



# Compensation of Third Order Resonances in the High Intensity Regime

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**MICHIGAN STATE**  
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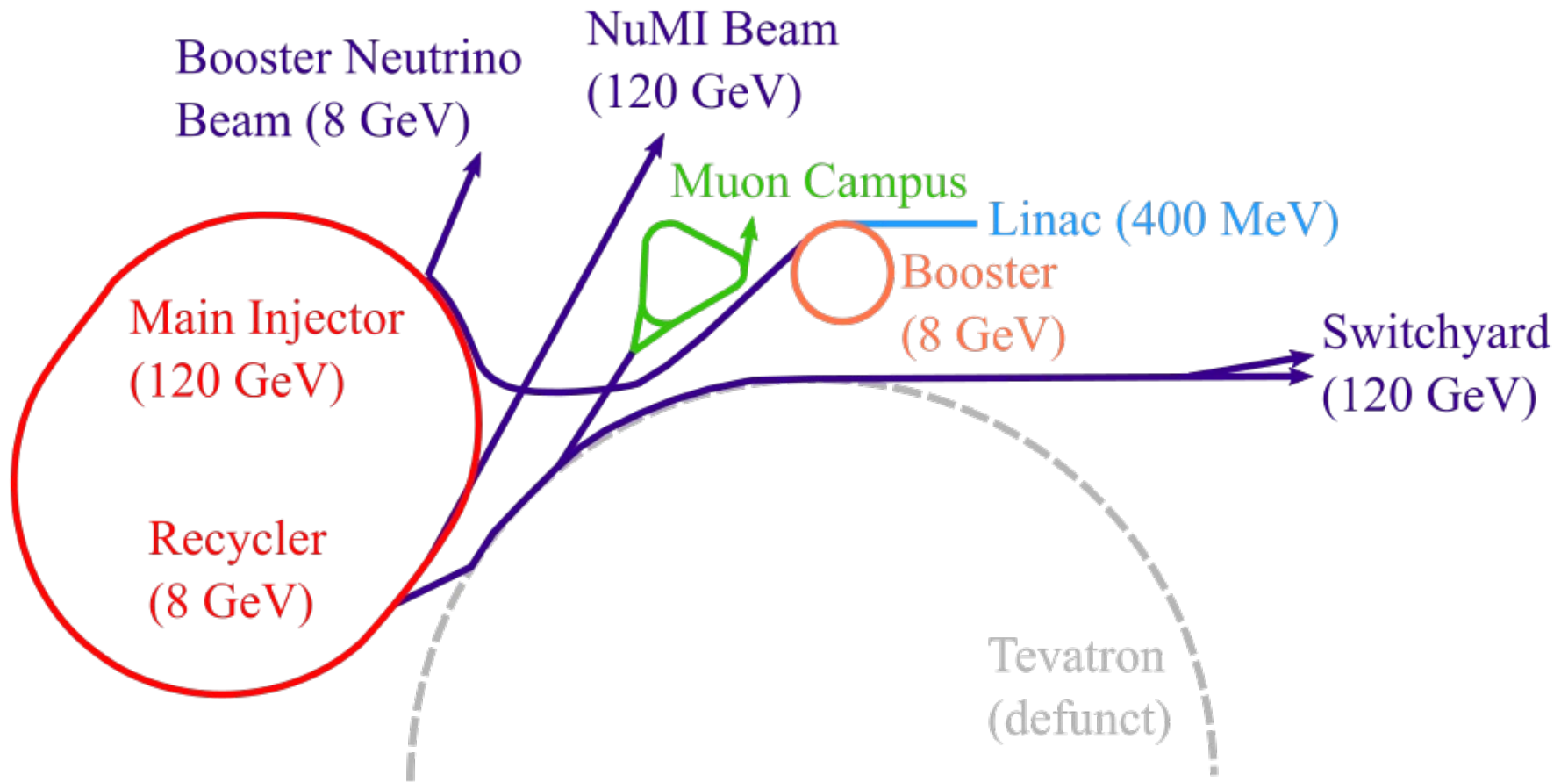
# Acknowledgments

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  - Osama Mohsen [THAFP04]
  - Mary Kate Bossard [THAFP03]
  - Meiqin Xiao [THBP28 & THBP30]
  - Eliana Gianfelice

# Fermilab Campus

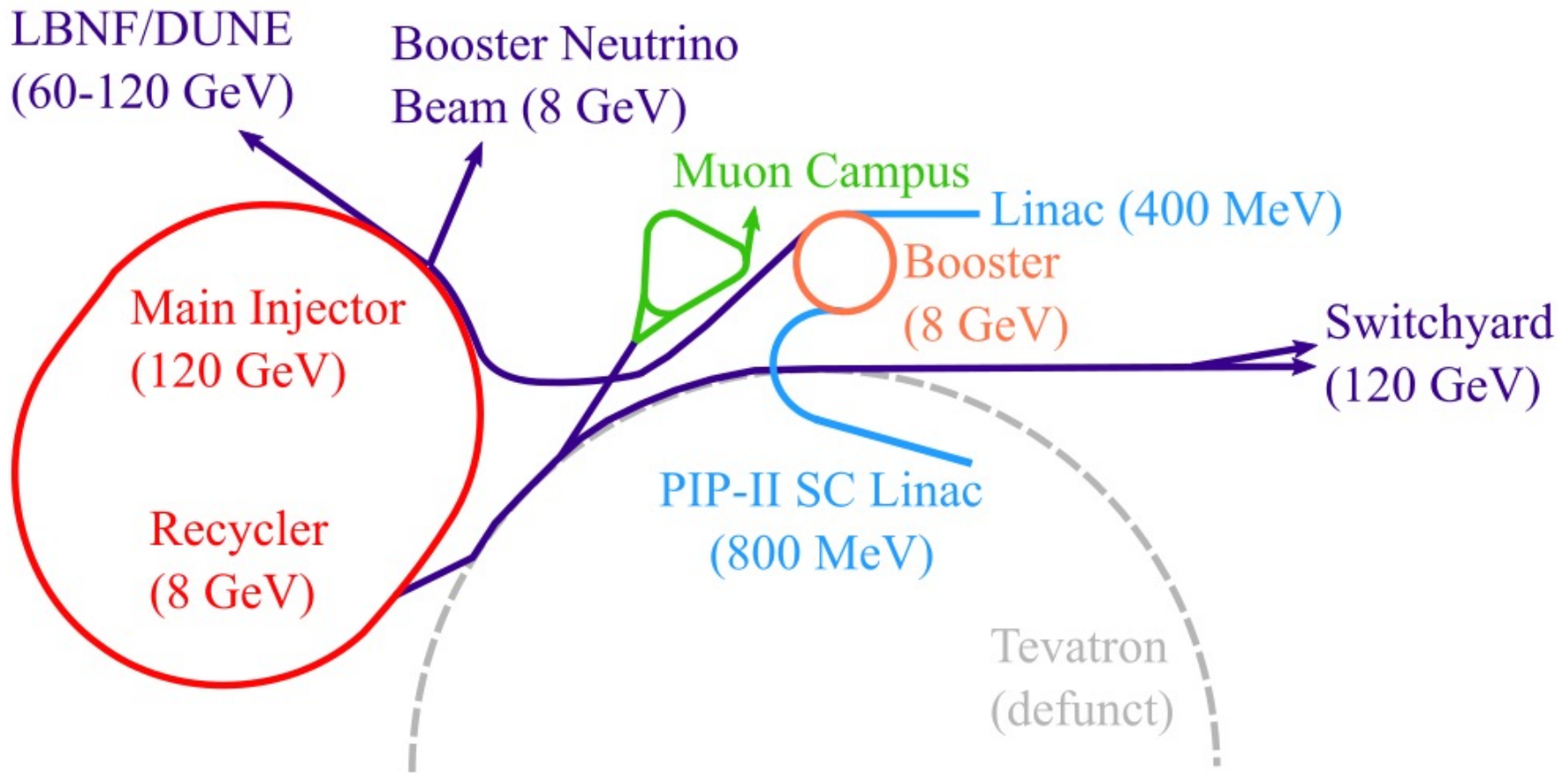


# Fermilab Accelerator Complex



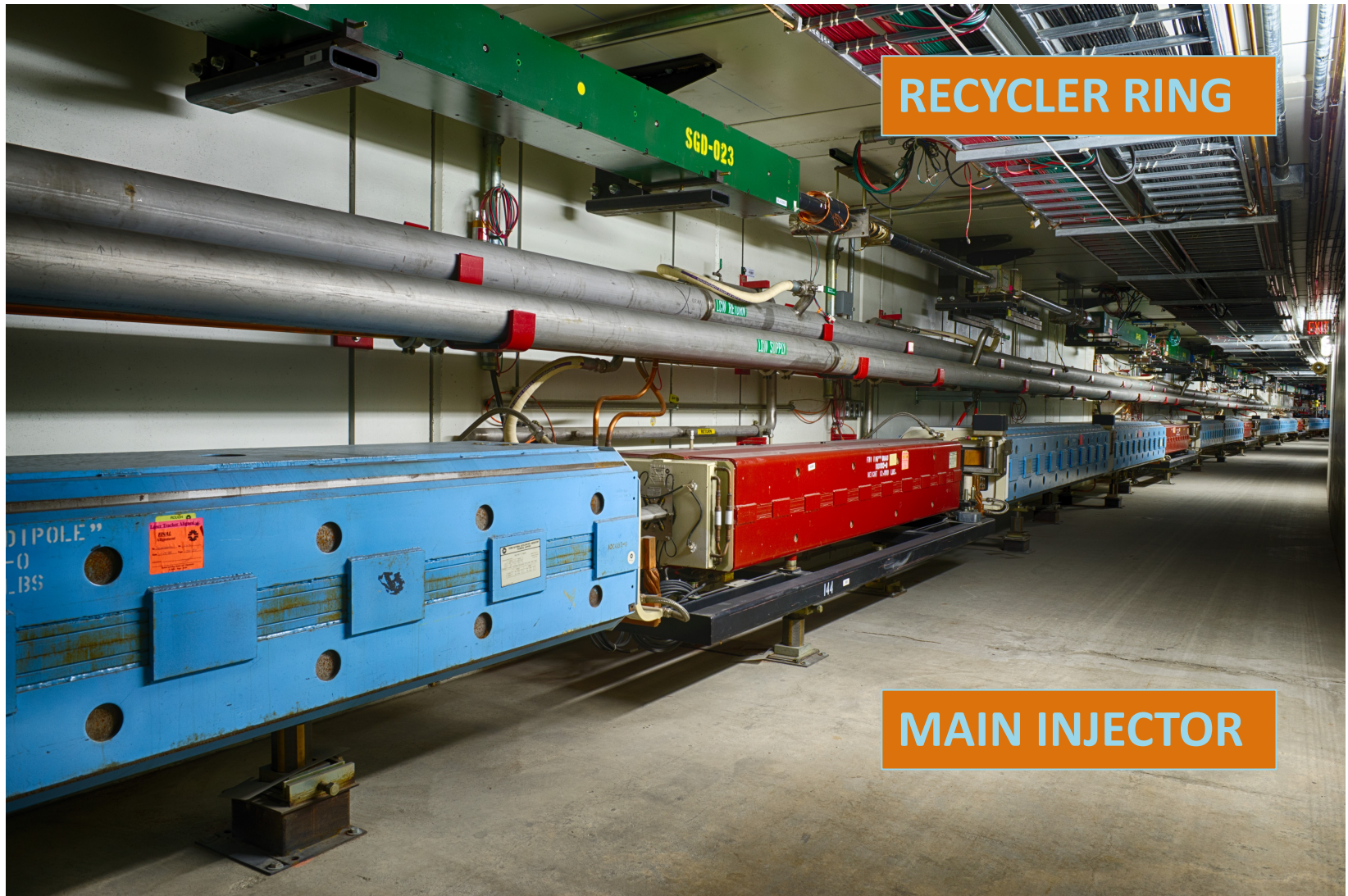
- R. Ainsworth et.al., "High intensity operation using proton stacking in the Fermilab Recycler to deliver 700 kW of 120 GeV proton beam", Phys. Rev. Accel. Beams, vol.23, no. 12, p. 121002

# 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



RECYCLER RING

MAIN INJECTOR

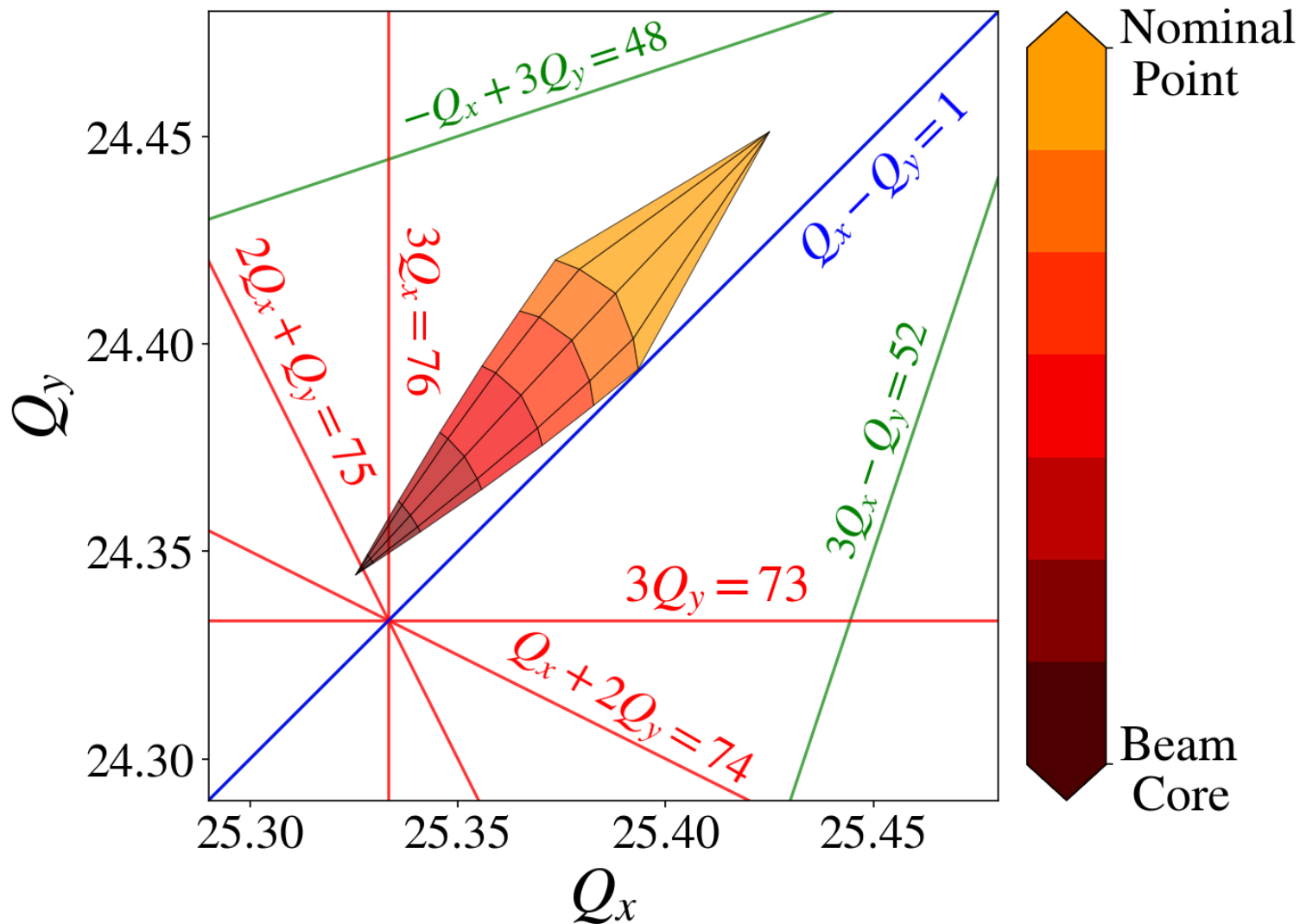
# Fermilab Recycler Ring

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	$-8.6 \times 10^{-3}$	
Superperiodicity	2	
Horizontal Tune	25.43	
Vertical Tune	24.445	
Horizontal Chromaticity	-6	
Vertical Chromaticity	-7	
95% Normalized Emittance	15	$\pi$ mm mrad
95% Longitudinal Emittance	0.08	eV s
Intensity	$5 \times 10^{10}$ , $8 \times 10^{10}$ (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

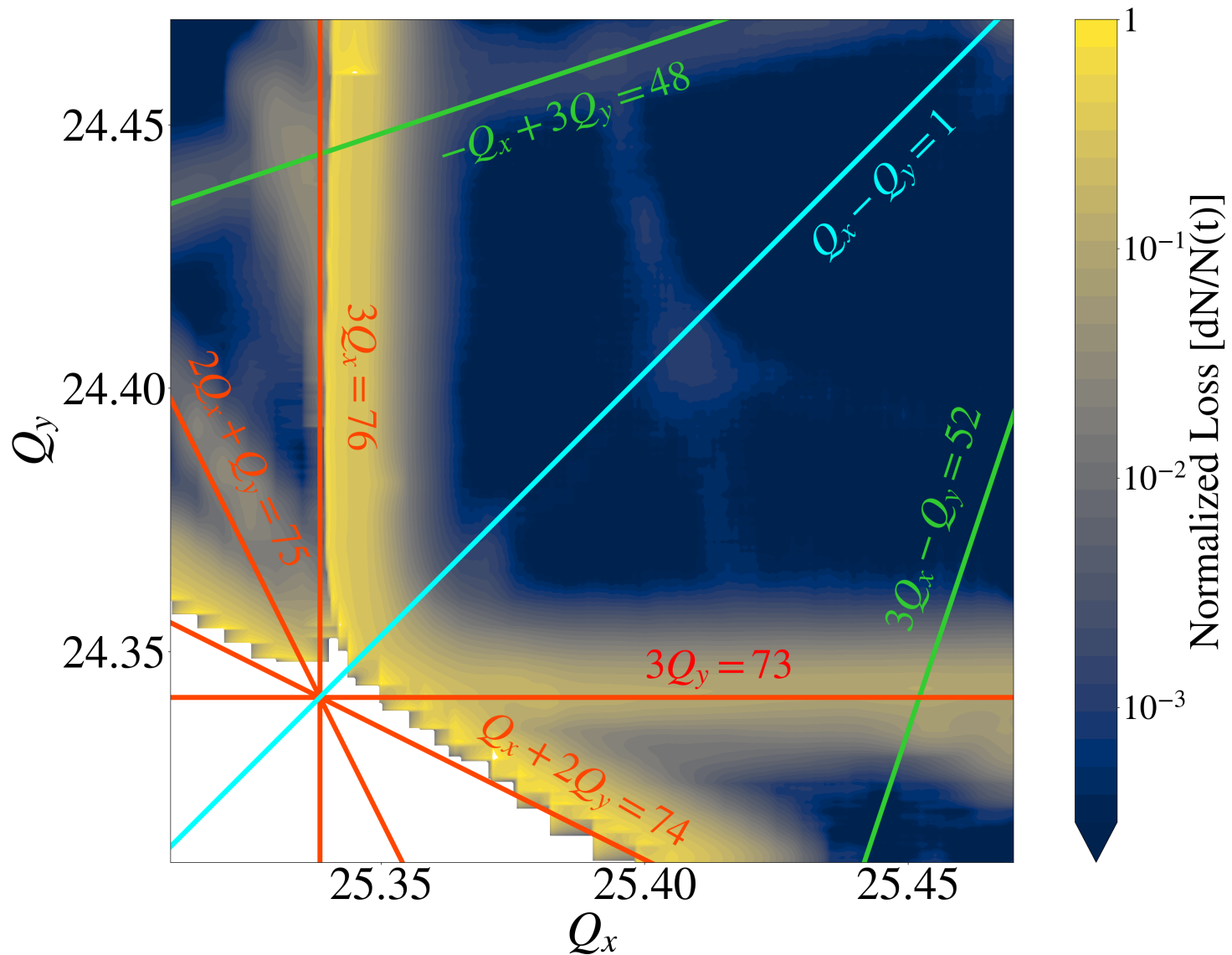


# Tune Diagram for PIP-II Intensities



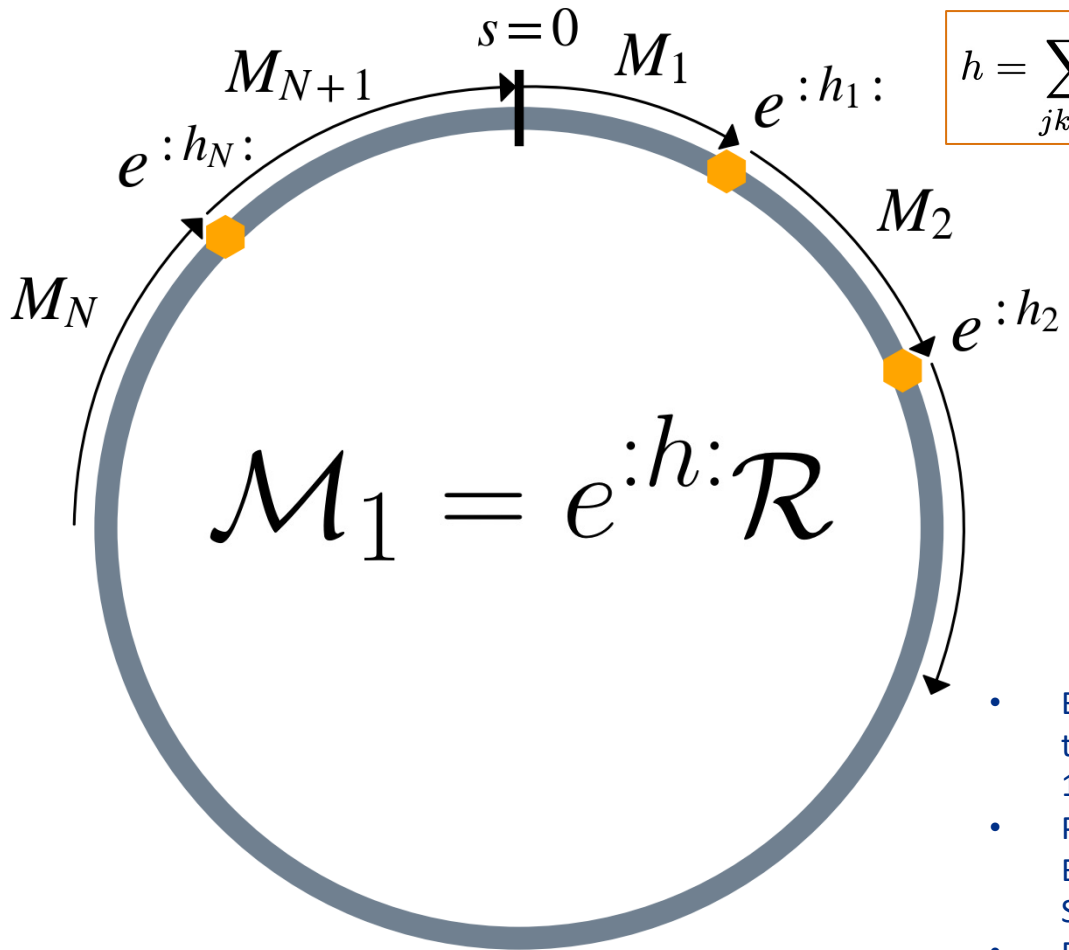
- F. Asvesta, et al.. <https://github.com/fasvesta/PySCRDT>

# Fermilab Recycler Ring



# Low Intensity Studies

# Global Third Order RDTs



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

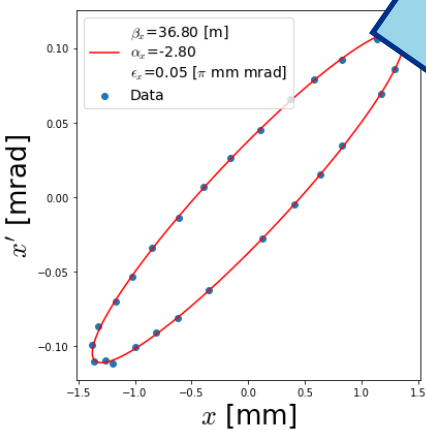
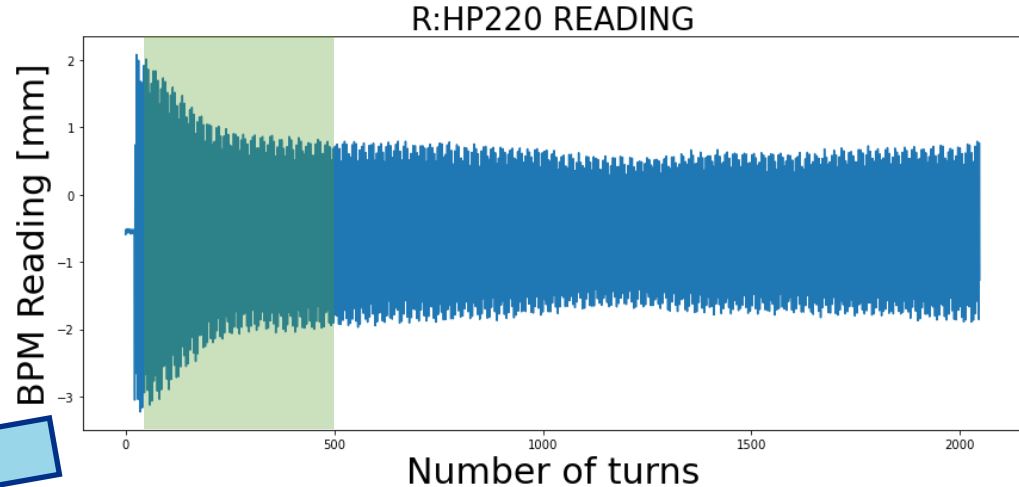
Res. Line	RDT	Sext. Term
$3Q_x = 76$	$h_{3000}$	Normal
$Q_x + 2Q_y = 74$	$h_{1020}$	Normal
$3Q_y = 73$	$h_{0030}$	Skew
$2Q_x + Q_y = 75$	$h_{2010}$	Skew

- 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.

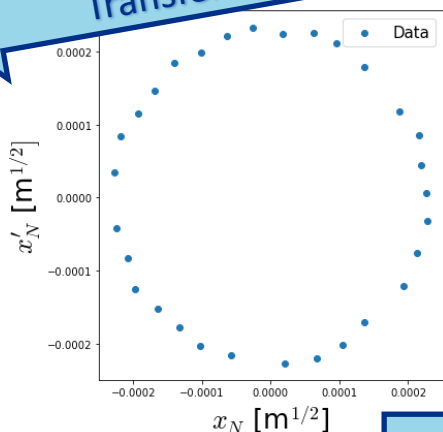
# Measurement of Global RDTs

## How to measure RDTs?

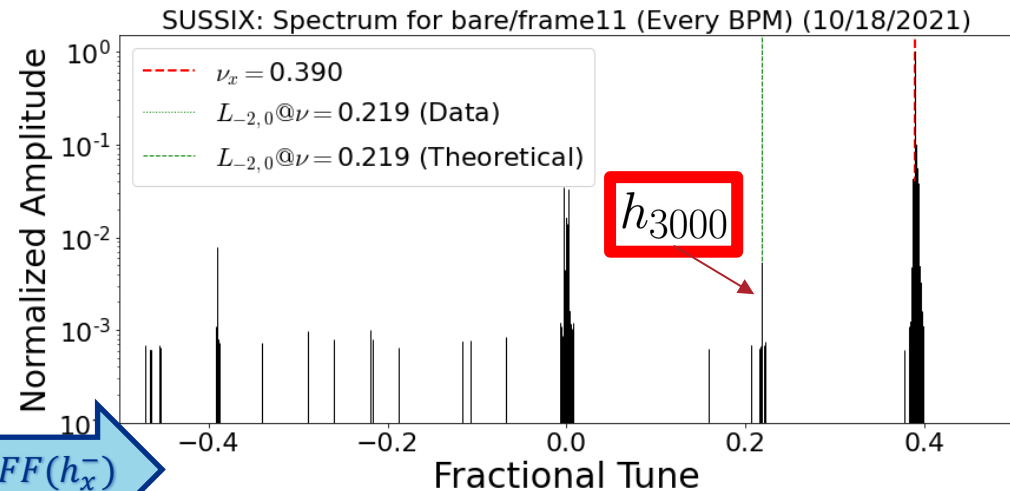
- Start from BPM data (104 BPMs)
- Estimate momentum coordinates from BPMs transfer matrices
- Get normalized phase space
- Get spectral decomposition of resonance basis



Transfer Matrices



NAFF( $h_x^-$ )

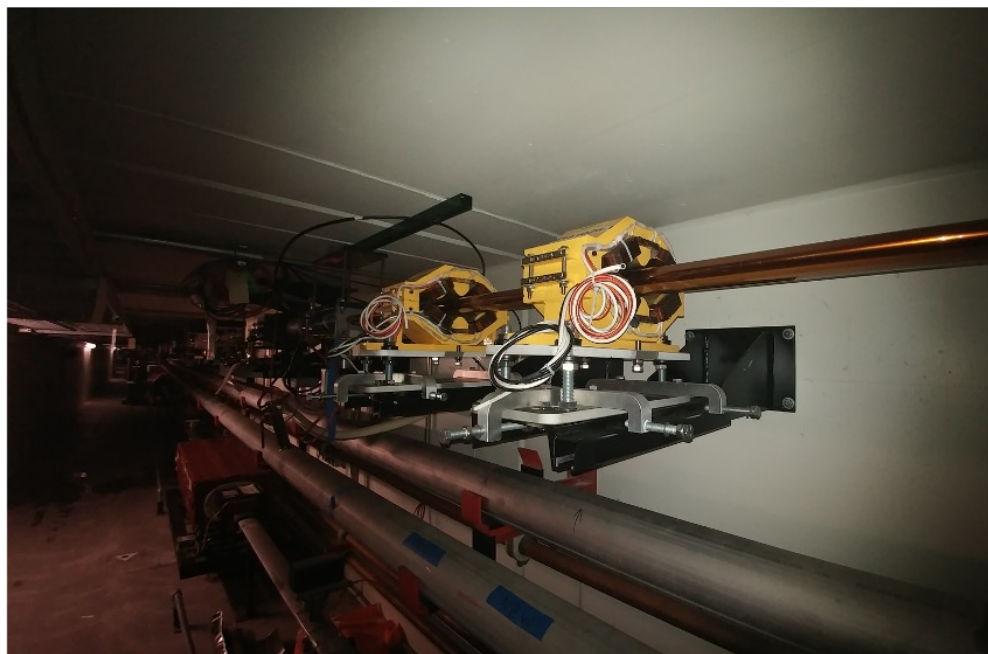


$$h_x^-(N) = x_{norm}(N) - ix'_{norm}(N)$$

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

# 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**

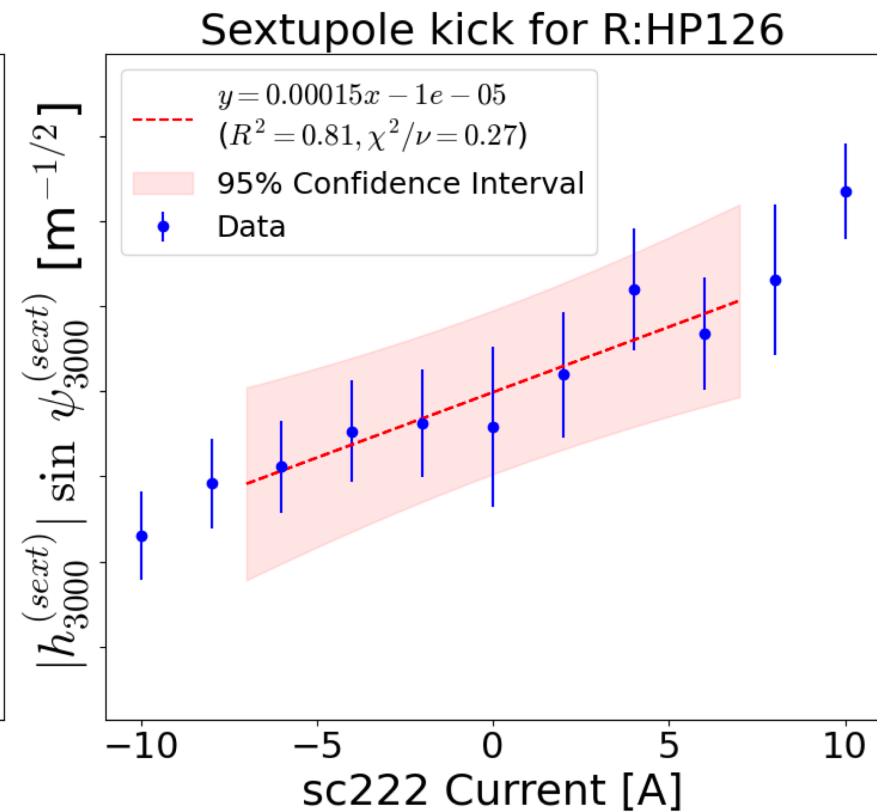
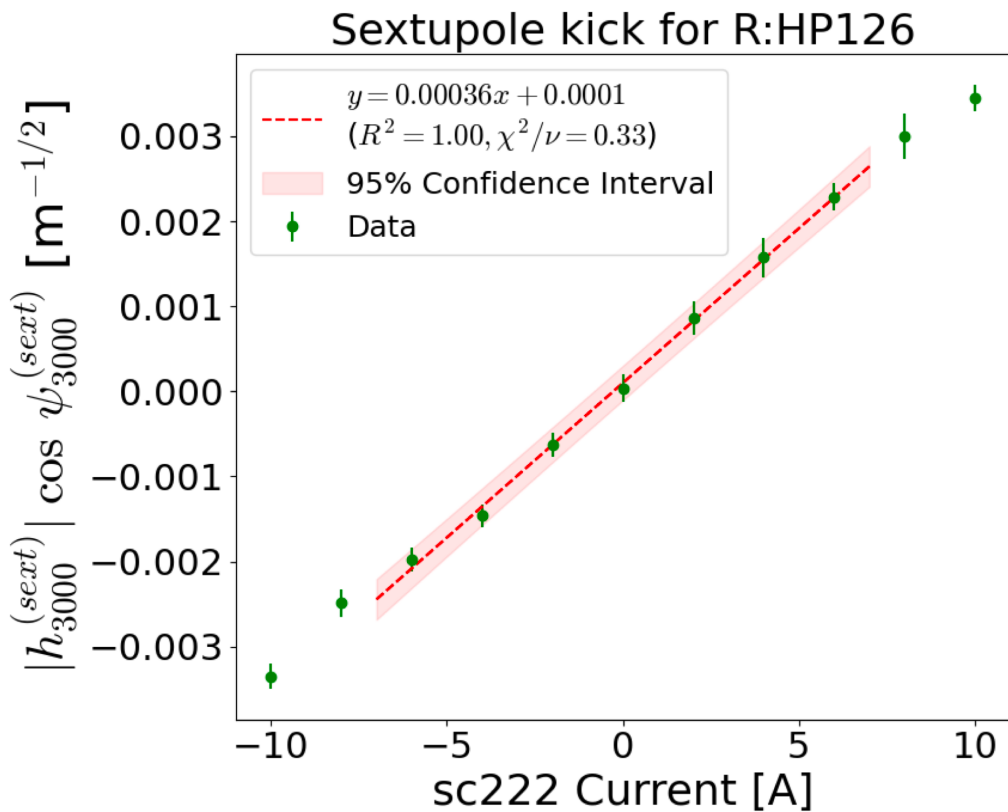


$$\begin{pmatrix} -|h_{3000}^{(bare)}| \cos(\psi_{3000}^{(bare)}) \\ -|h_{3000}^{(bare)}| \sin(\psi_{3000}^{(bare)}) \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} I_{sc220}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

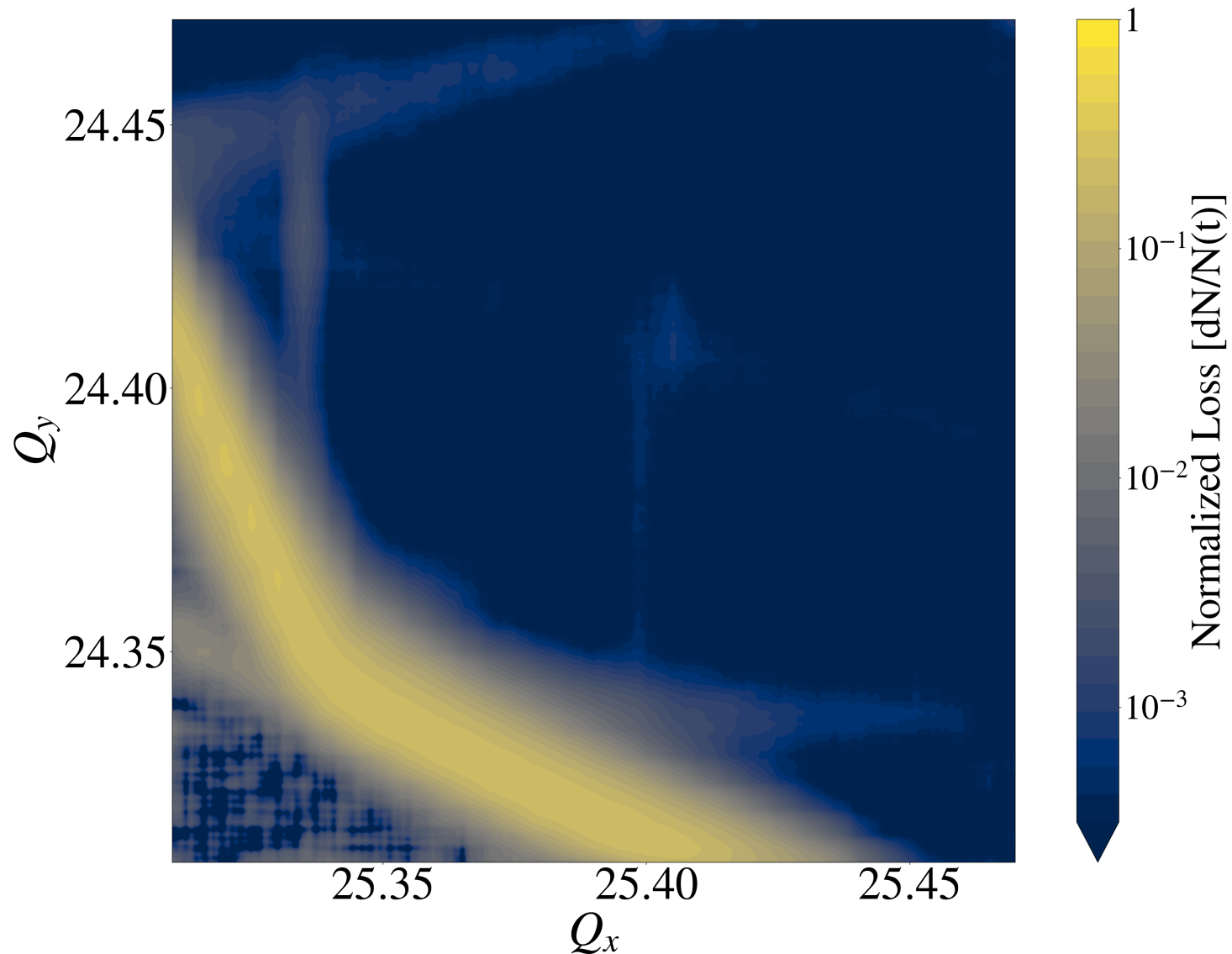
$$\vec{I}_{Comp} = \mathbf{M}^{-1} \vec{h}_{3000}^{(bare)}$$

# 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

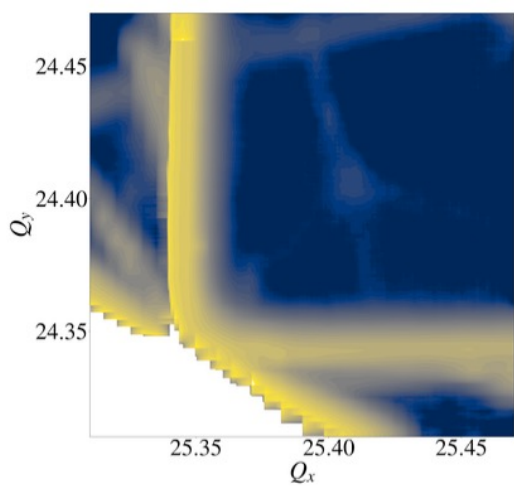


# Dynamic Loss Maps (Experimental)

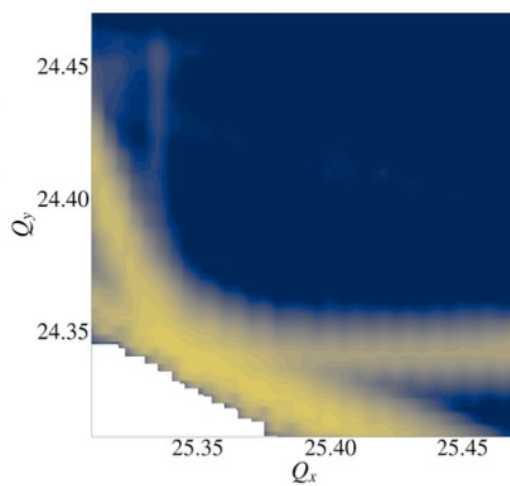




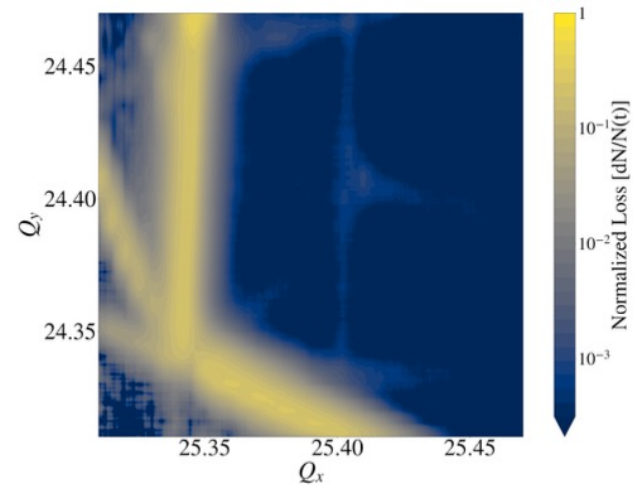
# Dynamic Loss Maps (Experimental)



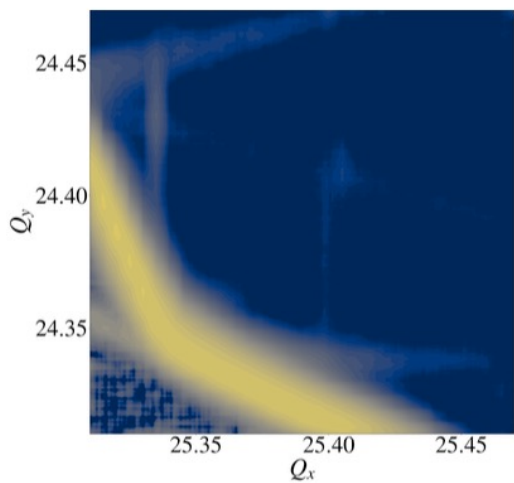
(a) Bare machine



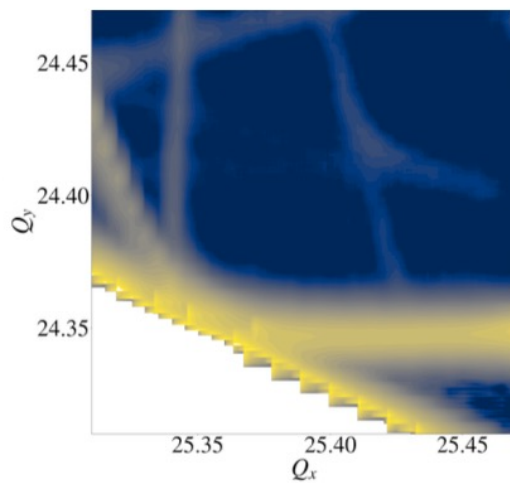
(b) 3 $Q_x$  Compensation



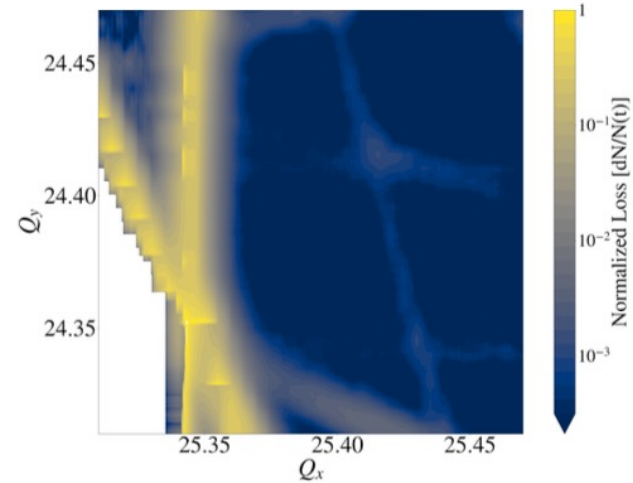
(c) 3 $Q_y$  Compensation



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

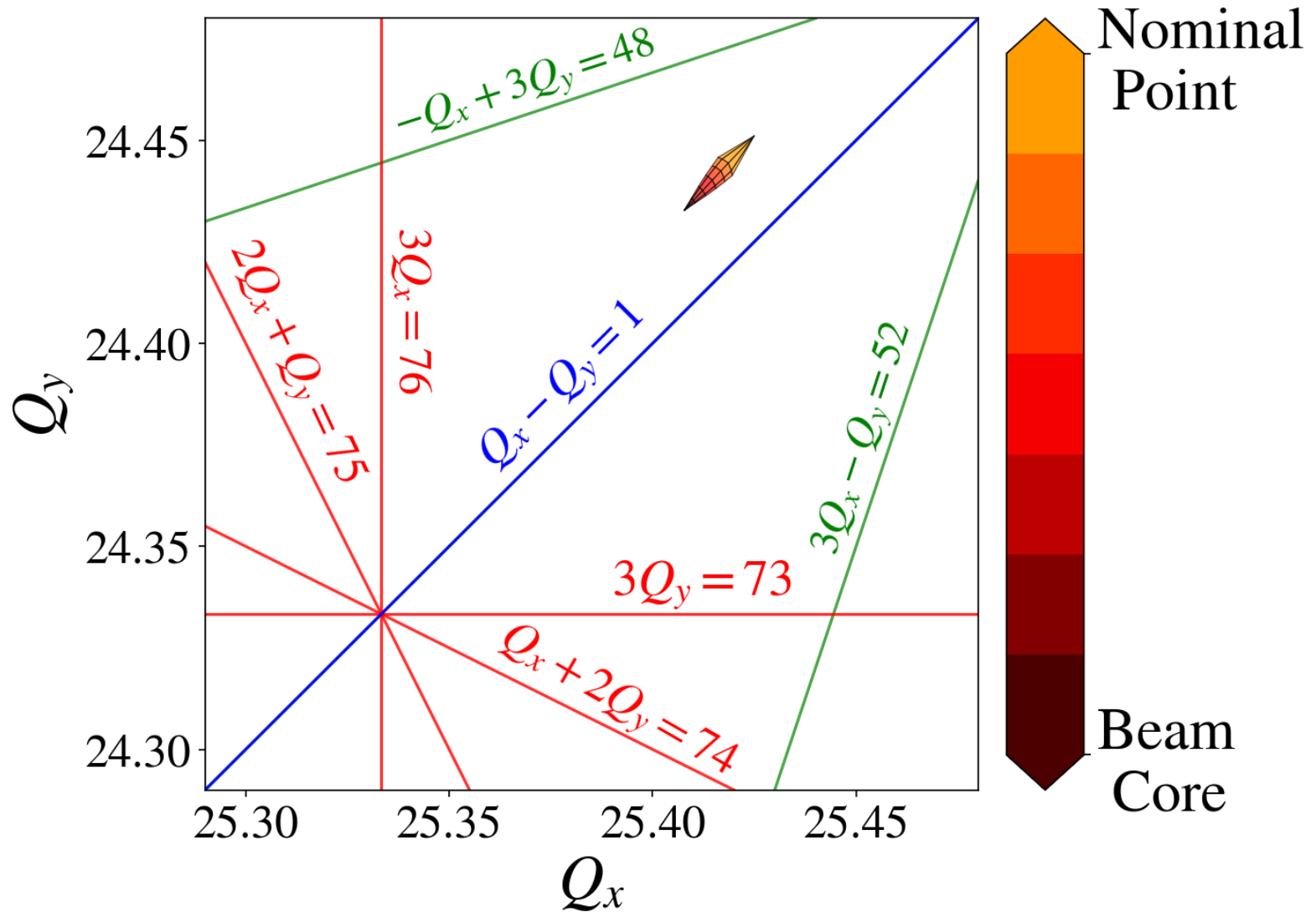


(e) 3 $Q_x$  and 2 $Q_x + Q_y$  Compensation



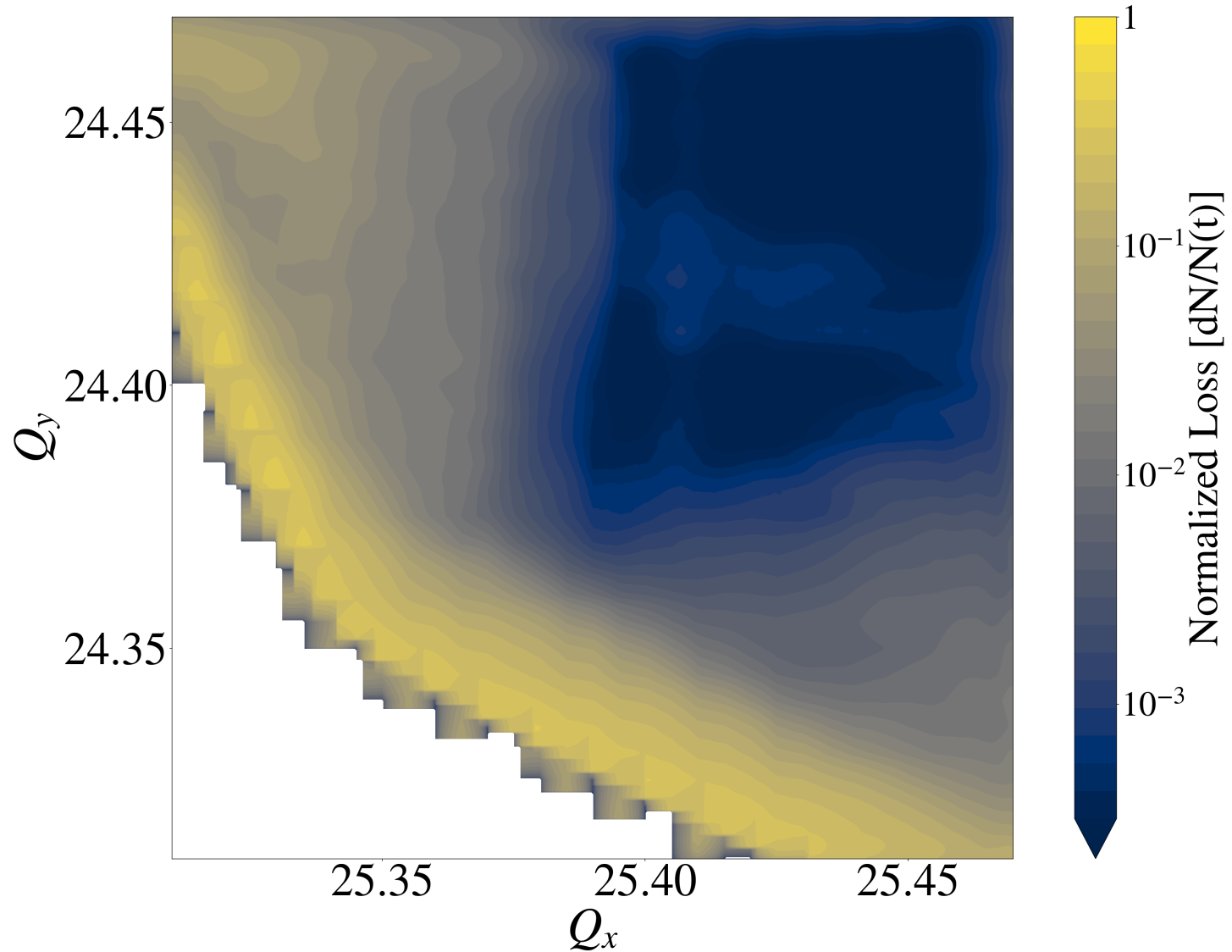
(f) 3 $Q_y$  and  $Q_x + 2Q_y$  Compensation

# Dynamic Loss Maps

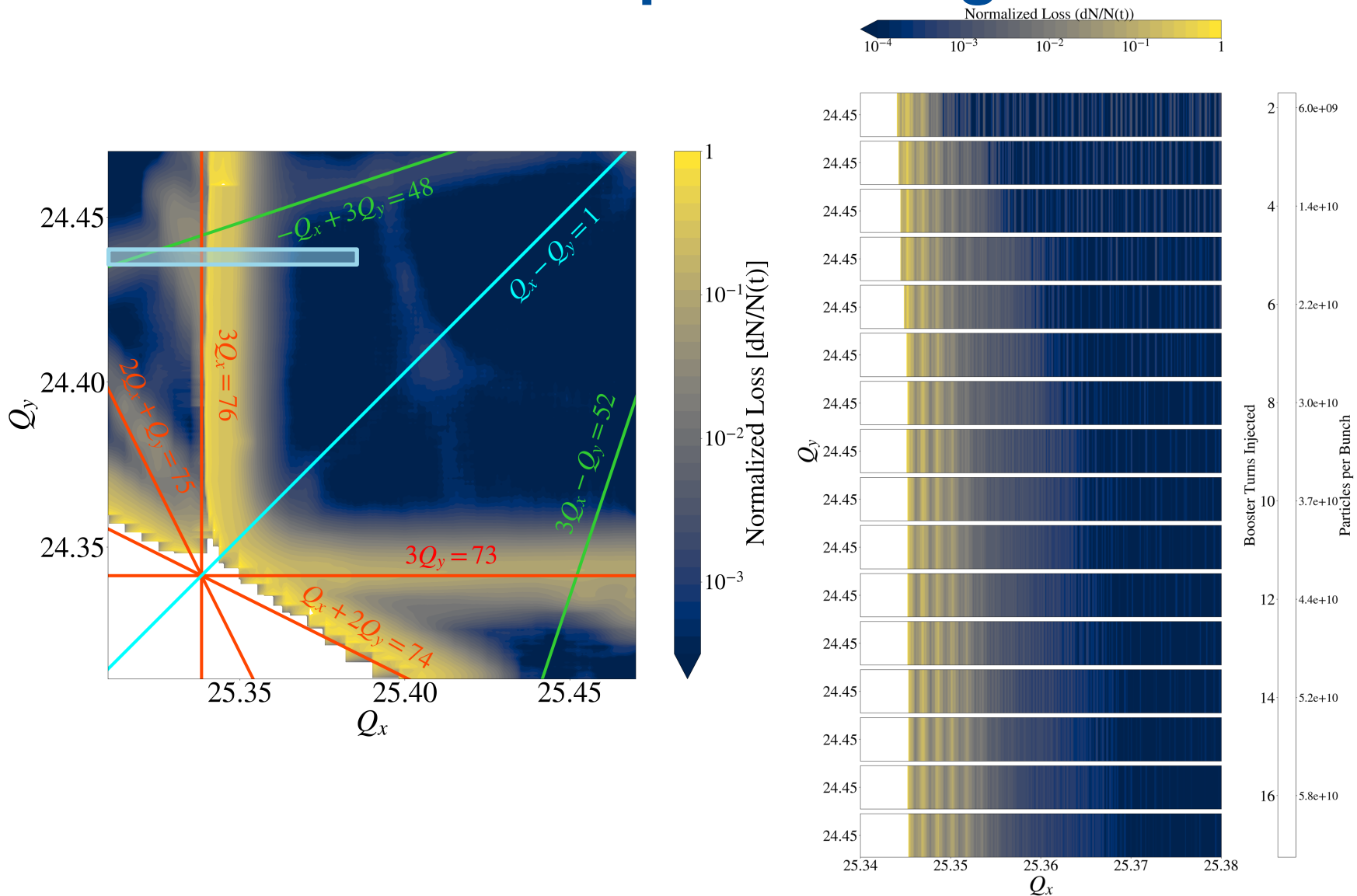


# High Intensity Studies

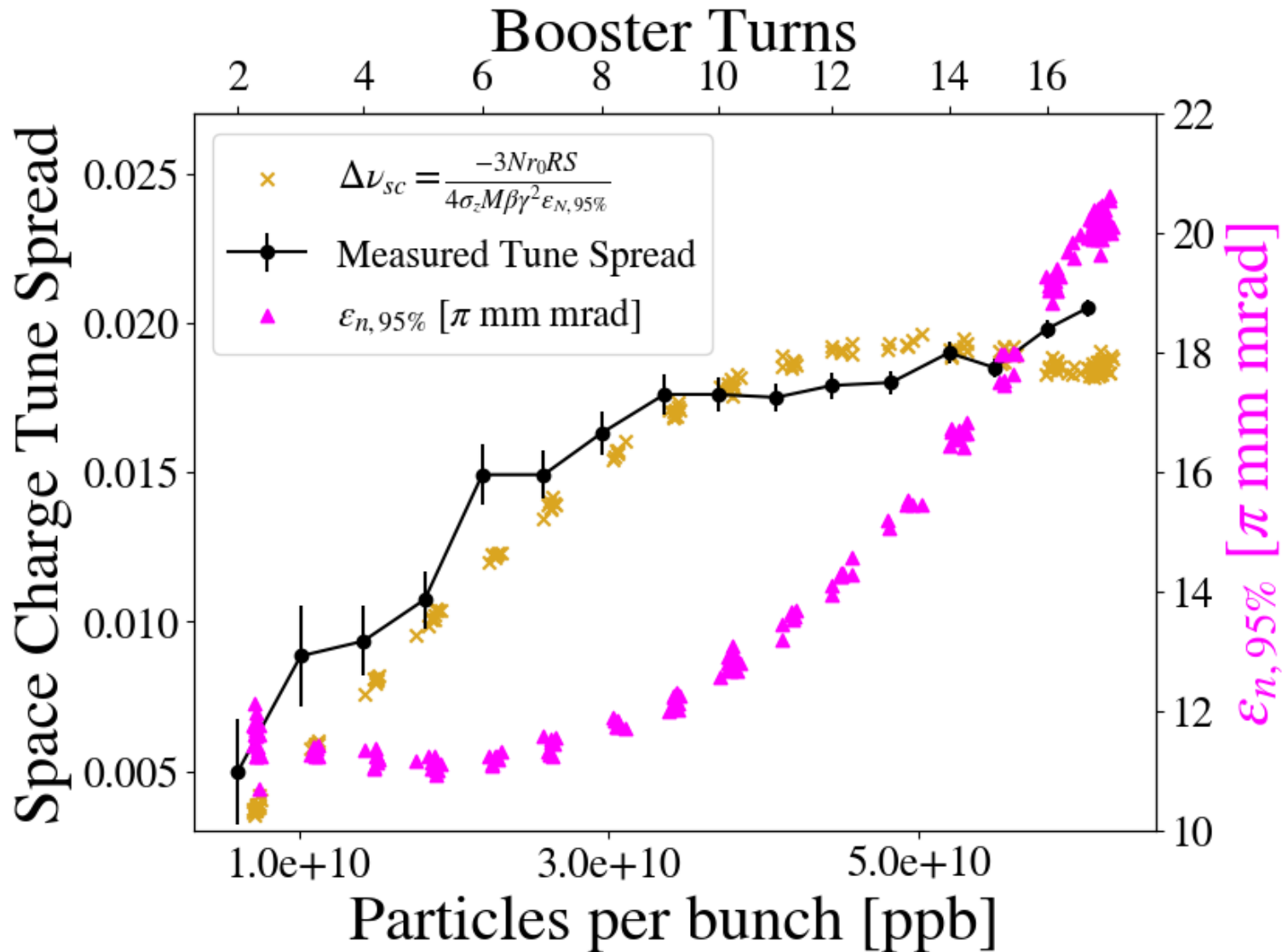
# High Intensity Loss Map



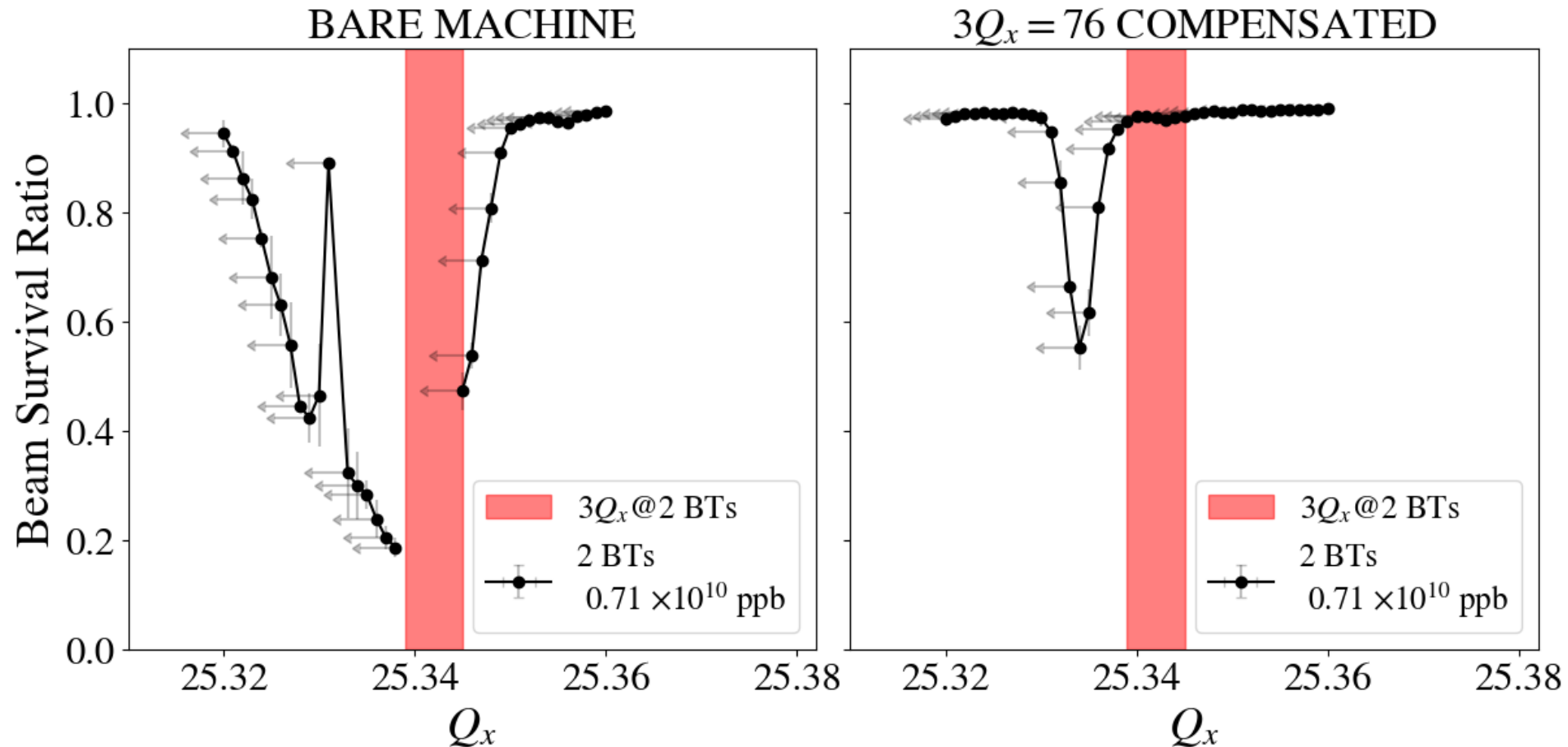
# Measurement of Space Charge Tune Shift



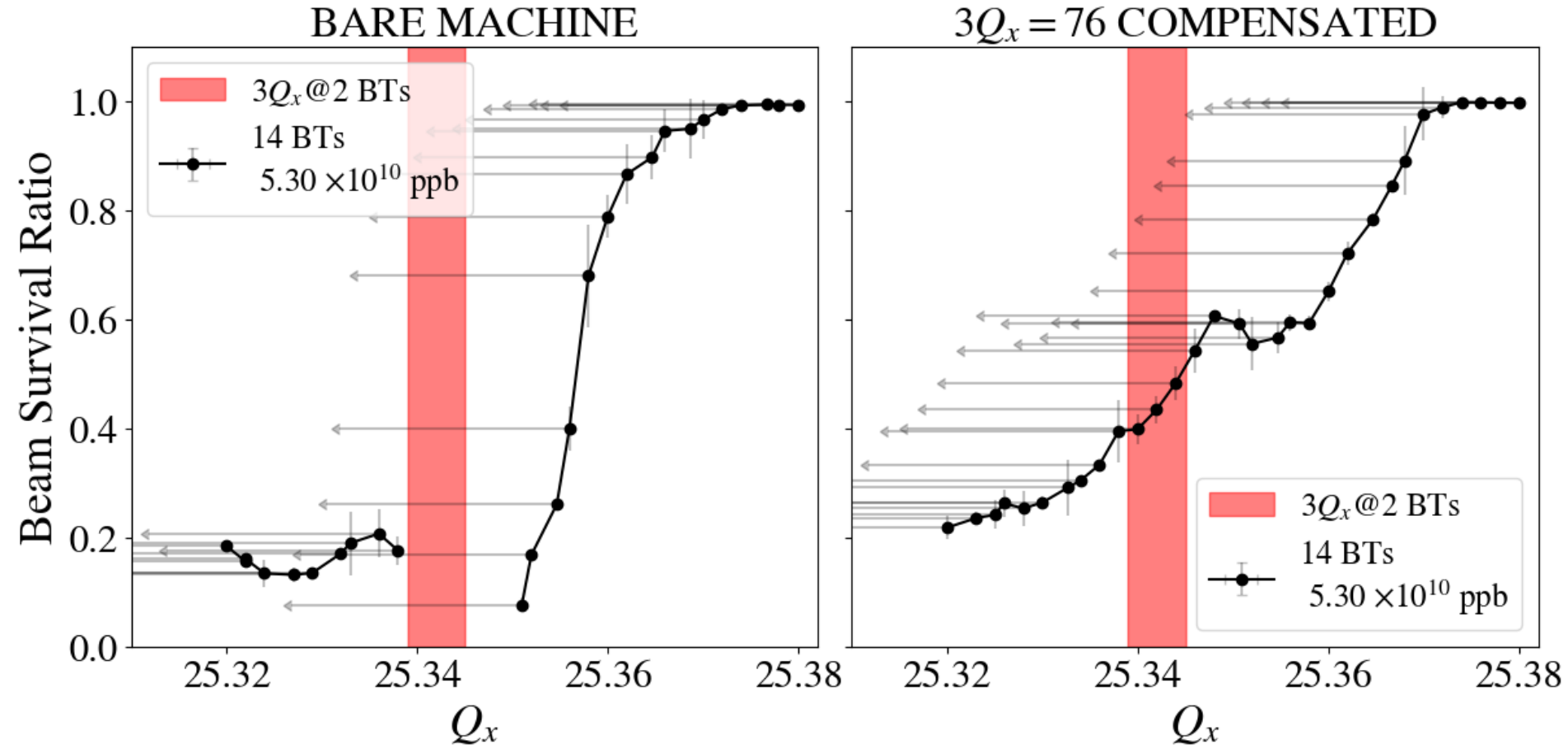
# Measurement of Space Charge Tune Shift



# Static Tune Scans at Low Intensities (Experimental)

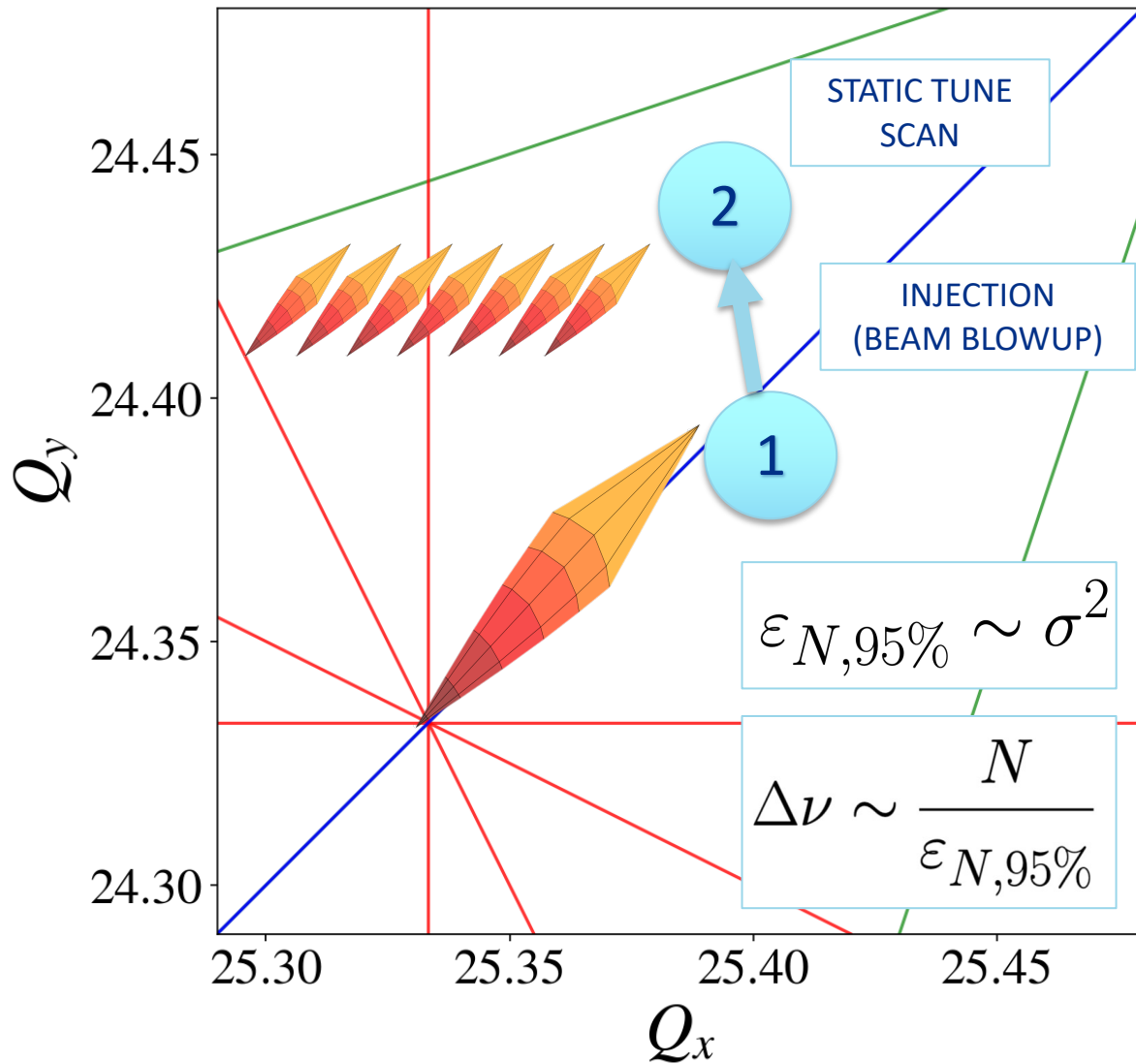
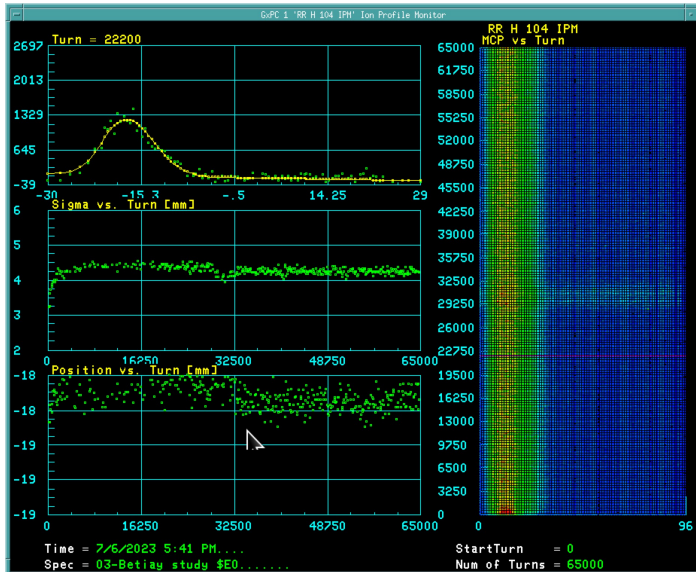
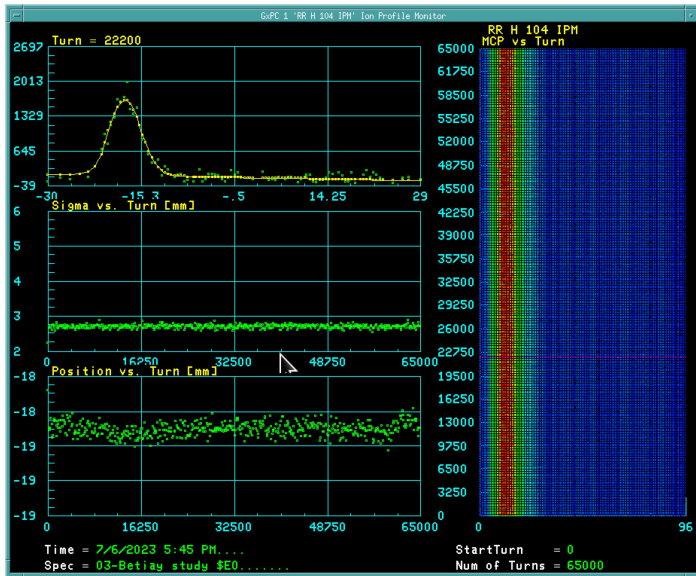


# Static Tune Scans at High Intensities (Experimental)



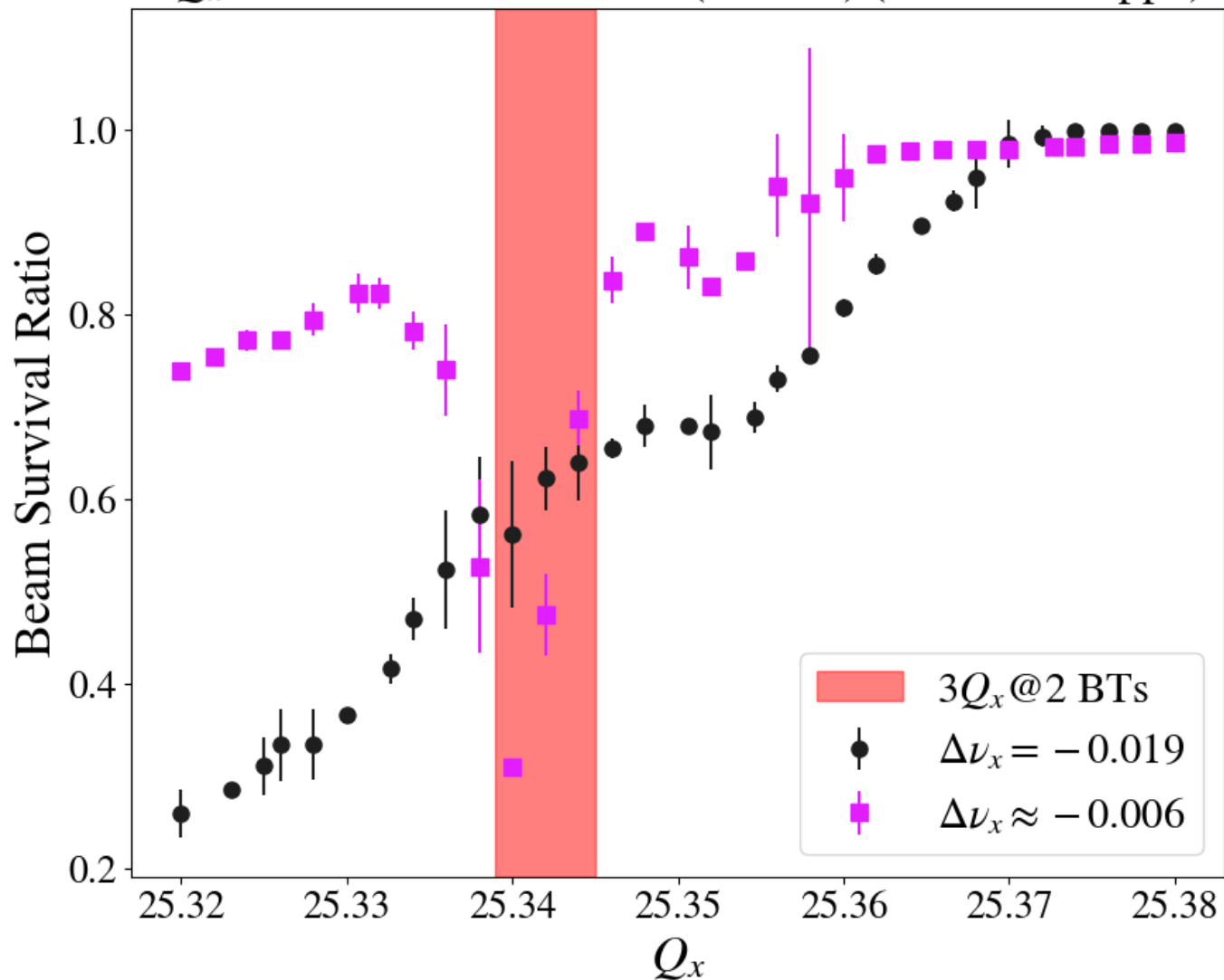


# Static Tune Scans with Wide Beam



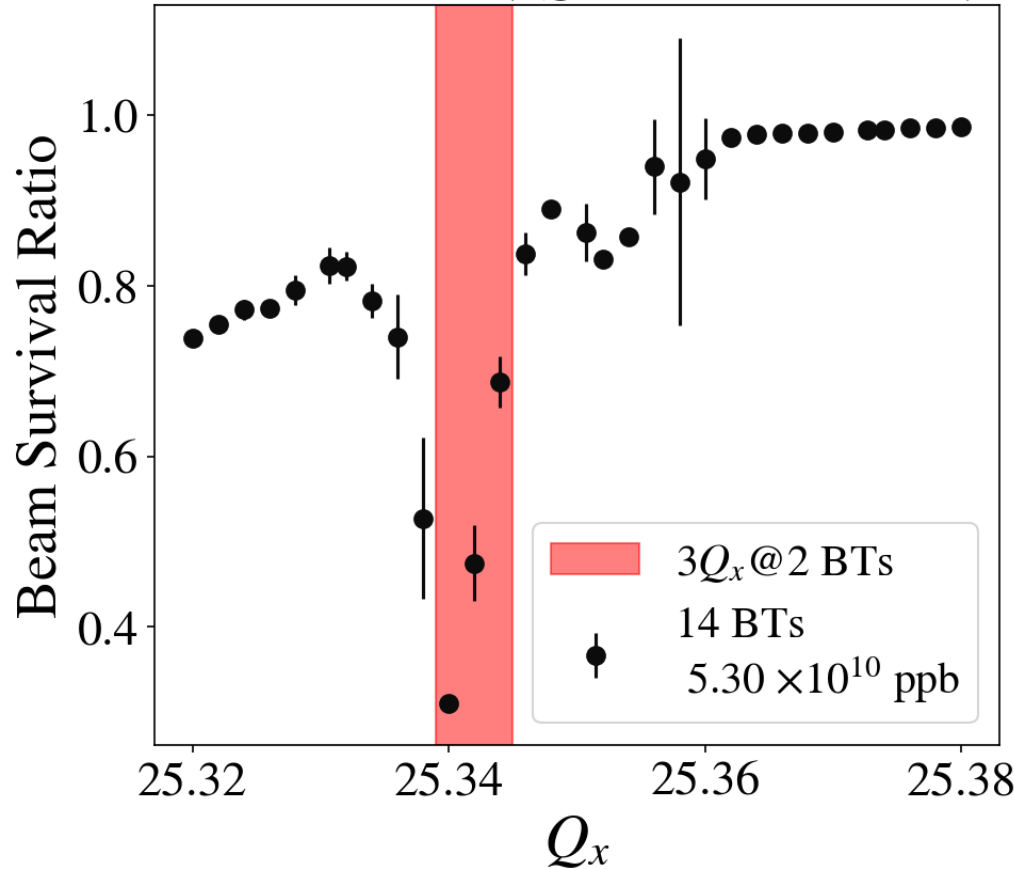
# Static Tune Scans with Wide Beam

$3Q_x = 76$  COMPENSATED (14 BTs) ( $\sim 5.3 \times 10^{10}$  ppb)

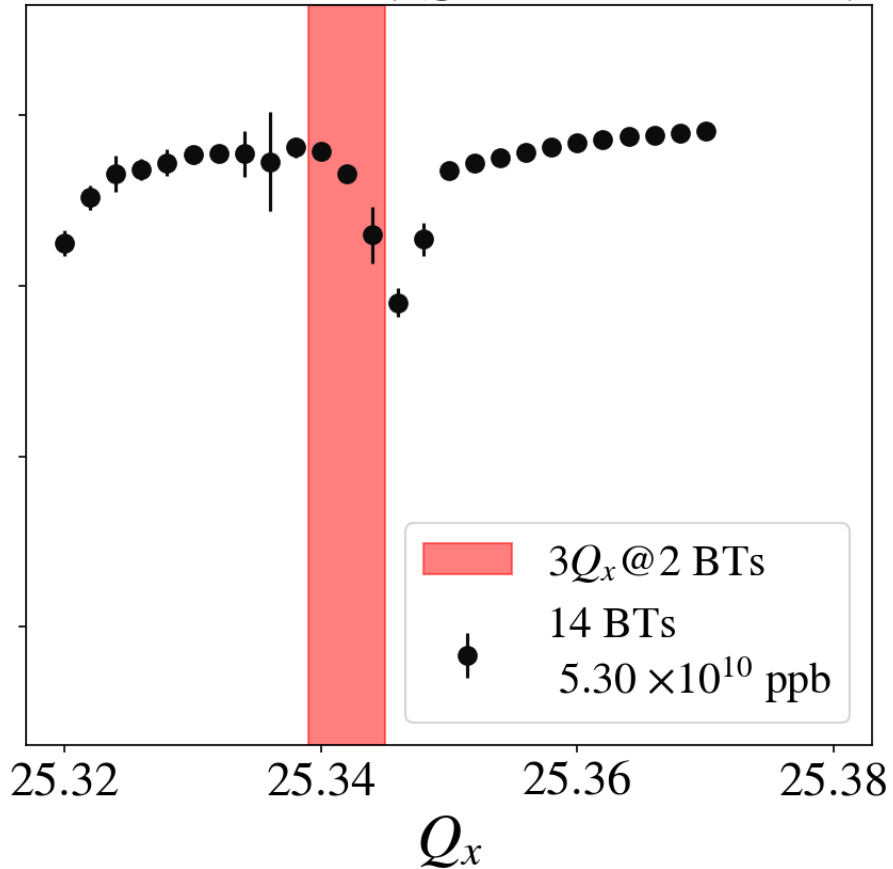


# Transverse Dampers and Resonances

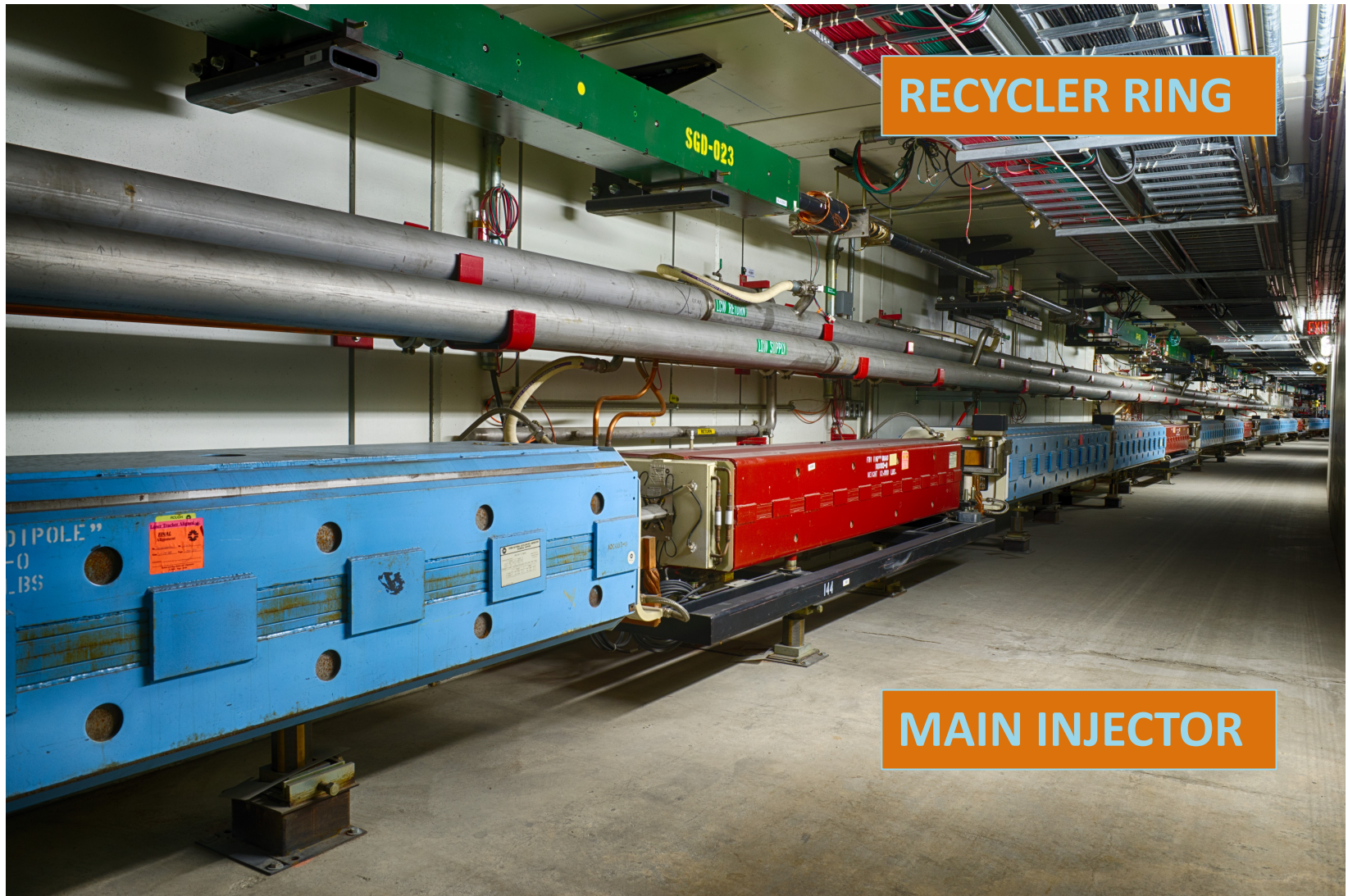
DAMPERS ON ( $3Q_x$  COMPENSATED)



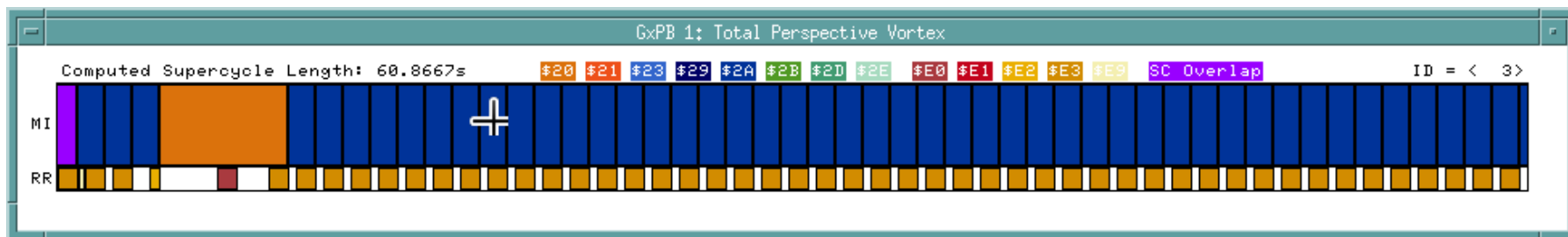
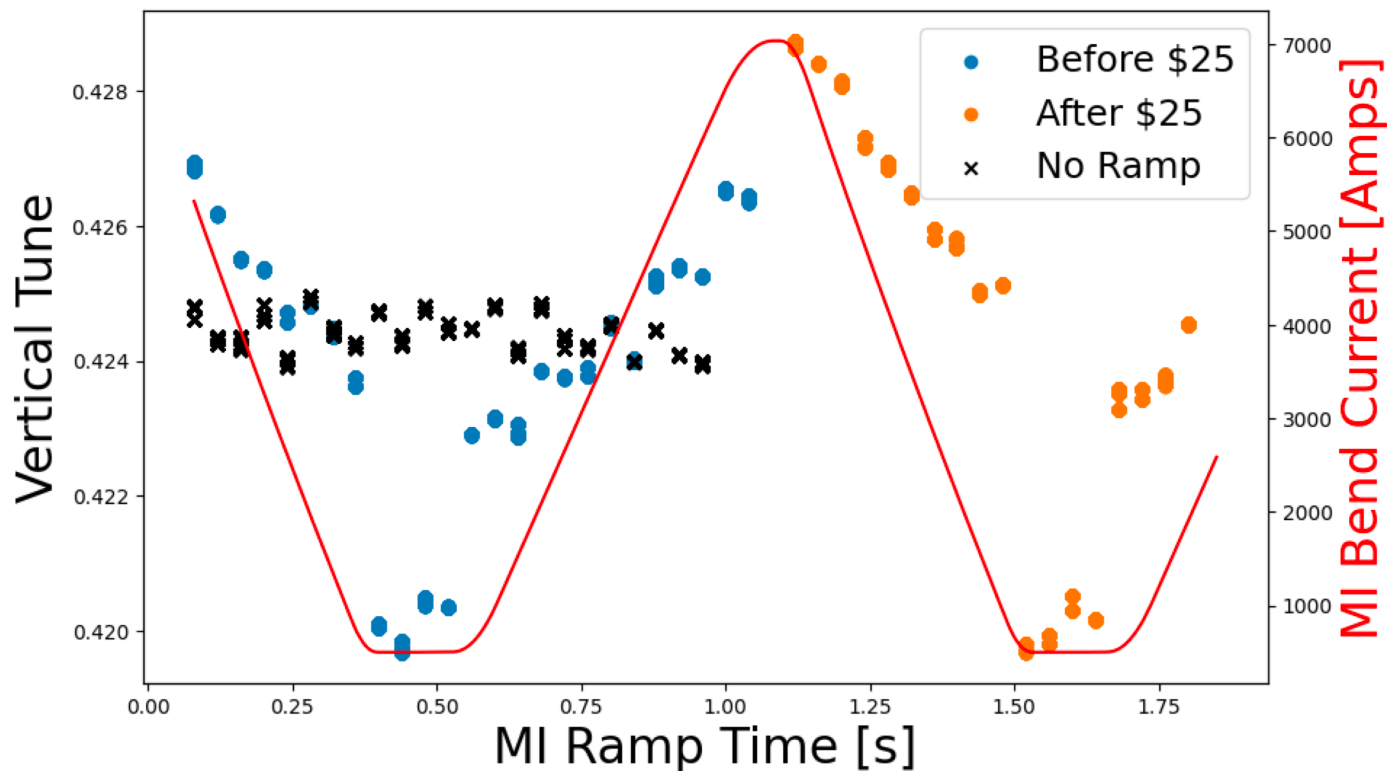
DAMPERS OFF ( $3Q_x$  COMPENSATED)



# High Intensity Operation

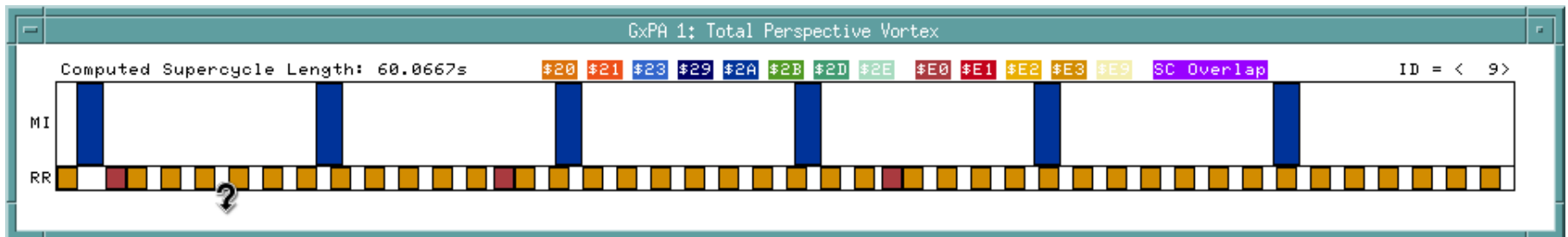
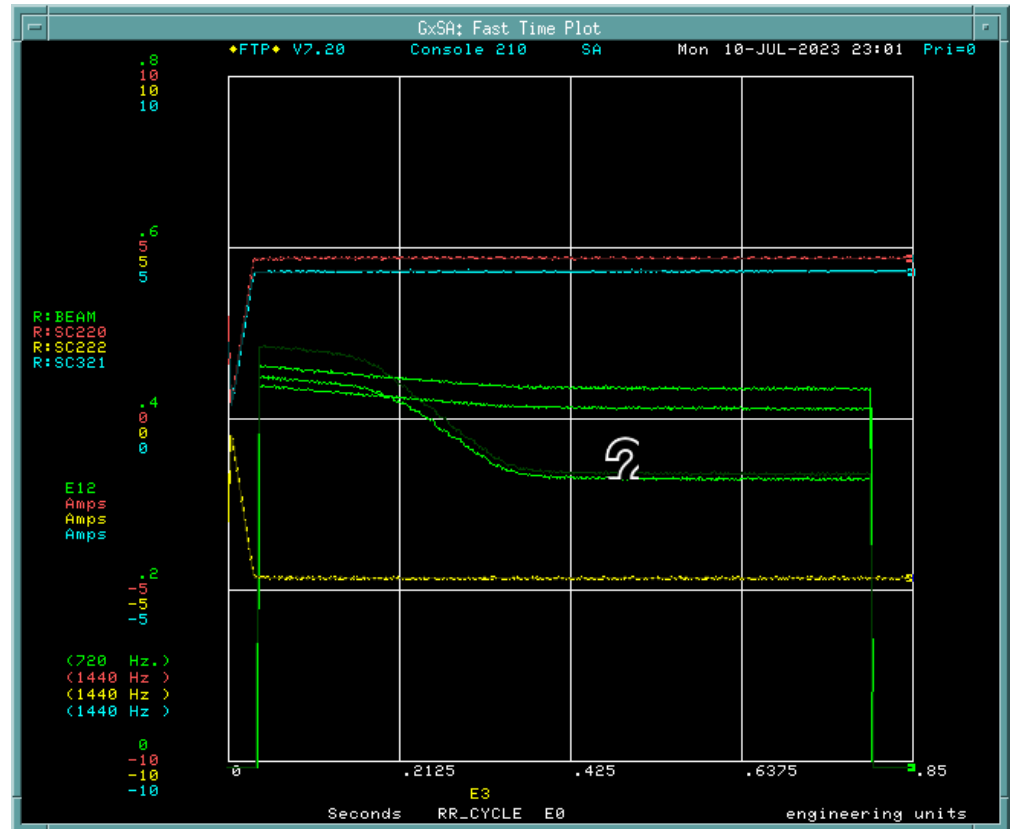
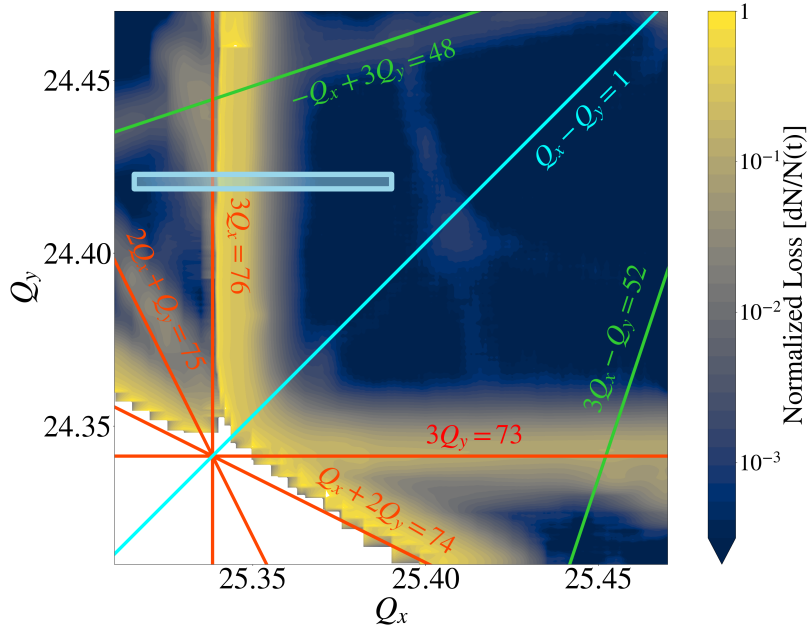


# MI effect on RR



- 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

# 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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