Argonne NATIONAL LABORATORY

25th North American Particle Accelerator Conference
September 30 - October 4, Pasadena CA

Upgrade of Argonne's CW SC Heavy Ion Accelerator

P.N. Ostroumov, Physics Division ANL

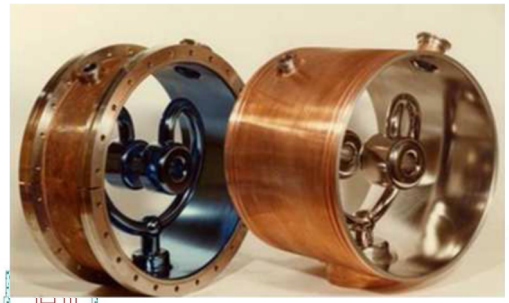
On behalf of: A. Barcikowski, Z. Conway, S. Gerbick, M. Kedzie, M.P. Kelly, S. Kim, S. Kutsaev, R. Murphy, B. Mustapha, R. Pardo, D. Paskvan, T. Reid, S. Sharamentov, G. Zinkann

Content

- Motivation for upgrade
  - Increase beam transmission efficiency
    - Radioactive beams from CARIBU
  - Increase intensity of ion beams
    - Stable ion beams up to 10 pμA, hundreds of electrical microAmps
- RFQ
  - Design, fabrication, assembly
  - Beam commissioning
- Cryomodule
  - Innovative features of the new cryomodule
  - Commissioning results
- Main goal of this talk is to present novel features of both RFQ and cryomodule
- Summary

Motivation

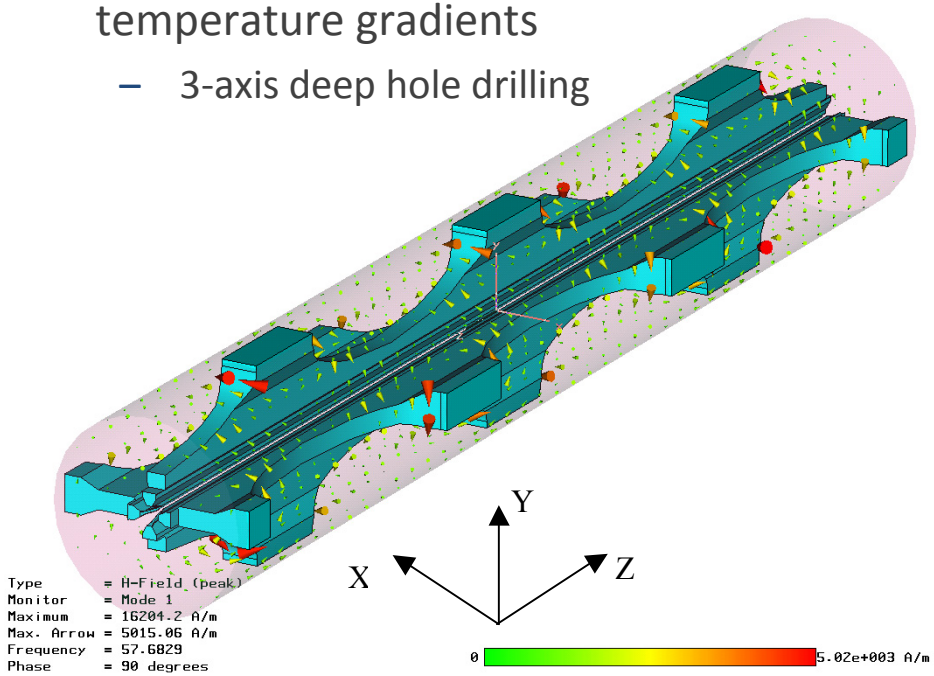
- ATLAS consisted of 12 cryomodules of 58 cavities total
  - Replace 3 split-ring cryomodules with 1 new cryomodule
- Increase beam acceleration and transmission efficiency by replacing 4 very low beta SC cavities with the normal conducting RFQ
- Increase intensity of stable ion beams
  - Limited by split-ring cavities, RF steering due to magnetic filed in the aperture
- Limited funding resulted in many innovative features for both RFQ and cryomodule



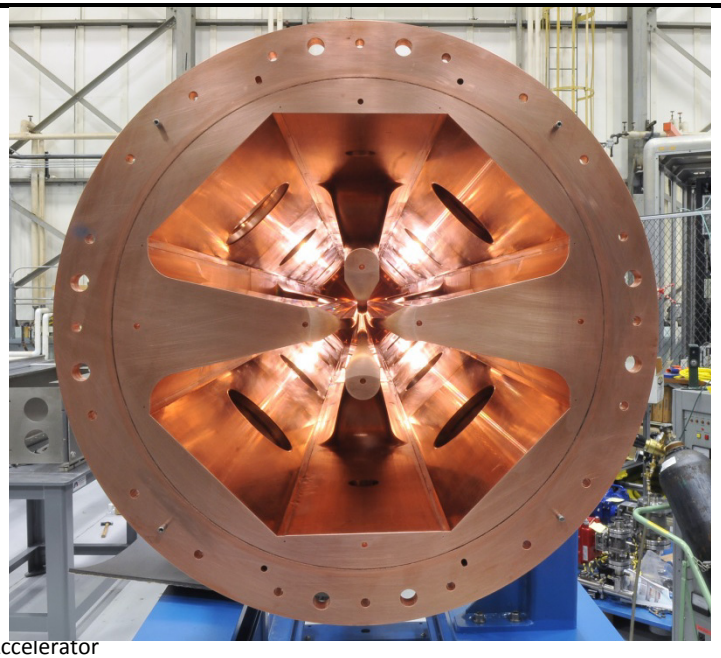
P.N. Ostroumov

ATLAS CW RFQ, Multi-Physics Design

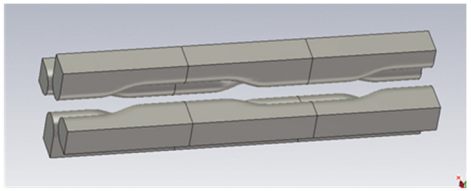
- Total voltage is 2.1 MV
- Novel multi-segment split-coax structure
  - Internal size is 19” only for 60 MHz
  - Strongly coupled segments
  - Reduced number of tuners
  - Bead pull measurements are not required
- Cooling system is optimized to reduce temperature gradients
  - 3-axis deep hole drilling

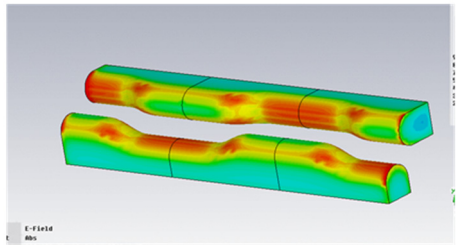


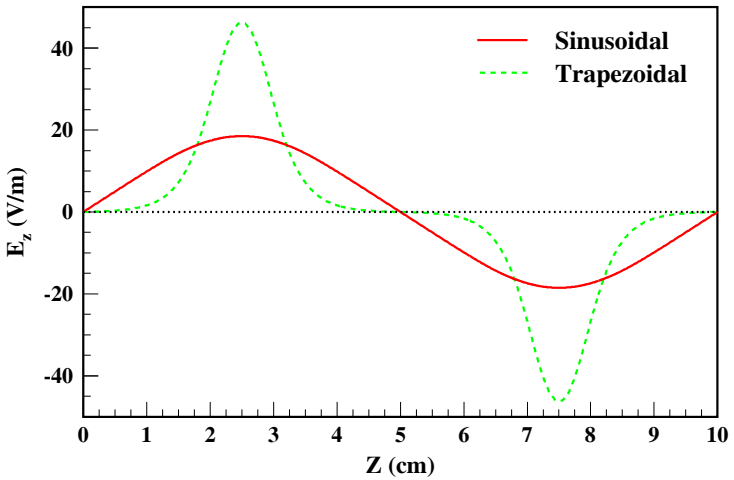
	Parameter	Value
1	Duty cycle	100%
2	q/A	1/7 to 1
3	Input Energy	30 keV/u
4	Output Energy	295 keV/u
5	Average radius	7.2 mm
6	Vane Length	3.81 m
7	Inter-Vane Voltage	70 kV
8	RF power consumption	60 kW



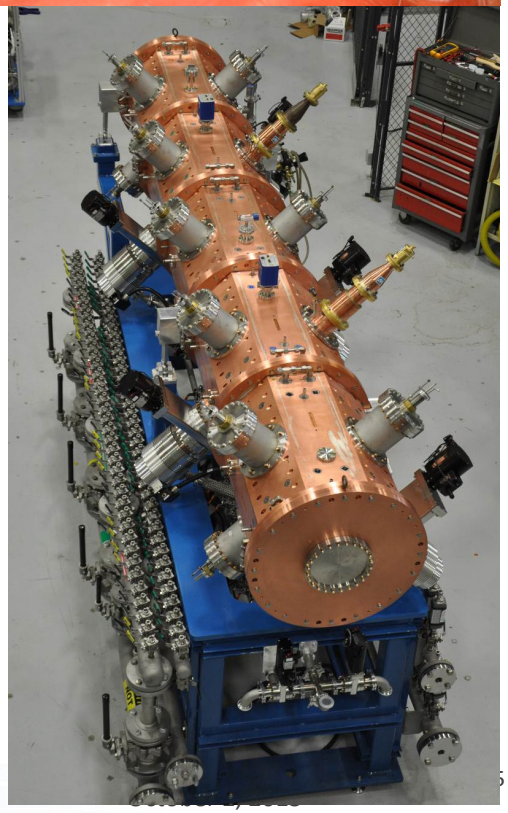
Fabrication, Trapezoidal Vane Tip Modulation





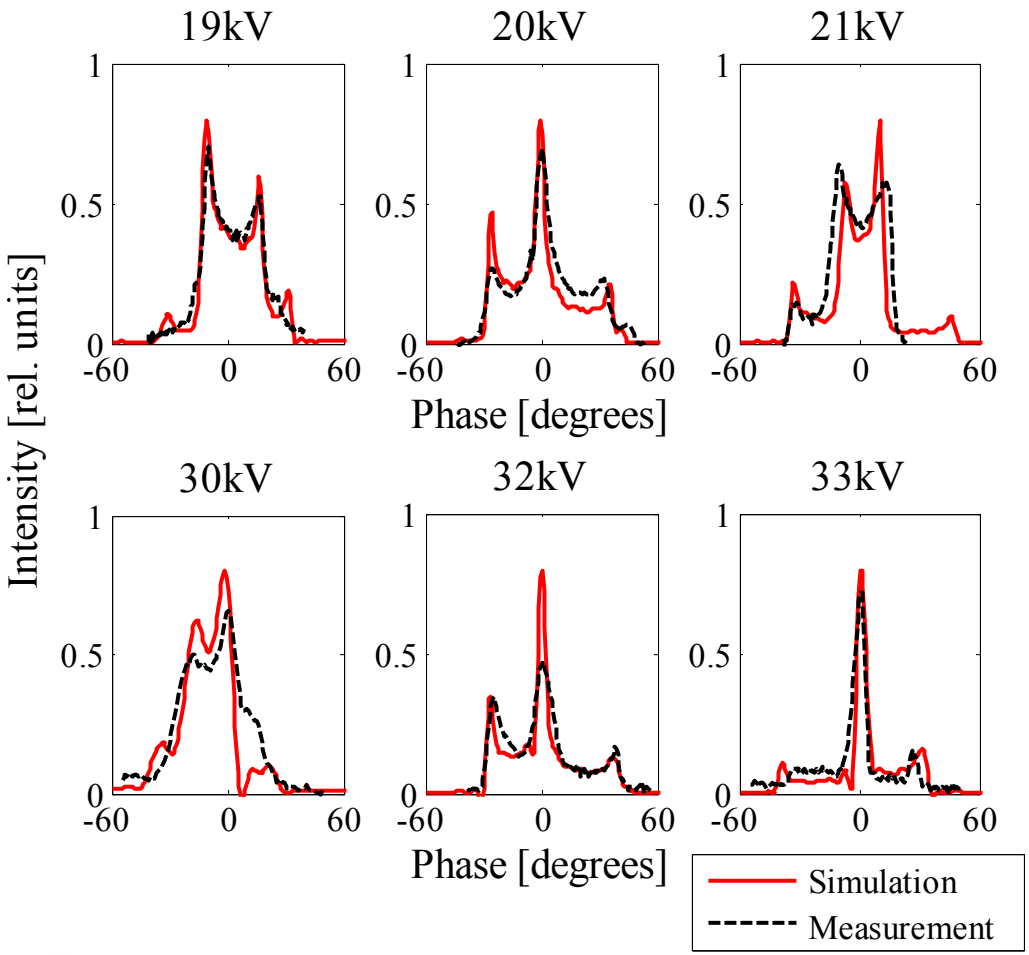


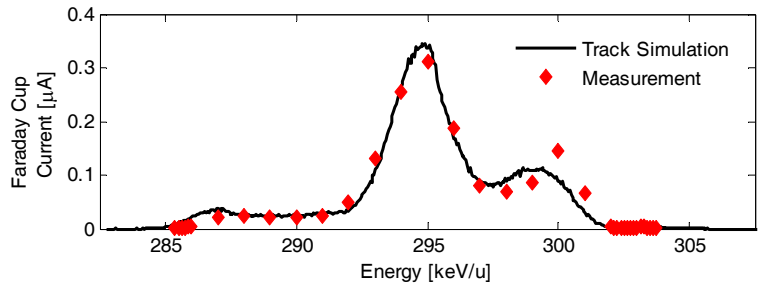
- Precise machining, 2-step high-T furnace brazing OFE copper
  - Q_0 is 94% of theoretical value
  - No alignment necessary

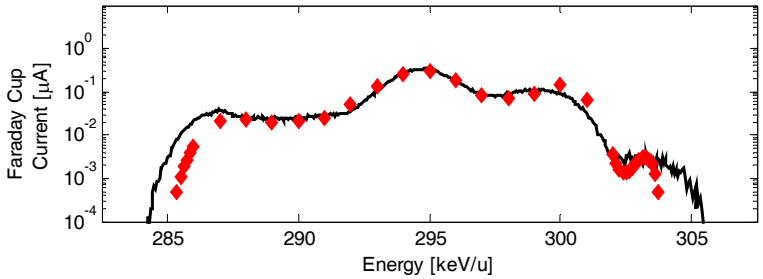


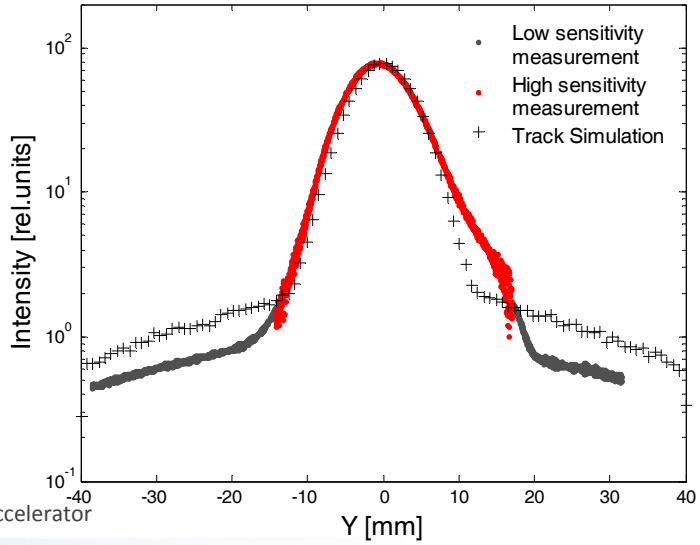
Bunch Shape, Energy Spread and Transverse Profile

- To reduce ATLAS downtime, off-line testing
- Results of the RFQ beam testing
  - Helium and Oxygen beams



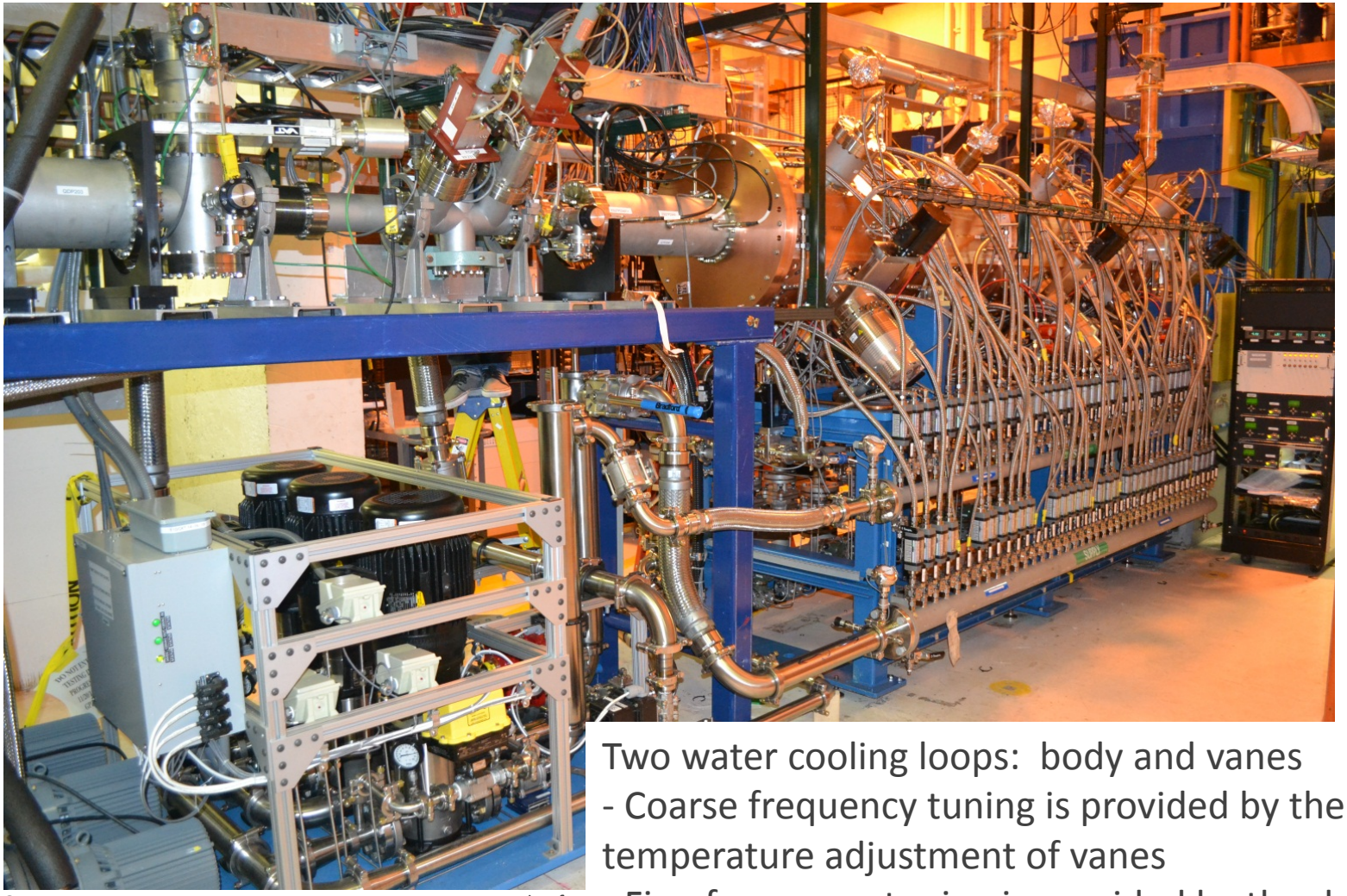






RFQ at Permanent Location

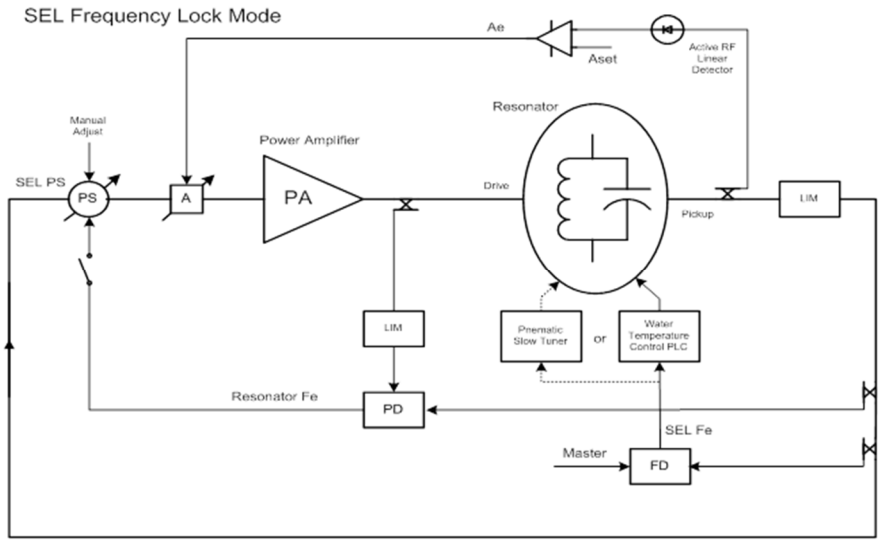
- Connected to the SC linac in October-November 2012
- In operation since January 2013

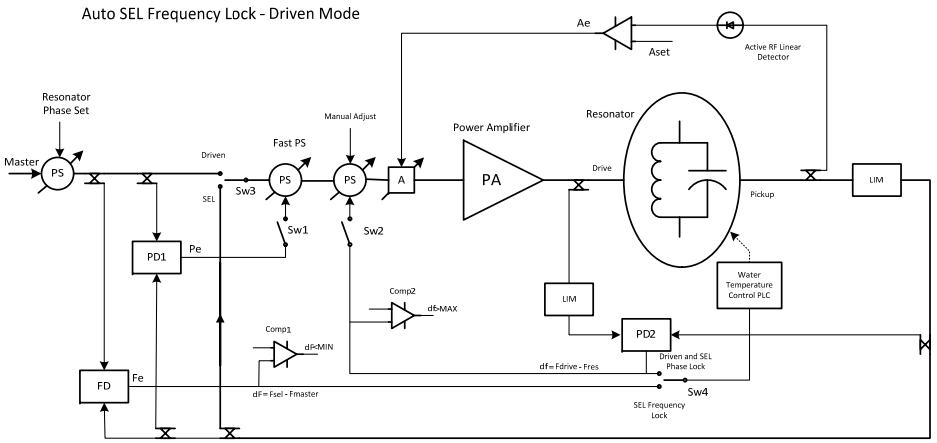


Two water cooling loops: body and vanes
- Coarse frequency tuning is provided by the temperature adjustment of vanes
- Fine frequency tuning is provided by the driver RF phase

RFQ RF Control System - Multiple Modes

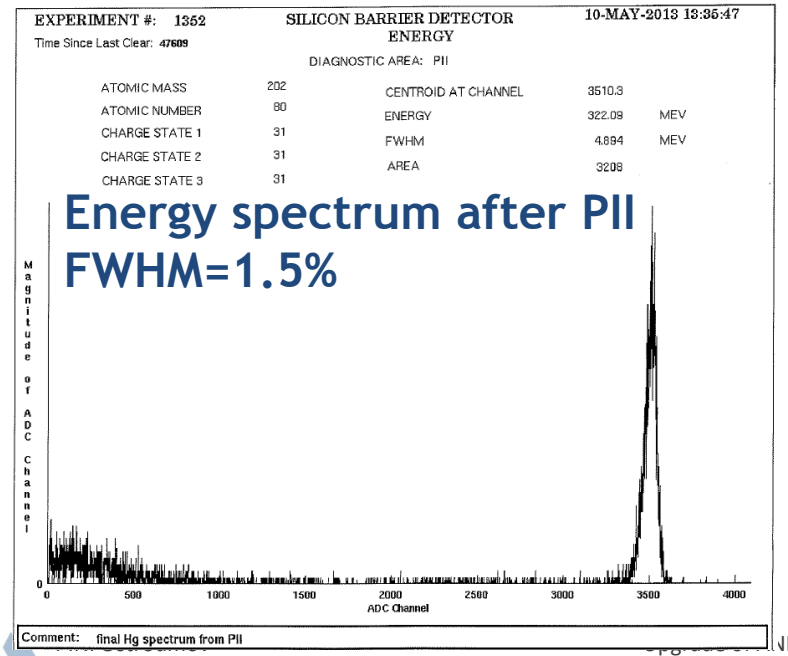
- Self-excited Loop-Frequency Lock Mode
  - Provides shortest resonator “on-frequency tune” time
  - Allows resonator detuning range, defined by Frequency Detector bandwidth (> 10 resonator bandwidths), while maintaining a matched condition for the 60kW amplifiers
  - Does not phase lock the cavity for beam acceleration
- Driven Mode
  - Power amplifiers are driven at the Master Oscillator frequency
  - Phase-locked operation at any level of RF power to support acceleration of different q/A

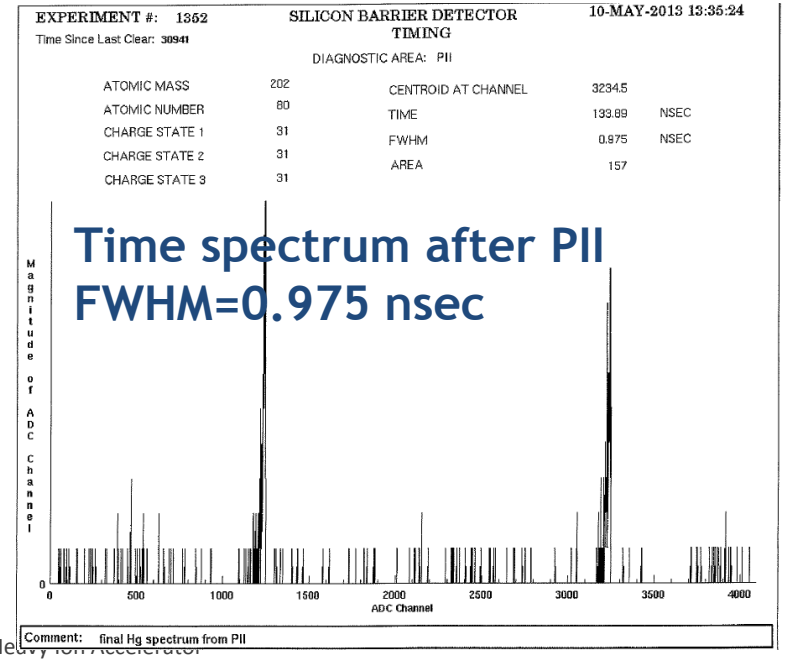




Measured RFQ+PII Energy and Time Profile, $^{202}Hg^{+31}$

- Initial conditioning reached 74 kV inter-vane voltage after 5 hours conditioning
  - Design Maximum is 70 kV
- No dark current or breakdowns observed during the operation
- Provides 83% acceleration efficiency through PII (~1.5 MeV/u) as designed
  - External multi-harmonic buncher provides very low longitudinal emittance
- Many ion beam species have been accelerated and used for experiments, from Li to U
- The RFQ has doubled the ATLAS beam transport efficiency and demonstrated excellent performance since its integration into the accelerator in January 2013.





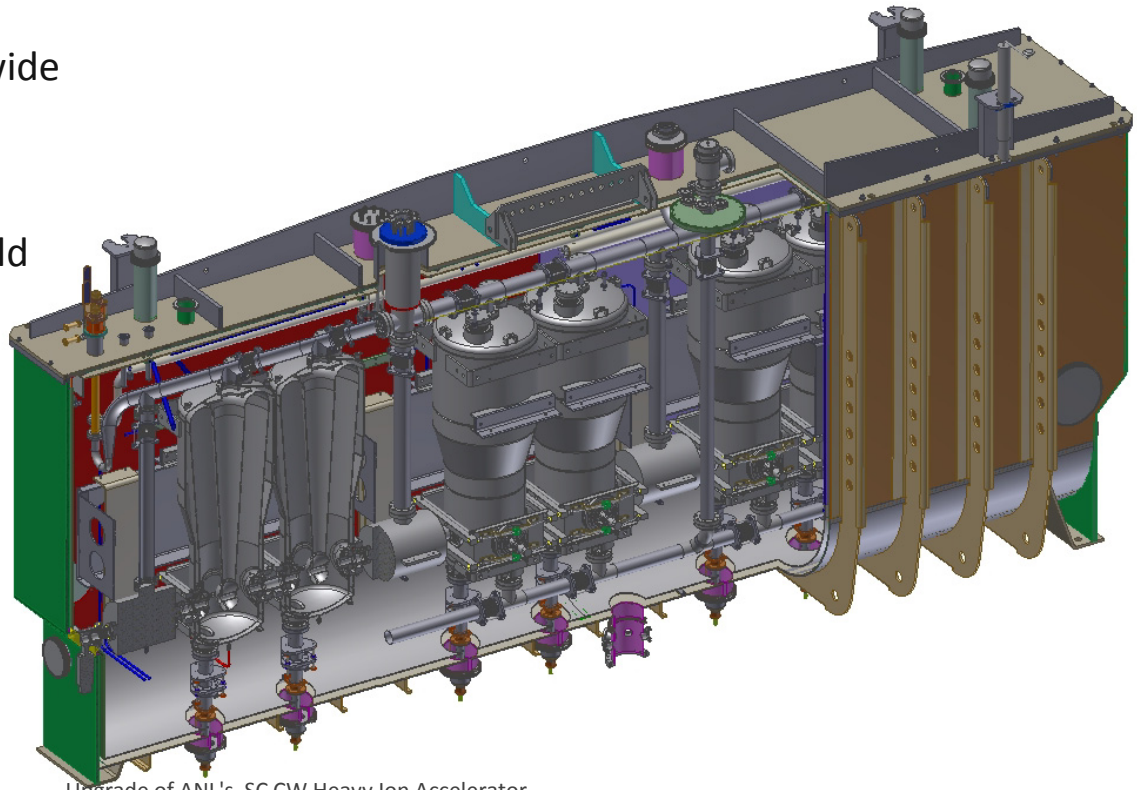
Cryomodule of 7 QWRs and 4 SC Solenoids

- Seven β = 0.077, 72.75 MHz quarter-wave cavities
- Four 9-Tesla superconducting solenoids
- Replaces 3 old cryomodules with split-ring cavities
- Total design voltage is 17.5 MV, 4.5K cryogenic load is 70 W
- Will be operated to provide ~20 MV, 4.5K cryogenic load is 85 W

5.2 m long x 2.9 m high x 1.1 m wide

Vacuum Vessel
Room Temperature Magnetic Shield
Aluminum Heat Shield
(MLI not shown)

Compact design, focusing period
Includes 2 cavities and 1 solenoid

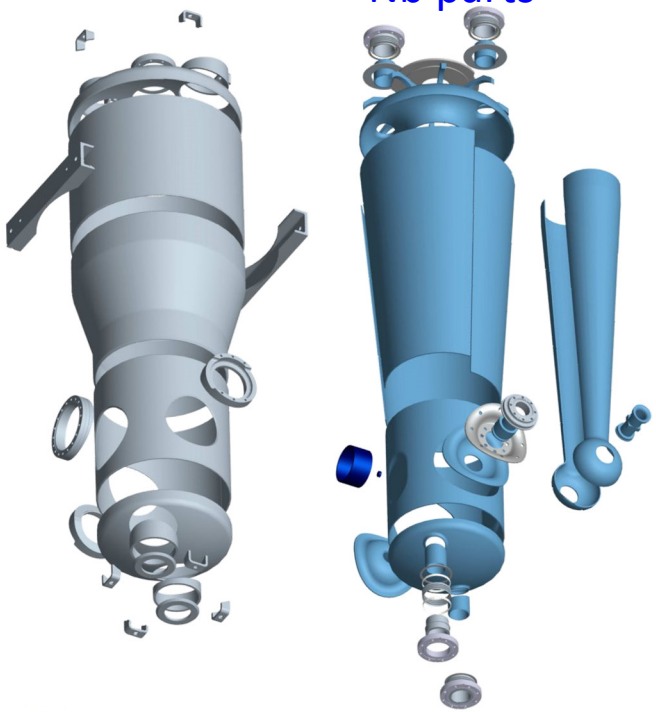


New 72.75 MHz QWR and Cryomodule

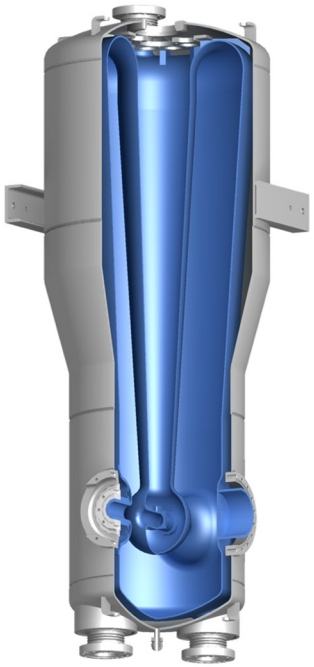
- Double conical highly-optimized design with steering correction
- Stainless steal helium jacket, brazed niobium–SS transitions
- Wire EDM instead of machining of EBW joints
- EP of the cavity after all fabrication work including He vessel is complete
- Central conductor was aligned to minimize microphonics

SS helium vessel

Nb parts



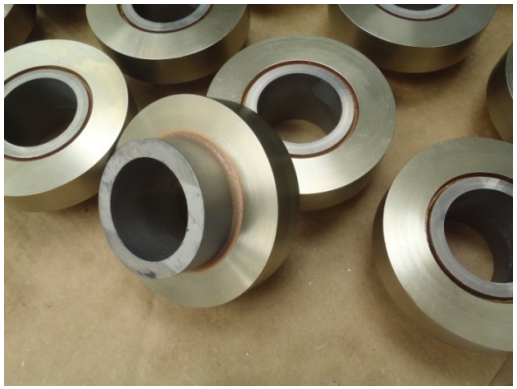
Cut-out view of the cavity assembly



	Design
V, max. voltage gain, MV	2.5
E_{PEAK}, MV/m	40
B_{PEAK}, mT	60
G, Ohm	26
R_{sh}/Q, Ohm	575
Cryogenic load at 4.5K, W	<10

Fabrication Steps: QWR Nb parts

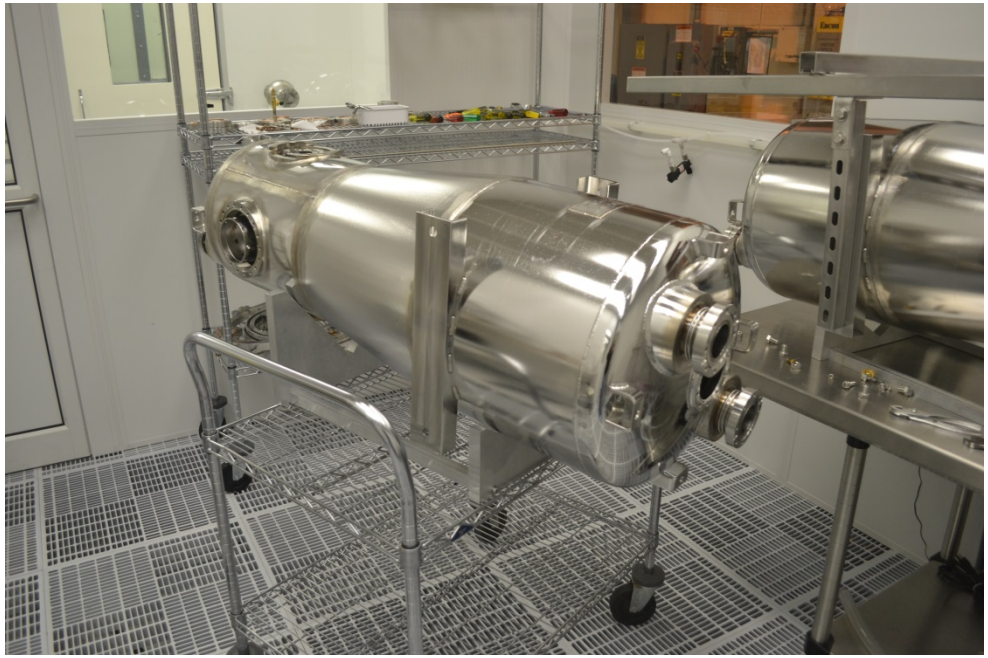
NB-SS transitions

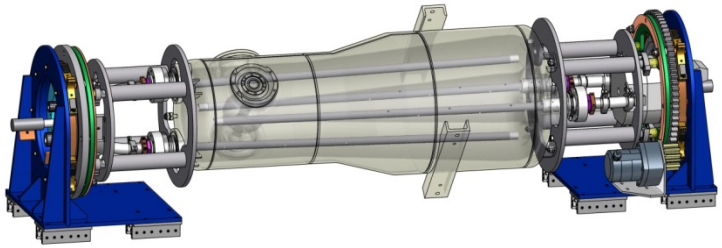


Wire EDM

Cavity RF Surface Treatment

- Improved upon ILC work to implement the worlds first low-beta cavity EP tool. This is similar to the ILC, but incorporates direct water cooling greatly improving polishing uniformity.
- For the first time: electropolishing after all fabrication work is complete.

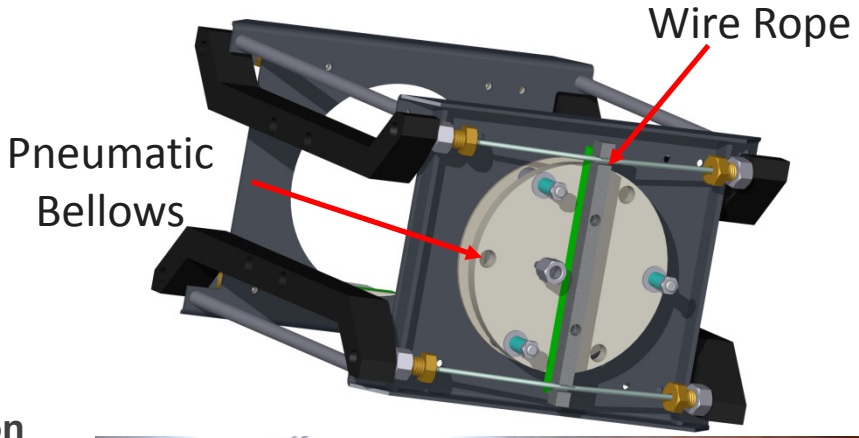


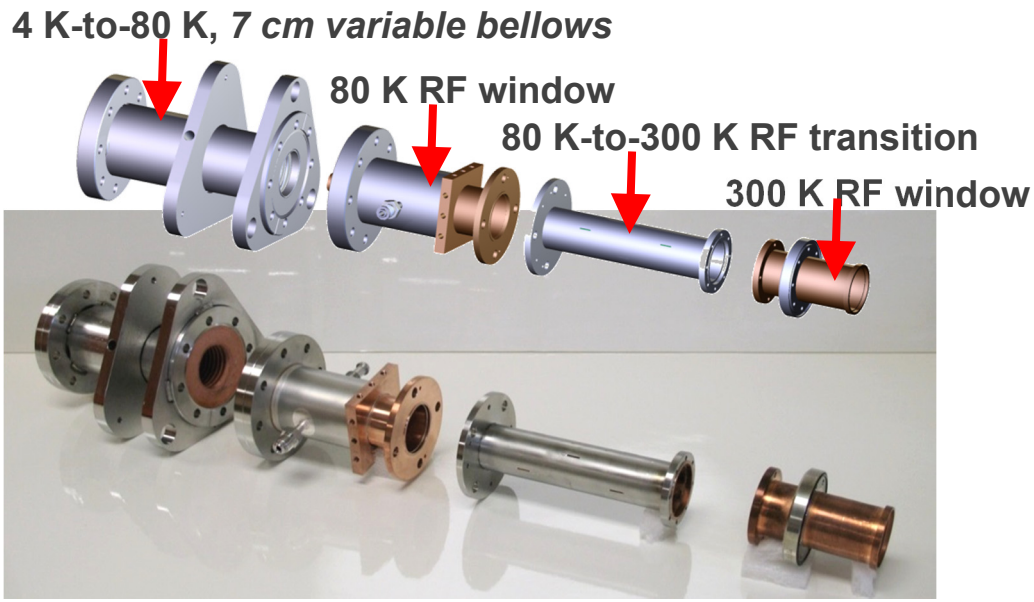


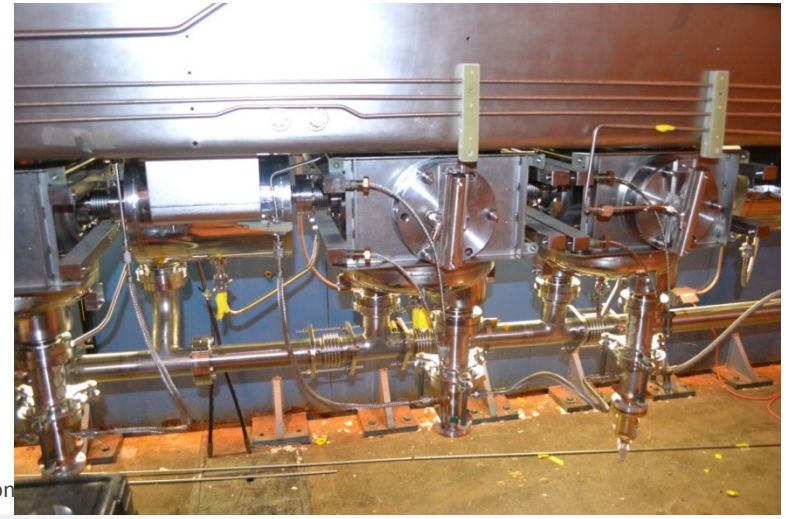
Power Coupler and Slow Tuner

- Capacitive couplers based on a 4 cm (1-5/8”) diameter, 50 W coaxial transmission line, 3” adjustable
- Two windows: LN2 cooled cold window and warm window
- 3 kW is sufficient to provide 40 Hz bandwidth

- Pneumatic slow tuner
- Helium pressure form 0 to 90 psi
- Elastic deformation of the cavity along beam axis



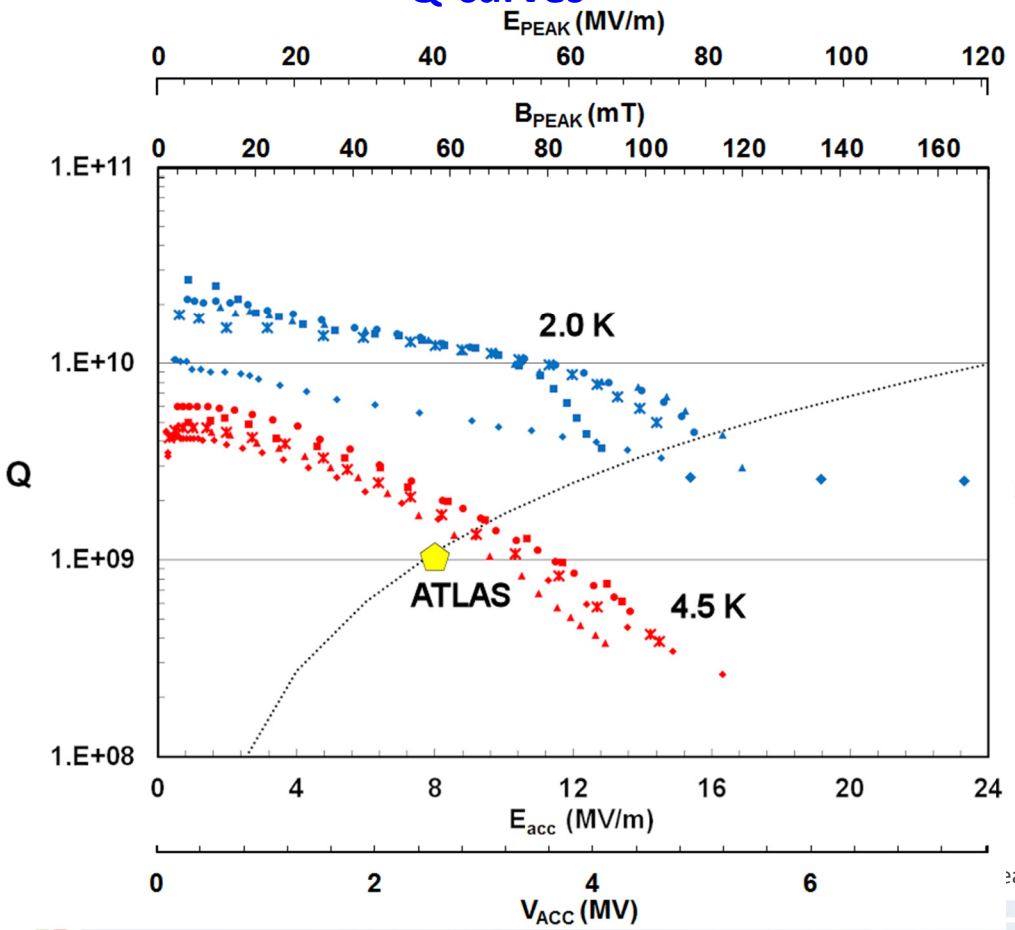




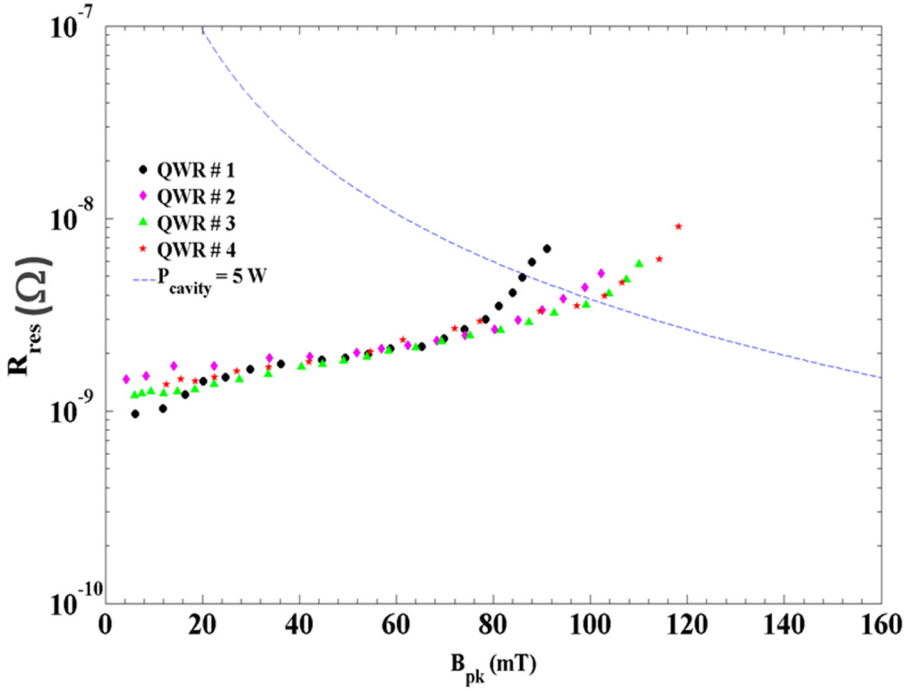
Test Results

- No X-rays up to E_{PEAK}= 60 MV/m
- Extremely low residual resistance, performance is similar as for the best ILC cavities
- All 7 cavities were tested in the cryomodule

Q-curves



Residual resistance at 2K

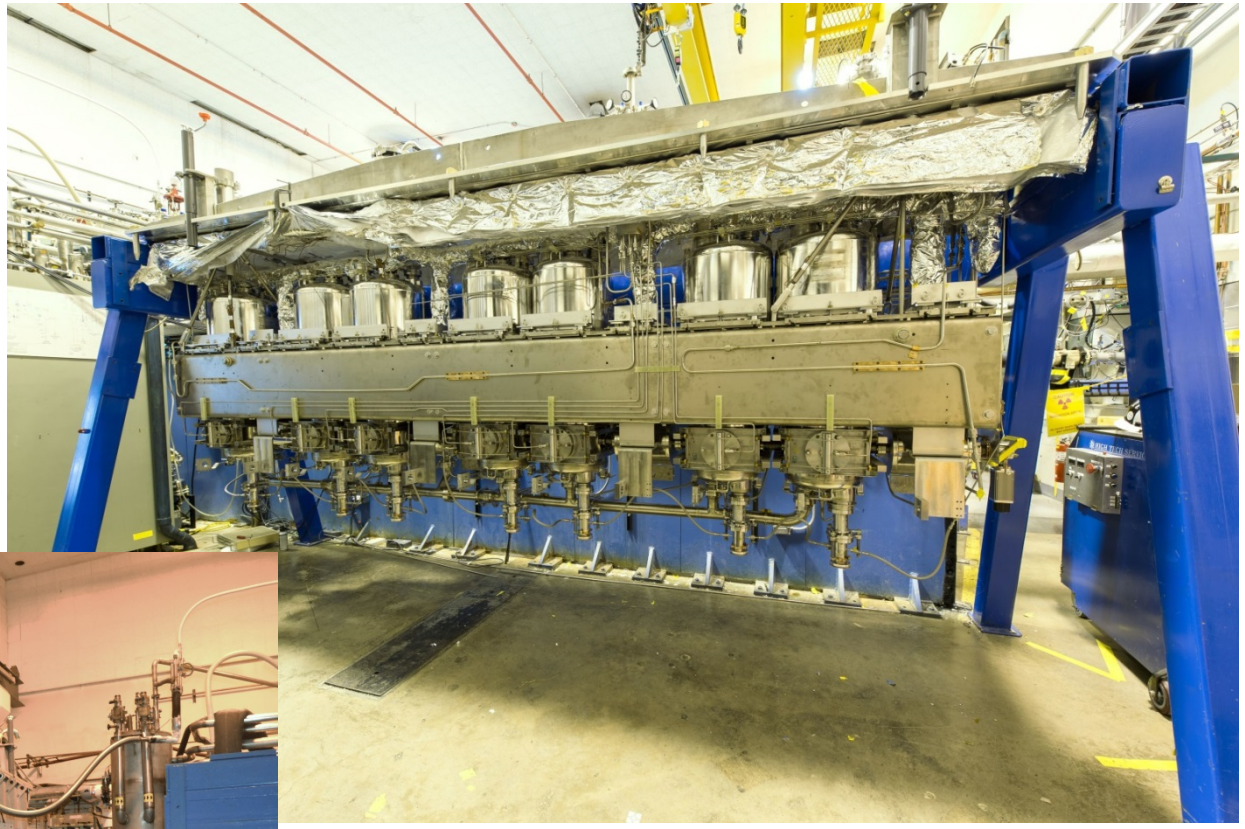


eavy Ion Accelerator

Assembly in Clean Room

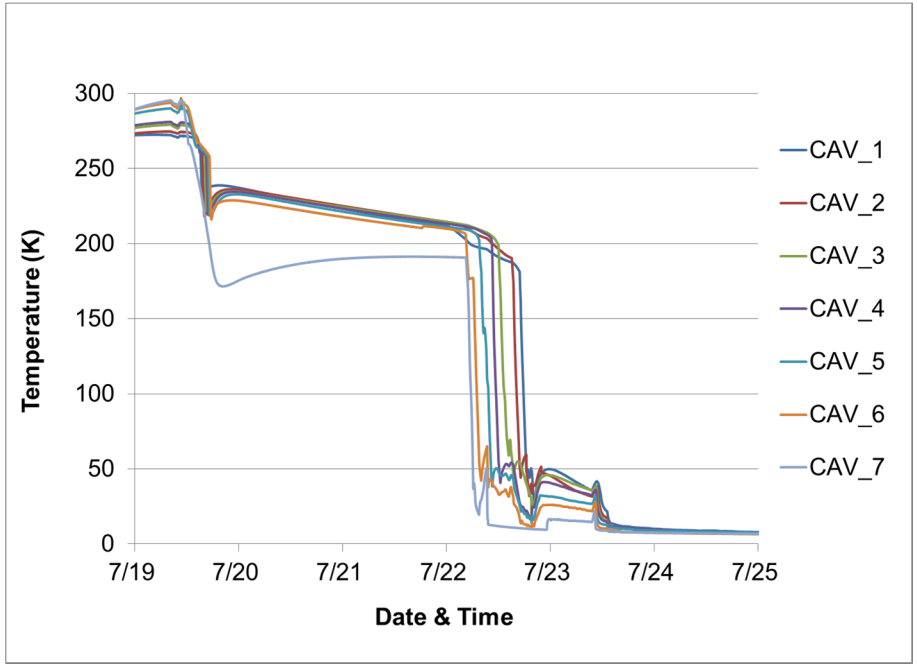
Cryomodule Assembly and Testing

- Off-line commissioning is complete
- Beam commissioning: November-December 2013



Cryomodule Off-line Commissioning

- Each cavity was cooled down quickly in the temperature range from 200K to 50K
- Due to variable RF couplers the multipactor conditioning took < 2 h per cavity.
- Each cavity is capable of providing an accelerating voltage >3 MV.
- Microphonics were measured to be below 5 Hz at the 5σ-level in all cavities
  - Each cavity is equipped with a 4-kW RF amplifier and variable coupler which provide up to a 40 Hz bandwidth for RF control.
- The pneumatic slow tuner: 17 kHz to 26 kHz at 70 psi. Can be increased by applying up to 90 psi.
- The cavities and solenoids were aligned by optical measurements. Alignment accuracy is ±250 μm for the solenoids and ±500 μm for the cavities
- The static 4 K heat load of the entire assembly was measured to be 11 Watts which is an extremely low number for such a complex cryomodule
- Installation into the beamline and commissioning with beam: October-December 2013



Summary

- The new CW RFQ with several novel features has been built and commissioned in 3 years
- RFQ has demonstrated optimal performance from day one and operates “24/7” at the National User Facility ATLAS
- High-performance cryomodule was designed, built and commissioned in 4 years
- Extremely low residual resistance of 1 nΩ at low field and 3 nΩ at B_{PEAK}=80 mT is demonstrated
- Record high accelerating voltages above 3 MV per cavity in the cryomodule are demonstrated.
- This results in 4 MV/m real-estate accelerating gradient in CW regime
- Alignment of multiple SC solenoids in the cold cryomodule is within ±250 μm