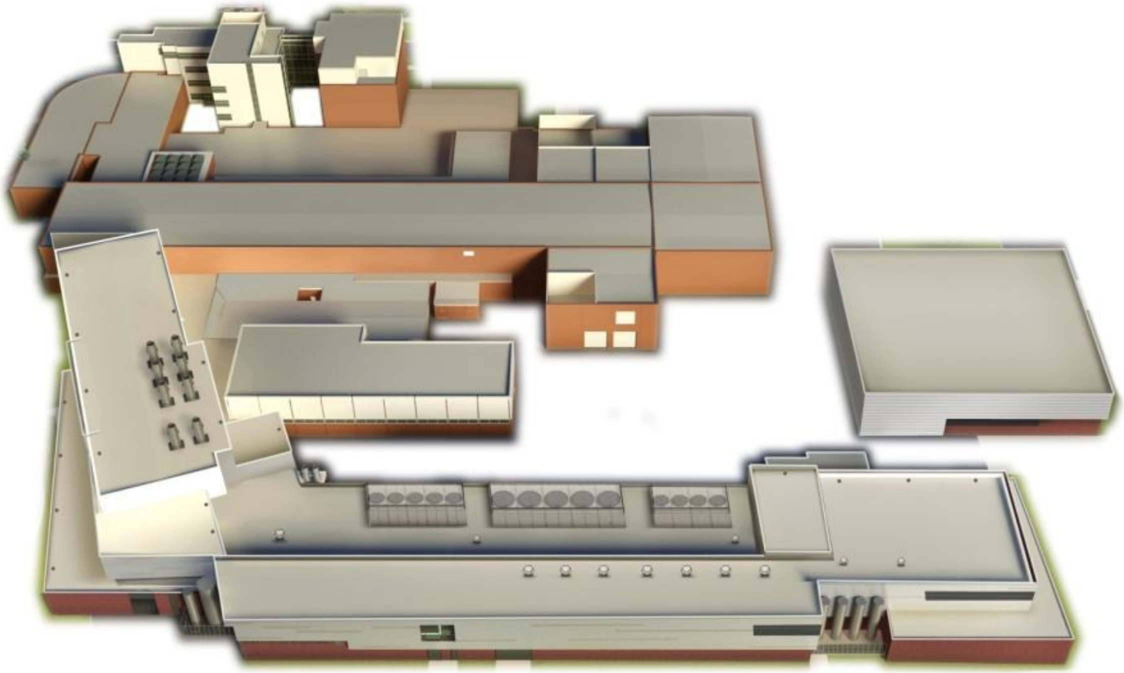
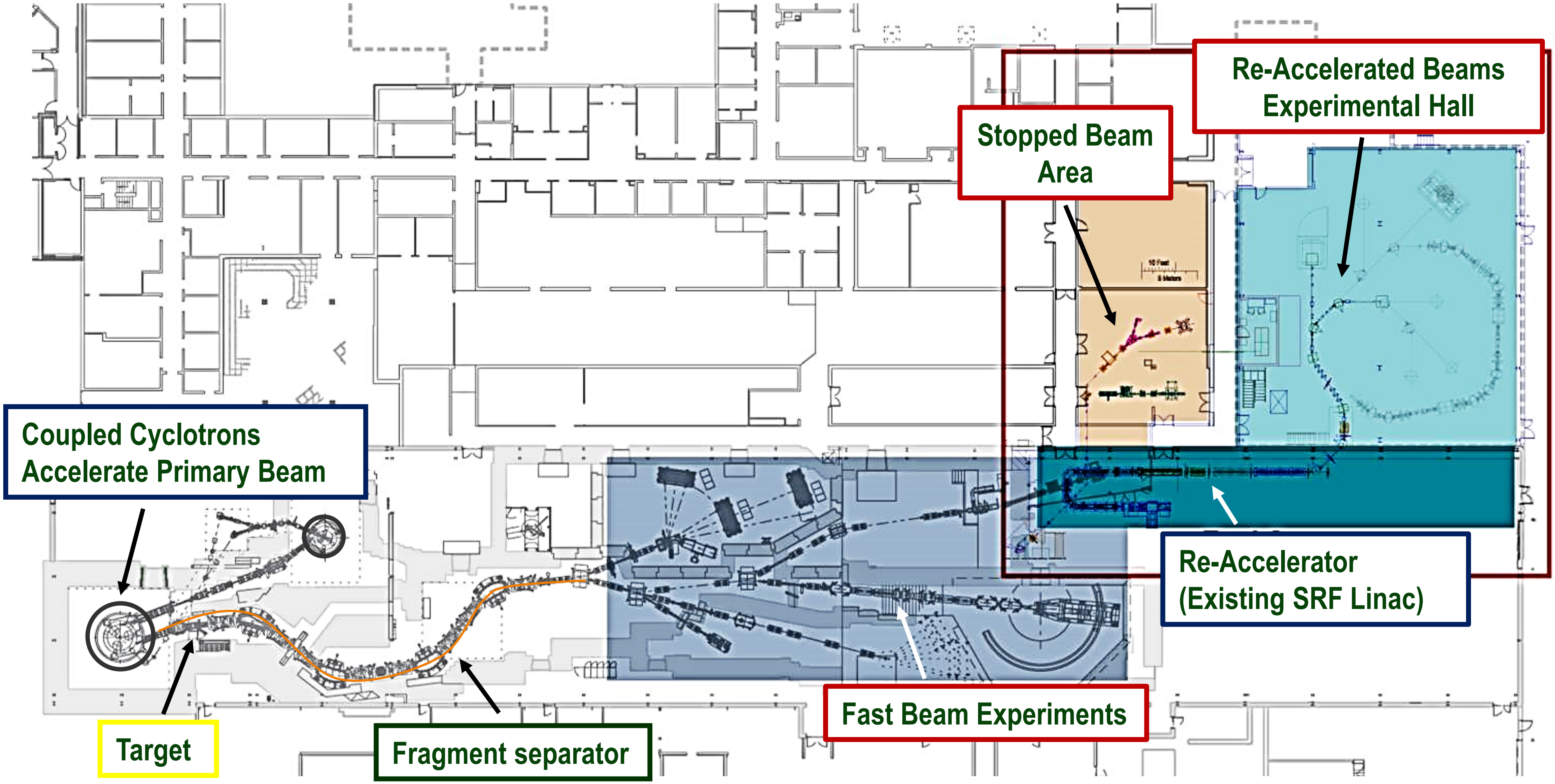


The FRIB Project At MSU

Matthaeus Leitner
SRF Department Manager

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Rare Isotope Production At MSU
NSCL Coupled Cyclotron Facility



http://www.nscl.msu.edu/interactivemap.html

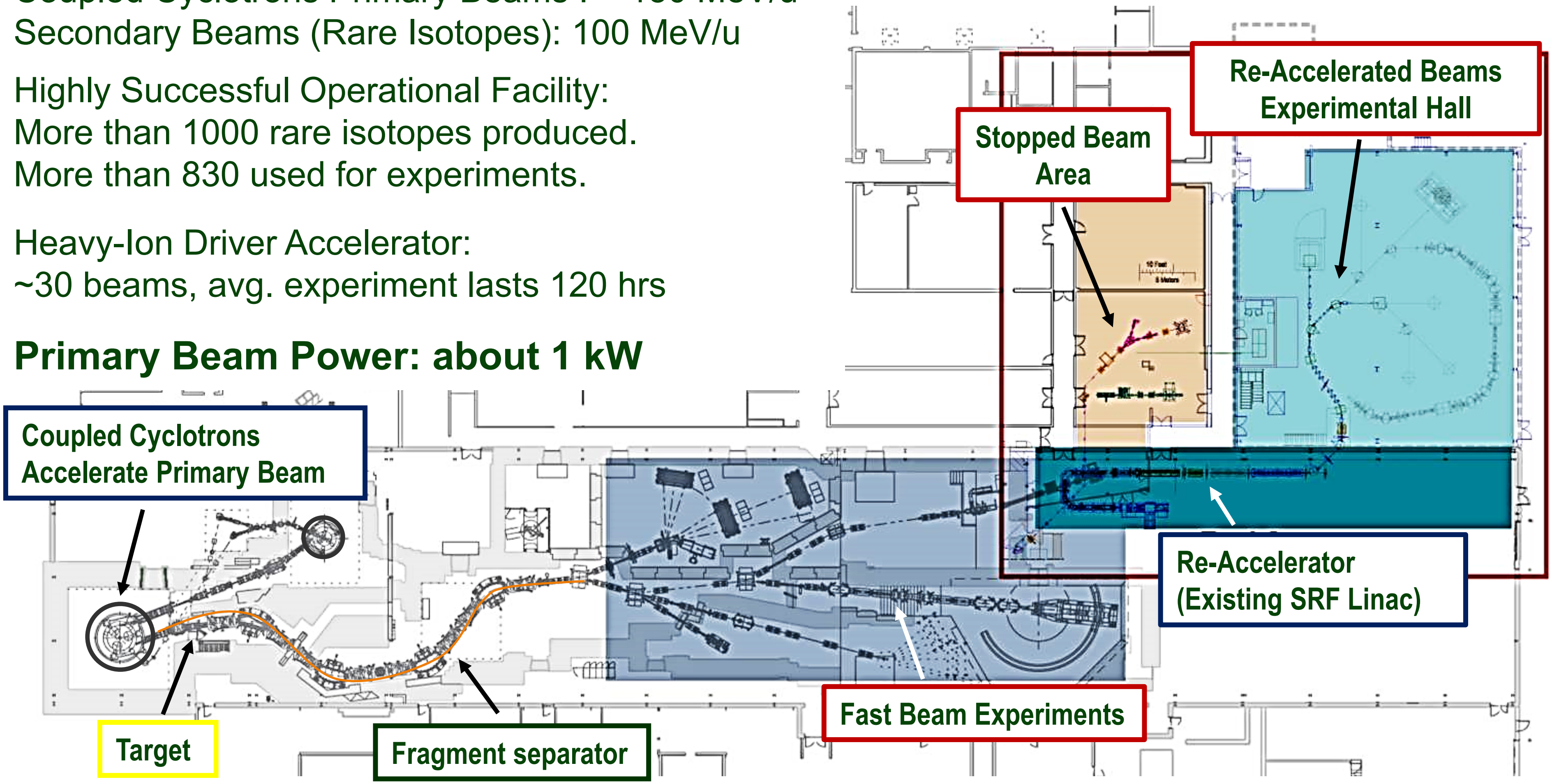
Rare Isotope Production At MSU
NSCL Coupled Cyclotron Facility

Coupled Cyclotrons Primary Beams : ~ 150 MeV/u
Secondary Beams (Rare Isotopes): 100 MeV/u

Highly Successful Operational Facility:
More than 1000 rare isotopes produced.
More than 830 used for experiments.

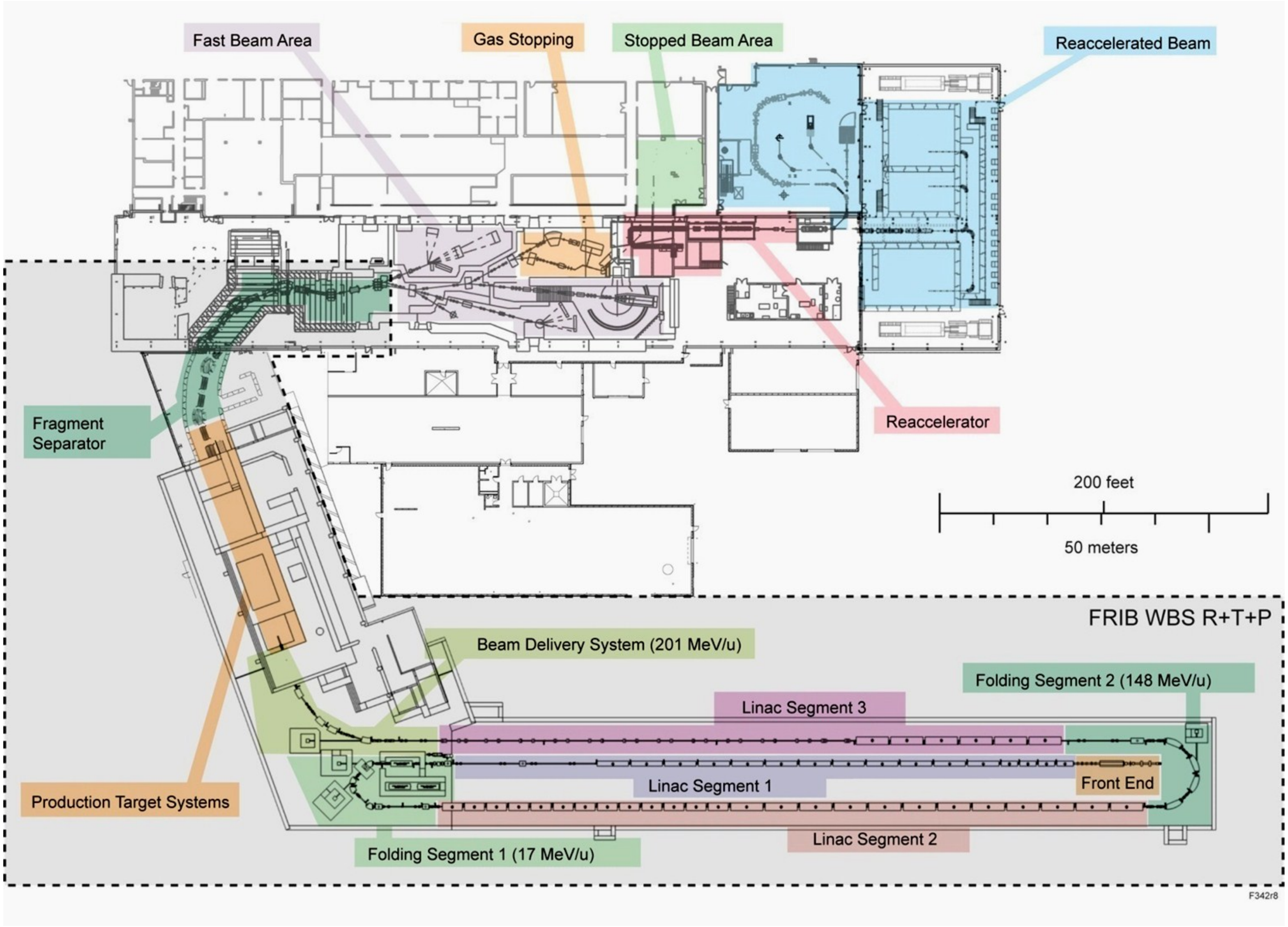
Heavy-Ion Driver Accelerator:
~30 beams, avg. experiment lasts 120 hrs

Primary Beam Power: about 1 kW

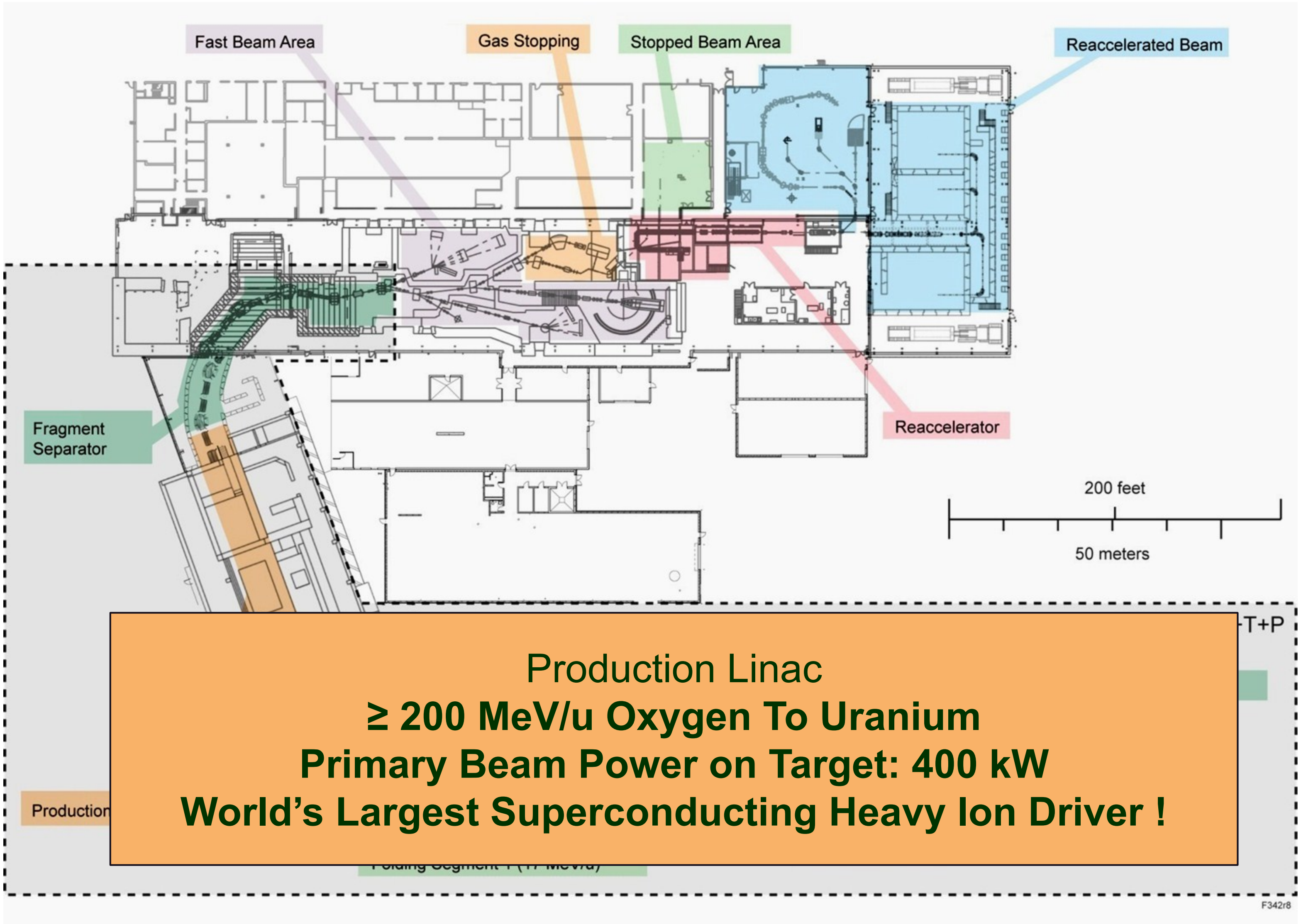


http://www.nscl.msu.edu/interactivemap.html

Future Of Rare Isotope Production At MSU: Facility for Rare Isotope Beams (FRIB)



Future Of Rare Isotope Production At MSU: Facility for Rare Isotope Beams (FRIB)



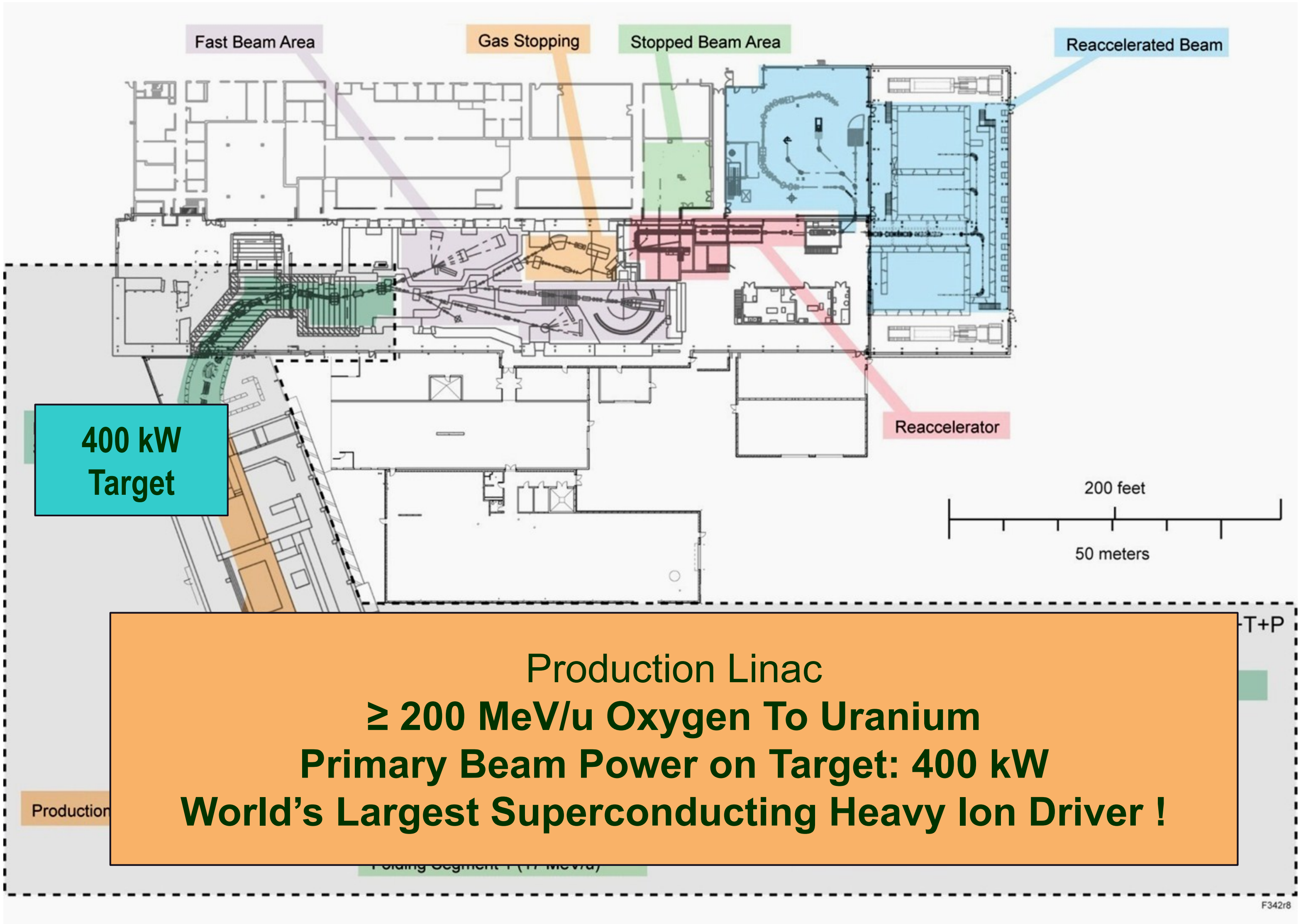
Production Linac

≥ 200 MeV/u Oxygen To Uranium

Primary Beam Power on Target: 400 kW

World's Largest Superconducting Heavy Ion Driver !

Future Of Rare Isotope Production At MSU: Facility for Rare Isotope Beams (FRIB)



400 kW Target

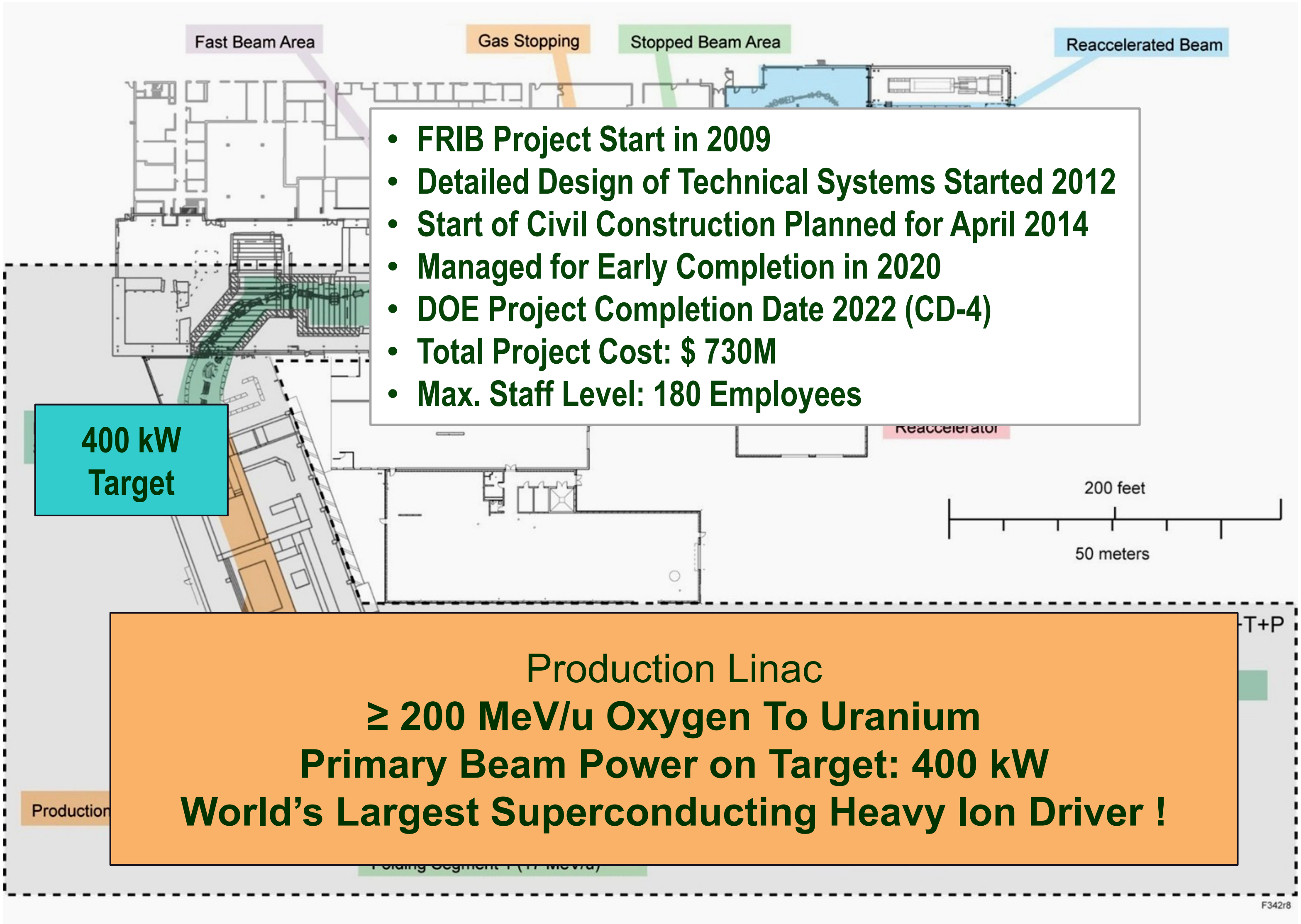
Production Linac

≥ 200 MeV/u Oxygen To Uranium

Primary Beam Power on Target: 400 kW

World's Largest Superconducting Heavy Ion Driver !

Future Of Rare Isotope Production At MSU: Facility for Rare Isotope Beams (FRIB)



- FRIB Project Start in 2009
- Detailed Design of Technical Systems Started 2012
- Start of Civil Construction Planned for April 2014
- Managed for Early Completion in 2020
- DOE Project Completion Date 2022 (CD-4)
- Total Project Cost: $ 730M
- Max. Staff Level: 180 Employees

400 kW Target

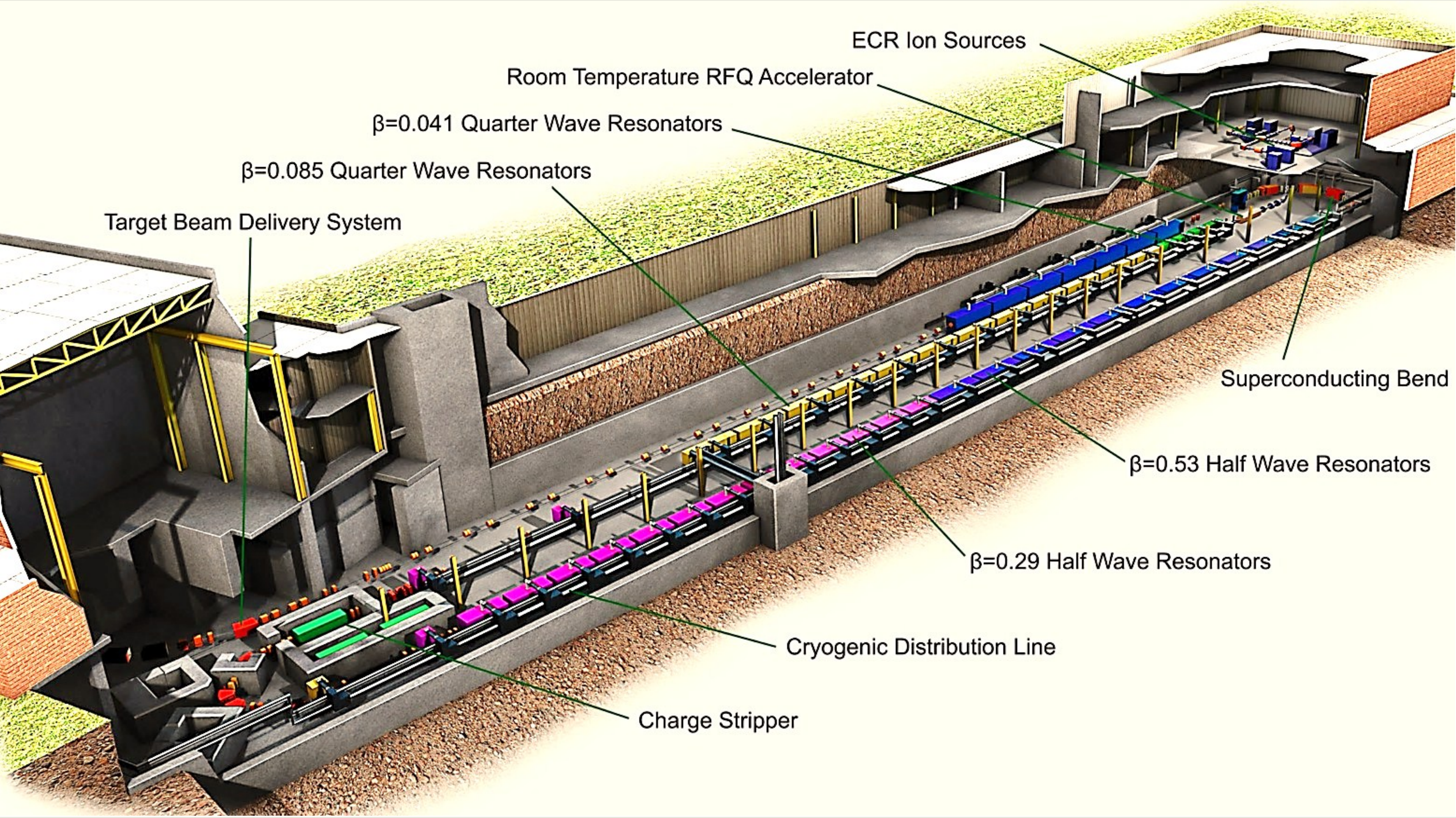
Production Linac

≥ 200 MeV/u Oxygen To Uranium

Primary Beam Power on Target: 400 kW

World's Largest Superconducting Heavy Ion Driver !

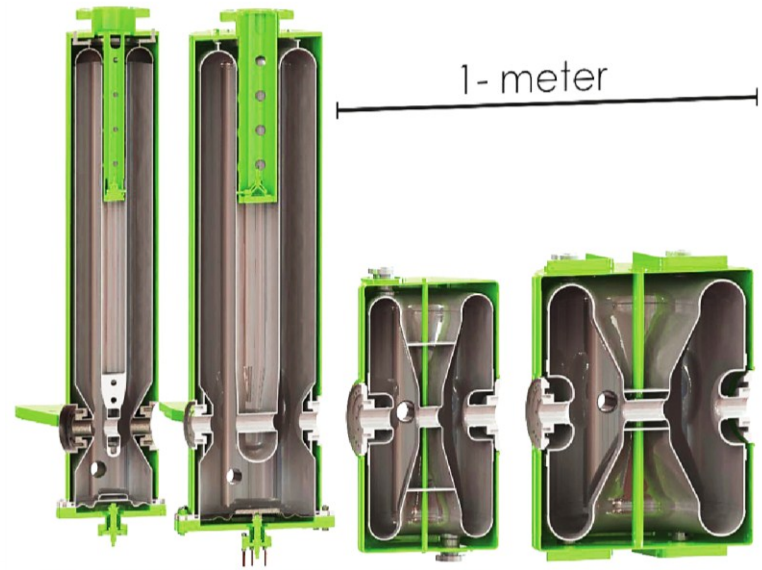
FRIB Superconducting Driver Linac
Layout Is Folded Into Three Accelerator Sections



J. Wei, et al, *The FRIB Project – Accelerator Challenges and Progress*, **HIAT 2012**, Chicago

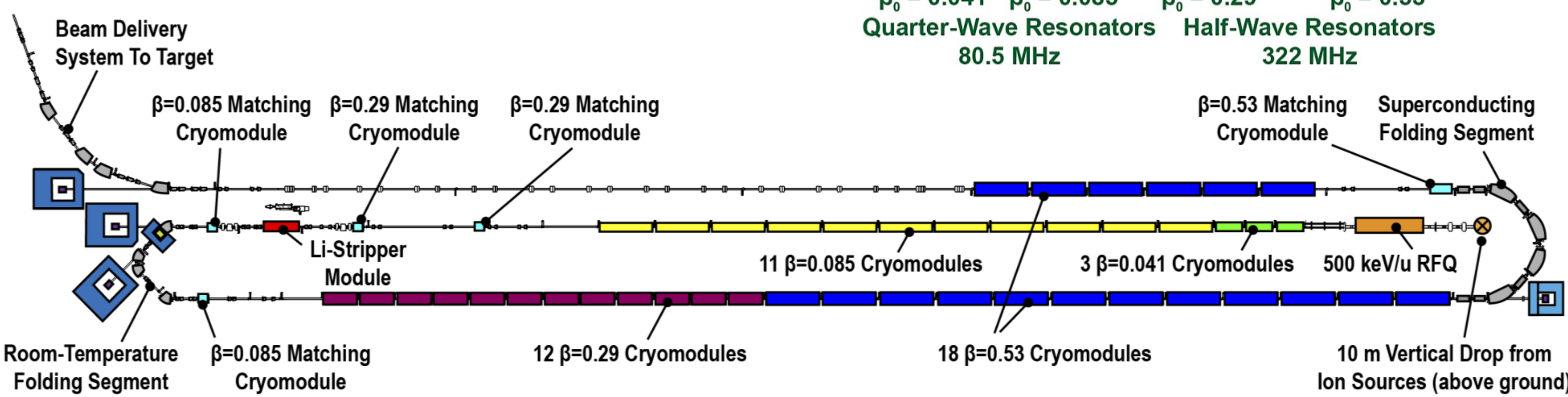
SRF Systems - Cavities

Cavity Type	Quantity of Cavities	Quantity of Modules	Quantity of Solenoids
β=0.041	12	3	6
β=0.085	88	11	33
β=0.29	72	12	12
β=0.53	144	18	18
Additional Bunching Modules	6 4 4	2 (β=0.085) 2 (β=0.29) 1 (β=0.53)	n/a
Total	**330**	**49**	**69**



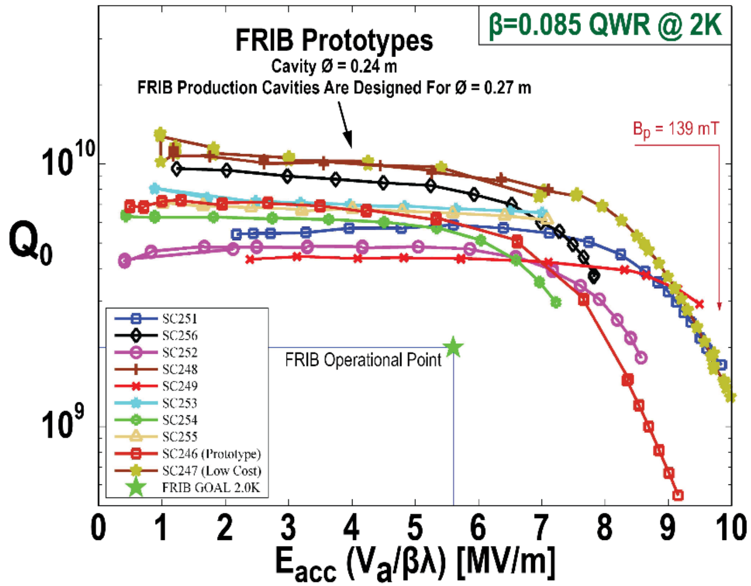
$\beta_0 = 0.041$ $\beta_0 = 0.085$
Quarter-Wave Resonators
80.5 MHz

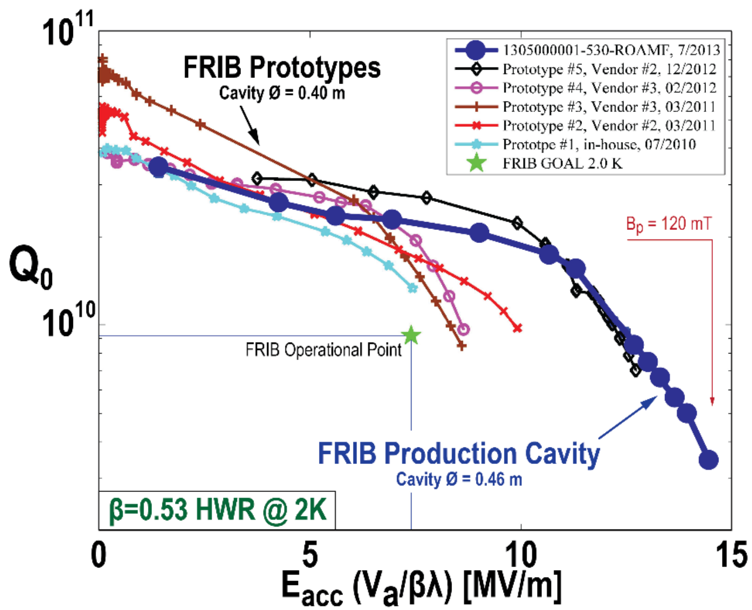
$\beta_0 = 0.29$ $\beta_0 = 0.53$
Half-Wave Resonators
322 MHz



A. Facco: THIOD02, K. Saito: MOP013, J. Ozelis: MOP067, J. Popielarski: MOP088

FRIB Has Implemented Cavity Designs With Significant Operational Safety Margin At Low Cavity Costs





FRIB Linac Operational Parameters

Cavity Type	QWR #1	QWR #2	HWR #1	HWR #2
β	0.041	0.085	0.29	0.53
Frequency [MHz]	80.5	80.5	322	322
Temperature [K]	2	2	2	2
Aperture [mm]	36	36	40	40
Cavity Ø [m]	0.18	0.27	0.29	0.46
βλ [m]	0.16	0.317	0.27	0.493
R/Q [Ω]	401.6	455.4	224.4	229.5
G [Ω]	15.3	22.3	77.9	107.4
Avg. Accel. V_a [MV]	0.81	1.78	2.09	3.7
$V_a/\beta\lambda$ [MV/m]	5.1	5.6	7.7	7.5
V_a/Cavity Ø [MV/m]	4.5	6.6	7.2	8.0
E_p at V_a [MV/m]	30.8	33.4	33.3	26.5
B_p at V_a [mT]	54.6	68.9	59.6	63.2
Dissipation at V_a [W]	1.32	3.88	3.55	7.9
Max. Beam Power [W]	313	690	1526	2701
Min. RF Bandw. [Hz]	40	40	30	30
Installed RF Power [kW]	0.7	2.5	3.0	5.0

- **BCP processing and 600 ºC furnace treatment**
- **Helium vessel made of titanium**
- **Max. Pressure Rating At 300 K: 2.2 atm**
- **Relief Pressure At 2 K: 10.8 atm**

SRF Systems – Procurement Status

- 23 FRIB-relevant cavity prototypes have been successfully tested
  - 8 β=0.041 cavities, 11 β=0.085 cavities, 5 β=0.53 cavities
- Production cavities are procured using a phased approach
  - 2 development cavities, undressed (no helium vessel) ⬅ **CONFIRM FINAL DESIGN**
  - 10 dressed pre-production cavities (with helium vessel) ⬅ **CONFIRM PRODUCTION**
  - Production cavities
- Production Cavities Fabrication Status:
  - First development cavities have been successfully fabricated and delivered
    - » β=0.53 Roark Welding & Engineering Co., Inc. (received and certified)
    - » β=0.29 Roark Welding & Engineering Co., Inc. (received)
    - » β=0.085 Pavac Industries, Inc. (delivery early 2014)
  - β=0.53 FRIB production contract placed for 144 cavities.
  - Rest of cavity production contracts will be placed by end of this year.

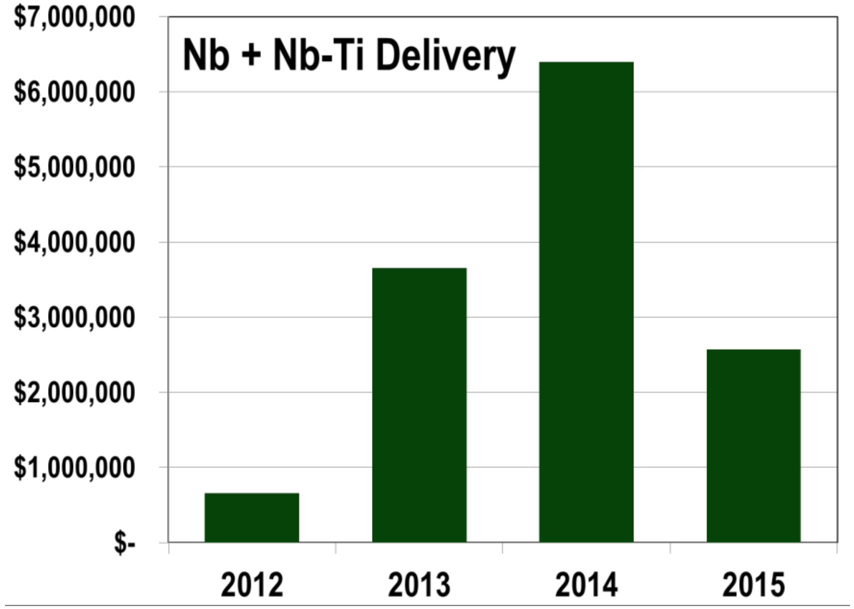
PAVAC INDUSTRIES INC.

ROARK C.F. Roark Welding & Engineering Co., Inc.

M. Leitner, et al, *Status of the Linac SRF Acquisition for FRIB*, **LINAC 2012**, Tel-Aviv

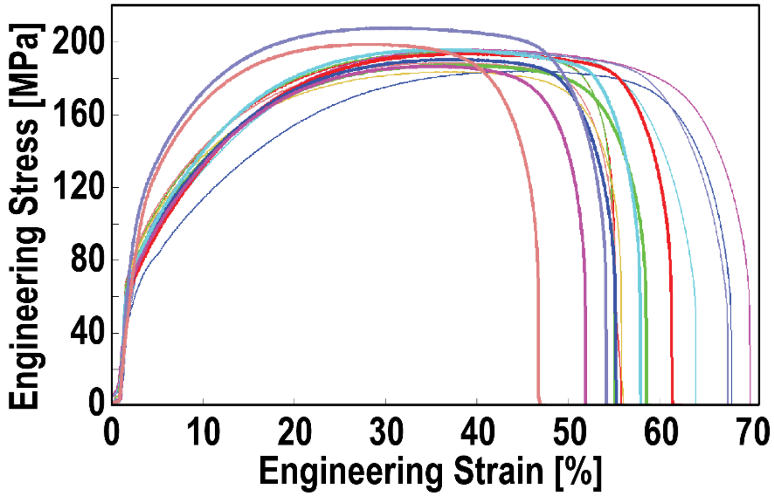
Niobium – Procurement Status

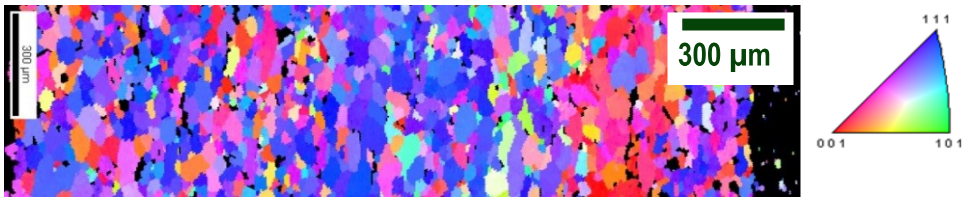
- FRIB project procured \$13.2M of niobium material
- FRIB niobium material contracts awarded to three vendors
  - Wah Chang – Niobium Titanium (Nb-Ti)
  - Tokyo Denkai – Residual Resistivity Ratio (RRR) Nb sheet
  - Ningxia – RRR Nb sheet and tube
- Niobium procurement broken into four task orders
- Niobium specifications
  - RRR > 250
  - Grain Size (ASTM #5): 64 µm
  - Yield Strength (0.2% offset): 7000 psi min.
  - Tensile Strength: 14000 psi min.
  - Elongation: 40 % min. longitudinal
  - Elongation: 35 % min. transverse
  - Hardness, HV 10: 60 max.



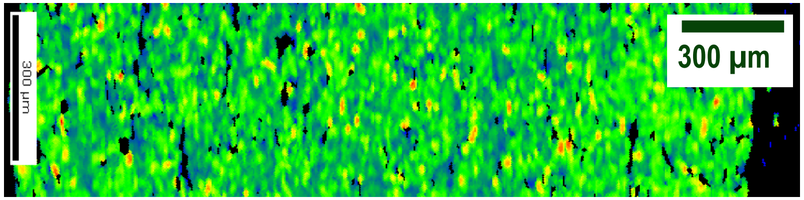
Niobium Acceptance Testing At FRIB Ensures Quality Control At Vendors

- Minimum of two samples per production lot are tested:
- Mechanical properties measured include
  - Ultimate strength (strain rate 5mm/min to fracture)
  - Yield strength (strain rate 5 mm/min to fracture)
  - Elongation (strain rate 5 mm/min to fracture)
  - Hardness (Hv microhardness) (100 grams load)
- Metallurgy properties measured include
  - Grain size (distribution)
  - Crystal orientation (not specified)
  - Recrystallization (>90%)

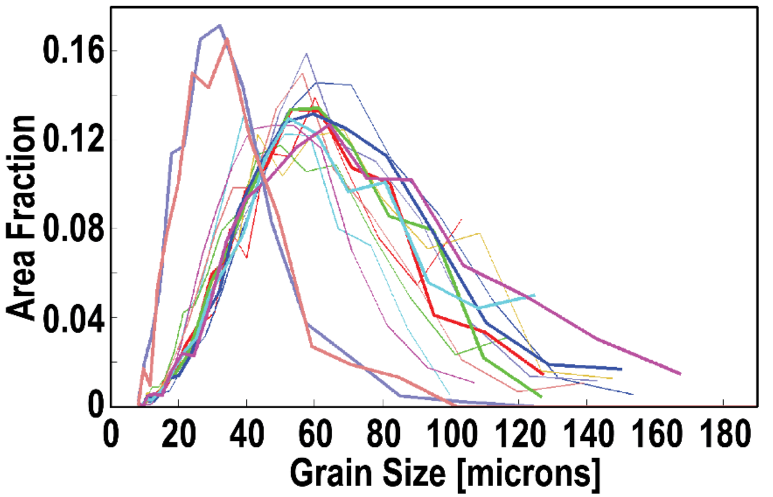




Crystal Orientation

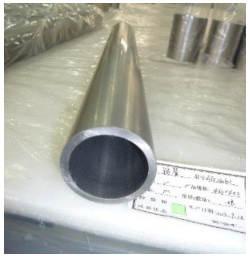


Misorientation Distribution



FRIB Requires Mass Production Of Large Niobium Sheets

- Largest sheets from Ningxia: 900 mm x 1070 mm x 2mm
- Tubes from Ningxia: 30 to 50 mm OD, 4 mm wall thickness
- Largest sheets from Tokyo Denkai: 620 mm x 620 mm x 3mm



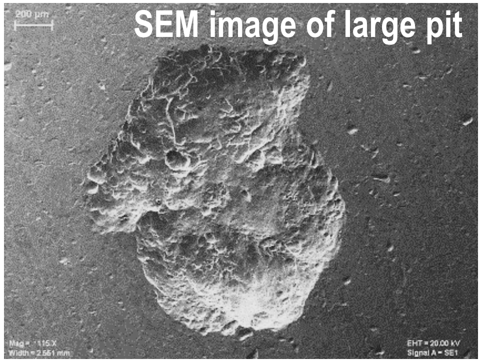
東京電解
Tokyo Denkai

宁夏东方钽业股份有限公司
NINGXIA ORIENT TANTALUM INDUSTRY CO.,LTD

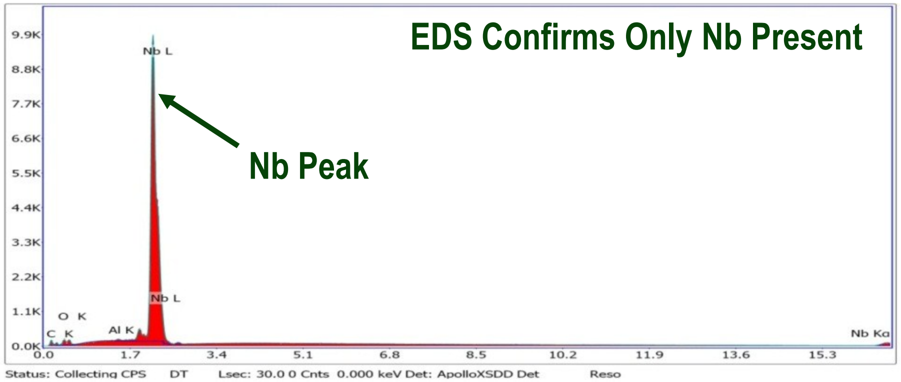
Large Sheet Production Is Susceptible to Pitting By Loose Niobium Particles

- Surface defects too deep to polish out
- Internal investigation initiated to determine root cause
  - Potential impurity concern (within material)
  - Potential surface contamination concern (introduced during rolling)
  - Potential annealing concern (orientation and dislocations)
  - Pit enhancement or generation from etching concern
- Experimental analysis at FRIB identified origin of pits:
  - Loose niobium particles imprinted during sheet rolling
  - Secondary Electron Microscopy images consistent with external particles embedded and later re-loosened
  - Energy-dispersive X-ray Spectroscopy confirmed that no impurities are found in or around pits, surface particles are niobium
- Quality improvements at vendor required
  - Improve cleanliness, implement clean zones throughout material fabrication

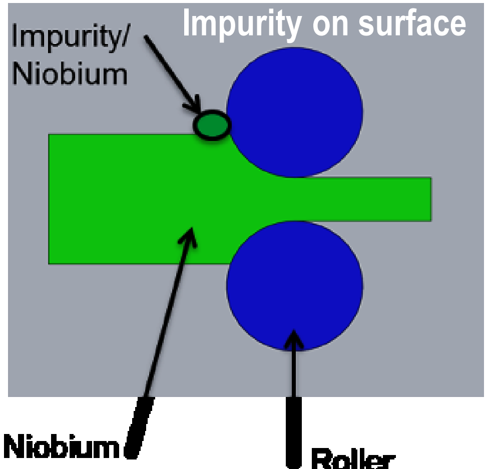
Pits observable by eye



SEM image of large pit



EDS Confirms Only Nb Present



Impurity on surface

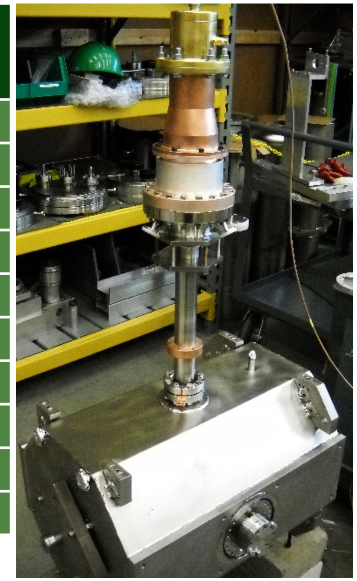
MICHIGAN STATE UNIVERSITY
CHEMICAL ENGINEERING & MATERIALS SCIENCE

Prof. Thomas Bieler

C. Compton: MOP033

QWR Will Utilize ANL Coupler With Cold Window And 90 Degree Bend, HWR Will Utilize SNS-Style Coupler With Single Warm Window

Coupler Type	QWR β=0.085	HWR β=0.53
Frequency [MHz]	80.5	322
Line Impedance [Ω] (*) will change to 75 Ω	50	50(*)
Cavity RF Bandwidth [Hz]	40	30
Installed RF Power [kW]	2.5	5
Max. Coupler Power Rating [kW]	4	10
Manual Coupling Adjustment	½ To 2 Times Bandwidth	
Coupler Interface	1-5/8" EIA	3-1/8" EIA
Total Heat Load To 2 K At Nominal RF Power [W]	0.13	0.6
Total Heat Load To 4.5 K At Nominal RF Power [W]	1.3	2.7
Total Heat Load To 55 K At Nominal RF Power [W]	7.1	6.2



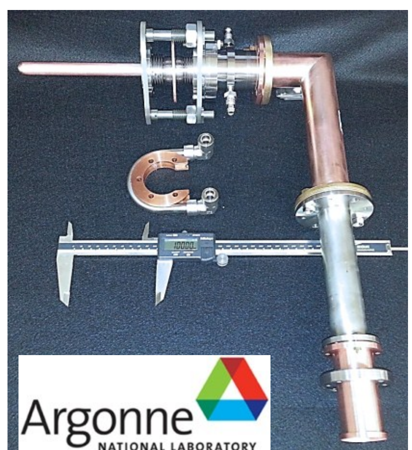
Adjustable Bellows
With 4.5 K Thermal Intercept

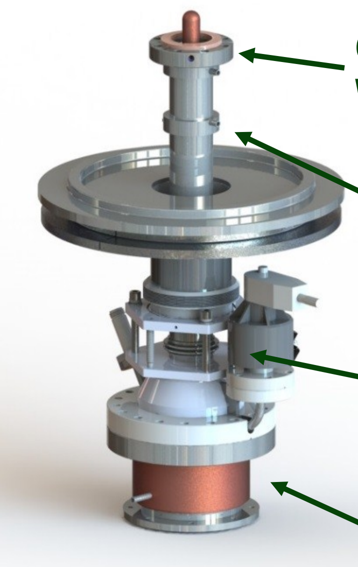
55 K Cold Window

90 Degree Bend

Warm Transition

Warm Window
At Cryomodule
Feedthrough





Cavity Flange
With 4.5 K Thermal Intercept

Coaxial Line
With 55 K Intercept

Adjustable Bellows For
Coupling Adjustment

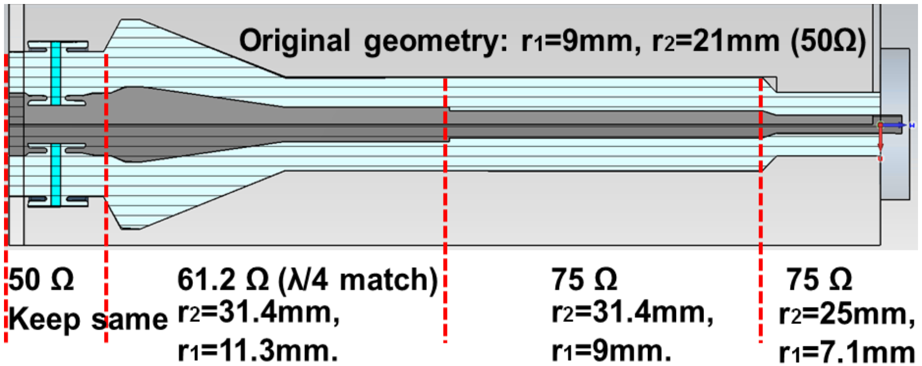
Single Warm Window

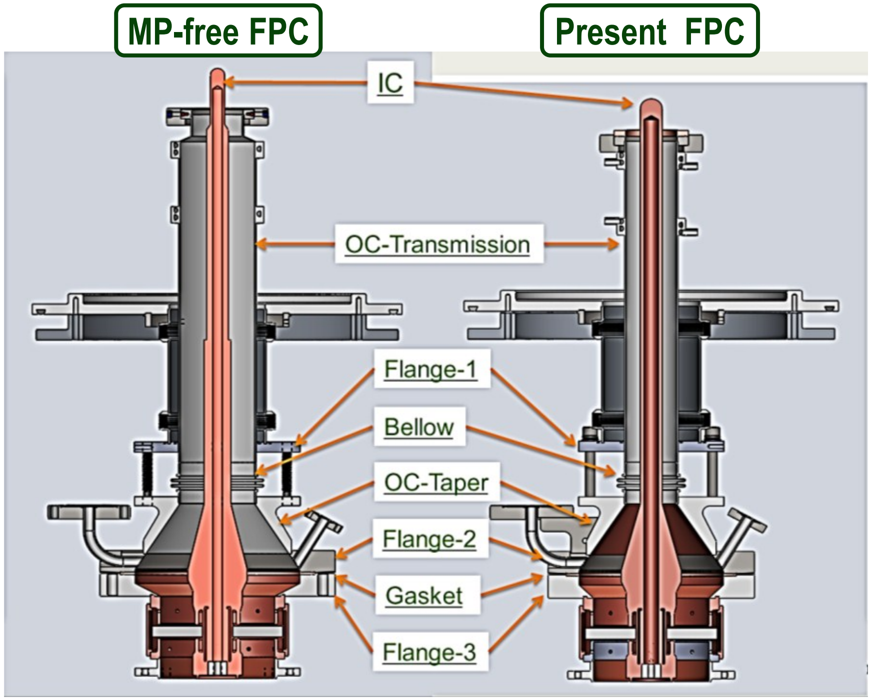
M.P. Kelly, et al, *Compact 4 kW Variable RF Power Coupler For FRIB Quarter-Wave Cavities*, **LINAC 2012**, Tel-Aviv

L. Popielarski: THP067, R. Oweiss: THP053

Multipacting Free HWR Coupler Development

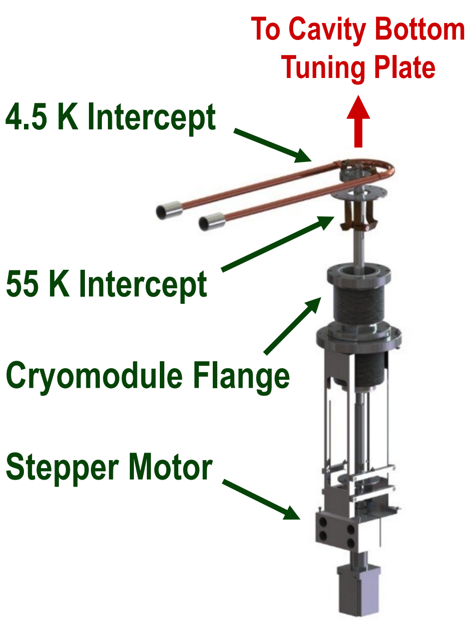
- Multipacting free coupler under development to mitigate risk of extended RF conditioning needs during FRIB operation
- Constraints: Compatible and interchangeable with the present coupler design
  - Same RF 50 Ω connector, same 3-1/8" RF port
- Simulations confirm: MP levels suppressed up to FRIB operation E_a
- Principle:
  Modification of the line impedance
  - **61 Ω, λ/4 stub to match 50 Ω to 75 Ω**



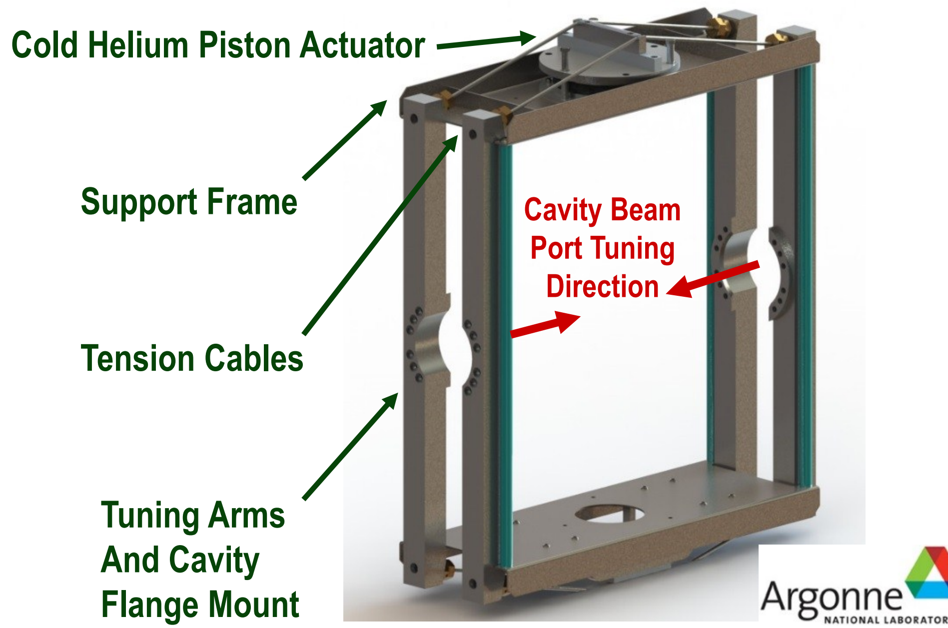


FRIB Cavity Tuner Designs Are Finalized Performance Has Been Validated

Tuner Type	QWR β=0.085	HWR β=0.53
Minimum Tuning Range [kHz]	30	120
Tuning Resolution (2% of Bandwidth) [Hz]	0.8	0.6
Maximum Backlash (5% of Bandwidth) [Hz]	2	1.5
Cavity Tuning Sensitivity (calculated) [kHz/mm]	~ 3.2	~ 236.2
Maximum Displacement [mm] (*) port-to-port	±7.5	-0.5 (*)
Cavity df/dp (Free Tuner) (calculated) [Hz/torr]	~ -1.4	~ -3.43
Cavity LFD (Free Tuner) (calculated) [Hz/(MV/m)^2]	~ -0.7	~ -3



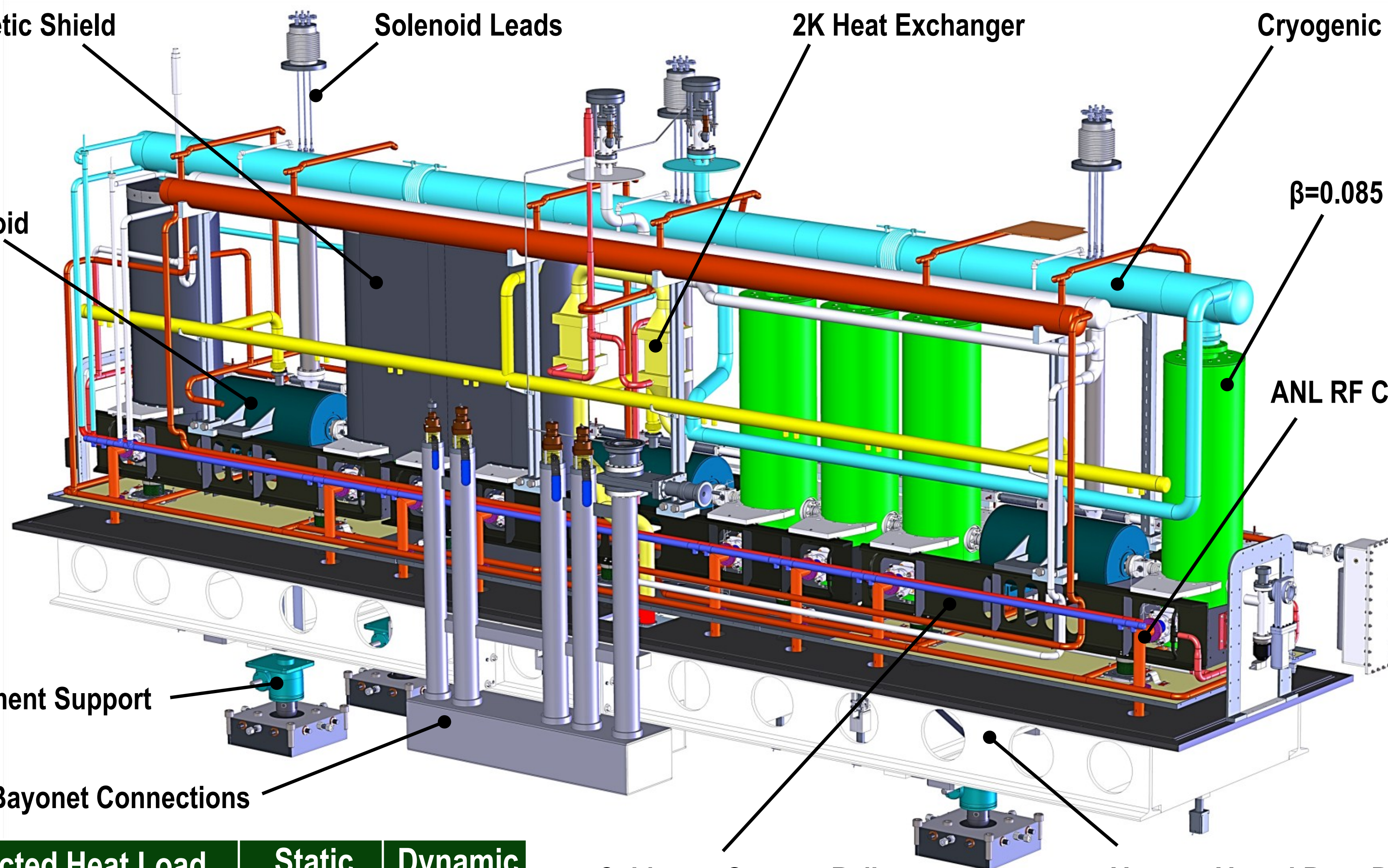
Increased cavity frequency tunability by welding “tuning puck” to tuning plate providing ±30 kHz final tuning range.



Test Status: Operational In ReA3 Cryomodules

Test Status: Operation Verified During Integrated Vertical Test

First FRIB-style Quarter Wave Cryomodule Under Construction: Cavities Operate At 2 K, Solenoids At 4.5 K



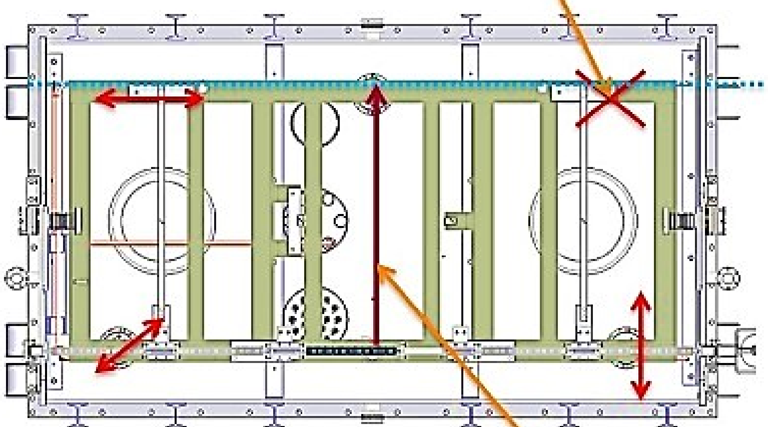
Projected Heat Load	Static	Dynamic
2 K	5.8 W	32.0 W
4.5 K	30.4 W	2.1 W
38/55 K	168.1 W	33.4 W

S. Miller: THIOA04

Novel Self-Aligning, Kinematic Support-System Has Been Tested During Several Cool-Downs And Functions Consistently At High Repeatability and Accuracy

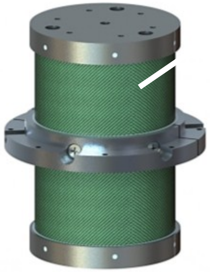
- Alignment of cavities and solenoids stay well within alignment specifications
- Optical target measurement results
  - Cavity alignment
    - » within +/- 0.003” (0.076 mm) horizontally
    - » within +/- 0.002” (0.05 mm) vertically
- Wire Position Monitor measurements
  - Cavity alignment
    - » within +/- 0.003” (0.076 mm) horizontally
    - » within +/- 0.001” (0.03 mm) vertically

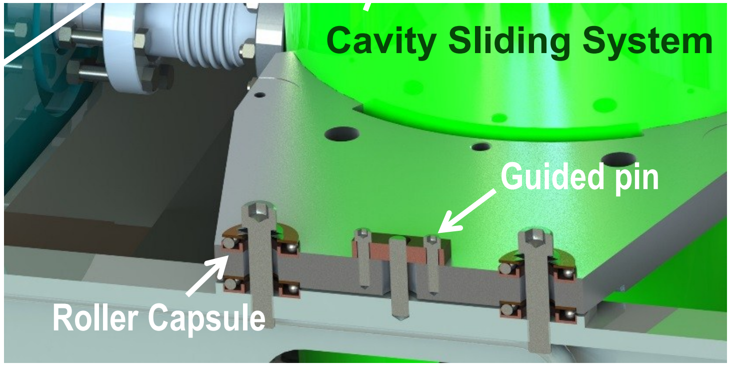
Fixed Support



Contraction Direction

G-10 Posts
With Linear Bearings





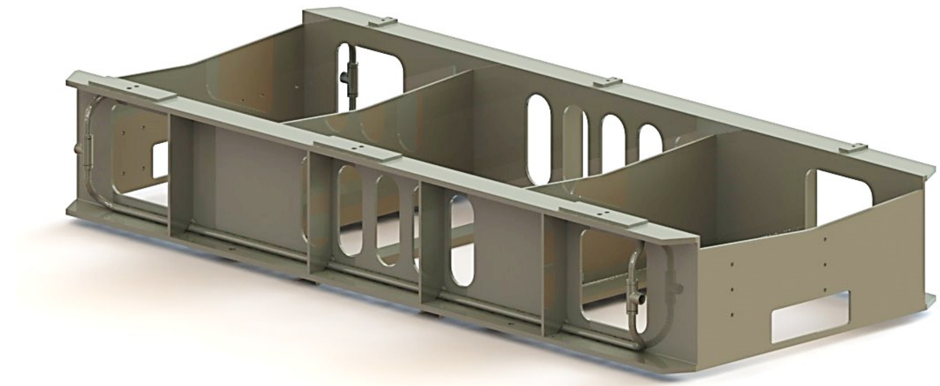
Cavity mount provides stress-free thermal contraction with significant anti-rocking stiffness – essential for quarter wave resonators

FRIB Develops Technical Innovations For Low-Beta Cryomodules

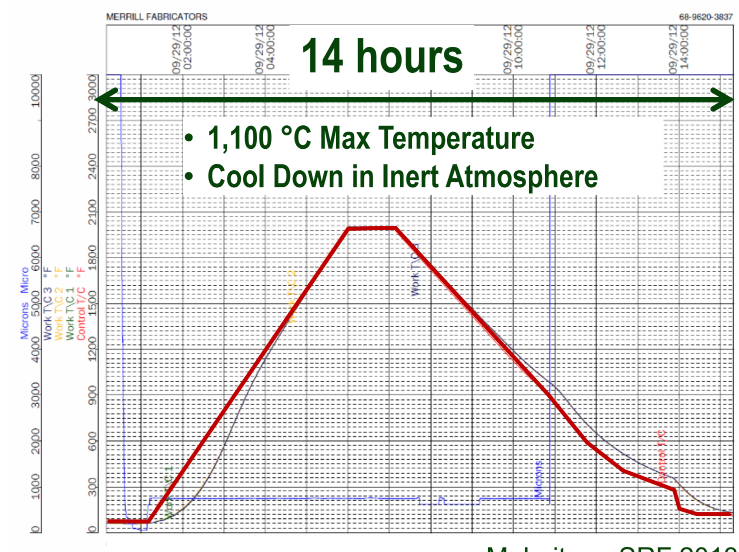
3D Shaped O-Ring
Separated Cavity / Cryomodule Isolation Vacuum

Rail Assembly Optimized For Mass Production
Self-Aligning Support System

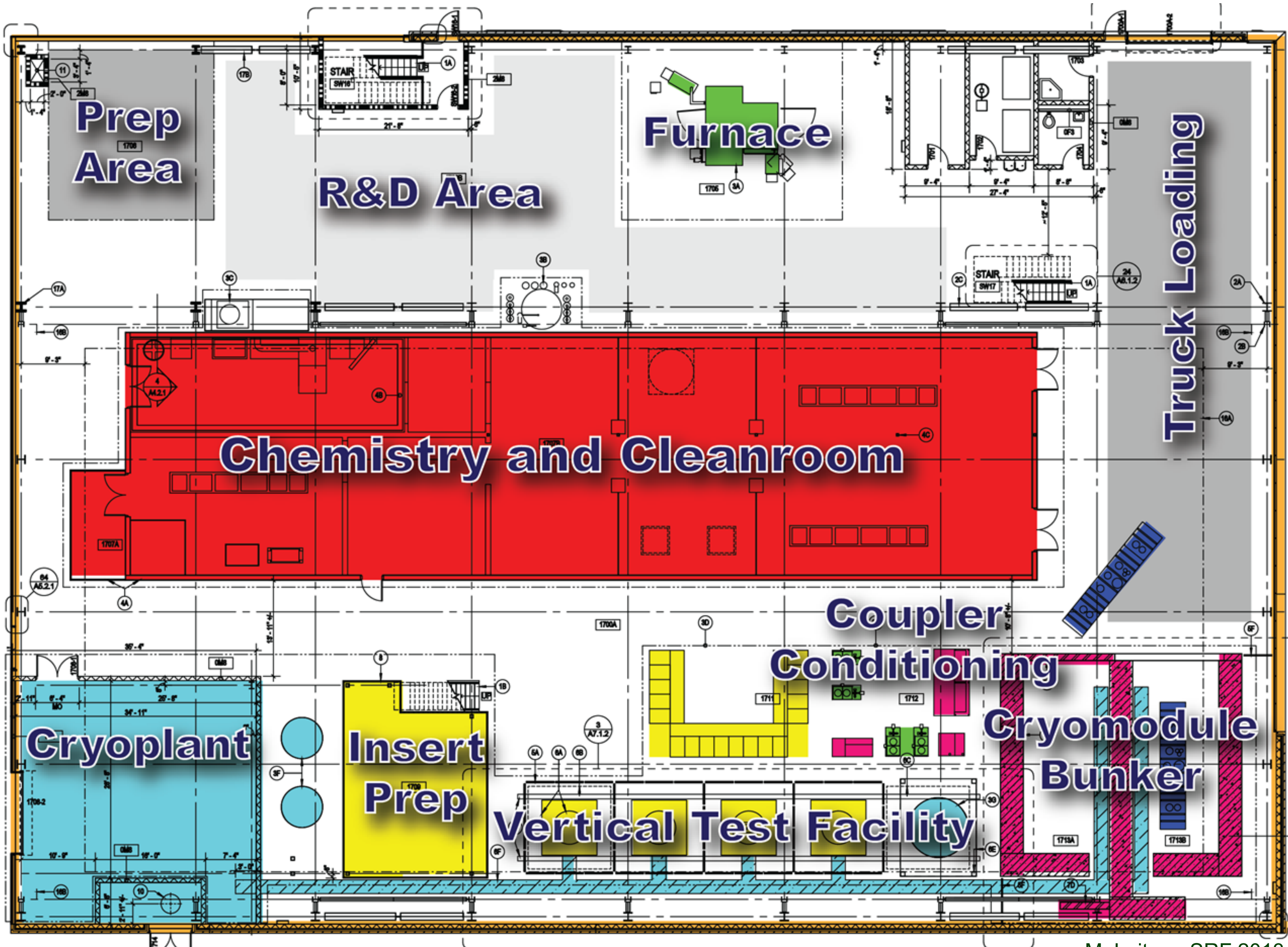
Custom Rail Heat Treatment
Full Stress Relieve To Minimize Distortion During Cool-Down
Reset To Austenitic State (Min. Permeability)



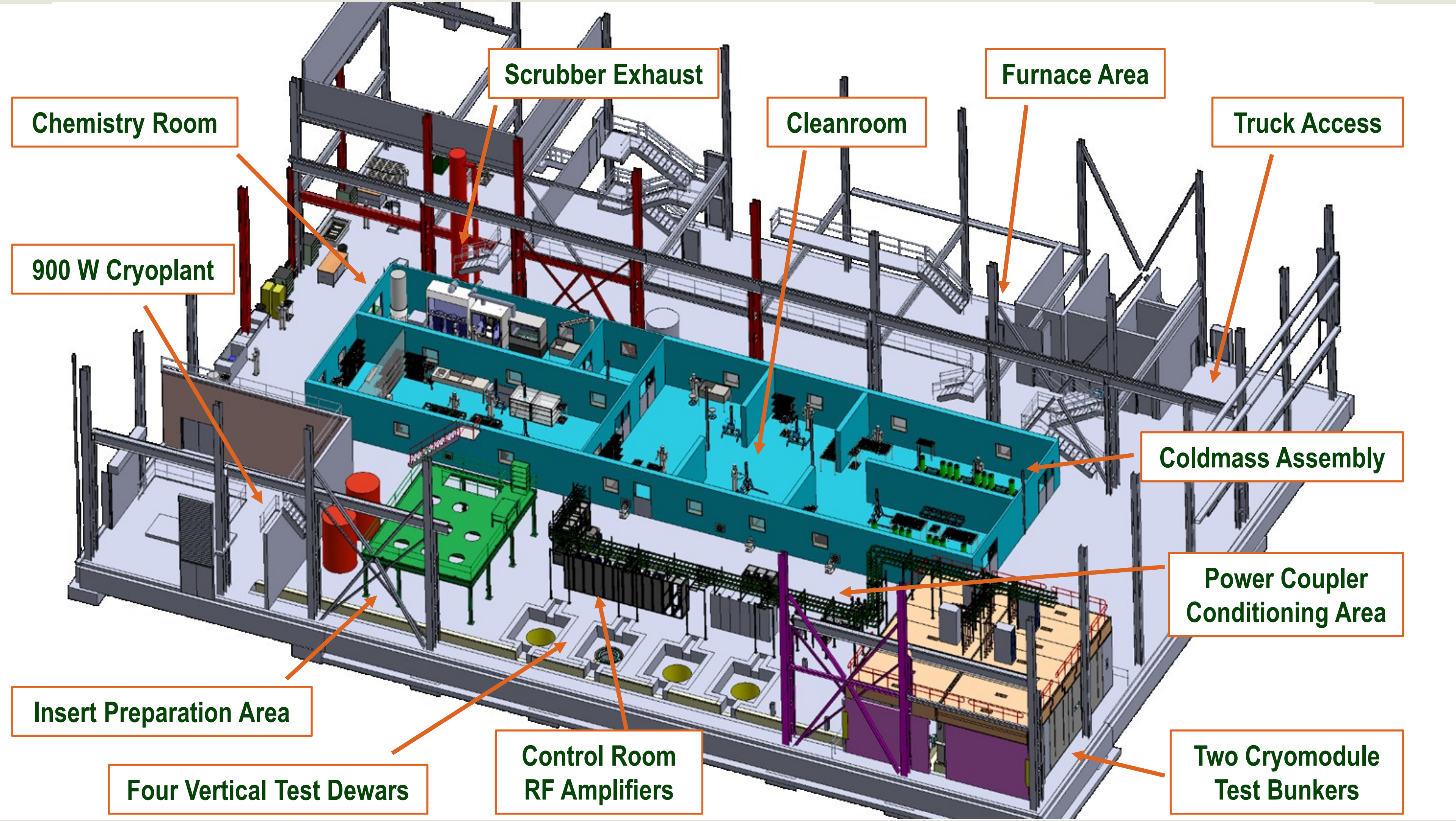
Heat Treatment Data from Vendor



SRF Mass Production Will Occur In New MSU SRF Facility
27,000 sq. ft. SRF High Bay - Building Completion: April 2014



SRF Mass Production Will Occur In New MSU SRF Facility 27,000 sq. ft. SRF High Bay - Building Completion: April 2014



SRF Mass Production Will Occur In New MSU SRF Facility 27,000 sq. ft. SRF High Bay - Building Completion: April 2014

Summary

- The U.S. Department of Energy – Office of Science has baselined the FRIB construction project: Cost $ 730M, Earliest Completion: 2020
- Linac tunnel construction is scheduled to start in April 2014.
- All FRIB SRF subsystem designs have been finalized and prototypes have been successfully tested.
- Cavity designs have been optimized for best performance at low fabrication costs: FRIB industrial production contracts have been awarded for all niobium material as well as β=0.53 cavities. Rest of cavity production contracts will be placed by end of this year.
- FRIB will build two more cryomodule prototypes before 2015 at which point cavity and cryomodule mass production will commence.
- Innovative FRIB cryomodule design incorporates features optimized for large-scale linac installations.
- MSU invests in significant SRF research infrastructure to establish future low-beta SRF center promoting campus-wide synergies and innovation.


THANK YOU

MSU SRF-2013 Presentations

TALKS

MOIOA01: M. Leitner, The FRIB Project At MSU
THIOA04: S. Miller, Low-Beta Cryomodule Design Optimized for Large-Scale Linac Installations
THIOD02: A. Facco, Faced Issues in ReA3 Quarter-Wave Resonators and their Successful Resolution

POSTERS

MOP013: K. Saito, SRF Developments at MSU for FRIB
MOP033: C. Compton, Quality Assurance and Acceptance Testing of Niobium Material for Use in the Construction of the Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU)
MOP067: J. Ozelis, Results From Initial Tests of The 1st Production Prototype Beta=0.29 and Beta=0.53 HWR Cavities for FRIB
MOP088: J. Popielarski, Vertical Cavity Test Program in Support of FRIB Development
TUP016: D. Kang, Effects of Processing History on Damage Layer Evolution in Large Grain Nb Cavities
TUP017: D. Kang, Study of Slip and Dislocations in High Purity Single Crystal Nb for Accelerator Cavities
TUP018: A. Mapar, Non-Schmid Crystal Plasticity Modeling of Deformation of Niobium
TUP037: A. Mapar, Dynamic Hardening Rule; A Generalization to the Classical Hardening Rule for Crystal Plasticity
TUP045: K. Elliot, An Investigation into the Role of Acid Velocity on Etching Uniformity in Niobium SRF Cavities
TUP067: S. Chandrasekaran, Hydrogen Saturation and the Thermal Conductivity of Superconducting Niobium
THP046: K. Saito, Magnetic Material Characterization & SC Solenoid Coil Package Design for FRIB
THP053: R. Oweiss, Development of Quality Control Procedures for the Processing of ReA3 Copper Plated Fundamental Power Couplers (FPCs)
THP067: L. Popielarski, Testing of Copper Plating Quality on ReA3 Coupler Bellows and Approach to Improved Plating for FRIB Production