FRIB Accelerator Beam Dynamics Design and Challenges

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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.

FRIB Project at MSU
Project of $680M ($585.5M DOE, $94.5M MSU)

- Dec. 2008: DOE selects MSU to establish FRIB
- June 2009: DOE and MSU sign corresponding cooperative agreement
- Sept. 2010: CD-1 granted; conceptual design complete & preferred alternatives decided
- April 2012: performance baseline & start of conventional facility construction readiness completed
- Sept. 2019: Early Completion
- March 2021: CD-4

Growth from more than 500 employees today at NSCL, MSU

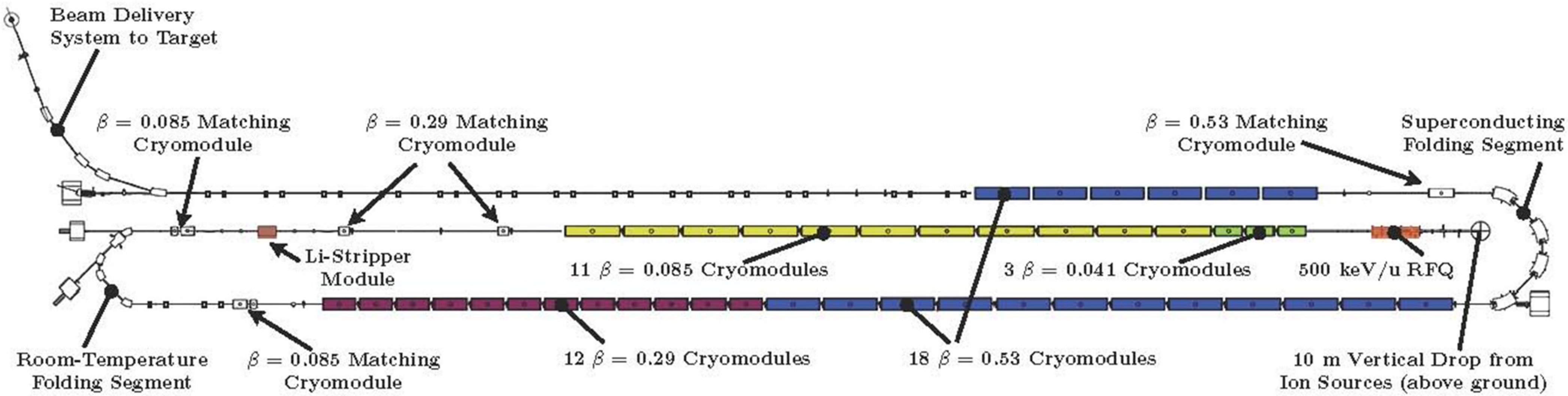
More than 1200 registered user at NSCL user group and at FRIB user organization

FRIB Linac (Heavy Ion) vs. Proton Machine

- Both produce high power beam → Deal issues with beam loss
- Lower radiation yield from heavy ions than that of proton with same beam loss at similar beam energy
  - Save shielding, but conventional BLMs not applicable at low energy
- Higher power-density for heavy ion beam loss (Bragg peaks high)
  - Easy to damage beam element
- Heavy ion beams for nuclear physics experiments are mostly high duty factor or CW, while pulsed proton beams required by neutron users in most cases
  - Lower peak current for HI→ small/negligible space charge effects
- Focusing not as frequent as space charge dominated proton
  - Cold solenoid inside cryomodule is still preferred/necessary
- Make use of low beta superconducting accelerating structure
  - Phase and amplitude of each cavity independently adjustable

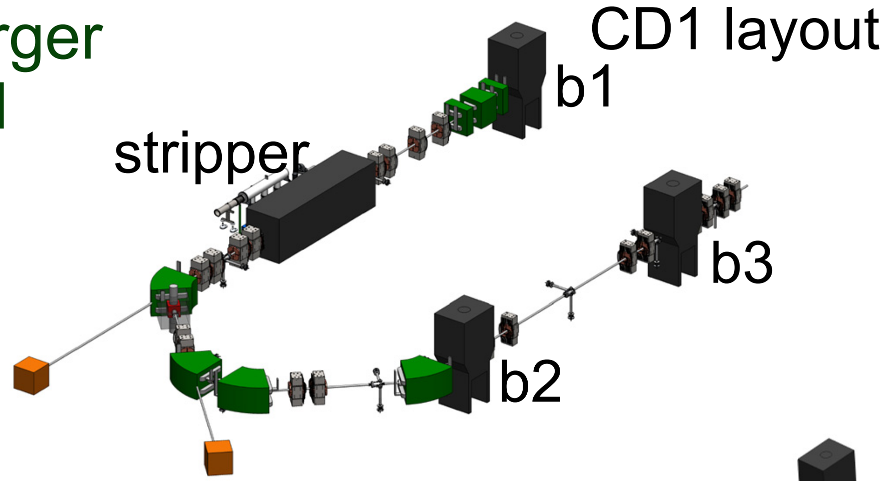
FRIB Linac Lattice and Beam Dynamics Requirements

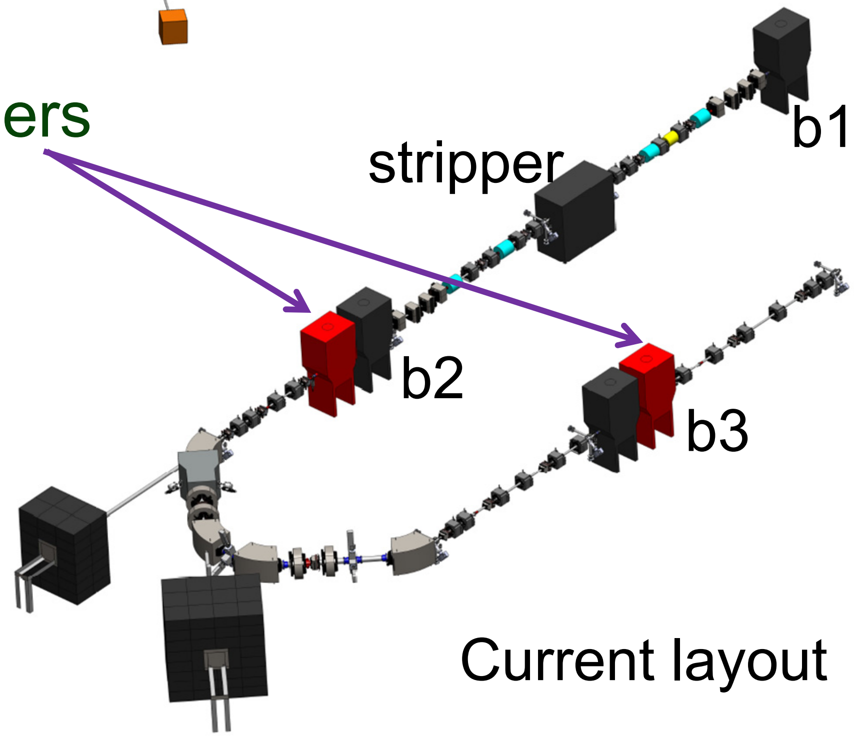
- 400 kW CW machine with uncontrolled beam loss limited to < 1 W/m
- Beam energy on target ≥ 200 MeV/u
- Accelerate all varieties of stable ions → Uranium is most challenging in design (two & five charge states before and after stripper, respectively)
- Minimize project construction costs → Compact double-folded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



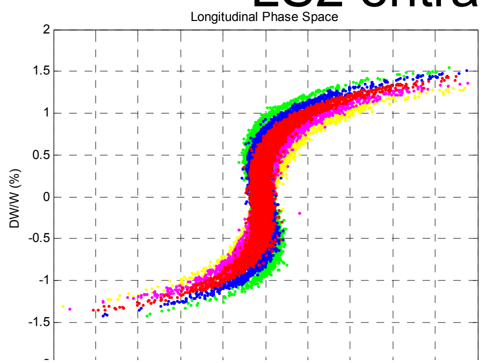
Example of Lattice Optimization at Stripper Area

- Measured liquid lithium stripper has a larger thickness variation than what anticipated
  - Produce smaller beam size on stripper
    - » Minimize transverse emittance growth
  - Accommodate larger energy spread
    - » Moved rebuncher b2 before bender
  - Provide space for differential pumping
- Space available to install additional bunchers to further improve performance

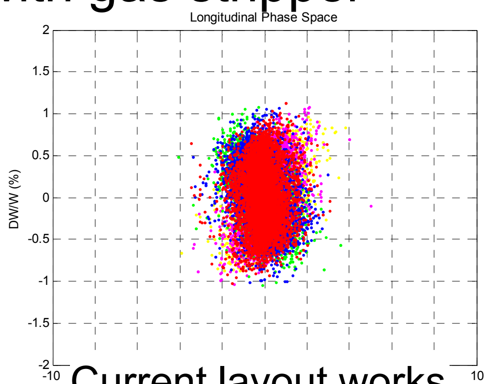




Longitudinal phase space at
LS2 entrance with gas stripper

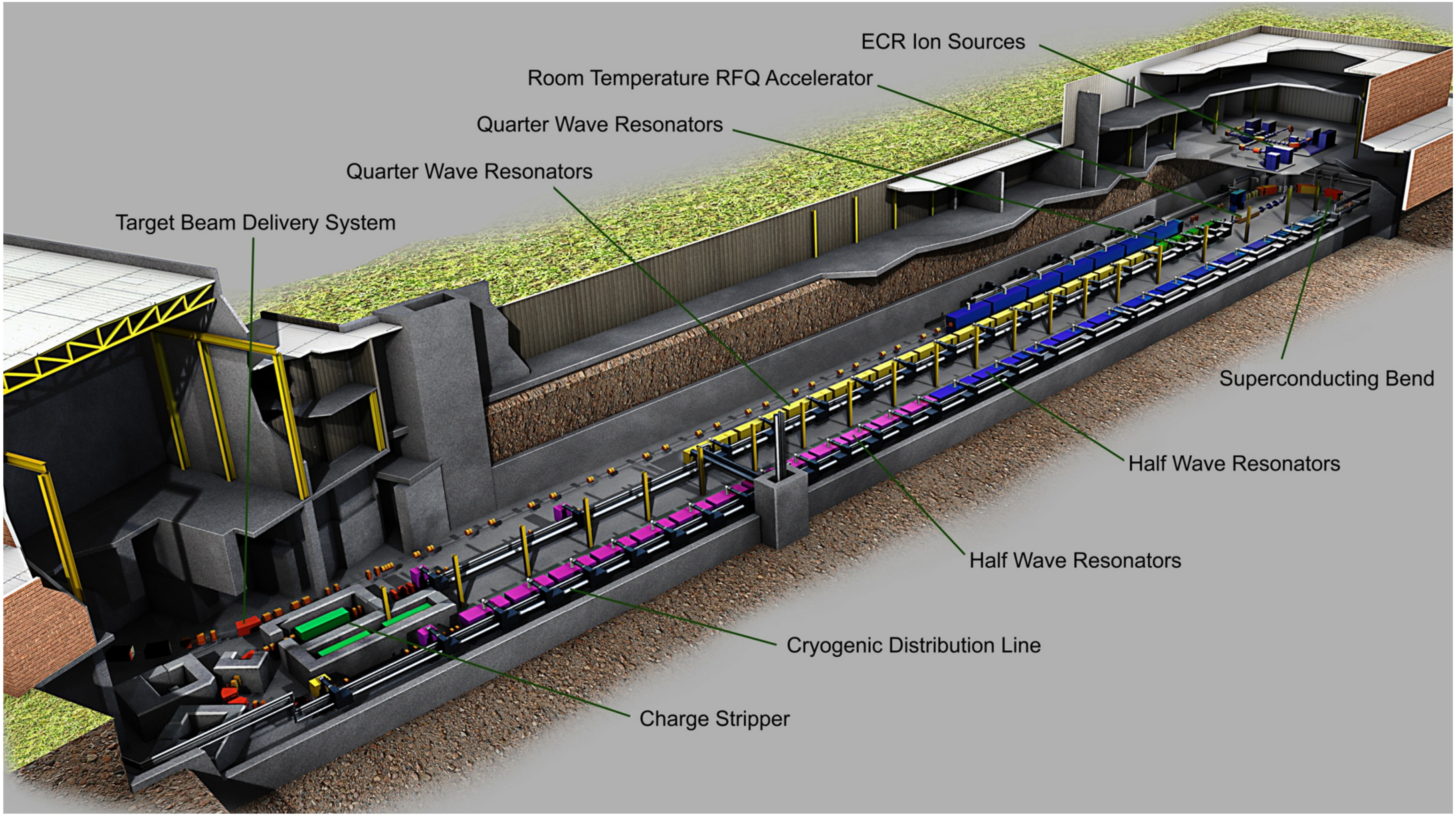


CD1 layout not work for He



Current layout works

FRIB Civil Design Completed
Close Integration Between Accelerator & Civil Designs

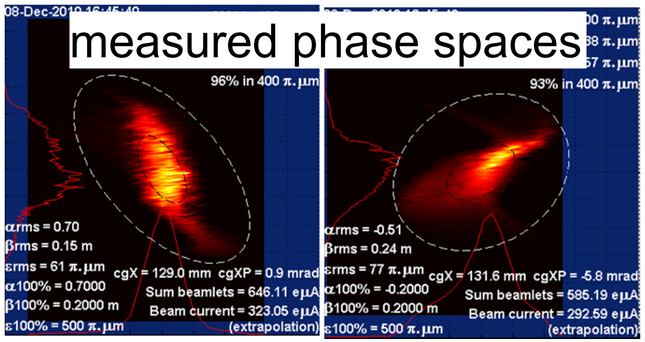


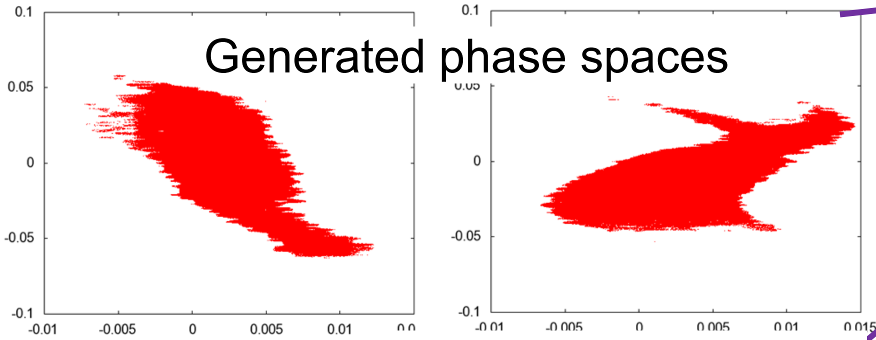
FRIB Accelerator Beam Dynamics Challenges

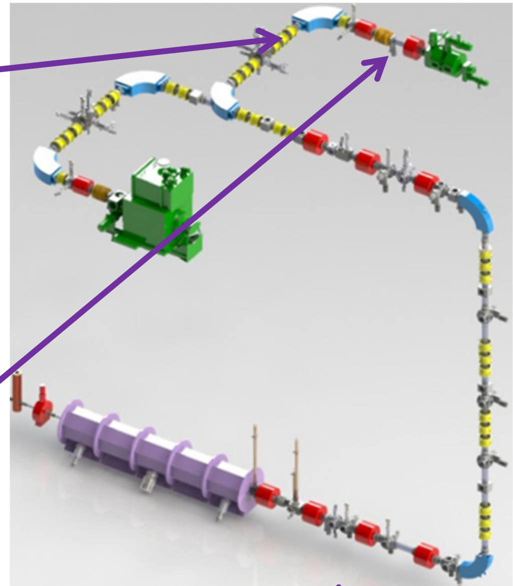
- Simultaneous acceleration of multi-charge-state beams
  - Large acceptance lattice
  - Velocity equalizer and HV platform scheme at LEBT
  - Achromatic and isochronous bending optics design
  - Superimposition of multi-charge states
  - Minimization of emittance growth at charge stripper
- Uncontrolled beam loss at ≤ 1 W/m (or 10^{-6}) level to avoid cavity quench and material damage, low cryogenic heat load, and facilitate hands-on maintenance
- Relatively small beam envelop and orbit excursion due to the limited aperture of low beta accelerating structures
- Tolerate larger alignment error of “cold” elements in cryomodules
  - SC solenoid to be aligned to ≤ 1 mm under cryogenic condition
- Meet stringent beam-on-target requirements

End-to-end Simulation Performed with Multi-charge-state Uranium Beam

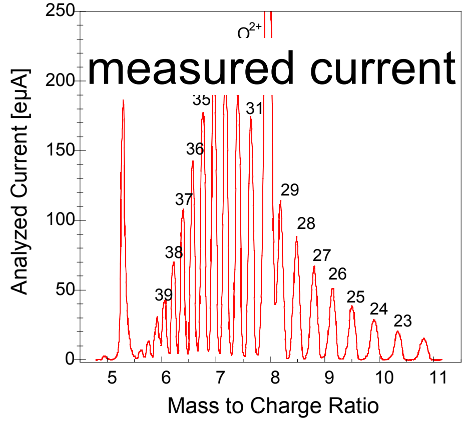
- Realistic initial particles generated based on measurements at VENUS
  - Two charge-states uranium beam

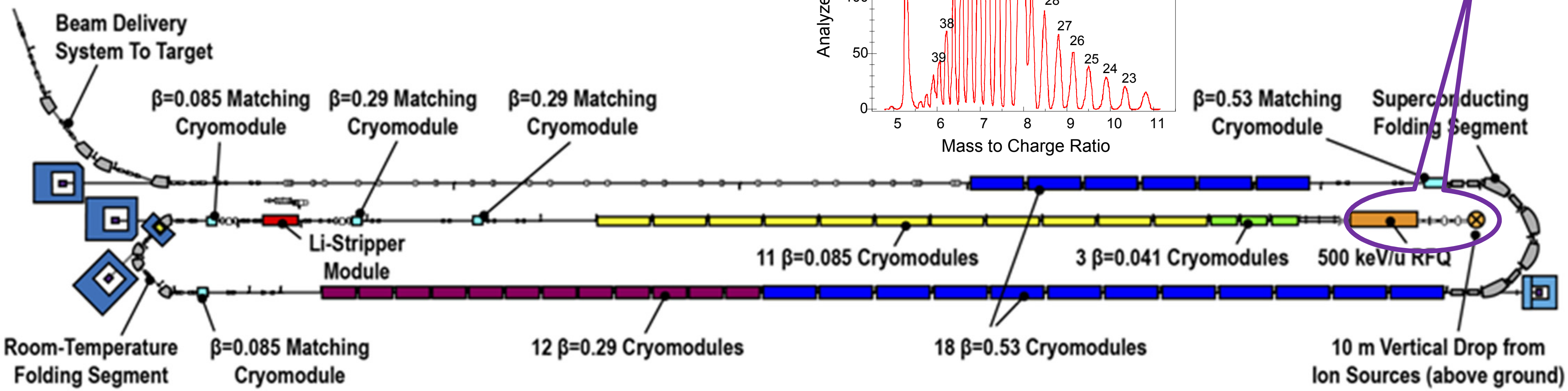






- Track particles all the way to target
  - 1 million particles

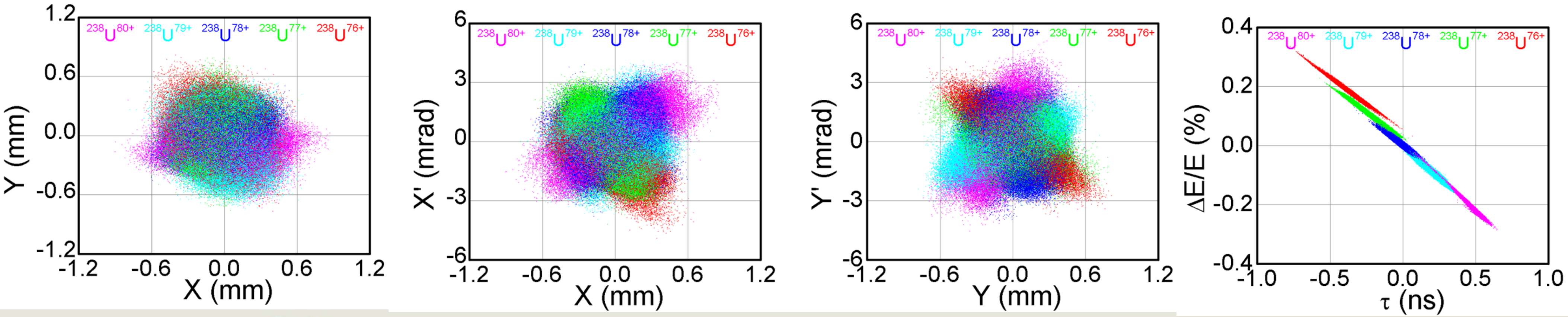




Meet Beam-on-target Requirements with Five-charge-state Uranium

- Beam-on-target requirements met even for the most challenging multi-charge state uranium beam

Parameter	Required	Achieved	Meet
Beam spot size (1 mm)	≥ 90%	96%	✓
Angular spread (±5 mrad)	≥ 90%	100%	✓
Bunch Length (3 ns)	≥ 95%	100%	✓
Energy spread (± 0.5%)	≥ 95%	100%	✓



Nominal Machine Errors Used in Beam Simulations

- Beam element placement errors

Name	Value	Distribution
Cold element displacement	±1 mm	Uniform
Warm element displacement	±0.4 mm	Uniform
Warm element rotation	±2 mrad	Uniform

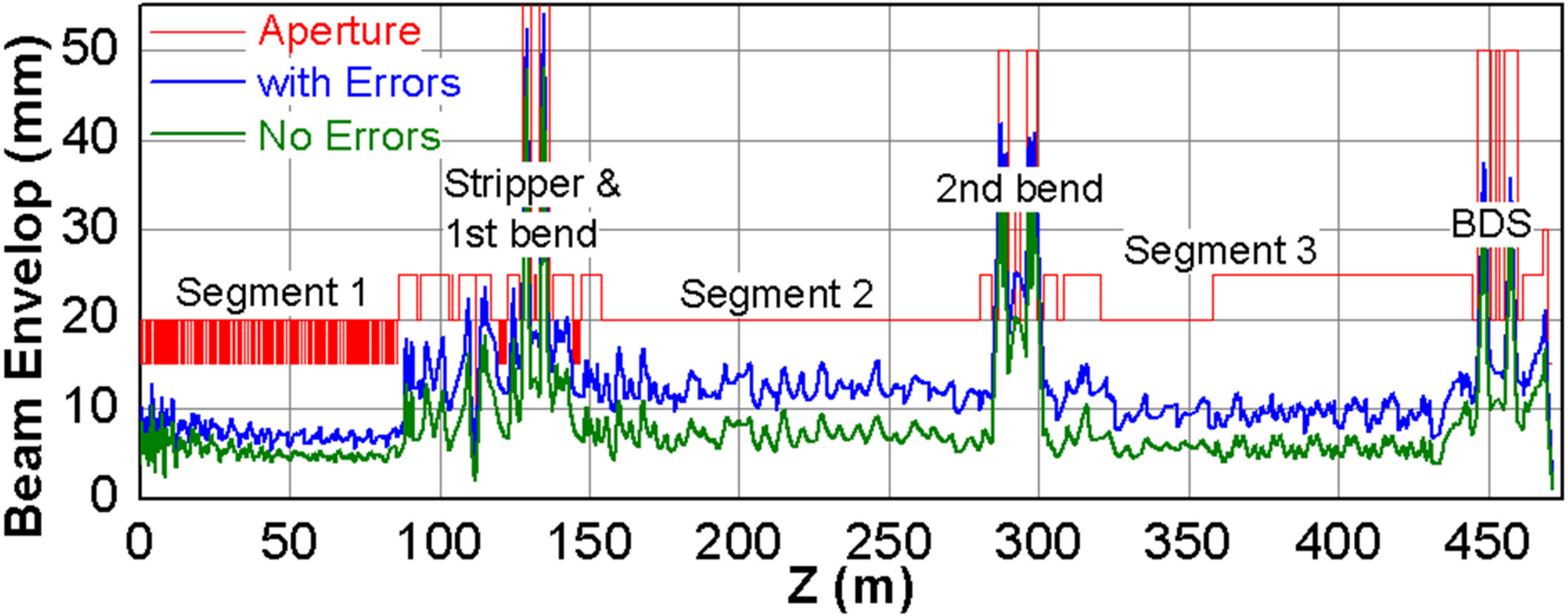
- Cavity RF errors

Name	Value	Distribution
RF amplitude fluctuation	±1.5%	Gaussian (σ=0.5%)
RF phase fluctuation	±1.5°	Gaussian (σ =0.5°)

Measured RF errors at MSU are much smaller

- BPM uncertainty with respect to focusing element
  - ±0.4 mm, uniform distribution
- Stripper thickness variation
  - ±20%, uniform distribution

Beam Evaluation Results with Machine Errors Beam Envelope Well Within Aperture



- Beam envelope growth mainly due to misalignment (correctors were on)
- RF errors cause significant longitudinal emittance growth but not coupled into transverse
- **No uncontrolled beam losses observed**
- Evaluation of room temperature magnets 3D fields effect ongoing

Beam Loss Evaluation Performed with Larger RF and Placement Errors

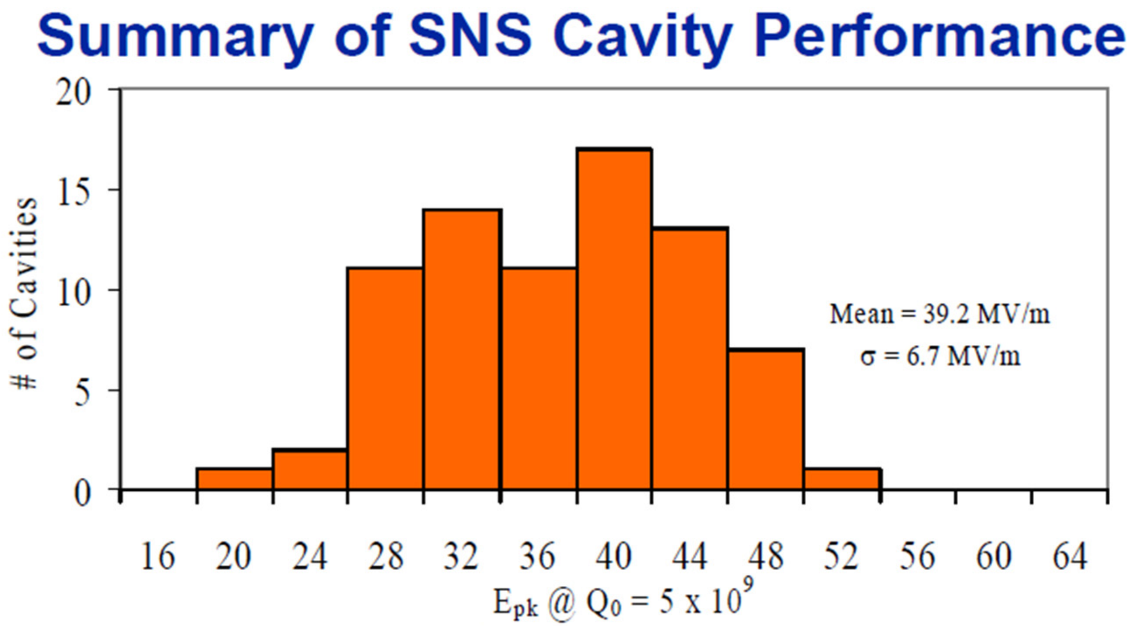
- Increased errors in simulation by 50% and 100% larger for all RF and positioning errors than the nominal ones
  - Performed 350 seeds with 1 million particles each

cases	nominal errors	50% larger errors	twice larger errors
no beam loss	100%	91%	60%
loss but <1W/m	0	7.8%	26%
loss > 1W/m	0	1.2%	14%

- Beam loss initiated in low energy side due to the larger RF errors
- Probability of beam loss >1 W/m increases sharply with errors
  - It's important to keep errors within nominal tolerances
- Space reserved for beam collimation/scraping in the warm transport sections (e.g., upstream of segment 2)

Scenarios of Fault Condition Studies

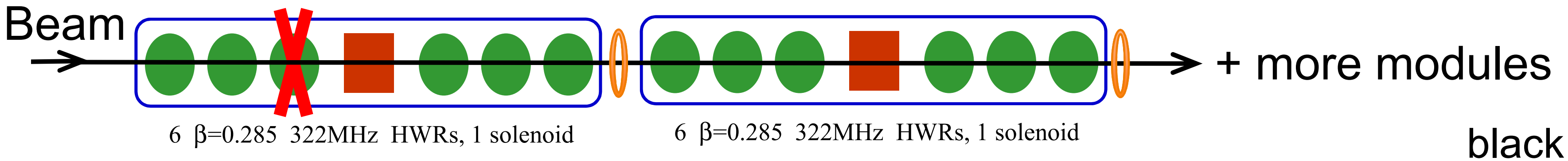
- Our studies show that following fault conditions seem manageable
  - Single cavity failure
  - Single solenoid failure
  - 20% lower cavity gradient
  - One cryomodule failure
  - ±20% randomly off nominal cavity voltage (lesson learned from SNS)

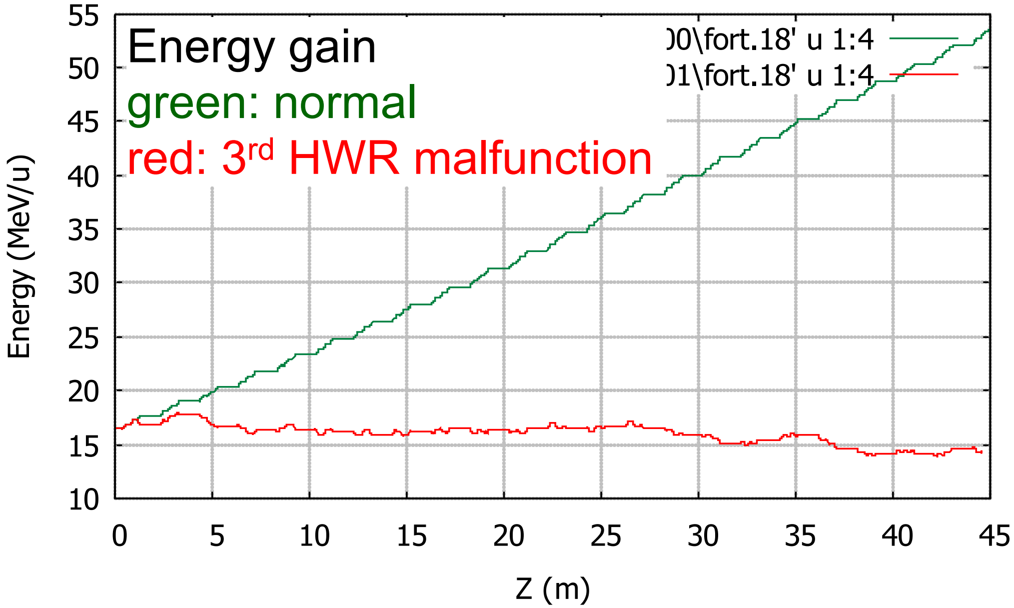


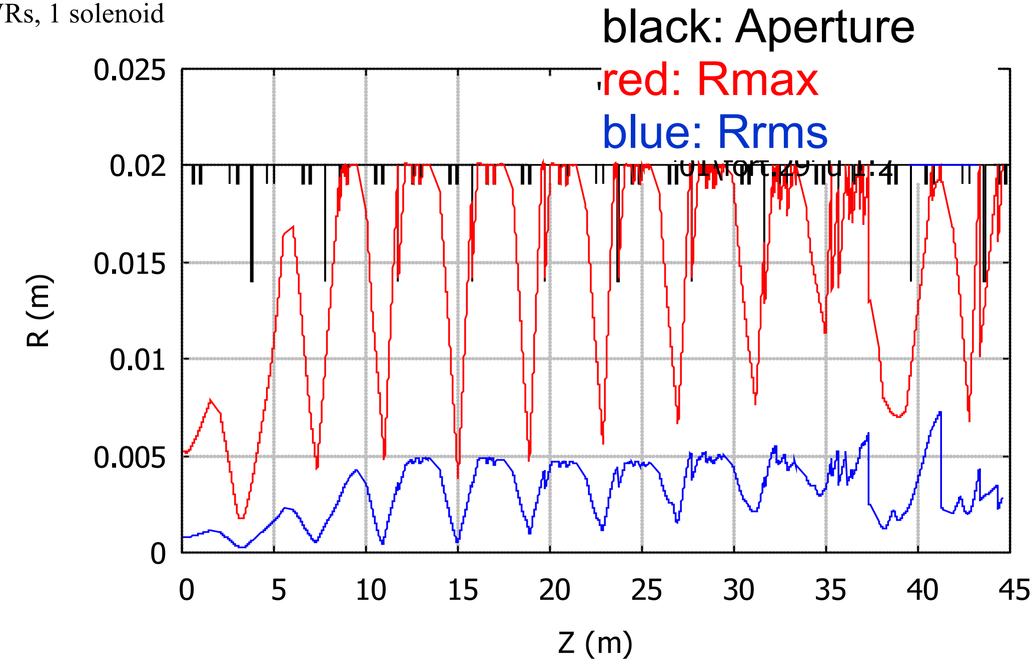
Joseph Ozelis at SRF'05

Example of Beam Loss Distributions with Single Cavity Failure and No Adjustment

- Malfunction of the control of the 3^{rd} beta=0.29 HWR in the 1^{st} b29 CM
- Warm scraper ring with aperture diameter of 28 mm installed



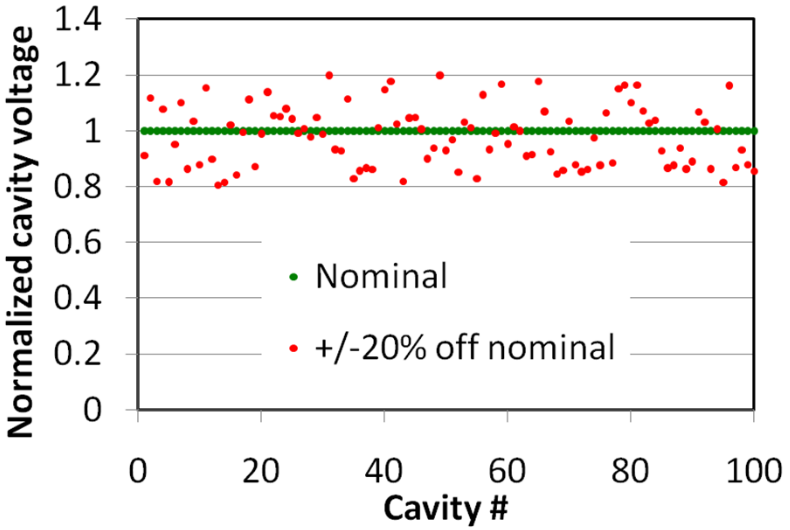




- All the beam lost in the β=0.29 cryomodules (3^{rd} to 10^{th})
- Electrical current of tens uA on one ring → enough signal to trig MPS

Example of ±20% randomly off nominal voltage for all QWRs

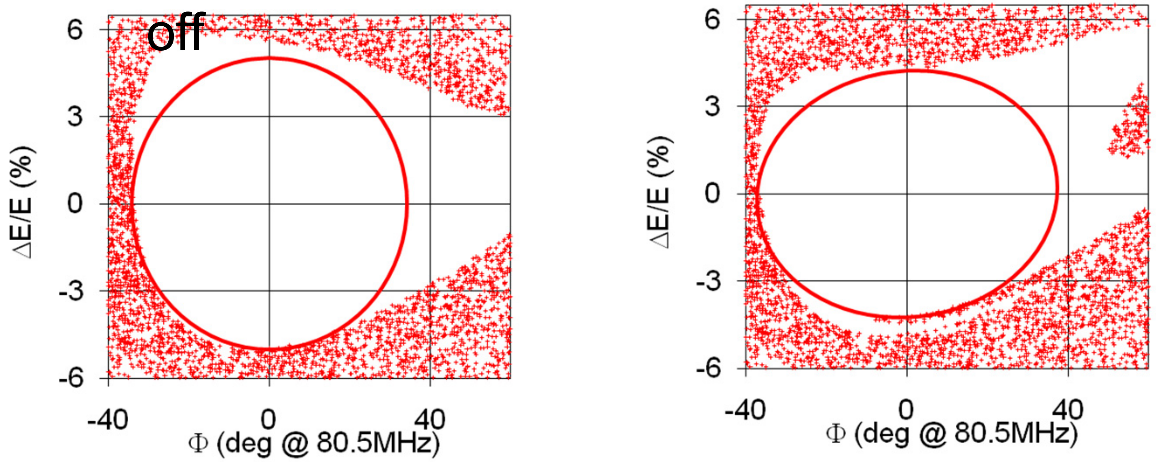
- Amplitudes of all QWR cavities are randomly off by maximum of ±20%, cavity phases are adjusted to keep the same synchronous phases as in the design case



Segment 1 longitudinal acceptance

30 π-ns-keV/u nominal voltages

27 π-ns-keV/u ±20% randomly off



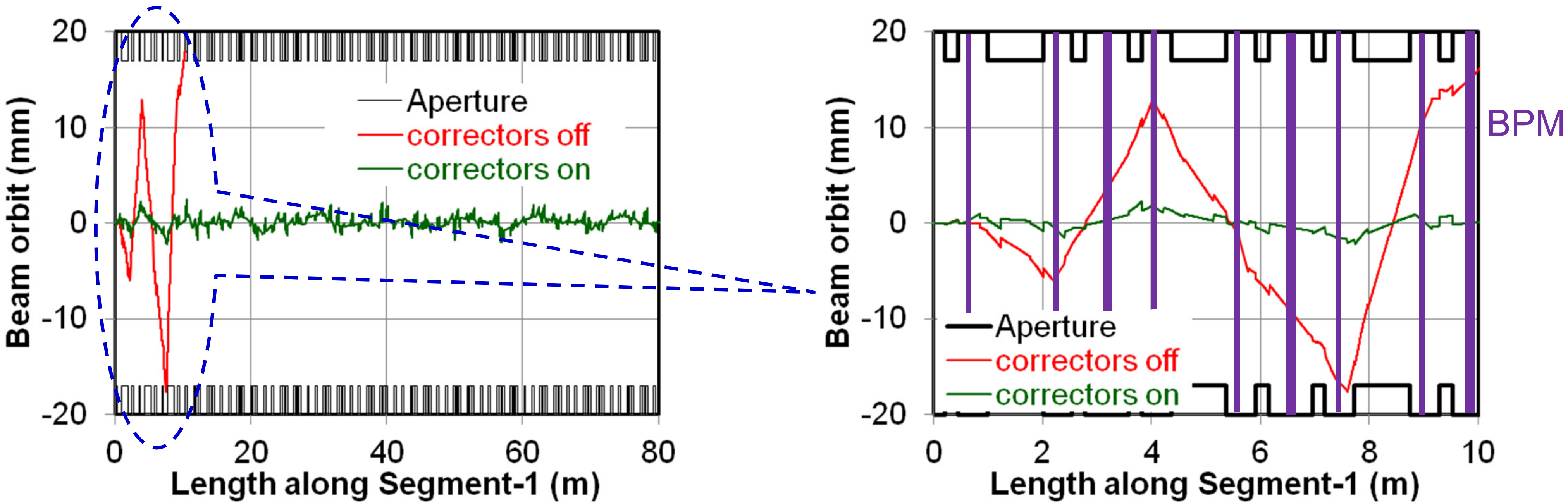
- Longitudinal acceptance reduced by 15%, not likely to lead to beam loss
- Output energy slightly changed (within ~1%)
- Matched conditions change, but input to linac can be adjusted to rematch

Beam Tuning Strategy Developed

- Use low current, short pulse, reduced rep rate to decrease beam power (protect damage to machine)
  - Beam current as low as 50 euA
  - Pulse duration as short as 50 us
  - Rep rate as low as possible (1 Hz, even single shot)
- Start with single charge state
  - Charge state controlled by selection slits
  - Tune with reference charge, check other charge state(s)
- Model-based on-line tuning
  - Reduce tuning and recovery time
  - Perform global optimization
- Cavity phase scaling
  - Cavity phase can be set based on the result of previous phase scanning

Beam Tuning – Orbit Correction Simulation Performed

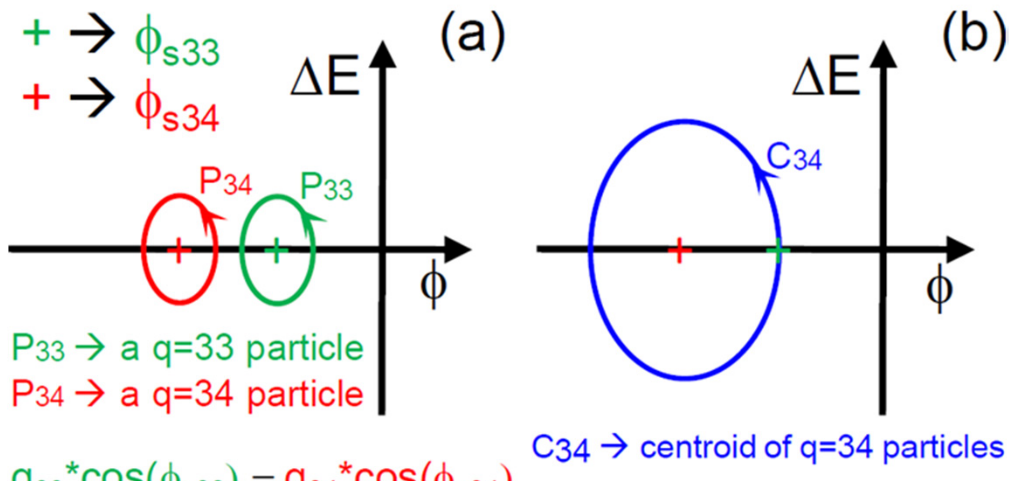
- Without orbit correction beam most likely will not thread through Segment 1 to the beam dump with solenoid misalignment of ±1mm



- Initial orbit correction needs section by section
  - Sufficient number of BPMs and steering correctors
    - » It still works with a couple of BPMs or corrector off
  - Model base orbit corrections will significantly reduce tuning time

Beam Tuning – Longitudinal Overlap of Two-charge-states Beam at Exit of LS1

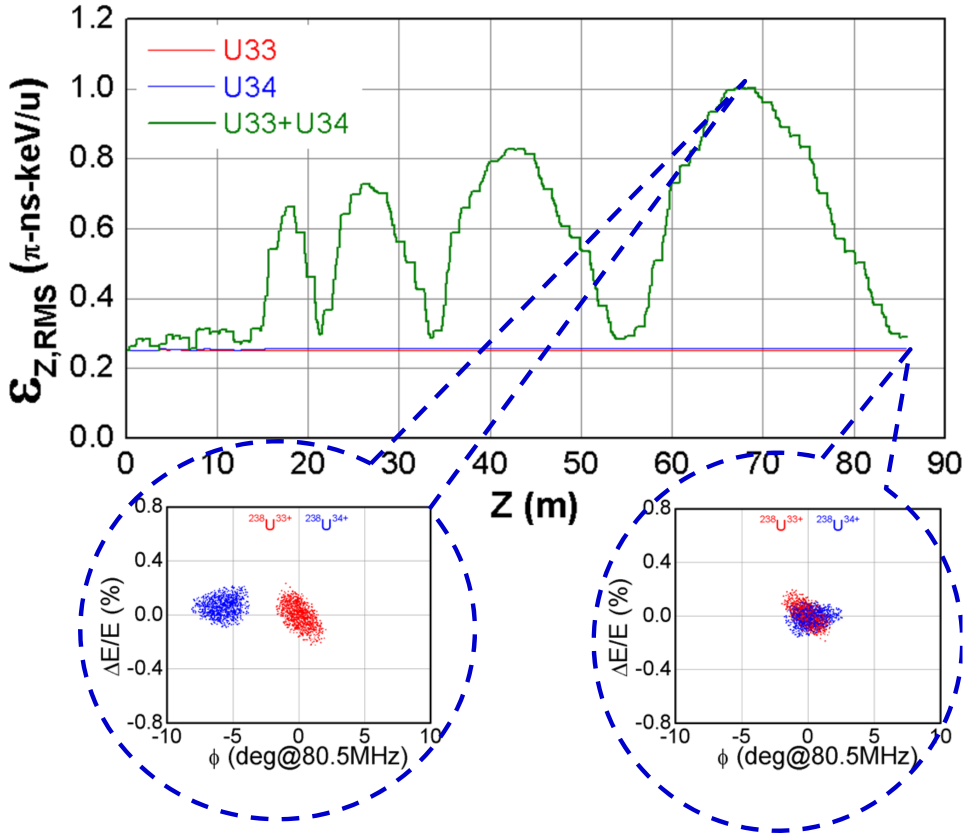
- Longitudinal oscillation of two-charge-state beam along Segment 1



$q_{33}{}^*\cos(\phi_{s33}) = q_{34}{}^*\cos(\phi_{s34})$

$$f_{loi} = f\sqrt{\frac{q_i E_o T\lambda \sin(-\phi_{si})}{2\pi mc^2\gamma_{si}^3\beta_{si}}}$$

where i=33 *or* 34



- Phase of cavities are adjusted for the overlap of the two-charge-state beam at the exit of Segment 1 by measuring the timing of each charge state beam

Summary

- FRIB project is proceeding with scope, schedule and cost baselined and ready for civil construction start
- FRIB linac design has been optimized and finalized, consistent with baseline requirements and future upgrades
  - Accelerator lattice footprint frozen since June 2011
- End-to-end beam simulations performed, and error and fault conditions explored
  - Results meet proposed baseline requirements
  - Beam simulation studies show that lattice design is robust
- Linac beam tuning strategies and algorithms studied, and virtual accelerator and on-line control mode being developed to support commissioning and operations

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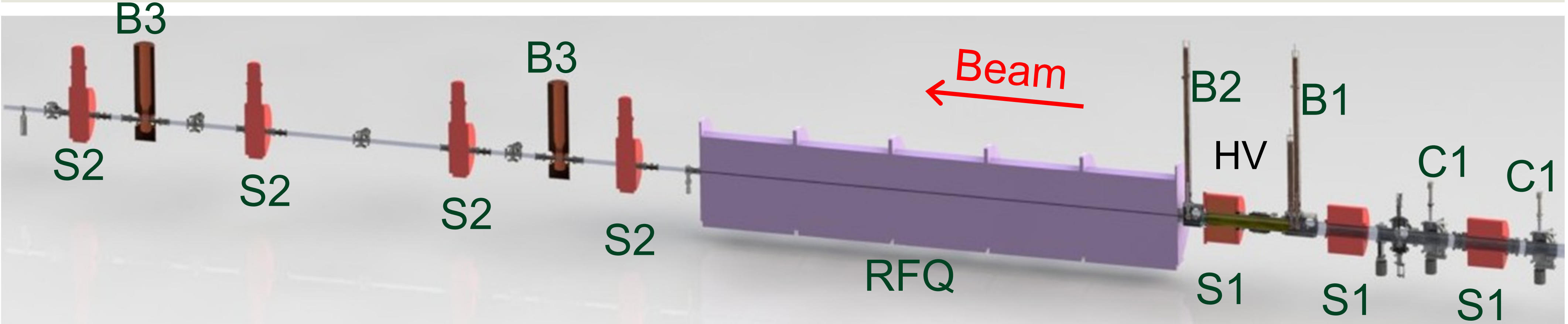
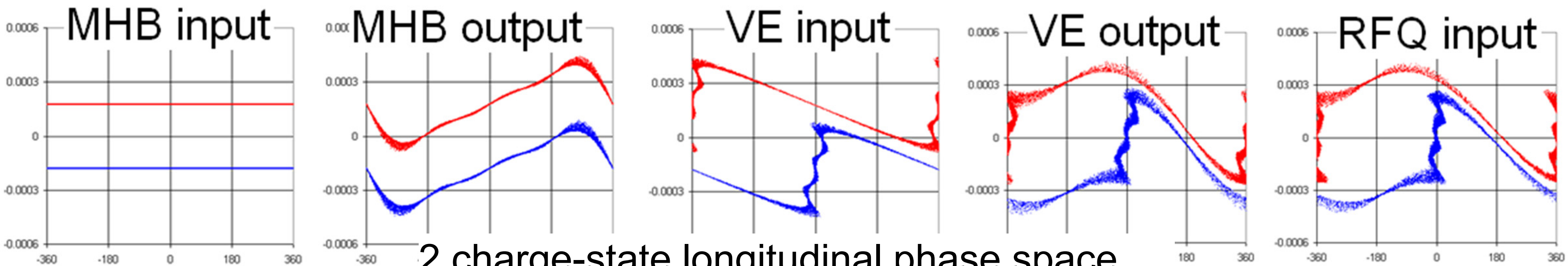
Backup Slides

Beam Dynamics Challenges – Prebunching at LEBT to Reduce Longitudinal Emittance



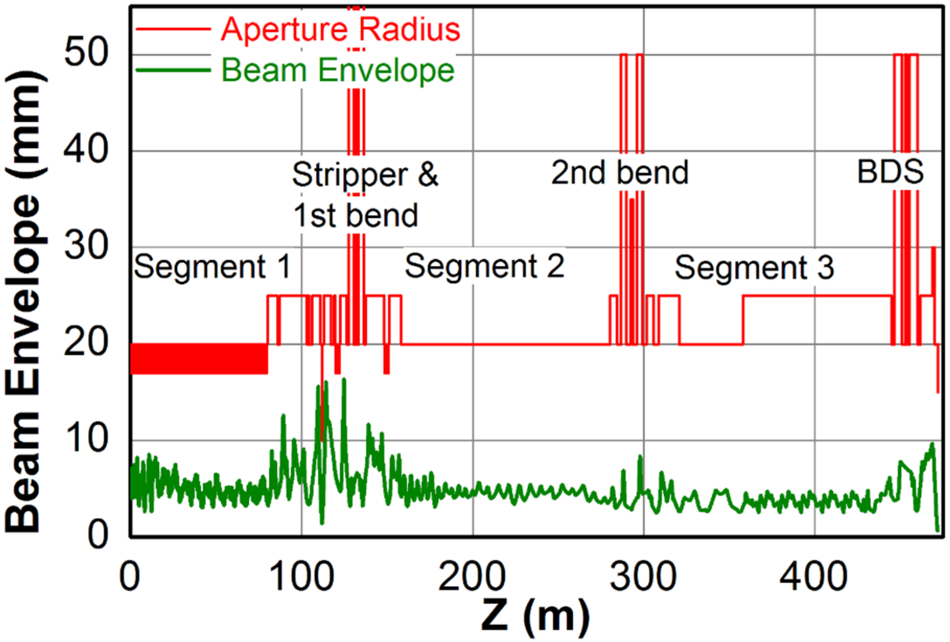


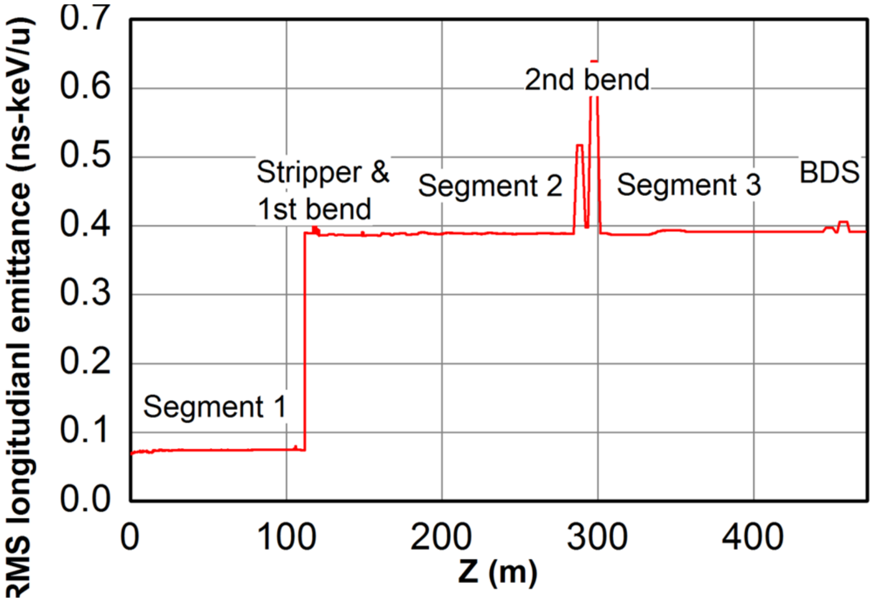
2 charge-state longitudinal phase space

- Two charge-state injection
  - Acceleration/deceleration cavity VE (B2): accelerate lower charge state beam and decelerate higher one (same bunch energy into RFQ)
  - HV section between MHB (B1) and VE (B2): adjust relative time flight difference between the two charge-state beams

End-to-End Simulation Performed with Argon Beam

- Argon is identified as one of the primary beam for commissioning
  - easy to produce
  - can accelerate >200MeV/u on target without stripper
- Single charge-state argon (q=10, A=36) selected from ion source
- Fully stripped into q=18, with same q/A as oxygen (8/16) after stripper





- Overall performance "better" than multi-charge uranium beam

Accelerator Availability & Upgradability
Design Supports Multiple Operational Scenarios

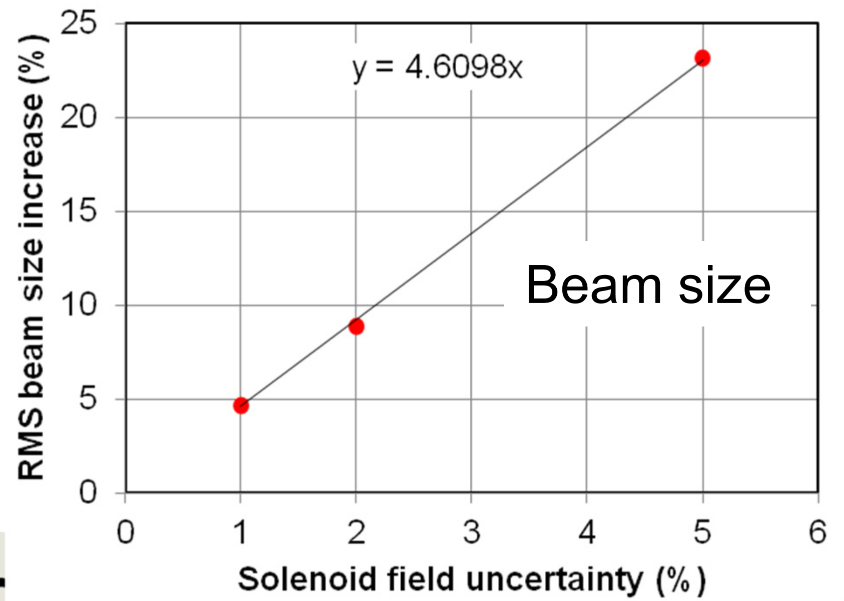
- Baseline scenario (200 MeV/u, 400 kW) with liquid Li stripper for U^{78+}
  - Multiple ion sources for enhanced availability
- Alternative scenario with He gas stripper for U^{71+}
  - Folding segment optics accommodates both stripping scenarios
- Fault scenario tolerated – comparable to SNS day-1 condition
  - Tolerate 20% cavity underperformance; single cryomodule failure; lower stripping efficiency (charge state down to U^{63+})
- Upgrade scenarios to 300 and 400 MeV/u supported

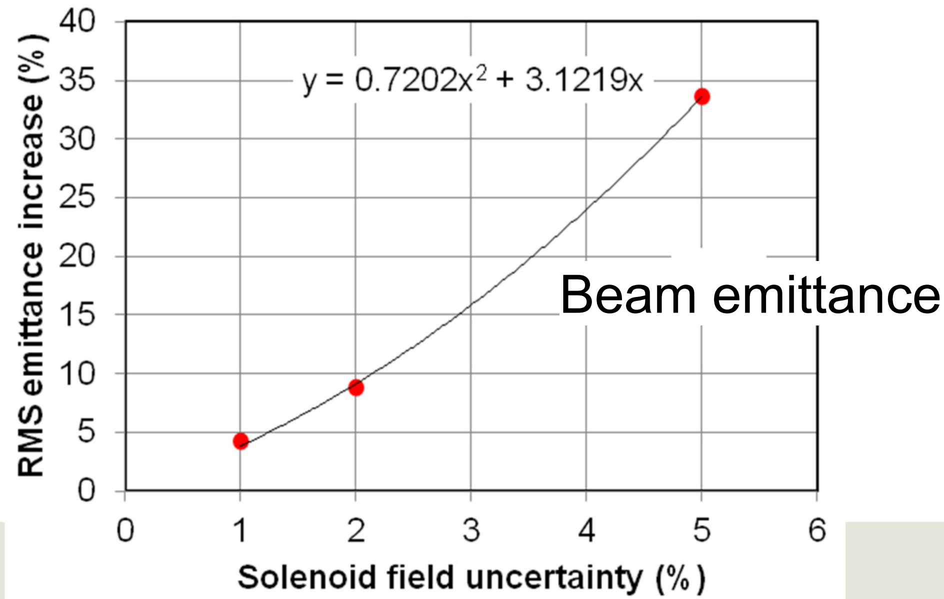
^{238}U beam

Scenario	**Charge state** (average)	**Energy [MeV/u]** (baseline)	**Energy [MeV/u]** (baseline + + 3 C.M.)	**Energy [MeV/u]** (baseline + + 12 C.M.)	**Energy [MeV/u]** (baseline + 12 C.M.) (35% gradient enh. for β=0.29 & 0.53)
Proposed					
Baseline	78+	202	228	306	413
Alternative	71+	179	202	275	375
Fault	63+	155	176	247	342

Beam Sensitivity to Solenoid Setting Errors/Fault

- Solenoid settings will deviate from design limited by diagnostics
  - Transverse matching along the linac will not be ideal
- Settings of all solenoids in Segment1 were assumed to have 1%, 2%, 5% uncertainty with 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



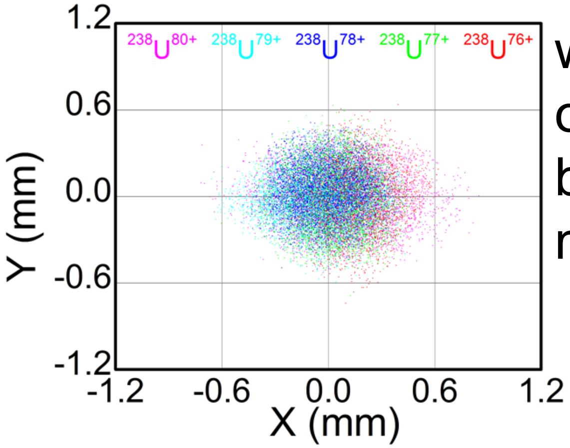


Vertical Kick from QWRs Compensated

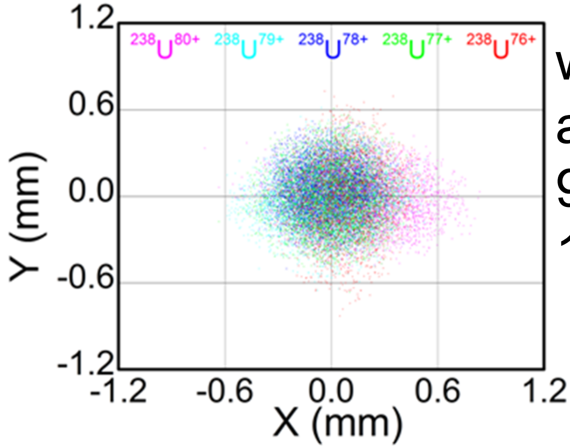
- Vertical kick due to the asymmetrical RF fields of QWR can be compensated by shifting cavity position vertically (0.2 mm for $\beta=0.041$ cavity and 1.5 mm for $\beta=0.085$ cavity)
  - » Maximum beam centroids offset reduced from ~5 mm to ~0.3 mm

Effect of Magnet Higher Order Multipoles

- Magnet higher orders in bending area
  - Dipoles non-uniformity (ΔB/B): ±0.3%
  - Combined function quadrupole/sextupole
    - » Quadrupole non-uniformity (ΔB/B): ±0.7%
    - » Sextupole non-uniformity (ΔB/B): ±5%
- Impact beam on target (without other errors)
  - Percentage of beam within 1mm changed from 96.4% into 93.5%
  - Non-uniformity of dipoles in second bending area seems more sensitive



without higher orders, 96.4% of beam within 1 mm on target

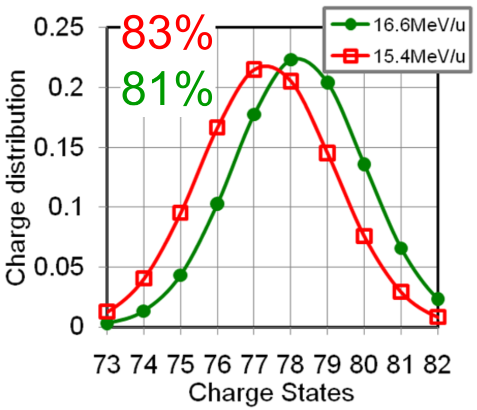


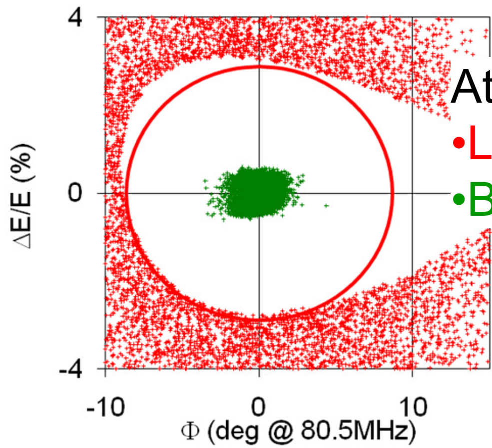
with higher orders and adjusted sextupoles, 93.5% of beam within 1 mm on target

- Beam simulation with 3D magnet fields to be performed

Example of One β=0.085 Cryomodule Failure and Lattice Recovery

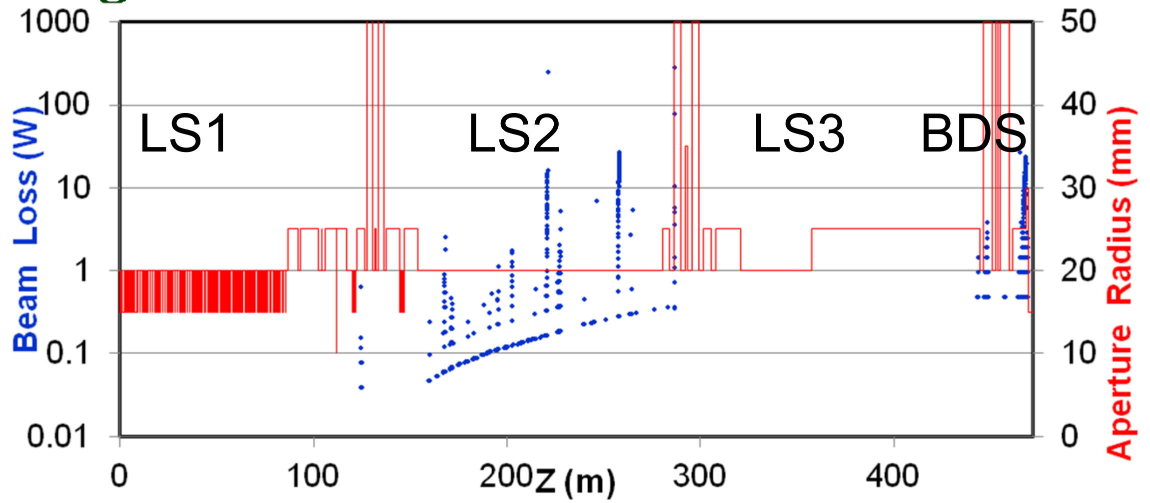
- Move the last β=0.085 cryomodule to replace the failed one
- Need 4 additional quads placed on the location of the moved module
- Reach 200 MeV/u on target
  - Segment 1 output energy 15.4 MeV/u instead of 16.6 MeV/u
  - Average from stripper keeps same <Q> = 78
  - 200 MeV/u segment 3 output by adjusting phase of 1.5° for β=0.53 cavities
- Transverse and longitudinal distribution on target can be recovered
  - Two charge states overlap in longitudinal plane before stripper by slightly adjust the phase of all β=0.085 cavities



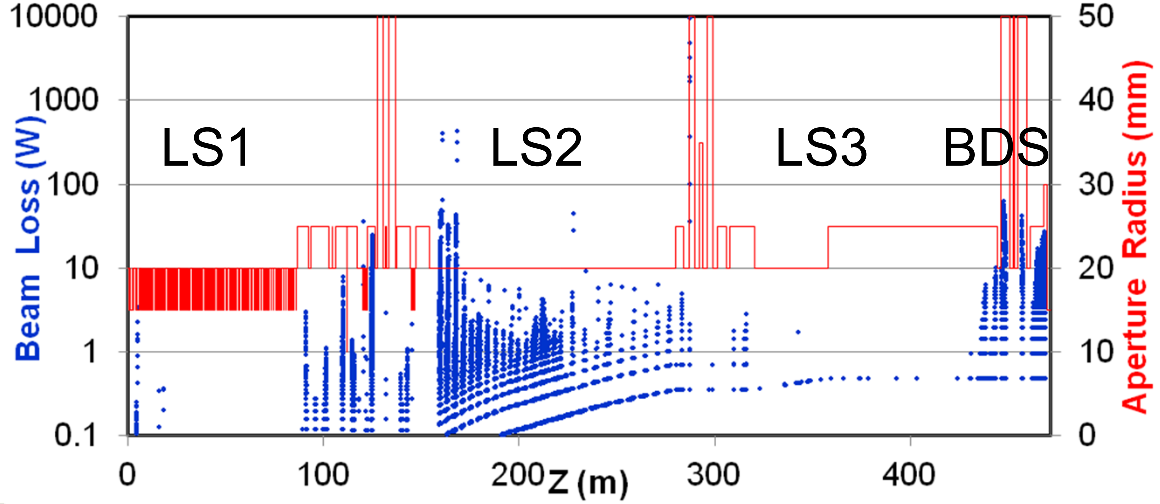


Beam Loss Distribution with Different Scenarios

- 2x larger RF jitter and 2x positioning errors than the nominal ones
  - Loss mainly distributed in the LS2, BDS and bending areas, but not in the LS1 and LS3



- 4x larger RF jitter, 3x larger input beam emittances
  - Loss still mainly distributed in the LS2, BDS and bending areas, occurred but probability was low in the LS1 and LS3
- Beam loss initiated in low energy side due to the larger RF errors



Beam Tuning – Twiss Parameter Matching Simulation Performed

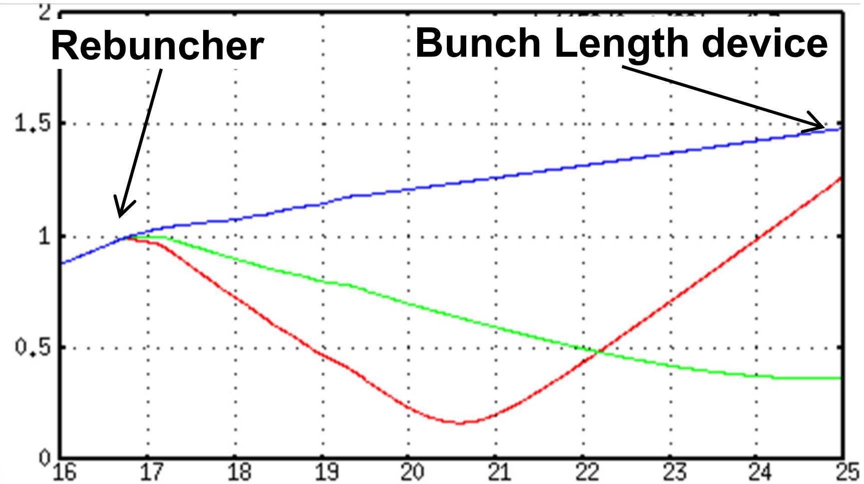
- Obtain Twiss parameters by measuring sigma matrix

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

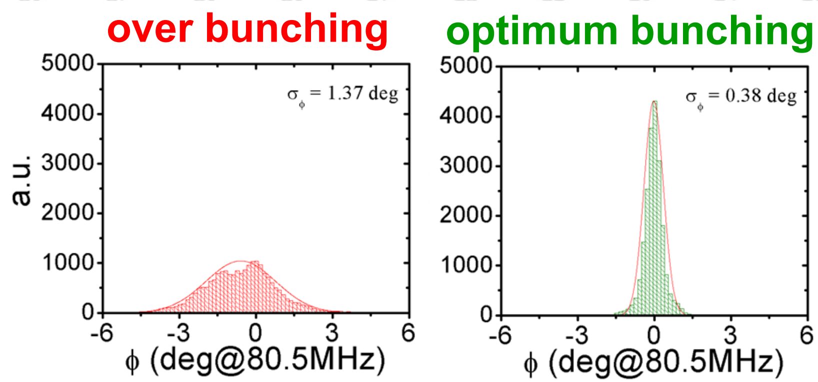
  - measured $(\sigma_{bl})_{11}$, known M_{11}, M_{12}, M_{22}
    obtained $(\sigma_r)_{11}, (\sigma_r)_{12}, (\sigma_r)_{22}$

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

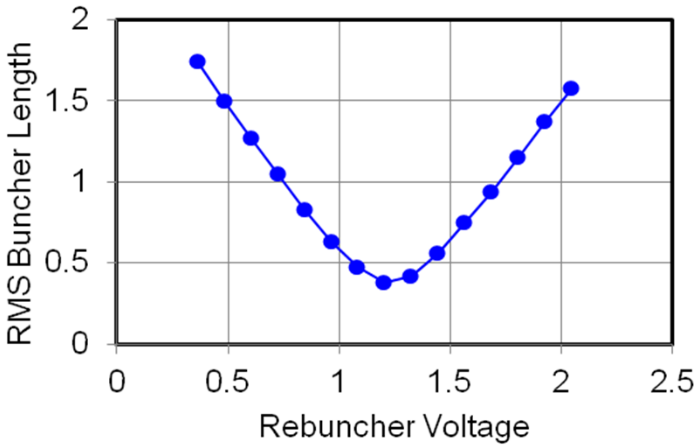
$$\beta_r = \frac{(\sigma_r)_{11}}{\varepsilon} \quad \gamma_r = \frac{(\sigma_r)_{22}}{\varepsilon} \quad \alpha_r = -\frac{(\sigma_r)_{12}}{\varepsilon}$$

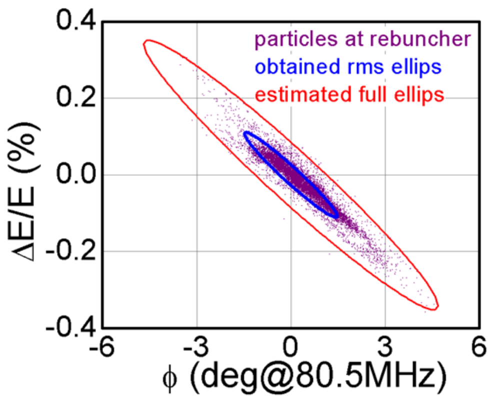


- Longitudinal matching to stripper
  - Measure bunch length vs. rebuncher voltage



Observed bunch length

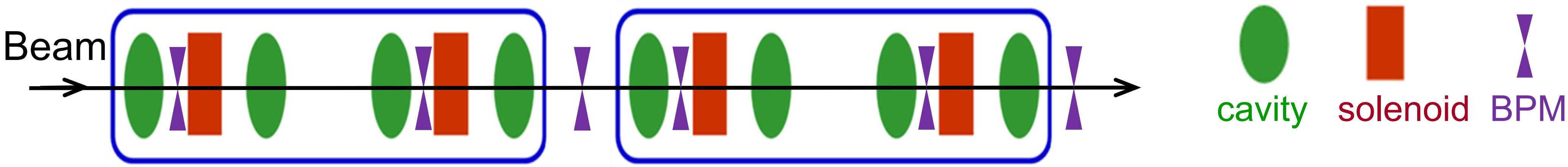




Obtained Twiss Parameters

- Same method applies transverse matching by quad/solenoid scanning

Beam Tuning – Cavity Phase Setup Simulation Performed

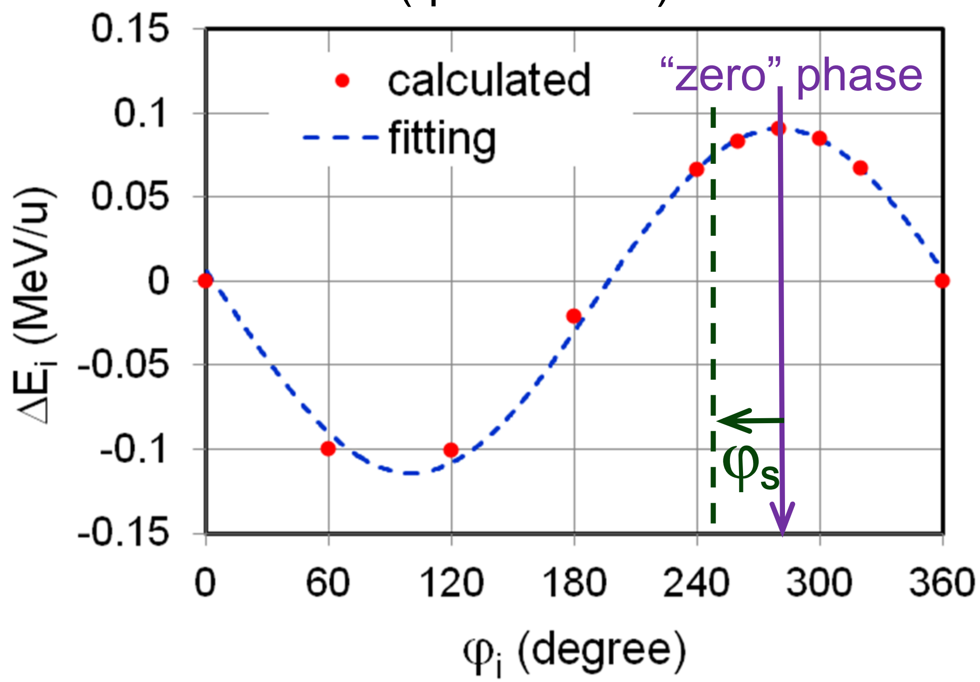


- Scan the cavity phase (φ_i) and measure the corresponding beam energy change (ΔE_i) using downstream BPMs
  - Find the "zero" phase where energy gain is maximum
  - Setup the cavity synchronous phase φ_s with respect to the "zero"
  - Obtain cavity voltage (V_c) by

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

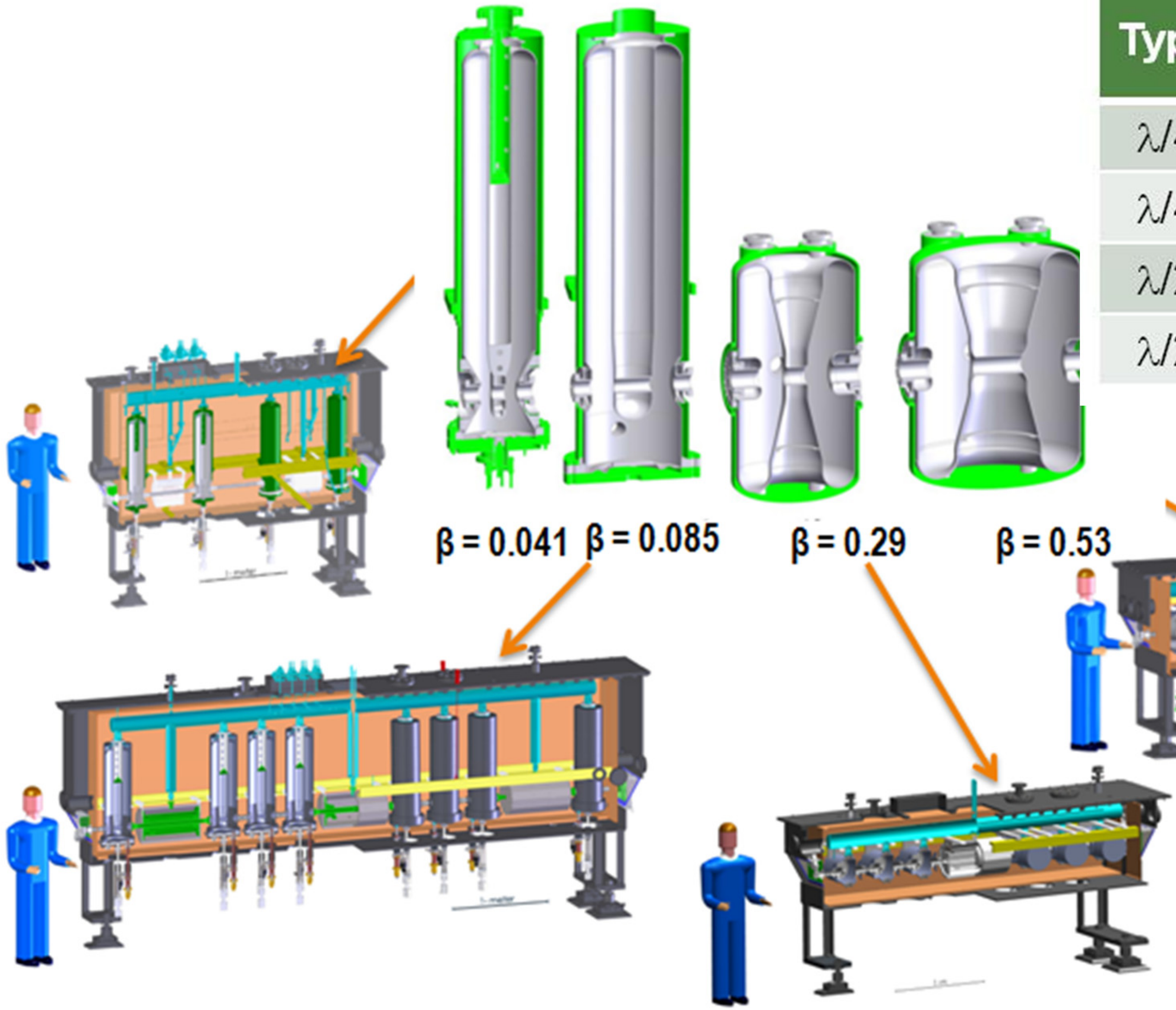
    - » Known q/A, φ_i
    - » Measured ΔE_i for φ_i
  - Downstream cavities off, solenoids may on during phase scanning

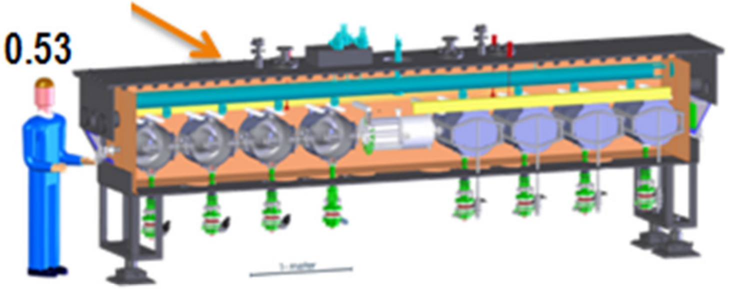
Phase scan of β=0.041 QWR with uranium (q/A=33/238) at 0.5MeV/u



FRIB Resonators and Cryomodules: Beam Dynamics Specifications

Type	β_0	f (MHz)	V_a (MV)	a (mm)
λ/4	0.041	80.5	0.81	34
λ/4	0.085	80.5	1.78	34
λ/2	0.29	322	2.09	40
λ/2	0.53	322	3.7	40





These apertures were recently increased by about 10 %.