Accelerator Challenges of Hadron Linacs and the Facility for Rare Isotope Beams –
Extending High Beam Power from Protons to Heavy Ions

Jie Wei and the FRIB Accelerator Team

HB'2014, East Lansing, November 10, 2014

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661.
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.

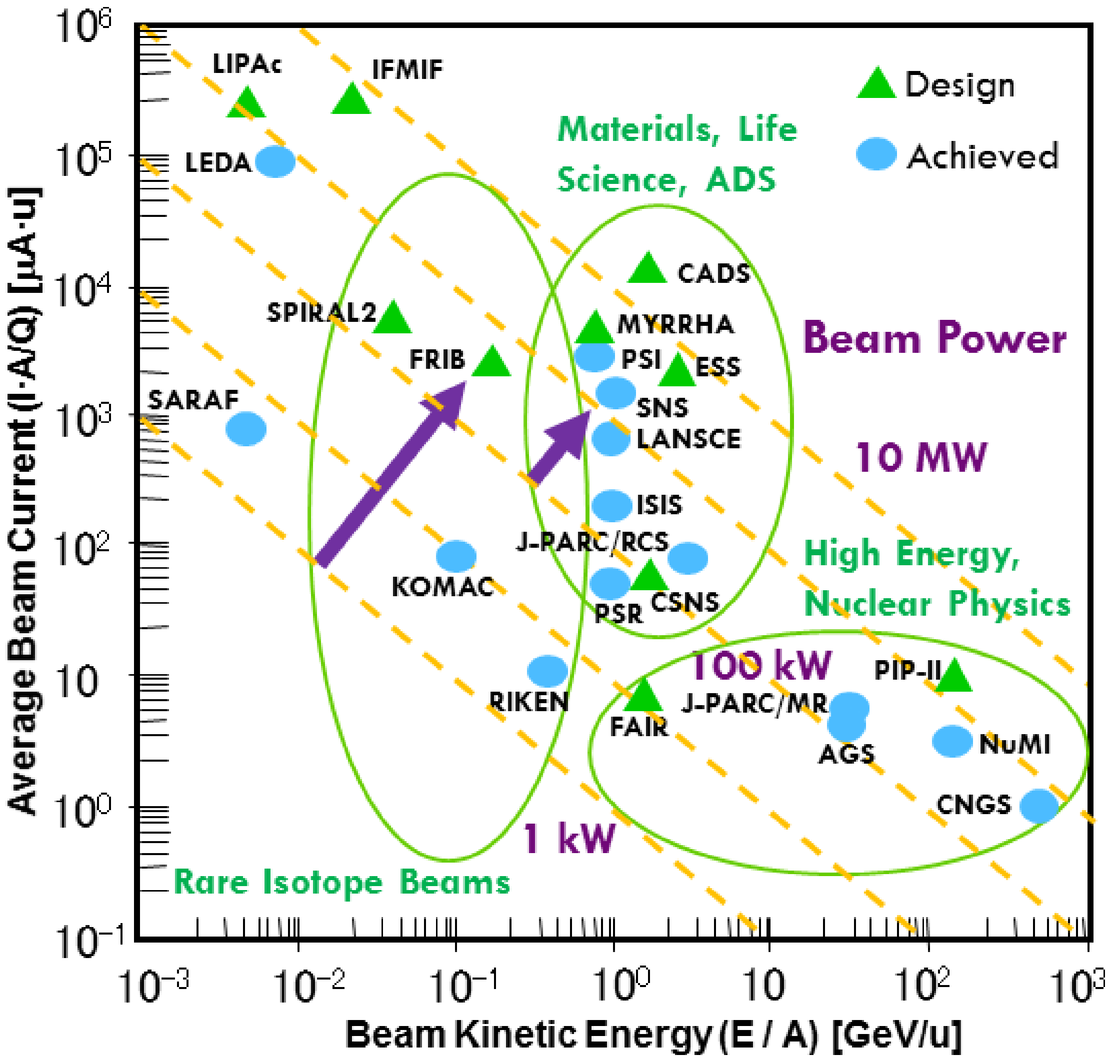
Outline

- Introduction
- Key technologies
- Accelerator physics challenges
- FRIB Project status
- Future perspectives

- Acknowledgements

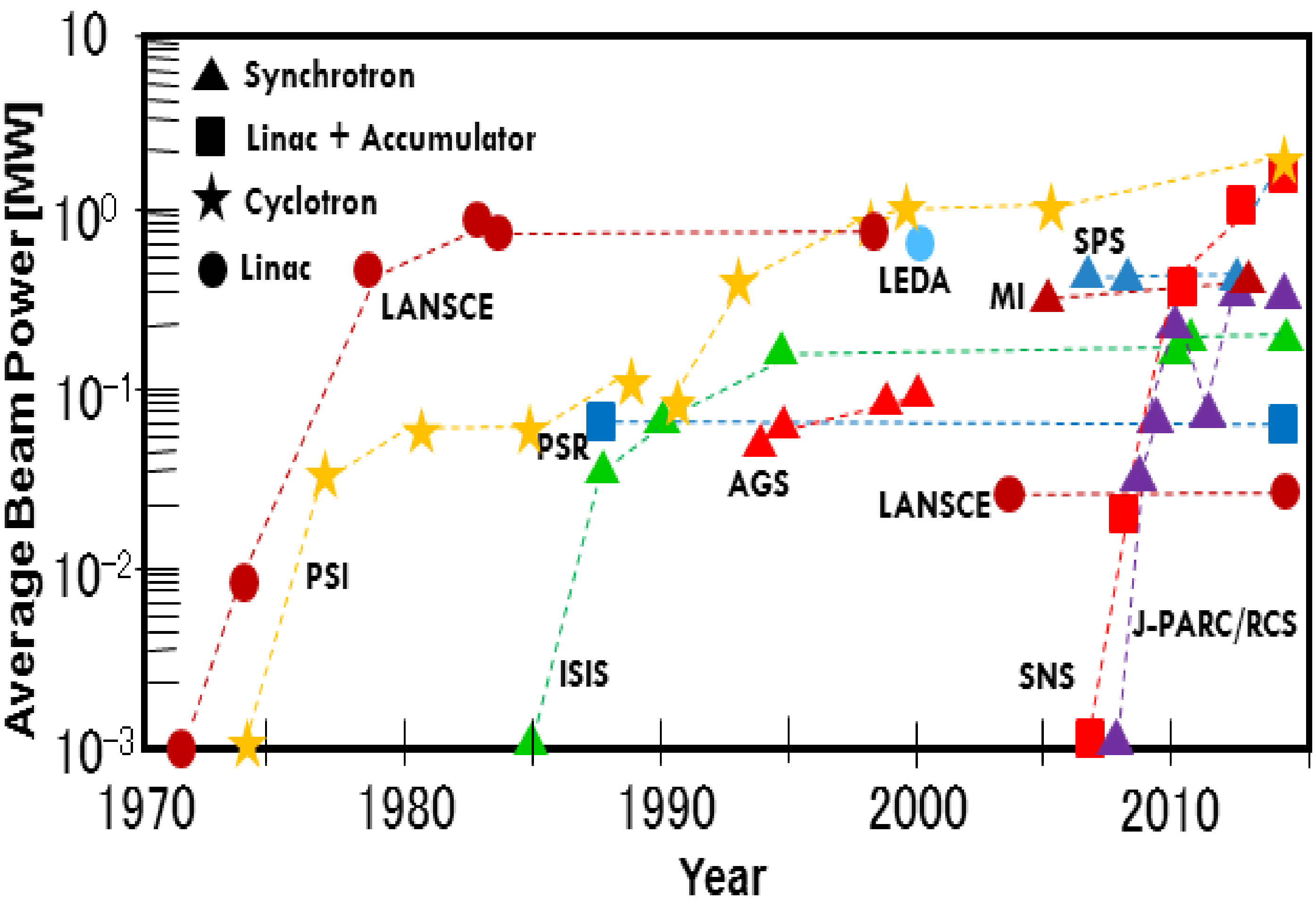
Accelerator Beam-power Frontier

- High energy, nuclear physics (ν, K factories)
  - 1 ~ 400 GeV proton
  - Linac + Synchrotron
- Material, life science, (SNS) accelerator-driven subcritical systems (ADS)
  - 0.5 ~ 3 GeV proton
  - Cyclotron, linac, rapid cycling synchrotron, accumulator
- Rare isotope beams (RIB)
  - 0.01 ~ 1 GeV/u heavy ion
  - Linac, cyclotron, synchrotron
- Material irradiation; isotope
  - ~0.02 GeV/u deuteron; linac



Historical Records of Beam Power

- Proton CW
  - LANSCE: ~ MW since 1980
  - PSI: ~ MW since 1995
- Proton pulsed
  - ISIS: ~ 0.1 MW since 1985
  - AGS ~ 0.1 MW since 1994
- Heavy ions
  - RIKEN, ATLAS, NSCL up to 7 kW
- ~100 MW R&D
  - LEDA 0.7 MW 2000



SNS: 1.4 MW Pulsed Proton on Target
Planned Linac Energy Increase to 1.3 GeV for ~ 2.8 MW

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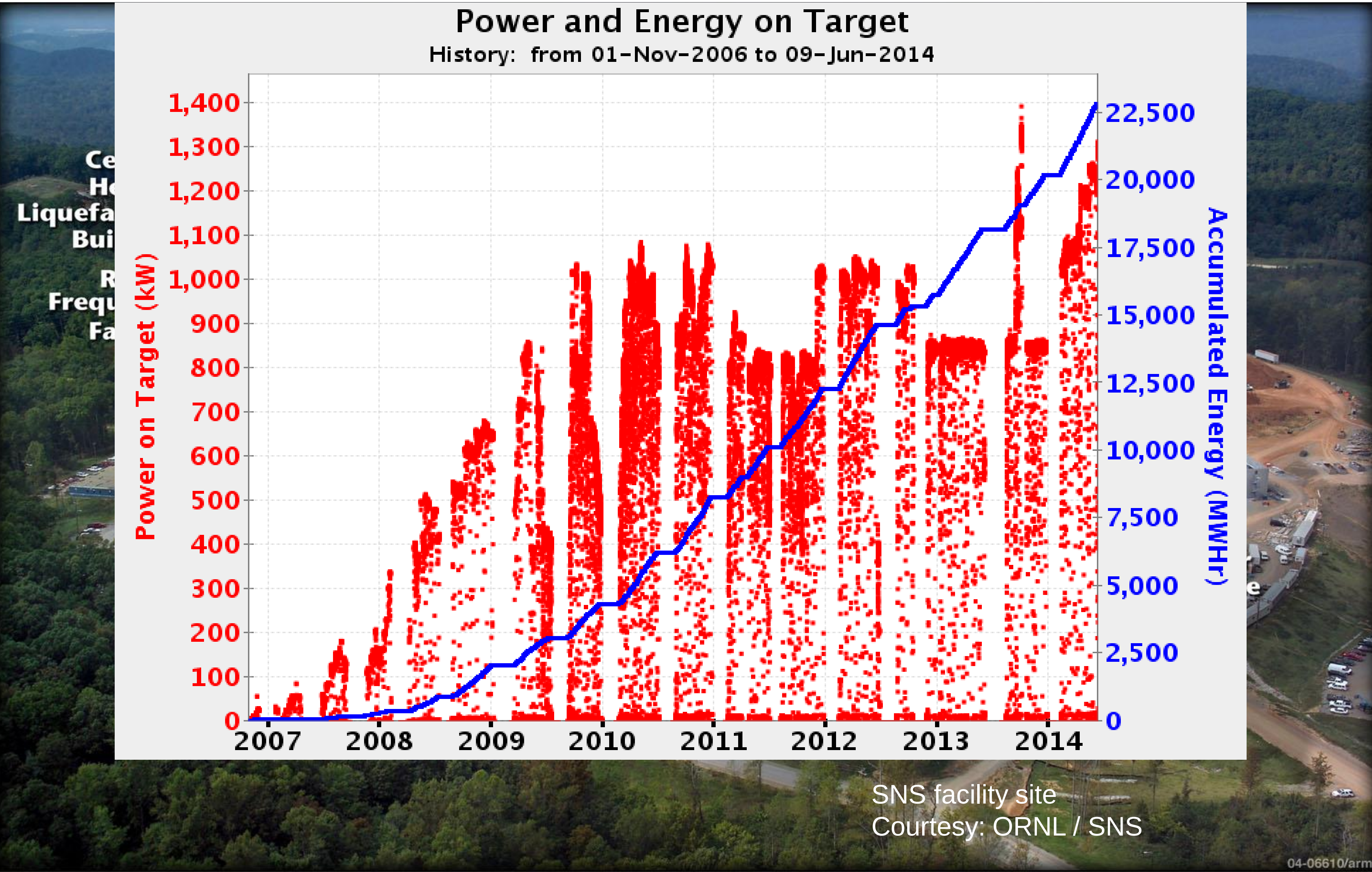
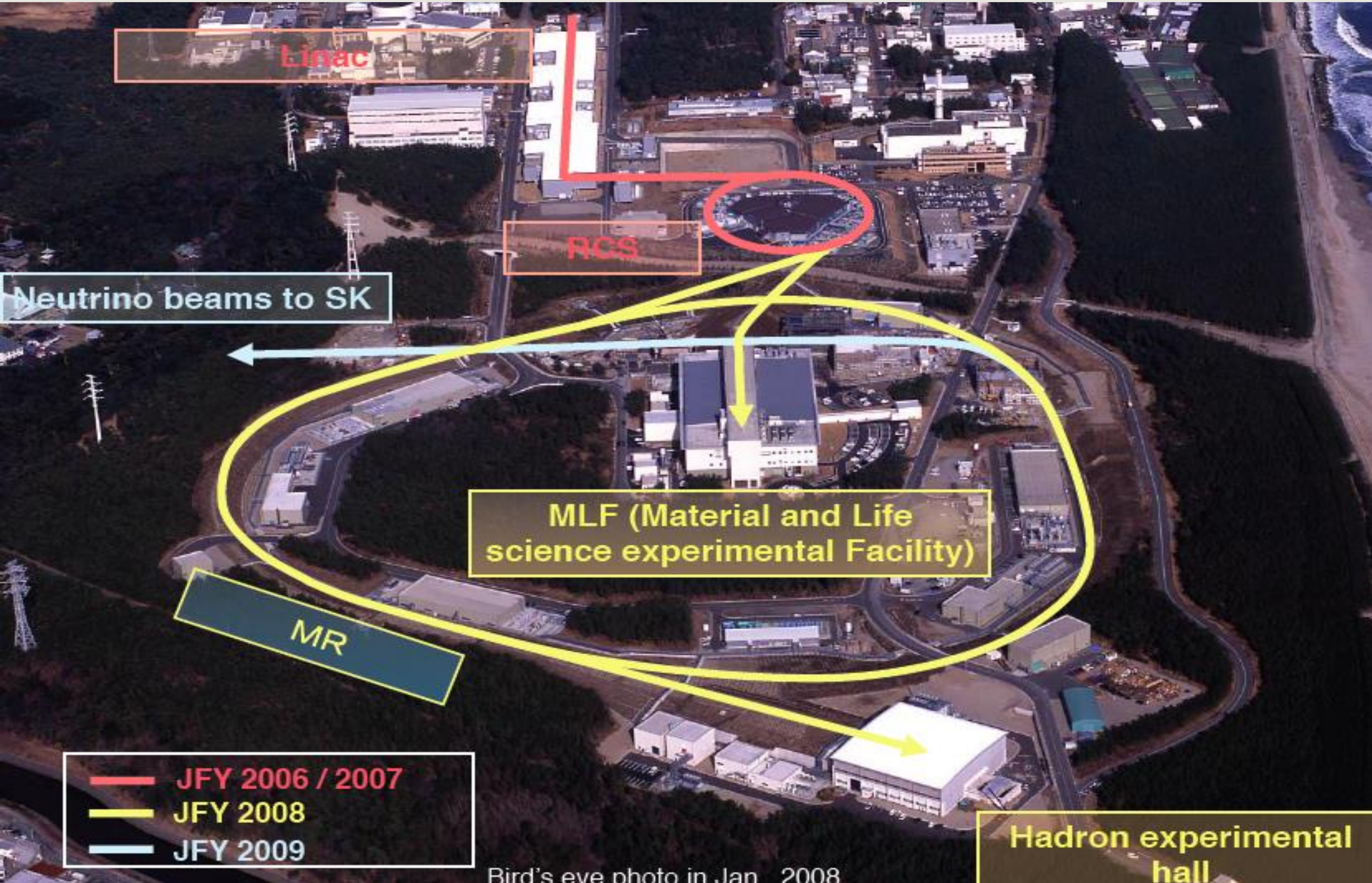


SNS facility site
Courtesy: ORNL / SNS

J-PARC: Marching Towards 1 MW Goal

Recovered from Earthquake; Commissioned 400 MeV Linac



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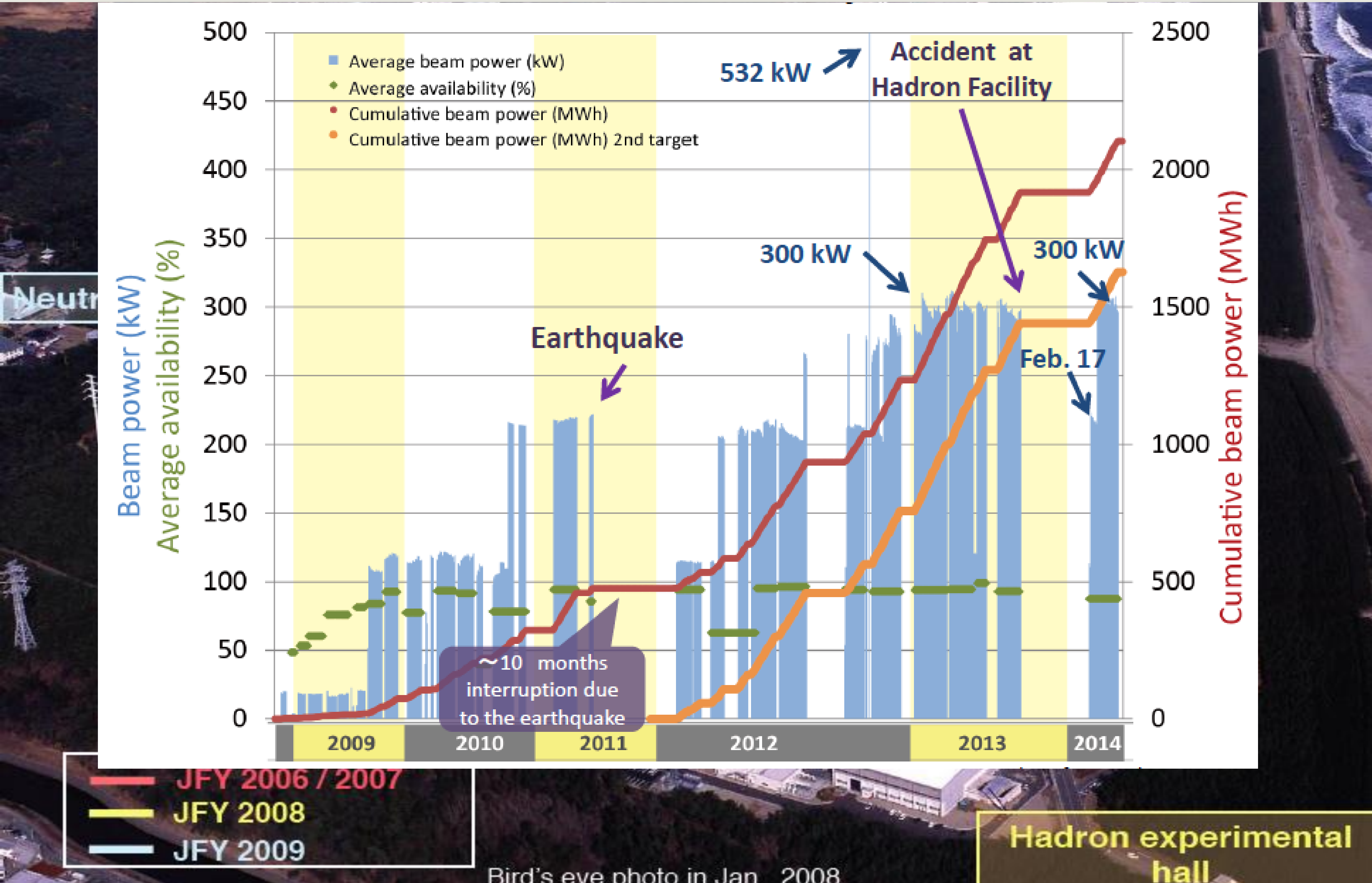
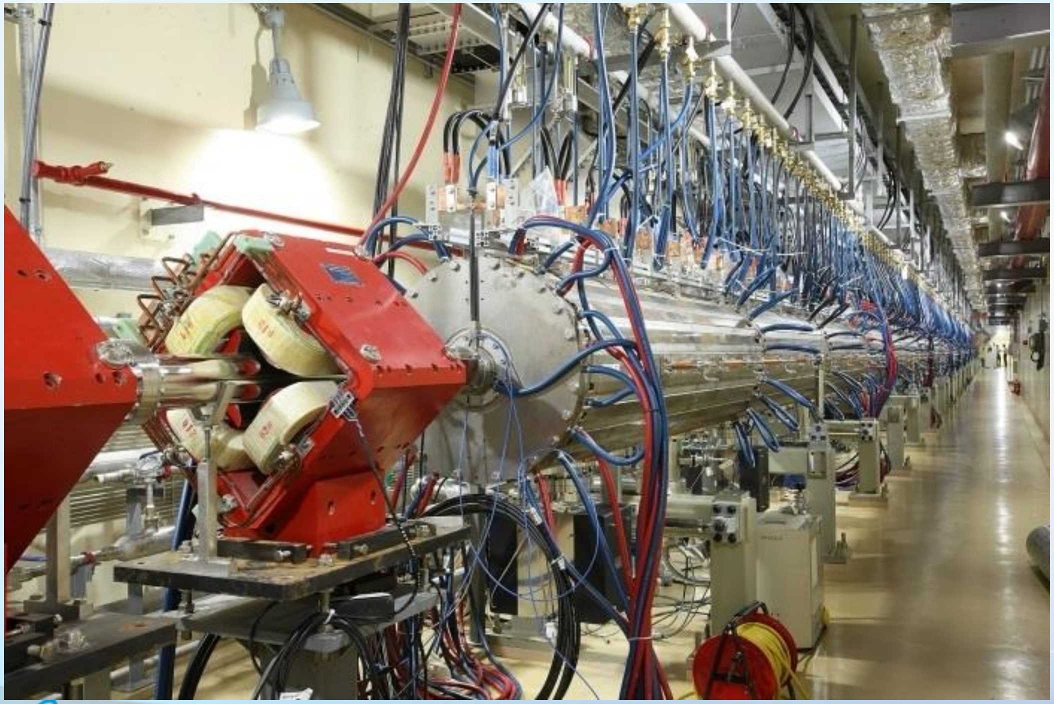


Status of KOMAC 100 MeV Proton Linac (1)

Korea Multi-purpose Accelerator Complex, Gyeongju, Korea
Korea Atomic Energy Research Institute

- **Developed as a National User Facility for Basic & Applied Research by Proton Engineering Frontier Project (2002-2012)**
  - **Structure: 50 keV Injector, 3 MeV RFQ, 20 MeV DTL-I, MEBT, 100 MeV DTL-II**
  - **RF Frequency : 350 MHz, Beam extractions: 20 MeV or 100 MeV**
- **Commissioned & Started beam service in July 2013 with 2 beamlines**
  - **Utilized in Bio-life, Materials, Energy-environment, Space, Nano, Isotopes, Basic Science, & Industrial applications**



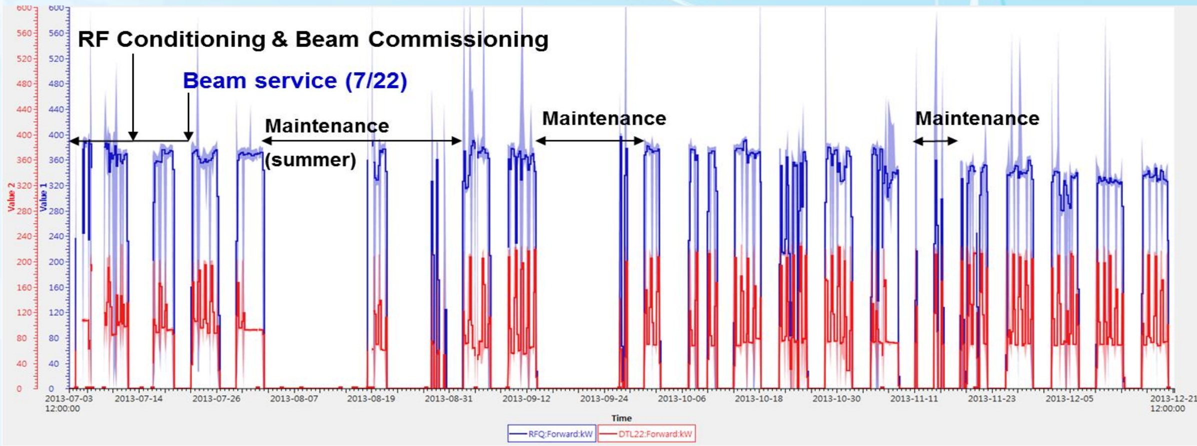
Key Parameters		
Output energy (MeV)	20	100
Peak beam current (mA)	20	20
Beam duty (%)	24	8
Avg. beam current (mA)	4.8	1.6
Pulse length (ms)	2	1.33
Repetition rate (Hz)	120	60
Avg. beam power (kW)	96	160

Status of KOMAC 100 MeV Proton Linac (2)

Korea Multi-purpose Accelerator Complex, Gyeongju, Korea

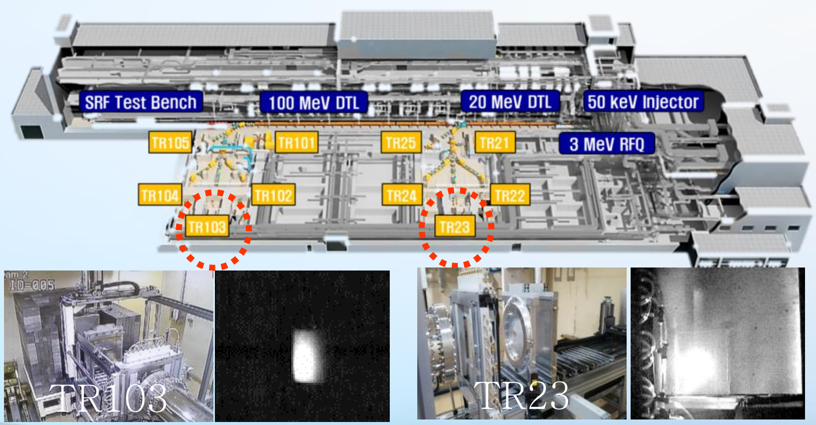
Korea Atomic Energy Research Institute

■ Accelerator Operation in 2013

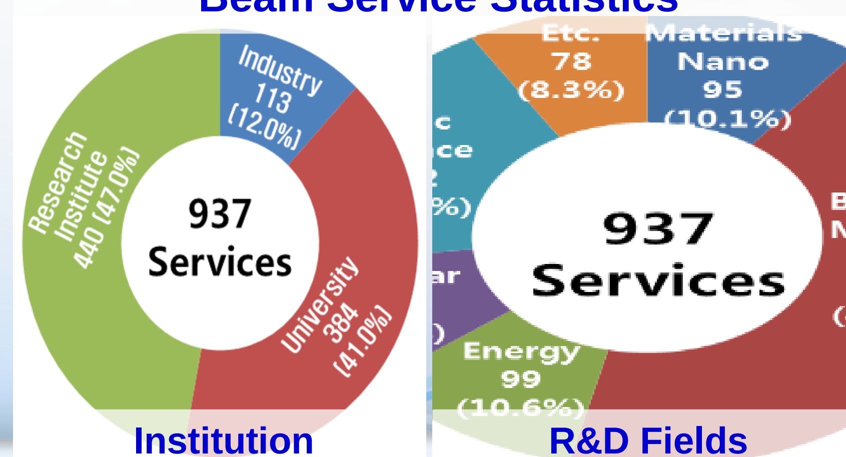


- ■ Operation : 2,290 hours
- ■ Beam on: 432.7 hours
- ■ Availability : 82%
- ■ Operation Conditions
  - Energy : 20 & 100 MeV
  - Beam power : 1 kW

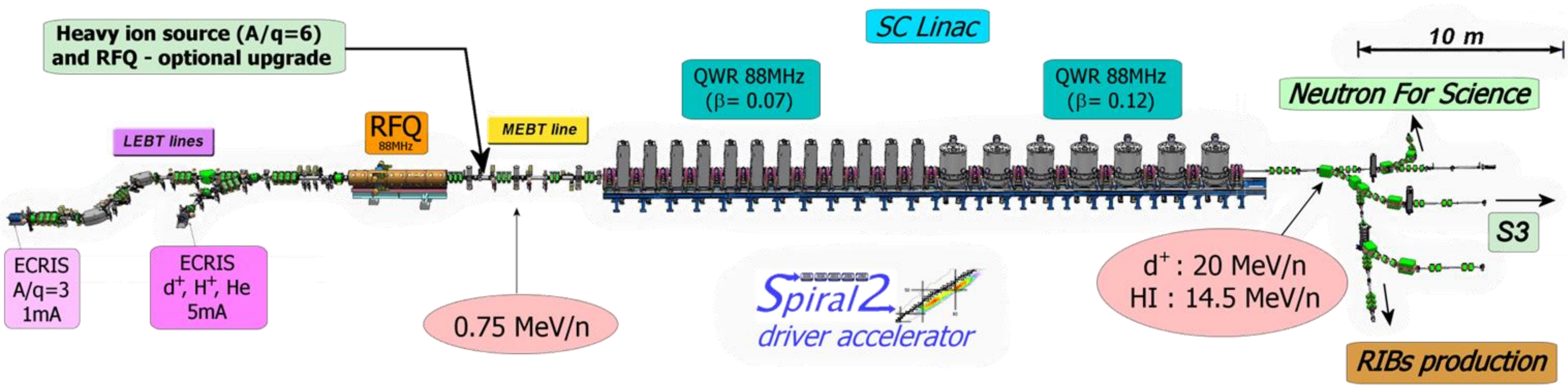
■ User Service in 2013 by 2 Beamlines (TR23 & TR103) : from July 22 – December 20, 2013



Beam Service Statistics



Accelerator Baseline Configuration



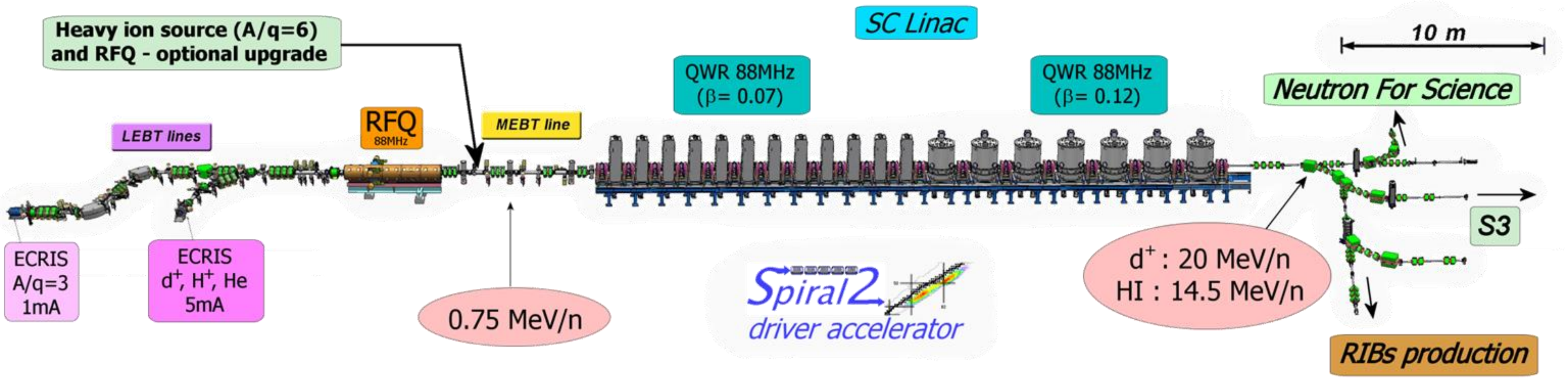
Particles	H^+	$^3He^{2+}$	D^+	Ions	
Q/A	1	2/3	1/2	1/3	1/6
I (mA) max.	5	5	5	1	1
W_O max. (MeV/A)	33	24	20	15	9
CW max. beam power (KW)	165	180	200	44	48

Total length: 65 m (without HEBT)

Slow (LEBT) and Fast Chopper (MEBT)
RFQ (1/1, 1/2, 1/3) & 3 re-bunchers

12 QWR beta 0.07 (12 cryomodules)
14 QWR beta 0.12 (7 cryomodules)
1.1 kW Helium Liquifier (4.5 K)
Room Temperature Quadrupoles
Solid State RF amplifiers (up to 20 KW)
6.5 MV/m max $E_{acc} = V_{acc}/(\beta_{opt}\lambda)$ with $V_{acc} = \int E_z(z) e^{i\omega z/c} dz$.

Accelerator Baseline Configuration



FRIB: Goal 400 kW CW p to U

Ground Broken in March 2014

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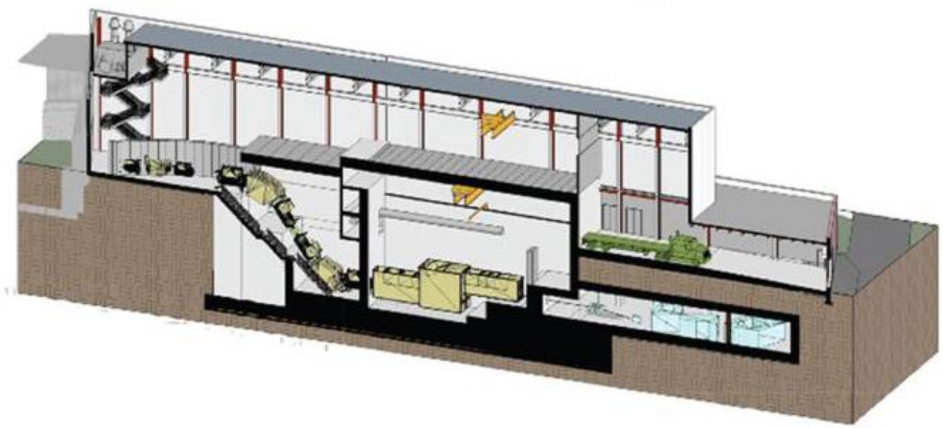
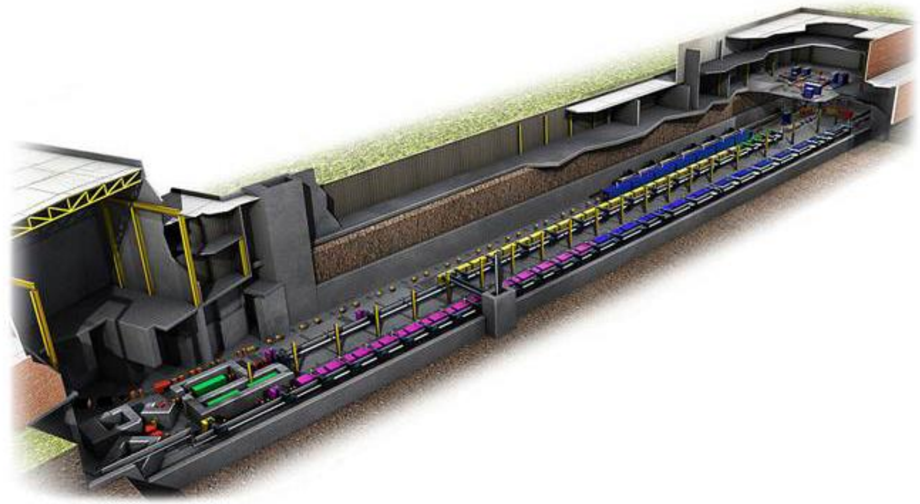
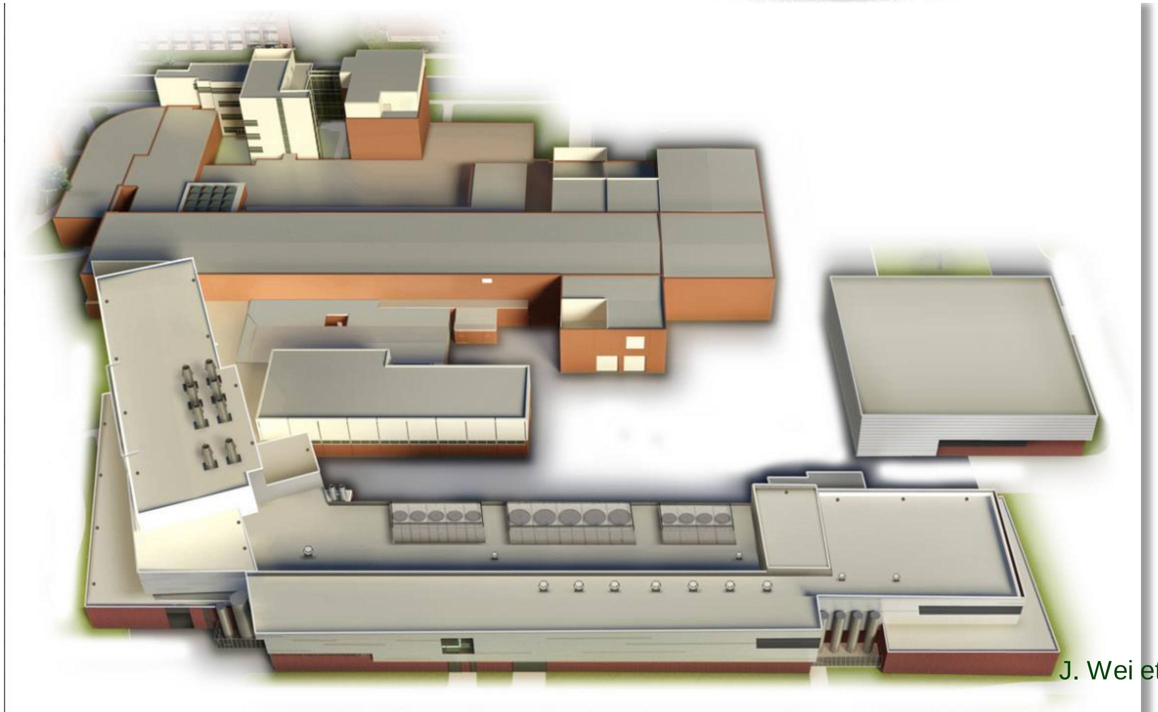




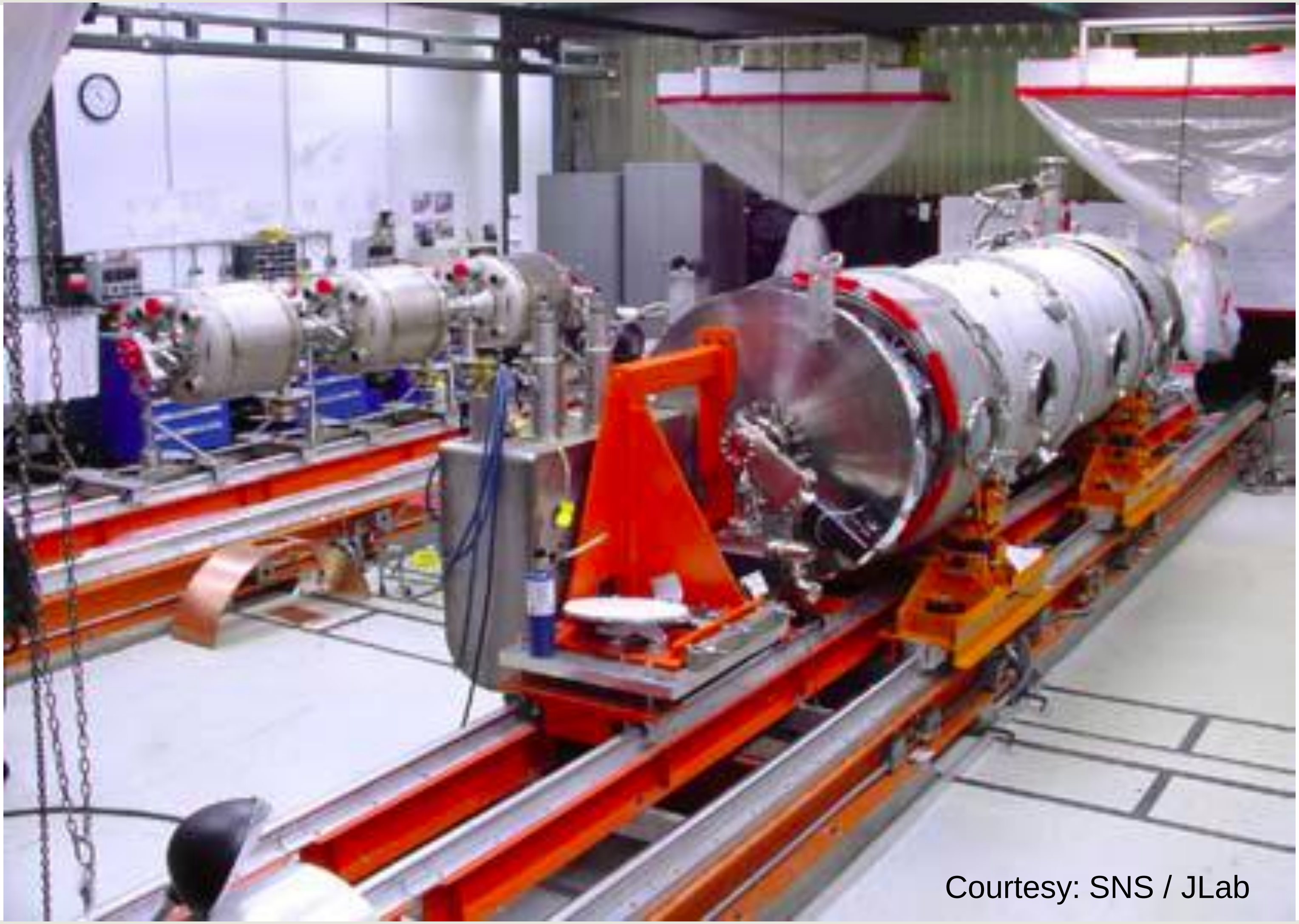


Key Technology Examples

- Superconducting RF
- Integrated Cryogenics
- Loss Detection and Machine Protection
- Collimation
- Ion Source
- RFQ
- Charge Stripping
- Target
- Radiation-resistant Magnets, Handling
- Site Specific Complications

Superconducting RF

SNS: First High-power Hadron Linac Extensively Using SRF

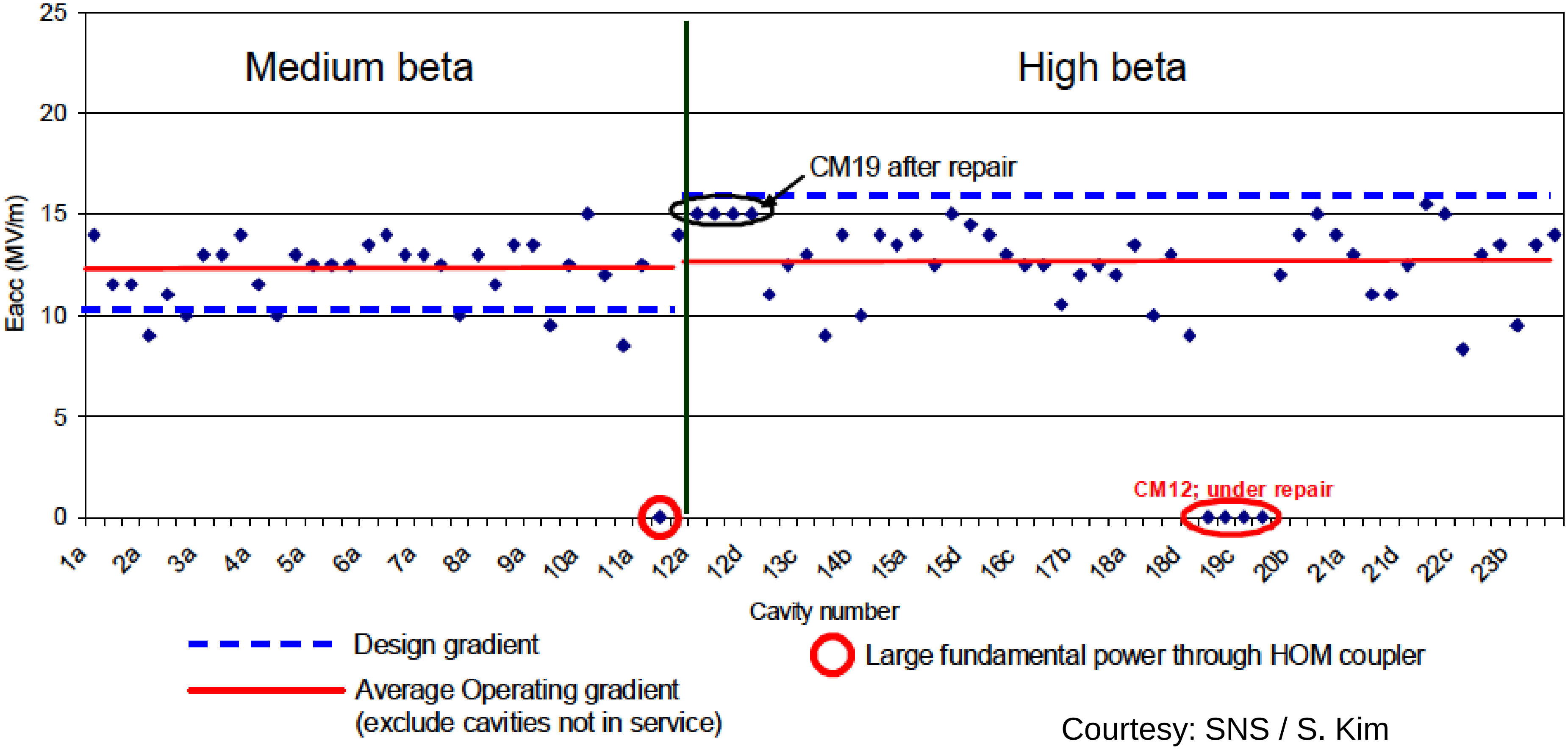


Courtesy: SNS / JLab

Note: ATLAS uses ~ 50 MV SRF for > 20 years

Superconducting RF

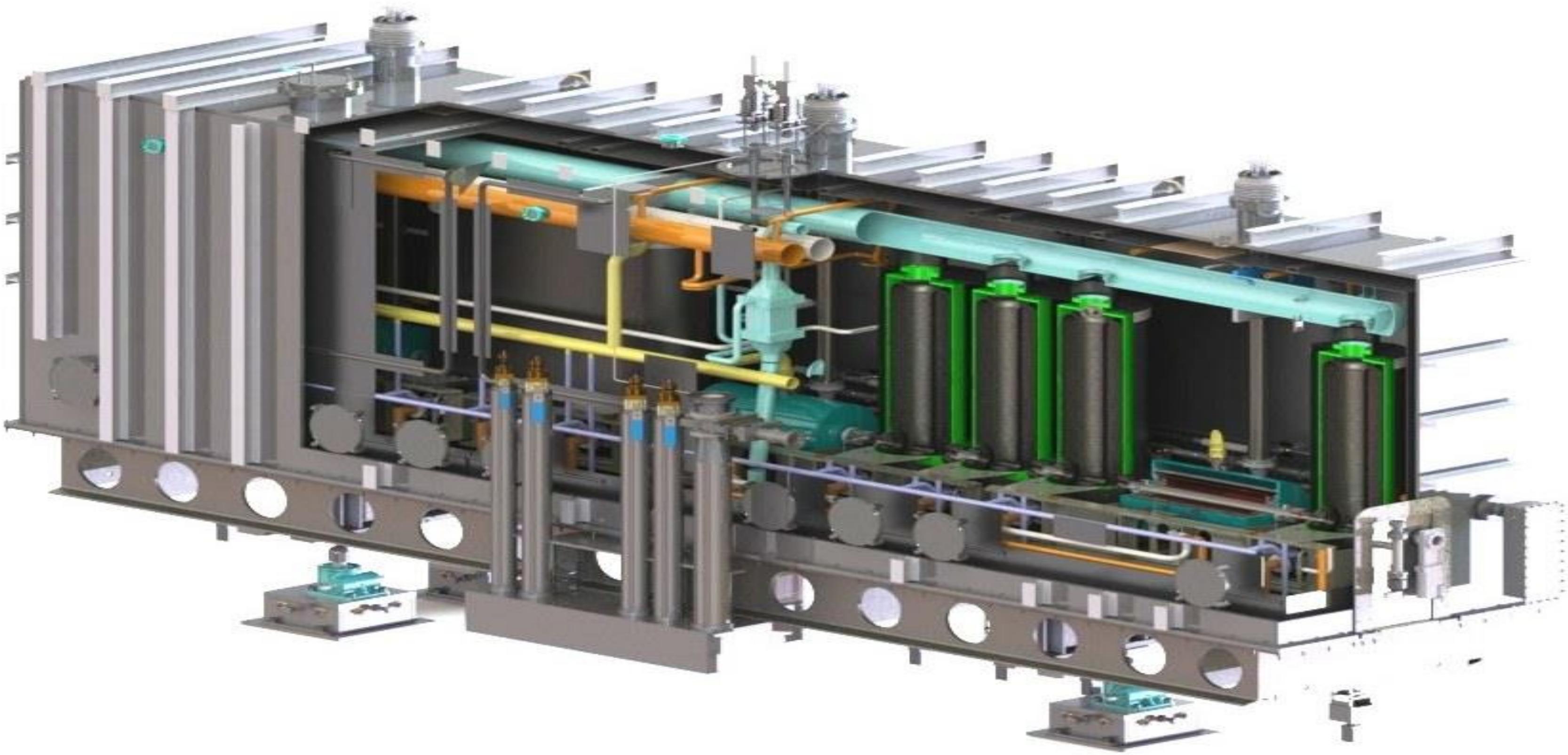
SNS: Actual Accelerating Gradient Largely as Designed



Courtesy: SNS / S. Kim

Superconducting RF
FRIB: CW Linac Using SRF from Low Energy (500 keV/u)

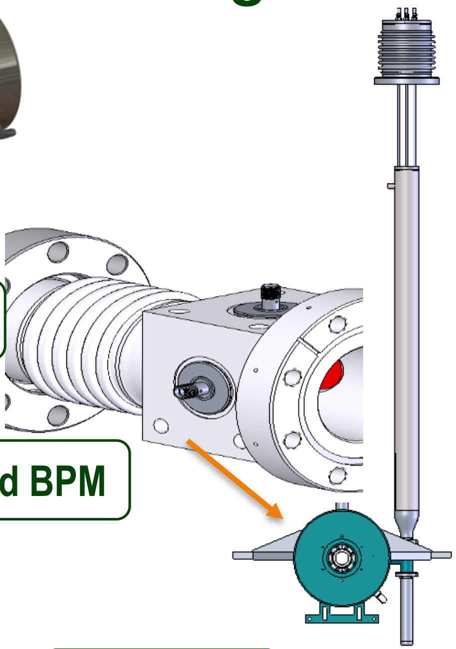
- Resonators (2 K) and magnets (at 4.5 K) supported from the bottom to facilitate alignment
- Cryogenic headers suspended from the top for vibration isolation



Superconducting RF

FRIB Subsystems: Resonators, Couplers, Tuner, Mechanical Damper, Solenoids, BPMs, Shieldings

QWR & HWR Cavities



QWR & HWR Cavities

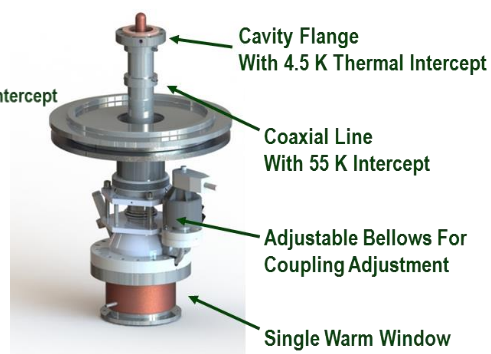
Cold BPM

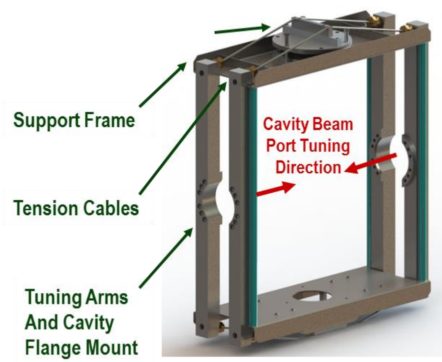
QWR Coupler

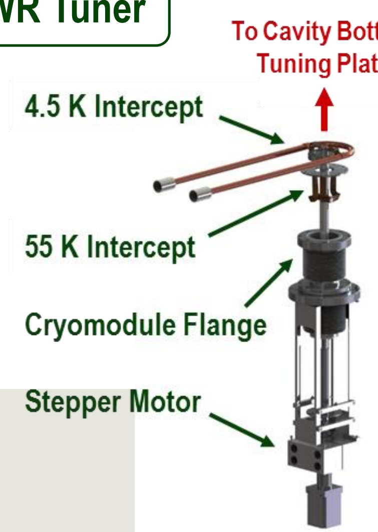
HWR Coupler

HWR Tuner

QWR Tuner

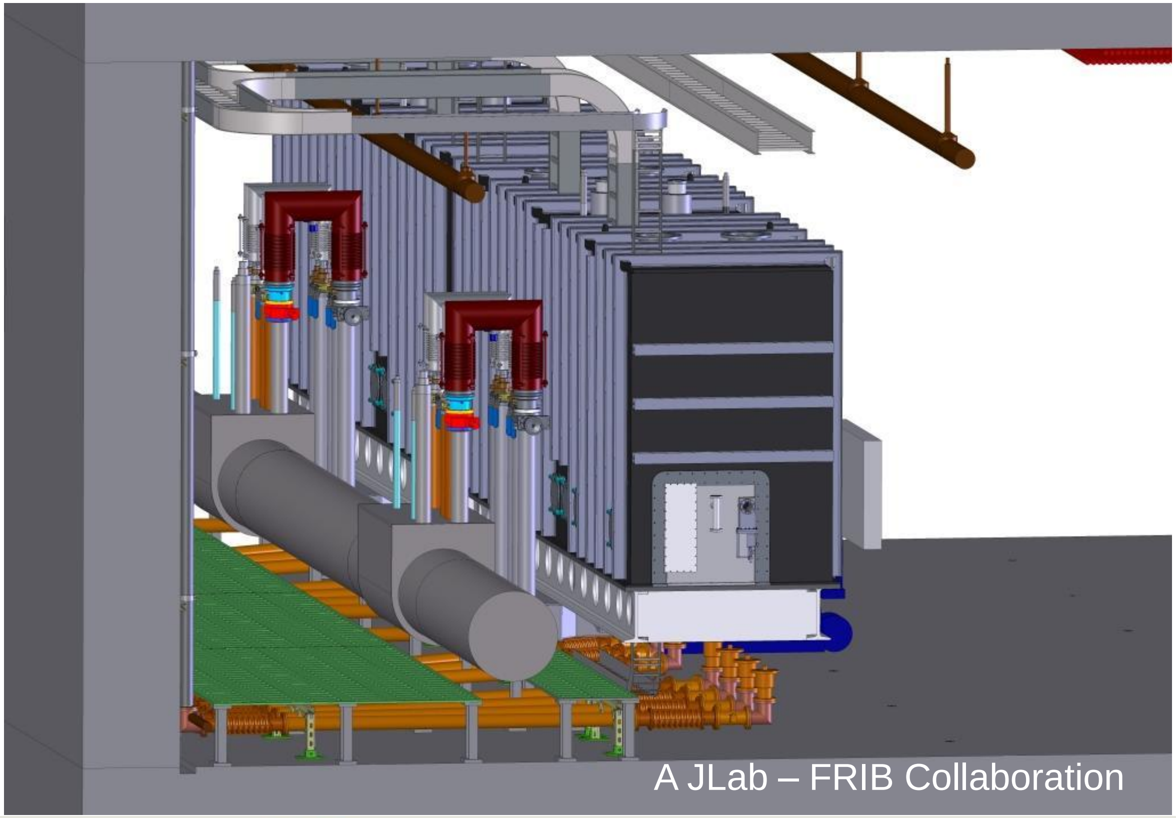






Integrated Cryogenics
Extending the SNS Practice to FRIB

- Cost significant: cryogenics systems accounts for ~ 20% linac cost
- An integrated design of the cryogenic refrigeration, distribution, and cryomodule systems is key to efficient SRF operations.



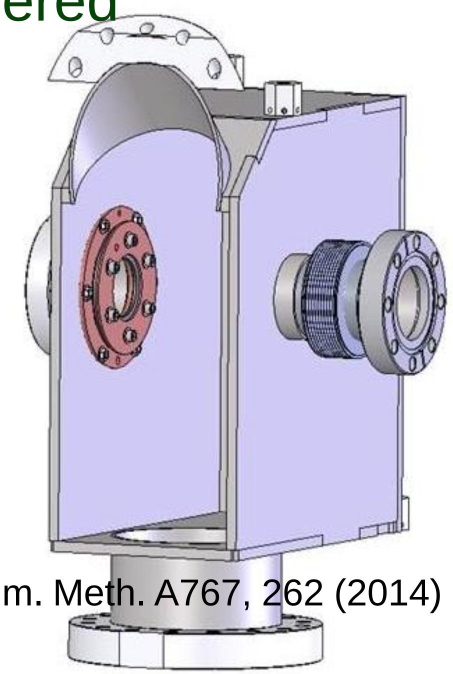
- Ganni cycle: floating pressure process
- Distribution lines segmented
- Cryomodules connected with U-tubes: maintenance
- 4-2 K heat exchangers housed inside cryomodules

Loss Detection and Machine Protection
Multi-time Scale Mitigation Necessary

- Low-energy ions has low detection sensitivity & high impact
- Must mitigate both acute & chronicle beam loss (by beam inhibition)

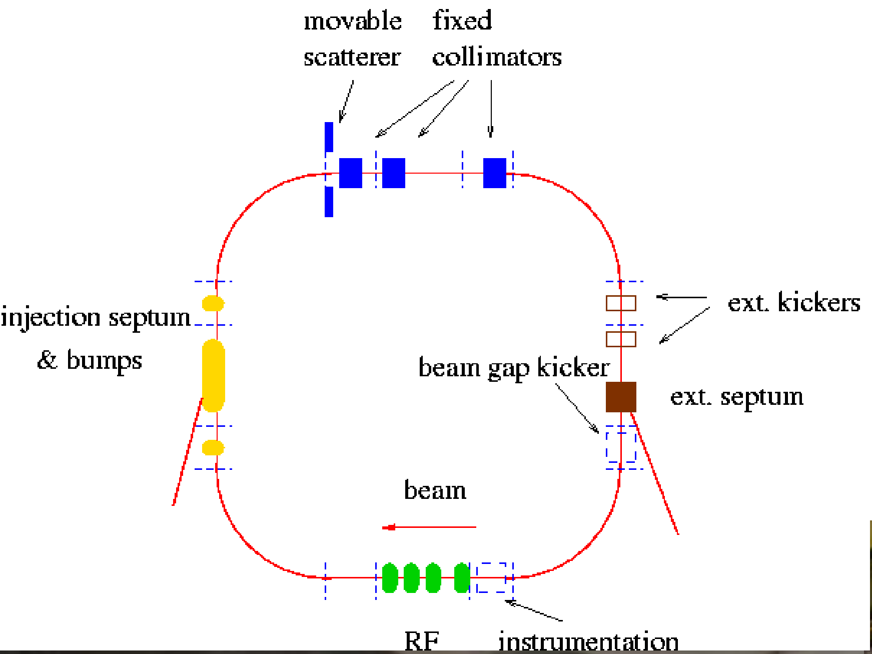
Mode	Time	Detection	Mitigation
FPS	~ 35 μs	LLRF controller; Dipole current monitor; Differential BCM; Ion chamber monitor; Halo monitor ring; Fast neutron detector; Differential BPM	LEBT bend electro-static deflector
RPS (1)	~ 100 ms	Vacuum status; Cryomodule status; Non-dipole PS; Quench signal	As above; ECR source HV
RPS (2)	> 1 s	Thermo-sensor; Cryo. heater power	As above

- Halo monitor rings in development
- Differential BCM used
- Thermo-sensors considered



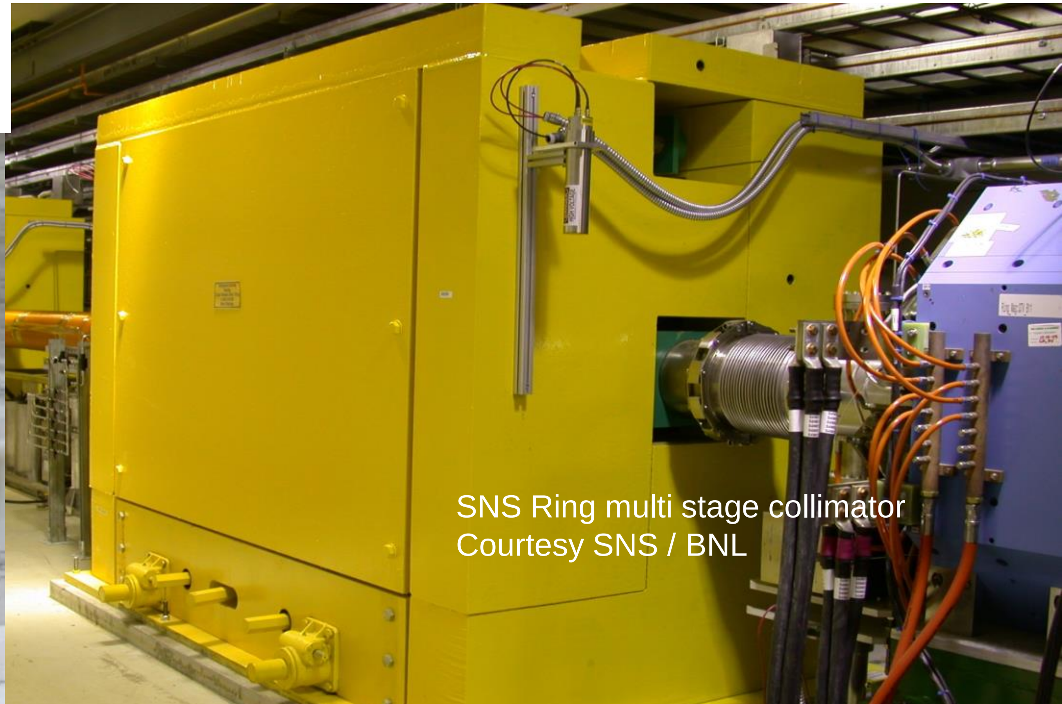
Z. Liu et al, Nucl. Instrum. Meth. A767, 262 (2014)

Beam Collimation
Halo & Beam Loss Control; Charge Selection



- Ring: 3D phase space collimation; multi-stage in transverse direction
  - SNS: dedicated collimation straight section
- Linac & transport: often combines with charge stripping
  - Heavy ion linac: charge selector

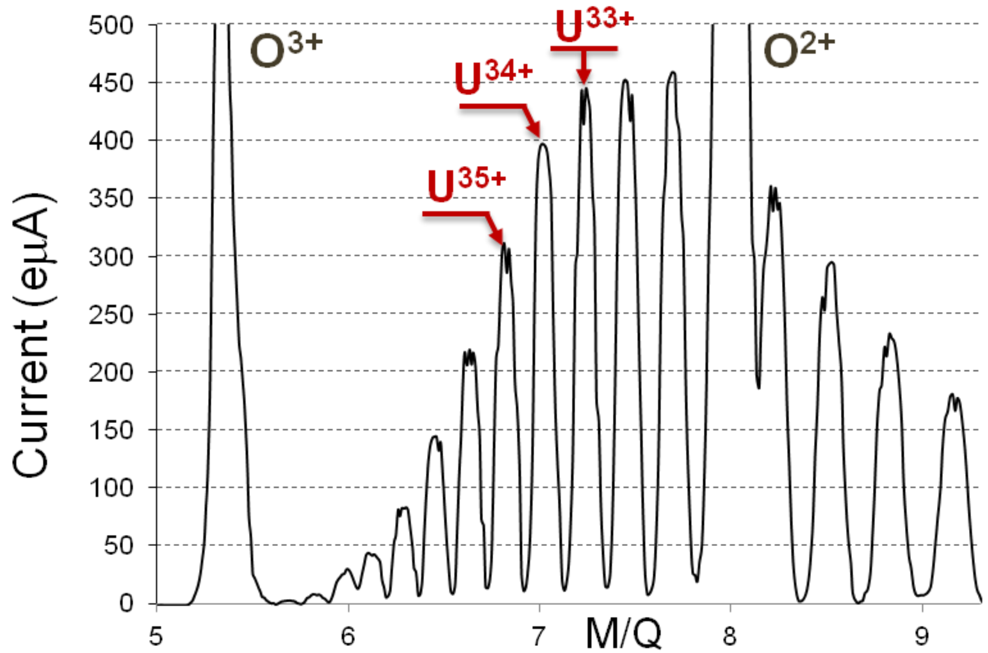
SNS Ring primary scraper
Courtesy SNS / BNL



SNS Ring multi stage collimator
Courtesy SNS / BNL

Ion Source

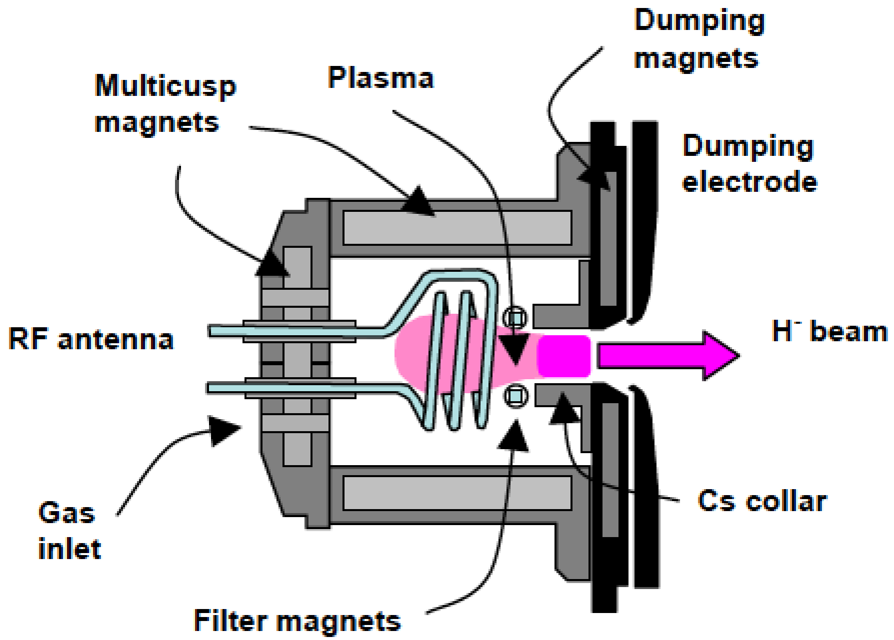
Sources for High Intensity/Duty Ions and for Pulsed H$^-$



LBNL VENUS ECR ion source test result
Courtesy: LBNL

- ECR source for high intensity (CW), high charge state beams
- Higher RF frequency and magnetic field (~28 GHz; RF power ~15 kW)
- SC sextupole & solenoid state-of-the-art SC technology

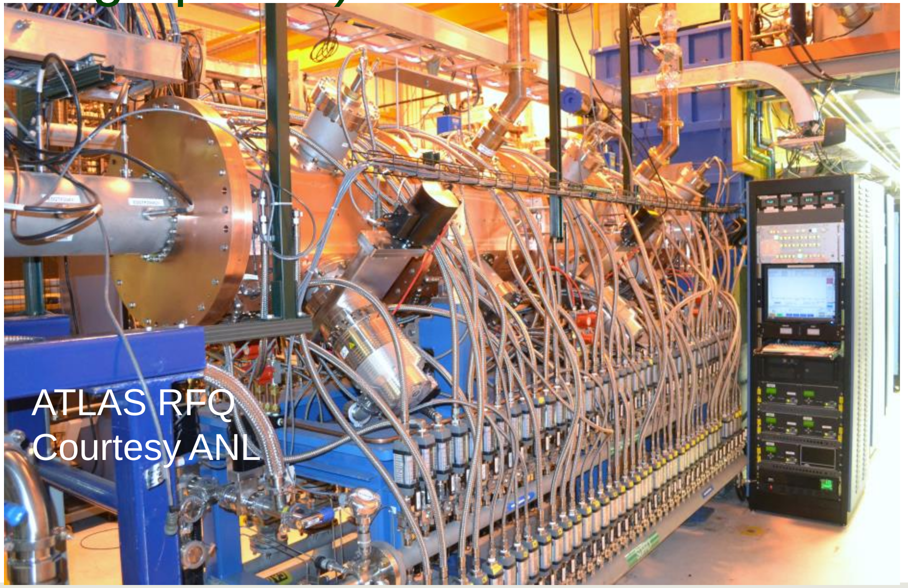
- Cesium-seeded, volume production sources are most promising for high current, long pulse, low emittance H$^-$ beams



Courtesy: ORNL / LBNL / SNS

RFQ
Extending LEDA Technology to Heavy Ions

- LEDA RFQ holds the power record accelerating 100 mA CW proton beam to 6.7 MeV (4-vane, variable voltage profile)
- Challenging mechanical / cooling design and fabrication process
- RFQ with trapezoidal vane modulation built/tested at ANL
- Heavy ion RFQ: low frequency, large dimension



RFQs Developed Worldwide

CPHS RFQ
Courtesy Tsinghua Univ.

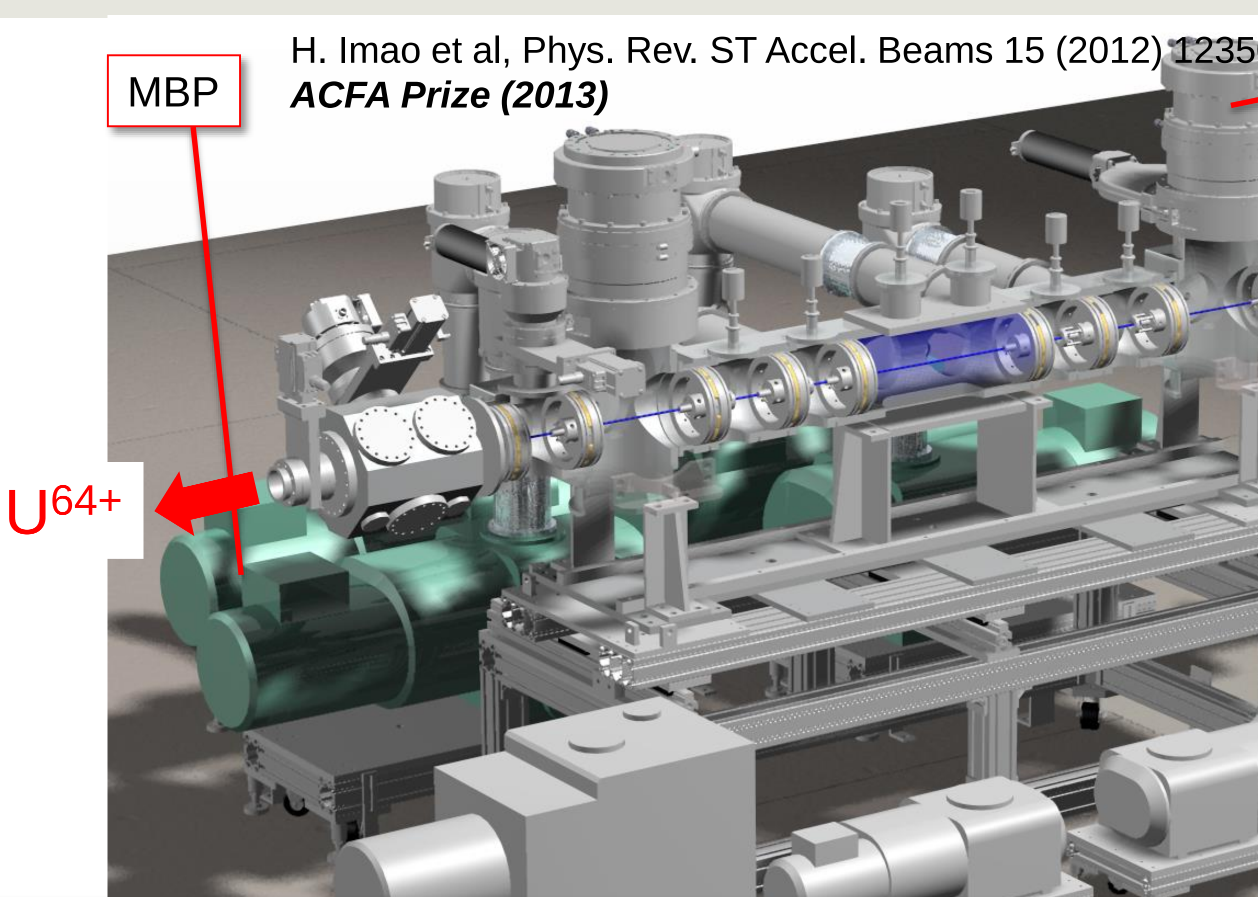
CADS ECR, LEBT, RFQ
Courtesy IMP

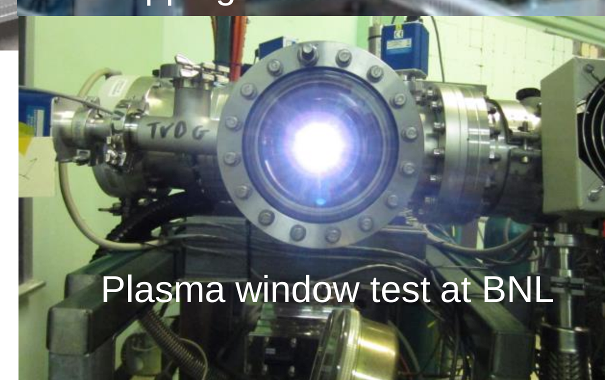
Charge Stripping: Heavy Ion

He Gas stripper for U @ 11 MeV/u; Plasma Window Test

H. Imao et al, Phys. Rev. ST Accel. Beams 15 (2012) 123501

ACFA Prize (2013)





- Large beam aperture: > ϕ 10 mm
- 8 order pressure reduction: 7,000 Pa => 10^{-5} Pa
- 5 stage differential pumping: 21 pumps
- He circulating volume: 300 m^3/day

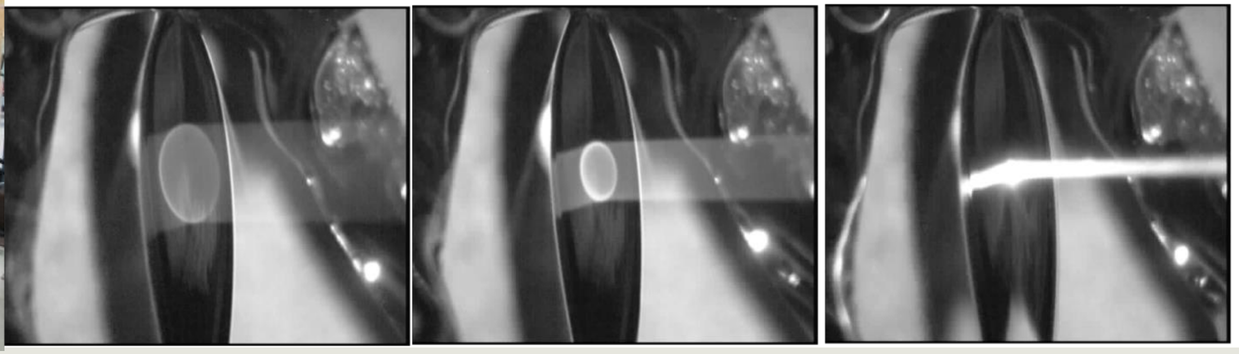
Plasma window successfully tested at BNL

- To ease the challenge of differential pumping

Charge Stripping: Heavy Ion
Liquid Lithium Film Tested with LEDA Source at ANL

- Liquid lithium film established with controllable thickness and uniformity
  - Liquid lithium film moving at ~50 m/s speed to remove deposited heat
  - Controlling uniformity to ~10% within beam spot area
- Beam power tests on liquid lithium film successfully performed at ANL
  - The film sustained ~200% of FRIB maximum power density deposition

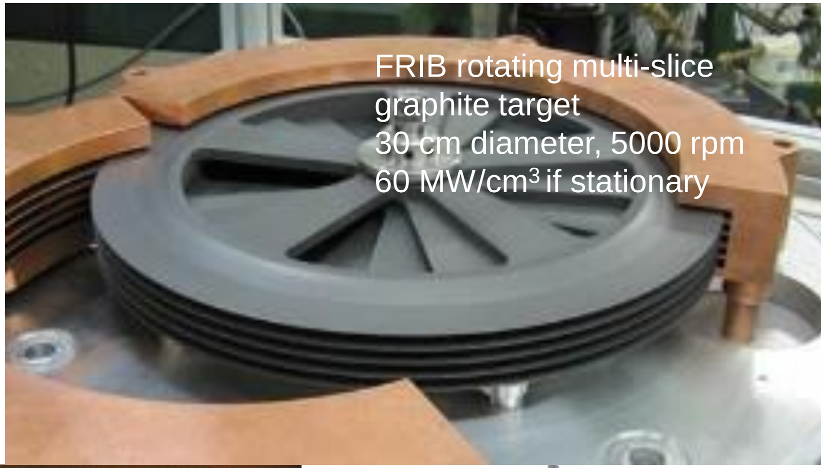
Liquid lithium film flowing at high speed (~ 50 m/s) intercepting a proton beam of about 60 kV at ANL. The test produced power deposition densities similar to the FRIB uranium beams.

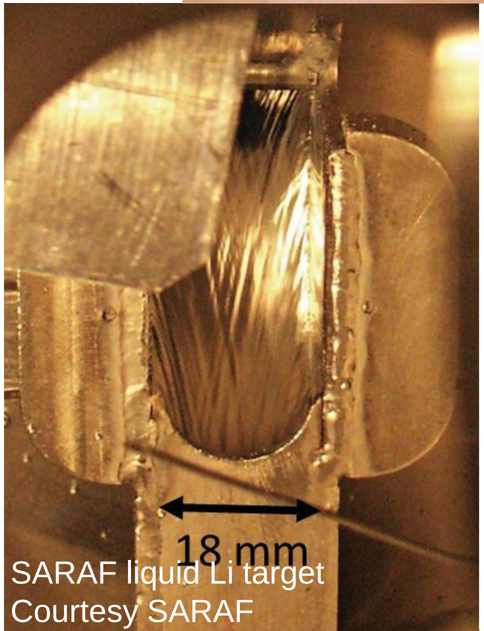


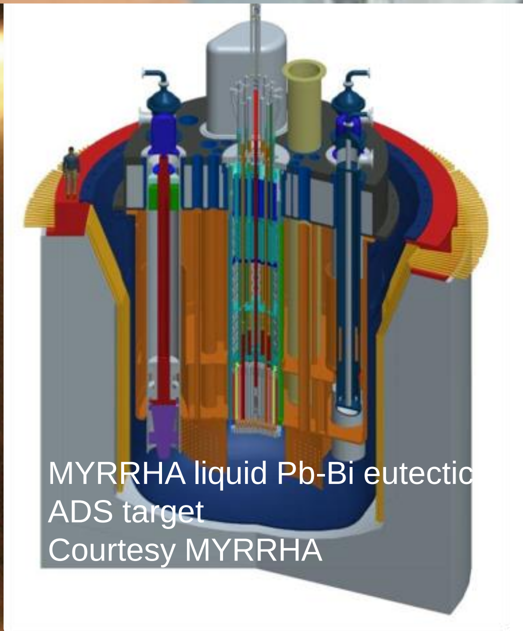
Target

Stationary, Rotating and Liquid Targets

- Target is often the bottleneck to high power applications
  - Neutron production targets: absorbs most beam power to an enlarged area
  - RIB target (FRIB): ~25% power onto 1 mm
  - High energy targets: < 5% power absorbed
- Non-stationary targets more often used
  - Liquid:
    - SNS, J-PARC: Hg
    - SARAF, IFMIF: Li
    - MYRRHA: PbBe
  - Rotating
    - FRIB …



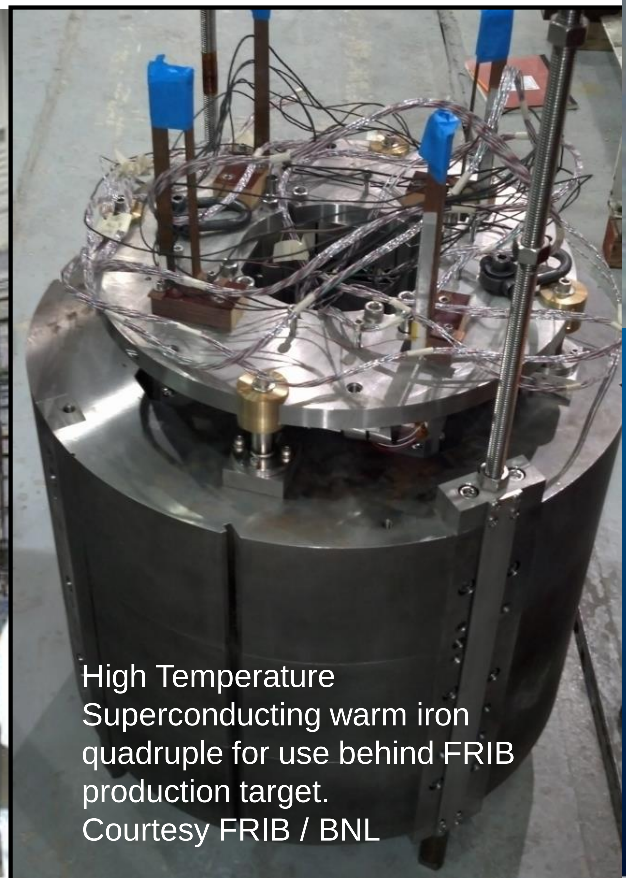




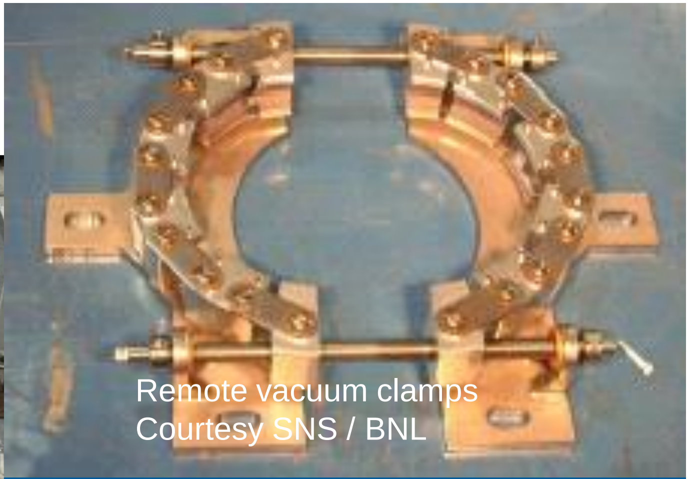
Radiation-resistant Magnets, Handling

- High radiation area near the target, collimator, beam dump require special attention

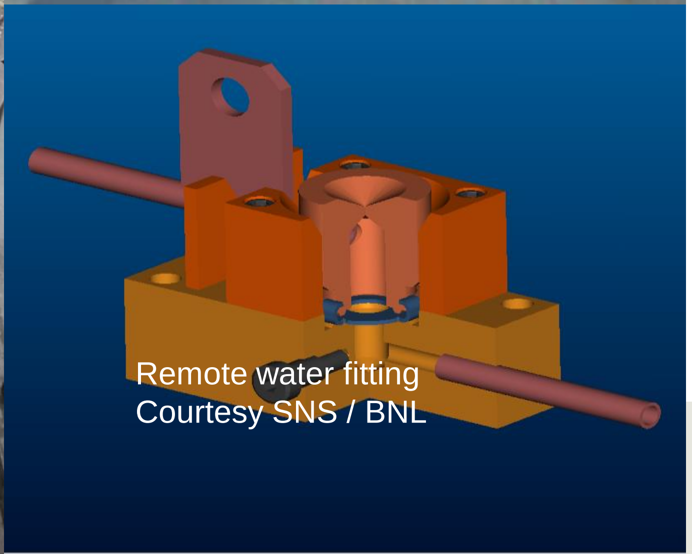
SNS RTBT mineral insulated radiation hardened magnets
Courtesy SNS / BNL



High Temperature Superconducting warm iron quadruple for use behind FRIB production target.
Courtesy FRIB / BNL



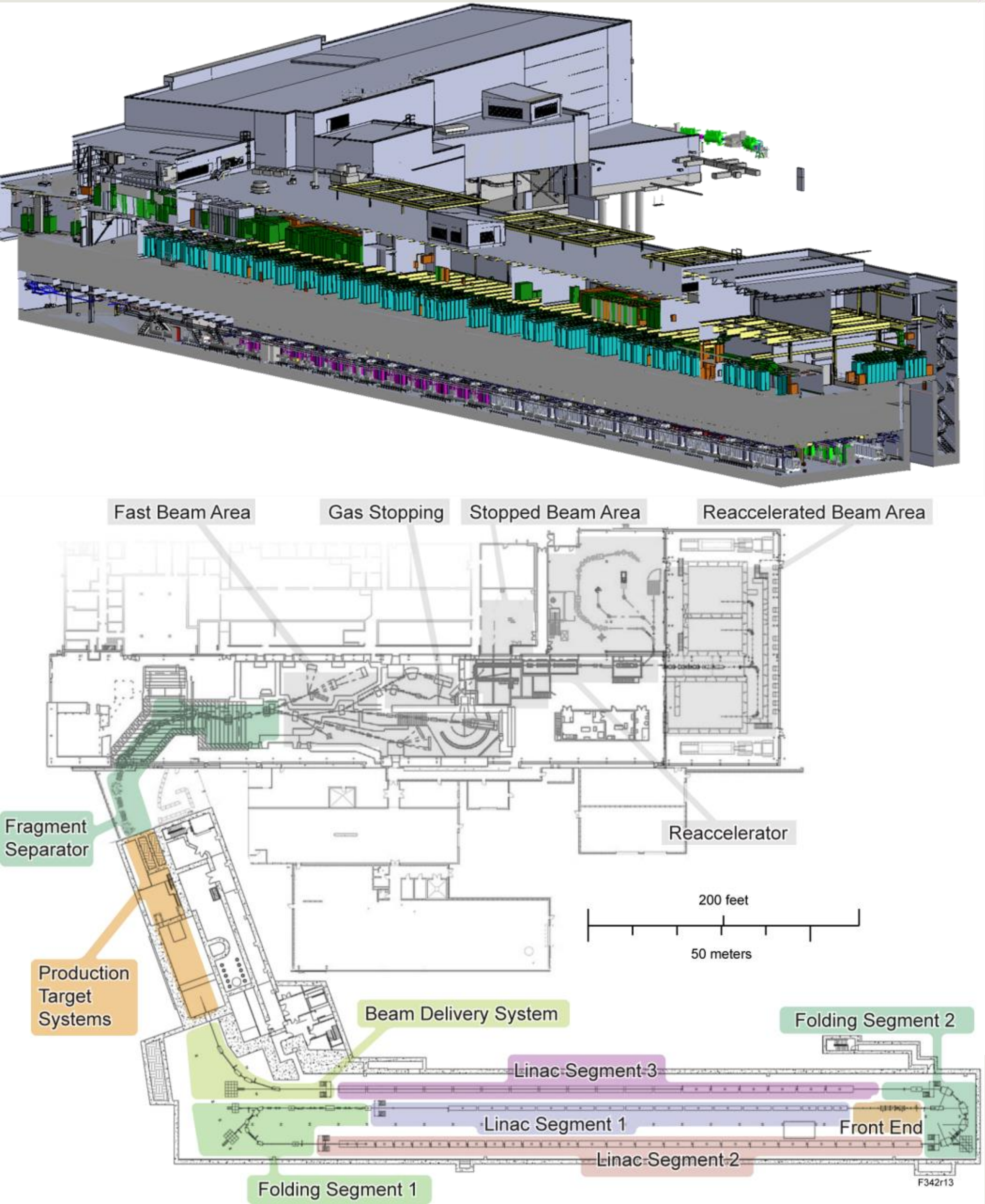
Remote vacuum clamps
Courtesy SNS / BNL



Remote water fitting
Courtesy SNS / BNL

Site Specific Complications

FRIB Sited in the Middle of University Campus



- Folder linac with 2^{nd} order achromat bends for wide momentum acceptance
- Beam loss at high energy interferes with loss detection of low-energy beams
- Hazard analysis upon beam faults complicated; installation and commissioning interlaced
- Vibration mitigation: linac service/utility area and cryogenics area are near the accelerator tunnel housing cryomodules

Design Challenge Examples

- Beam Loss Control
- Space Charge
- Multiple Charge State Acceleration

Beam Loss Control
Key to High-power Accelerator Design and Operations

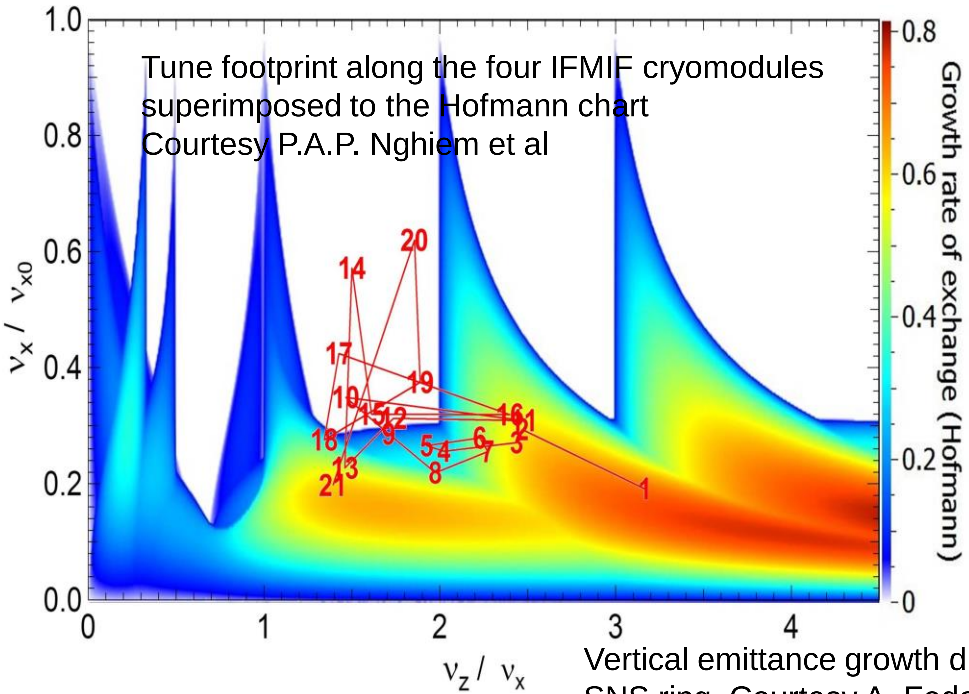
- Hands-on maintenance:
  - Proton: uncontrolled beam losses kept below ~ 1 W/m (activation ~ 1 mSv/h; 30 cm from surface; 4 h after machine shut down)
  - Heavy ion: ~ 1 W/m   (less stringent in activation but more demanding in machine protection; similar cryogenic heat load considerations)
- Personnel protection: commissioning, operation & fault conditions

Type and location	Energy [MeV/u]	Peak power	Duty factor
Uncontrolled loss	0 – 200	~1 W/m	100%
Controlled loss:			
Charge selector	12 – 20	42 kW	100%
Charge stripper	12 – 20	~1 kW	100%
Collimators	0 – 200	~1 kW	100%
Dump FS1-a	12 – 20	42 kW	0.03%
Dump FS1-b	12 – 20	12 kW	5%
Dump FS2	15 – 160	300 kW	0.03%
Dump BDS	150 – 300	400 kW	0.03%

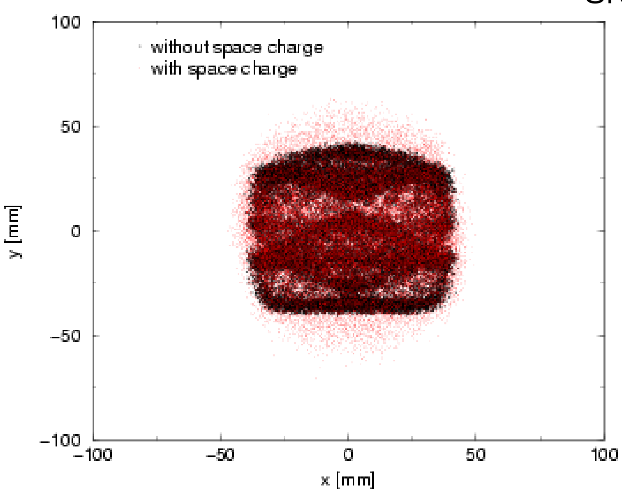
Space Charge

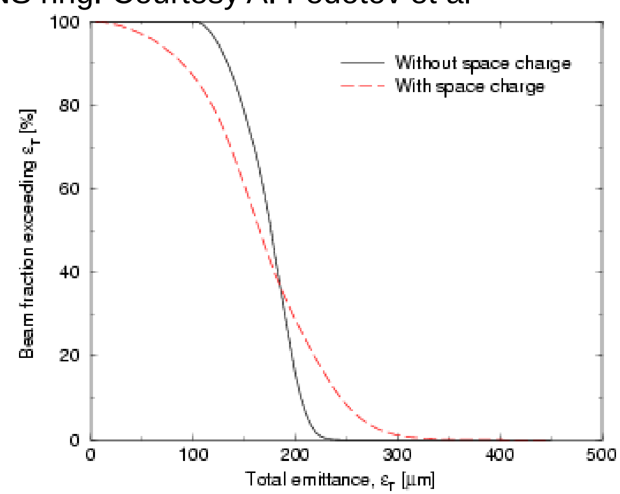
Performance Limiting for Low-energy Linac and Rings

- Linac: halo generated through core-halo parametric resonance; resonances between transverse longitudinal motion
- Ring: resonances & halo excited by lattice nonlinearity in the presence of space charge induced tune spread

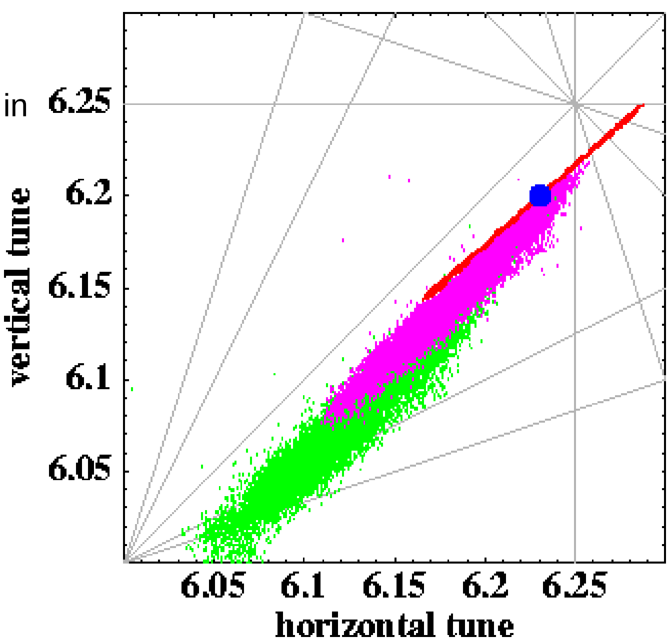


Tune footprint along the four IFMIF cryomodules superimposed to the Hofmann chart
Courtesy P.A.P. Nghiem et al





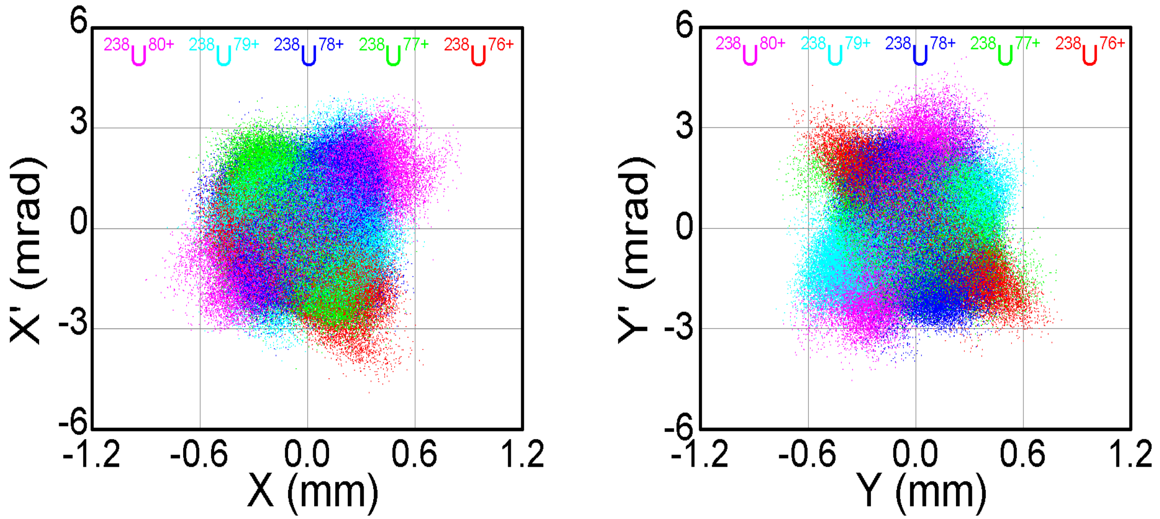
Vertical emittance growth due to space charge in SNS ring. Courtesy A. Fedotov et al



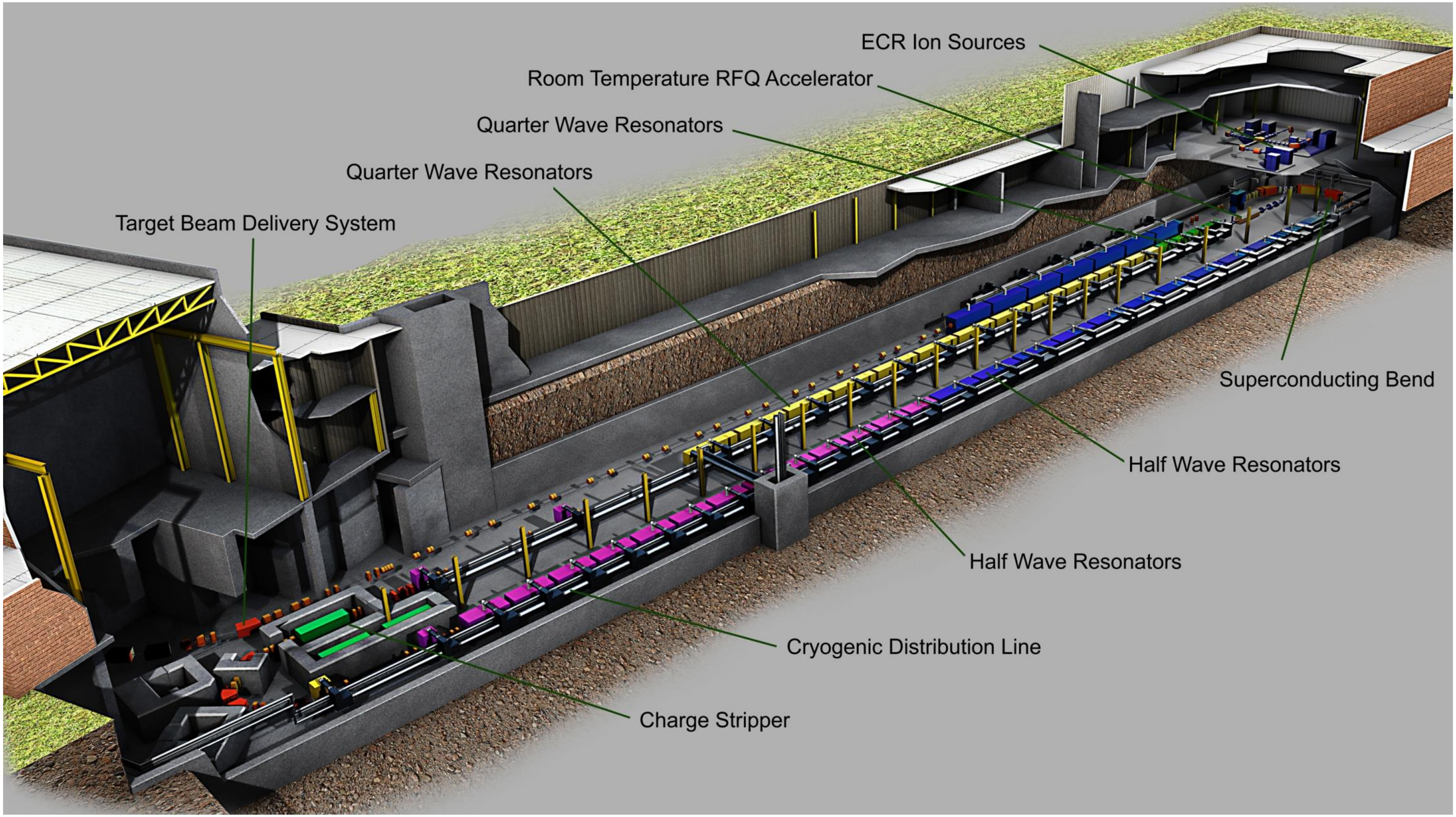
Multiple Charge State Acceleration
Demanded for Heavy Ions to Achieve High Power on Target

- Simultaneous acceleration of multiple charge state needed due to the broad charge spectrum upon stripping
- Challenges in optics design, diagnostics, fault recovery

Five charge states of the uranium beam designed to overlap at the FRIB target.



FRIB Project Status

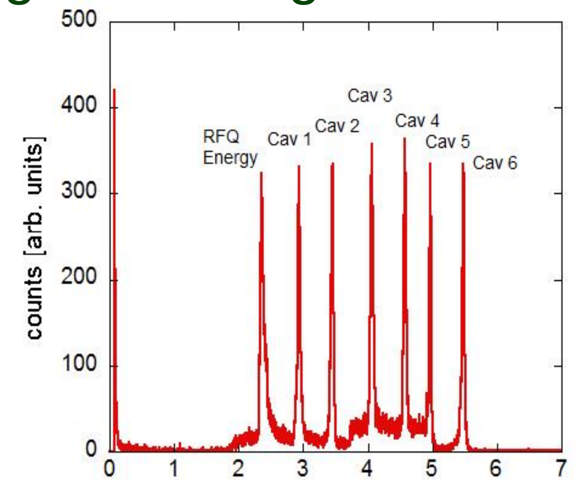


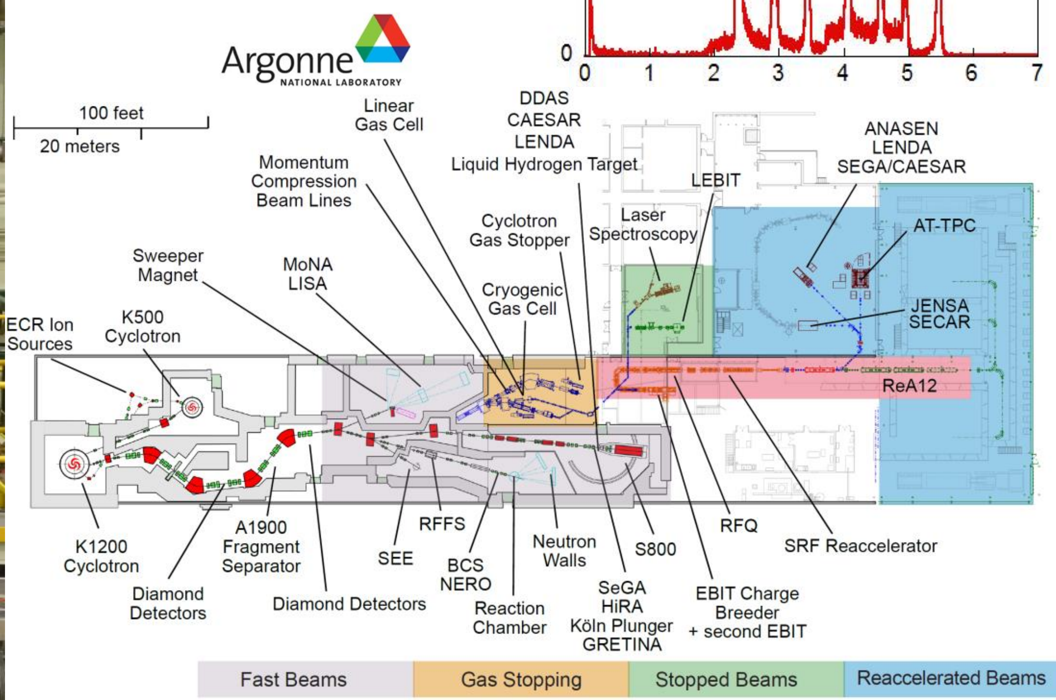
FRIB Accelerator Design Philosophy

- A full-energy linac driver to provide beam quality that user desires
  - Full-scale CW linac using superconducting RF low-β cavities
- Meet stringent requirements demanded by experimental programs
  - Up to 400 kW of beams are focused to a diameter of 1 mm (90%)
  - Energy spread of 1% (95% peak-to-peak), and bunch length of < 3 ns
  - Intensity range of 10^8 – diagnostics & controls requirements
- Support FRIB as a national scientific user facility
  - Availability
  - Maintainability
  - Reliability
  - Tunability
  - Upgradability

Cryomodule Performance Demonstrated: Rare Isotope ^{76}Ga Produced and Accelerated

- Superconducting cyclotrons accelerate ^{76}Ge beam to 130 MeV/u; ^{76}Ga produced; stopped in the ANL gas cell; Charge Breeding in the EBIT Source
- Re-acceleration in the ReA accelerator
  - Using Radio Frequency Quadrupole (RFQ) and β=0.041 cryomodules
- SRF technology mature for FRIB project

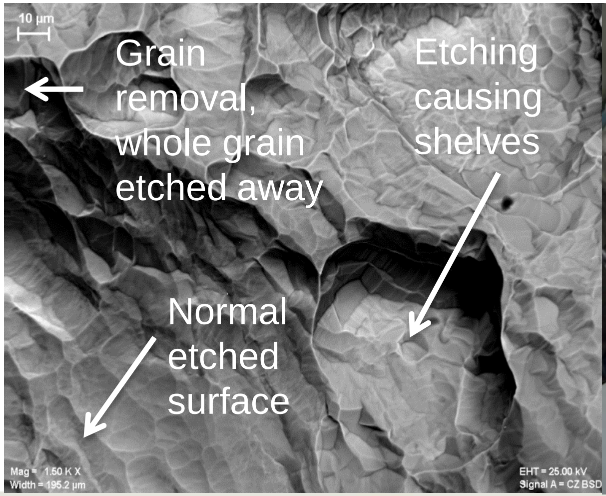




100% Acceptance Rate on Niobium Material

Received > 60% of the All Orders from 3 Industrial Providers

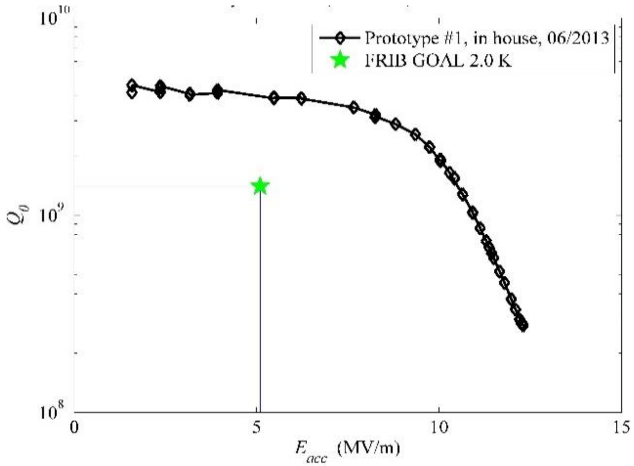
- Resolving issues before suspected product is shipped; complete transparency
- Promptly helping vendor mitigating issues: niobium pitting example
  - Environmental Scanning Electron Microscope (ESEM) and Orientation Imaging Microscope (OIM) analysis
  - Confirmed by eddy-current scans
  - Vendor visit & quality control plan in place
- Maintaining close working relationship with vendor
  - Share risks and interests with vendor, implementing due quality processes
  - Being flexible under a win-win situation: tube inner surface finish example



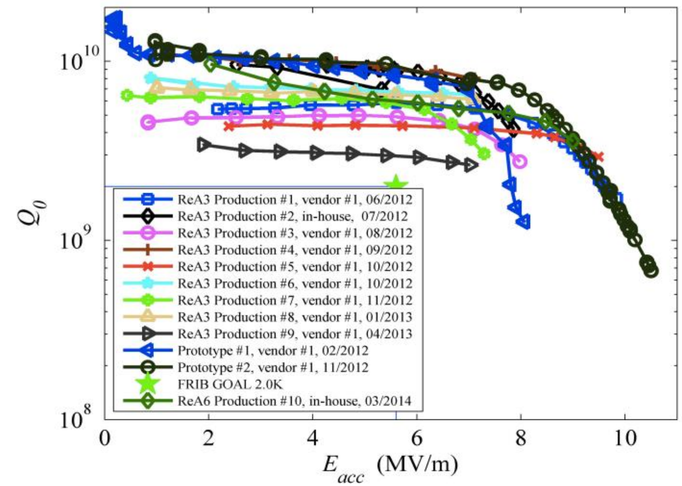

Nb sheet inspection at the vendor site

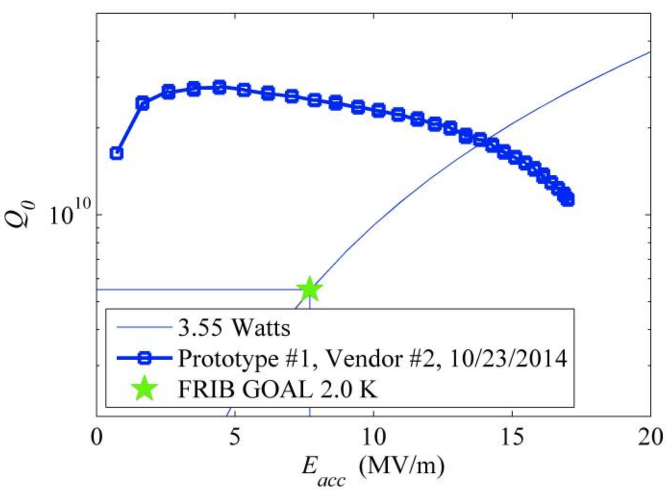

Nb materials delivered to MSU

All Type SRF Cavities Exceed FRIB Goals
Procured From 4 Industrial Vendors for Reduced Risk

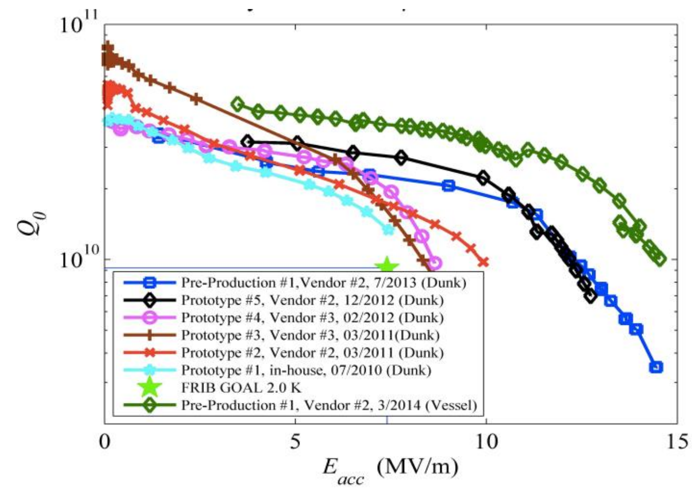


β_0 = 0.041 β_0 = 0.085
Quarter-Wave Resonators
80.5 MHz





β_0 = 0.29 β_0 = 0.53
Half-Wave Resonators
322 MHz



Working with the Best in the Nation and World

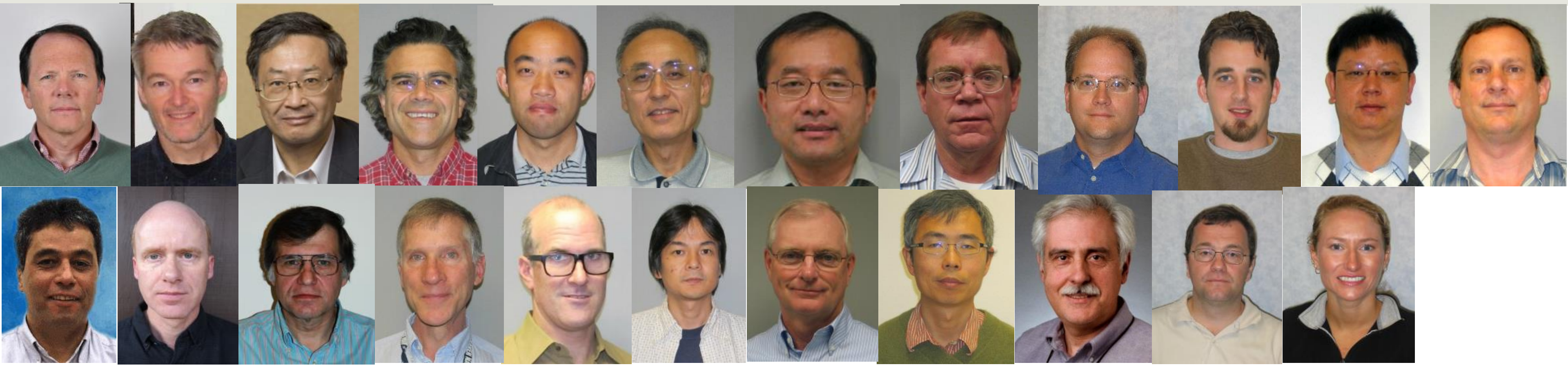
20 Work-for-Others Agreements

- Argonne National Laboratory (1+4*)
  - Liquid lithium charge stripper; Stopping of ions in gas; Fragment separator design; Beam dynamics; SRF
- Brookhaven National Laboratory (3)
  - Radiation resistant magnets; Plasma charge stripper*
- Fermilab (1)
  - Diagnostics
- Jefferson Laboratory (2+2*)
  - Cryogenics; SRF
- Lawrence Berkeley National Laboratory (1+2*)
  - ECR ion source; Beam dynamics*
- Oak Ridge National Laboratory (2)
  - Target facility; Beam Dump R&D; Cryogenic Controls
- Stanford National Accelerator Lab. (2*)

* complete

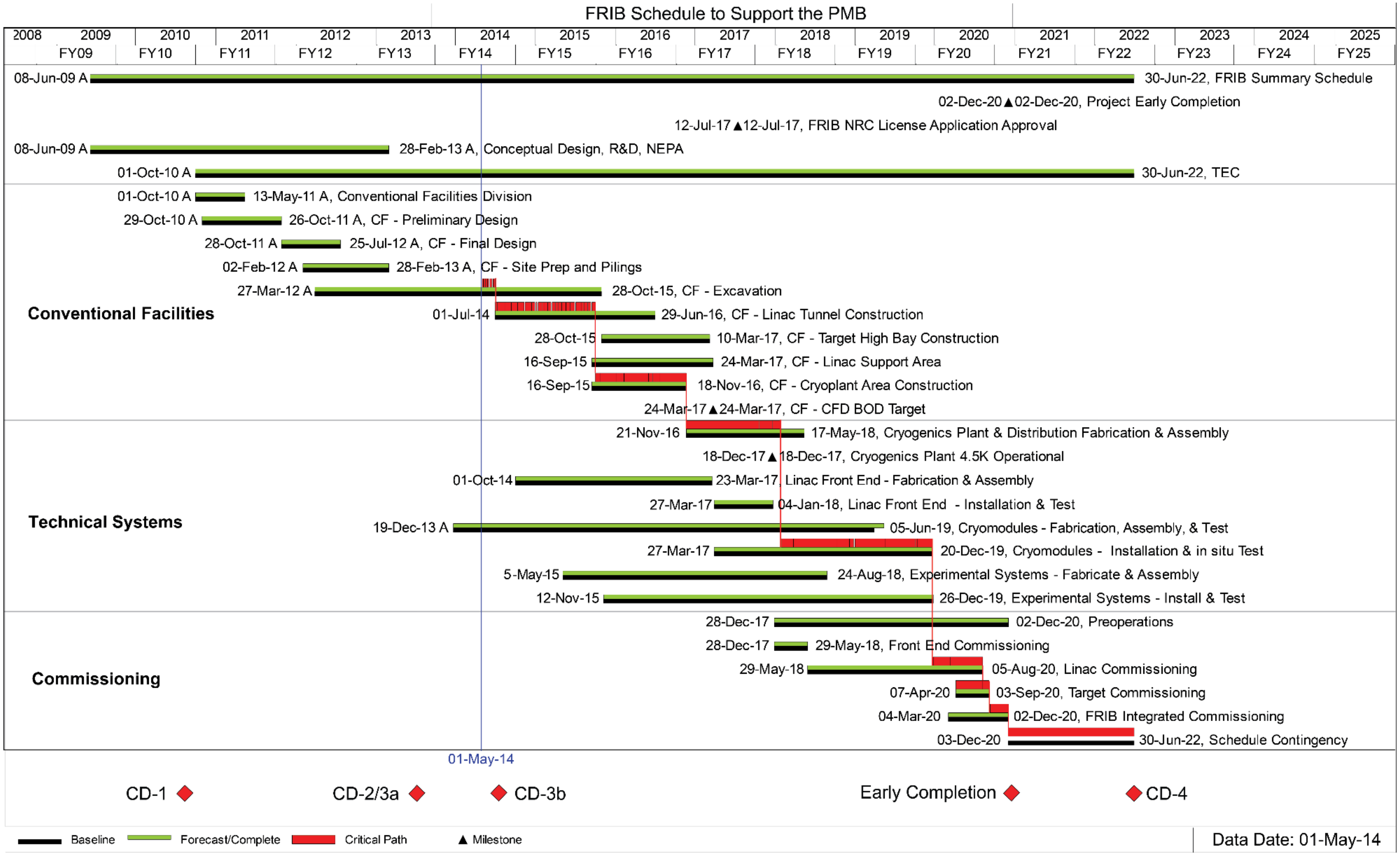
- Budker Inst. of Nuclear Physics (Russia)
  - Production target, diagnostics
- GANIL (France)
  - Production target
- GSI (Germany)
  - Production target
- INFN Legnaro (Italy)
  - SRF
- KEK (Japan)
  - SRF technology, SC solenoid magnets
- RIKEN (Japan)
  - Charge strippers
- Sandia
  - Production target*
- Soreq (Israel)
  - Production target*
- Tsinghua University & CAS (China)
  - RFQ
- TRIUMF (Canada)
  - SRF, beam dynamics

Attracted World Experts in Key Areas
Aggressively Strengthened Technical Team Leadership



- Grouping of seasoned leaders in accelerator physics and engineering
  - H. Ao (JAEA), N. Bultman (LANL), F. Casagrande (ORNL), A. Facco (INFN), F. Feyzi (Wisconsin U.), A. Ganshin (Cornell U.), L. Hoff (BNL), K. Holland (NSCL), M. Ikegami (KEK), S. Lidia (LBNL), S. Lund (LLNL), F. Marti (NSCL), D. Morris (NSCL), S. Peng (SLAC), L. Popielarski, E. Pozdeyev (BNL), T. Russo (BNL), K. Saito (KEK), G. Shen (BNL), S. Stark (INFN), B. Webber (FNAL), J. Wei (BNL), T. Xu (ORNL), Y. Yamazaki (J-PARC), Y. Zhang (ORNL) …

FRIB Schedule and Critical Path



Future Perspective

- Accelerator projects at the high-intensity frontier are flourishing worldwide with demands from science to applications
- Efforts worldwide are readying the technologies and designs meeting the requirements of user facilities with high reliability, availability, maintainability, tunability, and upgradability
- Heavy ion machines are joining the crowd towards MW power level
- For protons applications, we speculate to reach multi MW beam power using cyclotrons, synchrotrons or accumulators, and up to 100 MW with SRF linacs

Table 1: Major parameters of some proton and heavy ion accelerators at design, construction, and operation stage.

Project	Status	Primary Beam	Sec. Beam	Accel. Type	f_{rep} [Hz]	Beam Duty	Target Type	Energy [MeV/u]	Ave. Power [MW]
AGS	Achieve	p	μ, K	LN/SR	0.5	5e-7;.5 ^{t}	Ni; Pt	24000	0.1
SPS	Achieve	p	ν	LN/SR	0.17	3.5e-6 ^{t}	C	450000	0.5
	Goal	p	ν	LN/SR	0.17	3.5e-6	C	450000	0.75
MI	Achieve	p	ν	LN/SR	0.75	1.e-5 ^{t}	C	120000	0.4
	Goal	p	ν	LN/SR	0.75	1.e-5 ^{t}	C	120000	0.7
J-PARC	Achieve	p	ν, K, π	LN/SR	0.4;0.16	2e-6;.3 ^{t}	C; Au	30000	0.2; 0.02
MR	Goal	p	ν, K, π	LN/SR	1; 0.16	5e-6;.3 ^{t}	C; M ^{r}	30000	0.75; > 0.1
RIKEN	Achieve	d to U	RIB	LN/CY	CW	1	Be	345-400	0.007-0.002
	Goal	d to U	RIB	LN/CY	CW	1	Be	345-400	0.08 (U)
PSI	Achieve	p	n, μ	CY	CW	1	C ^{r}, Pb	590	1.4
	Goal	p	n, μ	CY	CW	1	C ^{r}, Pb	590	1.8
SNS	Achieve	p	n	LN/AR	60	0.06 ^{i}	Hg ^{l}	>940	1.3
	Goal	p	n	LN/AR	60	0.06 ^{i}	Hg ^{l}	1300	2.8
J-PARC	Achieve	p	n, μ	LN/SR	25	0.02 ^{i}	Hg ^{l}	3000	0.3
RCS	Goal	p	n, μ	LN/SR	25	0.02 ^{i}	Hg ^{l}	3000	1
LANSCE	Achieve	p, H^-	π, μ, n	LN	100	0.15	C ^{r}	800	0.8
PSR	Achieve	p	n	LN/AR	20	0.08 ^{i}	W	800	0.08
ISIS	Achieve	p	n, μ	LN/SR	40; 10	0.01 ^{i}	W	800	0.16; 0.04
	Goal	p	n, μ	LN/SR	40; 10	0.01 ^{i}	W	800	0.45; 0.05
SARAF	Achieve	p; d	n; -	LN	CW; 1	1	SST;Li ^{l}	3.9; 2.8	0.0039; -
	Goal	p, d	n, RIB	LN	CW	1	Li ^{l}; Be	40; 20	0.2
KOMAC	Achieve	p	-	LN	10	0.005	-	100	0.01
	Goal	p	-	LN	60	0.08	-	100	0.16
FRIB	Constru.	p to U	RIB	LN	CW	1	C ^{r}	>200	0.4
FAIR	Constru.	p to U	RIB, $\bar{p}$	LN/SR	0.2;0.5	<0.25 ^{i}	M ^{r}; Ni	1e3;3e4	0.012;0.001
SPIRAL2	Constru.	p,d,A/q≤3	RIB, n	LN/CY	CW	1	C ^{r}	33,20,14	0.2,0.2,0.04
CSNS	Constru.	p	n	LN/SR	25	0.01 ^{i}	W	1600	0.1
LIPAc	Constru.	d	n	LN	CW	1	Li ^{l}	4.5	1.1
PIP-II	Design	p	ν, μ	LN/SR	15	0.15 ^{i}	C; Al	1e5; 800	1.2; 0.1
ESS	Design	p	n	LN	14	0.04	W ^{r}	2000	5
IFMIF	Design	d	n	LN	CW	1	Li ^{l}	20	2 x 5
CADS	Design	p	n	LN	CW	1	G+He	1500	15 – 30
MYRRHA	Design	p	n	LN	CW	1	Pb-Bi ^{l}	600	1.5 – 2.4

Notation: LN for Linac; CY for Cyclotron; SR for Synchrotron; AR for Accumulator; C for graphite; M for metal; RIB for rare isotope beams; Superscripts r for rotating and l for liquid targets, i for linac beam duty and t for beam duty on target.

- Other operating or proposed projects include LEDA, PSR, HIAF, RAON, CPHS and those proposed at CERN (SPL, LAGUNA-LBNO, SHIP) and RAL

Coauthors

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Acknowledgements

- We thank D. Berkovits, Y.S. Cho, J. Erickson, R. Ferdinand, S. Fu, J. Galambos, R. Garoby, V. Ganni, R. Garnett, F. Gerigk, E. Gschwendtner, S. Henderson, S. Holmes, O. Kamigaito, O. Kester, J. Knaster, T. Koseki, M. Lindroos, P. Nghiem, K. Oide, S. Ozaki, M. Plum, T. Roser, M. Seidel, A. Taylor, J. Thomason, D. Vandeplassche, H. Zhao, F. Zimmermann for information and advice.

- We thank the FRIB Accelerator Systems Advisory Committee chaired by S. Ozaki for their valuable guidance, colleagues who participated in FRIB accelerator peer reviews including A. Aleksandrov, G. Ambrosio, D. Arenius, W. Barletta, G. Bauer, G. Biallas, J. Bisognano, S. Bousson, S. Caspi, M. Champion, M. Crofford, D. Curry, R. Cutler, B. Dalesio, G. Decker, J. Delayen, N. Eddy, H. Edwards, J. Error, J. Fuerst, K. Kurukawa, J. Galambos, J. Galayda, G. Gassner, J. Gilpatrick, C. Ginsburg, S. Gourlay, M. Harrison, S. Hartman, S. Henderson, G. Hoffstaetter, J. Hogan, S. Holmes, M. Howell, R. Kersevan, N. Holtkamp, H. Horiike, C. Hovater, D. Hseuh, H. Imao, R. Janssens, R. Keller, J. Kelley, P. Kelley, J. Kerby, A. Klebaner, J. Knobloch, R. Lambiase, M. Lamm, C. LoCocq, C. Luongo, K. Mahoney, J. Mammosser, T. Mann, W. Meng, N. Mokhov, Y. Momozaki, G. Murdoch, H. Okuno, R. Pardo, S. Peggs, T. Peterson, C. Piller, J. Power, T. Powers, J. Preble, D. Raparia, T. Roser, M. Ross, R. Ruland, J. Sandberg, R. Schmidt, W.J. Schneider, D. Schrage, I. Silverman, J. Sondericker, W. Soyars, C. Spencer, R. Stanek, M. Stettler, J. Stovall, Y. Than, J. Theilacker, J. Tuozzolo, V. Verzilov, R. Vondrasek, P. Wanderer, M. Wiseman, P. Wright, L. Young, and A. Zaltsman, and colleagues who advised and collaborated with the FRIB team including A. Burrill, A.C. Crawford, K. Davis, X. Guan, W. Hartung, K. Hosoyama, A. Hutton, S.H. Kim, P. Kneisel, K. Macha, G. Maler, E.A. McEwen, S. Prestemon, J. Qiang, T. Reilly, R. Talman, J. Vincent, X.W. Wang, Q.Z. Xing.

- The FRIB accelerator design is executed by a dedicated team of the FRIB Accelerator Systems Division with close collaboration with the Experimental Systems Division headed by G. Bollen, the Conventional Facility Division headed by B. Bull, the Chief Engineer's team headed by D. Stout, and supported by the project controls, procurements, ES&H of the FRIB Project, by the NSCL, and by the MSU.

- Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661

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