FRIB

Beam Physics and Technical Challenges of FRIB Driver Linac

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Representing FRIB Accelerator Systems Division (ASD) of Michigan State University (MSU) and Its Collaborators

The 7th International Particle Accelerator Conference, IPAC2016

MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

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Yamazaki Representing

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K. Hosoyama, M. Masuzawa, K. Tsuchiya: KEK

This Work Done and Future FRIB Work to be Done not Solely by FRIB, but by World Wide Accelerator Community, in Particular, Low- β, SC RF Community, the Following FRIB Collaborators All over the World and the Industries

- ANL
  - Liquid lithium stripper
  - Beam dynamics verification; β=0.29 HWR design; SRF coupler and tuner validation
- BNL
  - Plasma window & charge stripper, physics modeling, database
- FNAL
  - Diagnostics, SRF processing
- JLab
  - Cryoplant; cryodistribution design & prototyping
  - Cavity hydrogen degassing; e-traveler **
  - HWR processing & certification*
  - QWR and HWR cryomodule design
- LANL
  - Proton ion source
- LBNL
  - ECR coldmass design; beam dynamics
- ORNL
  - Diagnostics, controls
- SLAC**
  - Cryogenics**, SRF multipacting**, physics modeling

- RIKEN
  - Helium gas charge stripper
- TRIUMF
  - Beam dynamics design, physics modeling **
  - SRF, QWR etching*
- INFN
  - SRF technology
- KEK
  - SRF technology, SC solenoid prototyping, AP
- IMP
  - RT Magnets, SC solenoid
- Budker Institute, INR Institute
  - Diagnostics
- Tsinghua Univ. & CAS
  - RFQ
- ESS
  - AP*
- Hiroshima University
  - AP
- DTRA
  - RFQ power supply**

* Under discussion or in preparation

** Completed

FRIB Context

- 8 June 2009 – DOE-SC and MSU sign Cooperative Agreement
- September 2010 – CD-1 approved, DOE issues NEPA FONSI
- April 2012 – Lehman review, baseline and start of civil construction
- August 2013 – CD-2 approved (baseline), CD-3a approved (start civil construction pending FY2014 federal appropriation)
- March 2014 – Start civil construction
- 24-26 June 2014 – DOE-SC OPA CD-3b (technical construction) Review
- 26 August 2014 – Dr. Patricia Dehmer, the DOE Office of Science Acquisition Executive for FRIB, approved *Critical Decision CD-3b: Start of Construction of the Accelerator and Experimental Systems for the Facility for Rare Isotope Beams (FRIB) Project*.
- October 2014 – Technical Construction started
- September 2021 – Early completion goal
  - Tunnel and first *surface* buildings (ECR and frontend) complete in 2015
    - » First beam from ECR in 2016
    - » Install and test RFQ in CD-4 position and configuration (avoids moving RFQ)
- June 2022 – CD-4 (project completion)

Civil Construction: 10 Weeks Ahead
Front-end building 16 months ahead of baseline

- Using civil construction to drive schedule
- Optimized construction sequence (front-end building)
  - Affords 16 extra months for technical divisions and avoids extra work
    - » Test RFQ in place, install ECR early and develop beams (early operations)

(MSU civil construction experts and local constructors have been constructing 552 buildings in the MSU campus. Superb people.)

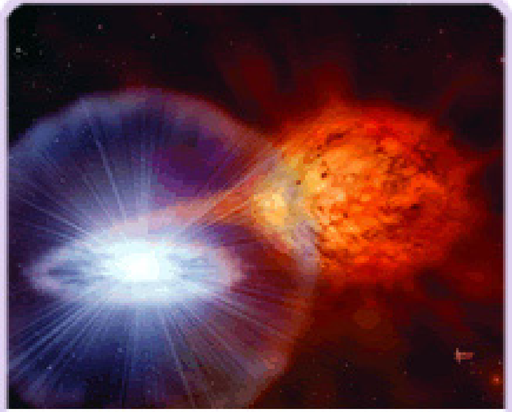
Outline

- What is FRIB, MSU?
- FRIB driver linac challenge and multi-charge state acceleration
  - FRIB heavy ion linac is joining the Proton Beam Power Front like SNS and J-PARC with a tremendous number of SRF resonators
- High Bragg Peak challenge
- Production Challenge
- Summary

What is FRIB, MSU?

Facility for Rare Isotope Beams (FRIB)
Intellectual Curiosity Guided Scientific Project

- After the Big Bang, at the end of the first generation stellar objects, why and how have supernovae been exploded in the universe?
- Why and how have a wide variety of chemical elements been created for giving birth to living objects? And so forth.
- For that study, we need to discover isotopes as rare as possible, and to study them as precisely as possible.
  1. The beam power as high as possible: 400 kW, > 200 MeV/u
  2. Ion species to accelerate as many as possible: proton to Uranium (all stable ions)
  3. Quality beams as high as possible: low emittance both longitudinally and transversely



thermonuclear explosion

Photo Credit: David A. Hardy & PPARC

- With state of art, high technology, available at present and in near future

Over 1300 Users Engaged and Ready for Science

- Users are organized as part of the independent FRIB Users Organization (FRIBUO) www.fribusers.org
  - Chartered organization with an elected executive committee
  - 1,354 members (98 U.S. colleges and universities, 12 national laboratories, 50 countries) as of September 2015
  - 19 working groups on instruments
  - 21-22 August 2015, Low Energy Community Meeting, MSU

  "The highest priority in low-energy nuclear physics and nuclear astrophysics is the timely completion of the Facility for Rare Isotope Beams and the initiation of its full science program."

- Science Advisory Committee
  - Review of equipment priorities (2-3 March 2015)

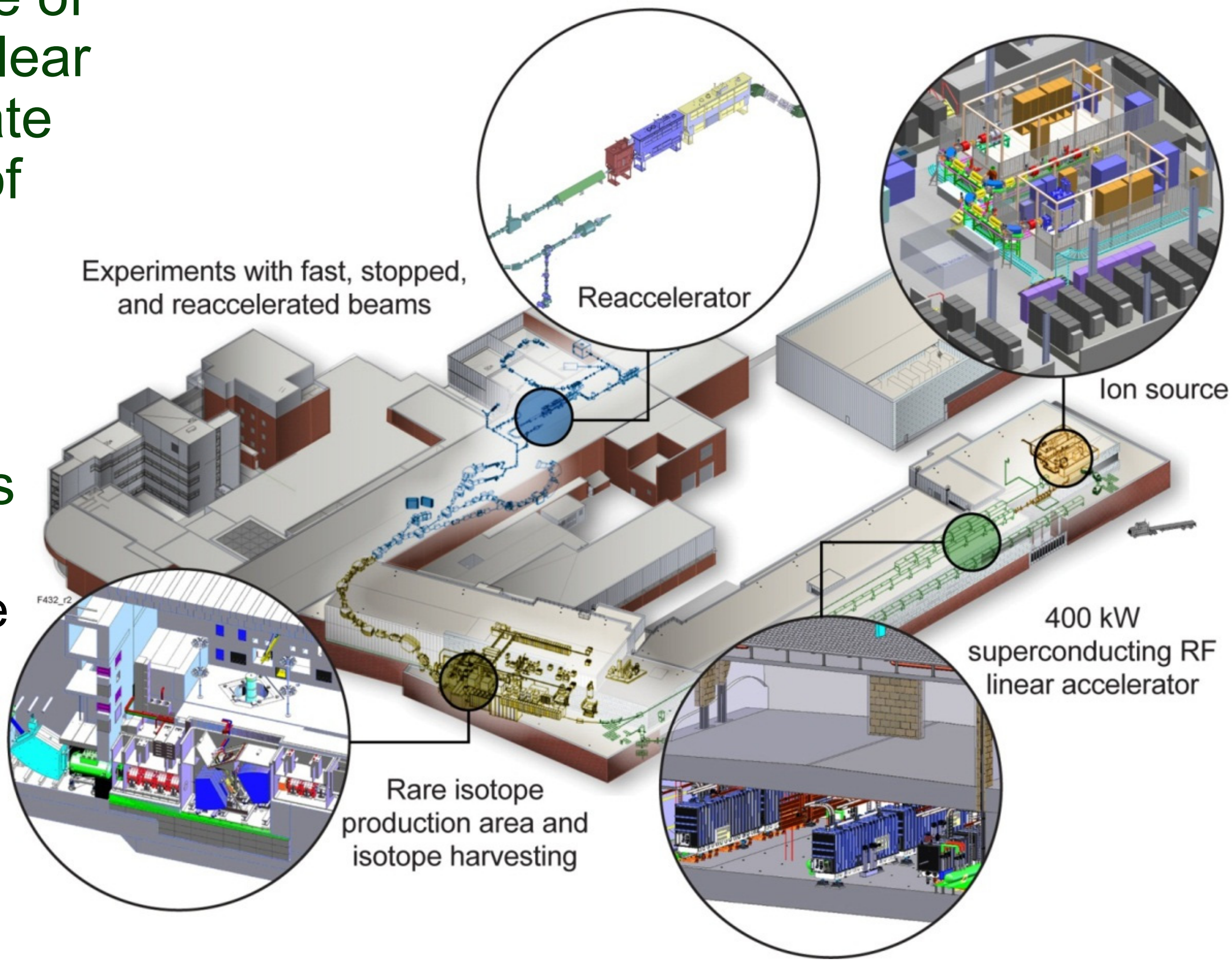
  "FRIB will cover a wide range of topics at the forefront of nuclear science"

  "Significant scientific opportunities will be realized with the addition of several classes of experimental equipment"

- **Early Completion Strongly Demanded By Users**

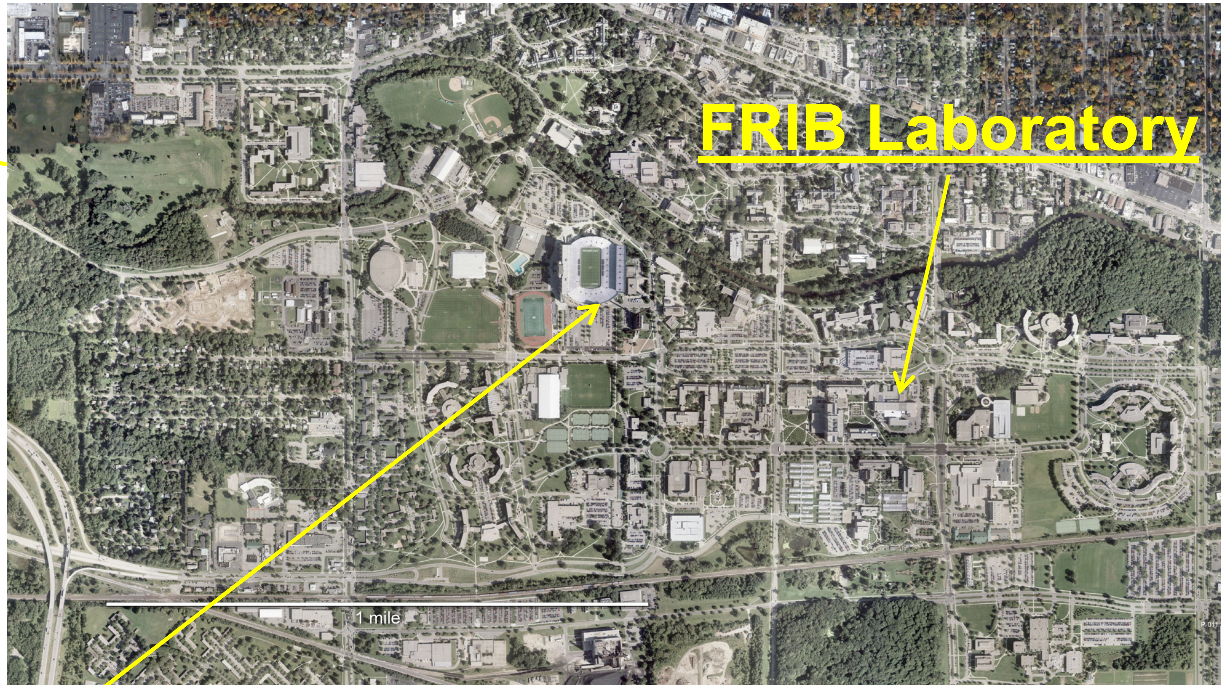
FRIB Key Features

- Funded by DOE Office of Science Office of Nuclear Physics, Michigan State University and State of Michigan
- Up to 400 kW beam power (5 x10^{13} ^{238}U/s)
- Separation of isotopes in-flight
  - Fast development time for any isotope
  - Suited for all elements and short half-lives
  - Fast, stopped, and reaccelerated beams



Michigan State University (MSU) with Spartan Spirit

57,000 people; 47,000 students, 92 sq km; $1.8B annual revenue; 552 buildings
US No. 4 Biggest University

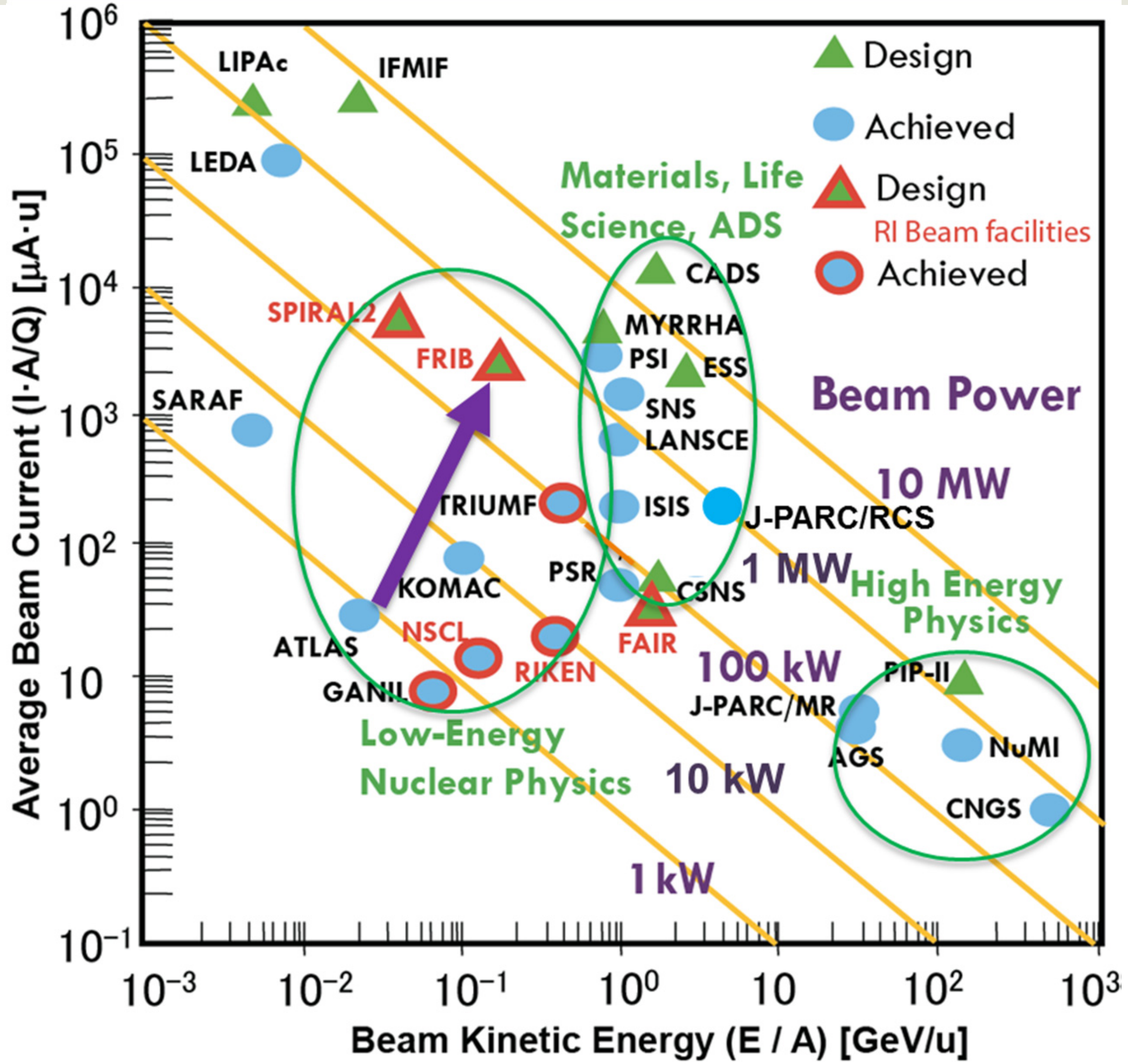


FRIB Driver Linac Challenge

Multi-Charge State Acceleration

FRIB Heavy Ion Linac Joining the Proton Beam Power Front like SNS and J-PARC

- During the past decade, proton accelerators raised beam power to ~ 1 MW
  - SNS (USA): 1 MW pulsed; SRF linac/accumulator
  - J-PARC (Japan): 0.3 MW pulsed to be 1 MW this fall; warm linac/RCS
  - PSI (Switzerland): 1.4 MW CW; cyclotron
- FRIB is in the same energy and power category (400 kW)
  - From proton to ^{238}U
  - Using SRF linac from 0.5 MeV/u to > 200 MeV/u



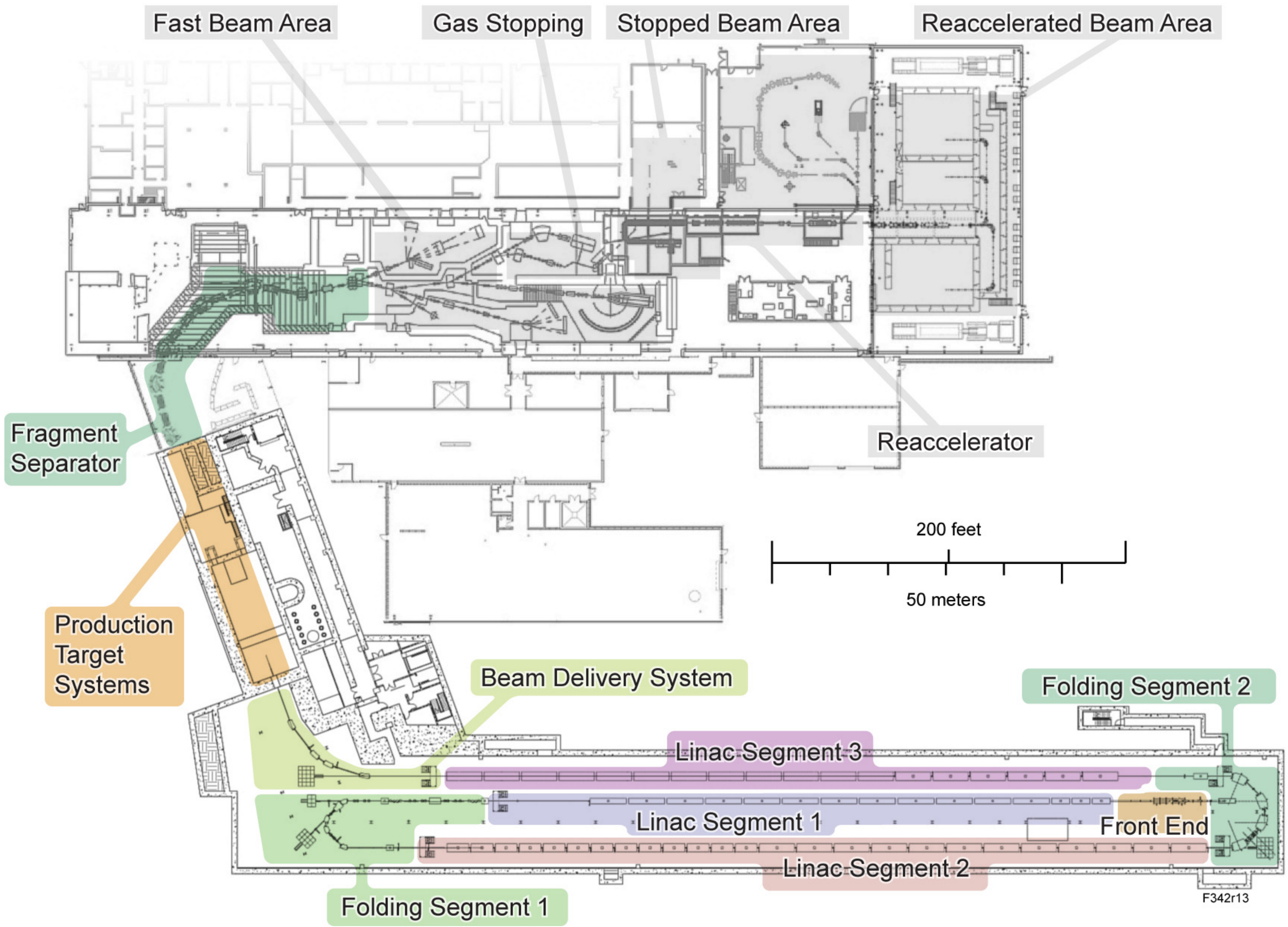
Beam-on-Target Parameter Requirements Established to Maximize Scientific Outputs
1 mm, 0.5 mrad, 3 ns, 0.5 %

- Low emittances needed both longitudinally and transversely
- Beam quality requirements established to efficiently and precisely separate one ion from another

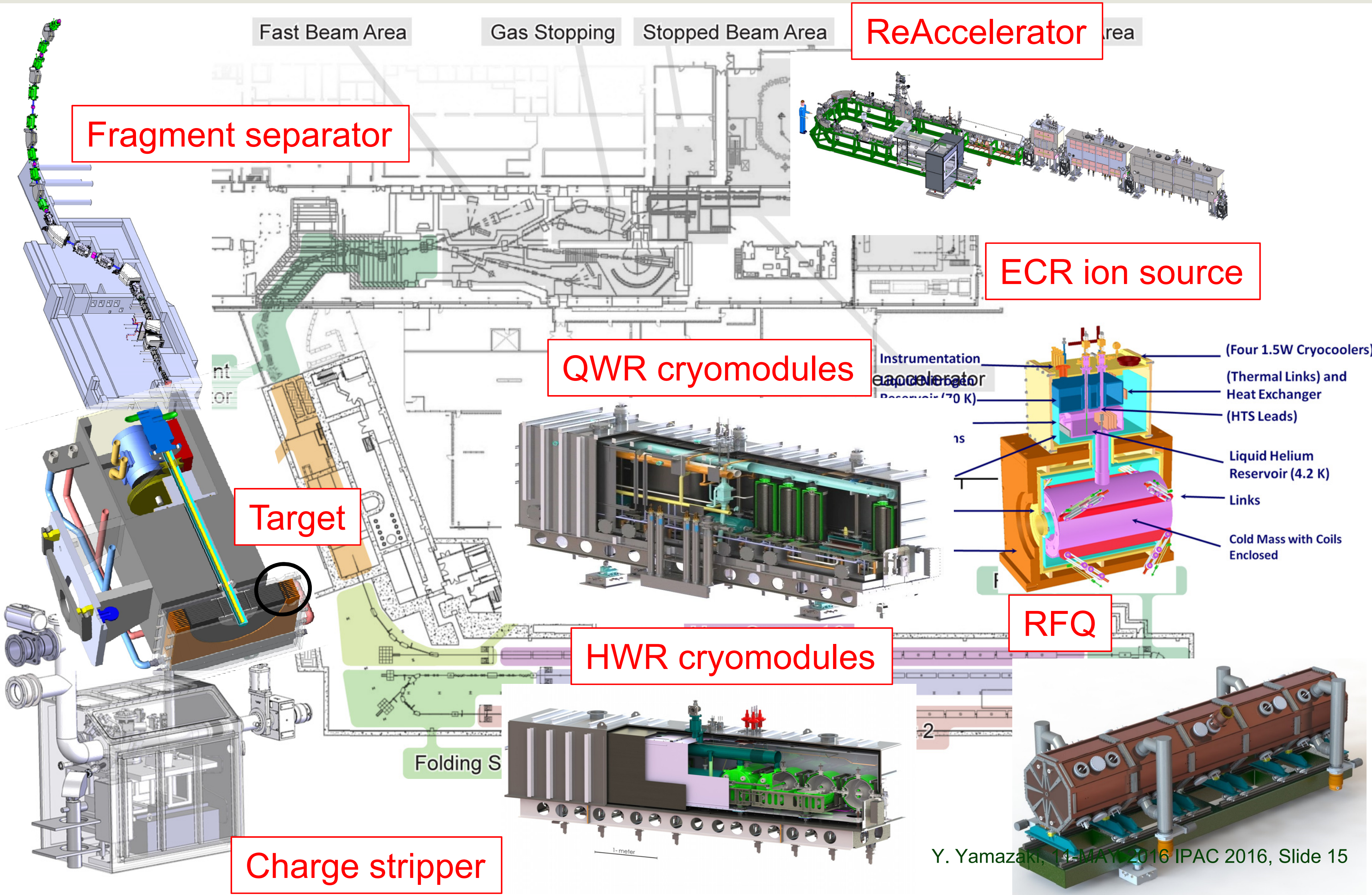
	Parameter	Description	Baseline	Basis/Comments
1	Beam spot size (diameter) $2\Delta r$	Contains 90 % of beam, incl. fluctuations	1 mm	Necessary for beam purity - scientific reach
2	Beam angular' spread r'	Horizontal and vertical, contains ≥ 90% of beam, incl. fluctuations	≤ ± 5 mrad	Prevent primary beam hitting dipole – facility efficiency- operational cost
3	Bunch length $2\Delta z = 2\Delta\phi/2\pi f$	Contains 95 % of beam	3 ns	Particle identification (TOF measurement) Upgrade option: 95 % in ≤ 1.5 ns and 99.9 % in ≤ 3 ns → necessary for RF separation of rare isotopes (spacing a few ns) – important for very proton-rich isotopes – scientific reach
4	Beam energy spread ΔW	Contains 95 % of beam, incl. fluctuations	≤ ± 0.5 %	Selection of rare isotope between magnetically separated primary beam charge states so as to not truncate scientific reach Upgrade option: ≤ ± 0.2 %
5	Beam trajectory on target reproducibility	Position and angle w.r.t. fragment separator magnet axis	≤ ± 0.1 mm, ≤ ± 3 mrad	Position necessary for beam purity - scientific reach Angle necessary to prevent primary beam hitting dipole Upgrade option: ≤ ± 0.1 mm, ≤ ± 2 mrad
6	Beam energy reproducibility		≤ ± 0.5 %	Facility efficiency - operational cost
7	Beam power control dynamic	Without time structure change (not chopping)	10^{-5} – 1	Characterization of rare isotope beams for experiments; physics experiments requirements Upgrade option: 10^{-8} – 1
8	Bunch repetition rate		80.5 MHz or 40.25 MHz	Particle identification (TOF measurement) Upgrade option: 80.5, 40.25, or 20.125 MHz → necessary for RF separation of rare isotopes (spacing a few ns) – important for very proton-rich isotopes – scientific reach

FRIB Accelerator Complex Subsystems

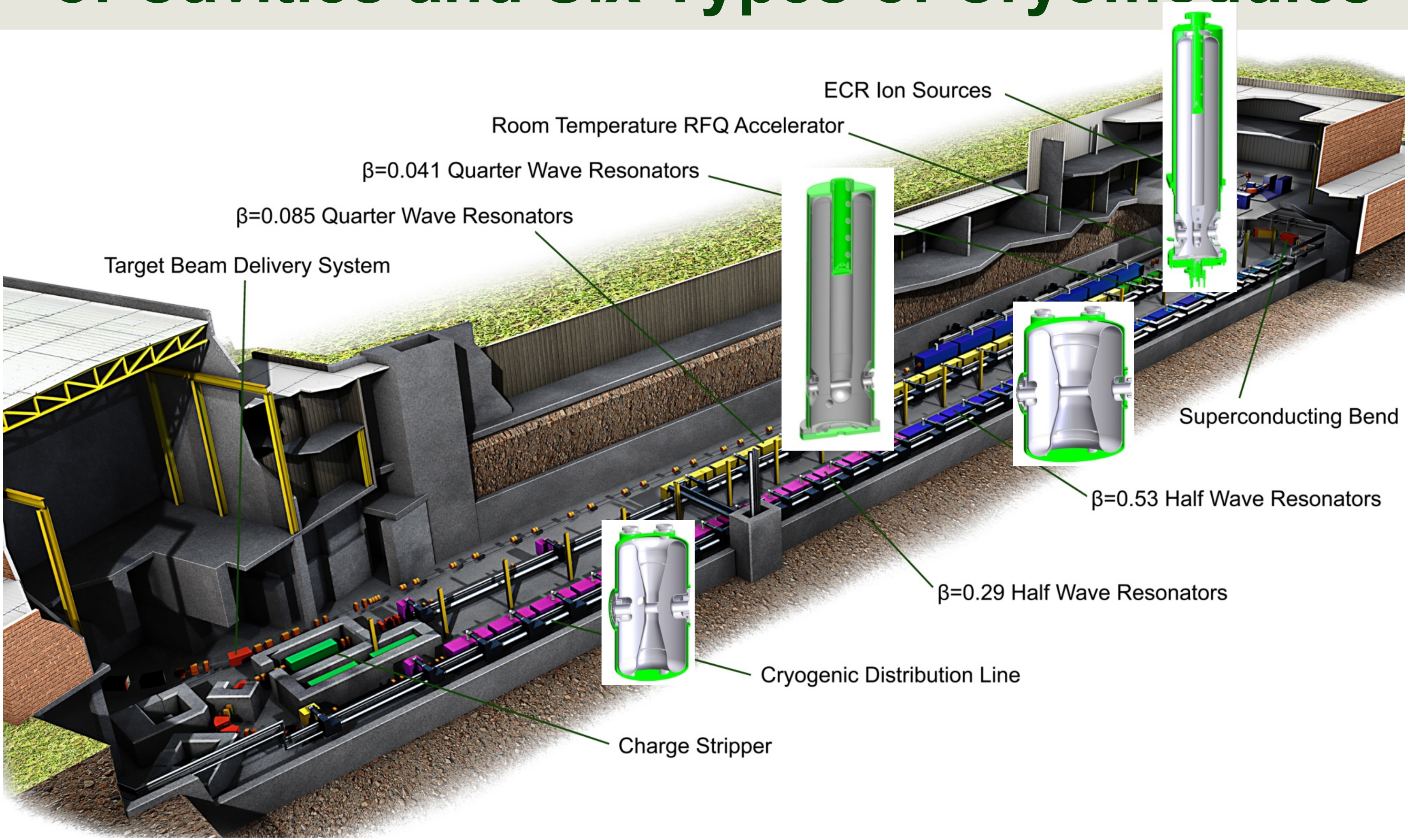
Quarter Wave Resonator (QWR), Half Wave Resonator (HWR)



FRIB Accelerator Complex Subsystems
Quarter Wave Resonator (QWR), Half Wave Resonator (HWR)



FRIB Driver Linac Challenge with Four Types of Cavities and Six Types of Cryomodules



FRIB Cryomodule Schematic Layout

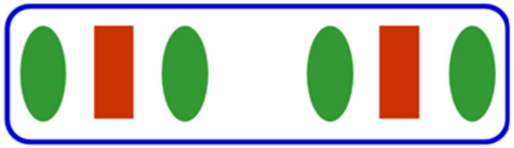
Based on AP Requirements

= cavity = solenoid

Linac Segment 1

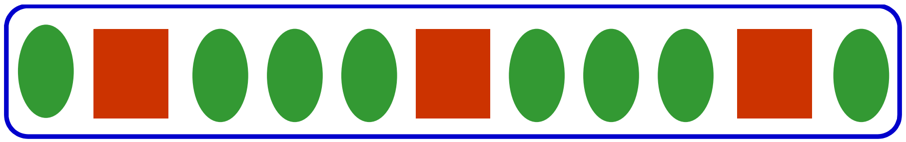
input 0.5 MeV/u

4 β=0.041 (0.8 MeV/u) 80.5MHz QWRs, 2 solenoids



3 cryomodules → output 1.4 MeV/u

8 β=0.085 (3.4 MeV/u) 80.5MHz QWRs, 3 solenoids

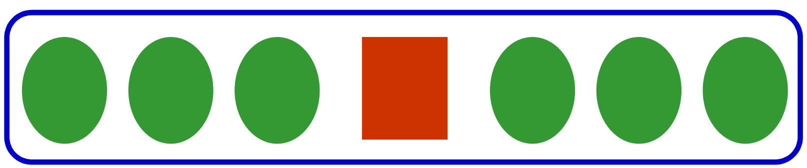


11 cryomodules→ output 16.6 MeV/u

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

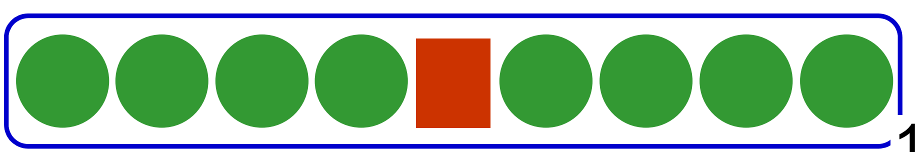
Linac Segment 2 & 3

6 β=0.29 (42 MeV/u) 322MHz HWRs, 1 solenoid



12 cryomodules → output 55 MeV/u

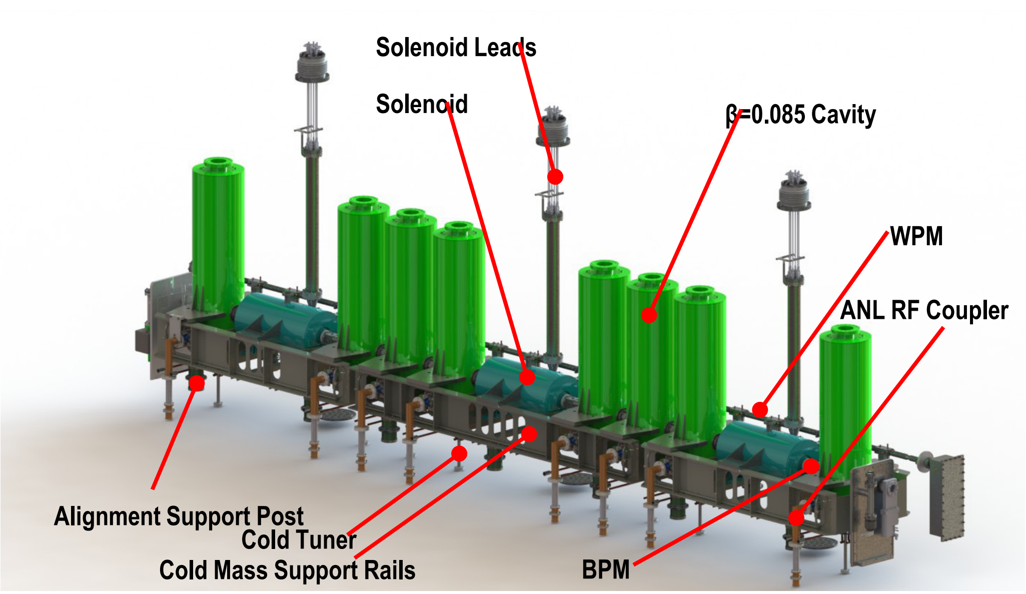
8 β=0.53 (168 MeV/u) 322MHz HWRs, 1 solenoid



18 cryomodules → output >200 MeV/u

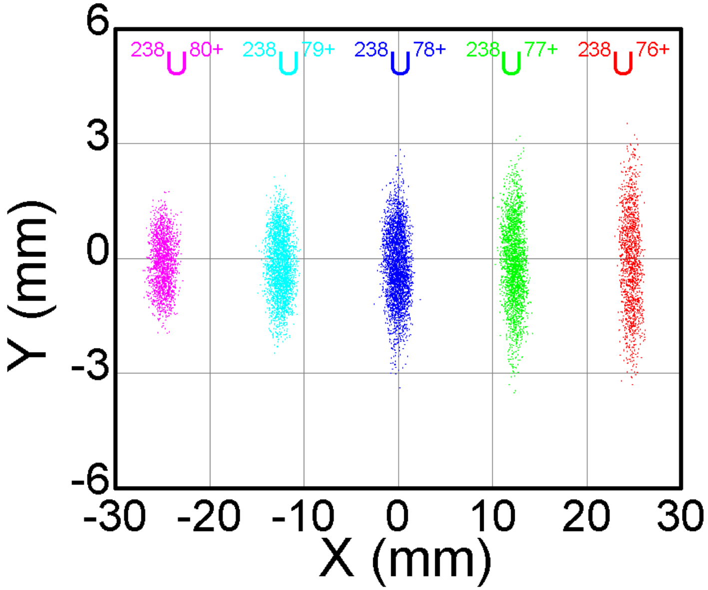
Inside LS1 Cryomodules, Cold BPMs Attached to Focusing Solenoids, Located Close to Cavities

- Frequent, strong focusing both longitudinal and transverse is a must
- It is key how closely and accurately the focusing solenoids are located to SC cavities
- The magnetic fields to be shielded to the extreme



Focused Efforts to Meet Multi-charge-state Transport Challenges

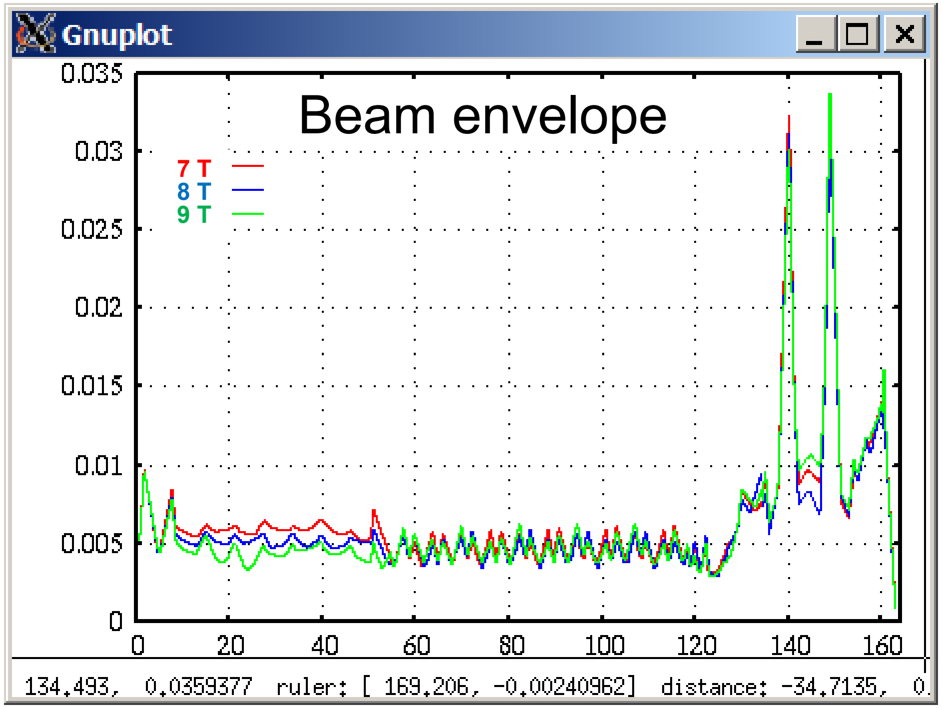
- Charge stripping (last ASAC) and multi-charge state acceleration are required for the efficient acceleration and high intensity. The beam dynamics analysis should take care of these aspects.
- In general, one-path Folding Segment beam dynamics and magnets are easy to design and to build, but here these multi-charge state has to be transported and focused to the target with a diameter of 1 mm and ± 5 mrad.
- Arcs should be achromatic and isochronous to the second order

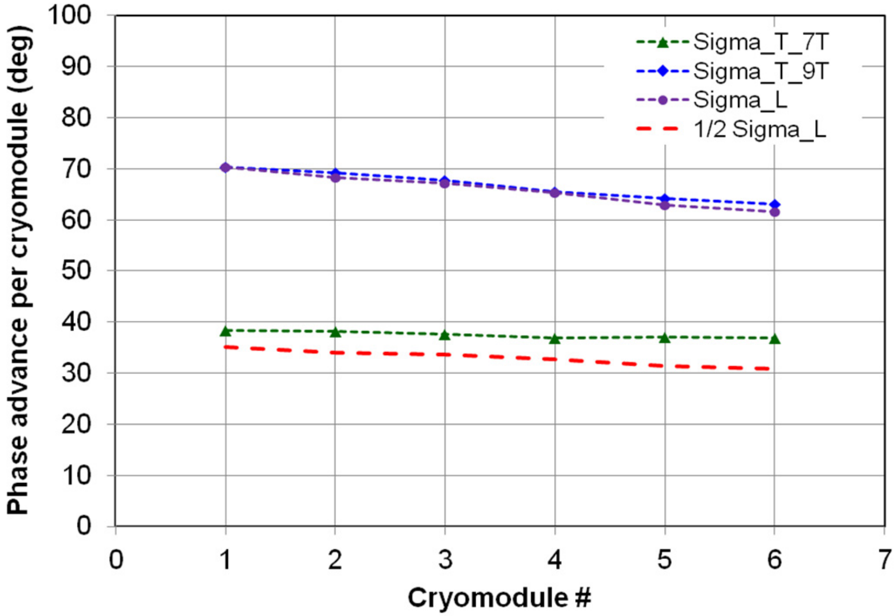


Uranium ion beams with various charge states after charge selection slits

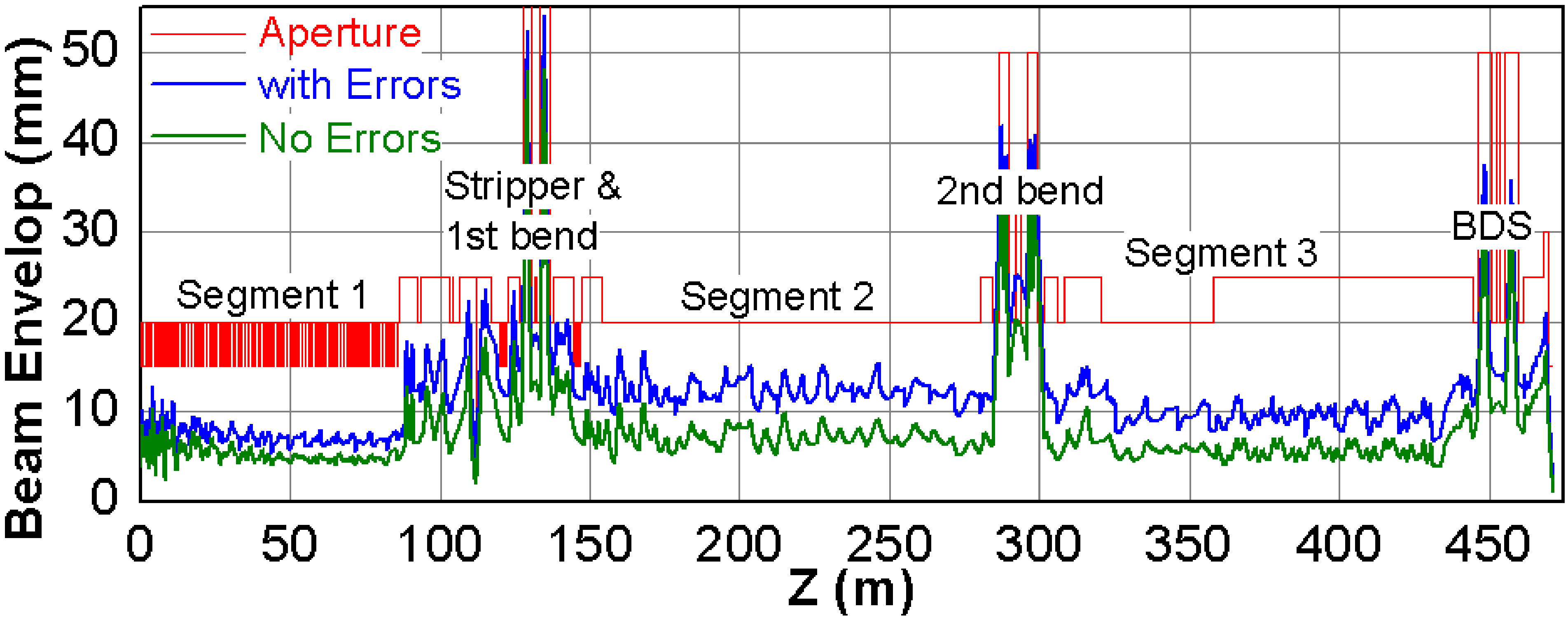
B_0 = 7 T is Very Close to the Parametric Resonance, then, B_0 = 8 T is the Lowest Possible Value Practically

- The fast crossing of the parametric resonance is sometimes allowed, but not for several periods
- The following figures show the beam envelopes and phase advances in the Linac Segment 3





Beam Simulation Results with Machine Errors Beam Envelope (3D Fields To Be Performed)

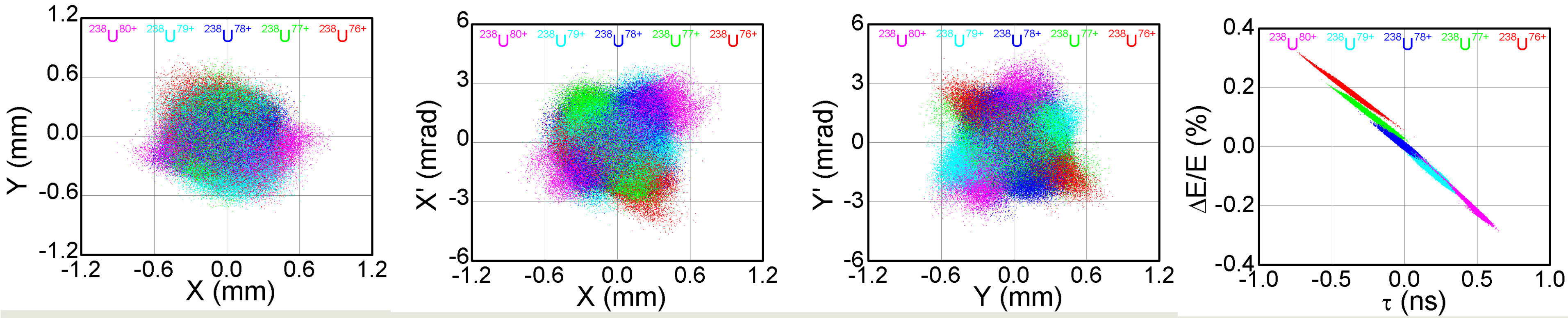


- Beam envelope growth mainly due to misalignment
- RF errors cause significant longitudinal emittance growth but not coupled into transverse
- **No uncontrolled beam losses observed**

Meet Beam-on-Target Requirements With Five-Charge-State Uranium

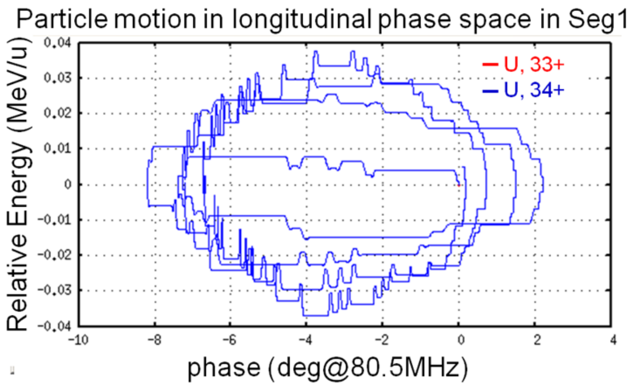
- Beam-on-target requirements met
  - Both bunch length and beam energy spread can be further improved with a rebuncher in the quadrupole lattice

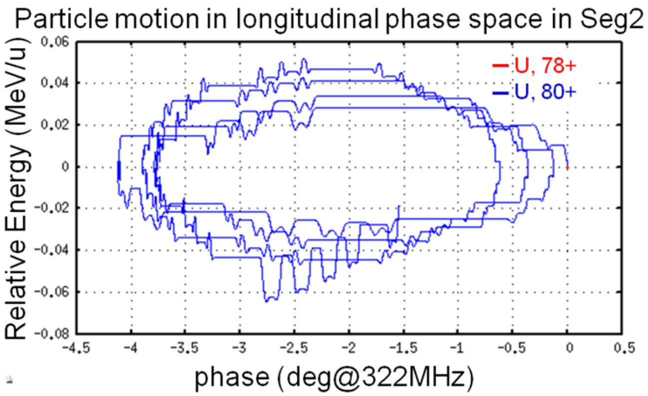
Parameter	Required	Achieved	Meet
Beam spot size (1 mm)	≥ 90%	95.6%	√
Angular spread (±5 mrad)	≥ 90%	100%	√
Bunch Length (3 ns)	≥ 95%	100%	√
Energy spread (± 0.5%)	≥ 95%	100%	√



Gradual RF Phase Variation along a Linac to be More Tolerable than Random Error

- It is possible with reasonable care to control the RF phase with an RMS accuracy of +/- 0.25 degree for 325 MHz, cavity by cavity, but not for an entire linac, since the reference line is thermally expanded or contracted, giving rise to a large phase error. Therefore, sometimes the reference line is made of optical fiber with OE converters housed in a lengthy thermostatic chamber, which is definitely very expensive.
- However, if the RF phase variation is adiabatic, that is, sufficiently slower (longer) than the synchrotron frequencies (wavelength), the large variation should be tolerable, since the particles can follow that variation
- The figures below show how the particles are executing the synchrotron oscillation, ensuring this adiabaticity

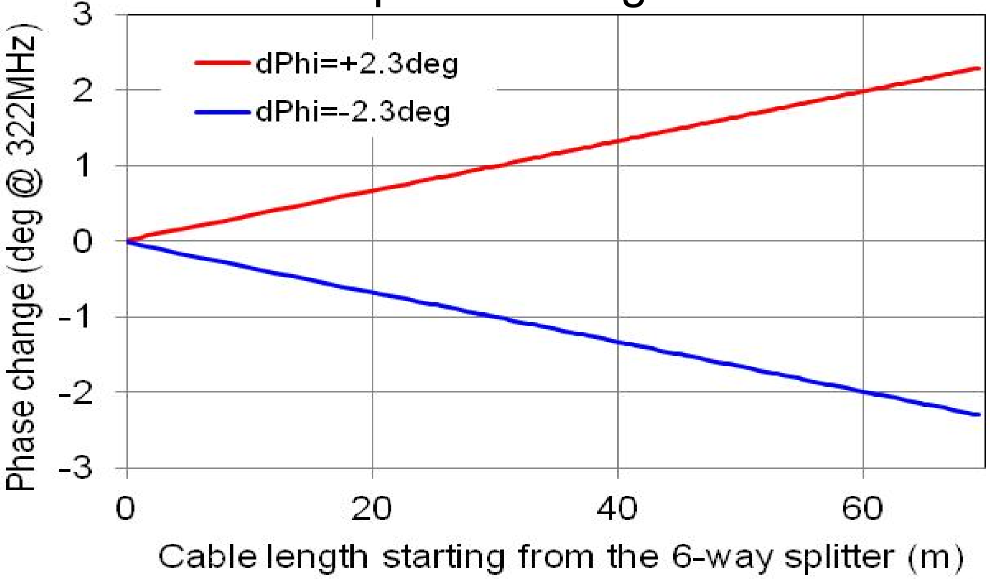




Larger Phase Variation Assumed in Beam Simulation for Safety Side

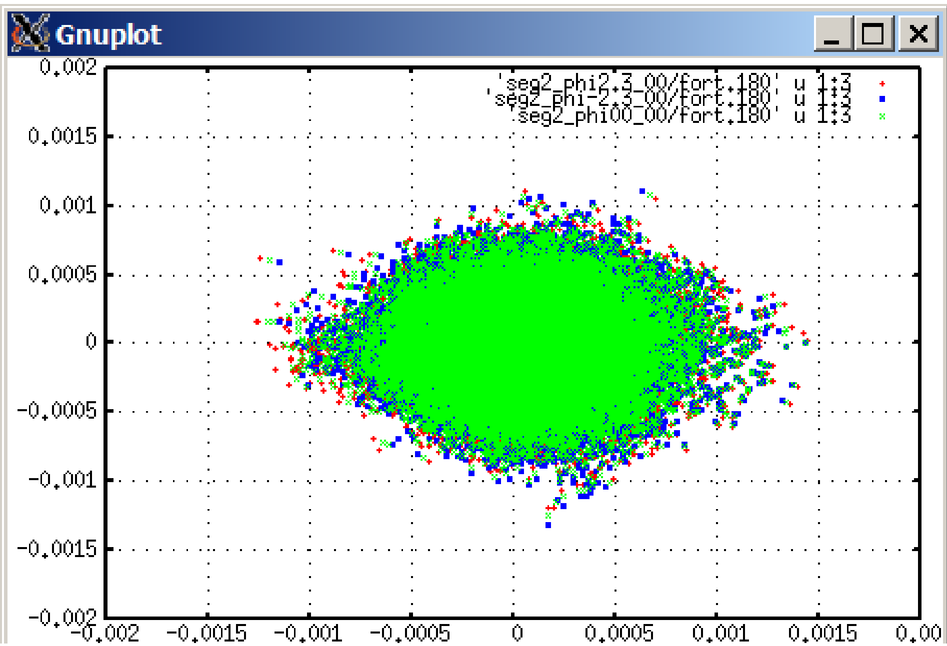
- The measured data: 0.25 deg at 322 MHz per 100m per degF
- Temperature change: 12 (±6°F, worst case, unlikely)
- **Reference phase changes linearly along cable length** with max phase change of ±2.3 deg at 322 MHz or ~ ±20ps (corresponding to cable length of 80 m)

Assumed reference phase change for one of the legs

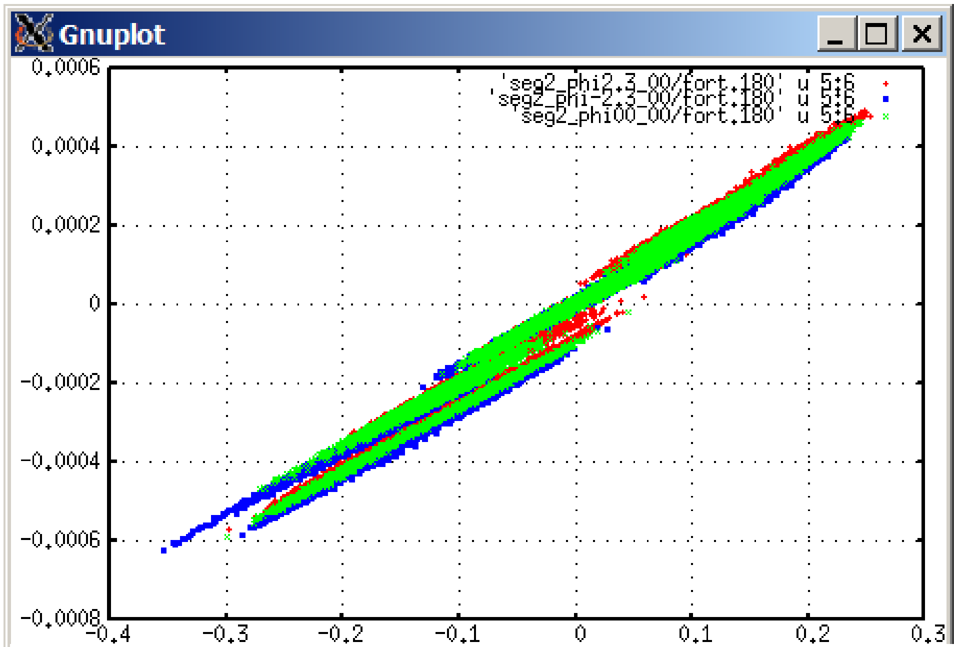


Beam Simulation Results Validate the Phase Reference Scheme [2]

5-charge-state uranium beam distributions on target do not differ much among the cases of maximum phase change of +2.3 deg in red, -2.3 deg in blue, and no change in green



Transverse distribution on target in normalized units



Longitudinal distribution on target in normalized units

High Bragg Peak Challenge

High Bragg Peak Challenge

The beam loss power density ratio of an ion with a charge number of Z and a mass number of A to proton with the same beam energy per nucleon (the same velocity) and the same beam power is given by (Livingston & Bethe, Rev. Mod. Phys. 9, 263 (1937))

$$\frac{[d\,(E/A)/dx]_{ion}}{[d\,(E/A)/dx]_{proton}} = \frac{Z^2}{A}$$

36 for uranium (Z = 92, A = 238)

This is for the heat shock.

Note that the radiation damage is much worse.

1 W/m Beam Loss cannot be a Criterion

- A criterion of 1 W/m widely used for the allowable beam loss is based upon the radioactivity, still enabling hands-on maintenance for 1 GeV proton beam loss. Neutron yield and radioactivity produced by the proton beams are approximately proportional to the beam power at a beam energy between 500 MeV and 3 GeV, but they are getting less as the beam energy lowers, in particular, very small at an energy below 70 MeV. Furthermore, since the radioactivity to be generated by the uranium beam loss is by a factor of approximately several ten (by nearly the ratio of ranges) lower than the proton case, the radioactivity is not the primary issue of the HI beam loss, although it still needs due care. In other words, the beam loss criterion of 1 W/m is not applicable here.

- This also implies that the beam loss is very hard to detect by means of commonly used radiation based Beam Loss Monitor (BLM). Further worse for the FRIB specific case, the low energy linac is located in parallel to the high energy linac. The beam loss radiation at the former can be drowned out by that at the latter. In addition, x rays from SC cavities make it also difficult to distinguish the beam loss radiation from the x rays. The difficulty in beam loss detection is a very serious issue, if one considers the relatively small beam bore radii of the SC cavities under the extremely high beam loss power density.

Most Dangerous is Acute Beam Loss

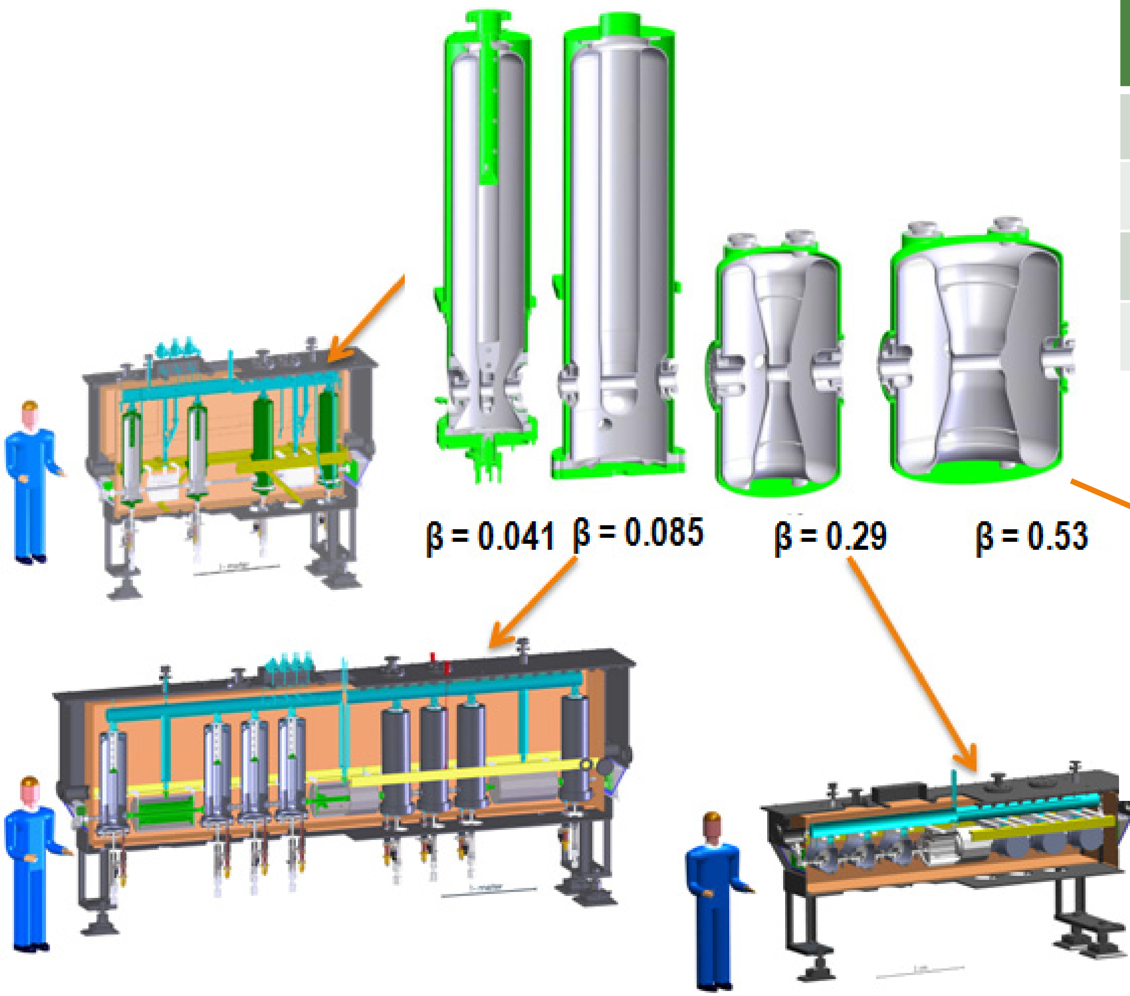
- The most dangerous are acute (fast) beam losses at some of SC cavities, when an upstream cavity trips. Since the admittances at the SC cavities are designed larger than those at the stainless steel beam pipes inside the focusing SC solenoids, that is, the beta function $\beta(s)$ is the maximum at the focusing elements, no beam is lost at any cavity under normal operational condition, theoretically speaking. Here, the admittance A is defined in such a way that $(A\beta(s))^{1/2}$ is the bore radius. However, once a cavity trips, the beam energy is lowered, invalidating the above admittance definition, that is, the beta function. The beam is over-focused to hit the cavity surface. Any malfunctioning of other components than cavities takes some time to give rise to beam loss, since the components have some stored energy to decay. Thus, the MPS can be activated in time to stop the beam to be lost, after detecting the malfunctioning. On the other hand, the cavity trip can immediately exhaust its stored energy, leaving no time to stop the beam loss.

- The extensive study of cavity trip events showed that the maximum possible power dissipation on a cavity is a little less than 5 kW. An FRIB MPS response time of 35 μs can then protect the FRIB cavities from acute beam loss damage, if scaled [16] from the SNS MPS response time of 20 μs. Here, the MPS is activated by LLRF control detecting the cavity trip and/or Halo Monitor Rings (HMRs) and/or differential current monitoring.

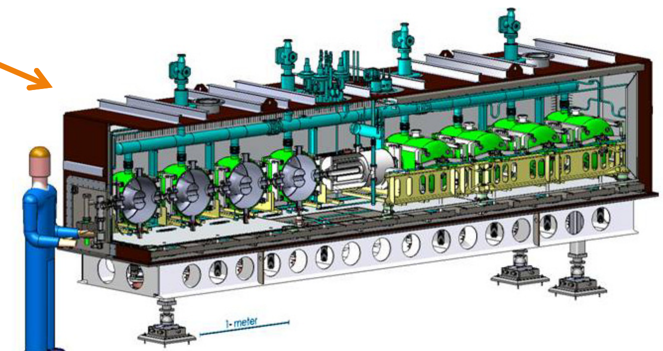
Chronic Beam Loss on Cryogenics

- Actually, the FRIB MPS implements a redundant, multi-layer scheme, responding to these fast events and chronic (slow) beam losses.
- Allowable chronic beam loss in the high power heavy ion SC linac may be limited by the allowable heat load on cryogenics. The average beam loss of 1 W/m throughout all the CMs amounts to 10 % of the cryogenics heat load. The present budget for the beam loss heat load is 25 W in total [1], being of an order of 0.1 W/m in average.
- The temperature sensor to be installed to the CM beam pipes can monitor this order of beam loss. Note that the heavy ion radiation damages on solid materials are much more than estimated by the stopping power ratios. The temperature sensors are crucial in order to protect the beam pipes from the long-term radiation damages.

Aperture Increased by 40 %



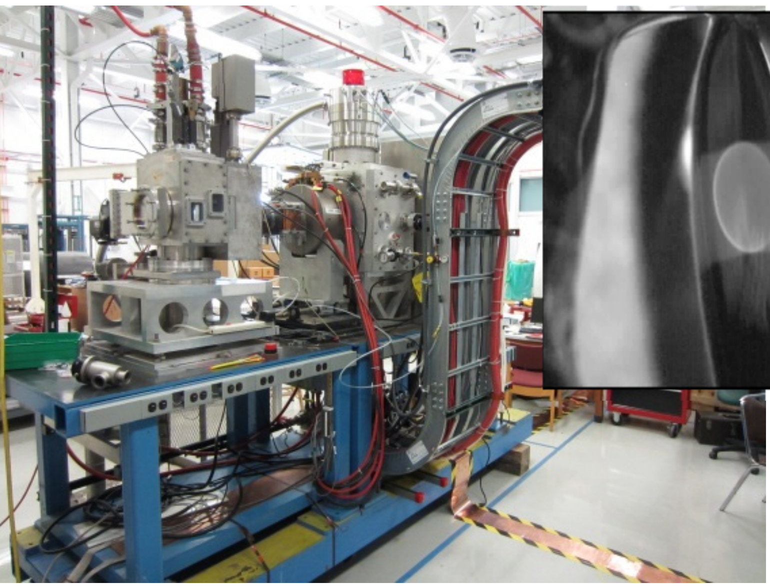
type	β_0	f (MHz)	V_a (MV)	a (mm)
λ/4	0.041	80.5	0.81	36
λ/4	0.085	80.5	1.78	36
λ/2	0.29	322	2.09	40
λ/2	0.53	322	3.7	40

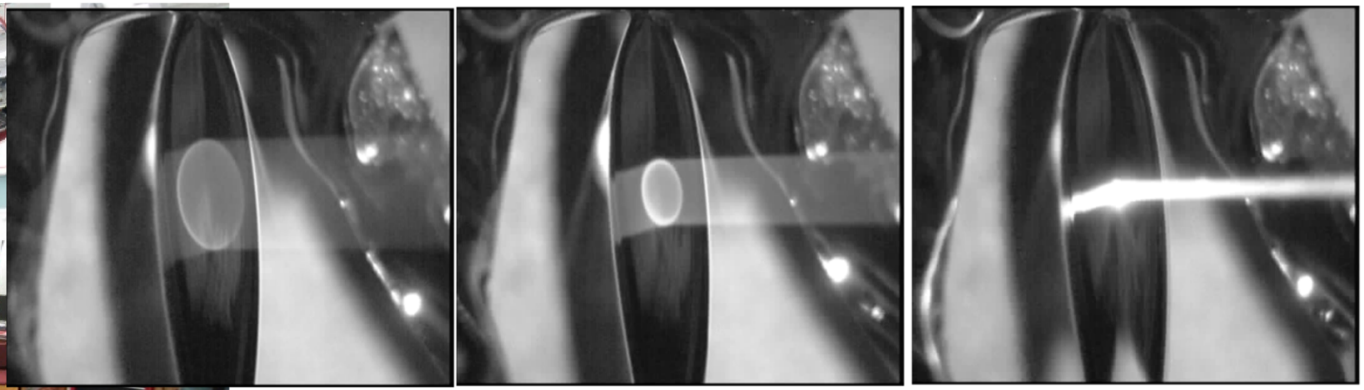


These design apertures were increased by about 40 % from 30 mm diameter

Charge Stripper Using Liquid Lithium Film
Successful LANL IS Restoration at MSU & Beam Power Test at ANL

- Liquid lithium film established with controllable thickness and uniformity
- Los Alamos LEDA source beam commissioned at MSU
  - Beam commissioned at MSU after restoring with new cooling and power supply system after more than 10 years of storage.
- Beam power tests on liquid lithium film successfully performed at ANL
  - The film sustained ~200% of FRIB maximum power density deposition





Los Alamos NATIONAL LABORATORY EST. 1943

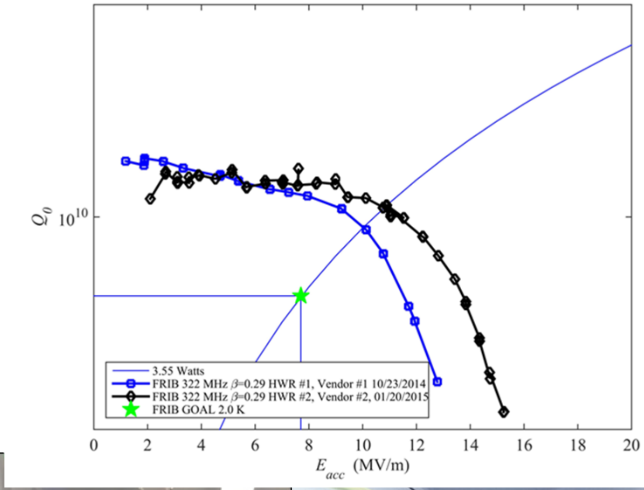
Argonne NATIONAL LABORATORY

Production Challenge

SRF Production Infrastructure Project on Track

Demonstrating In-house Work Capability

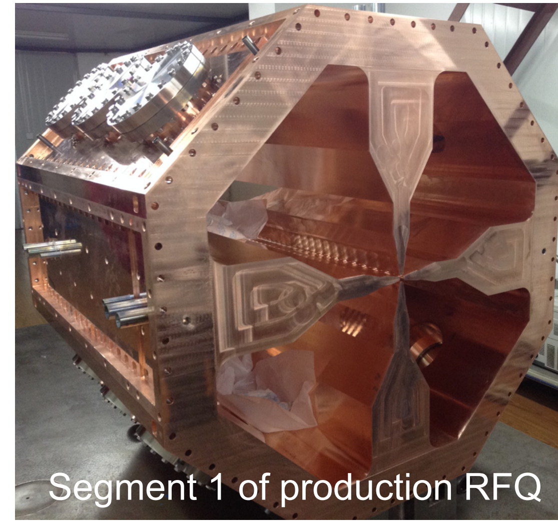
- A test bed for FRIB tunnel / service building construction & technical installation
- Cavity processed and assembled in new facility surpasses FRIB goal
- RF test area acquisition and installation done
- New cryoplant ready



First cavity etch completed and equipment ready for pre-production cavities

RFQ Segment 1 to 4 (among 5 Segments) Successfully Built
Quality Control of Remote Industrial Vendor Demonstrated

- Tsinghua Univ. providing quality control and coordination
- Weekly or bi-weekly three-party teleconferences followed by action items
- Frequent FRIB staff visits & risk mitigation
- Complete transparency and prompt issue mitigation
- Planning early RFQ commissioning in tunnel
  - Project schedule allows up to a year of high power test in the tunnel upon accelerated tunnel Ready For Equipment (RFE)



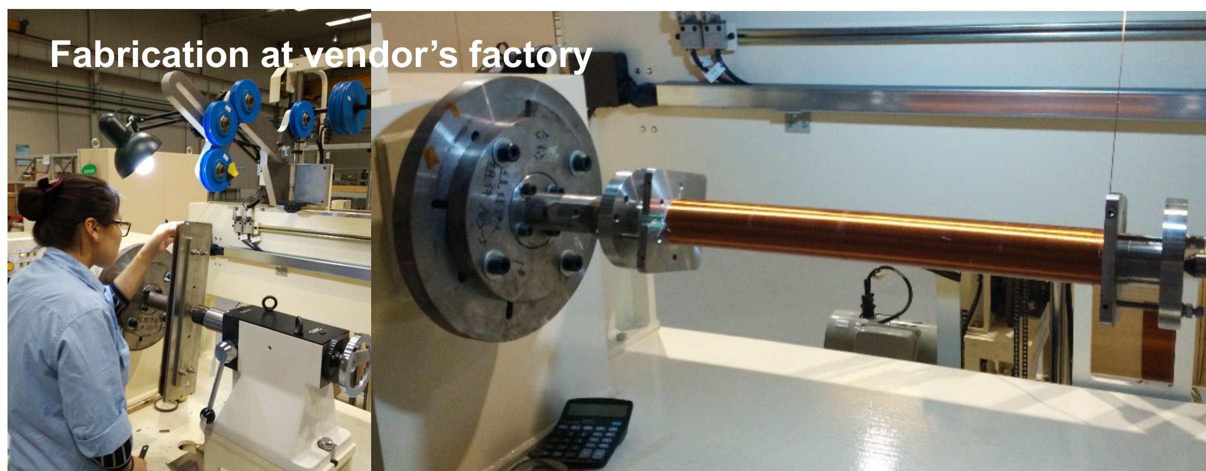
Segment 1 of production RFQ

FRIB staffs inspecting the RFQ at vendor site frequently

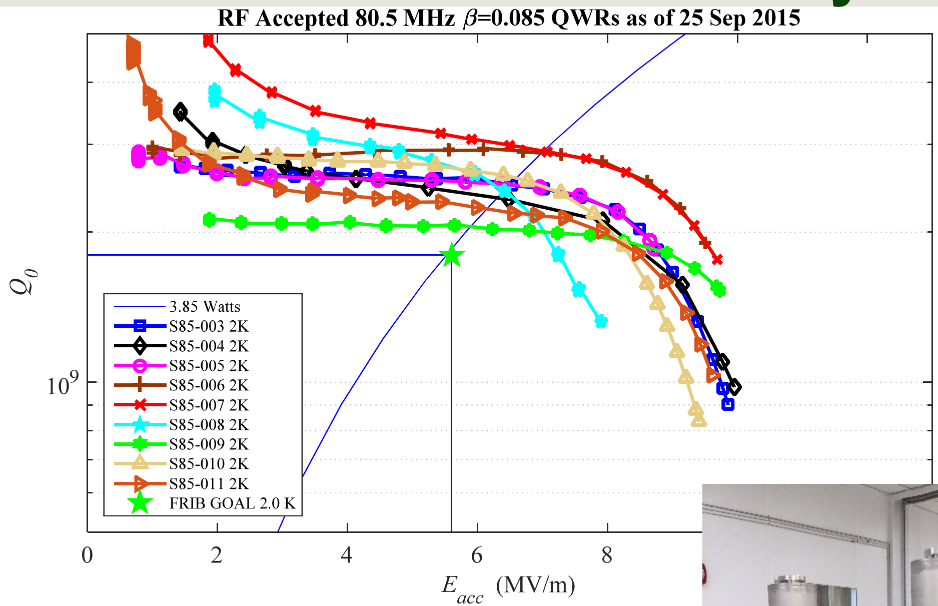
Superconducting Solenoid Acquisition Ongoing

- The prototyping effort with KEK technically successful
- Fabricated 4 solenoids in-house for the first β=0.085 production cryomodule
- Procurement solicitation succeeded with multiple vendors
- Following the successful 3-party model of RFQ acquisition
- Engaging IMP in quality control and monitoring a remote vendor
- Now, KEK and vendor’s Japanese parent company joined

In-house Fabrication


Fabrication at vendor’s factory

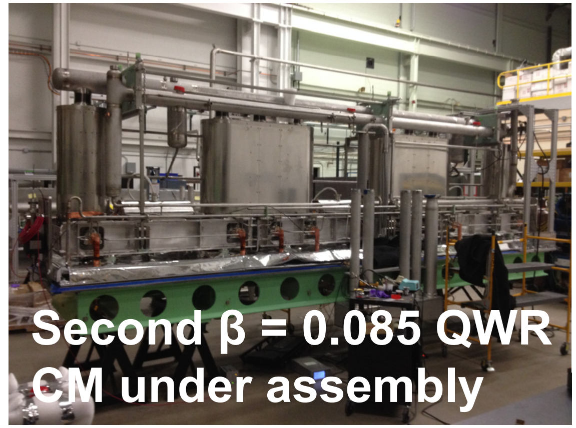
Performance of the Eight Preproduction Cavities by the Vendor Exceeded the FRIB Requirements and Used for the Cryomass



The First β = 0.085 QWR Cryomoass

FRIB Cryomodules (CMs) Assembly Progressing to Production Phase

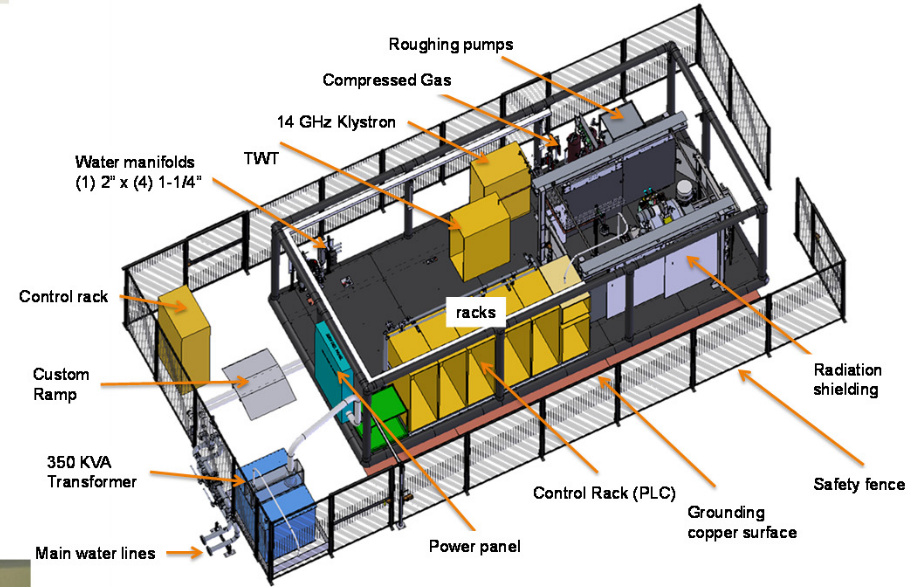
Finalizing 2 K test with vibration management and RF control after successful 4 K test

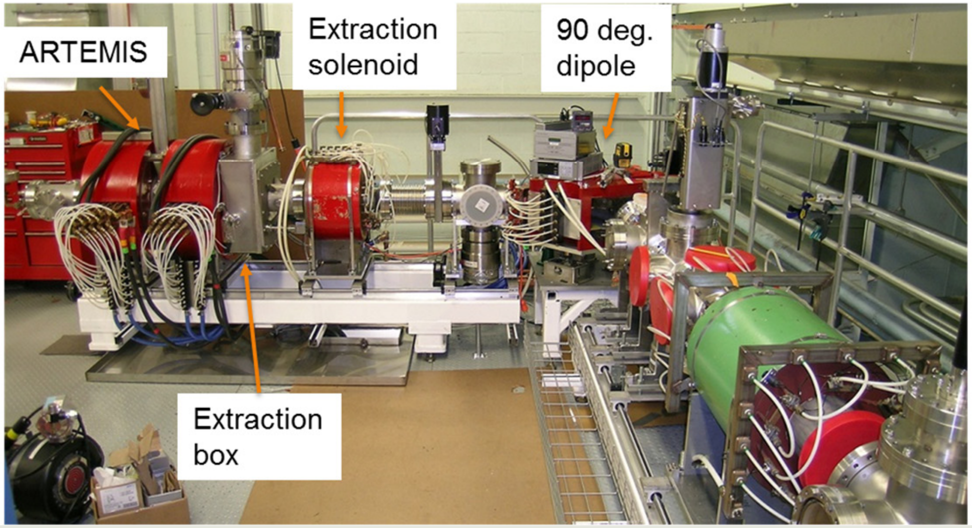


β = 0.54 Half Wave Resonator (HWR) Cryomoass completed

FRIB RT Ion Source Near Completion
High Voltage Platform Construction Started

- Aiming at installation of the Room Temperature (RT) source as soon as the building is Ready-for-Equipment
- High-voltage and radiation hazard mitigation process pursued
- Parallel efforts in developing the high-power superconducting ion source





Summary

Summary

- FRIB Accelerator Systems are marching full speed on technical construction managing technical aspects, in-house readiness and vendor delivery
- The FRIB driver linac is a front runner for the future high beam power ion accelerators, making a full use of SRF technology.
- The technologies developed for the FRIB shall contribute a lot to the future prospect of this exciting field.
- In particular, we are placing strong focusing solenoids closely to SRF cavities with a high alignment accuracy.
- More accuracy shall be required for the higher beam power hadron linac with a strong space charge force.
- The FRIB is on the way for these ultimate machines.
- Many laboratories and universities all over the world are collaborating for FRIB completion
- Please join the collaboration to participate in this exciting challenge

LINAC 2016: 9/25 (Sun) ~ 9/30 (Fri)
Good Season for Outing – Lake Michigan

See You Again at East Lansing, Michigan This Fall