Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Resonance Correction Studies at the FNAL Recycler Ring

Cristhian Gonzalez-Ortiz

Space Charge Workshop

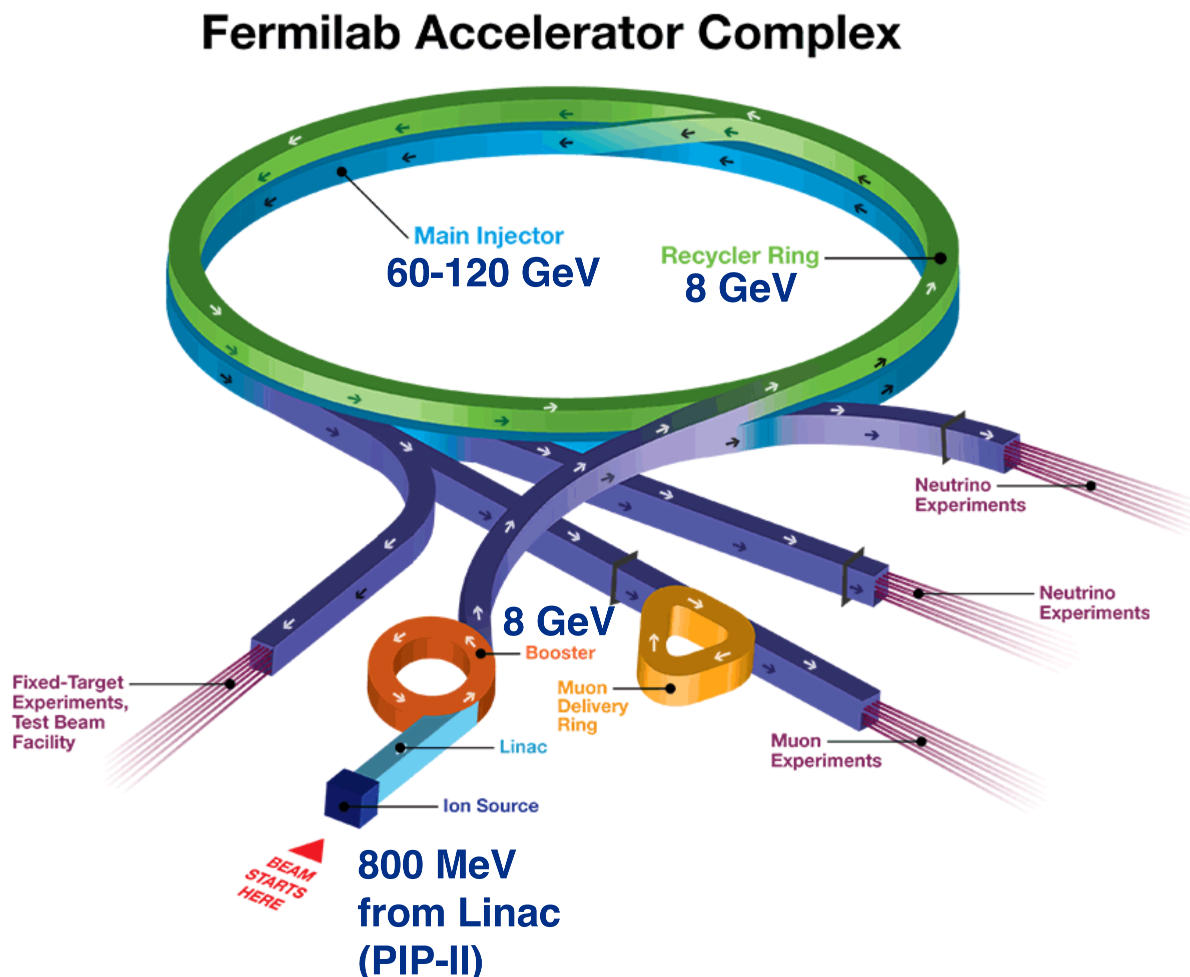
October 24, 2022

MICHIGAN STATE UNIVERSITY

FNAL Accelerator Complex

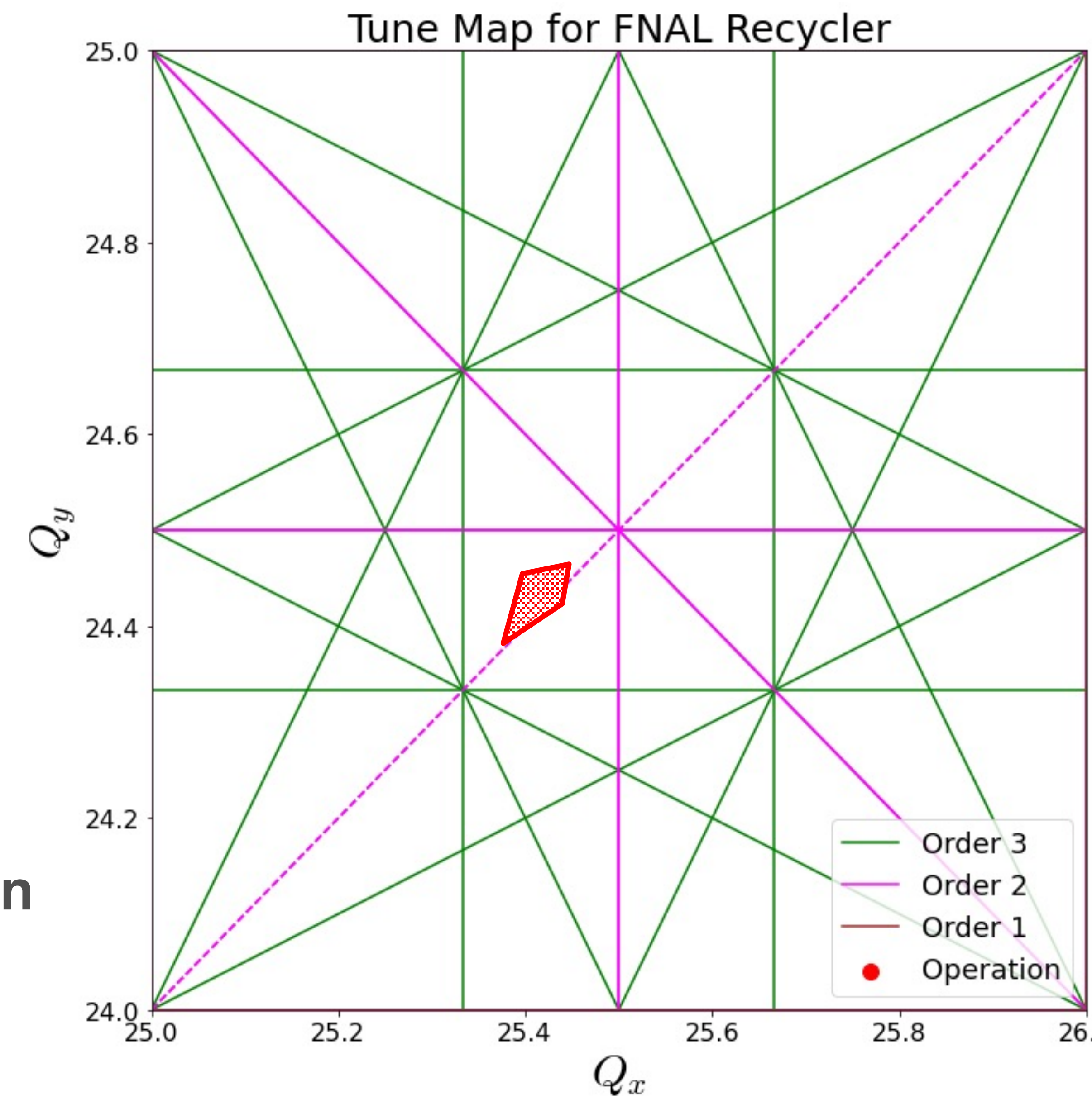
- **F**ermi **N**ational **A**ccelerator **L**aboratory located in Batavia, IL
- **PIP-II** plan is to increase the beam power to the experiments
  - 1.2 MW proton beam to the DUNE experiment
- Main injector/Recycler required to **increase beam intensity by 50%**
  - **Space charge tune shift** will lead to the excitation of multiple **resonance lines**

Fermilab

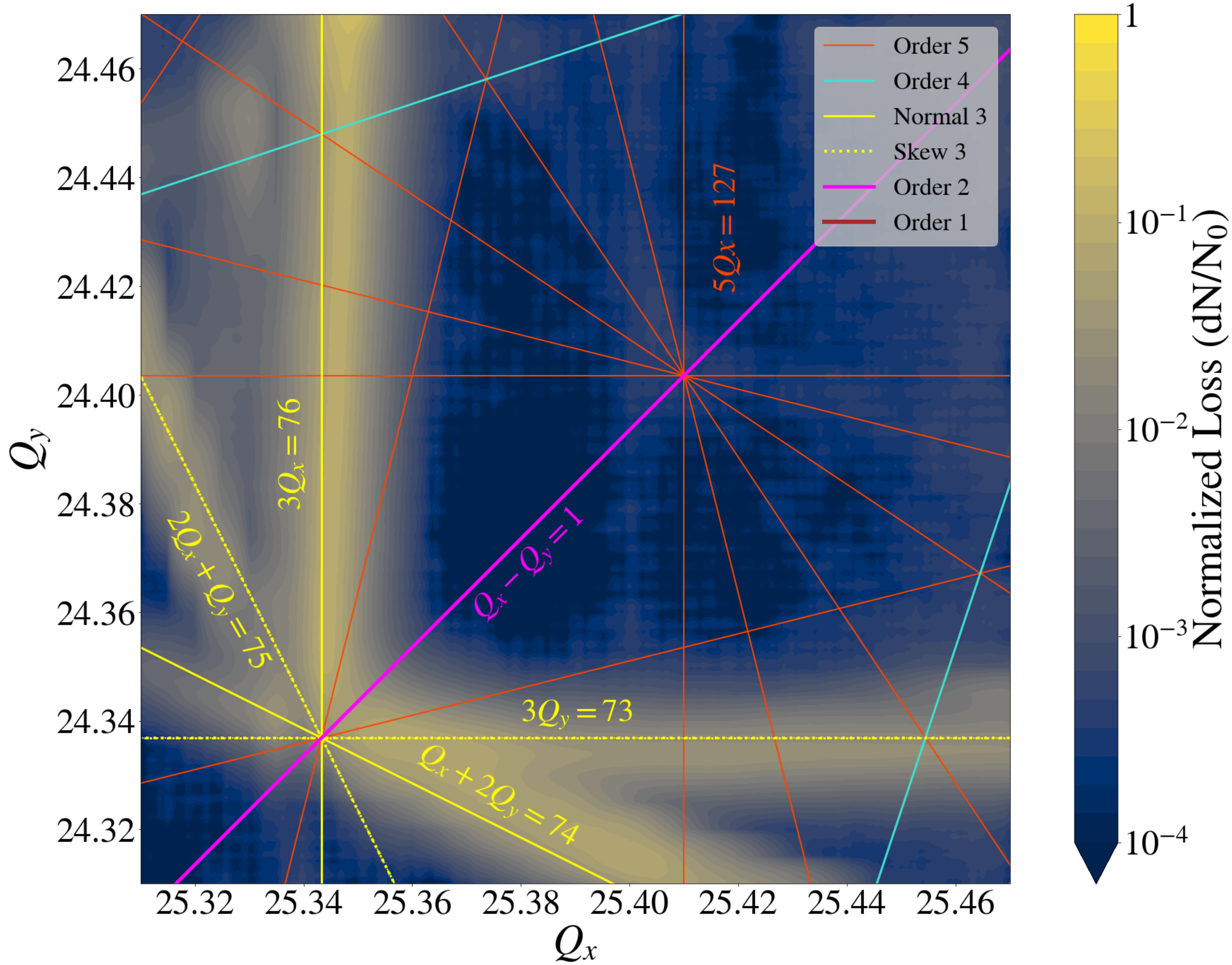


FNAL Recycler Ring

- **Nominal operational tunes**:
  - $Q_x \approx 25.42$
  - $Q_y \approx 24.43$
- **Coupling resonance** is corrected with **skew quadrupoles**
- **Increased intensity** will lead to **larger space charge effects**
- The following experimental results were done at **low proton intensities** (Single Particle Dynamics)

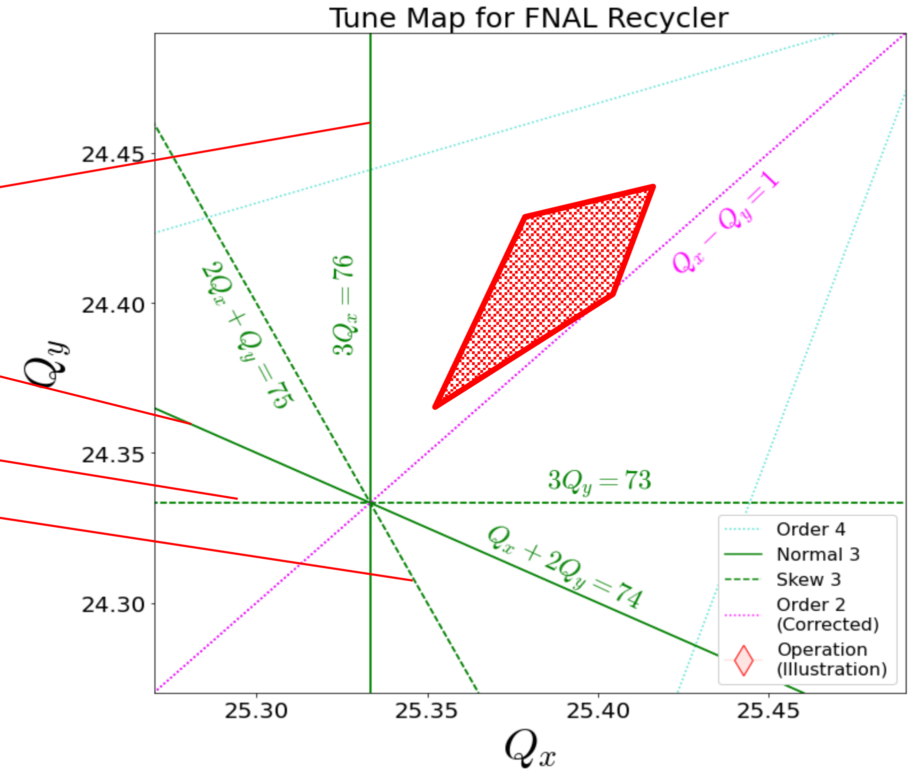


Resonance Correction Studies



Resonance Correction Studies

- **Resonance Driving Terms** (Hamiltonian coefficients) $h_{jklm} \in \mathbb{C}$
  - $\boldsymbol{3Q_x = 76 \longrightarrow h_{3000}}$
  - $Q_x + 2Q_y = 74 \longrightarrow h_{1020}$
  - $\boldsymbol{3Q_y = 73 \longrightarrow h_{0030}}$
  - $2Q_x + Q_y = 75 \longrightarrow h_{2010}$
- **RDTs** define the particle dynamics through the **one-turn map** of the accelerator



$$\mathcal{M}_1 = e^{:h:}\mathcal{R} \longrightarrow \vec{\eta_f} = \mathcal{M}_1\,\vec{\eta_0}$$

$\mathcal{M}_1$: One-Turn Map

$\vec{\eta_0}$: Initial Phase Space coordinates

$\vec{\eta_f}$: Final Phase Space coordinates after one turn

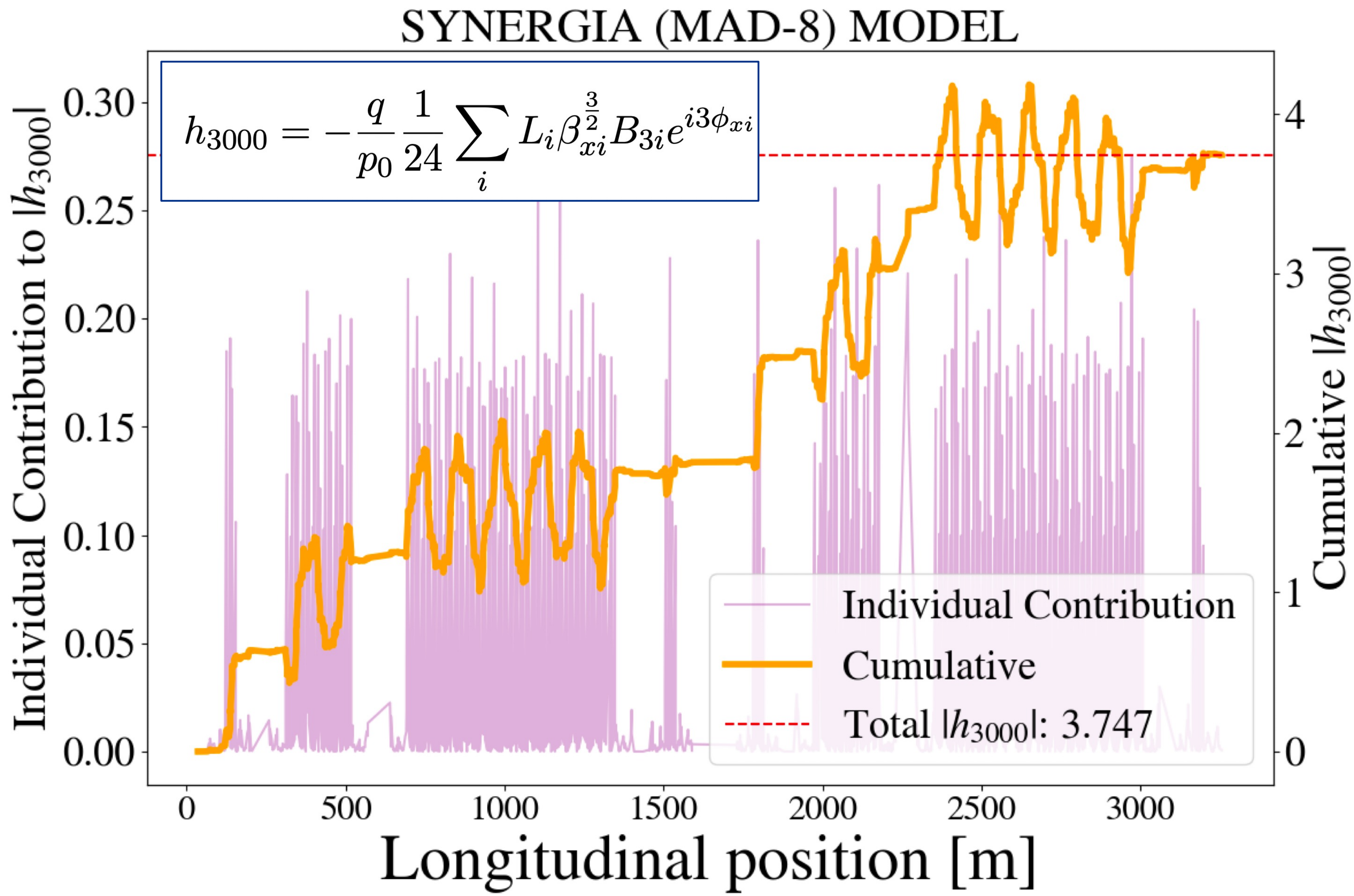
$$h = \sum_{jklm} h_{jklm}(2J_x)^{\frac{j+k}{2}}(2J_y)^{\frac{l+m}{2}}\,e^{i[(j-k)\phi_x+(l-m)\phi_y]}$$

Exponential Lie Operator:

$$e^{:f:}g = g + [f,g] + \frac{1}{2}[f,[f,g]] + \ldots$$

Resonance Driving Terms

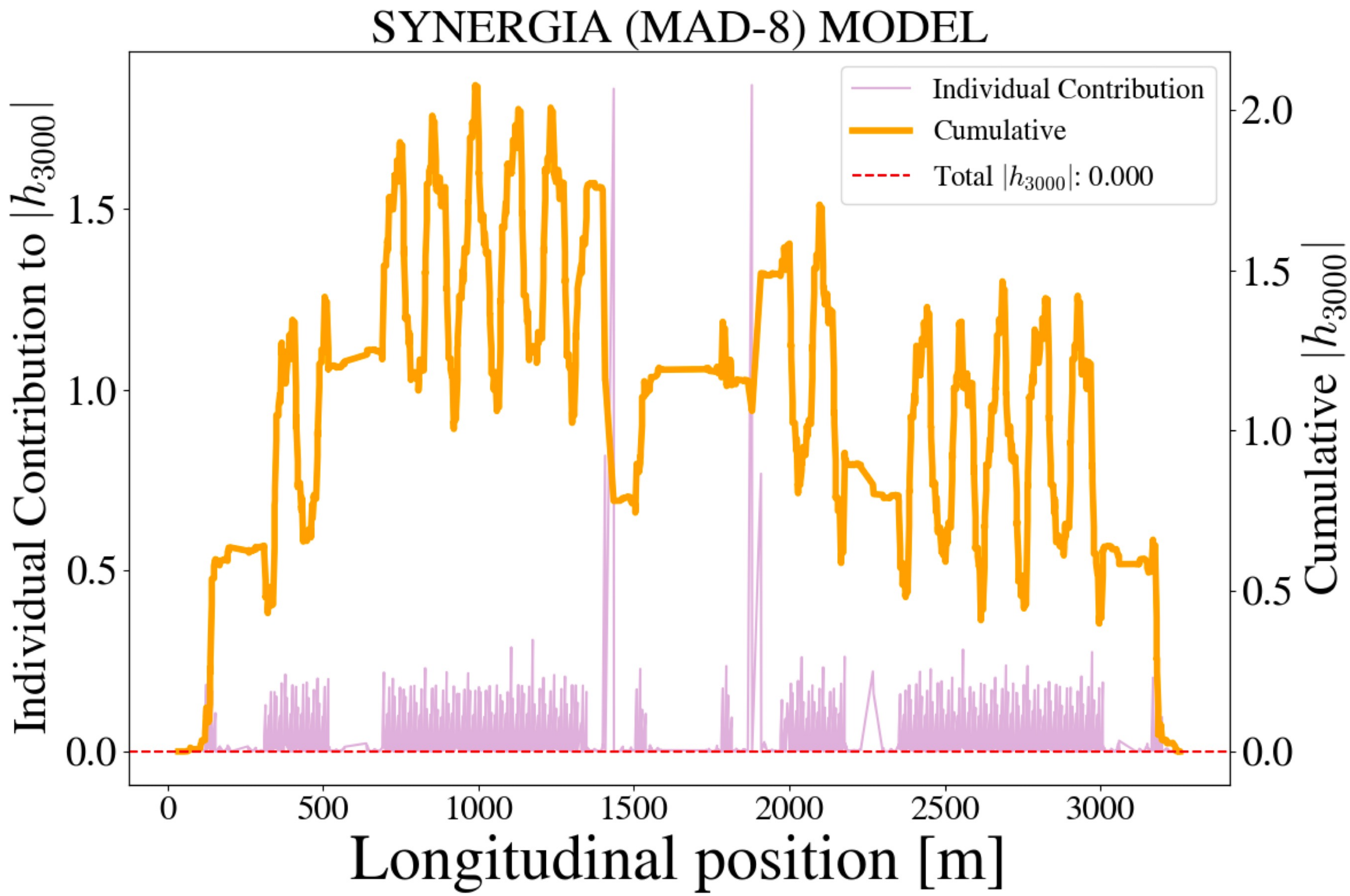
$$h_{jklm} = -\frac{q}{p_0}\frac{1}{2^n}\frac{1}{n}\binom{n}{l+m}\binom{j+k}{j}\binom{l+m}{l}\sum_i L_i \beta_{xi}^{\frac{j+k}{2}} \beta_{yi}^{\frac{l+m}{2}} V_{ni} e^{i[(j-k)\phi_{xi}+(l-m)\phi_{yi}]}$$



Fermilab

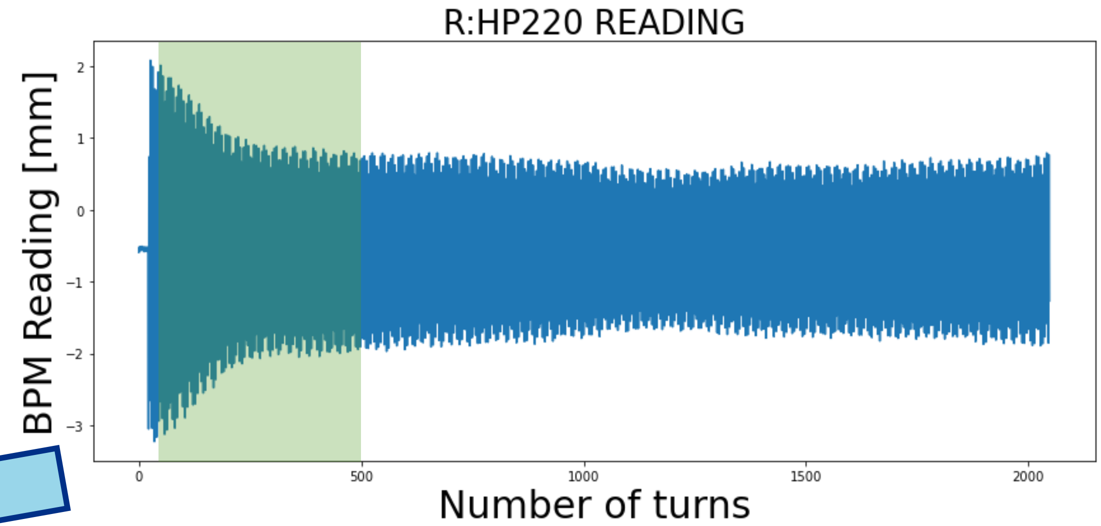
Compensation of $3Q_x = 76$

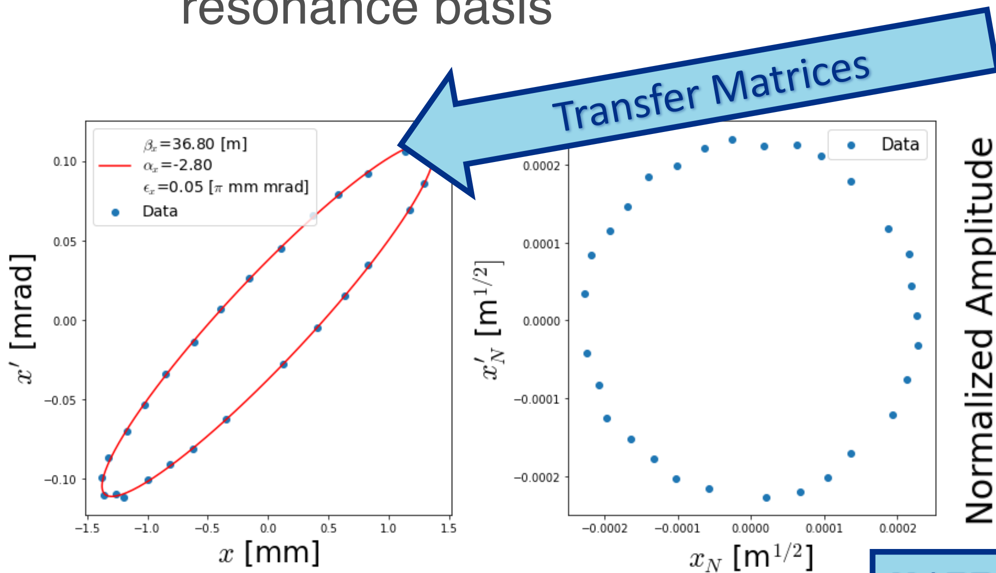
- **Theoretically,** this looks like introducing sextupole kicks in such a way **the total RDT equals zero**

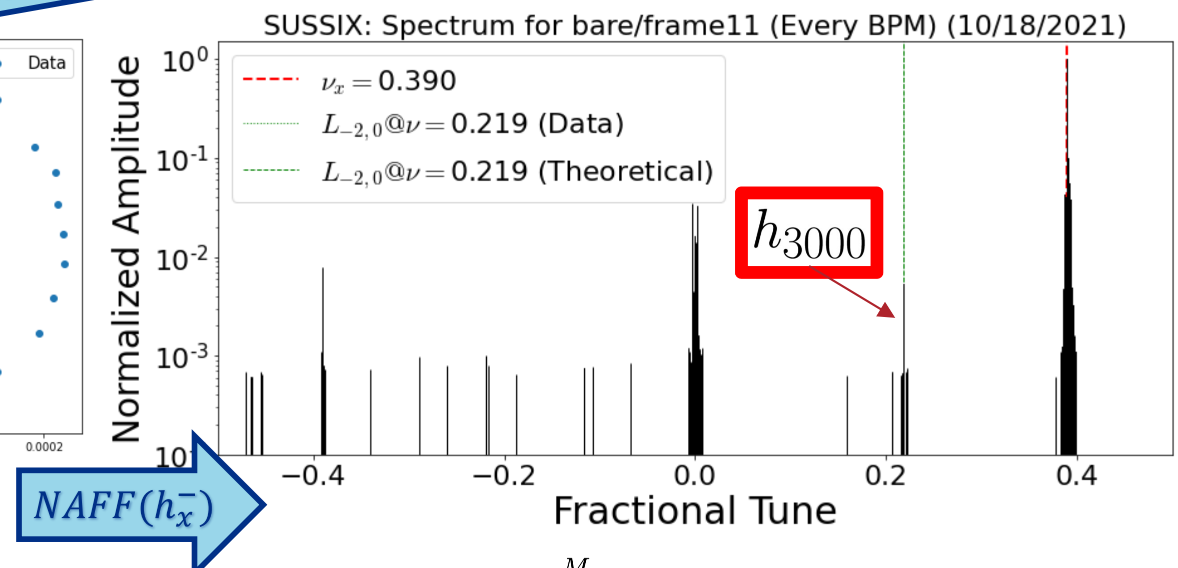


Resonance Driving Terms

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





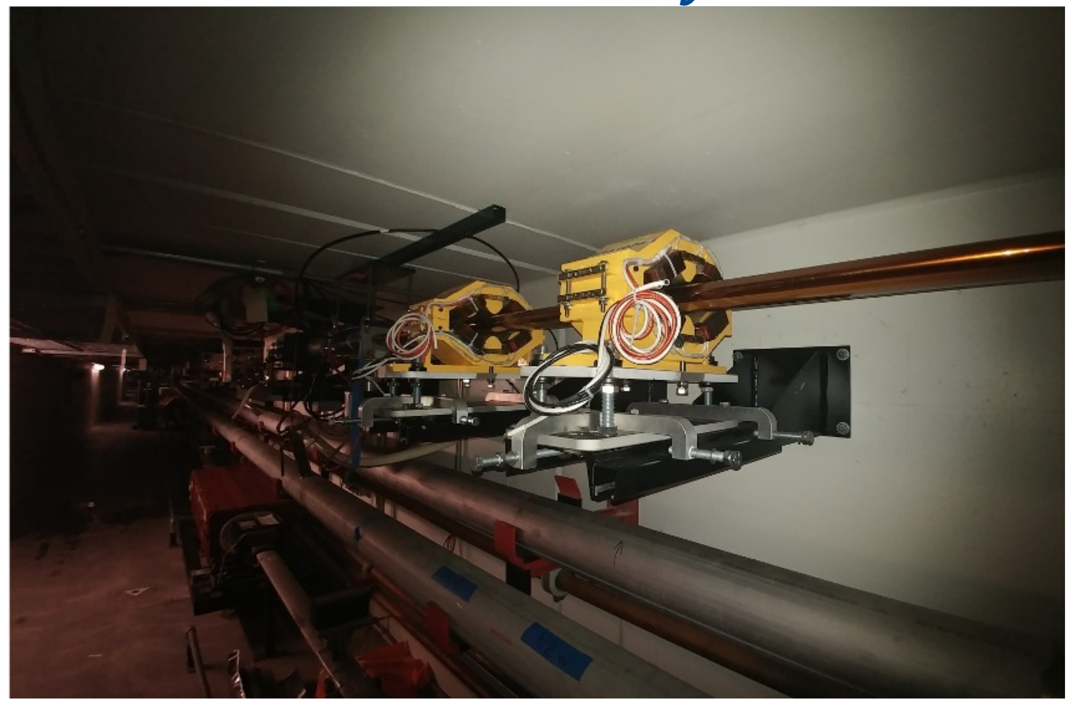


$$h_x^-(N) = x_{norm}(N) - i x'_{norm}(N)$$

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

Compensation of $3Q_x = 76$ and $3Q_y = 73$

- 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**

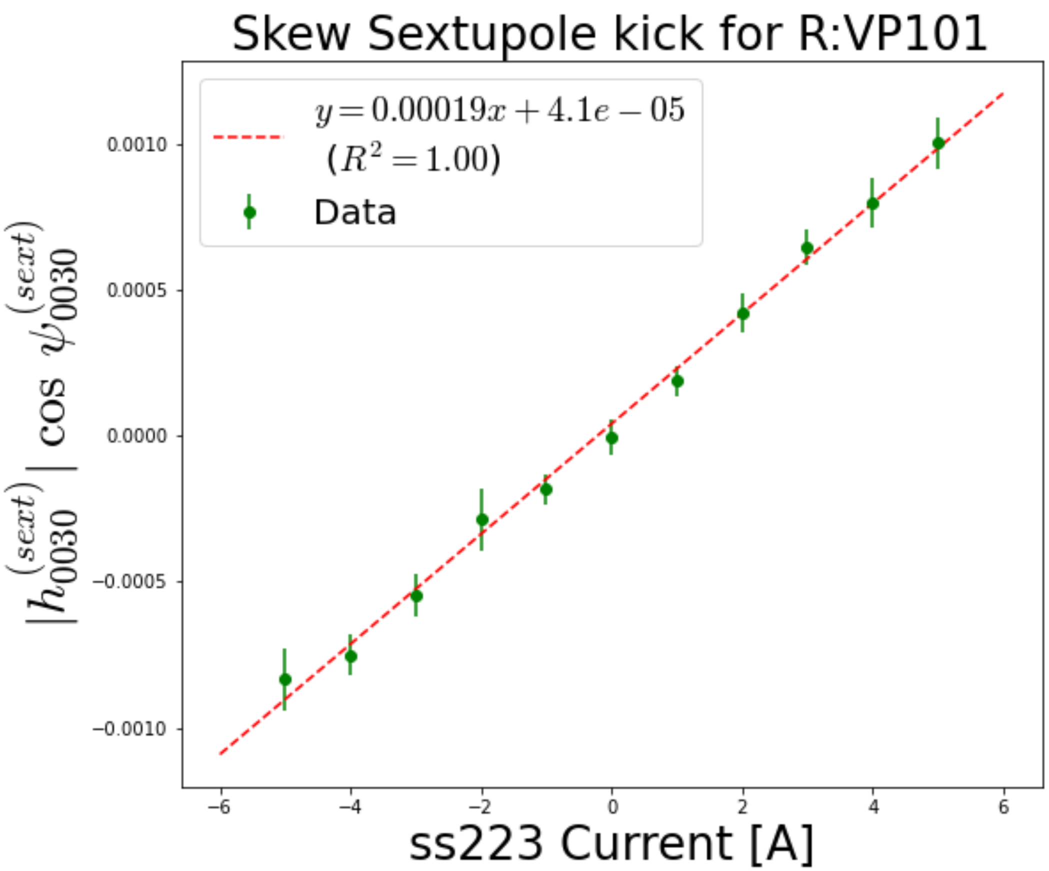


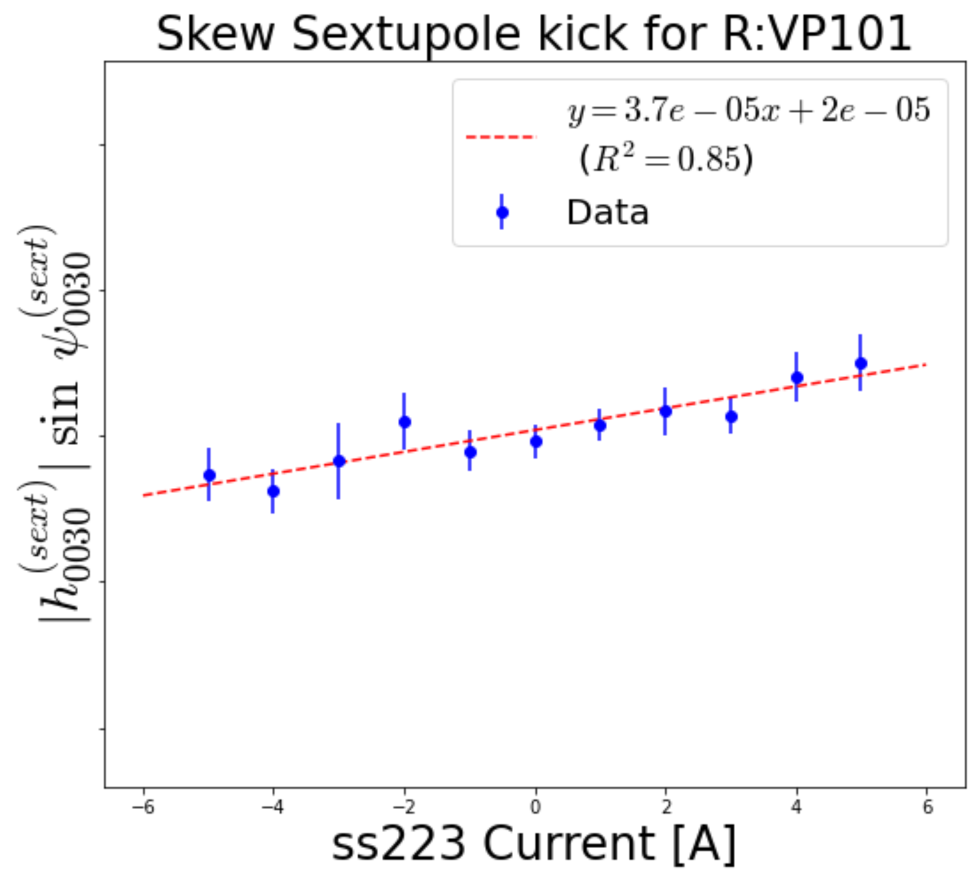
$$\begin{pmatrix} -|h_{3000}^{(bare)}|\cos\left(\psi_{3000}^{(bare)}\right) \\ -|h_{3000}^{(bare)}|\sin\left(\psi_{3000}^{(bare)}\right) \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{pmatrix} \begin{pmatrix}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

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

Compensation of $3Q_y = 73$

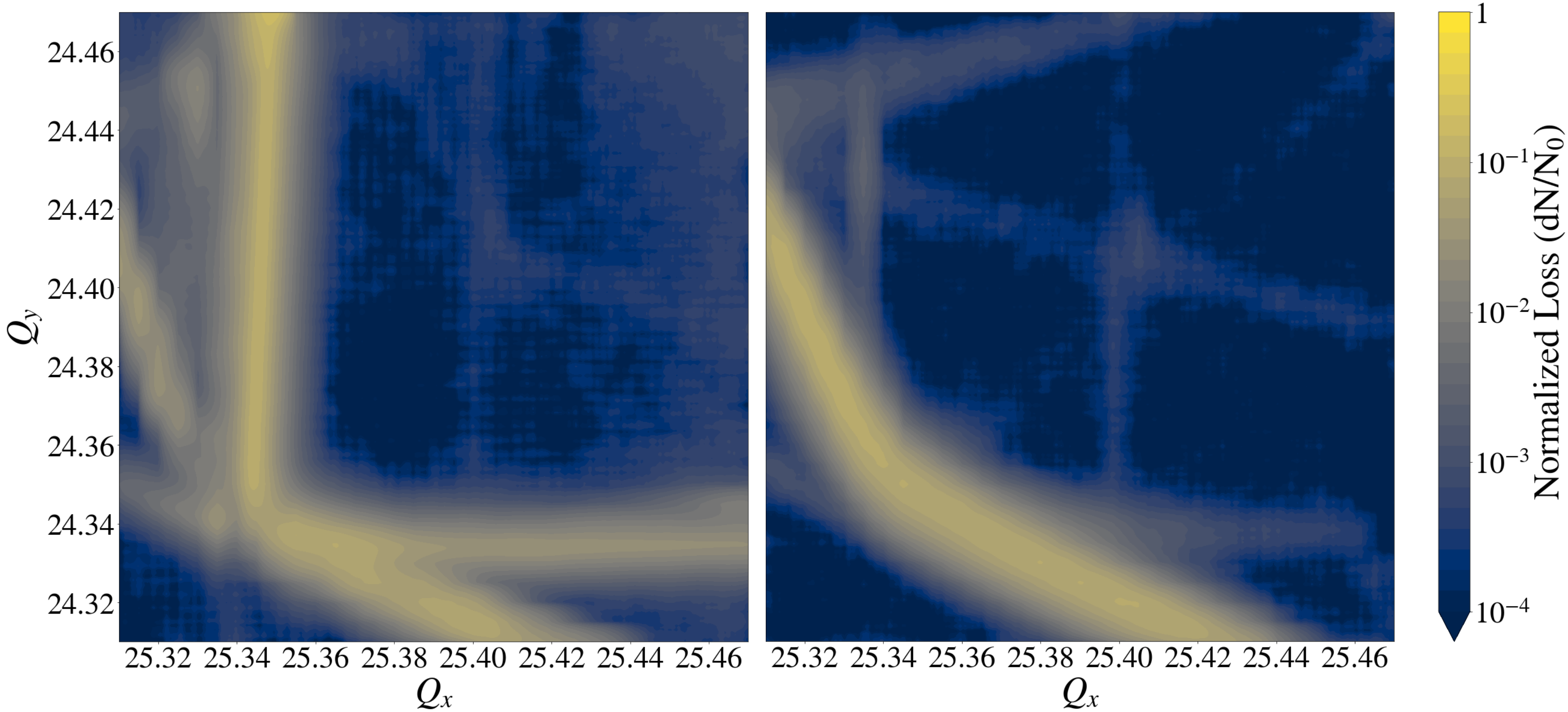
- **Real part** and **imaginary part** of $h_{0030}^{(ssext)}$ can be retrieved for each skew sextupole
- **Coupling to RDT** from skew sextupoles can be retrieved from slope





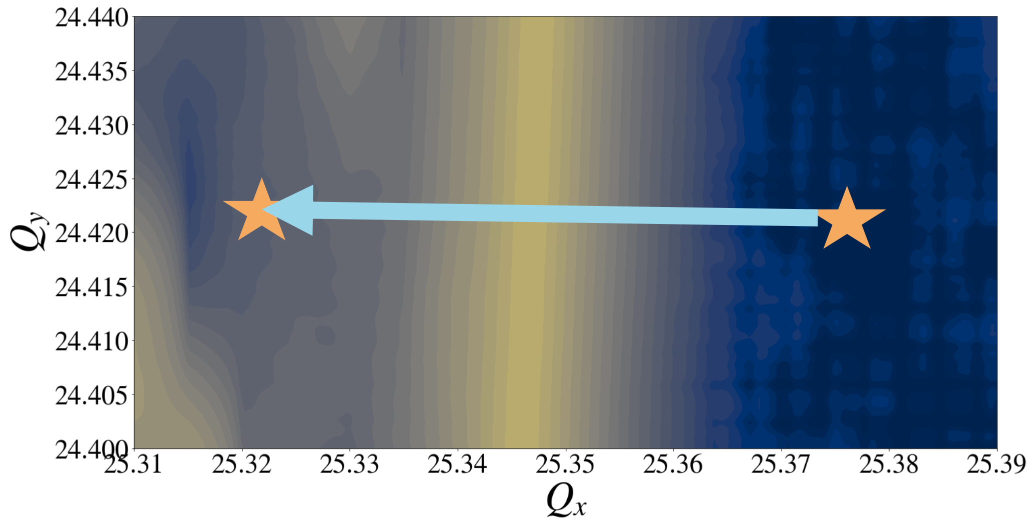
Simultaneous compensation of $3Q_x$ and $3Q_y$

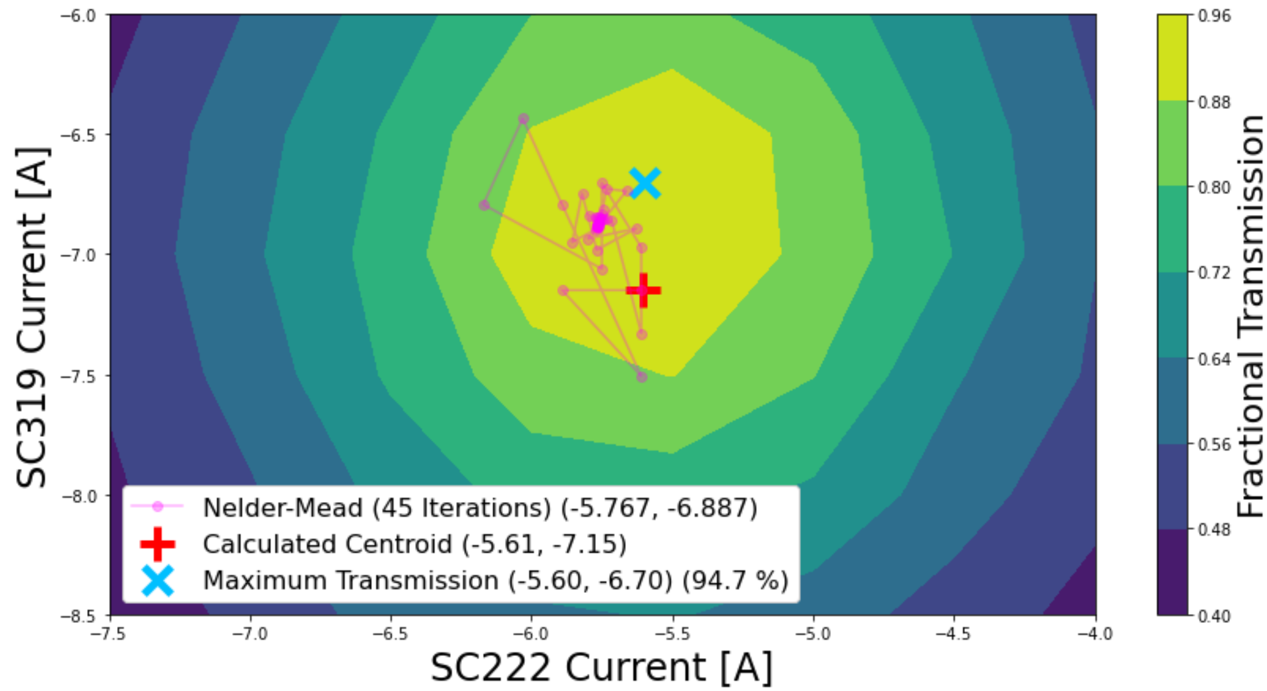
BARE MACHINE (NO COMPENSATION)	WITH BOTH COMPENSATION SEXTUPOLE CURRENTS ON



Compensation of $3Q_x = 76$

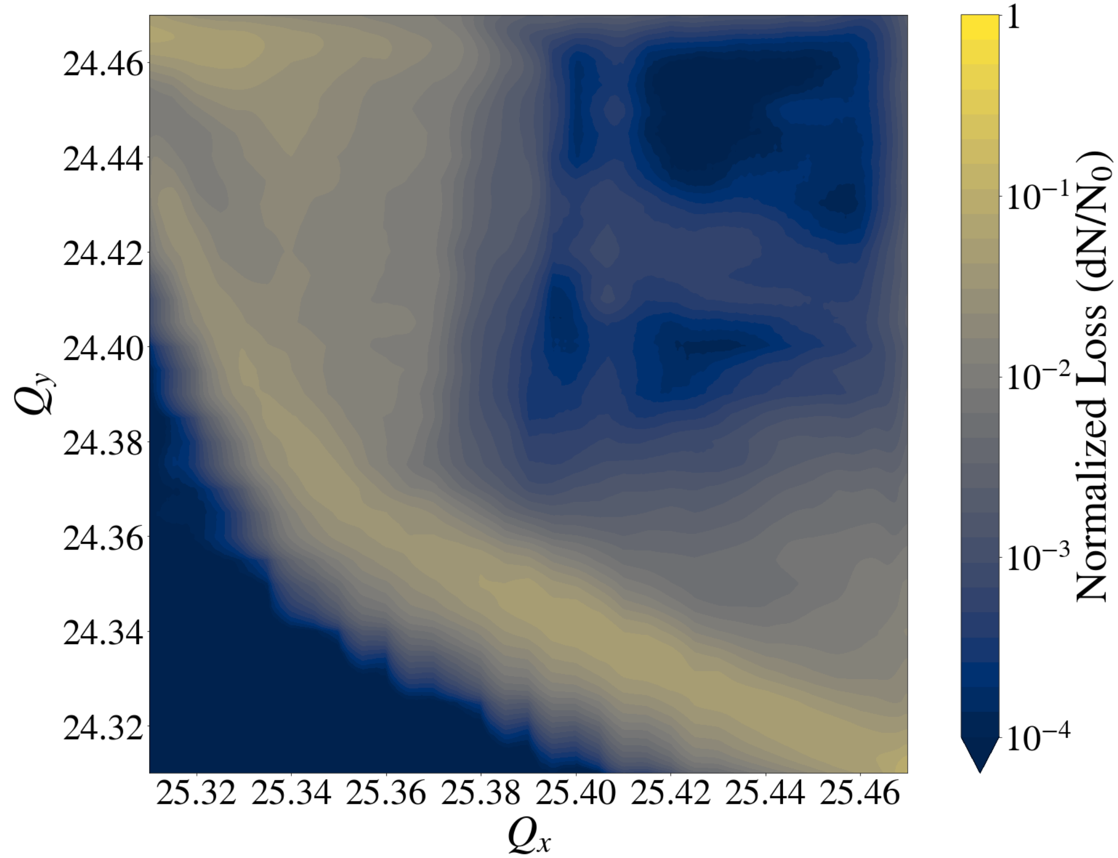
- We can build **transmission plots** at different sextupole currents to verify our predicted operation point maximizes transmission
- The experimental transmission maximum is around 10% away from our predicted compensation point
  - Model difference
  - Amplitude detuning
  - Longitudinal effects





Summary and Conclusion

- We have demonstrated how to simultaneously compensate two third order resonance lines in the Recycler Ring.
- Operationally, we are partially compensating for $3Q_x = 76$, since we might be making other lines worse.
- How does space charge affect our measurements of Resonance Driving Terms?



Summary slide, 5^{th} ICFA mini-workshop on Space Charge
Theme: Bridging the gap in space charge dynamics

In 1-2 sentences, summarize the content of this presentation:
This presentation shows the compensation procedure for third order resonances at low intensities, using the RDT (Resonance Driving Terms) method at the FNAL Recycler Ring.

From your perspective, where is the gap regarding space charge effects?
From my perspective, the gap exists between space charge physics' predictions and current diagnostics to measure these predictions.

What is needed to bridge this gap?
We need a better understanding of what observables we can use in our machines in order to probe space charge effects with current diagnostics.

THANK YOU! QUESTIONS?

References

- Urschutz, P. (2004, September). *Measurement and Compensation of Betatron Resonances at the CERN PS Booster Synchrotron*. Technical University of Vienna.
- C.E. Gonzalez-Ortiz, R. Ainsworth, and P.N. Ostroumov, "*Third-Order Resonance Compensation at the FNAL Recycler Ring"*, in Proc. IPAC 22, Bangkok, Thailand, Jun. 2022, pp. 195-198. doi:10.18429/JACoW-IPAC2022-MOPOST050
- Lee, S. Y. (2018). *Accelerator Physics (Fourth Edition)* (4th ed.). WSPC.
- Goldstein, H., & Safko, J. P. C. P. (2011). *Classical Mechanics* (3RD, INTERNATIONAL ECONOMY EDITION ed.). Pearson Education.
- Bartolini, R., & Schmidt, F. (1997). Normal Form Via Tracking or Beam Data. *Particle Accelerators*, 93–106.