Accelerator Physics Advances at FRIB

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Outline

- Contaminant ion beams from ECRIS
- Linac Folding Segment 1 (FS1)
  - Charge selection after stripping
  - Collimation of contaminant beams
  - Room temperature buncher
  - Acceptance of FS1 and Linac Segment 2
- Linac commissioning
  - Results of the Front End commissioning
  - Preparation for commissioning of first 3 cryomodules
- FRIB energy upgrade to 400 MeV/u
  - Development of 644 MHz elliptical cavities

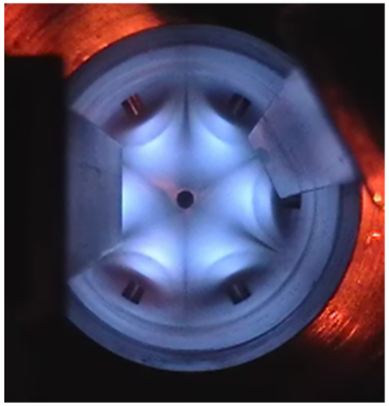
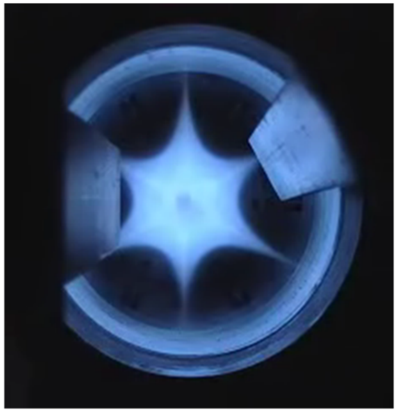
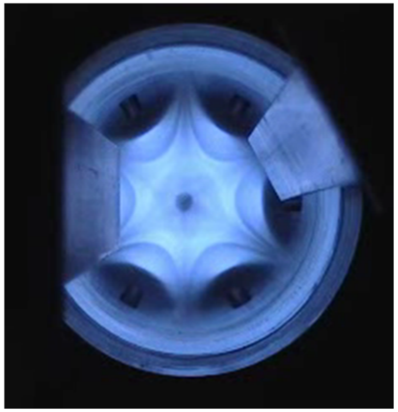
Variety of Ion Beams Extracted from ECR Ion Source

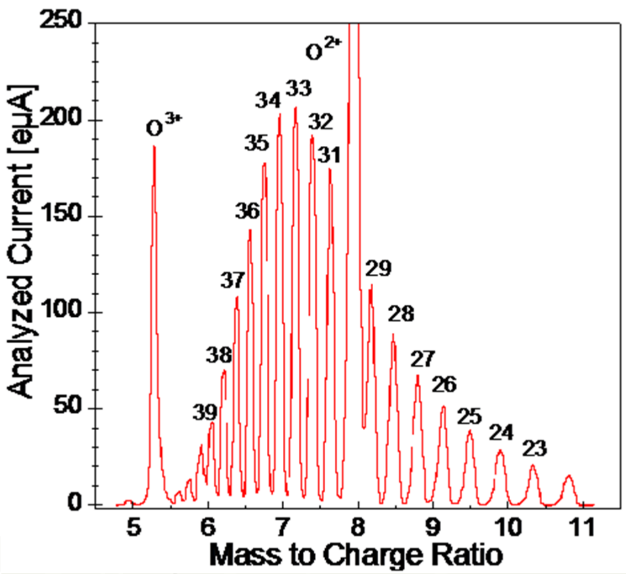
FRIB Ion Beams

Ion	Z	A
O	8	16
O	8	18
Ne	10	20
Ne	10	22
Ar	18	36
Ar	18	40
Ca	20	40
Ca	20	48
Ni	28	58
Ni	28	64
Se	34	82
Kr	36	78
Kr	36	86
Zr	40	96
Mo	42	92
Cd	48	106
Sn	50	112
Sn	50	124
Xe	54	124
Xe	54	136
Sm	62	144
Dy	66	156
Er	68	162
Yb	70	168
Yb	70	176
Os	76	184
Pt	78	190
Pt	78	198
Hg	80	196
Hg	80	204
Pb	82	204
Pb	82	208
Bi	83	209
U	92	238

Ionization is in plasma chamber

Extracted beam include residual gas ions and ions of residues

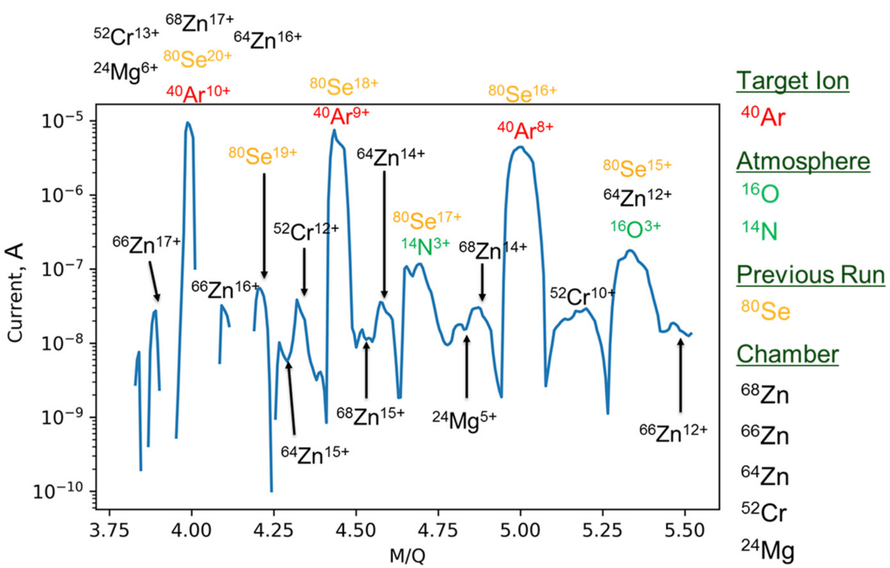


Beam of interest	Contaminant	Δ(A/q)
$^{238}U^{34+}$	$^{14}N^{2+}$	0
$^{238}U^{35+}$	$^{204}Hg^{30+}$	0
$^{78}Kr^{18+}$	$^{82}Se^{19+}$	0.02
$^{78}Kr^{19+}$	$^{82}Se^{20+}$	0.01
$^{86}Kr^{19+}$	$^{48}Ca^{10+}$	0.02
$^{82}Se^{17+}$	$^{58}Ni^{12+}$	0.01
$^{48}Ca^{10+}$	$^{82}Se^{17+}$	0.02

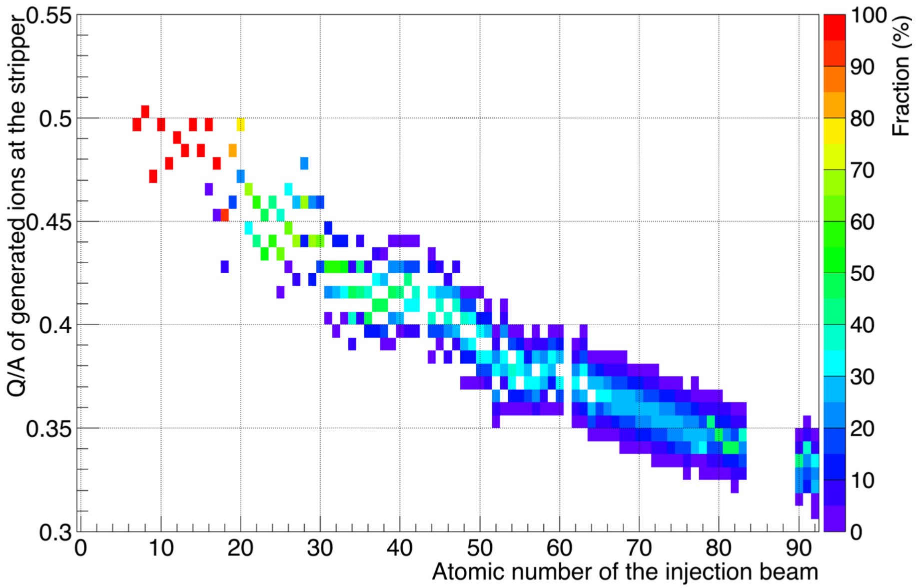
Modification of q/A after Stripper

- Obviously, q/A after the stripper strongly depends on atomic number
- Contaminant ions have trajectories different from main beam after the stripper
- Detailed study was performed for uranium case, Q/A= 0.328
  - Contaminants' Q/A from 0.35 to 0.5

Ion species extracted from ECRIS

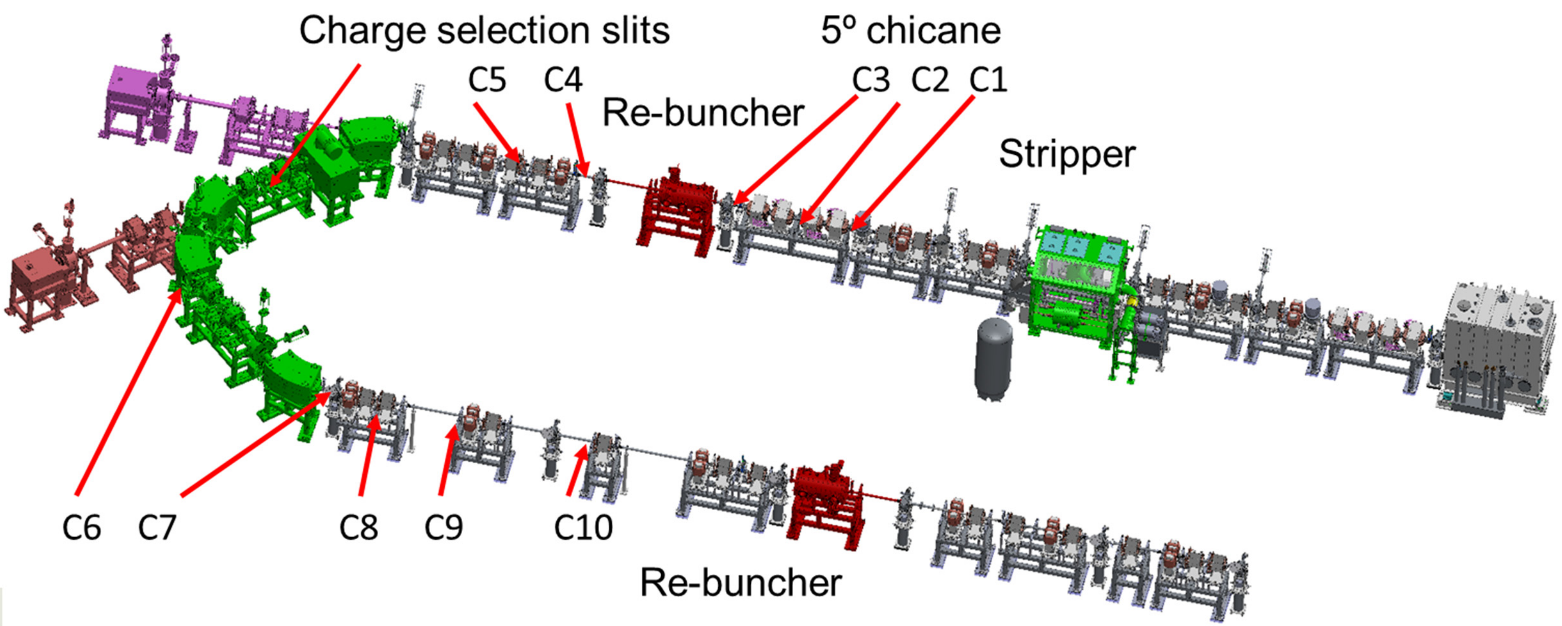


Q/A after the charge stripper for various ions



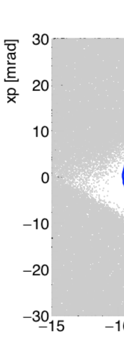
Layout of Folding Segment 1 with Collimators

- Beam energy is in the range from 16 MeV/u to 20 MeV/u
- Power on charge selection slits is below 7 kW for any ion beam
  - Thanks to multi-q acceleration for many ion species, $-0.03 \leq \Delta q/q \leq 0.035$
- Power on C1 is ≤1.7 kW, nitrogen contaminant in uranium beams
- Power on C2-C5 is ≤ 300 W; power on C6-C10 is ≤ 10 W;

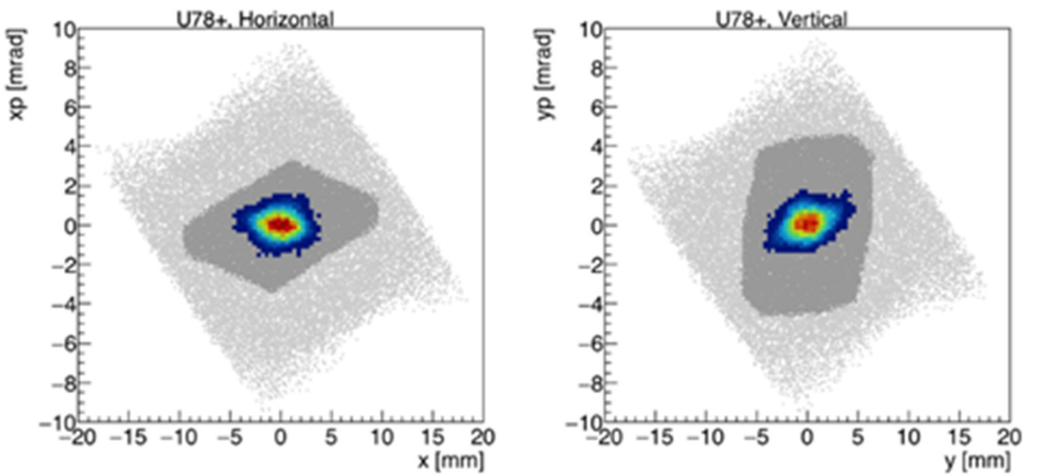


Beam Collimation and Acceptance

- RFQ acceptance vs LS1 acceptance
  - RFQ normalized 1.4 π mm × mrad
  - LS1 normalized 2.7 π mm × mrad
  - Beam emittance after the RFQ is always lower than the acceptance of LS1
  - Centering beam is essential



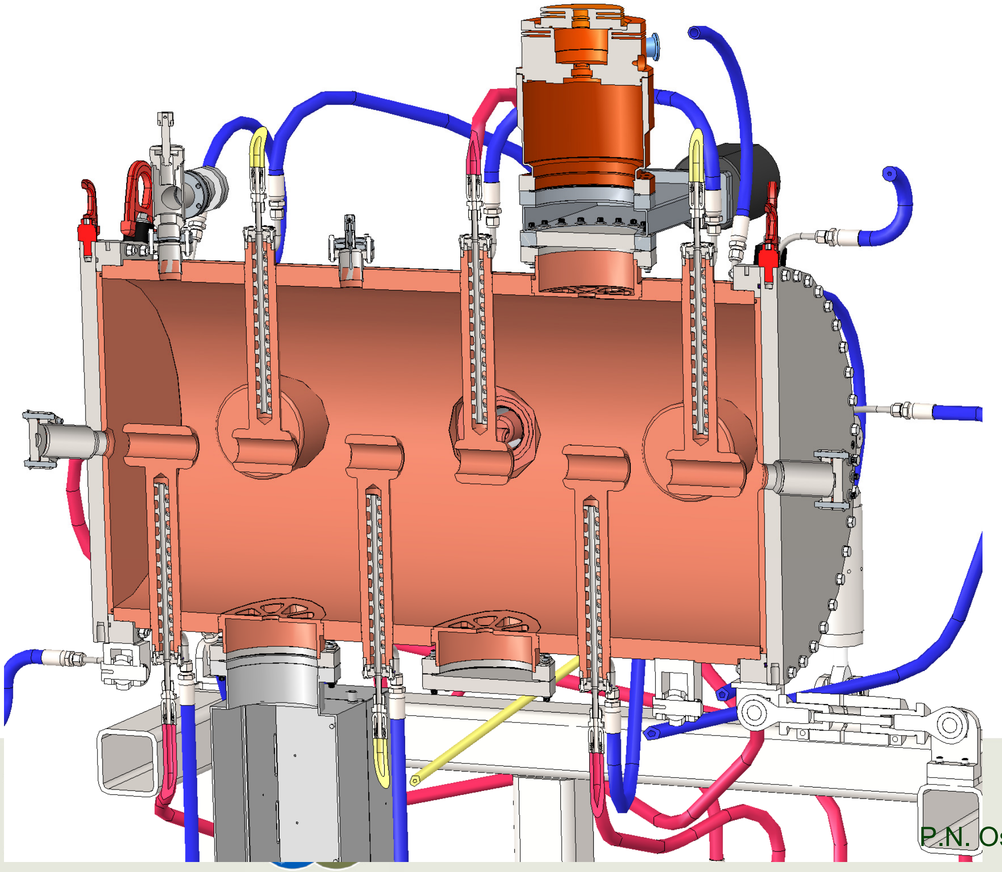
- LS2 acceptance vs FS1 acceptance
  - The collimators on FS1 filter a halo of uranium beam in the transverse phase space



Room Temperature Buncher

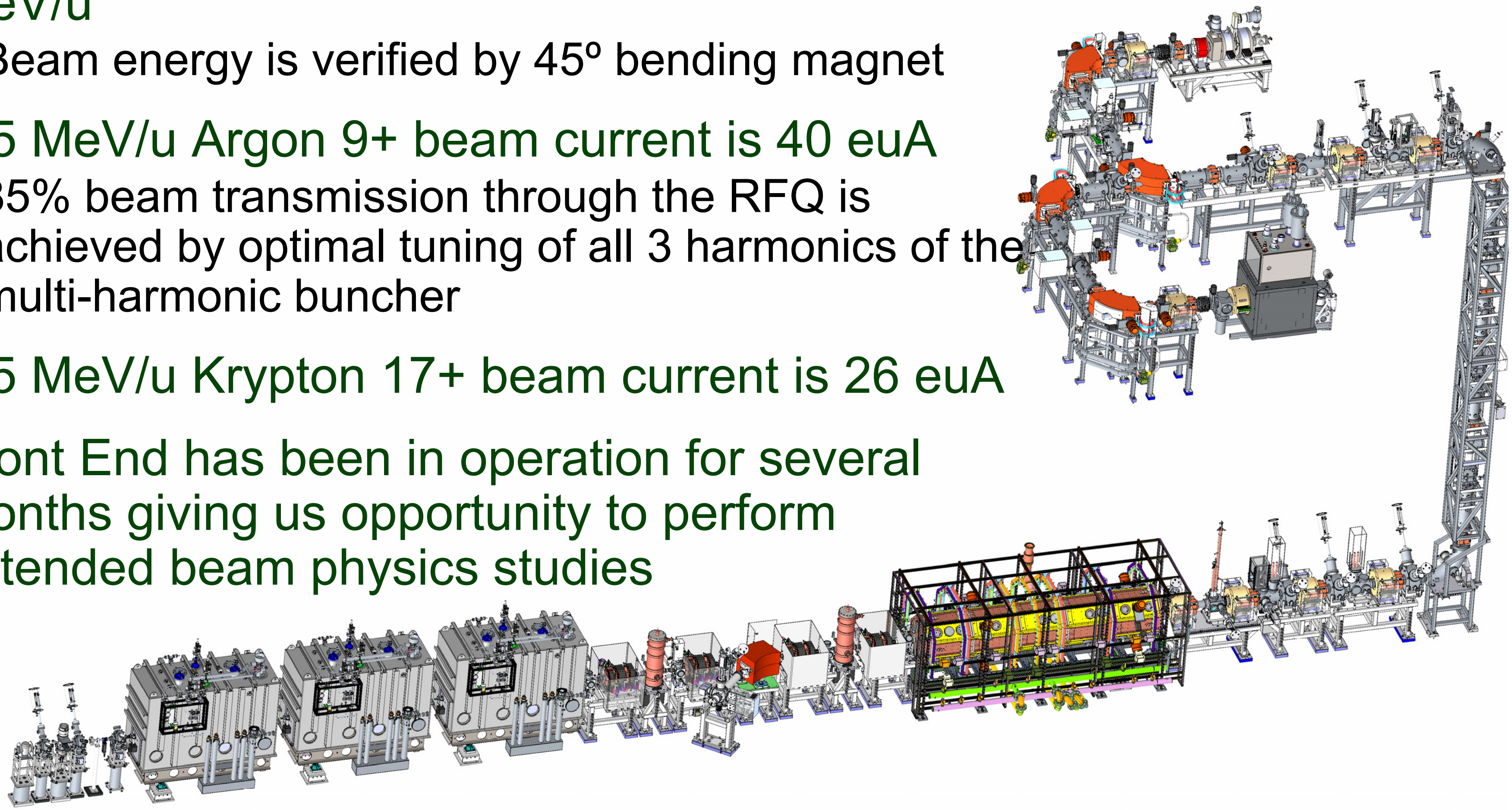
- Replaces 4-cavity cryomodule
- Performance is not critical to beam losses
- Contamination is not an issue unlike in SC cavities

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



Front End Commissioning Completed

- Argon and Krypton beam accelerated up to 0.5 MeV/u
  - Beam energy is verified by 45º bending magnet
- 0.5 MeV/u Argon 9+ beam current is 40 euA
  - 85% beam transmission through the RFQ is achieved by optimal tuning of all 3 harmonics of the multi-harmonic buncher
- 0.5 MeV/u Krypton 17+ beam current is 26 euA
- Front End has been in operation for several months giving us opportunity to perform extended beam physics studies

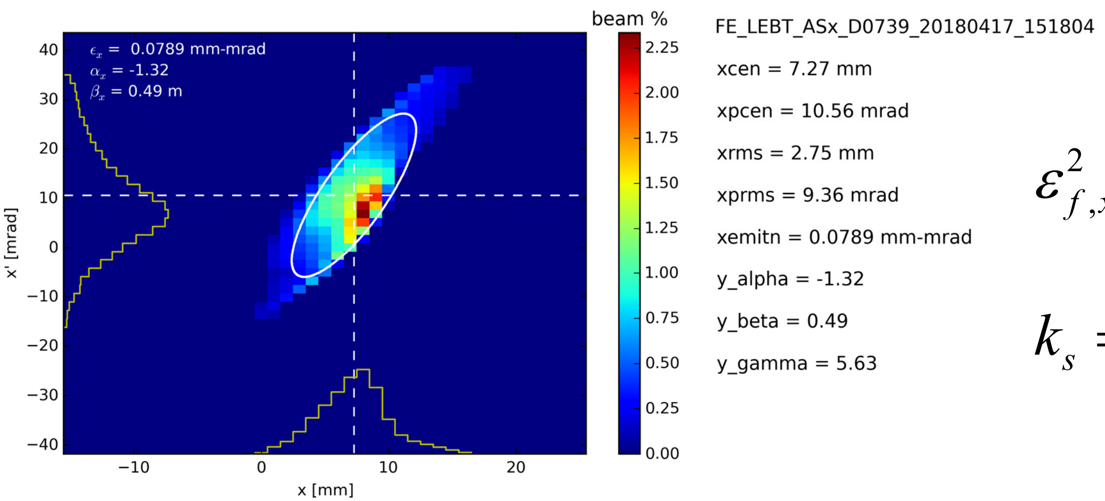


Beam Parameters at Allison Scanner Location

- Ar^{9+}, 20 ~ 25 eμA

	ε_x	α_x	β_x	ε_y	α_y	β_y	Coupling term available
Envelope	0.093	-1.44	0.460	0.078	0.851	1.20	Yes
EQ scan	0.099	-3.30	1.30	0.064	0.279	0.981	Yes
Allison scanner	0.079	-1.85	0.656	0.044	0.266	1.124	No

- Magnetized beam emittance, Allison scanner can not resolve coupling

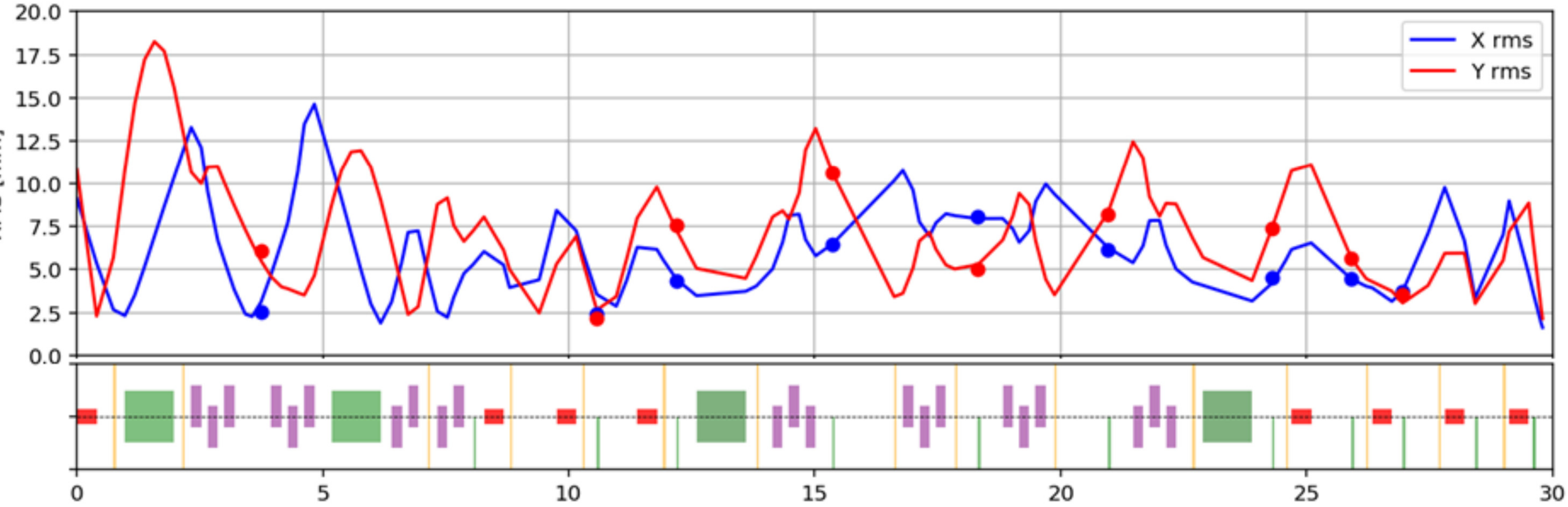


$$\varepsilon_{f,x}^2 = \varepsilon_{i,x}^2 + \frac{k_s^2}{4}\langle xx\rangle_i^2 + k_s\langle xx\rangle_i\langle xy'\rangle_i$$

$$k_s = \frac{qB}{mv}$$

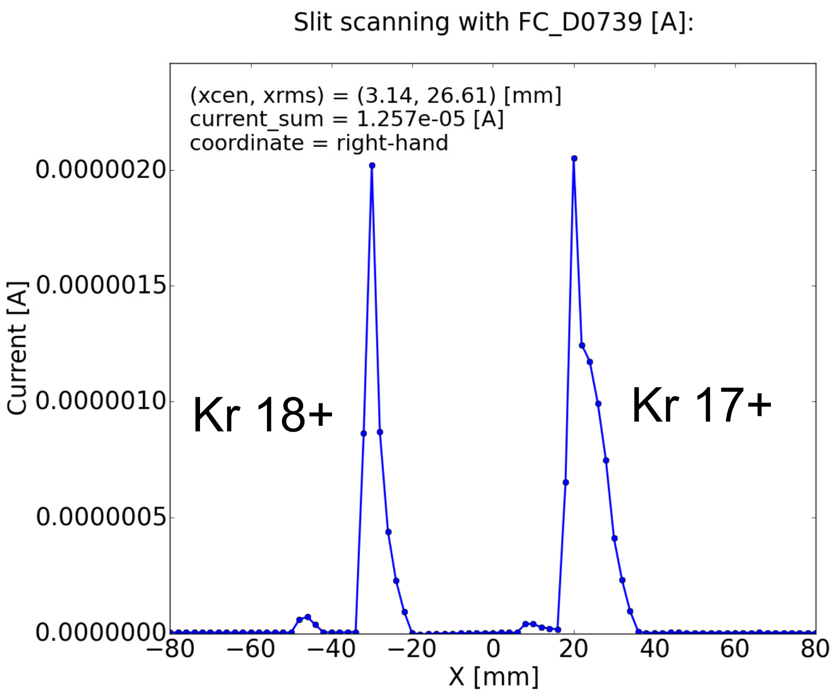
Beam Envelopes Reconstructed from Profile Measurements Along LEBT

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



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

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

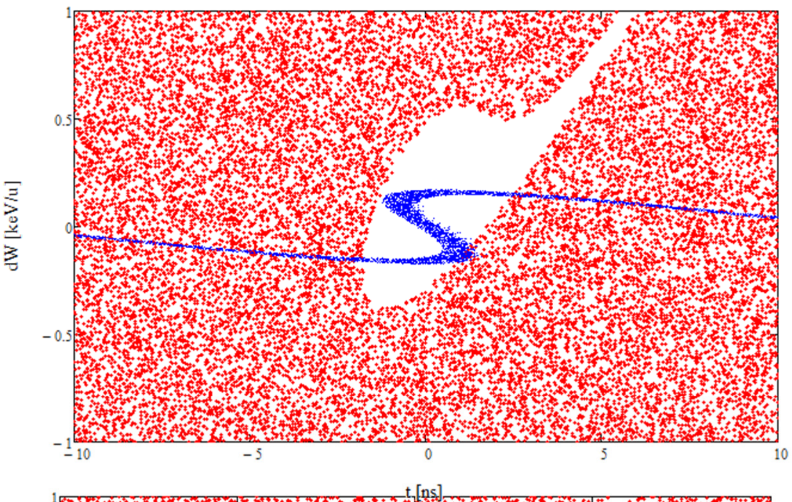


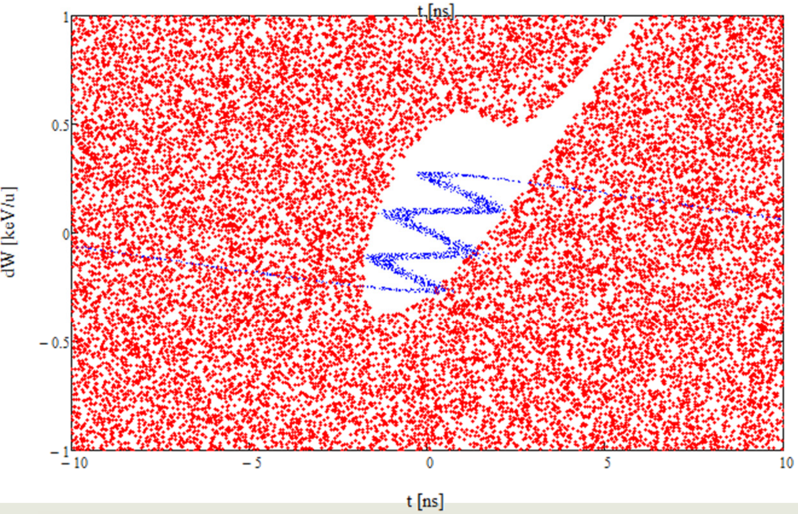
17+ & 18+ selected at slit

Optimized for 17.5+ with 100x attenuation

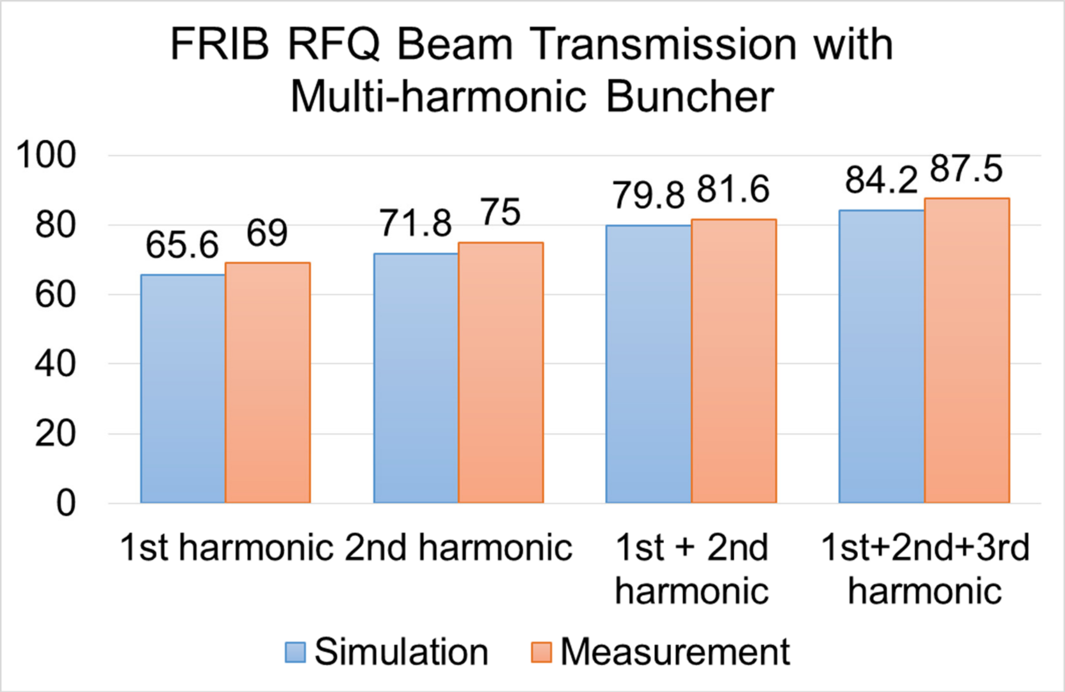
86Kr	RFQ FC0998 (uA)	MEBT FC1102 (uA)	Efficiency (%)
17+	0.2	0.056	28
18+	0.16	0.07	44
17+&18+	0.36	0.122	34

Transmission in RFQ Increased with Multi-Harmonic Buncher



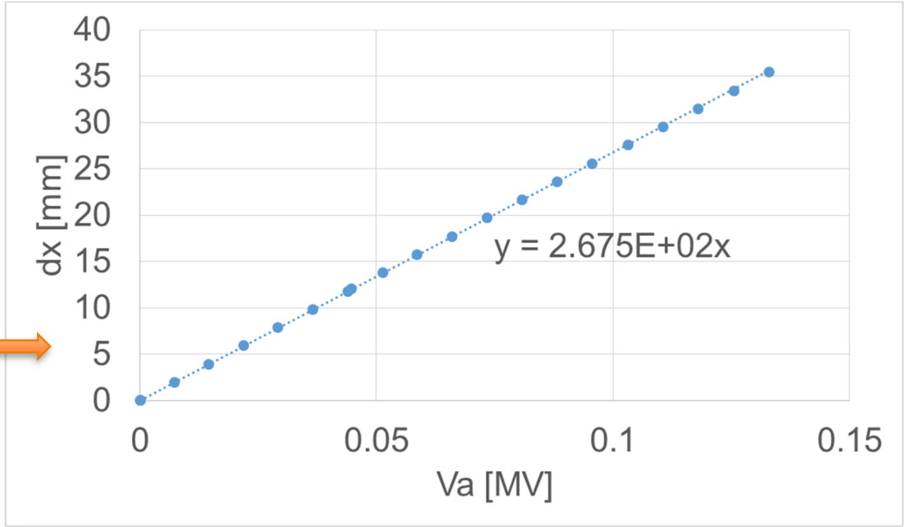


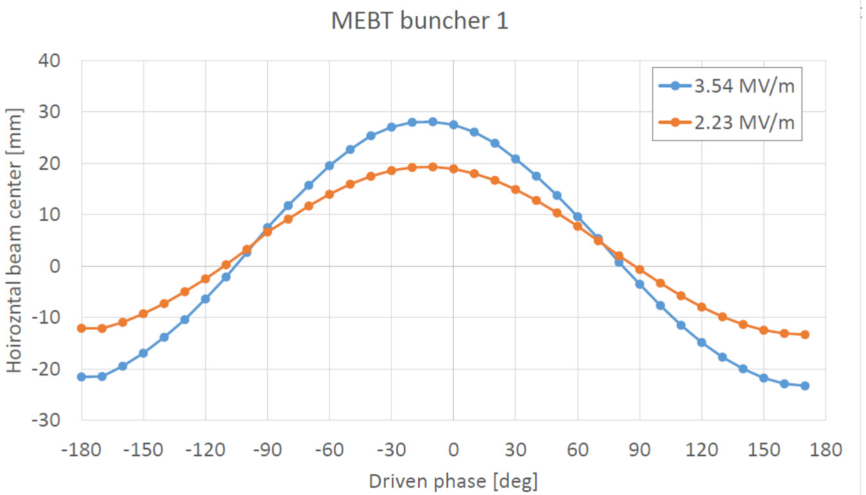
- Bunching phase is found for each harmonic at some power level
- Combined level of RF power in all 3 harmonics optimized by iteration after phase setting for all harmonics

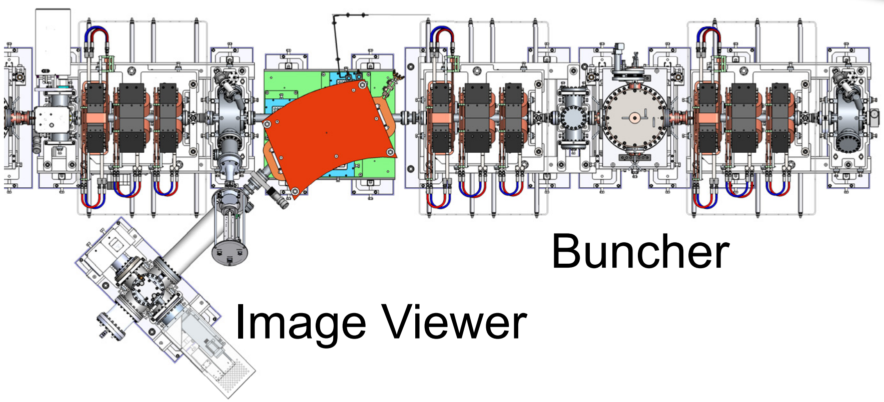


Calibration of MEBT Buncher Voltage with Beam

- Beam position on the image viewer behind the 45º magnet depends on MEBT buncher voltage and phase
- Maximum beam center shift as a function of the buncher voltage (amplitude) from simulations
- Measured data

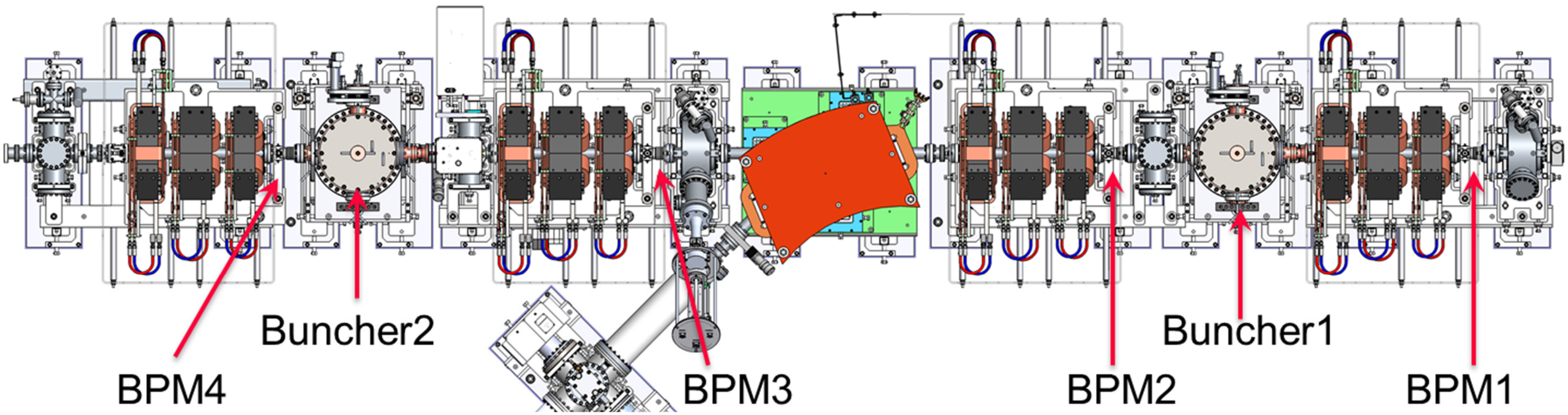






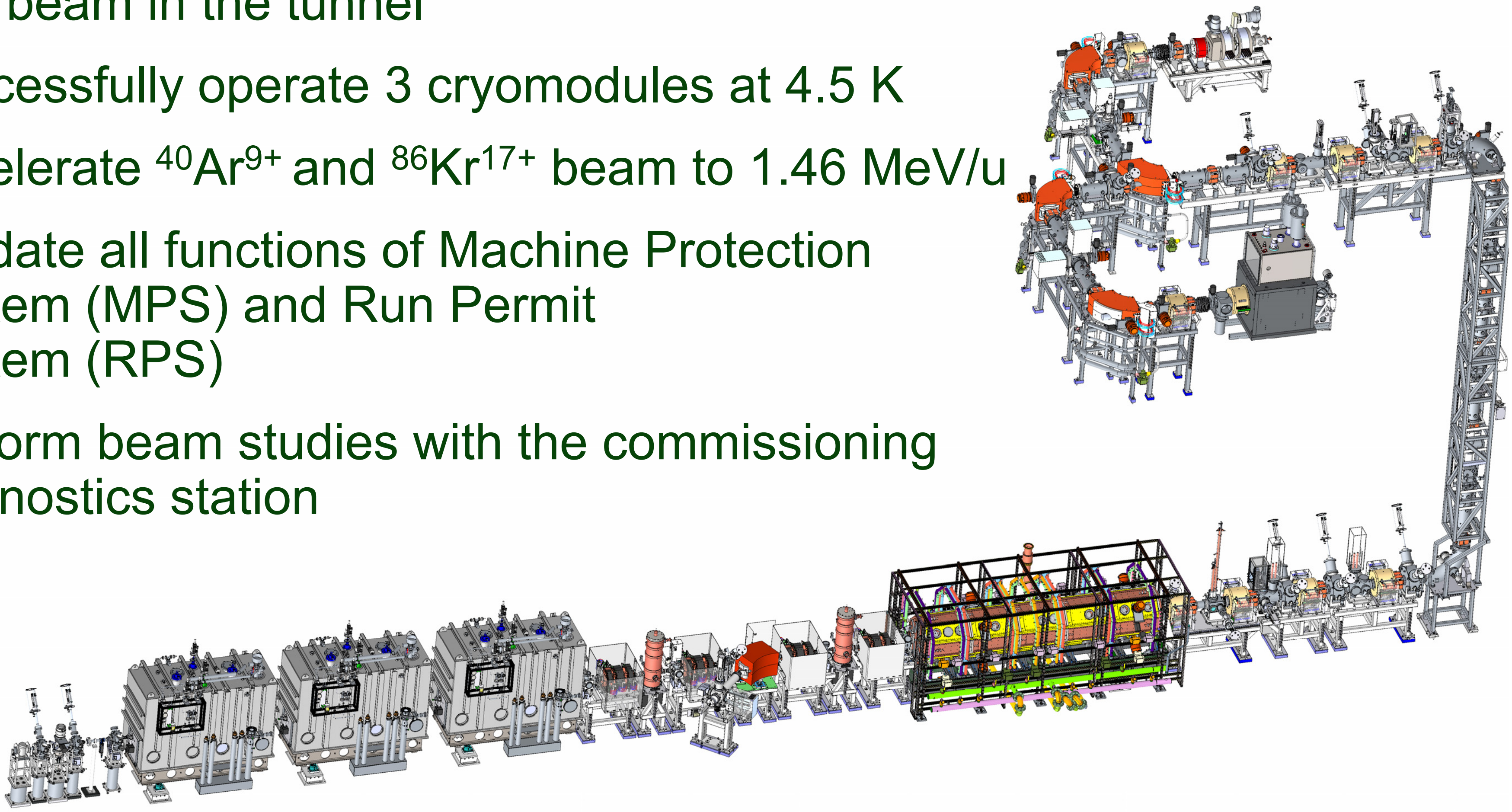
TOF Beam Energy Measurements

- Signal delays in all 4 BPM cables were measured and synchronized
- Beam induced phase difference on BPM2 and BPM3
  - Signal delays in BPM2 and BPM3 were calibrated
- Buncher is in maximum acceleration phase
  - Energy =0.51980 MeV/u
- Buncher is in maximum deceleration phase
  - Energy =0.49208 MeV/u
- Buncher voltage: 61.6 kV, consistent with the measurements downstream of the bending magnet



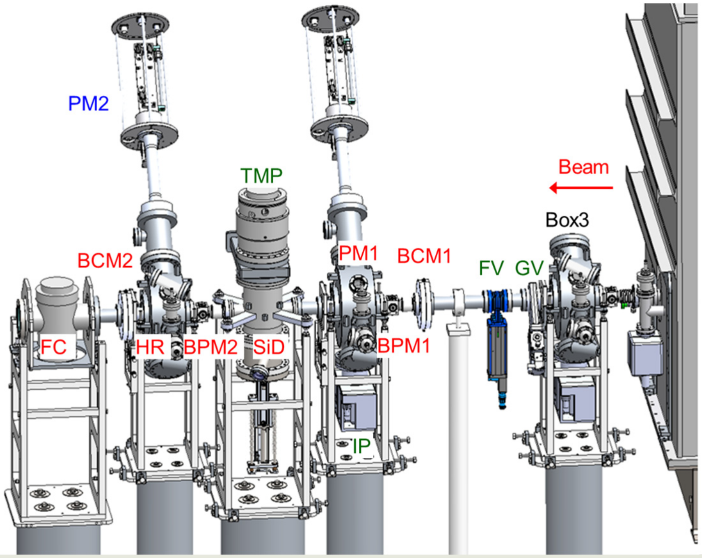
SC Linac: First 3 Cryomodules Will Be Commissioned This Summer

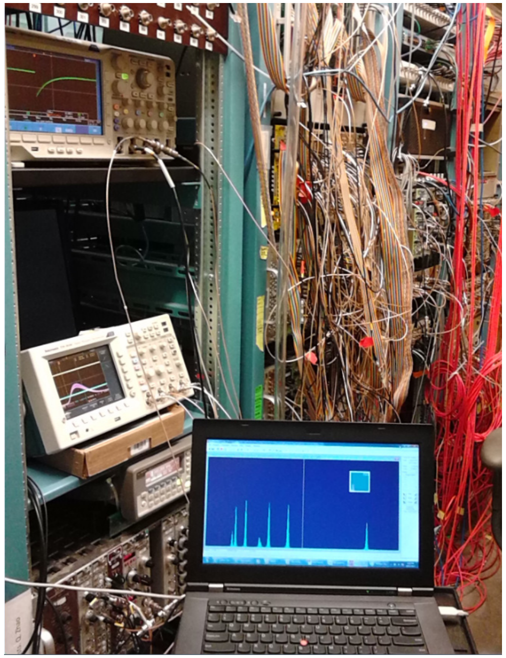
- Establish access control and implement safety measures for operation with beam in the tunnel
- Successfully operate 3 cryomodules at 4.5 K
- Accelerate $^{40}Ar^{9+}$ and $^{86}Kr^{17+}$ beam to 1.46 MeV/u
- Validate all functions of Machine Protection System (MPS) and Run Permit System (RPS)
- Perform beam studies with the commissioning diagnostics station



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



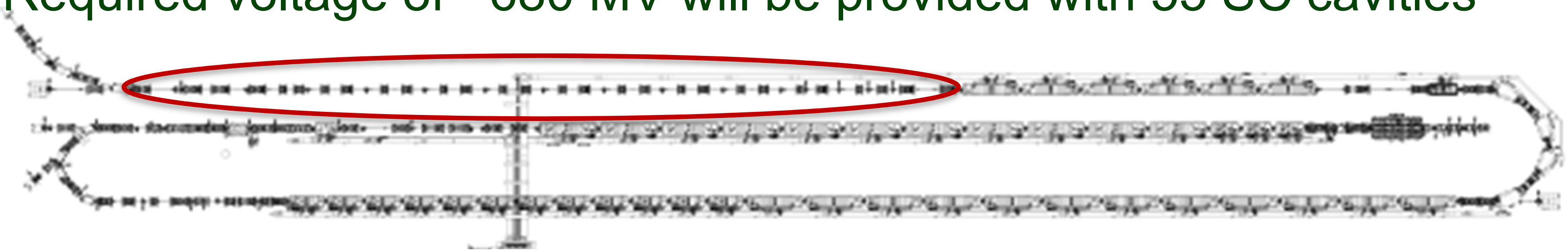


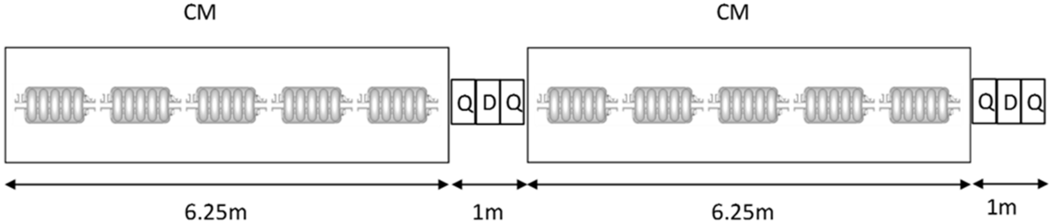
Commissioning Plan

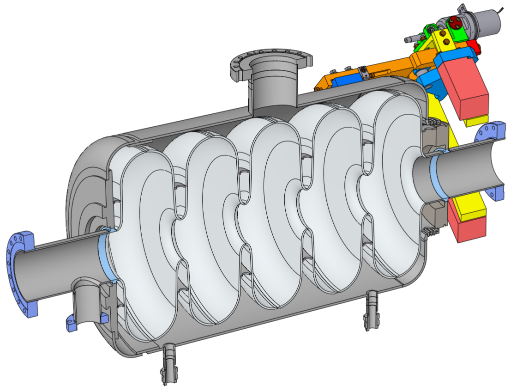
- Operation of MPS and RPS is not required in the beginning: beam power is < 2 Watts
  - Ar or Kr beam power is controlled by attenuators in LEBT
- Transport 0.5 MeV/u beam to D-station and achieve ~100% beam transmission through all cryomodules
- Perform phase and amplitude scan of the MEBT buncher 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

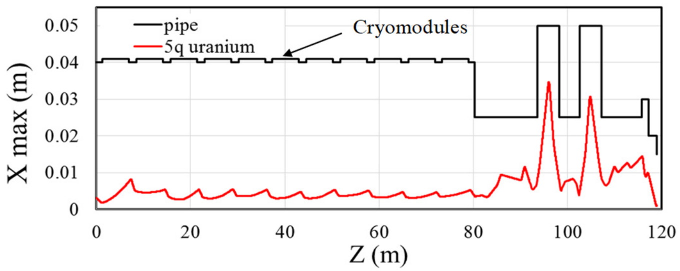
FRIB Energy Upgrade

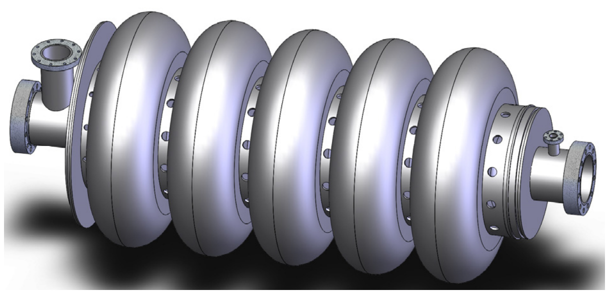
- Uranium from 200 MeV/u to 400 MeV/u
- Required voltage of ~680 MV will be provided with 55 SC cavities

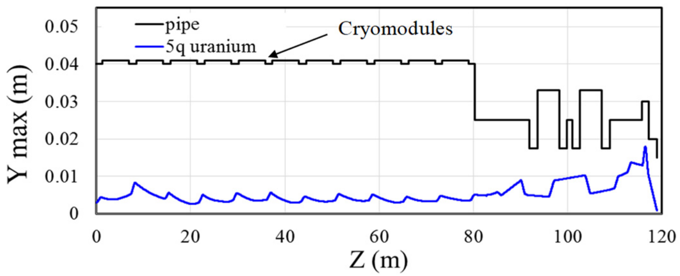












Summary

- Contaminant ion beams extracted from ECR ion source can result in beam losses in the folding segment
  - Set of collimators are developed to intercept contaminant ions and beam halo due to charge-exchange reactions
  - Room temperature re-bunchers replaced SC cavities in the area critical to beam losses
- Front End commissioning is complete
  - All key performance parameters (KPPs) are demonstrated
- Main results of beam physics studies in Front End
  - Beam envelopes and central trajectory are consistent with simulations
  - Phase & amplitude setting of individual RF cavity with BPMs is established
  - Simultaneous transport and acceleration of 2q krypton beam is demonstrated
- Commissioning of three $\beta=0.041$ cryomodules is planned for this summer
- SC prototype cavities are being developed for FRIB energy upgrade
  - Uranium from 200 MeV/u to 400 MeV/u, protons up to 1 GeV