Beam Simulation Studies for FRIB

Qiang Zhao

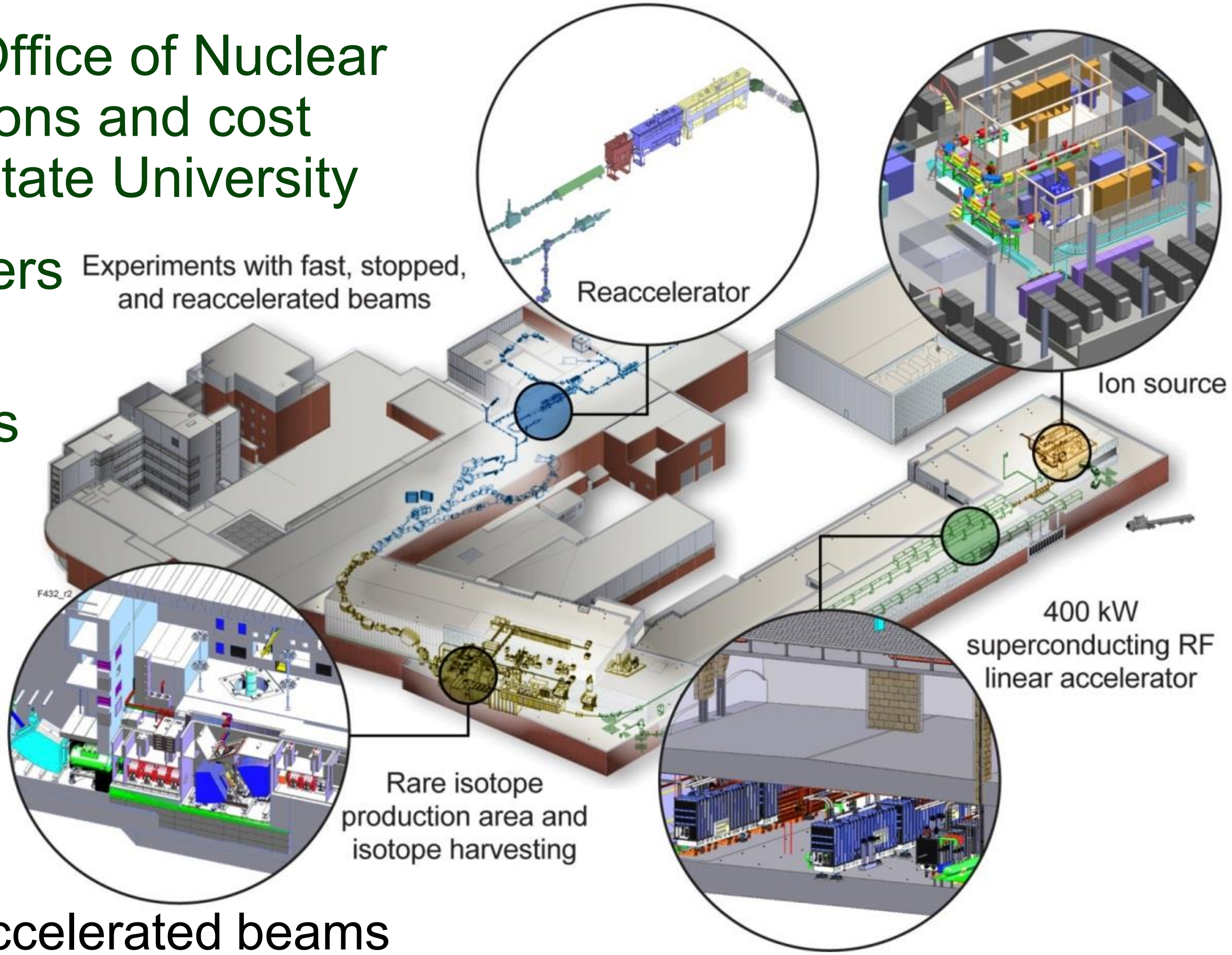
Michigan State University

HB2016   Malmö, Sweden

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Facility for Rare Isotope Beams
A Future DOE-SC National User Facility

- Funded by DOE–SC Office of Nuclear Physics with contributions and cost share from Michigan State University
- Serving over 1,300 users
- Key feature is 400 kW beam power for all ions (e.g. 5×10^{13} ^{238}U/s)
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - All elements and short half-lives
  - Fast, stopped, and reaccelerated beams



Heavy Ion Linac Development at MSU

- 1999-2004: Design of RIA (Rare Isotope Accelerator)
- 2005-2006: Design of ISF (Isotope Science Facility)
- 2005- now: ReA (Reaccelerator) Facility
  - ReA3 (operation), ReA6 (developing), ReA12 (designed)
- FRIB (Facility for Rare Isotope Beams) project
  - 2008/12 MSU site selected
  - 2009/06 Cooperative Agreement signed by DOE-SC and MSU
  - 2010/09 Alternative Selection and Cost Range approved
  - 2013/08 Performance Baseline approved
  - 2014/03 Civil construction started
  - 2014/10 Technical construction started
  - currently under construction and reached 63% completion
    - » Beam commissioning will start at ion source this Fall
  - Project completion in June 2022, early completion goal in Dec. 2020

MOPM1P80
M. Ikegami

FRIB under Construction

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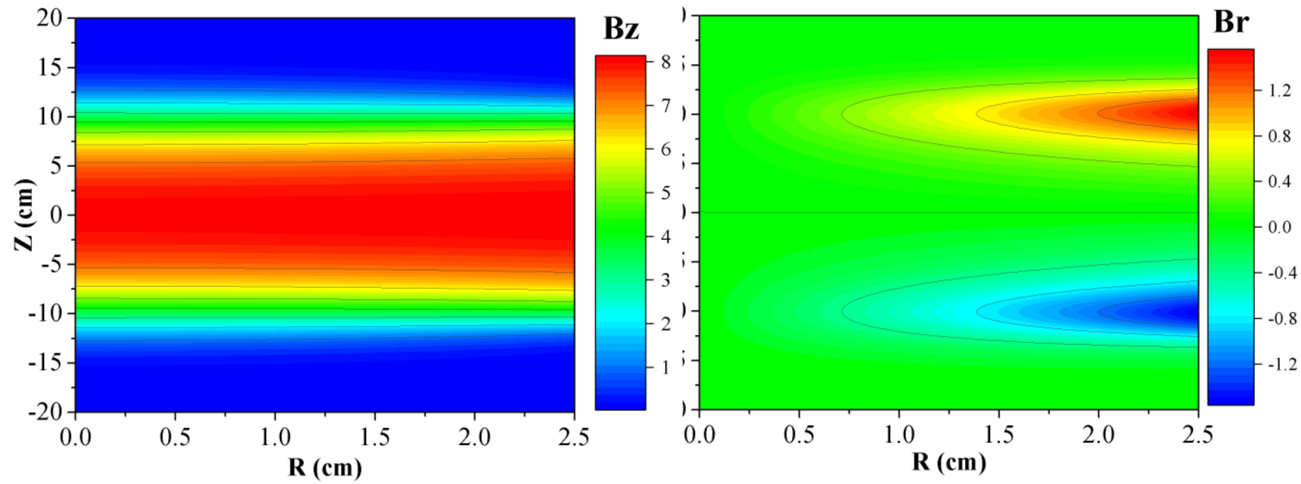
Solenoid Model in Beam Simulation
Relationship between Hardedge and 3D Field

- 3D field map



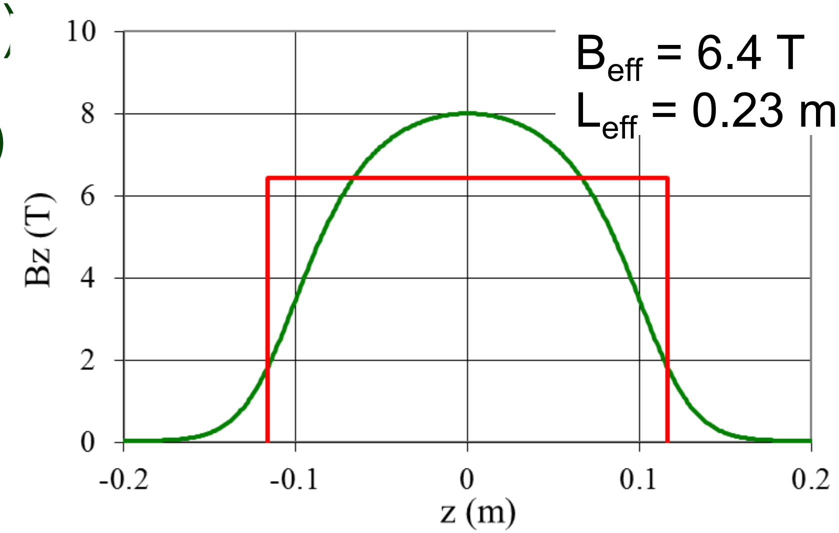
- Hardedge model
  - effective field B_{eff}
  - effective length L_{eff}

$$\int_{-\infty}^{\infty} B_z^2(0,0,z)dz \equiv B_{eff}^2 \cdot L_{eff} \quad \text{(focusing)}$$

$$\int_{-\infty}^{\infty} B_z(0,0,z)dz \equiv B_{eff} \cdot L_{eff} \quad \text{(rotation)}$$

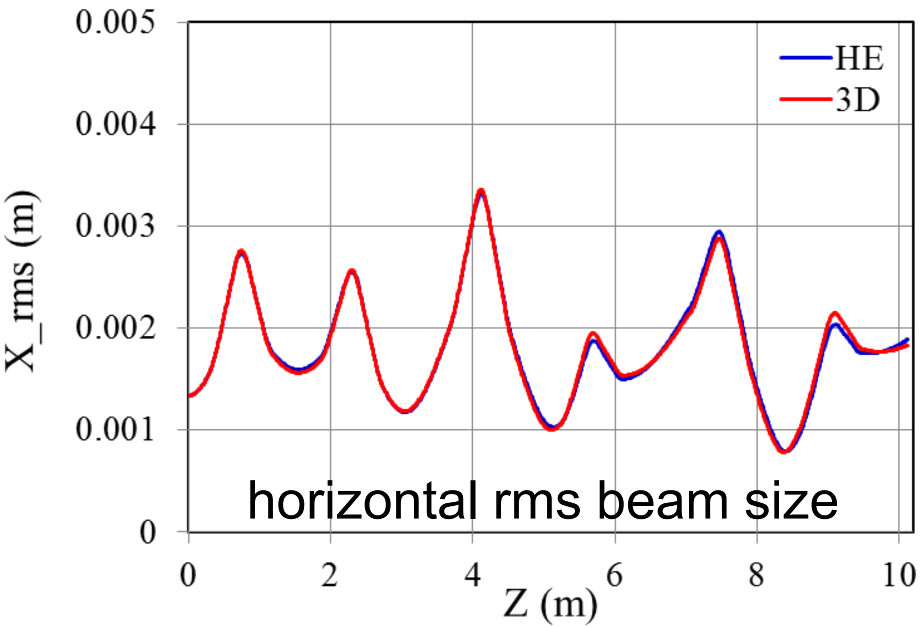
$$B_{eff} = \frac{\int_{-\infty}^{\infty} B_z^2(0,0,z)dz}{\int_{-\infty}^{\infty} B_z(0,0,z)dz}$$

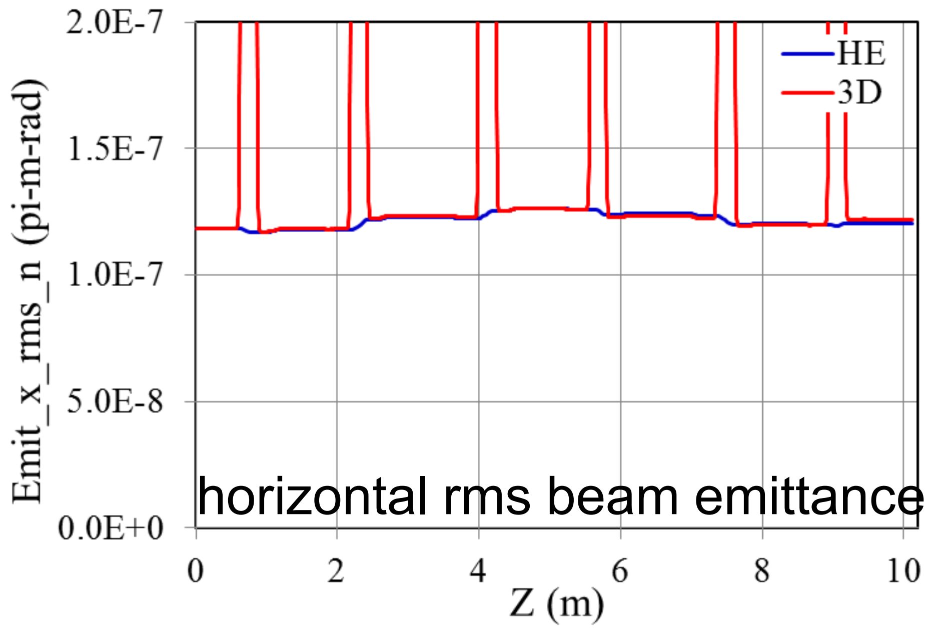
$$L_{eff} = \frac{\left(\int_{-\infty}^{\infty} B_z(0,0,z)dz\right)^2}{\int_{-\infty}^{\infty} B_z^2(0,0,z)dz}$$



Beam Simulation through Solenoid: HardEdge vs. 3D Field Map

- Beam sizes almost identical (horizontal rms beam size shown)
- Emittances agreed very well (horizontal rms beam emittance shown, the red spikes were due to the calculation in laboratory frame, they would disappear if done in rotation frame)

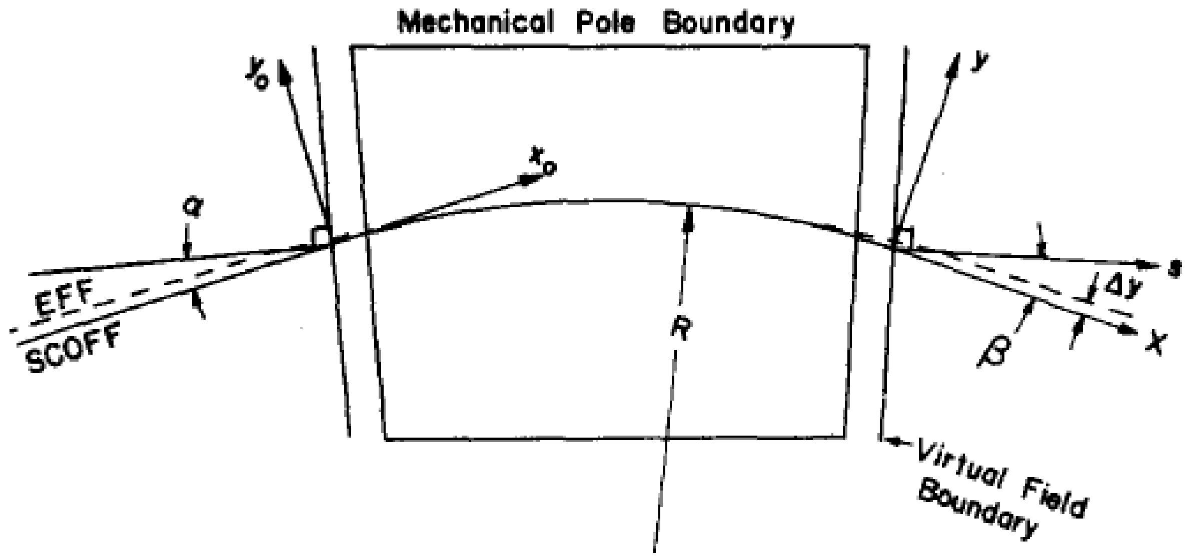




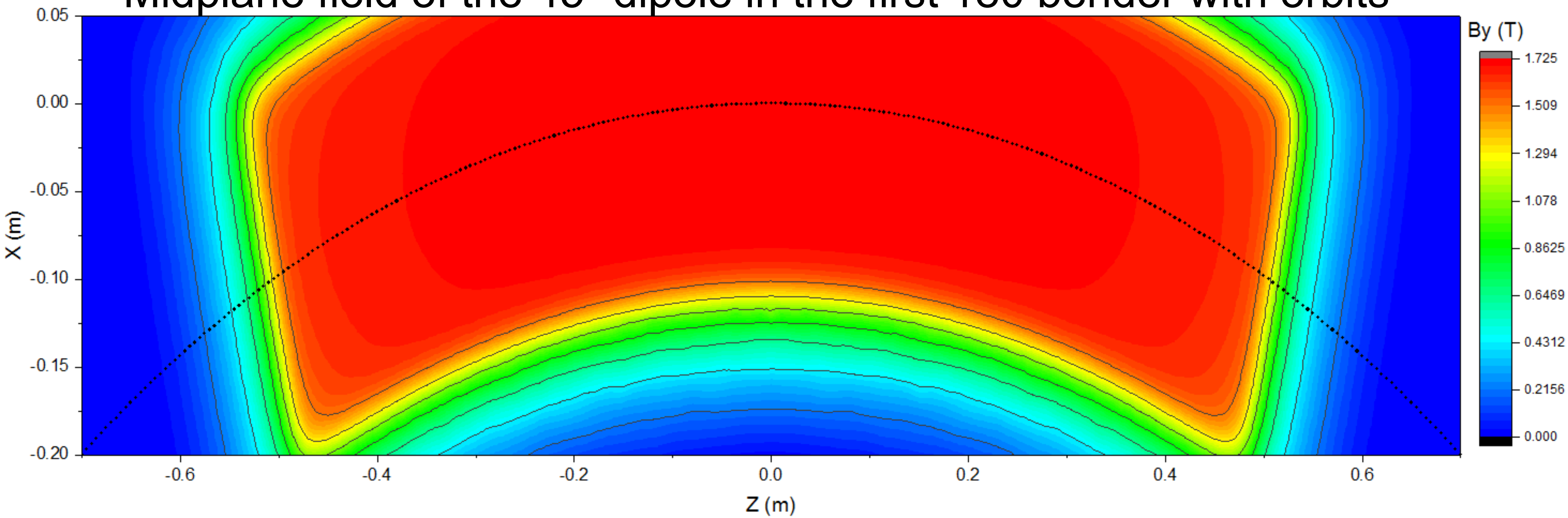
Orbit Displacement due to Dipole Fringe Field

- H. A. Enge, RSI,1964

  Due to fringe field effect of dipole, displacements of the beam center line at both entrance and exit (a "zeroth-order" effect)

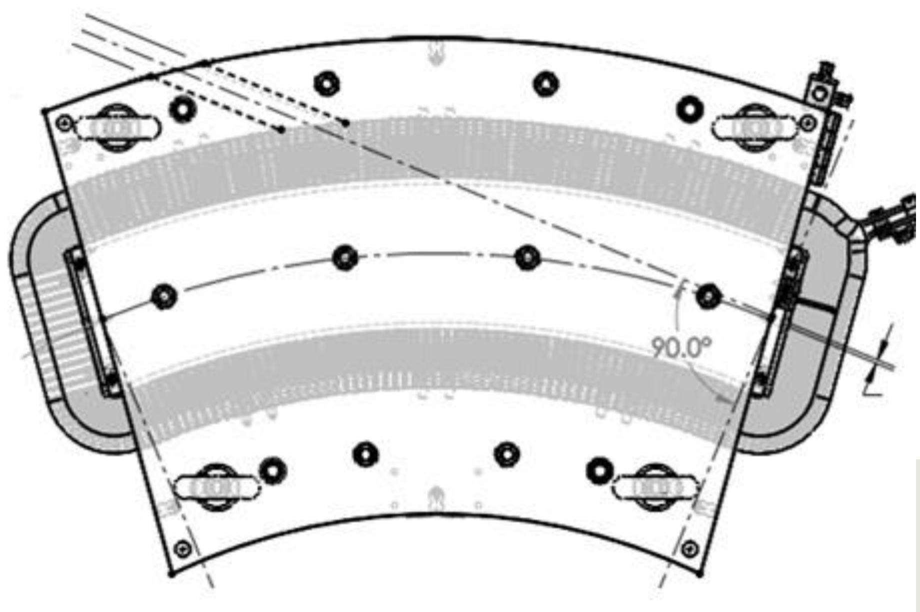


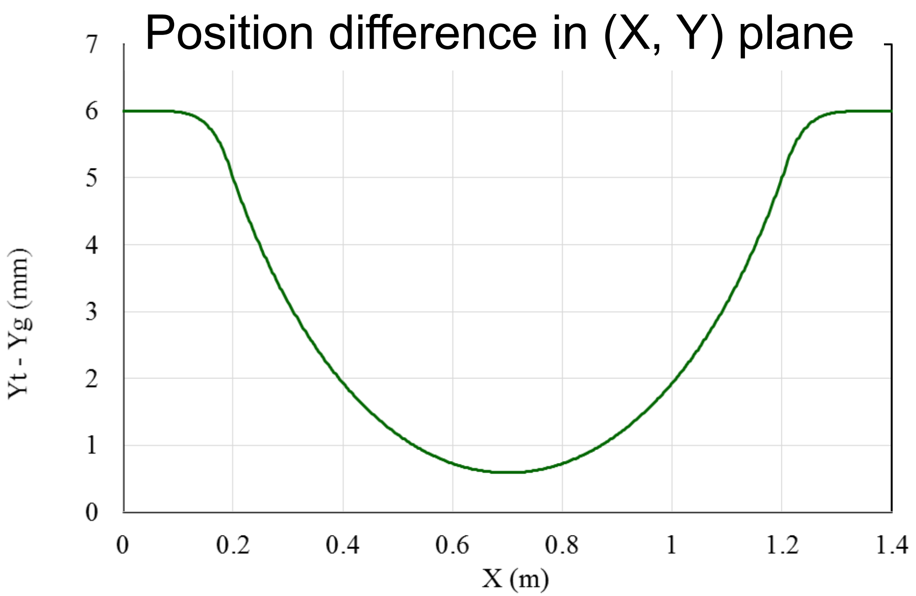
Midplane field of the 45º dipole in the first 180 bender with orbits

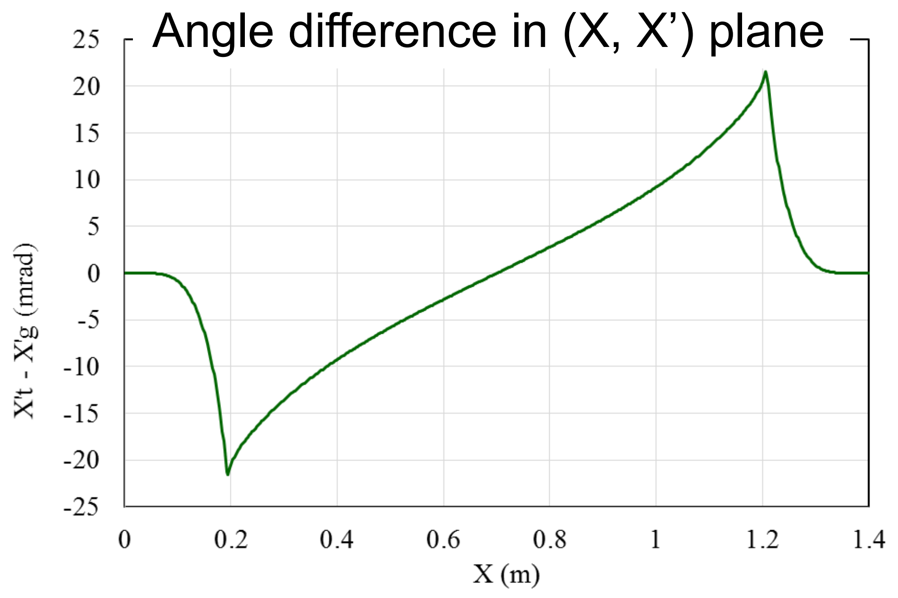


Orbit Difference in the Midplane of 45º Dipole

- Orbits difference between 3D map field and hard-edge model of dipole
- A few different excitation currents used to take account of saturation
- Displacement of magnet implemented into fabrication drawings

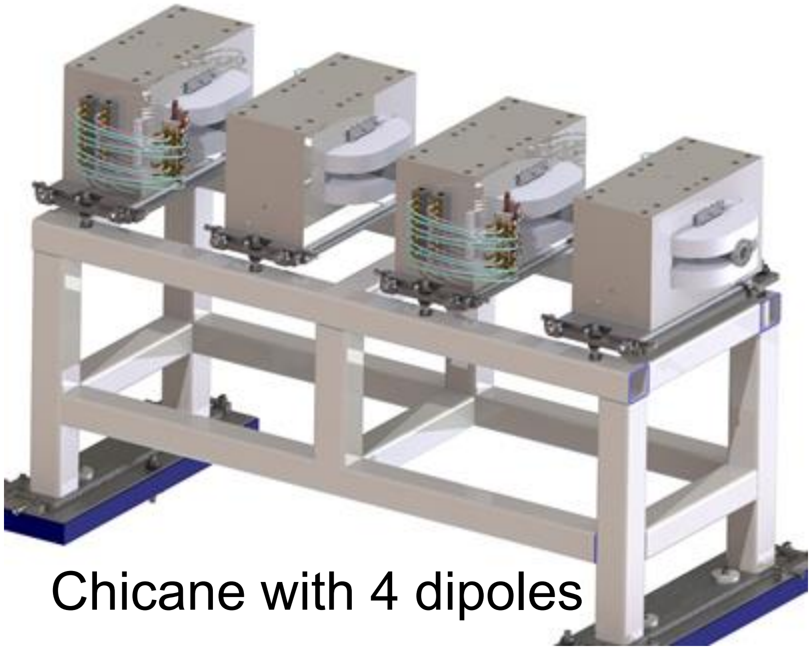




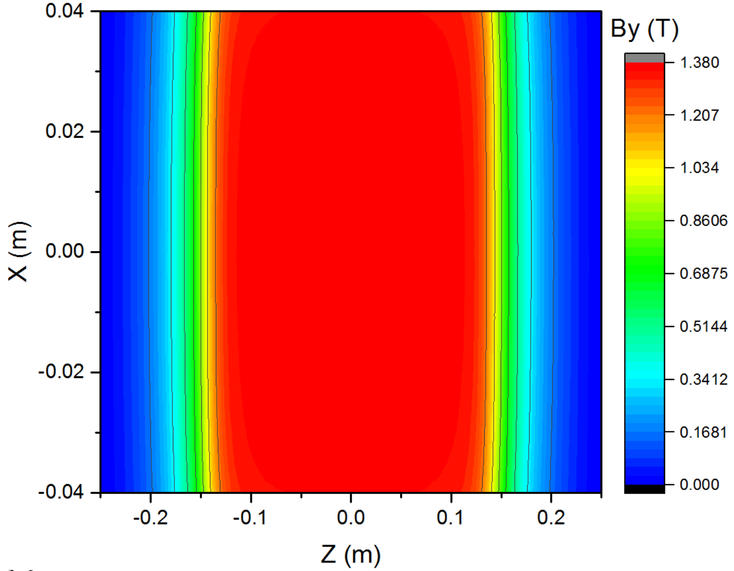


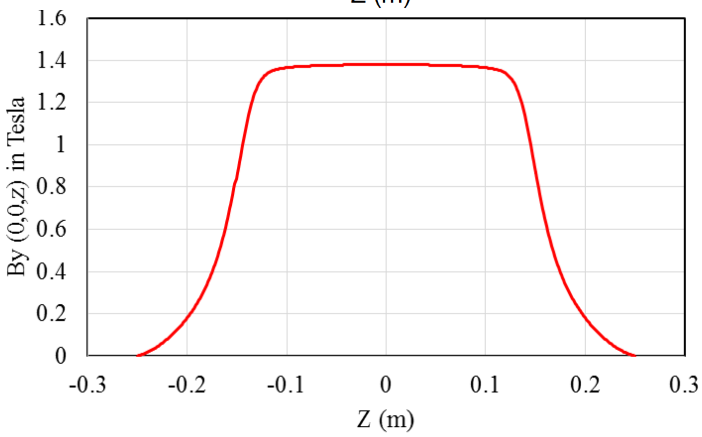
3D Magnetic Field Used in Beam Simulation

- Four-dipole chicane in stripper area
- 3D magnetic map field calculated
- Particles tracked through the chicane



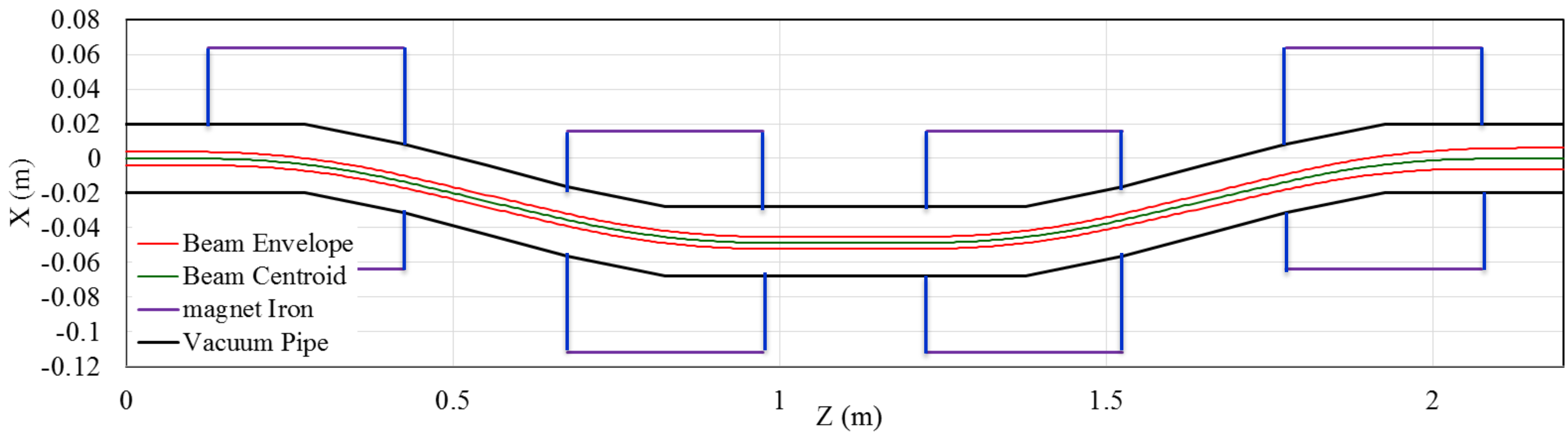
Chicane with 4 dipoles

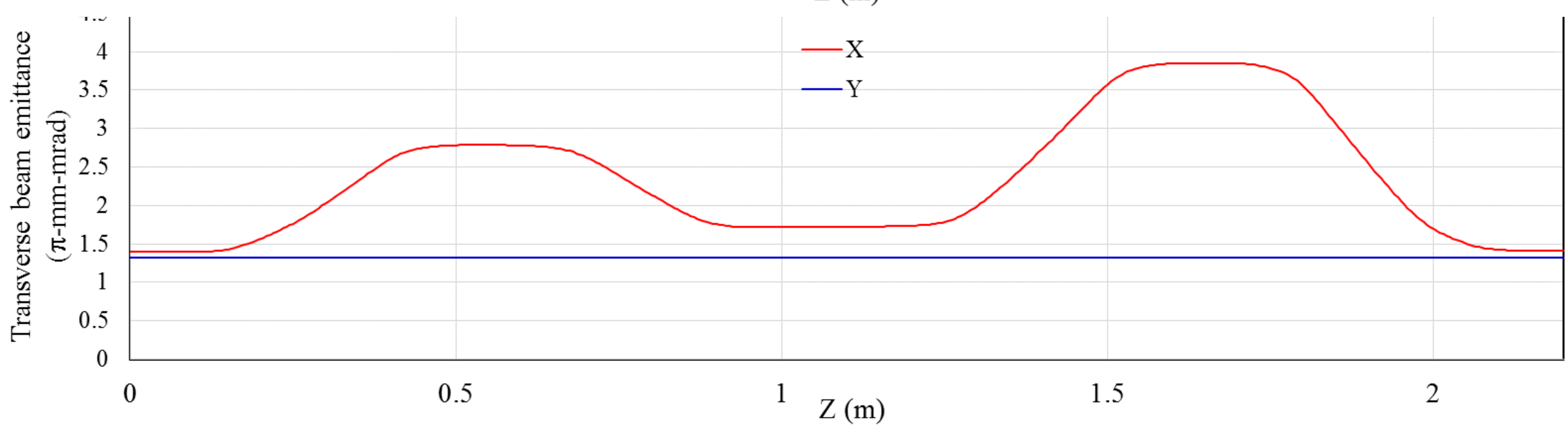




Beam Envelope and Emittance along Chicane

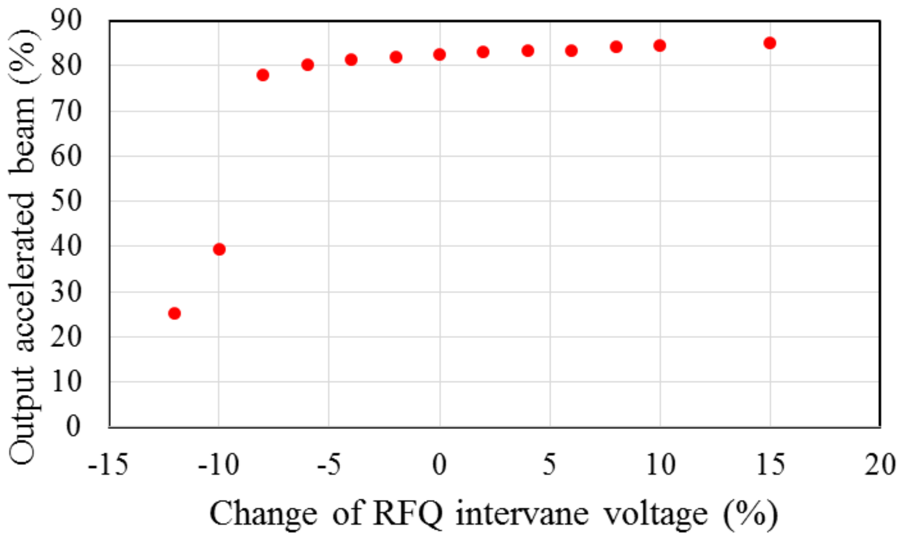
- Beam envelope well within vacuum chamber
- No beam emittance growth at chicane exit (1M multi-charge particles)

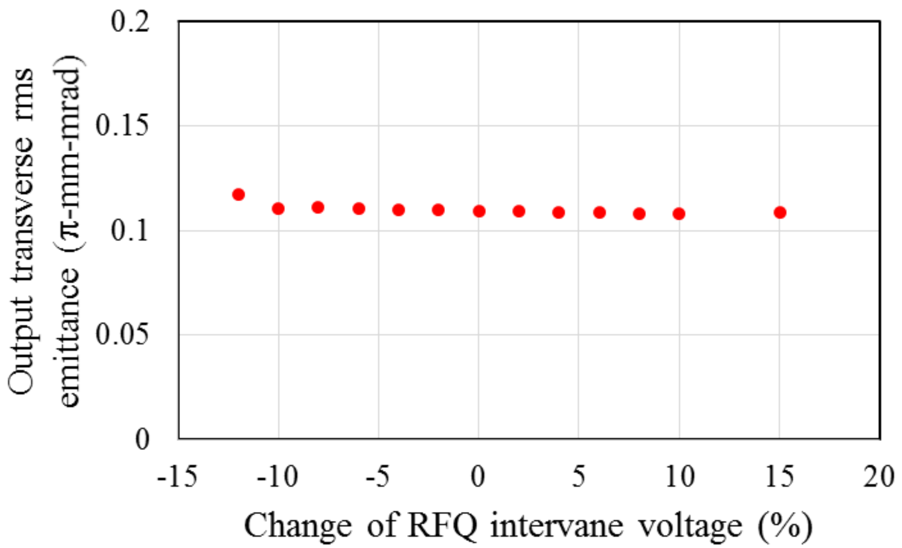


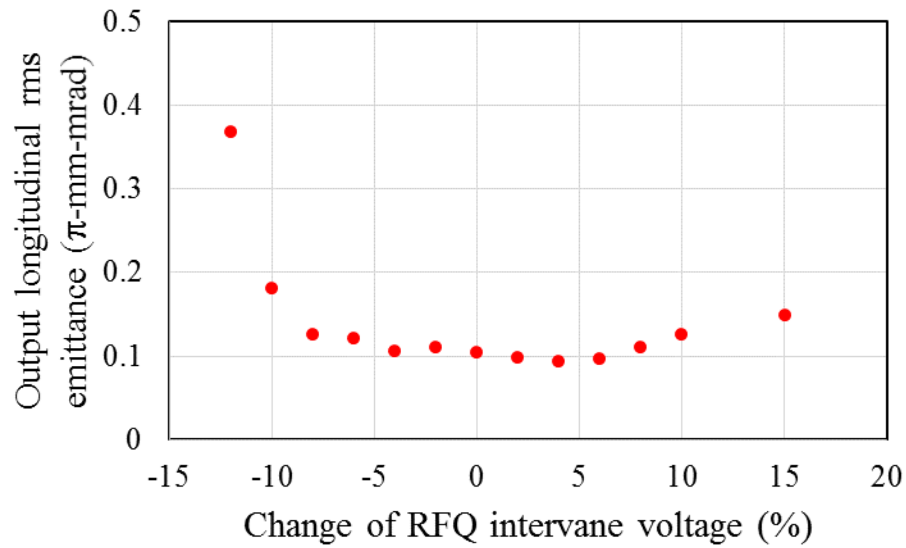


Output Beam Sensitivity to RFQ Voltage

- Beam transmission drops quickly with the decrease of RFQ voltage
- Output transverse emittance is insensitive to RFQ voltage
- Output longitudinal emittance increases with change of voltage
- Beam insensitive to RFQ voltage change of about ±5%

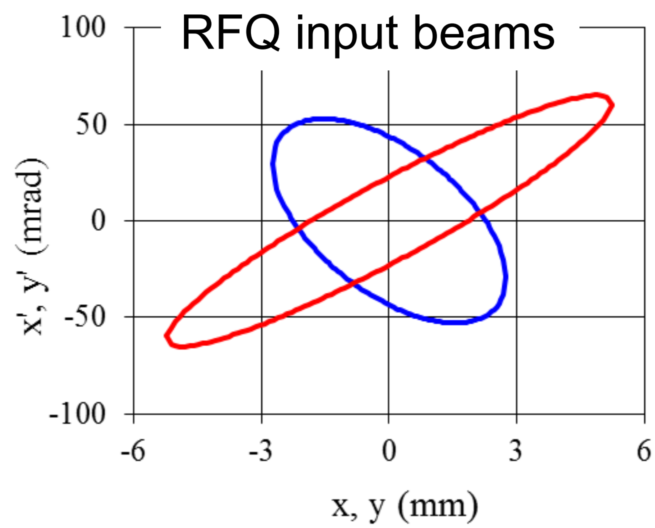


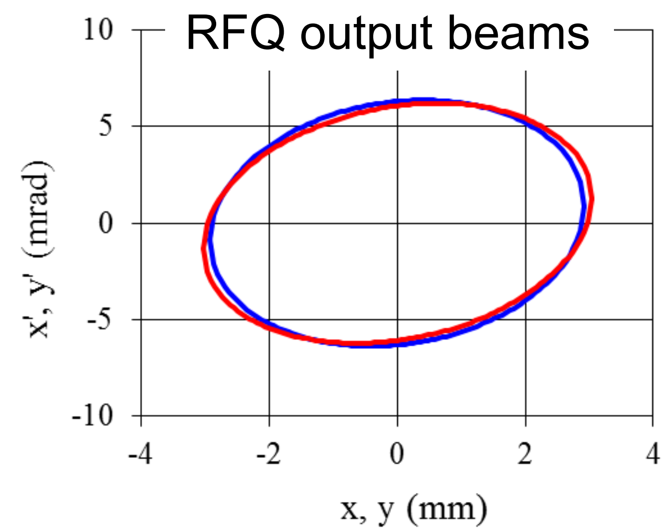


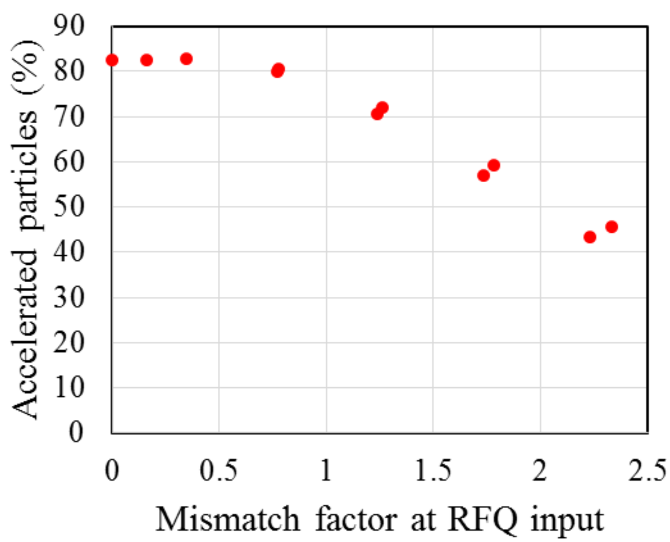


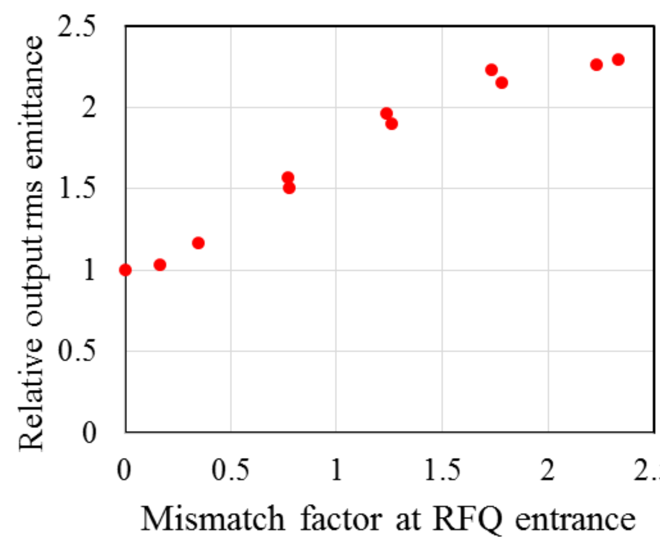
Effect of Transverse Beam Mismatching at RFQ Entrance

- Mismatched beam at RFQ input does not cause much mismatch at output
- Mismatch at RFQ input decreases RFQ transmission
- Mismatch at RFQ input increases beam emittance at RFQ output



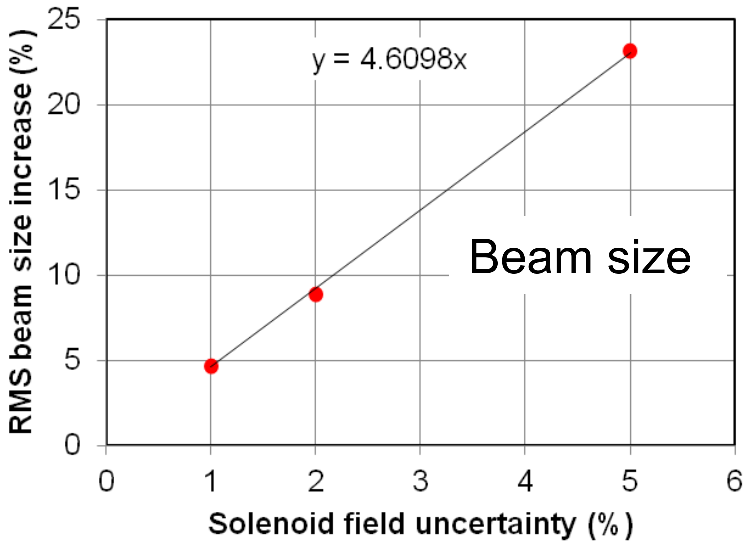


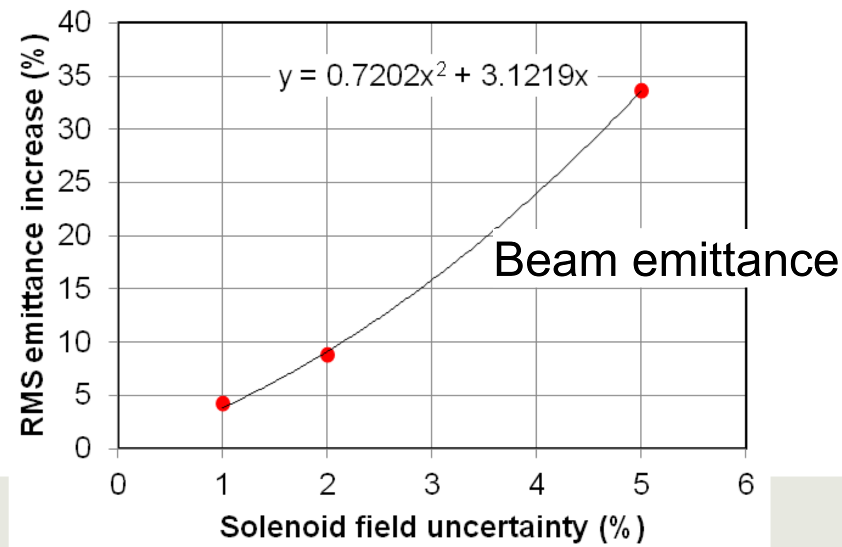




Beam Sensitivity to Solenoid Setting

- Solenoid real settings will be deviated from design
  - Transverse matching along the linac will not be ideal
- Settings of all solenoids in Segment1 were assumed to have 1%, 2%, 5% uncertainty with respect to designs in uniform distribution
  - Each has 100 seeds
  - RMS distribution of beam size increase seems linearly with setting errors
  - RMS distribution of emittance grows faster than that of beam size
- Dynamic errors (e.g. power supply fluctuations) typically much smaller

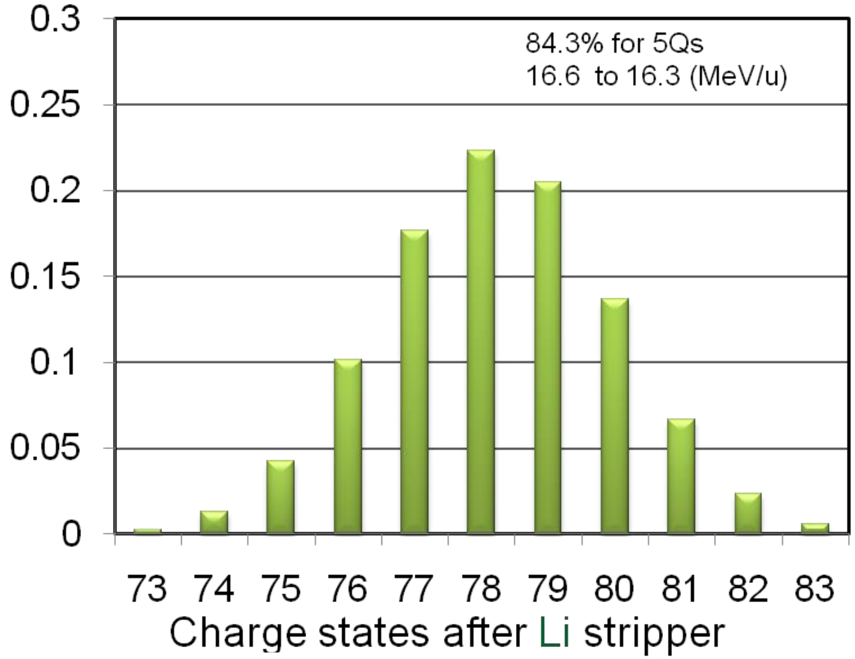


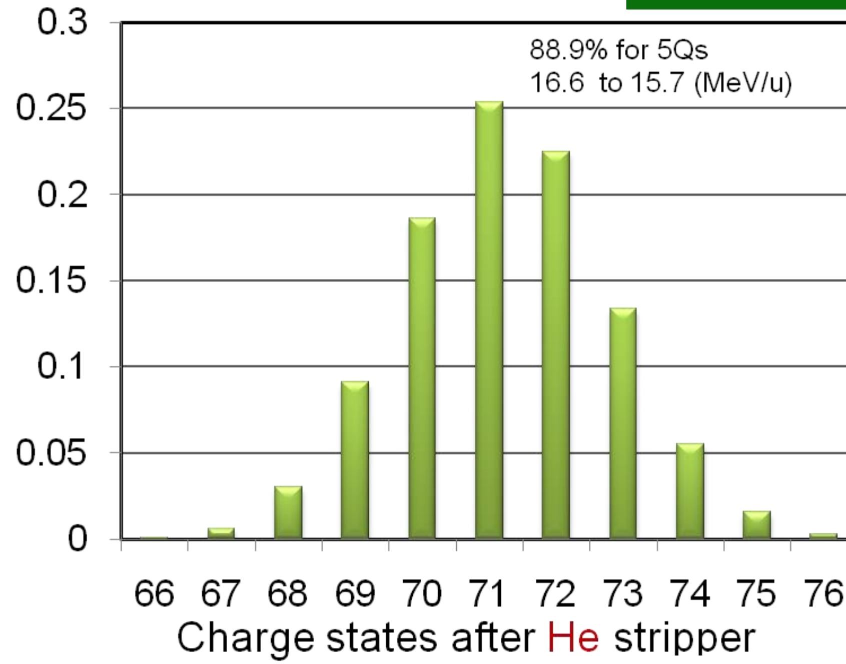


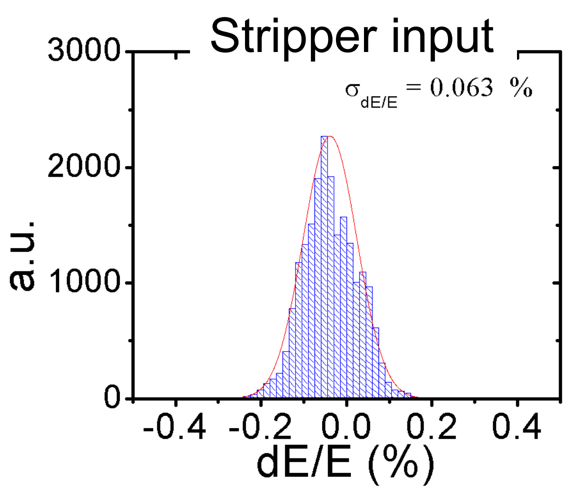
Liquid Lithium and Helium Gas Stripper

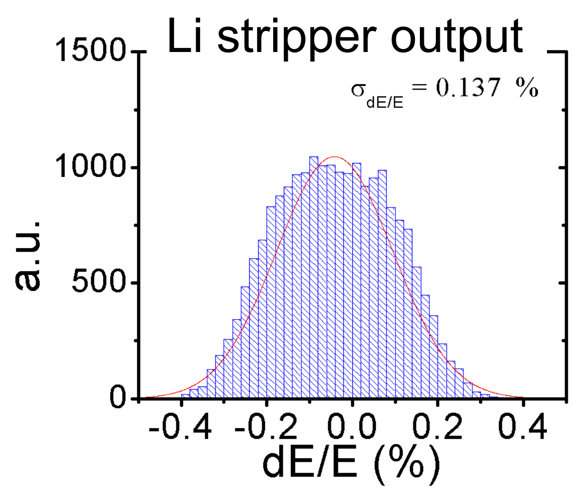
TUPM2X01
F. Marti

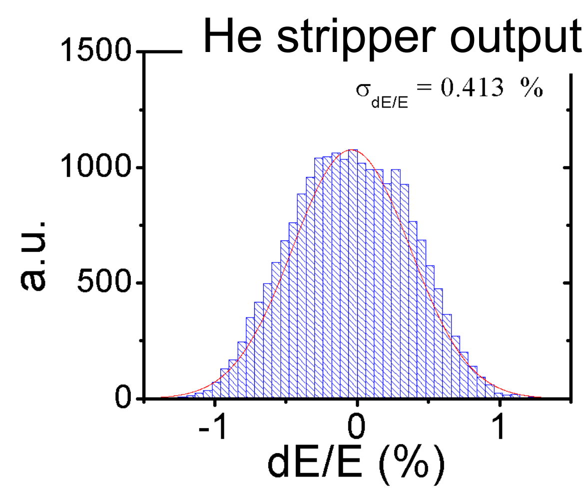
- Gas stripper → lower charge states & higher energy spread











Twiss Parameter Matching for Beam Tuning

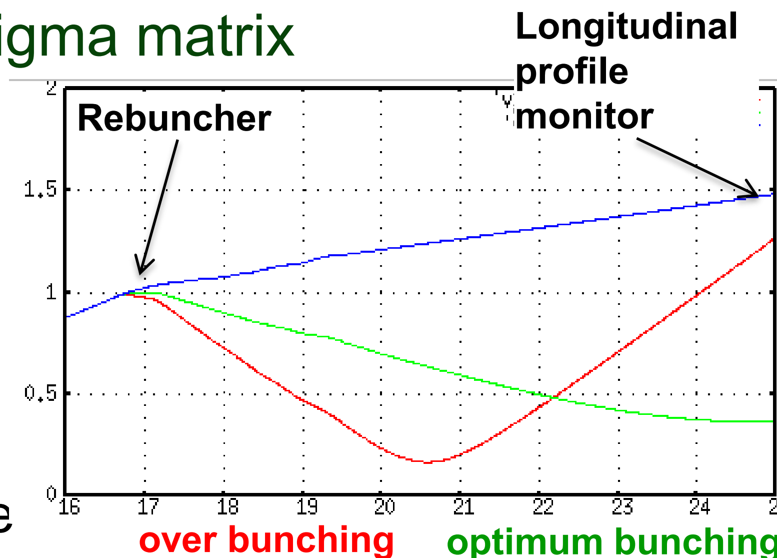
- Obtain Twiss parameters by measuring sigma matrix

$$(\sigma_{bl})_{11} = M_{11}^2 \cdot (\sigma_r)_{11} + 2M_{11} \cdot M_{12} \cdot (\sigma_r)_{12} + M_{12}^2 \cdot (\sigma_r)_{22}$$

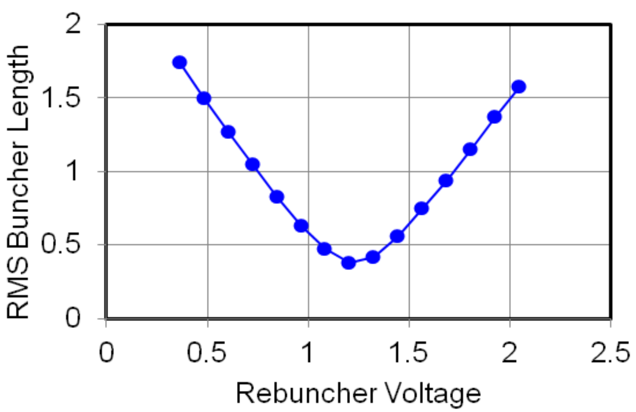
  - measured $(\sigma_{bl})_{11}$, known M_{11}, M_{12}, M_{22}
    obtained $(\sigma_r)_{11}, (\sigma_r)_{12}, (\sigma_r)_{22}$

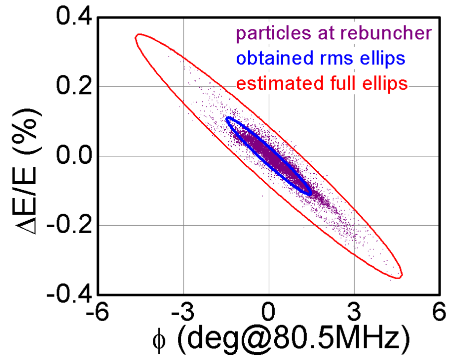
$$\varepsilon = \sqrt{(\sigma_r)_{11} \cdot (\sigma_r)_{22} - (\sigma_r)_{21}^2}$$

$$\beta_r = \frac{(\sigma_r)_{11}}{\varepsilon} \quad \gamma_r = \frac{(\sigma_r)_{22}}{\varepsilon} \quad \alpha_r = -\frac{(\sigma_r)_{12}}{\varepsilon}$$

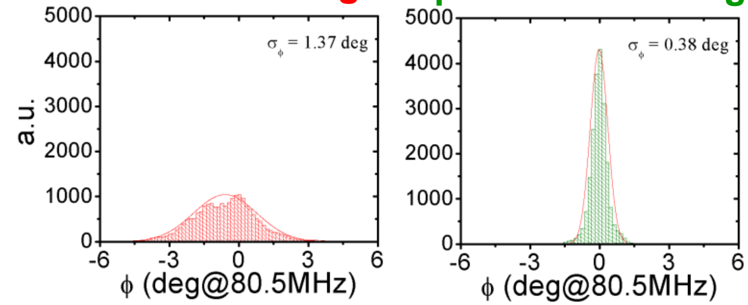


- Longitudinal matching to stripper
  - Measure bunch length vs. rebuncher voltage





Obtained Twiss Parameters



Observed bunch length

- Same method applies transverse matching by quad/solenoid scanning

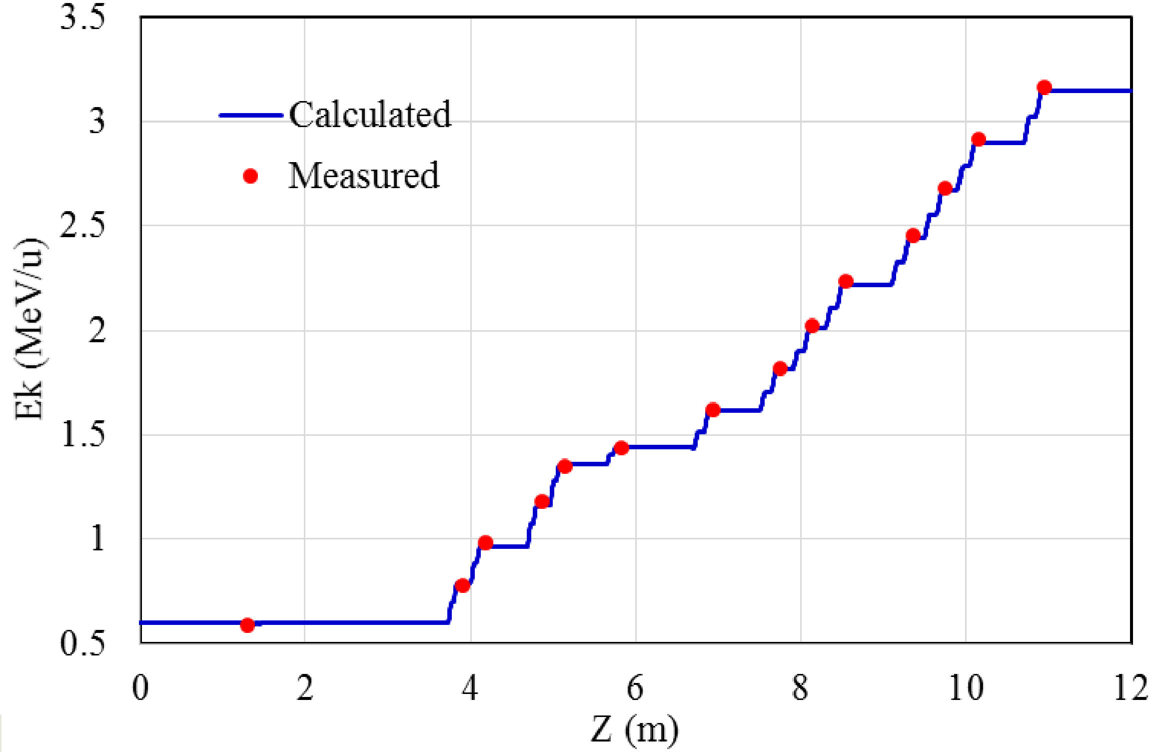
Calibrate Superconducting Resonator Voltages with Beam Energy Measurement

- Beam energy gain measured for each resonator
- Voltage accuracy is about a few percent based on beam measurement
- Energy gain along ReA3 linac - Calculated vs. Measured

$$\Delta E_i = \frac{q}{A} \cdot V_c \cdot \cos \varphi_i$$

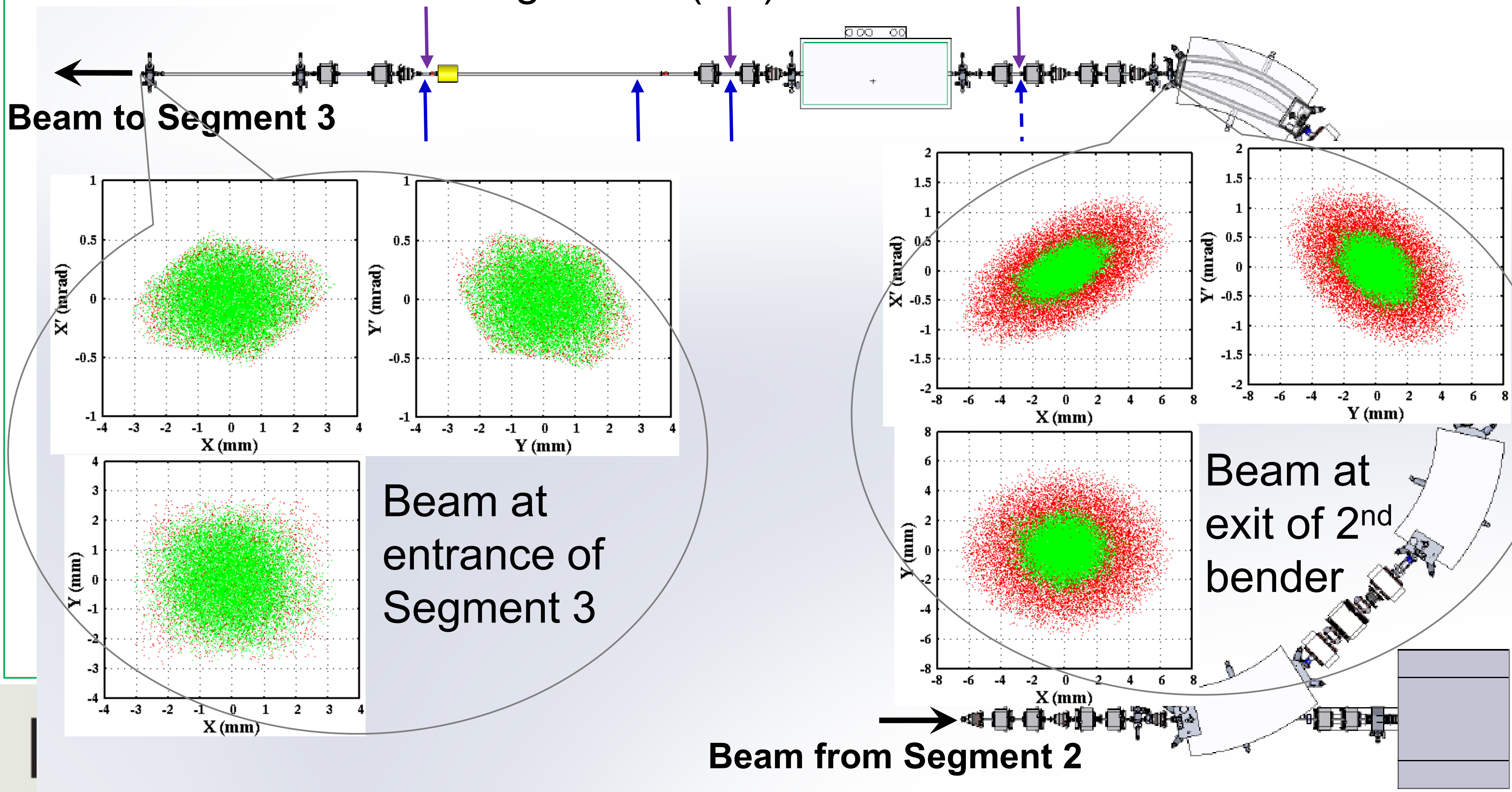
ΔE_i - energy gain
V_c - effective cavity voltage (cavity voltage * TTF)
φ_i - cavity phase

Helium beam with Q/A = 1/4



Beam Collimation at Warm Area

- Space reserved in warm area for possible beam collimation
  - 3 sets of slits (~60° phase advance) in both vertical and horizontal planes
  - **Larger emittance beam** vs. **normal one** at the exit of second bender (right) and the entrance of Segment 3 (left)



Summary

- FRIB accelerator has been designed, lattice performance has been evaluated, and it is under construction
- Beam simulation studies related to commissioning are being performed
  - Update more realistic data of each component in simulations
  - Beam sensitivity to component performance
  - Beam tuning for machine commissioning
  - Beam collimation to limit uncontrolled loss

Acknowledgements

- Coauthors: M. Ikegami, S. Lund, F. Marti, E. Pozdeyev, J. Wei, Y. Yamazaki
- We would like to thank the contributions and help from our colleagues at MSU: N. Bultman, E. Burkhardt, P. Chu, C. Compton, D. J. Crisp, J. Crisp, A. Facco, F. Feyzi, P. Gibson, I. Grender, P. Guetschow, M. Guillaume, W. Hartung, Z. He, L. Hoff, K. Holland, A. Hussain, M. Johnson, G. Kiupel, S. Krause, A. Lapierre, S. Lidia, Z. Liu, S. Miller, G. Morgan, D. Leitner, M. Leitner, D. Morris, S. Nash, J. Popielarski, X. Rao, R. Rencsok, R. Ronningen, T. Russo, K. Saito, D. Sanderson, M. Shupter, R. Swanson, M. Syphers, A. Villari, R. Webber, W. Wittmer, X. Wu, O. Yair, B. Yonkers, A. Zeller, Y. Zhang, W. Zheng and many others.
- We are especially grateful to A. Aleksandrov, J. Billen, J. Bisognano, K. Crandall, H. Edwards, J. Galambos, R. Garnett, S. Henderson, G. Hoffstaetter, N. Holtkamp, B. Laxdal, W. Meng, P. Ostroumov, S. Ozaki, R. Pardo, S. Peggs, J. Qiang, D. Raparia, T. Roser, R. Ryne, J. Stovall, T. Wangler, Q. Yao, W. Yang, L. Young, etc. for their valuable advice, discussions, or collaborations.

FRIB Accelerator Layout

- 400 kW CW machine with uncontrolled beam loss limited to < 1 W/m
- Meet beam-on-target requirements (e.g. energy ≥ 200 MeV/u)
- Accelerate all varieties of stable ions → Uranium is most challenging in design (two & five charge states before and after stripper, respectively)
- Minimize project construction costs → Compact double-folded layout
- Maintain potential enhancement → Energy upgrade, ISOL targets, light ion injector