# Upgrade of the FRIB ReAccelerator

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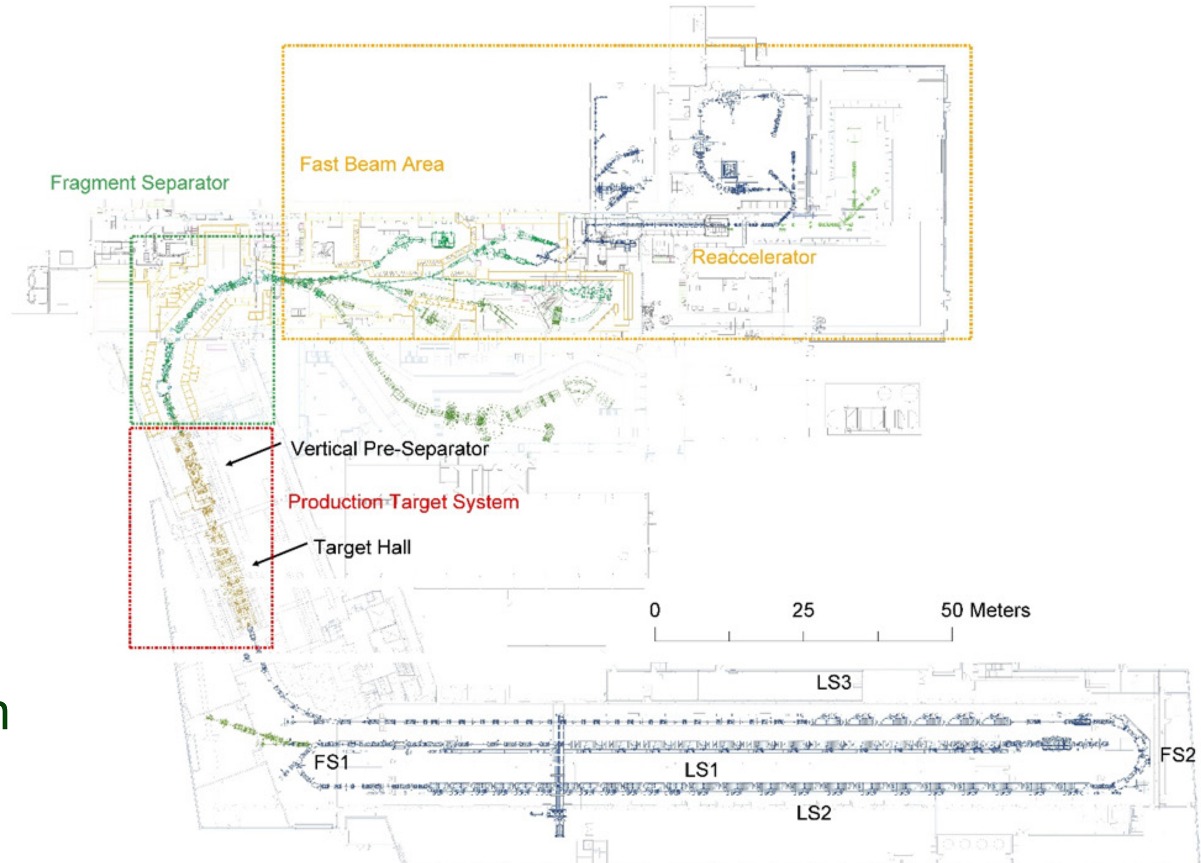
# Outline

- Short introduction to the Facility for Rare Isotope Beams (FRIB)
- Rare isotope beam production
  - Stopping and reacceleration
- The ReAccelerator
- The upgrade (ReA6)
  - Batch Mode Ion Source (BMIS)
  - Room-temperature Rebuncher
  - Cryomodule for ReA6
  - Diagnostics
- Commissioning
- Experiments with rare isotope beams
  - Cleaning contaminants
- Summary

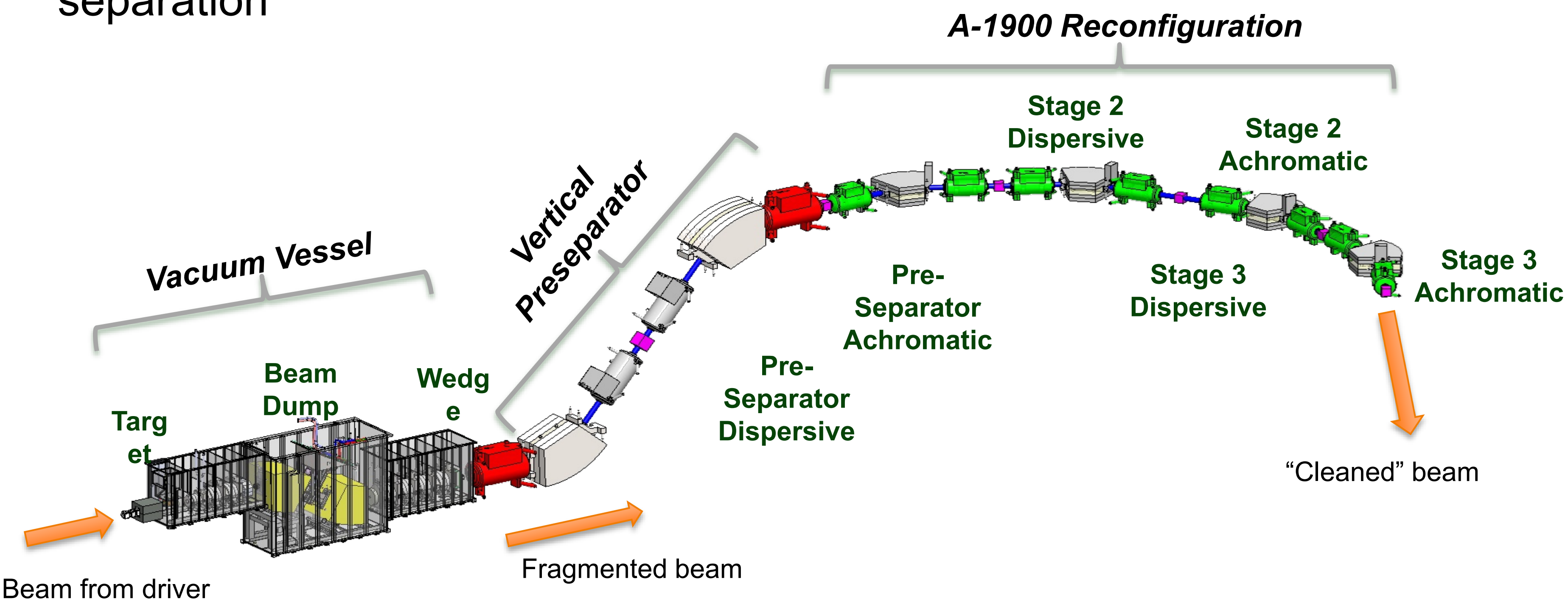
# Facility for Rare Isotope Beams (FRIB) Enables Science Program

- FRIB enables science with fast, stopped and reaccelerated beams from projectile fragmentation and fusion-fission – world-unique feature
  - Fast beams
  - Stopped beams
  - Reaccelerated beams
- Driver linac
  - $^{16}O$ to $^{238}U$ beams
  - 200 MeV/u for 238U
  - 400 kW
- Completed commissioning at 1kW in January 2022
  - Power ramp up over 5 years
- First 3 fast beam experiments performed with
  - FRIB decay station initiator
  - S800 spectrometer with GRETINA gamma array



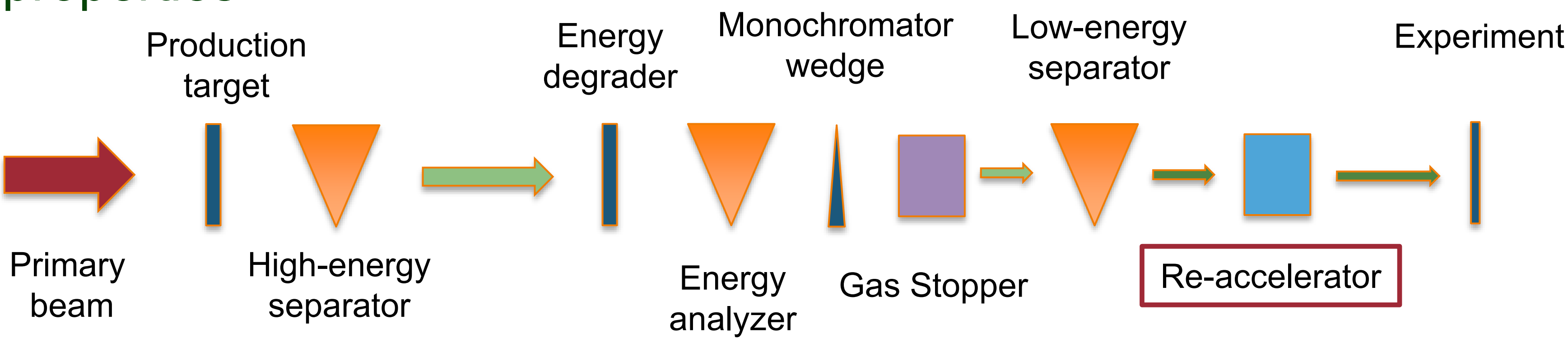
# Multi-stage FRIB Fragment Separator Allows for Optimized Rare Isotope Production

- Multi-stage separator provides versatility and optimum configuration
  - Multiple intermediate achromatic and dispersive optical image planes
  - Isotope selection by magnetic rigidity and energy loss in degraders
  - Slit systems and wedge degraders allow for optimized rare isotope separation



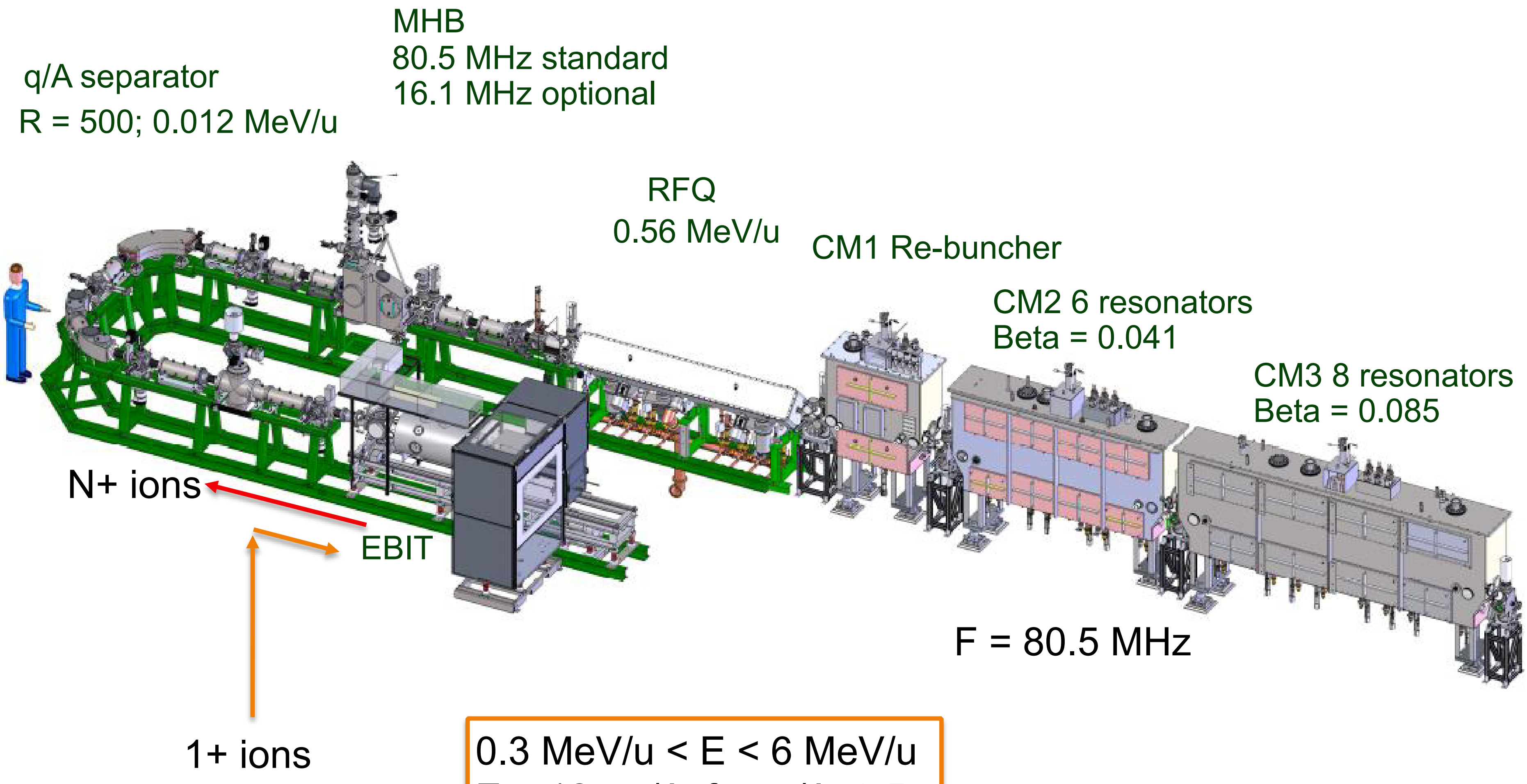
# Stopping with Reacceleration Allows Improved Beam Quality at Low Energies

- Stopping and reacceleration extends research capabilities of heavy-ion fragmentation facilities to lower energies, whilst improving beam properties




Making reaccelerate rare isotope beams is a complex multi-step process, which needs careful optimization of each of them to provide high efficiency

# The ReAccelerator (ReA3)



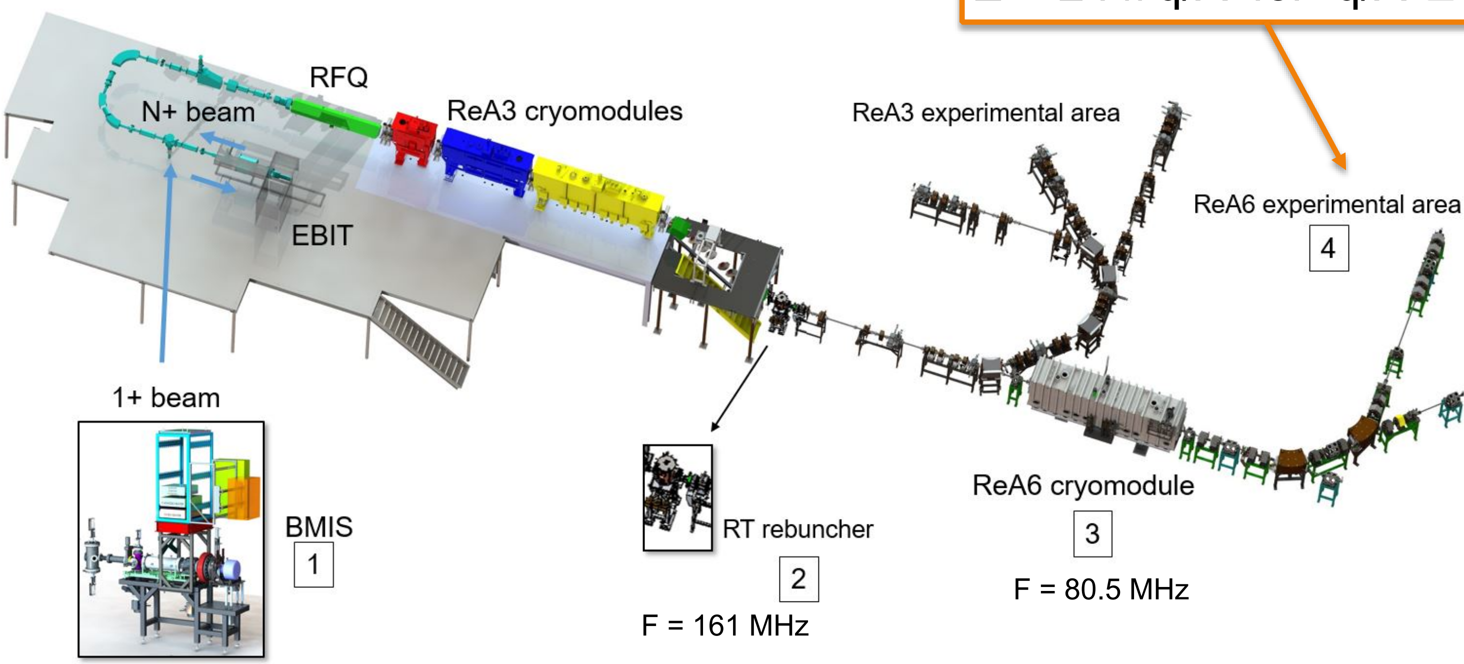

0.3 MeV/u < E < 6 MeV/u
E = 12 x q/A for q/A ≤ 5

# The ReA Update (ReA6)

## Expanding Science Opportunities with Reaccelerated Beams at Higher Energies

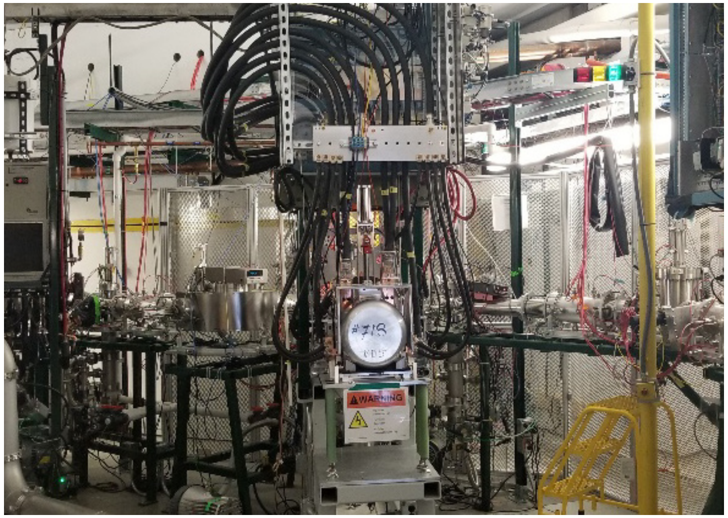
- Upgrades of the ReA facility
  - Batch Mode Ion Source (1)
  - RT rebuncher (2)
  - ReA6 cryomodule (3)
  - ReA6 experimental areas (4)

0.3 MeV/u < E < 12 MeV/u
E = 24 x q/A for q/A ≤ 5



# Batch Mode Ion Source (BMIS)

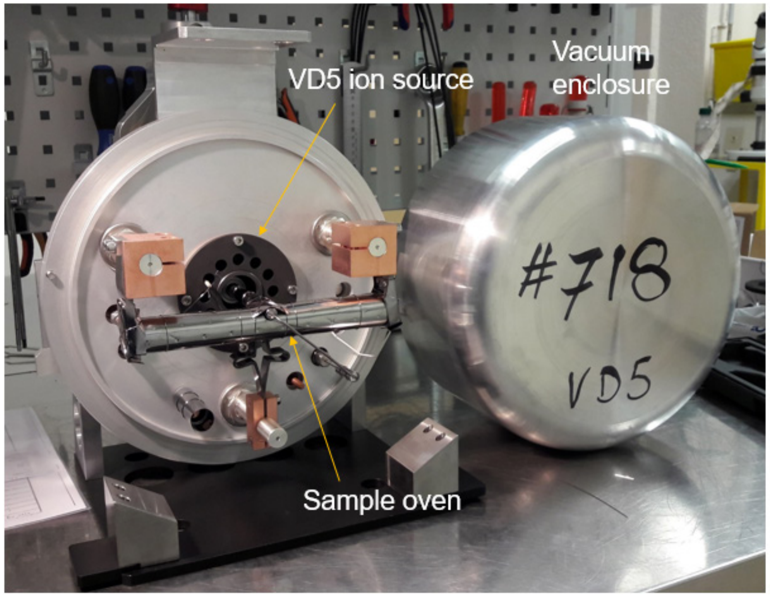
- Using of CERN/ISOLDE Target-Ion-Source system to provide RIB
  - “Target” replaced by samples of radioactive (relatively long living)
  - Provided rare isotope beams available during A1900 reconfiguration (pre-FRIB)
  - Continued use planned during FRIB era as alternative RIB beam stand-alone facility
  - Evaporated sample material is transferred to the VD5 ion source (variation of forced electron ion beam induced arc discharge FEBIAD)

# Techniques Developed for Beam Production

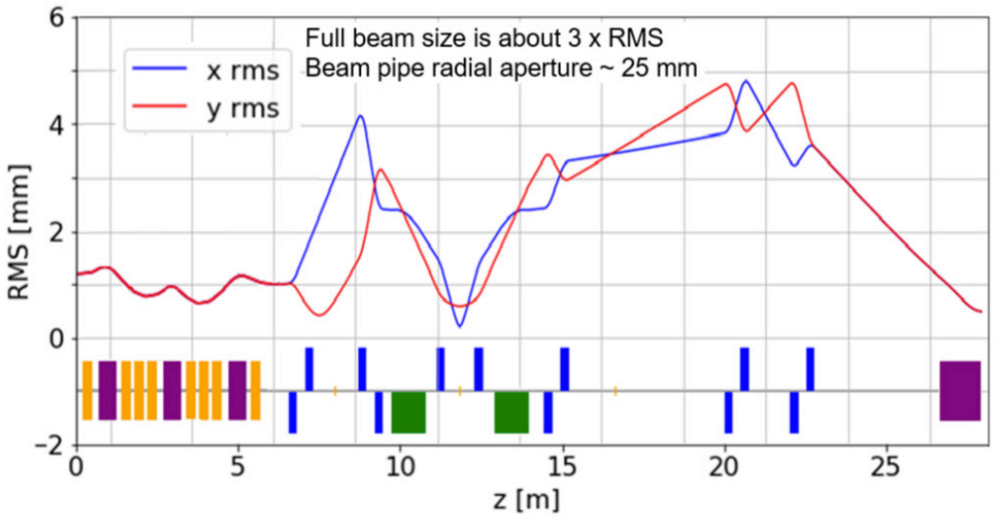
- Depending on the element, different production techniques were developed. Examples:
  - B-10 (T1/2 = 1.51E+6 y) and Be-7 (T1/2 = 53 d): use of NF3 as a reaction gas to create BeF2+ in-situ, working temperature around 1,000 C
  - Si-32 (T1/2 = 153 y): extracted as SiO+ at about 700 C.
  - Al-26 (T1/2 = 7.17E+5 y): $^{26}$Al2(SO4)3 combined with NF3 in-situ for extracting $^{26}$AlF at about 1,000 C

- Stable beams of $^{50}$Cr, $^{58}$Fe, $^{86}$Kr and $^{120}$Sn also produced



# Beam Optics Defined Positioning and Strengths of all Optical Elements

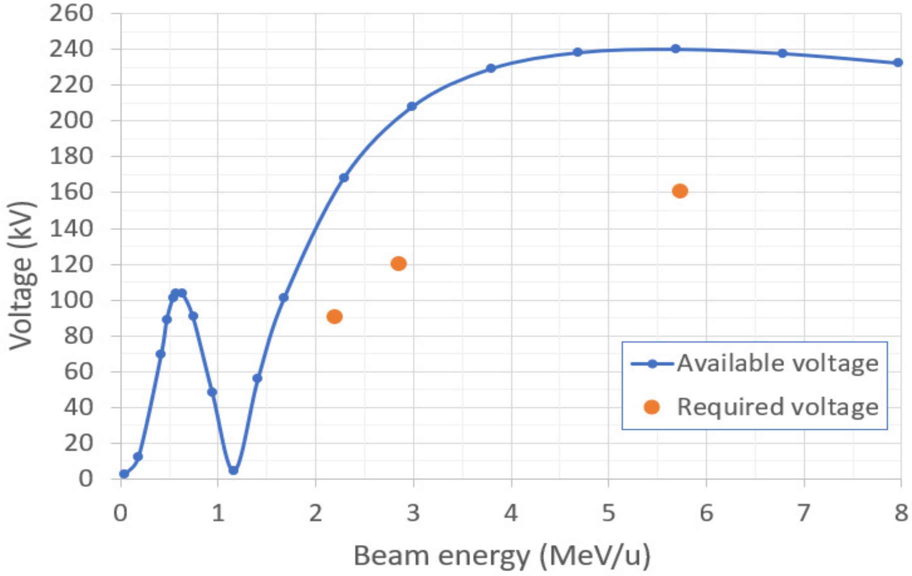
- Calculation of the beam envelope from the entrance of the ReA6 cryomodule to the end of each new beamline performed
  - FRIB type cryomodule can be used
  - Quadrupole design of FRIB intermediate energy branch and steerers of ReA3 are well adapted

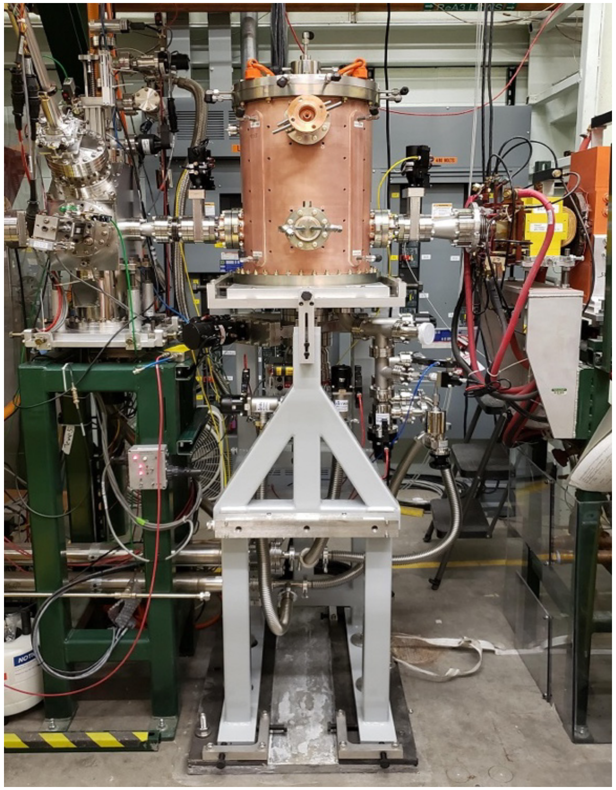



Calculated beam envelope RMS (mm) from the entrance of the ReA6 cryomodule to the end of the SOLARIS beamline; the two dipoles are represented by the green squares, quadrupoles by the blue rectangles (up horizontal focusing and down vertical focusing)

# Room-Temperature Rebuncher
## Longitudinal Matching Between ReA3 and ReA6

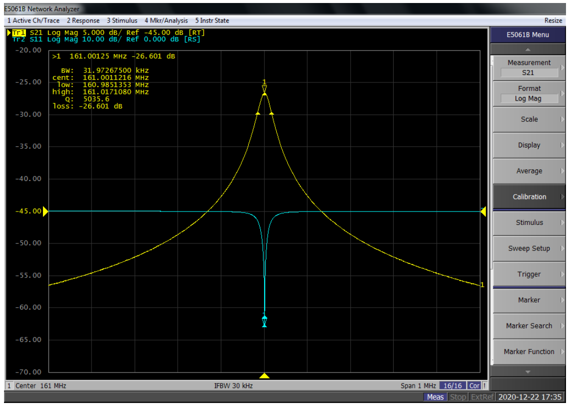
- Cavity is a double gap quarter-wave resonator operating at 161 MHz
  - Reduce the operating voltage by a factor 2 from main frequency (second harmonic of 80.5 MHz)
  - 0.6 m high cavity
  - Inner tank diameter 0.3 m
  - $\beta_{opt} = 0.1$
  - Can provide de-bunching for ReA3 users (minimizes beam energy spread in ReA3)

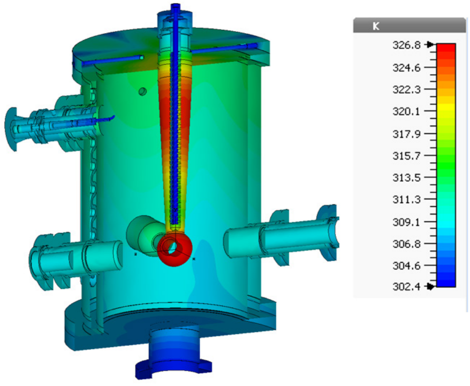


# Rebuncher Overall Behavior

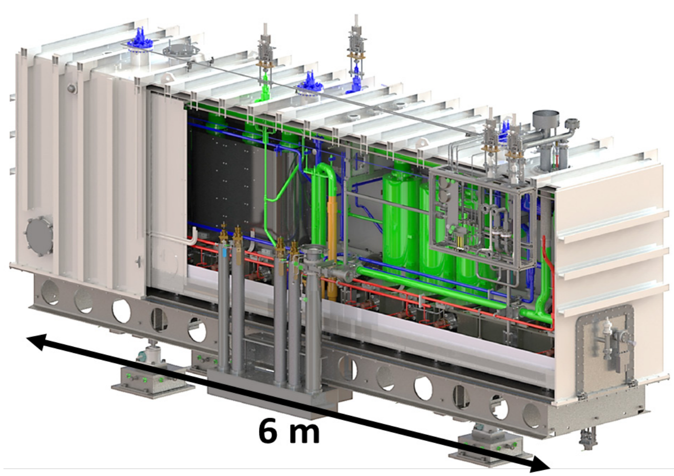
- Cavity was installed and commissioned in February - March 2021
  - Temperature gradient (calculation) between stem and drift tube is around 12 K
  - Effective Q loaded measured during assembling 5,000
  - Maximum voltage of 200 kV achieved at 5 kW input RF power (0.6 Kilpatrick units maintained peak surface fields moderate) and reflected power less than 1%
  - RF conditioning was conservative and took about a week to reach maximum voltage
  - Operation does not require re-conditioning if vacuum is not broken



# New Cryomodule for ReA6

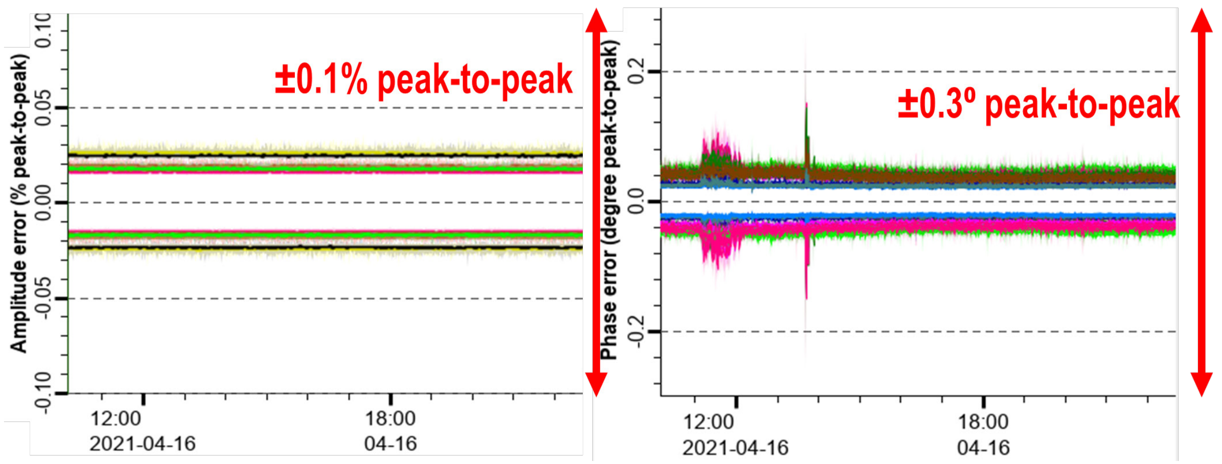
- The cryomodule is a FRIB β=0.085 quarter-wave resonator (QWR), the same used in FRIB linac
  - Minimize risks as this is a validated cryomodule
  - Compatible with schedule of the project as this cryomodule was built in the same assembly line of FRIB
  - Contains 8 QWR resonators and 3 superconducting solenoids

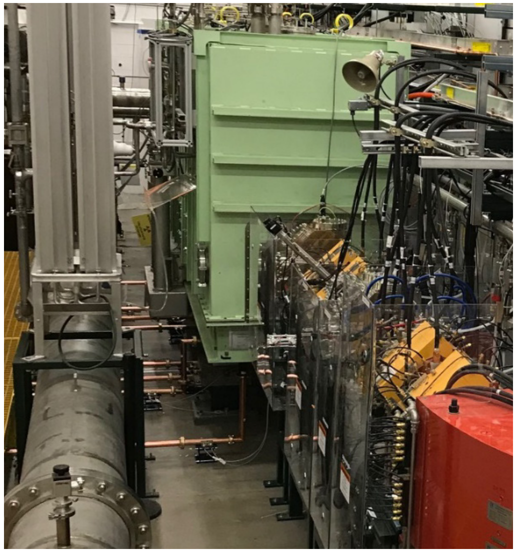



| Parameter | Value |
|---|---|
| 8 Cavities | |
| Operating Temperature | 4.3 K |
| Frequency | 80.5 MHz |
| β | 0.085 |
| Accelerating gradient $E_{acc}$ | 5.6 MV/m |
| r/Q | 455 Ohm |
| Geometric factor $G = Q_0 {*} R_s$ | 22 Ohm |
| Peak surface electric field $E_{peak}^*$ | 33 MV/m |
| Peak surface magnetic field $B_{peak}^*$ | 69 mT |
| Solenoid integrated with XY dipole steering coils | |
| Bmax | 8 T |
| Max operation current | 100 A |

# Characteristics of the Cryomodule

- In the commissioning the design accelerating gradient of 5.6 MeV/m for β=0.085, was achieved
- Phase and amplitude stabilities met requirements of ±0.3º and ±0.1% with ample margins



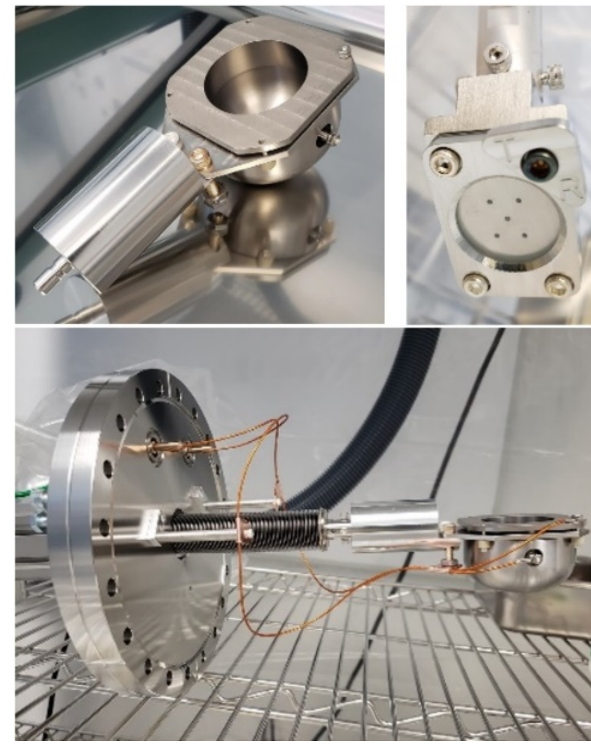



Peak-to-peak amplitude and phase errors of all eight cavities in the ReA6 cryomodule, measured for 12.5 hours. Average accelerating gradient was 6 MV/m and the cavities were operated at 4.3 K. Colors represent each resonator

# Diagnostics Largely Based on Proven Pre-existing Designs

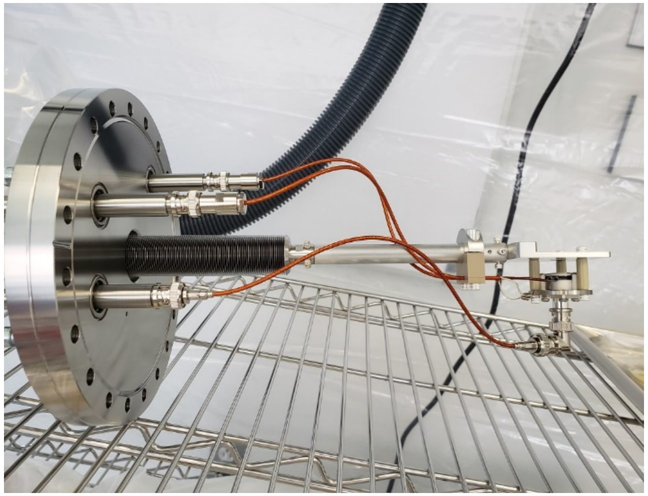
- Faraday cups installed upstream, downstream of the cryomodule and in experimental beamline
  - Hemispherical shaped cups fabricated with niobium and electron beam repeller
    - 40 mm aperture
    - Bias 500 V (nominal using 48 V)
    - Reliably measuring down to 10 fA

- Scintillator viewers for transverse size and shape
  - 45 deg wedge shaped holder supporting a 1.5 mm thick by 19 mm diameter CsI (TL) crystal
  - Analog 1/3” CCD bullet camera with 25 mm focal length lenses fed into a 16-channel digital video encoder

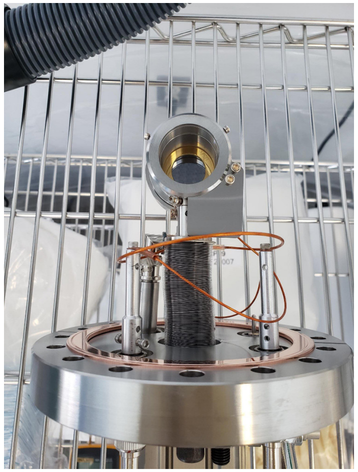


# Particle Detectors for Low Intensity Beams

- Commercial 14.5 mm diameter 2-stage microchannel plate (MCP) with sub-nanosecond rise time placed just in front of the ReA6 cryomodule allows bunch length measurements of attenuated beam for tuning phase and amplitude of the rebuncher

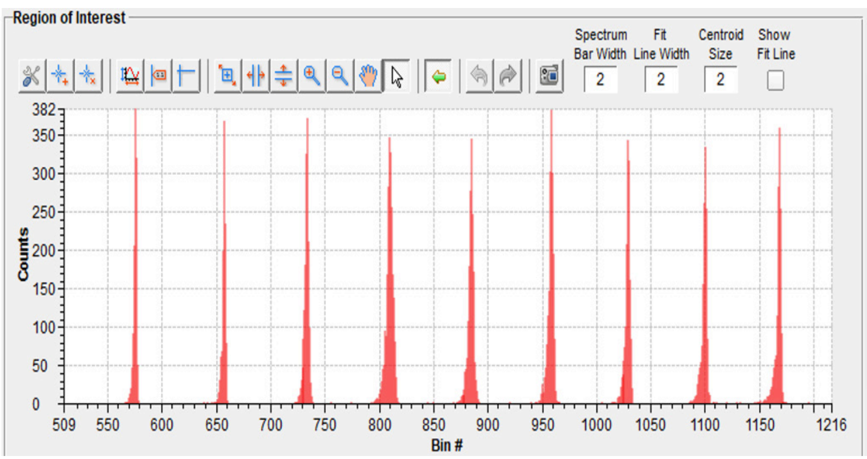


- Single ion-implanted silicon detector with 500 µm depletion depth and 19.5 mm diameter active area
  - Phasing of the linac
  - Identification of contaminants
    - » Different masses direct implantation
    - » Isobars, when preceded by a thin aluminum foil (with or without a hole)
    - » Radiation decay (beta) when preceded by a thin aluminum foil



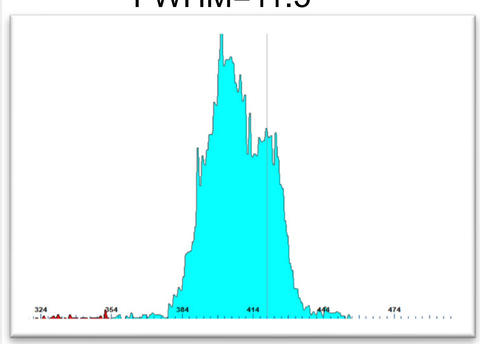
# Commissioning Results

- Beams of $^{14}N$ (6+) and $^{20}Ne$ (9+) accelerated to the designed 10.2 MeV/u
  - Tuning was automated using zero degree silicon detector in the end of the linac (about 3 minutes per resonator)
- Scaling from one to another beam automatic and fast (5 minutes), only small steering correction needed (15 minutes)
- New rebuncher used to focus longitudinally beam in the entrance of the linac
  - Longitudinal shape was optimized to 11.5 degrees
- Transport efficiency close to 100%




Energy gain per resonator

FWHM=11.5º

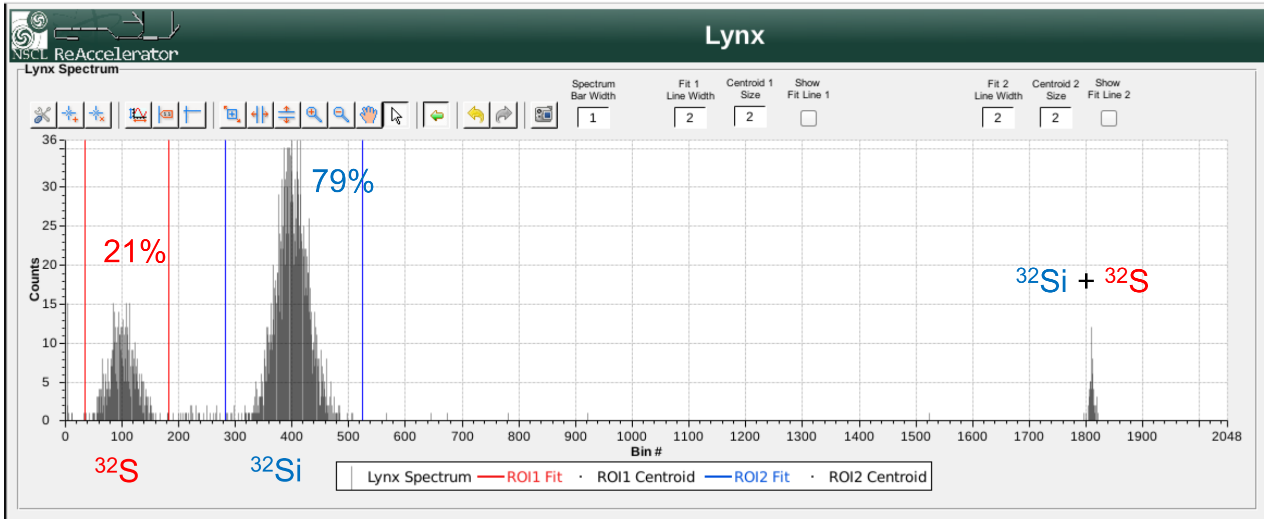


Longitudinal distribution


Viewer image in SECAR beamline, beam is < 1 mm

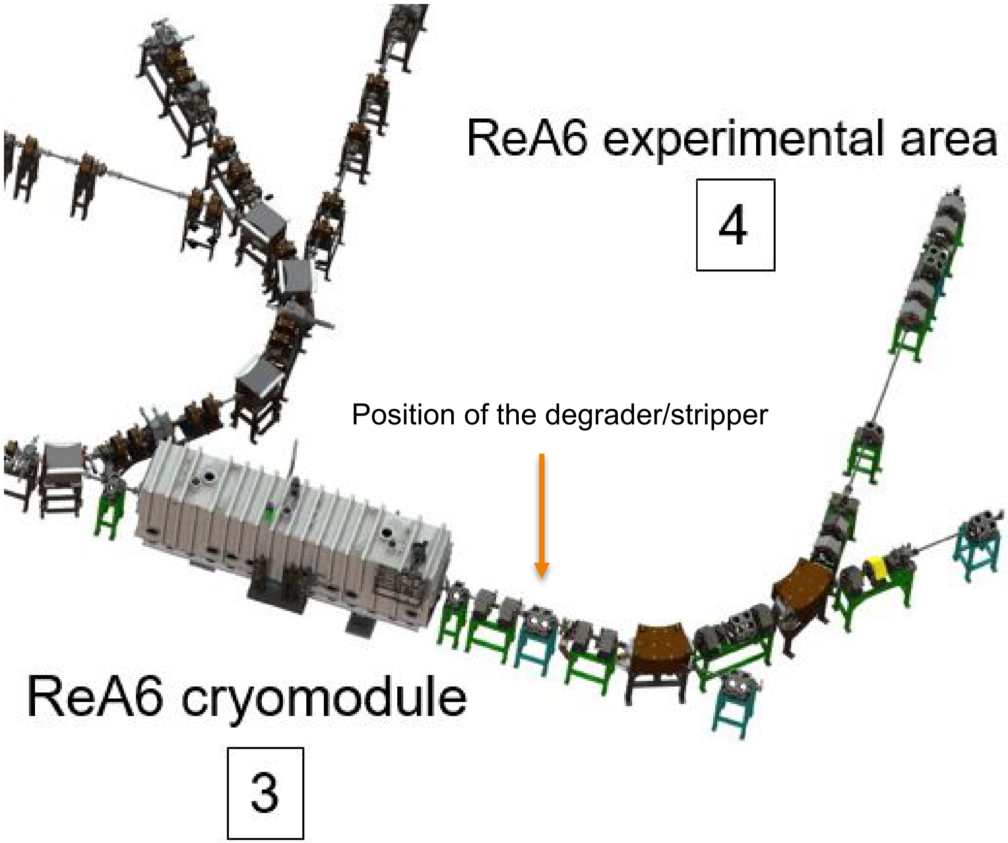
# Contamination Measurement

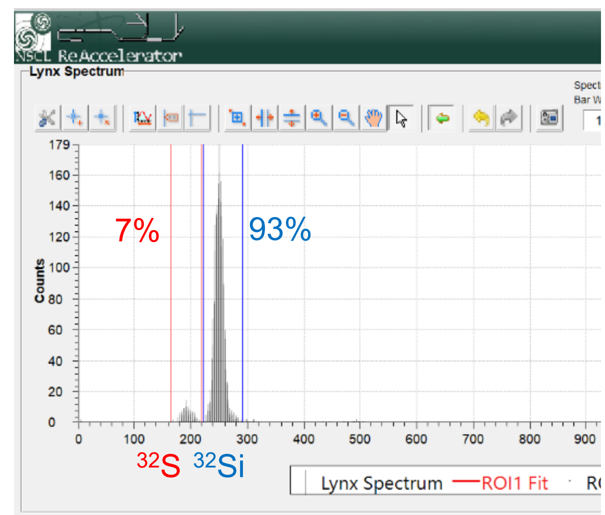
- Beams accelerated by ReA can be contaminated by other isotopes with similar Q/A
  - $^{10}$Be has isobar $^{10}$B contamination
    - » Contamination has origin in BMIS and the $^{10}$Be rare isotope sample
  - $^{32}$Si has isobar $^{32}$S contamination
    - » Contamination has origin in BMIS and the $^{32}$Si rare isotope sample
- Contamination can be identified using Silicon detector with aluminum foil



# Purity can be Improved with a Degrader/Stripper

- Degrader/stripper installed before the beam analyzer
  - Charge state change + difference in energy loss allows selection
  - Contamination reduced from 21% to 6% for $^{32}$Si beam



# Beams Provided for Experiments

- 10 experiments were performed in ReA6 in both beamlines, some of the beams are listed below

| Isotope | Energy (MeV/u) | Intensity (pps) | Source |
|---|---|---|---|
| $^{7}Be$ | 7.4 | $10^5$ | BMIS |
| $^{10}Be$ | 9.6 | $10^6$ | BMIS |
| $^{14}N$ | 10.2 | $2.0 \times 10^7$ | EBIT residual |
| $^{16}O$ | 10.2 | 5000 | Colutron |
| $^{20}Ne$ | 10.2 | $10^6$ | Colutron |
| $^{32}Si$ | 8.45 | $10^6$ | BMIS |
| $^{50}Cr$ | 9.5 | $10^6$ | BMIS |
| $^{86}Kr$ | 3.85 | $3.0 \times 10^7$ | BMIS |
| $^{112}Sn$ | 3.85 | $10^6$ | Colutron |
| $^{116}Sn$ | 3.81 | $10^6$ | Colutron |
| $^{120}Sn$ | 3.73 | $10^6$ | BMIS |

# Summary

- The upgrade of the FRIB reaccelerator is completed providing beam energy increase from 3 MeV/u to 6 MeV/u for ions with q/A = 4 (12 MeV/u for q/A = 2)
- The upgrade included
  - New BMIS ion source for rare isotope beams
  - New room temperature rebuncher
  - New FRIB-style cryomodule
  - 2 new beam lines
- Commissioning was successful and experiments were performed since then
- Contamination issues are mitigated with degrader/stripper method when possible

Thank you