FRIB: Accelerator Physics Update and Initial Commissioning

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MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

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Outline

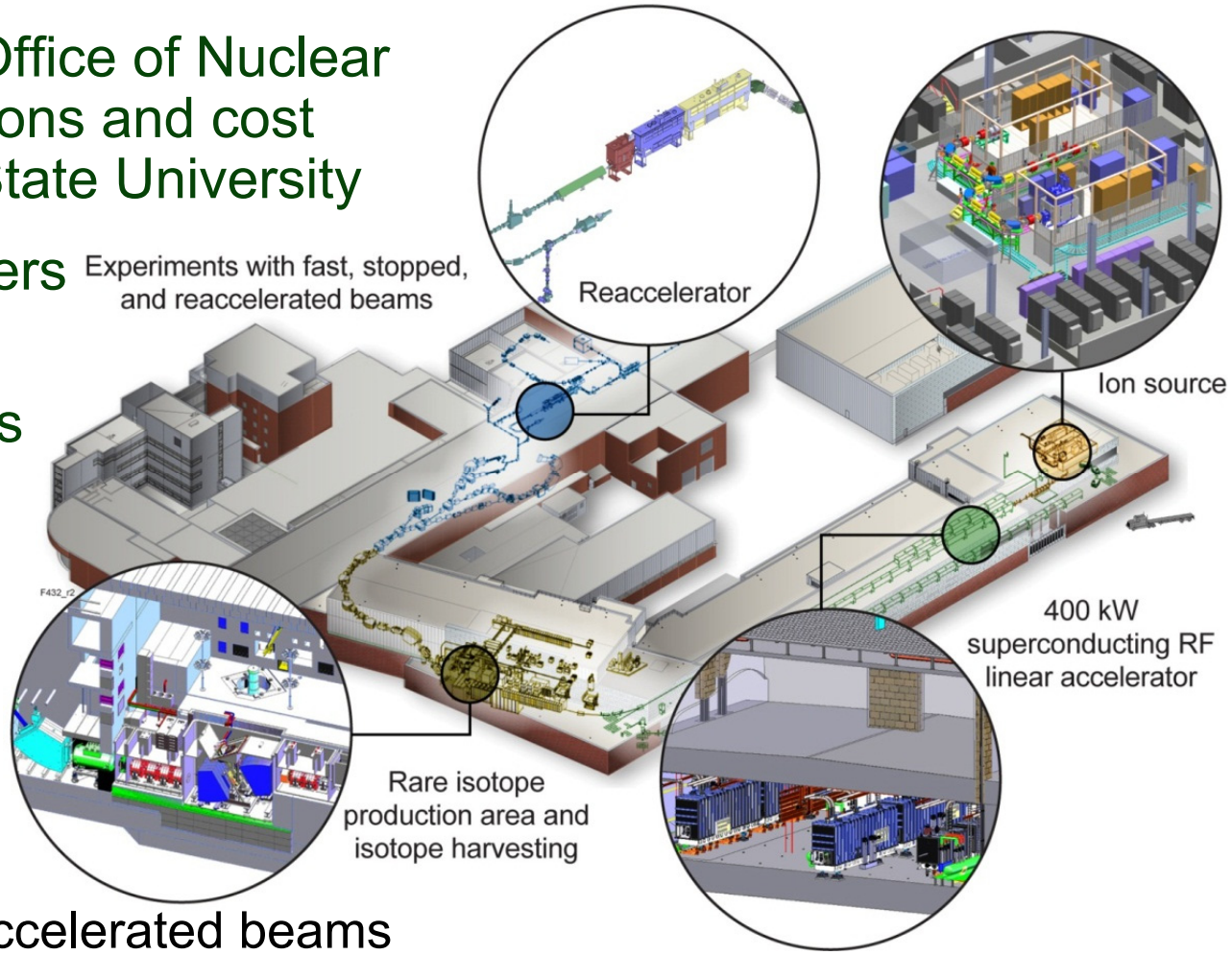
- Introduction
- Recent accelerator physics studies
  - Collimation of contaminant beams
  - Beam tuning in final focusing area
  - Implement of warm rebuncher
  - FRIB energy upgrade
- FRIB linac commissioning
  - Front-End beam commissioning completed
    - » Beam measurement results
  - First three-cryomudule commissioning started
    - » Superconducting resonators conditioned
    - » Commissioning diagnostics station installed
- Summary

T. Maruta
WG-B Wed. 11:00

J. Popielarski
WG-C Tuesday 9:30

Facility for Rare Isotope Beams (FRIB)
A Future DOE-SC National User Facility

- Funded by DOE–SC Office of Nuclear Physics with contributions and cost share from Michigan State University
- Serving over 1,300 users
- Key feature is 400 kW beam power for all ions (e.g. $5x10^{13}$ $^{238}U/s$)
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - All elements and short half-lives
  - Fast, stopped, and reaccelerated beams

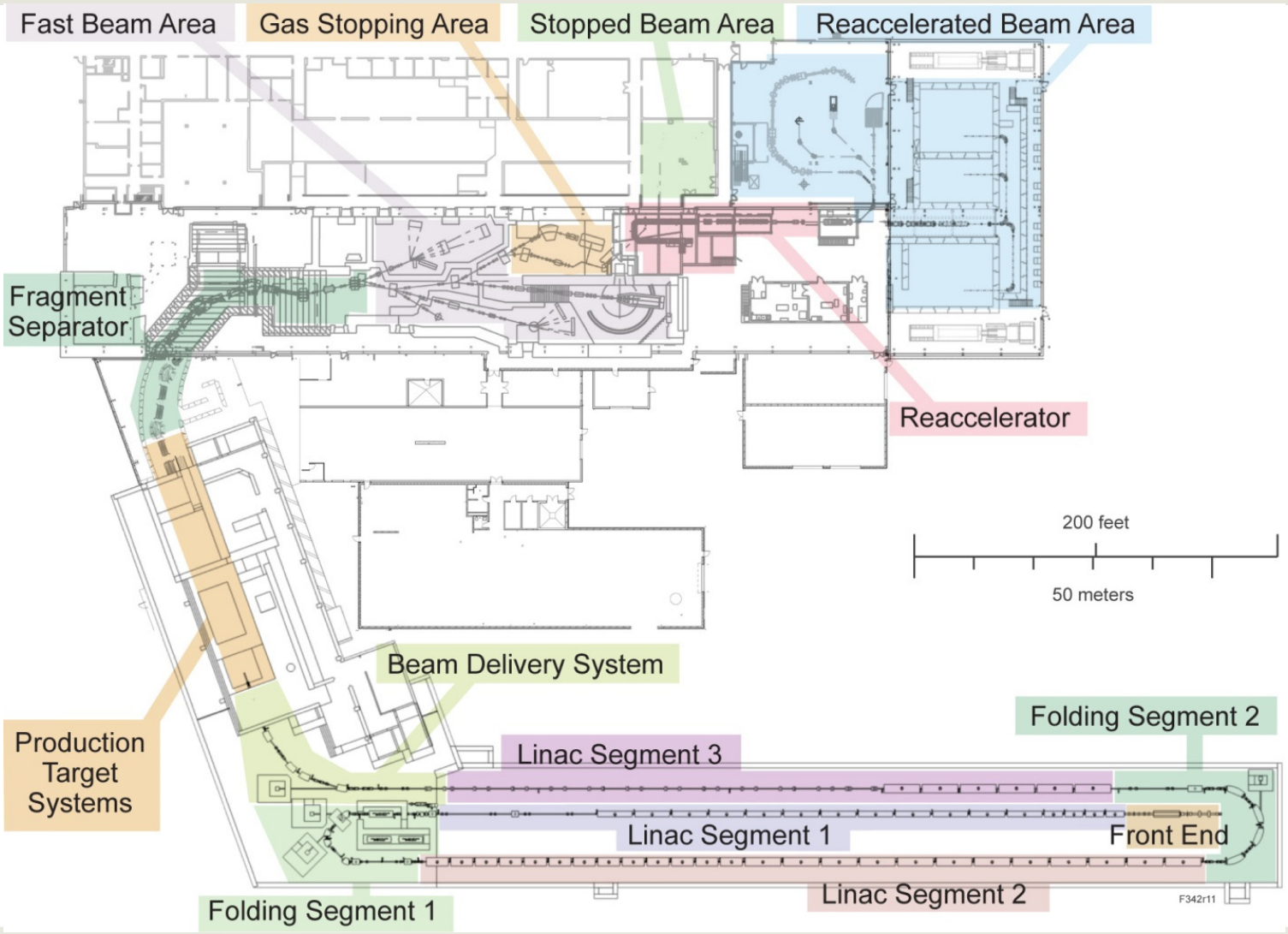


FRIB Project Timeline
$730.0M ($635.5M DOE + $94.5 MSU)

- Dec. 2008: DOE selected MSU to establish FRIB
- June 2009: DOE and MSU signed corresponding Cooperative Agreement
- Sept. 2010: CD-1 approved (Alternative Selection and Cost Range)
- Aug. 2013: CD-2/3A granted (Performance Baseline and Start of Civil Construction)
- Aug. 2014: CD-3B approved (Start of Technical Construction)
- Sept. 2016: Existing Artemis ECR ion source recommissioned
- Sept. 2017: LEBT commissioned with beam
- Oct. 2017: RFQ accelerated beam
- Feb. 2018: Front-End commissioning completed

- July 2018: Beam commissioning of first three cryomodules
- …
- Jan. 2021: Early Project Completion Goal
- June 2022: CD-4 approval (accomplish Key Performance Parameters)

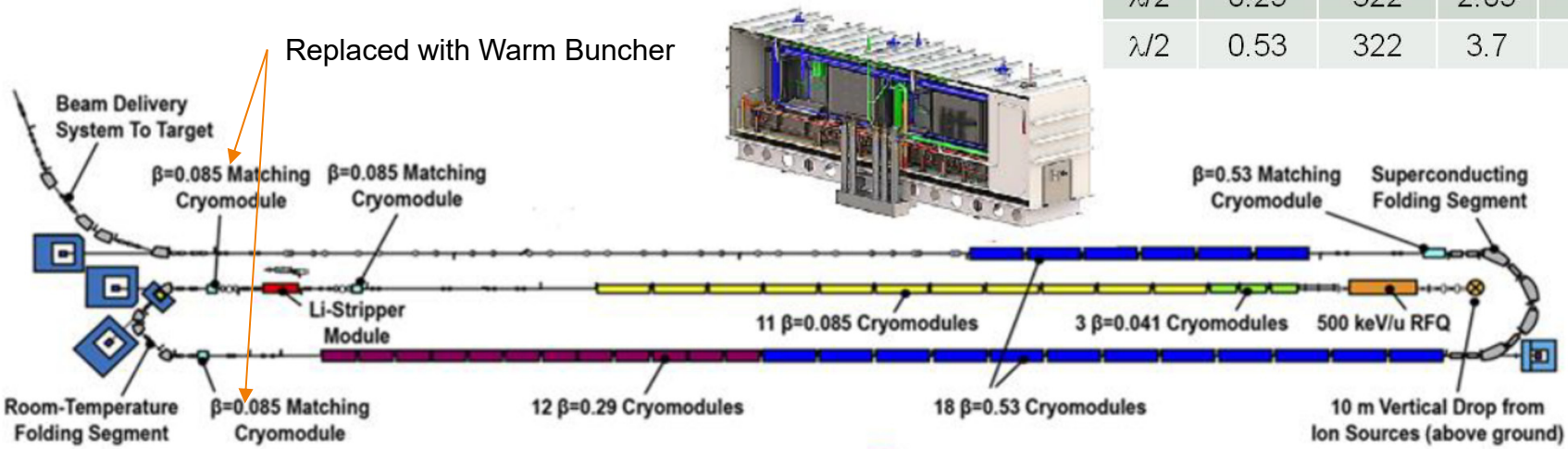
FRIB Technical Components

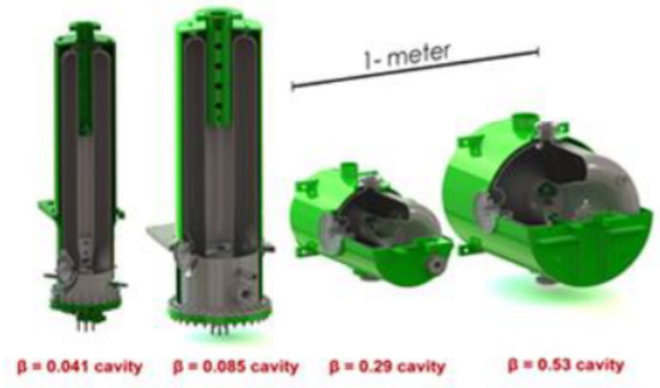


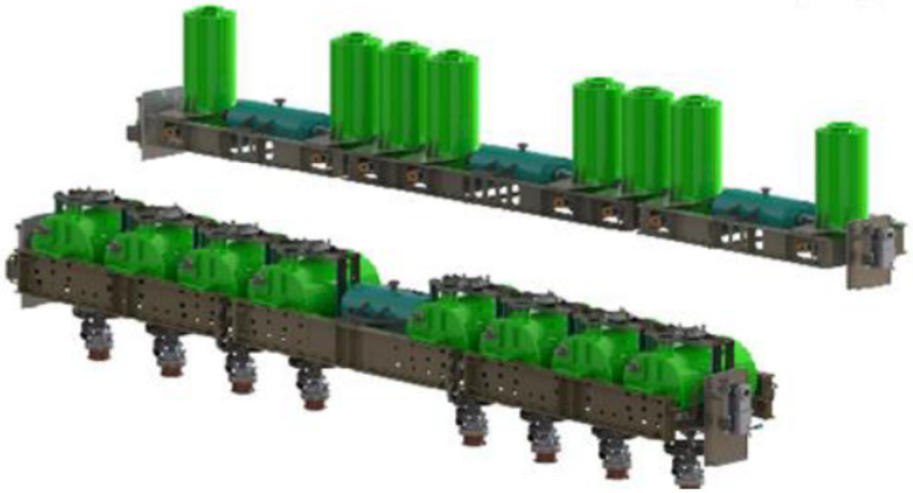
FRIB Superconducting Driver Linac Overview

- A total of 46+3 cryomodules needed
  - 25 cryomodules assembled
  - production rate of one per month

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



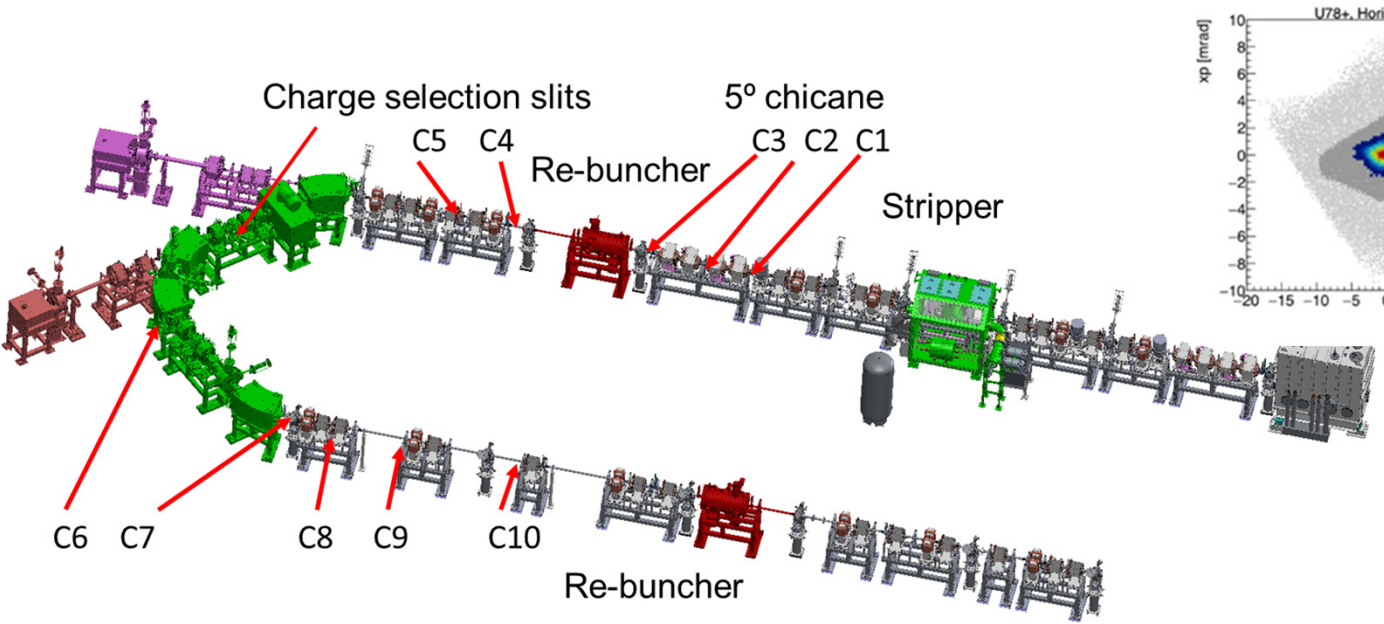


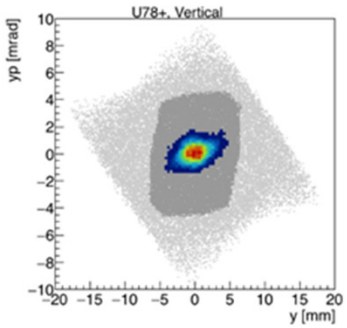


Contaminant Beam Collimation after Stripper

T. Maruta
WG-B Wed. 11:00

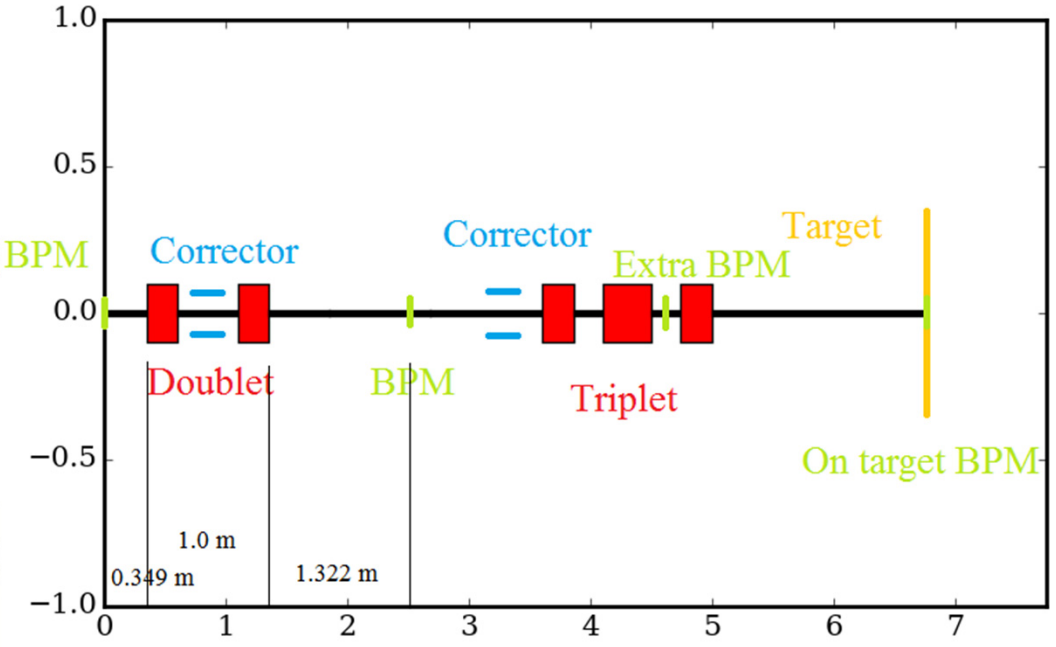
- FRIB will provide variety of ion beams for users
- There may be contaminant ions (similar q/A to main beam, e.g. $^{14}N^{2+}$ for $^{238}U^{34+}$) from ECRIS, but will have different trajectories after charge stripper
  - Contaminant beams may have significant power
- A series of collimators have been implemented in the warm area after stripper to limit acceptance and remove those contaminant ions, as well as halo beam developed by charge-exchange reaction





Wider Adjustment of Beam Position on Target

- Beam-on-target requirements
  - 90% of beam should be within 1 mm diameter spot
  - Beam centroid divergence must be much less than 1 mrad
  - …
- Additional beam-on-target requirement was requested by target group
  - Beam spot on target should be adjustable within +/- 3mm range to compensate for possible systematic displacements of the target
- Final focusing area before target
  - A doublet + a triplet
  - Two pair of steerers
  - 2 + 1 BPMs
- Elements in high radiation area

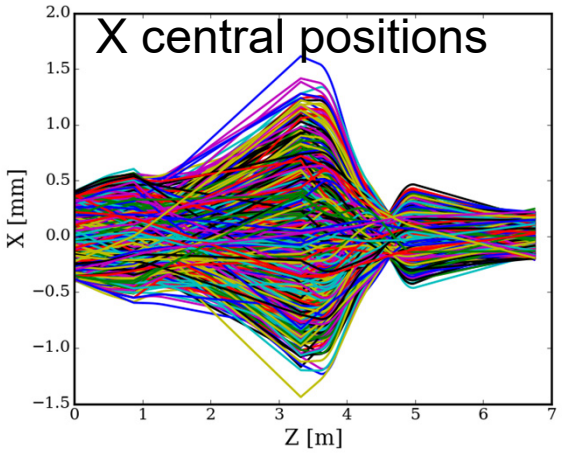


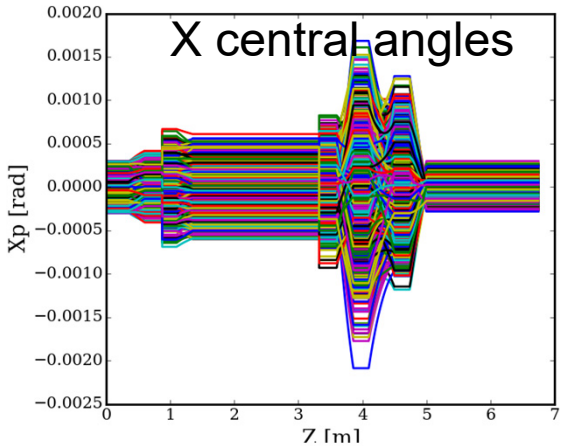
Assumed Imperfection in Simulation Study

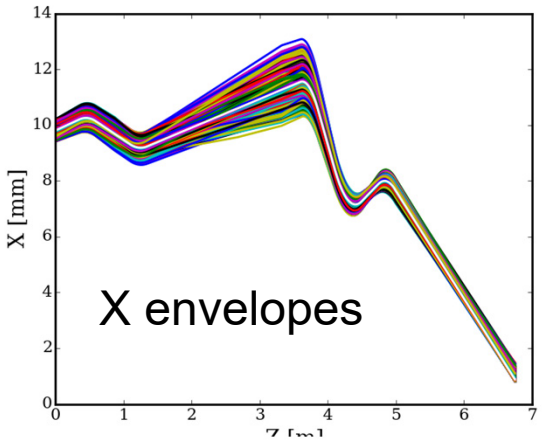
- Initial beam position (X,Y) shift: 0.4 mm
- Initial beam angle (Xp, Yp) shift: +/- 0.3 mrad
- Initial beam mismatch factor up to: 0.2
- Quadrupoles uncorrelated shift: +/- 0.4 mm
- Quadrupoles correlated shift: +/- 1.0 mm
- Quadrupoles rolling: +/- 8.0 mrad
- BPM misalignment: +/- 0.2 mm
- Quadrupole strength error: 5%
- All assumed uniform distribution

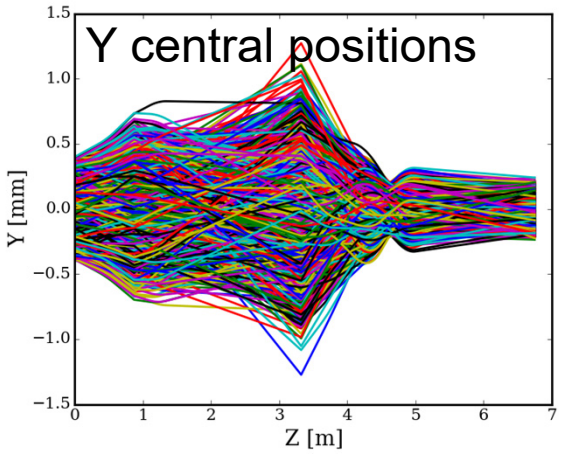
Simulation Study in Final Focusing Area

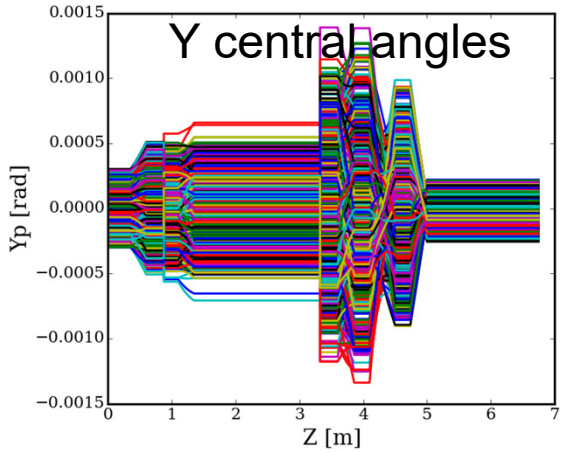
- Results of 10,000 seeds

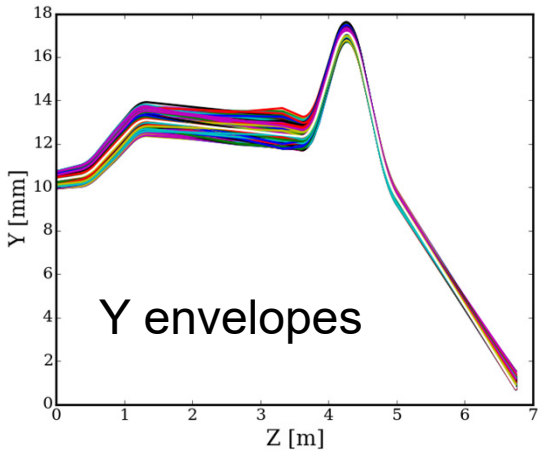












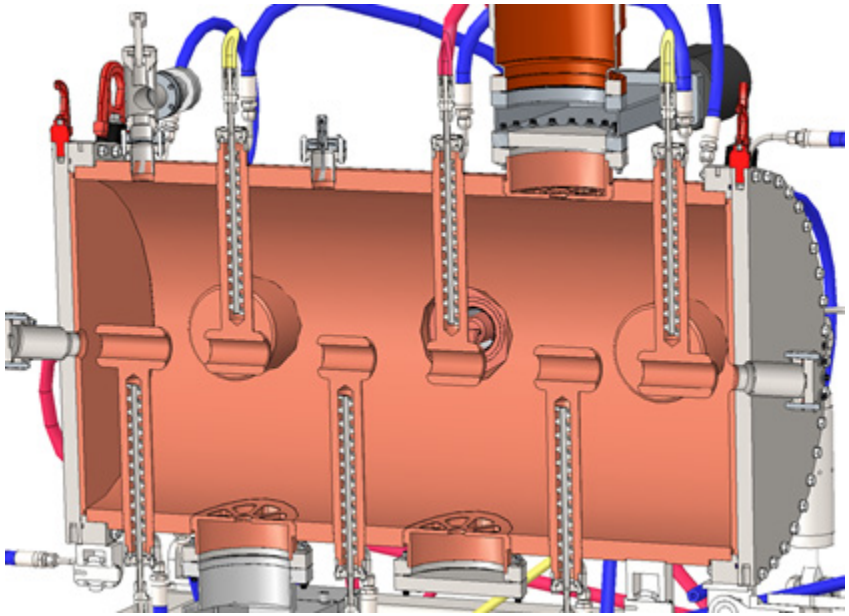
Conclusion of Final Focusing Area Study

- BPM resolution is the main factor to influence the bean center on target, needs <0.1 mm
- Quadrupole rolling error of < 2mrad and quadrupole strength error of <0.5% will be acceptable
- Initial beam mismatch factor should be less than 0.1
- Quadrupole shifts, yaws and tilts have no big influence since they are correctable, given that steerers have maximum capability, quadrupole shift should be < 0.8 mm
- Current configuration of steerers and BPMs is able to steer beam 3 mm horizontally or vertically with maximum beam angle under 0.24 mrad

Room Temperature Buncher Implemented

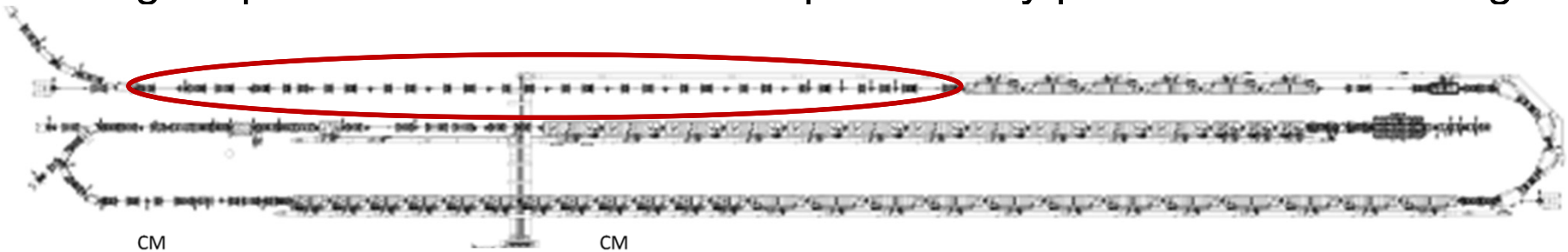
- Due to the high probability beam loss on the rebuncher after stripper, the cryomodule of 4 superconducting resonators replaced by a 7-gap room temperature IH structure
- Transit time factor is large than 0.7 for various beams

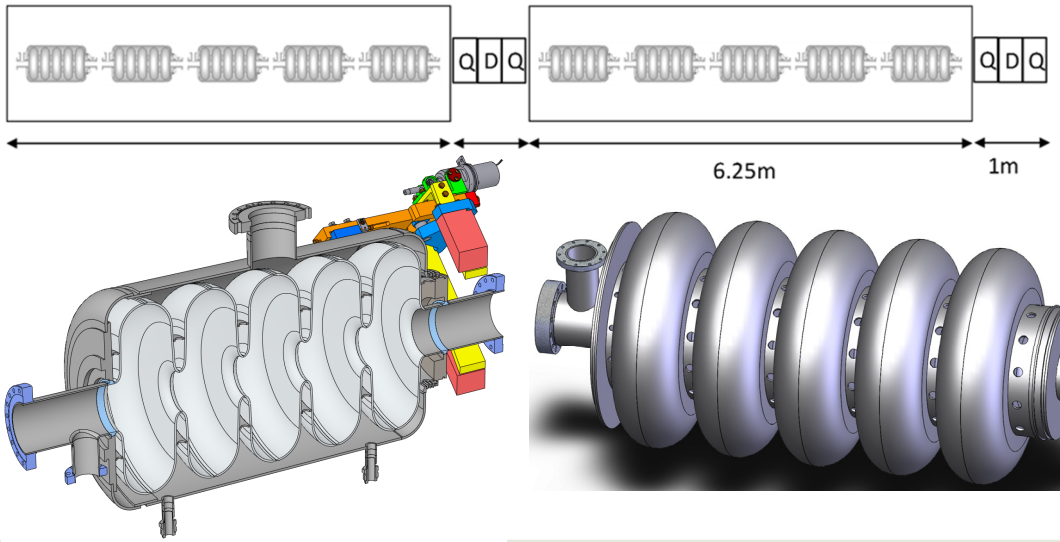
Parameter	Value
Frequency	161.0 MHz
Beta geometrical	0.185
Tuning range	± 650 kHz
Aperture	36mm
Maximum voltage	1.0 MV
Peak field at 1 MV	0.6 Kilpatrick
Resonator length	1.2 m
Energy range	13 – 22 MeV/u

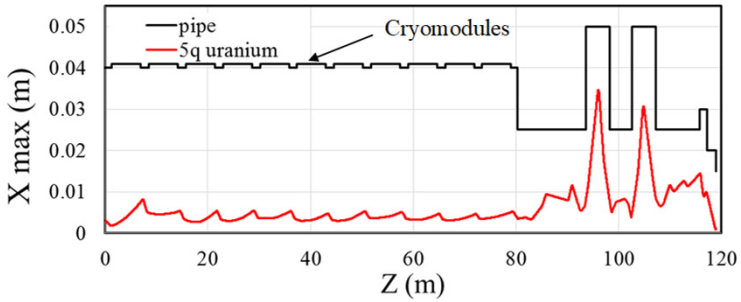


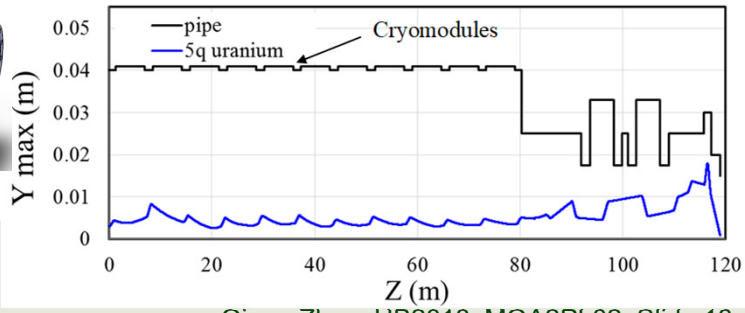
Study of FRIB Energy Upgrade

- Boost uranium beam from 200 MeV/u to 400 MeV/u driven by users
- 80 m space reserved fitting in 55 cavities in 11 cryomodules
  - A larger apuerture 5-cell 644 MHz elliptical cavity provides 12 MV voltage



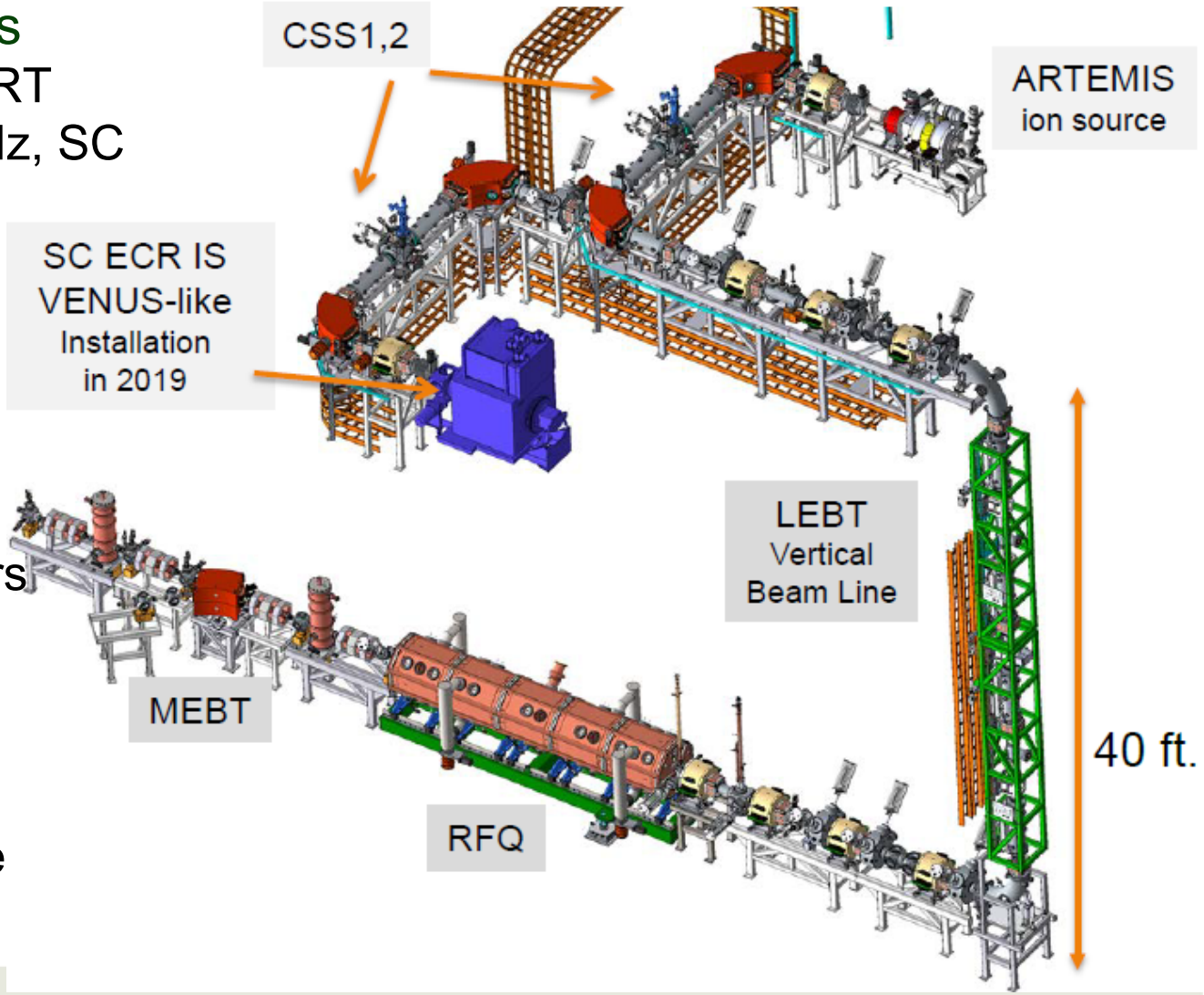






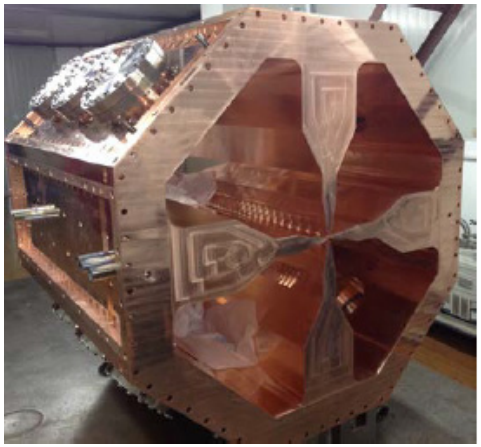
Front-End Layout and Its Major Systems

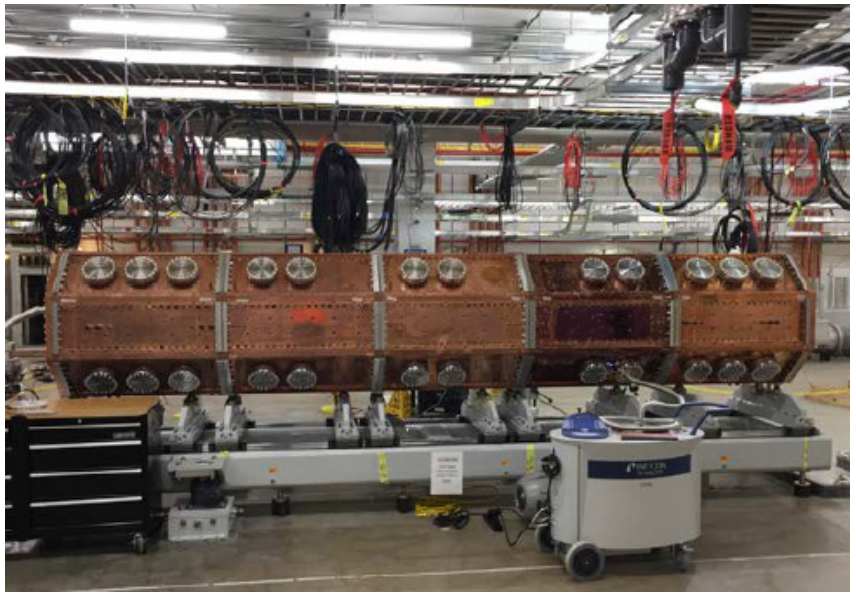
- Two ECR ion sources
  - ARTEMIS –14 GHz, RT
  - VENUS type – 28 GHz, SC
- LEBT (12keV/u)
  - Electrostatic quads
  - Solenoids
  - Chopper
  - MHB
  - Emittance meters
  - Wire scanners/viewers
  - Faraday cups
- RFQ (next slide)
- MEBT
  - Triplets, 45deg-dipole
  - Rebunchers
  - BPMs



Radio Frequency Quadrupole Linac

Parameter	Value
Frequency (MHz)	80.5
Injection/extraction energy (keV/u)	12 / 500
Q/A	1/3 – 1/7
Transmission efficiency (typ.)	> 80%
CW RF Power (kW), Uranium	100
Length (m)	5

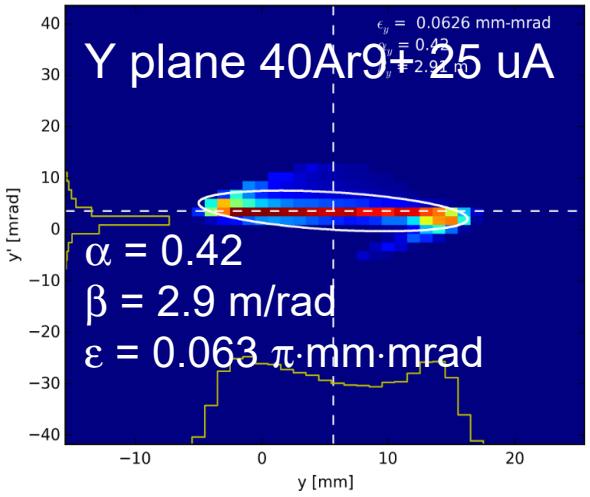


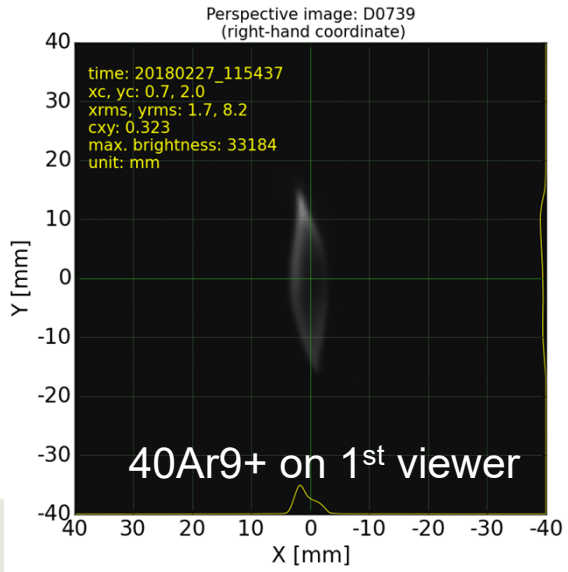


- 4-vane, 5-section, ramped voltage
- Construction completed in 6/2016
- Installed tunnel in 11/2016
- Integration test completed in 8/2017
- First beam acceleration in 9/2017

Beam Measurements in LEBT – Samples

- Allison Scanner

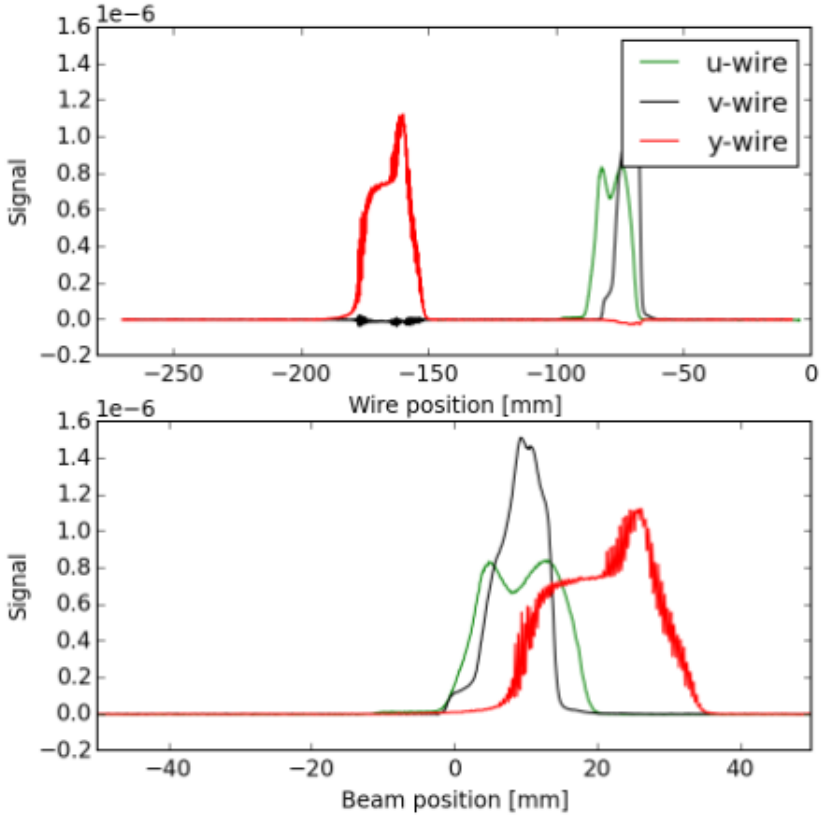




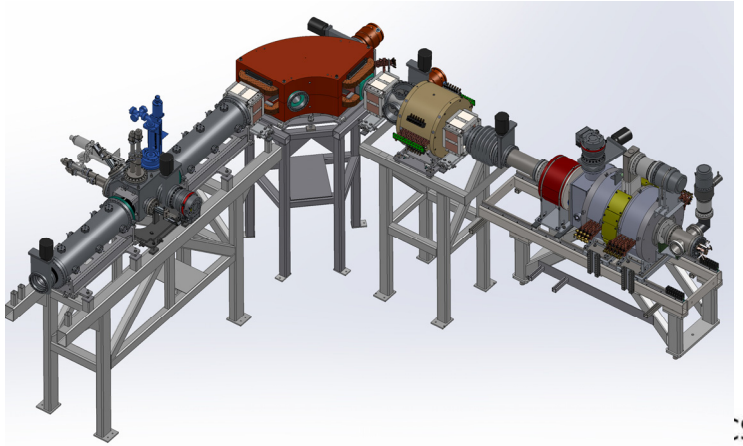
- View plate

3-wire scanner

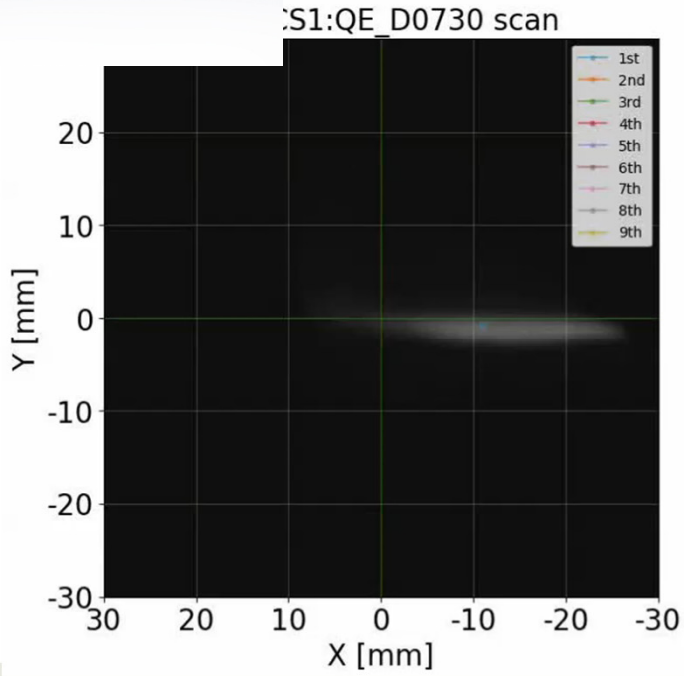
Horizontal, vertical, 45deg diagonal

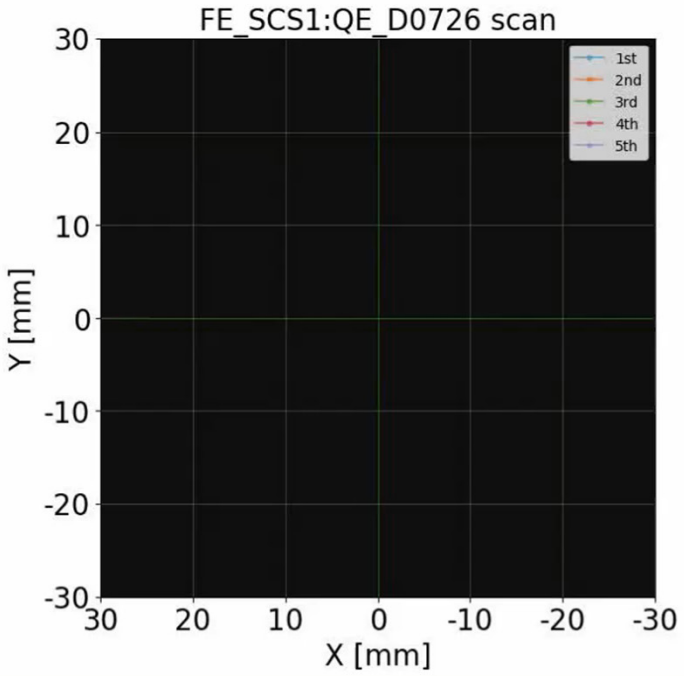


Development of Application Software



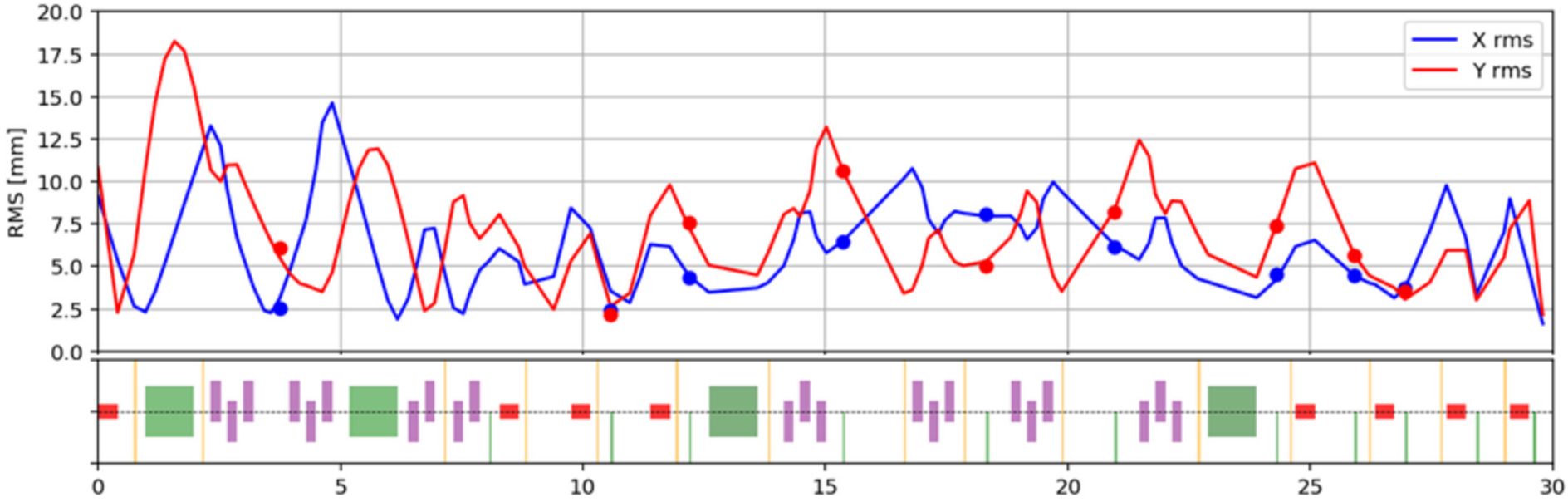
- The beam center is steered with upstream steerers until insensitive to the variation of quadrupole strength





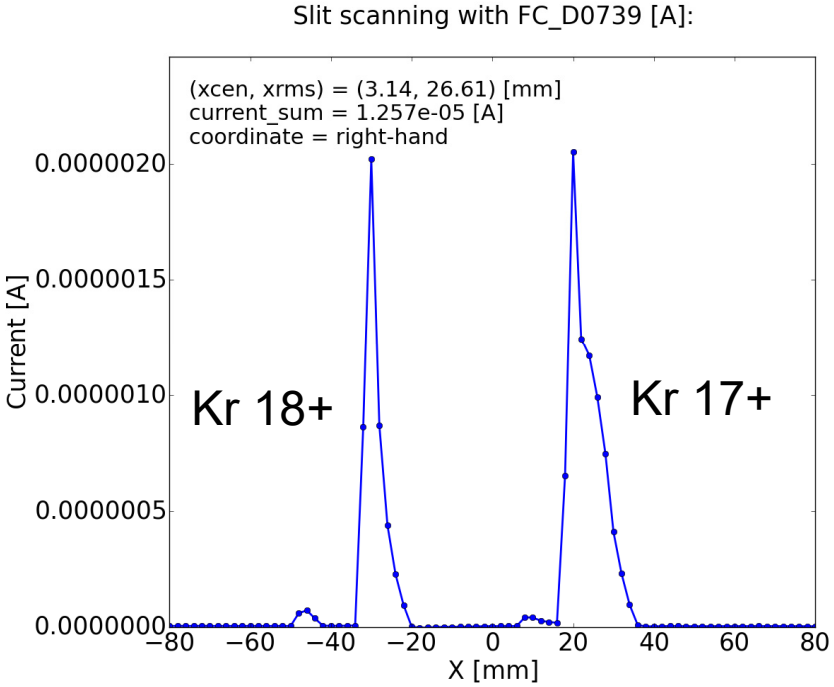
Beam Envelopes Reconstructed from Profile Measurements Along LEBT

- $^{40}Ar^{9+}$, 65 euA
- Beam parameters obtained by fitting to match measured rms beam sizes from all profile monitors
- Simulations agree with measurements



Kr^{17+} and Kr^{18+} Simultaneously Transported in LEBT and Accelerated in RFQ

- Both $^{86}Kr^{17+}$ (33uA) and $^{86}Kr^{18+}$ (27uA) transported to the entrance of the RFQ
  - Set electrostatic elements for 17+, scale magnetic elements for 17.5+
  - ~100% transmission achieved, beam profiles measured



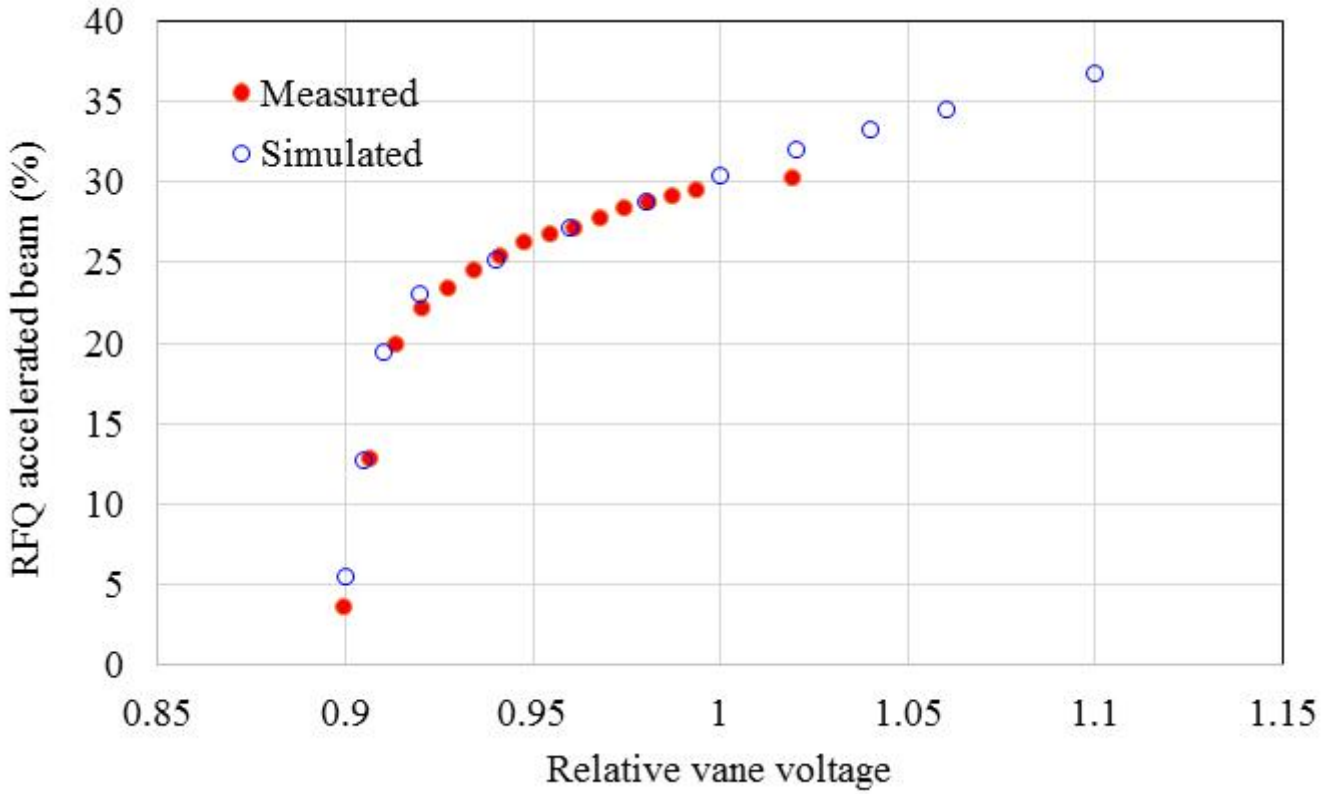
17+ & 18+ selected at slit

Optimized for 17.5+ with 100x attenuation

86Kr	RFQ FC0998 (uA)	MEBT FC1102 (uA)	Efficiency (%)
17+	0.2	0.056	28
18+	0.16	0.07	44
17+&18+	0.36	0.122	34

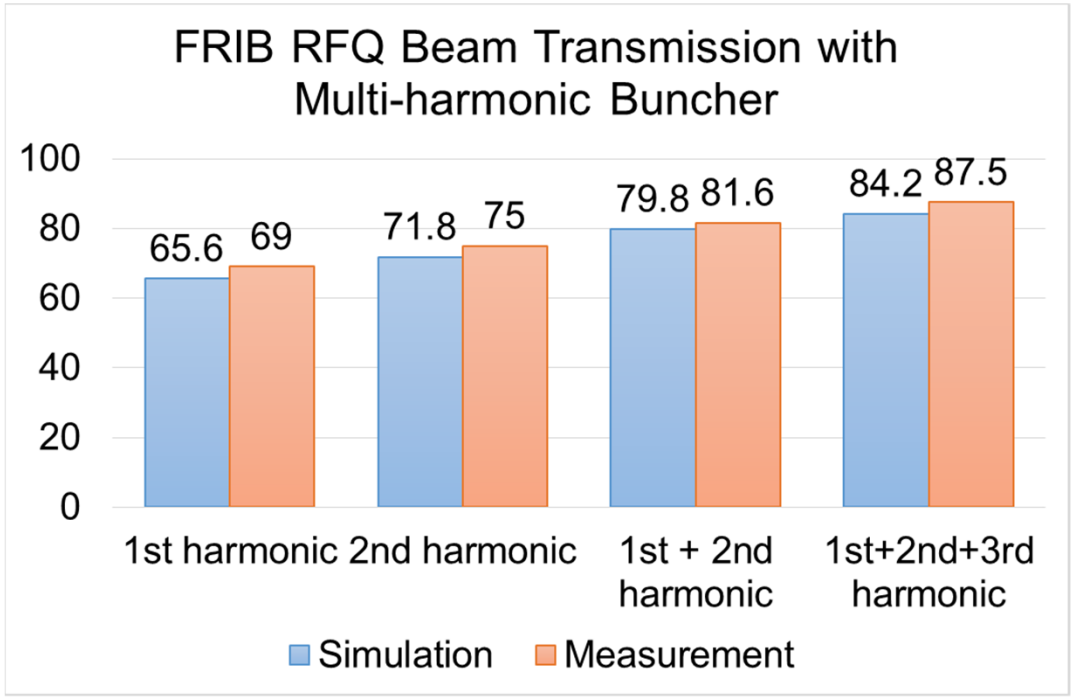
DC Beam Transmission through RFQ

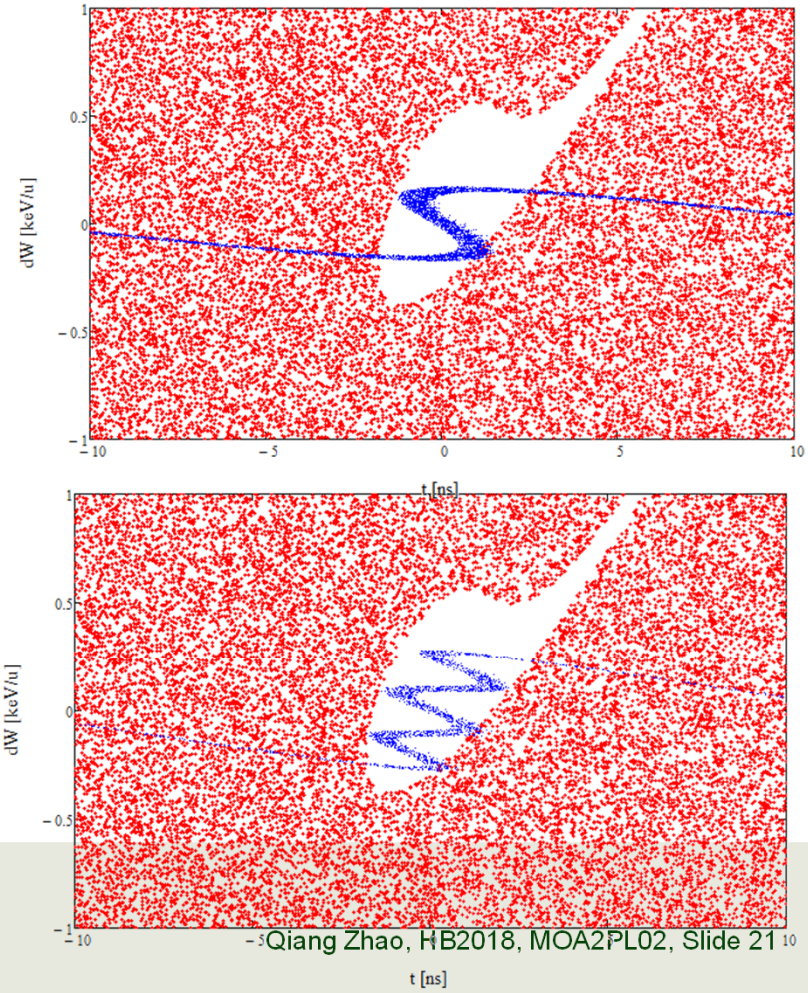
- DC beam (MHB off) Transmission (accelerated) through RFQ as function of vane voltage
  - Measurement agrees with simulation



Beam Transmission in RFQ Increased with Multi-Harmonic Buncher in LEBT

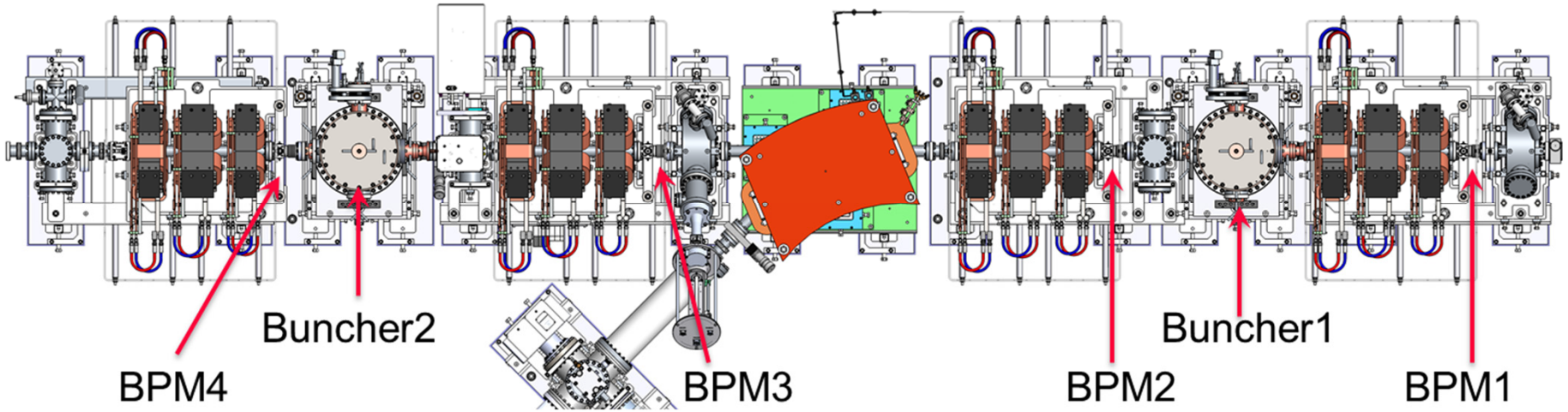
- Bunching phase is found for each harmonic at some power level
- Combined level of RF power in all 3 harmonics optimized by iteration after phase setting for all harmonics





MEBT Beam Energy Measurement using BPMs

- Beam arrival time in first 3 BPM were measured, respectively, with respect to the rf reference clock
  - Signal delays for each BPM were calibrated
- Set Buncher1 for maximum acceleration phase
  - Measured beam energy of 0.5198 MeV/u
- Set Buncher1 for maximum deceleration phase
  - Measured beam energy of 0.4921 MeV/u
- Obtained Buncher1 voltage of 61.6 kV, consistent with the measurements downstream of the bending magnet



Front-End Commissioning Completed

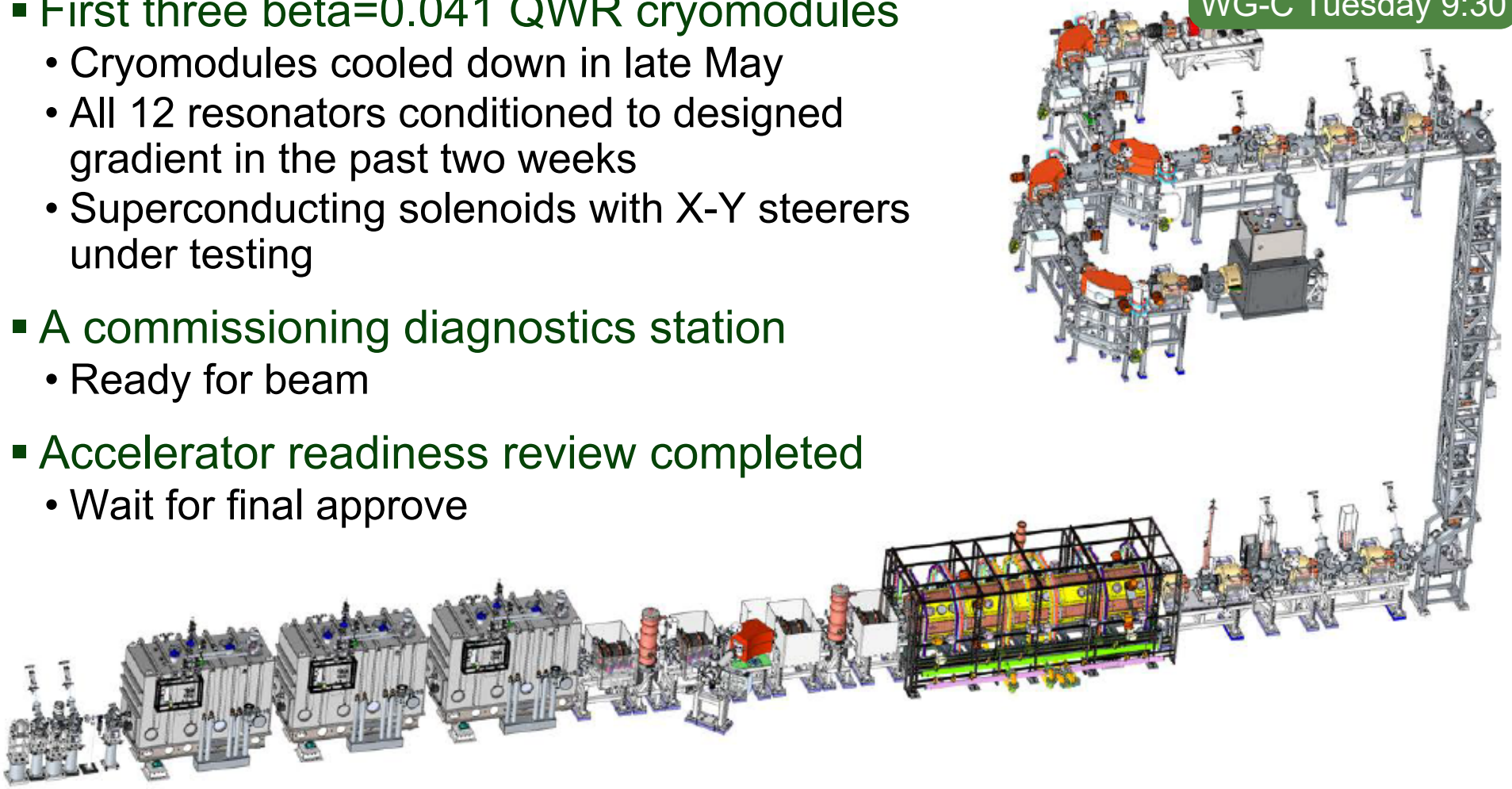
- Front-End has been in operation for about five months, Major hardware systems are running reliably and stably
- Accelerator Physics group performs beam test studies to improve understanding of beam parameters, beam optics and transport, and to develop and test high level software and algorithms
- Front-End is used to commission diagnostics, instrumentation, Machine Protection System and Run Permit System
- Front-End operation also provides opportunity to test and improve operational procedures

First Three Cryomodules and the Commissioning Diagnostics Station Installed

Commissioning of the First 3 Cryomodules

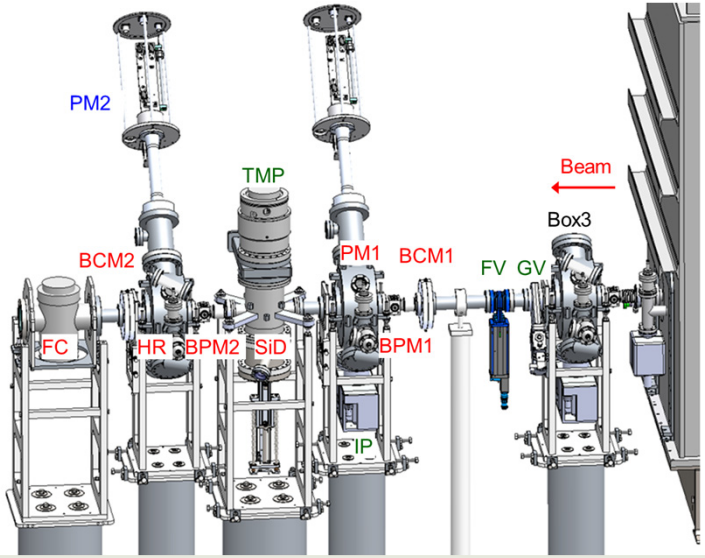
J. Popielarski
WG-C Tuesday 9:30

- First three beta=0.041 QWR cryomodules
  - Cryomodules cooled down in late May
  - All 12 resonators conditioned to designed gradient in the past two weeks
  - Superconducting solenoids with X-Y steerers under testing
- A commissioning diagnostics station
  - Ready for beam
- Accelerator readiness review completed
  - Wait for final approve

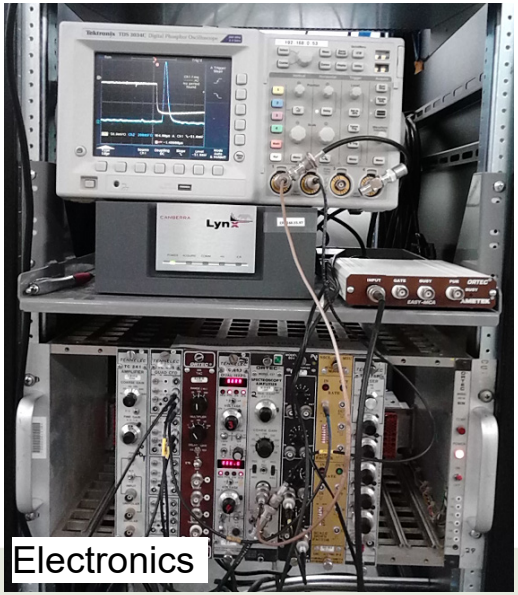


Beam Measurements with D-station

- Beam position and bunch phase
- Transverse profile, rms emittance reconstruction
- Absolute energy, energy spread, time spread, contaminant ions and their relative intensity
- Beam halo signal
- Absolute beam current (pulsed) and differential signal
- Bunch longitudinal profile, longitudinal rms emittance reconstruction



Installed in beamline


Electronics

Commissioning Plans for the First 3 Cryomodules

- Operation of MPS and RPS is not required in the beginning: beam power is < 2 Watts
  - Ar or Kr beam power is controlled by attenuators in LEBT
- Transport 0.5 MeV/u beam to D-station and achieve ≥90% beam transmission
- Perform phase and amplitude scan of the MEBT buncher and SC cavities sequentially and set phases and amplitudes to the design values
  - Measurements with silicon detector (SiD)
  - Adjust solenoid fields and, if necessary, dipole fields to transport >90% beam
- Test and activate MPS and RPS with beam
- Perform phase and amplitude scan of the second MEBT buncher and each subsequent super conducting (SC) cavities with pulsed ≥5 eμA beam
  - Measurements by BPMs
    - » Cavities' phase scan will be performed with scripting programming
    - » Distances between the BPMs from actual alignment data
    - » Absolute energy after each SC cavity will be measured
  - Virtual accelerator model is available in the controls network

Summary

- Accelerator physics studies to address various emerged issues or improve performance
  - Developed sets of collimators to intercept possible contaminant beams and beam halo
  - Wider beam position tuning on target twill be provided
  - Explored beam tuning sensitivity in the final focusing area
  - Room temperature rebunchers replaced superconducting ones in the area critical to beam losses
  - Designed 400 MeV/u energy upgrade with elliptical cavities
- FRIB Front End has been successfully commissioned with both $^{40}Ar^{9+}$ and $^{86}Kr^{17+}$ beams
  - Beam properties were measured, consistent with simulations
  - Diagnostics and MPS/RPS verified
- First three cryomodule of the linac is ready for beam commissioning
- FRIB project is on track

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