Beam Commissioning and Isotope Purification for FRIB User Experiments

Speaker: Kei Fukushima

Marc Hausmann, Kyung Hwang, Tomofumi Maruta, Peter Ostroumov, Alexander Plastun, Mauricio Portillo, Bradley M. Sherrill, Mathias Steiner, Oleg Tarasov, Tong Zhang, Qiang Zhao

Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824 USA

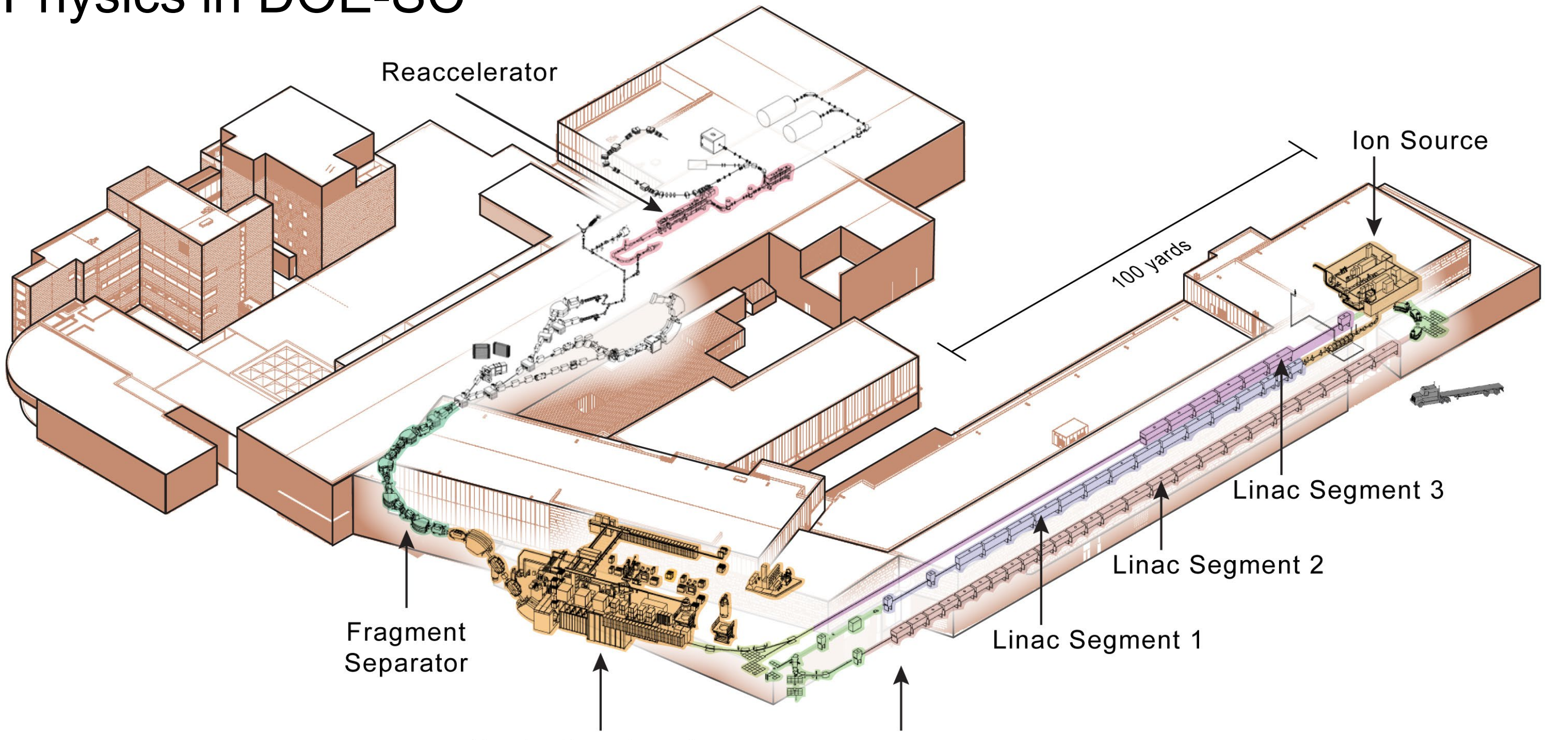
This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.

Outline

- Introduction
  - FRIB Linac, Fragment Separator (ARIS), Experimental beamlines
- Status of FRIB since operation starts
  - Recent upgrades, multi-charge-state operation
- ARIS configuration and operation
  - Beam commissioning of ARIS for user operation
  - Experimental beamline tuning for user stations
  - Complexity of ARIS and Challenges
- Summary

Facility for Rare Isotope Beams @MSU
- Exploring new, unexplored regions of the nuclear chart

- Designed to accelerate all stable ions above 200 MeV/u with 400 kW
  - FRIB Construction Completed in Jan. 2022 On Cost and Five Months ahead of Schedule
  - FRIB is now a DOE-SC scientific user facility for rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC



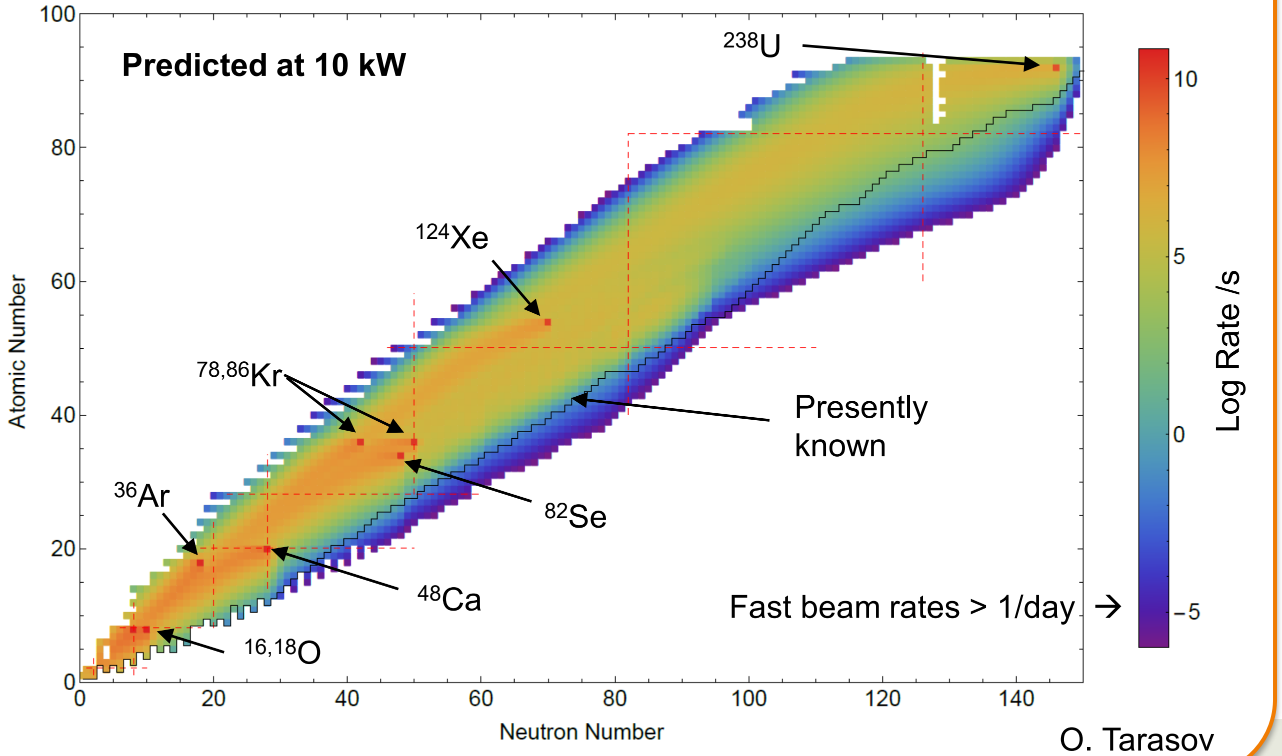
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

Facility for Rare Isotope Beams @MSU
- Exploring new, unexplored regions of the nuclear chart

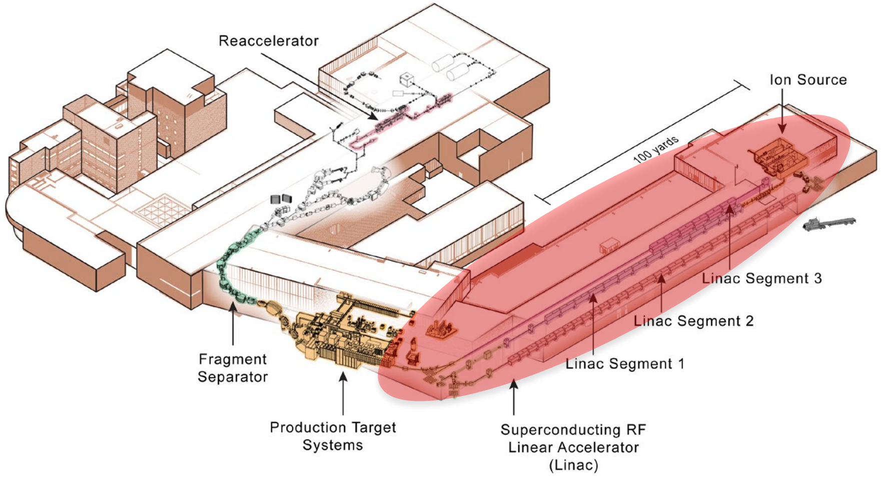
- Designed to accelerate all stable ions above 200 MeV/u with 400 kW
  - FRIB Construction Completed in Jan. 2022 On Cost and Five Months ahead of Schedule
  - FRIB is now a DOE-SC scientific user facility for rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC

FRIB ribbon cutting ceremony

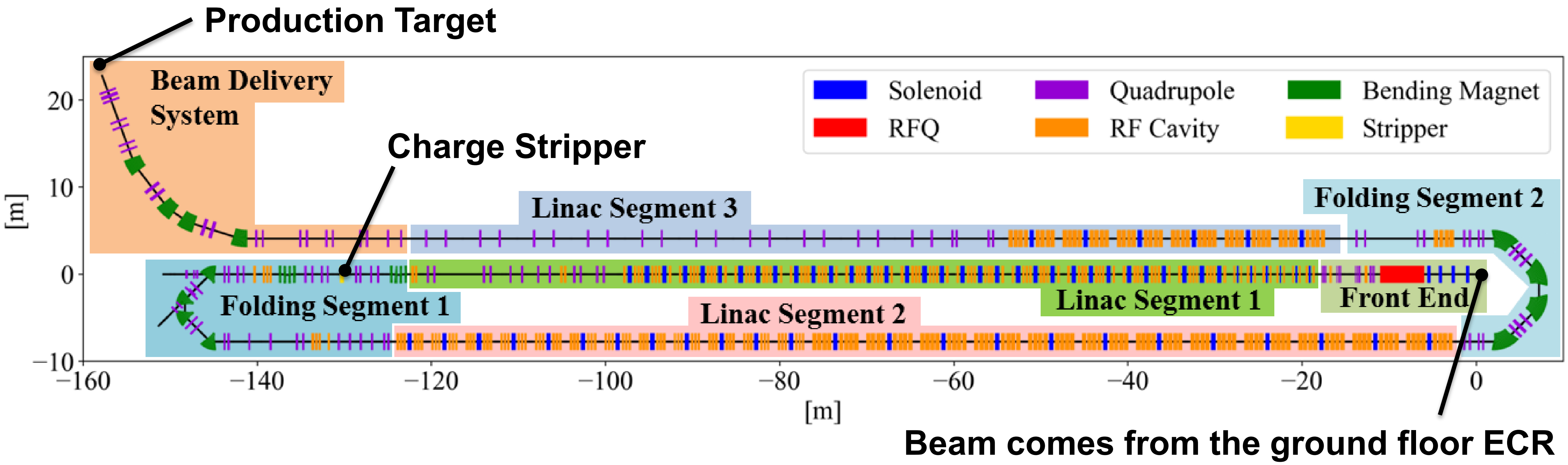
Rare Isotope Beam Rates in FRIB



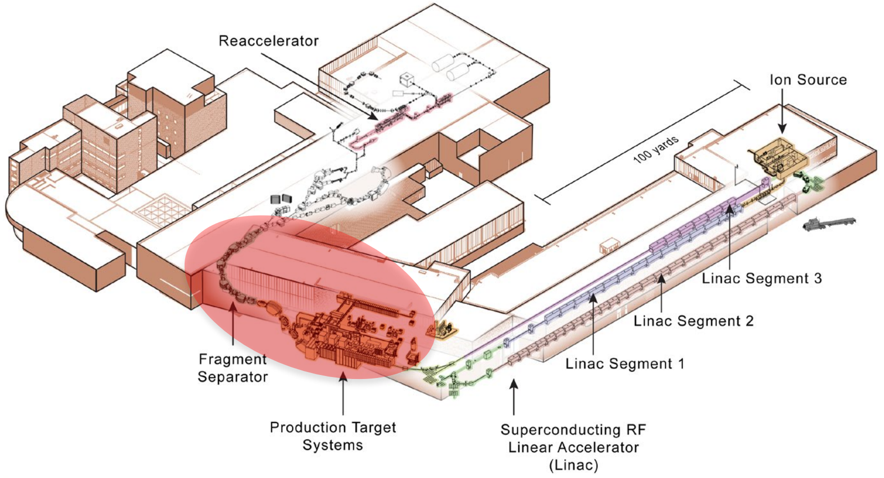
FRIB Outline: Linac



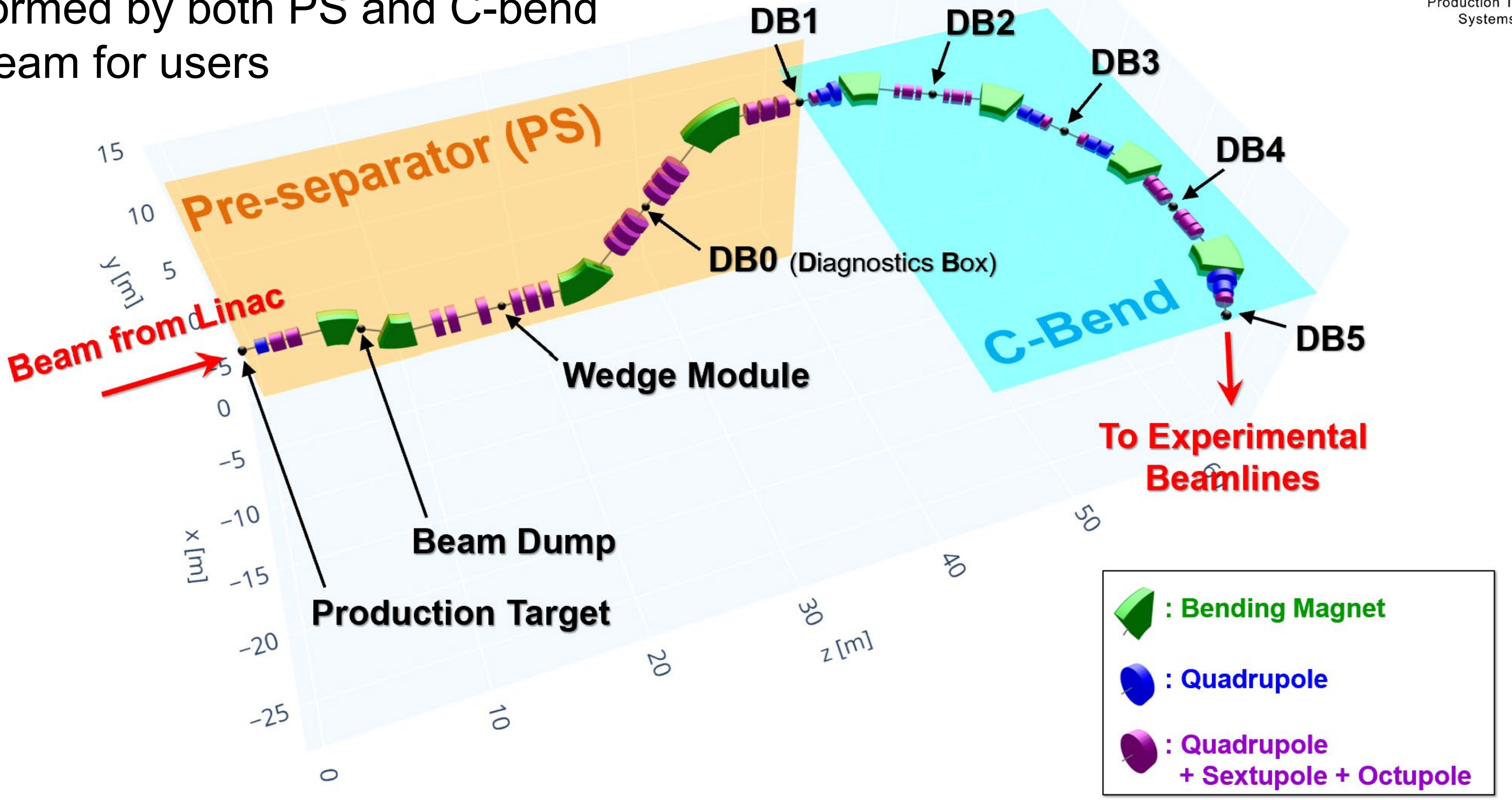
- Linac, target, and dump are located 10m underground
  - 3 super-conducting linac segments (LS1~3)
  - Charge stripper is located after LS1
    - » Liquid Lithium stripper and Rotating carbon stripper



FRIB Outline: Fragment Separator

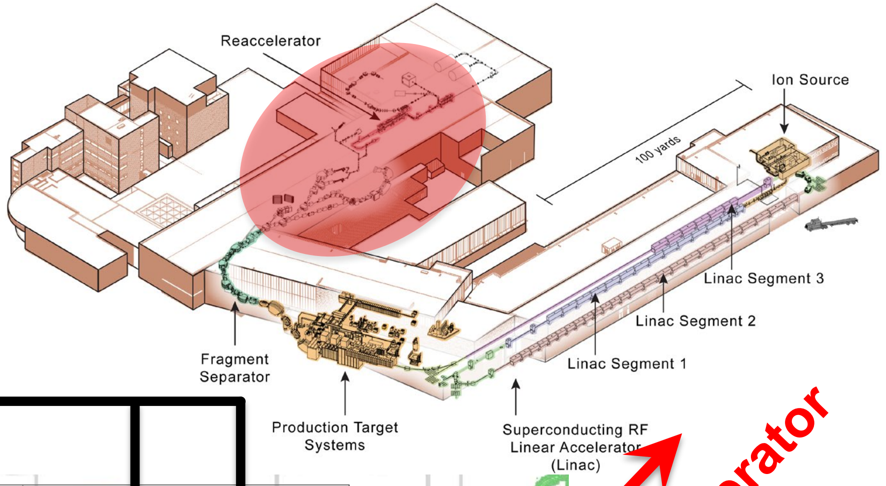


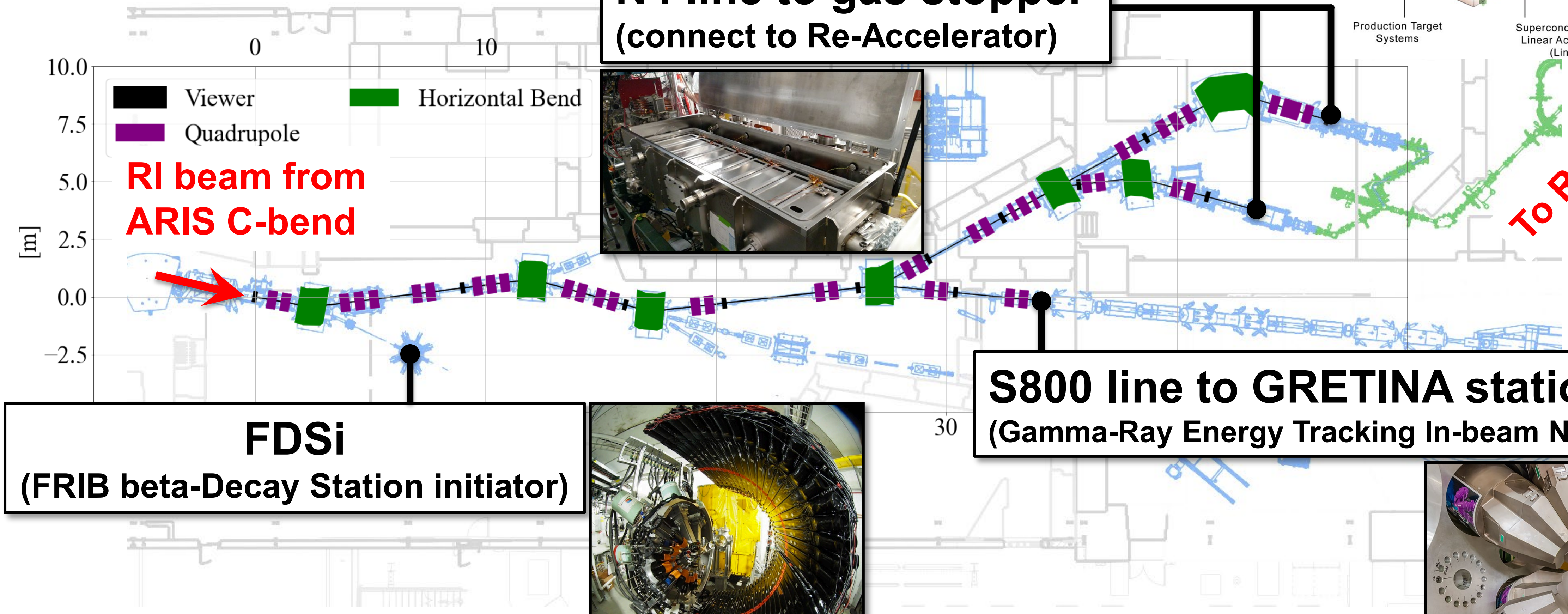
- Advanced Rare Isotope Separator (ARIS)
  - In-flight separation of projectile fragments
  - Transport rare isotope (RI) beam to ground level in vertical pre-separator
  - Separation performed by both PS and C-bend
  - Identify the RI beam for users



FRIB Outline: Experimental Beamline

- Serves science with the unique availability of fast, stopped, re-accelerated beams





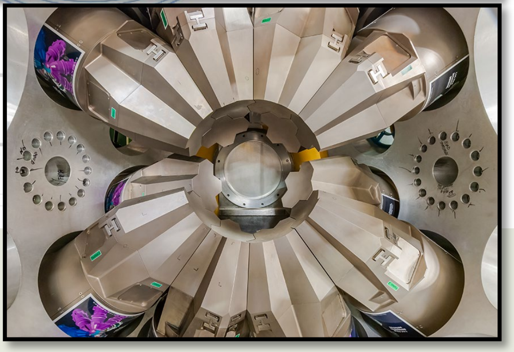
RI beam from ARIS C-bend

N4 line to gas stopper
(connect to Re-Accelerator)

To Re-Accelerator

FDSi
(FRIB beta-Decay Station initiator)

S800 line to GRETINA station
(Gamma-Ray Energy Tracking In-beam Nuclear Array)



Current Status of FRIB

- FRIB has steadily ramped up beam power to 5 kW
- More than 250 unstable isotope beams have been delivered to FRIB experiments

Date	Objective	Destination	Primary beam	Energy	Power
May 2022	User experiment 21062	FDSi	^{48}Ca	173 MeV/u	1 kW
Jun 2022	User experiment 21069	FDSi	^{82}Se	165 MeV/u	1 kW
Aug 2022	User experiment 21007	S800	^{70}Zn	173 MeV/u	1 kW
Nov 2022	User experiment 21072	FDSi	^{36}Ar	210 MeV/u	3 kW
Dec 2022	User experiment 21003	S800	^{124}Xe	227 MeV/u	3 kW
Dec 2022	User experiment 22601	N4	^{36}Ar	210 MeV/u	3 kW
Jan 2023	User experiment 23602	N4	^{124}Xe	227 MeV/u	3 kW
Feb 2023	User experiment 22501	ARIS	^{198}Pt	186 MeV/u	3 kW
Feb 2023	User experiment 21049	N4	^{124}Xe	227 MeV/u	5 kW
Mar 2023	User experiment 23603	N4	^{36}Ar	210 MeV/u	5 kW
Mar 2023	User experiment 21009	S800	^{48}Ca	197 MeV/u	5 kW
Apr 2023	User experiment 21034	S800	^{124}Xe	227 MeV/u	5 kW
May 2023	User experiment 23605	N4	^{40}Ar	200 MeV/u	5 kW
Jun 2023	User experiment 21014	S800	^{64}Zn	240 MeV/u	5 kW
Jul 2023	User experiment 21009A	S800	^{48}Ca	197 MeV/u	5 kW
Jul 2023	User experiment 21001A	S800	^{48}Ca	217 MeV/u	5 kW

- **Performed 8 primary beams, up to 240 MeV/u**

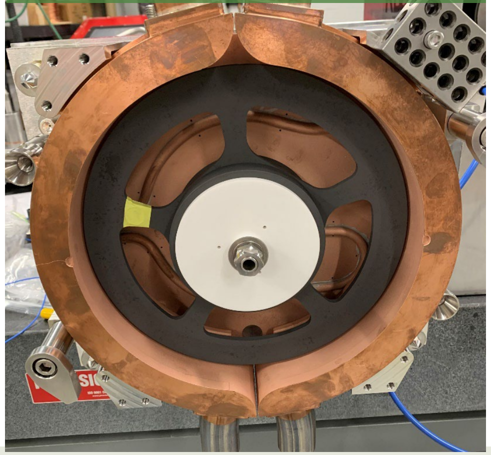
- Can be delivered if scheduled

Primary beam	Max energy [MeV/u]
^{36}Ar	290
^{40}Ar	262
^{48}Ca	242
^{70}Zn	241
^{64}Zn	254
^{78}Kr	254
^{86}Kr	230
^{82}Se	227
^{124}Xe	228
^{198}Pt	188
^{208}Pb	184
^{209}Bi	186

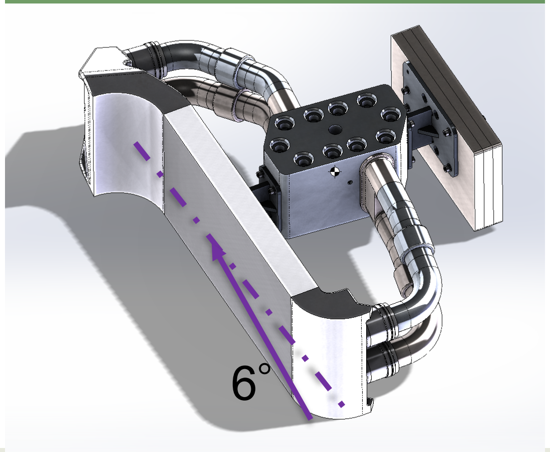
Upgrades for Power Ramp Up after the First Experiments in 2022

- Support 5 kW and more power operation:
  - Static drum target replaced with the rotating Carbon target
  - Flat beam dump replaced with the S-shape beam dump
- Improve the performance of isotope separation and rate
  - 2 quadrupole doublets in pre-separator replaced with larger aperture triple
  - Install 3 corrector (steering) magnets in pre-separator
- All installed

Rotation Target

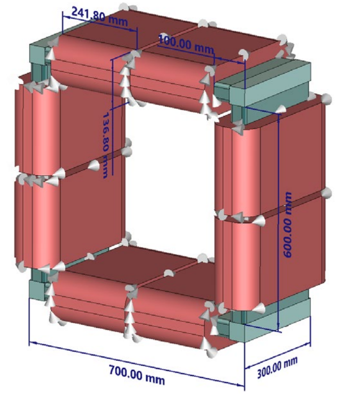


S-Shape Beam Dump



New Triplet (CIQT4)

New Corrector



FRIB
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

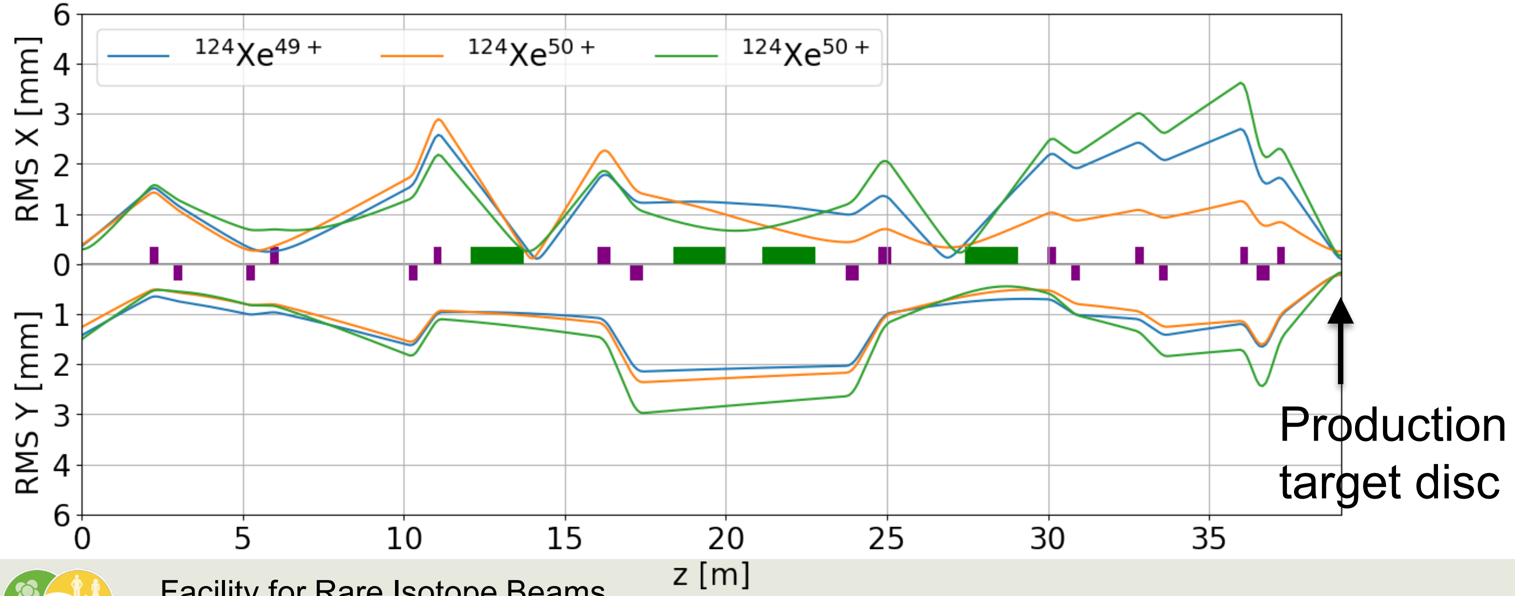
Adopted Multi-Charge-State Acceleration as Normal Operation

- Pros
  - Delivery of x2~x3 higher power heavy ion beams to the target compared to single charge state
    - » ^{124}Xe stripping efficiency is 33% into 50+ and 77% into 49+,50+,51+
    - » Extremely beneficial if the ion source has intensity limitation e.g., ^{198}Pt beam
  - Reduction of power deposition on the charge selection slits downstream of the stripper
    - » Less activation of cooling water and air
    - » Less prompt radiation and induced radio activation
- Cons
  - Beam tuning takes more time (~42 hours for new beam)
    - » Align the transverse position of the center charge state (e.g. $^{124}Xe^{50+}$) in each quadrupole in the bend section
    - » Tune neighbor charge state (e.g. $^{124}Xe^{49+}$, $^{124}Xe^{51+}$) to the same transverse position after the bend section
    - » Tune sextupoels in the bend section to minimize the position offset in 6D phase space
    - » Measure Twiss parameters for each charge state in each section
    - » Find the optimum quadrupole setting to match transversely by using an envelope simulation

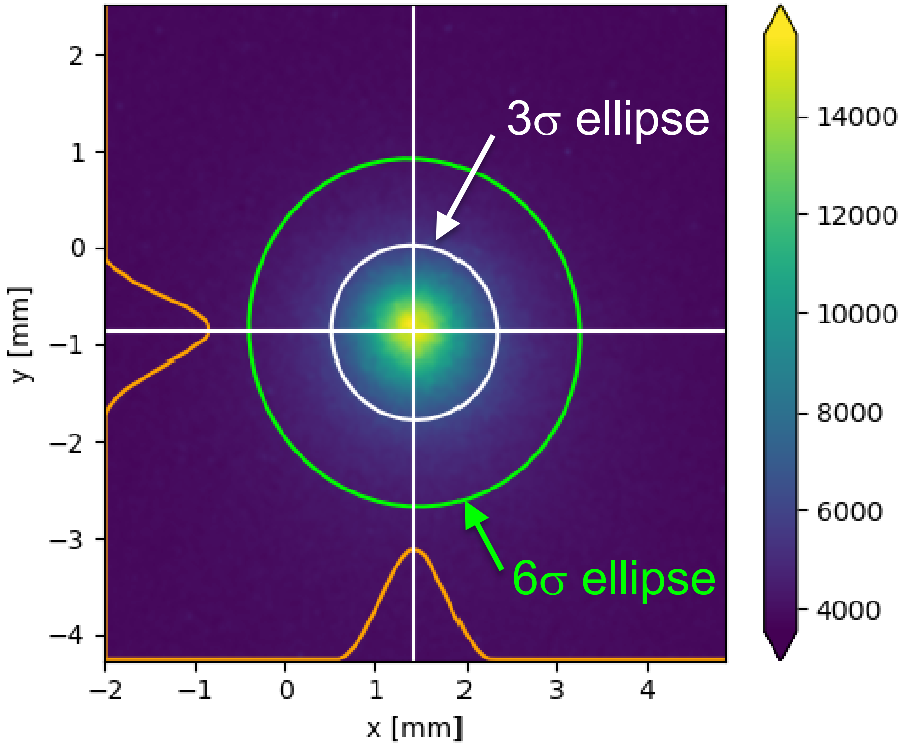
Adopted Multi-Charge-State Acceleration as Normal Operation

- Accelerated multi-charge-state beams after the stripper
  - ^{124}Xe: 49+, 50+, 51+ (3q, operation)
  - ^{198}Pt: 66+, 67+, 68+ (3q, operation)
  - ^{64}Zn: 28+, 29+ (2q, operation)
  - ^{48}Ca: 19+, 20+ (2q, demonstration)

^{124}Xe-3q beam envelope in final focusing system (phase space measured by profile monitor)



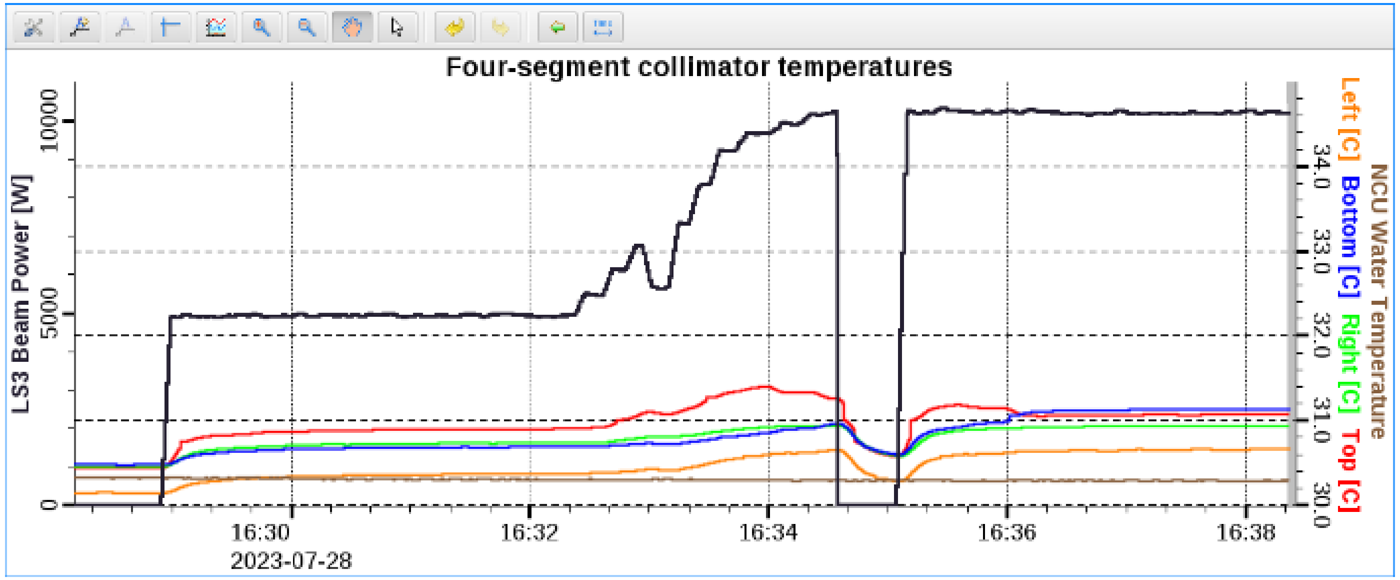
^{124}Xe-3q Beam image on target disc w/o rotation, RMS size x,y = 0.3, 0.3 [mm]



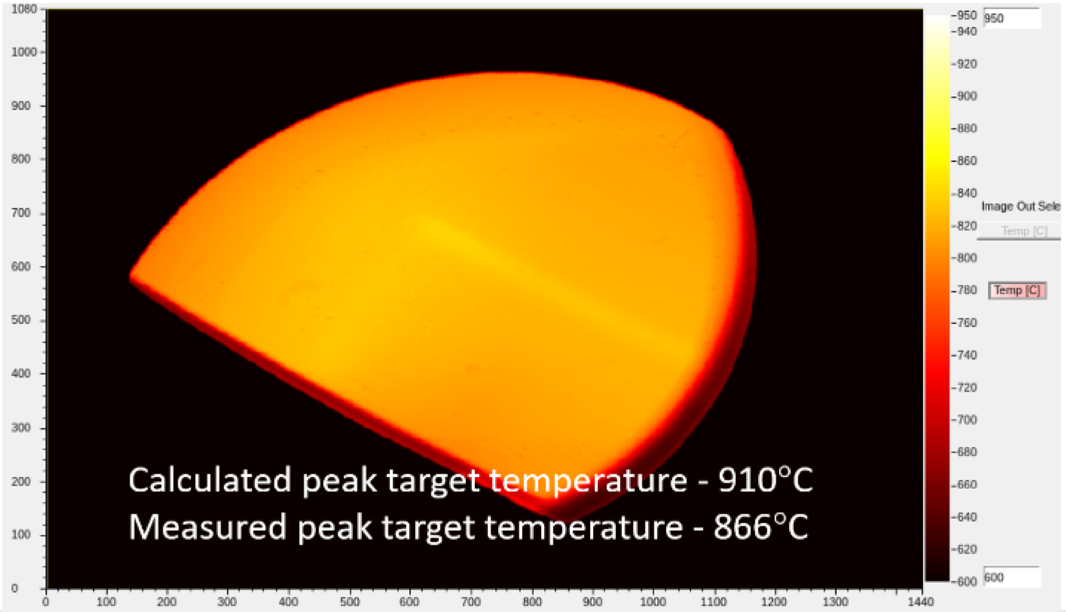
Demonstrated 10 kW Beam Before Shutdown This Summer

- Send 10 kW - ^{48}Ca and ^{36}Ar beam to the 8 mm Carbon target and S-shape beam dump, measured peak temperature by the thermal camera
- No major issue found, and 10 kW operation will start within a year

Beam power history and the temperatures of the collimator upstream of the target disc



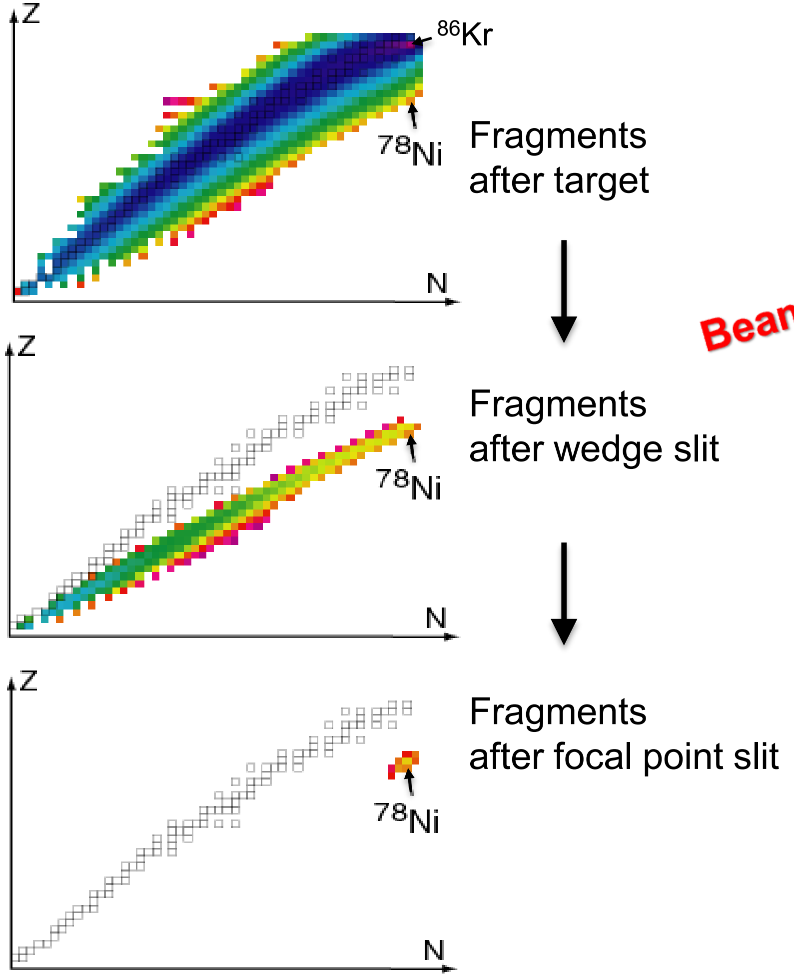
Thermal image of the target disc

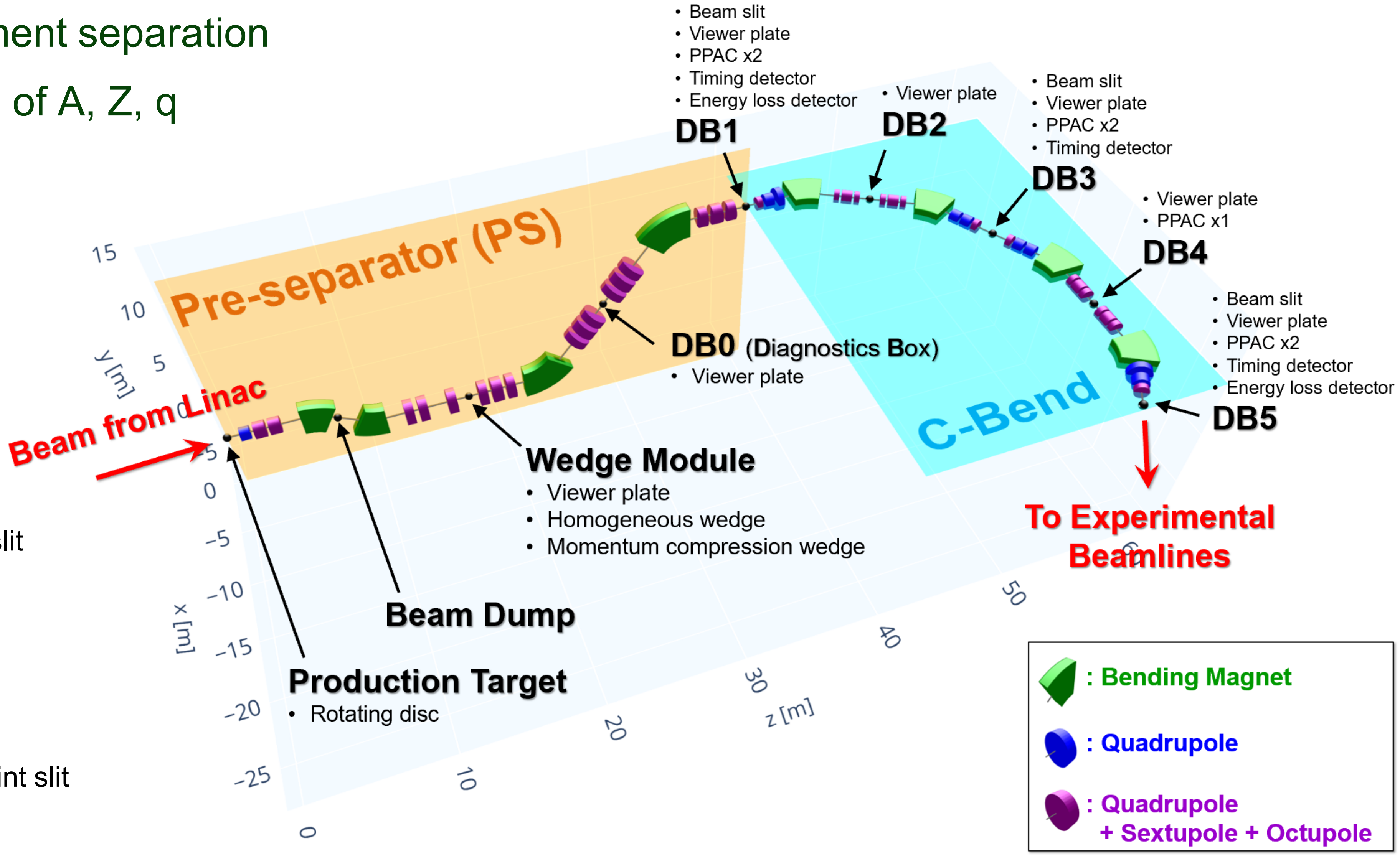


Isotope Purification in ARIS

- Up to 3-stage in-flight fragment separation
- Atom-by-atom identification of A, Z, q

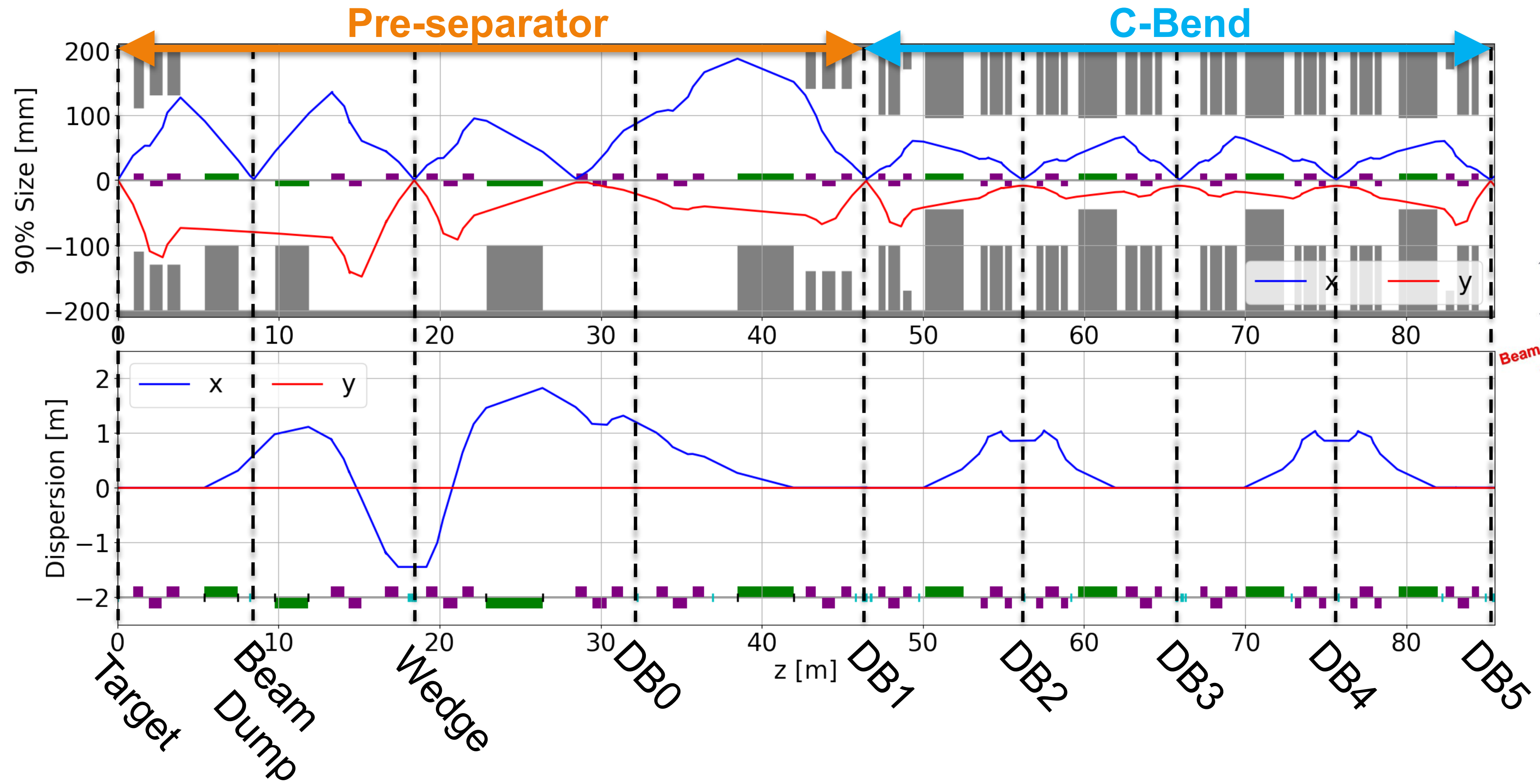
Example: ^{78}Ni from ^{86}Kr

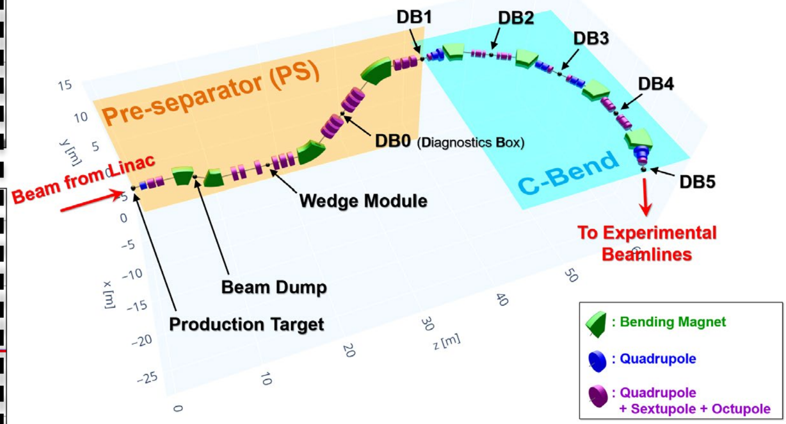




Beam Optics Design of ARIS

- Multi-stage separation
  - Pre-separator applies 3x momentum compression by wedge material
  - C-bend can operate as one or two achromatic focusing for more separation
  - Beam Optics Designed by COSY infinity (X: dispersive, Y: non-dispersive plane)

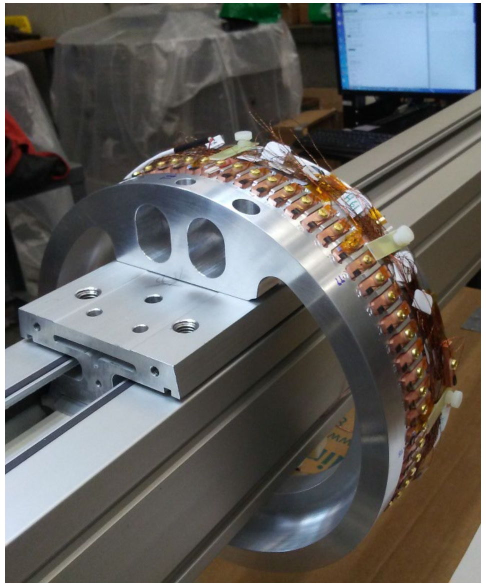




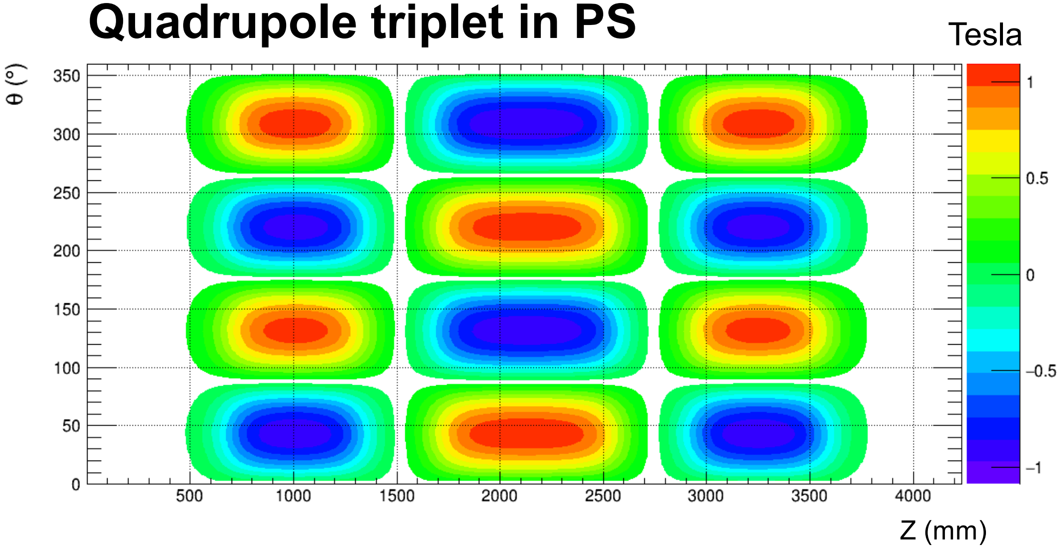
Magnet Mapping Completed Offline

- ARIS magnets contain Quad, Sext, and Octupole, and inducible independently
- Mapping completed for all higher multipole fields offline (most magnets are superconducting)
- Mapping results are fit by Enge function including the induced current and used in beam dynamics code for optics calculation

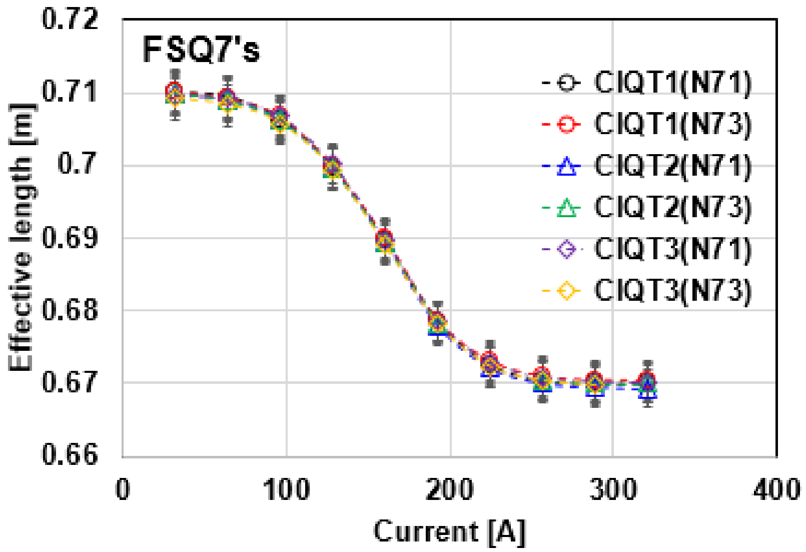
Mapper: hall sensor every 5 degree about a ring



Quadrupole triplet in PS



Effective length for each quad with the same design

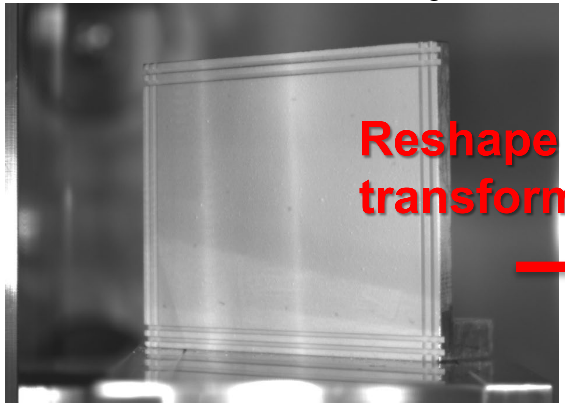


FRIB
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

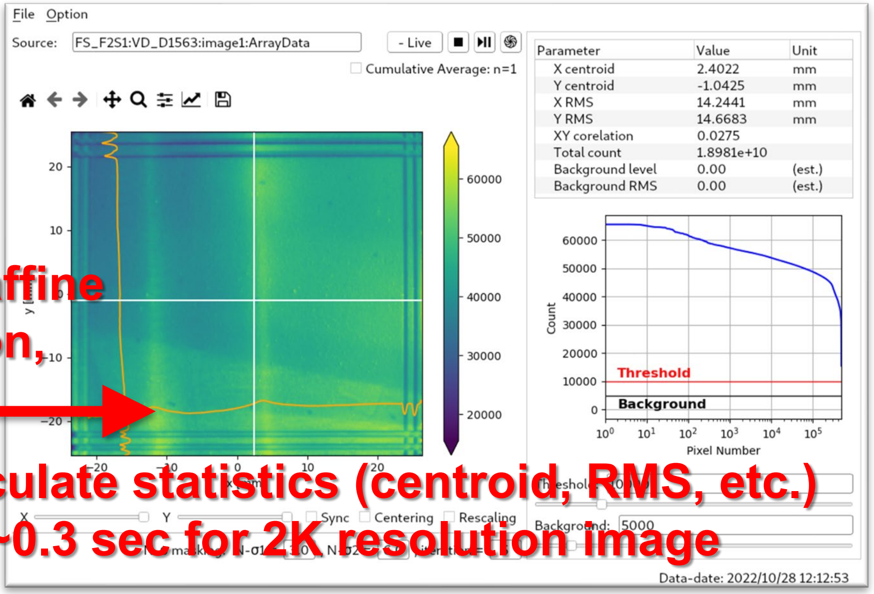
Viewer and PPACs Installed and Calibrated

- Installed viewer plate and PPAC (Parallel Plate Avalanche Counter)
- Viewer plate
  - Pros
    - » Fast measurement ~0.5 sec
    - » Large enough compared to the beam
  - Cons
    - » Required beam power ~0.2 W

- Raw camera image

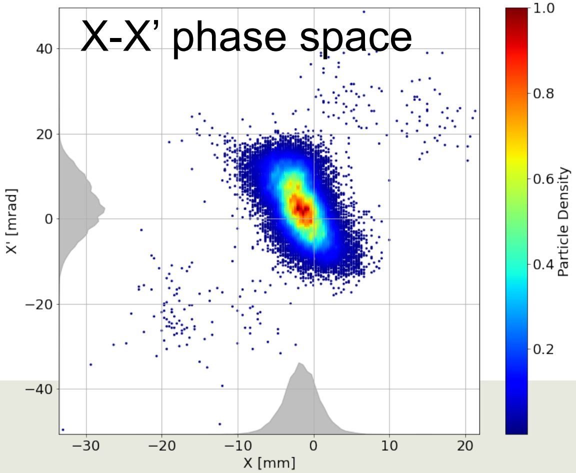


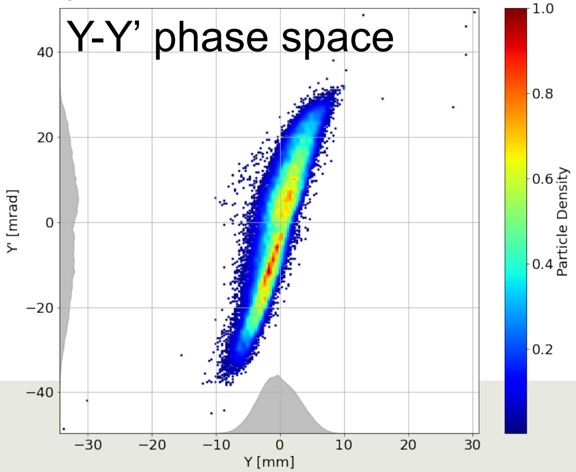
- Viola (Online Viewer App.)



- PPAC
  - Pros
    - » Trackable particle event by event
    - » Phase space measurement by two PPACs
    - » Measurable a very low-intensity beam
  - Cons
    - » Slow measurement ~5min
    - » Maximum rate is limited by trigger system ~2000 pps

- PPACs result at DB5 (^{64}Fe)

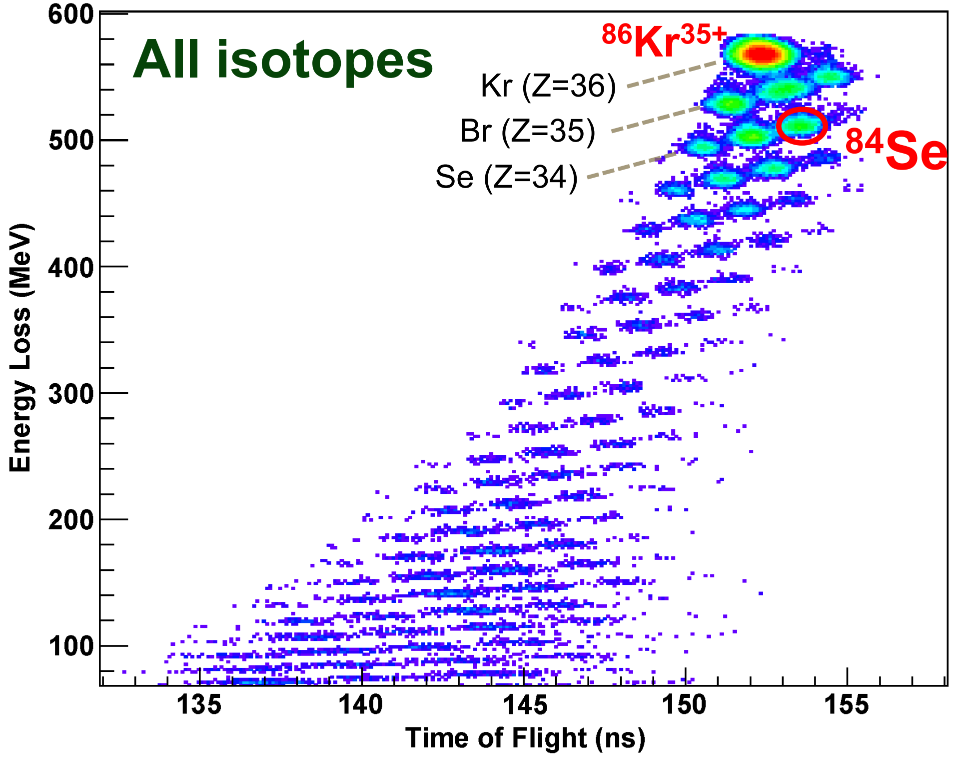


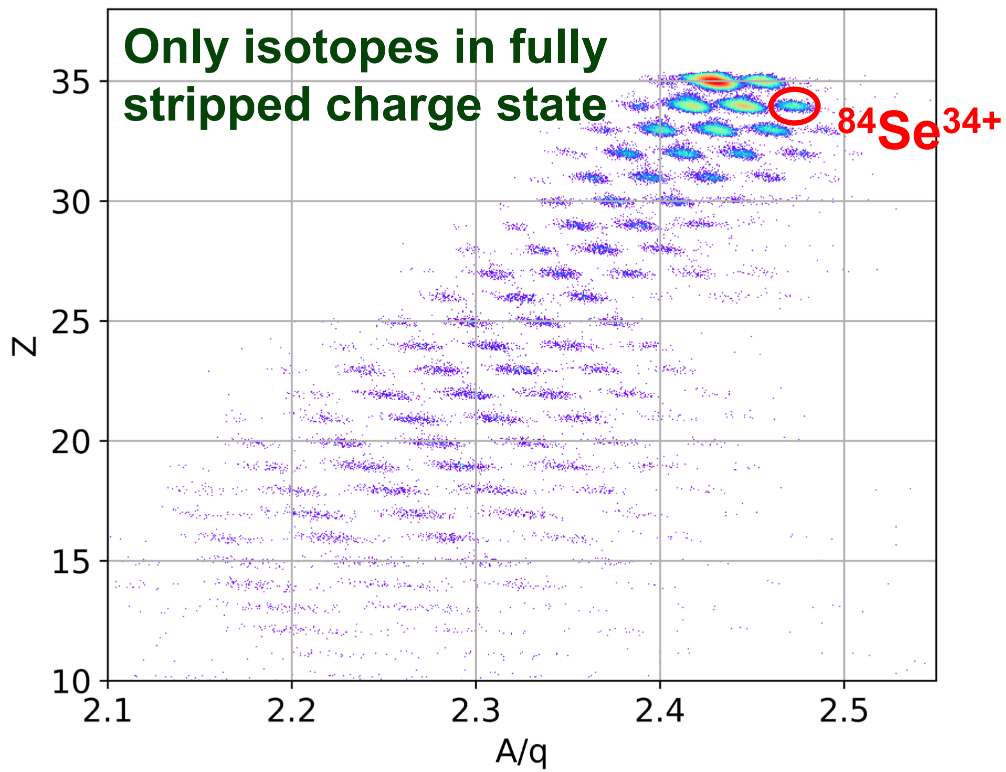


Particle Identification (PID) Performed in ARIS

- Particle identification (PID) performed by measurements of energy loss, total kinetic energy, and time-of-flight

>> Identify and calculate particle rates of the RI beam for user



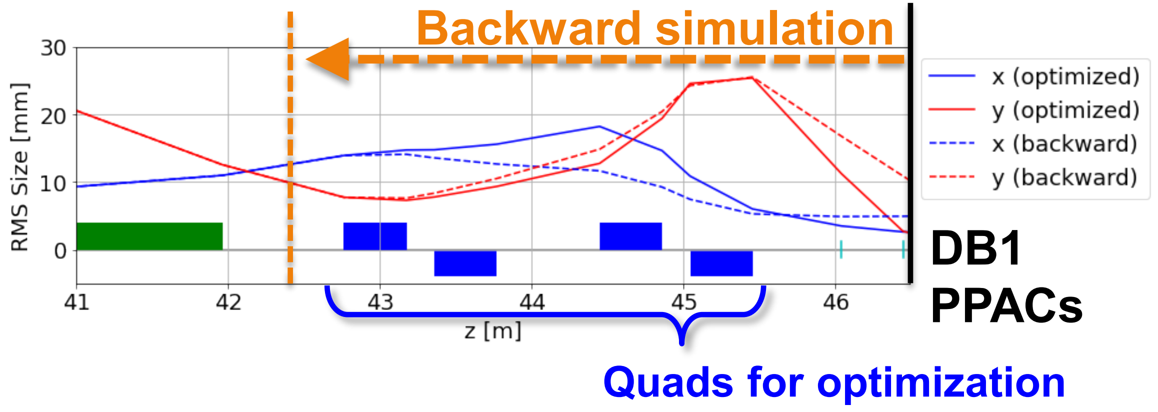


Transverse Matching Performed to Improve the Separation

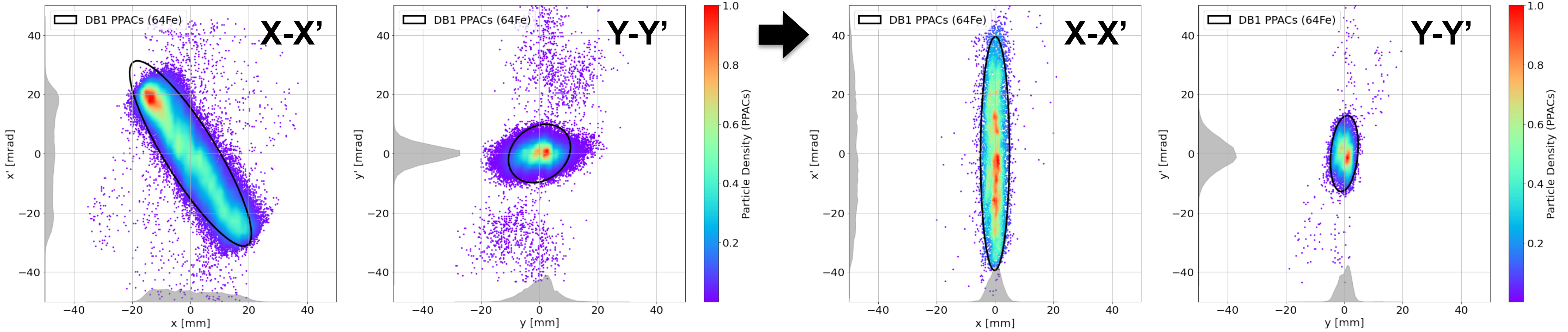
- Quadrupole optimization for Twiss parameter matching
  1. Measure the phase space at the matching point
     » PPACs measure the beam phase space directly
     » Quadrupole scan provides the beam phase space also
  2. Simulate backward to 3~4 upstream quadrupoles
  3. Optimize quadrupoles by using simulation
     » 4-knobs optimization takes **~1 sec** by using FLAME[1] simulation
  4. Apply optimized quadrupole settings to the real machine

>> The entire procedure takes ~10 minutes.

- Beam envelope simulation result



- ^{64}Fe phase space at DB1 PPACs **before matching**
- Phase space **after matching**

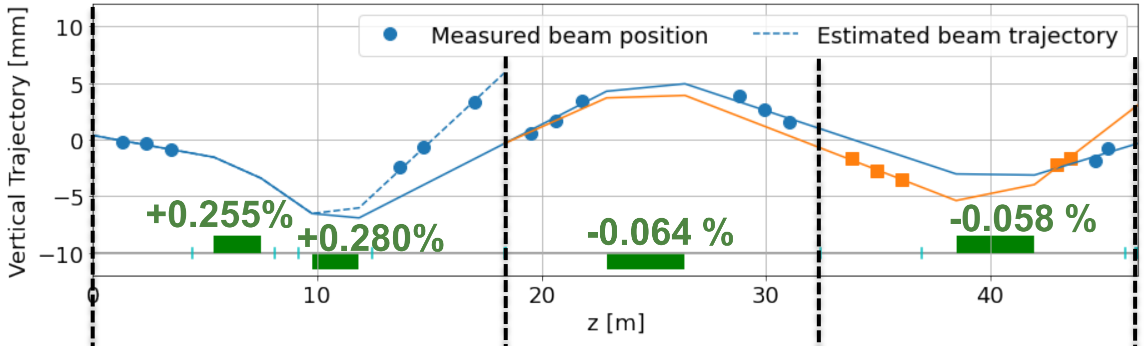


[1] FLAME (https://frib-high-level-controls.github.io/flame-utils/)

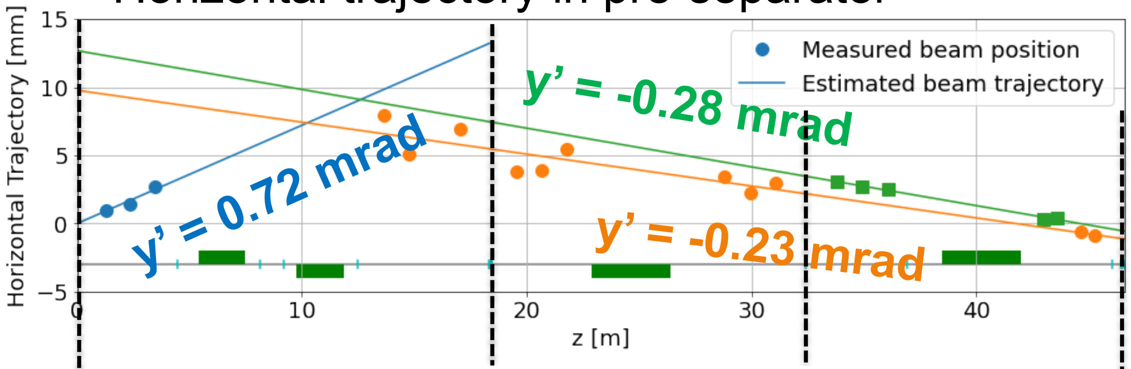
Beam-Based Alignments Performed by Q-offsetting Method

- Quadrupole offsetting method
  1. Inject parallel beam from linac and turn off all quadrupoles, sextupoles, and octupoles in ARIS
  2. Turn on a quadrupole one by one and check the centroid shift at the downstream viewer
  3. The amount of the centroid shift gives the beam centroid offset against the magnetic center
  4. Simulate the beam trajectory to reproduce the kick from the quadrupoles
  5. Difference between the trajectory and the centroid offset shows the misalignment of the quadrupoles

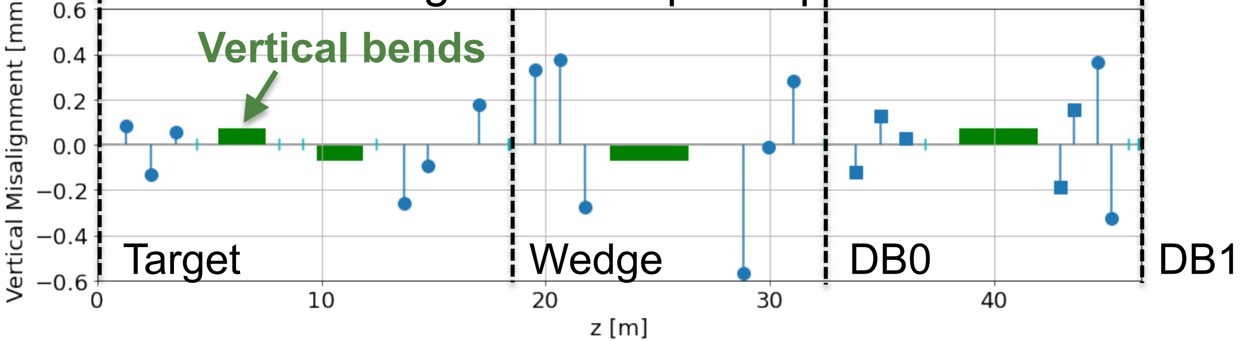
- Vertical trajectory in pre-separator



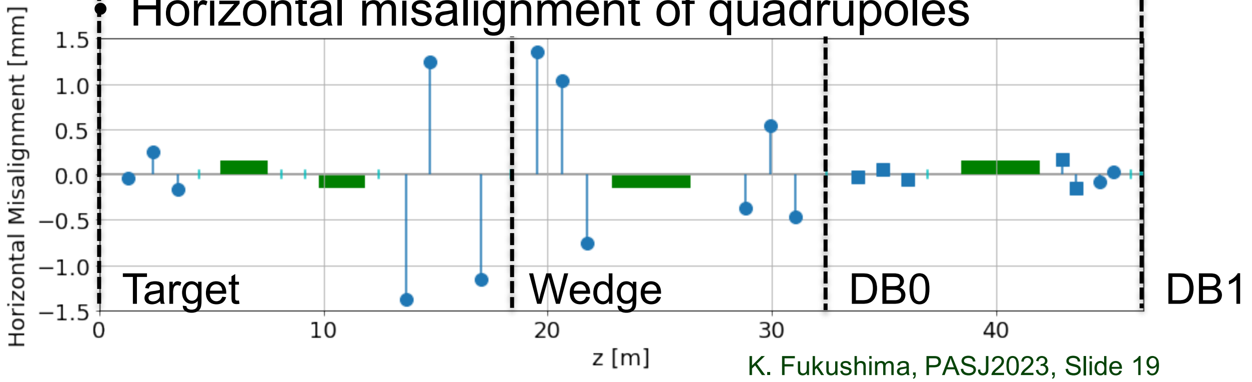
- Horizontal trajectory in pre-separator



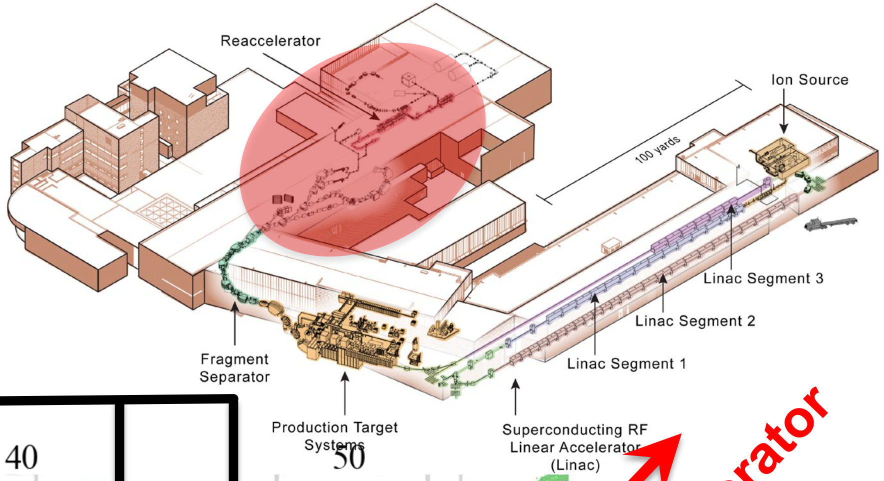
- Vertical misalignment of quadrupoles



- Horizontal misalignment of quadrupoles

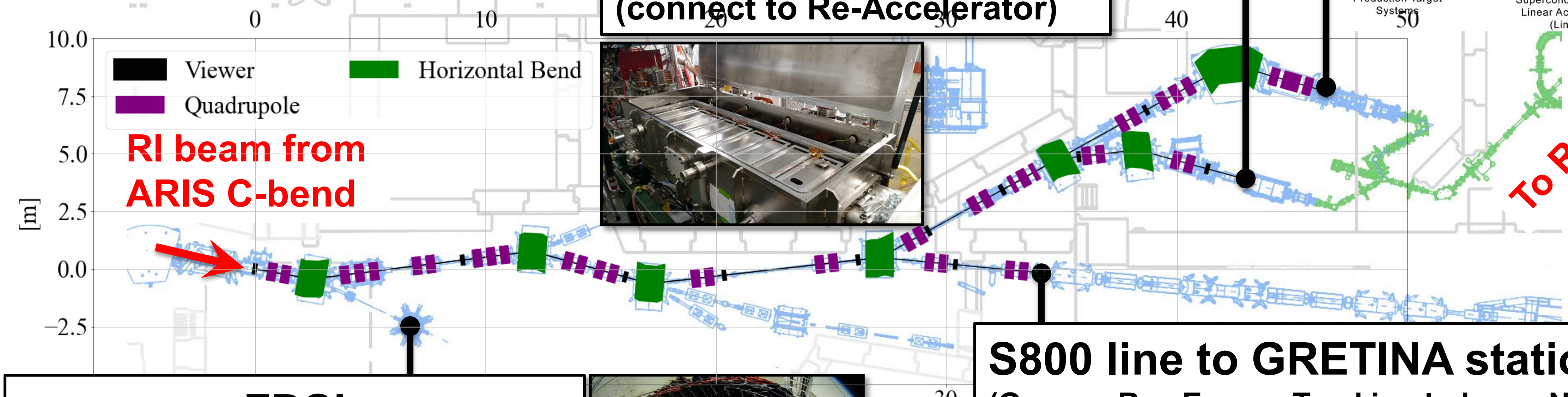


Experimental Beamline



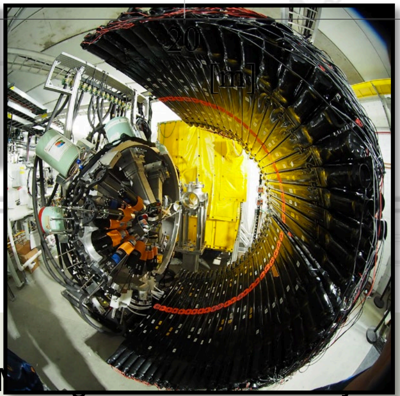
- Serves science with the unique availability of fast, stopped, re-accelerated beams

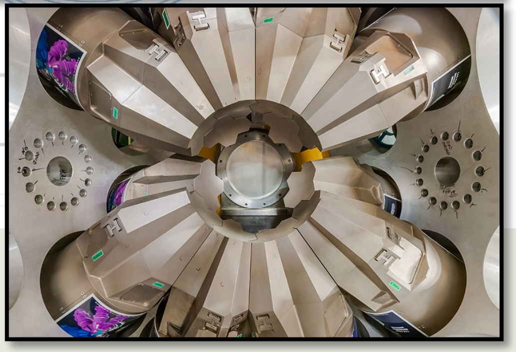
N4 line to gas stopper
(connect to Re-Accelerator)



S800 line to GRETINA station
(Gamma-Ray Energy Tracking In-beam Nuclear Array)

FDSi
(FRIB beta-Decay Station initiator)



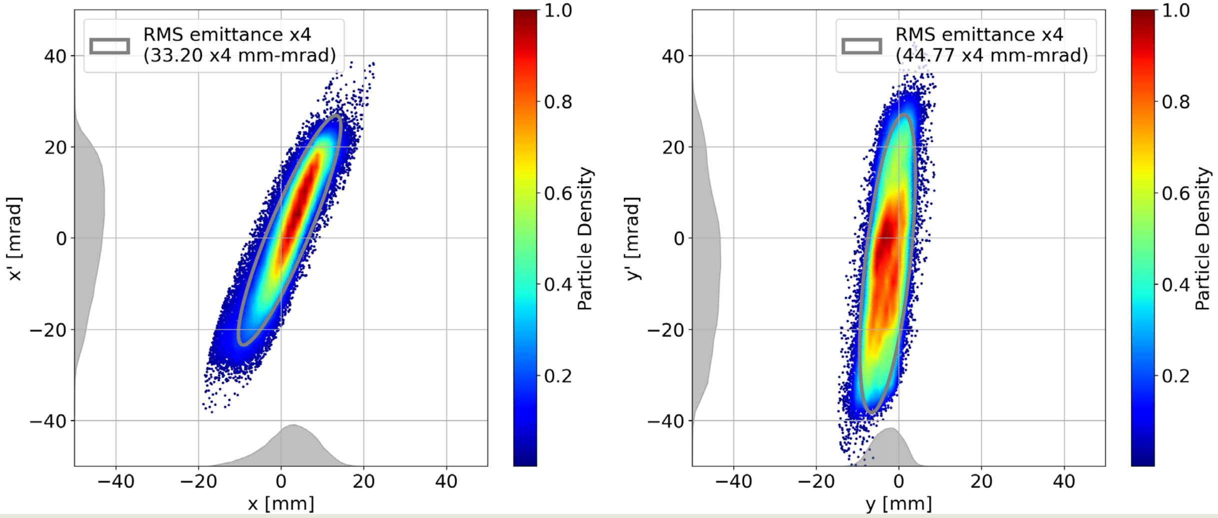


Beam Tuning in Experimental Beamlines

- The fragments sent from ARIS differ in each experiment due to the different slit settings etc.
- Transverse matching at DB5 transports the beam to the user station with the highest efficiency
- Mostly, more exotic fragments setting from ARIS have larger emittance to maximize the total rate by sacrificing the purity

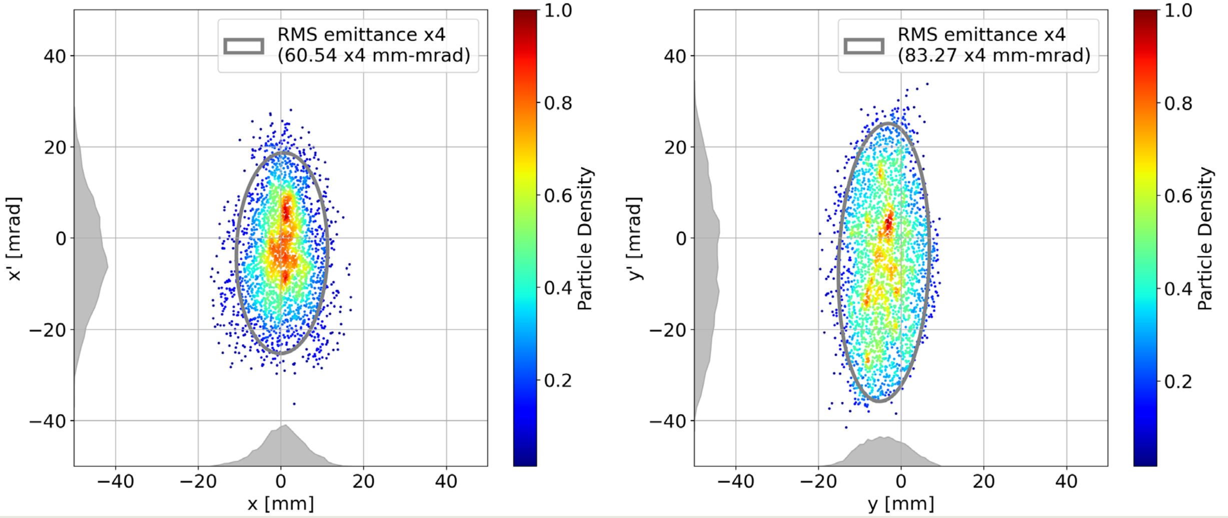
^{28}P (2.3e6 pps @ 5kW)

Geom. RMS Emittance X, Y = 33.2, 44.8 [mm-mrad]



^{42}Si (12 pps @ 5kW)

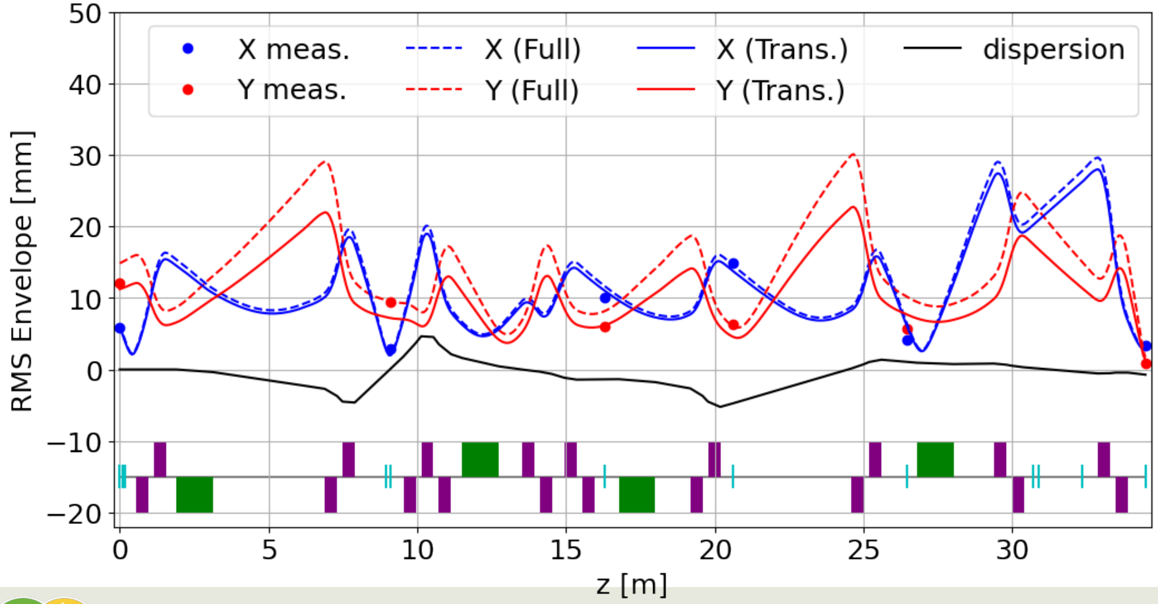
Geom. RMS Emittance X, Y = 60.5, 83.3 [mm-mrad]



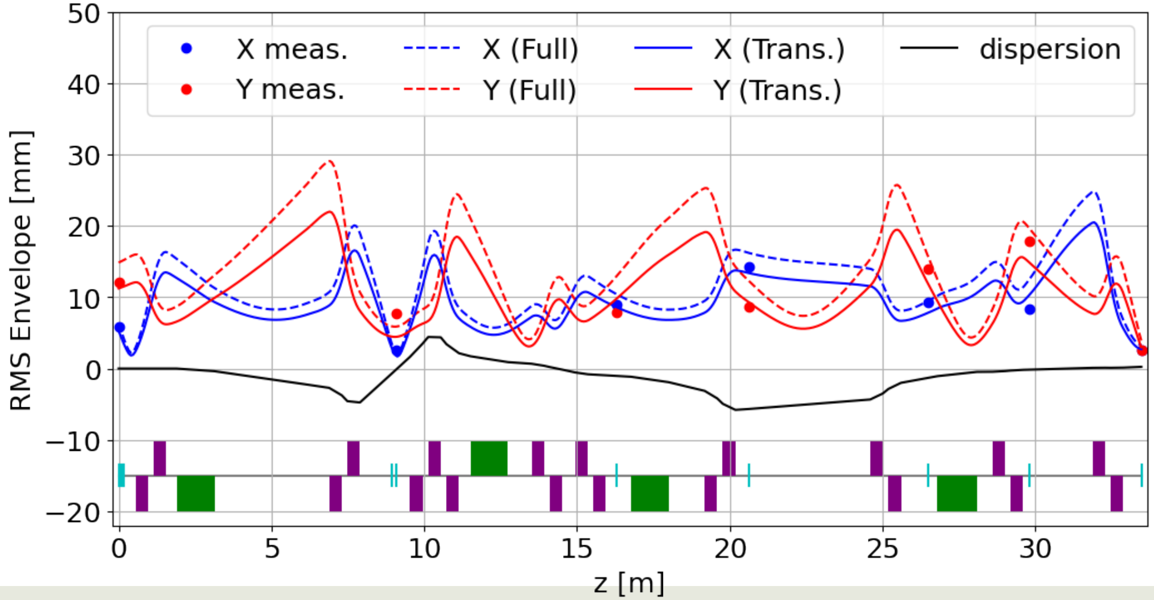
Envelope Simulation and Beam Size Measurements

- Verified beam sizes at each viewer plate, and it is consistent with the simulation result
- Simulated transmission is consistent with the measurements also
  - Centroid trajectory is corrected by viewers, but the tuning knobs (steering magnets) is not enough
- Conclusion: Performed optimum beamline setting for users

^{29}Mg beam envelope DB5 to S800
Calculated transmission 74% (82% in exp.)



^{29}Mg beam envelope: DB5 to N4 gas stopper
Calculated transmission 64% (50% in exp.)



Complexity of ARIS and Challenges

- Experimental beamlines consist of legacy magnets, and the apertures are small
- User request the maximum rate at their detector even in worse purity
  - In current beam power (~5 kW), we can only open slits to increase the rate of fragments
    - » The beam emittance from ARIS gets larger than the initial estimation
    - » Once the power is ramped up, ARIS serves more separation by narrower slits, and squeezes the emittance
- Unique mixed vertical and horizontal separation with momentum compression
  - Performance of the momentum compression depends on the wedge quality
    - » Dispersion must be matched to the effective wedge angle and thickness
  - Momentum compression converts longitudinal emittance to transverse emittance in dispersive plane
    - » Legacy experimental beamlines did not designed for the large vertical emittance
- High order correction with 33 sextupoles and 27 octupoles
  - All superconducting, ramping time is slow
  - Sextupole excite dipole component also, could be compensate by additional corrector magnets
  - Tuning requires more time, but currently the user operation schedule is prioritized

Summary

- FRIB conducted 16 experiments, delivered ~250 unstable isotope beams in the first year
- Linac performed up to 5 kW, 240 MeV/u with various primary beam
- The performance of ARIS has been successful in user experiments, but areas for improvements exist
- Demonstrated 10 kW beam to the rotating Carbon target and S-shape beam dump
- Performing phased development of target/dump system

Phase	~1 kW	~10 kW	~20 kW	~50 kW	to 400 kW
Production Target	Static Mult-Position	Single-Slice Rotating	Single-Slice Rotating	Single to Multi-Slice Rotating	Multi-Slice Rotating
Beam Dump	20 deg. Static (Flat shape)	6 deg. Static (S-shape)	6 deg. Static (S-shape, better cooling)	Rotatable beam dump, 1 mm wall	Rotatable beam dump, 0.5 mm wall

Completed!

WE ARE HERE!

- (Upgrade to 400 MeV/u, R&D in progress)

Ongoing Accelerator Projects in the U.S.

Lots of opportunities are available in the accelerator field in the U.S.

- Facility for Rare Isotope Beams (FRIB) @ MSU
  - $730 million (completed) + $529 million for next **5 years** operation
- Electron-Ion Collider (EIC) @ BNL
  - $1.7 ~ $2.8 billion, aiming to complete in **2031**
- Spallation Neutron Source (SNS) - Second Target Station @ ORNL
  - $1.8 ~ $3 billion , aiming to complete in **2037**
- Proton Improvement Plan-II (PIP-II) @ FNAL
  - $978 million, aiming to complete in **2033**
- Linac Coherent Light Source II High Energy (LCLS-II-HE) @ SLAC
  - $290 ~ $660 million, aiming to complete in **2030**

Acknowledgements

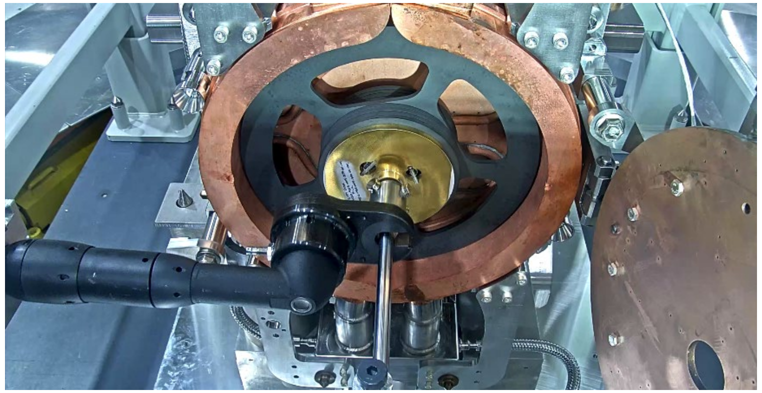
- This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.

- Backup.

Beam Development for User Experiments

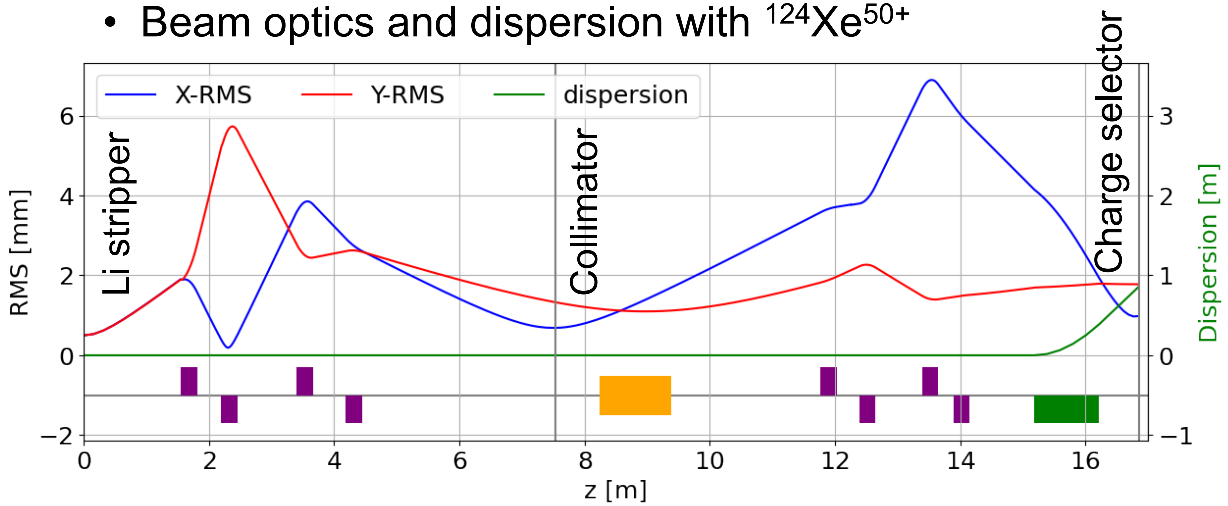
- Once the experiment proposal is approved:
  - Optimize and install primary beam energy, target disc thickness, and wedge thickness
- Primary beam development (PDT)
  - Development of new primary beam setting takes ~42 hours
  - Restoring of primary beam setting takes ~24 hours
- Secondary beam development (SDT)
  - Measure the effective thickness of each material
  - Optimize the detector setting for lighter or heavier ions
  - Perform particle identification by ARIS detectors
  - Maximize the rate of the fragment of interest (FOI)
    - » Rigidity scan: find FOI energy center by scanning the dipole field
    - » Transverse matching: optimize the phase space at the slit
  - Total ~1 week including communication with users

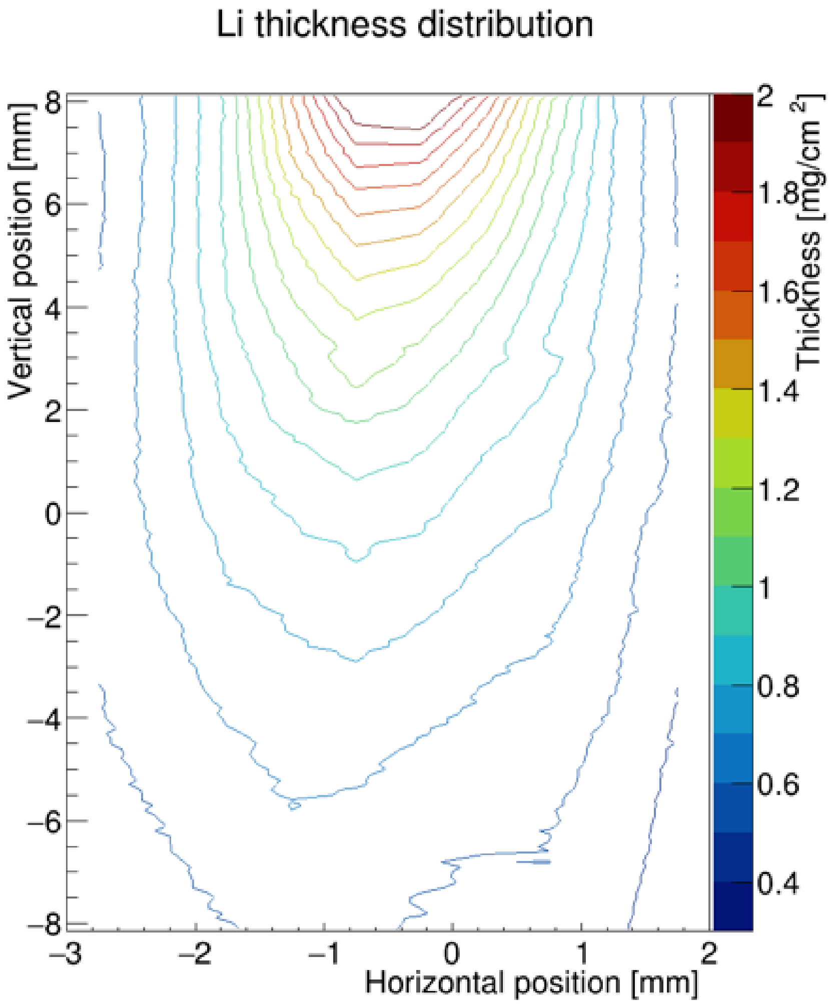
- Target Disk Changes by Remote Handling



Future Mitigation Approach of Stripper Effects on Beam

- Measured liquid Li stripper thickness distribution shows the thickness and uniformity have a trade-off
  - Thicker LLi provides more stripping efficiency
  - Non-uniformity causes more energy spread
- SRIM simulation with the measured thickness distribution agreed with the measured energy spread by using special optics
  - Beam optics and dispersion with $^{124}Xe^{50+}$

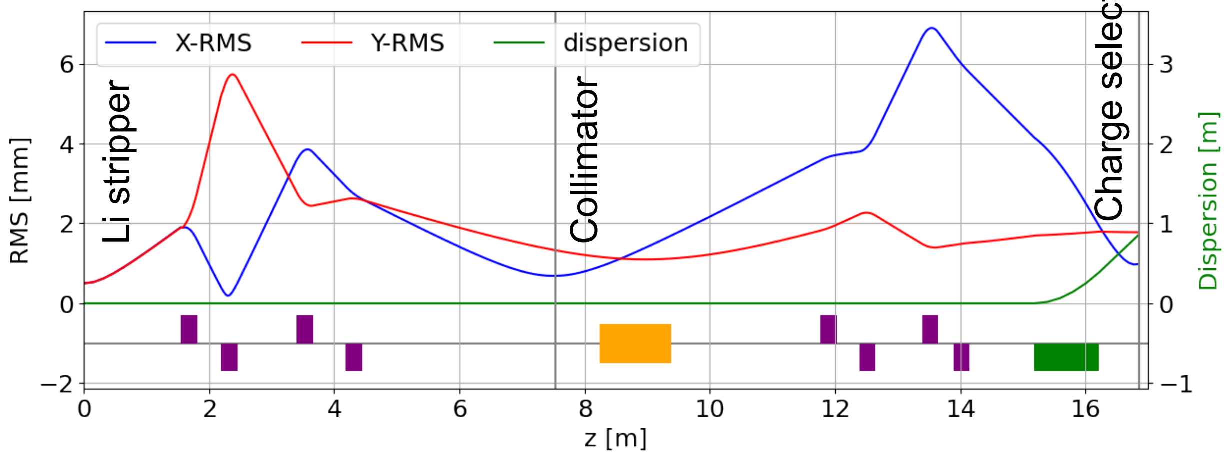


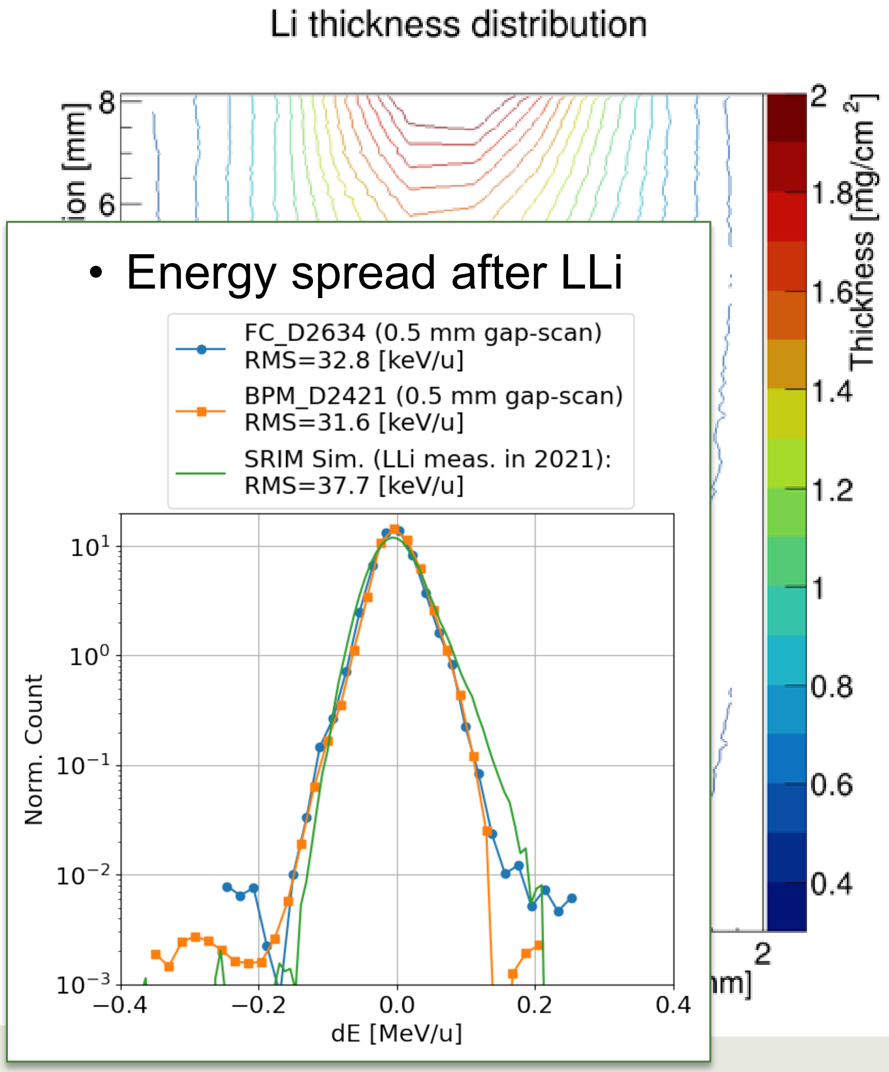


Future Mitigation Approach of Stripper Effects on Beam

- Measured liquid Li stripper thickness distribution shows the thickness and uniformity have a trade-off
  - Thicker LLi provides more stripping efficiency
  - Non-uniformity causes more energy spread
- SRIM simulation with the measured thickness distribution agreed with the measured energy spread by using special optics

- Beam optics and dispersion with $^{124}Xe^{50+}$





Optics Base Solution: Reduce the Beam Size on Stripper

- Reduce beam size on LLi stripper to minimize beam energy variation after the stripper
  - Requires replacement of the quadrupoles in upstream and downstream of the stripper
  - RMS beam size on the stripper could be from 0.5 mm to 0.25 mm