# Longitudinal beam dynamics in FRIB and ReA linacs

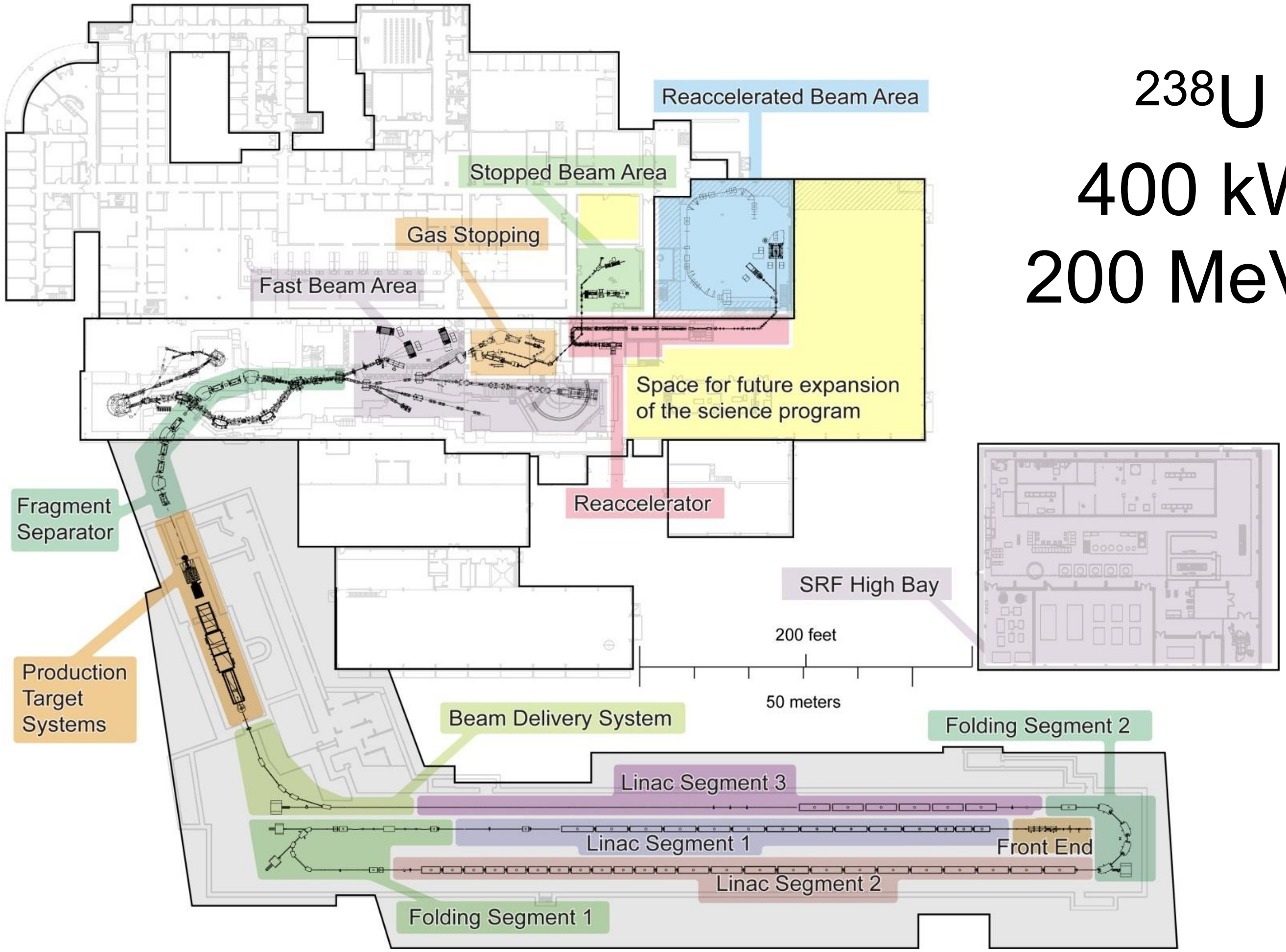
**Alexander Plastun,**

Peter N. Ostroumov, Antonio C.C. Villari, Qiang Zhao

October 24, 2018

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.

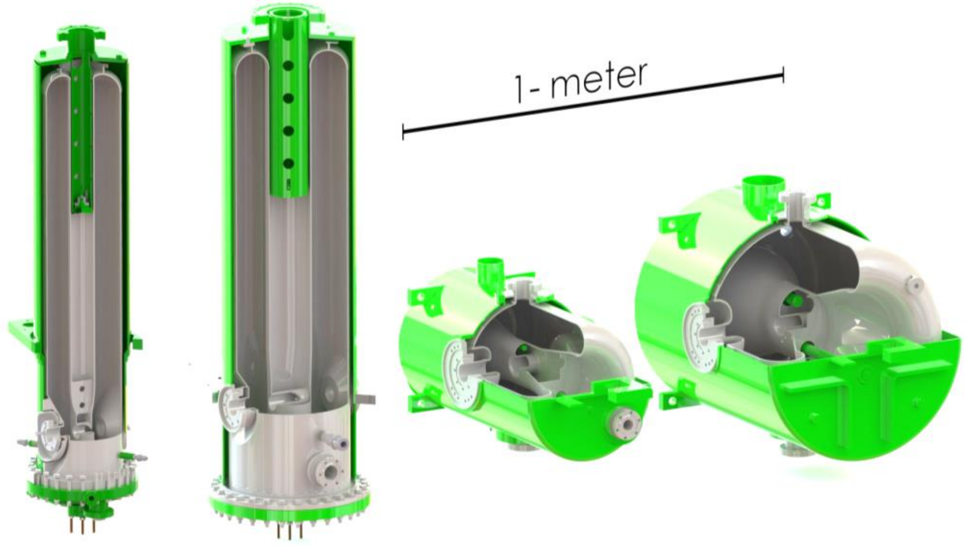
# Facility for Rare Isotope Beams




$^{238}U$

400 kW

200 MeV/u




| | QWR 80.5 MHz $\beta = 0.041$ | QWR 80.5 MHz $\beta = 0.085$ | HWR 322 MHz $\beta = 0.29$ | HWR 322 MHz $\beta = 0.53$ |
|---|---|---|---|---|
| # | 12 | 100 | 72 | 148 |

332 SRF cavities!
+ RT RFQ & Bunchers

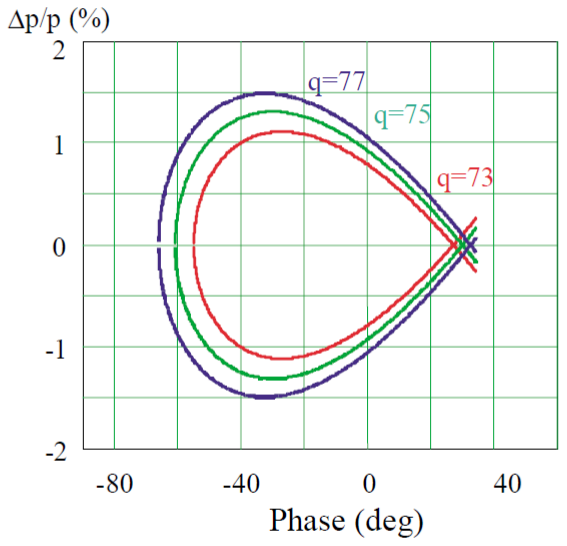
$^{238}U$ charge states: +76 +77 **+78** +79 +80

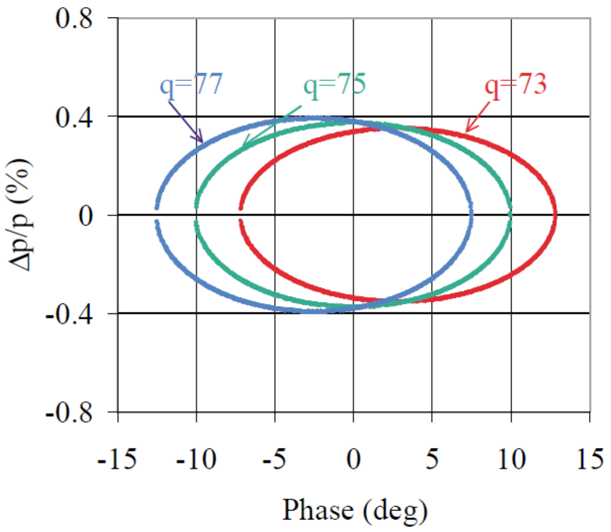
Beam Losses < 1W/m

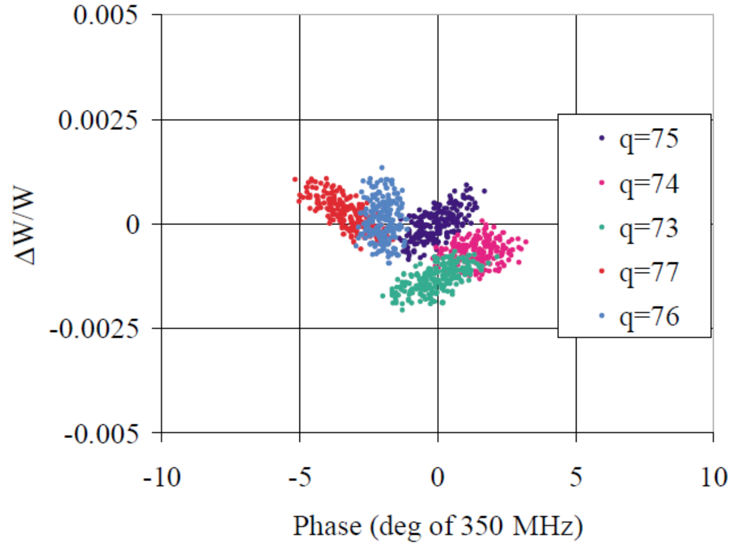
# Multi-charge state acceleration

Acceleration of several charge states is possible. Synchronous phases are joint through the condition:

$$\left(\frac{q}{A}\right)_i \cos\varphi_{s,q} = \frac{q_0}{A}\cos\varphi_{s,0}$$




P.N. Ostroumov and K. W. Shepard, Multiple-charge beam dynamics in an ion linac,
*PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS*, VOLUME 3, 030101 (2000)

# FRIB Front-end + CMA

FRIB Front End consists of
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- Beamlines to separate beam charge states
- Magnetic and electrostatic lenses to transport the beam
- Dipole magnets and e-bends to bend beam trajectory
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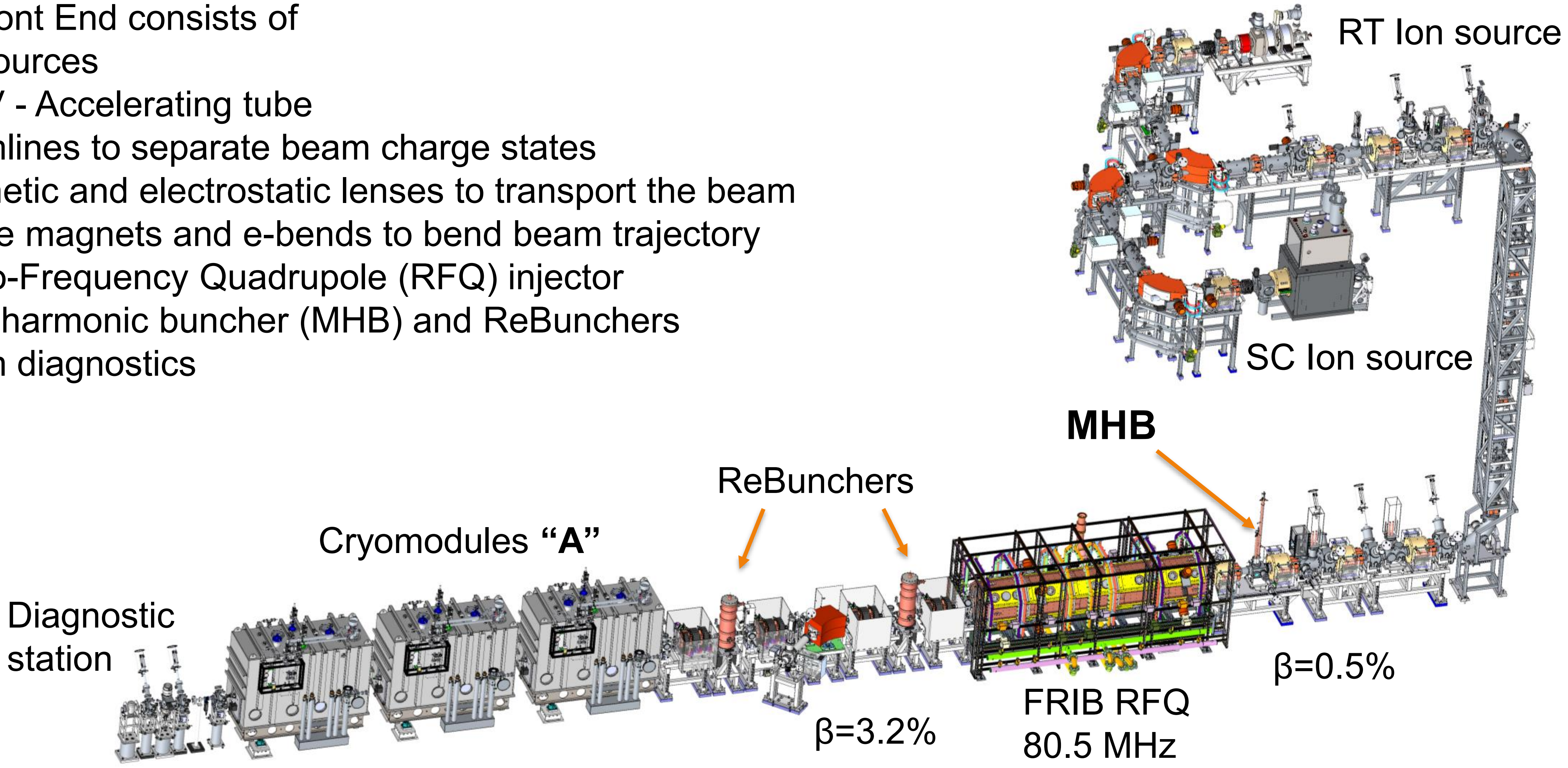
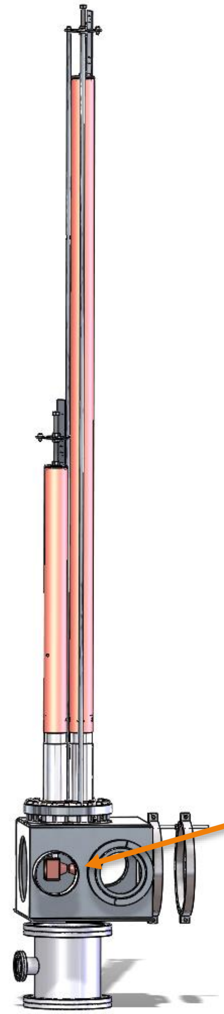
- Multi-harmonic buncher (MHB) and ReBunchers
- Beam diagnostics




β=v/c

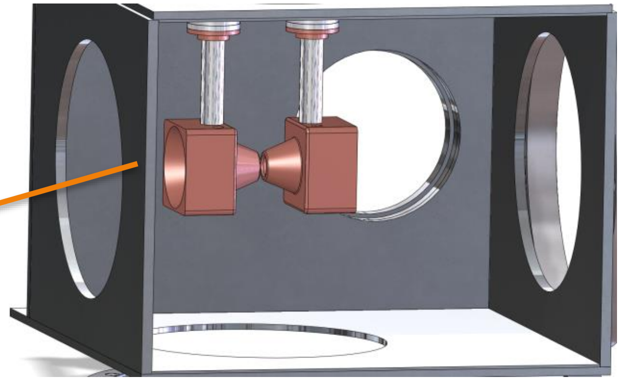
# Multi – Harmonic Buncher



Multi-Harmonic Buncher resonates at 3 harmonics – 40.25 MHz, 80.5 MHz, 120.75 MHz

Purpose of MHB is to:

- Provide small **longitudinal emittance** of the beam
- Provide bunched beam - no need to bunch inside the RFQ, i.e. **RFQ** can be **shorter**
- Provide **matching** with the RFQ acceptance



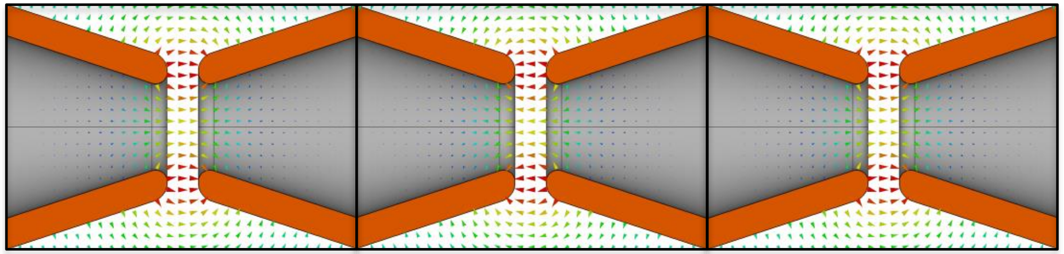
We didn't have any tools to characterize the beam longitudinal emittance…

# Simulation-based tuning of MHB

## Real MHB

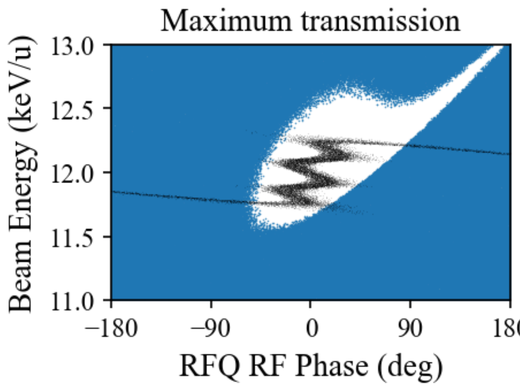
Maximize the beam transmission through the RFQ

## Simulation model of the MHB

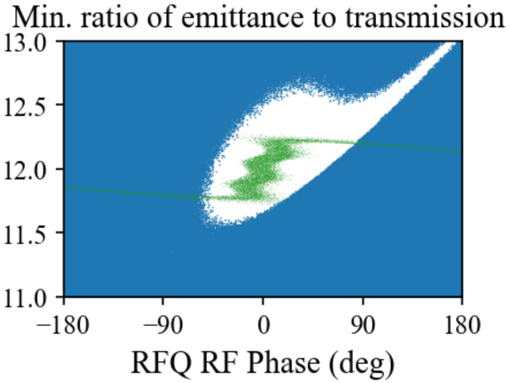


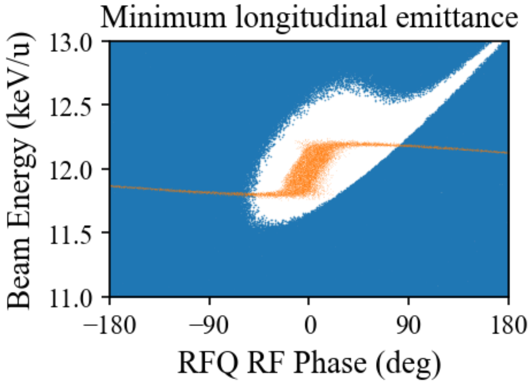
40.25 MHz 80.5 MHz 120.75 MHz

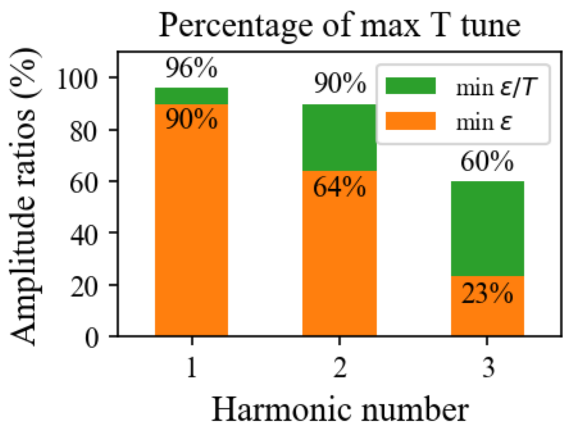
| MHB Tune | Long. emittance, rms (π·keV/u·ns) | RFQ+MEBT Transmission |
|---|---|---|
| Max T | 0.103 | 83.8% |
| Min ε/T | 0.079 | 81.6% |
| Min ε | 0.074 | 76.3% |




White area represents RFQ acceptance

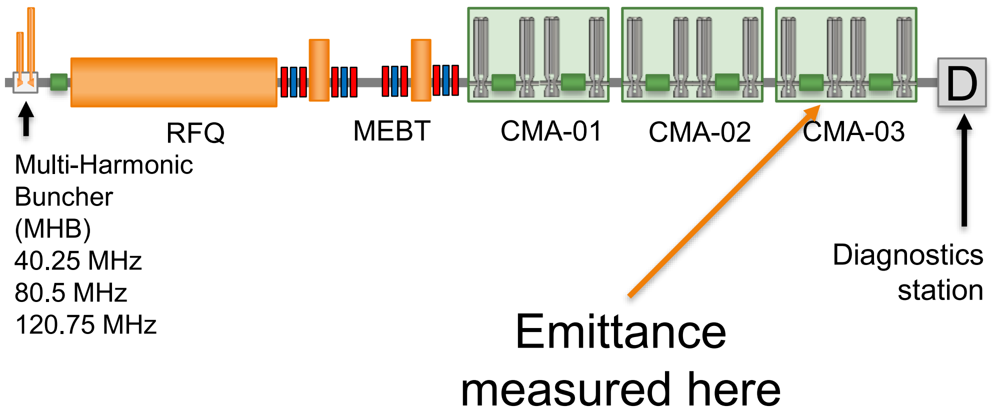


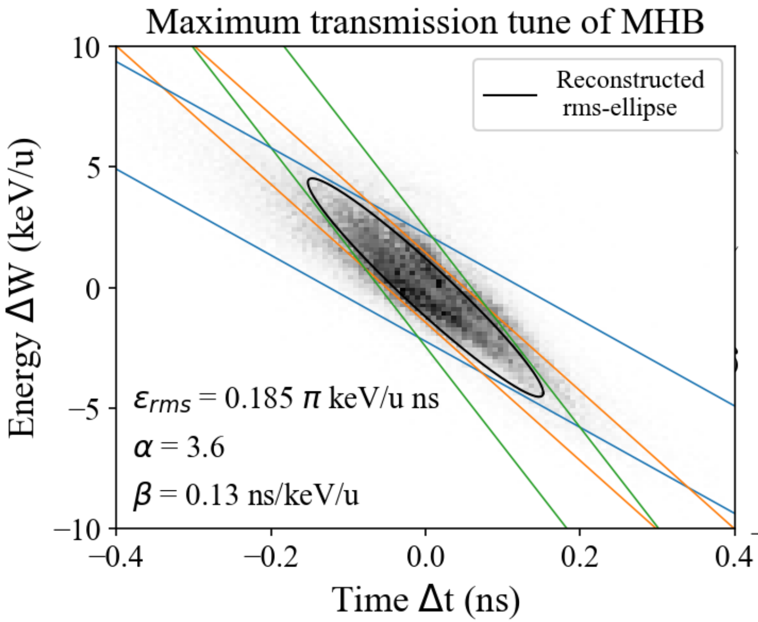



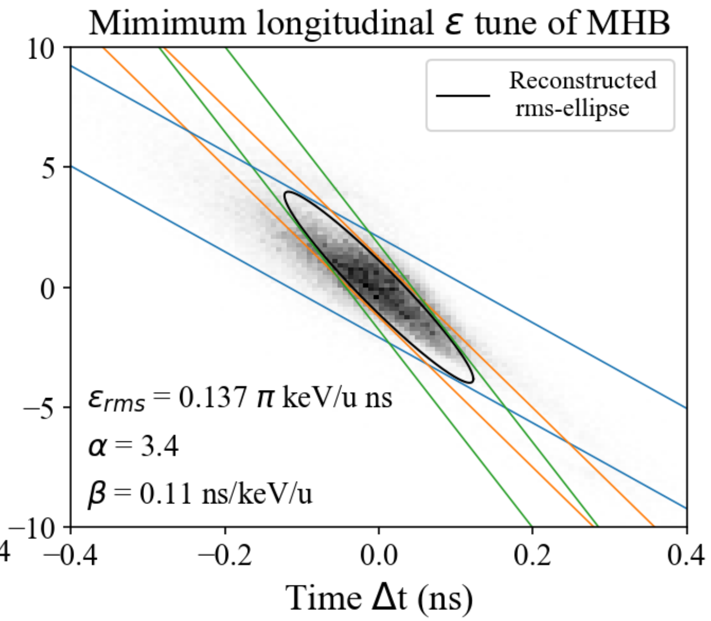



# Emittance measurements

Emittance was measured only after the first three cryomodule commissioning using the cavity field scan.



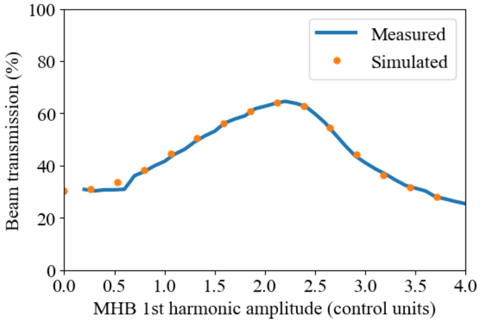



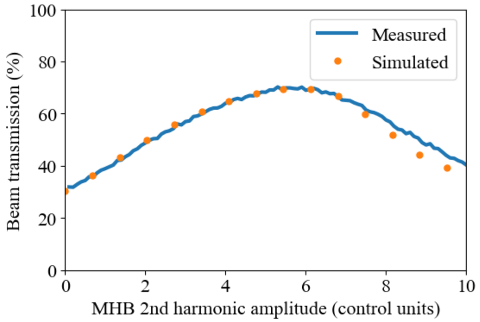

| MHB Tune | Maximum Transmission | Minimum ε |
| --- | --- | --- |
| Simulated emittance (π·keV/u·ns) | 0.14 | 0.12 |
| Measured emittance (π·keV/u·ns) | 0.19 | 0.14 |

# Simulation-based tuning of the MHB

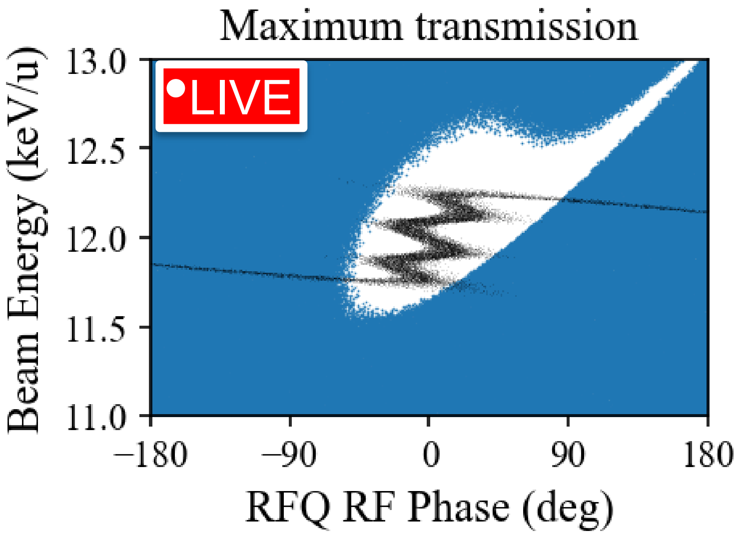
## 1D scans of MHB harmonics



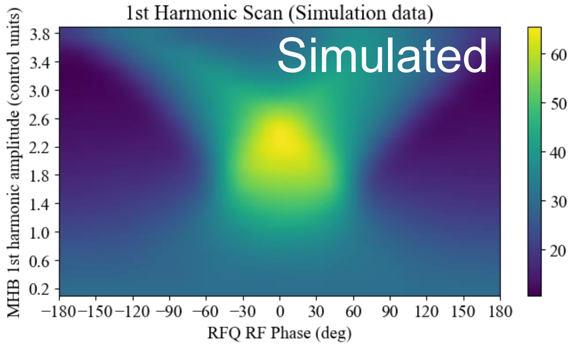

Single 1st harmonic scan

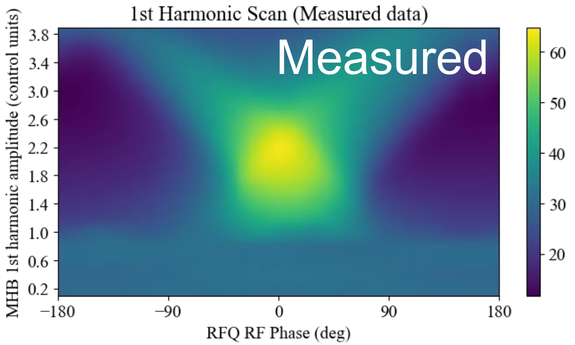



Single 2nd harmonic scan

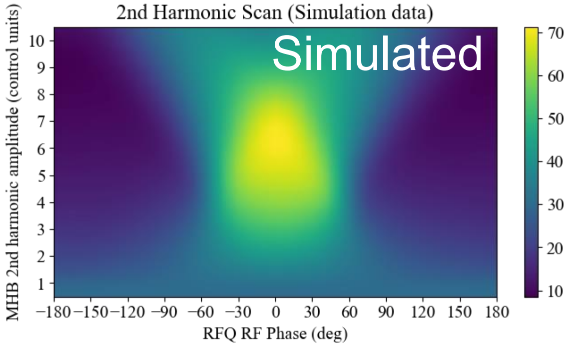


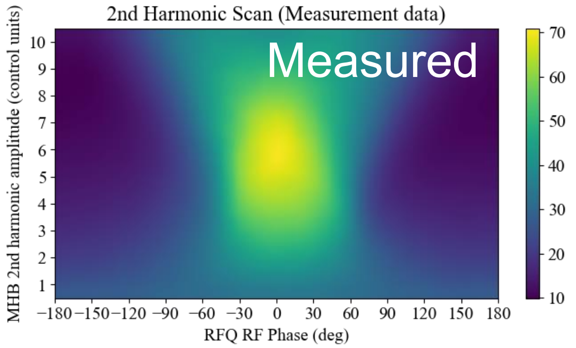

## 2D scans of MHB harmonics




Single 1st harmonic scan




Single 2nd harmonic scan

3rd harmonic calibration considers combination of the 2nd and 3rd harmonics.

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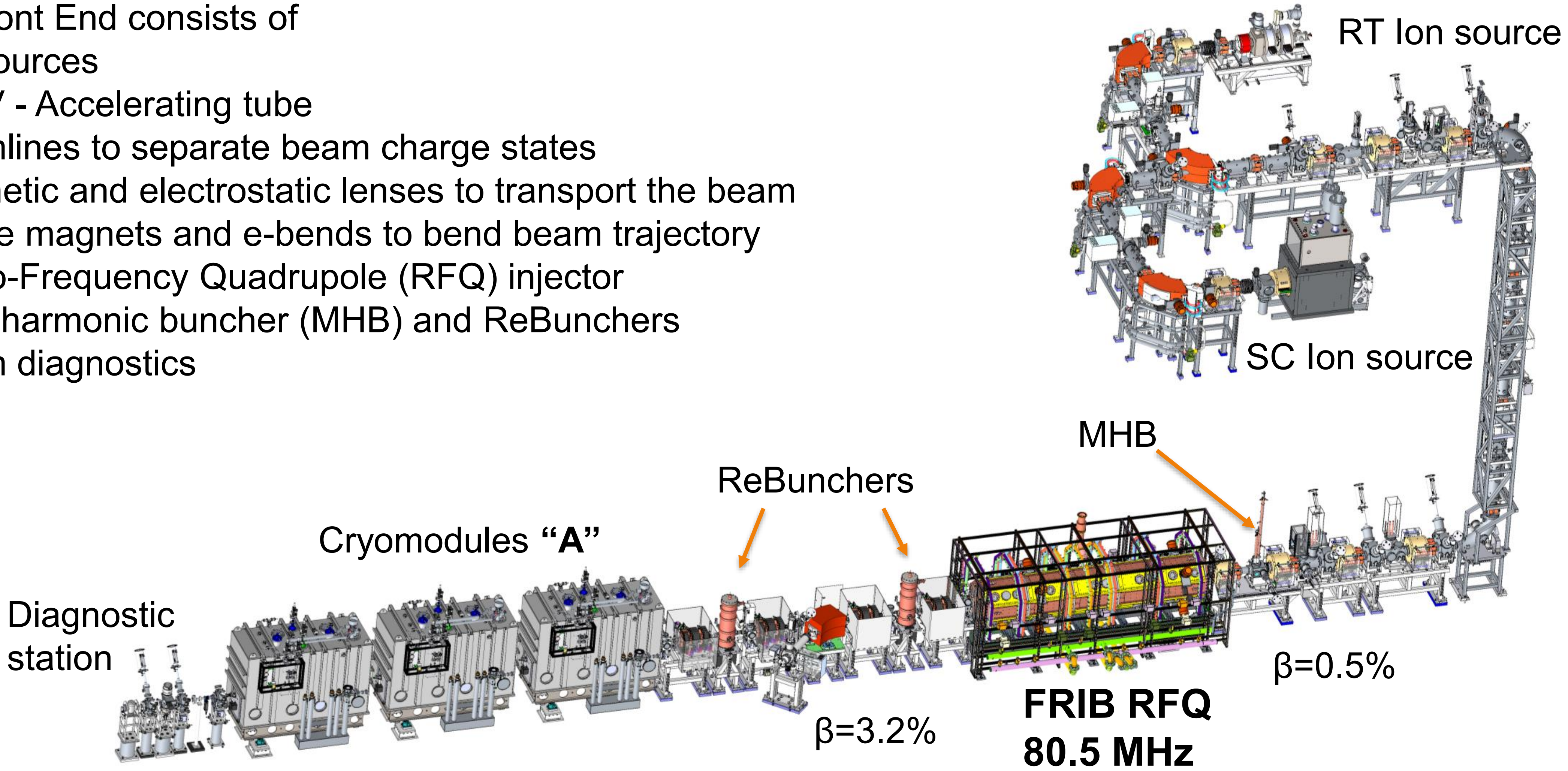
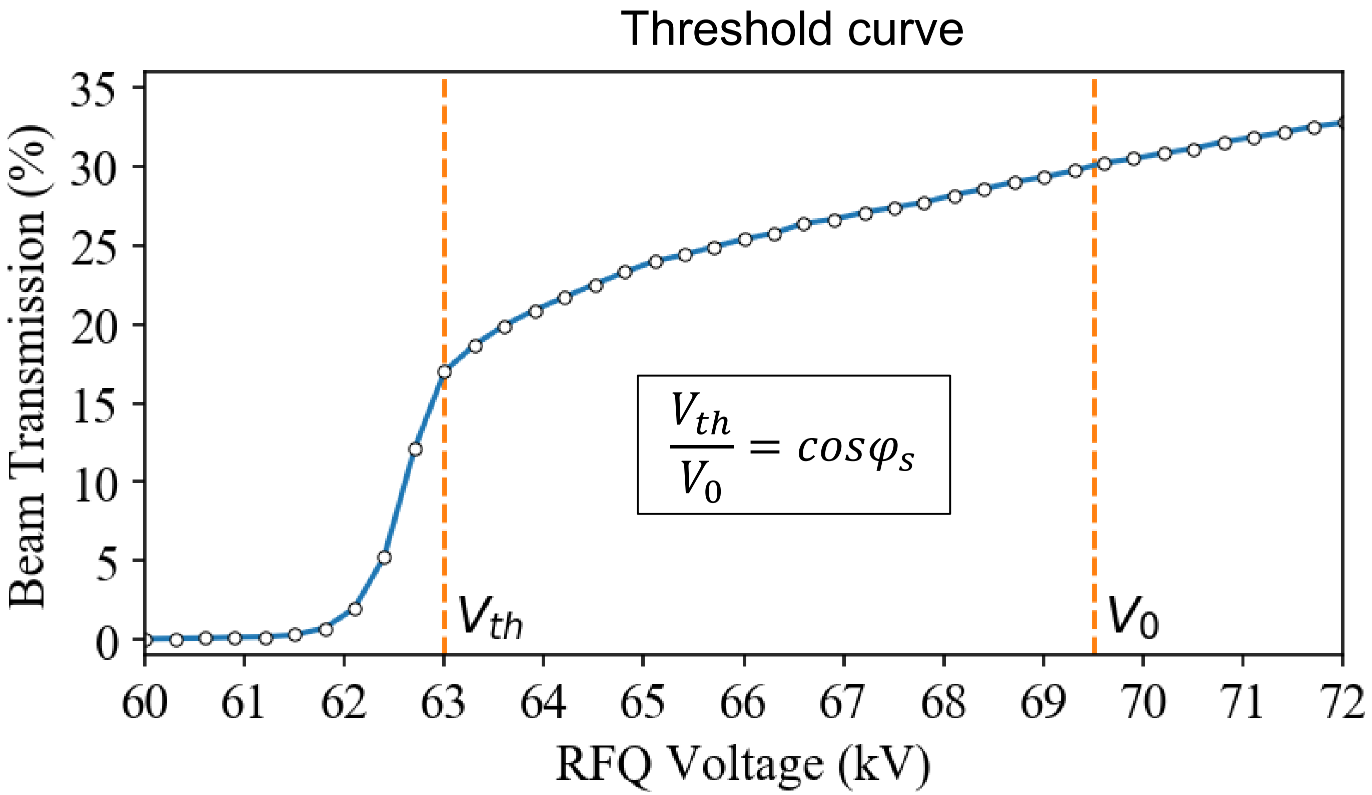


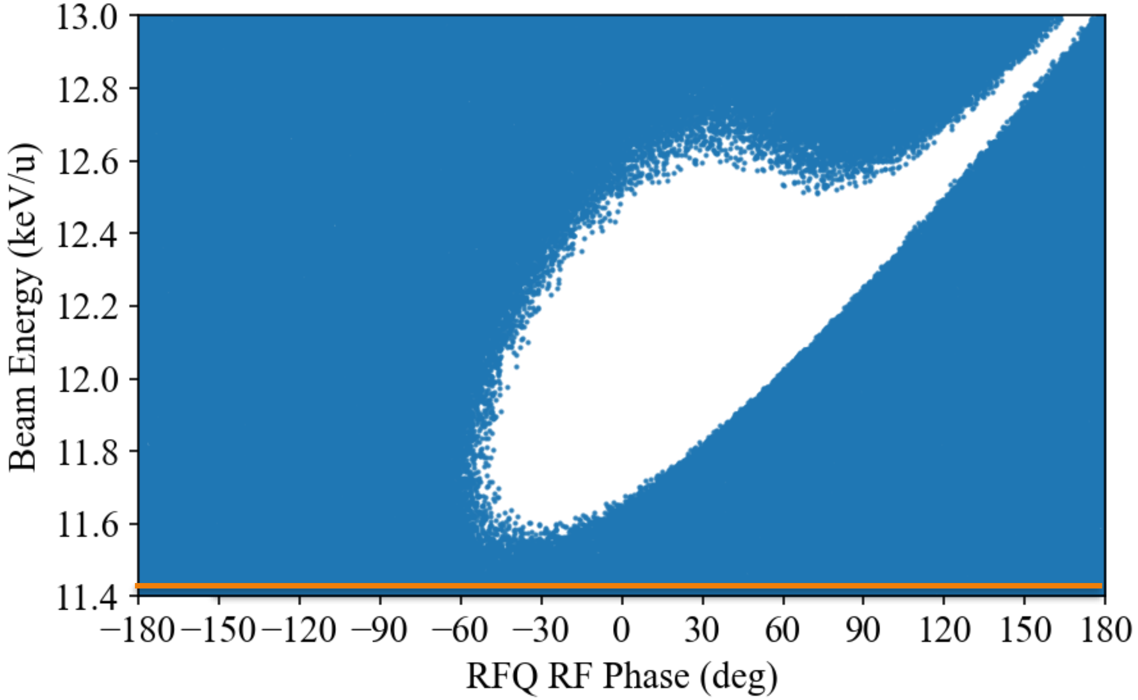

$\beta$=v/c

# RFQ

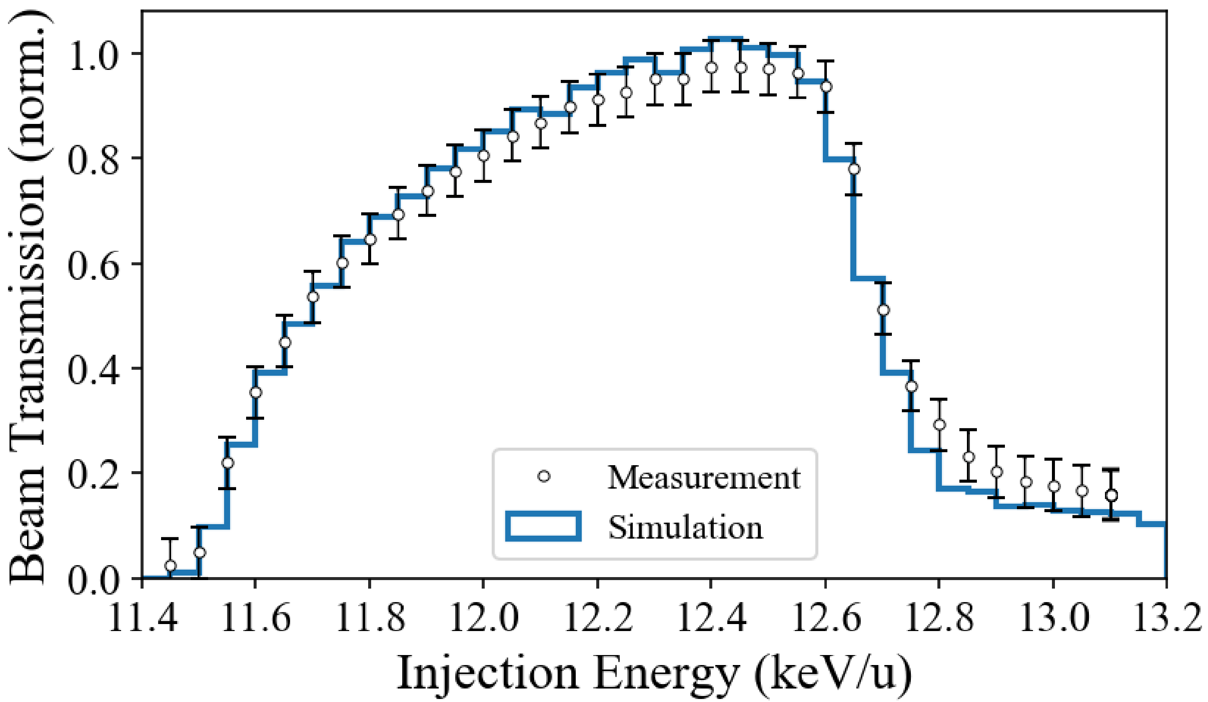
RFQ phase is always zero. Voltage is calibrated by *Threshold voltage* measurement.



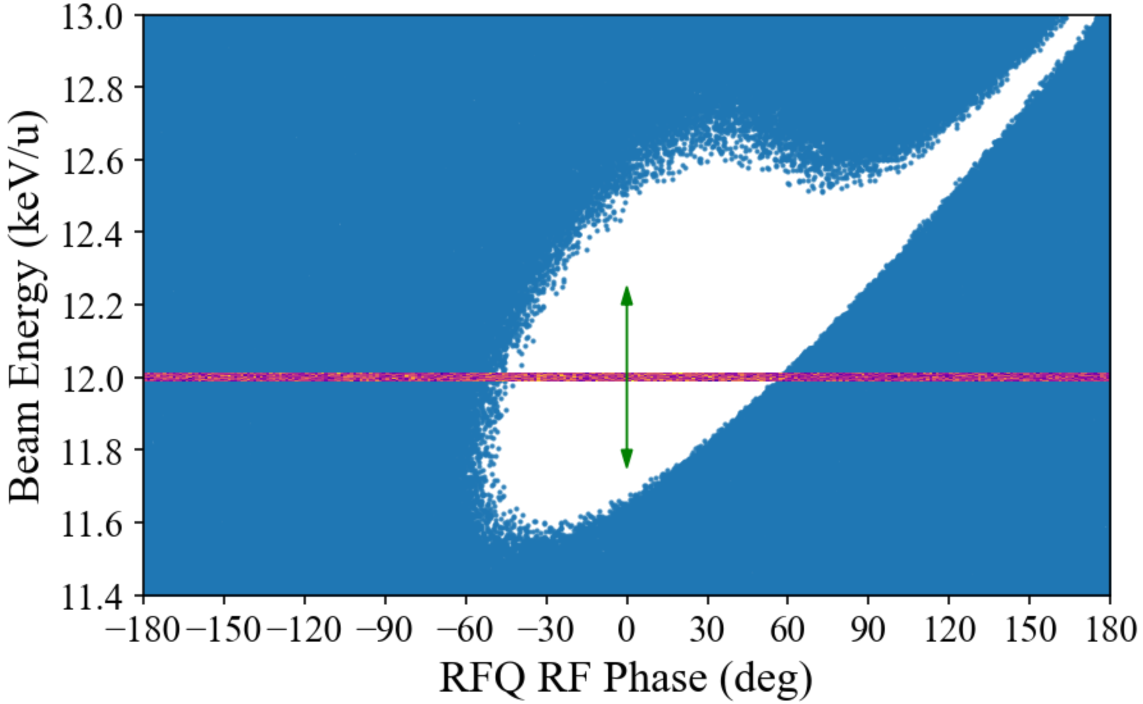
# RFQ



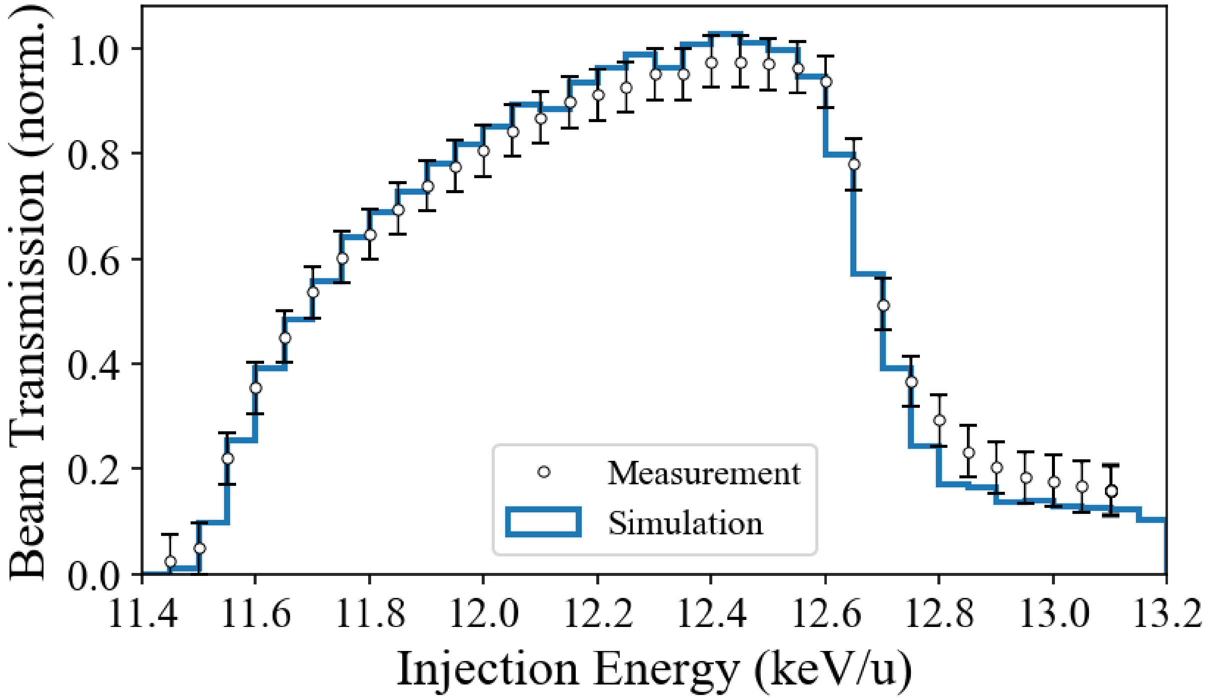

Energy profile of the RFQ acceptance



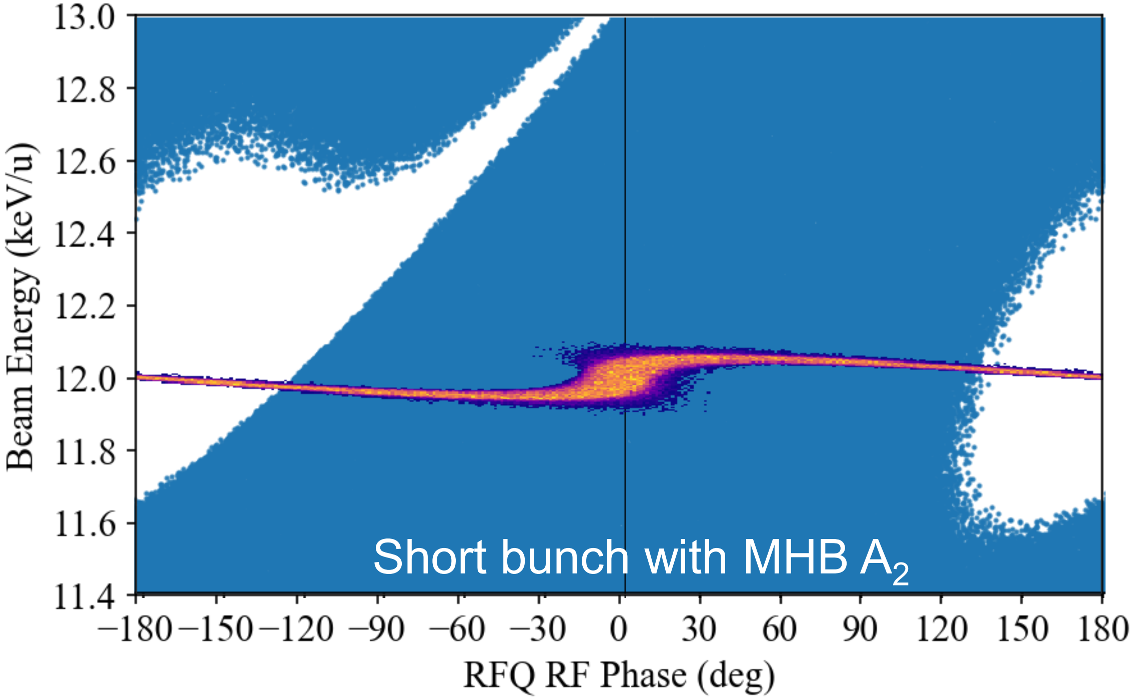
# RFQ

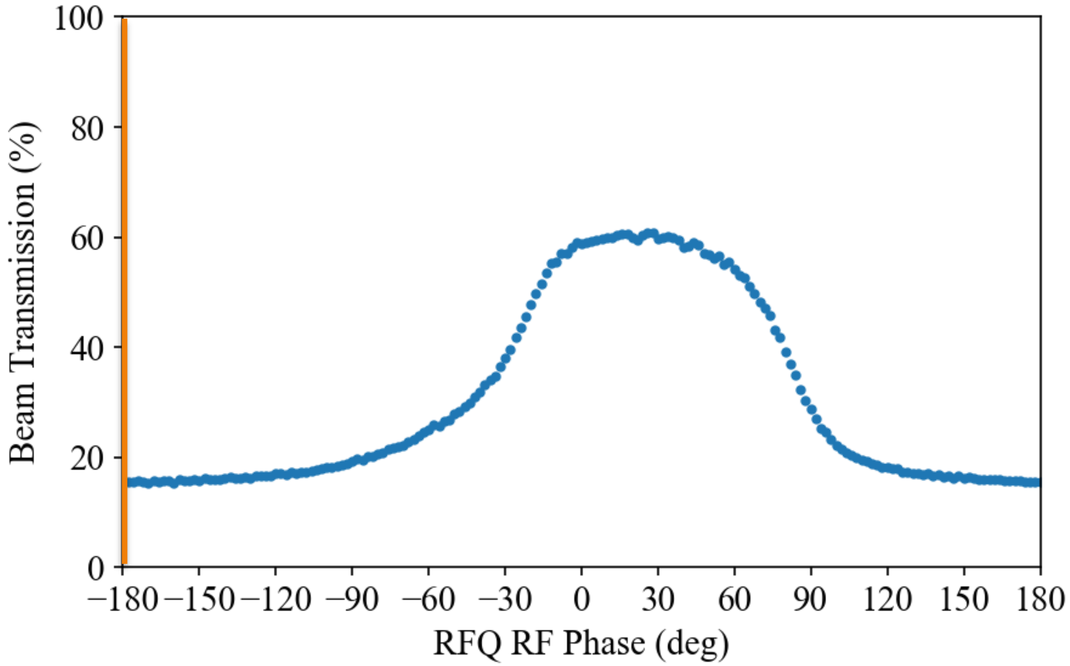



Energy profile of the RFQ acceptance



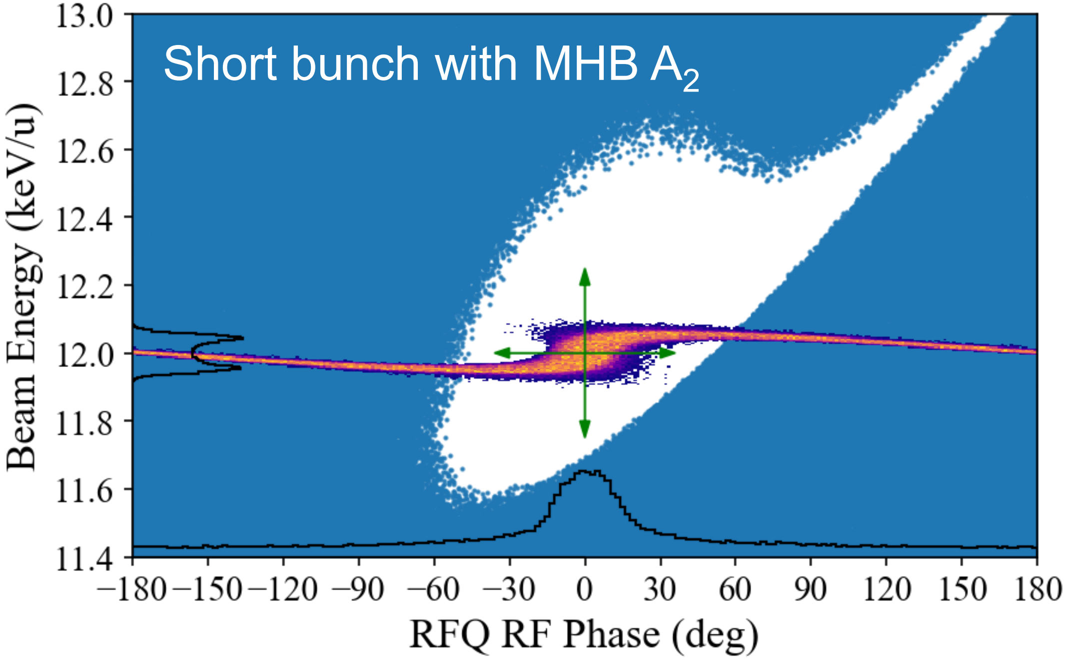
# RFQ Acceptance

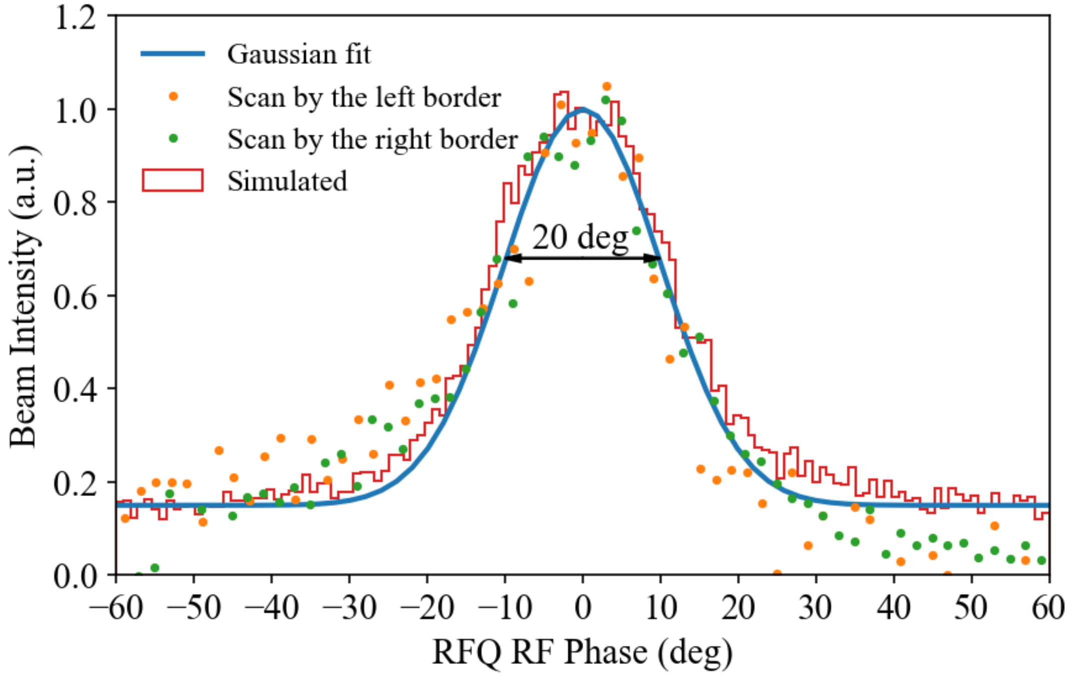



Convolution: $$T(\varphi) = \int_{-180^\circ}^{180^\circ} I_b(\theta) \cdot A(\varphi - \theta) d\theta$$

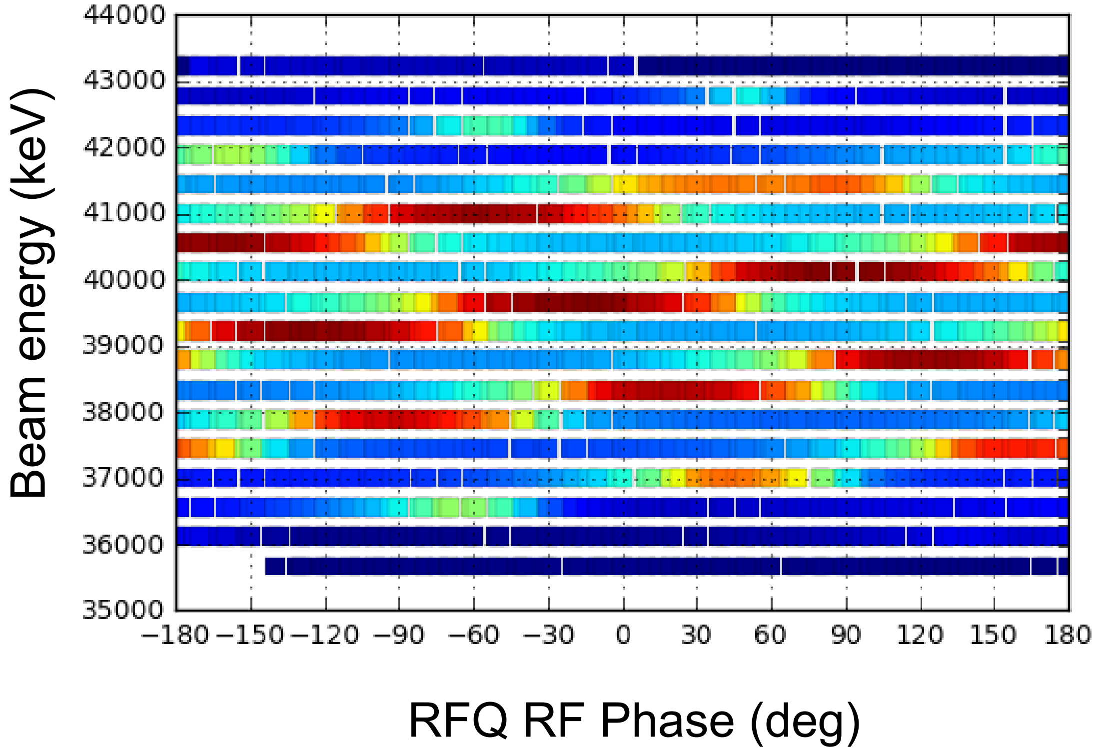
# RFQ Acceptance

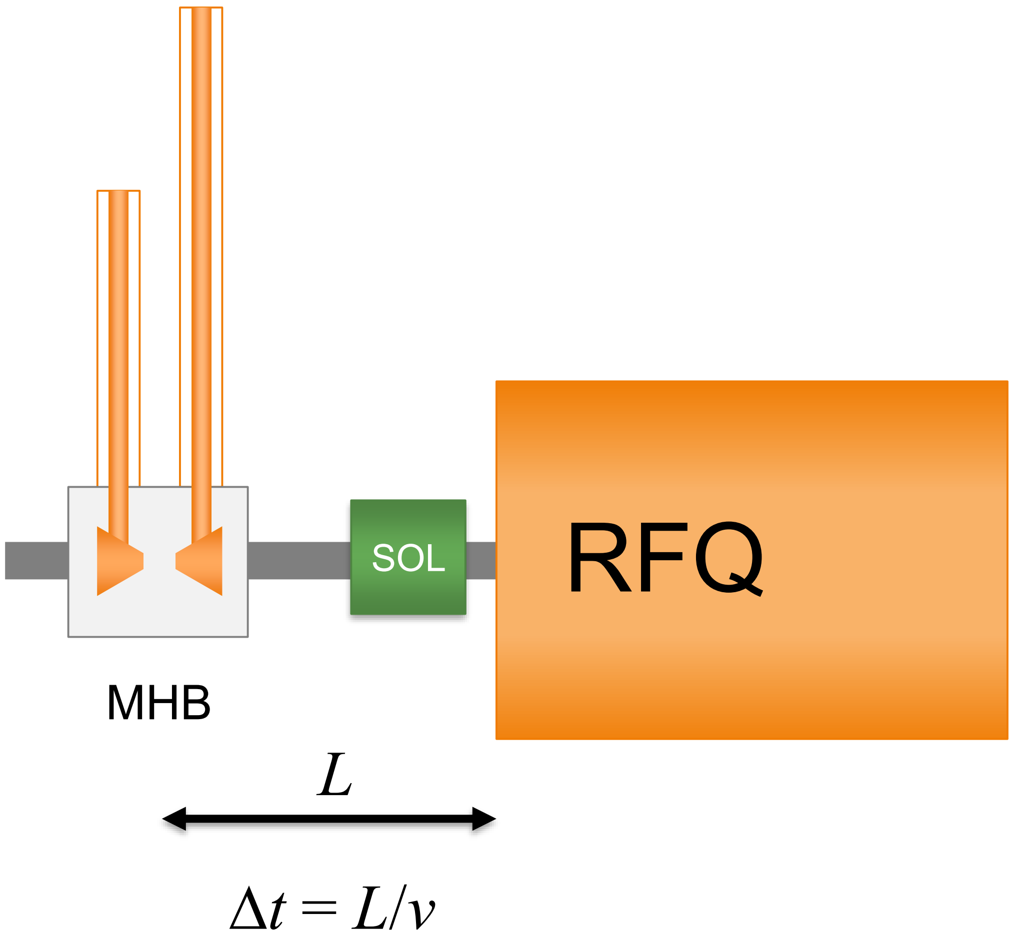


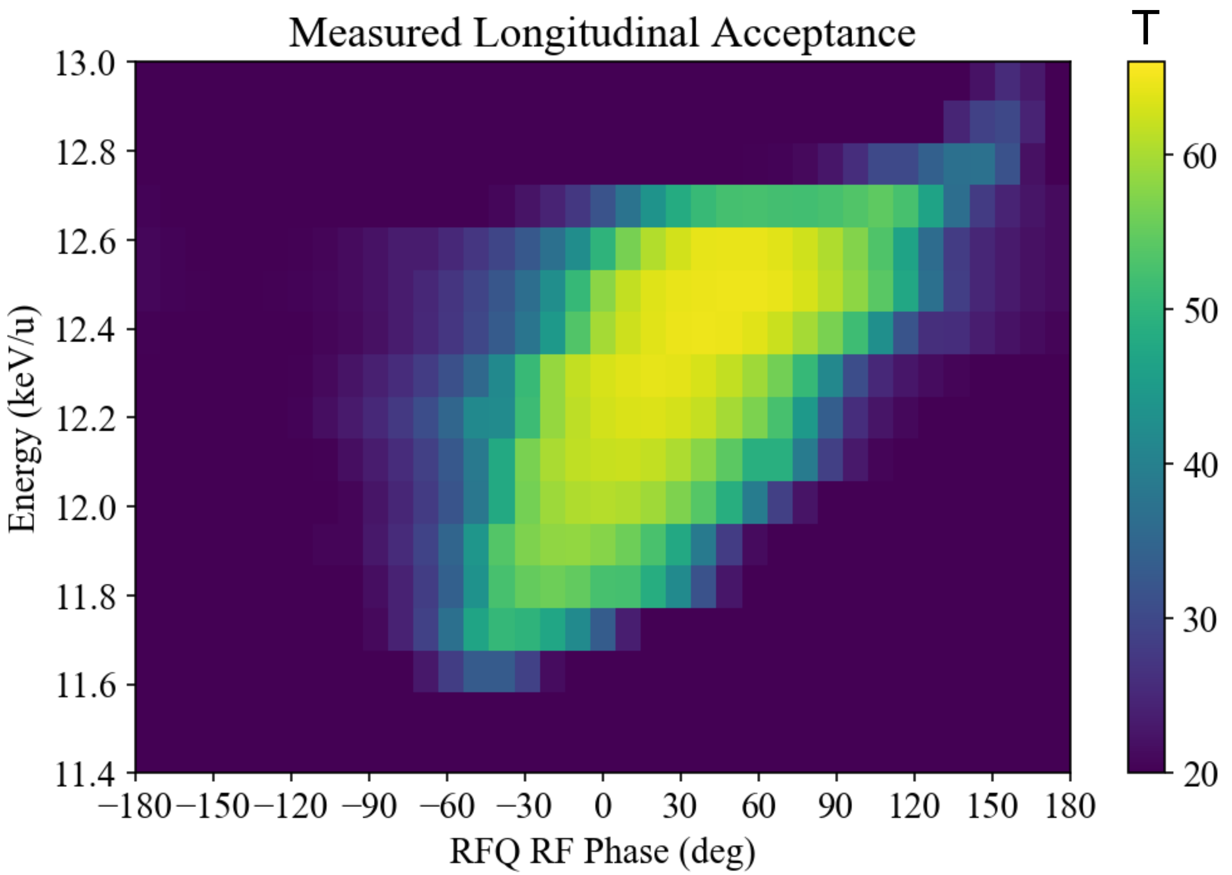

Convolution: $T(\varphi) = \int_{-180°}^{180°} I_b(\theta) \cdot A(\varphi - \theta) d\theta$

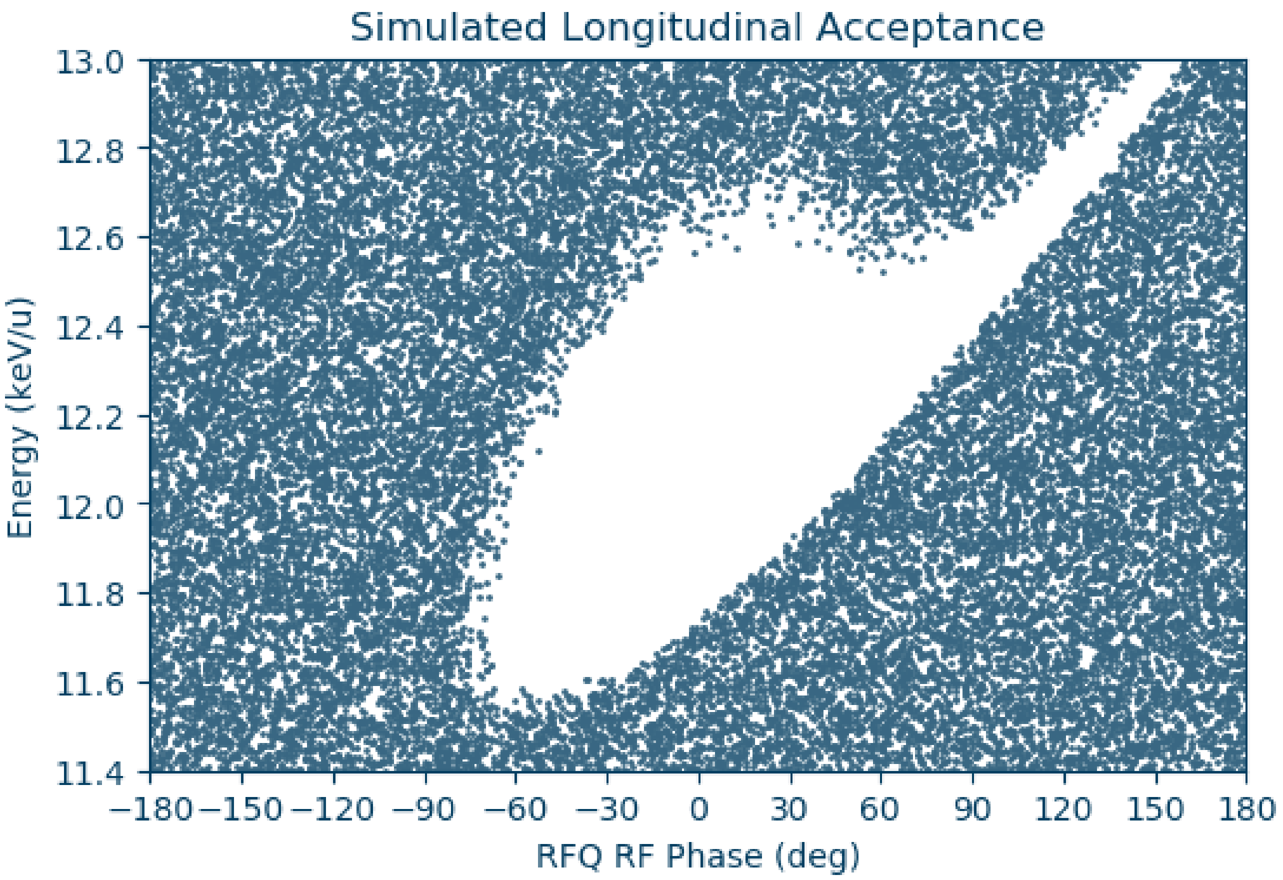
# RFQ Longitudinal Acceptance



# RFQ Longitudinal Acceptance



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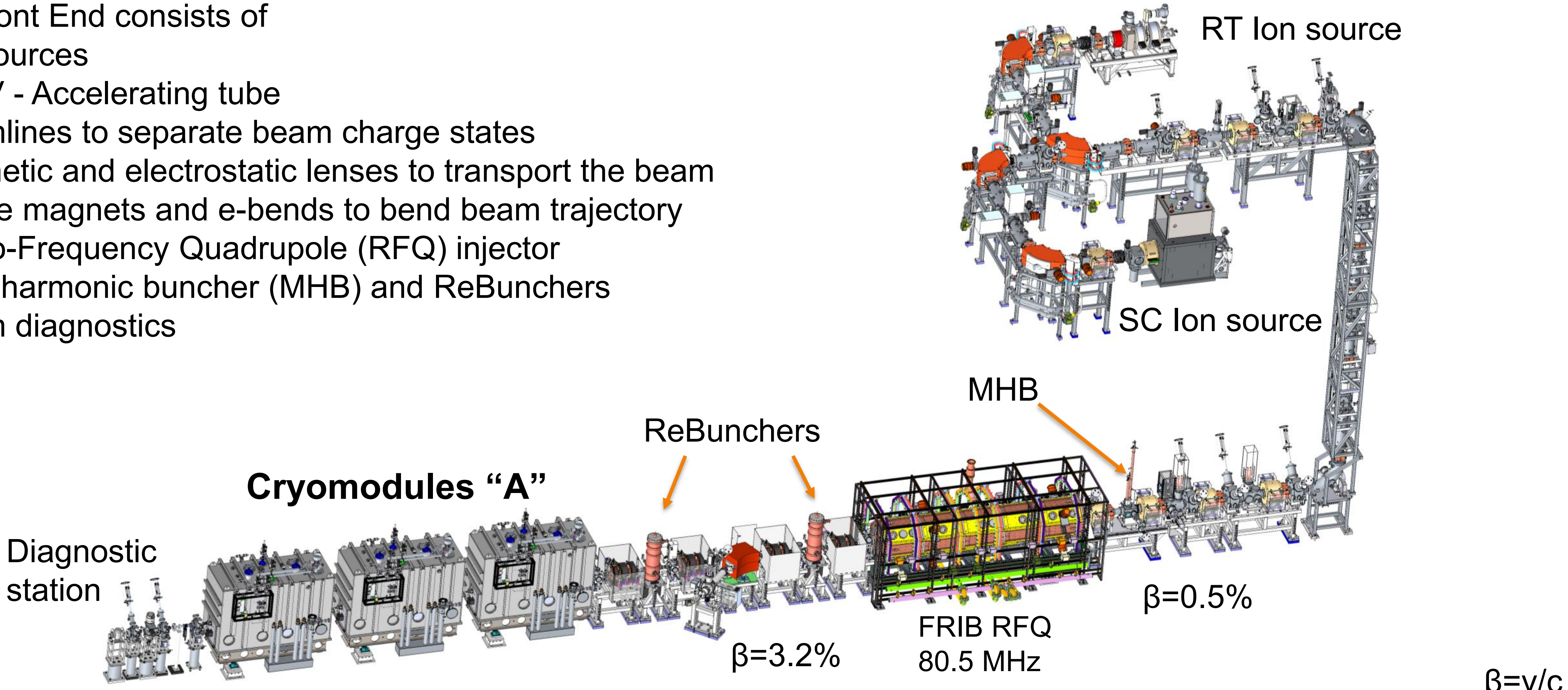
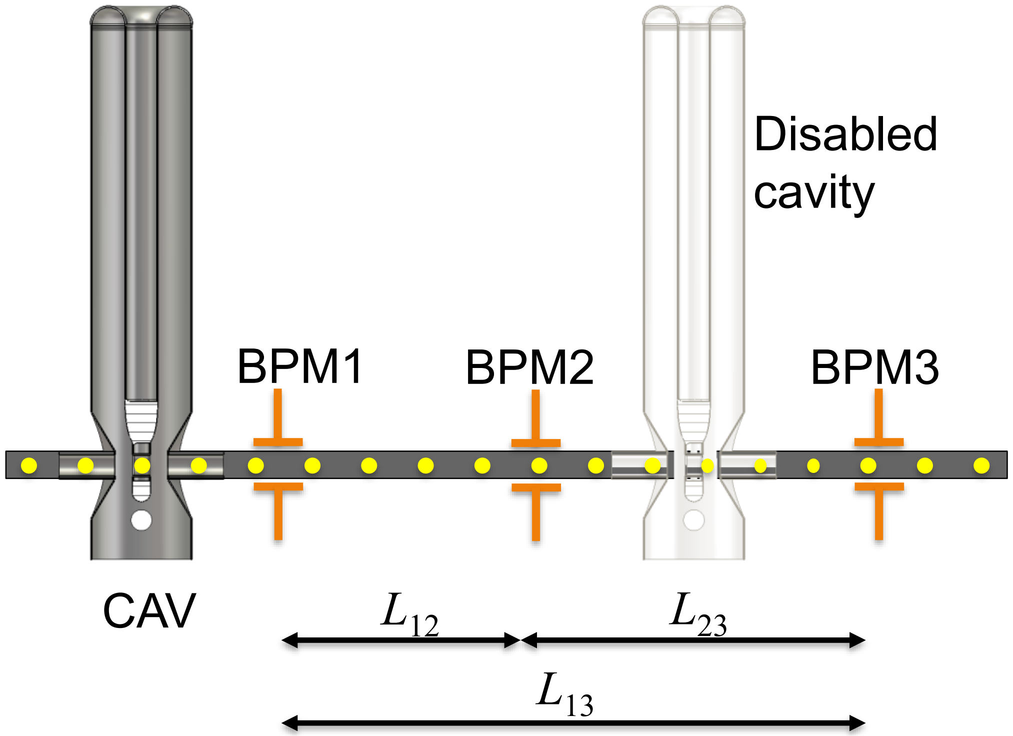
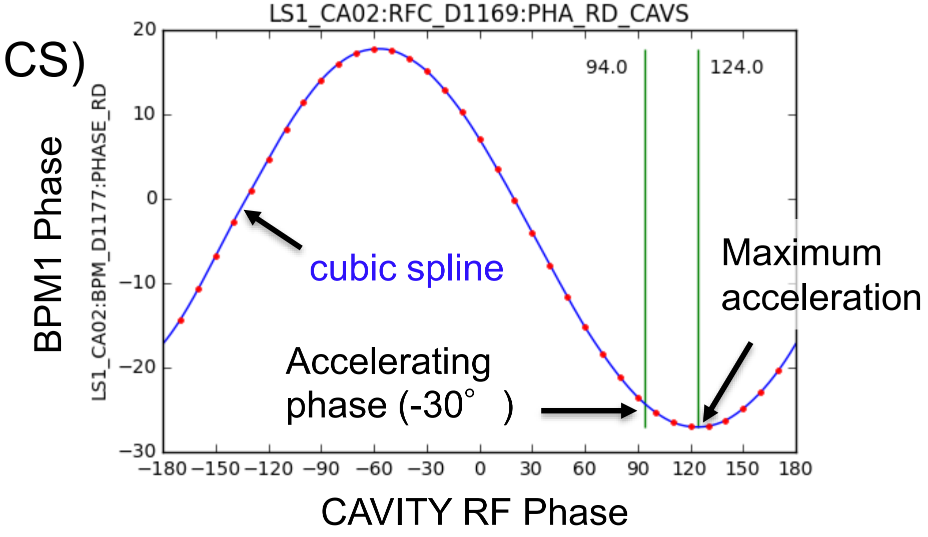


# Cavity tuning




- Phase scan:
  (Python script + EPICS)




- Energy gain Time-of-Flight measurement :

$$L_{12} = N\beta\lambda + \beta\lambda\frac{\varphi_2 - \varphi_1}{360°}$$

$$L_{23} = M\beta\lambda + \beta\lambda\frac{\varphi_3 - \varphi_2}{360°}$$

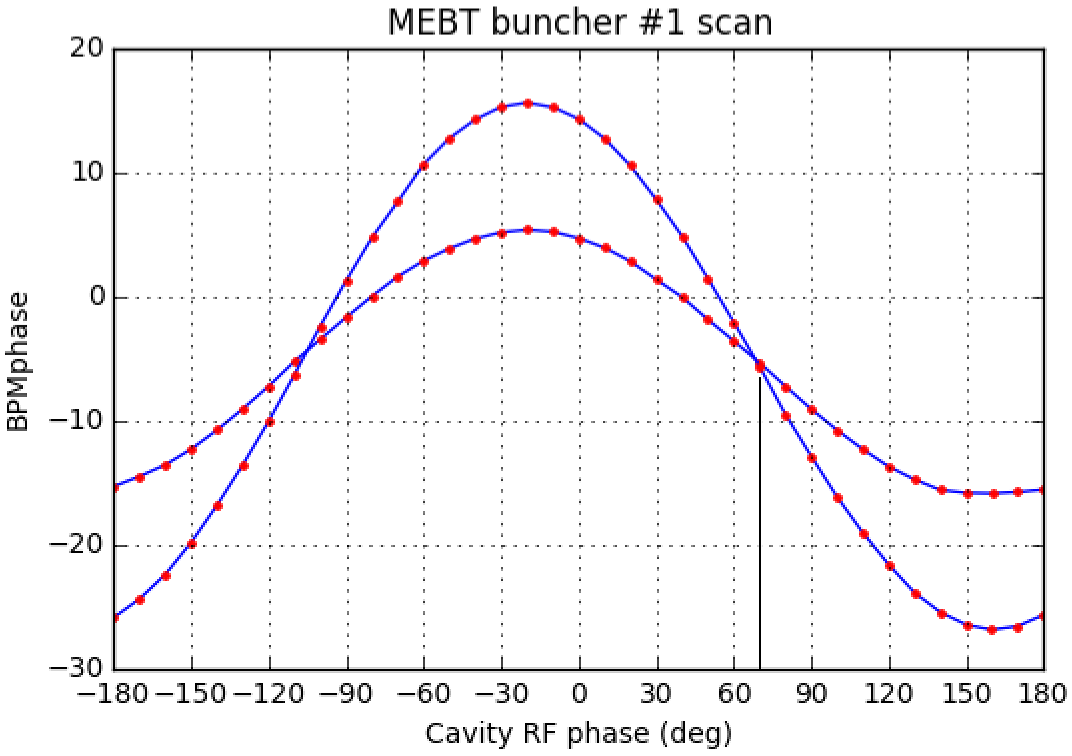
$$L_{23} = K\beta\lambda + \beta\lambda\frac{\varphi_3 - \varphi_1}{360°}$$

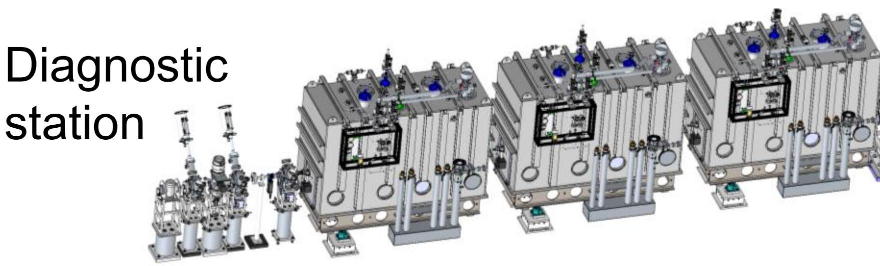
$N, M, K$ - integers

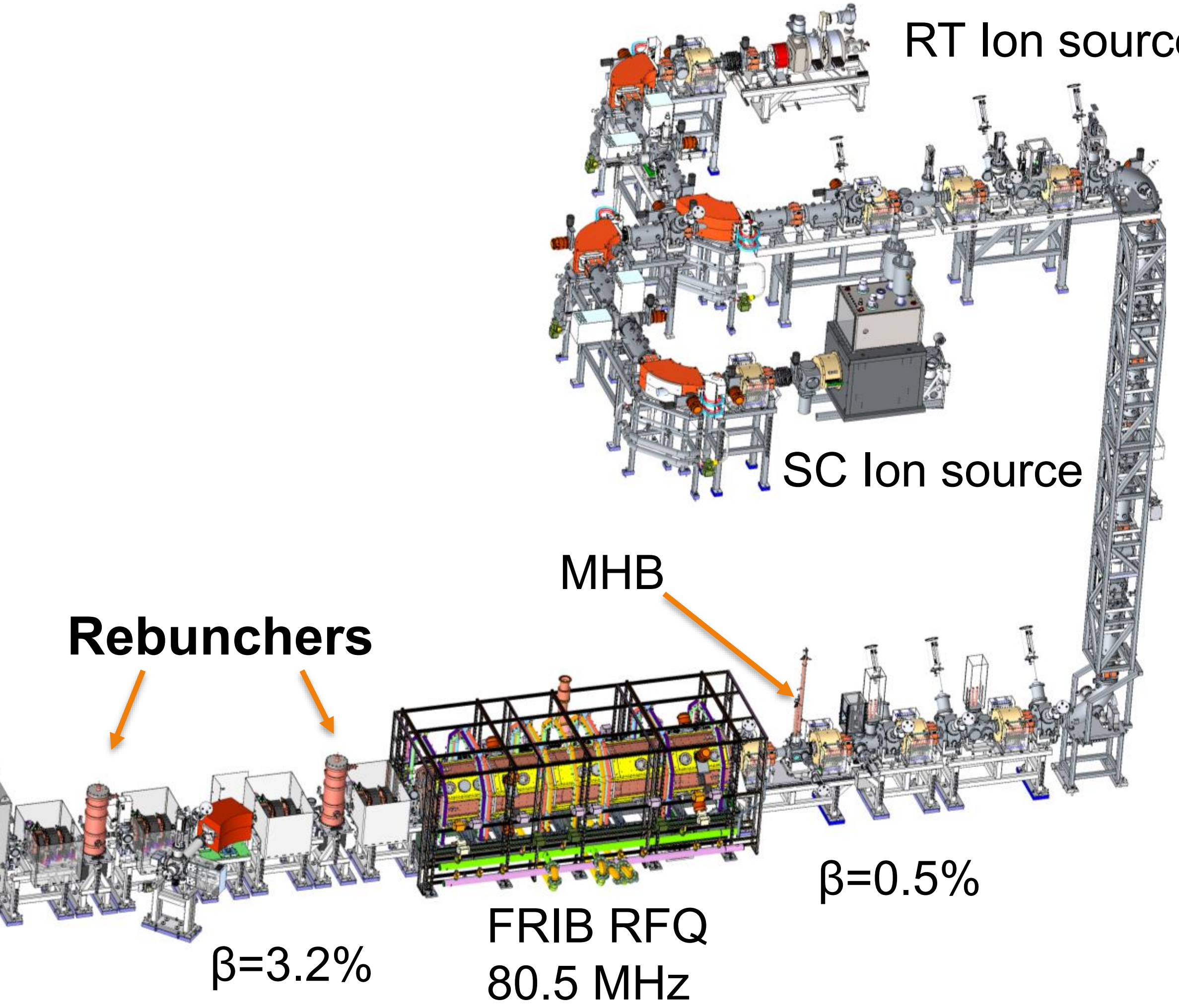
$$W = W_0\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right)$$

$$U_{eff} = \frac{\Delta W}{q cos\varphi}$$

# Rebuncher scan

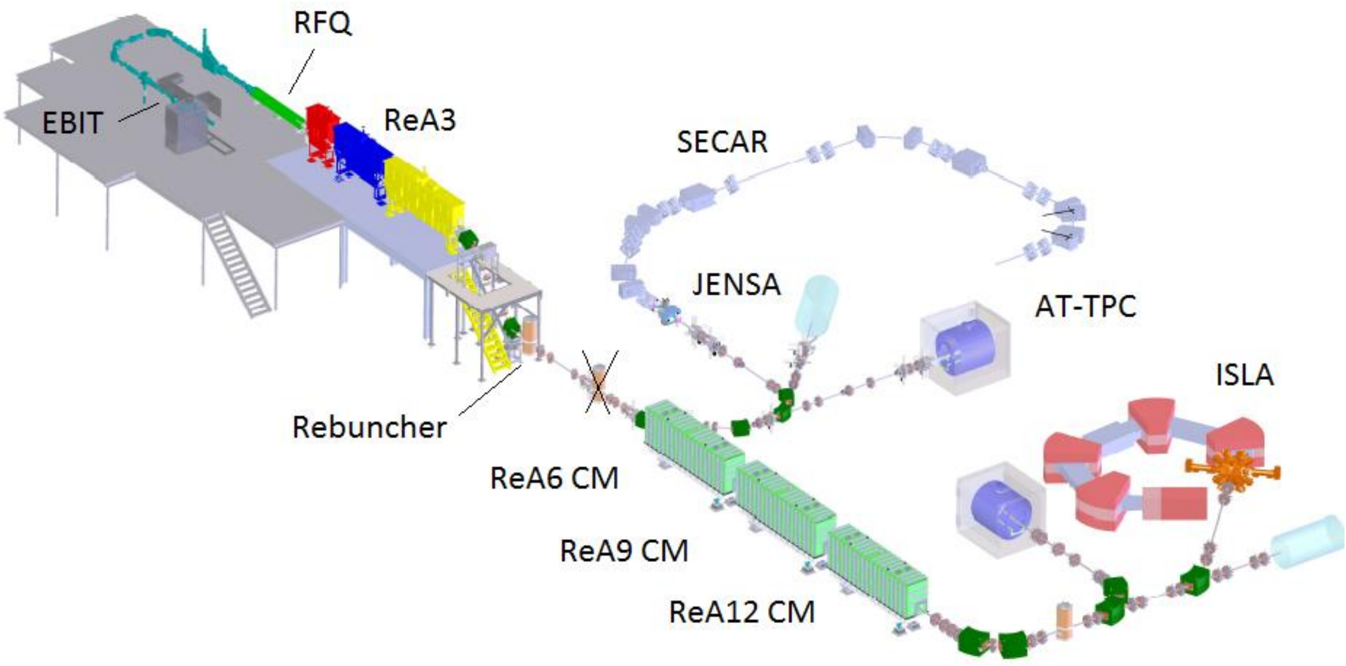


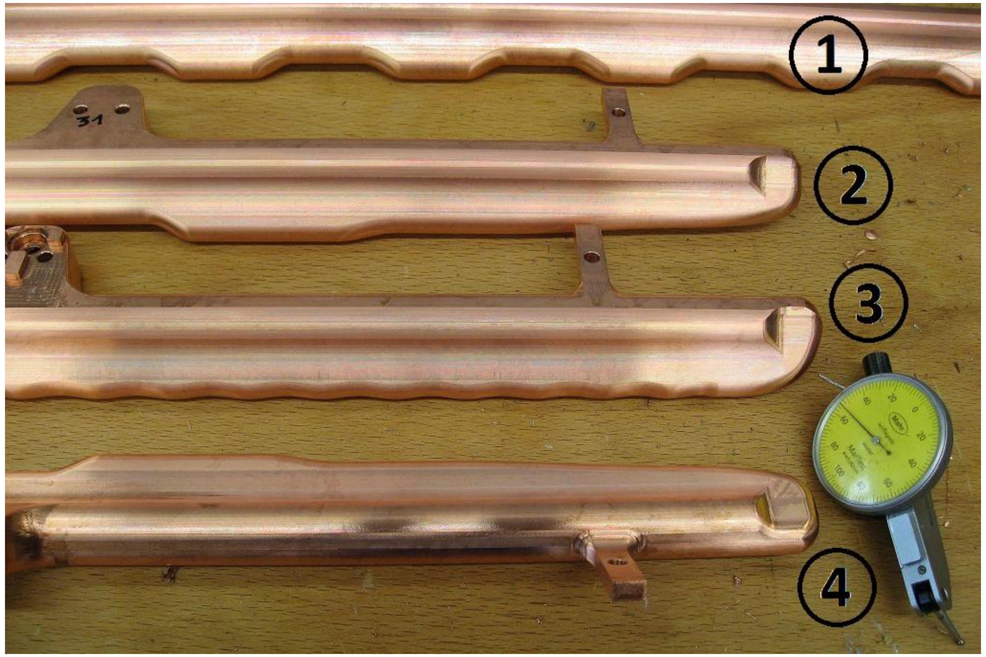




β=v/c

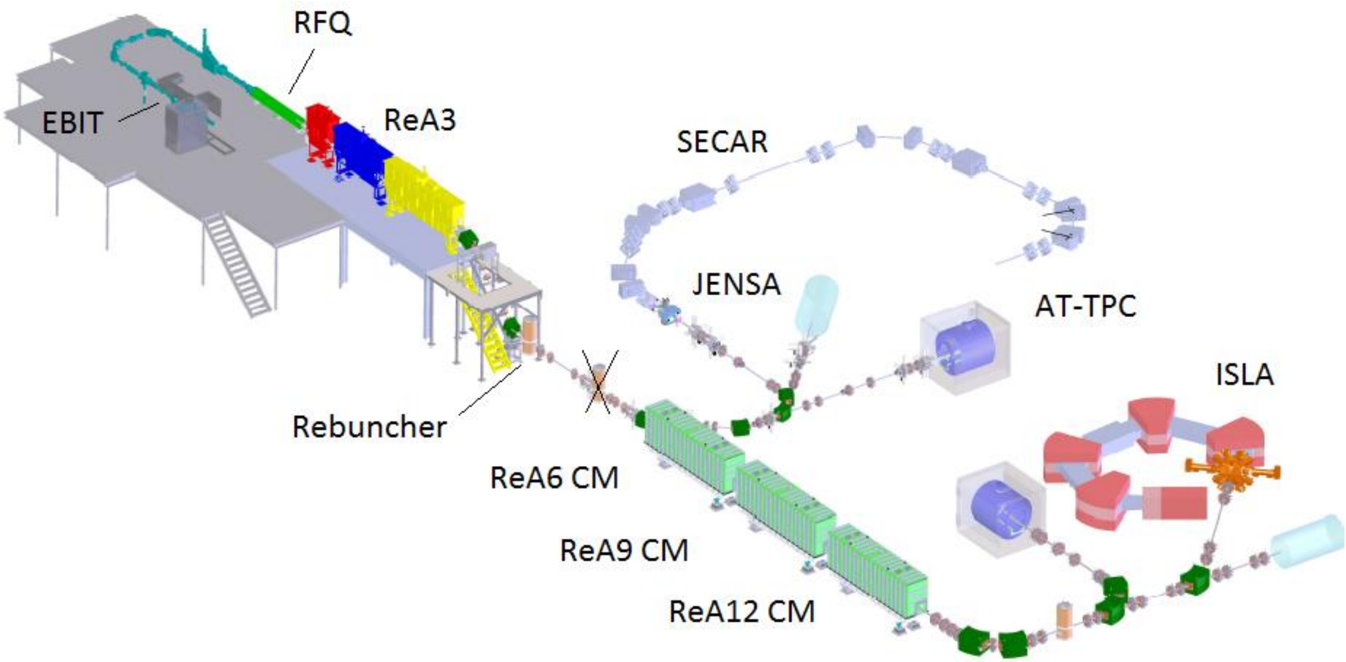
# MSU Reaccelerator Upgrade

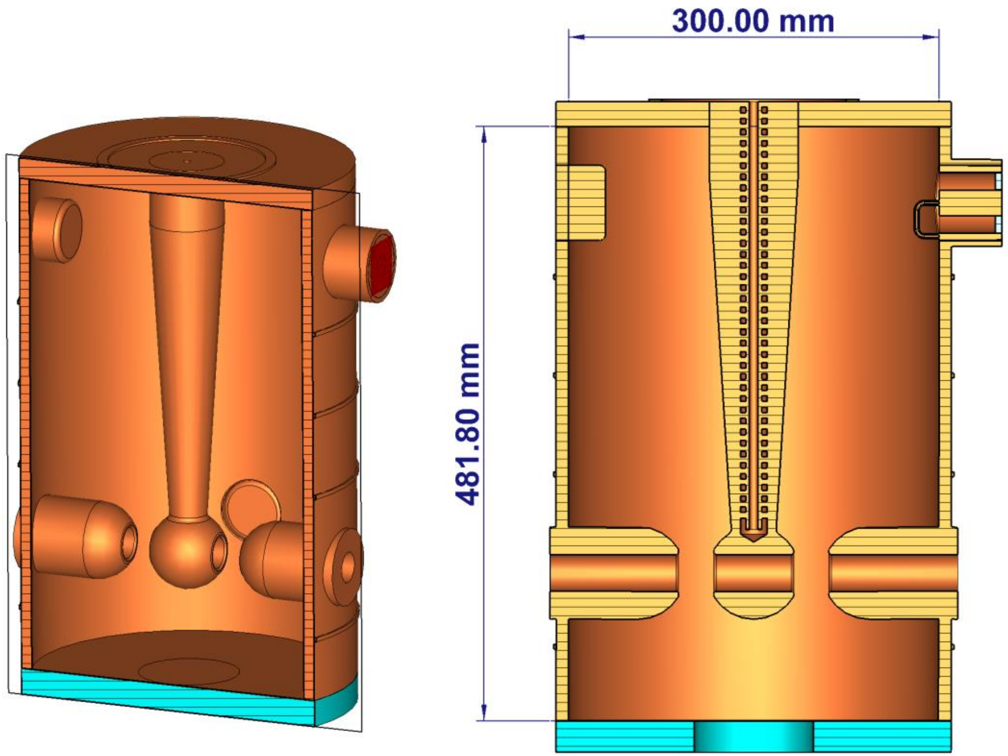



New RFQ electrodes with trapezoidal simulation
Designed with CST VBA Macro

# MSU Reaccelerator Upgrade




Rebuncher for ReA6.
Multiphysics design performed in CST.

# Computations at FRIB

- Multiphysics Design & Simulations
- Optimization
- Control & Measurements

# Acknowledgements

Authors would like to thank our colleagues for their help with the experiments:

Tomofumi Maruta, Takashi Yoshimoto, Haitao Ren, Jeff Stetson, Shane Renteria, Guillaume Machicoane, Eduard Pozdeyev, Colin Morton, Scott Cogan, Steve Lidia, Sang-hoon Kim, Shen Zhao, and many other physicists and engineers of FRIB.

Authors thank Brahim Mustapha from ANL for the support with TRACK code.

This material is based upon work supported by the National Science Foundation under Grant No. PHY-1565546.

Thank you for your attention!