HIAT-12

Heavy Ion Superconducting Linacs: Status and Upgrade Projects

P.N. Ostroumov

Physics Division

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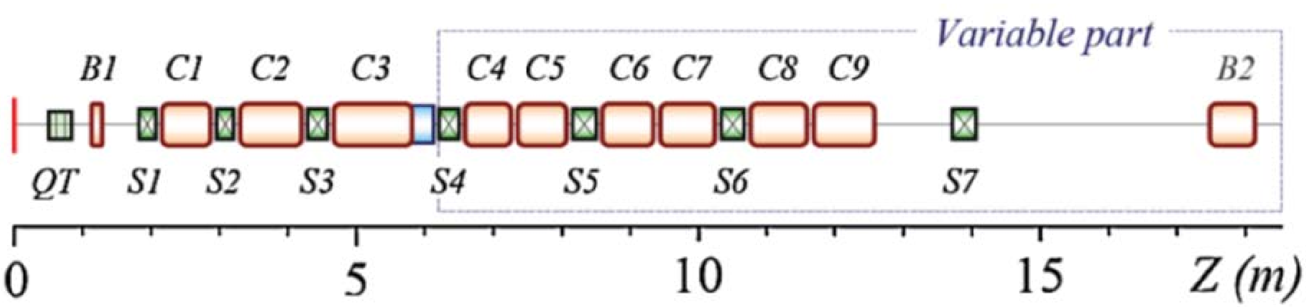
Content

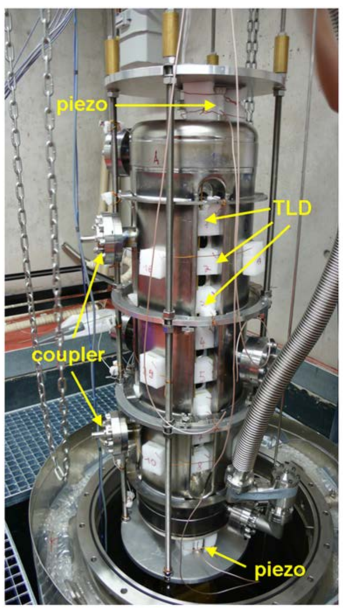
- New Projects and Upgrades
  - GSI (Germany)
  - LRF (Huelva University, Spain): ***new!***
  - RISP (Korea): ***new!***
  - HIAF (IMP, China): ***new!***
- ATLAS Upgrades
- CW RFQ for SC heavy-ion linacs
- SC Technology at ANL
  - Main steps for cavity construction
  - Cavity sub-systems
  - Performance: accelerating gradients and residual resistance
- Realistic design parameters for new SC linacs
- Application to SARAF Phase II
- Summary

GSI Upgrade: SC CW Linac

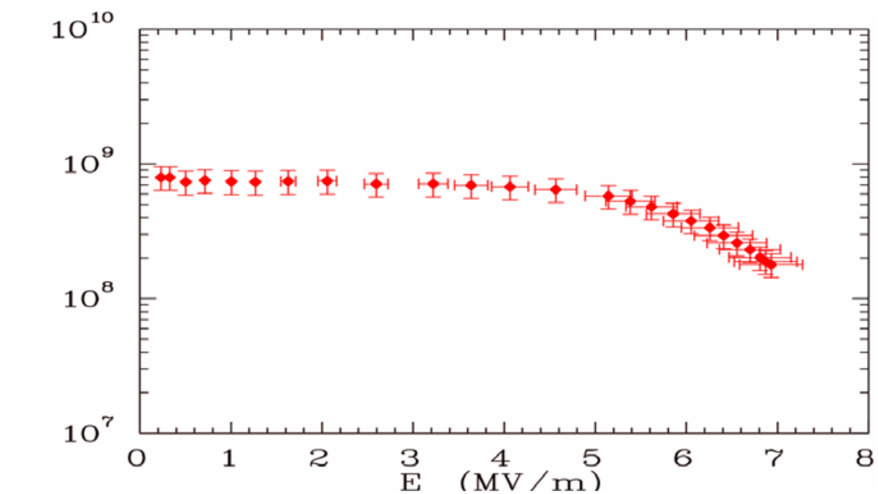
- Primary motivation is research in the field of Super Heavy Elements
- q/A=1/6, 1 mA ion beam, output energy is 7.5 MeV/u, variable from 3.5 MeV/u
- Multi-gap CH cavities, focusing by SC solenoids

Injector:
1.4 MeV/u, RFQ and IH



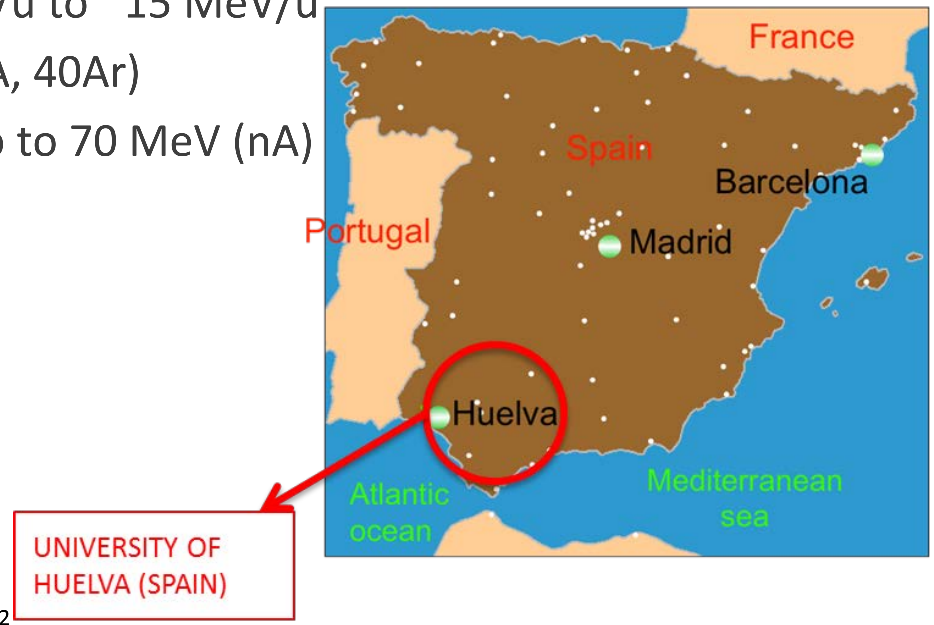


Q vs E plot



LINAC Research Facility (LRF-Huelva)

- RESEARCH & APPLICATION PROGRAM
  - Basic nuclear physics: reactions & structure, astrophysics, superheavies; exotic isotopes (IGISOL)
  - Materials for Fusion and Fission energy
  - Aerospace
  - Medical applications: Radioisotopes & Proton therapy
- Wide range of heavy ions
  - Wide range of energies, from keV/u to ~15 MeV/u
  - Maximum intensity for HI (~100uA, 40Ar)
  - Protons up to 30 MeV (~1 mA); up to 70 MeV (nA)

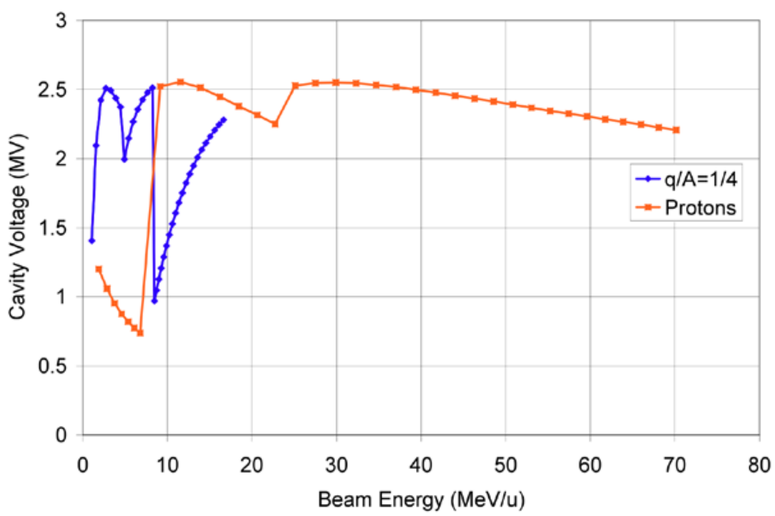


LRF Main Parameters

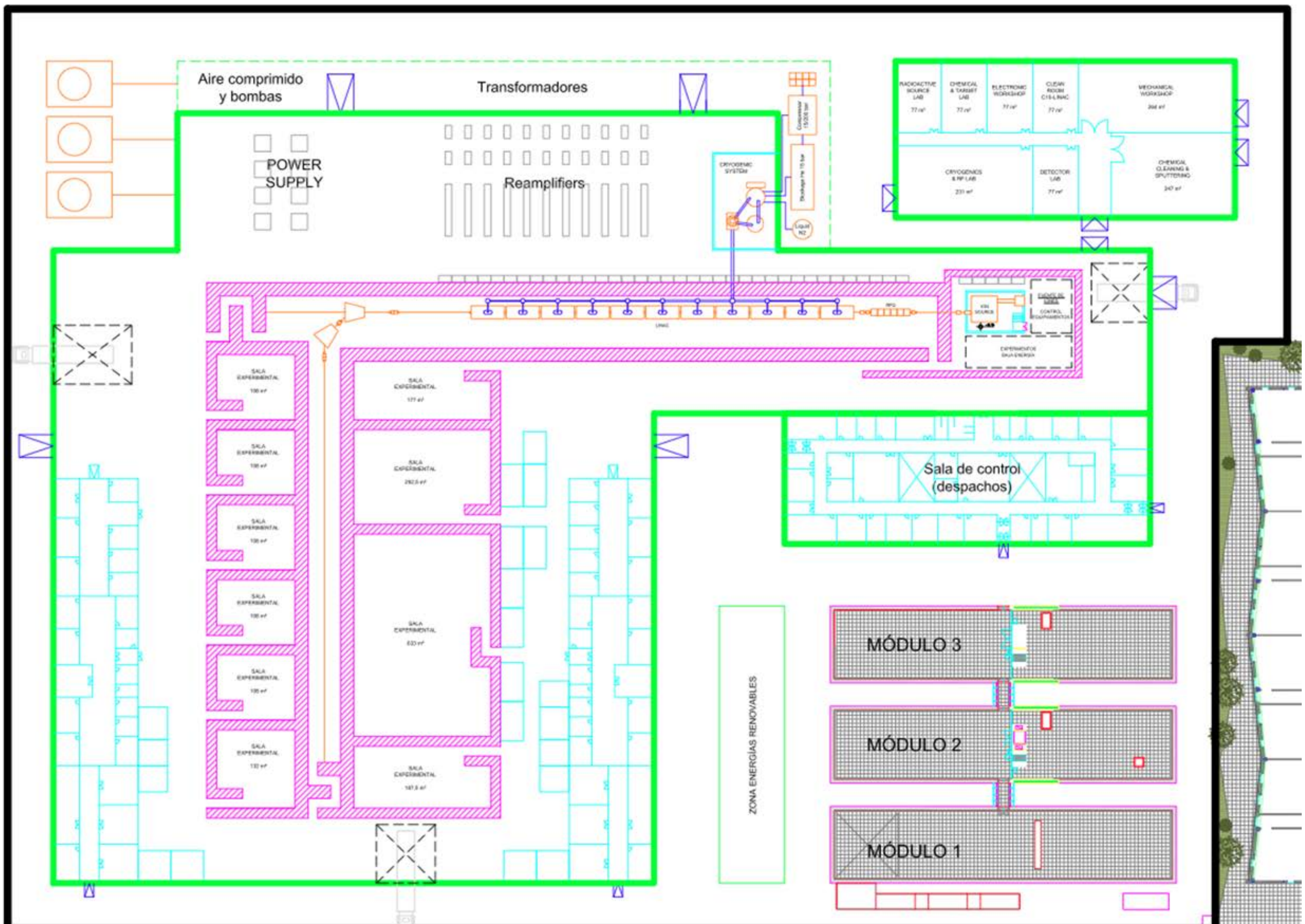
Parameter	Value	Time	Comments
Ion Species	Heavy ions, protons		ECR ion source
Current Range	~1-2 mA (protons) ~ 500uA – 10 uA HI		HI intensities depends strongly on Q/A
PHASE 1	20 MeV protons 9 MeV/u HI	~3 years	Auxilliary, Cryogenics, Ion source, LEBT, RFQ, 2 x cryomodules (7 x SC), 2 beam lines
PHASE 2	55 MeV protons 15 MeV/u HI	2 years	2 x Cryomodule, Ext. Cryogenics, full experimental hall, IGISOL
PHASE 3	72 MeV protons 18 MeV/u HI	1 year	1 x Cryomodule, proton therapy line

Table 5. Main parameters of the Linac

	Frequency, MHz	β_{OPT}	Number of cavities	Comments
MHB*	36.375 (the 1st harmonic)	N/A	1	
RFQ	72.75	N/A	1	Based on ANL 60.625 MHz RFQ
QWR1	72.75	0.077	7	Design is available as ANL/ATLAS upgrade cryomodule
QWR2	109.125	0.15	7	Design is available as ANL/ATLAS upgrade cryomodule
HWR	181.875	0.25	14	Prototype cavity (f=170 MHz) was demonstrated at ANL

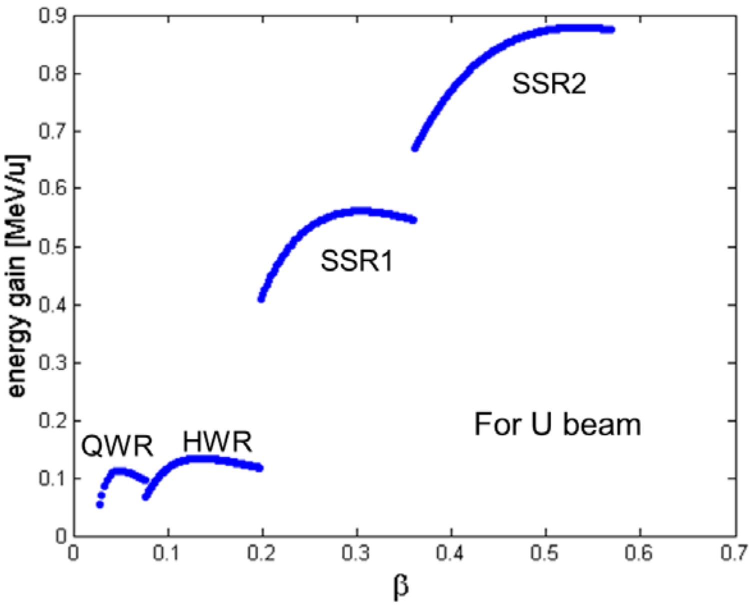


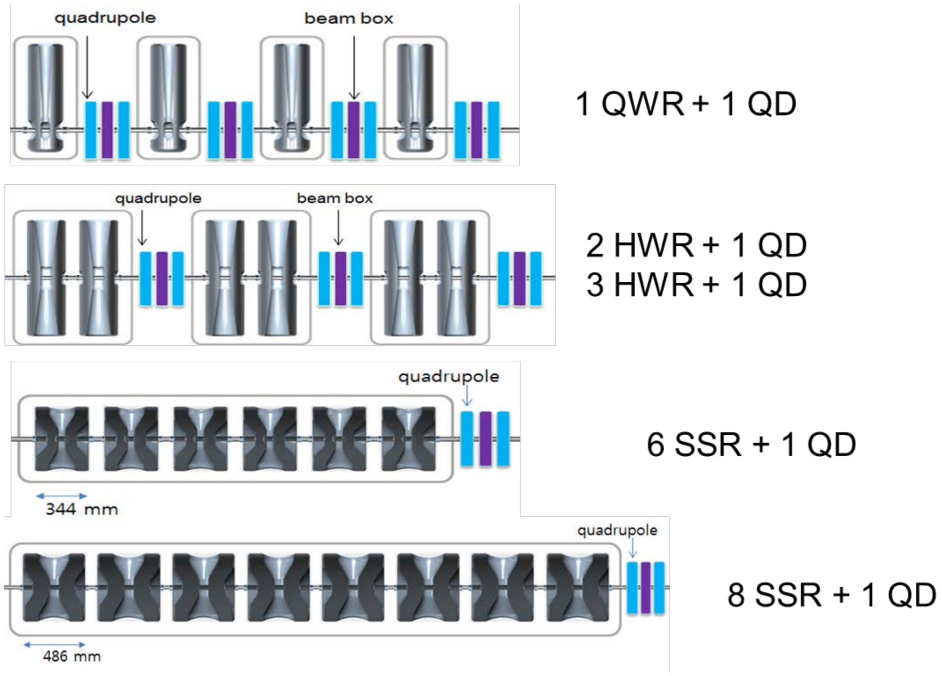
Civil Construction Already Started



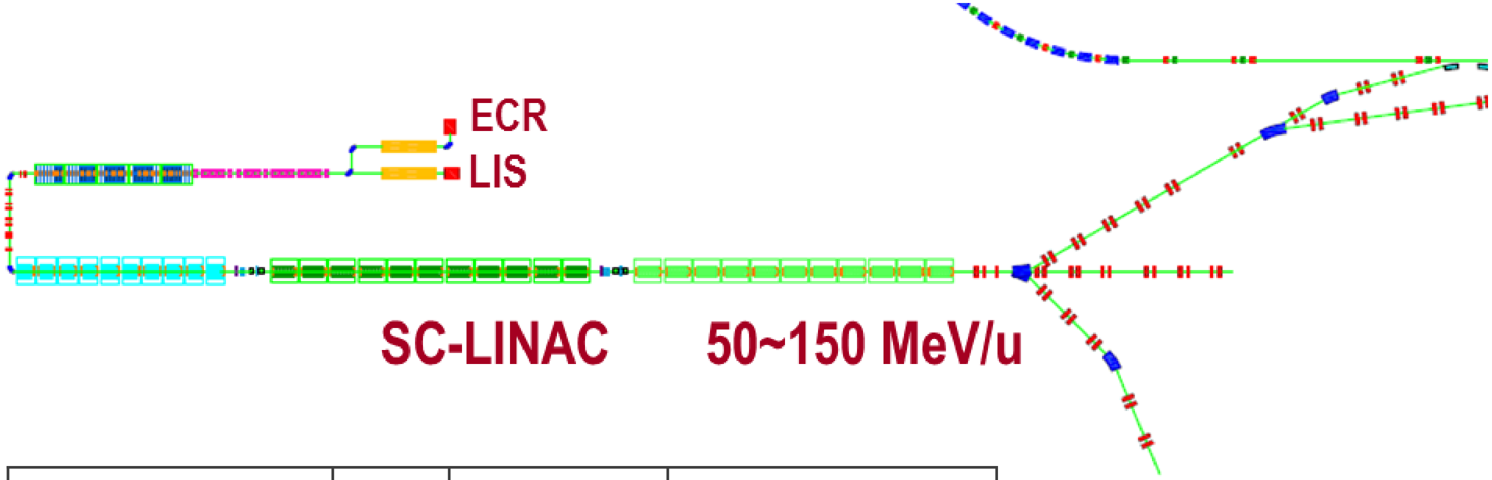
Accelerator Complex for RISP (Korea)

- SC Driver Linac 200MeV/u for ^{238}U, 600 MeV for p, 400 kW beam power
  - Isotope Facility
  - High power ISOL driver
- Cavities: QWR, HWR and 2 types of SSR, fundamental frequency is 81.25 MHz
- Focusing by quadrupole doublets





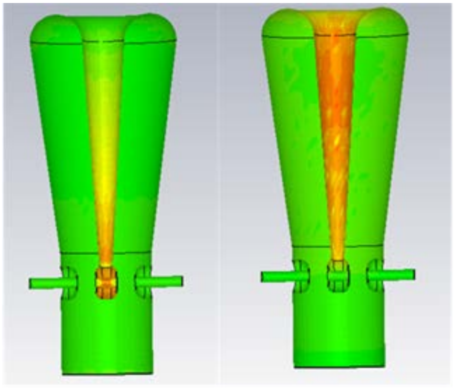
Heavy-Ion Accelerator Facility (HIAF) at IMP, China



SC-LINAC (0.5Hz, 1ms)	$^{18}O^{6+}$	150 MeV/u	1.0 pmA
	U^{34+}	50 MeV/u	0.04-0.4 pmA
	U^{76+}	150 MeV/u	0.008-0.08 pmA

Scope

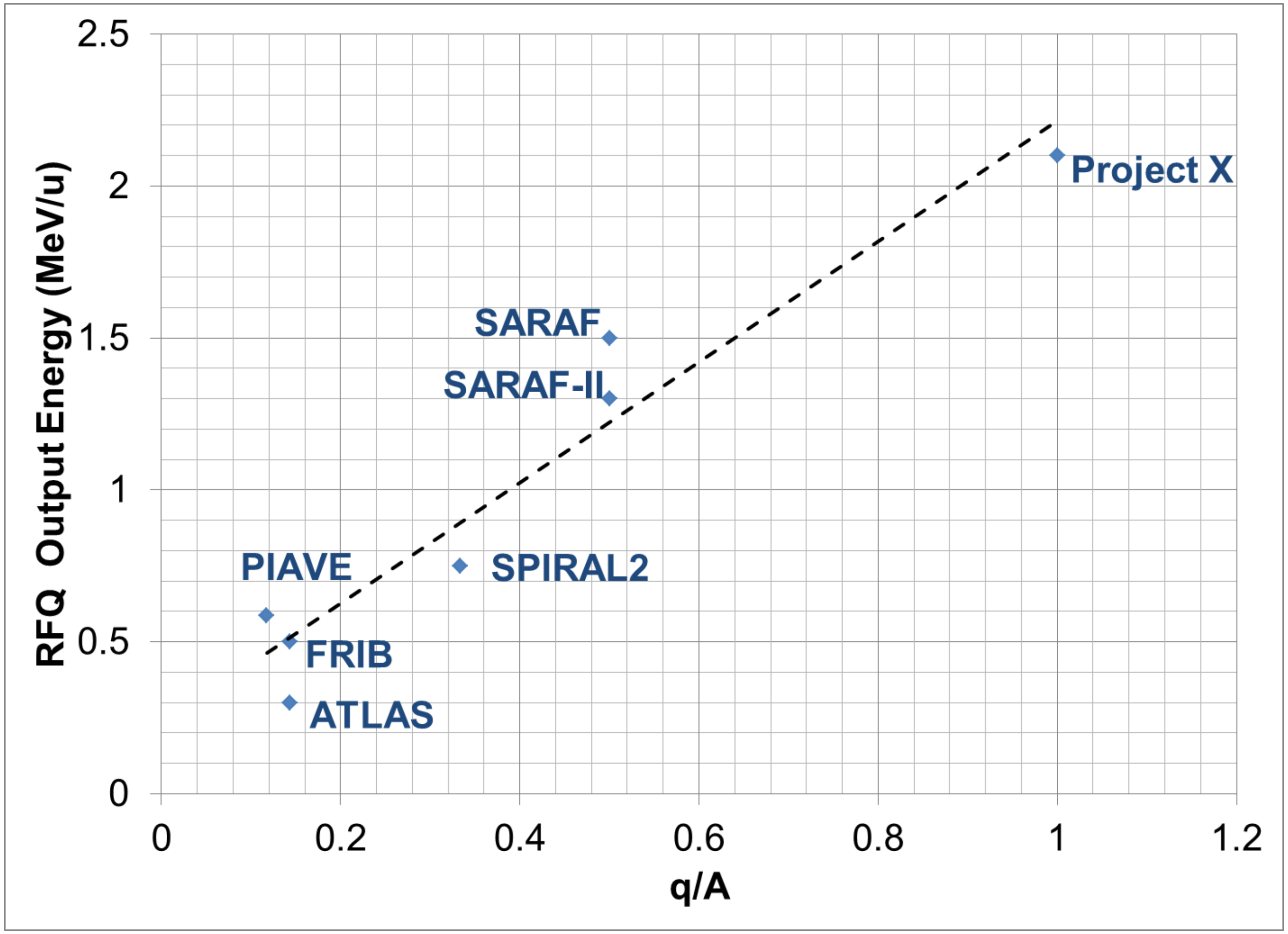
1. Production of r/a ions
2. High pulse current for injection into synchrotron



SC Linacs: Beam Physics

- High intensity heavy ion beams: multiple charge state acceleration
  - Form extremely low longitudinal emittance by using MHB and RFQ
  - Avoid effective emittance growth of multi-q beams
  - Form time and transverse focus on the stripper
  - Multi-q isopath transport after stripping
  - High-quality of accelerating and focusing fields
    - QWRs with steering compensation
    - Axial symmetric fields in TEM-class SC resonators
  - Moderate tolerances for RF errors: phase 0.5 rms, amplitude 0.5% rms
  - Alignment of cold cavity-solenoid strings
    - Cold BPMs and dipole coils in the solenoids
  - Small transverse beam size on the fragmentation target
  - Quick turn around for tuning to different q/A
- High intensity light ion beams
  - Space charge in the front end
  - A section with adiabatic transition for beam dynamics is required between RFQ and high-gradient SC linac

Transition Energy from RFQ to SC Linacs

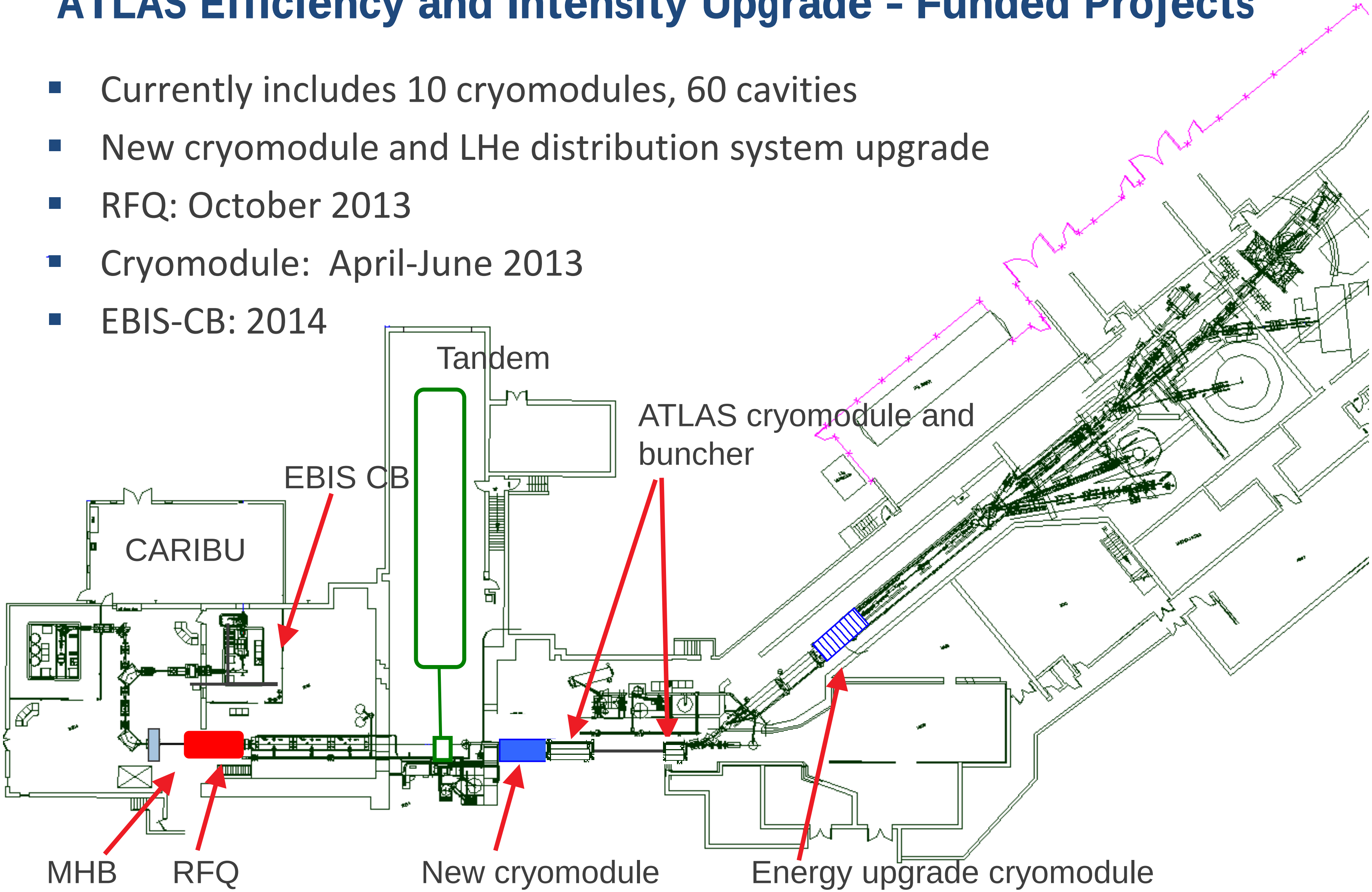


SC technology is the most critical technology for CW ion accelerators

- Main parameters of SC accelerating cavities for CW operation:
  - Accelerating gradient (cavity voltage, peak fields, design E_{ACC}): **real-estate**
  - Cavity voltage and surface resistance: **cryoplant size**
  - For given surface resistance there is an optimal cost (capital + operation) of the Linac as a function of cavity voltages
    - Simple for e-linacs
    - More complicated for heavy-ion linacs due to several cavity types
- 2K operation is more economic than 4K
- Cost per voltage is proportional to cavity $(\beta_{OPT})^{-k}$
- Cost of the accelerator is roughly proportional to cavity count

ATLAS Efficiency and Intensity Upgrade - Funded Projects

- Currently includes 10 cryomodules, 60 cavities
- New cryomodule and LHe distribution system upgrade
- RFQ: October 2013
- Cryomodule: April-June 2013
- EBIS-CB: 2014

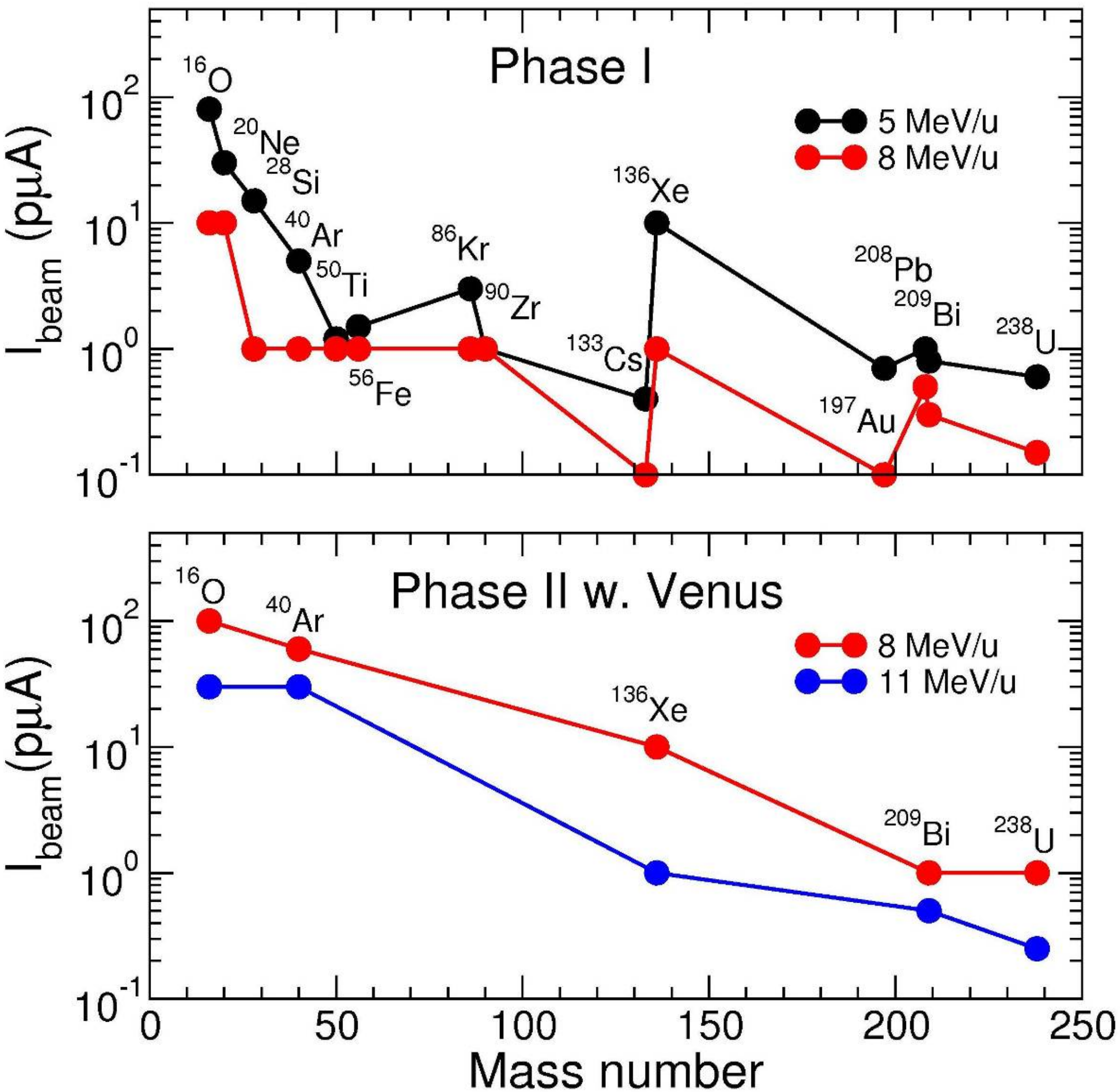


ATLAS Energy Upgrade Cryomodule in Operation Since July 2009

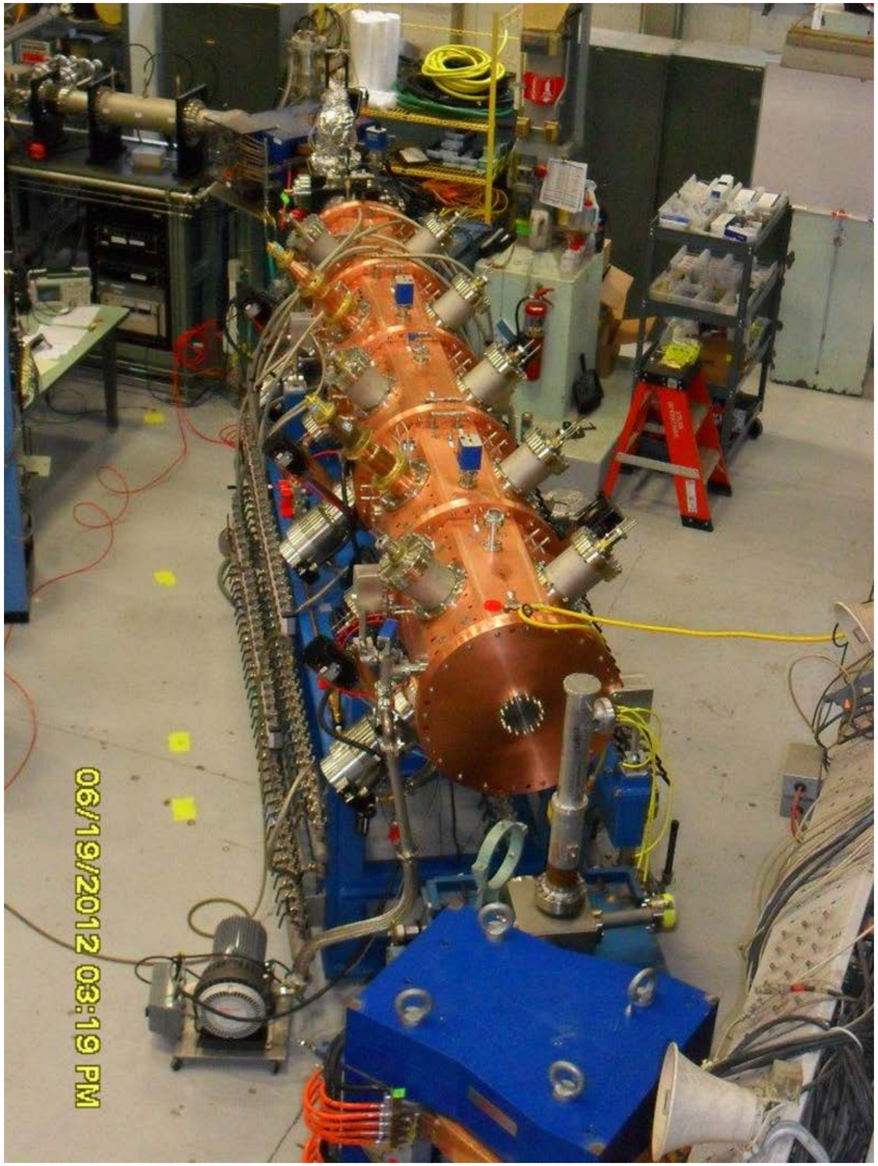
- 7 QWRs, 1 SC solenoid
- Total accelerating voltage is 14.5 MV, 2.1 MV/cavity
- All 7 cavities perform as designed
- One cavity provides 40% higher voltage

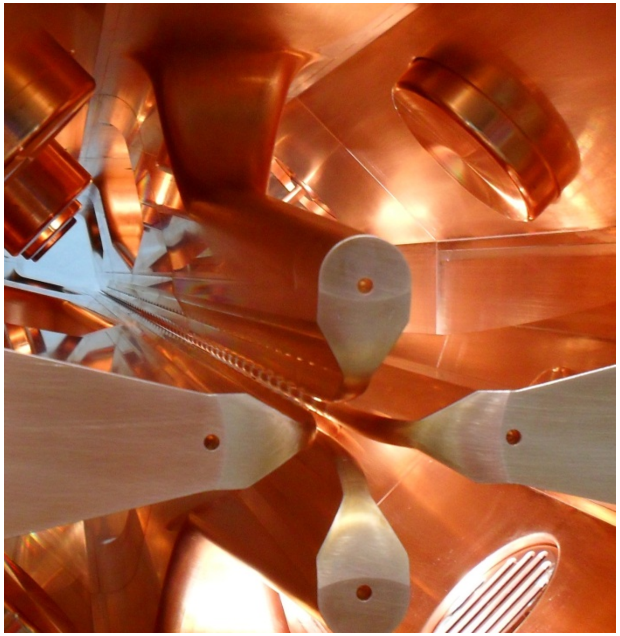
ATLAS Beam Intensities After Upgrades

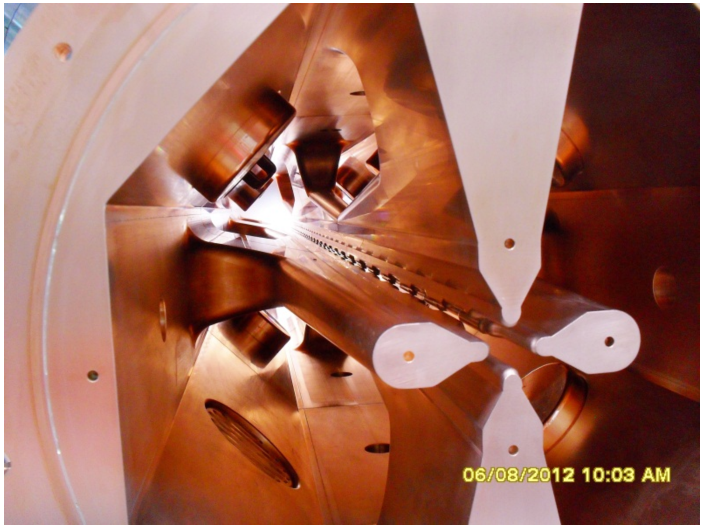
- Funded
  - Intensity is limited by the ECR
  - For light ions intensity is limited by shielding
- Expected funding
  - VENUS type ECR
  - Accelerator Shielding
  - Infrastructure improvement



ATLAS CW RFQ





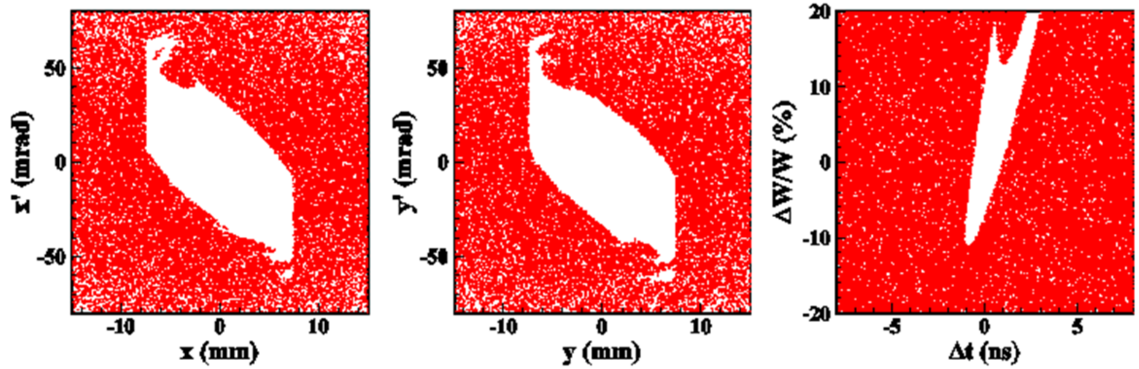


ANL RFQ Highlights

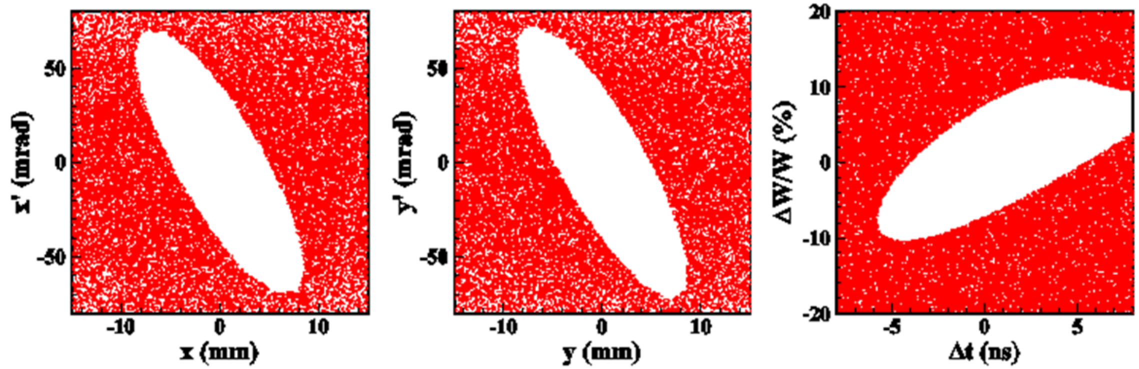
- Highly coupled EM structure
  - "flat" field distribution, non-operational modes are separated more than by 10 MHz
  - "bead-pull" tuning is not required
- Conservative design, peak field is 1.5 Kilpatrick
- Trapezoidal modulation
  - Increases shunt impedance by 60%
- A short output radial matcher to form axially-symmetric beam
- Fabrication: 2-step brazing in a high temperature furnace
- No "cold model"– was directly built from CST MWS geometry
- Measured Q-factor is ~93% of the MWS calculated Q for annealed OFHC copper

Acceptance

- Current PII
- The first SC cavity
  - β=0.009
  - Aperture = ϕ *12* mm

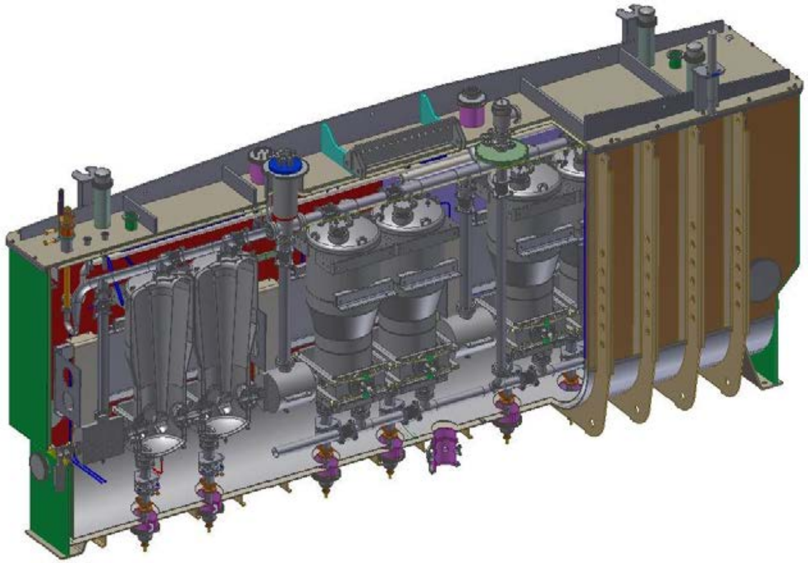


- With new RFQ



New Cryomodule, Project Started on 9/01/2009

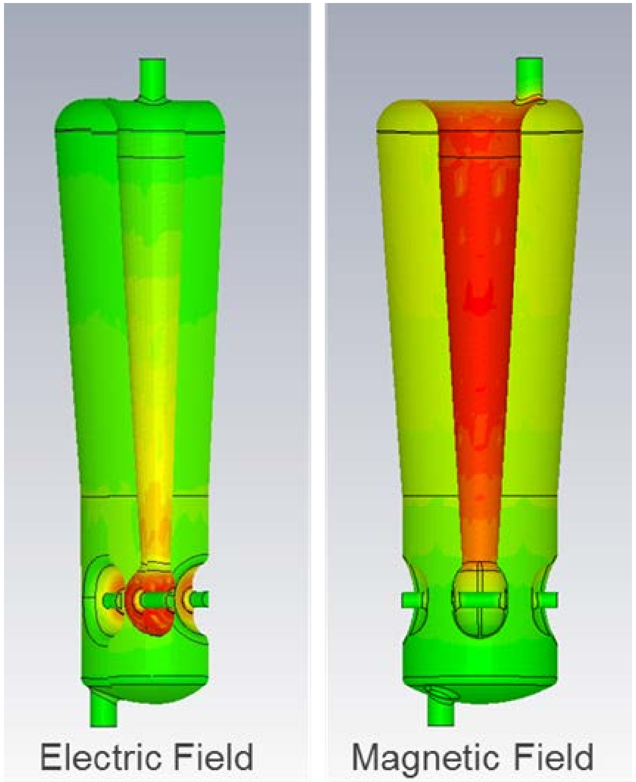
- Cryomodules
  - Long cryomodules containing seven 72. 75 MHz cavities (β_{OPT}=0.077) and 4 SC solenoids
  - Separate cavity and isolation vacuum
  - Vertically loaded, clean room work is minimized
- Length – 5 meters, design voltage 17.5 MV; 2.5 MV/cavity
- Available voltage ~4 MV with very low res. resistance
- Replaces 3 existing cryomodules with split-rings
- Beam commissioning is in 2013

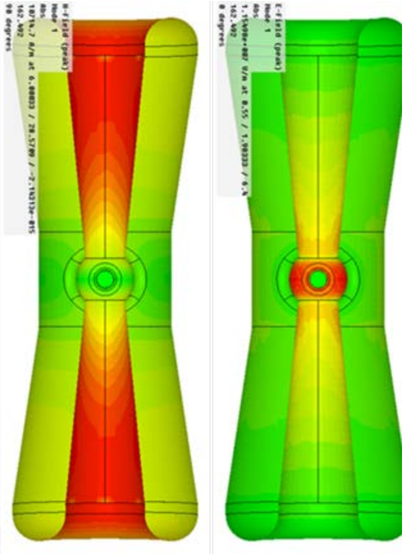


SC Cavity Performance

- **EM design and mechanical design**
- **Fabrication technology**
- **RF surface processing**

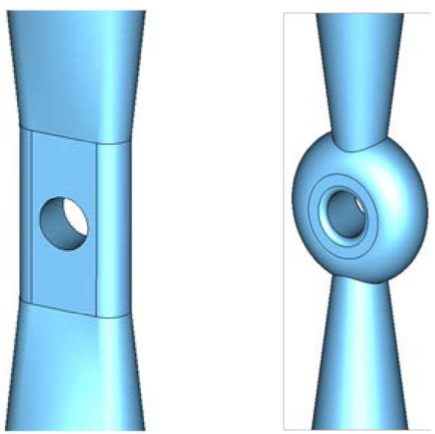
- **First step: EM design**
- Reduce E_{PEAK}/E_{ACC}, B_{PEAK}/E_{ACC}
  - Conical center and outer conductor
  - Triple spokes: conical spokes
- Maximize $R_{sh}G$
- Beam aperture is defined from application; for Heavy Ion Driver accelerators it is in the range from 30 mm to 40 mm

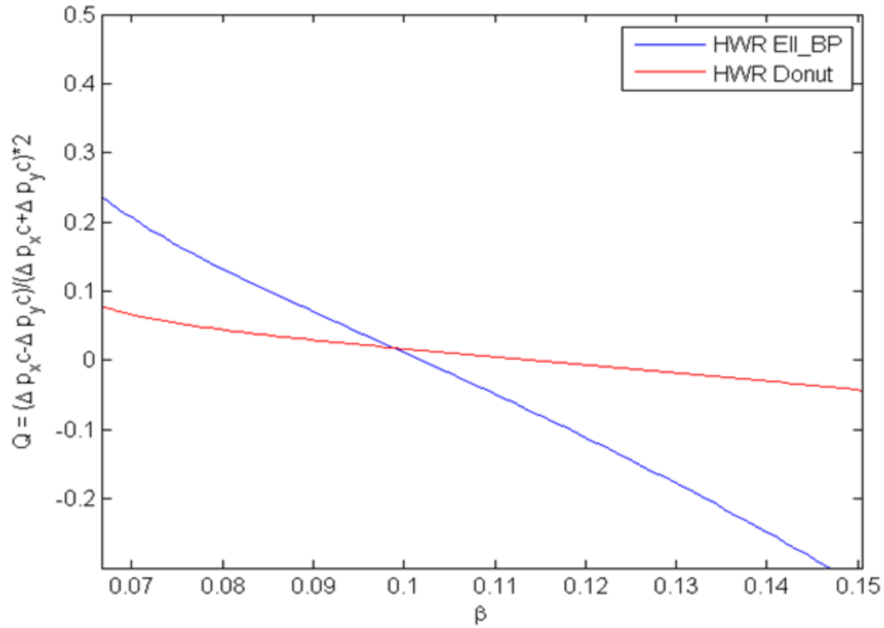




Accelerating Field Quality

- QWR: beam center steering, quadrupole component of the E-field
  - Shaping of the drift tubes to compensate magnetic force with electric force
  - Displacement of the cavity axis: works well for fixed velocity profile
- HWR: quadrupole component of E-field
  - Elliptical aperture
  - “Donut” shape of the drift tube (higher shunt impedance)





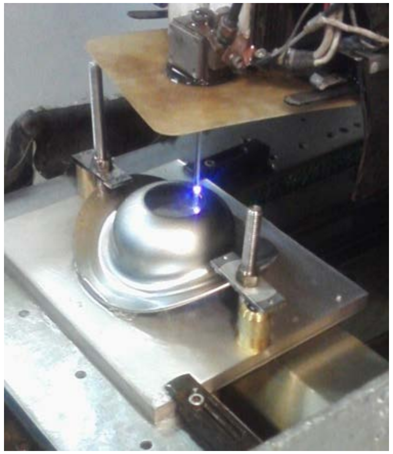
Mechanical design and Engineering Analysis

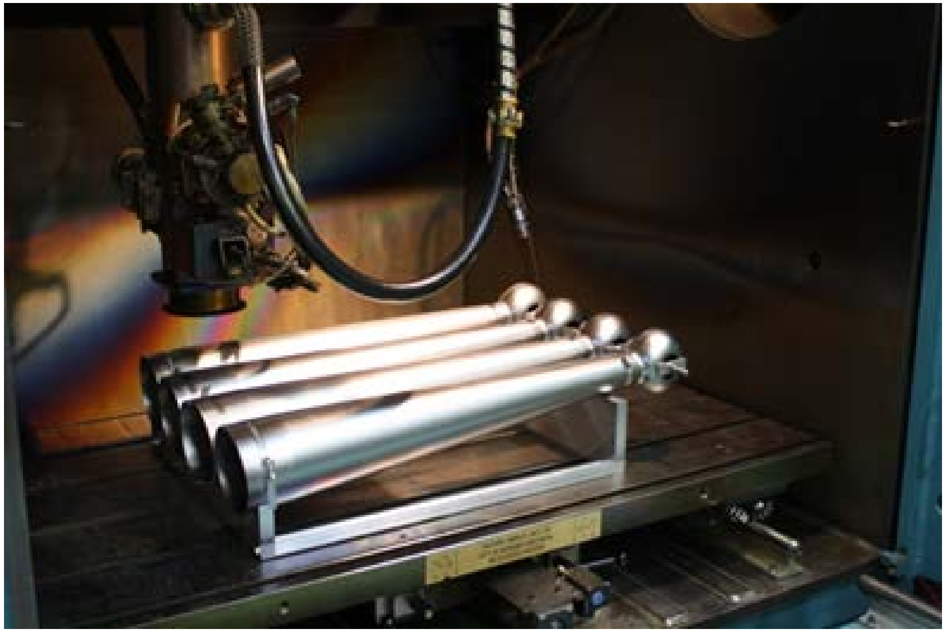
- **Compact** mechanical design to maintain a high real estate accelerating gradient;
- Provide coupling ports enabling **advanced RF surface processing** techniques (electropolishing and high pressure water rinsing);
- Integrate a coupling port for a **RF coupler**;
- Facilitate the **integration** of several cavities and their sub-systems (RF coupler and tuners) into the **cryomodule**;
- Provide a means for cavity **alignment** in the cryomodule;
- Ensure that the **stresses** in the niobium and the stainless steel parts are below the maximum allowable limits;
- Satisfy **pressure vessel** requirements according to the ASME code
- **Minimize the sensitivity of the resonant frequency to fluctuations in helium pressure**
- Ensure that the **slow tuner** operation provides a sufficient tuning range and that the correlated cavity deformations remain well below the plastic limit;
- If necessary, integrate a **fast tuner** with a required tuning window;
- Create a complete set of **fabrication drawings**.

Fabrication

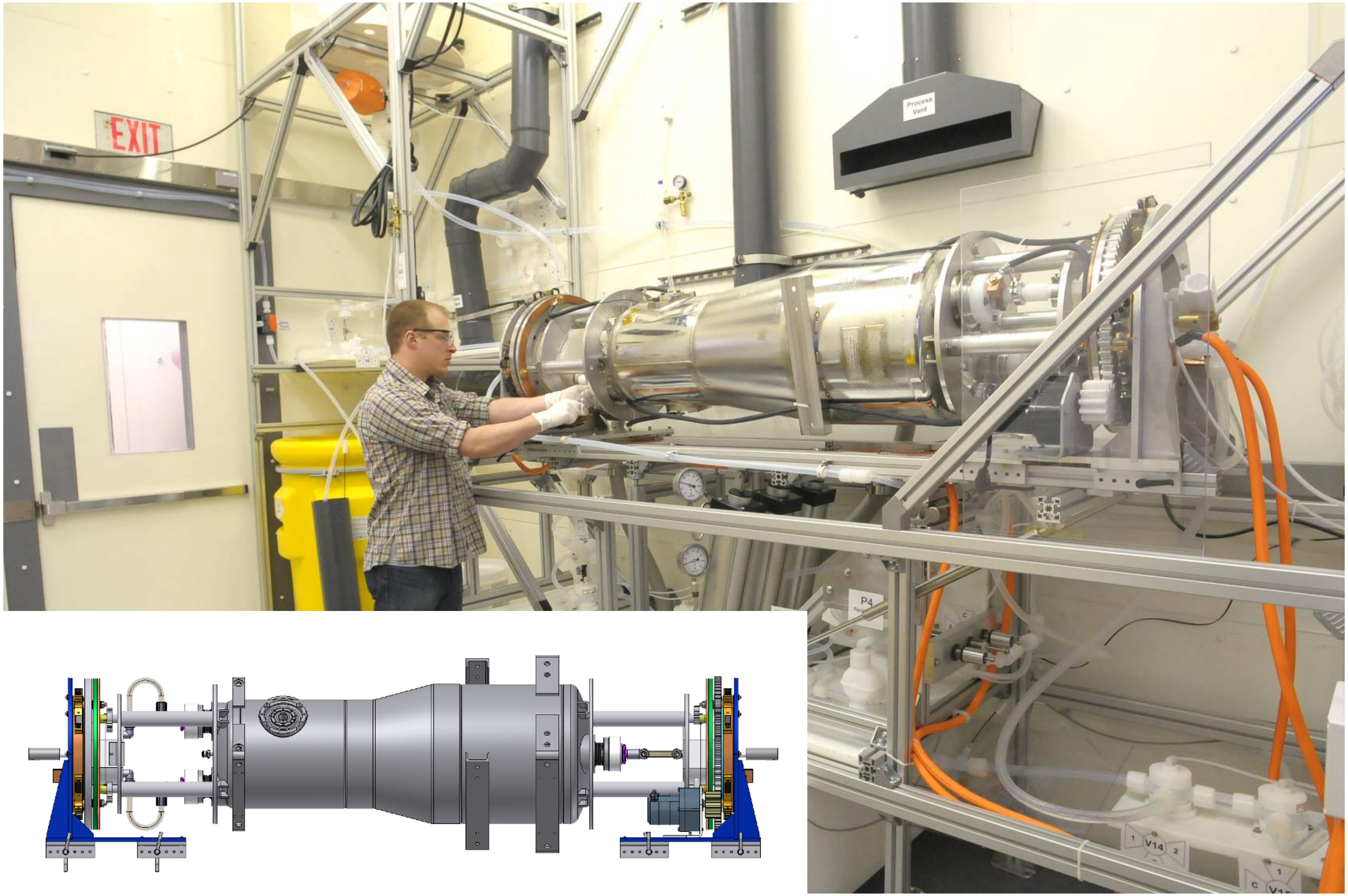
- Niobium sheet forming
- Wire EDM
- Brazed Nb-SS transitions
- Electron Beam Welding
  - BCP weld preparation
  - Pre-weld manual HPR on weld surfaces, class 1000 bag; un-bag in chamber
- SS vessel installation

Wire EDM





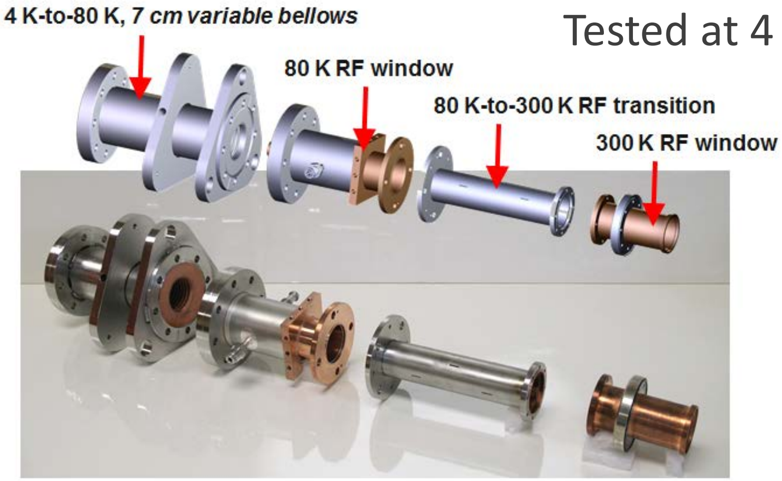
Electropolishing at ANL



72 MHz QWR

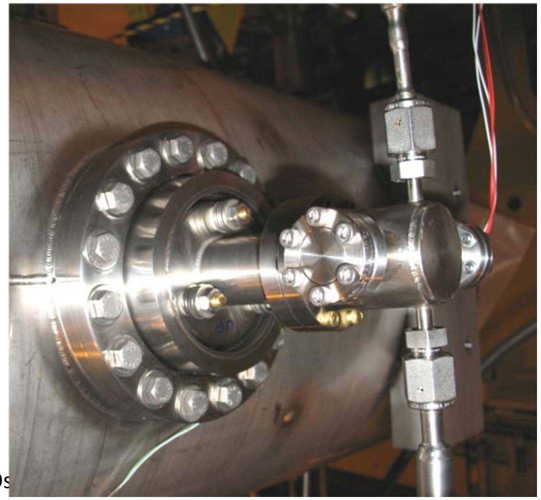
- Outstanding test results

Sub-Systems: RF Coupler, Slow and Fast Tuners

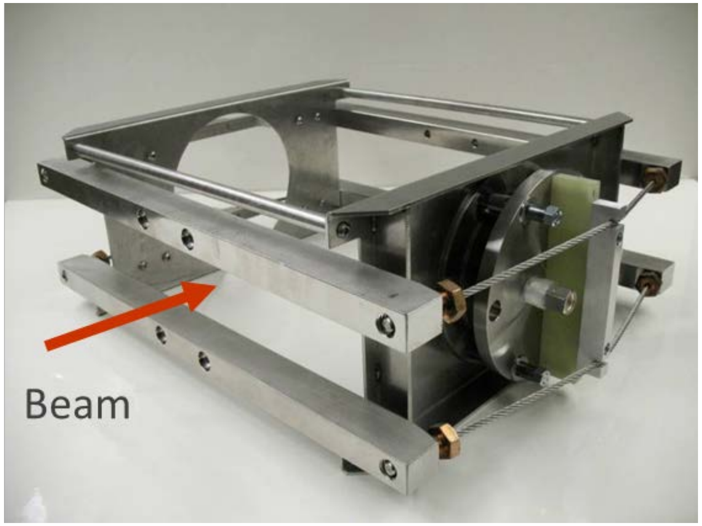


Tested at 4 kW, 72 MHz

Piezoelectric tuner



Pneumatic Slow Tuner



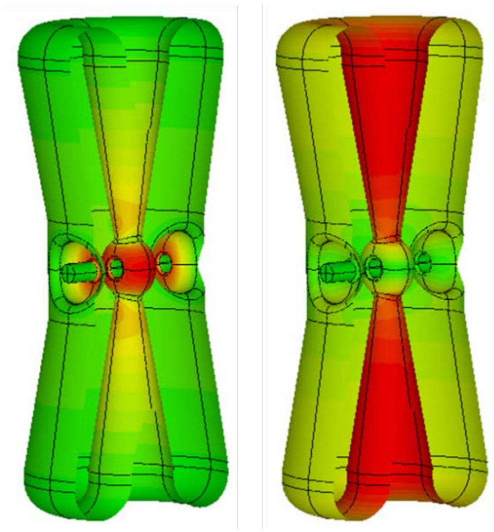
Design Parameters for a CW Heavy Ion Linac

- Realistic design parameters for future SC linacs

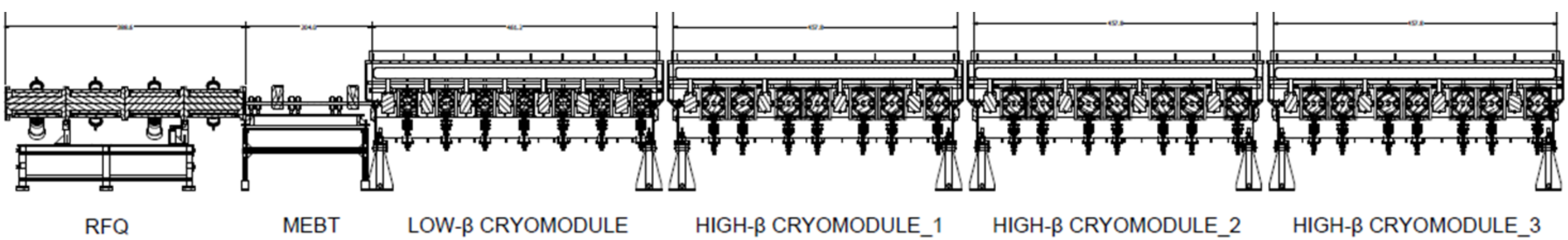
Year	1999	2003	2012	2012 Demo	201X	ILC pulsed
E_{PEAK}, MV/m	21	27.5	**40**	**117**	**60**	70
B_{PEAK}, mT	75	80	**80**	**165**	**100**	140
Operational T, K	4	4 & 2	**2**	**2**	**2**	2
Residual Resistance, nΩ	25	25 & 10	**4-10**	**high**	**4-10**	4.7

Phase II of SARAF at SNRC (Israel), 200 kW beam

- Particles: protons and deuterons
- Beam current – 5 mA
- Beam total energy – 40 MeV
- Highly optimized HWRs

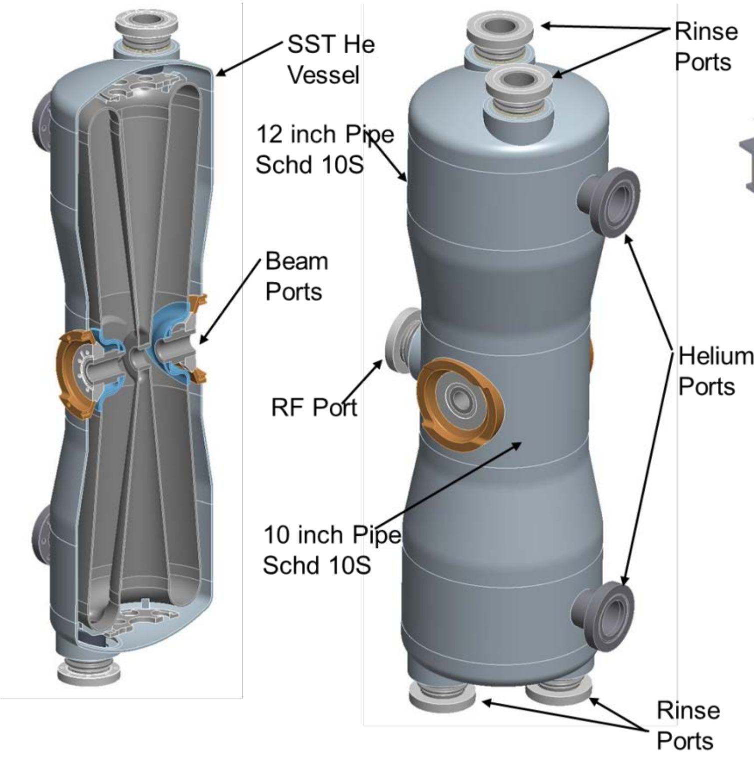


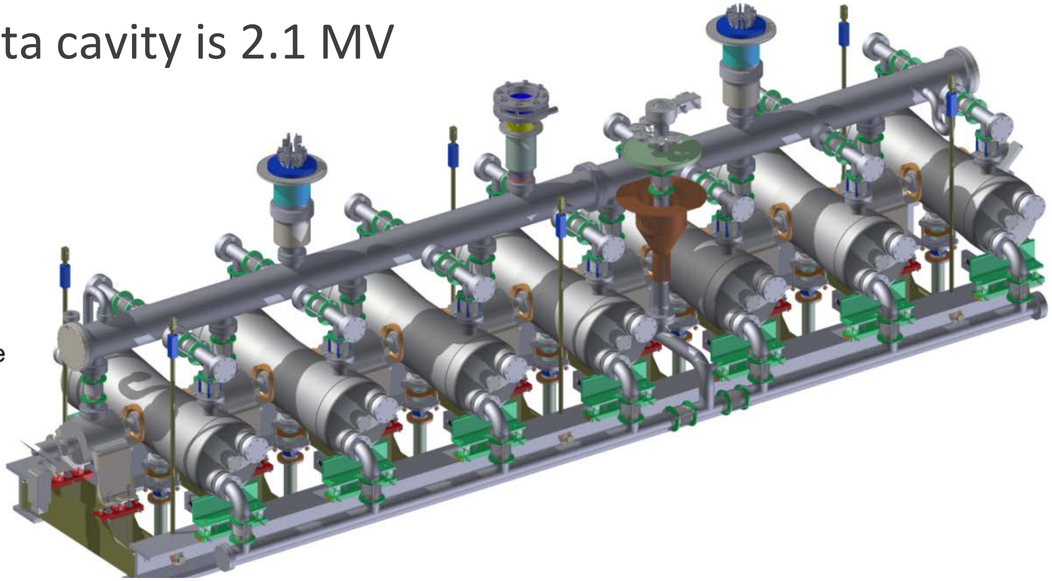
Cavity Parameters	Type I	Type I I
Frequency, MHz	176	176
β_{OPT}	0.089	0.16
Number of cavities	7	21
Aperture, mm	33	36
Leff, cm	15.2	27.3
Ep/Ea,	5.3	4.6
Bp/Ea, mT/MV/m	5.7	5.6
R/Q, Ω	231	291
G, Ω	40	60

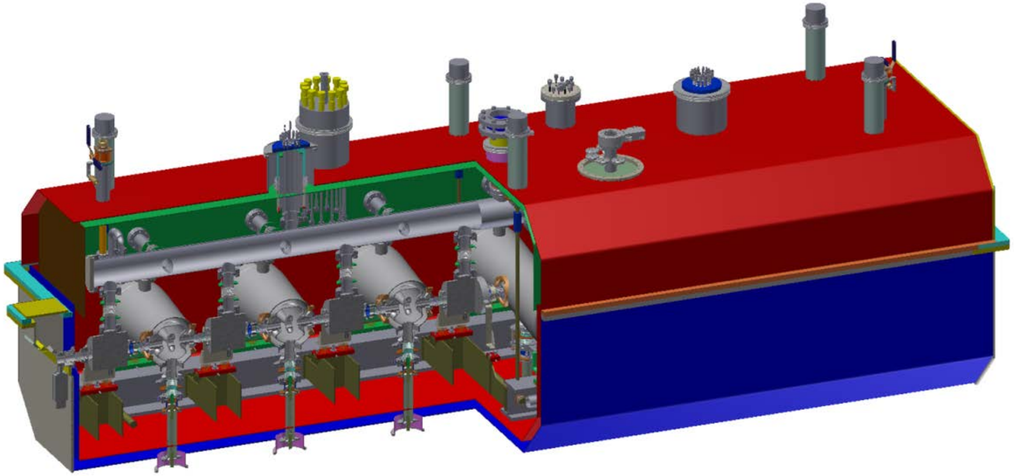


176 MHz HWRs for SARAF

- Design voltage per high-beta cavity is 2.1 MV
- Expected voltage is ~4 MV





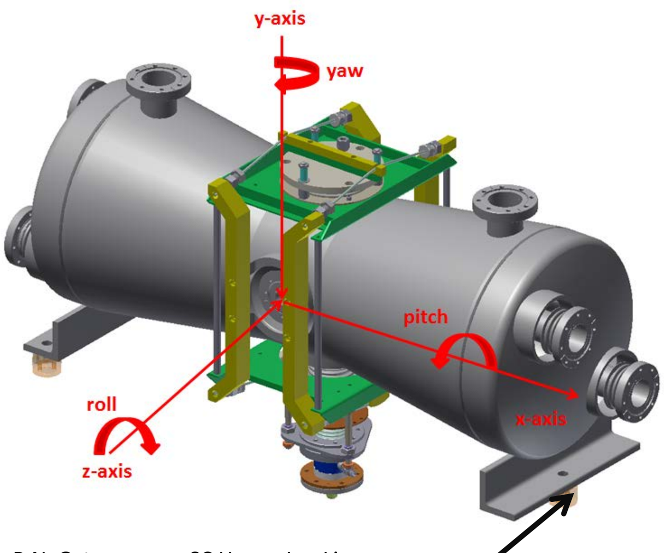


SARAF Cryomodule Design Highlights

- Titanium strongback
- Compact SC solenoid (35 mm aperture)
  - Dipole coils for H and V steering
  - Return coils to dramatically reduce edge field
- Cleanable BPM
- Alignments system
  - Predictable displacement during the cool-down
  - Tolerances ±250 µm

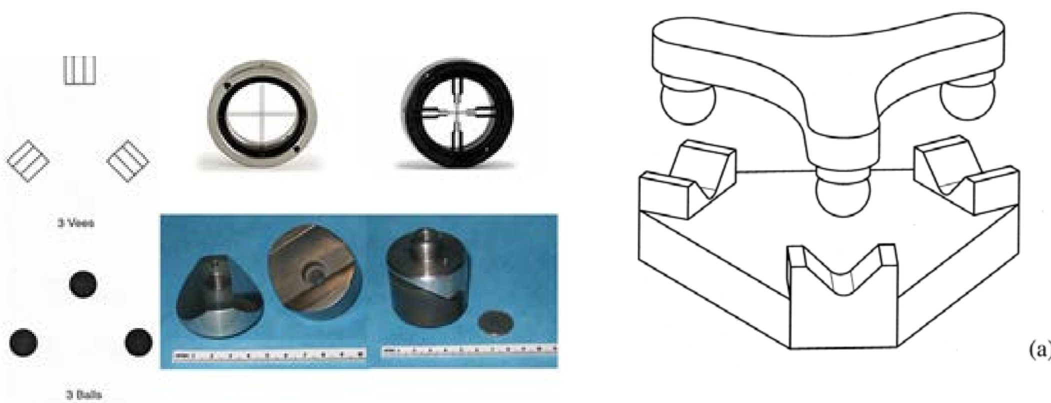
Solenoid

BPM 2.5 cm along Z



Alignment Pucks

Kinematic Maxwell Configuration



Summary

- Since HIAT-09
  - Several new HI accelerators received funding
  - Several substantial upgrades of existing facilitates were funded
  - Advanced proposals for new HI facilities were developed
- We observe substantial progress in technology of CW heavy-ion accelerators
- These technologies are in demand for
  - Multi-purpose high-power ion & proton linacs (science and applications)
  - CW proton (H-minus) accelerators for fundamental science
  - Accelerator Driven Systems
  - Isotope production for medicine

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