FRIB

FRIB Project: Moving to Production Phase

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On behalf of FRIB, MSU

MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

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Outline

- FRIB Project
- Challenges in the FRIB SRF
- Status of the SRF hardware production, not included cryomodule production

S. Miller FRAA 06

- Plans for ramping to full production
- For future large proton/ion SRF Linac projects
- Summary

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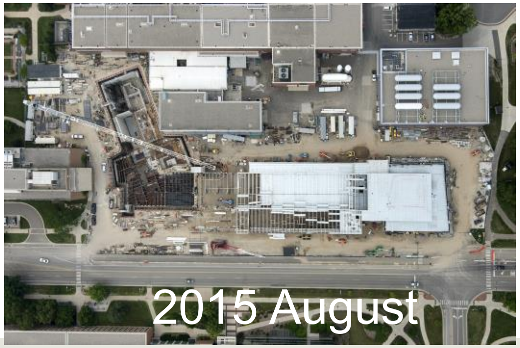
** FNAL, **INFN-LNL Italy, *** KEK Japan, ****TRIUMF Canada.*

FRIB Project Overview

- Goal of the FRIB: Create cutting-edge nuclear physics by the various isotope produced by an 200 MeV/u ion driver linac.
- Build a 200 MeV/u@ 400 kW SRF high intensity heavy ion linac in MSU campus.
- DOE/MSU jointed project under Cooperative Agreement, project cost shared by both, total cost $730M.
- CF construction started in March 2014
- Accelerator system construction started October 2014
- Completion of Infrastructure in SRF highbay in November 2015
- Early beam commissioning to be 2017 – 2020 starting with the Front End
- Final completion in 2022

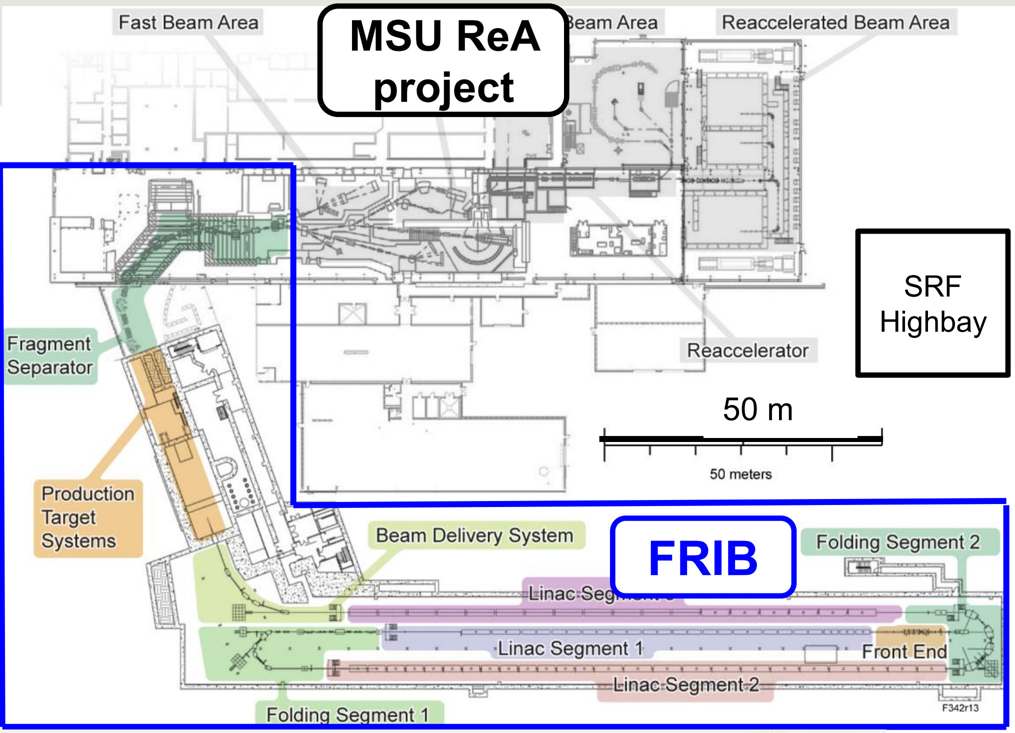
FRIB tunnel

FRIB accelerator building site

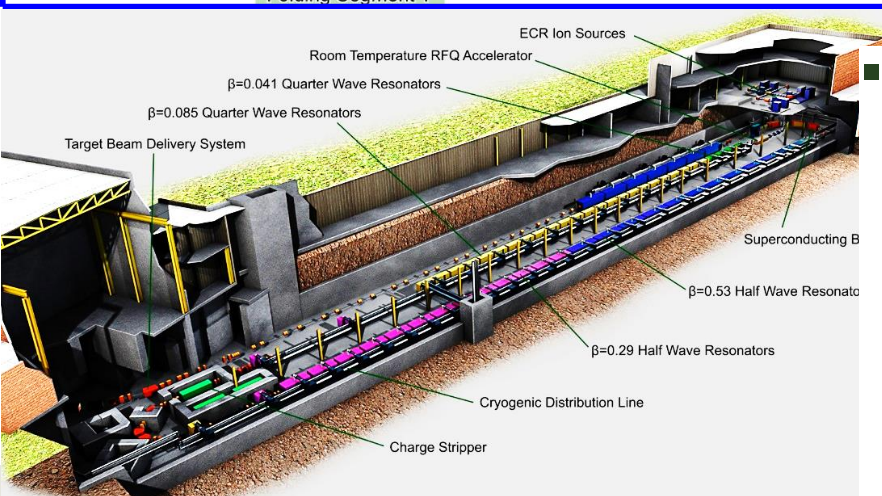


SRF highbay

FRIB SRF Linac Goal and Features



- Delivers FRIB accelerator as part of a DOE-SC national user facility with high reliability & availability
- Three folded SRF linac (~500 m)
- Accelerate ion species up to ^{238}U with energies > 200 MeV/u
- Provide beam power up to 400 kW satisfy beam-on-target requirements
- Future energy upgradability > 400 MeV/u by filling vacant slots

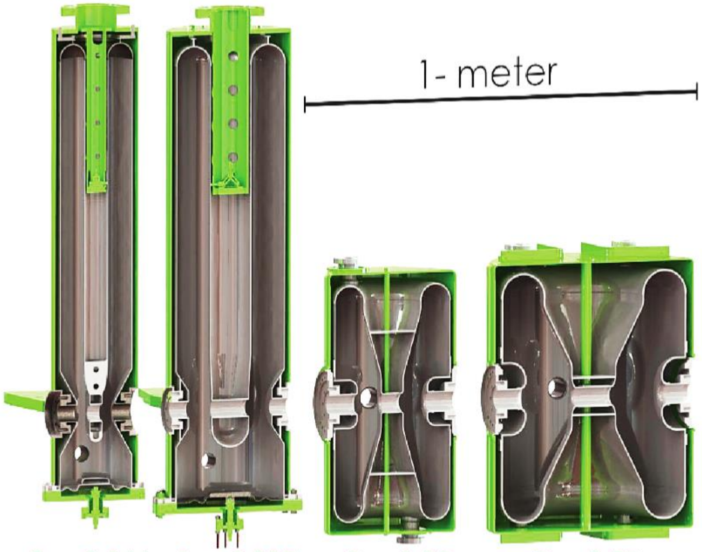


- **Features**:
  - Heavy ion beam intensity frontier machine, e.g. 5x10^{13} ^{238}U/s, 250 times higher than ATLAS
  - All SRF from low beta to medium beta section and 2K operation
  - Large nuclear physics user (~1300 users) facility

FRIB SRF Linac

All SRF cavities from beta 0.041 to 0.53, four type cryomodules, one cavity - one RF source (semiconductor amp.), high gradient CW operation at 2K

Cavity Type	QWR	QWR	HWR	HWR
β_0	0.041	0.085	0.285	0.53
f [MHz]	80.5	80.5	322	322
V_a [MV]	0.810	1.80	2.09	3.70
E_{acc} [MV/m]	5.29	5.68	7.89	7.51
E_p / E_{acc}	5.82	5.89	4.22	3.53
B_p / E_{acc} [mT/(MV/m)]	10.3	12.1	7.55	8.41
R/Q [Ω]	402	455	224	230
G [Ω]	15.3	22.3	77.9	107
Aperture [m]	0.036	0.036	0.040	0.040
$L_{eff} \equiv \beta\lambda$ [m]	0.153	0.317	0.265	0.493
Lorenz detuning [Hz/(MV/m)^2]	< 4	< 4	< 4	< 4
Specific Q_O@VT	1.4E+9	2.0E+9	5.5e+9	9.2E+9
Q_L	6.3E+6	1.9E+6	5.6E+6	9.7E+6

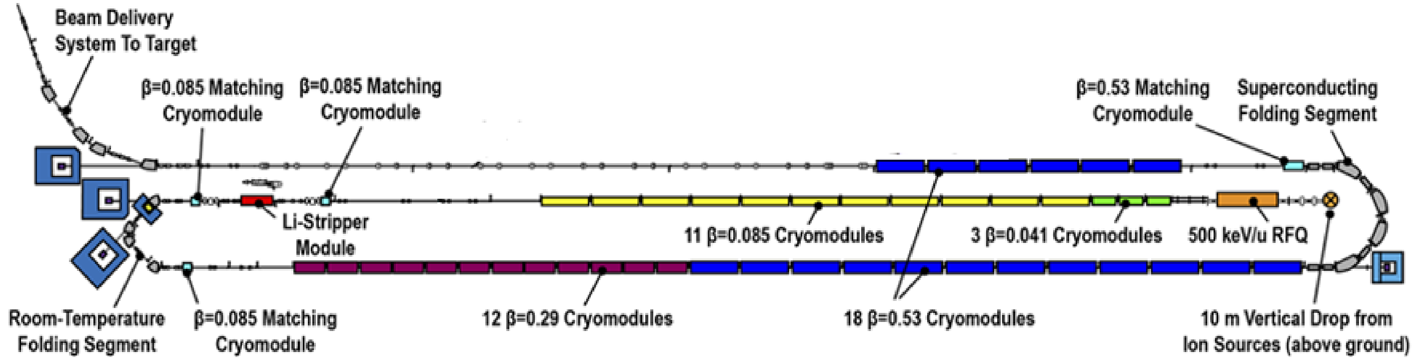


β_0 = 0.041 β_0 = 0.085 β_0 = 0.29 β_0 = 0.53

Quarter-Wave Resonators 80.5 MHz

Half-Wave Resonators 322 MHz

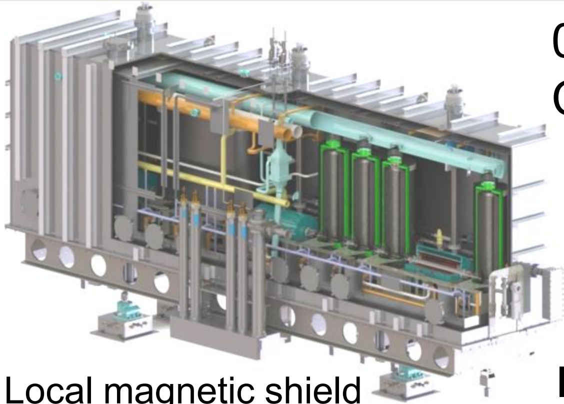
N= 12 88 72 144



FRIB Cryomodule Designs and Features

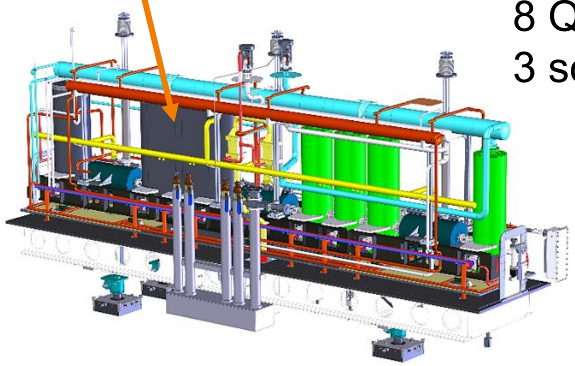
Example for 0.085QWR and 0.53HWR, 0.041/0.085 both QWRs and 0.29/0.53 both HWRs are similar

S. Miller FRAA 06

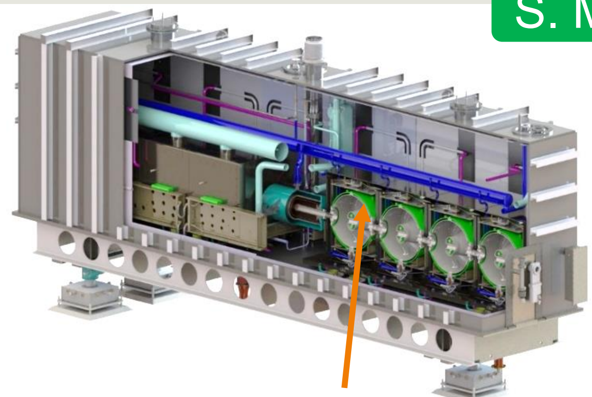


0.085QWR Cryomodule

Local magnetic shield

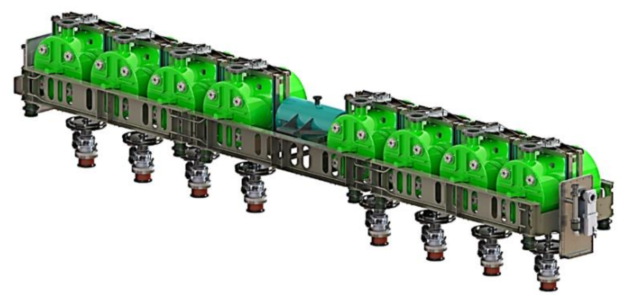


Includes 8 QWRs and 3 solenoids



0.53HWR Cryomodule

Local magnetic shield



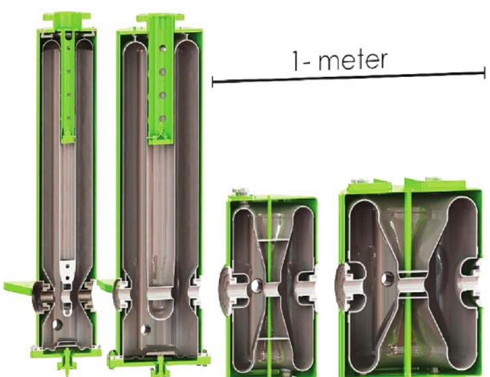
Includes 8 QWRs and 1 solenoids

Design of CM0.041 and CM0.29 are in WFO Jlab

- **FRIB Cryomodule Features**
  - **Local magnetic shield**: cost reduction for magnetic shielding and reliable shielding
  - **Bottom-up supported design**: optimized for mass-production and efficient precision-assembly
  - **2K operation**: enhanced cavity performance and less micro-phonics by stable pressure control

Main Hardware of FRIB SRF and Scope

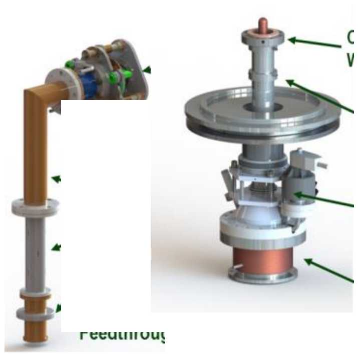
Cavity Type	Frequency & Cavity type	Quantity of Cavities	Quantity of Modules	Quantity of Solenoids
β=0.041	80.5 MHz, QWR	12 + 4 spare	3 + 1 spare	6 + 2 spare
β=0.085	80.5 MHz, QWR	88 + 8 spare	11 + 1 (Marching CM)	33 + 3 spare
β=0.29	322MHz, HWR	72	12	12
β=0.53	322MHz, HWR	144	18 +1 (Matching CM)	18
Marching Cryomodules		12 + 4 spare 3 + 1 spare	0.085 CM 3 +1 spare 0.53 CM 1	n/a
Total		332 + 16 spare	48 + 3 spare	69 + 5 spare



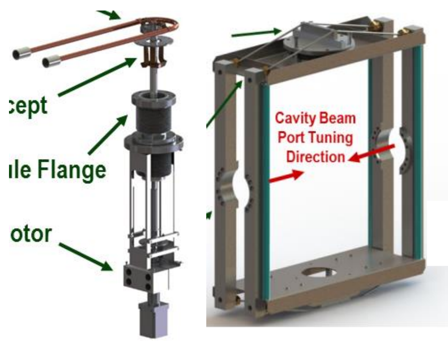
β_0 = 0.041 β_0 = 0.085 β_0 = 0.29 β_0 = 0.53

Quarter-Wave Resonators 80.5 MHz Half-Wave Resonators 322 MHz

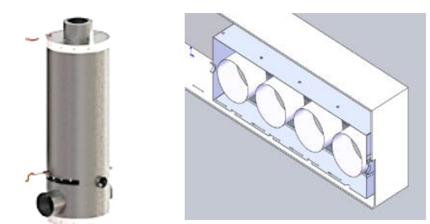
(1) Cavities



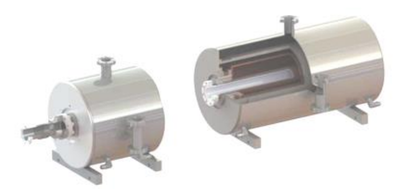
(2) QWR/HWR power couplers



(3) QWR/HWR Tuners



(4) QWR/HWR Magnetic shields



(5) SC 25/50cm solenoid packages

SRF Technical Challenges in FRIB SRF and Resolution

- **First Large Scale SRF LINAC β = 0.041 to 0.53**
  S. Miller FRAA06
  - Four different types of cryomodule: 0.041QWR, 0.085QWR, 0.29HWR, and 0.53HWR
  - How to manage so many different components.
  - Other labs help FRIB: Jlab for 0.041/0.29 MC design, ANL for coupler and tuner designs
- **Solenoid in the cryomodule**
  S. Chandrasekaran et al. TUPB102
  - FRIB is challenging to build compact SRF Linac with high beam quality
  - Detail investigation cavity/solenoid fringe field interaction
  - Designed solenoid package well optimized fringe field
- **Tighter Alignment Tolerance**
  S. Miller FRAA06
  - Smaller cavity bore diameter: 36 mm (0.041QWR), 40 mm (other type of cavity)
  - Longitudinally tolerance 1 mm and transversely 0.5 mm
  - Innovated bottom-up supported design cryomodule
- **Narrow Band width 30 – 40 Hz, Cavity Frequency Control in the Production**
  C. Compton WEBA03
  - Stack up tuning, innovated virtual EBW welding
  - Developed deferential etching (QWR)
  - Puck height control
- **High Gradient Cavity Operation at 2K**
  L. Popielarski et al. TUPB022
  - Eacc = 5 – 8 MV/m, Ep = 27 - 34 MV/m, Bp= 55 - 69 mT, Cavity design with lower Bp/Eacc ratio
  - Developed high QA control procedure

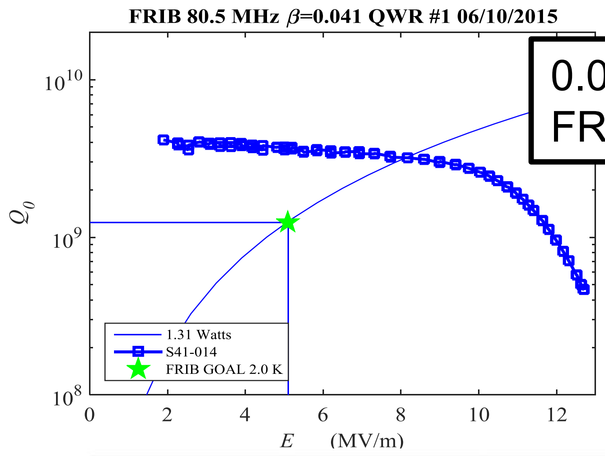
FRIB Requirements for SRF Hardware and Validation Status

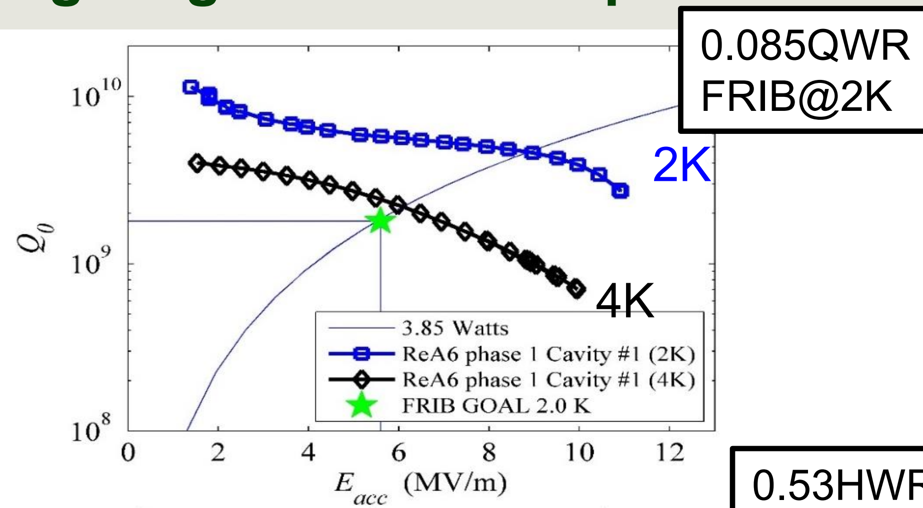
Hardware	Hardware Detail	Requirement	Validation	Comment
Cavity	0.041QWR (80.5MHz)	Eacc = 5.29 MV/m @ Q_O = 1.4 $\times 10^9$	Done	2 K operation
	0.085QWR (80.5 MHz)	Eacc = 5.68 MV/m @ Q_O = 2.0 $\times 10^9$	Done	2 K operation
	0.29HWR (322 MHz)	Eacc = 7.89 MV/m @ Q_O = 5.5 $\times 10^9$	Done	2 K operation
	0.53HWR (322 MHz)	Eacc = 7.51 MV/m @ Q_O = 9.2 $\times 10^9$	Done	2 K operation
Coupler	QWR (80.5 MHz)	4 kW @CW	Done (Dewar integration test)	Working in ReA
	HWR (322 MHz)	8 kW @CW	Done (Bench mark test)	KEK/SNS type
Tuner	QWR	Tuning range 30 kHz Tuning resolution 0.8 Hz	Done (ReA, ReA3 CM, ReA6-1)	Tuner plate + puck at bottom flange
	HWR, ANL type Pneumatic tuner	Tuning range 120 kHz Tuning sensitivity 1.5 Hz	Done (Dewar integration test) Continued design update	ANL type pneumatic tuner
Magnetic Shield	Local shielding	μ > 10000 @ 25 K Remnant field at high H_{RF} area of the cavity < 15 mG	Done (ReA, ReA3, ReA6-1)	Local magnetic shield at 25K
Solenoid Package	Main Solenoid (25cm/50cm) with bucking coil	8 T (NbTi)	Done (ReA, ReA3, ReA6-1)	4.5 K Operation
	Steering dipole	0.03 Tm (25 cm), 0.06 Tm (50cm)	Done (ReA, ReA3, ReA6-1)	4.5 K Operation

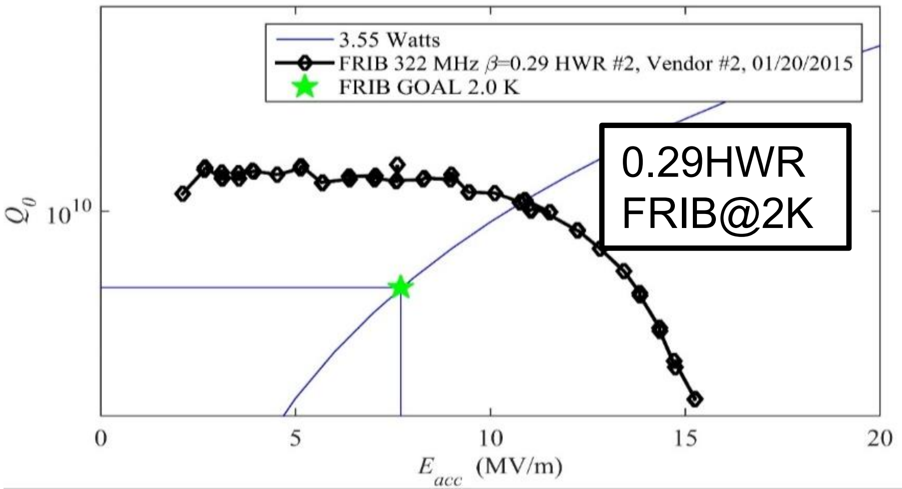
- Cavity preparation: BCP, Hydrogen degassed at 600 ^{O}C for 10 hr, and no 120 ^{O}C baking so far
- Solenoid: 8 T main solenoid with bucking coil to cancel the fringe field, X-Y beam steering dipoles

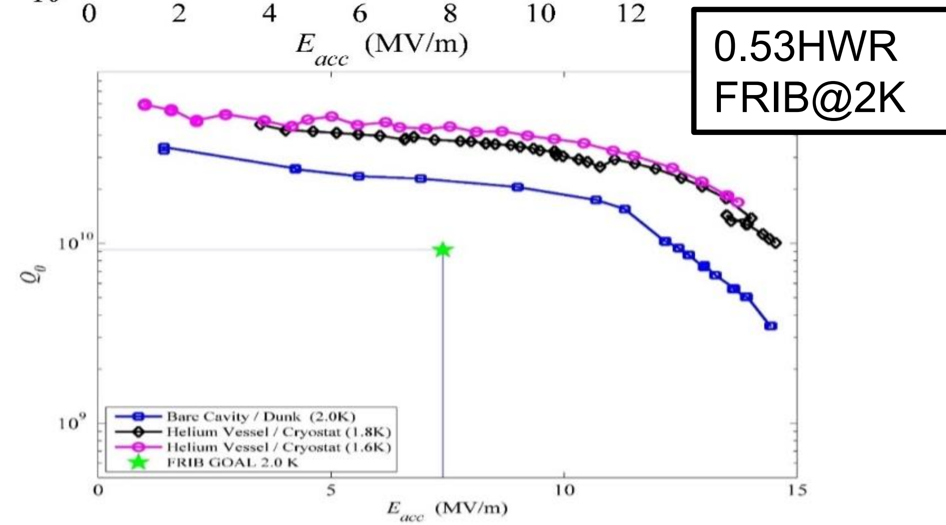
FRIB Cavity Design Validation

Processed by BCP, enough margin against FRIB requirements







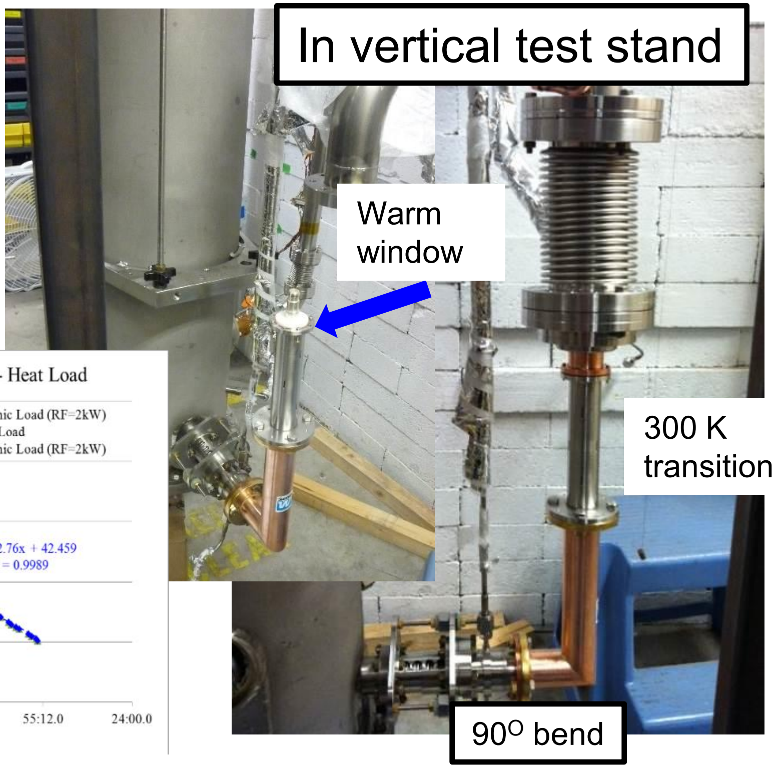


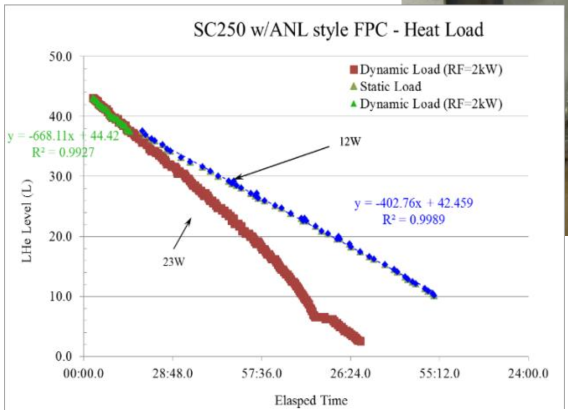
- Pushed away high Q-slope by improved RF cavity design with lower Bp/Eacc.
- Less field emission by FRIB develop high pressing QA control

Validation Test of 90^{O} Bend QWR FCP
Confirmed stable operation for long run

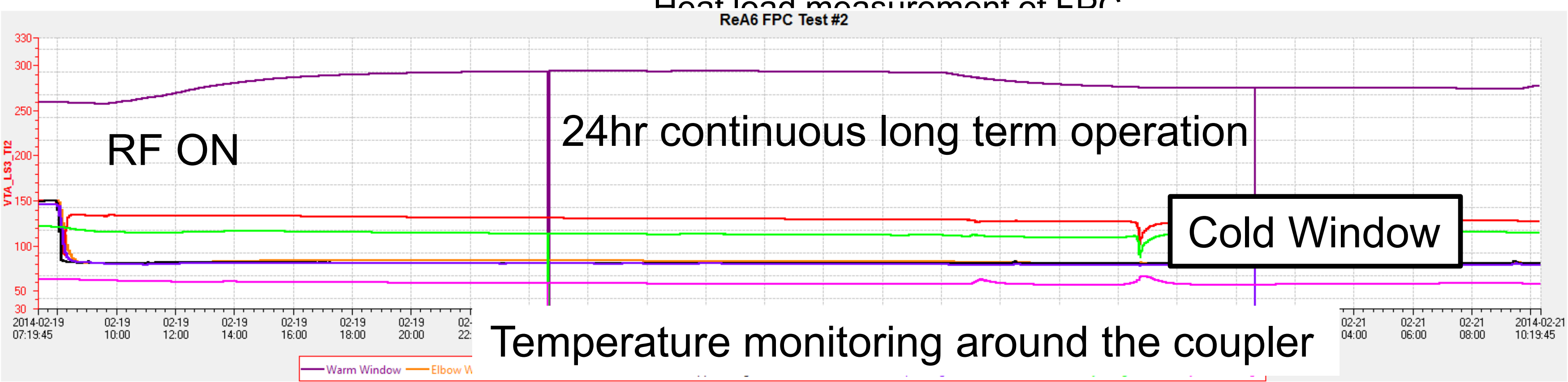
- **Validation**
  - 80.5 MHz QWR couplers are adjustable, not variable Adjustment is a possibility only for a microphonics mitigation Pumping slots were added on the outer conductor to evacuate in insulation vacuum
  - QWR coupler with 90^{O} bend was successfully tested on a ReA3 QWR at MSU
  - Succeeded long run operation in VT
    - Total load: 23W
    - Static load 12W
    - Cavity dynamic load 12W
    - Heat load < 1W,

      Stable operation for 24hr continuous
    - No heat up





Heat load measurement of FPC



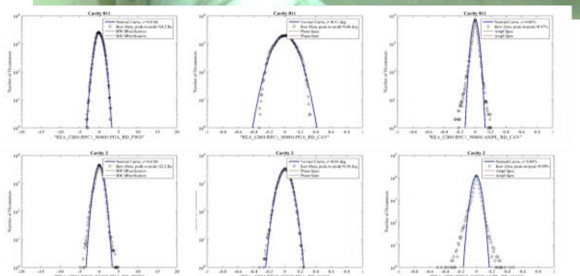
ReA6-1 CM Integration Validation

- Validated the alinement tolerance by Bottom up supported design
  - Confirmed alignment within 0.5 mm in transverse
  - Twice cool down/warm up and confirmed reproducibility

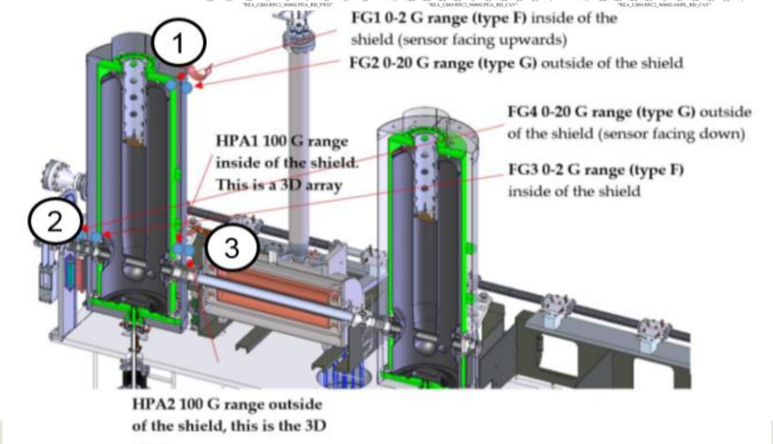
S. Miller FRAA 06

- Validated stable operation of the integration system: Cavities/FPCs/Tuners/Solenoid package
  - Demonstrated stable operation 24 hr
  - Confidence for band width control
- Validated local magnetic shield benefits (A4K)
  - Meets FRIB remnant field < 15 mT
  - Needless of degaussing process
  - Very small field around cavity short area under 8T solenoid package operation, expected no Q-drop at cavity quench

S. Chandrasekaran et al. TUPB102



Process	Fluxgates (mG)				Hall probes (mG) at beam port facing solenoid (low sensitivity at small fields) ③							
	Top of cavity ①		Bottom of cavity ②		In				Out			
	In	Out	In	Out	X	Y	Z	Mag.	X	Y	Z	Mag.
After cool down (shield T=24.5 K)	2.5	8.1	3.0	209.3	-850	-370	240	958	0	1000	1000	1414
During solenoid operation	-161.6 ±1.2	-361.2 ±2.1	1659.5 ±20.7	872.0 ±20.2	-6253 ±979	-3000 ±2438	-11350 ±1382	13596 ±2246	-55000 ±2800	-29900 ±2524	-91100 ±860	110849 ±1459
After solenoid operation	30.7 ±0.6	27.6 ±1.2	15.9 ±1.2	290.9 ±0.3	770 ±800	4317 ±833	3133 ±289	5434 ±835	5400 ±2800	-1967 ±1701	7733 ±1097	9906 ±1999
After full degauss	4.2 ±0.7	8.7 ±1.1	0.5 ±1.7	207.6 ±1.6	103 ±907	4133 ±1828	2667 ±2060	5058 ±2519	1933 ±2483	-4000 ±3378	-2767 ±3402	6719 ±1588
After CM warm-up	0 ±0.1	-5 ±0.1	0.6 ±0.1	205 ±0.1	16708 ±83	13845 ±67	7278 ±51	22887	-22061 ±90	-1836 ±62	-5217 ±74	22744



Production Strategy, Validation, and Production Status

- **Development phase: Produce 2 articles with MSU, Technology transfer to vendor for build to print, and vendor certification**
- **Preproduction phase: Produce 10 articles by the vendor own, judge the mass-production capability of the vendor, develop issues in mass production and resolve them.**
- **Production phase: Mass-production**

Component	Status, V(Validation), VC (Vendor Certification)				Delivery and Needed Date
Nb materials	NbTi flange (done), Nb sheets (done), Seamless pipes (**done**)				FRIB production Nb material has been done
Cavity with Helium jacket	0.041QWR Vendor A			Production (19) **done**	All 0.041QWRs has been delivered
	0.085QWR Vendor B/C	Development (2) **Done V, VC**	Preproduction (10) **Delivered 10, done all**	Production (102) **Started mass-production**	Needs 8 by 1st Sep. 2015 (FRIB first 0.085CM)
	0.285HWR Vendor D	Development (2) **Done V, VC**	Preproduction (10) **Delivered 3**	Production (72)	Needs by Aug. 2017
	0.53HWR Vendor D	Development (2) **Done V, VC**	Preproduction(10) **Delivered 10**	Preproduction (138)	Need by Apr. 2016
Fundamental Power Coupler	QWR parts Vendors	QWR FPC (2) **Done V, VC**	Preproduction (8) **Delivered 8 Aug. 2015**	QWR FPC(104)	Needs 8 by 1st Sep. 2015 (FRIB first 0.085CM)
	HWR Vendor E	Development (2) **Done V, VC**	HWR FPC (2) to be delivered Oct. 2015	HWR (217)	Need by Apr. 2016 (FRIB 1st CM)
Tuner	QWR Vendor F	Development (8) **Done V, ReA3**	Production(112) **Delivered (8), tuning plates**		Needs by Sep. 2015
	HWR Tuner	Development (2) Done by integration test but still finalizing design	**Production (217)**		Need by Jun. 2016 (FRIB 1st 0.53CM Prototype))
Solenoid	25cm Vendor G	Development (1) **Done V**		Production (6)	Need by March 2017
	50cm Vendor G/MSU	Development (1) **Done V**	Preproduction (4) in MSU, completed for preproduction CM Other in vendor G	Production (62)	Need 3 by Sep. 2015 for FRIB first 0.085 CM

Delivery Examples of SRF Components
So far, ~ 50 cavities delivered

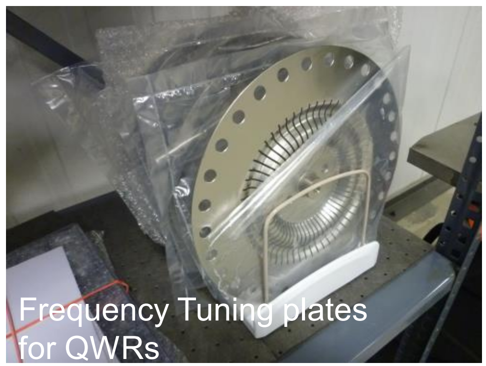

Niobium material for FRIB production cavities


Microphonic dampers


Pneumatic tuner on 0.53 HWR


50 cm solenoid package ready for cold test


0.041 QWRs


Frequency Tuning plates for QWRs


0.085 QWRs and 0.53 HWRs


0.085 QWR FPCs


Magnetic shield and solenoid package on the rail of ReA6-1 CM

Infrastructure for FRIB Production

SRF Highbay, constructed by MSU fund, ready for cavity test in Sept. 2015

- FRIB is finalizing infrastructure for the production in SRF Highbay fund by MSU
- Functionalities of the SRF Highbay
  - Acceptance inspection, working already
    - Dimensional inspection by CAM
    - Cold shock test, Leak check
  - Cavity processing and assembly, working already
    - Large cleanroom
    - Cavity etching (BCP) system
    - High pressure rinsing system
    - Ultrapure water system
    - Hydrogen degassing furnace
  - Cavity vertical test system, Mid-November 2015
    - 2 Dewars and 4 cold inserts
  - Cold mass assembly, started Sep. 2015 (FRIB 0.085 first CM)
  - 900W liquid helium system, liquid helium in 3000L Dewar in Sep. 2015
  - Cryomodule two bunker test systems, under preparation


CMM measurement


Large cleanroom


BCP facility


Cavity asssembly


HPR system


Vacuum furnace

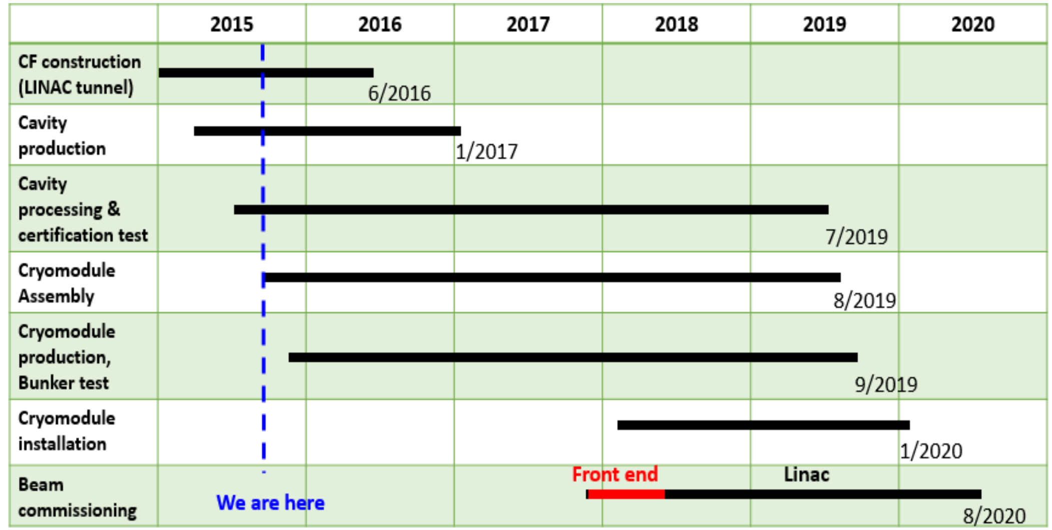

Cold box and 3000L Dewar

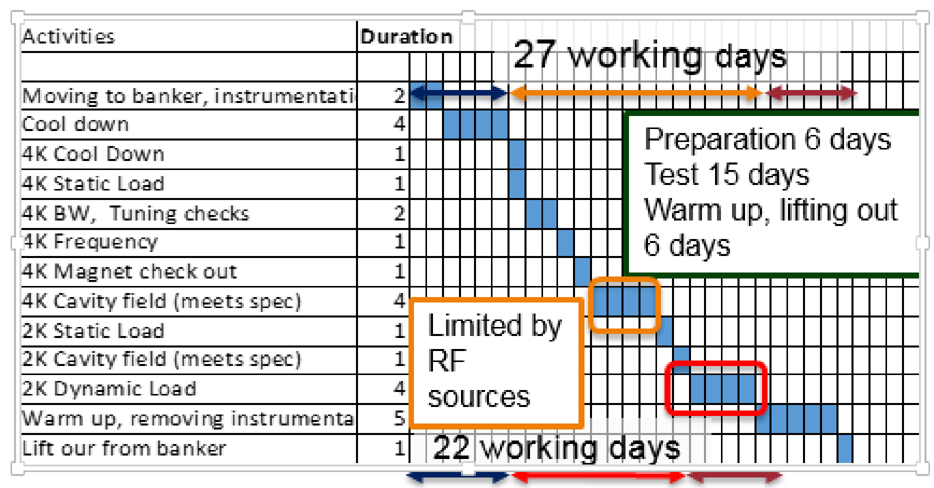

Vertical test area

Ramping to Full Production

- So far ~ 50 cavities have been delivered. 7 cavities /month, now speeding up and complete cavity delivery by 1, 2017
- FRIB needs 8 -9 cavities/month in average
- SRF full production Mid- November 2015 expected 11 -12 cavities/month with 20% downtime and 20%rework
  Meets FRIB requirement !!
- From ReA3, ReA6-1 cryomodule assembly experiences, a 27 working days needs one bunker test.
- FRIB cryomodule production rate is 1.5 CMs per month, which can be met by two bunker systems
- Cryomodule installation to be started from 2/2018

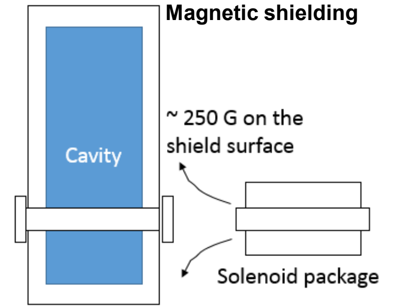
FRIB master schedule related to SRF construction

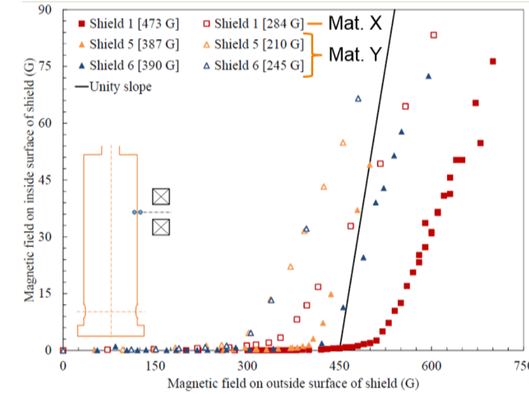


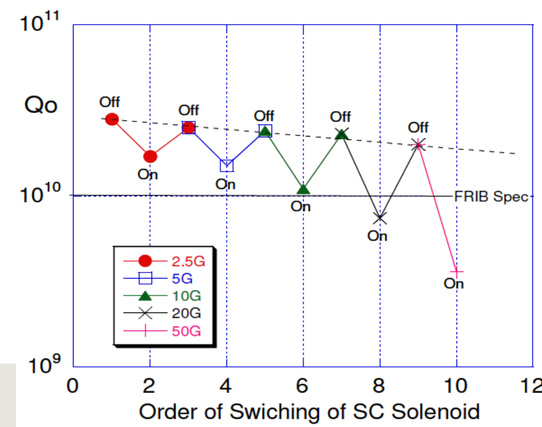


For Future Large Scale Proton/Heavy Ion SRF Linac

- **Solenoid Package in the Cryomodule**
  - FRIB is challenging to build the compact SRF linac with high beam quality
  - Need quick strong focusing heavy ion beam at low energy
  - Increase real state gradient to make short FRIB SRF linac
- **FRIB confirmed this scheme is good choice for QWRs with local magnetic shield scheme**
  - The fringe field around cavity short area is small enough to not occur the Q-drop at cavity quench, for instance ReA6-1 result 162 mG at the full operation of 8 T solenoid and dipoles
  - Local shield allows needless of degaussing procedure, which benefits on Operationability of cryomodule
- **Need careful solenoid package design**
  - The magnetic shield penetration field starts at ~ 250 G (defined as 1 G increased)
  - Solenoid package has to be designed as fringe field strength is less than ~ 250 G on the magnetic shield, need well optimized bucking coil location.





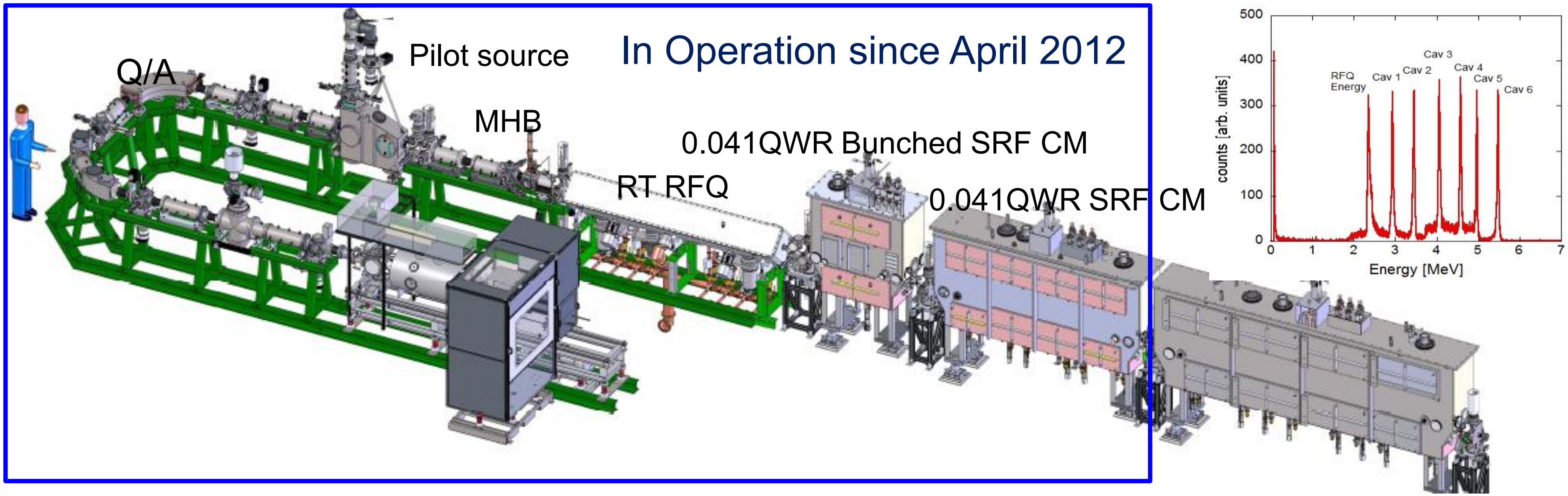


Summary

- FRIB construction started on March 2014 and to be completed in 2022, early commissioning is scheduled in 2017 – 2020 starting from the Front End.
- FRIB is the first large scale SRF linac from very low beta to medium beta.
- FRIB SRF linac is the intensity frontier heavy ion machine.
- FRIB is challenging many innovative concepts to build a compact SRF linac with high quality beam: solenoid in the cryomodule, bottom up supported cryomodule assembly, and high gradient cavity. These concepts have been successfully validated.
- All hardware components have been successfully validated and has been ordered vendors. FRIB project is moving well into production phase.
- Infrastructures in SRF highbay is going into full operation since Mid-November 2015, enhances the production rate double, and ready for full production.

ReA Project in MSU
MSU own project, beam operation of SRF linac

- MSU has strong nuclear physics activities in the world (NSCL, ReA)
- ReA is the reaccelerate rare isotope system up to 3 MeV (upgrade 12 MeV future near future), and first SRF LINAC at MSU
- Excellent test bench for FRIB QWRs for beta: 0.041 QWRs and 0.085 QWR cryomodules
- ReA joins finally FRIB (Reaccelerates rare isotopes produced by FRIB)



0.085QWR ReA3 SRF CM, accelerates up to 3MeV since 2014