Beam Dynamics in the Facility for Rare Isotope Beams (FRIB) Linac

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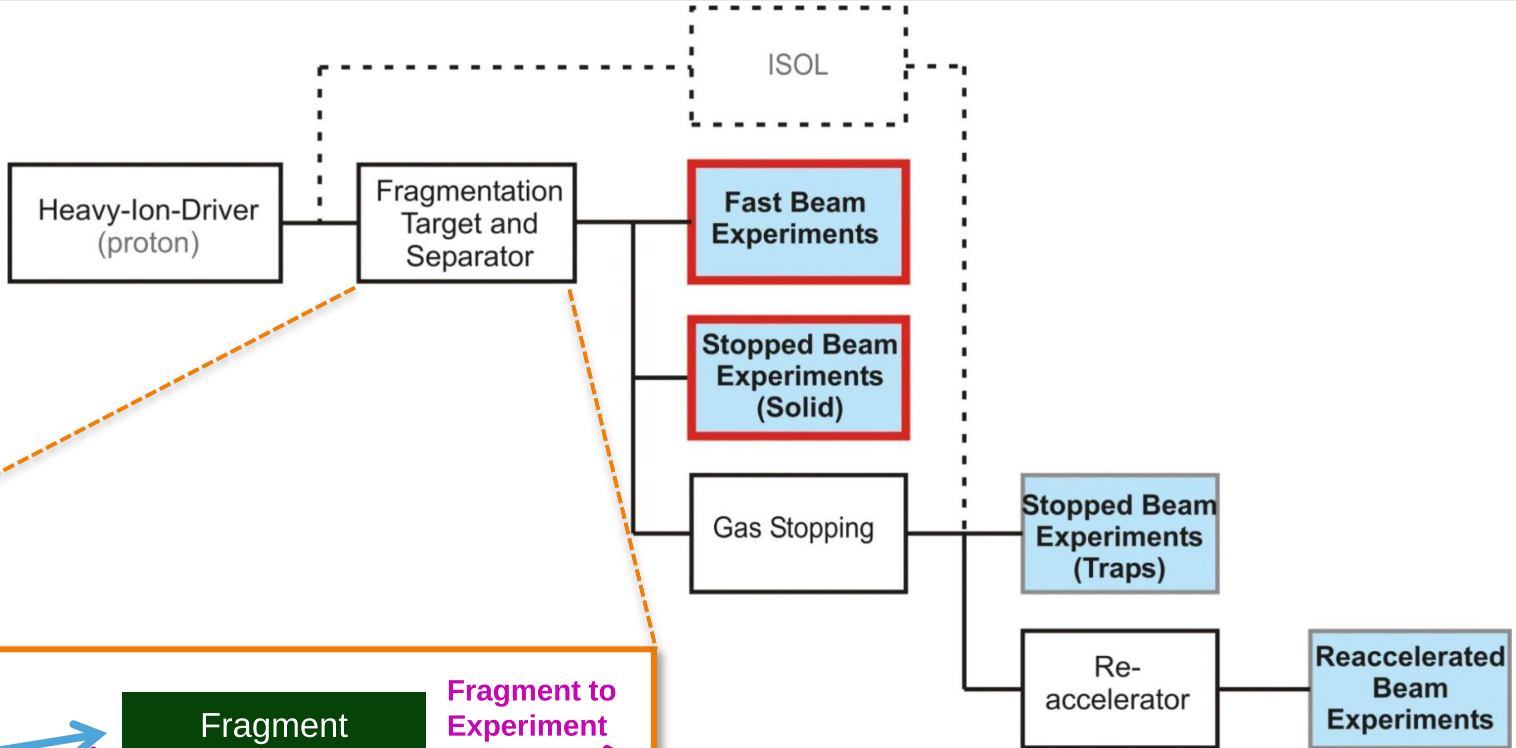
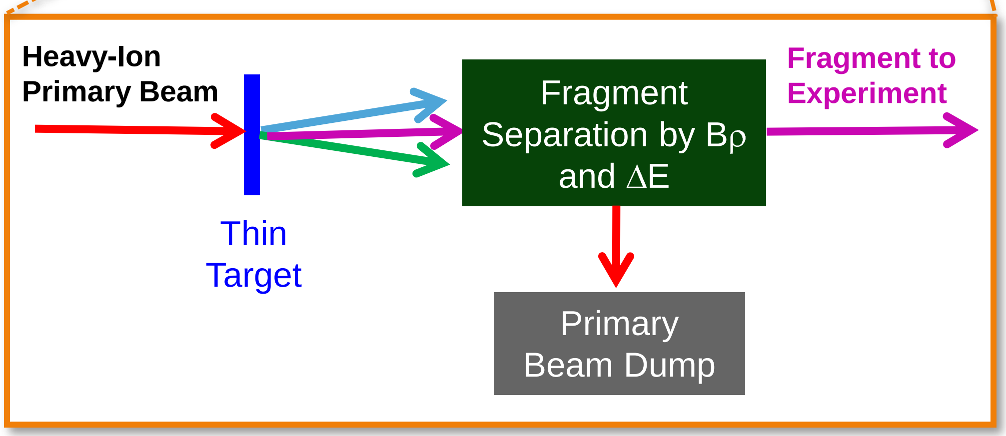
HB2010 Morschach, Switzerland

FRIB Rare Isotope Beams

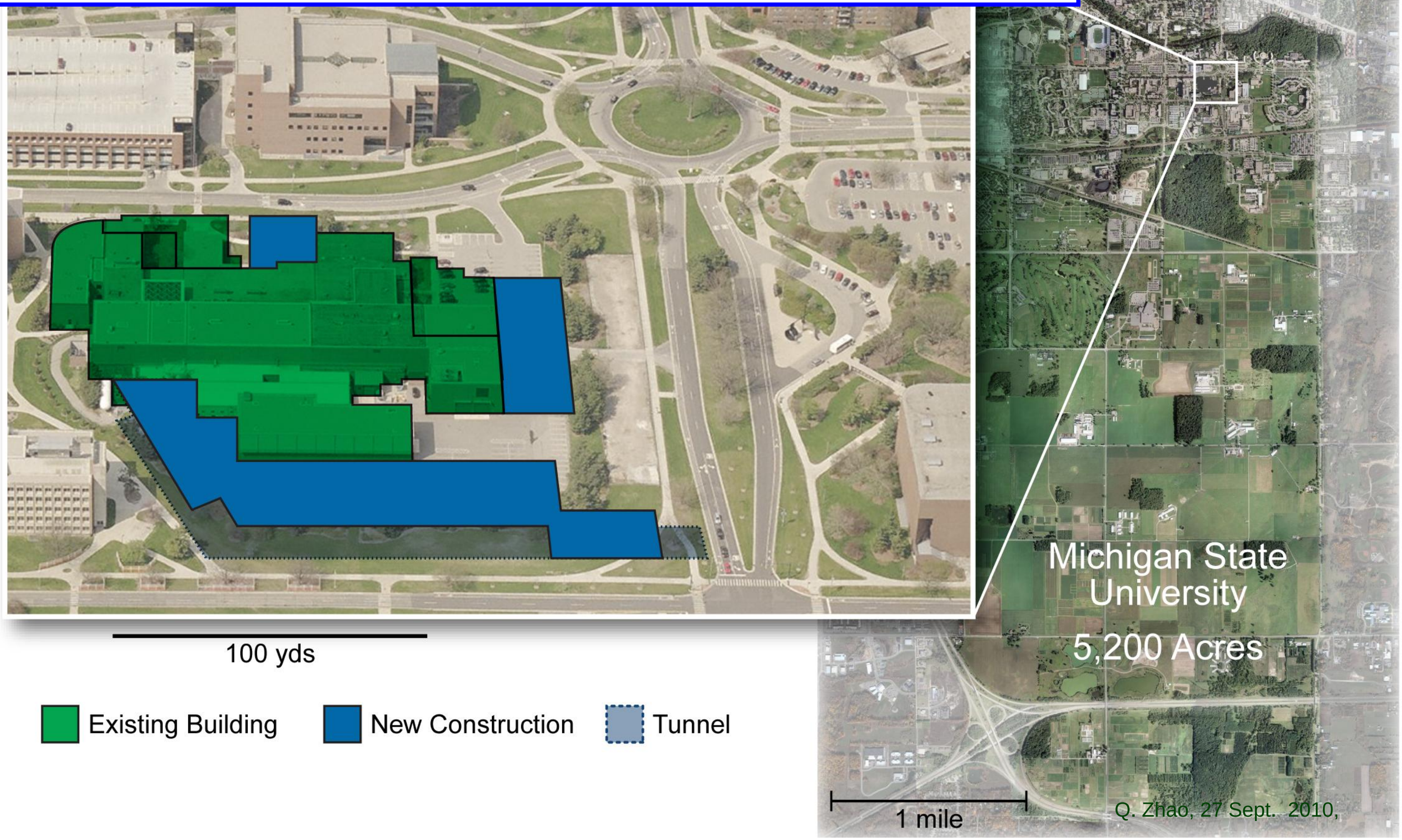
- **Heavy-ion linac can also accelerate light ions needed for an ISOL facility**





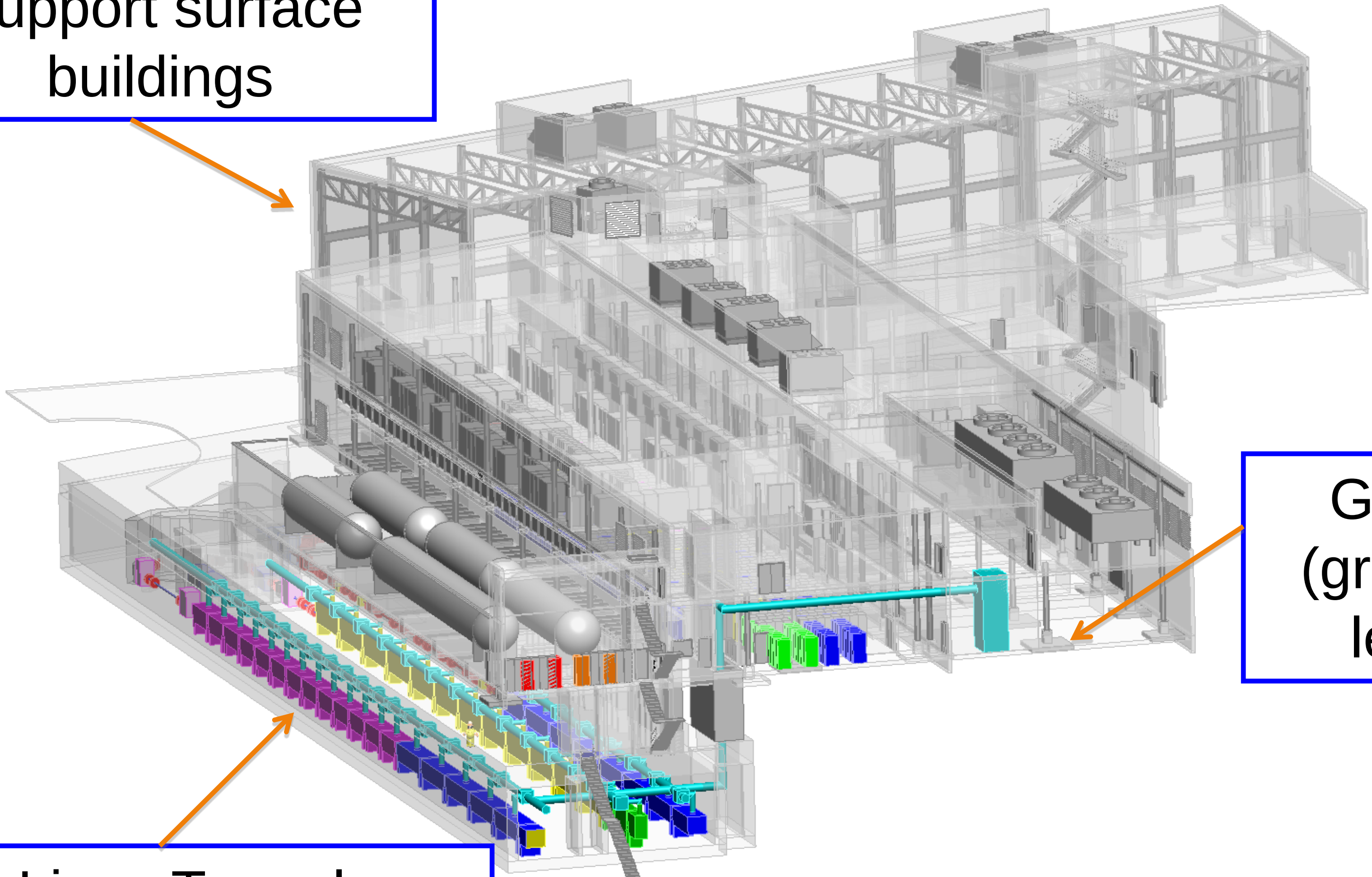
FRIB at MSU

- Begun 2009 with estimated completion ~2018
- Total Project Cost $615M



FRIB Linac Layout – [1]

Support surface buildings

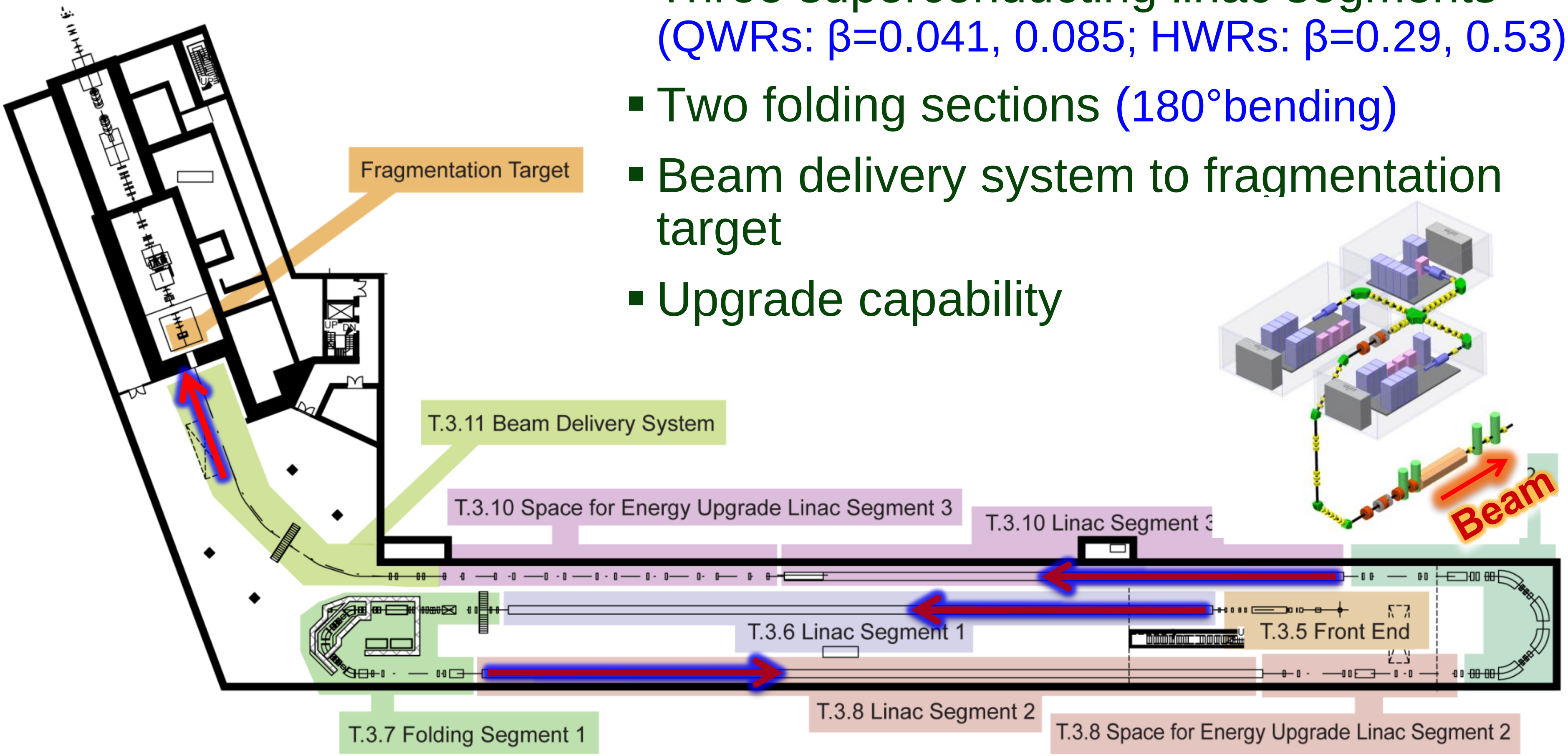


Grade (ground) level

Linac Tunnel
~40 ft
below grade

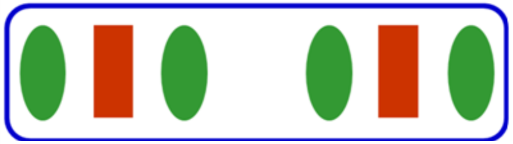
FRIB Linac Layout – [2]

- Front end (ECRIS, LEBT, RFQ, MEBT)
- Three superconducting linac segments (QWRs: β=0.041, 0.085; HWRs: β=0.29, 0.53)
- Two folding sections (180°bending)
- Beam delivery system to fragmentation target
- Upgrade capability



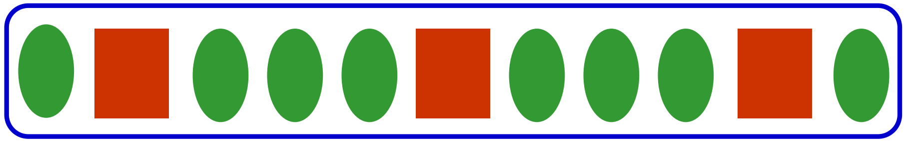
FRIB Linac Lattice

= cavity = solenoid



4 cryomodules → ouput →~1.4 MeV/u

4 β=0.041 80.5MHz QWRs, 2 solenoids

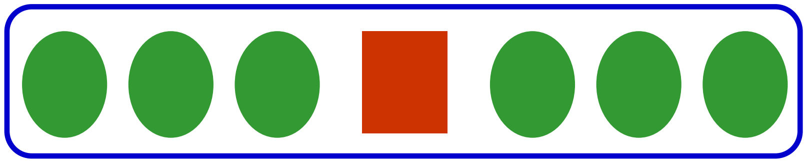


12 cryomodules→ output 16.6 MeV/u

8 β=0.085 80.5MHz QWRs, 3 solenoids

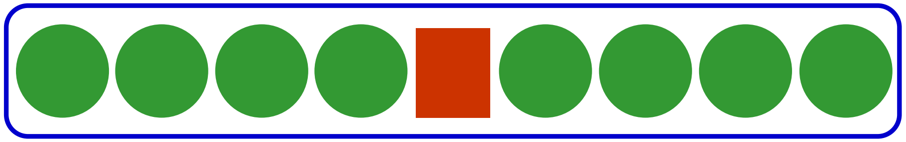
Linac Segment 1

Stripper foil: 33,34 → 76,77,78,79,80 for uranium



13 cryomodules → output 55 MeV/u

6 β=0.29 322MHz HWRs, 1 solenoid

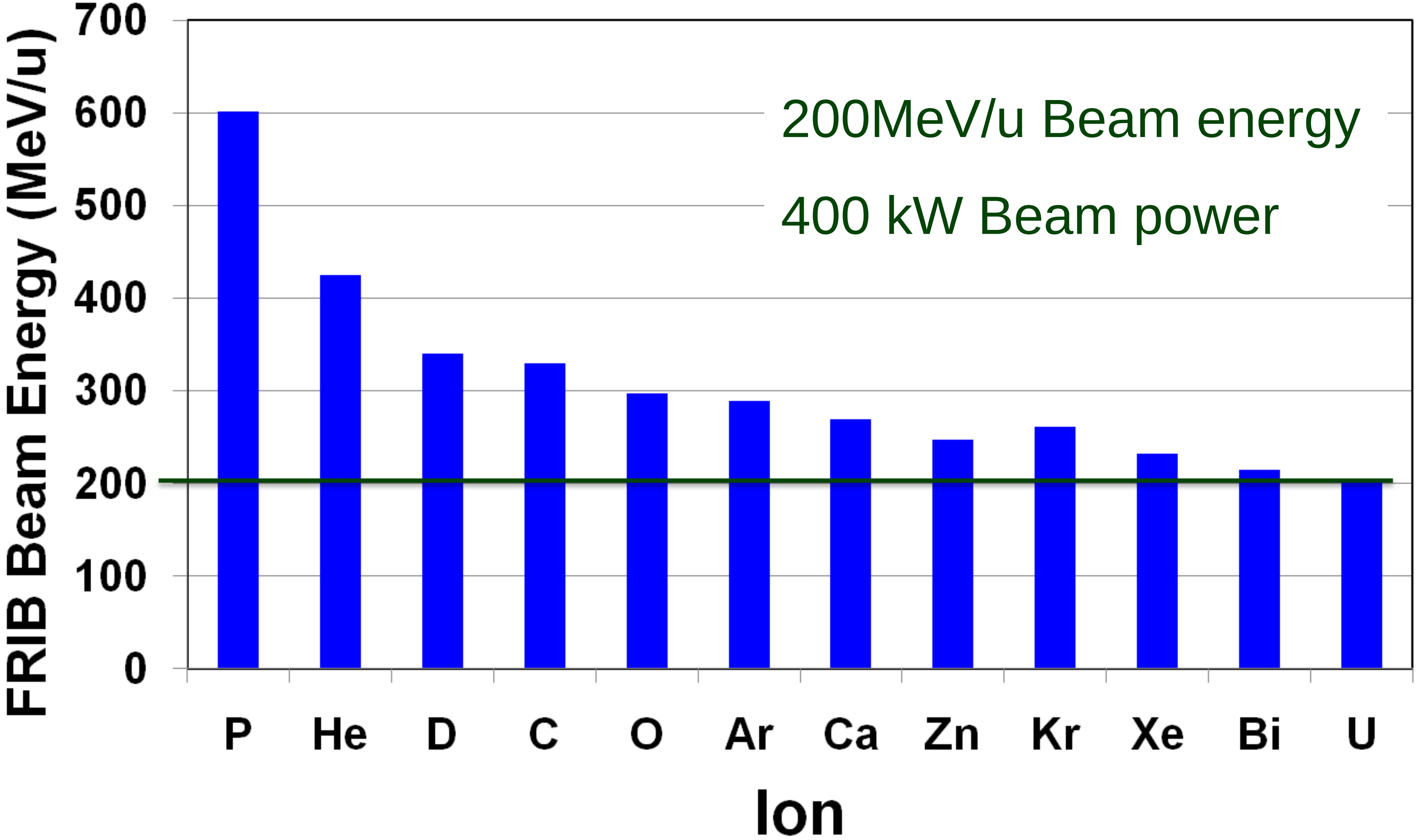


18 cryomodules → output >200 MeV/u

8 β=0.53 322MHz HWRs, 1 solenoid

Linac Segment 2 & 3

FRIB Linac Performance

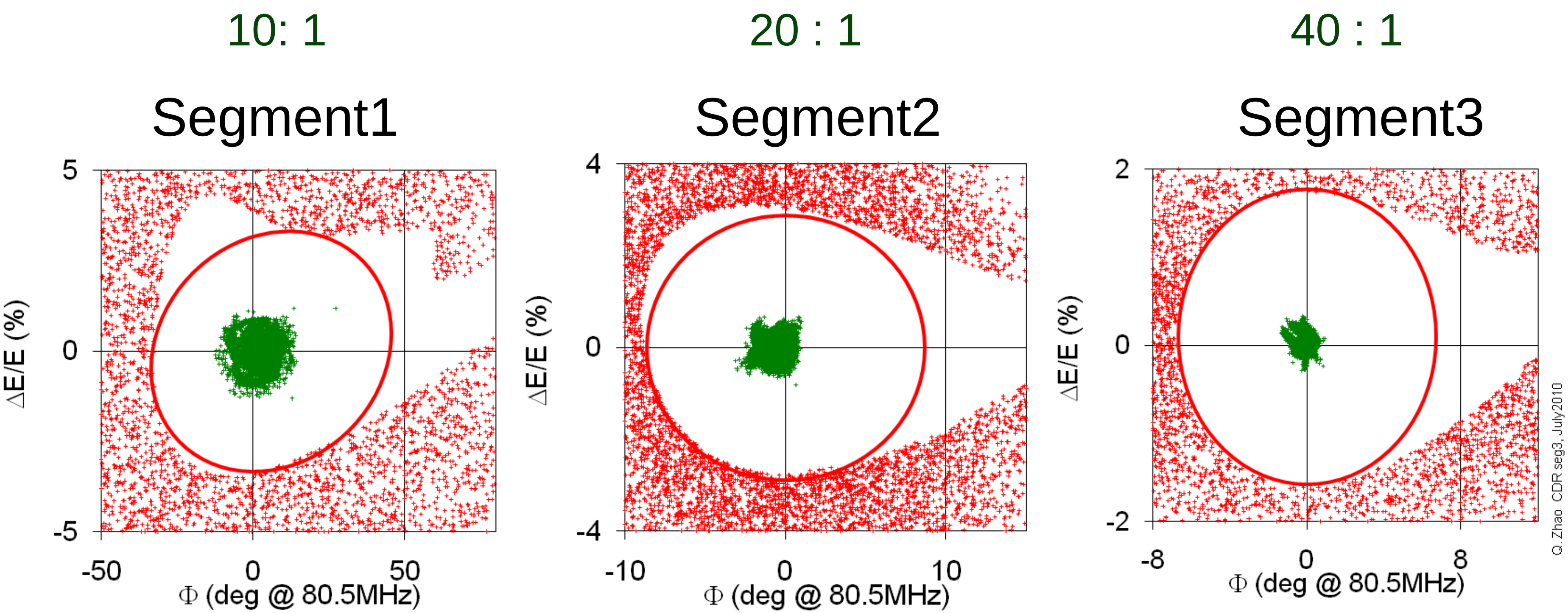


FRIB Linac Longitudinal Acceptance

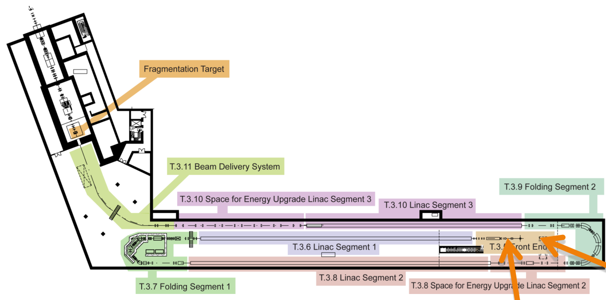
Large longitudinal acceptance

- Supports **multi-charge state** acceleration
- Reduces beam loss

Large acceptance to emittance ratios:

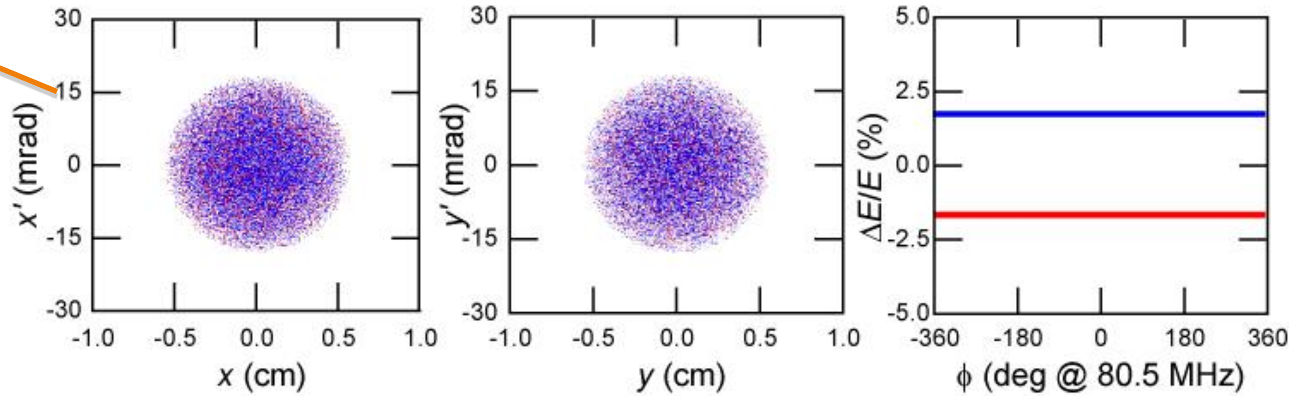


End-to-End Beam Simulations (1)



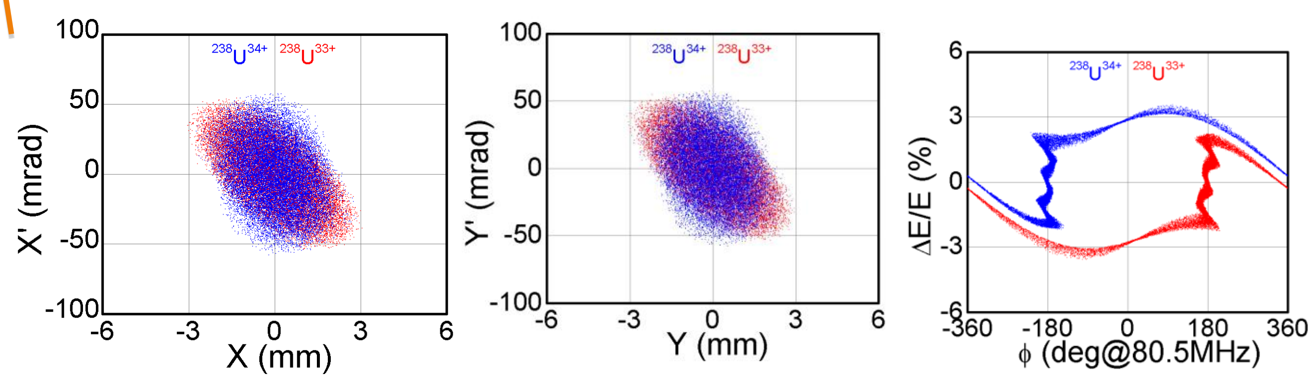
Front end LEBT entrance

- 12 keV/u
- Initial **2 charge states** in beam distribution



RFQ entrance

- 12 keV/u
- **2 charge states**
- Every other bucket



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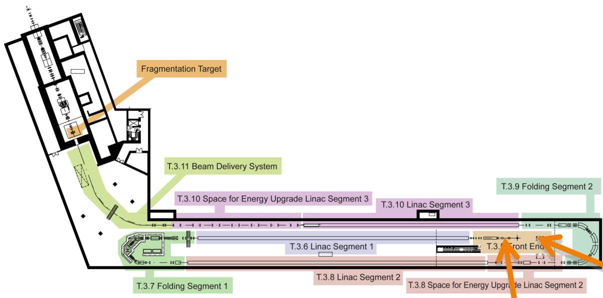

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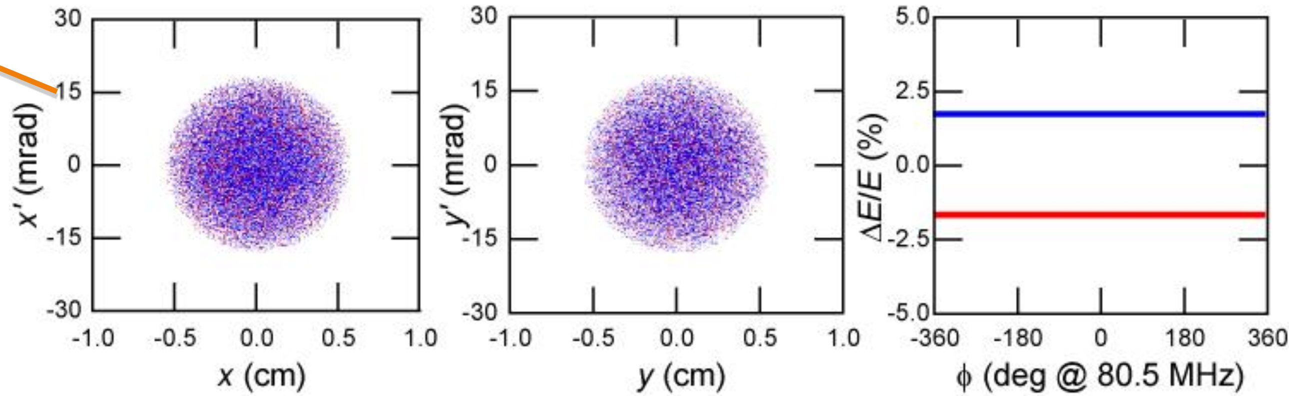

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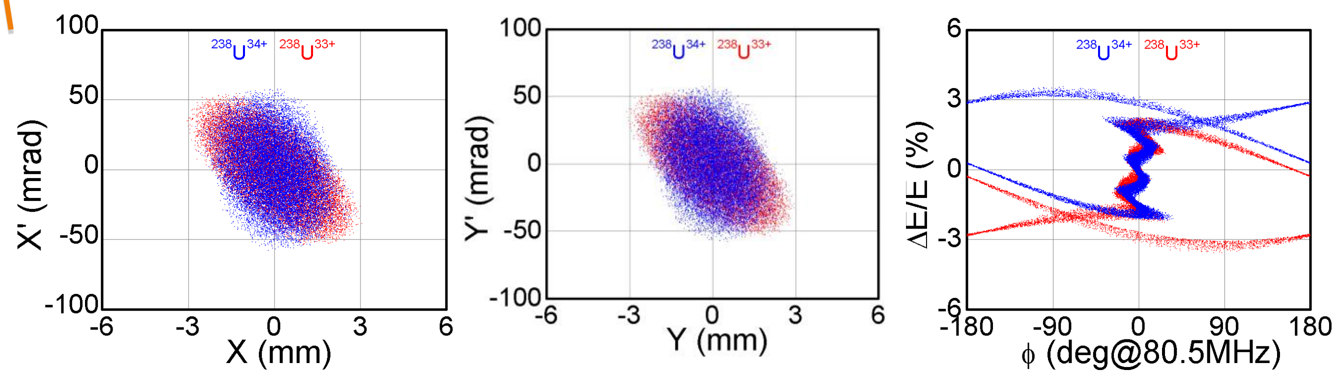
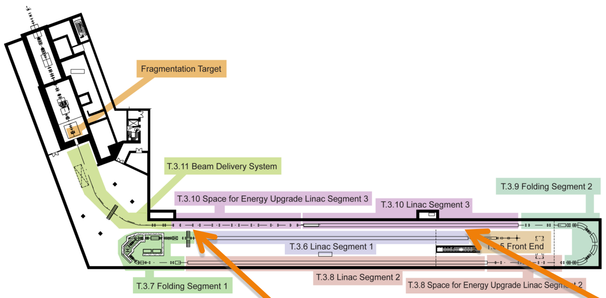
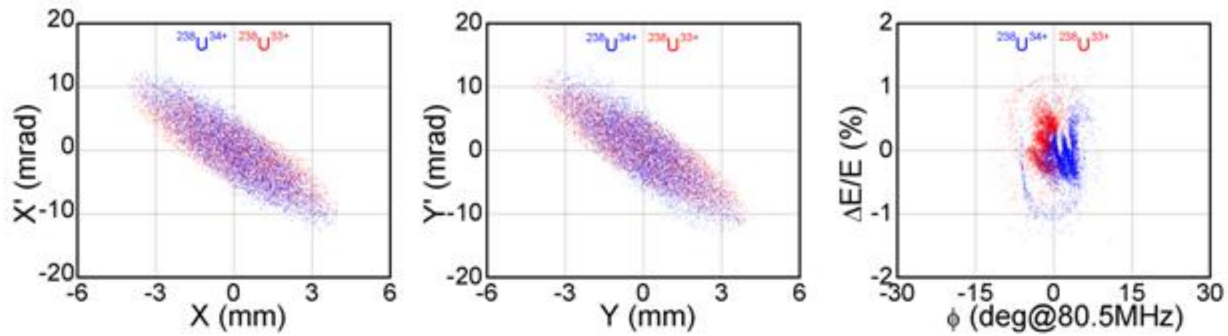


End-to-End Beam Simulations (2)



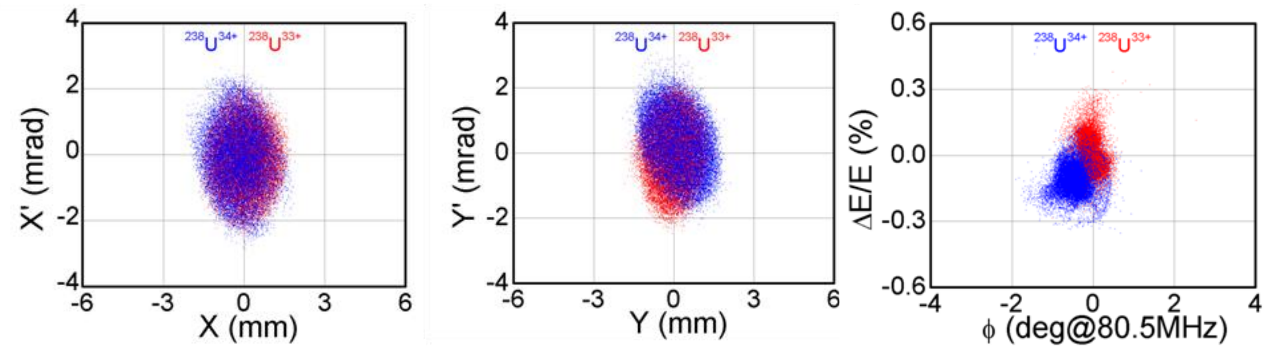
Linac Segment 1 entrance

- 0.3 MeV/u
- **2 charge states (33,34)** matched to linac



Linac Segment 1 exit

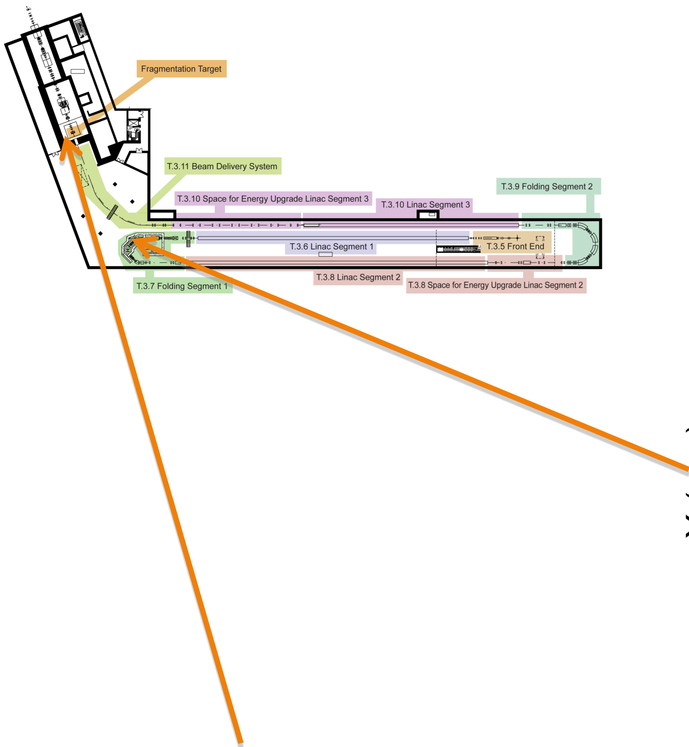
- 16.6 MeV/u
- **2 charge states** matched to stripper
  - minimize 6D emittance growth

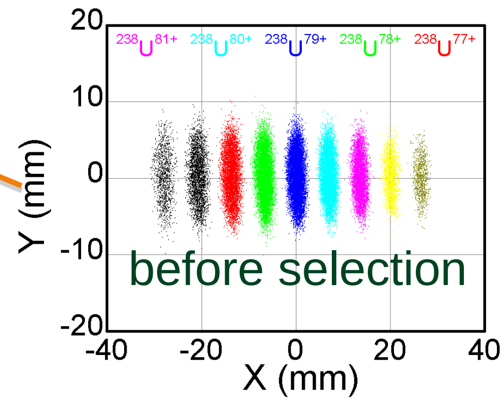


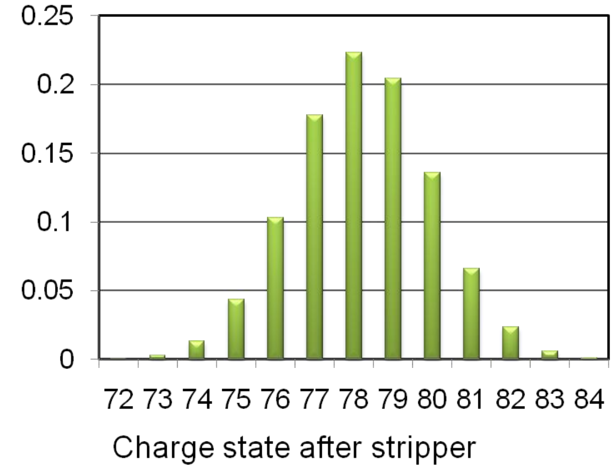
End-to-End Beam Simulations (3)

Charge state selection

- 16.3 MeV/u
- **5 charge states** **(**U^{76-80+} **)** selected
  - **Efficiency ~84%**

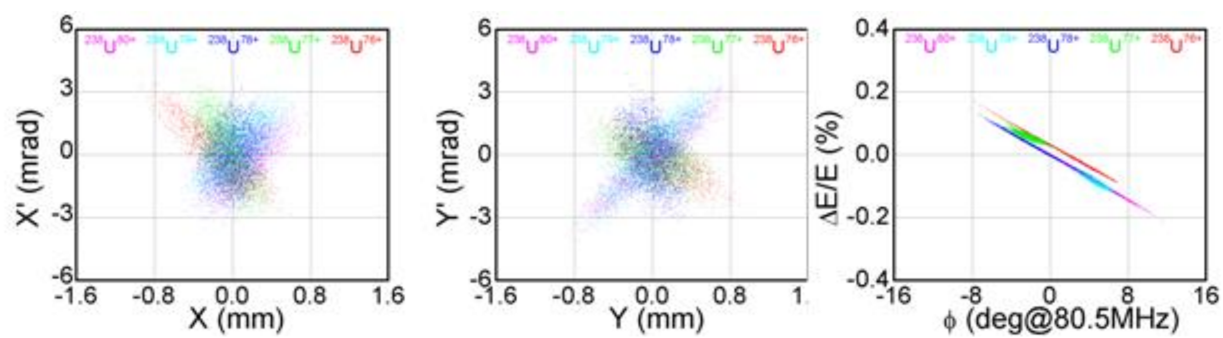






Production Target

- >200 MeV/u
- **5 charge states** within 1 mm



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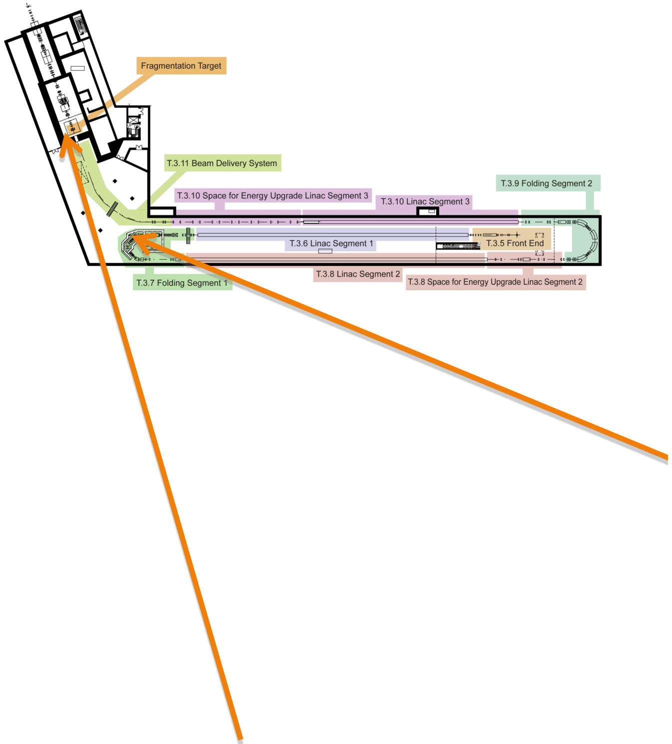
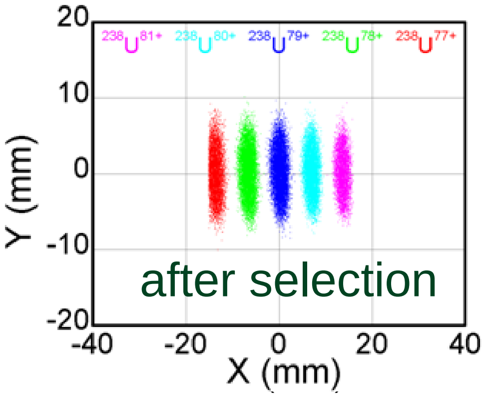
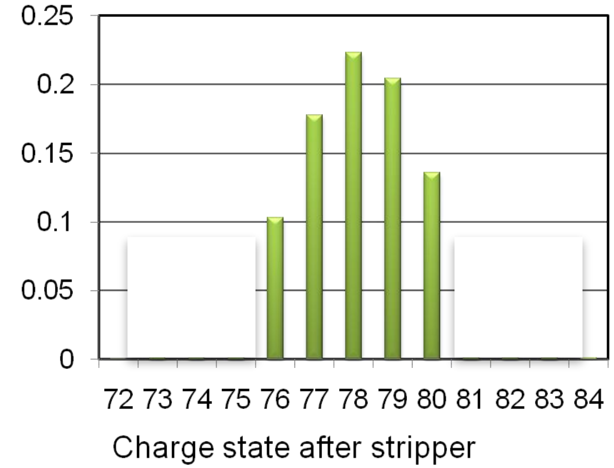
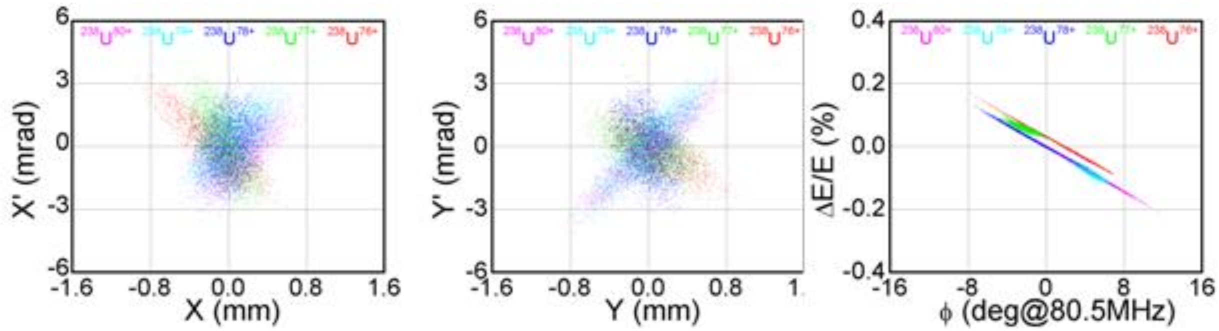


Charge state selection

- 16.3 MeV/u
- **5 charge states** (U^{76-80+}) selected
  - **Efficiency ~84%**





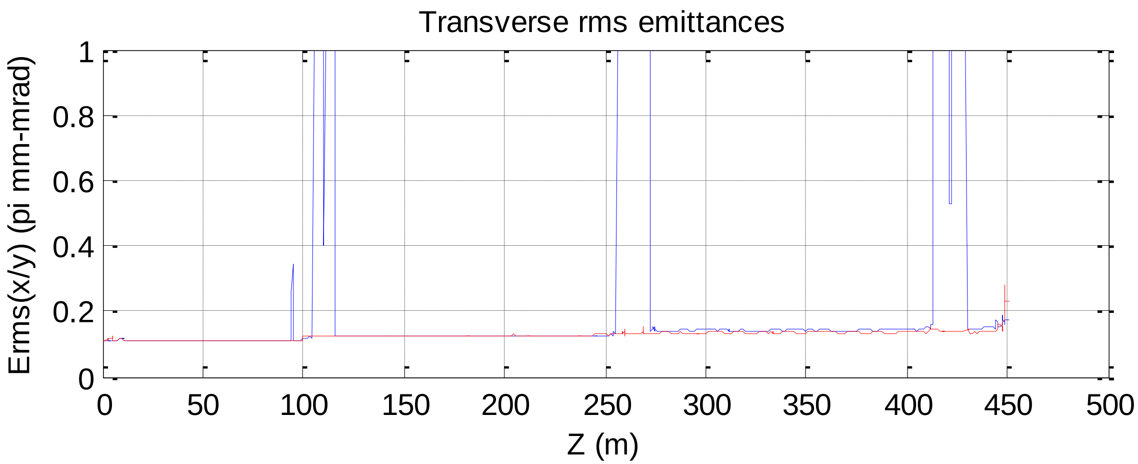


Production Target

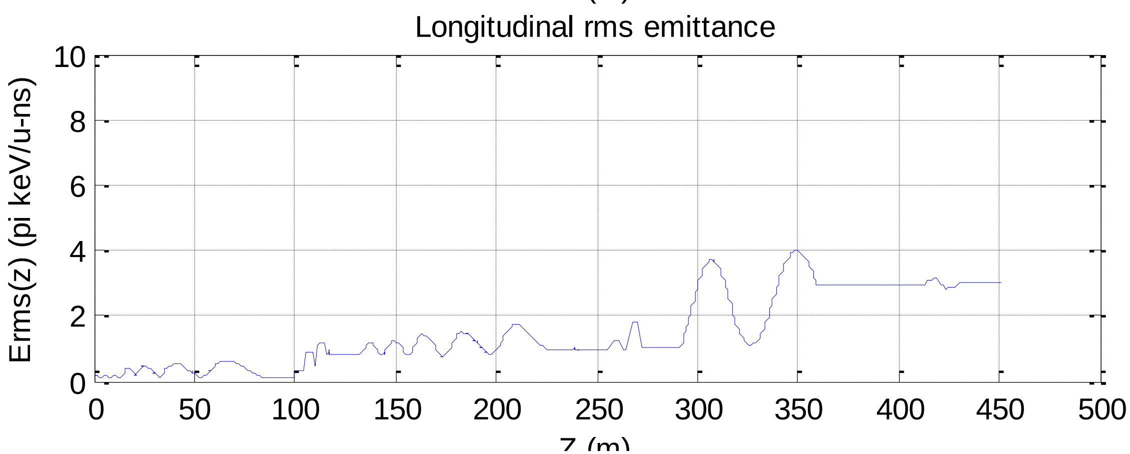
- >200 MeV/u
- **5 charge states** within 1 mm

End-to-End Beam Simulations (6)

Transverse emittance
- **Small growth (1.37x)**
- **Spikes due to multi-charge states in dispersion area**



Longitudinal emittance
- **Large growth (29x) due to multi-charge states**
  - **But small compared to acceptance**
- **Oscillation along linac due to multi-charge states**



Error Specifications

Misalignment tolerances

Displacement (cold elements)	±1 mm, uniform
Displacement (warm elements)	±0.4 mm, uniform
Rotation	±2 mrad, uniform

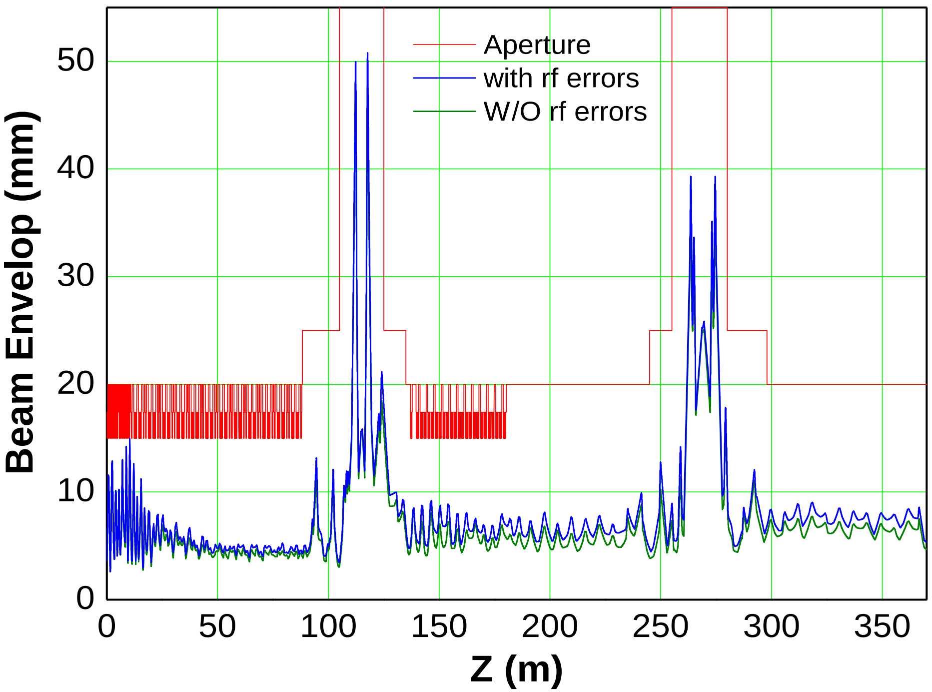
RF error tolerances

Amplitude Fluctuation	±1.5% Gaussian (σ=0.5%)
Phase fluctuation	±1.5° Gaussian (σ=0.5°)

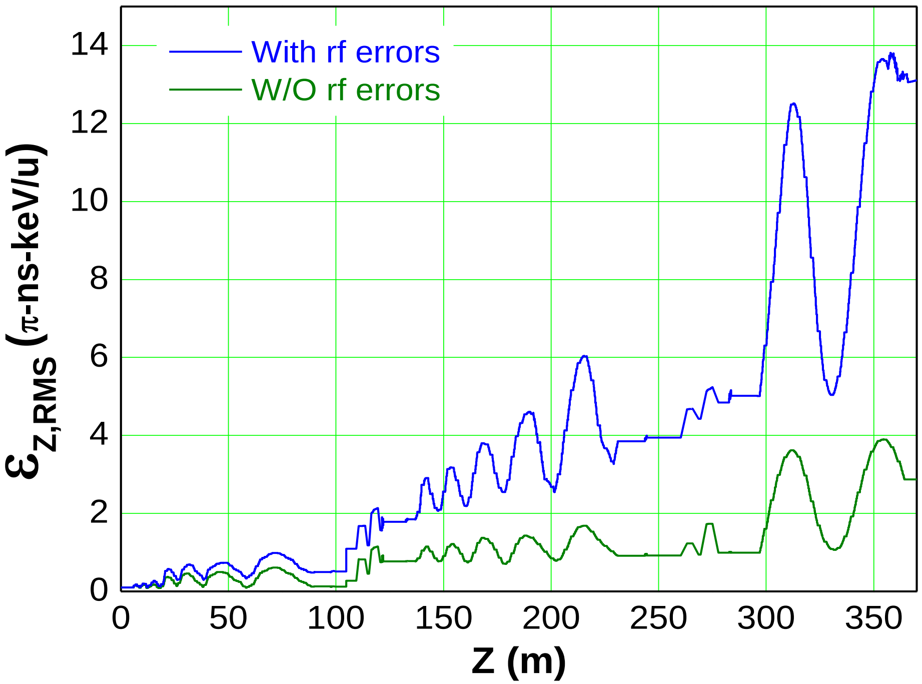
Stripper thickness variation ±10%, uniform

Linac Beam Loss Evaluations with RF Errors

- RF errors have minimum impact in transverse plane
- Acceptable longitudinal emittance growth (4.5x) due to rf errors
  - **- No uncontrollable beam loss**



Small beam envelope compared with aperture

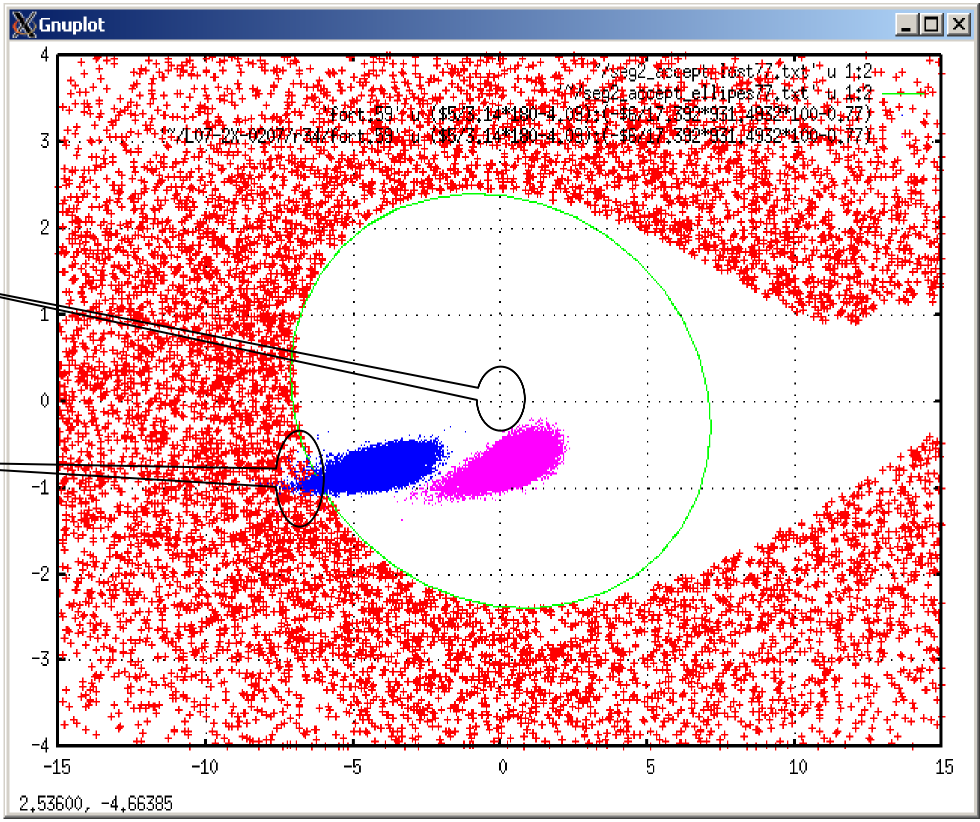


Longitudinal emittance oscillation along linac due to multi-charge states

Beam Loss with RF Errors 2X Specification

Longitudinal phase space and acceptance at Segment 2 entrance

- **Without errors** all charge states sit on top of each other at reference center
- **RF error** causes separation and off center - Leading to loss



5 charge-state beam distribution (blue and pink)

- blue originally from 34+, pink originally from 33+

Space Charge Effects important prior to RFQ

Space Charge Effects in LEBT before RFQ

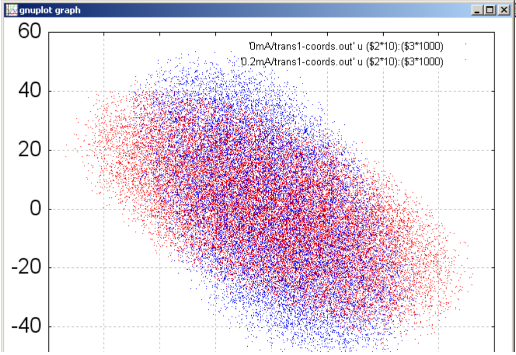
Small effect for heavy ions

- For uranium beam, transverse and longitudinal phase space regained by slightly (~1%) increasing focusing strength and buncher voltages

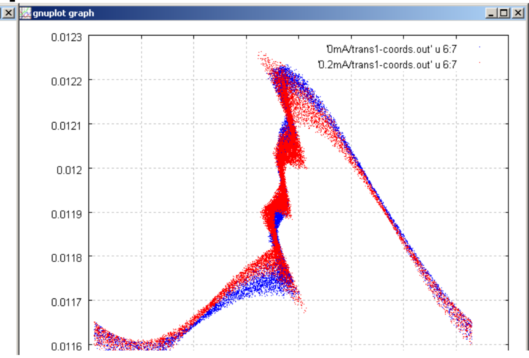
For light ions further study required

- Larger affect with smaller A/q

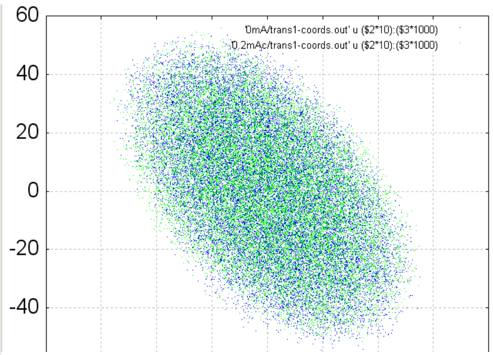
Uranium phase space at LEBT exit



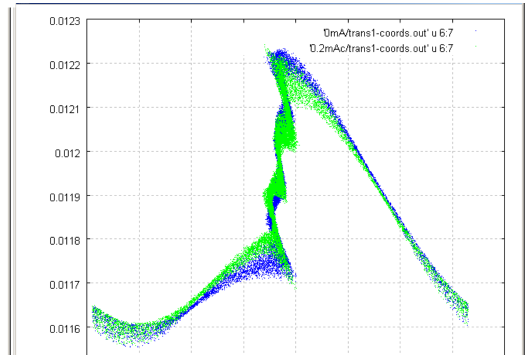
X-X': 0mA (blue), 0.5mA (red) no correction



Φ – Ek: 0mA (blue), 0.5mA (red) no correction



X-X': 0mA (blue), 0.5mA (green) with correction



Φ – Ek: 0mA (blue), 0.5mA (green) with correction

Summary and Conclusions

- **Conceptual design established for FRIB driver linac**
  - Room temperature front end
  - 3 superconducting linac segments with 2 folding sections
  - 1 beam delivery system
- **Beam dynamics simulations to conceptual level**
  - Development of robust lattice
    - » **biggest challenge is multi-charge states necessary to meet beam power requirement (400kW)**
    - » space charge effect largely non-issue
  - End-to-end simulations including errors & error specifications determined
- **Beam dynamics simulations demonstrate design requirements met**
  - Beam energy: ≥ 200 MeV/u for all ions
  - Beam power: 400 kW
  - Uncontrolled beam loss: < 1 W/m
- **Future efforts**

  High statistic simulations, failure mode & effects analysis, and commissioning plans

backup

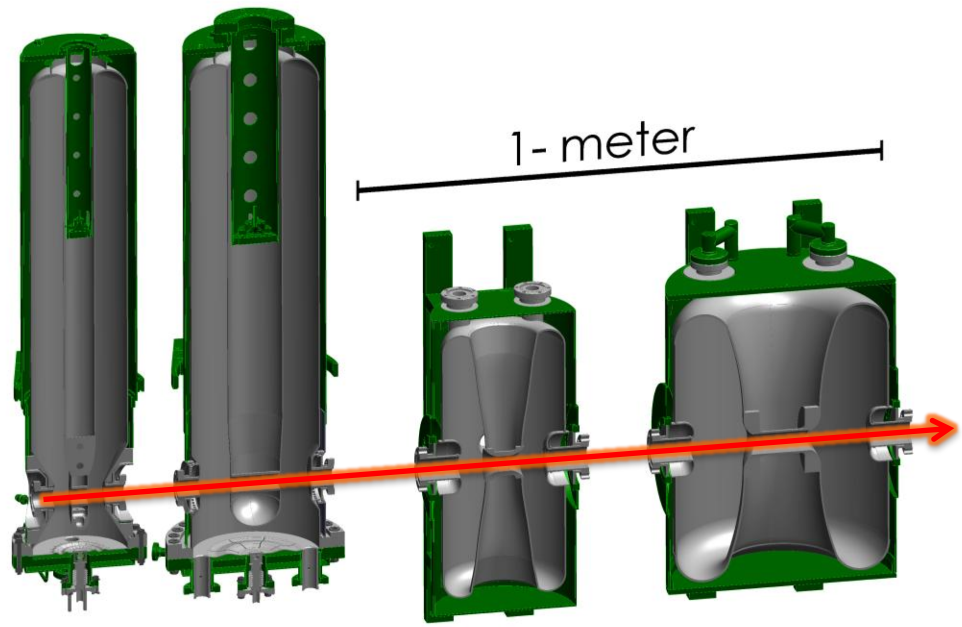
Computing Codes

- Electromagnet Design
  - POISSON, OPERA → magnet
  - ANALYST, ANSYS, Omega3P → rf cavity
- Lattice Design
  - PARI → RFQ
  - Matlab_based → linac with multi charge states
  - DIMAD → beam optics & misalignment correction
  - COSY → high order optics
  - TRACE3D → beam optics
- Particle Tracking
  - Dedicated benchmarked parallel codes
  - RIAPMTQ → RFQ (LEBT & MEBT)
  - IMPACT → ion source up to target except RFQ

FRIB Linac SRF Cavities

- Only 4 cavity types
- 1 frequency transition (between Linac Segment 1 and 2)

Type	$\lambda/4$	$\lambda/4$	$\lambda/2$	$\lambda/2$
β_{opt}	0.041	0.085	0.29	0.530
f(MHz)	80.5	80.5	322	322
Aperture (mm)	30	30	30	40
V_a (MV)	0.81	1.62	1.90	3.70
E_p (MV/m)	30.0	31.5	31.5	31.5
B_p (mT)	53	71	75	77
T(K)	4.5	4.5	2.0	2.0



Beam Loss Evaluation – Double Errors

- A example of previous lattice
- With specified errors – 0.6 billion particles
  - No uncontrolled beam losses
- Double specified errors – 2 billion particles
  - 1000 seeds with 2 million particles each
    - **85.6% of seeds no uncontrolled beam loss**
    - **12.8% of seeds loss < 1 W/m (design spec)**
    - **only 1.6% of seeds loss > 1 W/m**