Dealing with Radiation Issues in the FRIB Fragment Separator

Al Zeller

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Team

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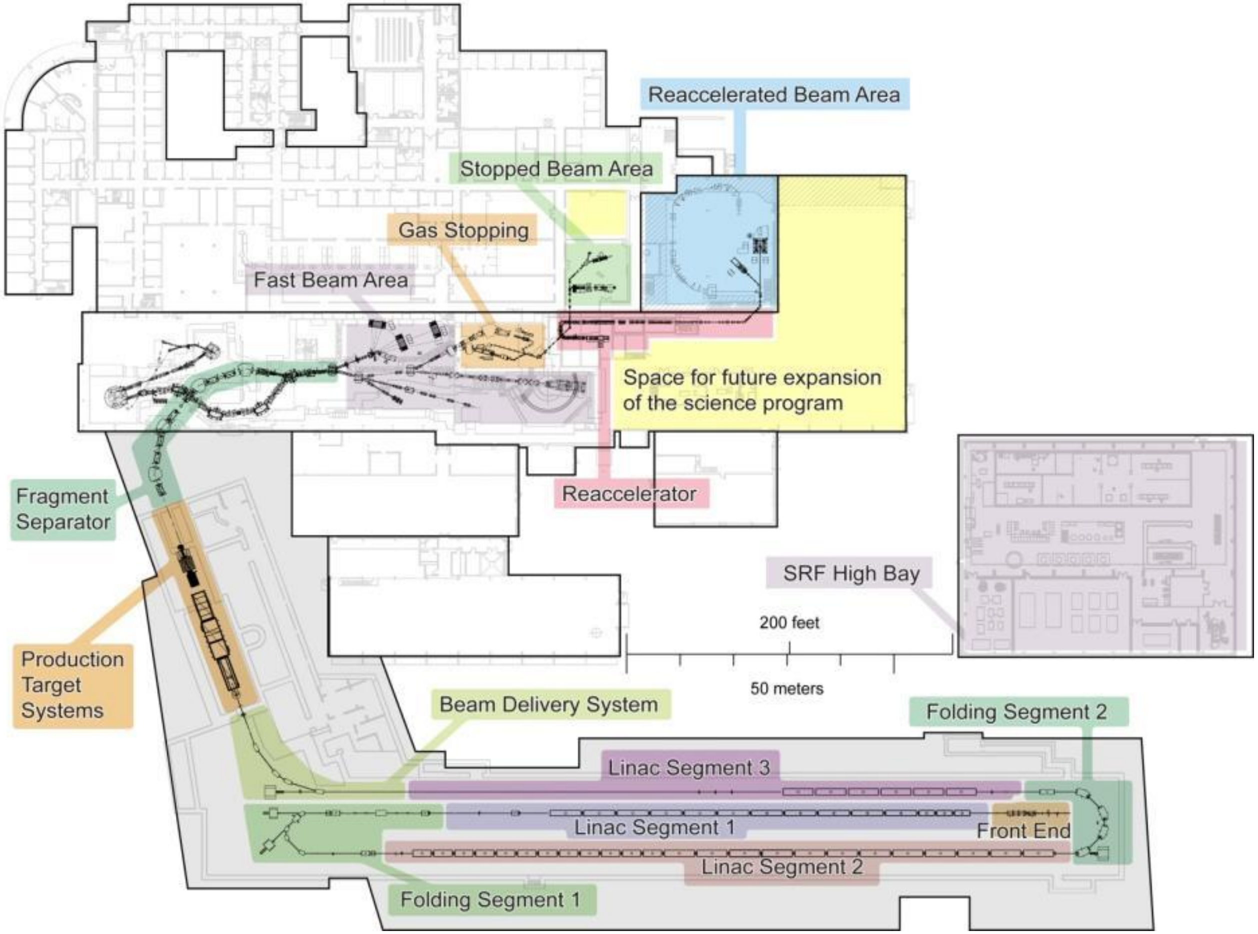
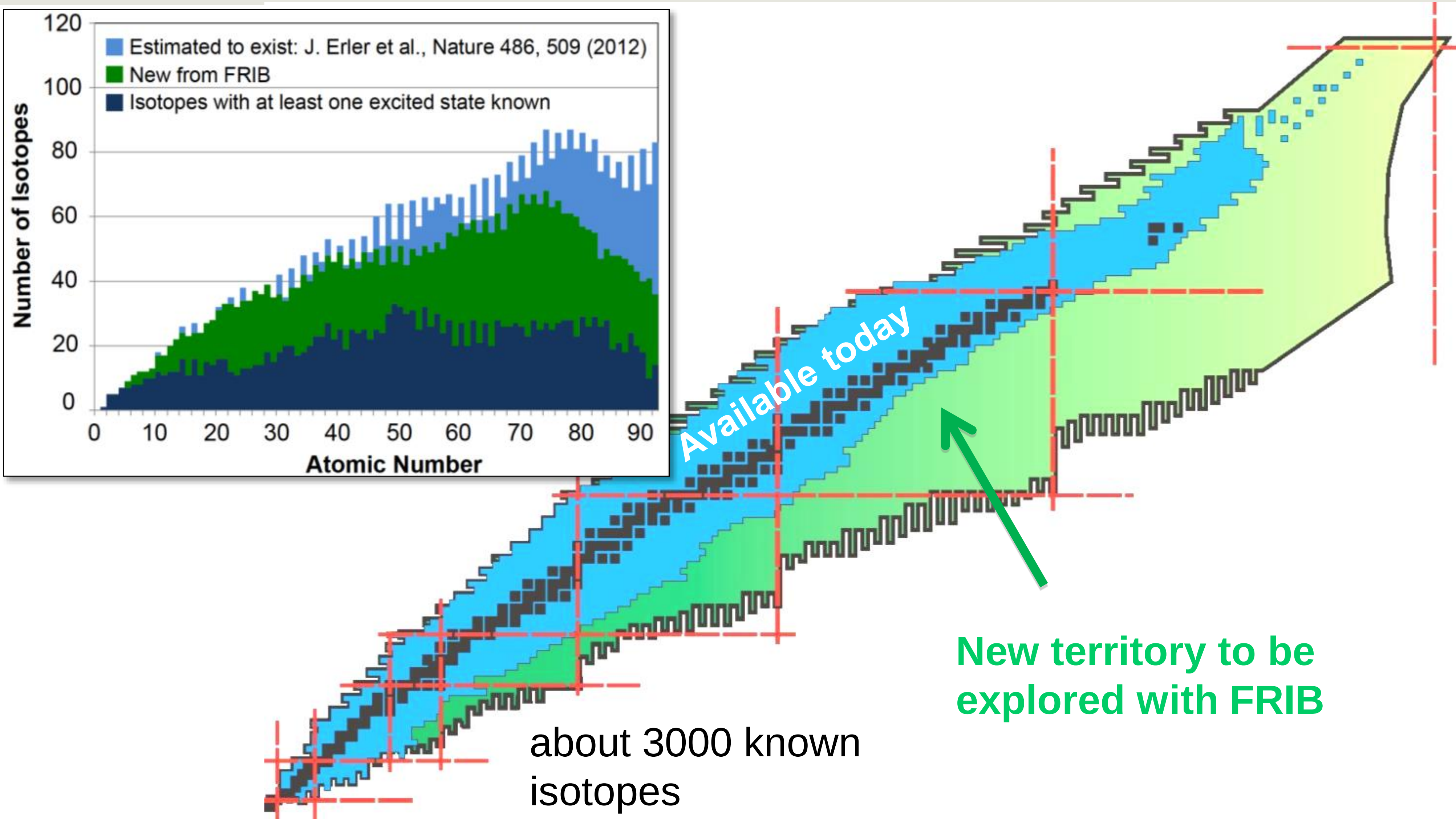
FRIB - Facility for Rare Isotope Beams
at Michigan State University

- Rare isotope production via in-flight technique with primary beams up to 400 kW, 200 MeV/u uranium
- Fast, stopped and reaccelerated beam capability
- Upgrade options
  - Energy 400 MeV/u for uranium
  - ISOL production – Multi-user capability



World-leading next-generation rare isotope beam facility

FRIB Beams Will Enable New Discoveries



New territory to be explored with FRIB

about 3000 known isotopes

Experimental Nuclear Physics at MSU

1958
MSU hires first accelerator expert

1961
NSF approves sector focused K50 cyclotron

1965
Research with K50; single turn extraction

1975
NSF approves superconducting cyclotron magnet prototype

1977
NSF approves K500 cyclotron

1978
NSAC recommends national user facility at MSU

1982
Research with stable beams from K500

1989
Research with stable beams from K1200

1990
Research with fast rare isotope beams from A1200

1996
NSF approves coupled cyclotron facility (CCF)

2001
Research with fast rare isotope beams from CCF

2002
Infrastructure for SRF linac R&D

2005
Research with trapped rare isotope beams

2006
MSU funds ReA3 reaccelerator project

2008
DOE selects MSU to establish FRIB

2010
Research with reaccelerated rare isotope beams from ReA3

2018
FRIB operations

Conventional Facilities Site Layout

Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

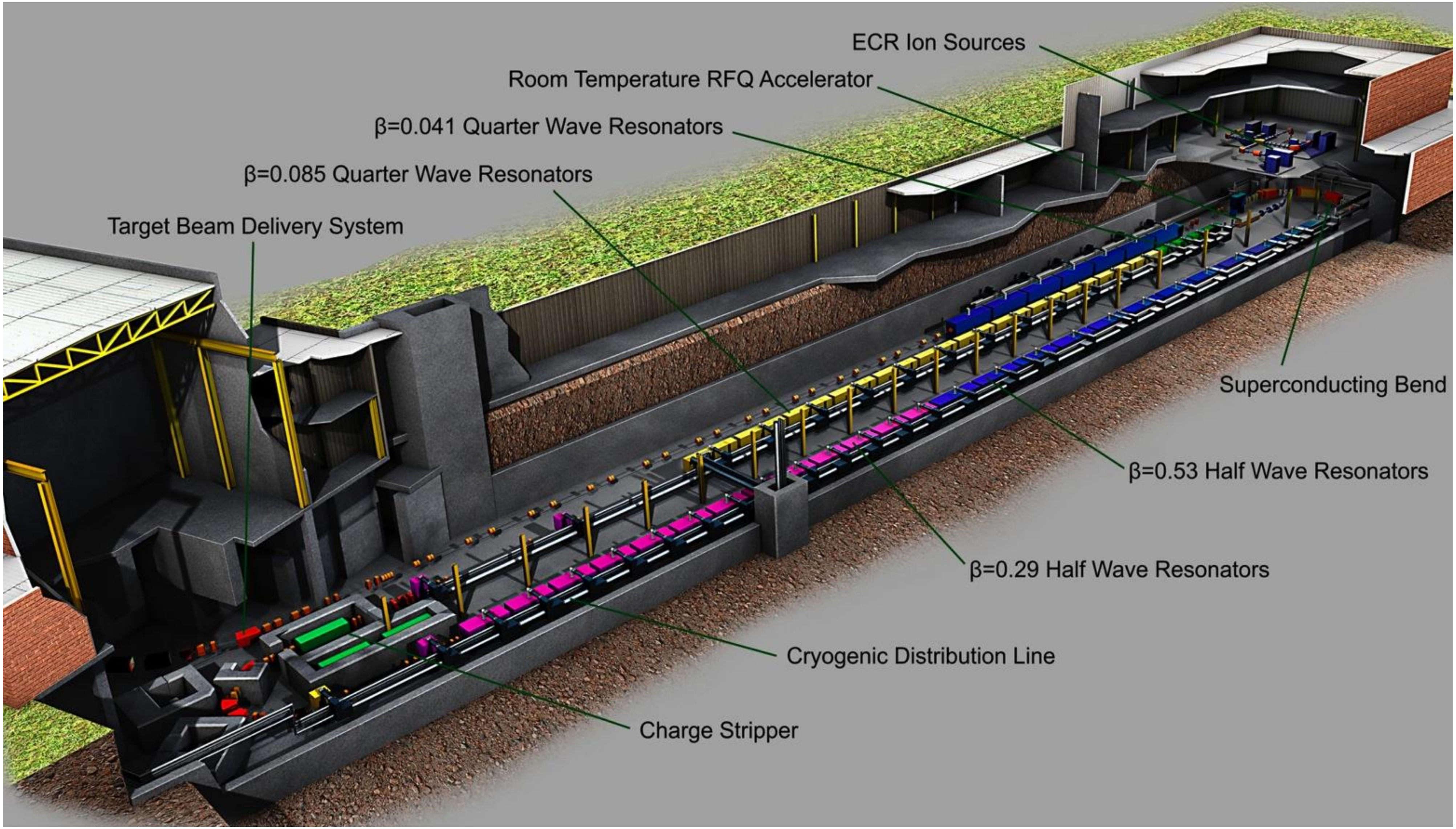
FRIB Construction Progress

- Excavation is ongoing
- Trade personnel installing tie-backs for earth retention system
- Dewatering wells are operating
    - Lowered water table to design level
        - » 20 feet below finished floor
        - » **As deep as the wells (25 m)**

Excavation for linac tunnel

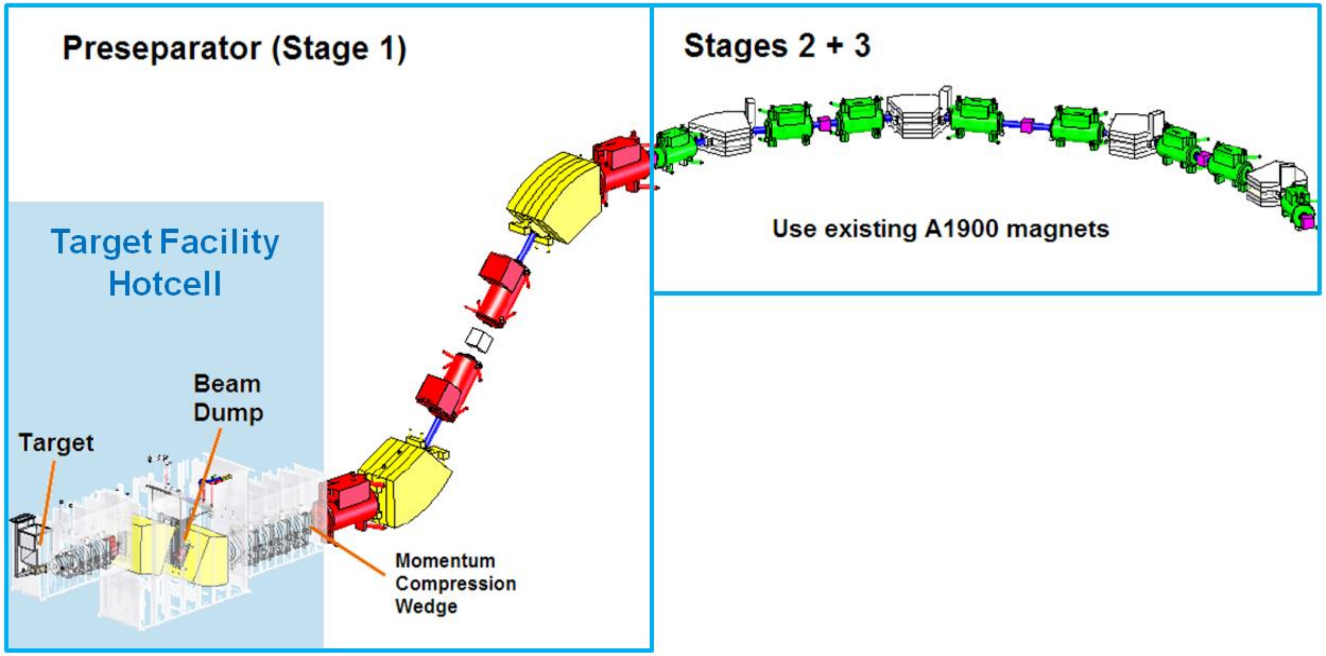
Excavation on west end of site

FRIB Driver Accelerator Layout



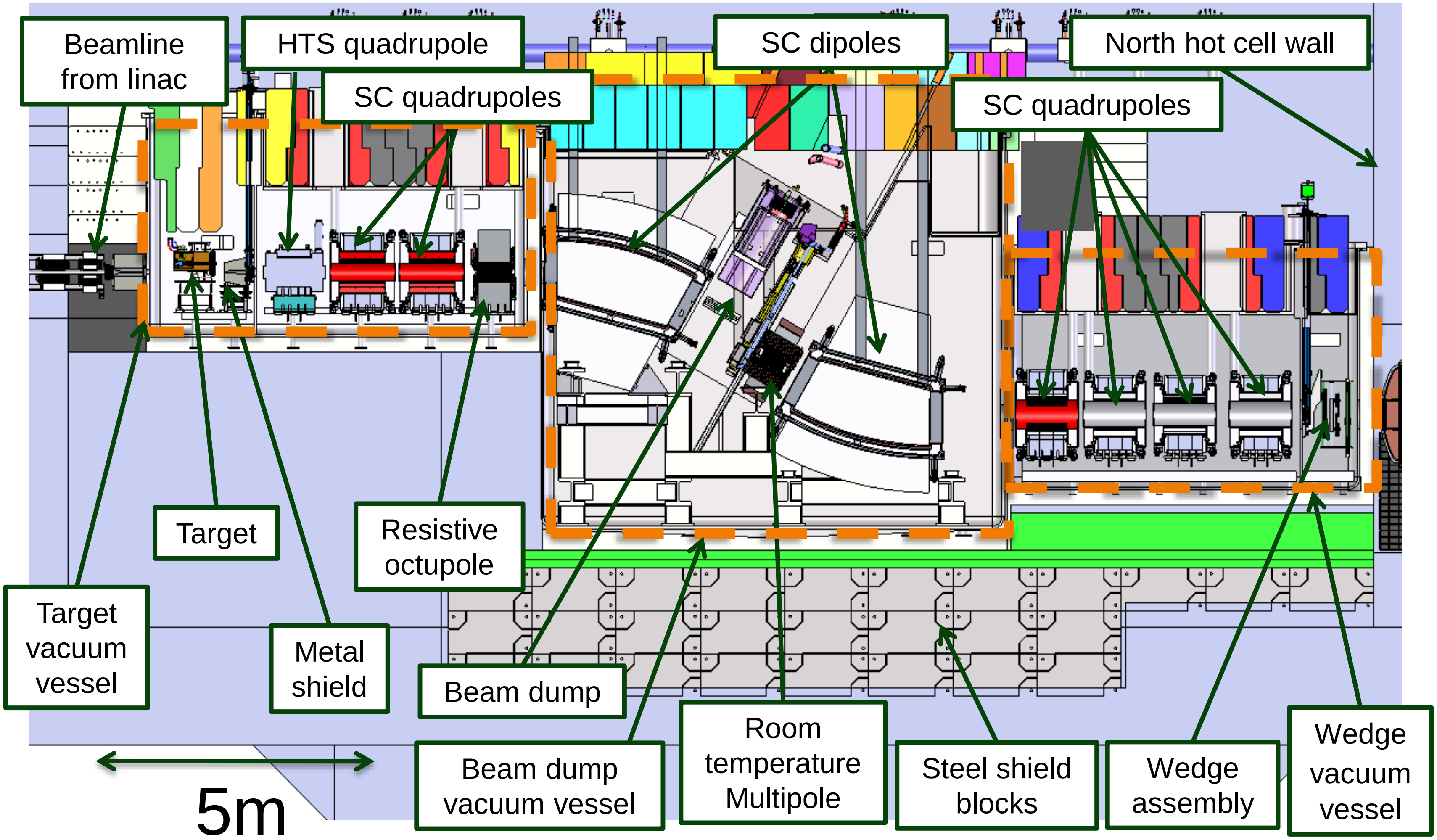
Fragment Separator

- Scope
  - In-flight separation of rare isotopes with high acceptance and high resolution
    - Leverage rare isotope production at 400 kW beam power
    - Provide purest-possible rare isotopes beam to maximize science reach
- Technical specifications
  - High-acceptance preseparator provides first beam purification step, provides defined location(s) for primary beam dump
  - 2 additional separation stages to guarantee high beam purity
  - Provide future upgrade opportunities for isotope harvesting

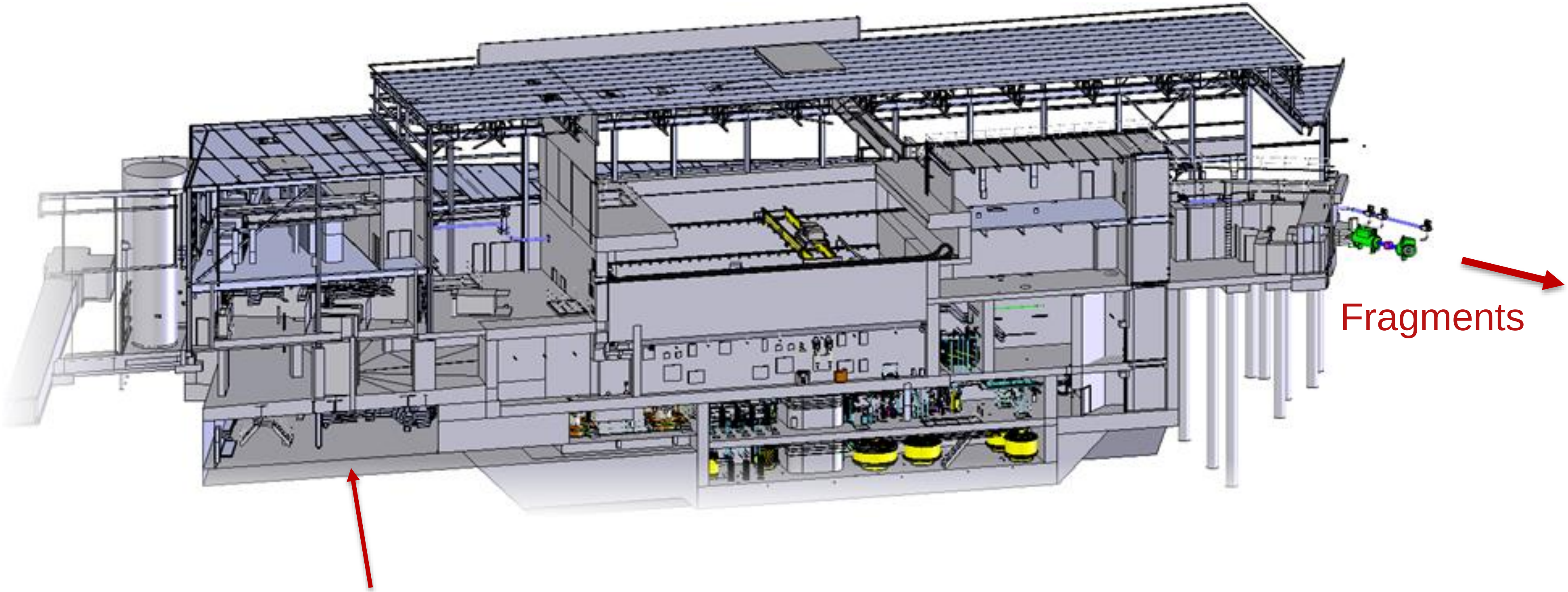


Fragment Separator Mechanical Design

- All components in high radiation area in vacuum vessels (~200 t)



Target Facility Design [1]

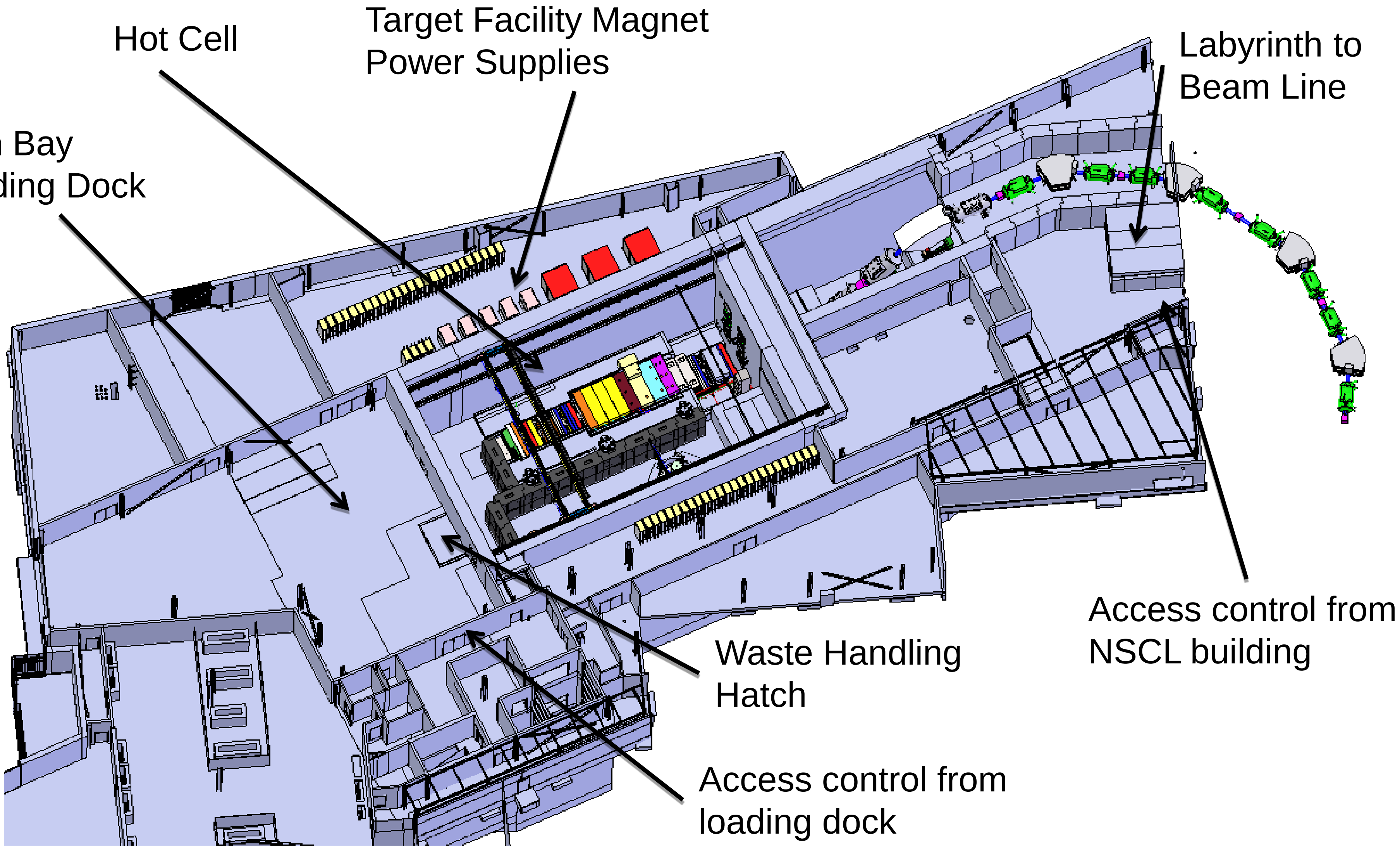


Fragments

End of beam delivery system

Target Facility Design

Interior Layout



Hot Cell

Target Facility Magnet Power Supplies

Labyrinth to Beam Line

High Bay Loading Dock

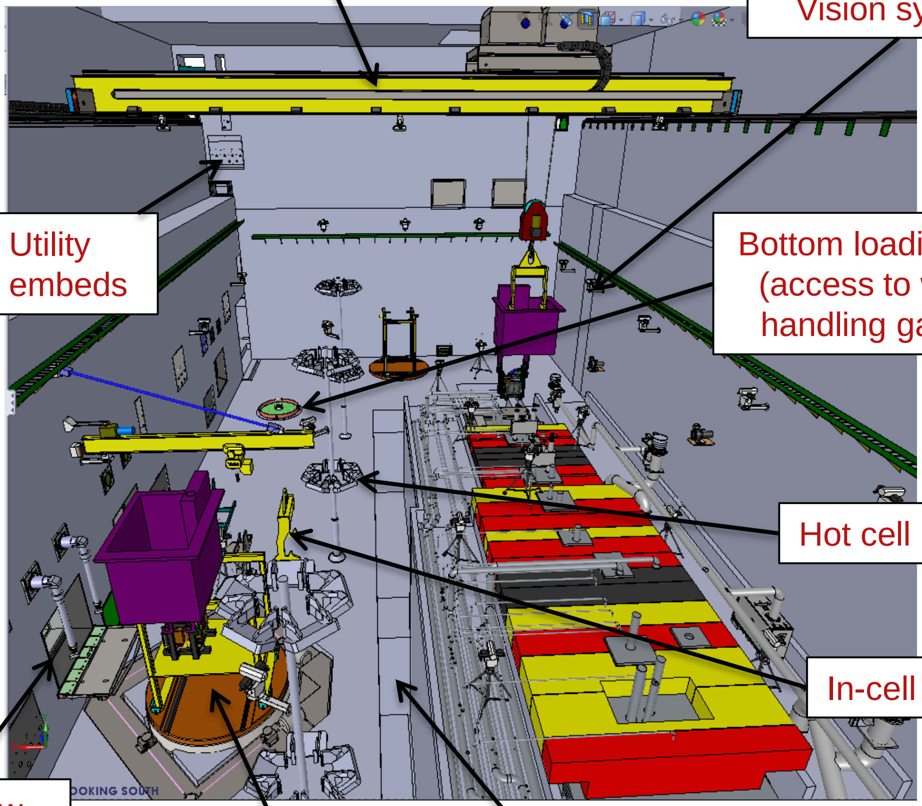
Access control from NSCL building

Waste Handling Hatch

Access control from loading dock

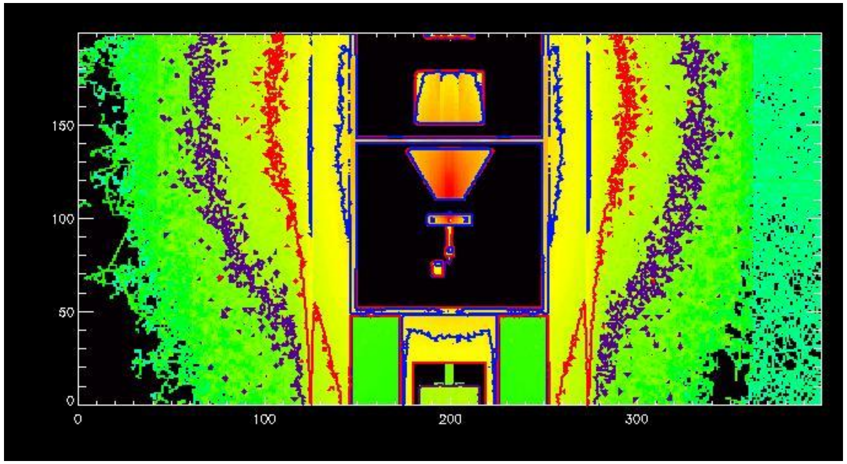
Target Facility Hot Cell

- Design a system that will maintain activated preseparator beam line components located in the hot cell and manage activated waste
- Overall approach
  - Hands on access with beam off and shielding in place
  - Remote operations with shielding removed or beam on
- Hot cell lighting design (LEDs)
- Design effort for remote handling tooling tracks equipment design

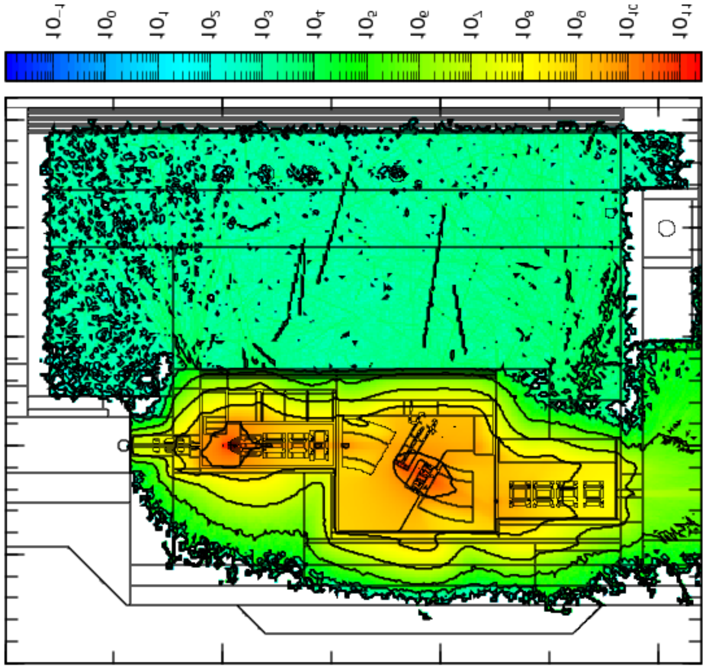


Radiation Transport

- Major radiation analysis complete including all needed for construction start and verification of planned hot-cell operation



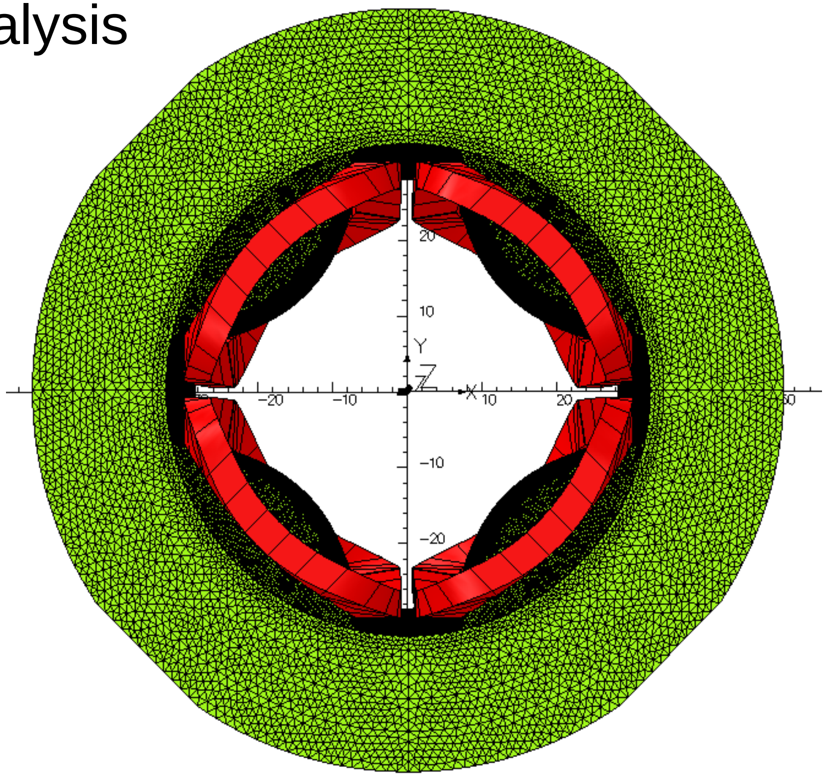
Heat map of zone close to Target



Hot Cell Dose Rates

Fragment Separator Magnet Design

- Fast initial optimization of yoke mass and field quality allowed mechanical design to proceed
- Full 3D TOSCA model for detailed optimization
  - Detailed flux distribution, forces, quench analysis
- Example: quadrupole FSQ9
  - Field gradient exceeds requirement by 12%
  - Effective length within 5% of goal
  - Integrated strength exceeds requirement



Meshed 3D model of FSQ9

Fragment Separator Magnet Design

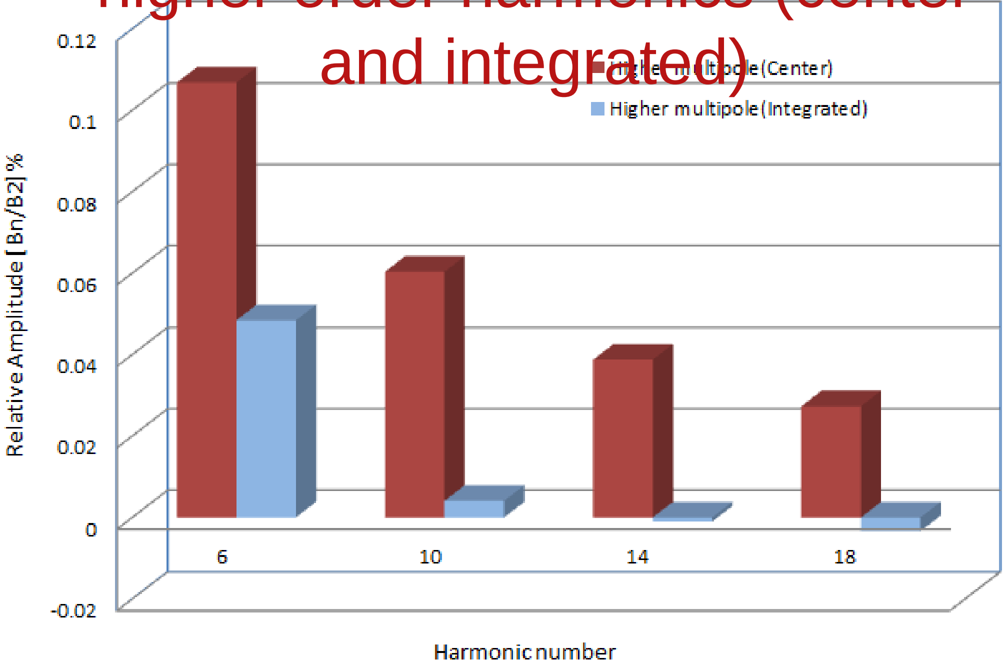
Magnet Field Quality Example: FSQ9

- 3D model shows pure quadrupole field at 0.1% level
  - Simulated field quality exceeds requirements
  - Similar, but longer magnet FSQ10 has even better field quality
- Beam physics analysis and implementation underway

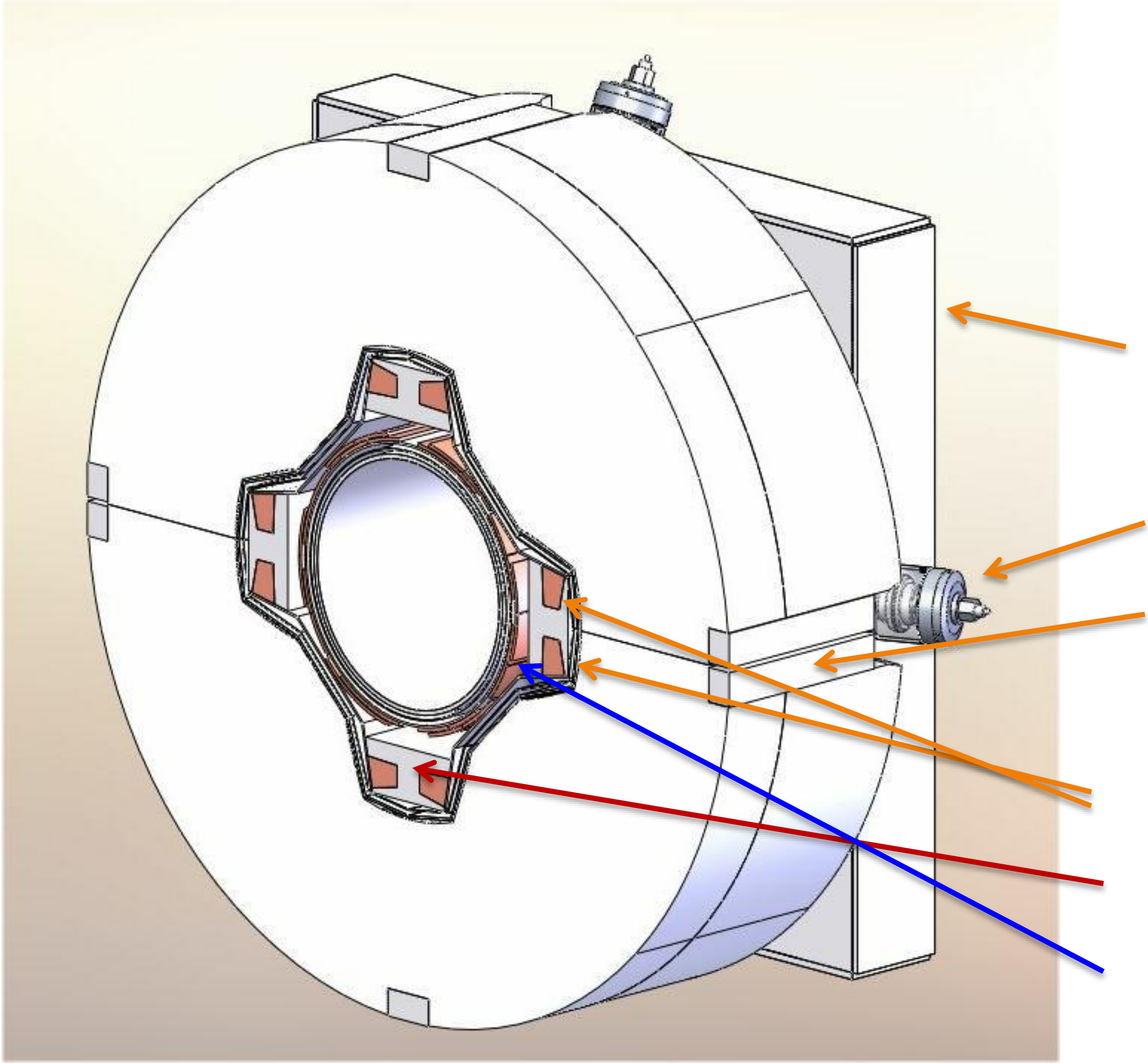
Harmonic analysis results for FSQ9

	FSQ9 (center, R = 12 cm)		FSQ9 (integrated, R = 12 cm)	
Order	Amplitude	Relative Amp.[%]	Amplitude	Relative Amp.[%]
2	-11432.5	100	-712519	100
6	-12.2	0.1	-345	0.05
10	-6.9	0.06	-29	0.004
14	-4.4	0.04	7.1	-0.001
18	-3.1	0.03	24	-0.003

Relative strength of FSQ9 higher order harmonics (center and integrated)



Warm iron quad (half)



Connection box

Link

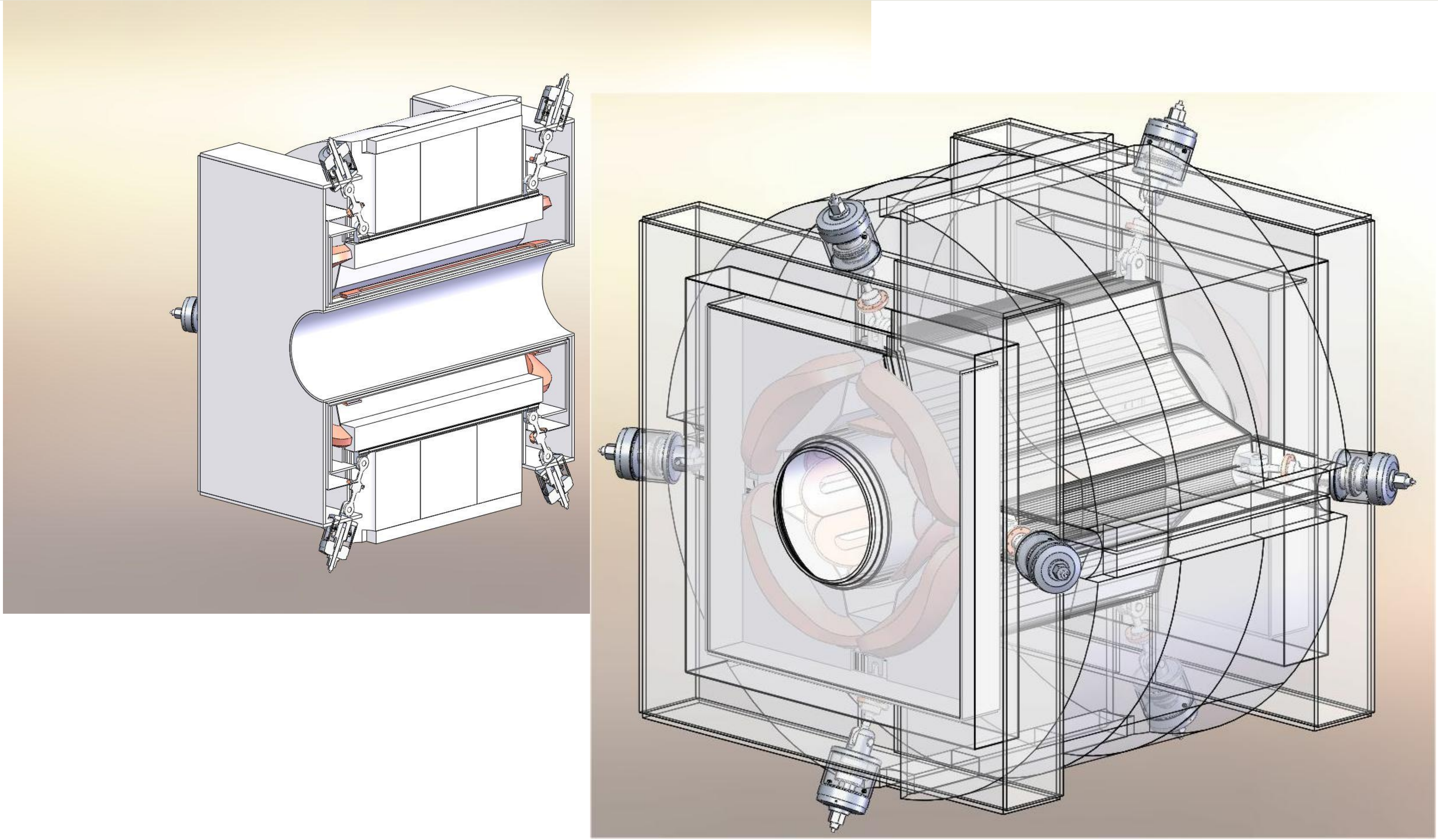
Yoke key

Quad Coil

Support

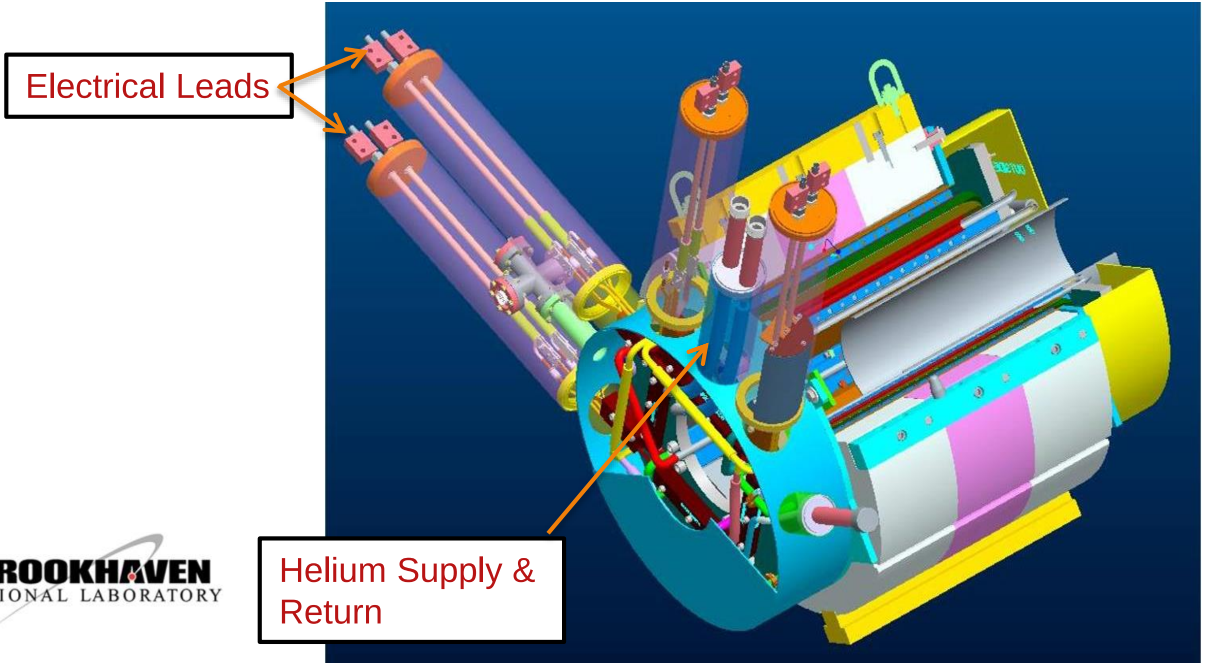
Multipole coils

Warm iron quad



Warm Iron HTS Quadrupole
Mechanical Design Completed

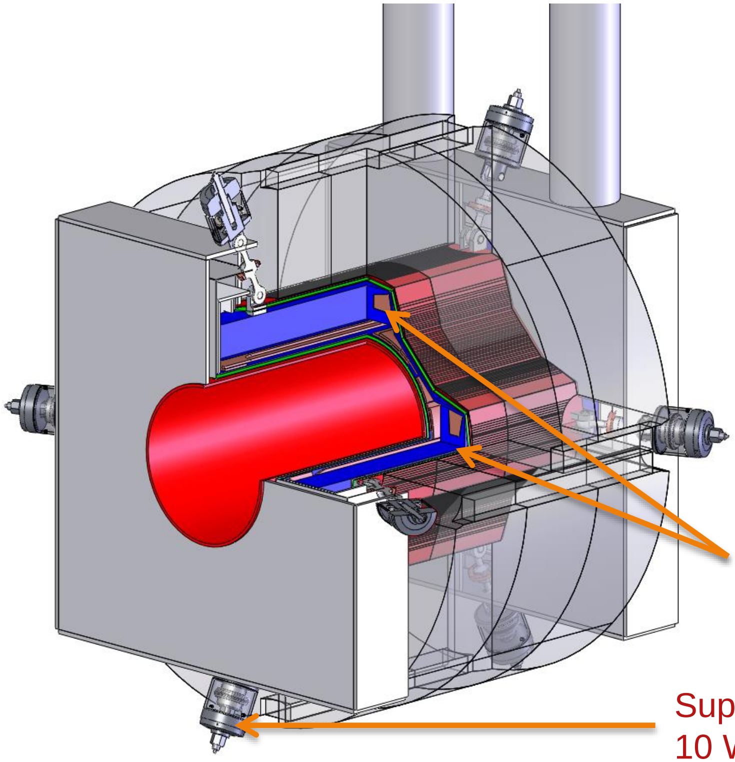
- Brookhaven National Lab (BNL) has designed a high temperature superconducting warm iron quad
  - Will be used as the first quadrupole after the target
  - MSU provided remote handling
- Cold mass complete
- Cryostat fabrication after cold testing


Electrical Leads

Helium Supply & Return

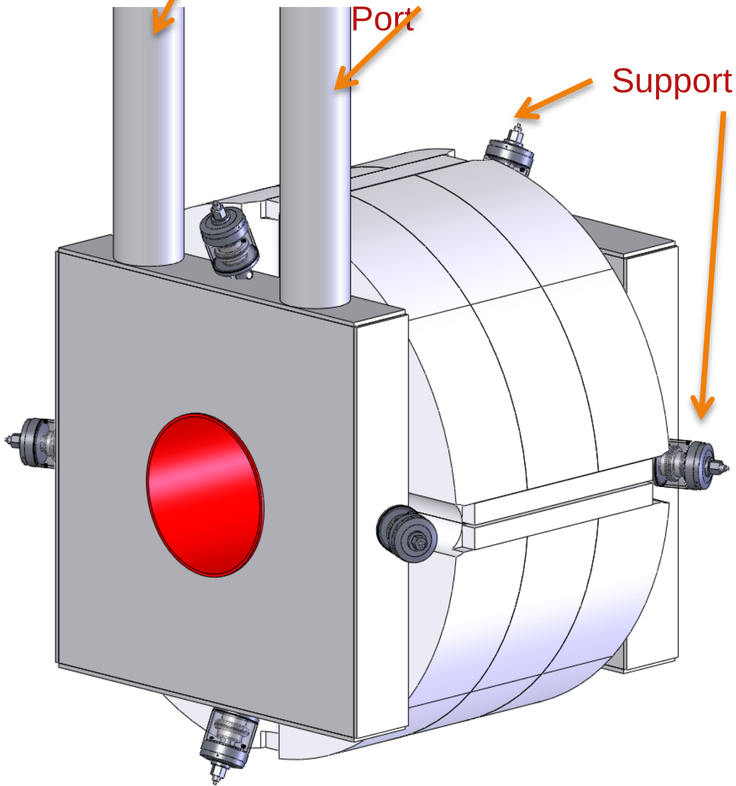
Warm Iron FRIB Quadrupole Features

- Warm iron quadrupole coils are not supported by the yoke iron like the cold iron quad design
  - Coils need a support structure to deal with coil forces of up to 40,000 kgf/linear m



Coil Backbone Support

Support Links Limited to 10 W Heat Load Total



Electrical Leads & Helium Return

Liquid Helium Supply Port

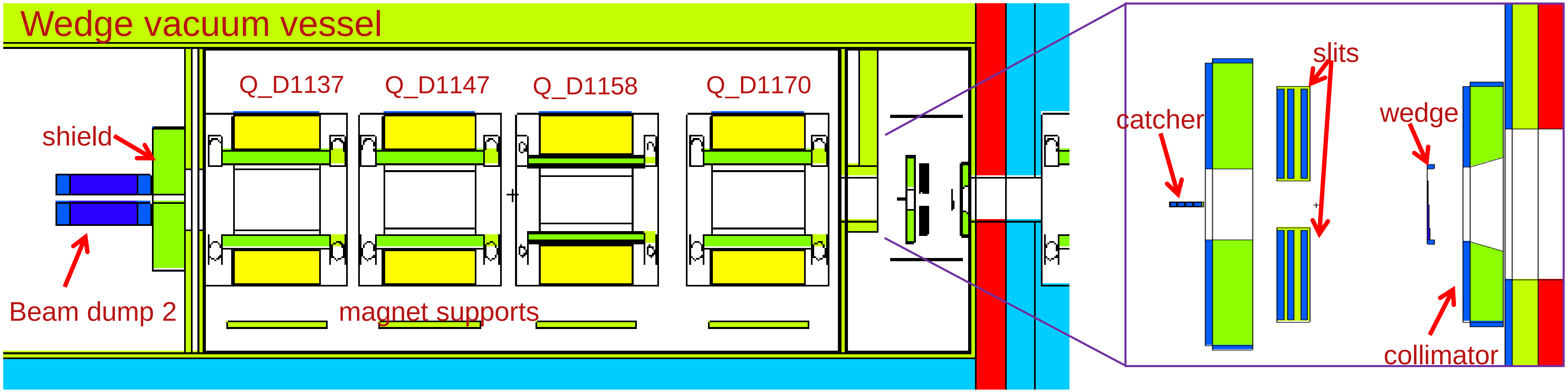
Support Links

MSU SC Magnet

Detailed Magnet Models for Simulations

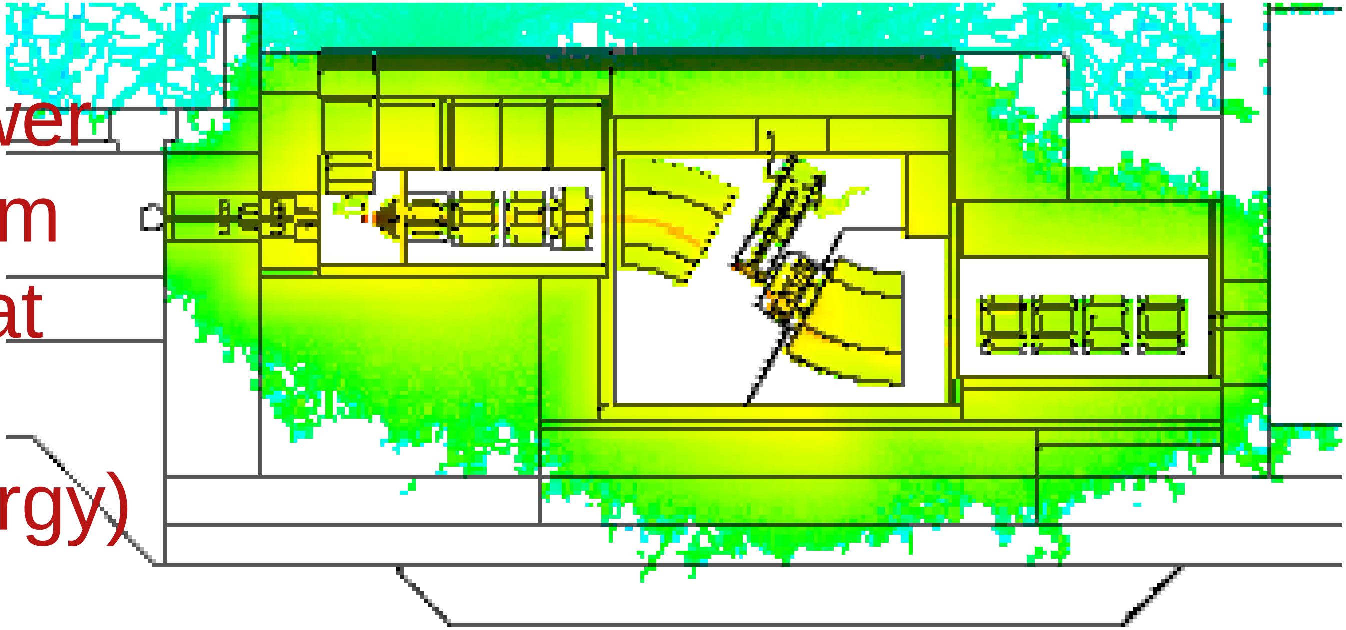
Basis for Reliable Prediction of Radiation Effects

- Power deposition in magnet structures drives the detailed design of magnet components, non-conventional utilities, cooling water loops, cryogenic requirements
- Continuous improvements of target, beam dump, and wedge vacuum vessel models that contain updated magnet components (geometry, dimensions, materials, structures)



Calculations of Radiation Power Deposition

- Power deposition in shielding drives detailed shielding design, such as concrete placement near the vacuum vessels
- Power deposition in magnet yokes and coils drives the detailed design of magnet components, non-conventional utilities, cooling water loops

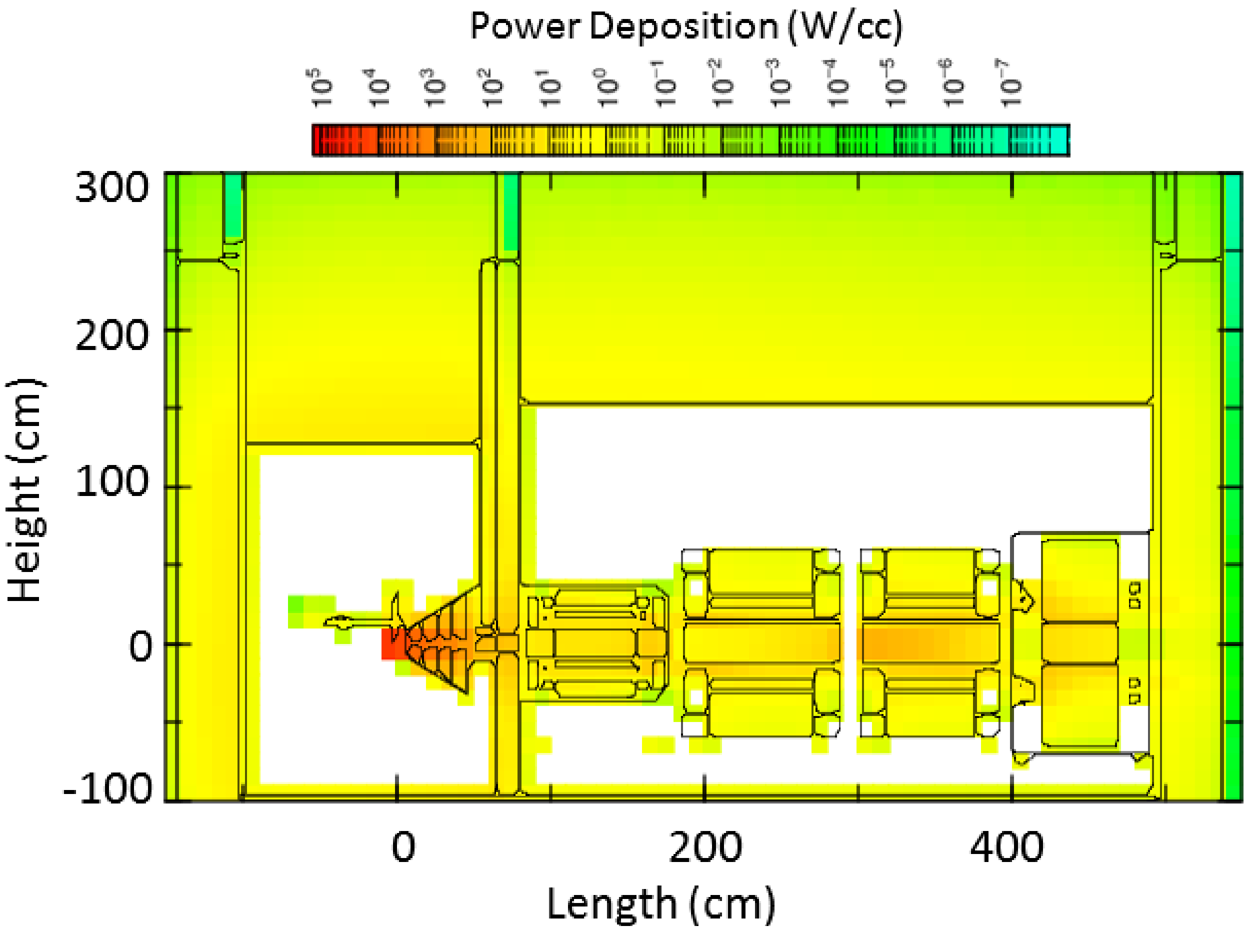


Radiation power deposition from Ca-48 beam at 239.5 MeV/u (baseline energy)

Calculations of Radiation Power Deposition

- Power deposition drives detailed vacuum vessel and external shielding design
  - Power deposition maps are used as a diagnostic tool to make sure there is no excessive heating

Radiation power deposition from ^{48}Ca beam at 549 MeV/u (upgrade energy



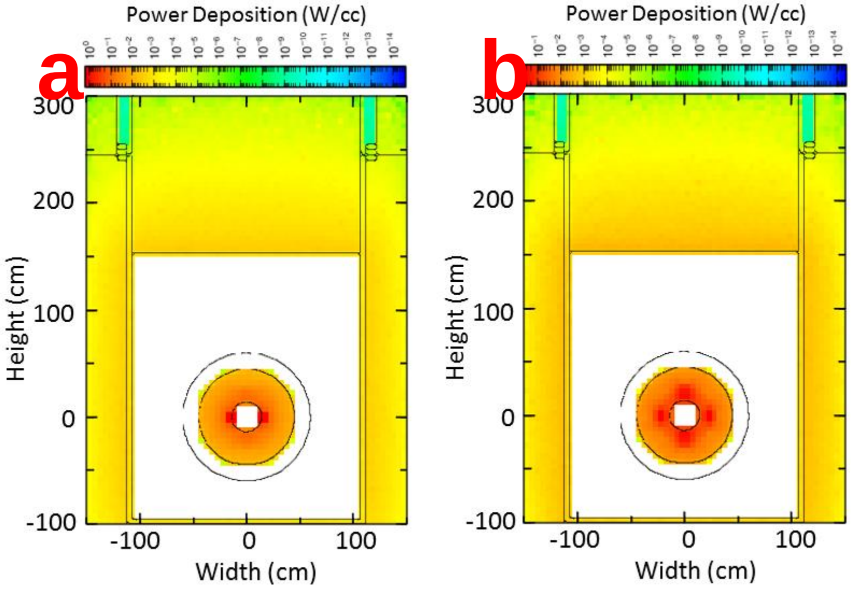
Magnet Thermal Shield Power Deposition Study
Supports Cryogenics Detailed Design

- 40 K thermal shield power deposition information also provided to the magnet designers and engineers for improvements towards detailed magnet shield cooling design and shield optimization
- Calculated heat loads become requirements for the cryogenic system

Power deposition in the target vacuum vessel magnet 40 K thermal shields

Beam (at 400 kW)	**^{48}Ca, 240 MeV/u**	**^{48}Ca, 549 MeV/u**
Magnet	Deposited power, W	
Q_D1024	12.7	120
Q_D1035	200	325

Power deposition in the front (**a**) and back (**b**) parts of Q_D1035 thermal shield



Magnet Yoke Power Deposition Study

Supports Cooling Loop Design

- Cooling will be provided to all magnet yokes in the hot cell
- Cooling may not be required for some magnet yokes
- Detailed heat load information is used to design water cooling loops
- Detailed heat load information also provided to the magnet designers and engineers for improvements towards final magnet designs

Power deposition in the target vacuum vessel magnet yokes

Beam (at 400 kW)	**^{48}Ca, 240 MeV/u**	**^{48}Ca, 549 MeV/u**
Magnet	Deposited power, W	
Q_D1013	60	330
Q_D1024	0.4	3
Q_D1035	4	50
S_D1045	550	7420

First 3 quads and resistive multipole

This analysis has been published in T40204-CA-000104 “Radiation Energy Deposition in Preseparator Magnets and Lifetime Estimates”; the numbers presented here are updated due to latest model changes reflecting design details

Study of Magnet Coil Lifetimes
Supports Choice of Coil Technology

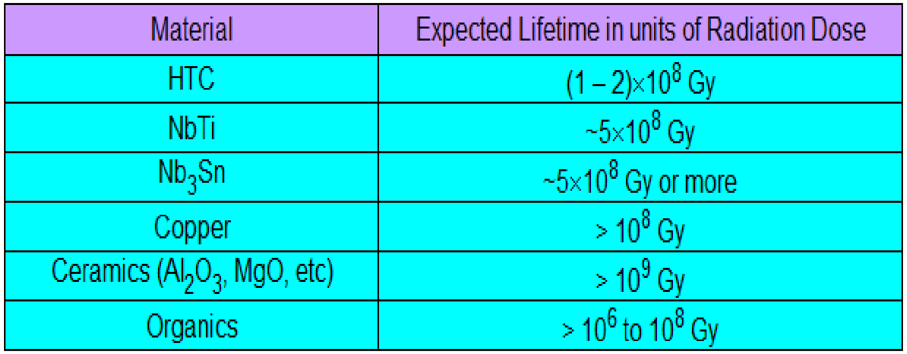
- Magnet coils lifetimes are comparable to the facility lifetime in the most conservative case
- Estimates of coil lifetimes are improved due to model changes catching up with design

Target vacuum vessel magnet coil dose rate and lifetime estimates

Beam (at 400 kW)	Coil Material	^{48}Ca, 240 MeV/u		^{48}Ca, 549 MeV/u	
Magnet		Dose, MGy/y		Dose, MGy/y	
Q_D1013	a	7		39	
Q_D1024	b	3		28	
Q_D1035	b	2		19	
S_D1045	c	8		72	

Magnet coil materials:
a) YBCO (HTS)
b) NbTi + Cu + Cyanate Ester
c) Stycast + Cu

Rnominal radiation tolerance in various materials



Material	Expected Lifetime in units of Radiation Dose
HTC	$(1-2)\times10^8$ Gy
NbTi	$\sim5\times10^8$ Gy
Nb_3Sn	$\sim5\times10^8$ Gy or more
Copper	$> 10^8$ Gy
Ceramics (Al_2O_3, MgO, etc)	$> 10^9$ Gy
Organics	$> 10^6$ to 10^8 Gy

This analysis has been published in T40204-CA-000104 “Radiation Energy Deposition in Preseparator Magnets and Lifetime Estimates”; the numbers presented here are updated due to latest model changes reflecting design details

Magnet Yoke Power Deposition Study Determines Cooling Loop Design

- Power deposition is highest after the beam dump
- Cooling is required for most magnet yokes
- Detailed heat load information is used to design water cooling loops
- Detailed heat load information also provided to the magnet designers and engineers for improvements towards detailed magnet designs

before beam dump

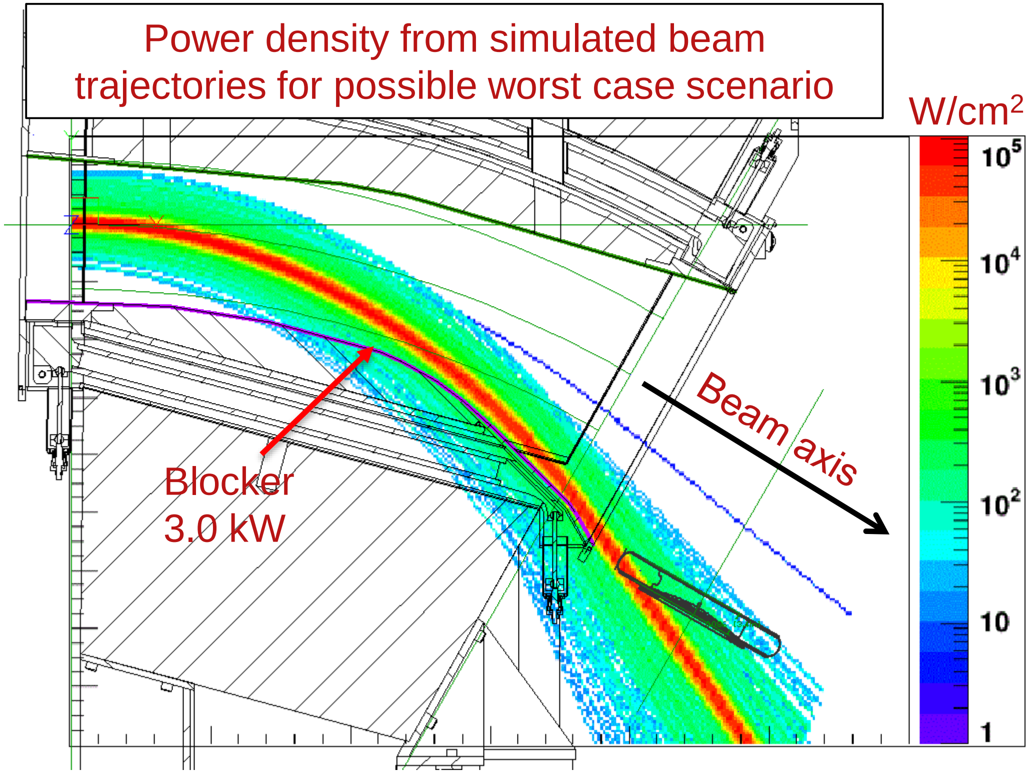
after beam dump

Beam (at 400 kW)	O-18	Ca-48
Energy, MeV/u	637	239.5
Magnet	Deposited power, kW	
Q_D1013	0.80	0.11
Q_D1024	0.30	0.04
Q_D1035	0.32	0.04
S_D1045	1.60	0.11
DV_D1064	1.84	0.19
S_D1092	16.2	3.20
DV_D1108	11.8	2.50
Q_D1137	1.54	7E-3
Q_D1147	0.08	2E-3
Q_D1158	0.03	8E-4
Q_D1170	0.02	5E-4

Magnet Design Integration

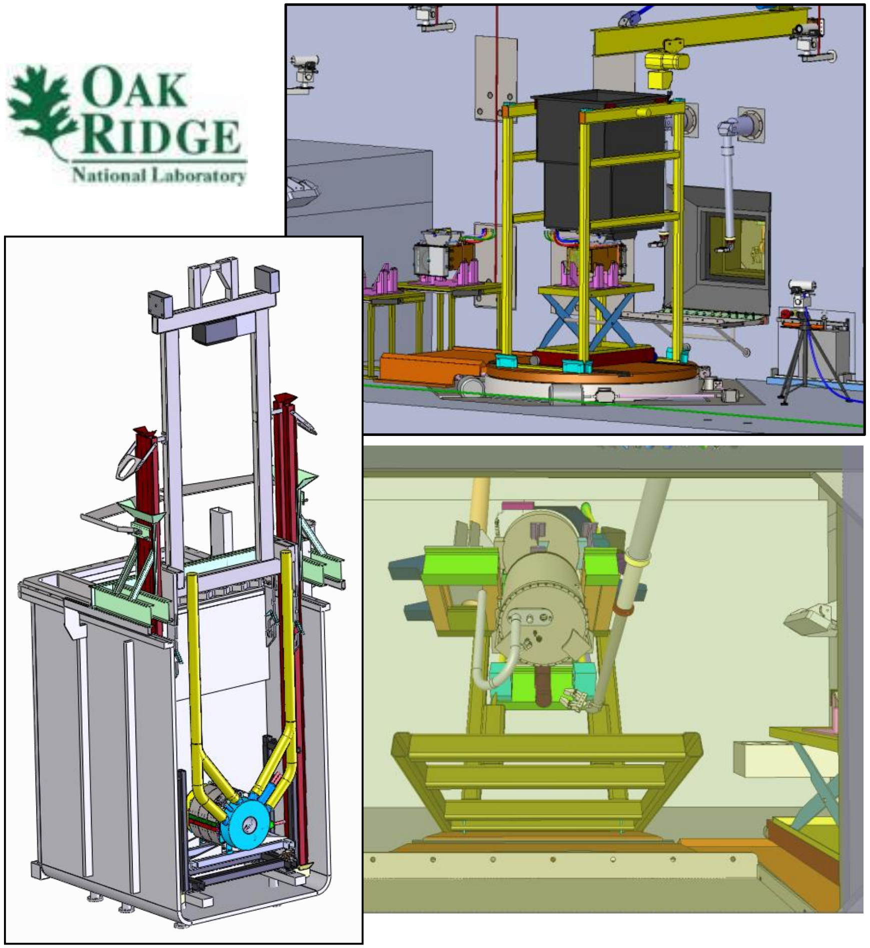
Dipole #1 Beam Interference Resolved

- Original split cryostat for first dipole found not feasible during final design
- Initial single-cryostat design had too small exit window
  - Primary beam (~ 300 kW beam power) would have hit cryostat
  - Settings for very neutron-rich light rare isotopes lead to large deflection of primary beam in first dipole (e.g. ^{18}O primary beam in ^{8}He setting)
- Interference resolved
  - Increasing dipole exit window opening
    - » Primary beam clears magnet hardware
  - Added blocker inside of dipole gap
    - » Stops intense fragments near primary beam
    - » Reduces heat load to cryostat
  - Special beam optics setting
    - » Controls primary beam envelope in both transverse directions
  - Beam physics and radiation transport simulations in good agreement


Power density from simulated beam trajectories for possible worst case scenario

Fragment Separator Remote-handling Equipment

- Technical design/specification of equipment to be procured complete, procurements released
  - Master slave manipulators
    - » Wall tubes delivered, shield plugs and manipulators delivery in August 2014
  - Shield windows
    - » Window Liners have been delivered, shield plugs and window delivery December 2014
  - Embeds - all delivered since March 2014
    - » S-bend utility, crane access, alignment and input enclosure; bottom loading port
  - 20-ton crane specs complete and reviewed
    - » Will be bid as part of CF bid package 5
- Remote tooling/handling design follows component design
  - Tooling design for Superconducting (SC) quadrupoles and dipole magnets substantially complete and reviewed
- Cold-test facility design nearly complete
  - Making use of master slave manipulators for design and procedure validation

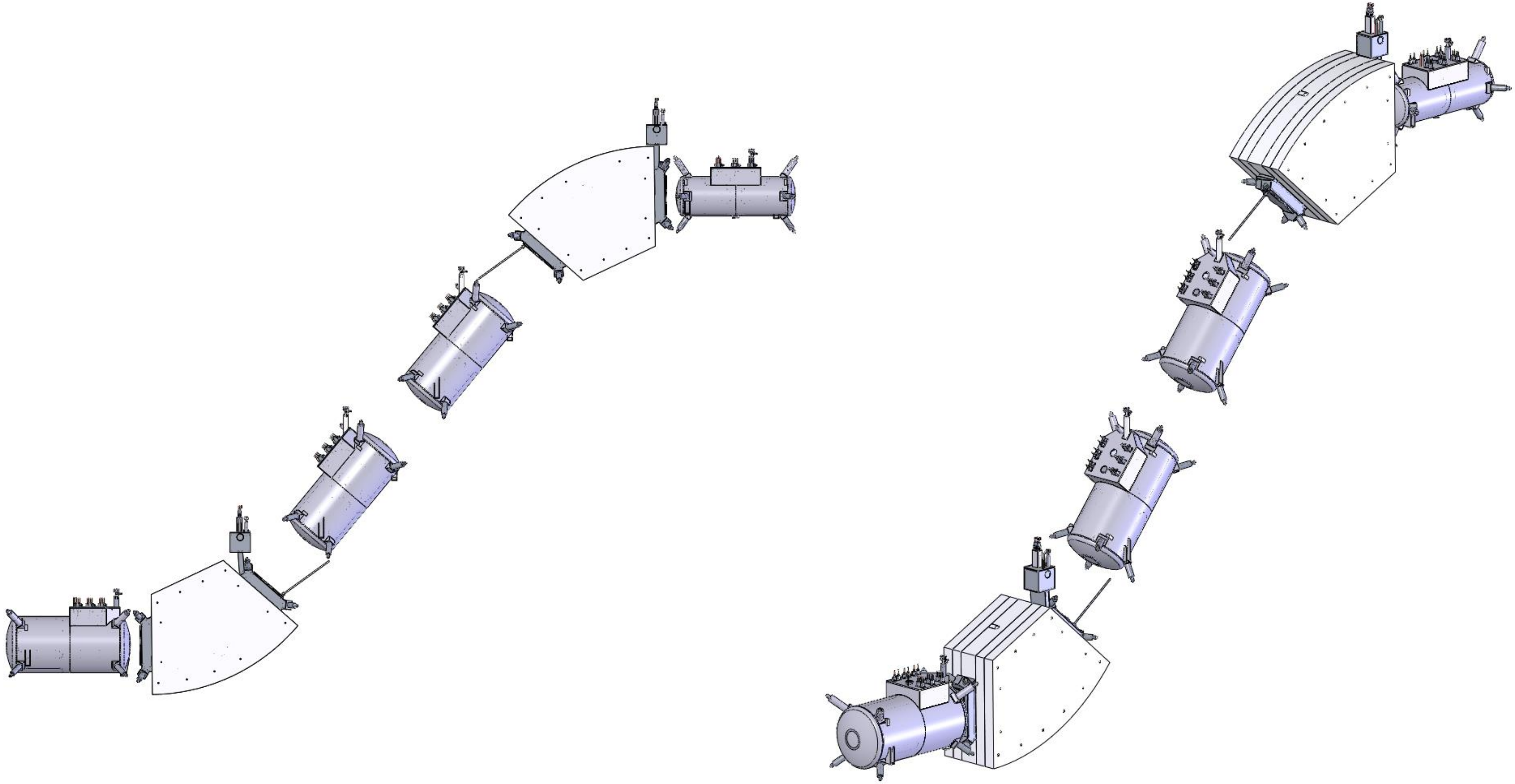


Installation Plan Established

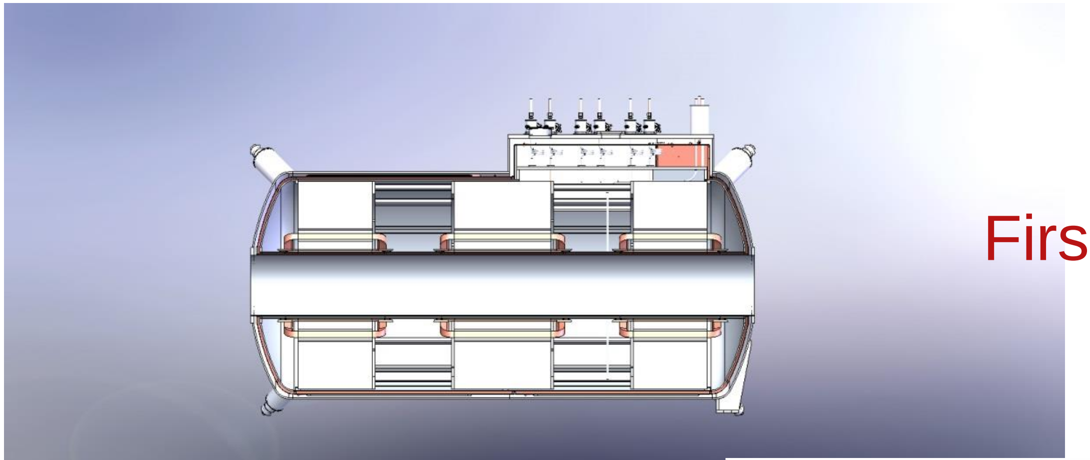
- Vacuum vessel installation with Conventional Facilities Division support prior to Beneficial Occupancy Date (BOD)
- Component installation in vacuum vessel using remote handling procedures
  - Magnets in hot cell vacuum vessels
    - » Initial installation August 2017 (remote handling equipment ready)
    - » Remote handling procedures validation August 2017 – February 2019
    - » Utility hookup and testing in February/March 2019
  - Target, beam dump, etc. will also be installed using remote handling equipment

Vertical Magnets

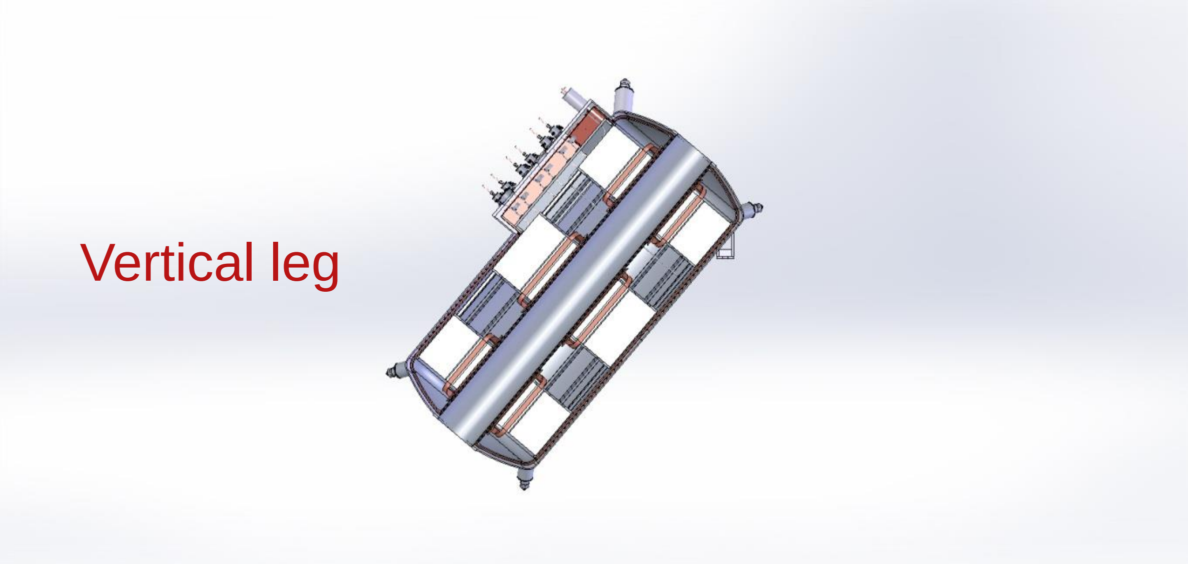
- Not in hot cell



Vertical Triplets



First triplet outside of the hot cell



Vertical leg

Schedule

- CD-3b review next month
- Begin technical construction summer-fall 2014
- Civil construction underway – begin to pour concrete in June
- Manage to early completion Oct 2020

Summary

- Preliminary design that supports initial operations
- Integrated into complete target facility
- Transition to HTS coils in future upgrades