Digital Twin for Booster & NSRL

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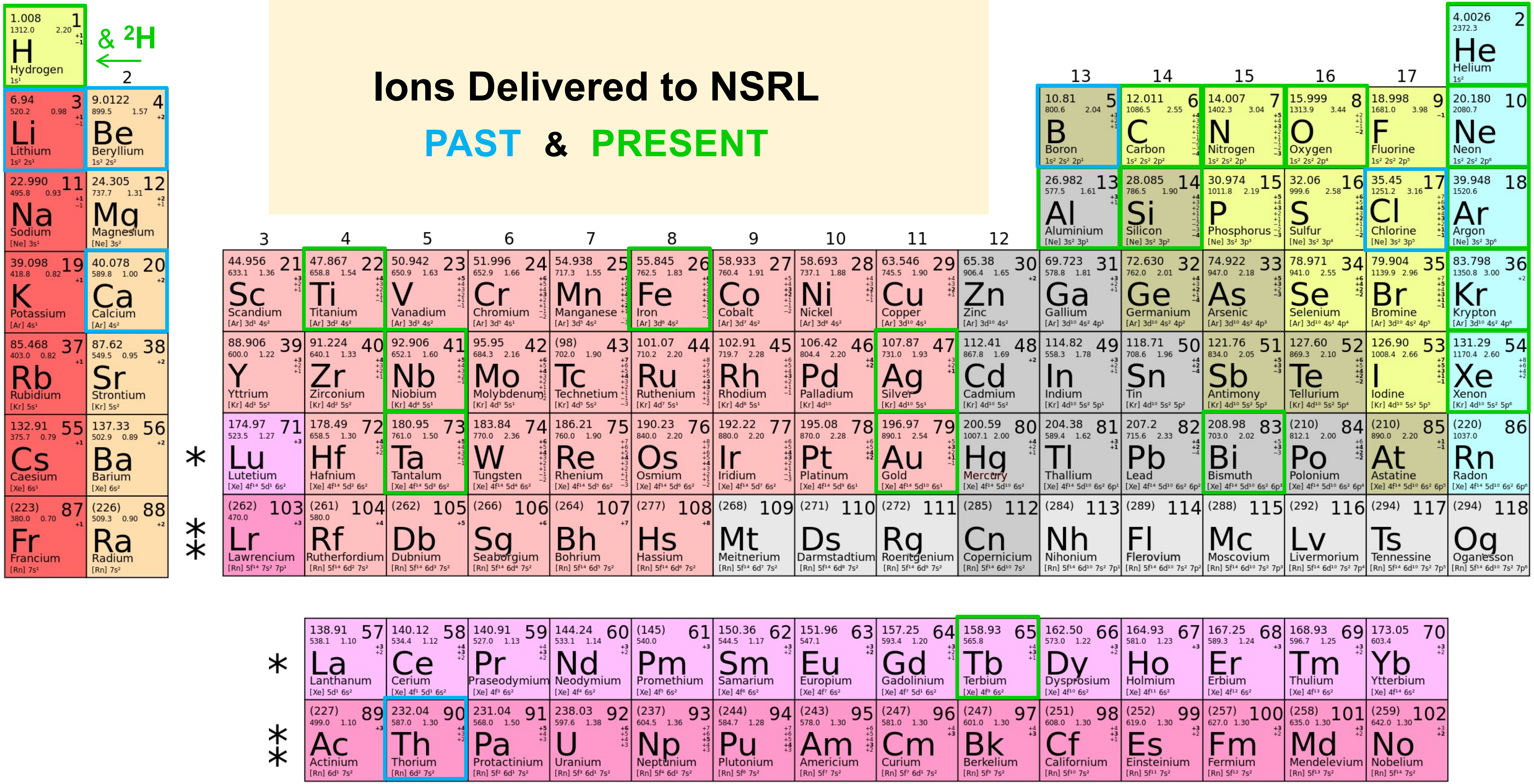
NASA Space Radiation Laboratory (NSRL)

- Understanding the risks and uncertainties from the space radiation environment is crucial for NASA missions:
- *"In space, astronauts are exposed to ionizing radiation that is quantitatively and qualitatively different from terrestrial radiation. This environment includes protons and high-Z, high-energy (HZE) ions together with secondary radiation, including neutrons and recoil nuclei that are produced by nuclear reactions in spacecraft materials or tissue."*

  - Risk of Radiation Carcinogenesis (2016)
  NASA HRP Space Radiation Element

Ions Delivered to NSRL

PAST & PRESENT



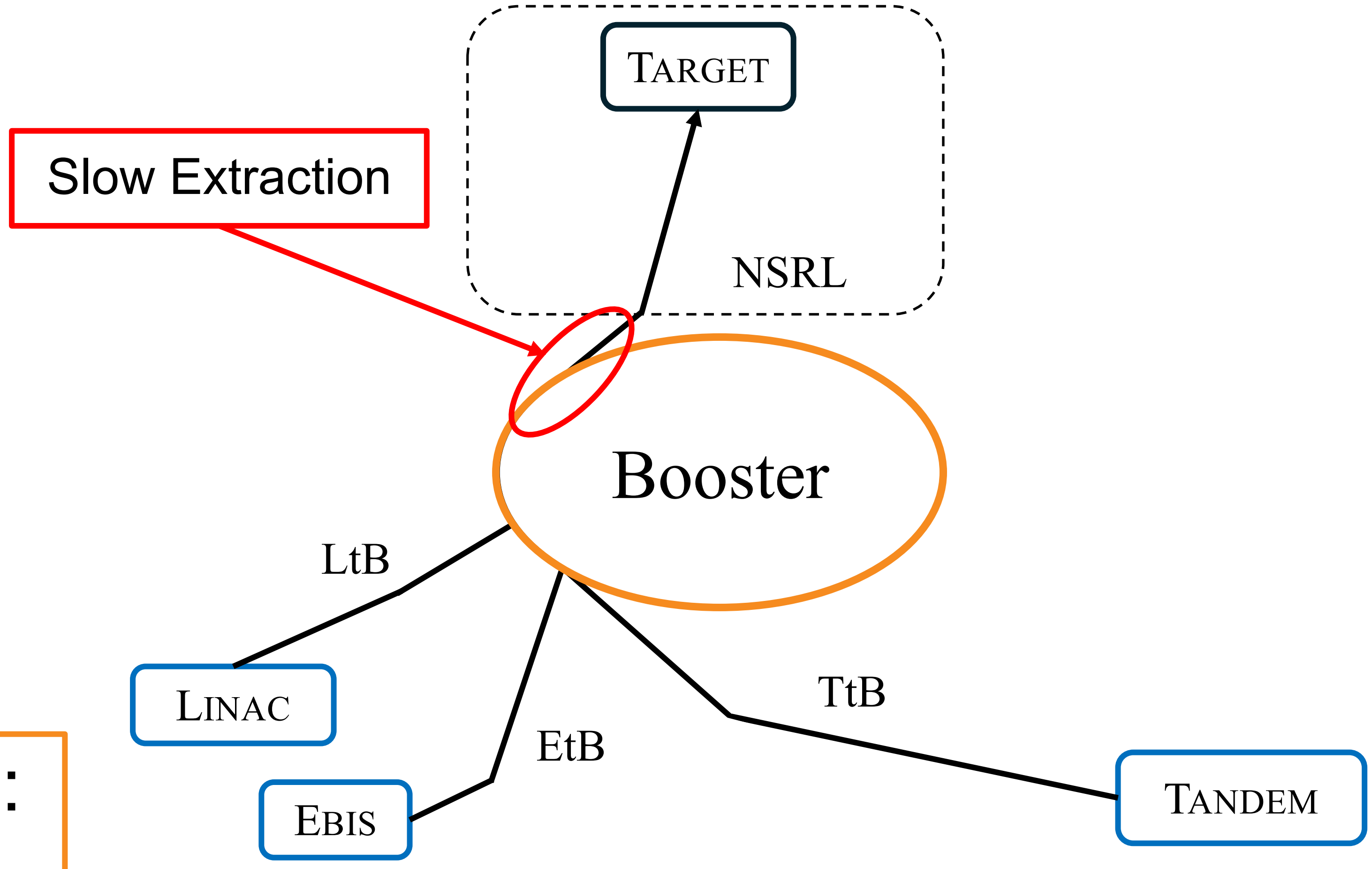
Sources & Synchrotron Complex

Source machines:

Linac (proton)

EBIS (ion)

Tandem Van de Graaffs (ion)

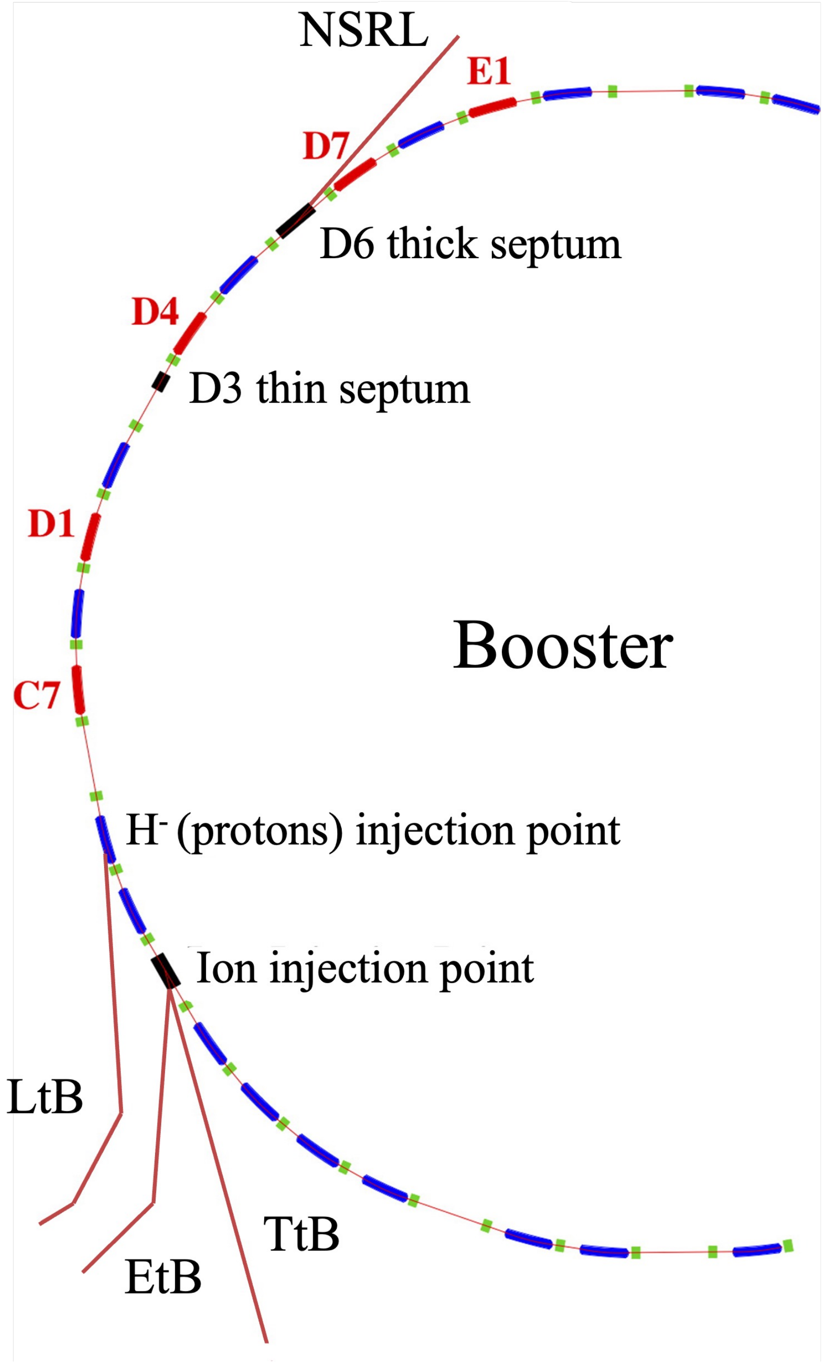


AGS Booster synchrotron:

Accelerate beam to KE between 50 and 2500 MeV/n

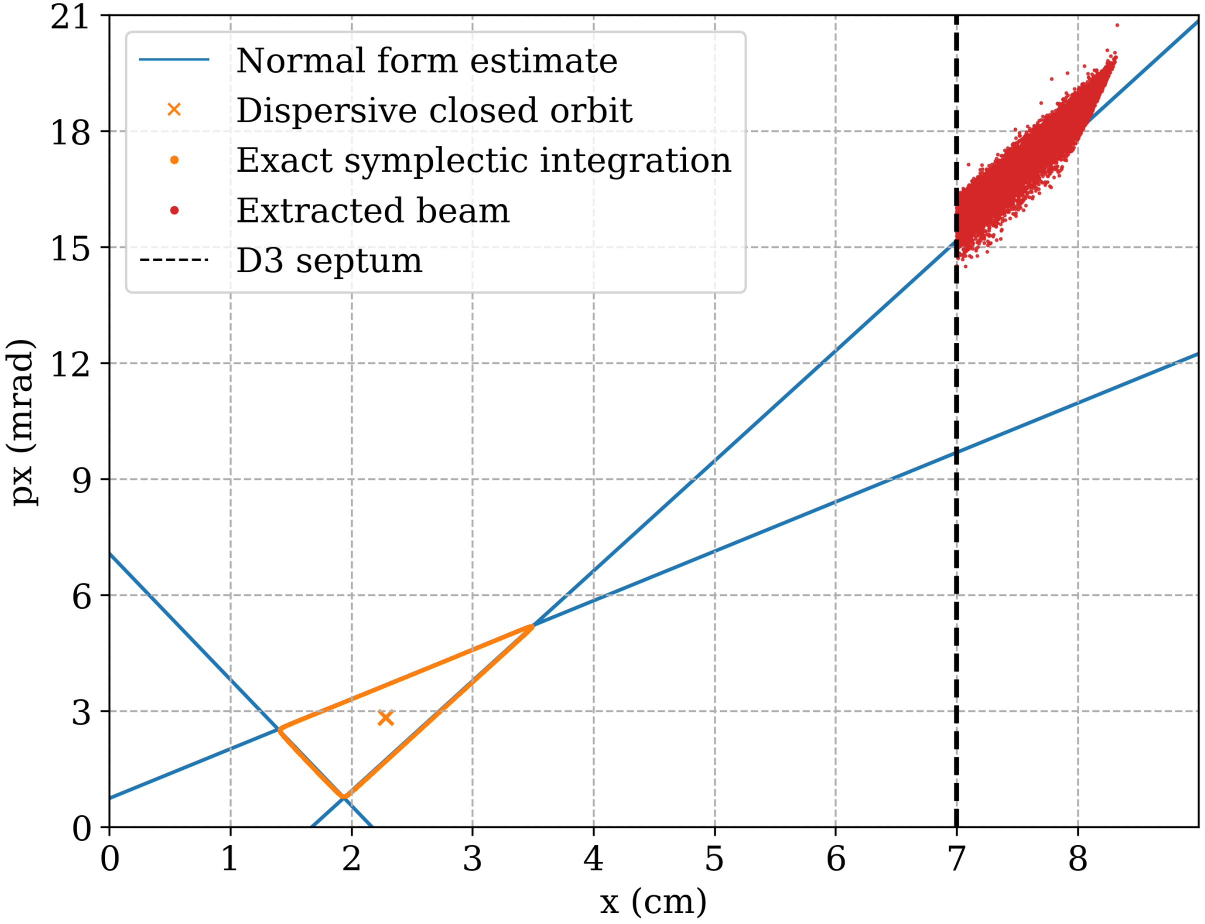
Booster extraction bump

- Local bump via back-leg windings on five Booster main magnets: C7, D1, D4, D7, E1
- Each main magnet has 16 main windings and 2 back-leg windings: $I_{total} = I_{dipole} + \frac{2}{16} I_{bump}$
- Bring closed orbit close to septa at D3 and D6
- Can be simulated in two ways:
  - dipole field errors
  - zero-length horizontal kicker in the middle of dipoles



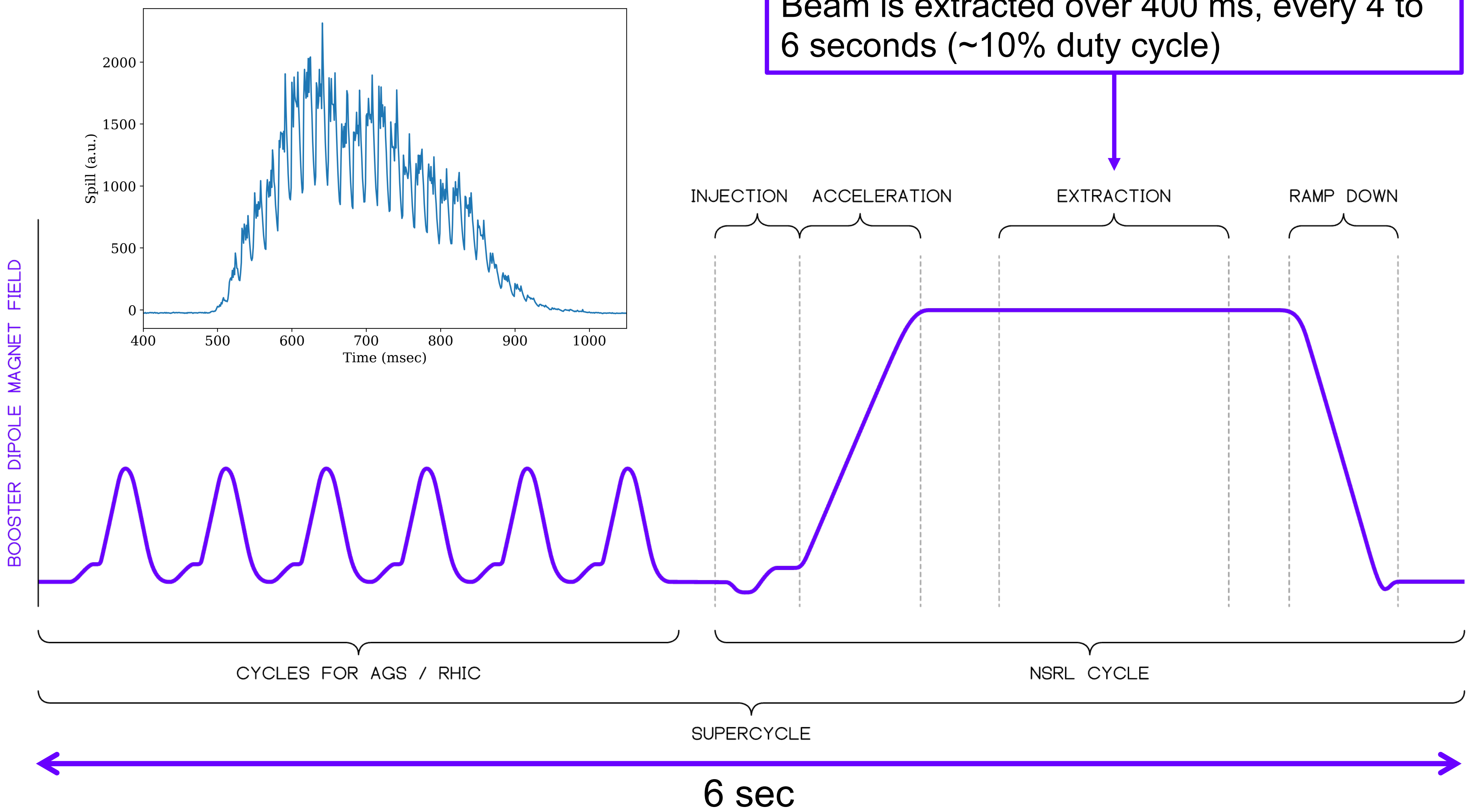
Resonant Slow Extraction

- Thin septum (0.76 mm) at D3 + thick septum (15.2 mm) at D6 in the Booster
- Third-integer (13/3) resonance created by four sextupoles: C8, F8, B4, E4
- Triangular stable region in horizontal phase space, brought closer to the septa via local extraction bump
- Particles with turn-by-turn orbit deviation larger than D3 septum thickness are extracted and kicked into D6 aperture



Extracted Beam Spill

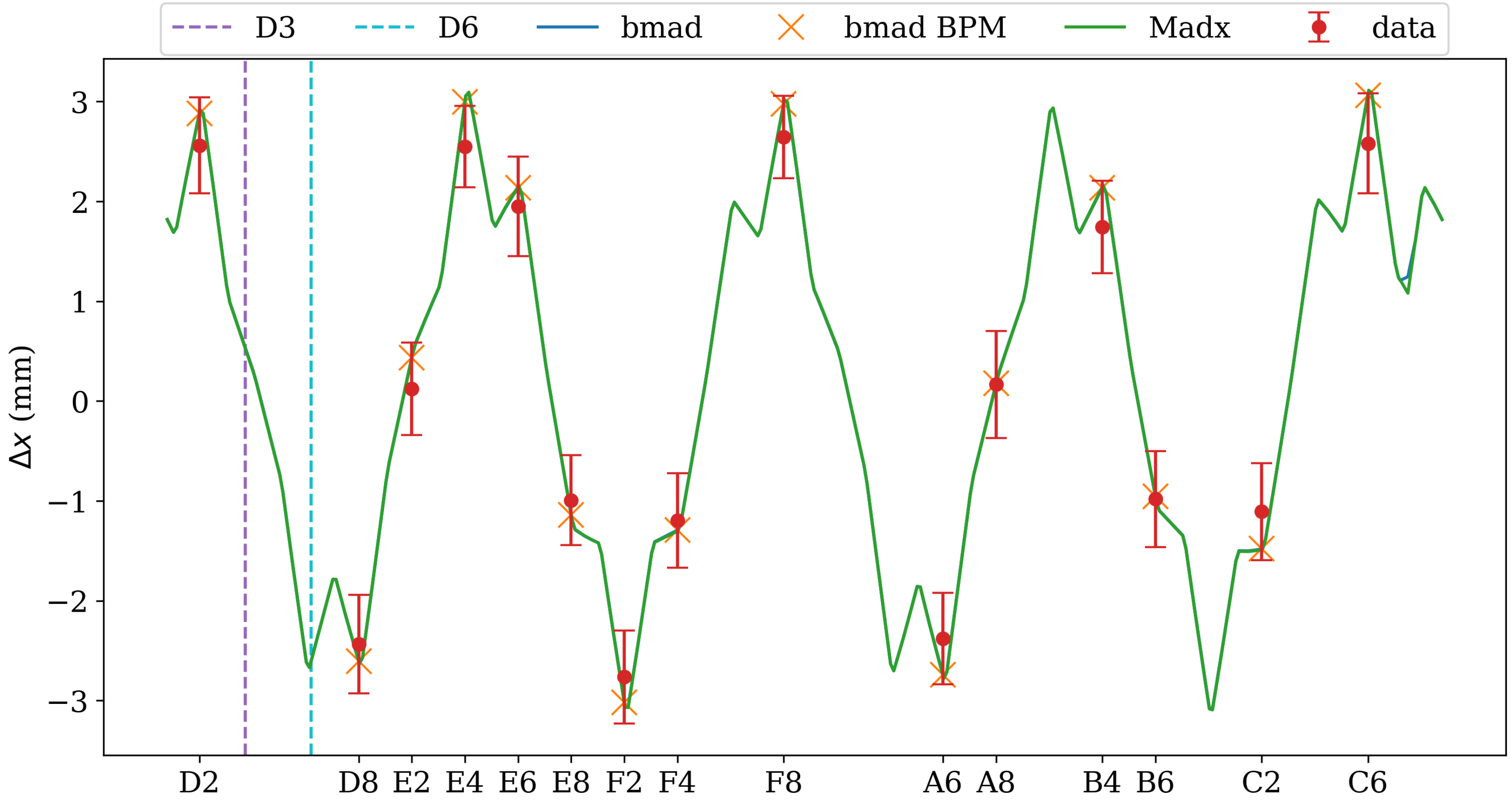
Beam is extracted over 400 ms, every 4 to 6 seconds (~10% duty cycle)



Bump simulation vs. measurement

618 MeV/n Silicon

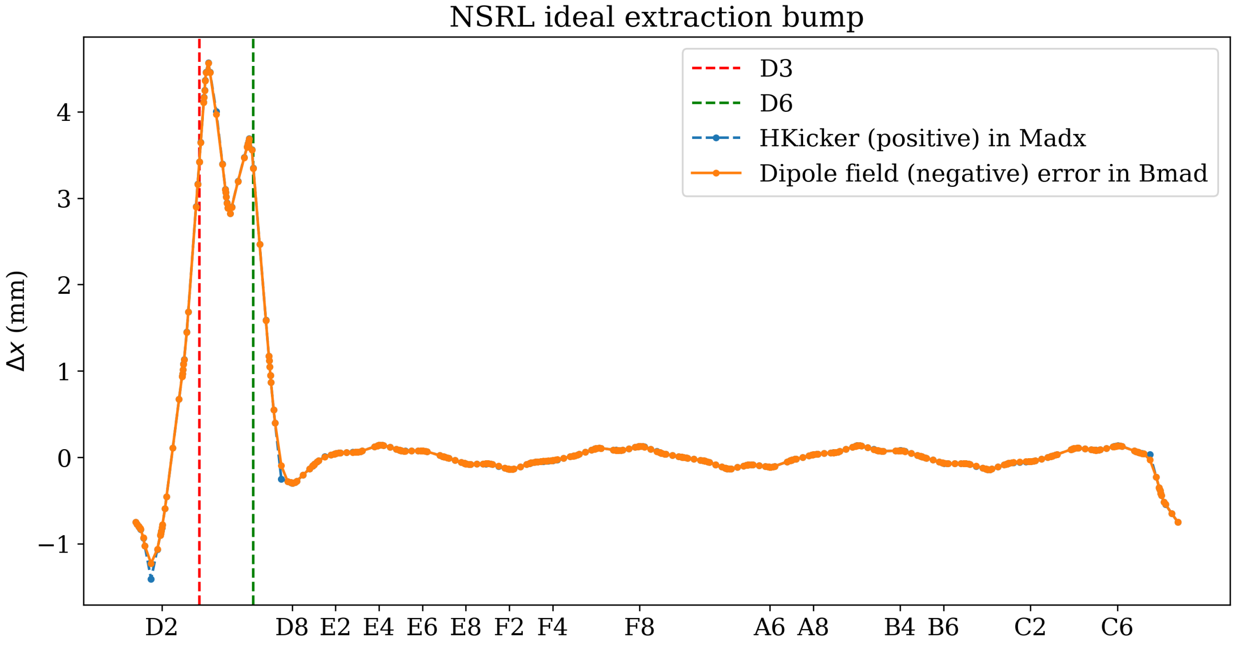
- Single bump measurement show good agreement with simulation
- Bump defined as horizontal kicker in MAD-X, dipole field error in Bmad

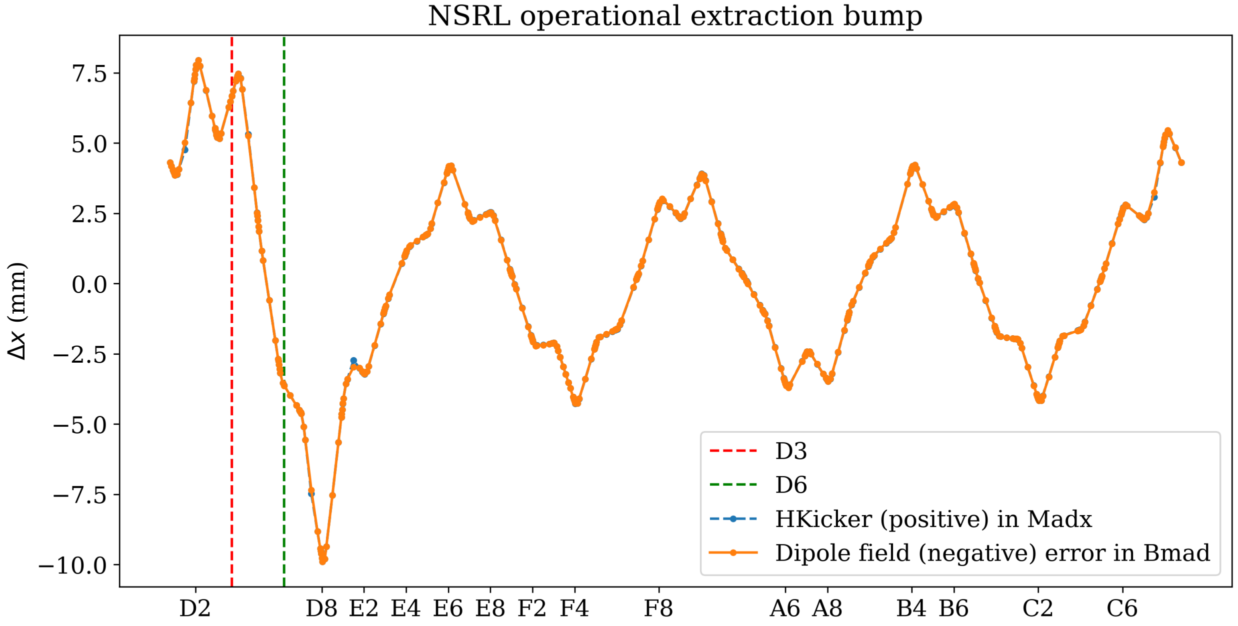


Bump design vs. Reality

618 MeV/n Silicon

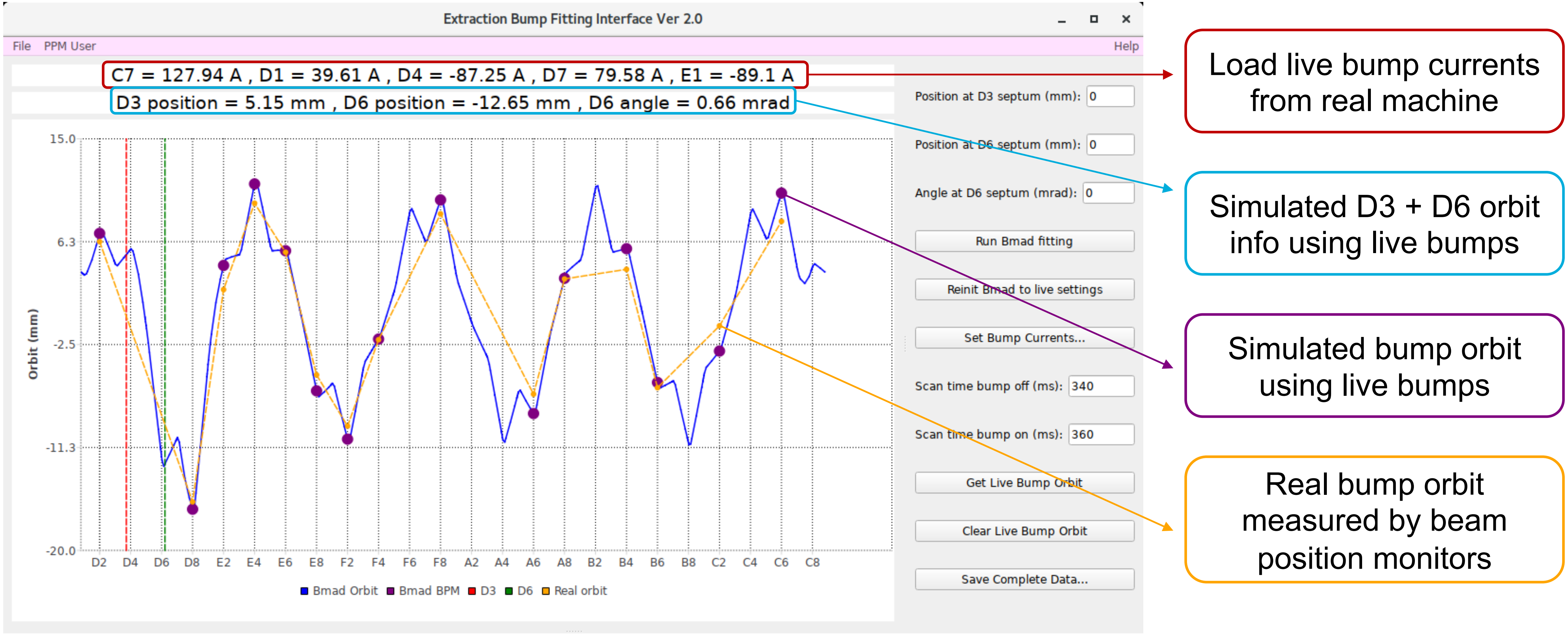
- Surprise discovery: operational bump is miles away from design bump due to years of blind tuning





Digital Twin for extraction bump

1 GeV/n Proton



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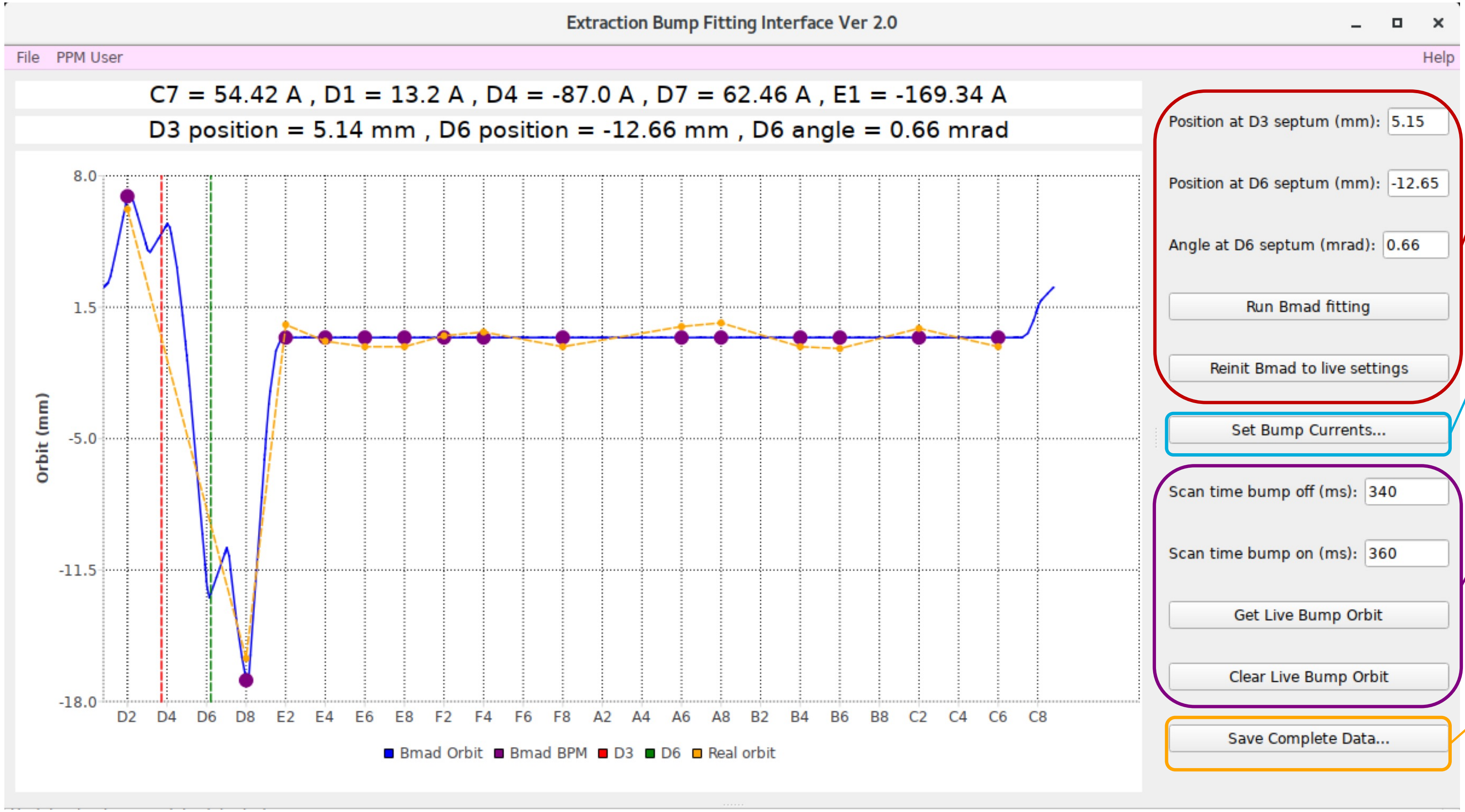


Use Bmad to fit any design bump shape

Send calculated bump currents to real machine

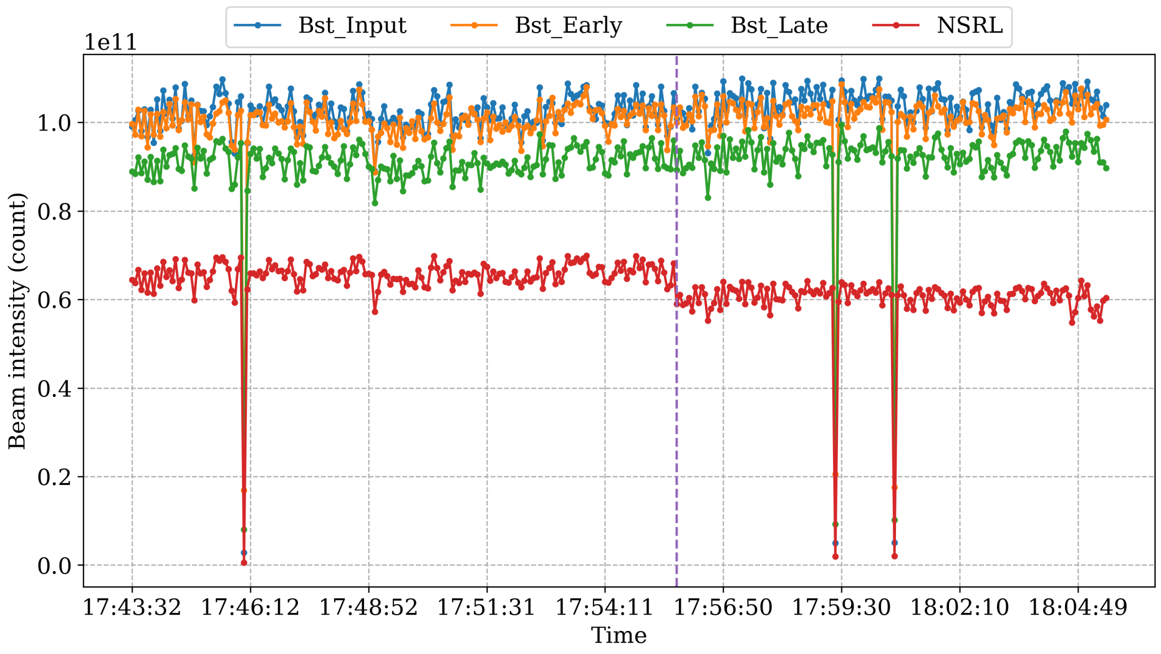
Time stamps in Booster cycle used to measure bump orbit

Save simulated and measured data

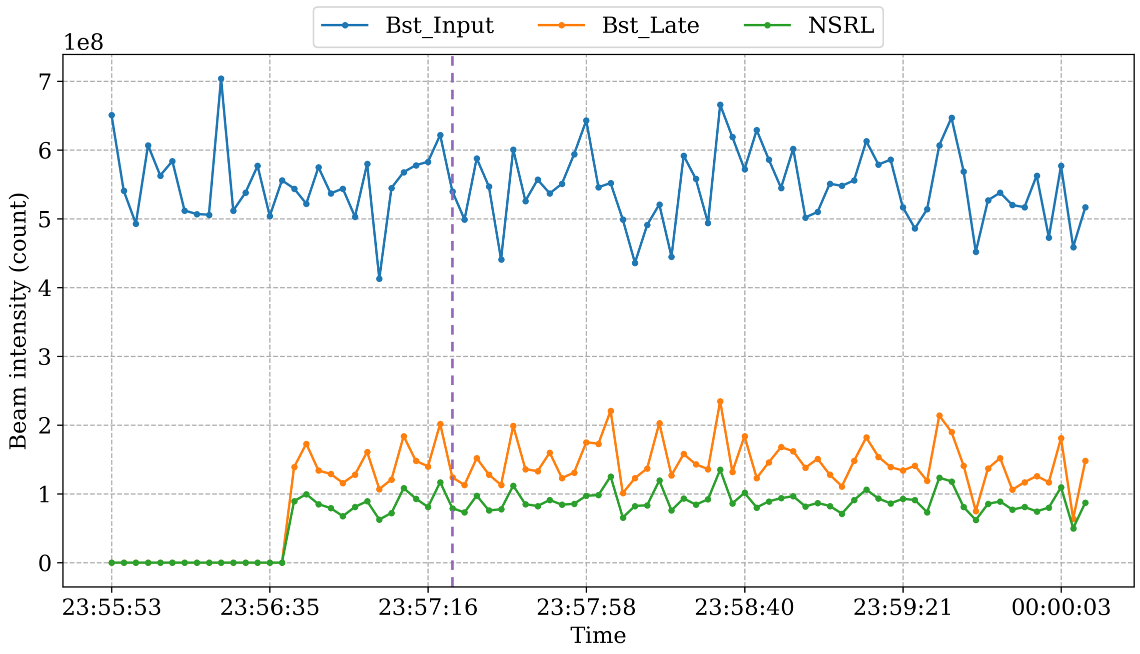
DT-assisted bump tuning

- Different configurations react differently to DT-assisted residual orbit minimization
- 1 GeV/n proton showed intensity drop, but 600 MeV/n Silicon didn’t
- Our understanding of the real Booster orbit is still lacking

1 GeV/n Proton

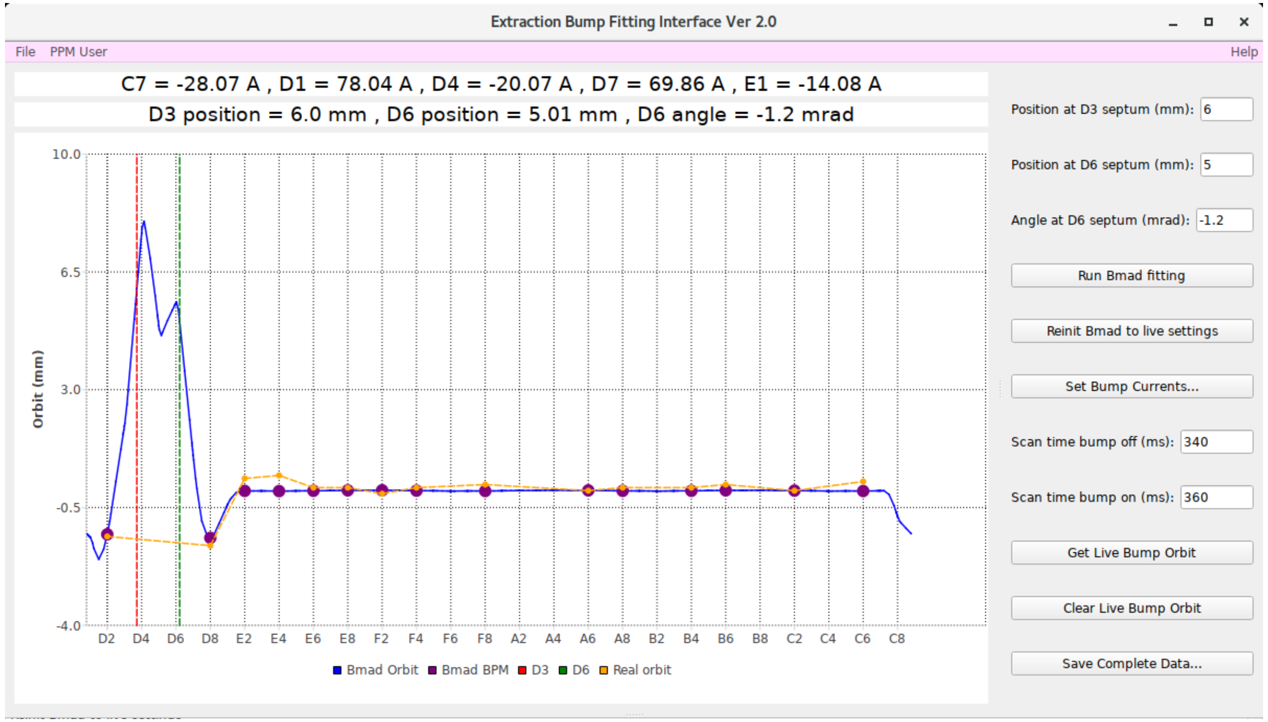


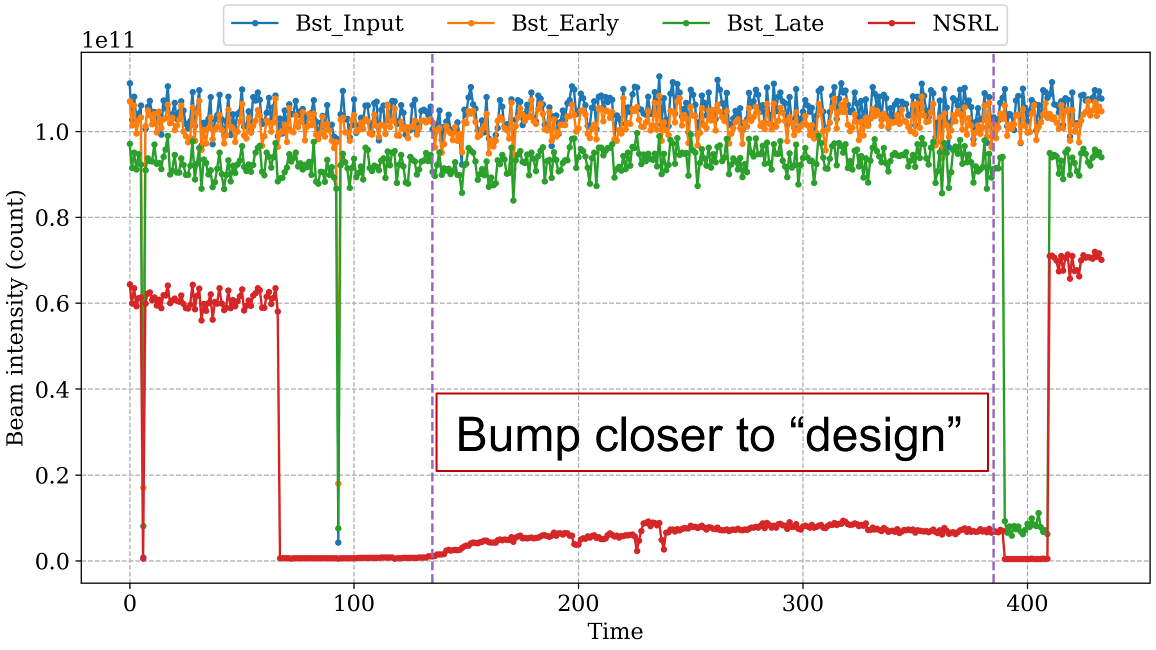
600 MeV/n Silicon



DT-assisted bump tuning

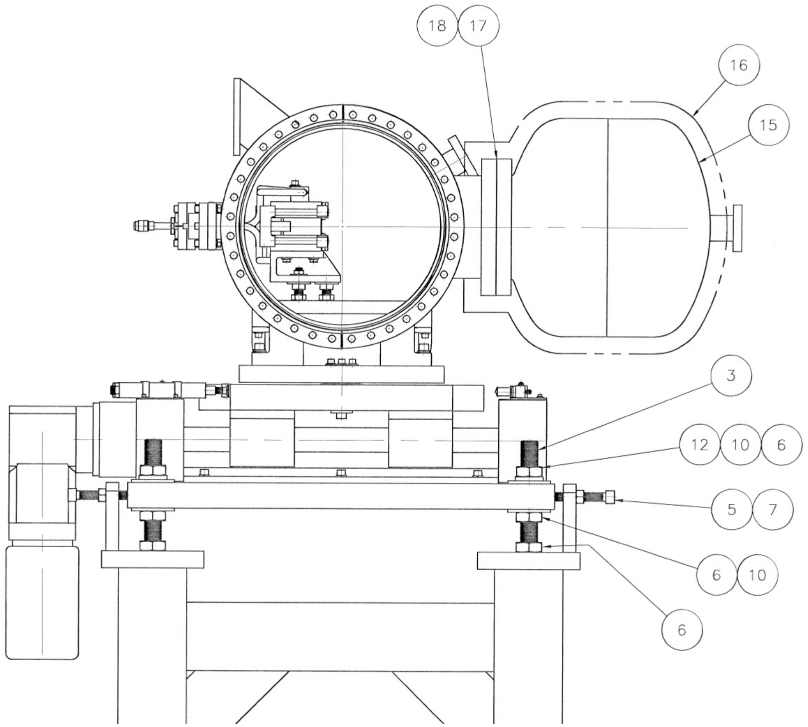
- Difficulty in recovering original design bump
  - Lack of BPMs around the two septa
  - D3 has been moved away from design location
  - D6 camera operational, no data analysis workflow, foil can't be in when flag is in



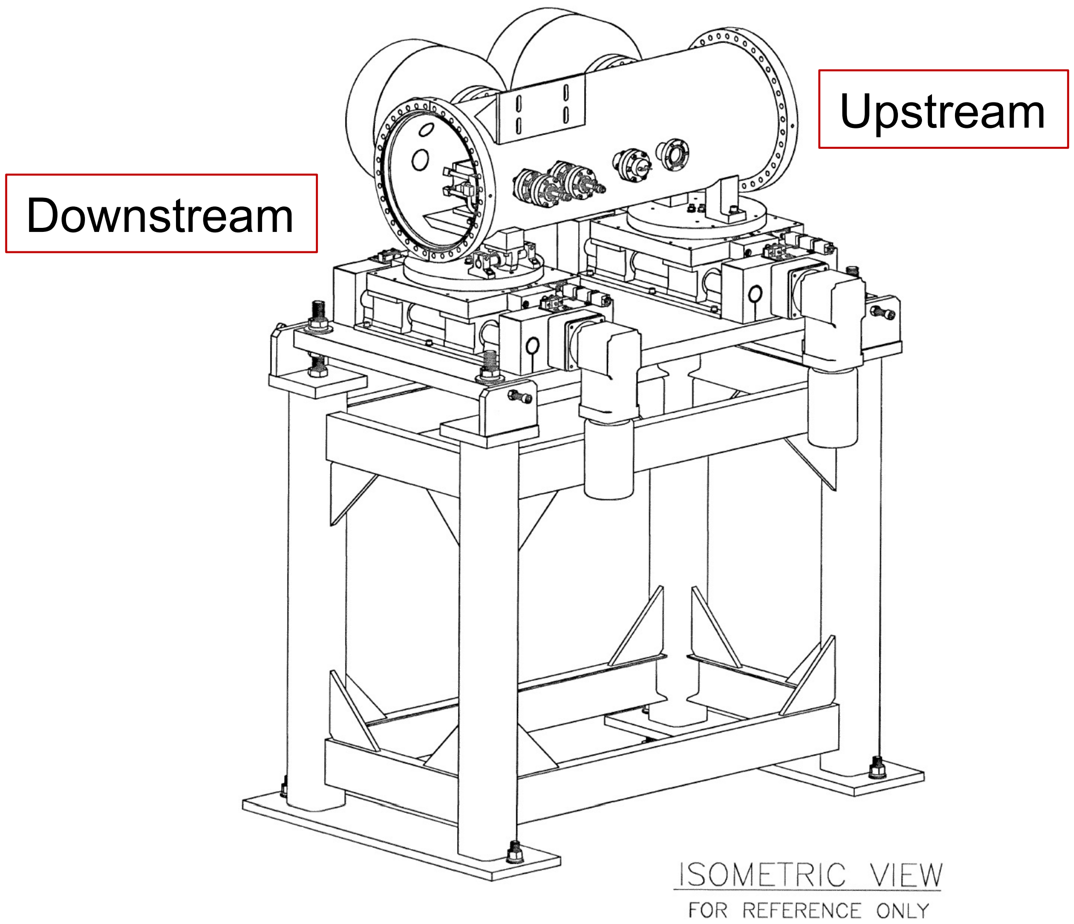


D3 septum

- D3 septum has upstream and downstream motion control with two step motors
- MCR hesitant to move D3 positions worrying it may not return to original place
- D3 kick adjustable via current, current often tuned to optimize intensity



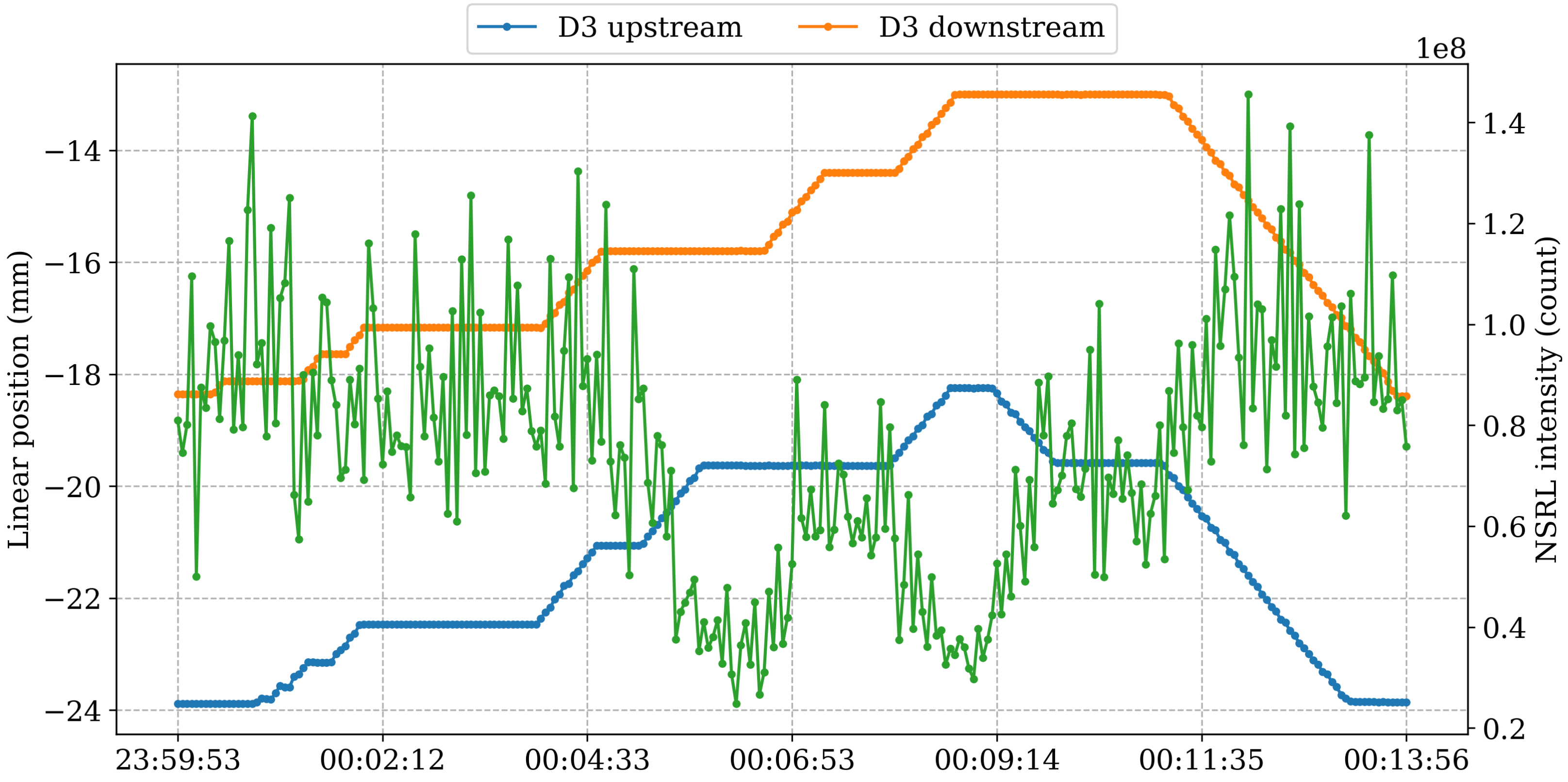
Upstream perspective



D3 septum position scan: July 03, 2026

600 MeV/n Silicon

- Only scanned positions not current due to time constraint
- Optimal combination of positions and current may improve intensity
- Both positions were able to return to the operational settings at the end of study



Slow Extraction simulation

1 GeV/n Proton

- Eiad’s SciBmad simulation takes real currents from main magnets, tune quads, chrom sextupoles, and bump windings

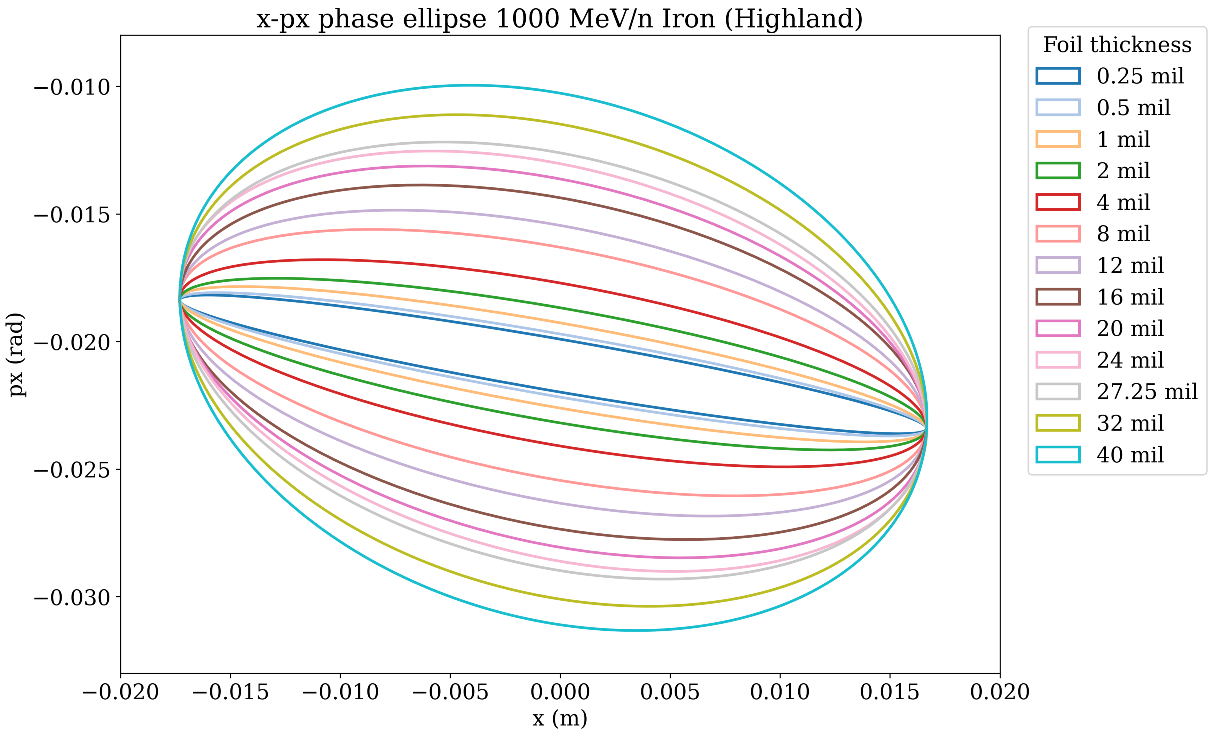
- **Issue with current simulation**: particles return to Booster closed orbit after D3 kick instead of getting extracted, no beam made it to D6

Foil Tracking: Bmad vs. FLUKA

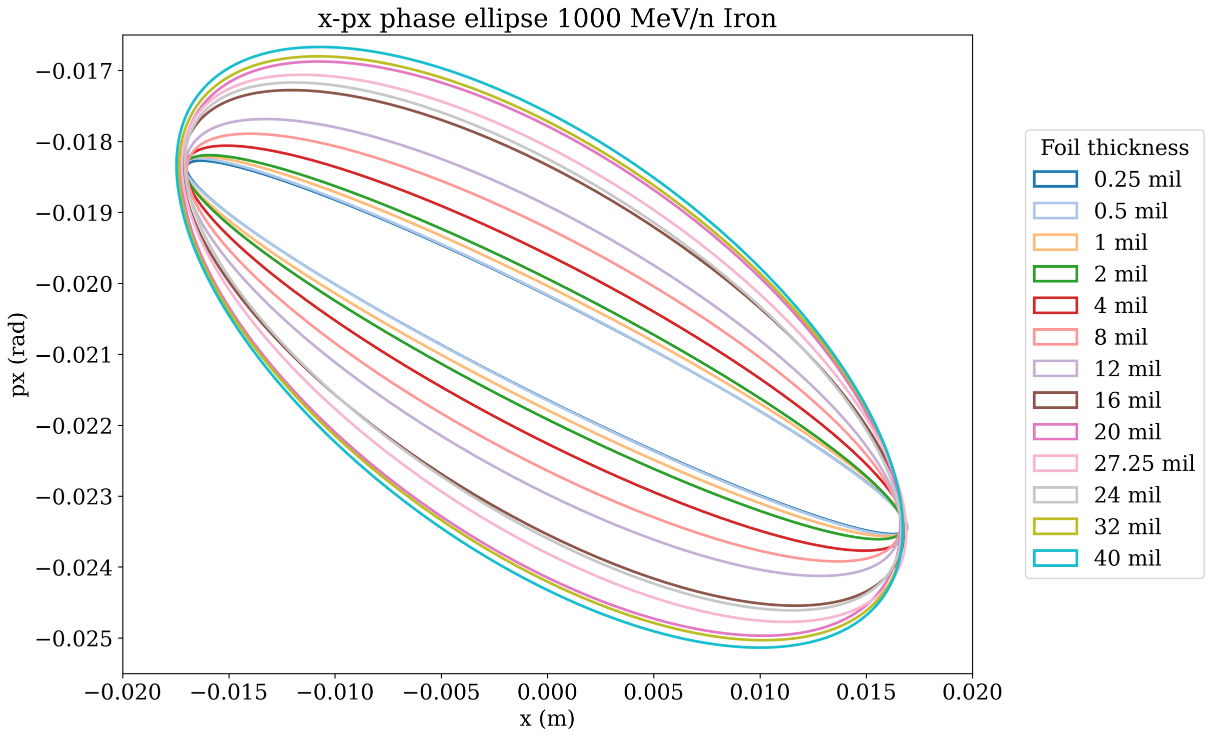
1 GeV/n Iron

- Ongoing investigation into the difference in foil tracking between Bmad and FLUKA

Bmad Highland

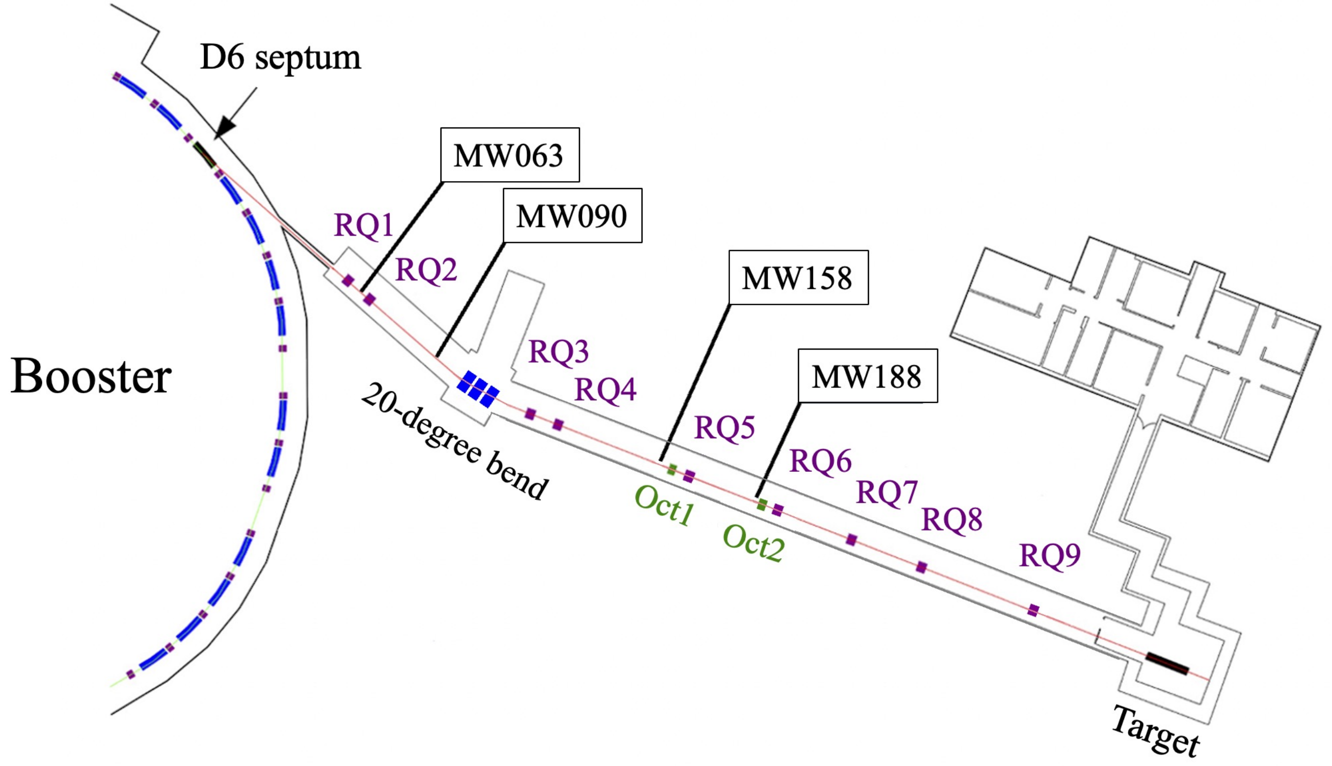


FLUKA



NSRL beam line

- Nine quadrupoles, three dipoles (20 degree), two octupoles, four multi-wires
- Designed to be achromatic after the 20-degree bend
- Two octupoles create uniform square beam at the target



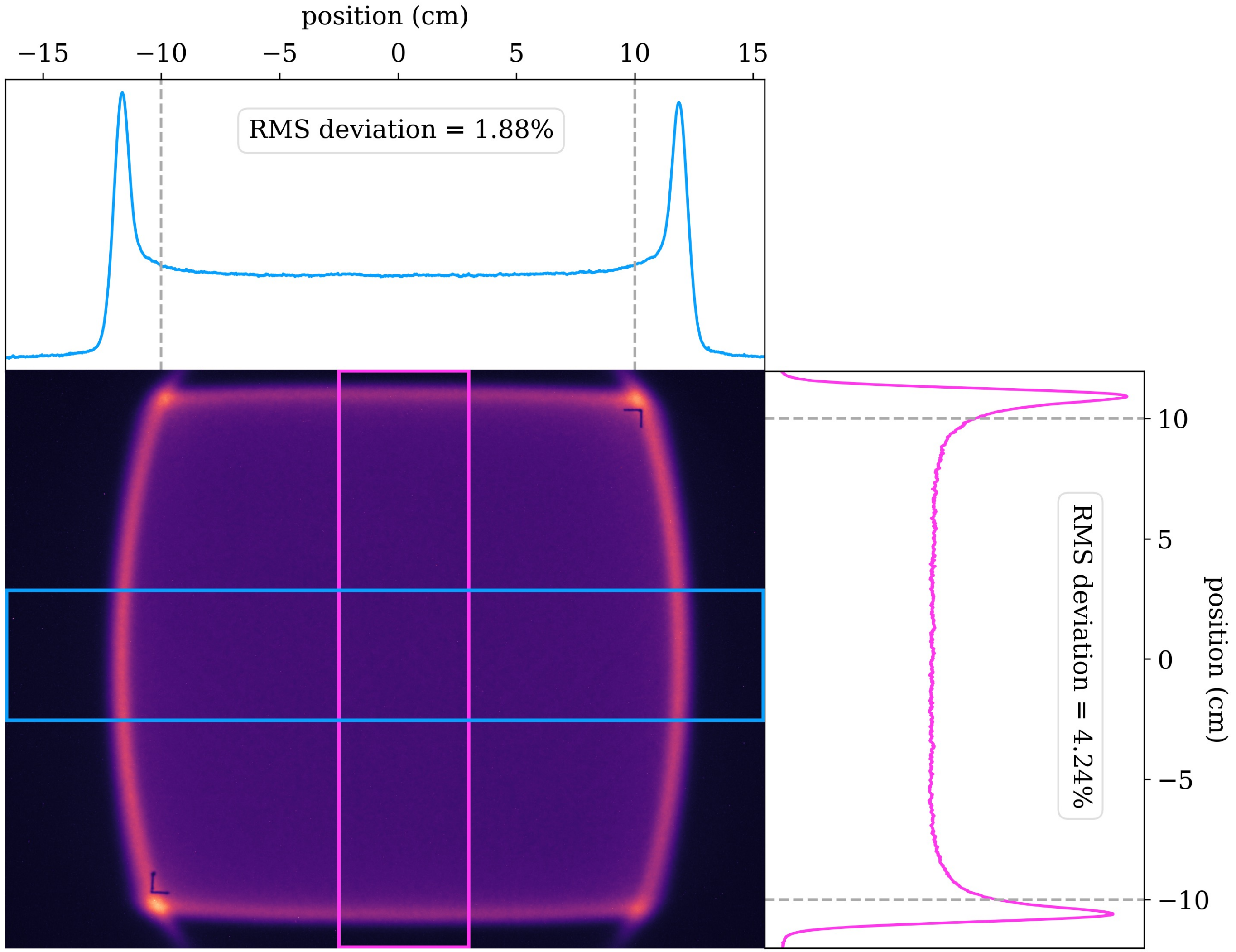
Uniform beam with octupoles

480 MeV/n Iron

- Uniformity is defined as the RMS deviation from the average beam intensity in the center uniform region

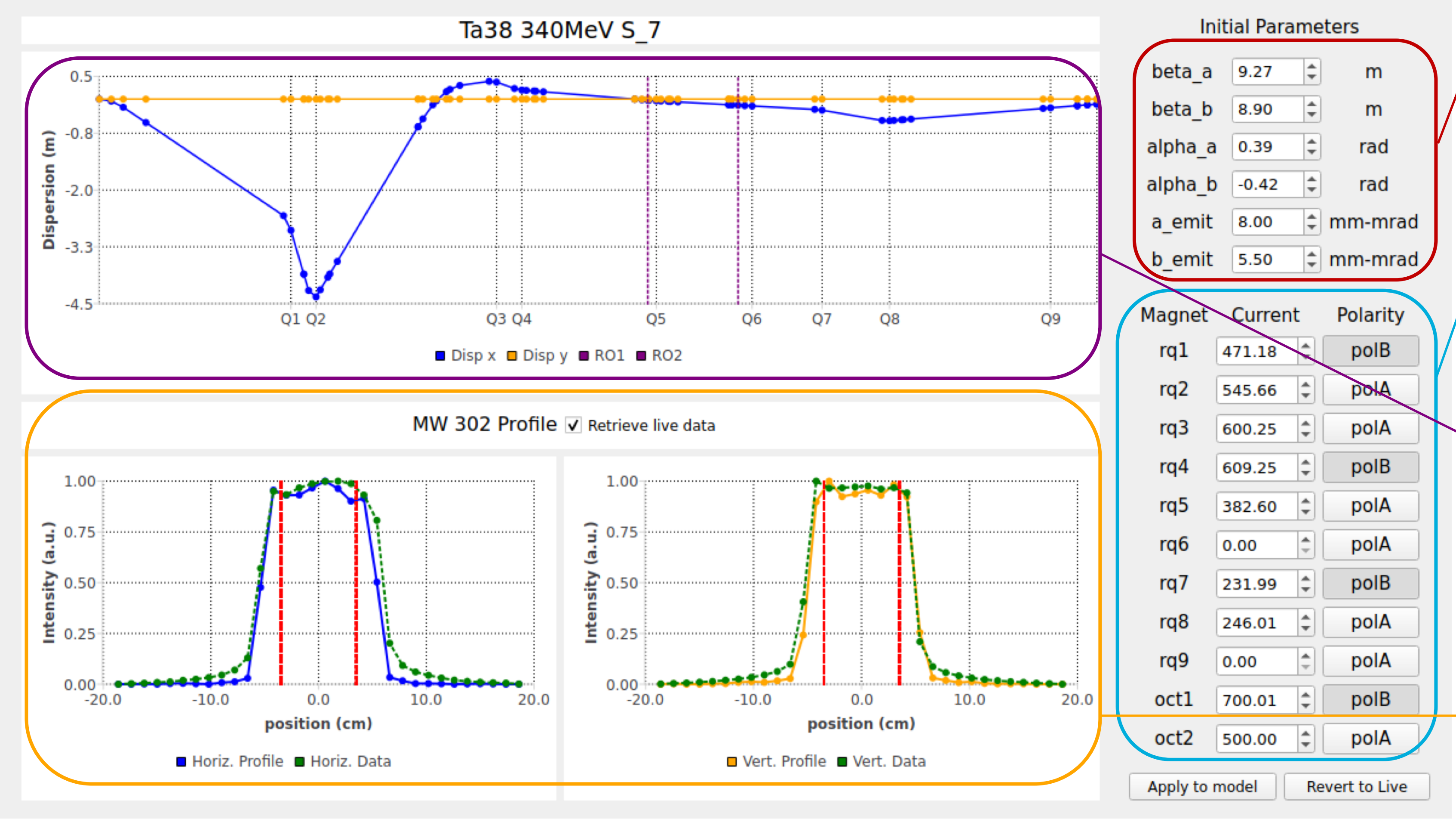
- Uniformity of $\leq 5\%$ is provided for NSRL experiments

$$U_{RMS} = \frac{\sigma}{\bar{x}} = \frac{1}{\bar{x}}\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$



Digital Twin for NSRL line

340 MeV/n Tantalum



Initial beam parameters used by model

Currents and polarities of quadrupoles from live machine

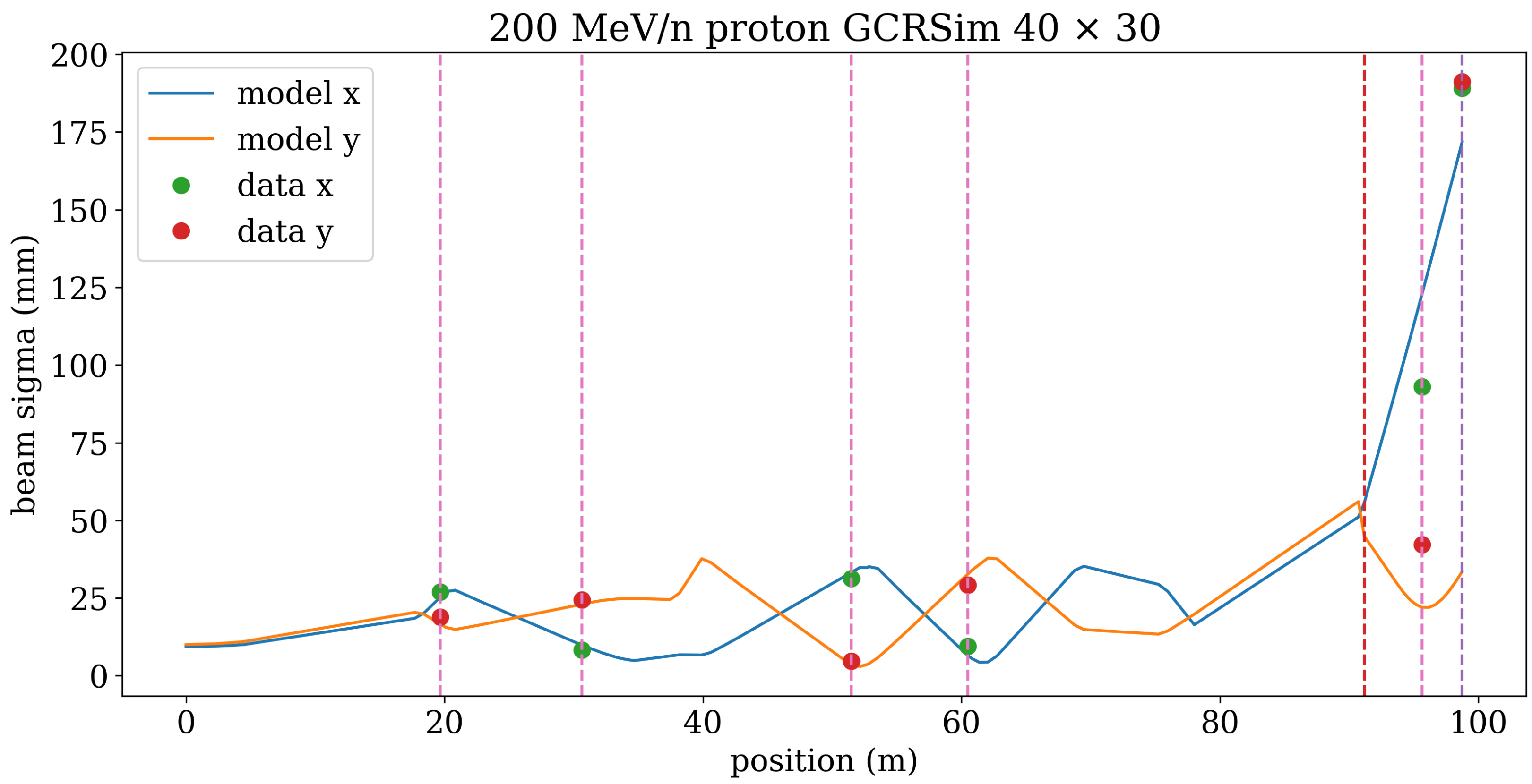
Simulated dispersion of NSRL line using live machine info

Simulated vs. real transverse beam profile at MW302

Overfocused beam with RQ9

200 MeV/n Proton

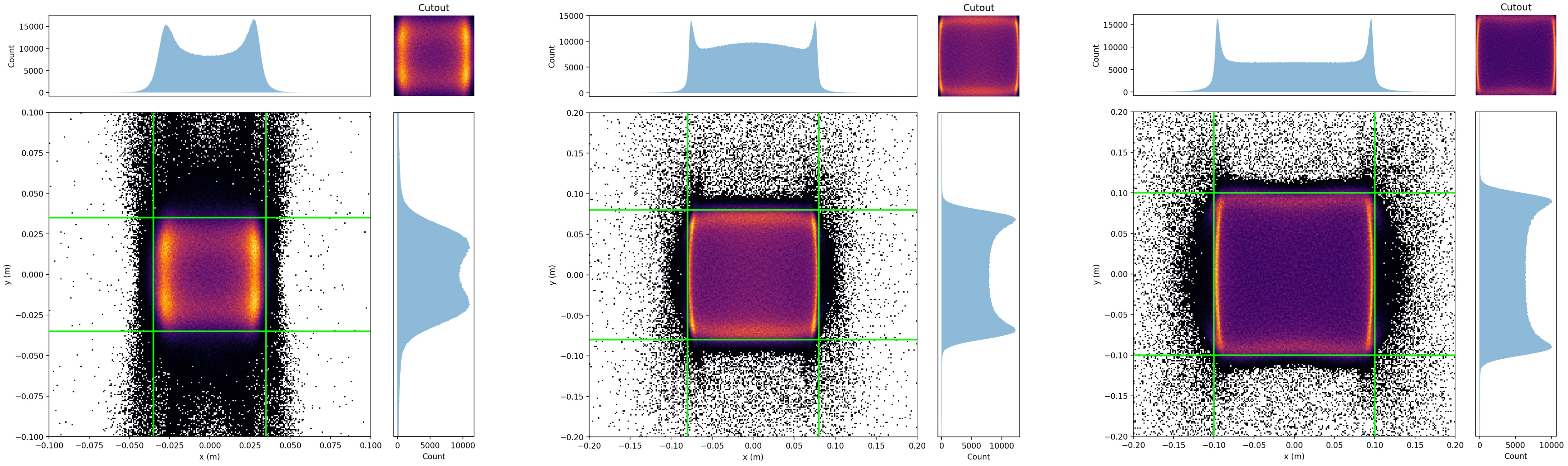
- Current Bmad model has trouble simulating overfocused setups with RQ9 on
- RQ9 is newly installed, not much documentation was found
- Beam sizes agree upstream but diverge at the end



BO for uniform beam

1 GeV/n Iron

- Built on Eiad's optimization script with SciBmad model
- Start with 10x10 archive and aim for different target sizes
- Single merit function can give good numerical value but less desirable profile



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