FRIB

SUPERCONDUCTING RESONATORS DEVELOPMENT FOR THE FRIB AND ReA LINACS AT MSU: RECENT ACHIEVEMENTS AND FUTURE GOALS

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U.S. DEPARTMENT OF ENERGY | Office of Science

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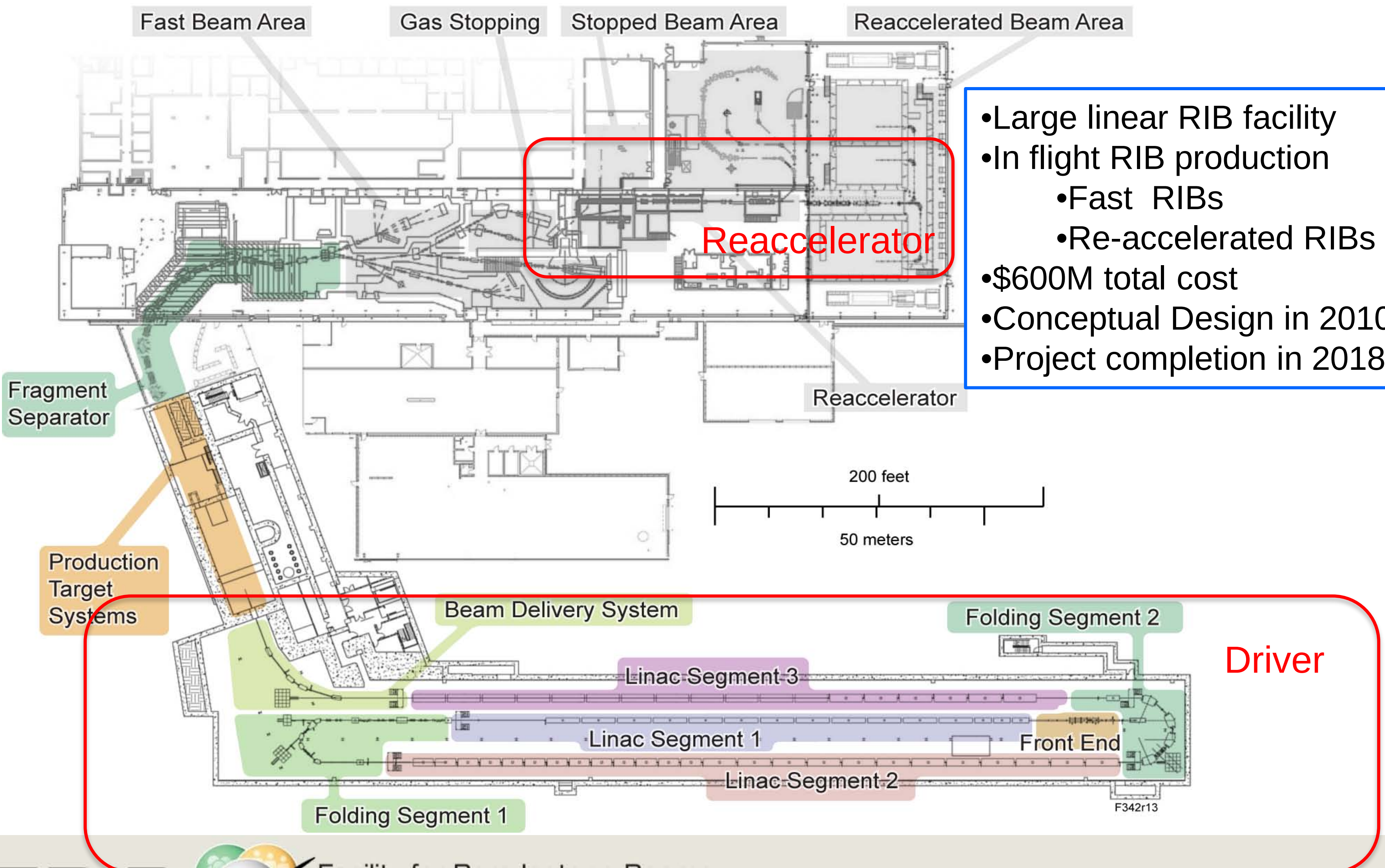
Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

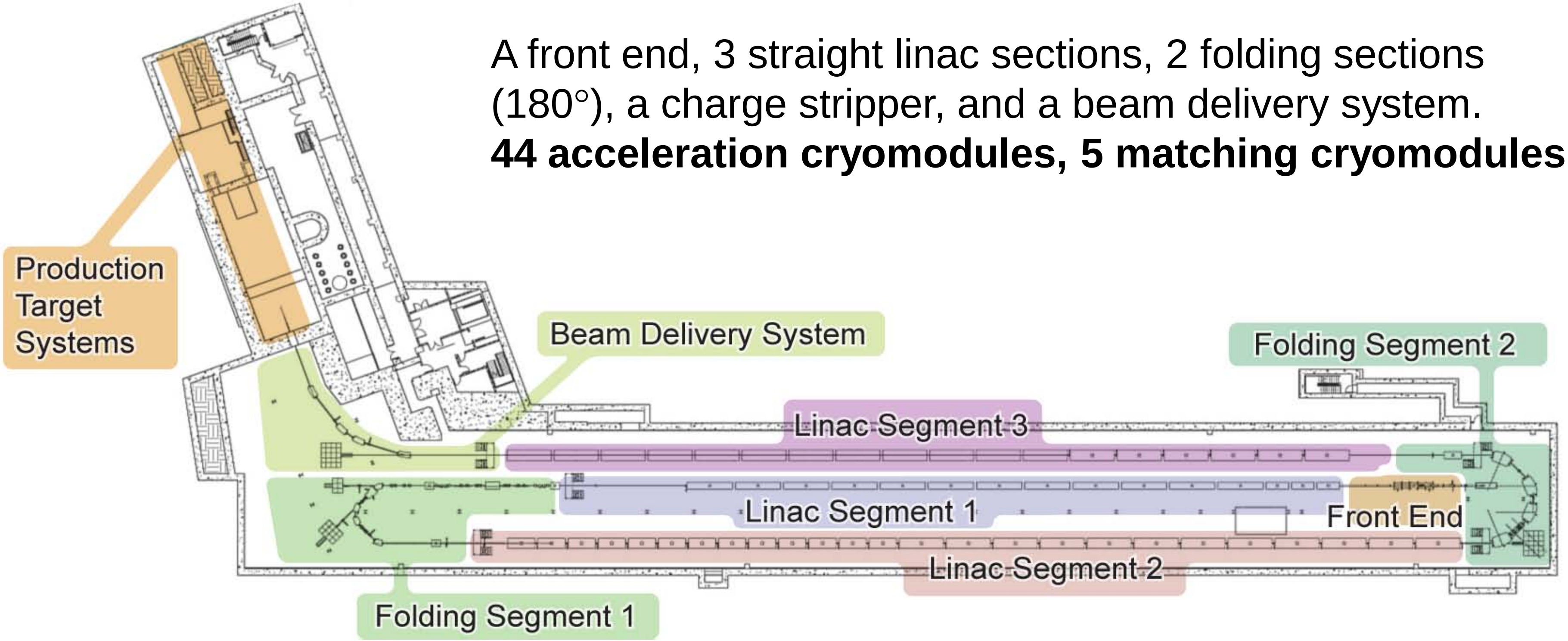
Facility for Rare Ion Beams



- Large linear RIB facility
- In flight RIB production
  - Fast RIBs
  - Re-accelerated RIBs
- $600M total cost
- Conceptual Design in 2010
- Project completion in 2018

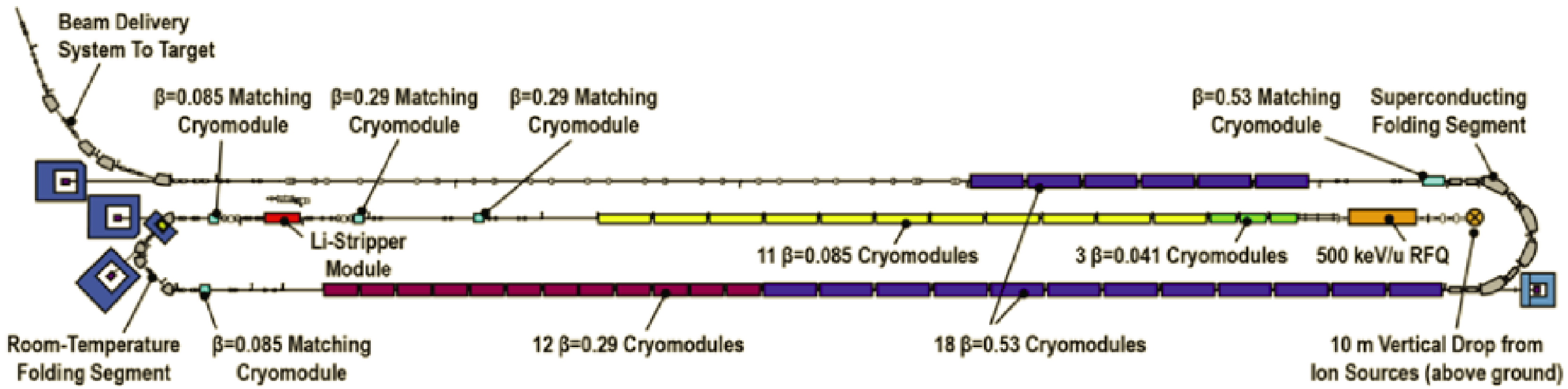
FRIB Driver Linac

A front end, 3 straight linac sections, 2 folding sections (180°), a charge stripper, and a beam delivery system.
44 acceleration cryomodules, 5 matching cryomodules



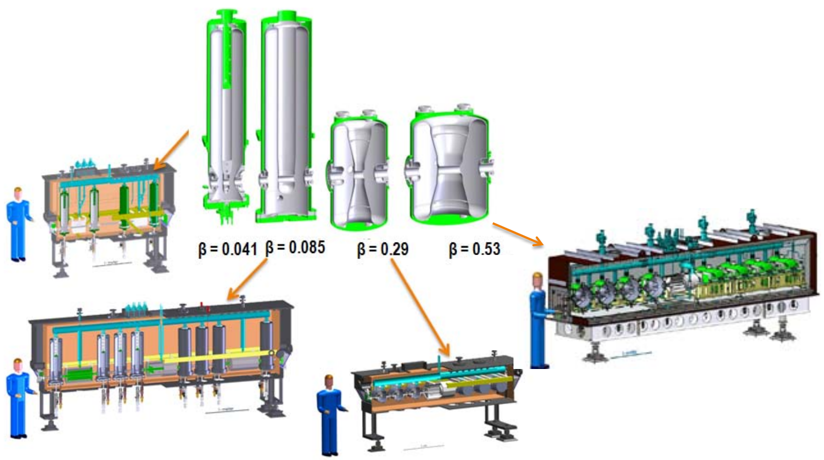
- Output beam energy above **200 MeV/u**
- Accelerate heavy ion beams up to **uranium**
- Beam power on target **400 kW**, with 90% beams within 1 mm diameter
- It is necessary to accelerate **2 to 5 charge states** simultaneously to reach the power goal
- In campus nuclear facility, sustain **low beam loss** and residual activation

FRIB Driver Facts



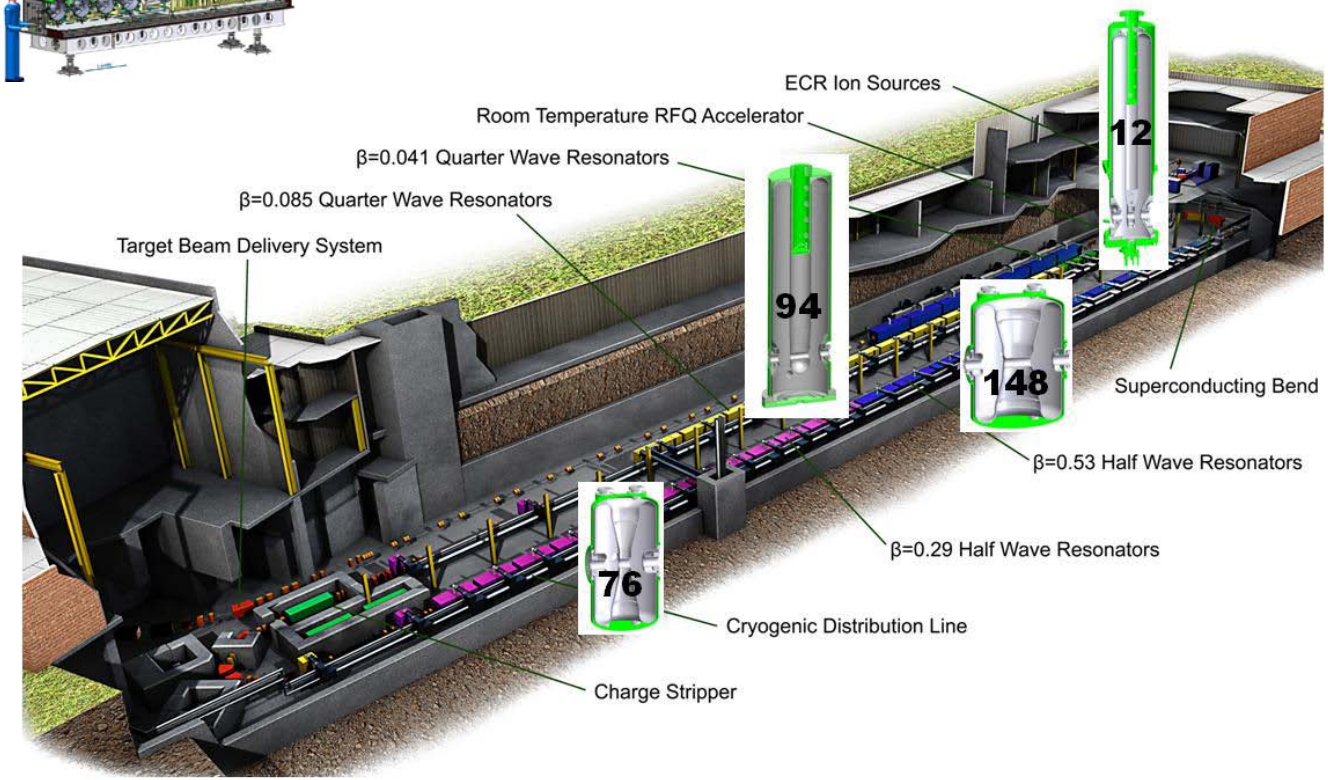
- The largest **superconducting low-β linac** worldwide
- The first one working at **2 K**
- Heavy ion beams of different A/q and **multi-charge beam transport** capability
- High beam current (0.66 mA)
  - beam loading in the kW range, large beam aperture, high reliability in operation
  - High performance to fulfill realistic specifications
- **>400 cavities to be built: low cost of resonators is mandatory**

FRIB Driver Linac: 330 SRF Resonators



type	β_0	F (MHz)	V_a (MV)	a (mm)
λ/4	0.041	80.5	0.81	34
λ/4	0.085	80.5	1.78	34
λ/2	0.29	322	2.09	40
λ/2	0.53	322	3.7	40

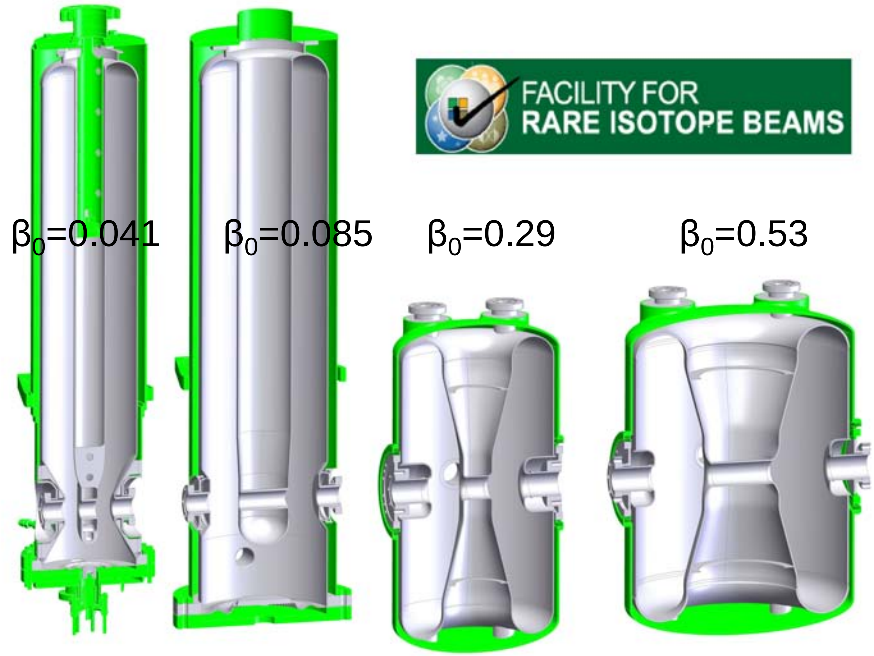
- 4 resonators types
  - 2 QWRs, 2HWRs
- 2 frequencies:
  - 80.5 and 322 MHz
- Large aperture:
  - 34 mm, 40 mm



FRIB resonators design guidelines

- high performance at low cost
  - Simplified geometries
  - Minimum number of ebw
  - No bellows
  - Thin Nb sheets
  - Ti He vessel, TIG welded
  - BCP surface treatment, no EP
- realistic design specifications
  - $R_{res} \leq 11$ nΩ
  - Df/dP ≤ 4 Hz/mbar
  - LFD ≤ 4 Hz/(MV/m)^2
- reliable operating conditions
  - $E_p \leq 35$ MV/m, $B_p \leq 70$ mT
  - Operation at 2 (2.1) K
  - Large extra E_a available

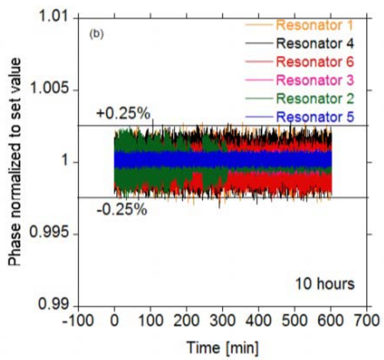
FACILITY FOR RARE ISOTOPE BEAMS

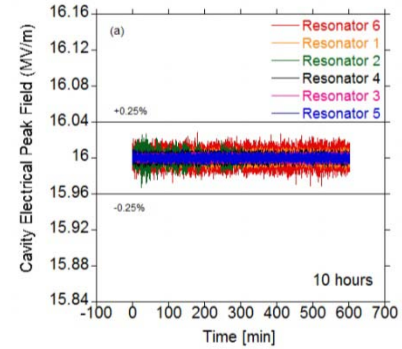


β_0	0.041	0.085	0.29	0.53
f (MHz)	80.5	80.5	322	322
V_a (MV)	0.81	1.8	2.1	3.7
E_p (MV/m)	31	33	33	26
B_p (mT)	55	70	60	63
R/Q (Ω)	402	452	224	230
G (Ω)	15	22	78	107
Aperture (mm)	34	34	40	40
$L_{eff} \equiv \beta\lambda$ (mm)	160	320	270	503

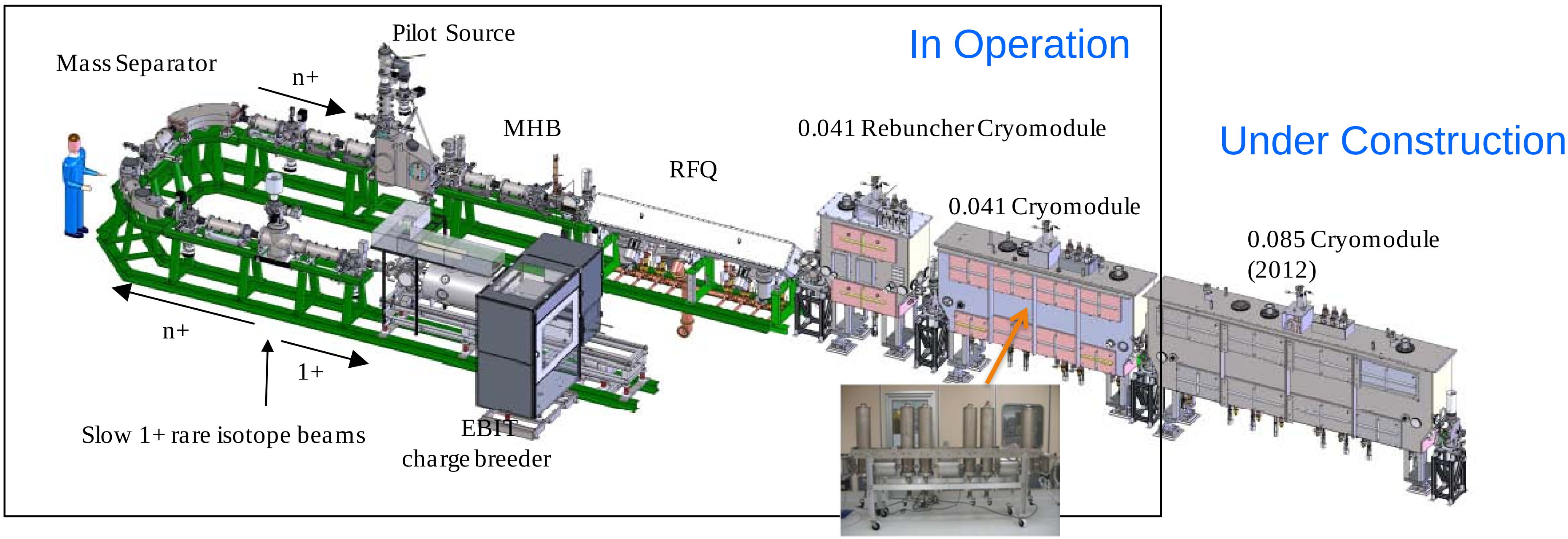
ReA3 Re-accelerator Linac

- First SRF linac at MSU, in operation since 1 year
- Excellent test bench for FRIB QWRs
- Similar QWRs as in FRIB
- Operation T=4.5K



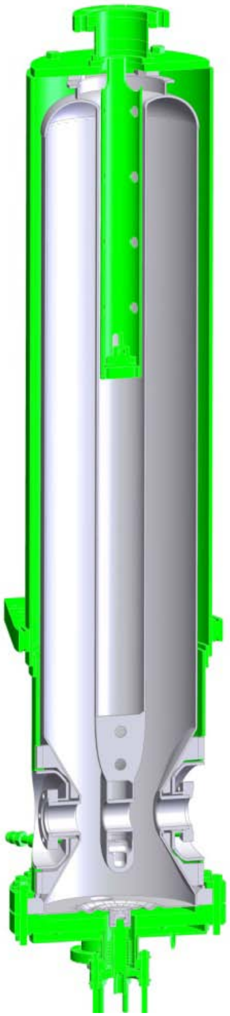


βo= 0.041 QWRs phase and voltage stability in operation

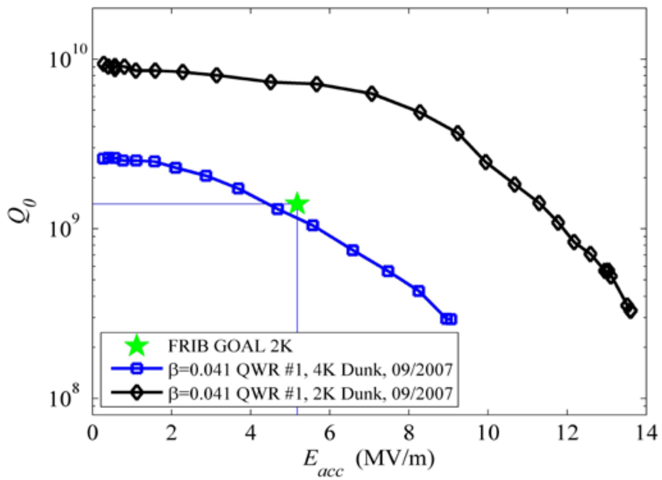


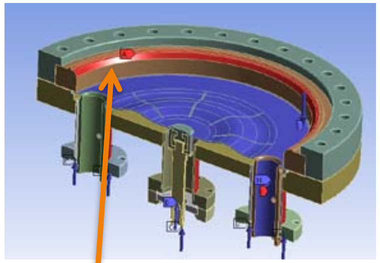
β_0=0.41 QWR – 1 Year of Operation in ReA3

- In FRIB
  - Operation foreseen at 2 (2.1) K, with E_p=30 MV/m, B_p=53 mT
- Naked test at 2 K
  - E_p=80 MV/m, B_p=140 mT
- In ReA3
  - Operation at 4.5K, E_p=16 MV/m, B_p=35 mT successfully achieved
  - 7 cavities operating on line
  - Reliable and reproducible phase and amplitude lock
  - **FRIB fields reached**, but plate overheating
- Bottom ring modified for improved plate cooling



Best results (naked cavity dunk test in 2007)

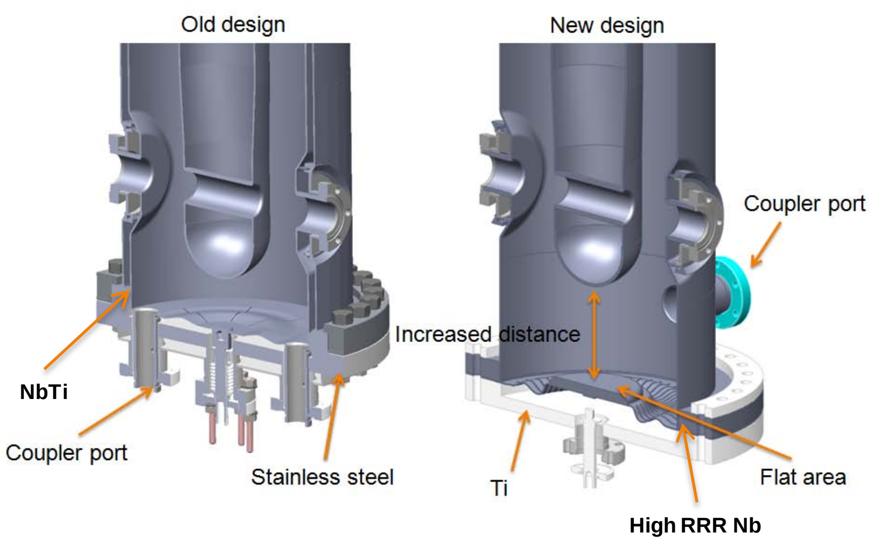


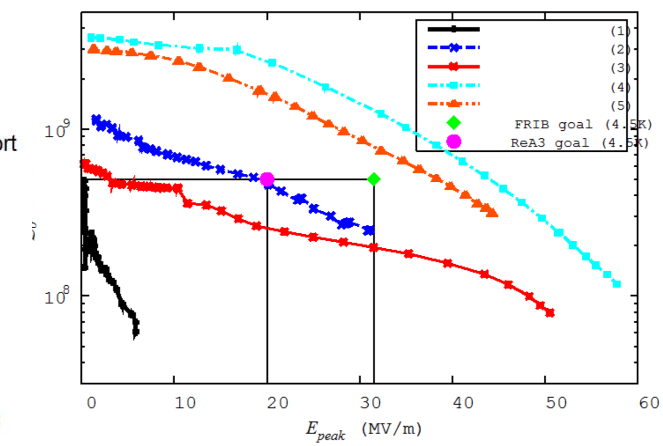


NbTi ring inReA3
high RRR Nb ring in FRIB

β_0=0.085 QWR – early problems, now solved

- ReA3, 1st generation β_0=0.085 cavities:
  - Bad RF joint due to a subtle differential contraction problem
  - insufficiently cooled tuning plate due to NbTi bottom ring
  - Design successfully modified in several steps
    - Distance tuning plate-inner conductor increased
    - Rf and vacuum contacts unified
    - Rf coupler moved from the tuning plate to the side
    - New slotted tuning plate for increased range





ReA3 β=0.085 refurbished QWR performance

- The 2 prototypes of ReA3 cavity largely **exceeded the FRIB goals** both at 4.2K and 2K
  - Resonators exceeded $\mathbf{E_p}$**=50 MV/m** and $\mathbf{B_p}$**=120 mT**
  - Q disease completely eliminated by 600º C baking
  - Flat Q at 2K up to E_p>40 MV/m and B_p>90 mT
- 9 existing QWRs are being refurbished for ReA3

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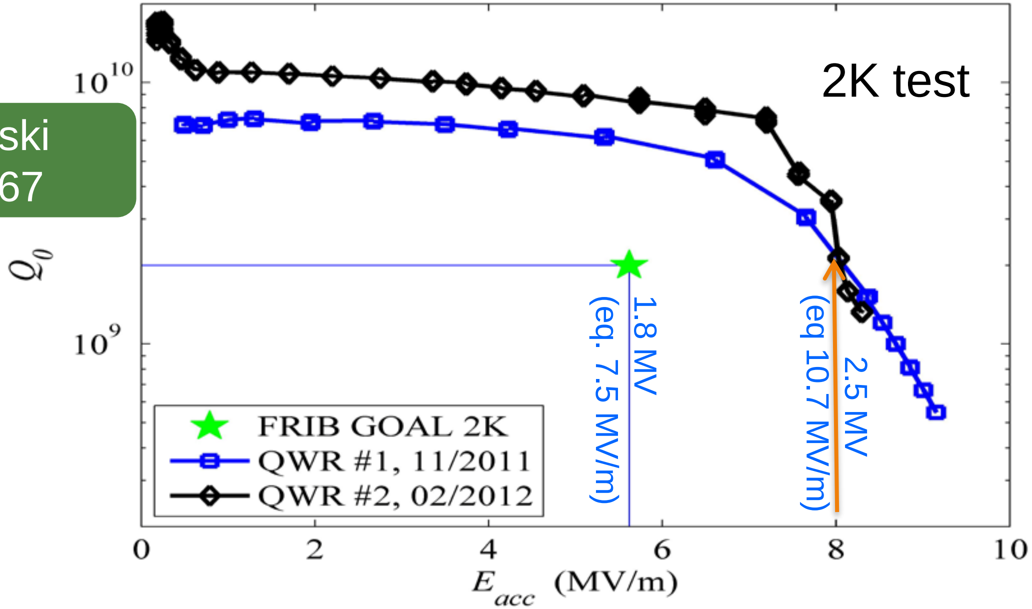
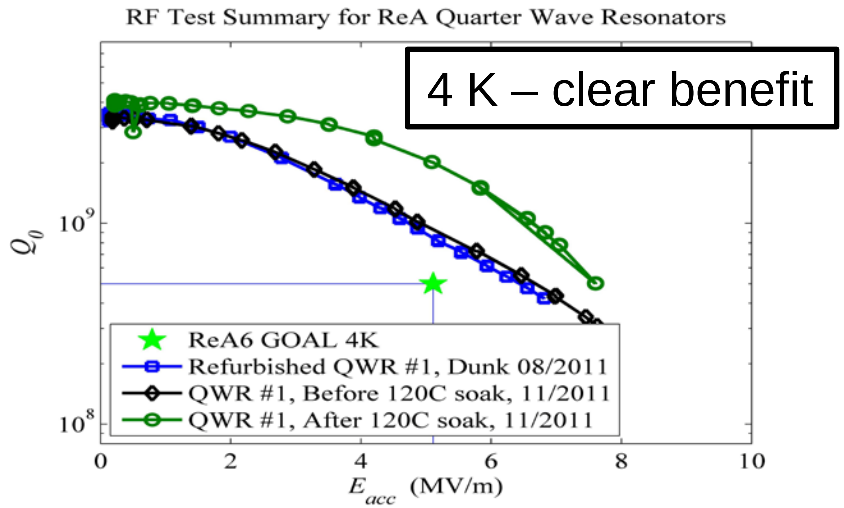
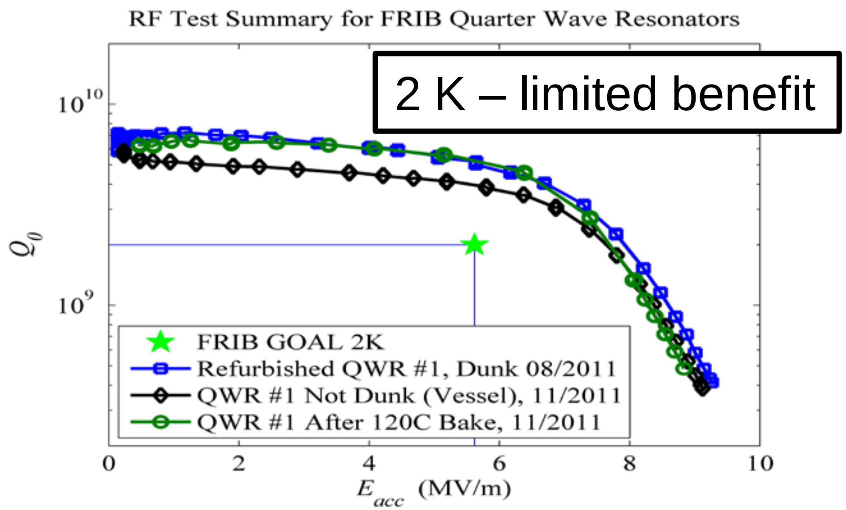


$L_{eff} \equiv \beta\lambda$=32 cm

4.2K Performance Enhancement with Low Temperature Baking

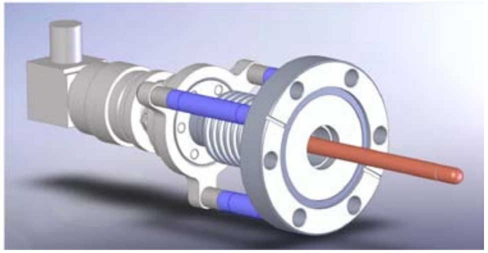
- Low temperature baking at 120° C under development at FRIB
- Applied to a QWR cavity
  - at 4.2 K significant improvement in Q
  - At 2 K modest improvement
- The treatment will be applied to ReA QWRs working at 4.5 K
- Extension to all FRIB cavities is under evaluation but not in the baseline processing plan
- Treatment of FRIB cavities showing Q slightly below specifications at vertical test is being considered fast procedure for cavity recovery

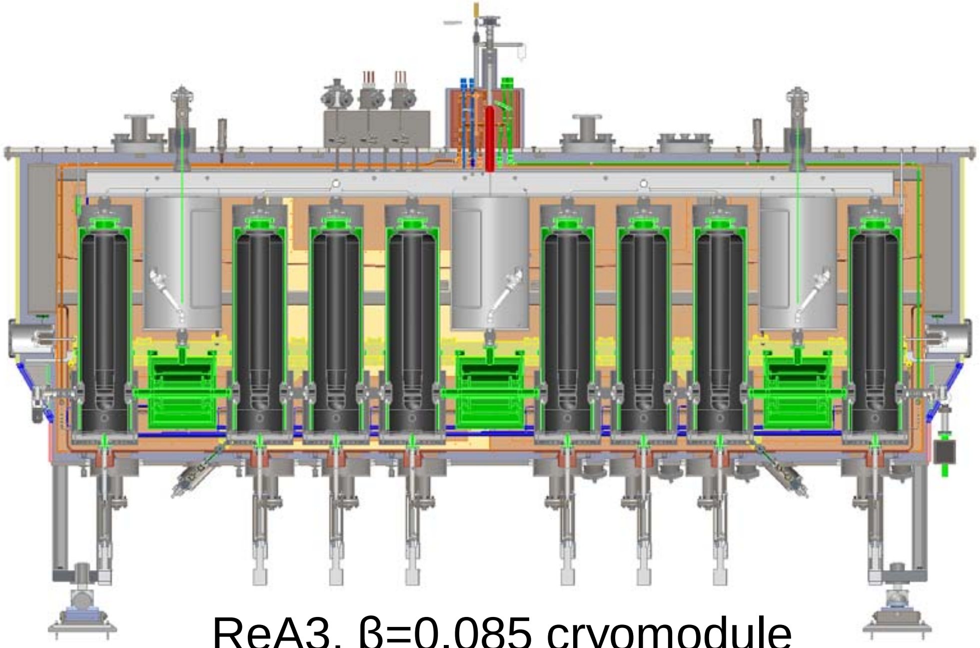




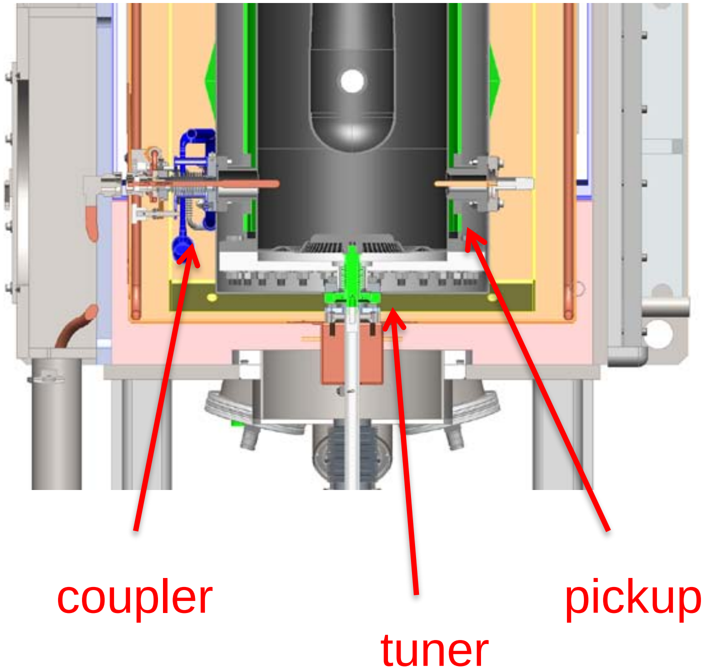
80.5 MHz, β=0.085 ReA3 Cryomodule

- Refurbishment of 10 existing ReA3 cavities
- ReA3 cryomodule under construction
  - In operation in 2012
- New cryomodule with upgraded QWRs in 2013
  - FRIB cryomodule prototype in ReA3



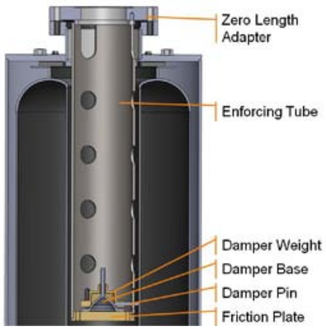


ReA3, β=0.085 cryomodule

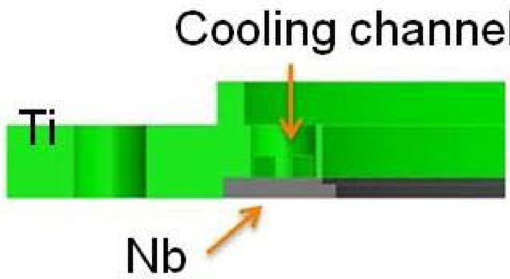


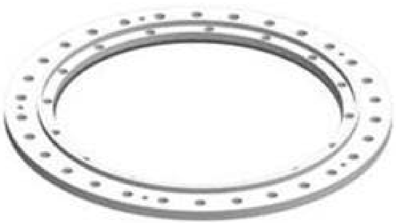
FRIB QWRs solutions

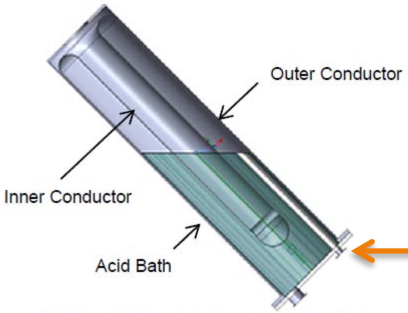
- Mechanical damper
  - damping of the inner conductor oscillations



- High RRR Nb ring: low cost design
  - New bottom ring made of Ti (or NbTi), with a small, high RRR Nb ring in contact with the tuning plate, directly cooled by liquid He



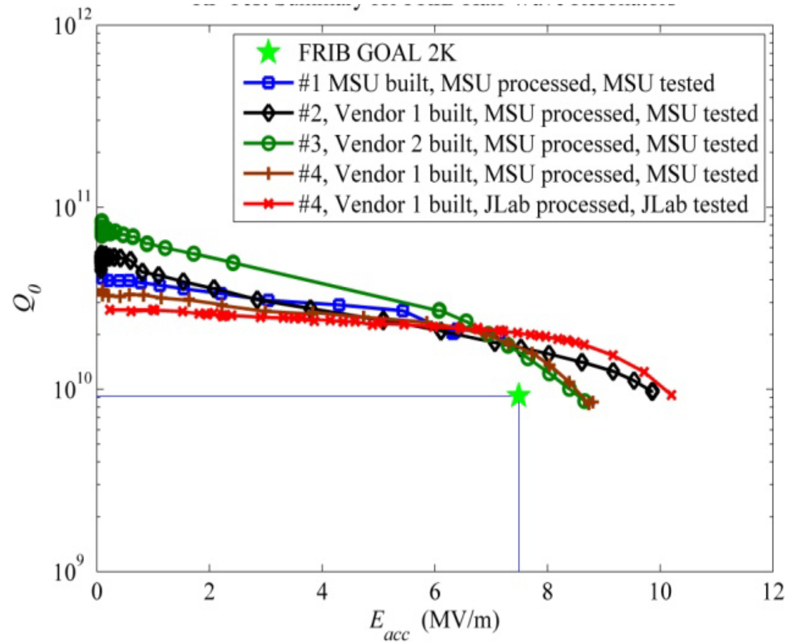


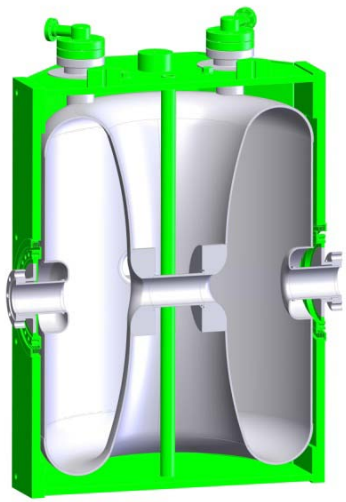


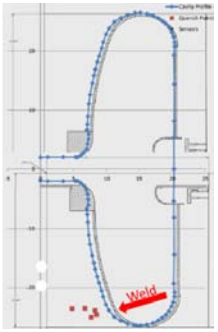
- Final cavity tuning
  - ±50 kHz spread in final f after construction
  - Differential etching if needed (±100 kHz)
  - Adjustable tuning puck welded after bulk etch and heat treatment (±30 kHz)

322 MHz HWRs Prototypes

- **β_0=0.53 prototypes from 2 different vendors reached FRIB specifications**
  - » V_{acc}=3.7 MV, E_p=31 MV/m, B_p=77 mT
- Results confirmed at Jlab
- Possibility for improvements detected in 1st generation HWR prototypes:
  - » B_p /E_a reduction
  - » Elimination of Ti bellows in He vessel
  - » Simplification of cavity welding procedure



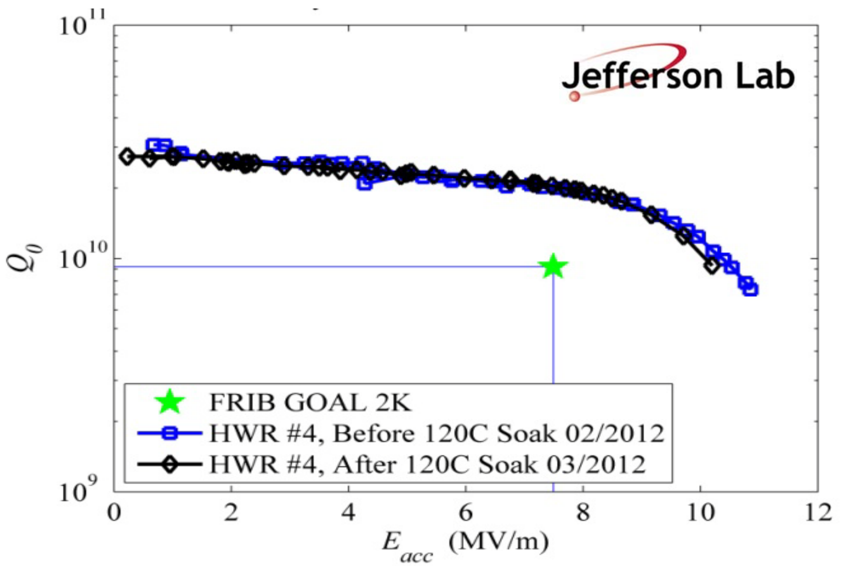


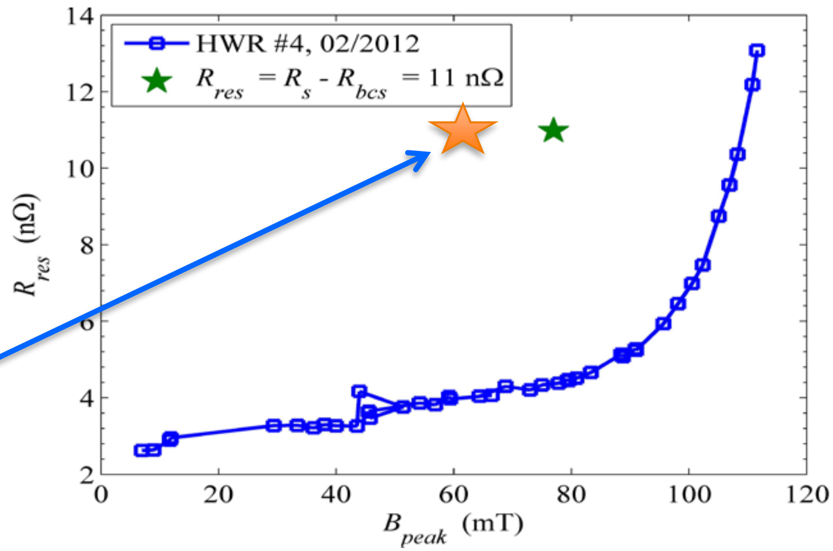


2° sound test: cavities limited by B_p

Prototype β=0.53 HWR Results Confirmed at JLab

- Test repeated at JLab
  - Verified calibration
  - Verified cavity performance
  - Verified cavity treatment
- FRIB specifications exceeded with a comfortable margin
- Rres<5 nohm up to 90 mT
- 120° C baking ineffective at 2K
- JLab is developing procedures for performing FRIB cavity treatment, assembly, and qualification

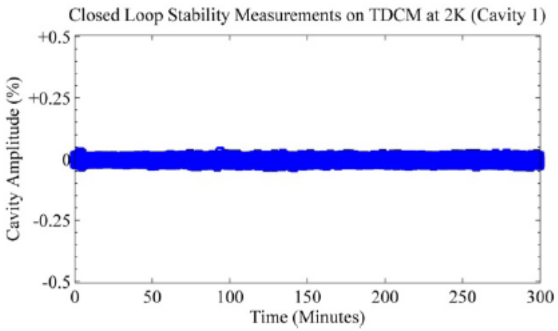


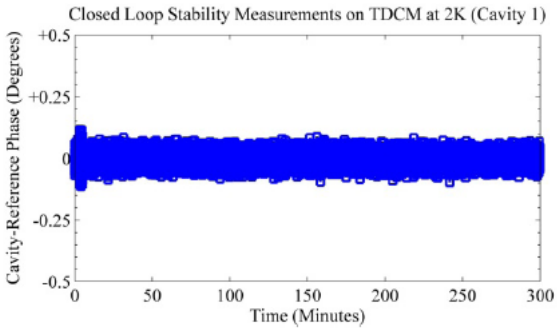


We have redesigned production cavities with lower B_p/E_a, shifting the B_p from 77 mT to 63 mT and achieving larger technical margin

Technology Demonstration Cryomodule Testing

- Aim
  - Develop HWR cryostat assembly procedures
  - Test prototype β=0.53 cavities with final couplers and in the presence of a SC solenoid
  - Cryogenic test of the module prototype
- Components
  - 2 β=0.53 HWRs already tested off line in VTA
  - 1 superconducting solenoid
- 2K test ongoing





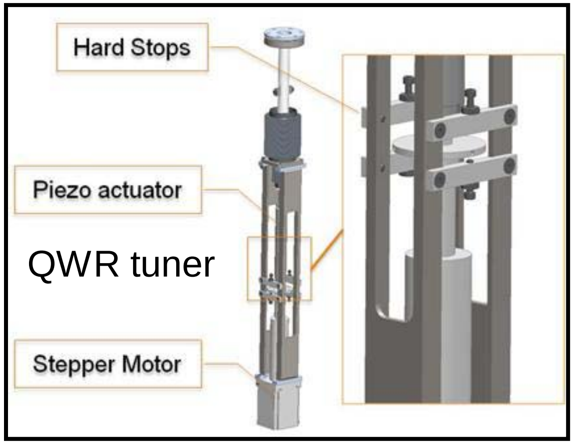
Phase and amplitude stability of HWR locked at low field at 2K

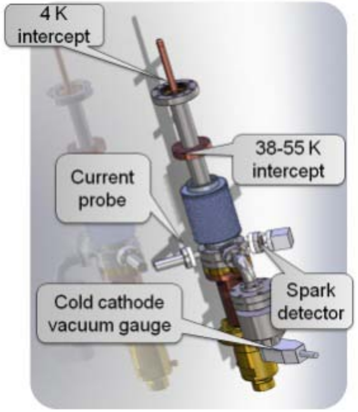
TDCM cold mass

TDCM installed in test bunker

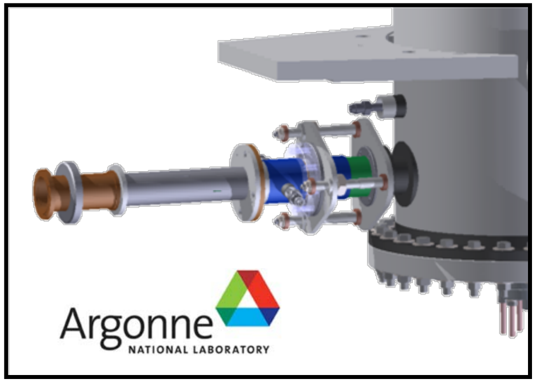
FRIB Couplers and Tuners

- β=0.041 QWR
  - Coupler: in operation; tested on line up to 1 kW, air cooling being implemented for 2 kW operation
  - Tuner: in operation
- β=0.085 QWR
  - Coupler: under development by ANL (new side coupler)
  - Tuner: in operation, same as for β=0.041 QWR
- β=0.053 and β=0.029 HWR
  - Coupler: 2 prototypes under testing at 2K, R&D ongoing
  - Tuner: prototypes under testing at 2K, R&D ongoing

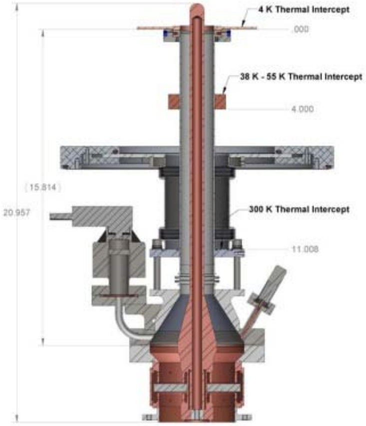




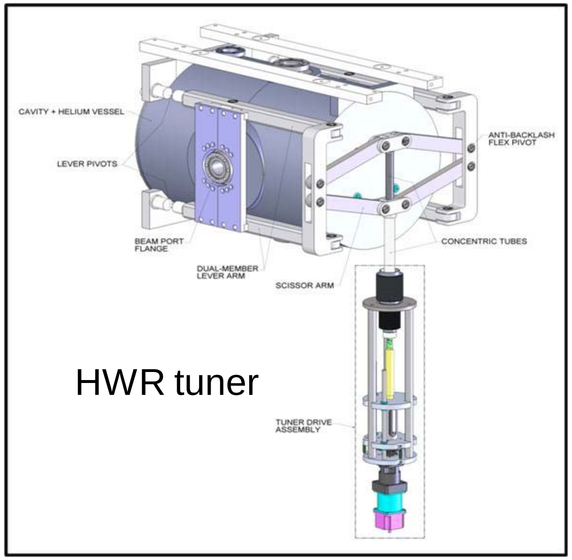
β=0.041 QWR coupler



β=0.085 QWR coupler

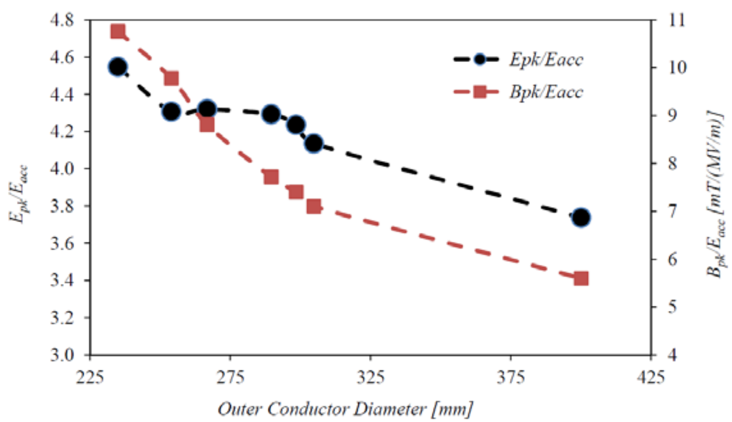


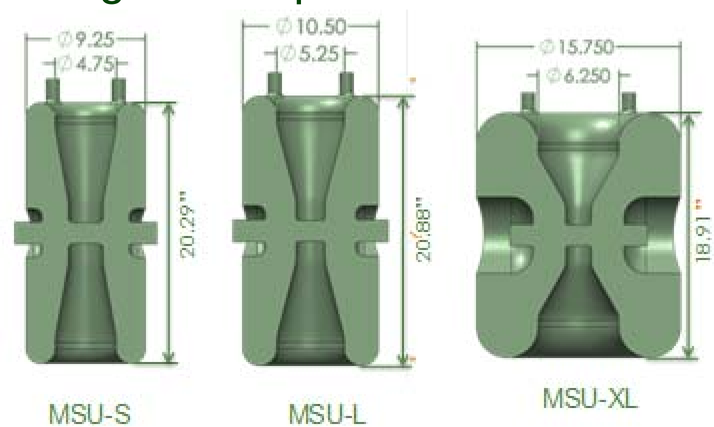
HWR coupler



FRIB Resonators Design Upgrade

- Scope: operation with higher gradient and larger safety margin
- Guidelines:
  - New cavities **fitting the present cryostats** (flange to flange distance)
  - mechanical design resembling the previous ones, sharing the same tuners and couplers as much as possible
  - peak magnetic fields reduced to increase safety margin on gradient: **B_p≤70 mT and E_p≤35 MV/m for all cavities** (old B_p: 77 mT)
  - Increased shunt impedance to allow operation at higher gradient without exceeding the specified cryogenic load
- All these conditions could be fulfilled by increasing the cavities diameter and modifying the mechanical design, but keeping the original design concept





Production Cavities: Increased Performance

- Increased performance: **lower E_p & B_p, higher R_{sh}**
- Increased aperture of QWRs from 30 to 34 mm
- Increased operation **E_a**: the FRIB driver linac could be shortened by 2 cryomodules
- FRIB operation gradient now more conservative, with **B_p≤70 mT , E_p≤35 MV/m**

cavity	E_p/E_a %	B_p/E_a %	R_{sh} %	E_a %
QWR085	-9%	-11%	+38	+10
HWR29	-3%	-28%	+47	+10
HWR53	-17%	-19%	+13	(+6)

Production cavities increase in performance and baseline E_a

β=0.29 β=0.53 β=0.085

FRIB and ReA Cavity Surface Treatment

- Effective surface treatment developed
- Steps
  1. Degrease cavity:Ultra-sonic clean with agent (Micro 90), rinse with DI water
  2. Buffered chemical polish & rinse:150 microns removal (bulk BCP), UPW rinse
  3. (if needed: differential etching in QWRs for frequency tuning)
  4. Hydrogen degas: 600° C for 10 hours vacuum furnace
  5. Degrease cavity & components:Ultra sonic clean Micro 90
  6. Light BCP & high pressure rinse (HPR): 30 micron removal, UPW rinse
  7. (If needed: 120° C baking for 48 hours)
  8. Assemble to test insert

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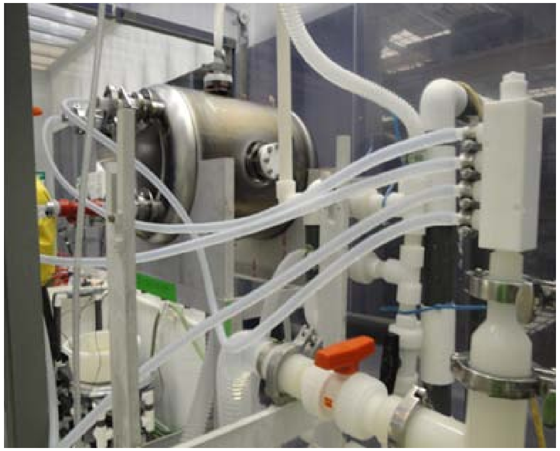
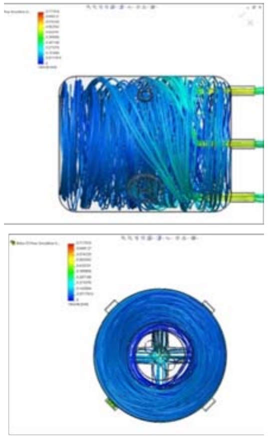
WEPPC065
WEPPC066

- Special procedures
  1. Optimized acid circulation for homogeneous Nb removal
  2. Temperature stabilized BCP, cavity water cooled during processing
  3. Liquid particle count during HPR for cleanliness control
  4. Surface particle count after HPR and drying
- Cavities resulting nearly field emission free, high Q, high E_p and B_p

Cavity Surface Treatment

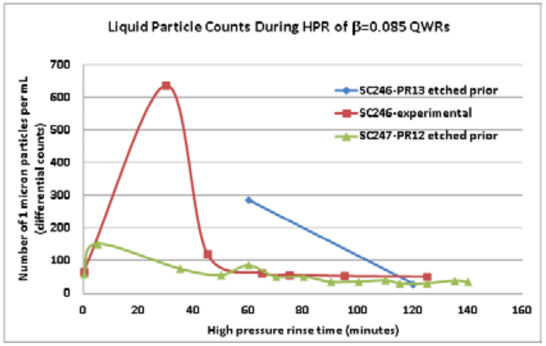


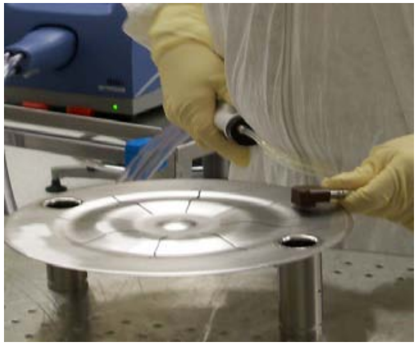
BCP setup



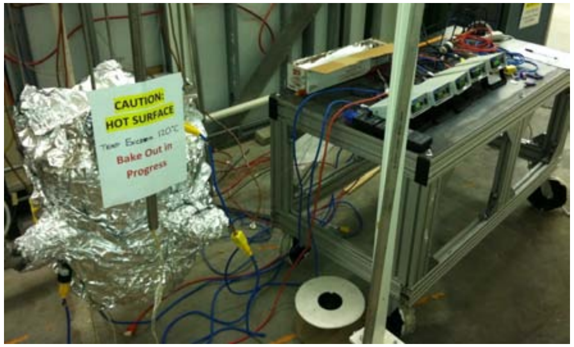
Optimized BCP flow

HV furnace for 600° C baking





Liquid (left) and surface particle count for HPR water and resonator cleanliness monitoring

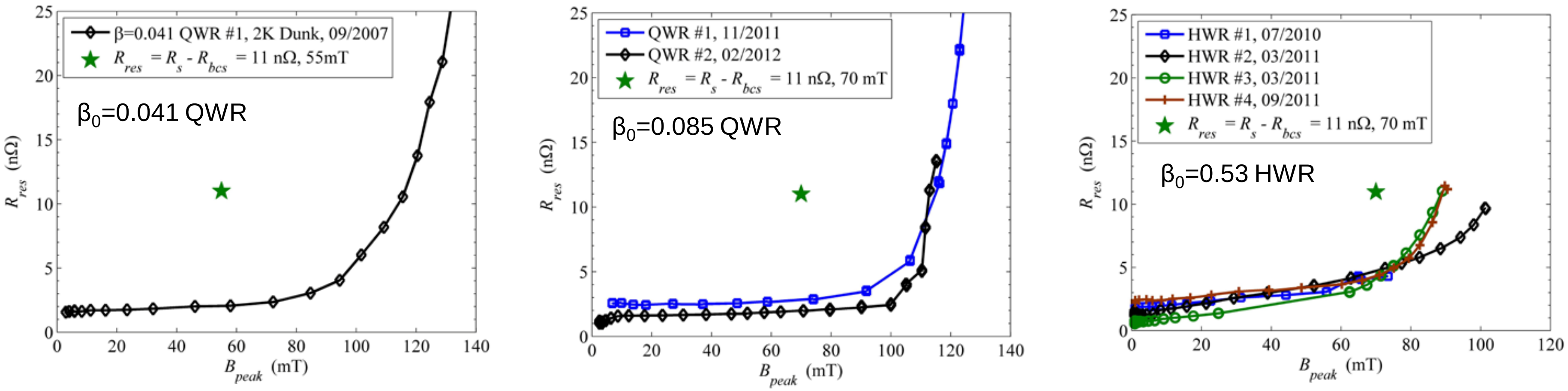


HWR 120° C bakeout setup

Experimental R_{res} in prototypes vertical test

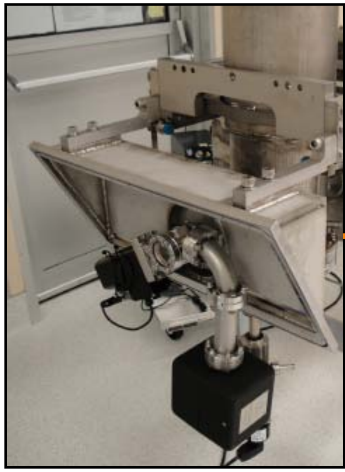
- R_{res} <5 nΩ measured in prototypes for $B_p \leq 70$ mT
  - Cavity surface treatment now mature and mastered
- Specified residual resistance in operation at 2 K: **R_{res} ≤11 nΩ**
  - This value is consistent with our vertical test experimental data

Cavity β	0.041	0.085	0.29	0.53
operation B_p (mT)	55	70	60	63



Residual surface resistance R_{res} vs. B_p measured in the FRIB prototypes at 2K

Cold Mass Assembly Cycle



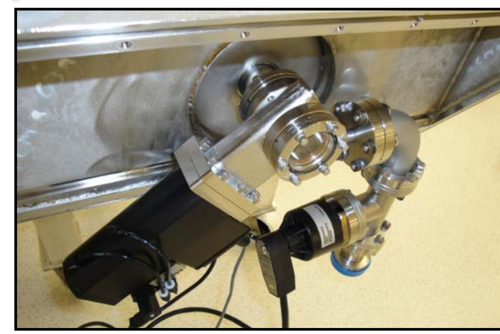
Window end assembly & vacuum components - vendors

Cavity – Certified From vertical test

Ti rails & clean room cart - vendors

Fundmental power Couplers – received ready to install

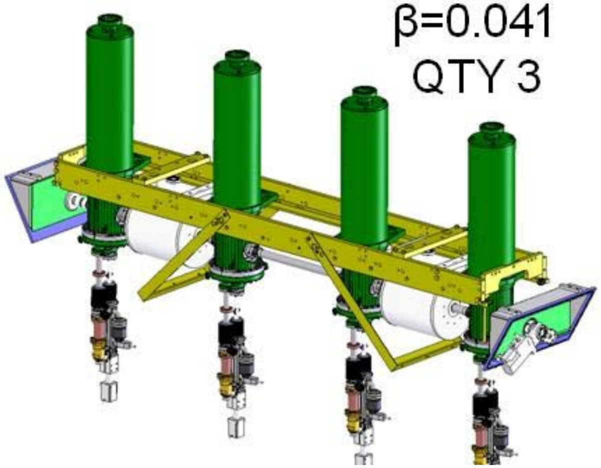
Solenoid (vendor) – cleaned at MSU



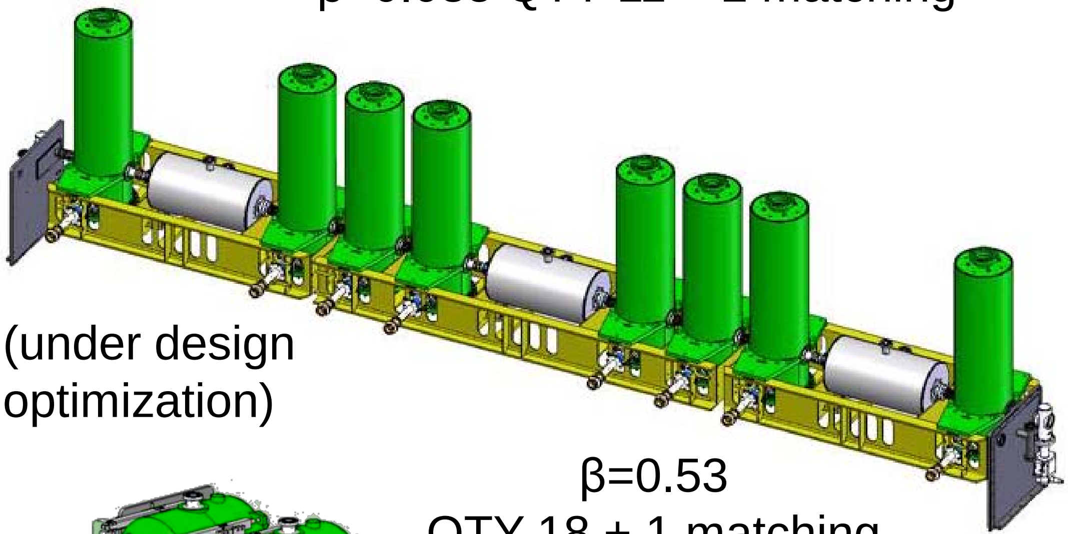
Window end assembly & vacuum components - vendors

FRIB Cold Masses

β=0.041
QTY 3

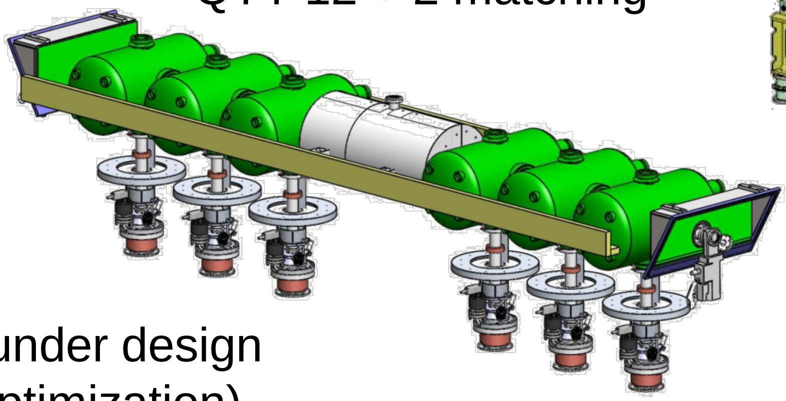


β=0.085 QTY 11 + 2 matching



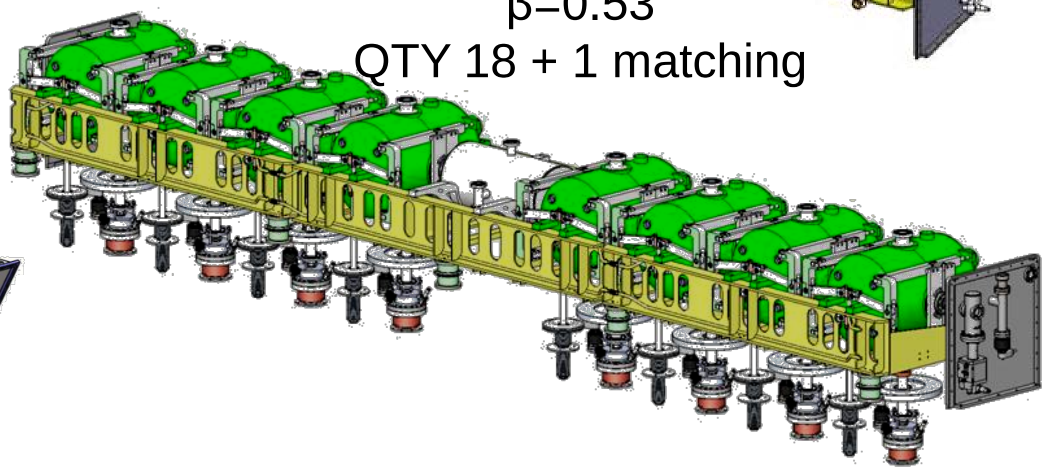
(under design
optimization)

β=0.29
QTY 12 + 2 matching



(under design
optimization)

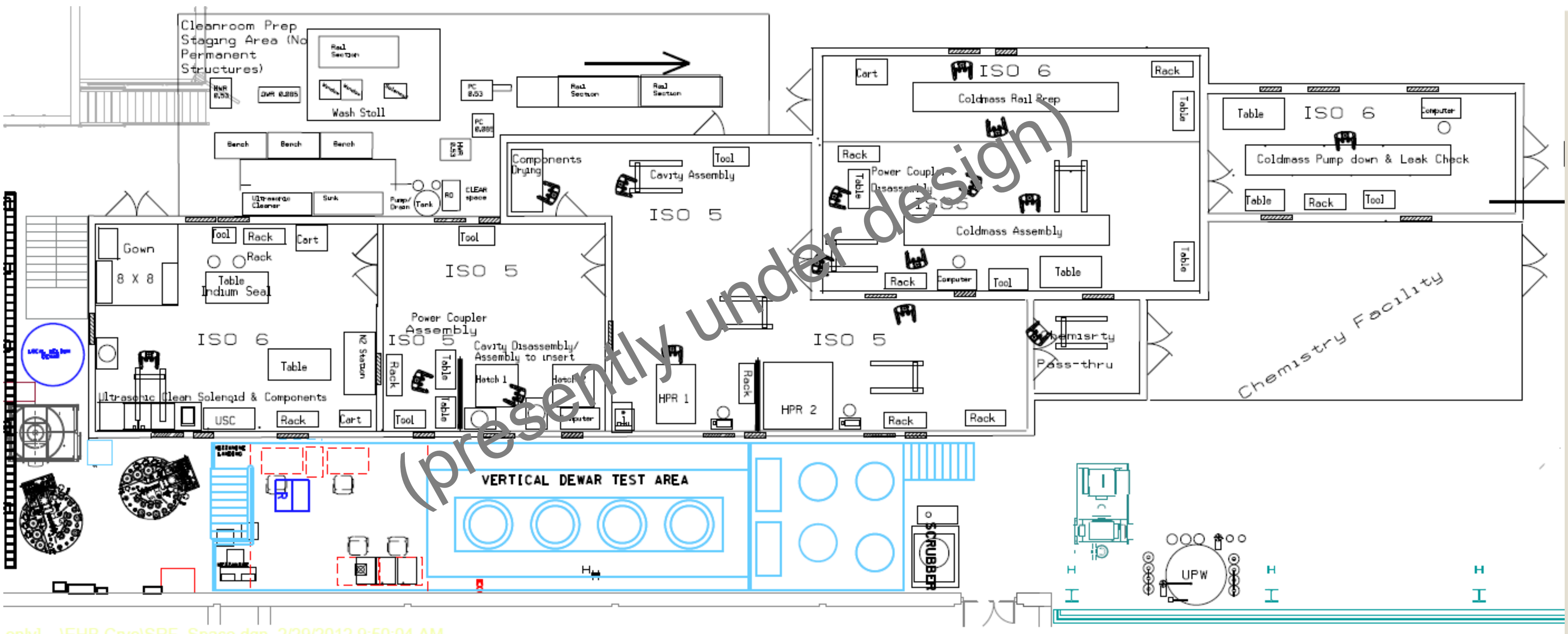
β=0.53
QTY 18 + 1 matching



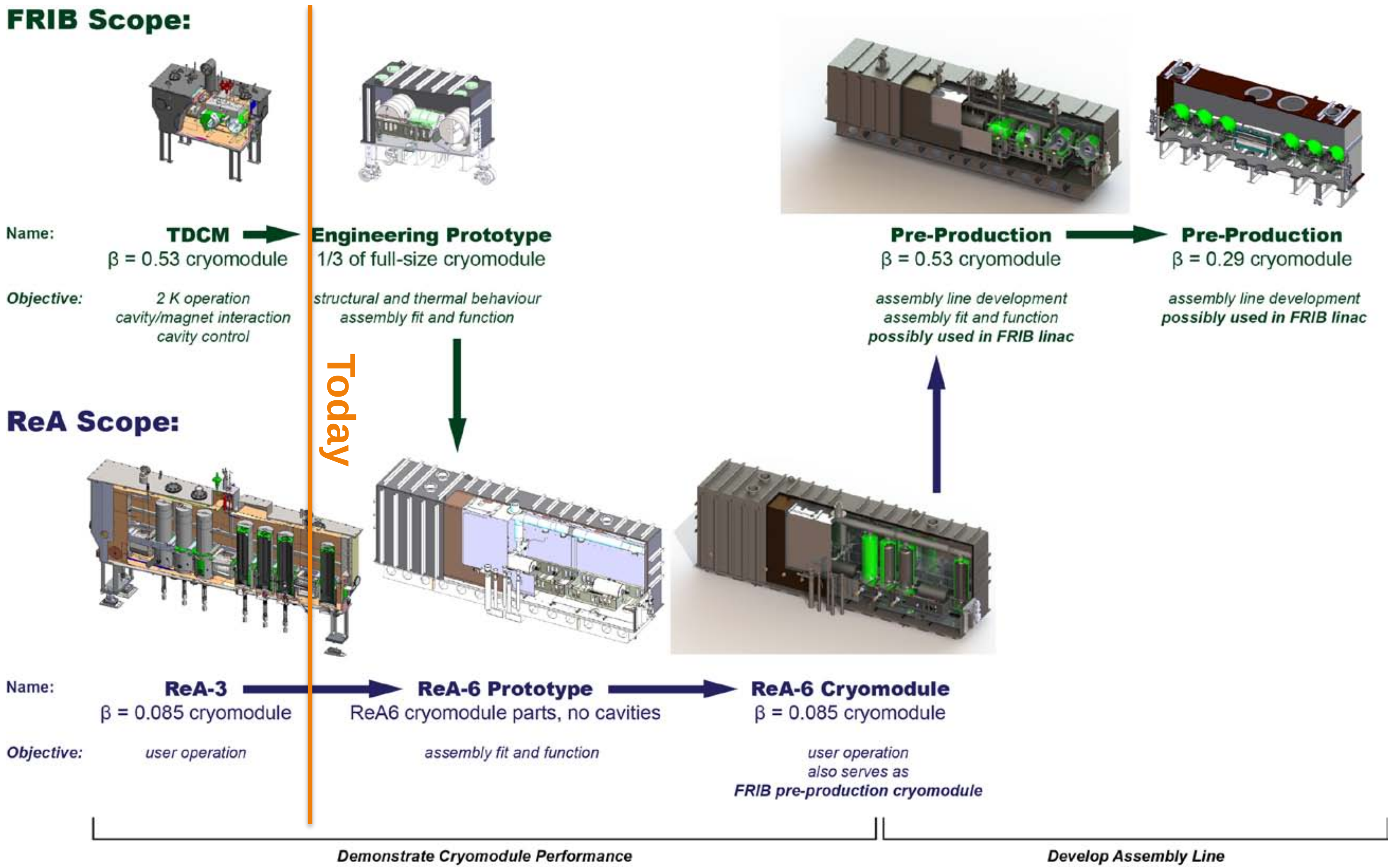
Total 49 plus 4 spares

Cavity Processing and Testing Infrastructure

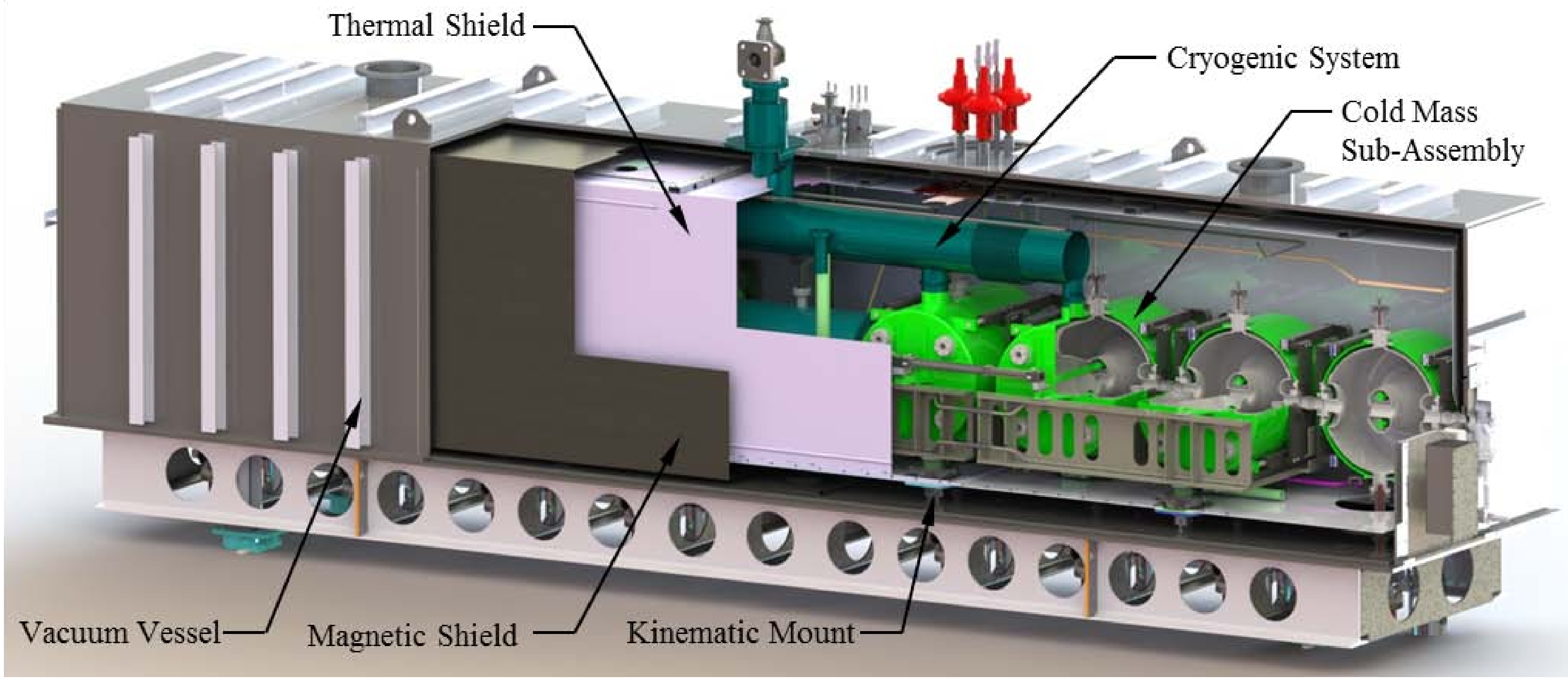
- Upgraded capability in the production phase from 2013
  - 5 cavities per week processed and tested
  - 2 cryomodule per month delivered and tested (1.5 average during production)



Cryomodule prototyping



FRIB Cryomodules



322 MHz, β = 0.53 Cryomodule

- New, bottom-up design
- 2K for resonators, 4.2K for SC Solenoids
- Same design scheme for all resonators

M. Johnson
WEPPD006

Y. Xu
WEPPD007

FRIB Cavity Production Schedule

Quarter Wave Resonators

Type	**Development Run** (with helium vessel)	**Pre-Production Run** (with helium vessel)	**FRIB LINAC**	10% excess	spare	**TOTAL**
	FY2011 - FY2012	FY 2012 - FY2013	FY2014 - FY2017			
β = 0.041	-	-	**12**	1	4	17
β = 0.085	2	10	**94**	9	11	126

Half Wave Resonators

Type	**Development Run** (no helium vessel)	**Pre-Production Run** (with helium vessel)	**FRIB LINAC**	10% excess	spare	**TOTAL**
	FY2011 - FY2012	FY 2012 - FY2013	FY2014 - FY2017			
β = 0.29	2	10	**76**	7	2	97
β = 0.53	2	10	**148**	14	0	174
TOTAL			**330**			**414**

Conclusions

- More than 400 SRF resonators of 4 types will be fabricated for FRIB
- Prototypes have been built and tested, reaching the required E_a and Q
- FRIB-type low-β QWRs are in operation in the ReA3 linac since 1 year
- Construction techniques and surface treatment are now mature, leading to high Q, high E_a resonators nearly field emission free in test cryostats
- The cryomodule development is ongoing
  - The Technology Demonstration Cryomodule (TDCM) is under testing at 2K
  - The ReA 3 high-β QWR cryomodule is under assembly
- The resonators design has been recently reviewed and assessed for the production cavities
  - Performance increased with lower E_p/E_a, B_p/E_a and higher R_{sh} and E_a
  - The total number of FRIB cryomodules has been reduced by two
- The cavity production phase has started with the construction of of 2 cavities per type ("development run") by 2012.

Acknowledgments

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