MOPM1P80

FRIB

Accelerator Physics Challenges in FRIB Driver Linac

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Facility for Rare Isotope Beams

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U.S. DEPARTMENT OF ENERGY | Office of Science

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Coauthors and Related Presentations

- Coauthors

K. Fukushima, Z. He, S. Lidia, Z. Liu, S. M. Lund, F. Marti, T. Maruta*, D. Maxwell, G. Shen, J. Wei, Y. Yamazaki, T. Yoshimoto, Q. Zhao; FRIB, MSU

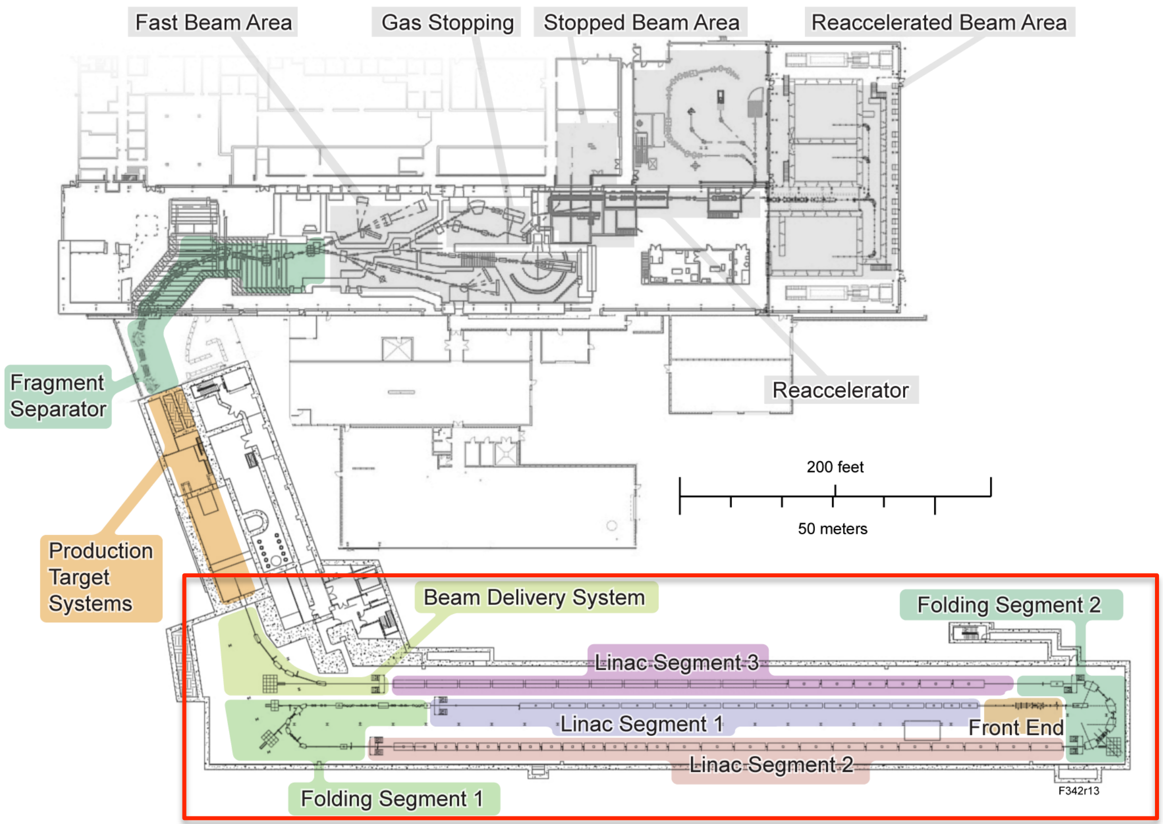
*On leave from KEK/J-PARC

- Related presentations
  - **TUAM5Y01**: Q. Zhao et. al., “Beam Simulation Studies for FRIB”
  - **TUPM2X01**: F. Marti et. al., “Heavy Ion Charge Stripping at FRIB”
  - **WEPM3Y01**: S. M. Lund and C. Y. J. Wong, “Efficient Particle In Cell Simulations of Beam Collimation in the FRIB Front-End”
  - **WEPM8X01**: Z. Liu et. al., “Collimation Design and Beam Loss Detection at FRIB”

Outline

- Overview of FRIB driver linac
  - Key features
  - Requirements
- Accelerator physics challenges
  - Online model development
  - Tuning scheme refinement
  - Contaminant loss study
  - Residual gas stripping loss study
  - Other technical challenges
- Construction status and schedule
- Summary

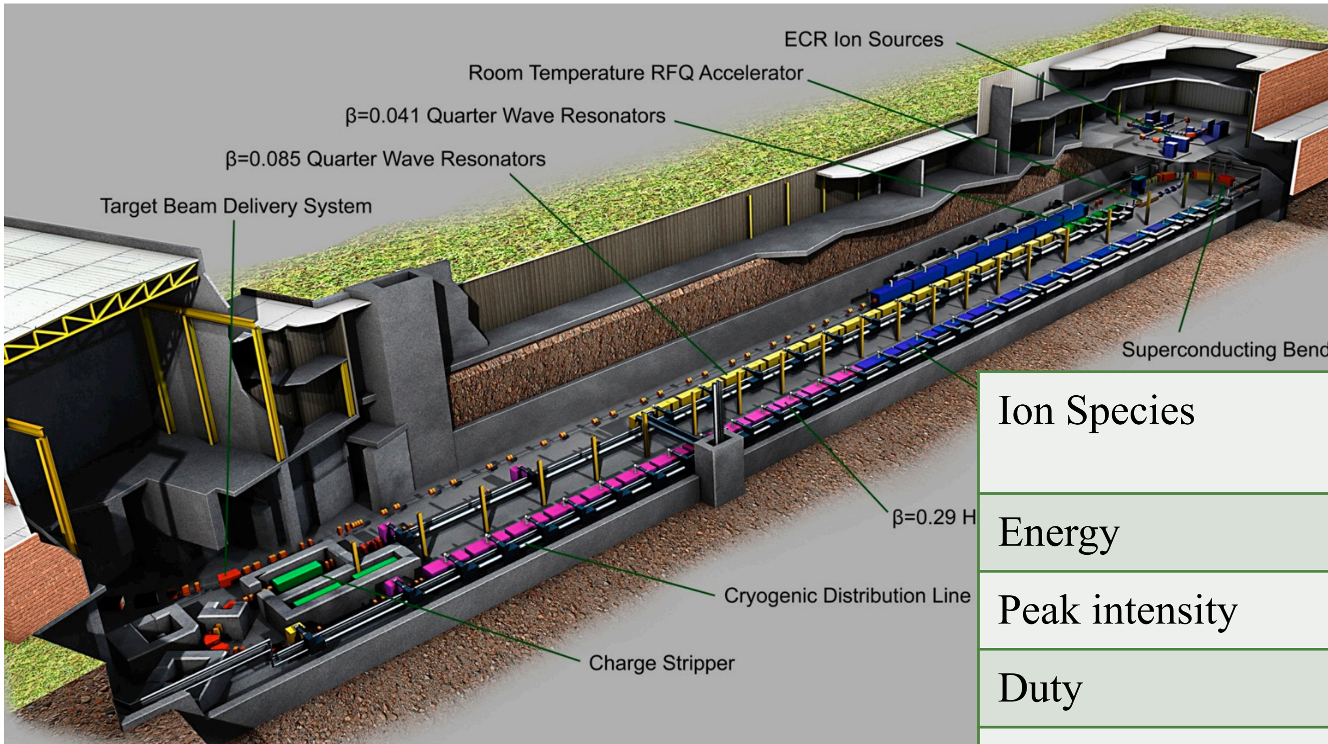
Overview of FRIB Driver Linac

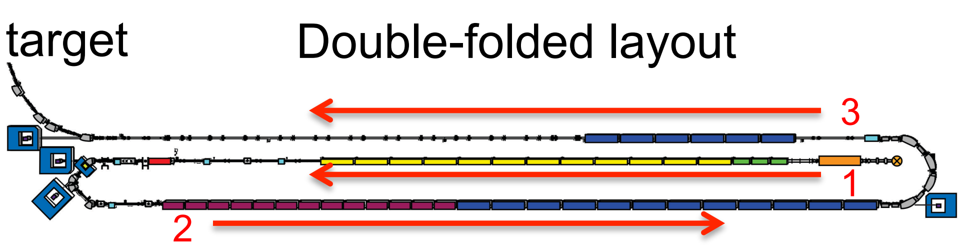


- Delivers primary beams to production target to support physics experiment utilizing various secondary particles
- Accelerate all stable ion species with energies of 200 MeV/u
- Provide beam power of 400 kW on target
- CW operation

- Under construction next to the existing NSCL (National Superconducting Cyclotron Laboratory) building
- Experimental facility for NSCL will be utilized for FRIB after reconfiguration

FRIB Driver Linac Layout
Folded Layout with Ion Source on Upper Level

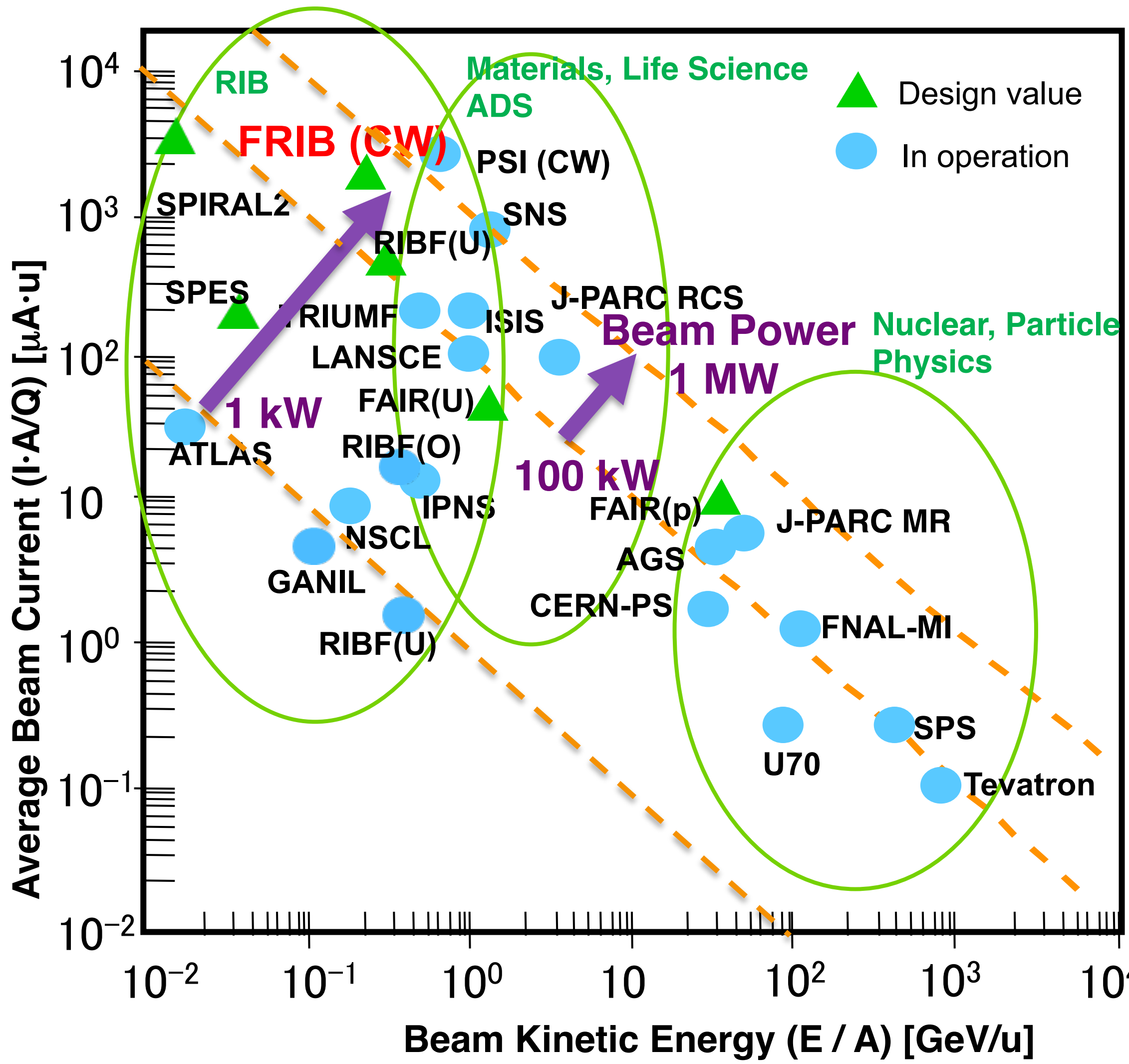




Ion Species	All stable ions up to uranium
Energy	200 MeV/u
Peak intensity	0.7 emA
Duty	100% (CW)
Average beam power	400 kW
Cavity type	SC QWR, SC HWR
Frequency	80.5/322 MHz
Status	Under construction

FRIB Among High-intensity Accelerators
Challenges Beam Power Frontier for Heavy Ion Accelerator

- 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; 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
  - More than two orders of magnitude beam power increase from existing heavy ion linac facility



Stringent Primary Beam-on-Target Requirements to Support Efficient Physics Experiments

- High beam quality on target is required to support efficient particle separation at secondary beam line

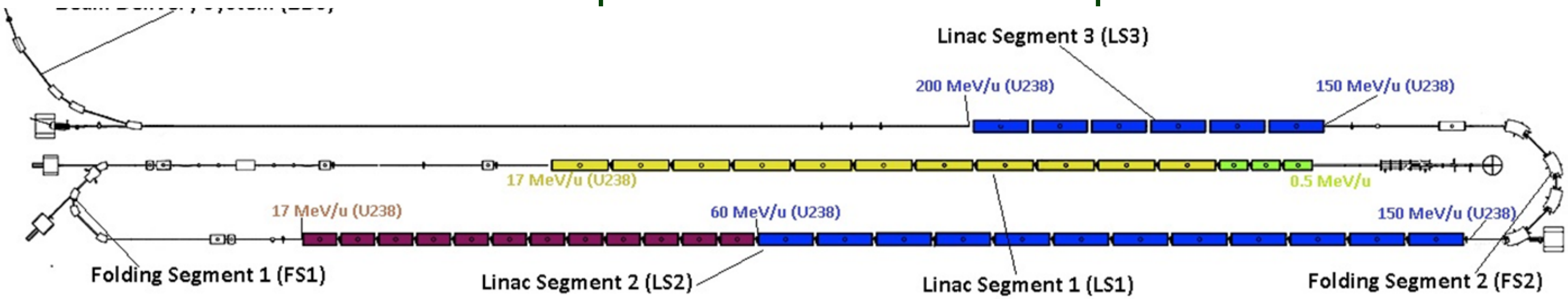
	Parameter	Description	Baseline	Basis/Comments
1	Beam spot size (diameter)	Contains 90 % of beam, incl. fluctuations	1 mm	Necessary for beam purity - scientific reach
2	Beam trajectory on target reproducibility	Position and angle w.r.t. fragment separator magnet axis	$\leq \pm$ 0.1 mm, $\leq \pm$ 3 mrad	Position necessary for beam purity - scientific reach Angle necessary to prevent primary beam hitting dipole Upgrade option: $\leq \pm$ 0.1 mm, $\leq \pm$ 2 mrad
3	Beam angular spread	Horizontal and vertical, contains $\geq$ 90% of beam, incl. fluctuations	$\leq \pm$ 5 mrad	Prevent primary beam hitting dipole – facility efficiency- operational cost
4	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
5	Beam energy reproducibility		$\leq \pm$ 0.5 %	Facility efficiency - operational cost
6	Beam energy spread	Contains 95 % of beam, incl. fluctuations	$\leq \pm$ 0.5 %	Selection of rare isotope between magnetically separated primary beam charge states so as to not truncate scientific reach Upgrade option: $\leq \pm$ 0.2 %
7	Bunch length	Contains 95 % of beam	3 ns	Particle identification (TOF measurement) Upgrade option: 95 % in $\leq$ 1.5 ns and 99.9 % in $\leq$ 3 ns → necessary for RF separation of rare isotopes (spacing a few ns) – important for very proton-rich isotopes – scientific reach
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

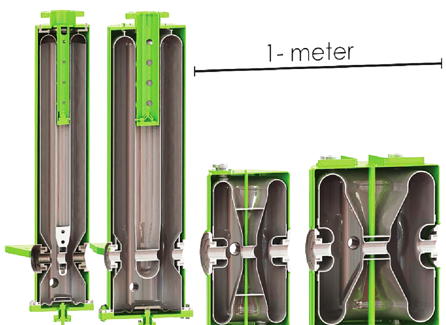
High Power and High Availability Requirements Pose Accelerator Physics Challenges

- High power: 400kW beam on target with CW operation
  - Beam loss mitigation
    - » Prompt and residual radiation
      - Prompt radiation shielding designed assuming line loss of 1 W/m
    - » Potential damage to SRF cavity
  - Machine protection
- High availability: 90% availability for 5,500 hours of beam-on-target (6,000-hour beam-in-linac) per year
  - Swift ion species switchover
    - » Due to nature of heavy ion facility, frequent ion species switch over will be requested
    - » Typically once in one to two weeks
    - » Deep understanding of accelerator and efficient model based tuning are essential

Superconducting RF Technology Extensively Adopted

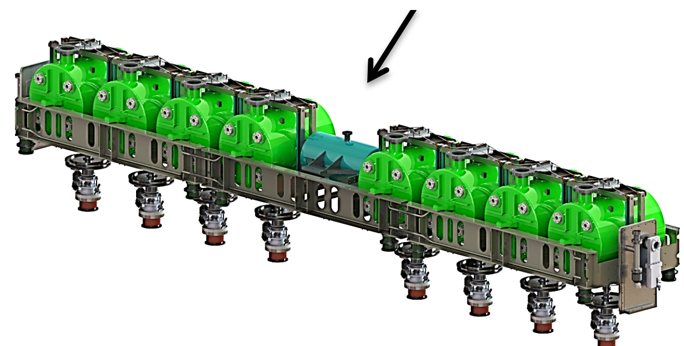
- Superconducting QWRs (Quarter Wave Resonators) and HWRs (Half Wave Resonators) are adopted to accelerate beams from 0.5 MeV/u to >200 MeV/u
- 332 SRF cavities with independent solid state amplifier





β_0 = 0.041 β_0 = 0.085 β_0 = 0.29 β_0 = 0.53
Quarter-Wave Resonators 80.5 MHz Half-Wave Resonators 322 MHz

β=0.085 QWR cryomodule



β=0.53 HWR cryomodule

Key Accelerator Physics Challenges Identified in HB2014

- Space-charge effects in low-energy front-end
  - Space-charge effects are important in front-end

WEPM3Y01: S. M. Lund, C. Y. J. Wong

- Acceleration of multi-charge-state beams
  - Up to five charge states are assumed to be accelerated simultaneously to achieve high beam intensity
  - Stringent beam-on-target requirements should be met for multi-charge-state beams
- Effect of non-axisymmetric field component at QWRs (Quarter Wave Resonators)
  - Non-axisymmetric nature of QWR induces dipole and quadrupole components
- Aperture optimization for beam loss detection
- Collimation of large angle scattered beams at a stripper

WEPM8X01: Z. Liu et. al.,

M. Ikegami et.al., HB2014 TUO4AB03

Additional Accelerator Physics Challenges

- Online model development
  - Flexible and powerful environment to develop commissioning software is essential to achieve availability goal
  - Online model is a key element for the environment
- Extended error studies and model enhancement to understand machine response to realistic errors
  - To deepen understanding of machine to optimize operation parameters and tuning procedures
- Contaminant ion species loss study
  - Specific beam loss mechanism for heavy ion accelerator with charge stripper
- Residual gas stripping beam loss study
  - Existence of arc section between linac segments needs to be addressed in mitigating uncontrolled loss from residual gas stripping

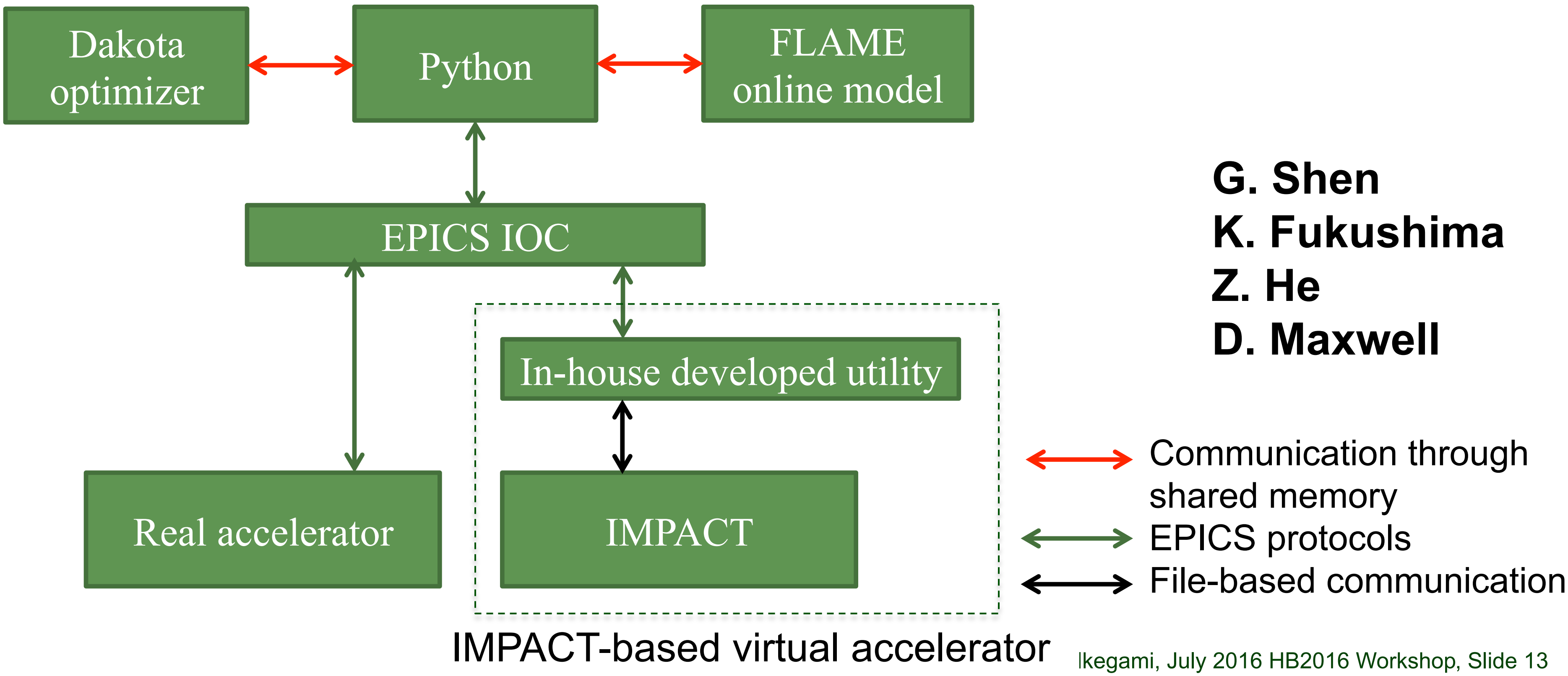
Online Model Development [1/3]
Two Modeling Engine Adopted to Complement Each Other

- Specific features
  - Multi charge state beam acceleration
  - Non-axial symmetric field in Quarter Wave Resonators
  - Charge stripping
- Strategy for online model development
  - In-house developed envelop model: FLAME
    - » Prototyped with Java and ported to C++ to improve performance and interface to C ++/Python
    - » Linear optics without space charge
    - » To cover basic tunings including orbit correction, rms matching, phase/amplitude tuning
  - IMPACT as backup
    - » Reference code in designing FRIB lattice
    - » Reasonable execution speed turning off space-charge (~1s for Linac Segment 1)
    - » To cover special tuning such as halo mitigation and 2^{nd} order achromat tuning
    - » Also serve as virtual accelerator to benchmark tuning algorithms

G. Shen / Z. He / K. Fukushima

Online Model Development [2/3]
Flexible and Efficient Scripting Environment Developed

- FLAME online model and Dakota optimizer with direct Python interface
- Dakota optimizer provides powerful optimization capability
  - Local, global, and hybrid optimization methods
- IMPACT-based online model to validate physics algorithm

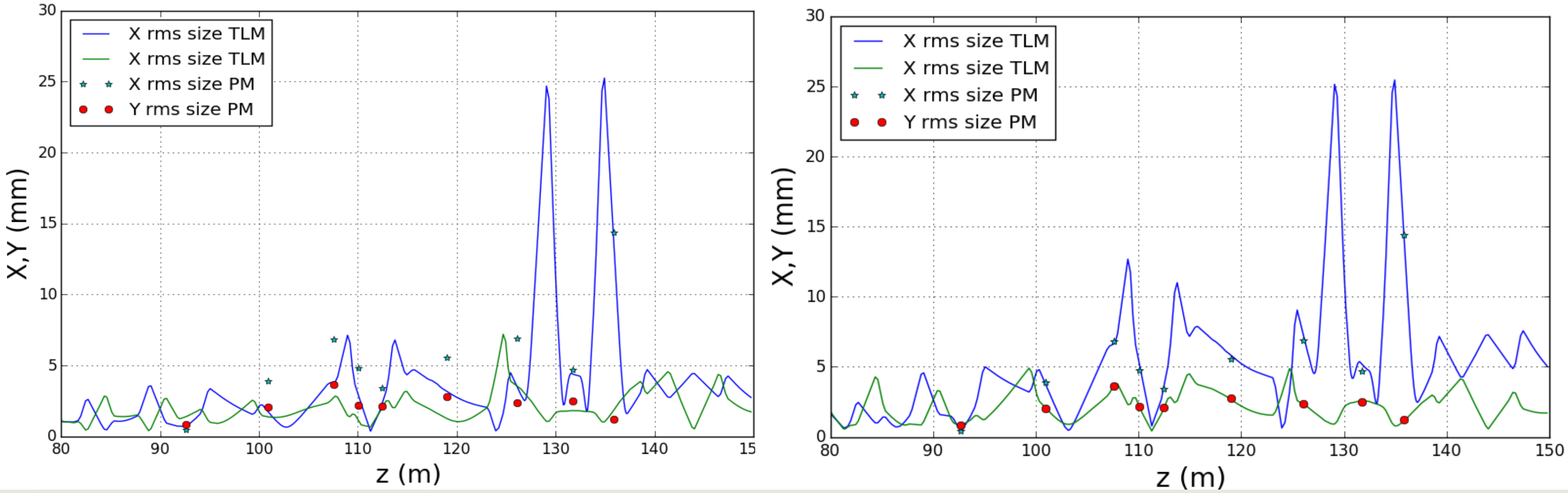


G. Shen
K. Fukushima
Z. He
D. Maxwell

Online Model Development [3/3]
Major Commissioning Applications Prototyped

- Major commissioning applications prototyped with developed environment
  - Phase/amplitude tuning for cavities
  - Orbit correction
  - Transverse/longitudinal matching
  - Energy manager (retuning with new cavity setting)
    - » Java prototype of FLAME has been used for prototyping so far
    - » We are converting them to use FALME

Example: Transverse matching to charge stripper

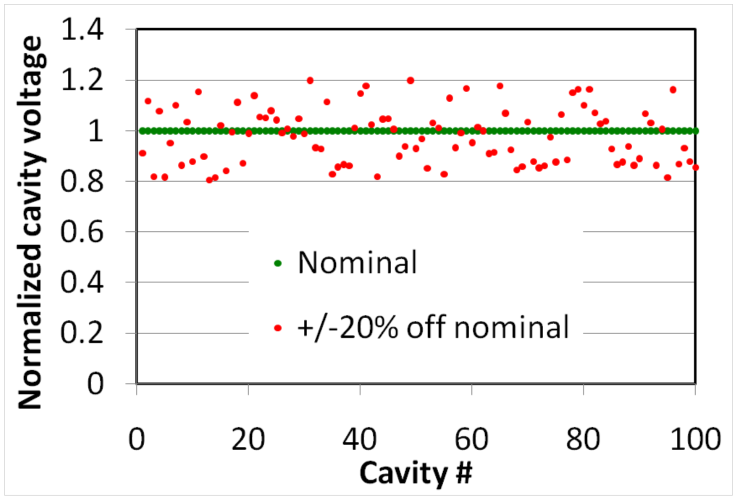


Z. He

Extended Error Studies

Example: Voltage Deviation for Quarter Wave Resonators

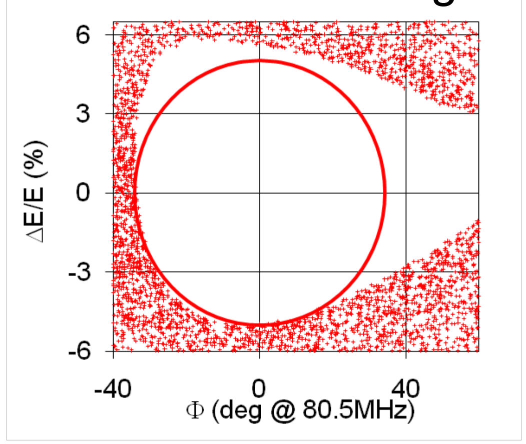
- Performance of each cavity is different in real life (assumed same in design)
- Amplitudes of all QWR cavities are randomly off by maximum of ±20%, cavity phases are adjusted to keep the same synchronous phases as in the design case (can be set in a real machine)

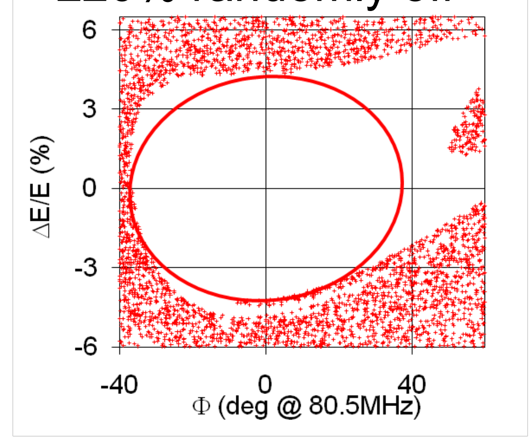


Segment 1 longitudinal acceptance

30 π-ns-keV/u nominal voltages

27 π-ns-keV/u ±20% randomly off

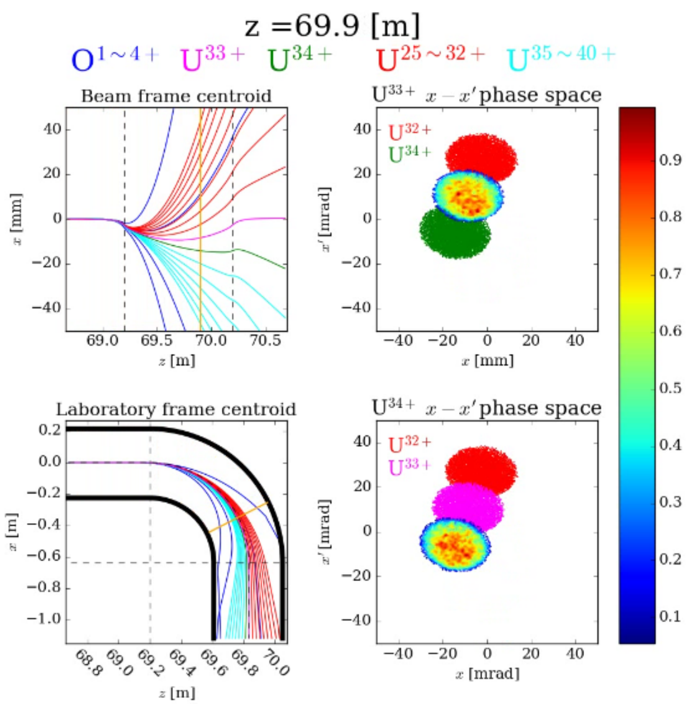


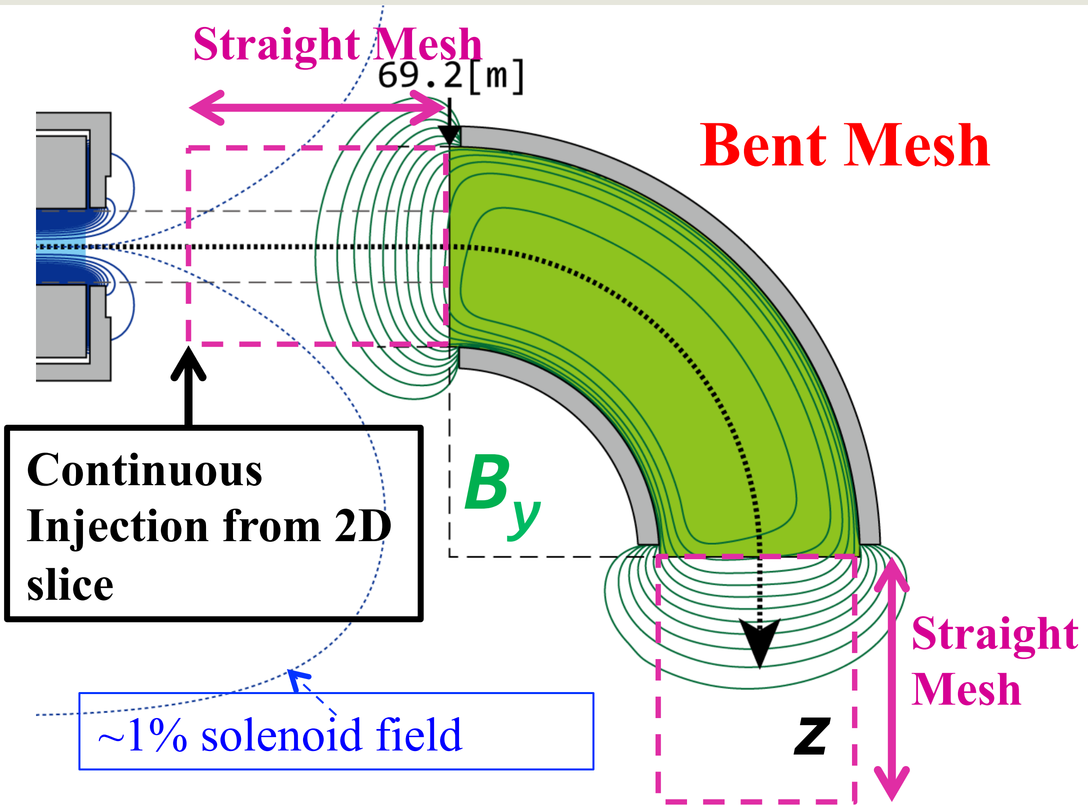


- Longitudinal acceptance reduced by 15%, but no beam loss occurred
- Output energy varied within ~1%
- Matched input conditions slightly change, but can be rematch at entrance

Q. Zhao (TUAM5Y01)

Continuing Efforts to Improve Front-End Model Example: Warp Simulation for Charge Selection





- 3D simulations of dipole bends with space-charge and full fringe help verify that early species separation preserves beam quality

S. Lund (WEPM3Y01)

Contaminant Ion Species Loss Study [1/2]
Loss Mechanism Identified

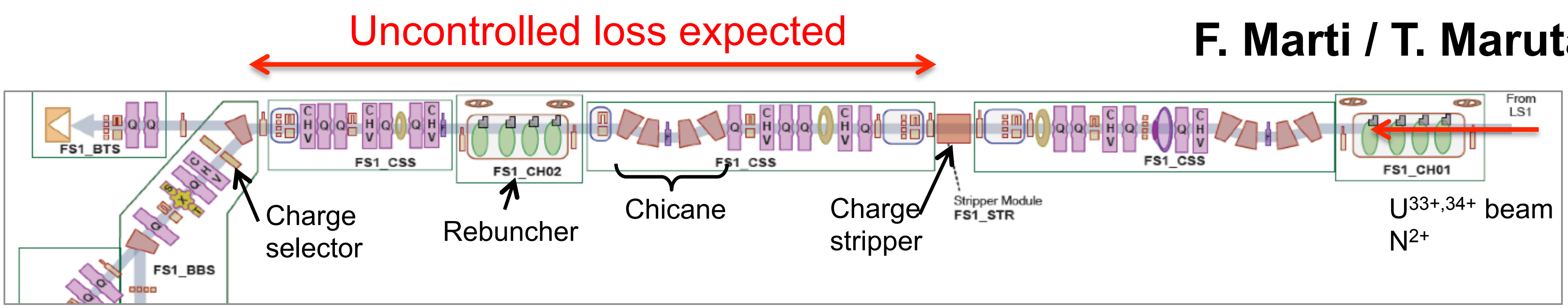
- In generating a heavy ion beam with ECR ion source, other ions but with similar Q/A can contaminate the beam
- Contaminant will be accelerated with intended ions
- After stripper, contaminant can have very different Q/A after charge stripper as lighter ions are easier to be fully stripped

Example: $^{238}U^{34+}$ (Q/A=0.143) → Stripper → $^{238}U^{78+}$ (Q/A=0.328)

$^{14}N^{2+}$ (Q/A=0.143) → Stripper → $^{14}N^{7+}$ (Q/A=0.5)

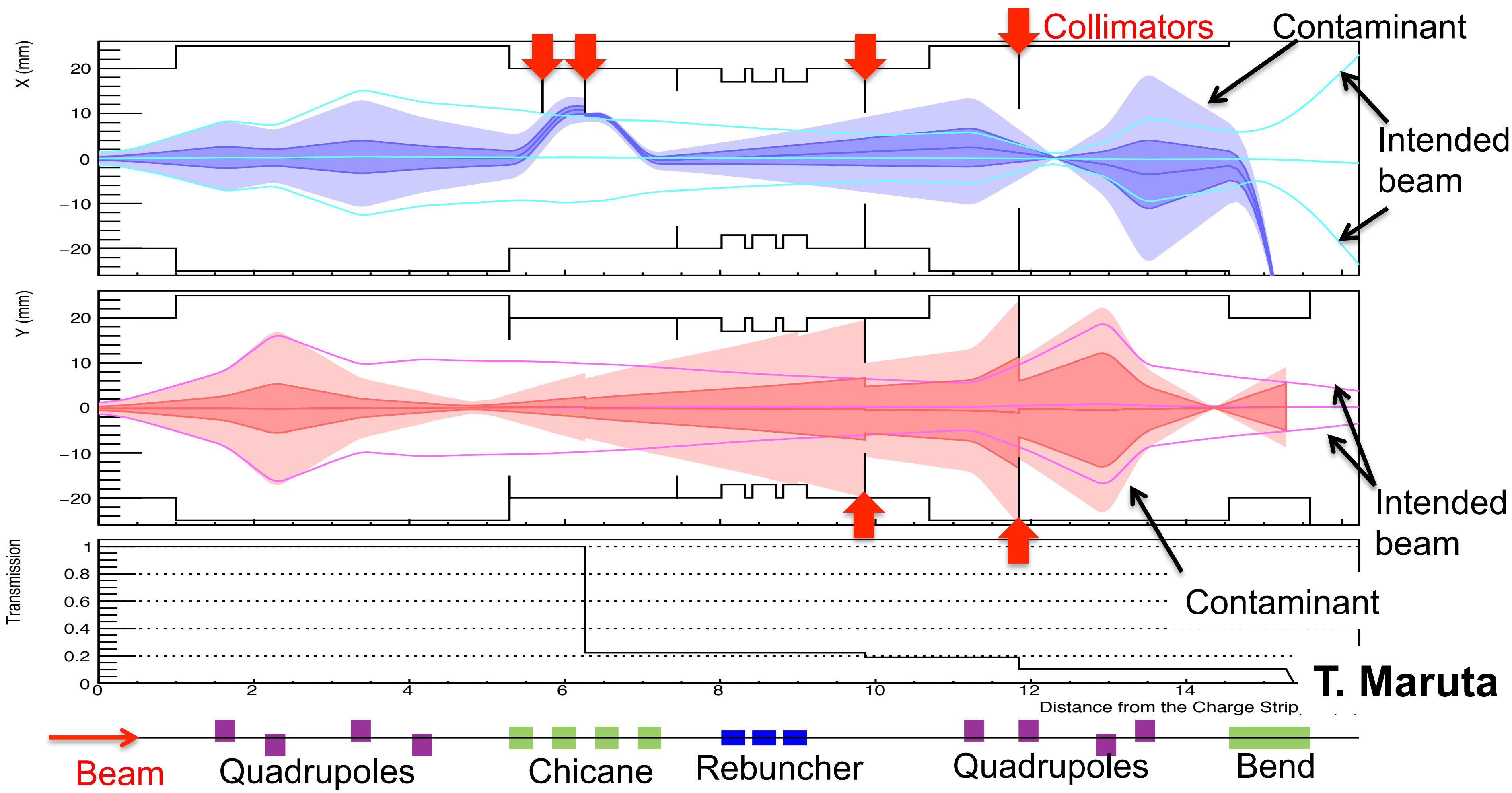
- Contaminant with very different Q/A has a mismatch to the optics, which can result in a beam loss after charge stripper

F. Marti / T. Maruta



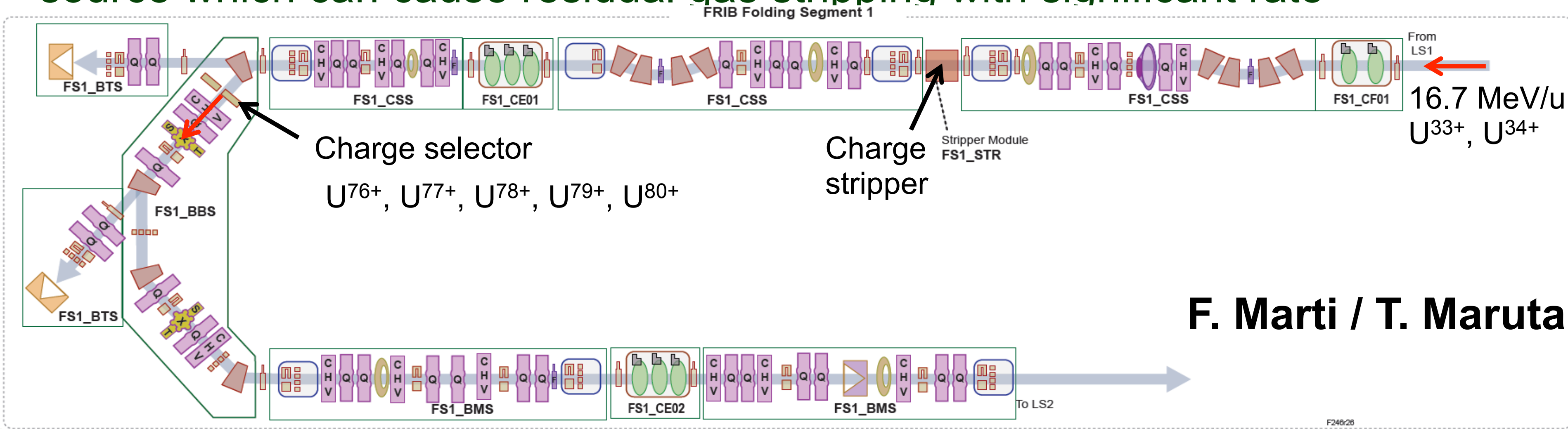
Contaminant Ion Species Loss Study [2/2]
Finalizing Collimator Design with Extensive Simulations

- Example simulation with IMPACT ($(Q/A)_{contaminant}/(Q/A)_{intended}=1.2$)



Residual Gas Stripping Loss Study [1/2]
Loss Mechanism Identified

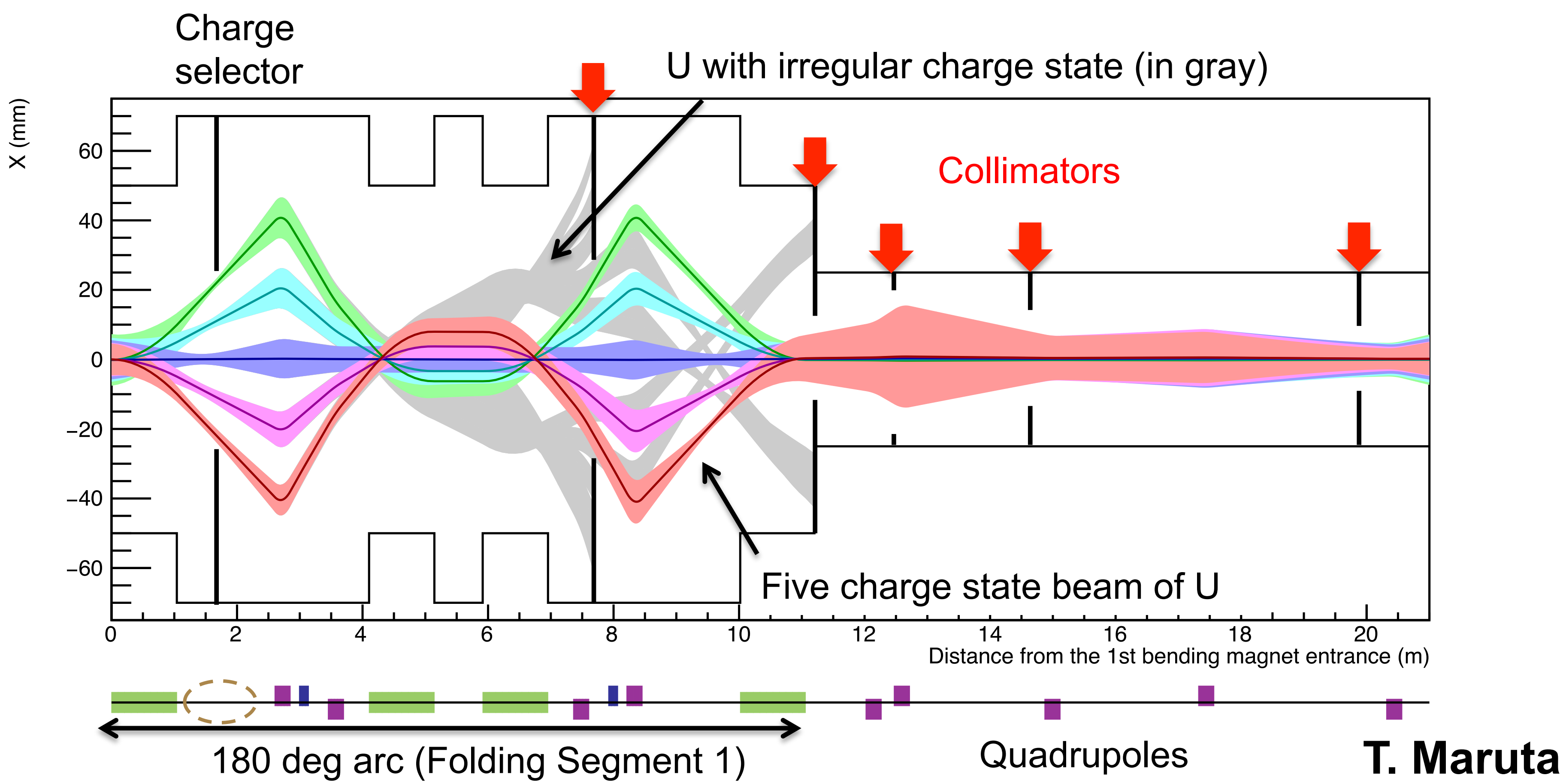
- FRIB driver linac is designed to accelerate up to five charge states
- If residual gas stripping occurs in linac segments, generated ions with irregular charge state likely stay in acceptance
- However, if residual gas stripping occurs in dispersive regions, generated ions with irregular charge state can have significantly different beam trajectory and result in a beam loss
- Charge selector located in the first folding segment will be a notable gas source which can cause residual gas stripping with significant rate



F. Marti / T. Maruta

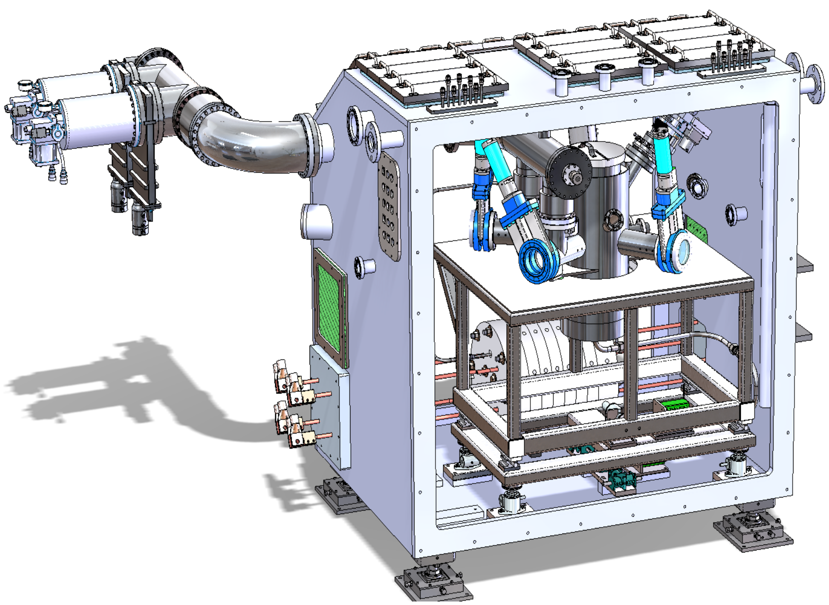
Residual Gas Stripping Loss Study [2/2]
Establishing Collimator Design to Localized Losses

- Example IMPACT simulation for a case where residual gas stripping is localized at charge selector



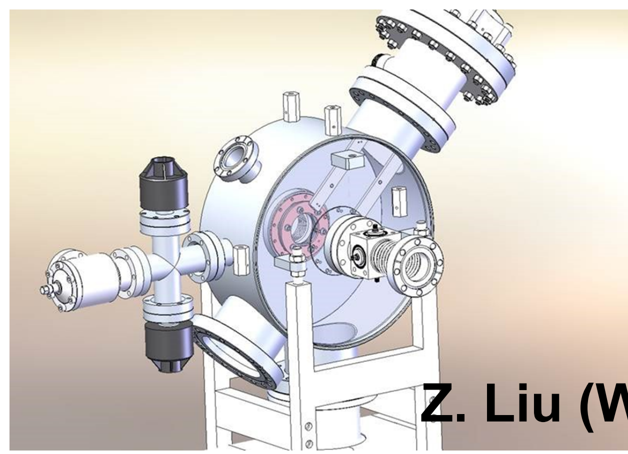
Technical Challenges
Specific to Heavy Ion High Power Accelerator

- Charge stripper for high power heavy ion beam
  - Liquid lithium film to sustain high energy deposition



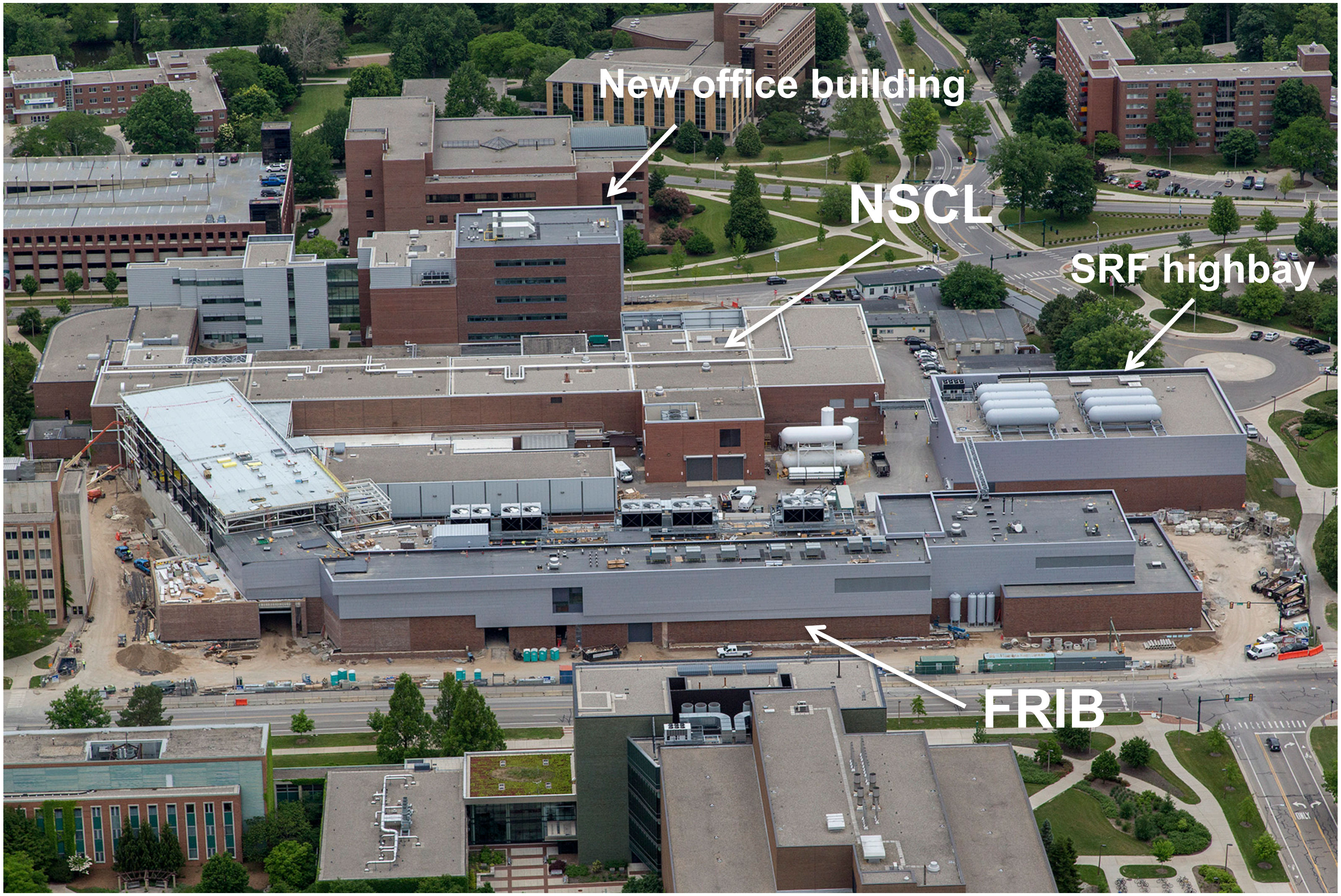
F. Marti (TUPM2X01)

- Machine protection against heavy ion beam loss
  - Detection of beam loss in low energy section
  - Planned to cover with multiple detection method with different sensitivity and response time
    - » Differential beam current monitoring
    - » Halo monitoring ring
    - » Neutron detector



Z. Liu (WEPM8X01)

Construction Status: Entire Facility
Bringing Building to Completion



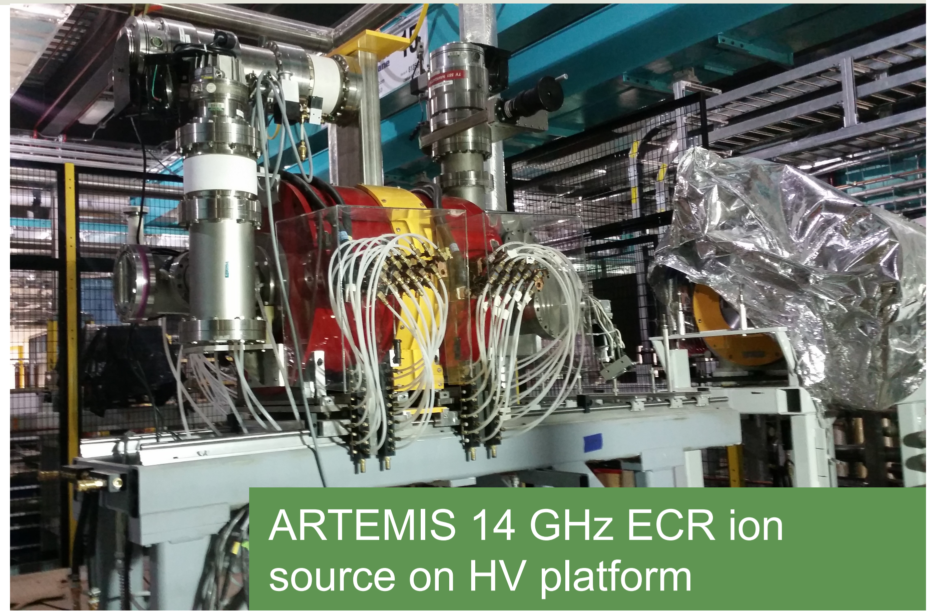
Construction Status: Linac Building
Transfer Line Installation Started; Completing Front-End Part

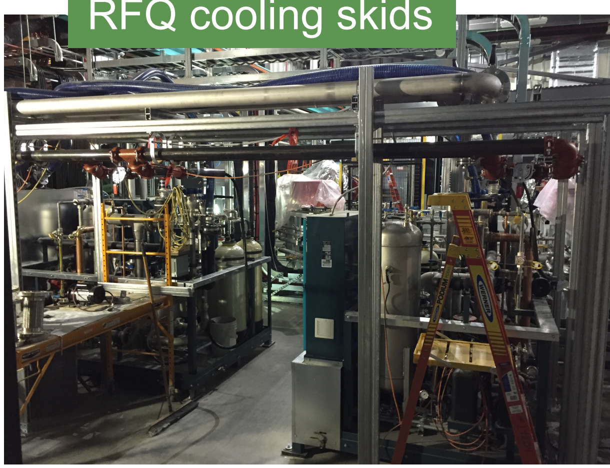
Transfer line installation in Linac Tunnel

Linac Surface Building
Ground Floor

Construction Status: Front End
Installation Started; Getting Ready for Commissioning


HV platforms, LEBT stands with magnets and solenoids


ARTEMIS 14 GHz ECR ion source on HV platform


RFQ cooling skids

ECR cooling skids


FE equipment racks installed

Path Forward

- September 2016: Ion source beam commissioning start
- December 2016: RFQ high power test start
- February 2017: RFQ beam commissioning start
- May 2018: Linac segment 1 beam commissioning start
- Fiscal year 2021: Start of user operation and beam power ramp up

Summary

- Key requirements for FRIB driver linac reviewed
- Accelerator physics challenges are identified and being addressed
  - Online model development
  - Tuning scheme refinement
  - Contaminant loss study
  - Residual gas stripping loss study
  - Other technical challenges
    - » Liquid lithium stripper development
    - » Heavy ion beam loss detection for machine protection
- Construction is on track
  - Front-end commissioning will be started in September 2016