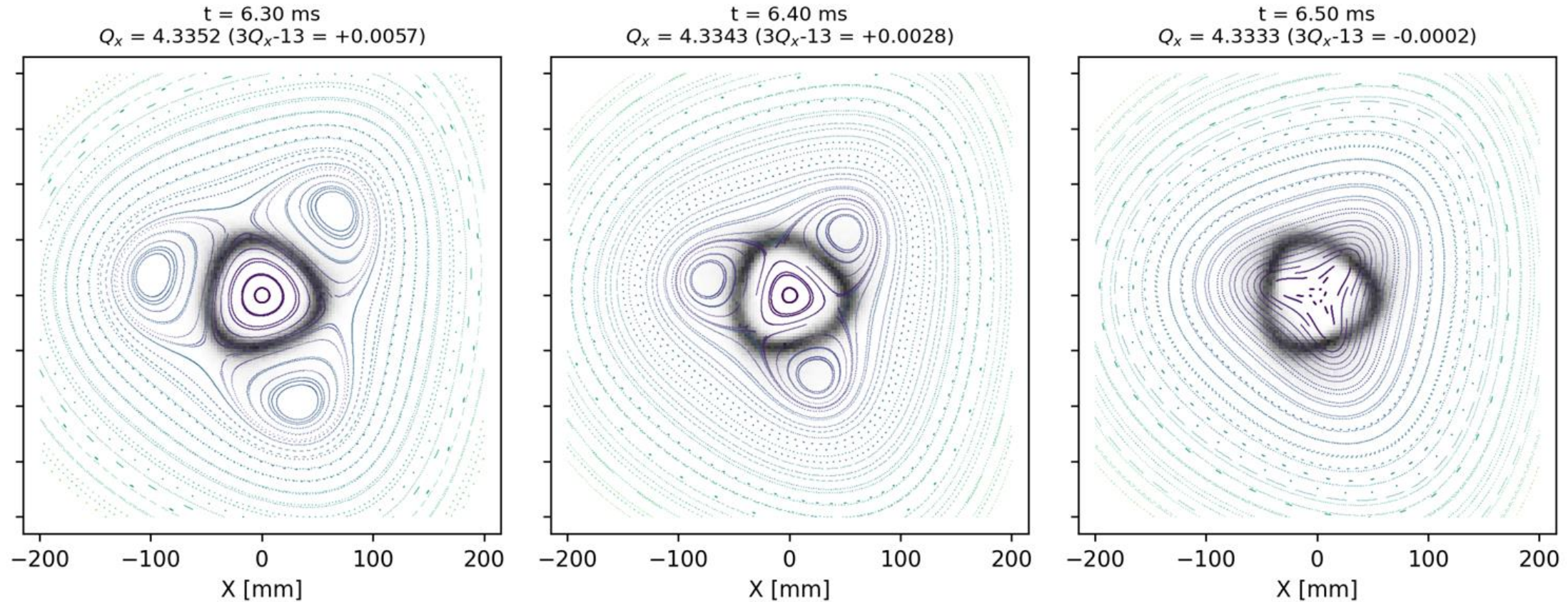
Phase space near resonance with only sextupole



The separatrix shrinks as the tune ramps – particles are peeled off along it.

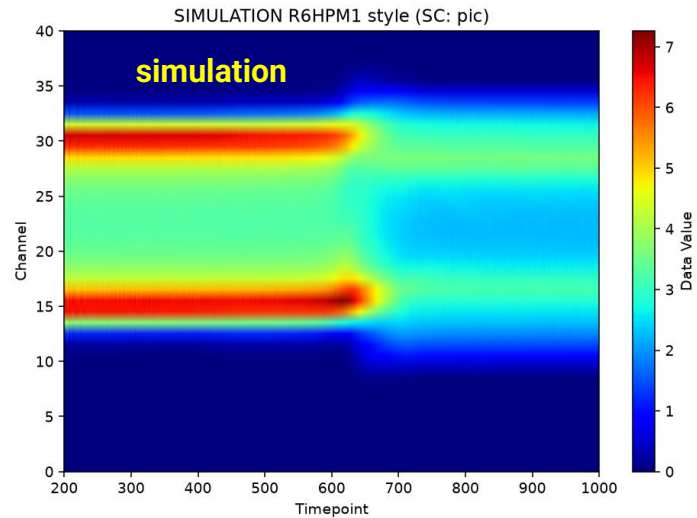
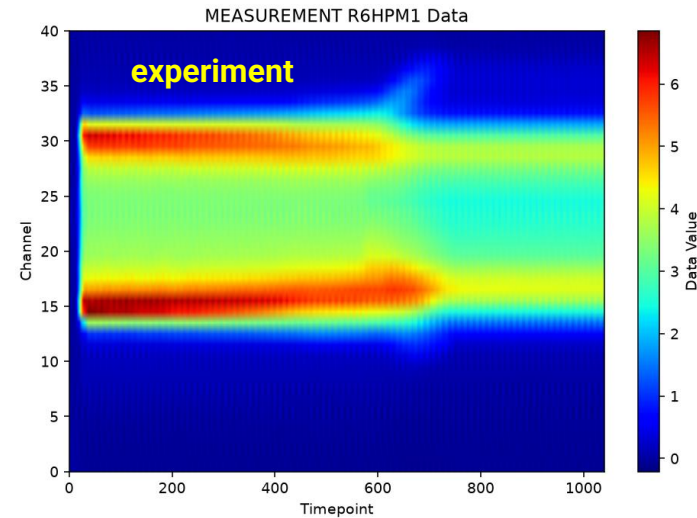
Modelling nonlinearity near resonance $3Q_x=13$

Additional fixed points appear when the octupole error is added

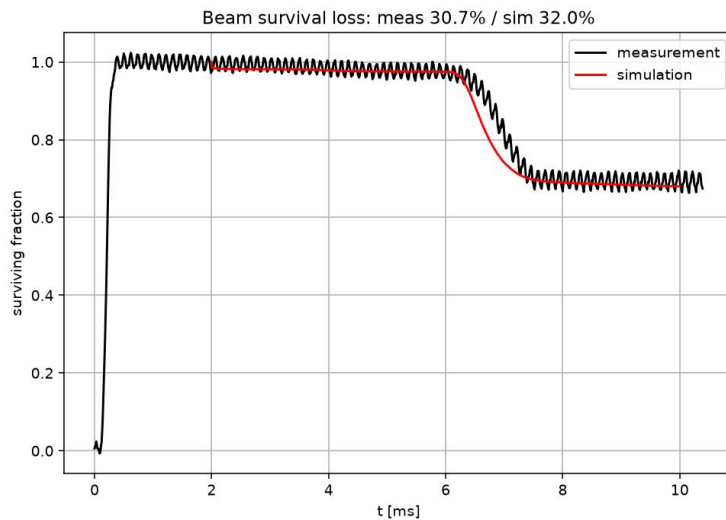
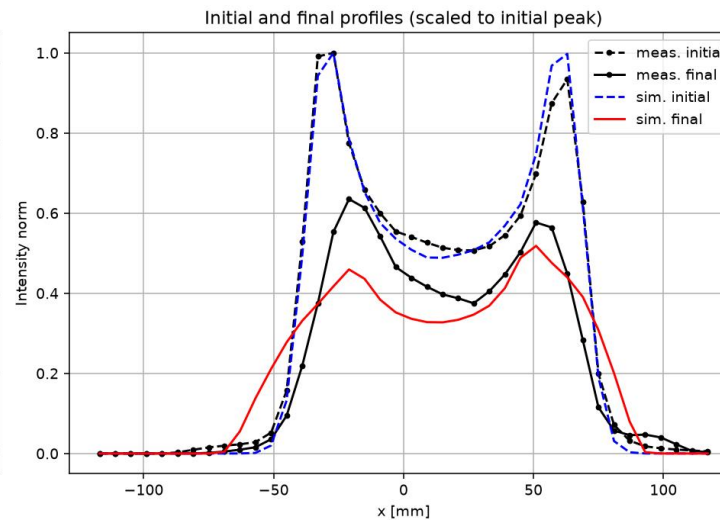


Appearing more fixed points by adding octupole error to the model

Modelling nonlinearity near resonance $3Q_x=13$

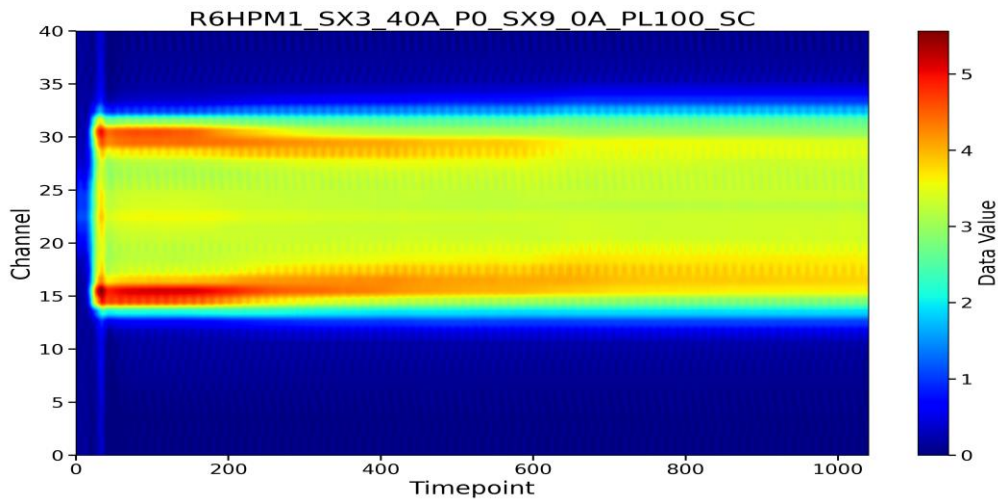


the predicted octupole error had to be increased by a factor of two to fit the model to experiment.

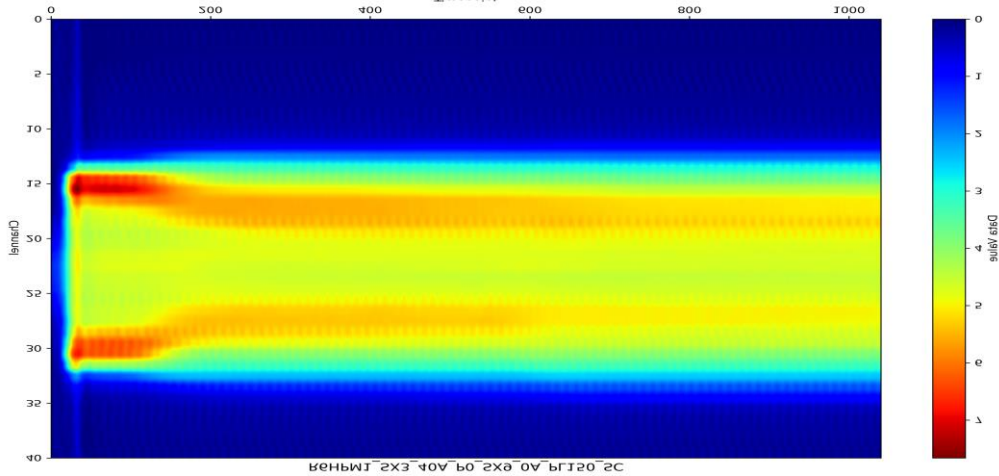


How 3Qx=13 compensation works with increasing beam intensity

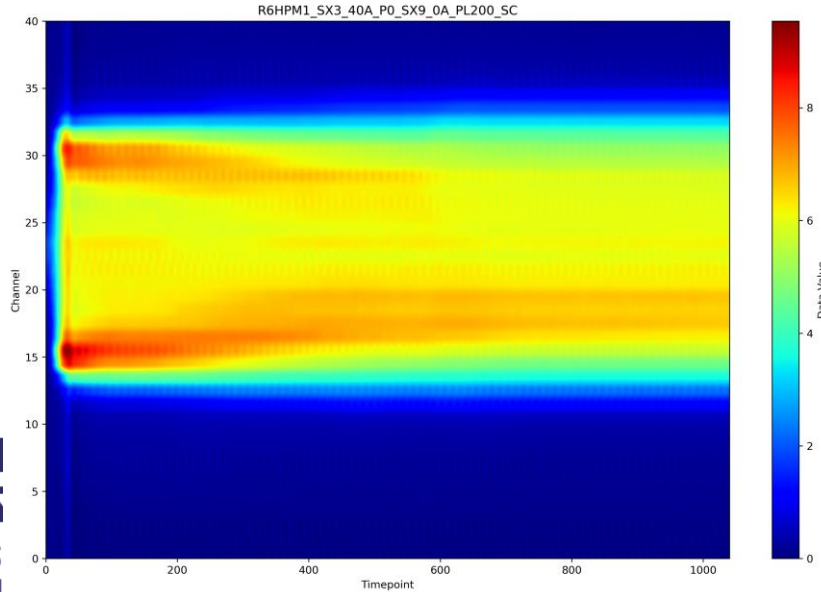
N=8.0e11 ppp



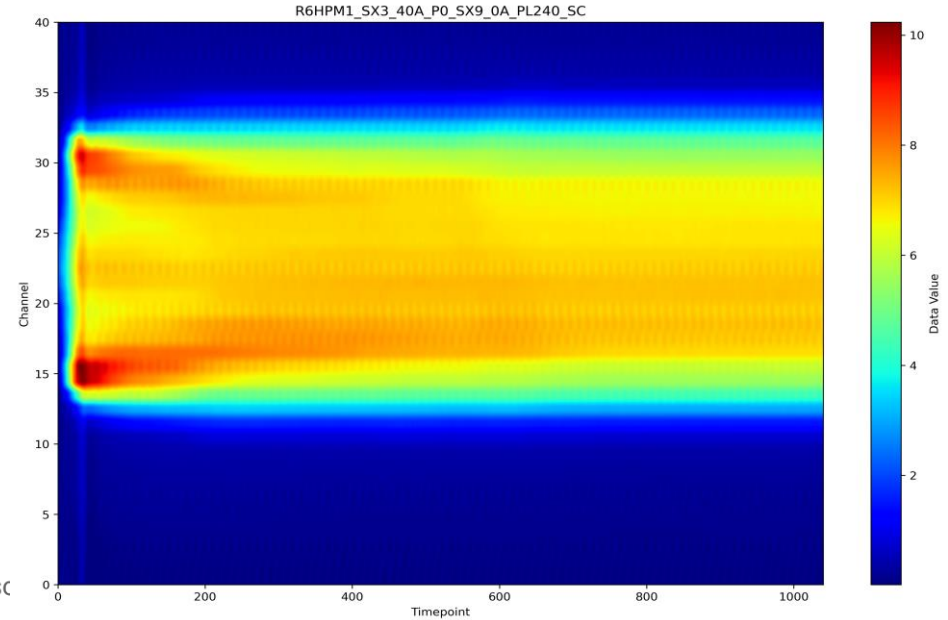
N=1.5 e12 ppp



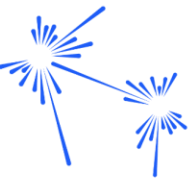
N=2.0 e12 ppp



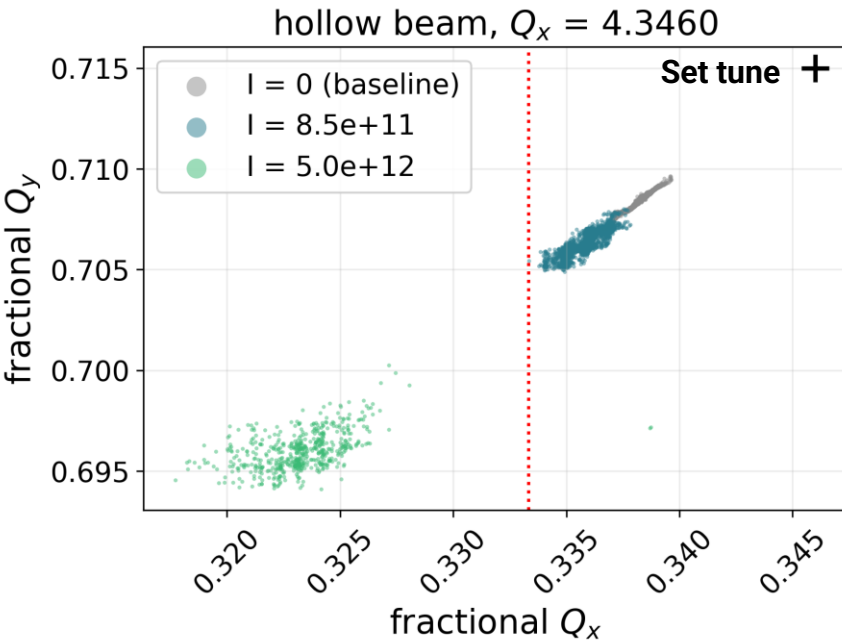
N=3.3 e12 ppp



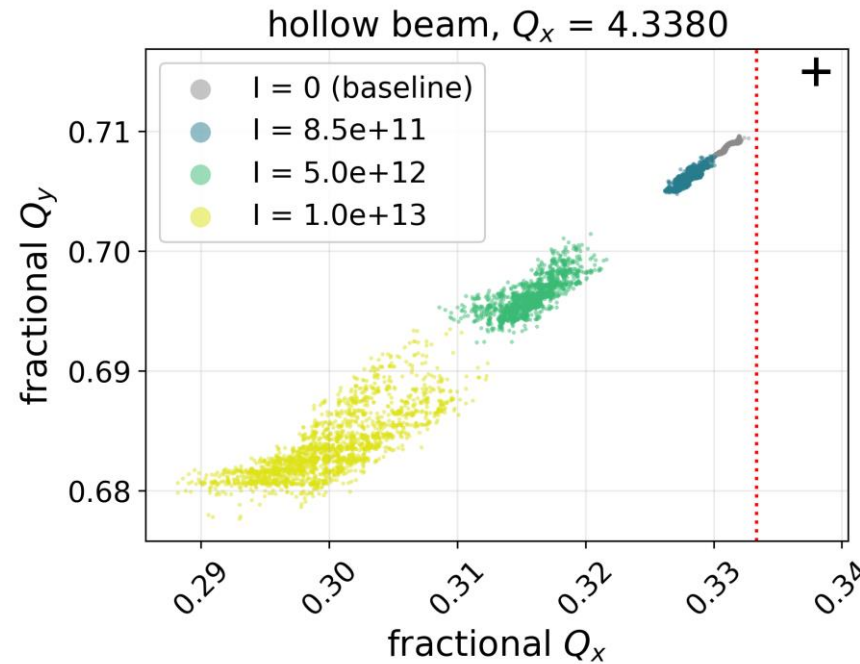
Tune footprints under space charge at different tune points



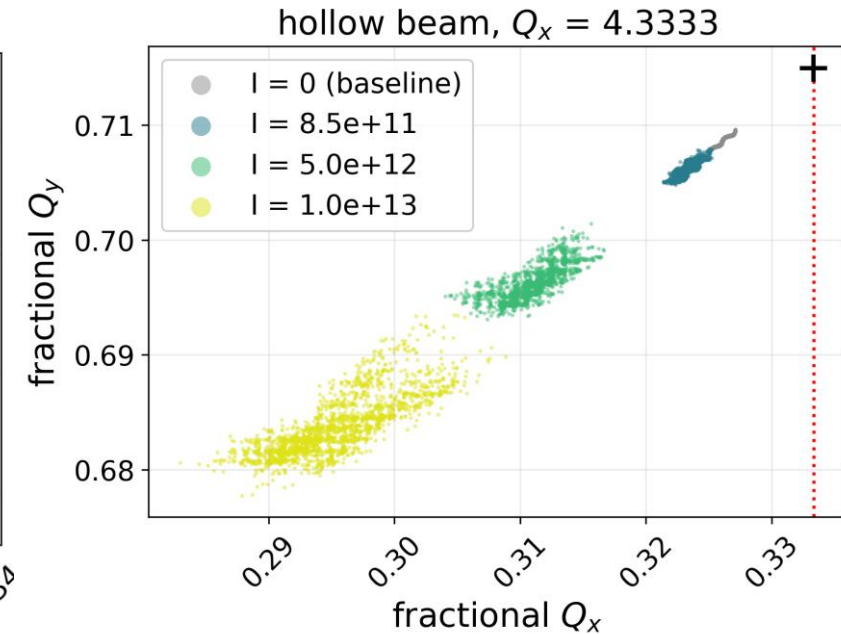
Incoherent tune footprint



Incoherent tune footprint



Incoherent tune footprint

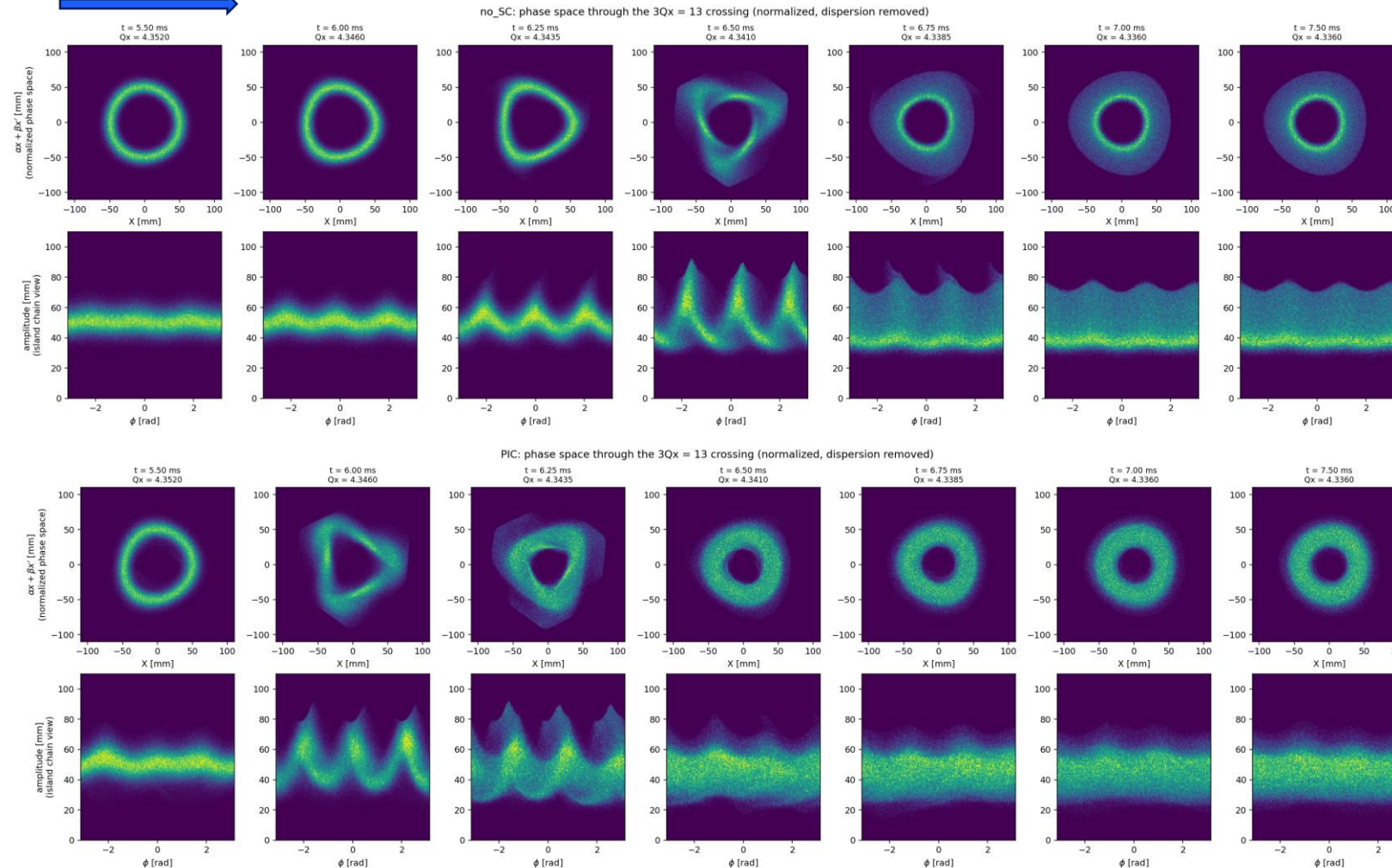


The footprint touches $3Q_x = 13$ before the set point does, so the beam crosses a resonance the tune programme never does



Phase space near resonance during tune ramp

Tune ramp direction



Zero intensity

Intensity = 8.5×10^{11} ppp

$3Q_x = 13$ island chain sweeps through the beam and transports trapped particles to large amplitude – with space charge the islands broaden and carry more of the core.

Summary and conclusion

- Measured tune loss maps fingerprint the machine: **loss concentrates on $3Q_x = 13$ and $Q_x + 2Q_y = 12$** , with a strong up/down crossing asymmetry — the observable everything else must explain
- One DC magnet per resonance: **a single sextupole at 40 A flattens $3Q_x = 13$; a single octupole at 50 A nulls $4Q_x = 17$** — coasting beam, tunes held; $|f_{3000}|$, $|f_{4000}|$ of the bare machine measured at the nulls
- The residual error reproduces the crossing by **chromatic selection** — mechanism right, magnitude wrong: the same sextupole strength does not give the same loss in the simulation
- Measurement-anchored PIC: **the footprint reaches $3Q_x = 13$ before the set point does** — redistribution starts early and ends in a flat halo plateau.
- The mechanism is **resonant trapping–transport**: the beam deforms into the $3Q_x = 13$ triangle and trapped particles ride outward; space charge broadens and feeds the chain

Next: Study stopband position, coherent vs incoherent — a stability diagram to **optimize the operational tune program**.



Add space charge: measurement-anchored PIC

Solver

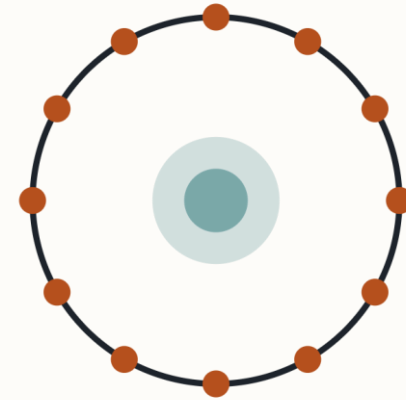
Xsuite PIC on the same dynamic tune ramp · averaged 2.5D FFT solver · 200 space-charge interaction nodes · verified against internal deposition, field and kick tests

Beam, anchored to monitors

Horizontal: fitted painted annulus 48.5–63.2 mm (R6HPM1) · Vertical: fitted hollow profile (R6VPM2) · Bounded parabolic δ , edge 3.0×10^{-4} , mean 1.55×10^{-3}

Scan

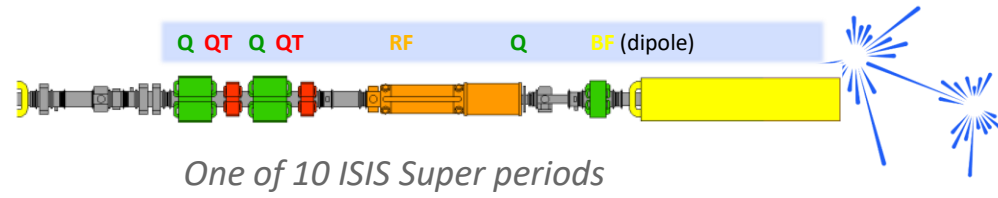
Intensity $0 \rightarrow 2.5 \times 10^{12}$ ppp across the 3Qx = 13 crossing, multi-seed ensembles



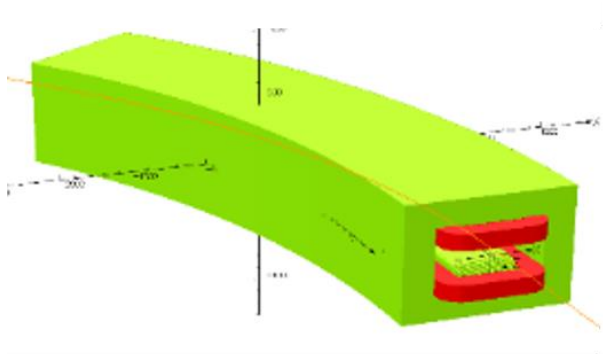
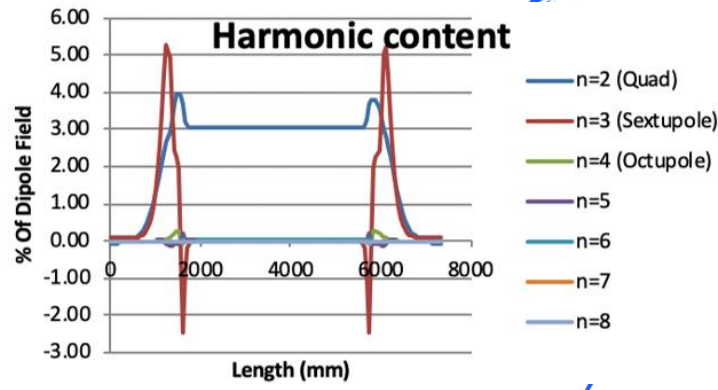
Self-consistent kicks distributed around the ring;
core-halo charge density solved each pass

MAGNET MODELLING

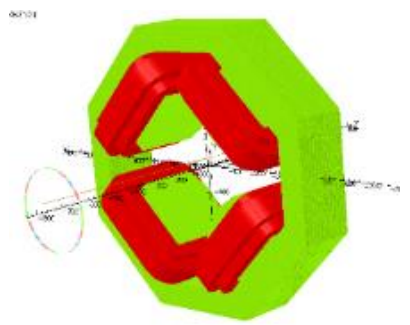
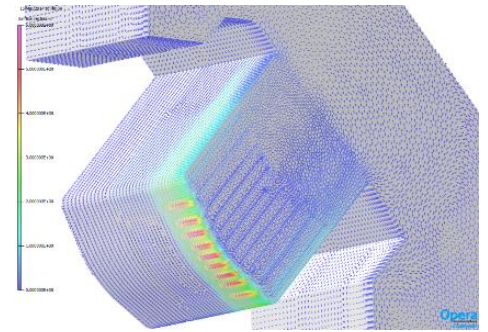
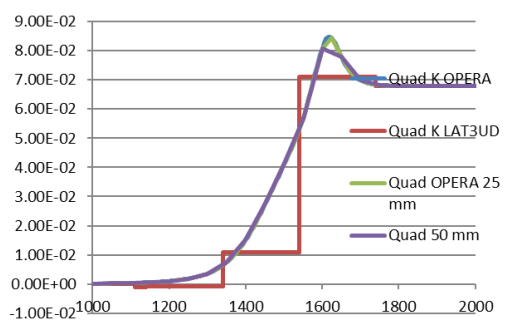
- Limited measurements available for ring magnets
- Matched OPERA simulations to measurements
- Produced models of each magnet type
- Incorporating non-linear multipole components into simulations, including fringe fields
 - Better TEAPOT/PTC PyORBIT models



ISIS Combined Function Dipole



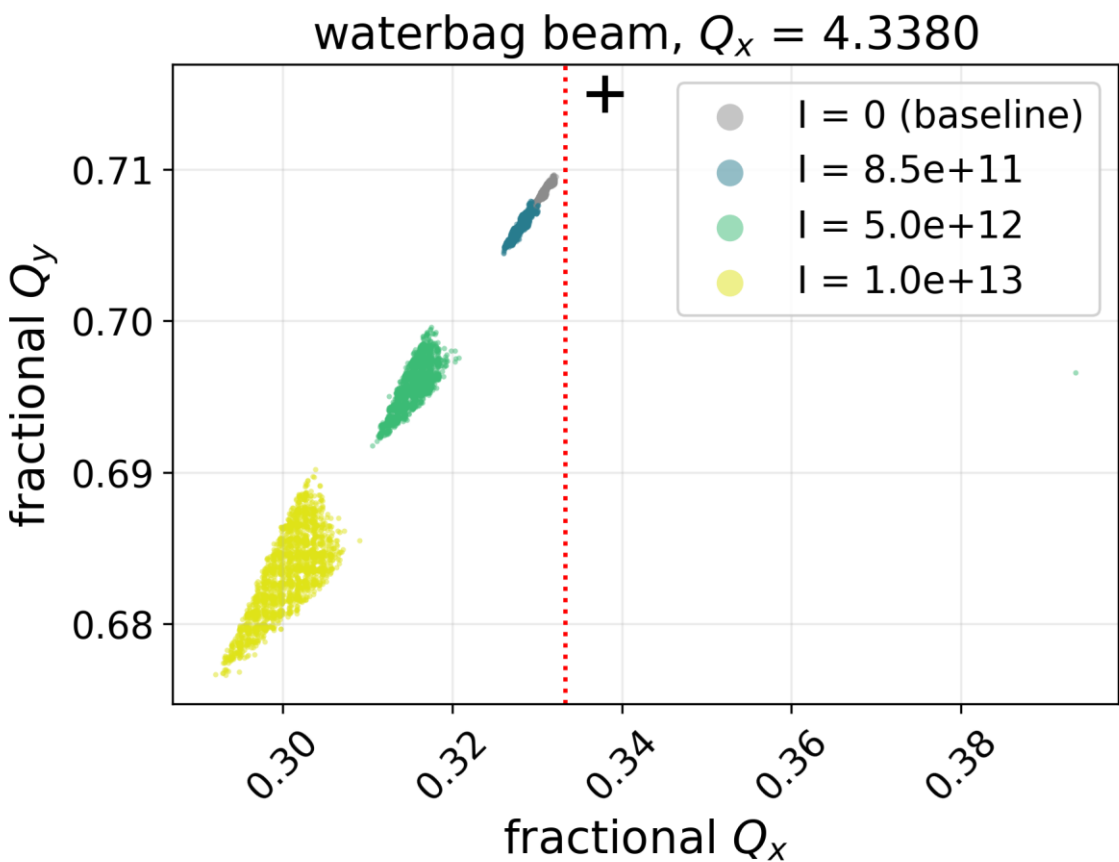
ISIS Quadrupole



Improved fringe fields

Space charge with waterbag distribution

Incoherent tune footprint



Incoherent tune footprint

