Commissioning of the Advanced Rare Isotope Separator ARIS at FRIB

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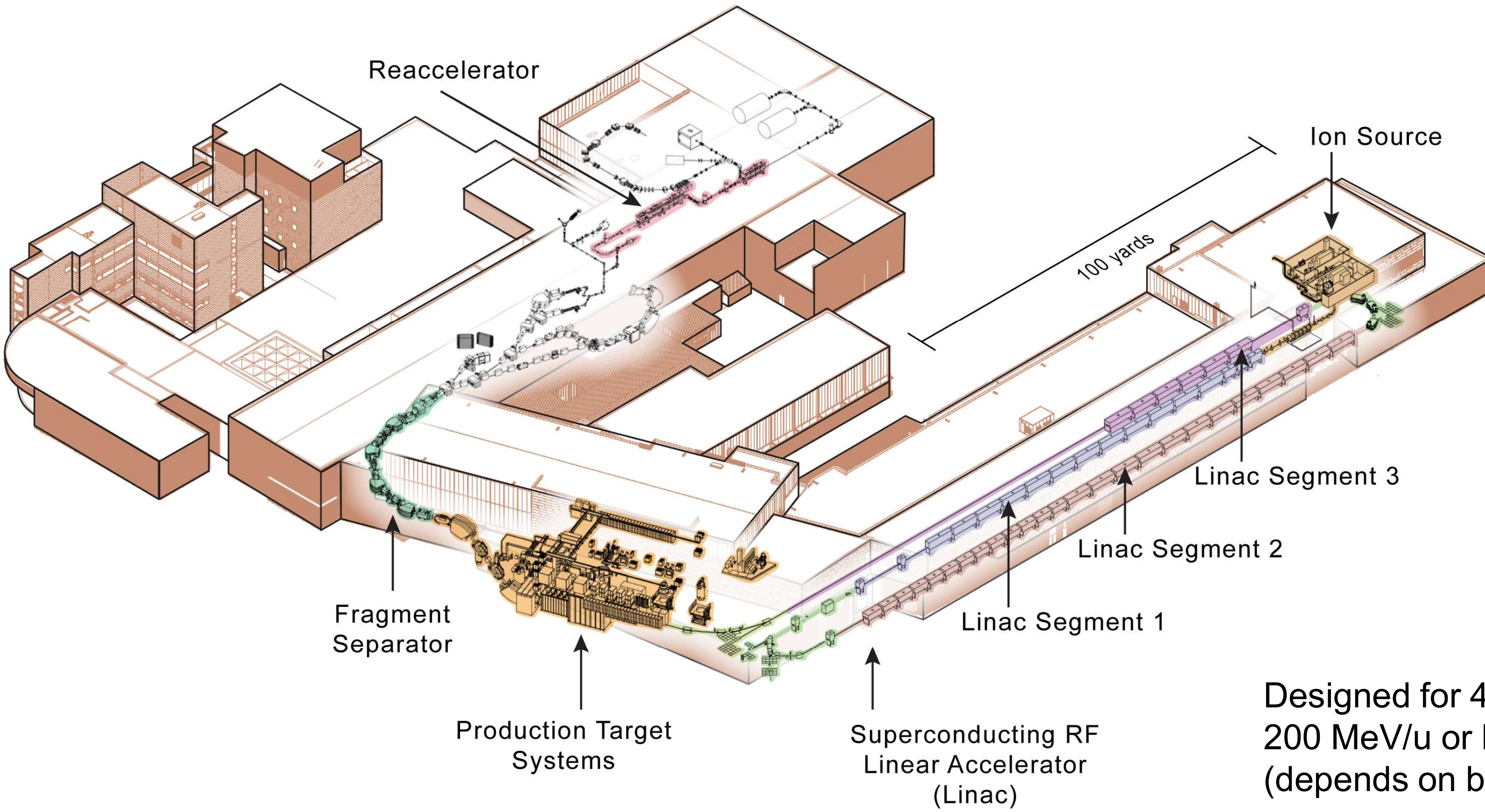
Outline

- Introduction/Layout
- Description of ARIS in-flight separator
  - Comparisons to previous facility
  - Optics properties
- Preparation of newly designed and built magnets
- Phased approach to power ramp up
  - Targets
  - Beam dumps
- Commissioning and first experiments

FRIB Layout

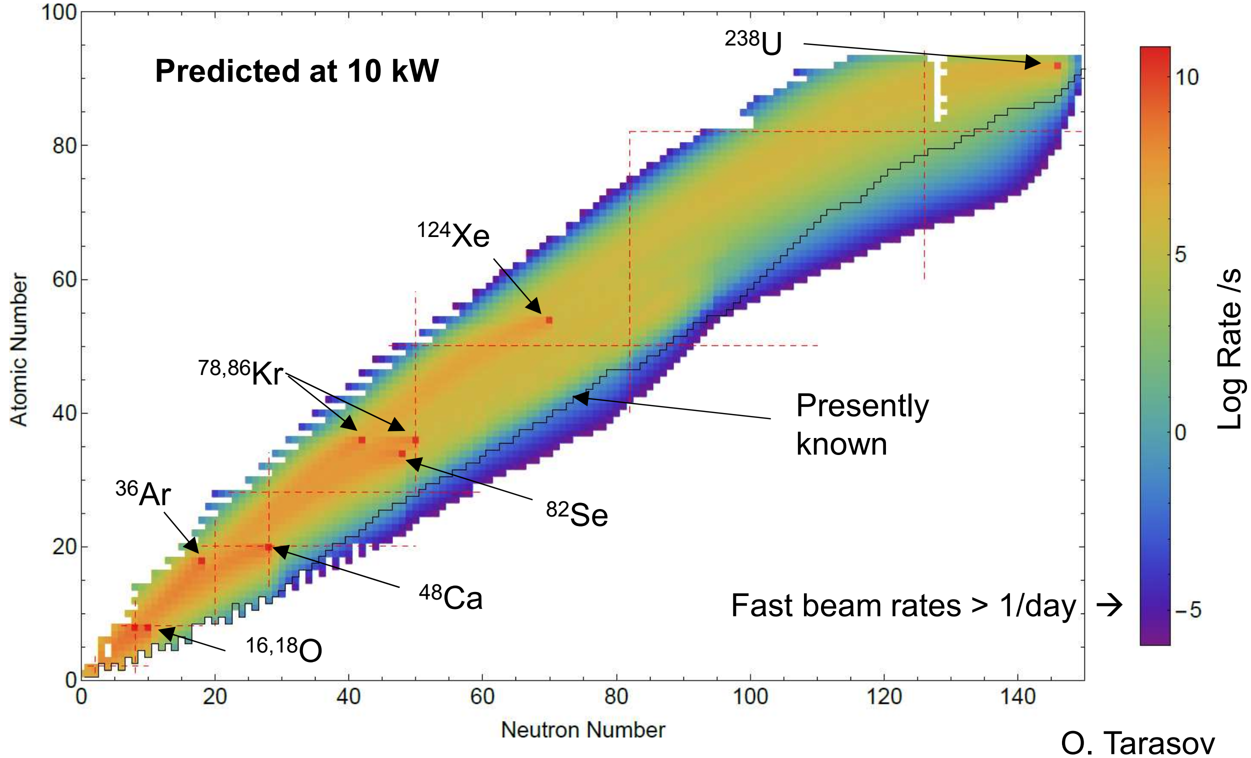
- Below ground linac and separator transport RIB's to ground level
  - Conceptual design started ~2010
  - Constructions started ~2014



Designed for 400 kW
200 MeV/u or higher
(depends on beams)

FRIB Primary Beams for First Experiments

- Many beams have already been developed at low power in linac
- Commissioning and early 2022 experiments
  - Started with 1 kW beams.   Next, 3 kW
- Working towards 10 kW operations in 2023 for most beams.



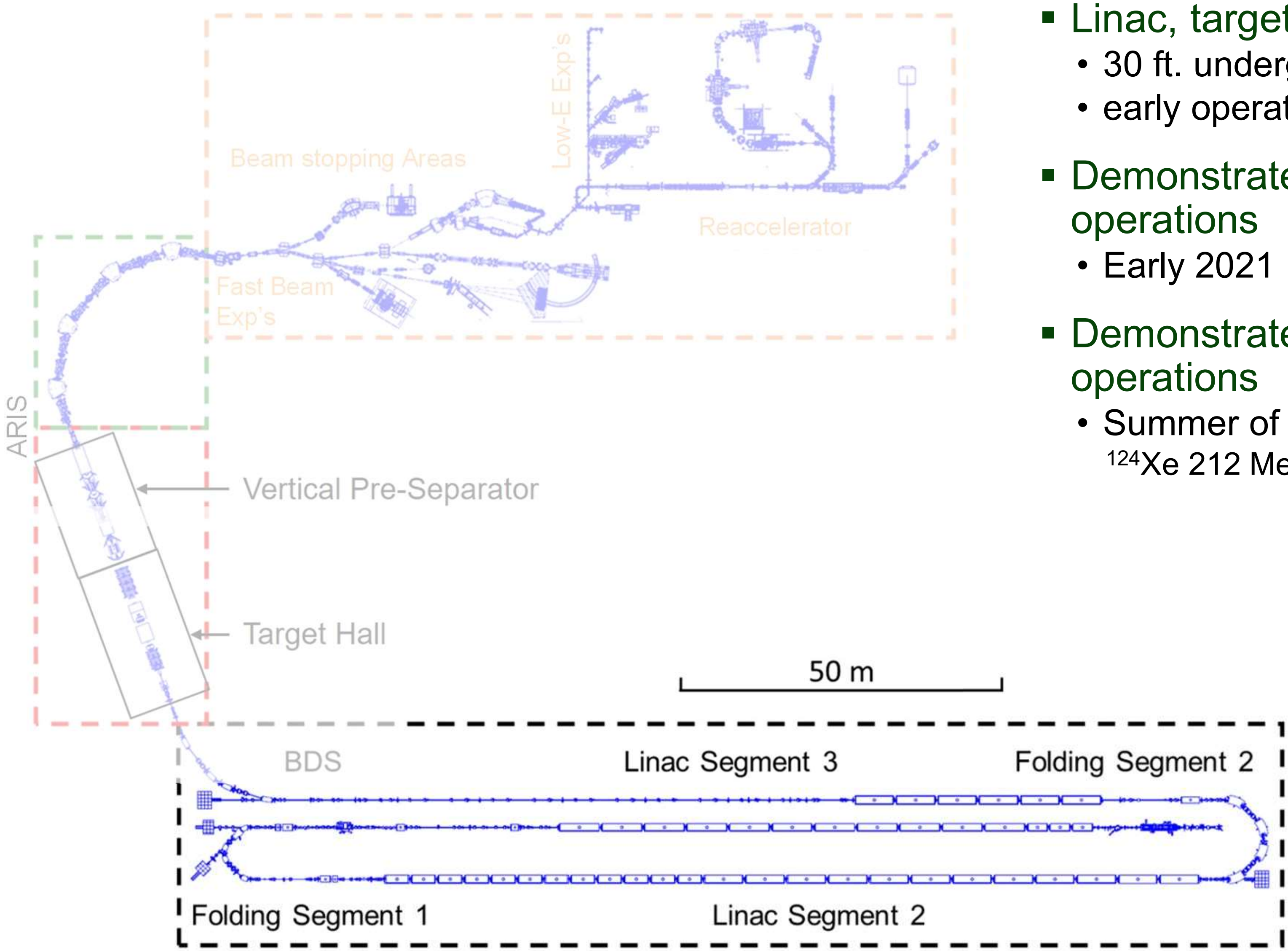
O. Tarasov

Used or ready for experiments

Beam	Early 2022 comm. & exper.	End Station
^{16}O		
^{18}O		
^{36}Ar		
^{48}Ca	April	FDSi
^{70}Zn*	July-Aug.	S800
^{82}Se	June	FDSi
^{78}Kr		
^{86}Kr		
^{124}Xe		
^{238}U		

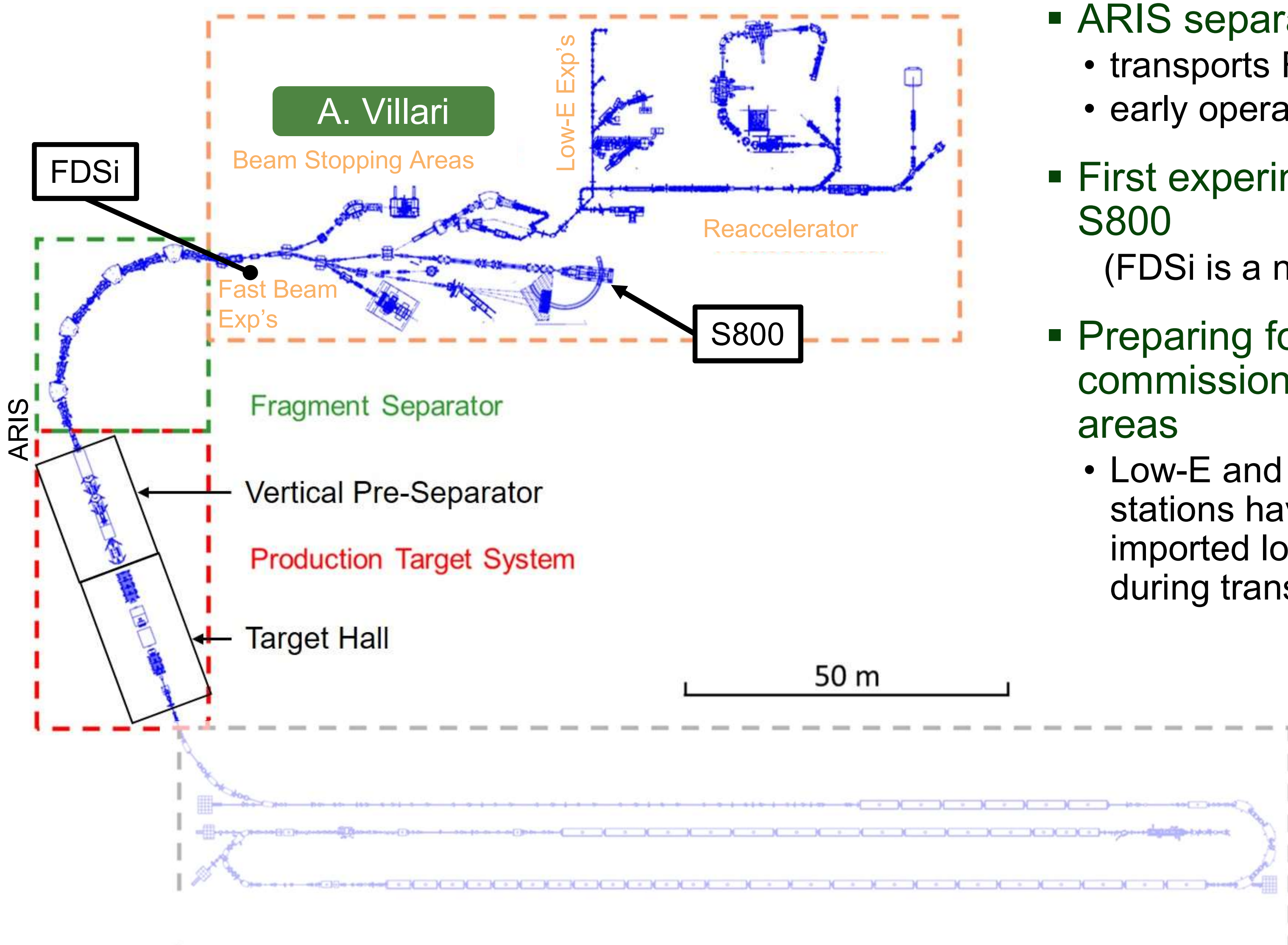
* ^{70}Zn not planned initially

FRIB Layout:
Linac



- Linac, target and dump
  - 30 ft. underground
  - early operations started in 2018
- Demonstrated 200 MeV/u operations
  - Early 2021
- Demonstrated multi-q state operations
  - Summer of 2021
    ^{124}Xe 212 MeV/u (49+, 50+, 51+)

FRIB Layout:
Separator and Experiment Areas



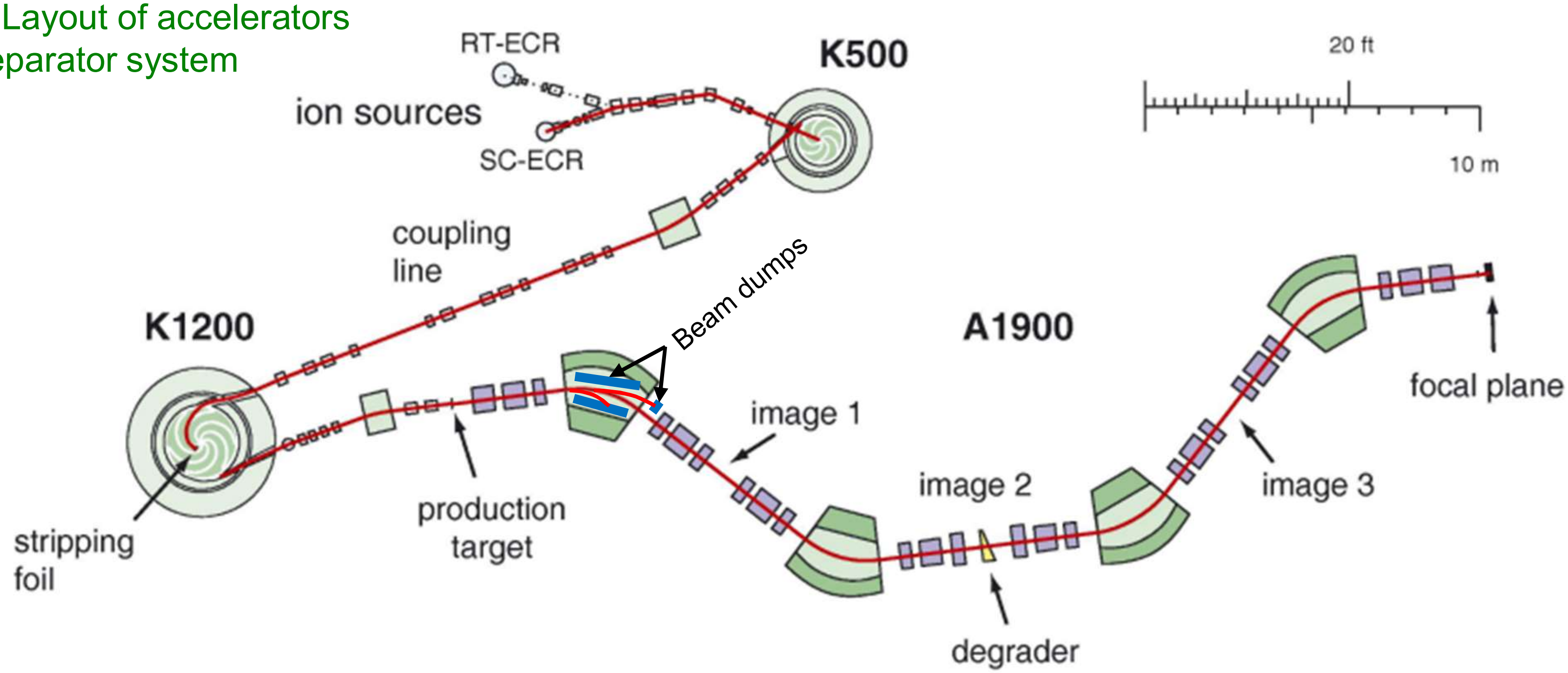
- ARIS separator
  - transports RIBs to ground level
  - early operations in 2022
- First experiments at FDSi and S800

  (FDSi is a new decay station)
- Preparing for re-commissioning of stopping areas
  - Low-E and Reaccelarator stations have been using imported long-lived sources during transition

Understanding Evolution to ARIS from Past

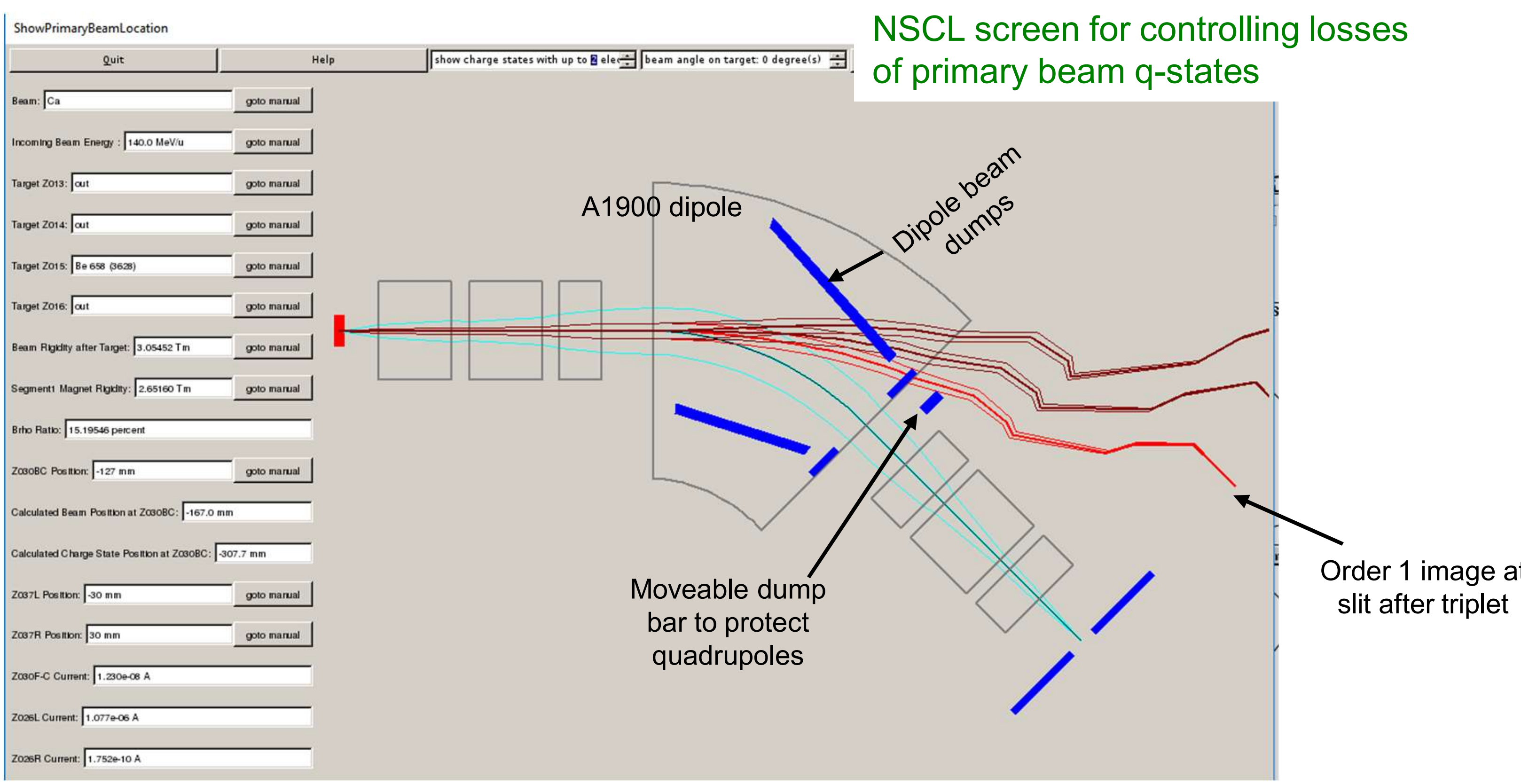
- Past NSCL facility
  - consisted of one-stage separation
  - static target for highest power operation (~2 kW max)
  - limited intensities due to
    - » acceptance limits of cyclotrons & lifetime of stripping foils

NSCL Layout of accelerators and separator system



NSCL method of dumping primary beams

- Dumping beam into or close to SC magnets
  - Not practical for operation and lifetime of equipment
    - » Power losses to cryo system sets limitations
    - » Designing for 400 kW operations very challenging

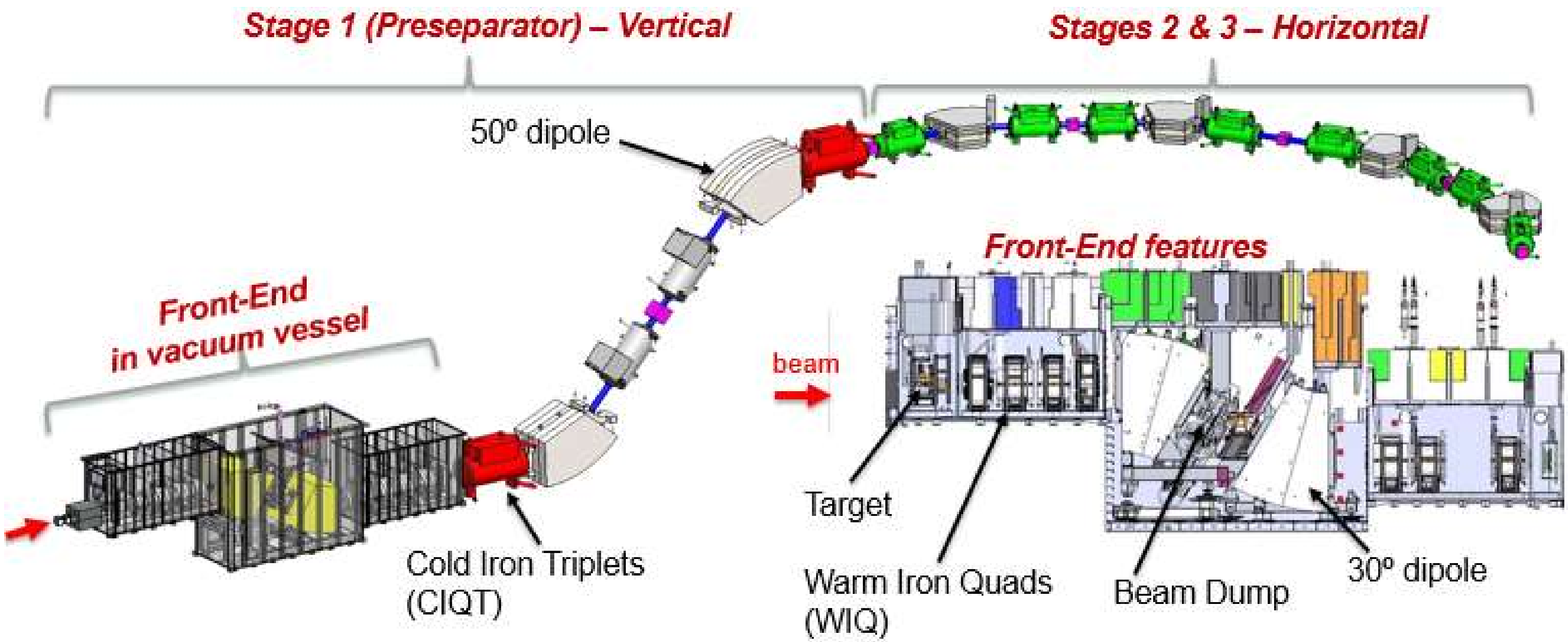


ARIS Fragment Separator

- Multi-stage separation
  - Reduces impurity rates for tracking at later stages
  - First stage applies ~3x momentum compression
    - » better matching to existing beam lines

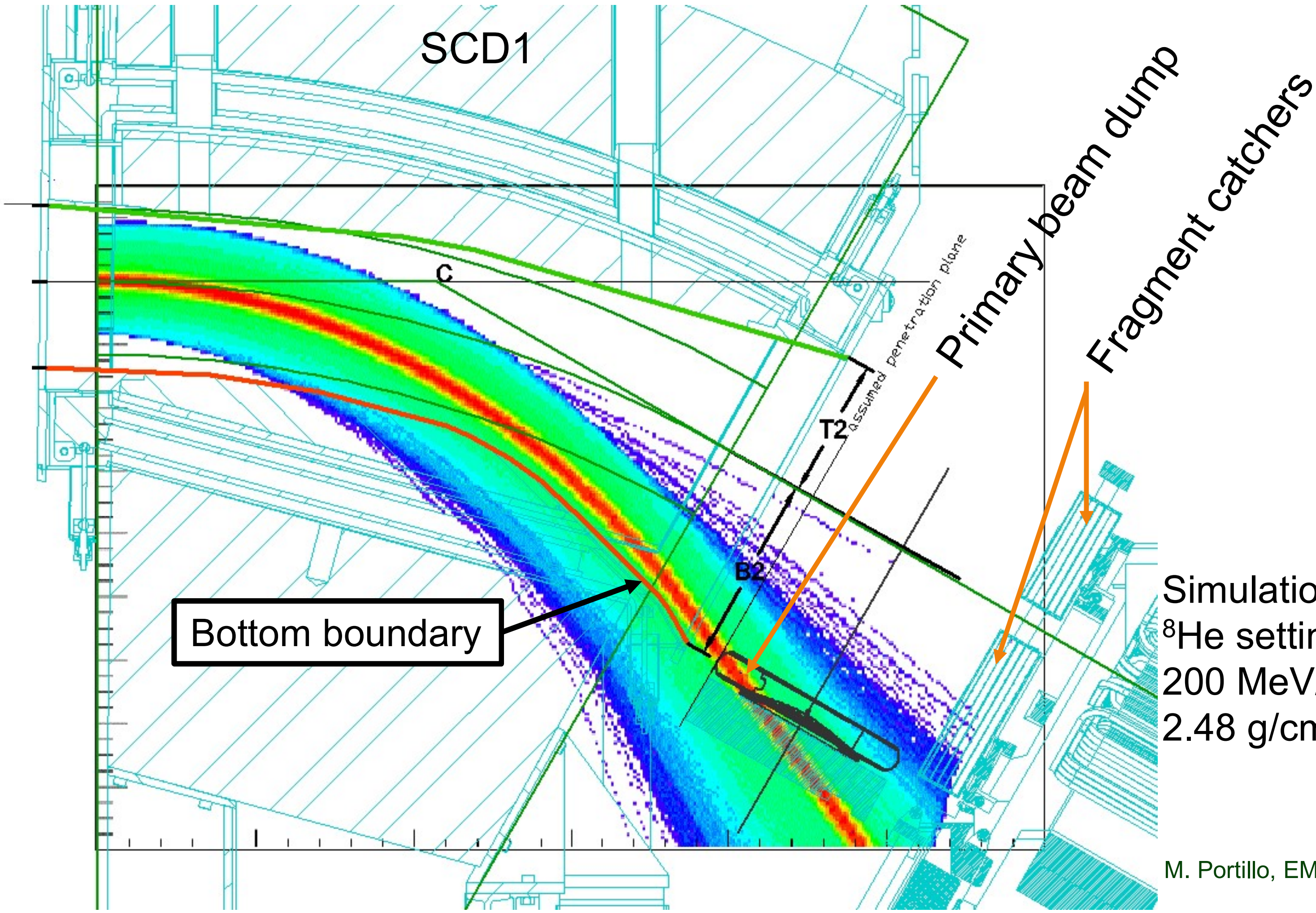
- Applies vertical separation
- Horizontal stages can operate as one or two achromatic foci
  - » Single stage mode offers higher resolving power but less acceptance

Hausmann, NIMB 317 (2013) 349.



ARIS design does not allow direct primary beam losses on dipole parts

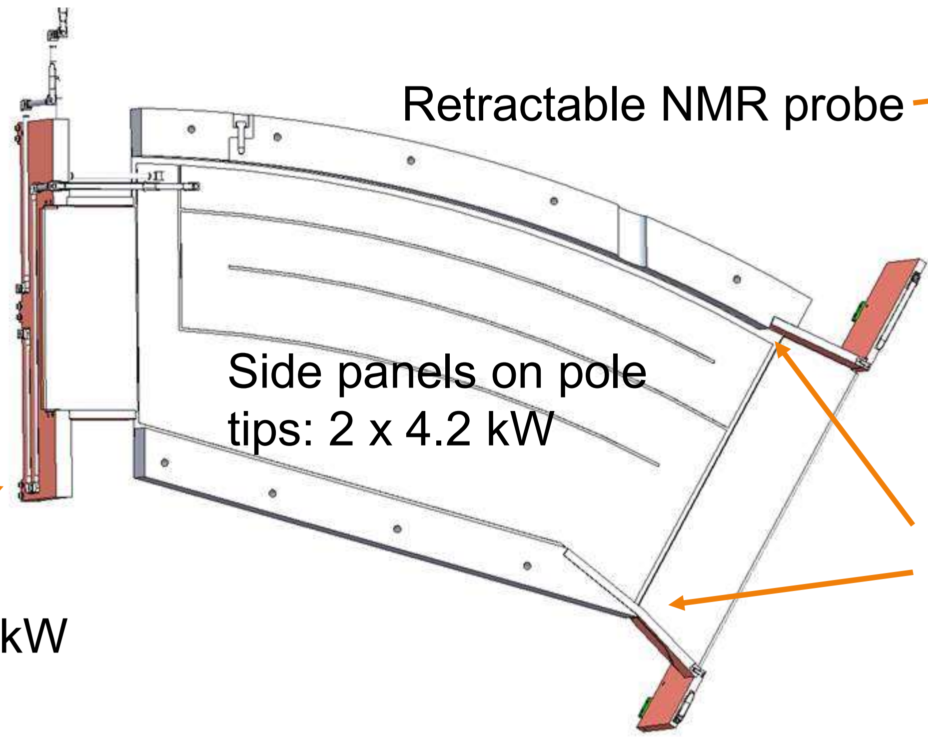
- First dipole will experience substantial stray beam losses
  - Apertures wide enough to minimize them

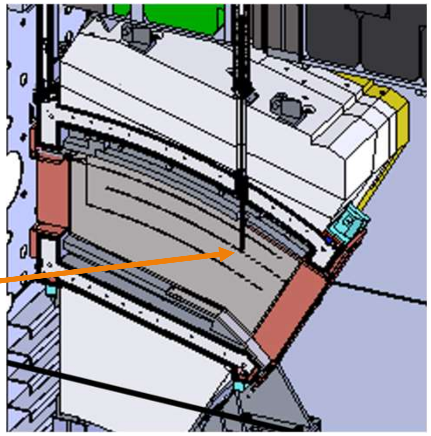


Simulation of power flux:
^{8}He setting from 400 kW
200 MeV/u ^{18}O
2.48 g/cm^2 C target

SCD1(type FSD1) Thermal Armor Design

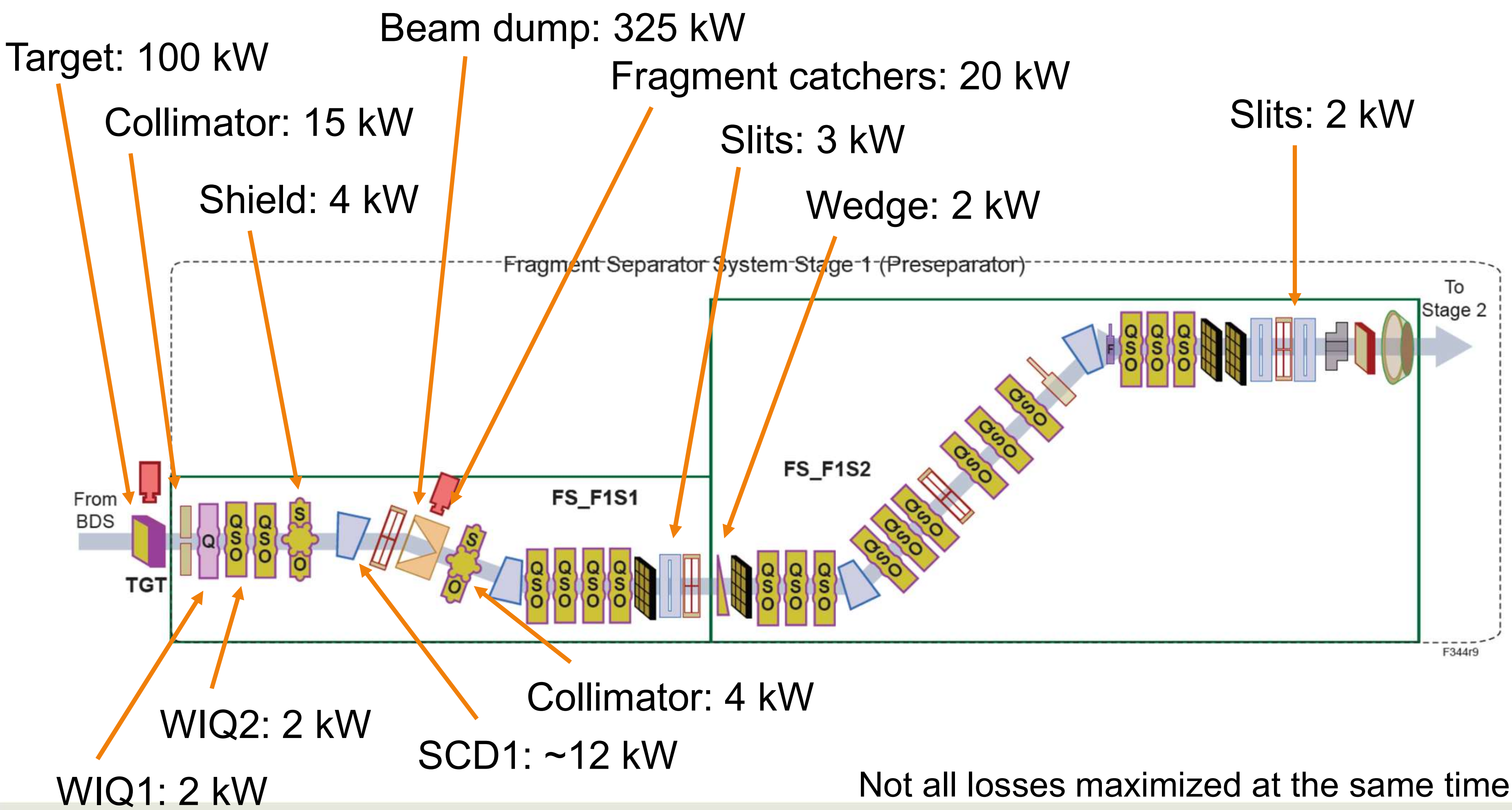
- Stray losses at first dipole (after target) are still considerable
  - Worst case scenarios were accounted for in thermal armor (shield) design
  - Maximum allowed power removal shown
  - Cooling lines on dipole pole tips also exist (not shown)





Most Beam Losses Expected in Preseparator

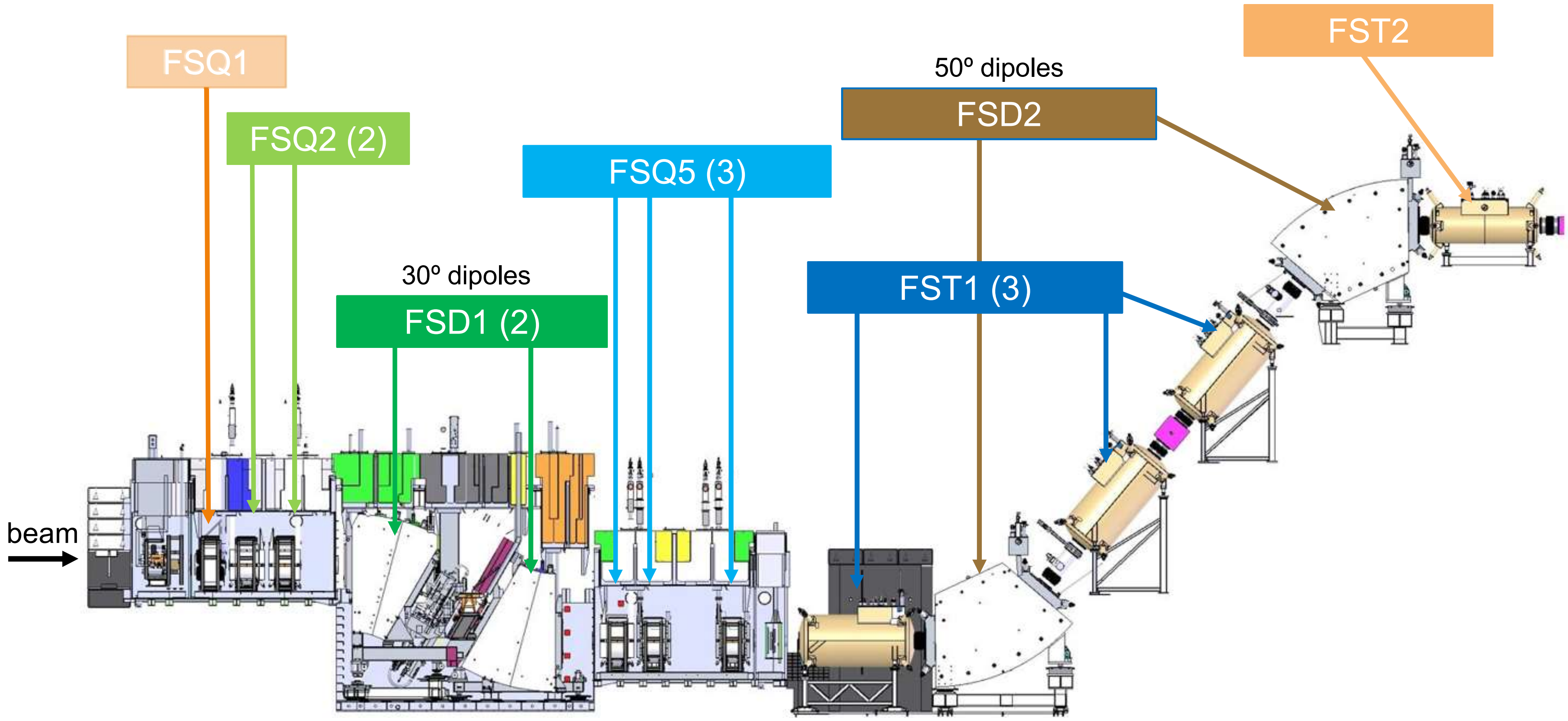
- Predicted maxima at 400 kW primary beam



Not all losses maximized at the same time

All Preseparator Magnets Designed and Built during FRIB Project

- Several types of magnets used to account for high power/radiation environment



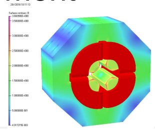
- FSQ1 uses room-temp. coils – spare acquired in early 2021
- FSQ5 – planning to build one more (spare and future optics upgrade)
- FST1 – CIQT (Cold Iron Quad Triplets) with Q7,Q8 quad. types – S800 triplets for spare
- FST2 – CIQT with Q9,Q10 types (smaller bore) – 2 smaller doublets used for spare

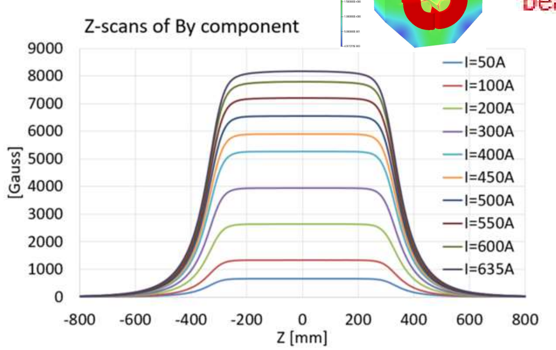
Preseparator Target Hall WIQ Types

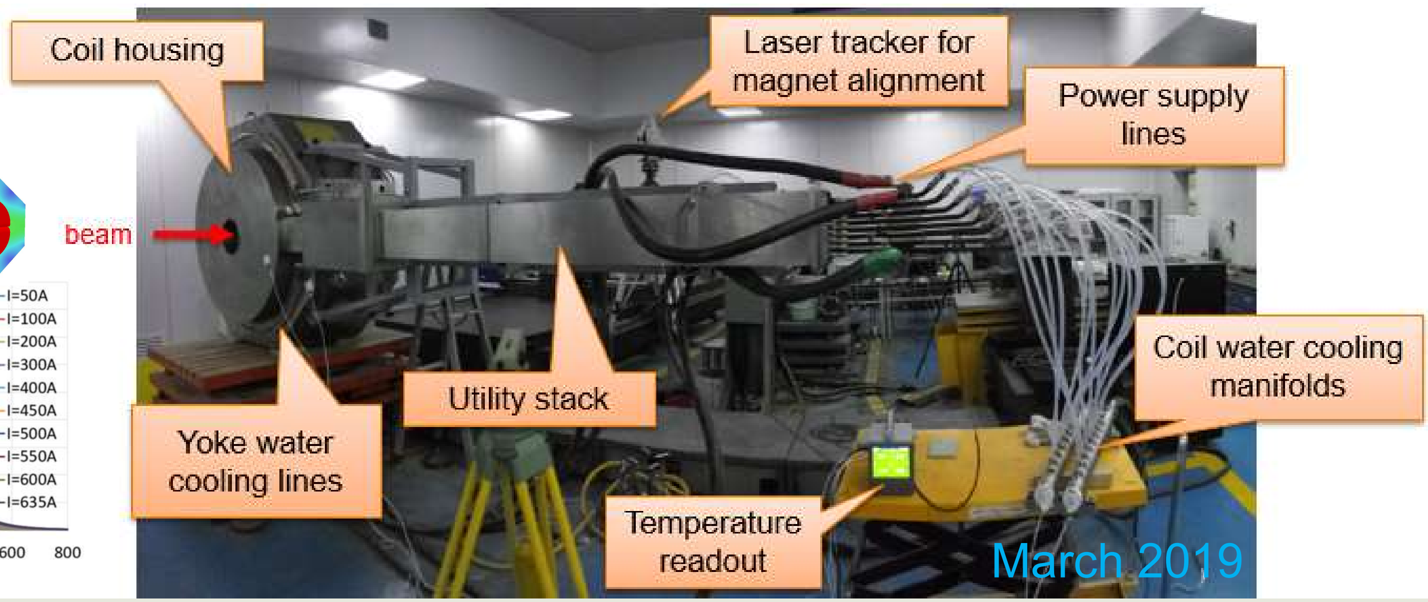
- Target Hall magnets all have Warm Iron yokes
  - Minimizes heat transfer to cryogenics
  - All but first quad have SC coils with nested sext. & octupoles
  - Yokes closest to target
    - » water cooled and
    - » thermal armor installed in bore region

Type	FSQ1(RT)	FSQ2	FSQ5
L_{eff} (m)	0.6	0.75	0.7
Full aperture (m)	0.208	0.22	0.4
Quad. g_M (T/m)	11.3	13.3	10
Sext. g_M (T/m^2)		4.5	6.1
Oct. g_M (T/m^3)		12.7	13.5

- FSQ1 (WIQ1) during testing/field mapping
- Maps in good agreement with model







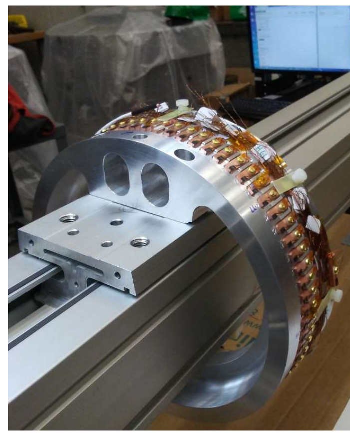
Mapped All SC Warm Iron Quadrupoles

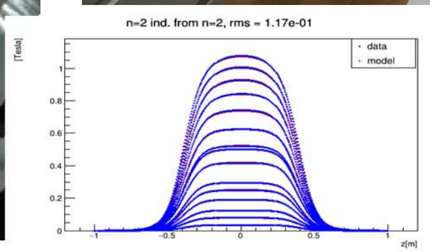
- FSQ2 & 5 designed, built, and mapped in-house
- Completed between 2018 and 2020

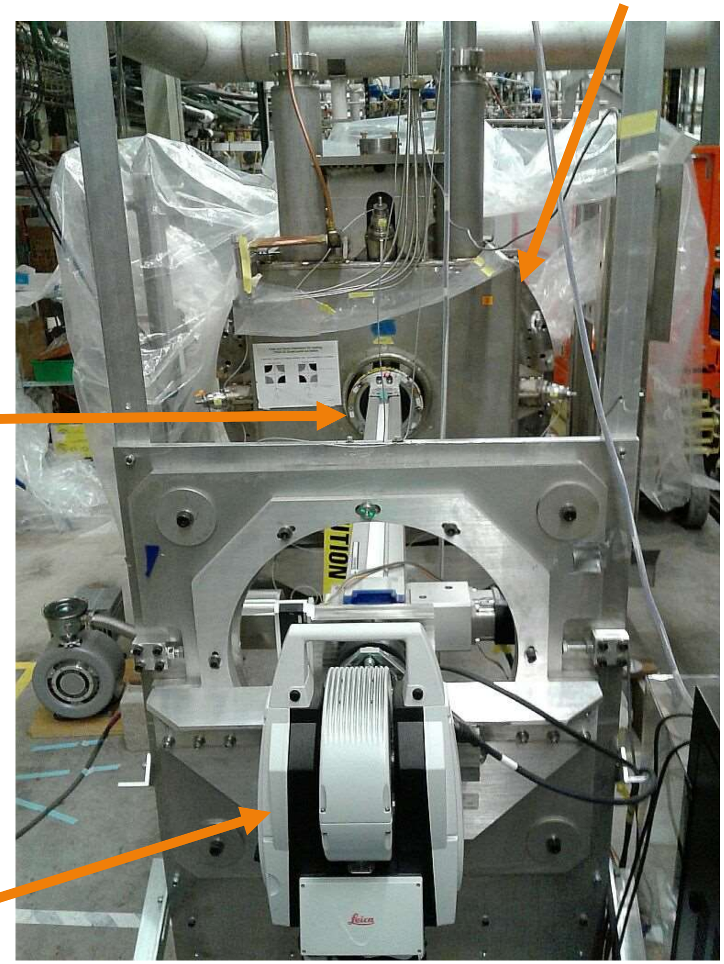
FSQ2 type multipole

Mapper: Hall sensor every 5º about a ring

Designed for remote assembly/disassembly in Target Hall





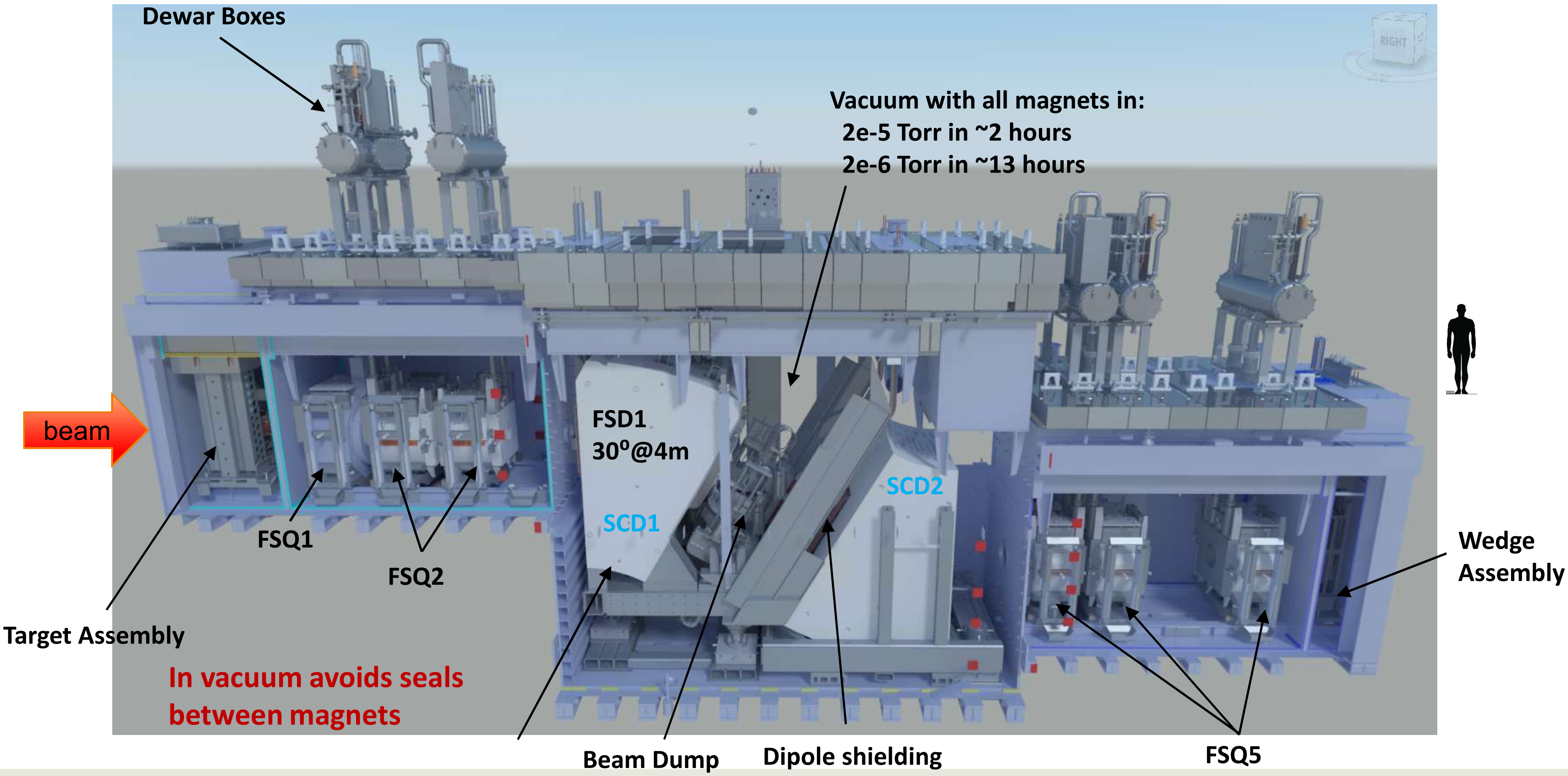


Laser tracker system for alignment data

Preparation of Target Hall Magnets

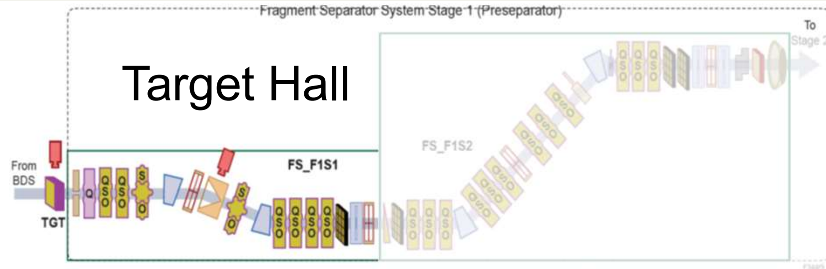
- Installation started 2019
  - Commissioned for use in Dec 2021.

Wei, Mod. Phy. Let. A (2022) 2230006.
First isotope separation and identification.



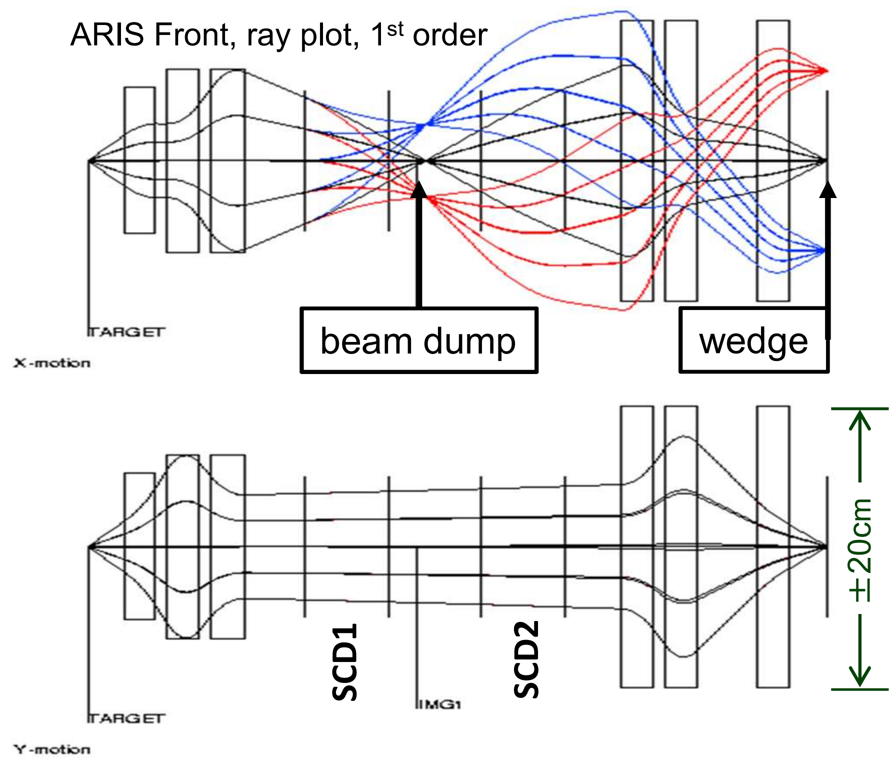
Preseparator Optics
Comparison to A1900 up to Wedge

- Some trade-offs in going to ARIS
  - » Less angular acceptance
  - » higher Brho
  - » higher Δp/p-accept
  - » gain in resolving power at dump



	A1900	ARIS
Brho max. [T-m]	6	8
Δp/p-accept. [%]	5.5	10
Angular acceptance		
Solid angle [msr]	7.5	6.4
dispersive [mrad]	±60	±40
non-disp. [mrad]	±40	±40
Properties at dump		
Dispersion [cm/%]	0.91	0.92
Resolving power	NA*	756
Properties at wedge		
Mx	2.35	-1.39
Dispersion [cm/%]	-5.91	-2.56
Resolving power	2515	1842

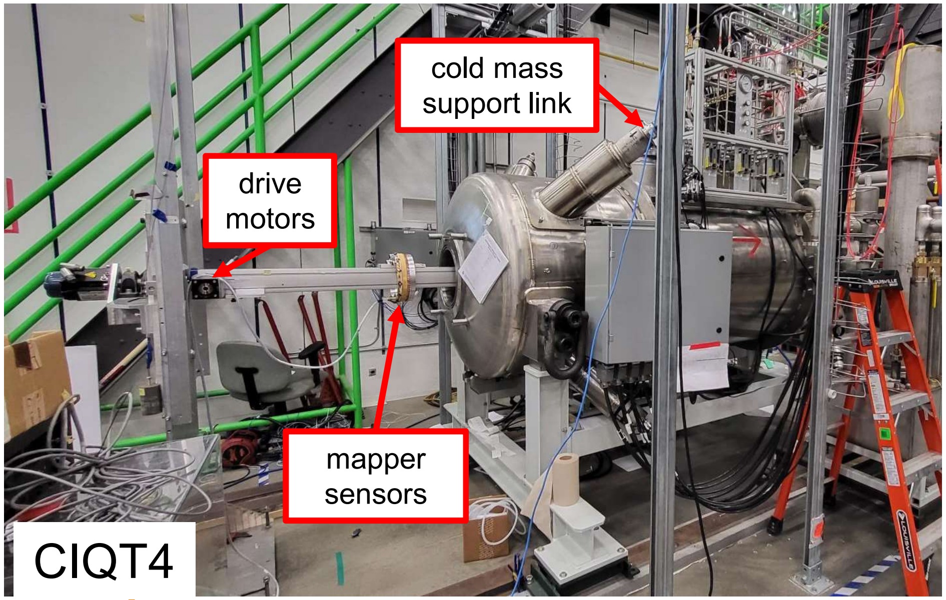
ARIS Front, ray plot, 1st order



1st order properties
Resolving power = Dispersion/X0*Mx, x0 is beam spot size at target (assumed 1 mm)
* Dump region does not have a focus along dispersive direction.

Mapped all Cold Iron Quadrupole Triplets

- Final (fourth) CIQT mapped in July 2022
  - Not used during commissioning
    - » Just installed Sept-Oct for upcoming beam time starting mid-November

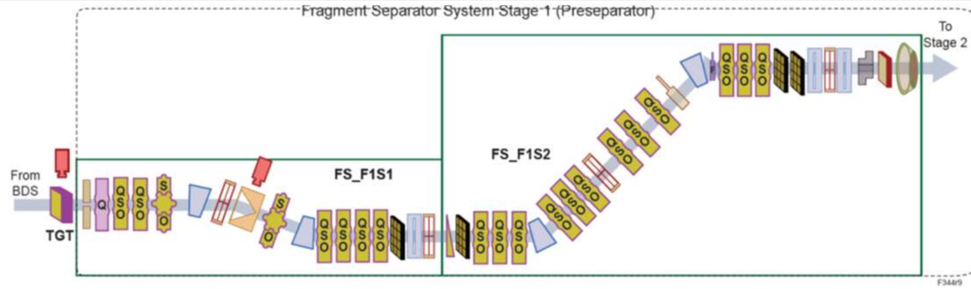


CIQT1-3: FSQ7, FSQ8; CIQT4: FSQ9, FSQ10

Type	FSQ7	FSQ8	FSQ9	FSQ10
L_{eff} (m)	0.65	0.8	0.65	0.8
Full aperture (m)	0.4	0.4	0.3	0.3
Quad. g_M (T/m)	9.3	9.9	8.5	9.8
Sext. g_M (T/m^2)	6.05	6.05	7.8	2.9
Oct. g_M (T/m^3)	13.5	13.5	22.5	13.7

Preseparator Optics
Comparison to A1900 up to Achromatic Focus

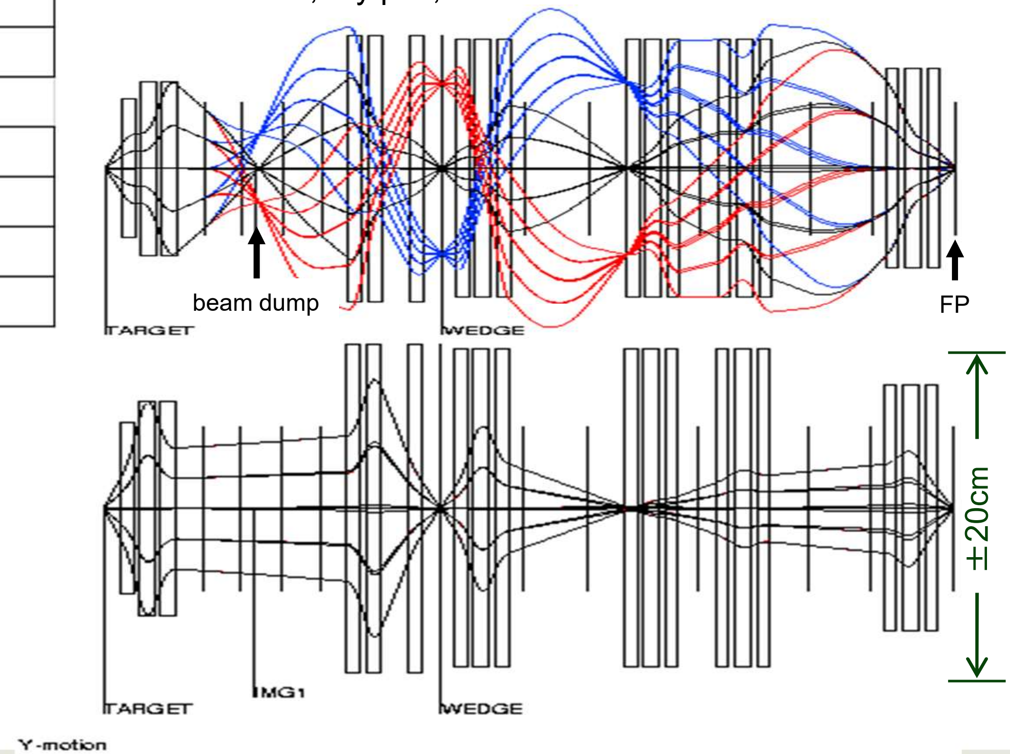
- ARIS normal mode design
  - Imposes compression factor κ≈3
  - Modes with κ=1 have less acceptance



Wedge to FP	**A1900**	**ARIS**
Dispersion [cm/%]	6.3	8.4
Properties at FP		
Mx	2.4	5.8
My	3.4	-1.5
κ=1/(δ|δ)tot	1	3.05
Total Length [m]	35.8	46.5

Mx is magnification in dispersive plane.

ARIS total, ray plot, 1st order

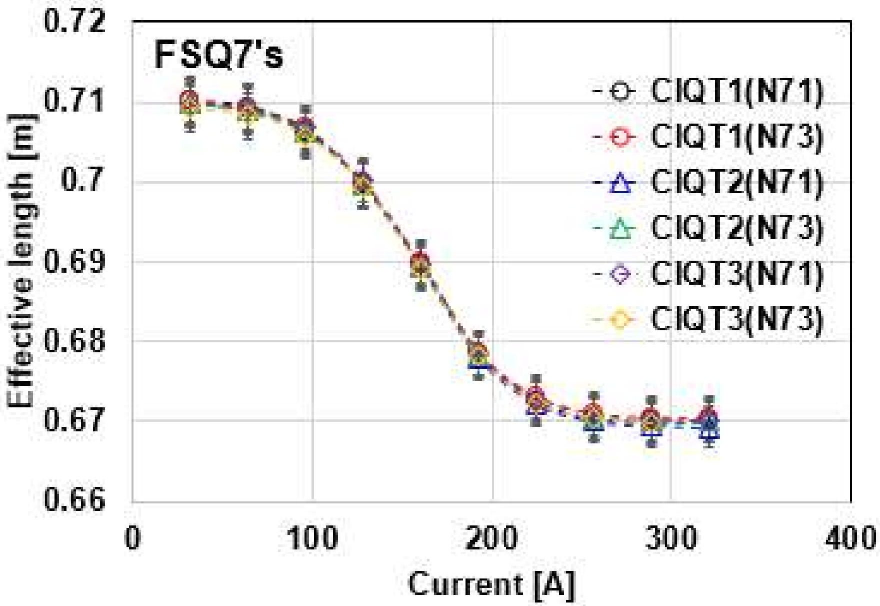


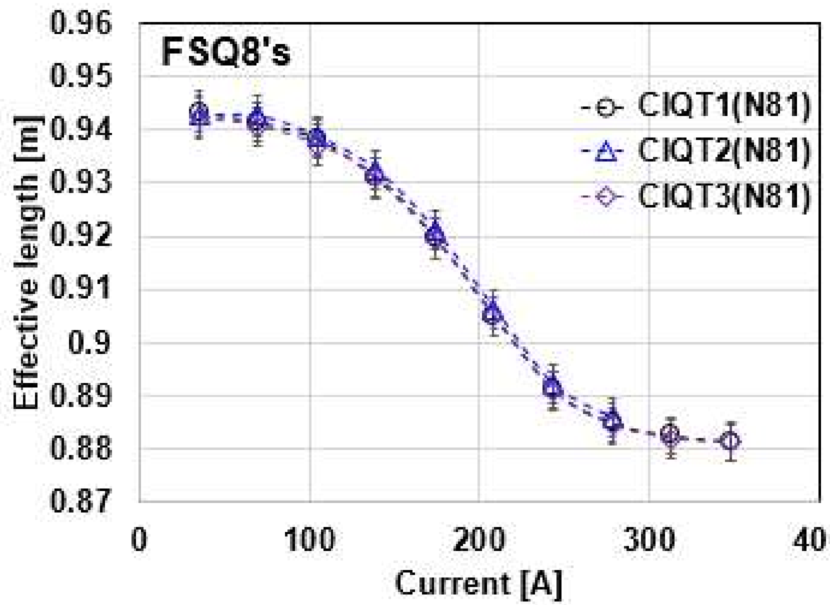
$$\kappa = \frac{1}{(\delta|\delta)_{tot}} = -\frac{(x|\delta)_2}{(x|x)_2(x|\delta)_1}$$

Bandura, NIMA 645 (2011) 182.

Common Magnet Types Show Agreement in Mapping Results

- Was mapping all of them worth it?
  - Yes.
    - » Some integrated strengths varied from average by ~1%
    - » Difference from model as much as ~2% in some regions
      - Noticeable difference in optics

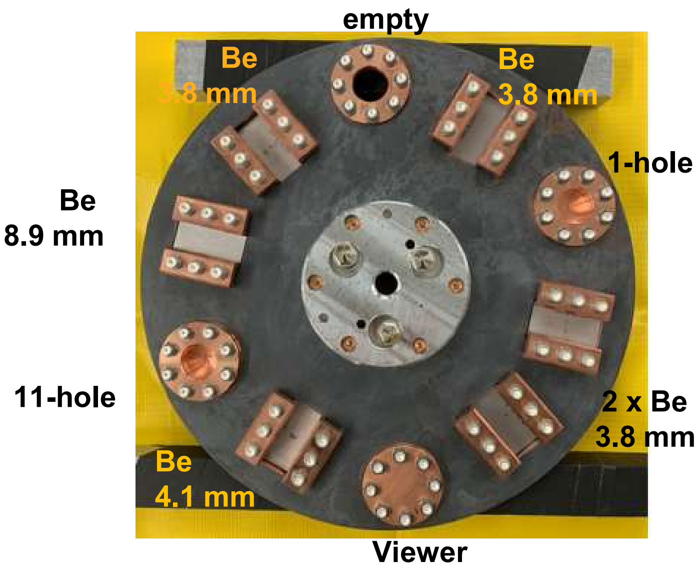




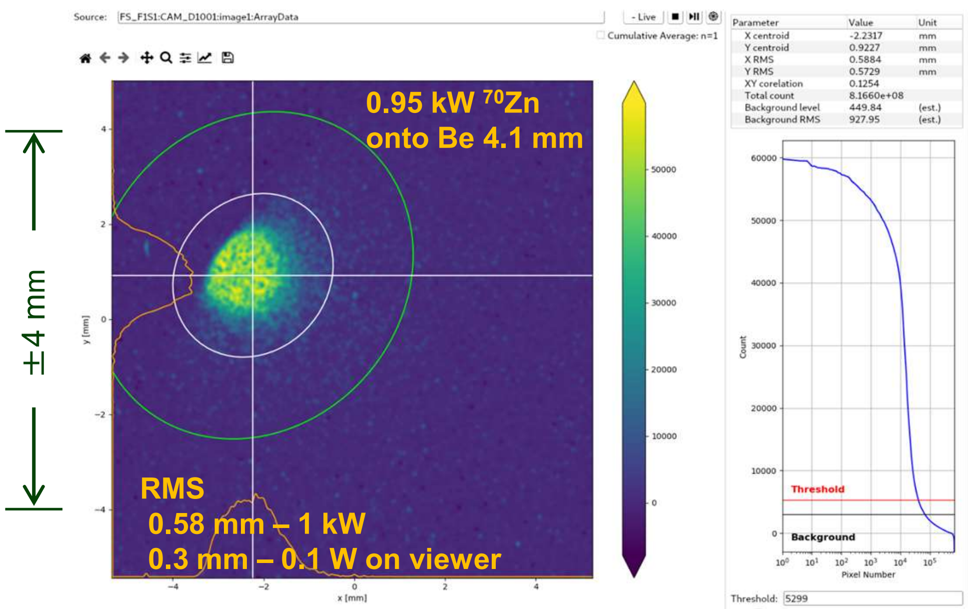
Phased Approach for Targets

- Three types of target modules to be used in power ramp up phases

- Commissioned with static multi-target
  - Allows visible spectrum cameras
  - 1 kW => 0.37 kW on 8.9 mm Be



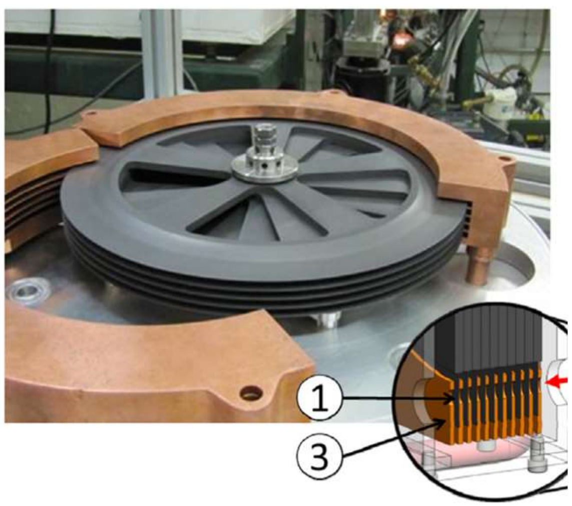
- 5 positions used on each Be
- 5e12 Gy max dose allowed



Next Phases Utilize a Rotating Target Module

- Single-slice installed Sep 2022
  - 50 kW max capability (depends on beam)
  - 1.9 g/cm^3 graphite
- Multi-slice operation projected for operation by 2025

1) entrance to multi-slice
2) Cu heat exchanger

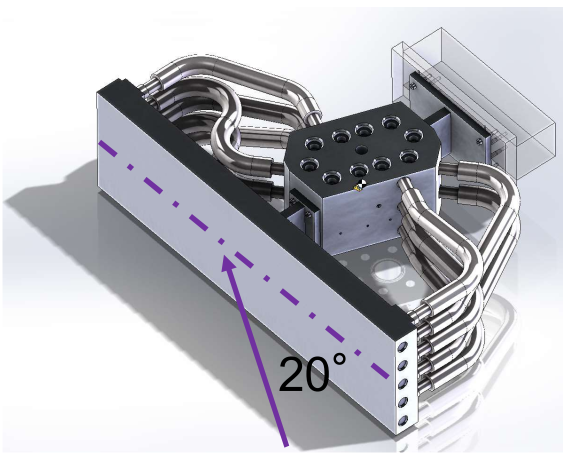


Pellemoine, NIMB 317 (2013) 369.

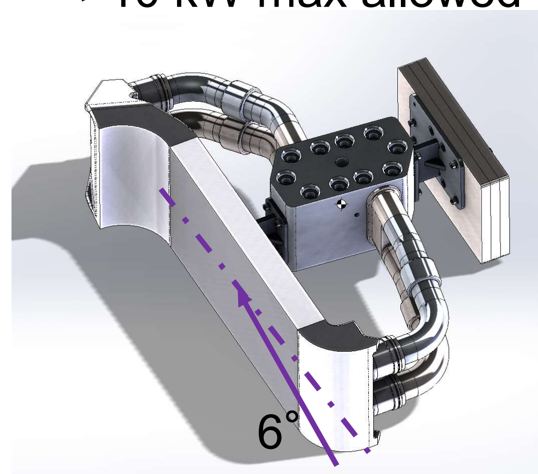
Various Beam Dump Systems

- Started with static beam dumps that are simpler to operate
  - Maximum power depends on beam

Commissioned with
20º static beam dump
Operated up to 1 kW



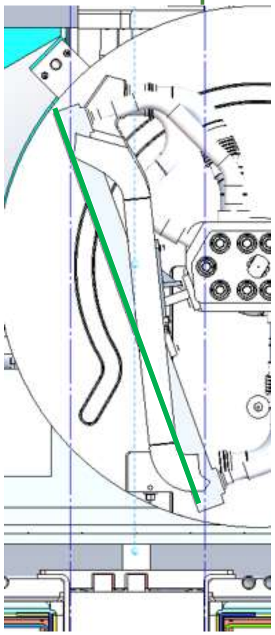
Next phase
6º static beam dump
>10 kW max allowed

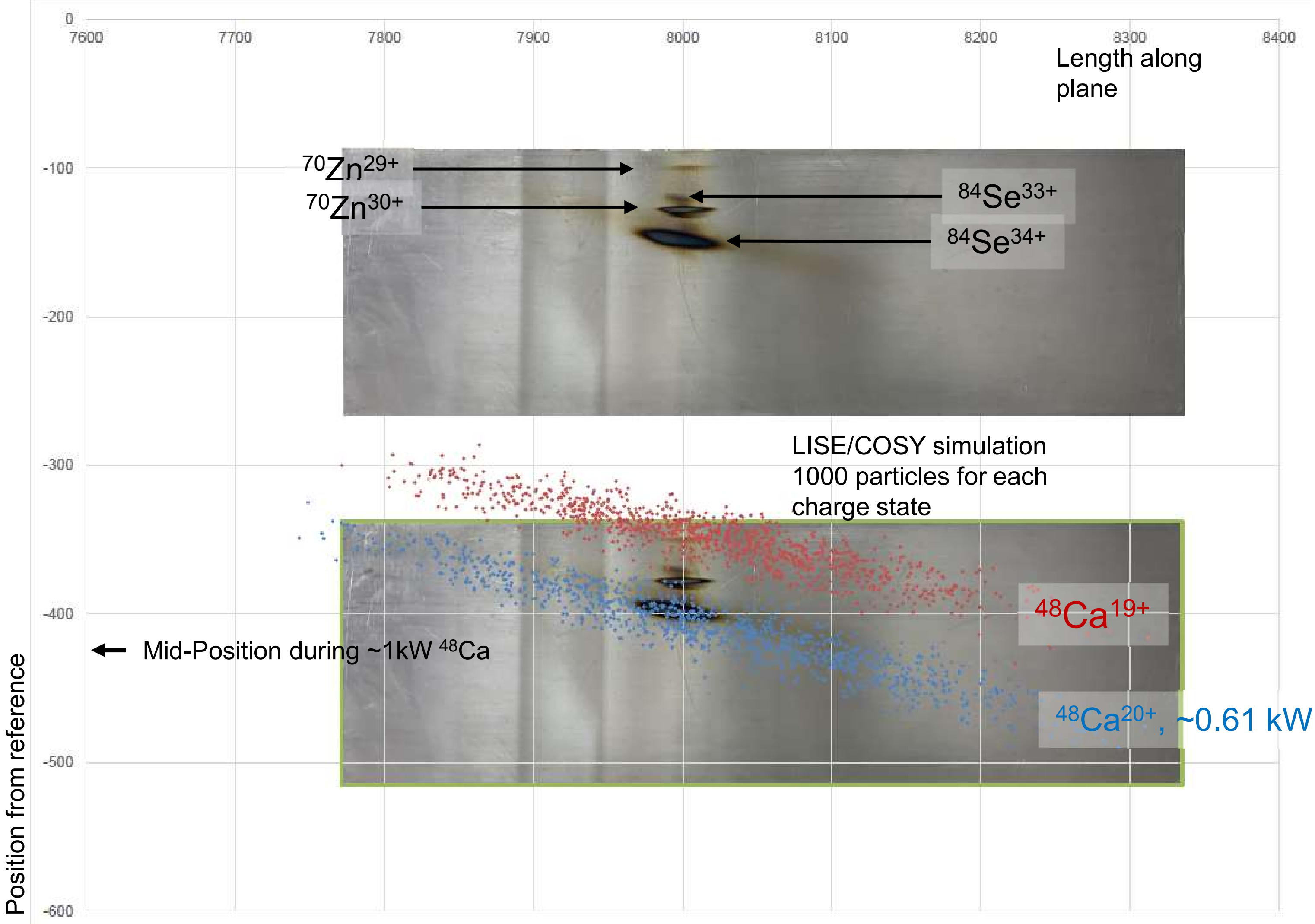


Primary beam does
not stop in water

Beam Markings on Dump Entrance Plane
in Agreement with Model

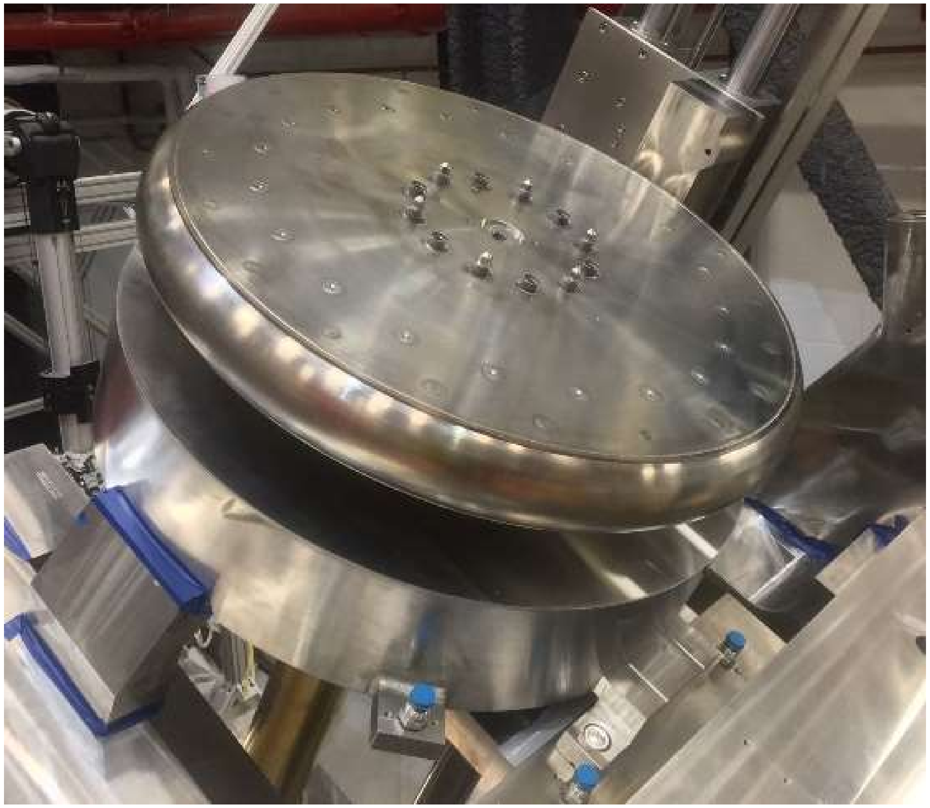
20º dump





Rotating Beam Dump Under Testing

- Designed for 400 kW operation
  - Maximum absorbed power ~325 kW
  - Most primary beam & other products stop in water
  - Start with 1 mm thick wall
    - » 400 kW for lighter beam operations
    - » ~40 kW for uranium
  - Working towards ~0.5 mm wall



Hausmann, NIMB 317 (2013) 349.

Preseparator Wedge Module Upgrades

- Upgrades to wedge systems are planned
  - Simplified lower power module used for first beams
    - » Hands-on maintenance allowed
  - Higher power modules ahead for remote handling
- 3 wedges per ladder at 3 stations

250 mm wide Al wedge (5083 Alloy)

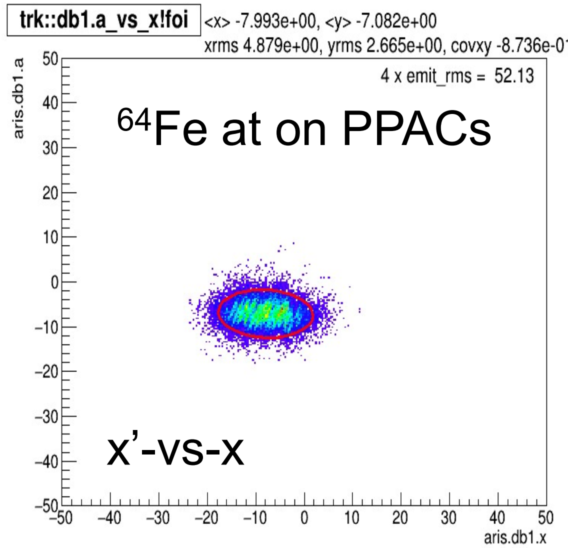
ARIS Beam Activities

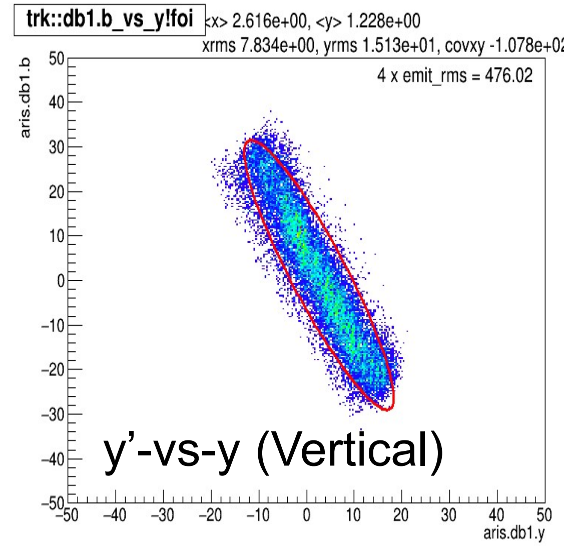
- Mainly commissioning developments, but also some experiments
  - Gradually (safely) ramping up beam power
    - » Note that machine & personnel protection systems also being commissioned

- 2021
  - Dec. – First rare isotopes separated and identified Dec. 2021
    - » Magnet polarity and misalignment studies; calibration of dipoles
- 2022
  - Jan. – First primary beam transport through all separator stages
    - » Magnet misalignment studies
  - Mar. – Power ramp up studies through Beam Delivery System (BDS)
  - April – Commissioning and experiments at FDSi (^{48}Ca, ^{82}Se)
  - July-Aug. – Commissioning and experiments at S800 (^{70}Zn)

Optics Correction Methods

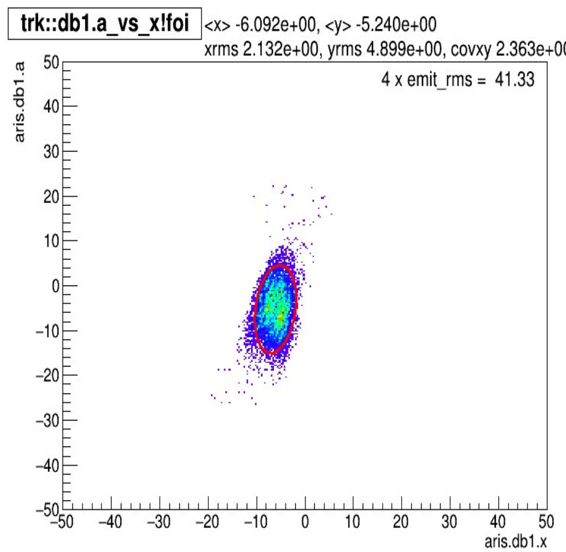
- Phase space measured
  - Preseparator focal plane
    - » No optics corrections

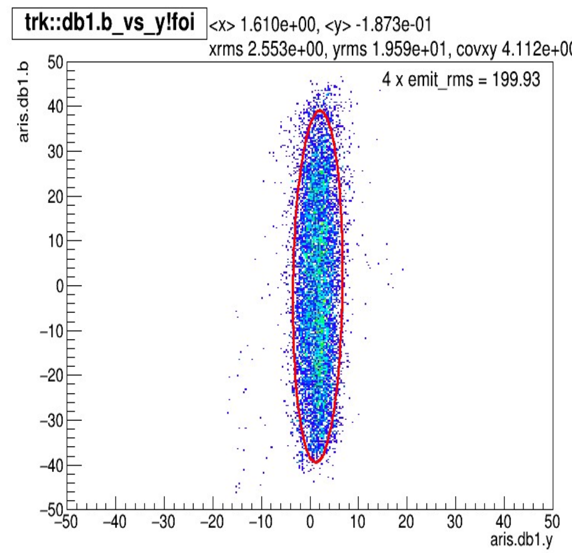




- After optics corrections
  - » Method described elsewhere in this conference

Kei Fukushima-Poster PS-6-3





Summary

- FRIB has completed all ARIS separator magnets
- ARIS commissioning was completed in early 2022
- Optics studies confirm expected optics and correction methods
- A phased power ramp up approach started; up to 1 kW
- Improvements from lessons learned are on-going

Acknowledgements

- For invitation and attention
- Collaborators

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