Compensation of Third Order Resonances in the High Intensity Regime

Cristhian Gonzalez-Ortiz

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MICHIGAN STATE UNIVERSITY

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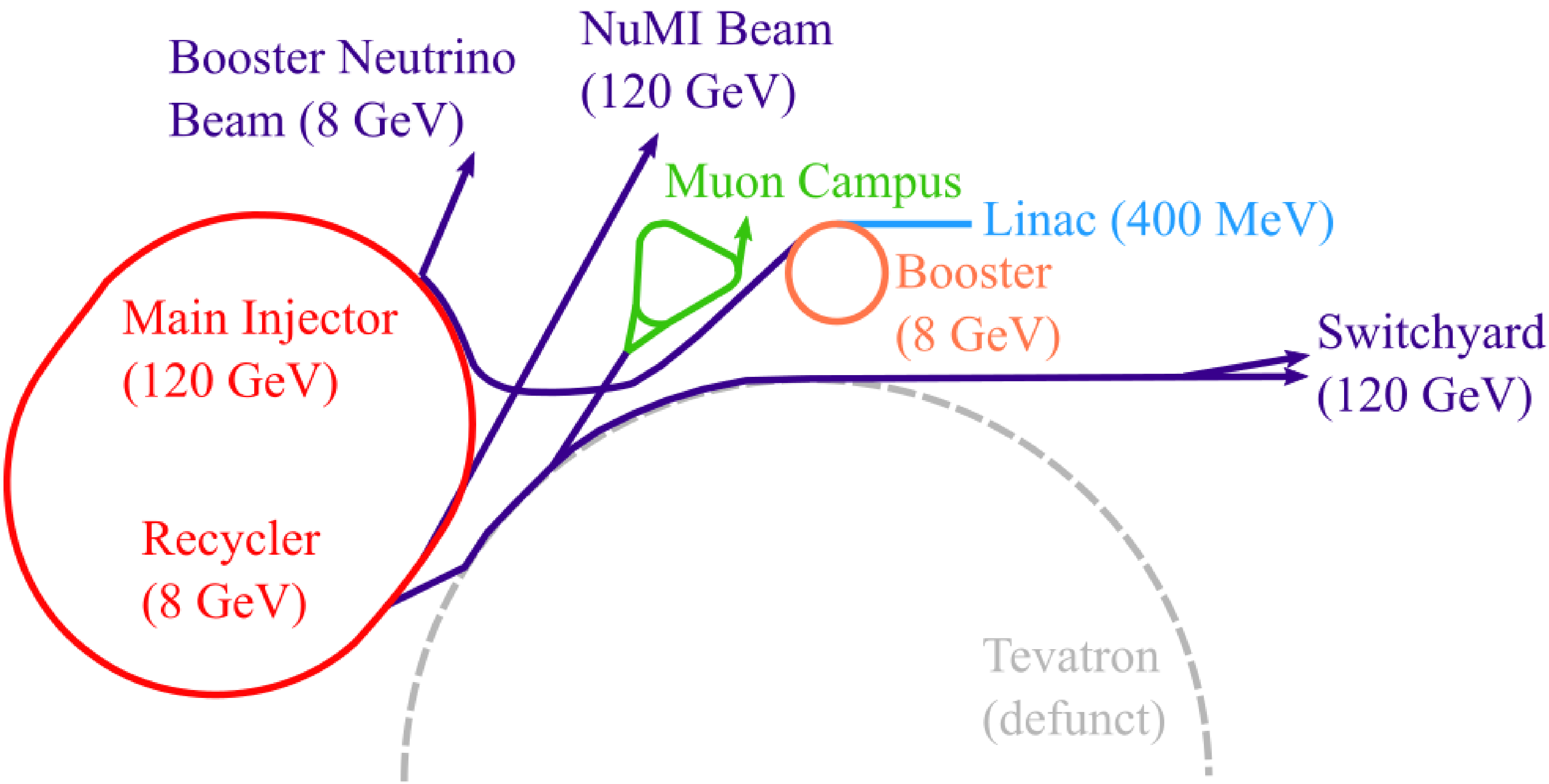
  - Meiqin Xiao [THBP28 & THBP30]
  - Eliana Gianfelice

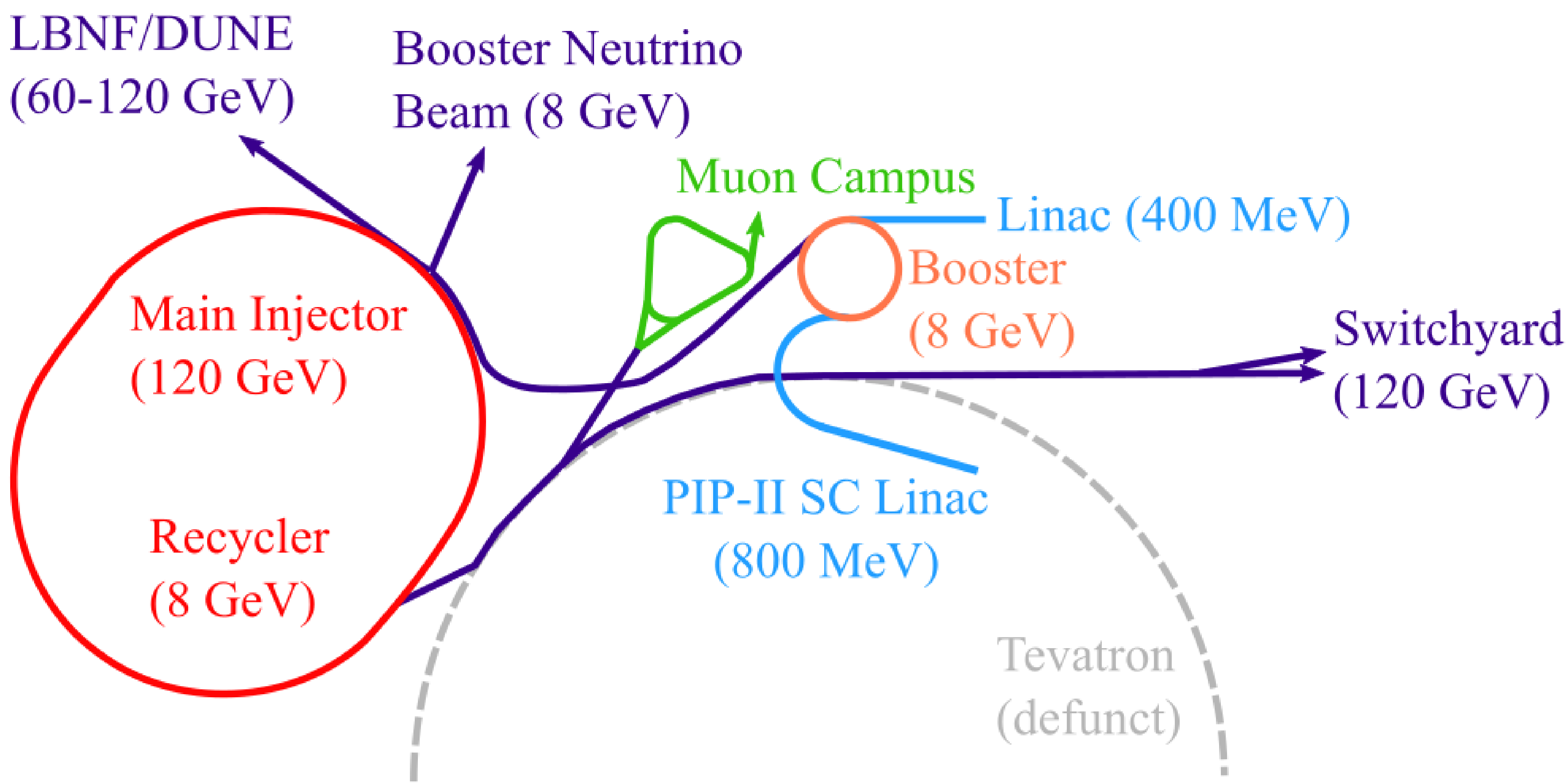
Fermilab Campus

Fermilab Accelerator Complex



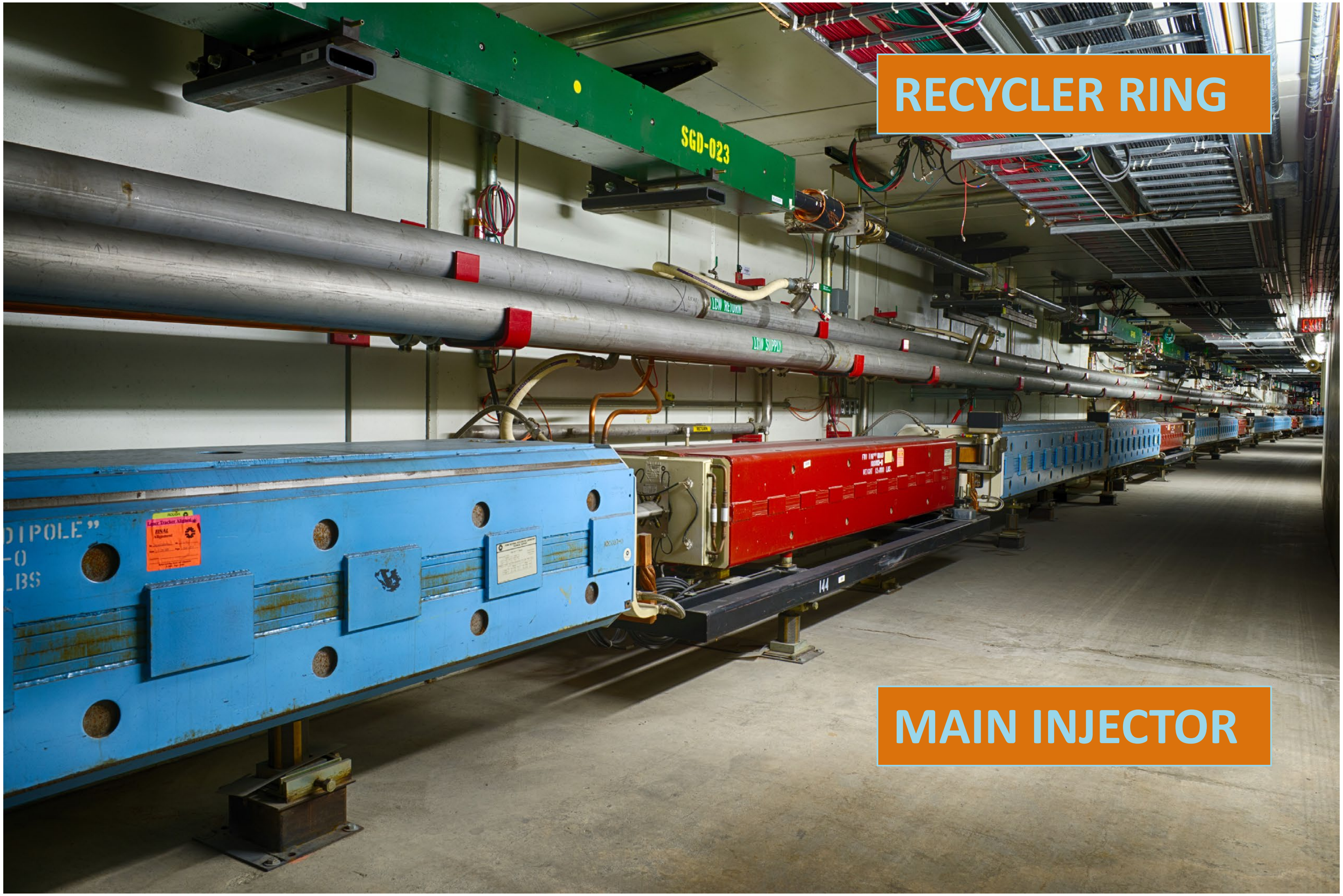
- R. Ainsworth et.al., "High intensity operation using proton stacking in the Fermilab Recycler to deliver 700 kW of 120 GeV proton beam", Phys. Rev. Accel. Beams, vol.23, no. 12, p. 121002

PIP-II (Proton Improvement Plan II)



- M. Ball et al. *The PIP-II Conceptual Design Report*. Tech. rep. FERMILAB-TM-2649-AD-APC1516858. Fermilab, Mar. 2017.

Fermilab Recycler Ring

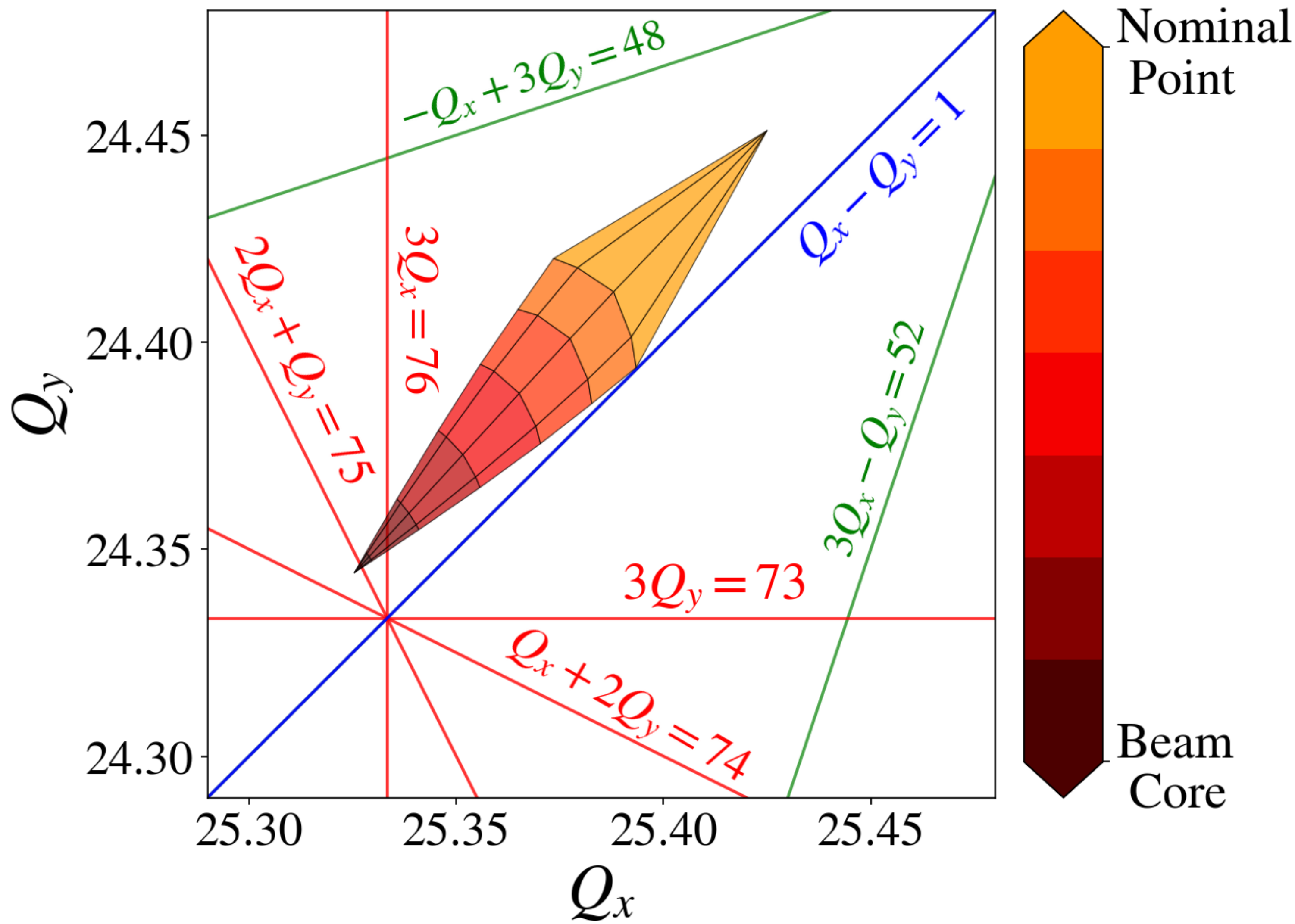


Fermilab Recycler Ring

Table 1: Typical Recycler Ring properties for beam sent to NuMI

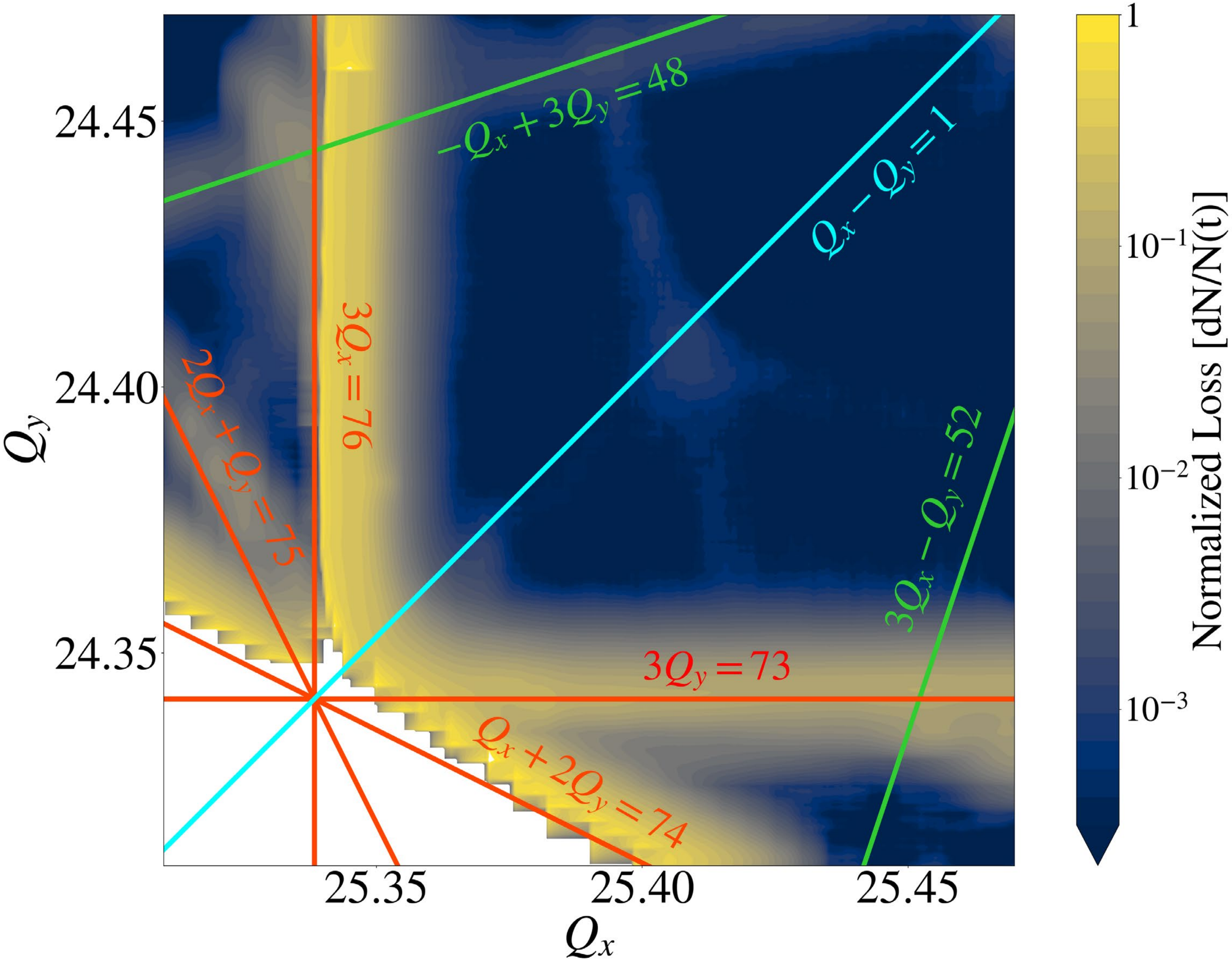
Parameter	**Value**	**Unit**
Circumference	3319	m
Momentum	8.835	GeV/c
RF Frequency	52.8	MHz
RF Voltage	80	kV
Harmonic Number	588	
Synchrotron Tune	0.0028	
Slip Factor	-8.6×10^{-3}	
Superperiodicity	2	
Horizontal Tune	25.43	
Vertical Tune	24.445	
Horizontal Chromaticity	-6	
Vertical Chromaticity	-7	
95% Normalized Emittance	15	π mm mrad
95% Longitudinal Emittance	0.08	eV s
Intensity	5×10^{10}, 8×10^{10} (PIP-II)	ppb
MI Ramp Time	1.2, 1.133, 1.067	s
Beam Power on Target	0.750, 1.20 (PIP-II)	MW
Booster Frequency	15, 20 (PIP-II)	Hz

Tune Diagram for PIP-II Intensities



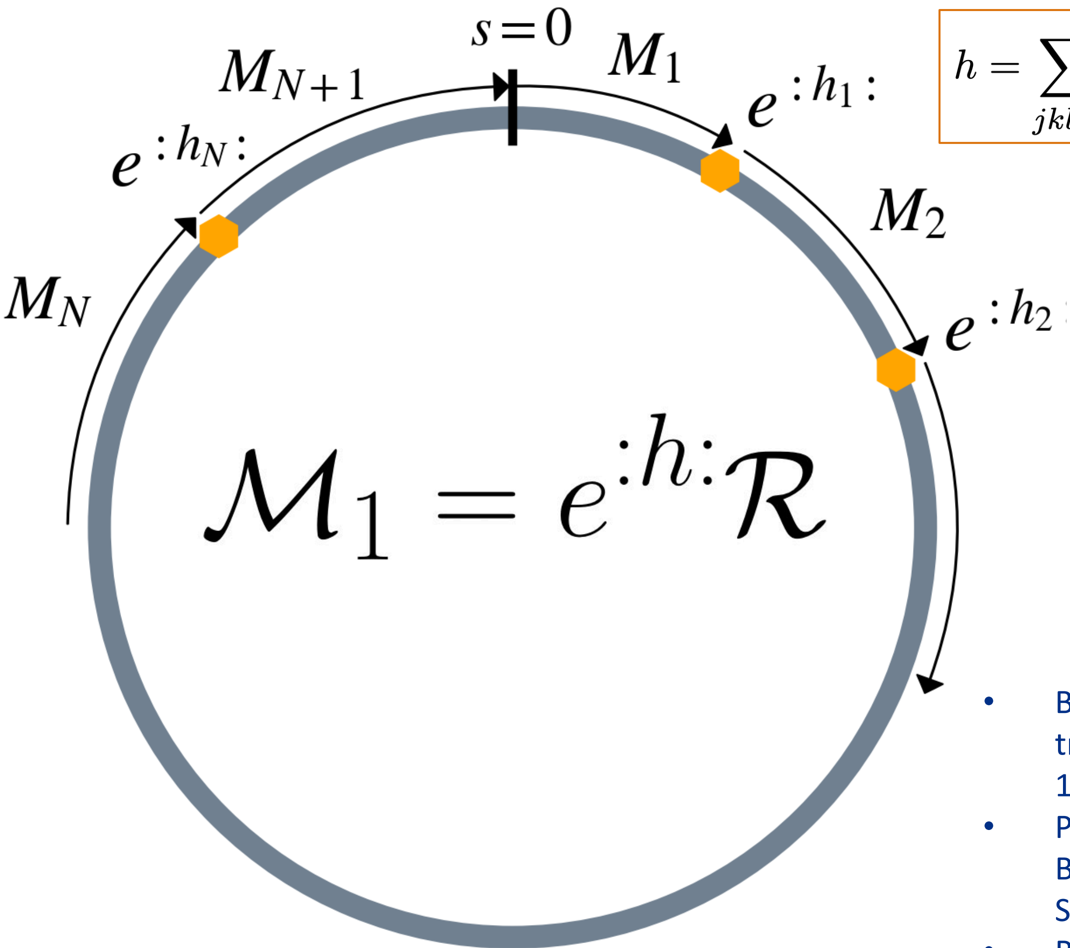
- F. Asvesta, et al.. https://github.com/fasvesta/ PySCRDT

Fermilab Recycler Ring



Low Intensity Studies

Global Third Order RDTs



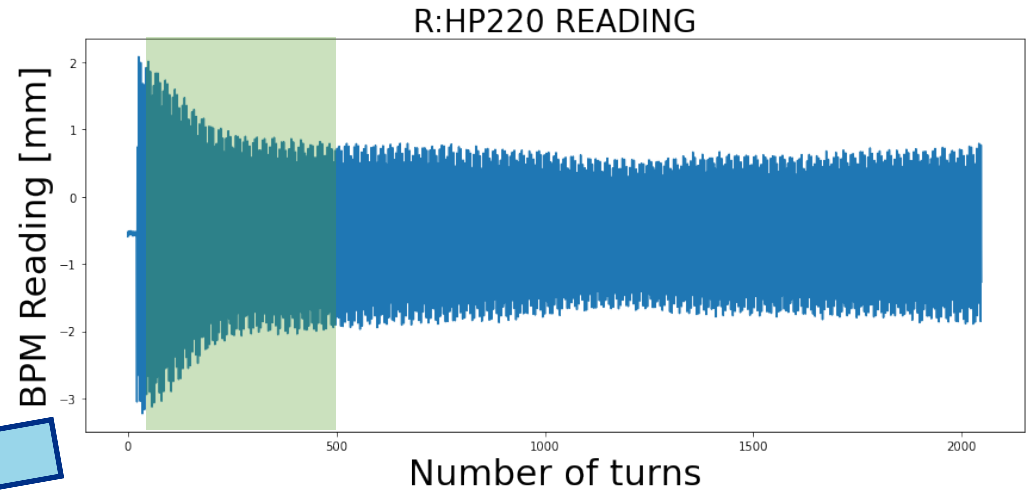
$$h = \sum_{jklm} h_{jklm} (2J_x)^{\frac{j+k}{2}} (2J_y)^{\frac{l+m}{2}} e^{i[(j-k)\phi_x + (l-m)\phi_y]}$$

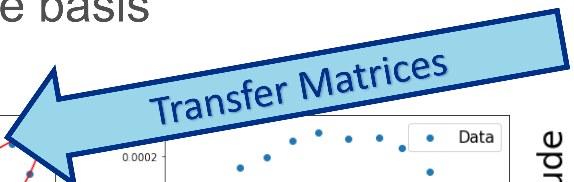
Res. Line	RDT	Sext. Term
$3Q_x = 76$	h_{3000}	Normal
$Q_x + 2Q_y = 74$	h_{1020}	Normal
$3Q_y = 73$	h_{0030}	Skew
$2Q_x + Q_y = 75$	h_{2010}	Skew

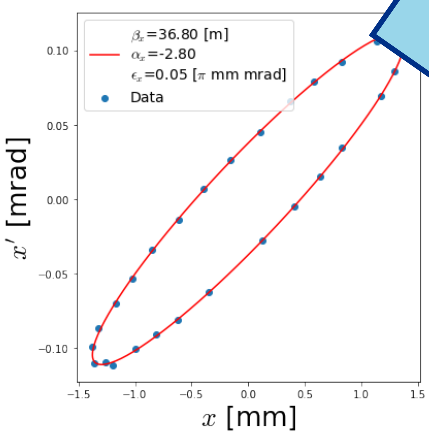
- Bartolini, R. and Schmidt, F., "Normal form via tracking or beam data", *Part. Accel.*, vol.59, pp.93-106, Aug. 1997
- P. Urschutz. “Measurement and Compensation of Betatron Resonances at the CERN PS Booster Synchrotron”. PhD thesis. Vienna, Austria, 2004.
- R. Tomas Garcia. “Direct Measurement of Resonance Driving Terms in the Super Proton Synchrotron (SPS) of CERN using Beam Position Monitors”. PhD thesis. Valencia, Spain, Jan. 2003.

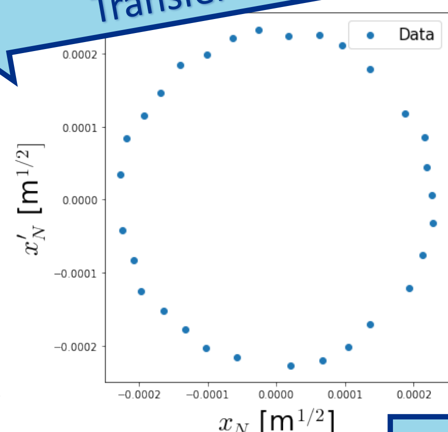
Measurement of Global RDTs

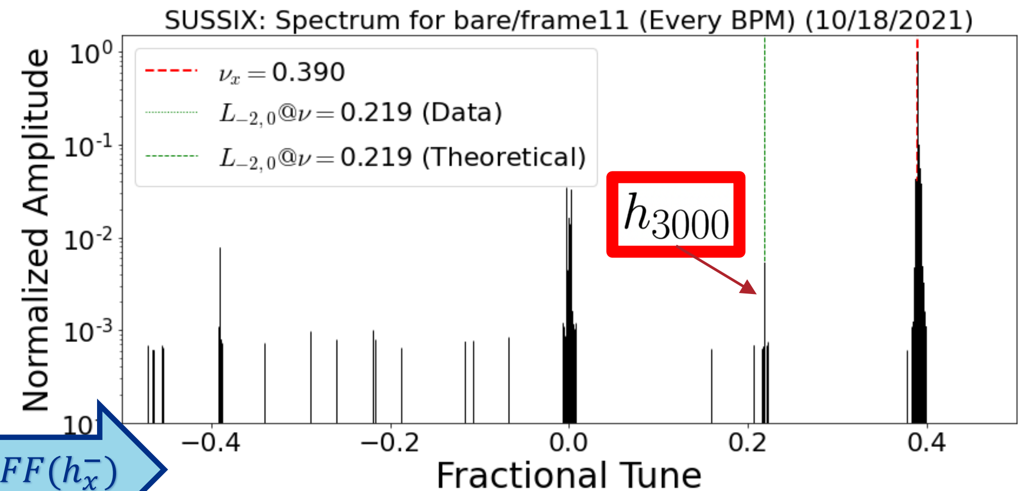
- **How to measure RDTs?**
  - Start from BPM data (104 BPMs)
  - Estimate momentum coordinates from BPMs transfer matrices
  - Get normalized phase space
  - Get spectral decomposition of resonance basis

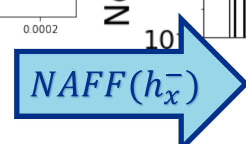












$$h_x^-(N) = x_{norm}(N) - i x'_{norm}(N)$$

$$h_x^-(N) = \sum_{j=1}^{M} a_j e^{i[2\pi(mx_j Q_x + my_j Q_y)N + \phi_j]}$$

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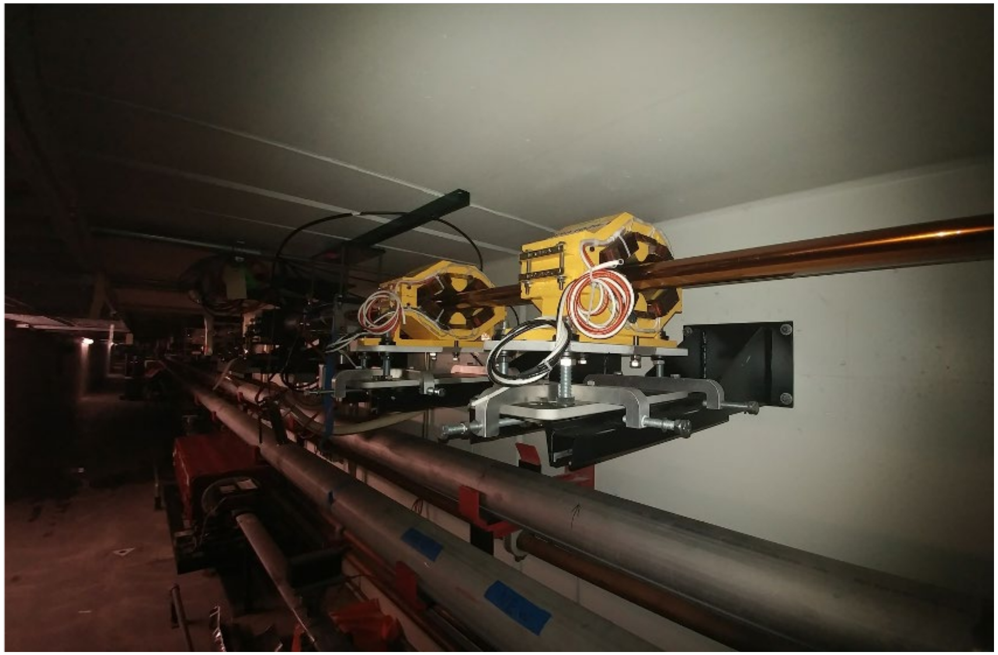
Compensation Scheme

- Use 4 dedicated **normal sextupoles** for compensation of $3Q_x = 76$
- Use 4 dedicated **skew sextupoles** for compensation of $3Q_y = 73$
- **Scan sextupole currents** and record **RDT sensitivity** (h_{3000} and h_{0030})
- Build **linear system** to cancel out **bare machine RDTs**
- Previously installed sextupoles were located so **chromatic effects** are **canceled out**

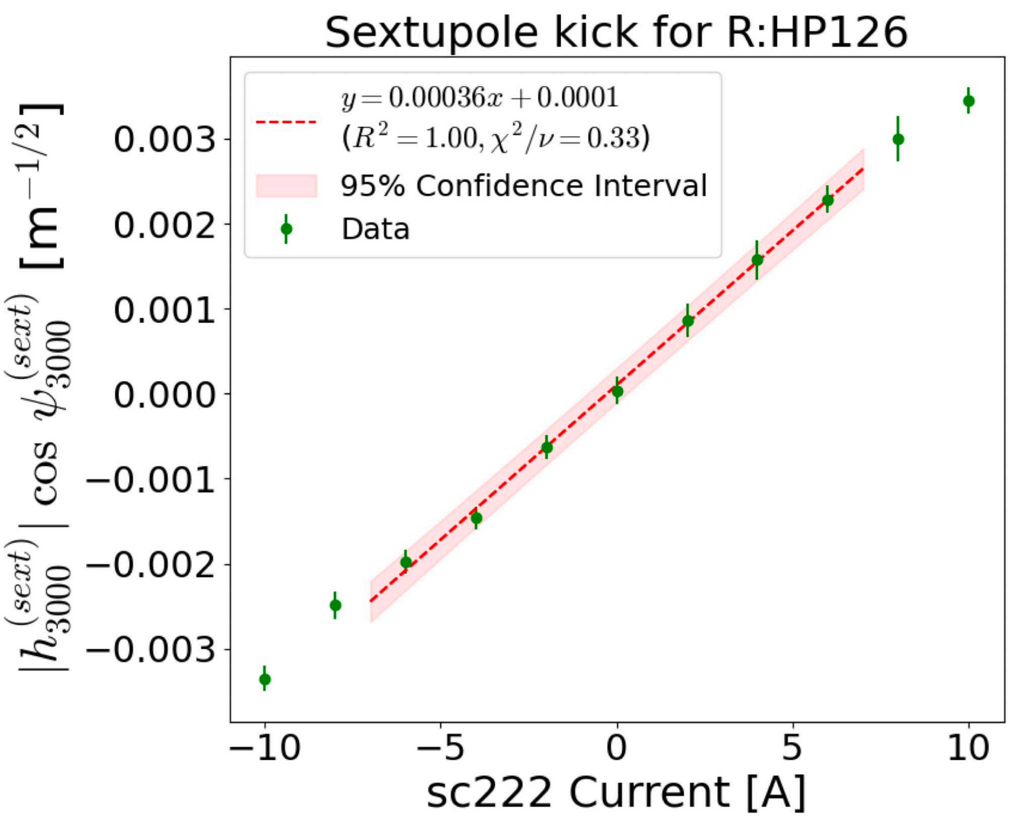


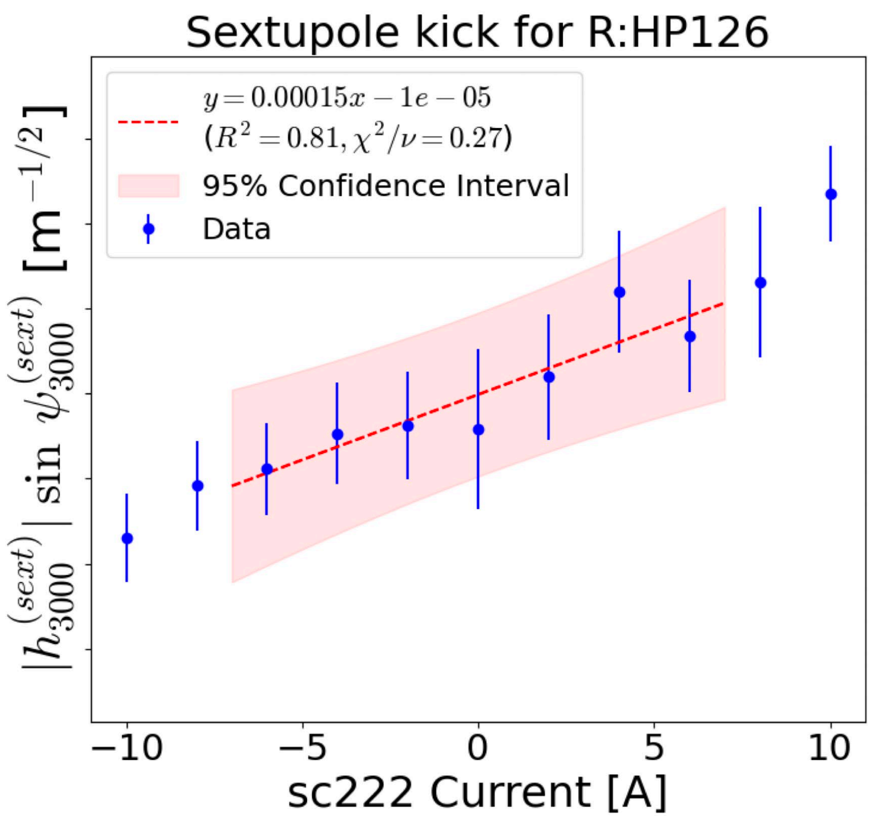
$$\begin{pmatrix} -|h_{3000}^{(bare)}|\cos\left(\psi_{3000}^{(bare)}\right) \\ -|h_{3000}^{(bare)}|\sin\left(\psi_{3000}^{(bare)}\right) \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} I_{sc220} \\ I_{sc222} \\ I_{sc319} \\ I_{sc321} \end{pmatrix}$$

$$\vec{I}_{Comp} = \mathbf{M}^{-1}\vec{h}_{3000}^{(bare)}$$

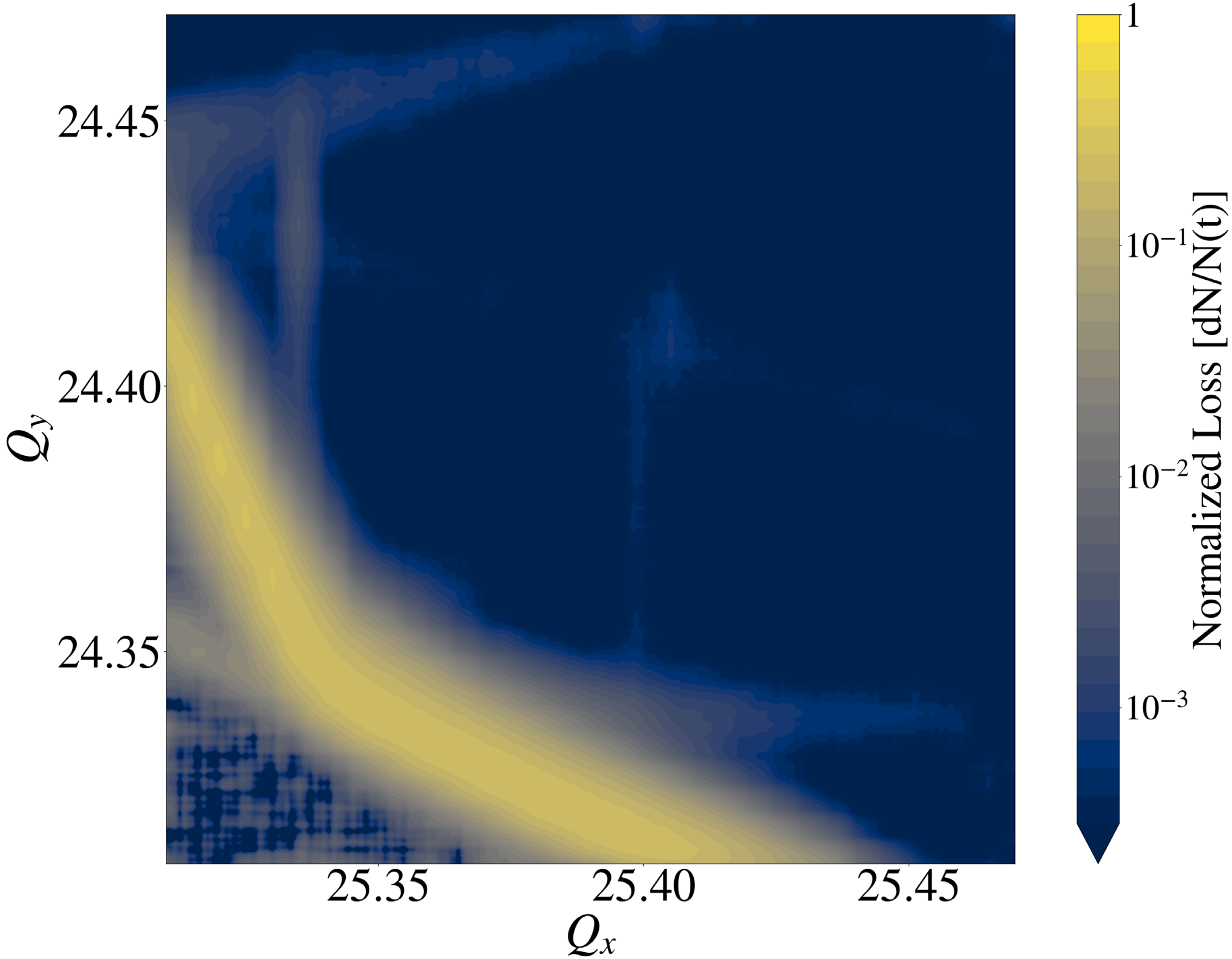
Compensation Scheme

- **Real part** and **imaginary part** of $h_{3000}^{(sext)}$ can be retrieved for each normal sextupole
- **Coupling to RDT** from sextupoles can be retrieved from slope

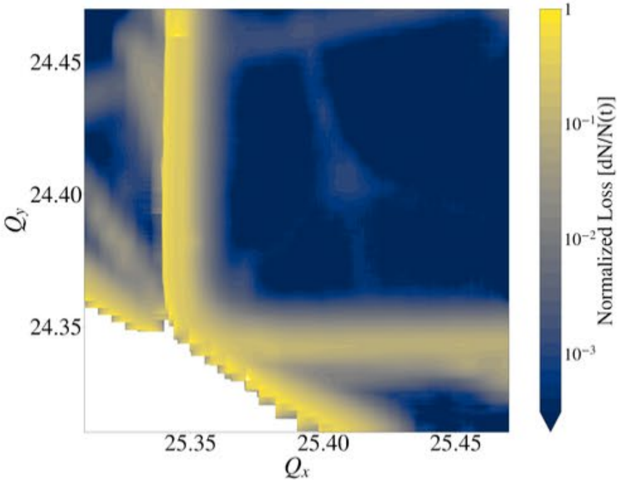




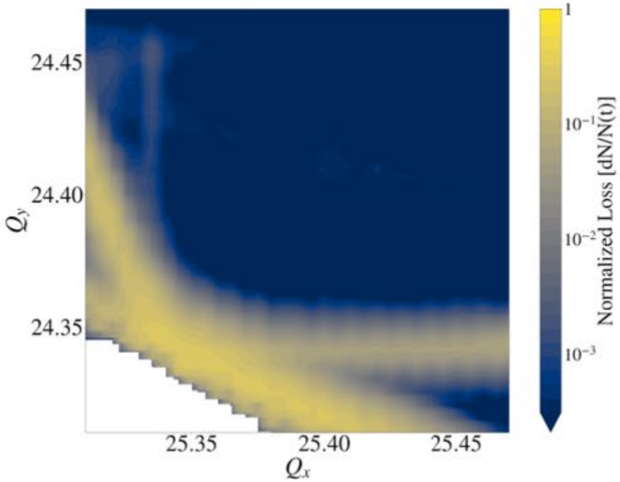
Dynamic Loss Maps (Experimental)



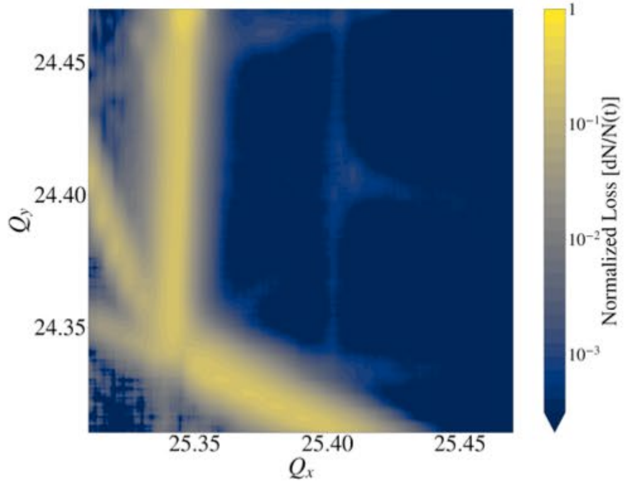
Dynamic Loss Maps (Experimental)



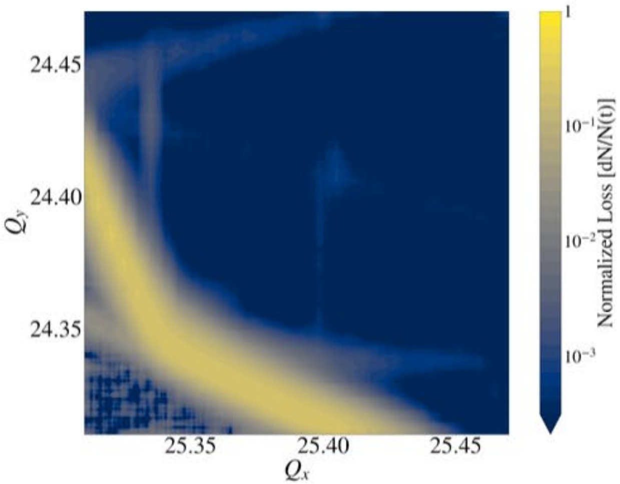
(a) Bare machine



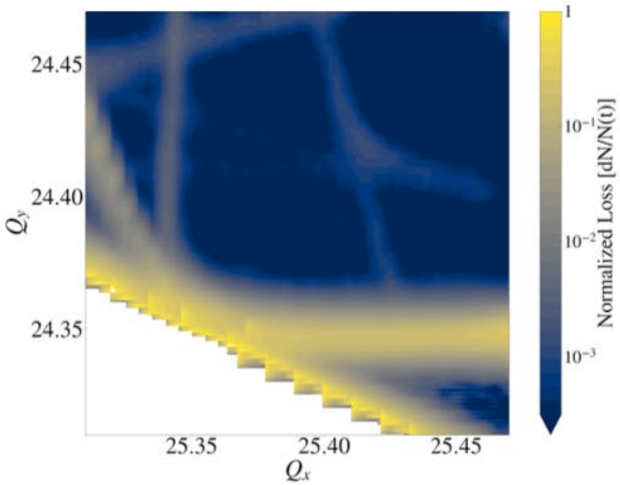
(b) $3Q_x$ Compensation



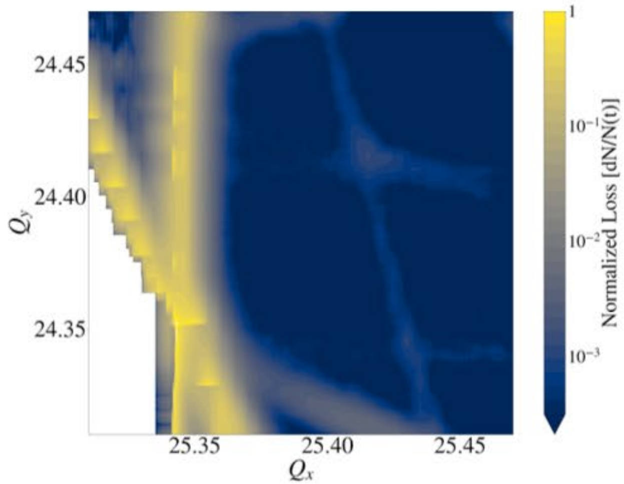
(c) $3Q_y$ Compensation



(d) $3Q_x$ and $3Q_y$ Compensation

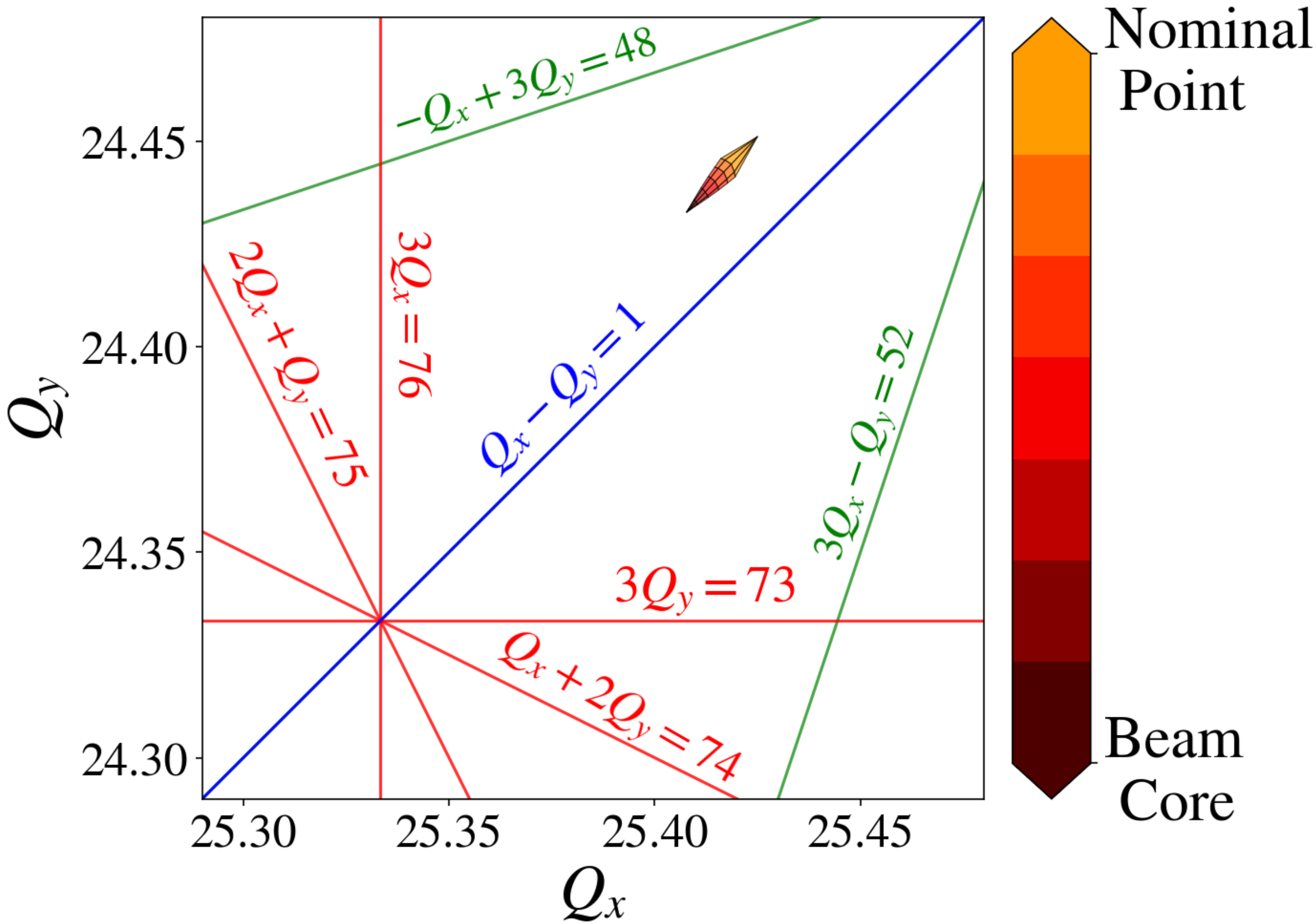


(e) $3Q_x$ and $2Q_x + Q_y$ Compensation



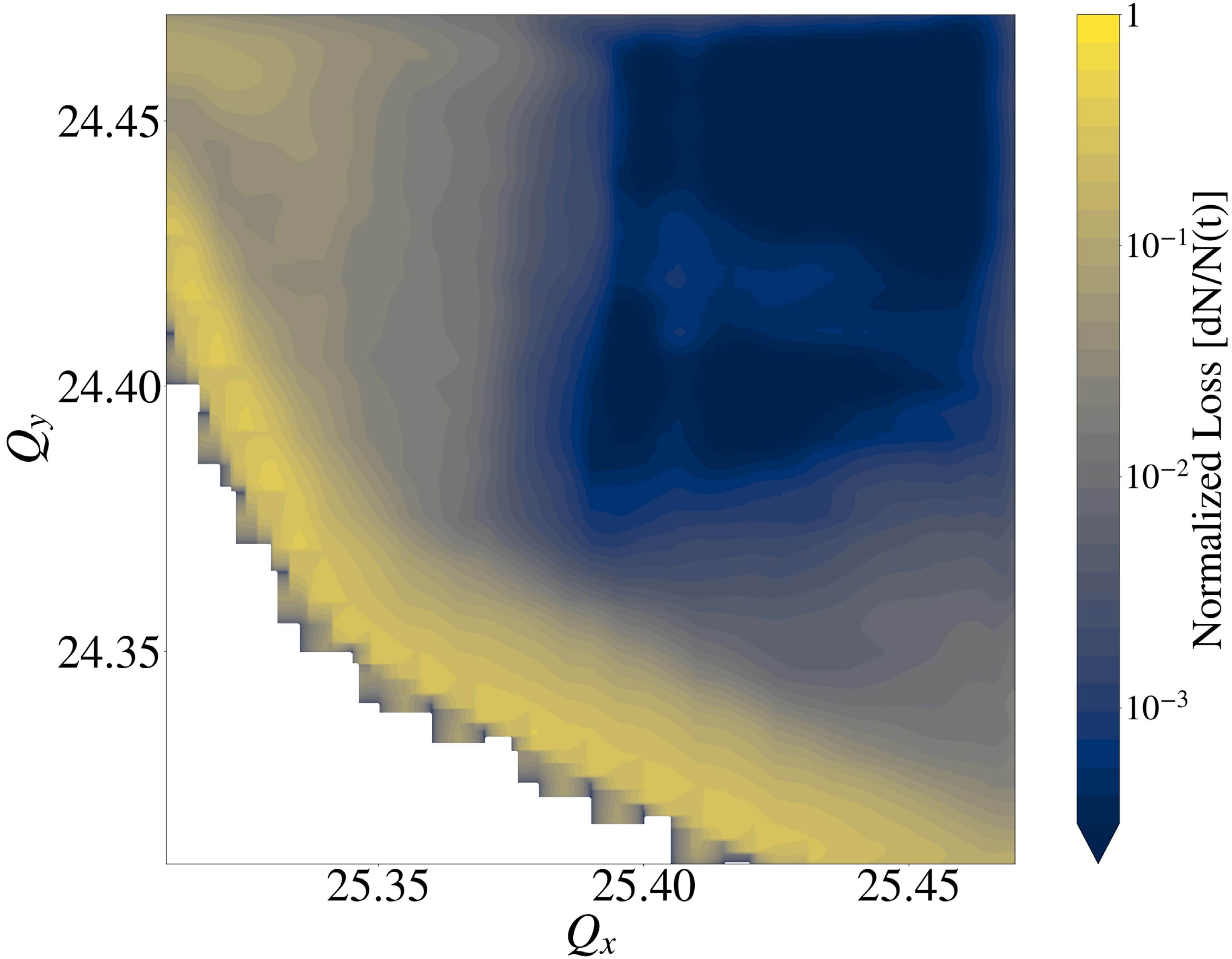
(f) $3Q_y$ and $Q_x + 2Q_y$ Compensation

Dynamic Loss Maps



High Intensity Studies

High Intensity Loss Map



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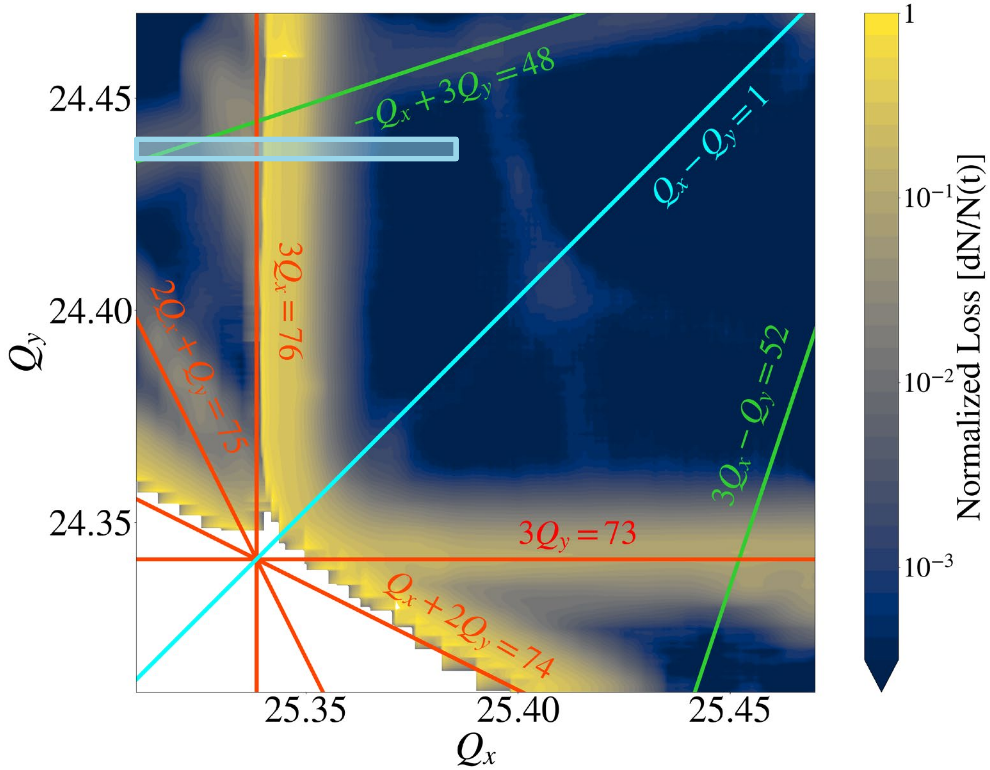
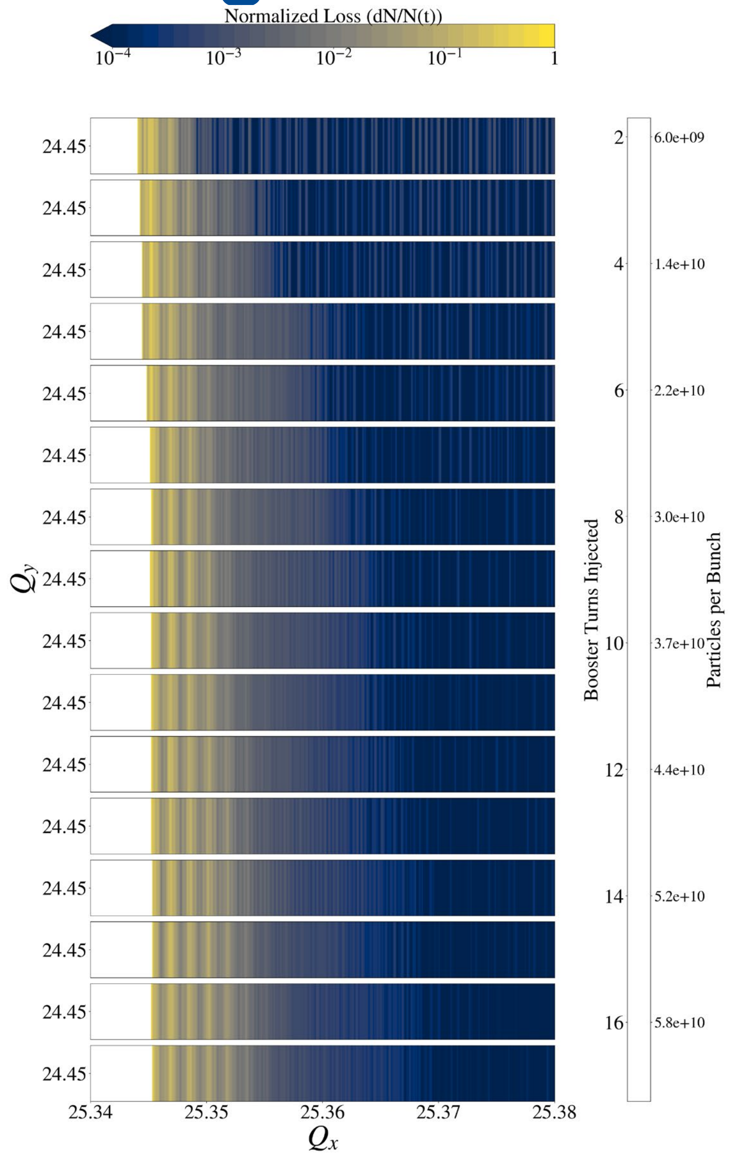
Measurement of Space Charge Tune Shift





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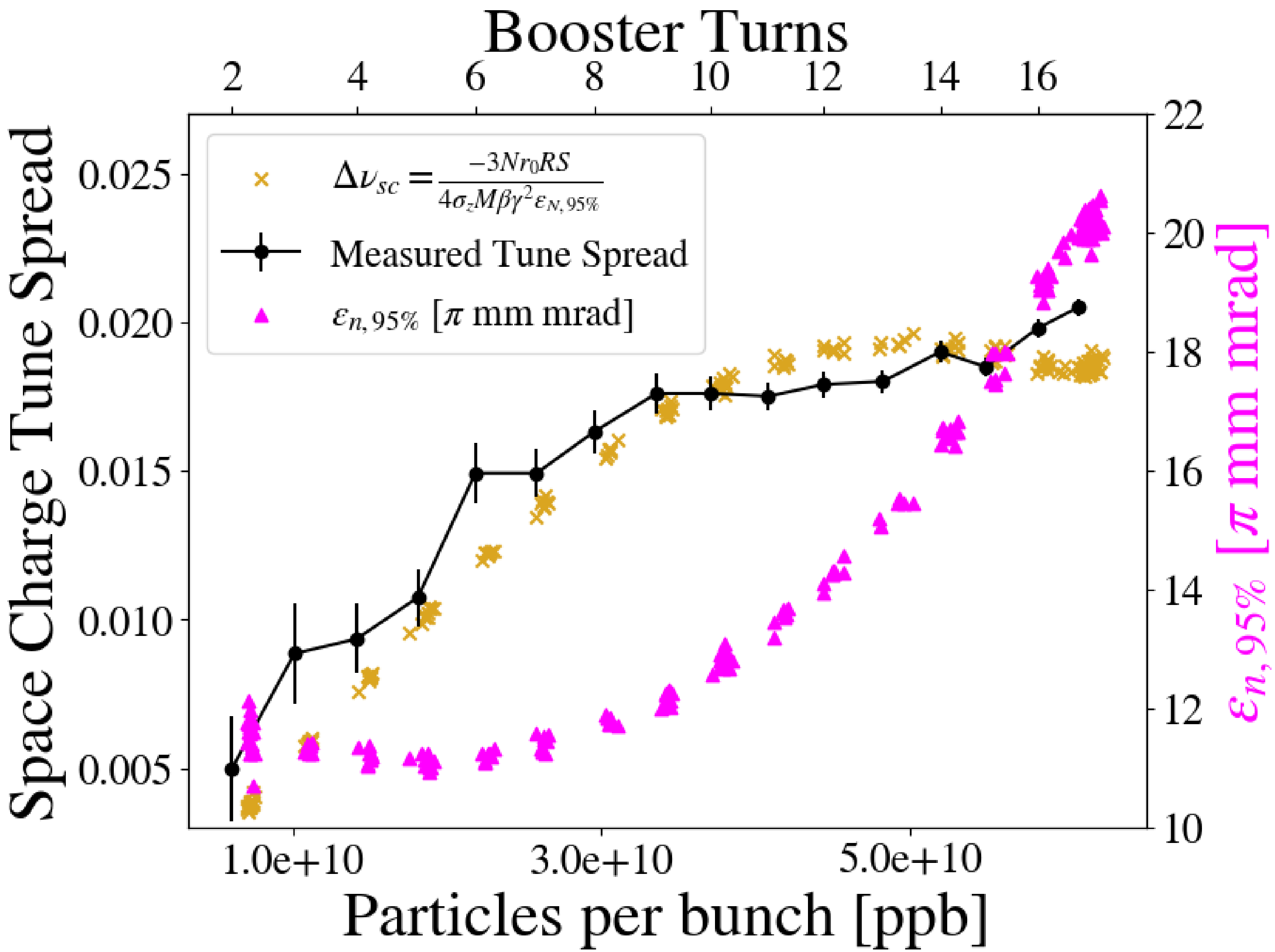
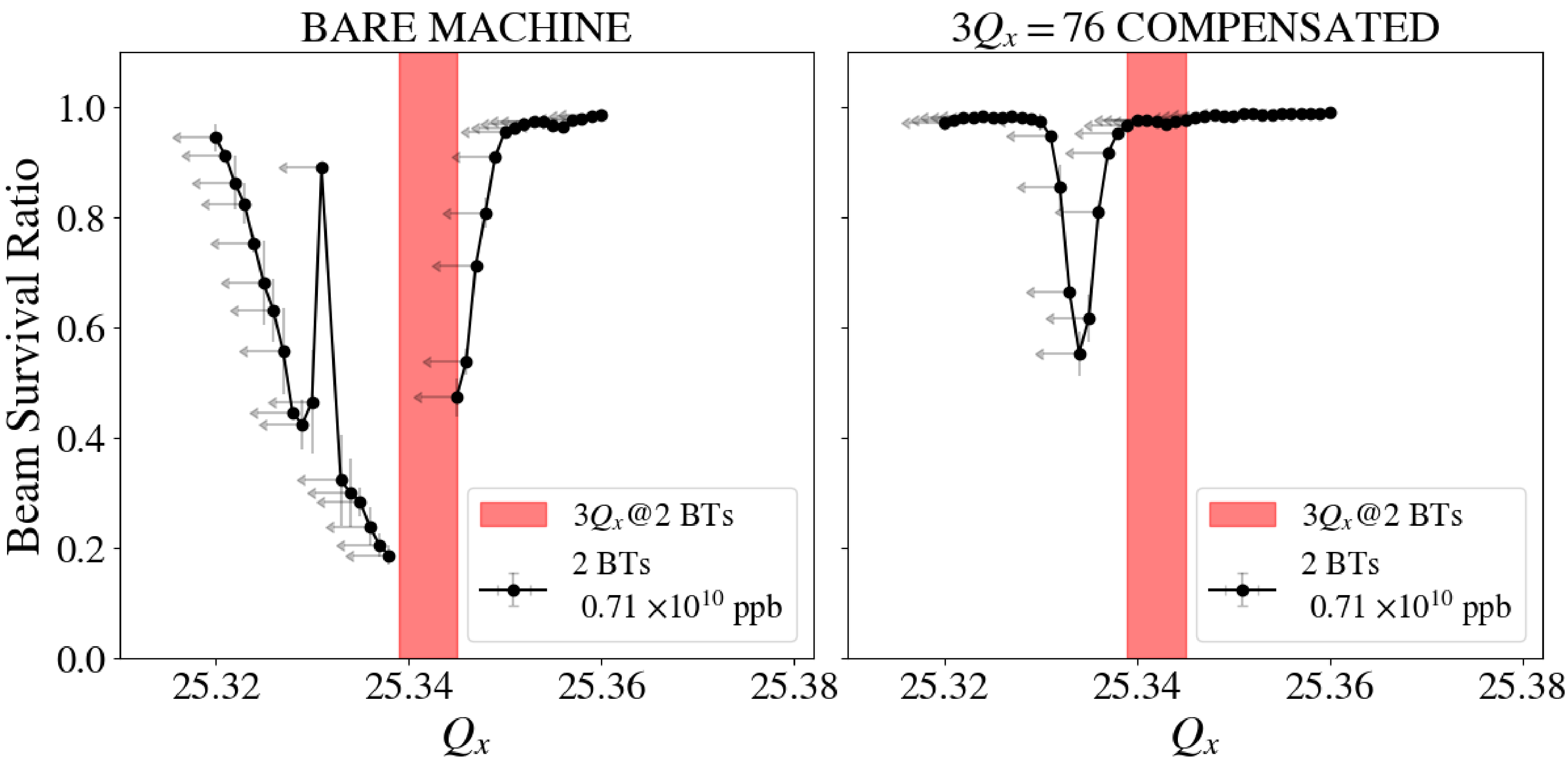
Measurement of Space Charge Tune Shift



Static Tune Scans at Low Intensities (Experimental)



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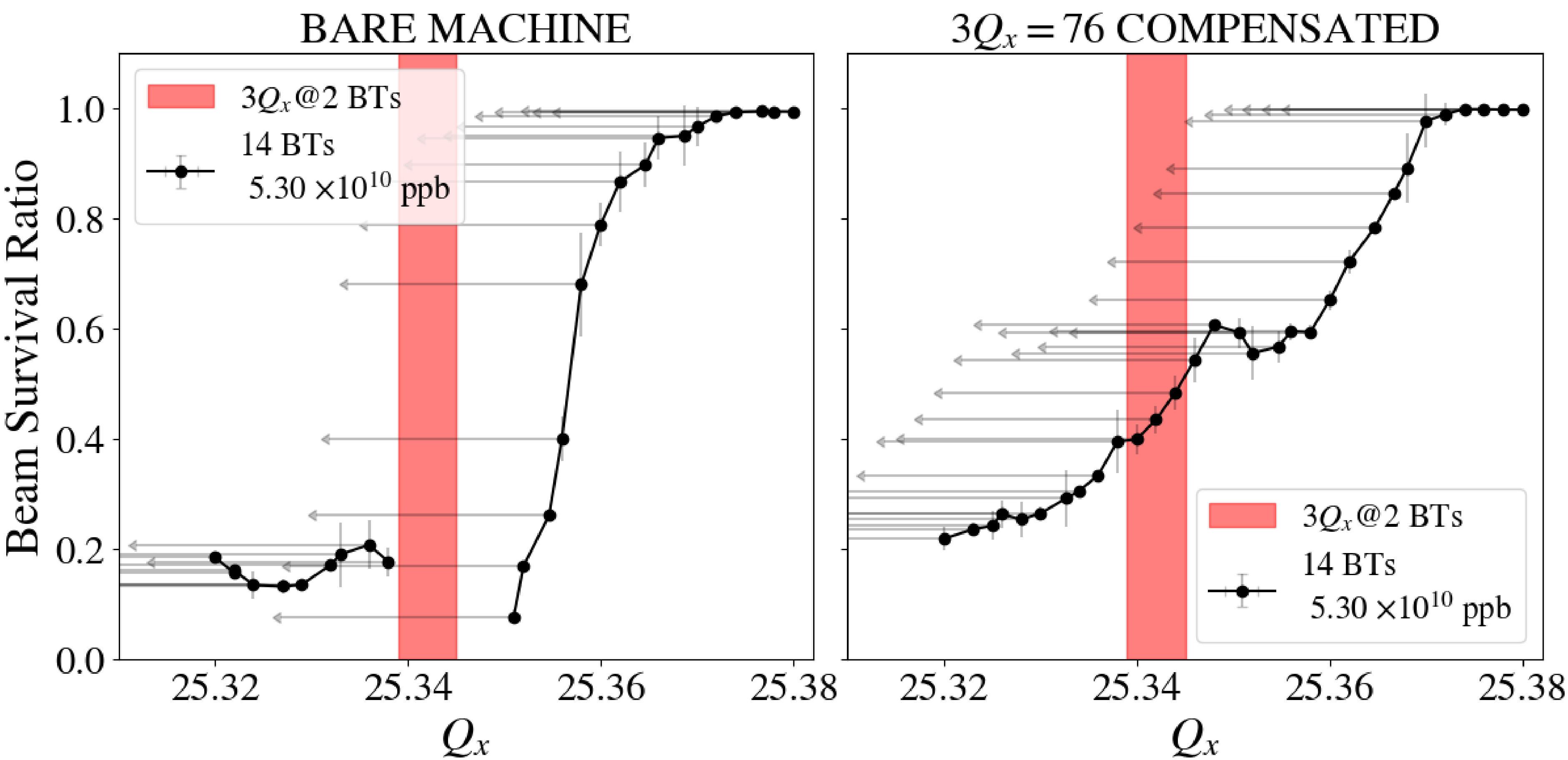
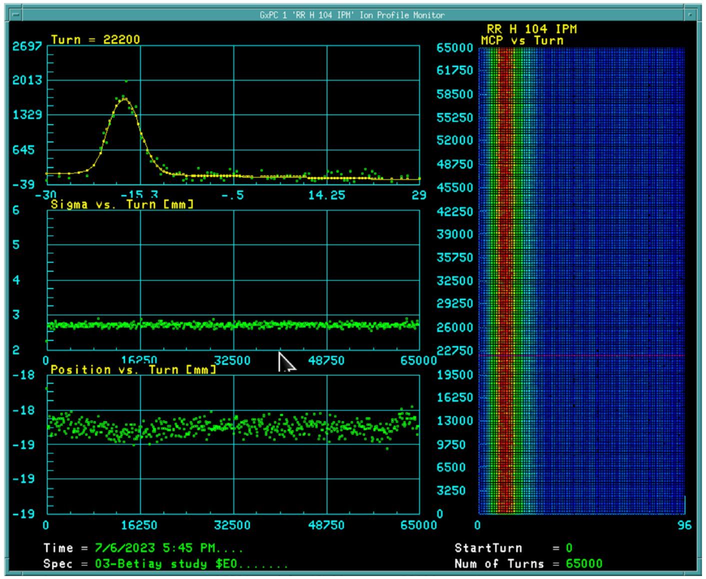
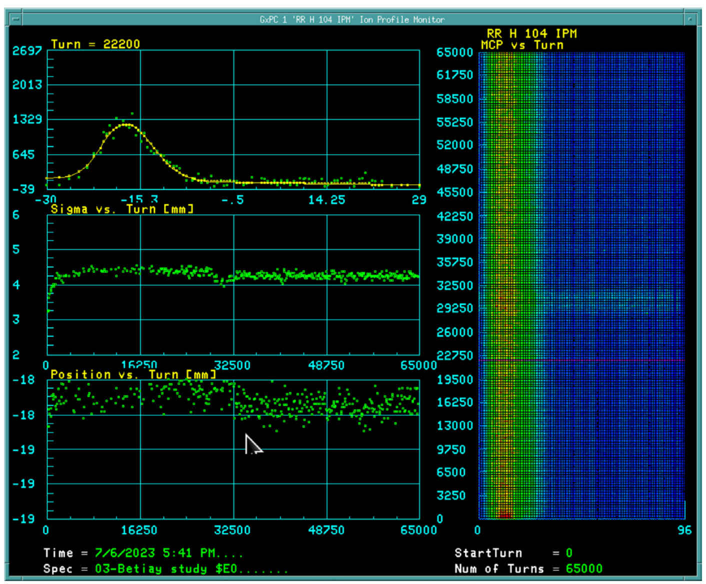
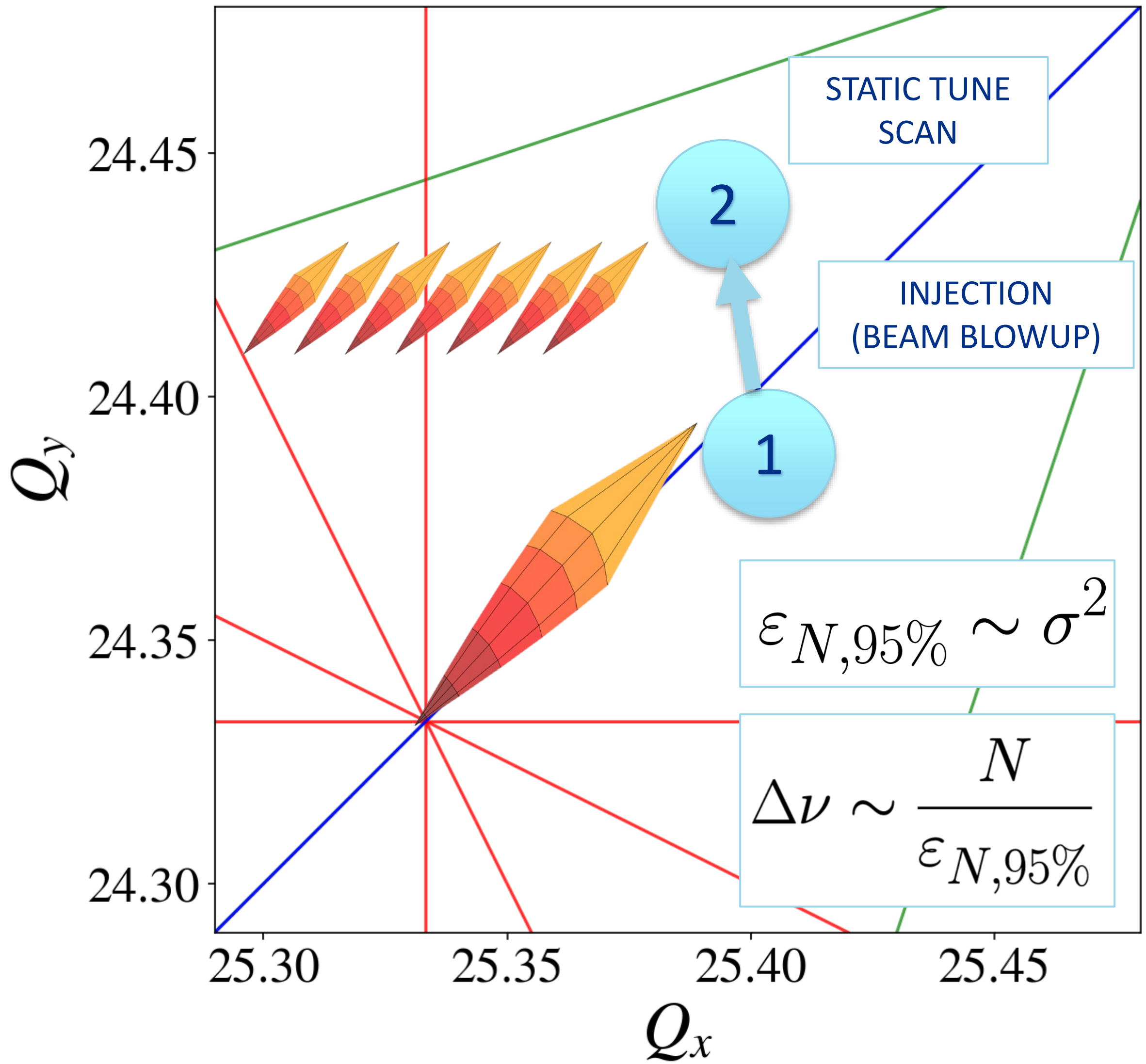
Static Tune Scans at High Intensities (Experimental)



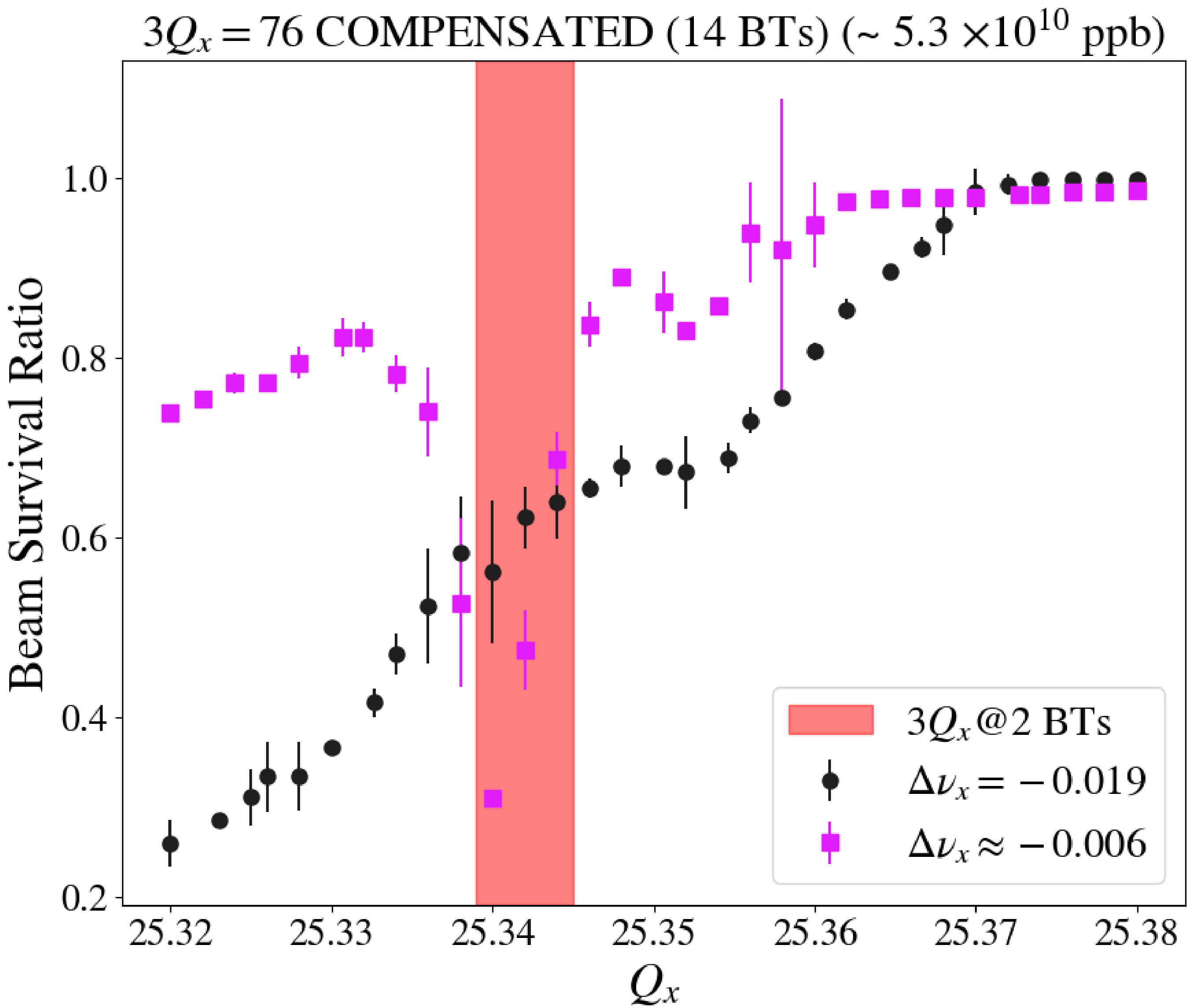
Static Tune Scans with Wide Beam







Static Tune Scans with Wide Beam



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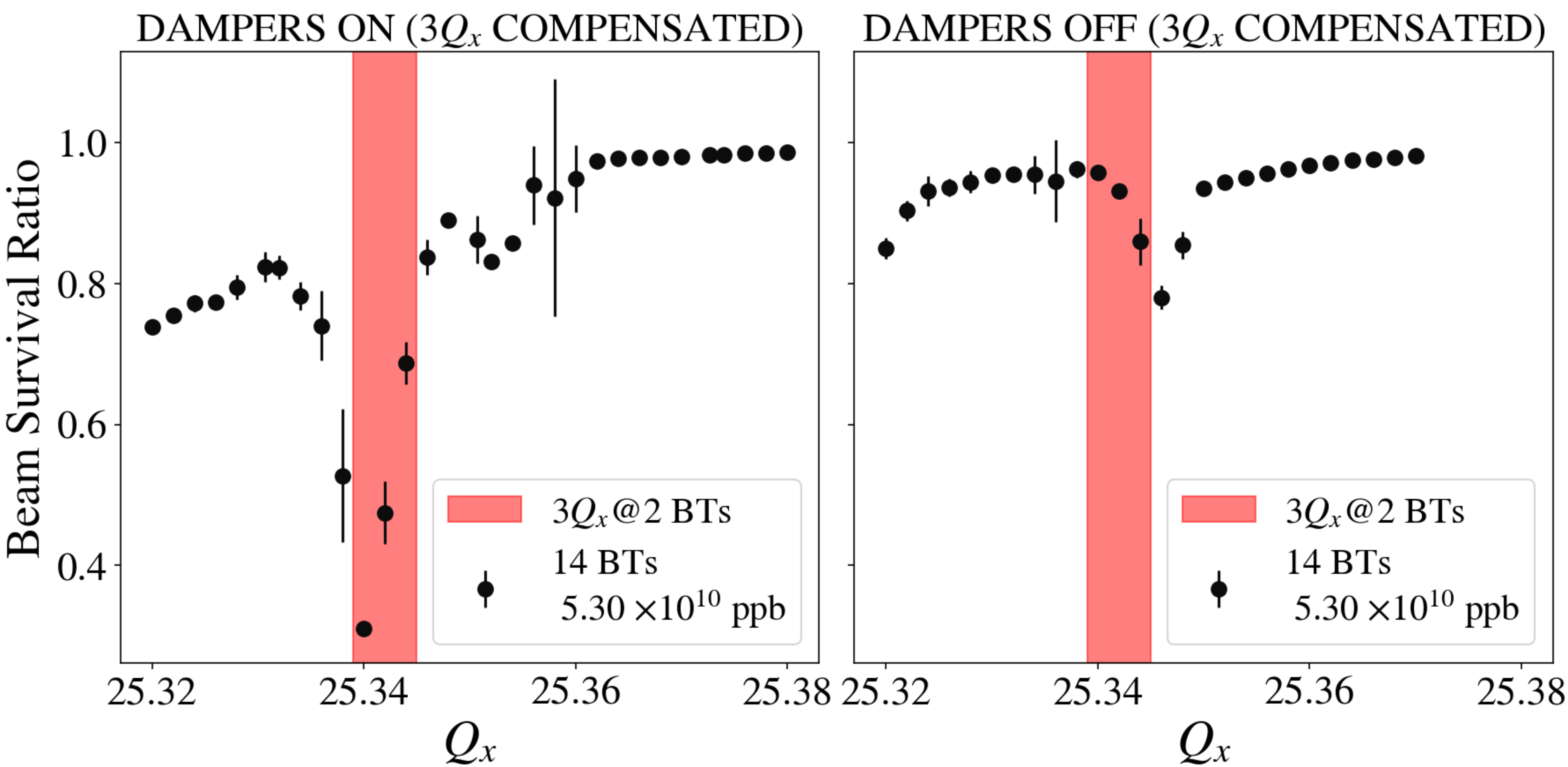
Transverse Dampers and Resonances



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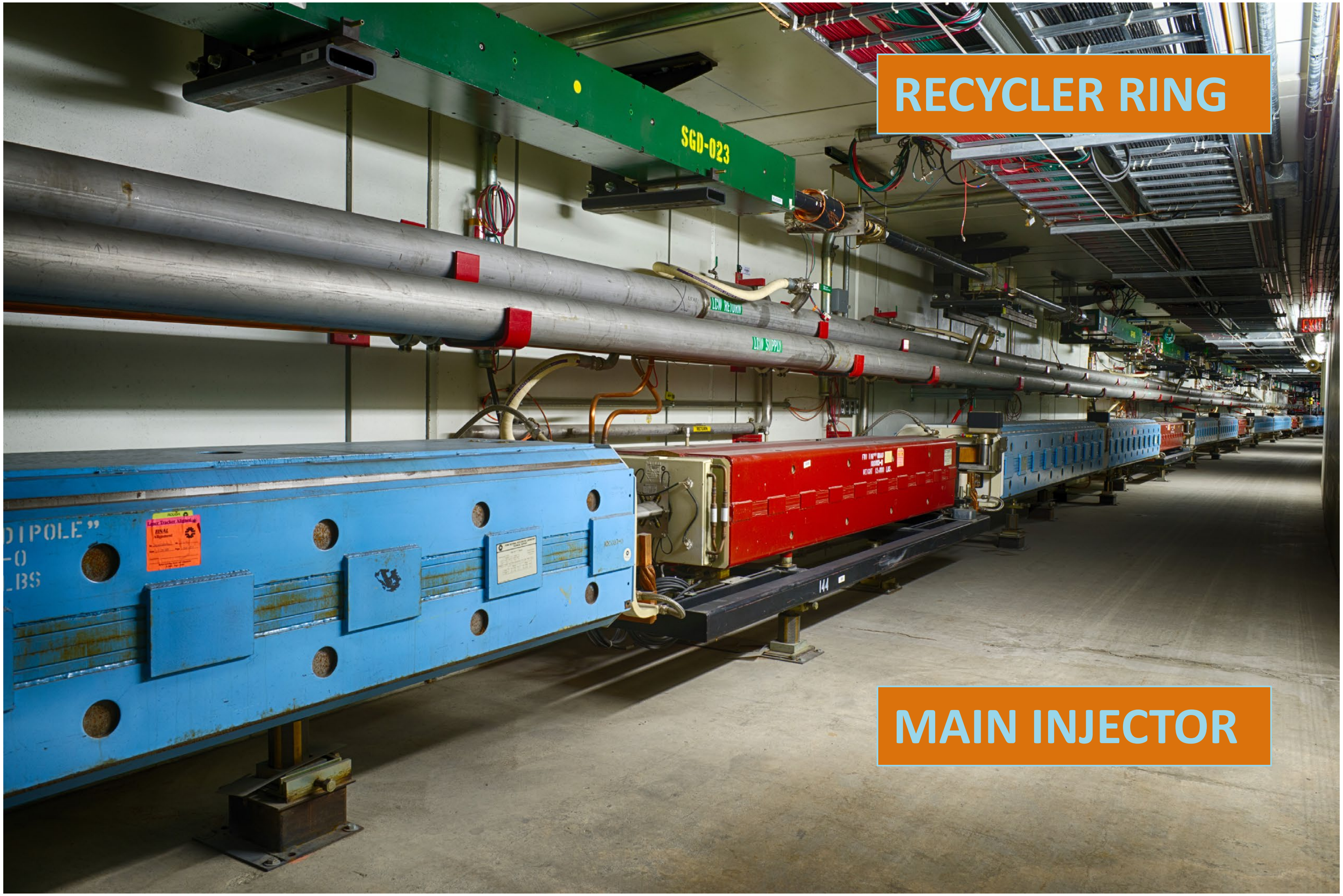
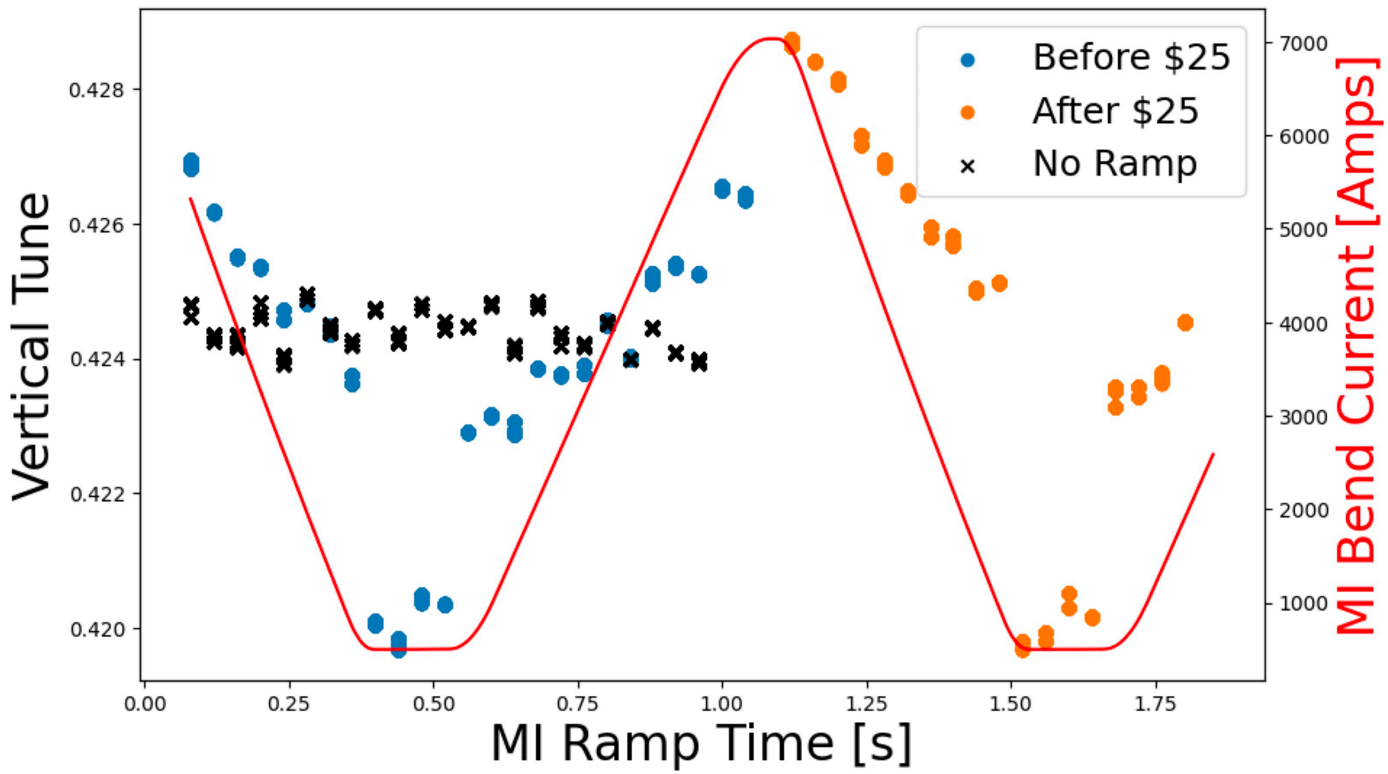
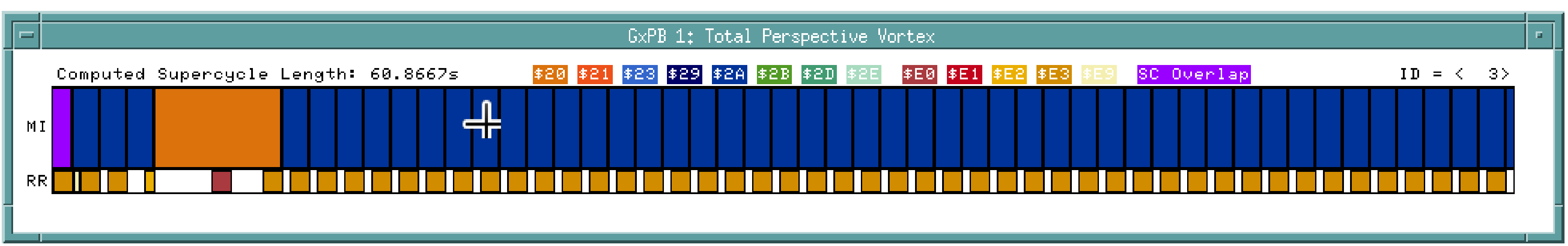
High Intensity Operation



MI effect on RR





- Chelidze, N. *et al.*, "The Effect of the Main Injector Ramp on the Recycler", in *Proc. NAPAC'22*, Albuquerque, New Mexico, United States, Oct. 2022

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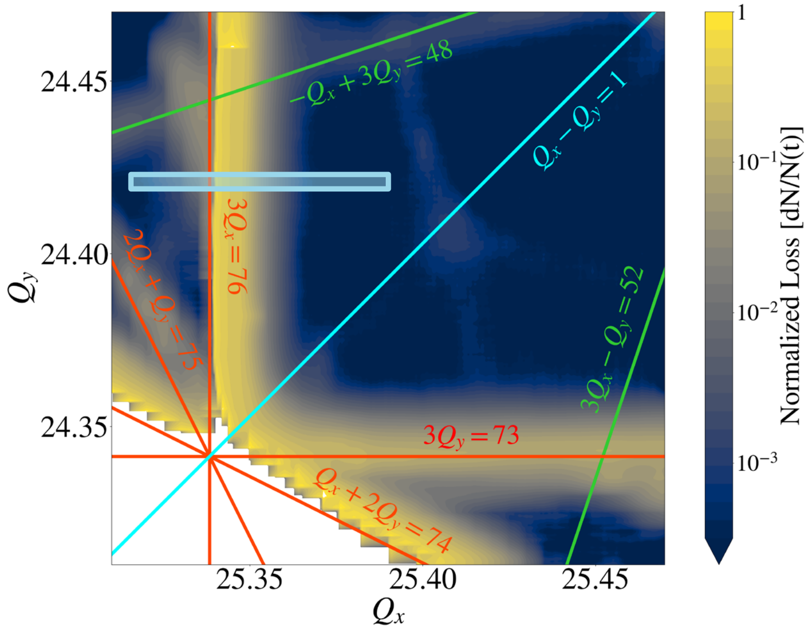
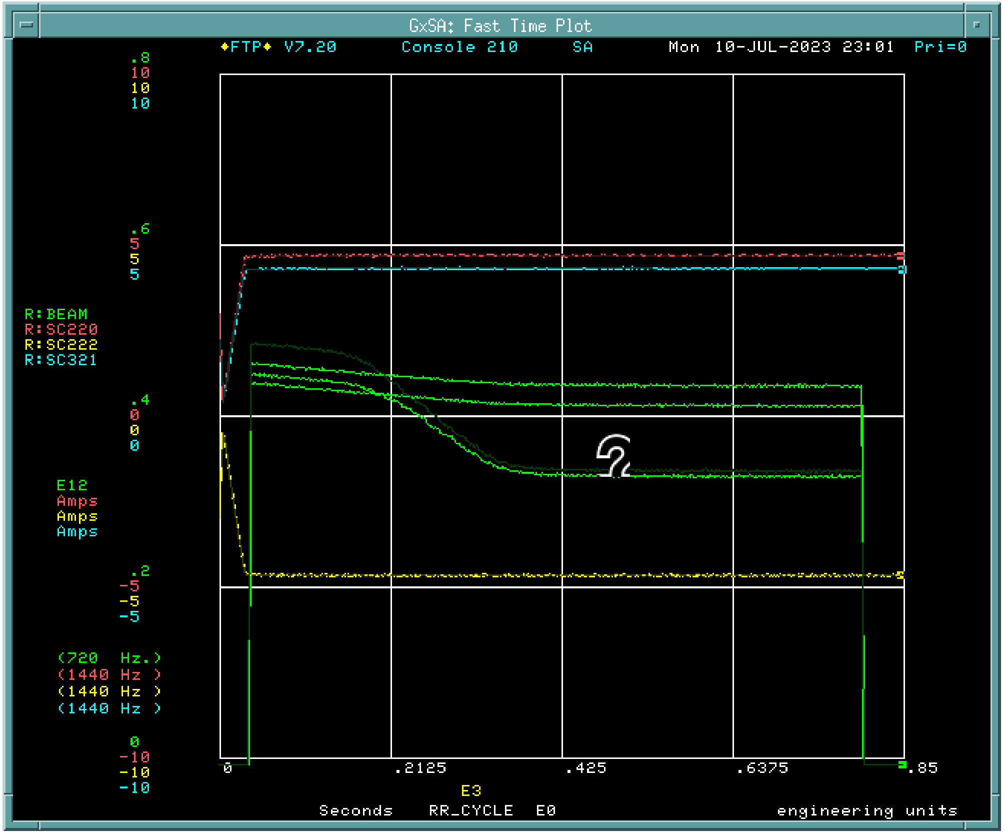
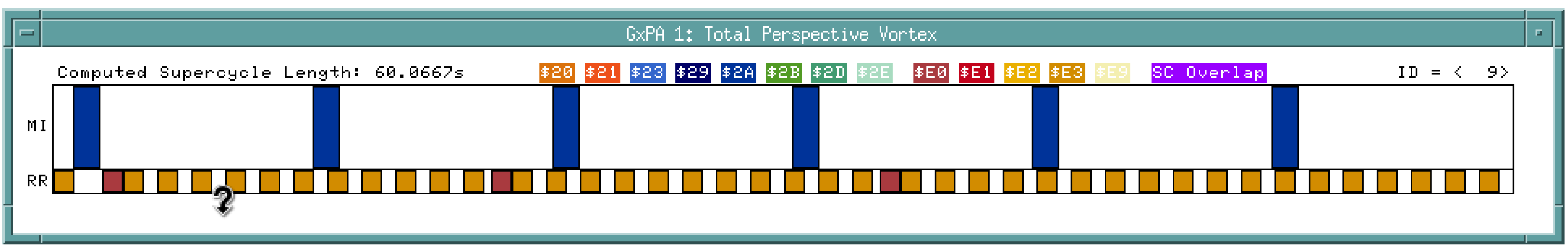
MI effect on RR







Conclusion and Future Work

- Cancellation of global third order RDTs allows to mitigate the harmful effect of third order resonances in the Recycler Ring
- At higher intensities, this compensation scheme is also beneficial to the beam survival ratio
- The incoherent space charge tune shift complicates things when trying to use beam-based measurements
- Further investigation is needed as to how the transverse dampers in the RR excite betatron resonances at high intensities

THANK YOU!

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