Multi-Charge-State Beam Dynamics in FRIB

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Introduction – FRIB Timeline

- Late 90s – Next generation nuclear facility (RIA) proposed
- Dec. 2003 – CD-0 released (mission need)

- Dec. 2008 – MSU site selected
- June 2009 – Cooperative Agreement signed by DOE-SC and MSU
- Sept. 2010 – CD-1 approved (preliminary baseline range)
- Aug. 2013 – CD-2 approved (performance baseline), CD-3a approved (start civil construction pending FY14 federal appropriation)
- Mar. 2014 – Civil construction started
- Aug. 2014 – CD-3b approved (start technical construction)
- Oct. 2014 – Technical construction started

- June 2022 – CD-4 (project completion), early completion goal in Dec. 2020
- ……

Introduction – FRIB Layout

J. Wei, MOZLR07

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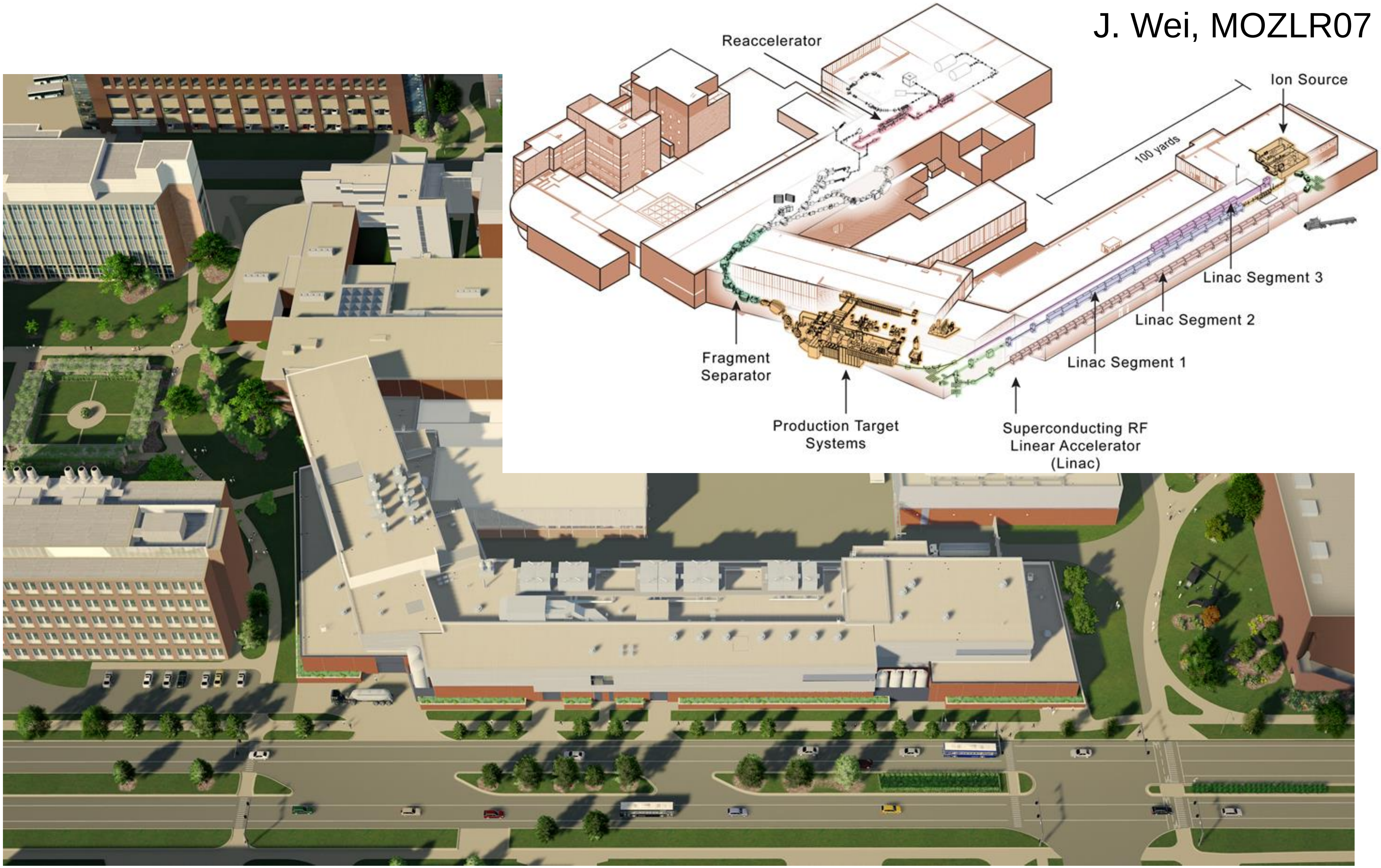
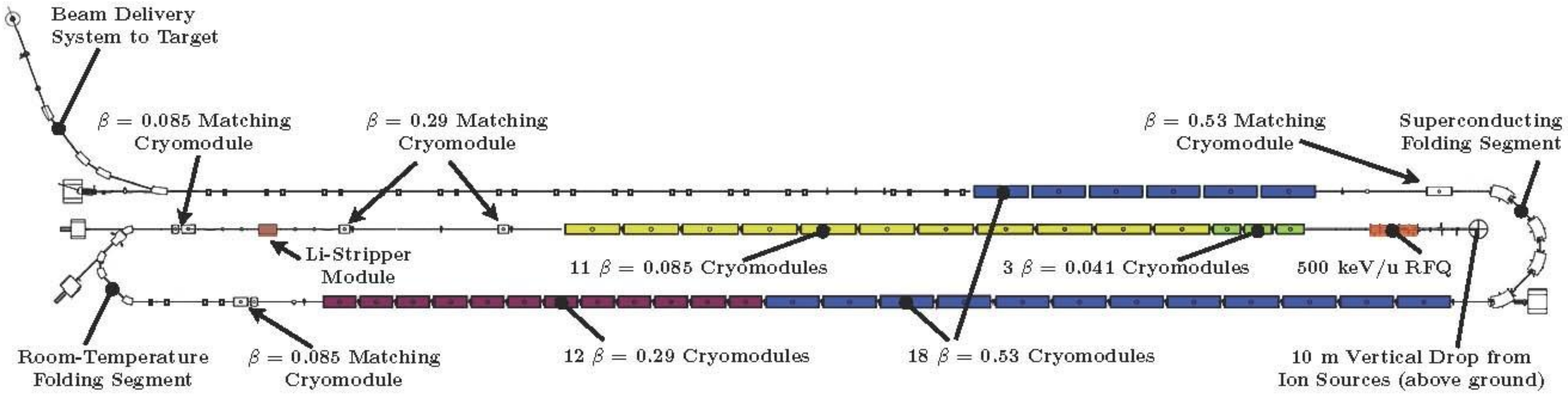
J. Wei, MOZLR07



FRIB Beam Dynamics Design Requirements

- 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

M. Ikegami, TU04AB03



Multi-Charge-State Simultaneous Acceleration

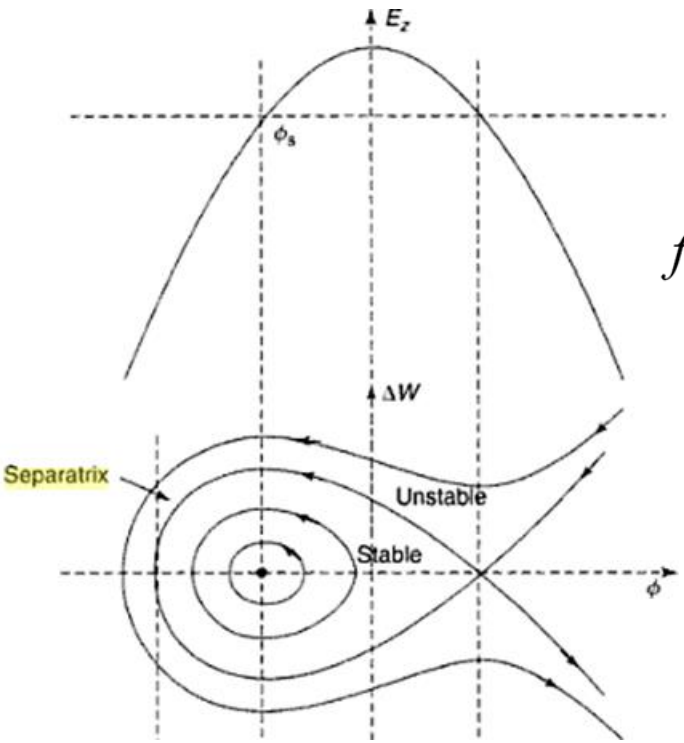
- Why heavy ions need multi-charge simultaneous acceleration
  - Meet intensity requirement and increase output efficiency
- Ch. Schmelzer, “Special Problem in Heavy Ion Acceleration” of “Part D Heavy Ion Linear Accelerator” in “Linear Accelerator” edited by P.M. Lapostolle and A. L. Septier, **1970**
  - The simultaneous acceleration of U^{23+} to U^{27+} increases the stripper yield from 15% for single charge state to more than 60% in the UNILAC
- H. Deitinghoff, “Calculations on the Possibility of the Simultaneous Acceleration of Ions with Different Charge States in a RFQ”, PAC95, **1995**
- P.N. Ostroumov, et al., “Multiple-charge Beam Dynamics in an Ion Linac”, “Multiple Charge State Beam Acceleration at ATLAS”, LINAC00, **2000**
- RIA → FRIB

FRIB Beam Dynamics Challenges for Multi-Charge-State Simultaneous Acceleration and Transport

- Lattice with large acceptance
  - Accommodate mismatch and offset among the charge states
- Manipulation of phase space
  - Prebuncher, velocity equalizer and HV platform scheme at LEBT
- Achromatic and isochronous bending optics design
  - Reduce emittance growth in both transverse and longitudinal planes
- Superimposition of multi-charge states at critical locations
  - Minimize emittance growth on charge stripper
  - Achieve small beam size on target

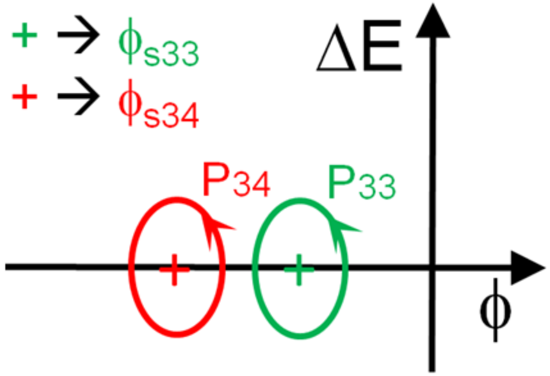
Longitudinal Motion of Multiple Charge States

Single charge state



Multiple charge states

Two particles

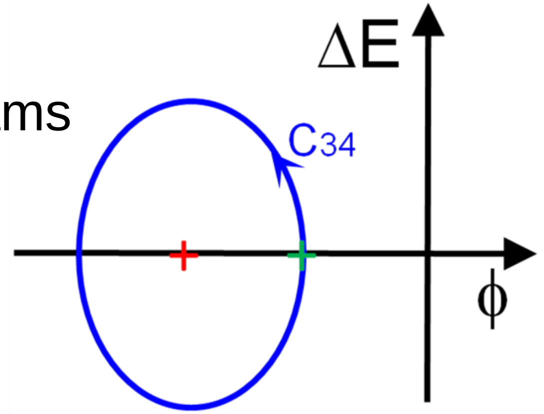


$q_{33}*\cos(\phi_{s33}) = q_{34}*\cos(\phi_{s34})$

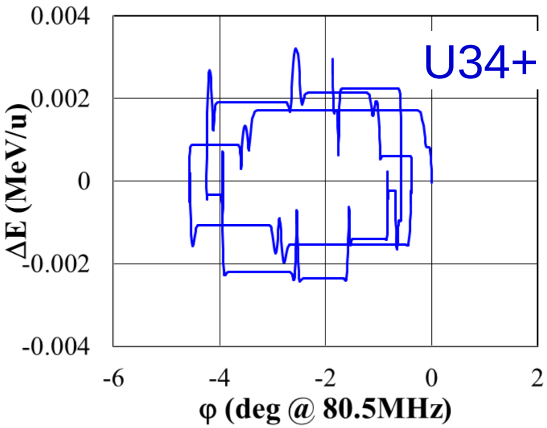
$$f_{loi} = f\sqrt{\frac{q_i E_o T\lambda \sin(-\phi_{si})}{2\pi mc^2\gamma_{si}^3\beta_{si}}}$$

where i=33 *or* 34

Two beams

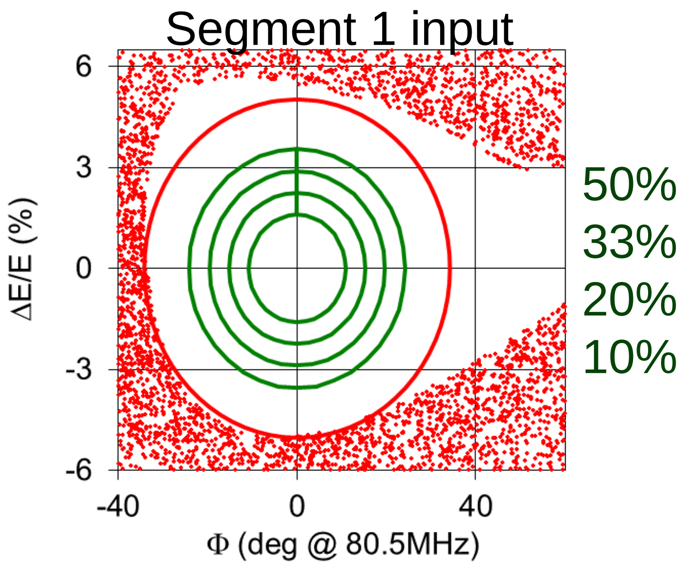


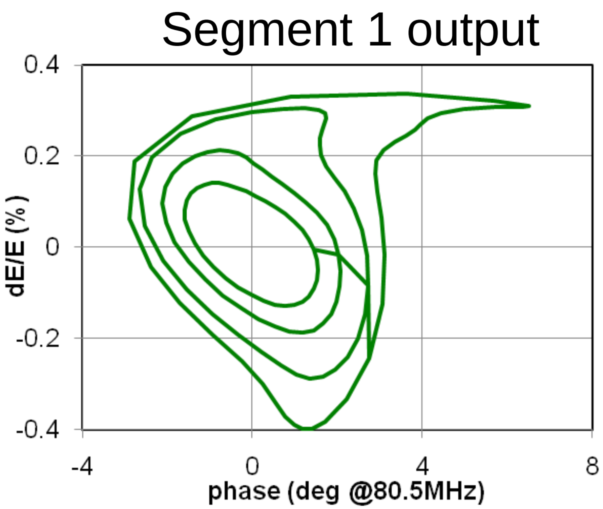
C34 → centroid of q=34 particles



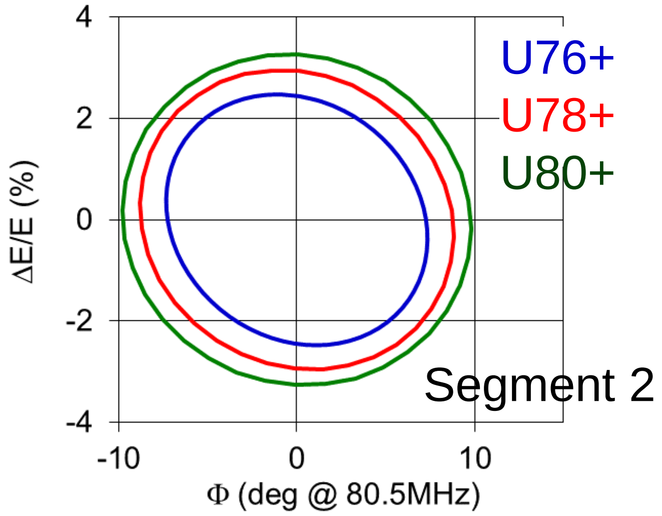
Large Ratio Acceptance/Emittance Required

- Longitudinal motion could be highly nonlinear





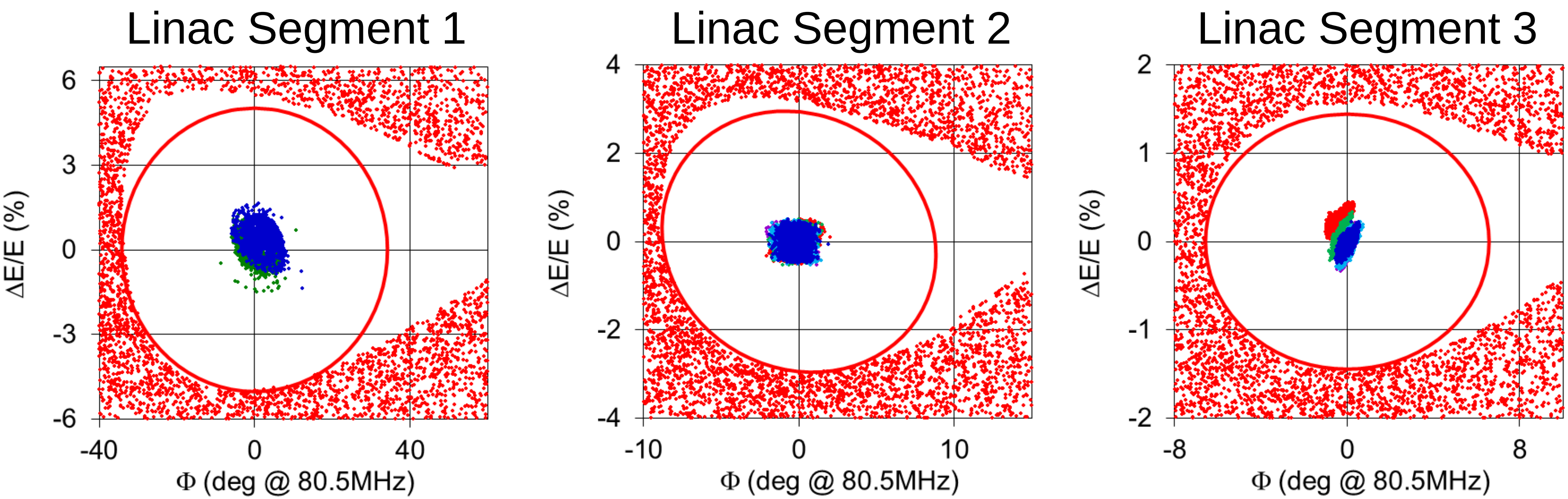
- Longitudinal acceptance of LS2
  - 80+ is about 25% larger than 78+
  - 76+ is about 30% smaller than 78+
- Errors will decrease acceptance while increase input emittance



FRIB Linac Longitudinal Acceptance

- Large longitudinal acceptance
  - Supports multi-charge state acceleration
  - Reduces beam loss initiated from longitudinal motion
- Large acceptance to emittance ratios:

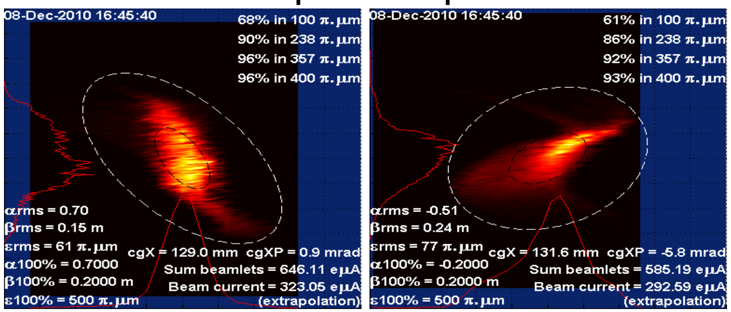
20: 1 | 25 : 1 | 30 : 1

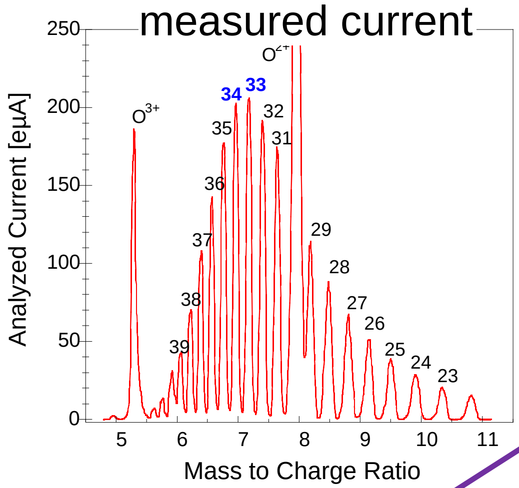


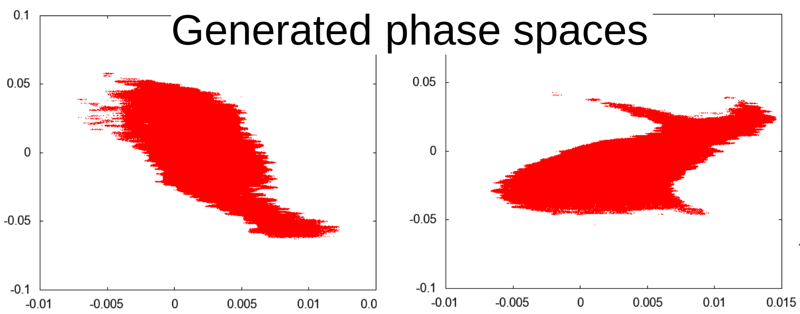
Front End Lattice Configuration

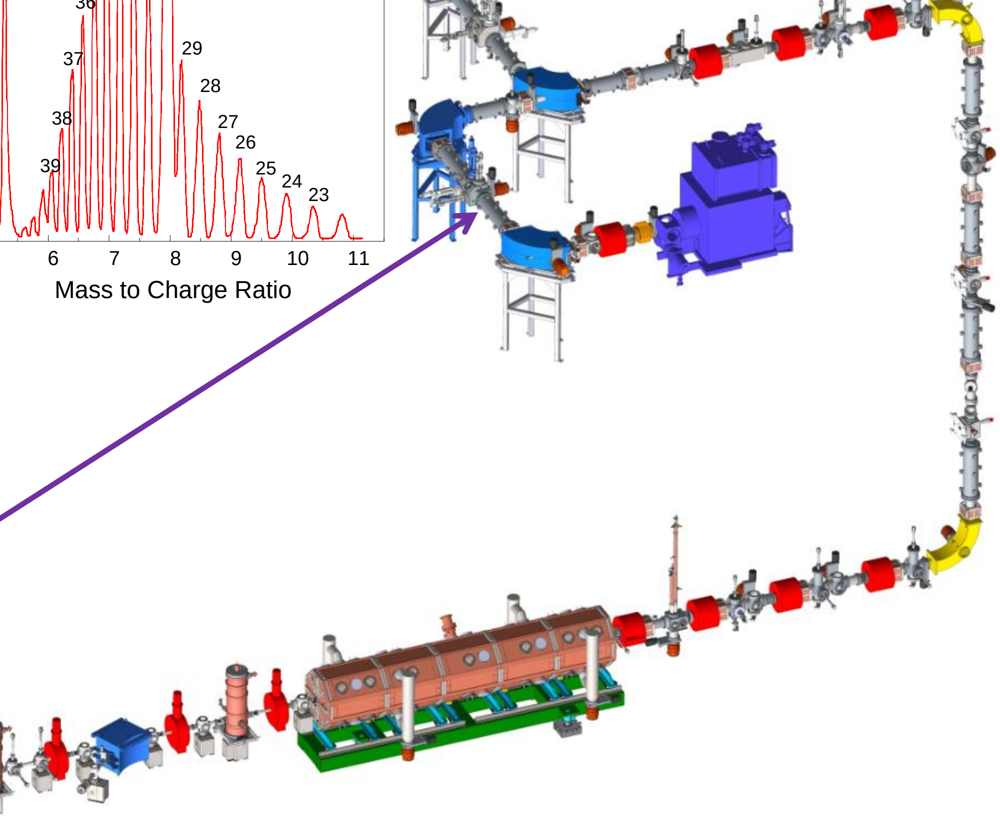
- Realistic initial particles generated based on measurements at VENUS
  - Two charge-states uranium beam

measured phase spaces







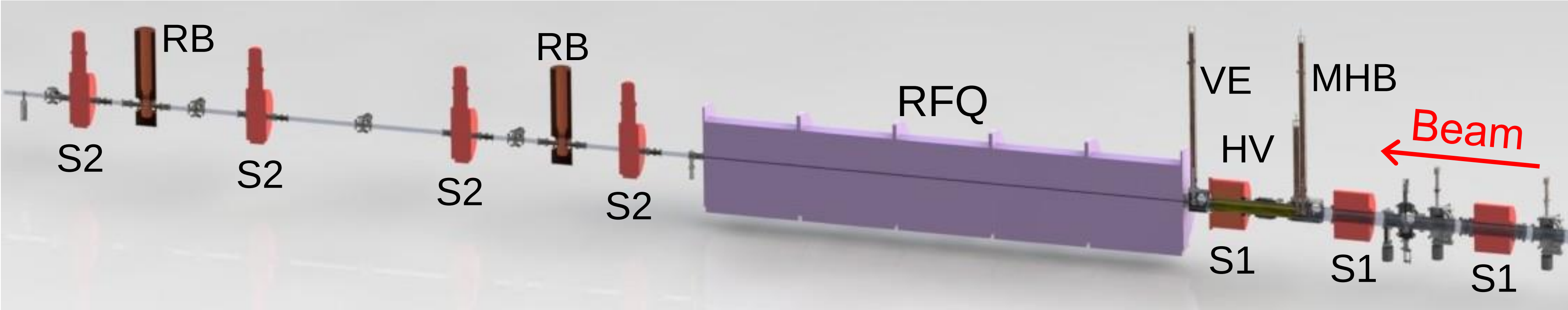


E. Pozdeyev, WE01AB03

S. Lund, MOPAB17

Longitudinal Phase Space Manipulation in FE

- External bunching and energy equalizing for two-charge-state beams reduce longitudinal beam emittance
  - Acceleration/deceleration cavity VE: accelerate lower charge state beam and decelerate higher one (same bunch energy into RFQ)
  - HV section between MHB and VE: adjust relative time flight difference between the two charge-state beams



  - U33+, U34+ in every other rf bucket

U33+
U34+

- Single charge-state injection
  - Both HV section and VE are off

A. Kolomiets, et al., PAC03

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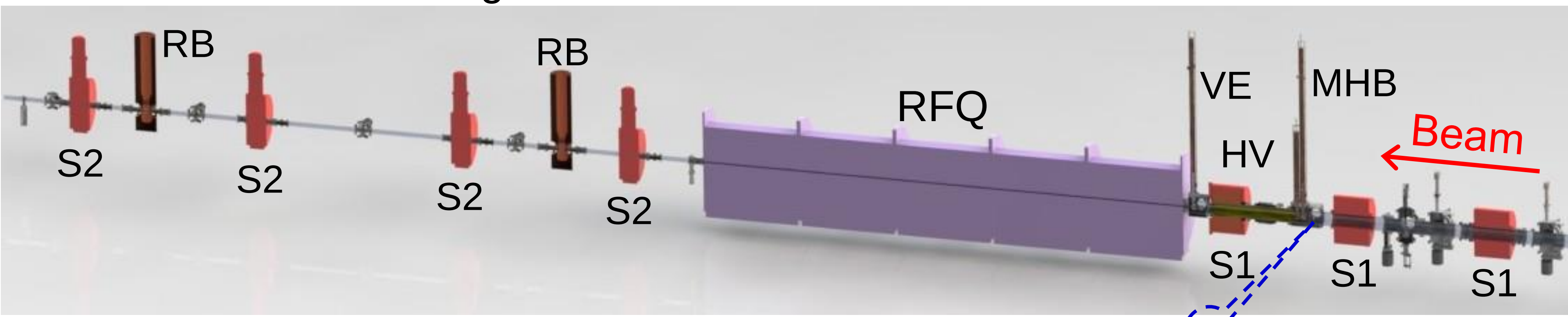

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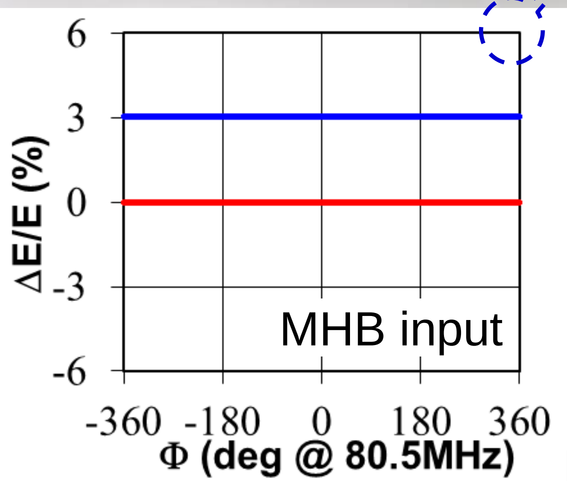

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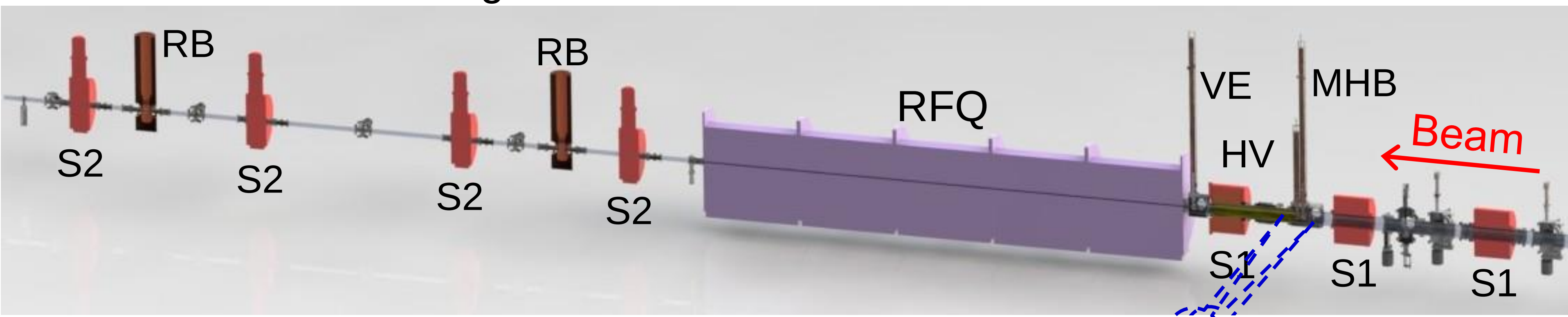

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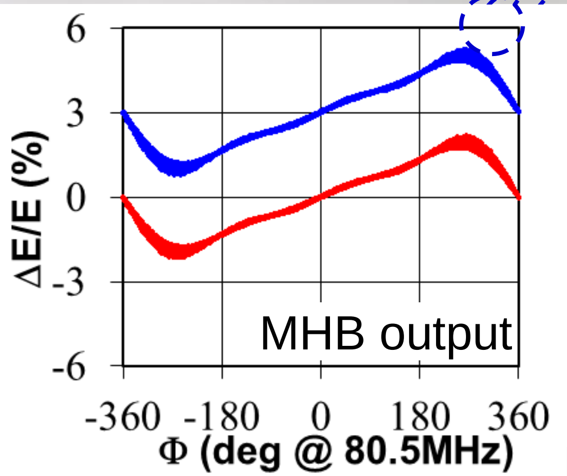

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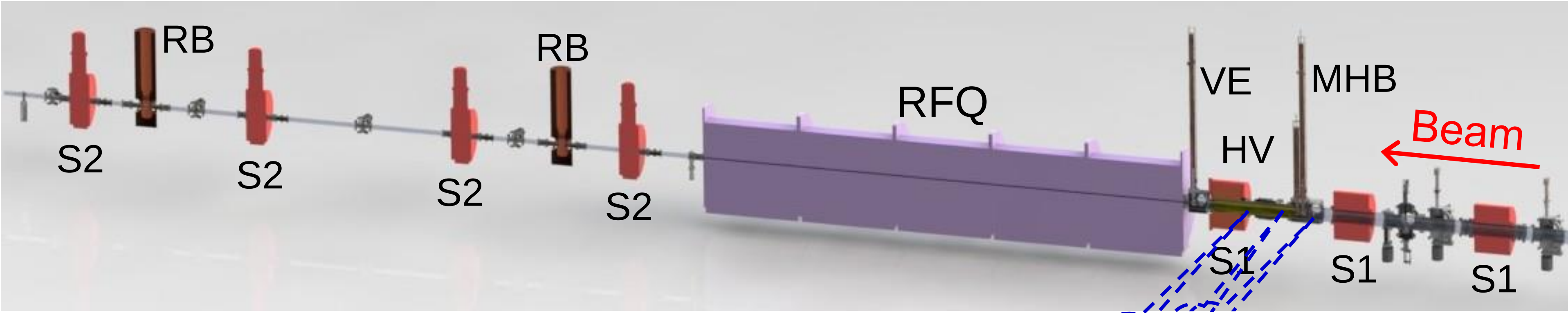

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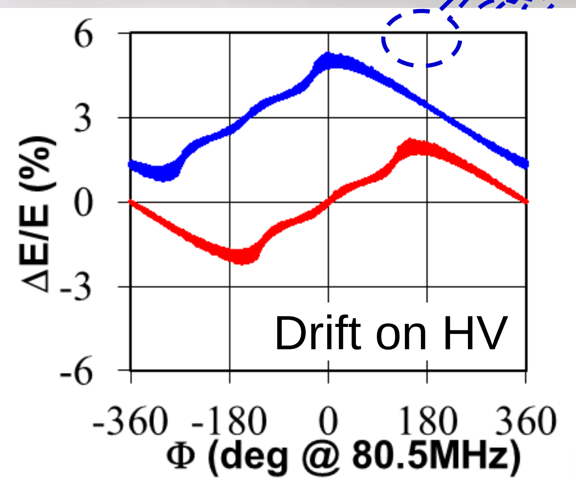

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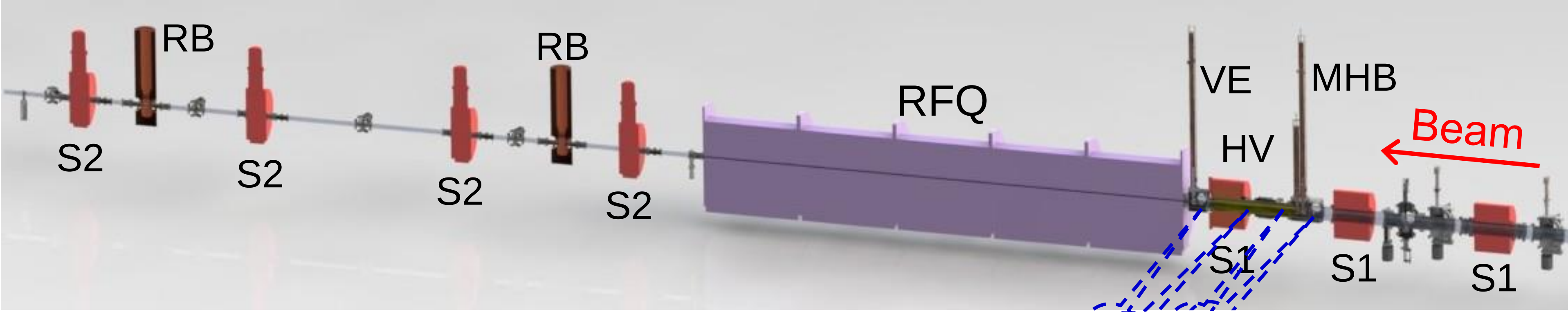

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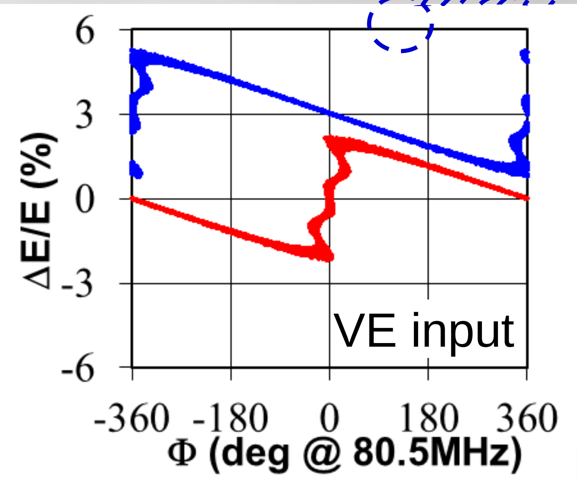

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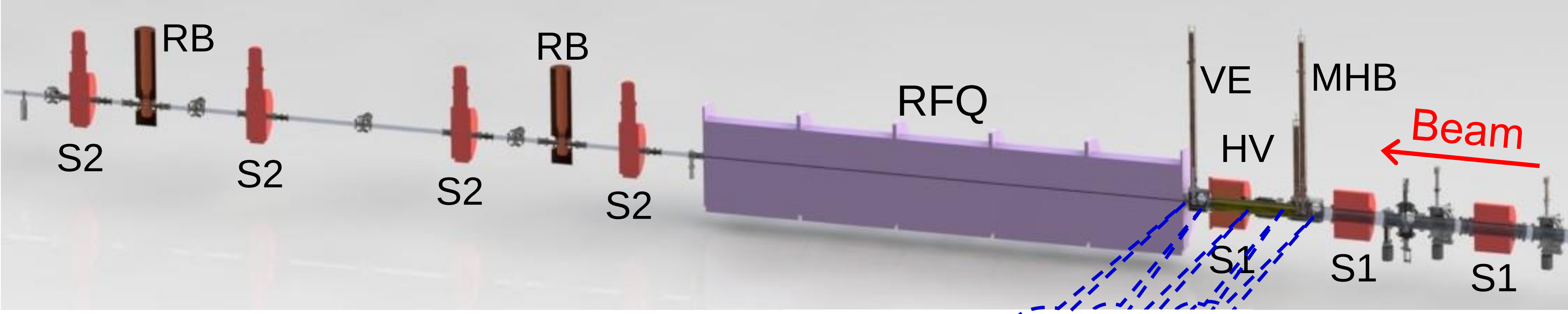

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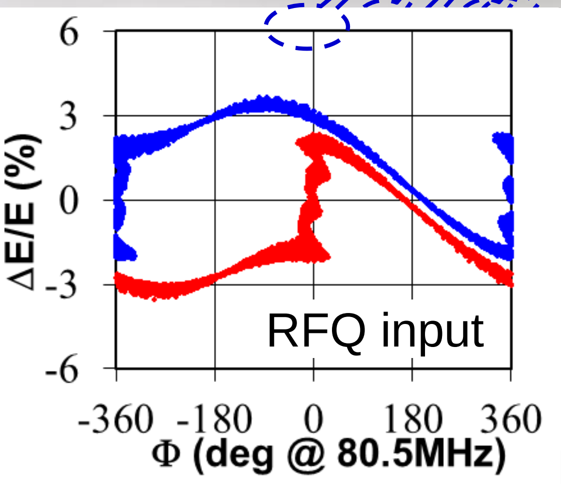

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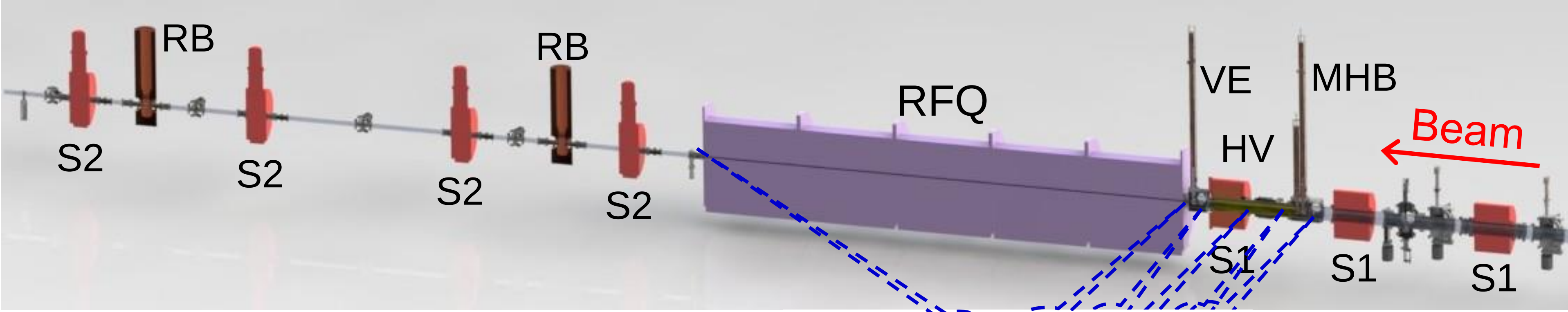

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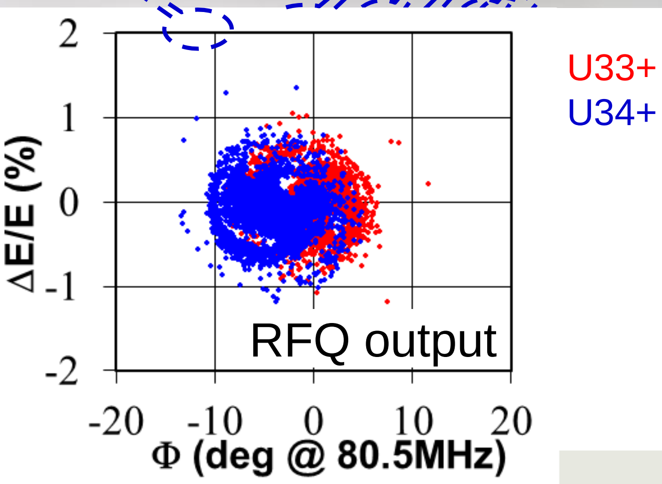

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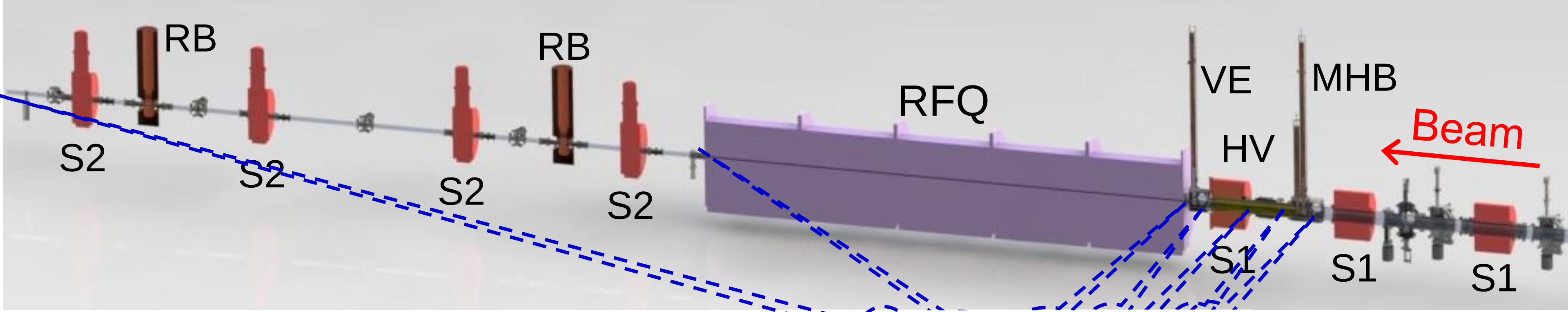

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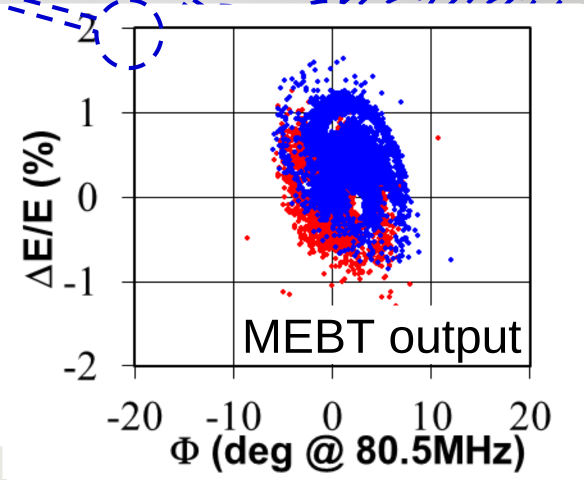

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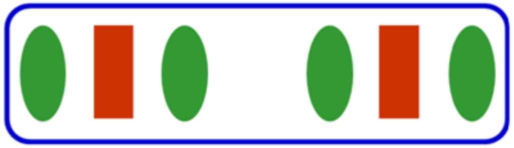
A. Kolomiets, et al., PAC03

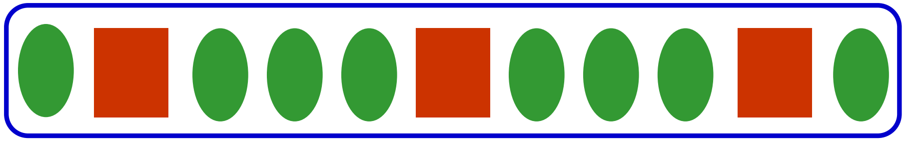
Linac Segment 1 Lattice

- 3 β=0.041 QWR cryomodules
  - 4 cavities
    - » f = 80.5 MHz
    - » V_a = 0.81 MV (2 gaps)
    - » a = 36 mm
  - 2 solenoids (each attached a BPM)
    - » Bo = 8 T
    - » L ~ 25 cm
  - Output energy: ~1.5 MeV/u
- 11 β=0.085 QWR cryomodules
  - 8 cavities
    - » f = 80.5 MHz
    - » V_a = 1.78 MV (2 gaps)
    - » a = 36 mm
  - 3 solenoids (each attached a BPM)
    - » Bo = 8 T
    - » L ~ 50 cm
  - Output energy: up to 20 MeV/u



β=0.041 cryomodule layout

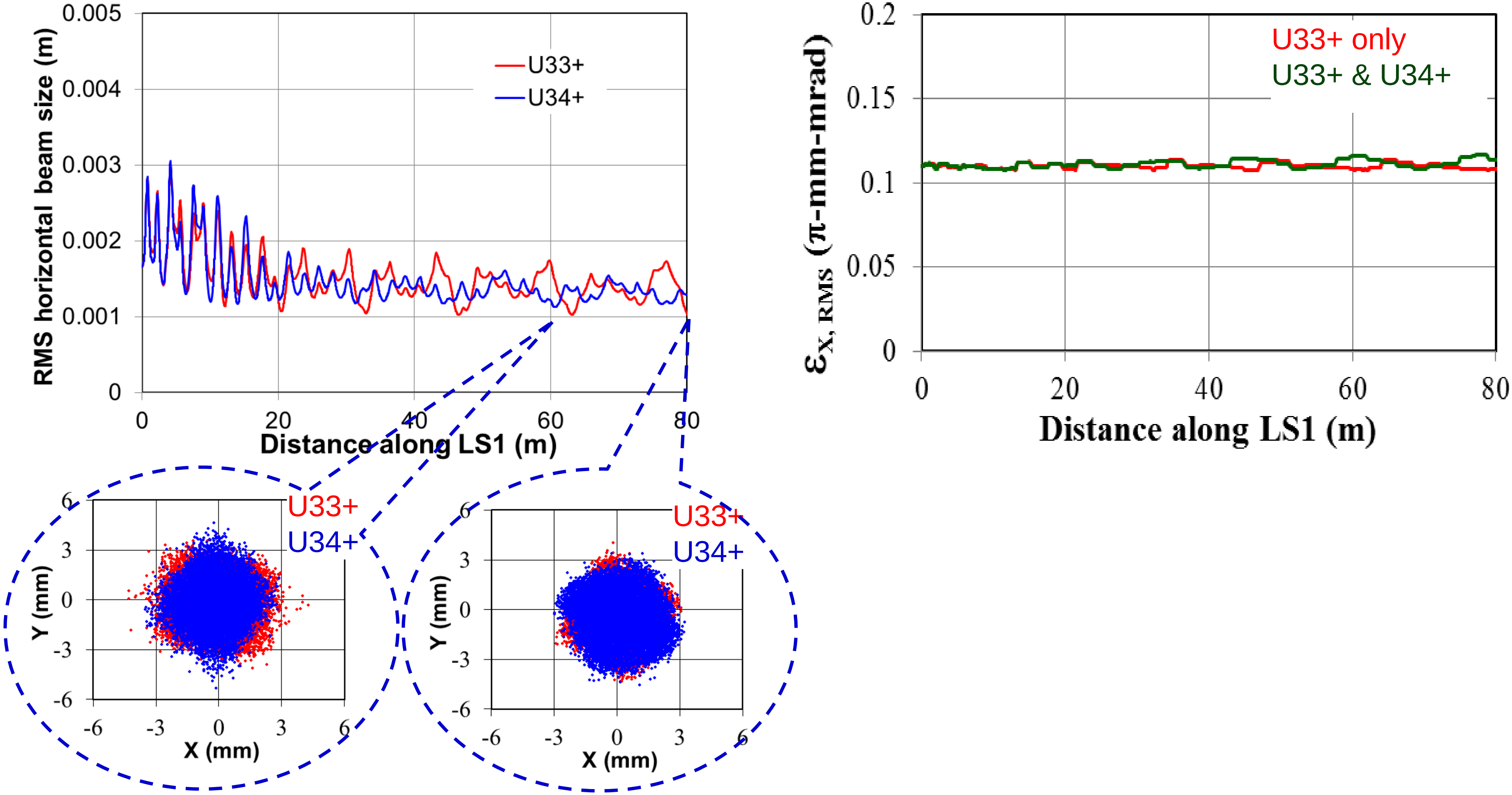
β_0 = 0.041 β_0 = 0.085
Quarter-Wave Resonators



β=0.085 cryomodule layout

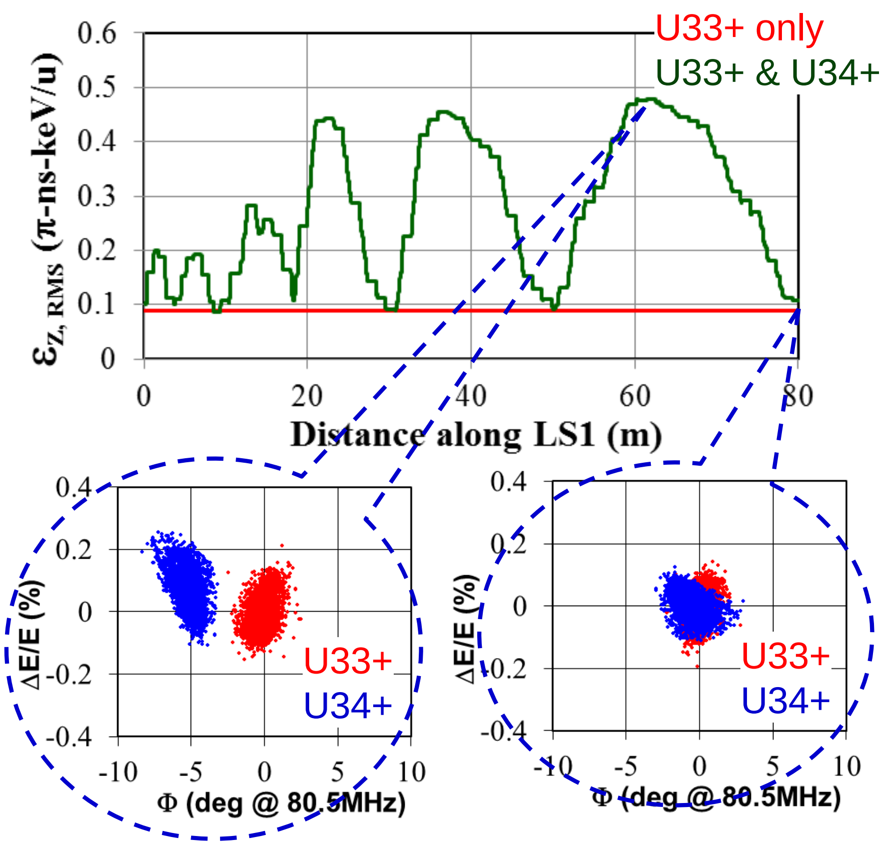
Transverse Beam Size and Emittance along LS1

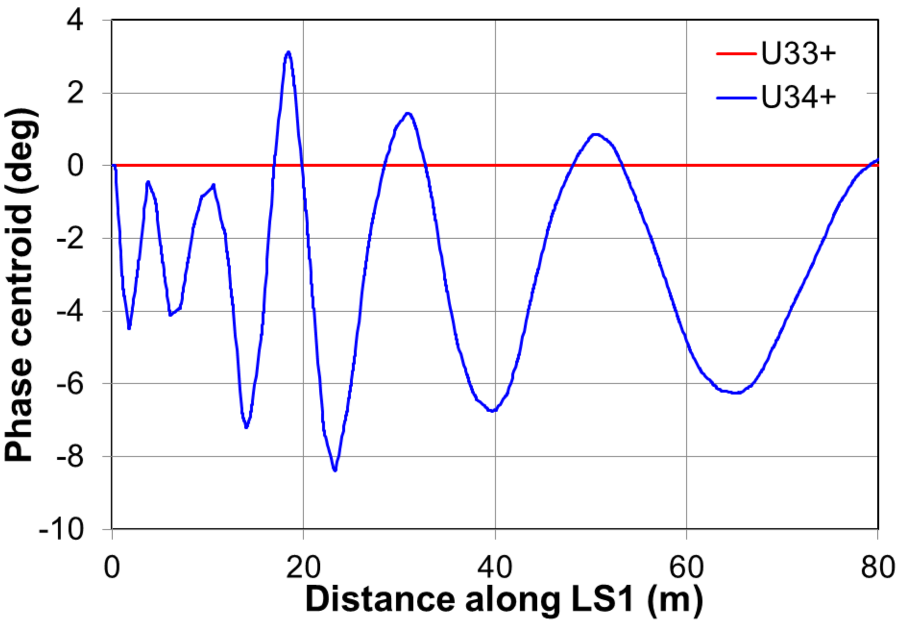
- Two charge states (U33+ & U34+) reasonably overlapped
  - Very similar transverse dynamics



Longitudinal Overlap of 2q Beam at LS1 Exit

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

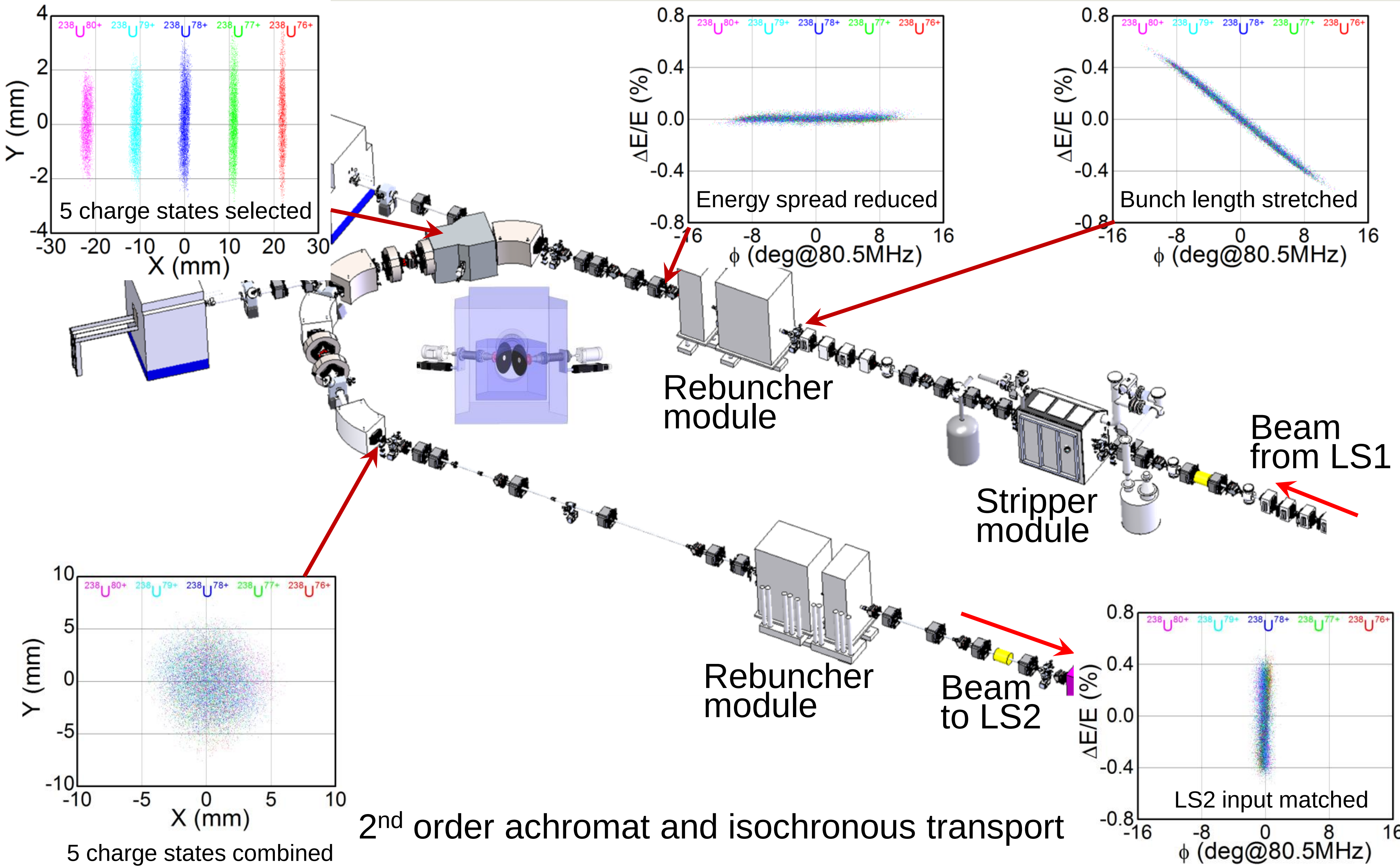




- Phase of cavities are adjusted for the overlap of the two-charge-state beam at the exit of Segment 1 by measuring the timing of each charge state beam

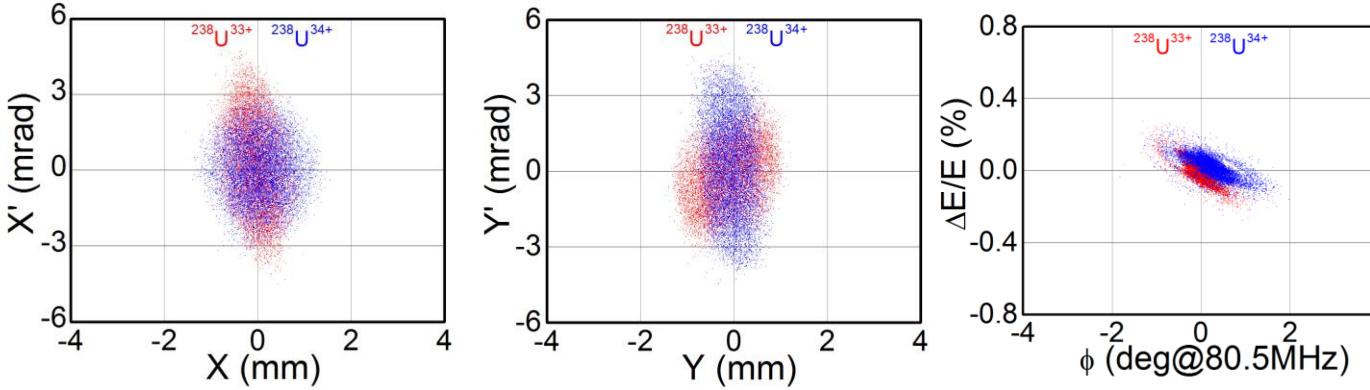
S. Lidia, WE02AB01

Charge Stripper and Selection in FS1

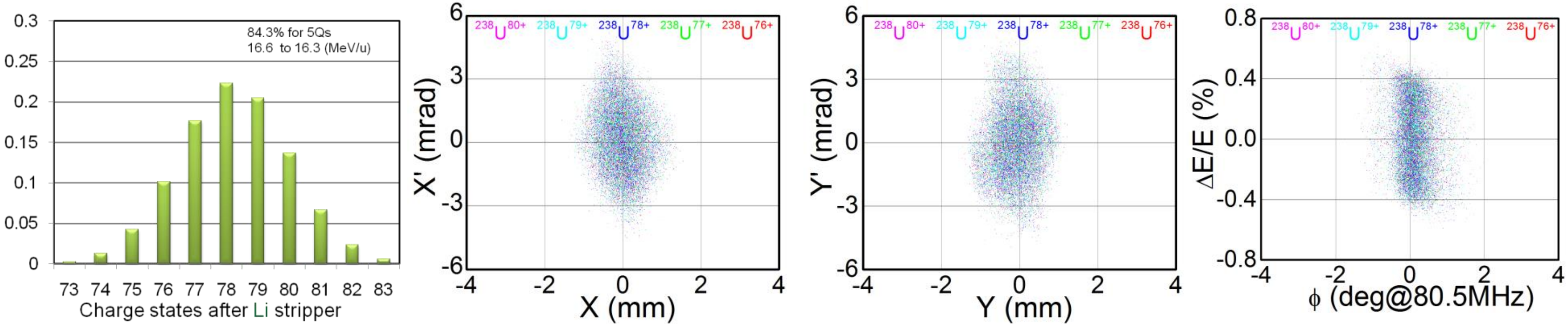


Uranium Beam Distributions at Li Stripper

- U33+ and U34+ at the input of stripper
  - Small beam size and short bunch length achieved

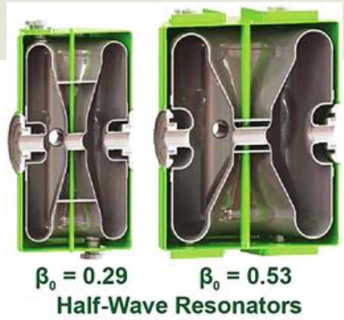


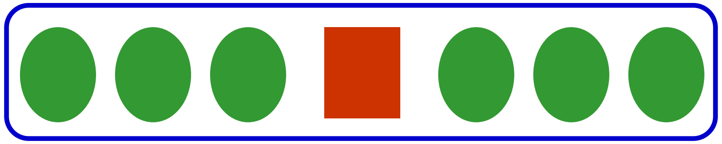
- Multi-charge state distribution at the output of stripper
  - 85% beam in 5 charge states (from U76+ to U80+)



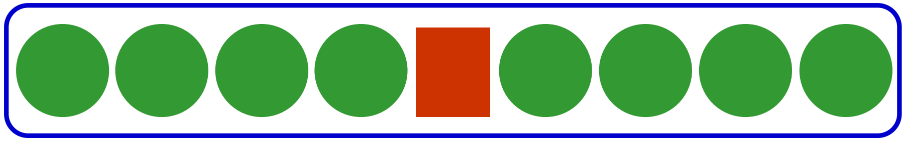
Linac Segment 2 Lattice

- 12 β=0.29 HWR cryomodules
  - 6 cavities
    - » f = 322 MHz
    - » V_a = 2.09 MV (2 gaps)
    - » a = 40 mm
  - 1 solenoid
    - » Bo = 8 T
    - » L ~ 50 cm
  - Output energy: ~55 MeV/u
- 12 β=0.53 HWR cryomodules
  - 8 cavities
    - » f = 322 MHz
    - » V_a = 3.7 MV (2 gaps)
    - » a = 40 mm
  - 1 solenoids
    - » Bo = 8 T
    - » L ~ 50 cm
  - Output energy: > 150 MeV/u





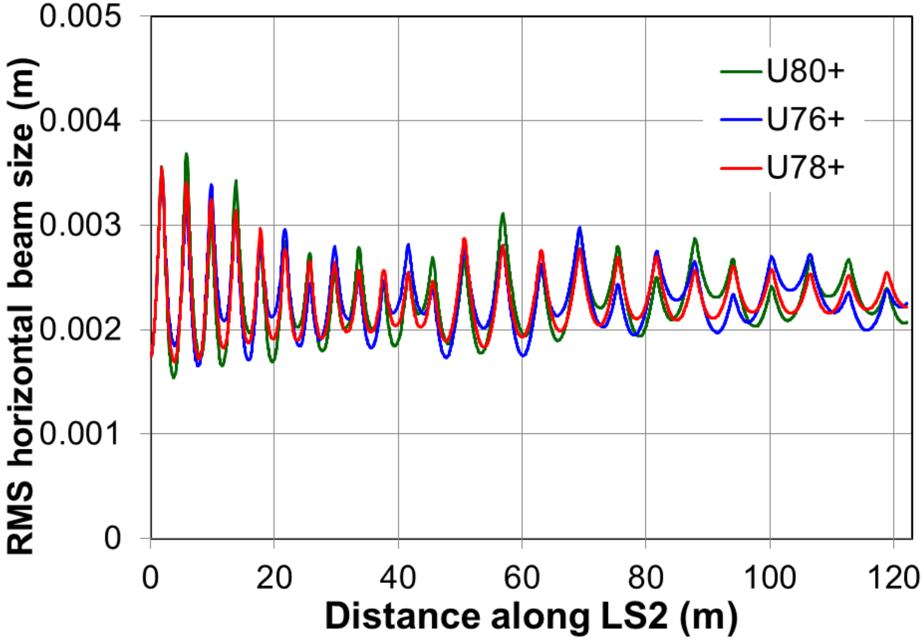
β=0.29 cryomodule layout

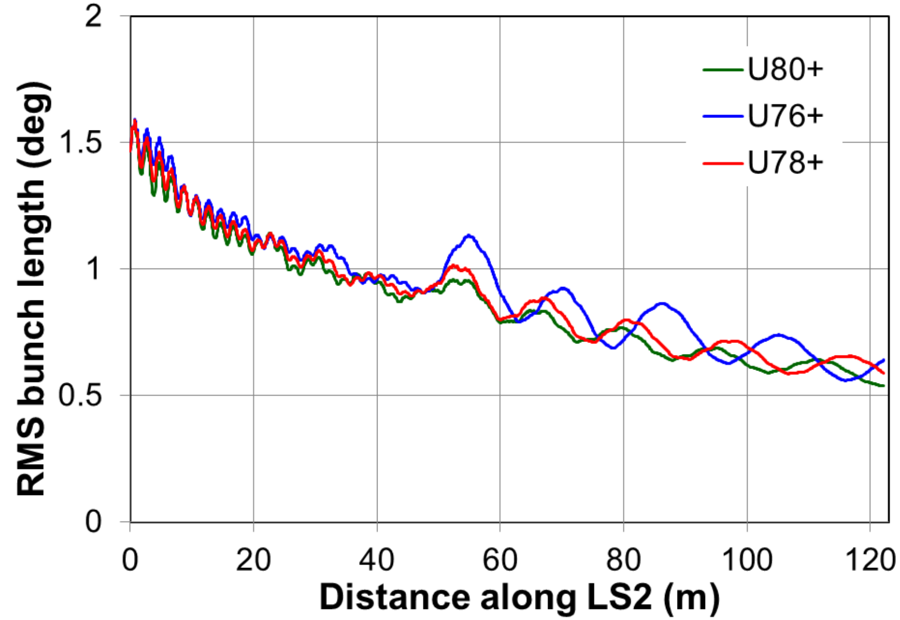


β=0.53 cryomodule layout

Beam Size and Bunch Length along LS2

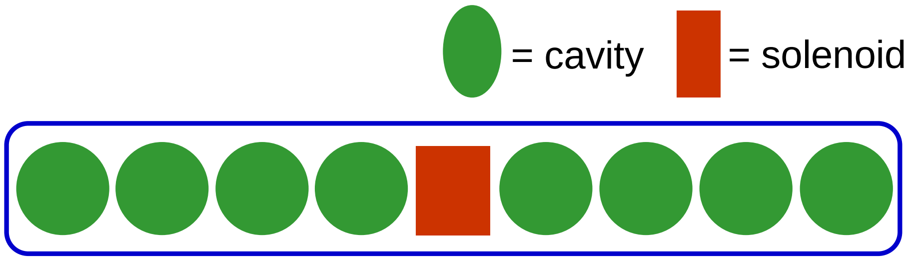
- Relatively small mismatch among U76+, U78+ and U80+ in Segment 2
  - Beam size not increase too much even with 5 charge states (U76+ – U80+)
  - The increased bunch length variation due to the transition from ↨=0.29 to ↨=0.53 cryomodule (no special matching taken)



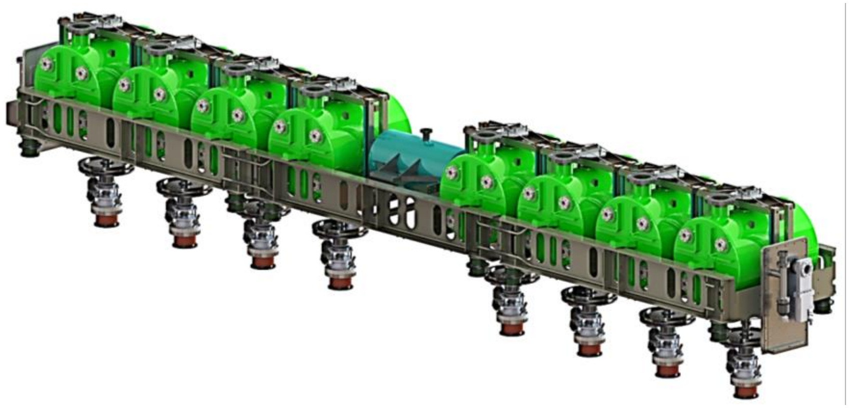


Linac Segment 3 Lattice

- 6 β=0.54 HWR cryomodules
  - 8 cavities
    - » f = 322 MHz
    - » V_a = 3.7 MV (2 gaps)
    - » a = 40 mm
  - 1 solenoids
    - » Bo = 8 T
    - » L ~ 50 cm
  - Output energy: > 200 MeV/u
- Quadrupole FODO lattice Space for u
  - Space for future upgrade
  - 12 β=0.54 HWR cryomodules
    - » Output energy: > 300 MeV/u

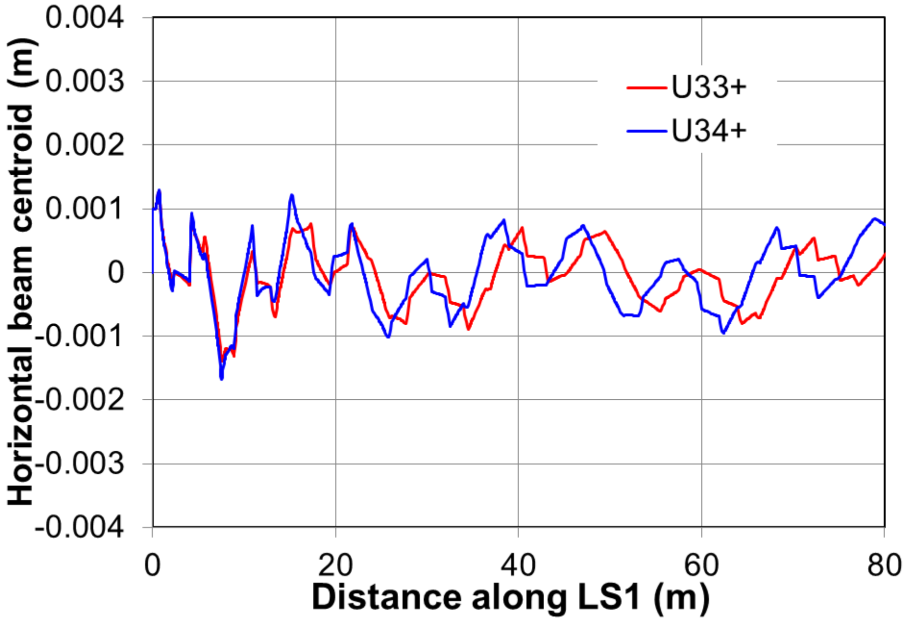


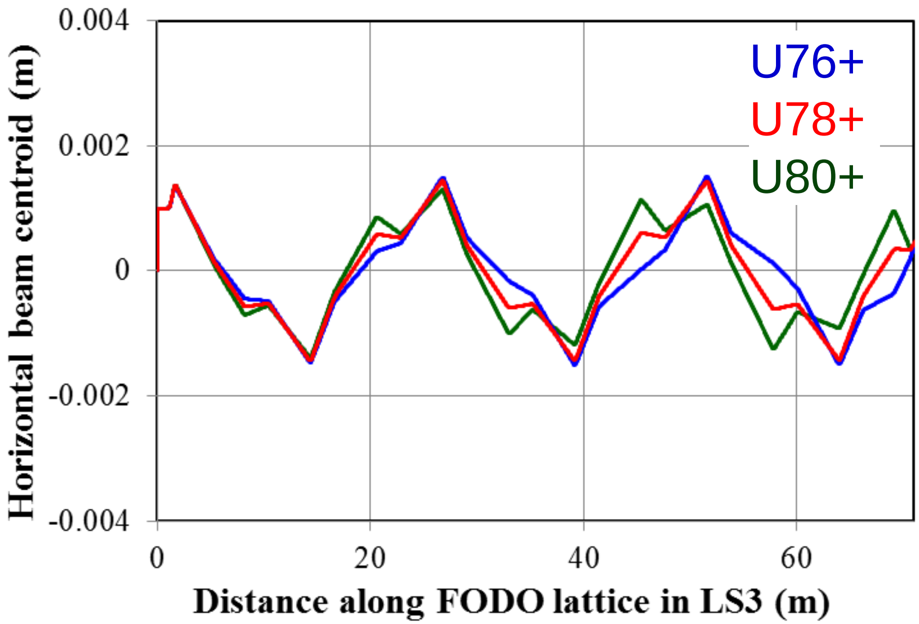
β=0.54 cryomodule layout



Orbit Kick Response for Different Charges

- Initial offset 1 mm for each charge state (can be measured by BPM)
- LS1 with solenoid focusing and cavity acceleration/defocusing
  - The difference between U33+ and U34+ developed but up to ~1 mm
- Quadrupole FODO lattice in LS3
  - All 5 charge states follow the same pattern
  - Maximum difference ~1 mm

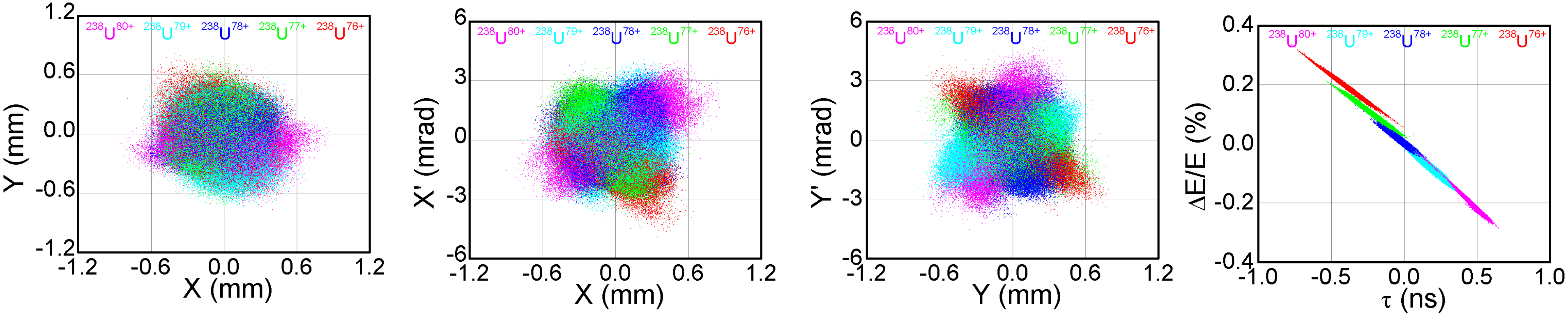




Five-charge-state Uranium Beam on Target

- Satisfy the beam-on-target requirements 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%	✓



Examples of Other Studies Being Performed

- Detailed tuning procedures of multi-charge beam being developed
  - Cavity phase setup and scaling
  - Transverse and longitudinal matching

- Element Failure Being Systematically Studied
  - Single cavity failure
  - Single magnet miss-power
  - Cavity gradient degradation
  - Cavity gradient variation
  - Cryomodule failure (both cavity and solenoid)
  - Stripper degradation

- Virtual accelerator and online modeling

Summary

- FRIB linac baseline lattice has been developed
  - Satisfy with baseline requirements
  - Support the start of civil and technical construction
  - Consistent with future upgrades
- Simultaneous acceleration of multi-charge-state beam is most challenge in FRIB linac beam dynamics
  - Lattice with large acceptance
  - Manipulation of phase space
  - higher order achromat bending transport
- Accelerator physics group continues actively working with other groups to further develop strategies and algorithms for machine commissioning
  - Beam tuning
  - Virtual and online accelerator

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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

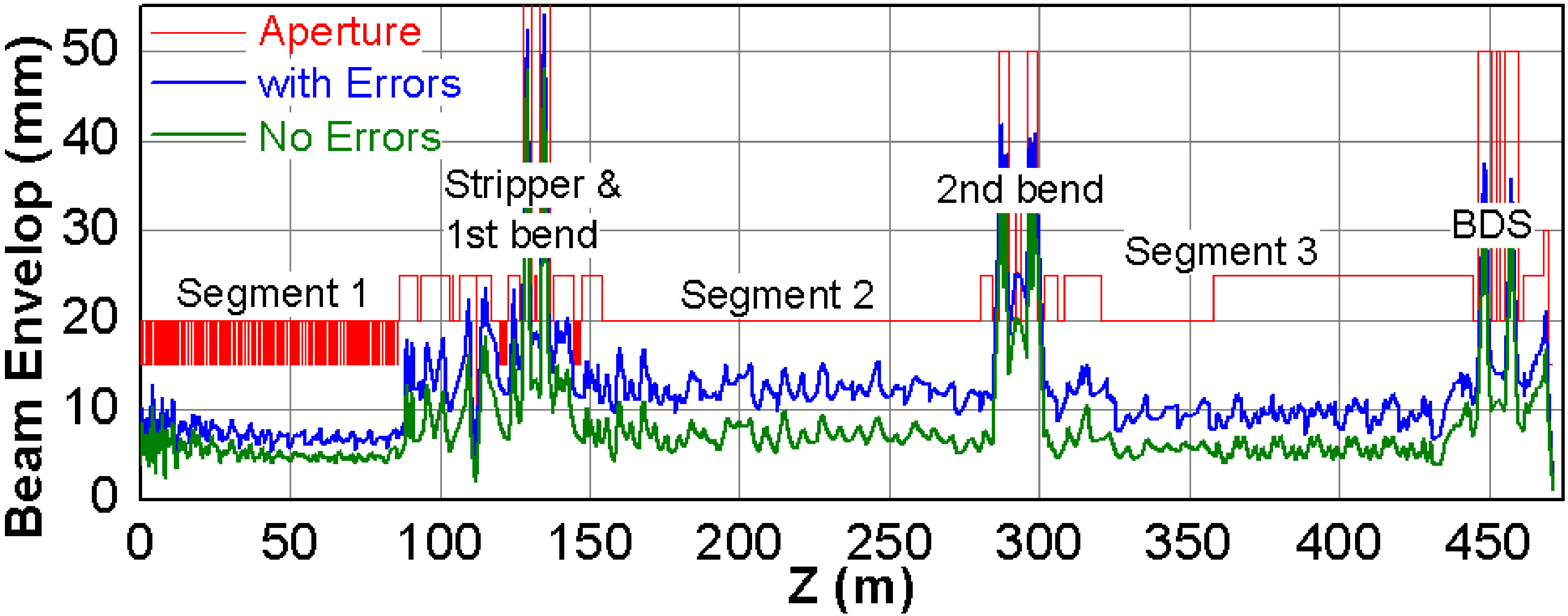
- Cavity RF errors (measured rf errors at MSU are much smaller)

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

- 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 growth (within aperture) mainly due to misalignment
  - Steering correctors turned on
- RF errors cause significant longitudinal emittance growth but not coupled into transverse
- No uncontrolled beam losses observed



Longitudinal Phase Space Manipulation in FE