Status of Superconducting Electron Linac Driver for Rare Ion Beam Production at TRIUMF

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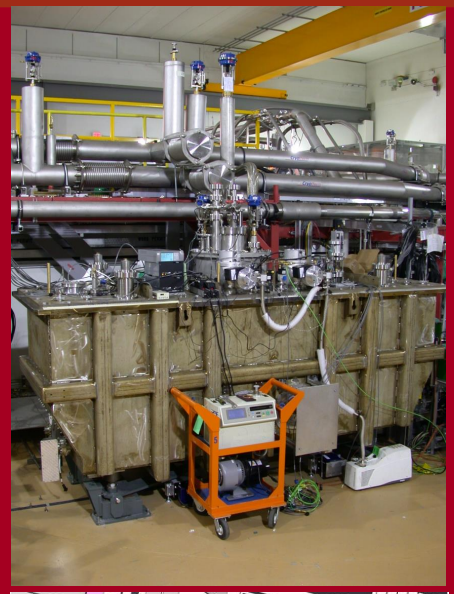
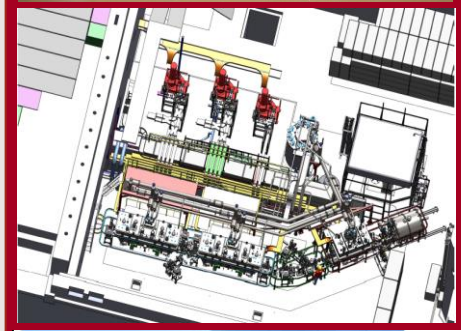
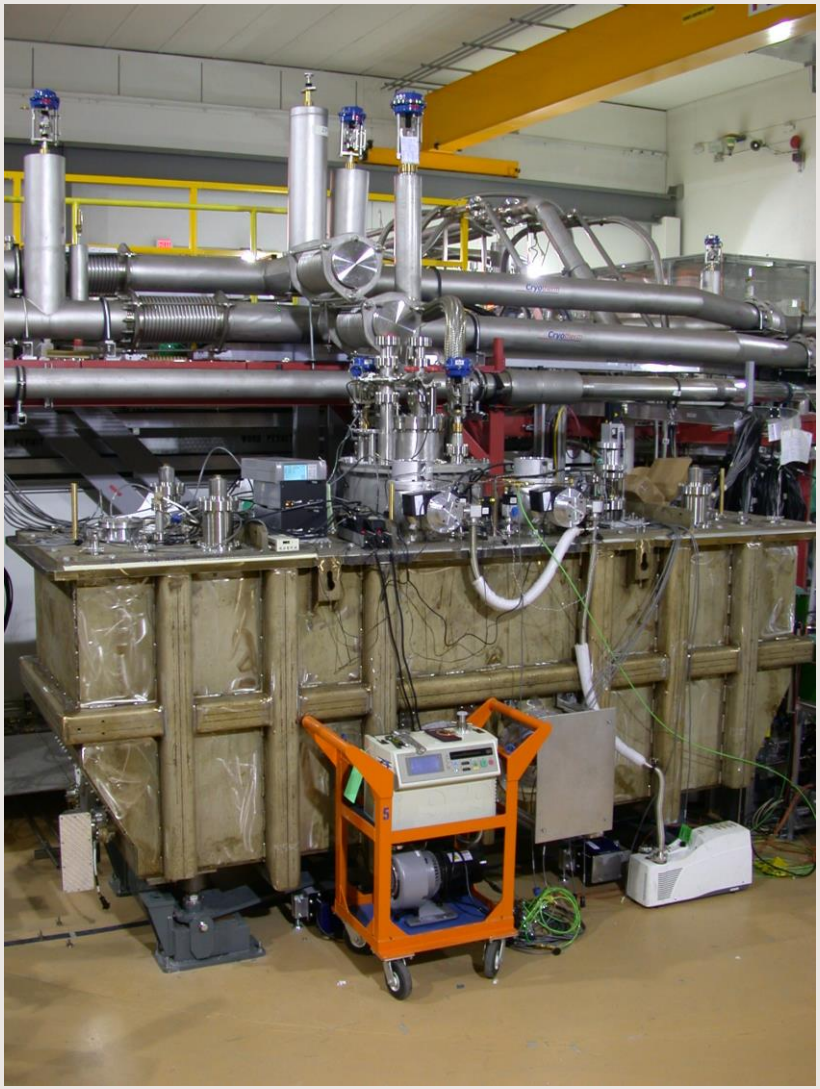




Outline

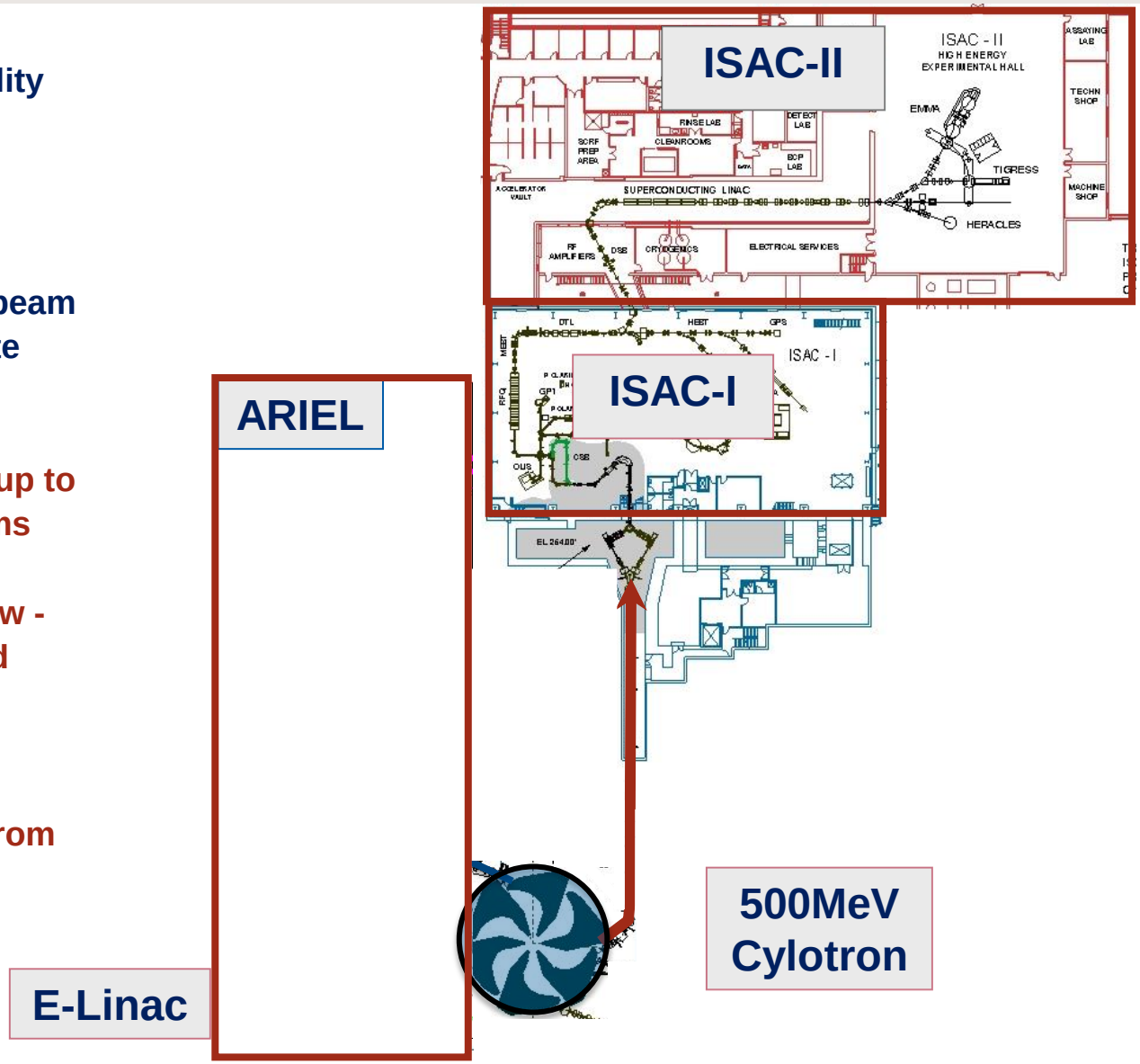
- ARIEL Project
  - E-Linac Specification
- E-Linac design
  - Major components
- Status and commissioning results
- Future plans



ARIEL and the e-Linac

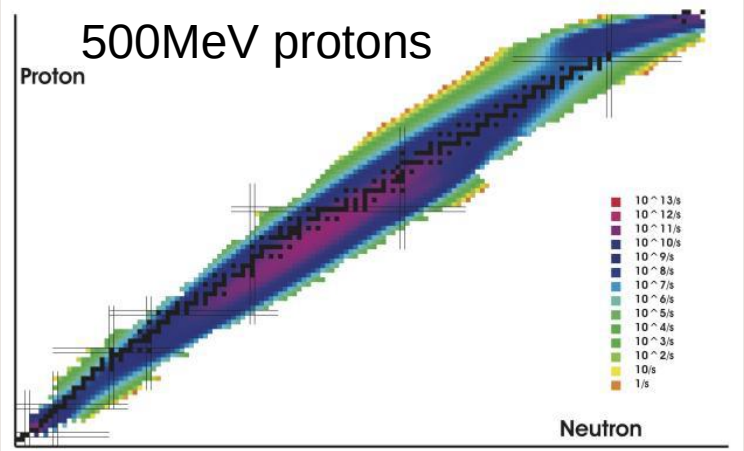
ARIEL Project (2010-2020)

- ISAC: World class ISOL facility for the production and acceleration of rare isotope beams (RIB)
- Presently utilize one driver beam at 500MeV and 50kW to create RIBs for ISAC
- Now adding ARIEL to allow up to three simultaneous RIB beams
- Add e-Linac (50MeV 10mA cw - 1.3GHz SC linac) as a second driver to create RIBs via photofission
- Add a second driver beam from the cyclotron

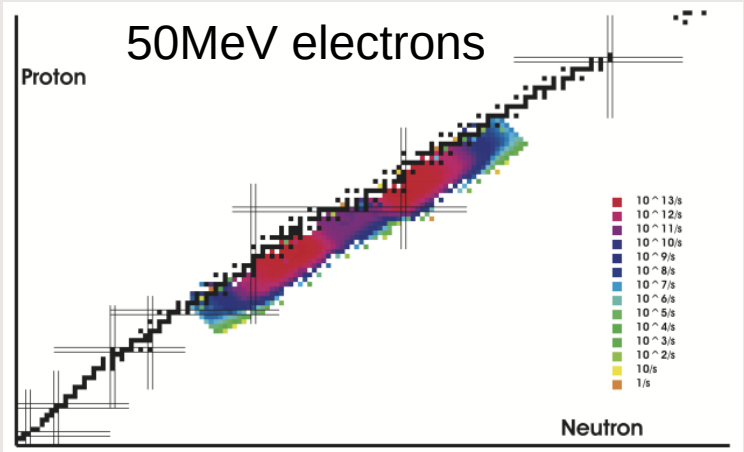


Why electrons? Why 50MeV?

- the electron linac is a strong complement to the existing proton cyclotron
  - Photofission yields high production of many neutron rich species but with relatively low isobaric contamination with respect to proton induced spallation
  - An energy of 50MeV is sufficient to saturate photo-fission production – fits the site footprint and project budget



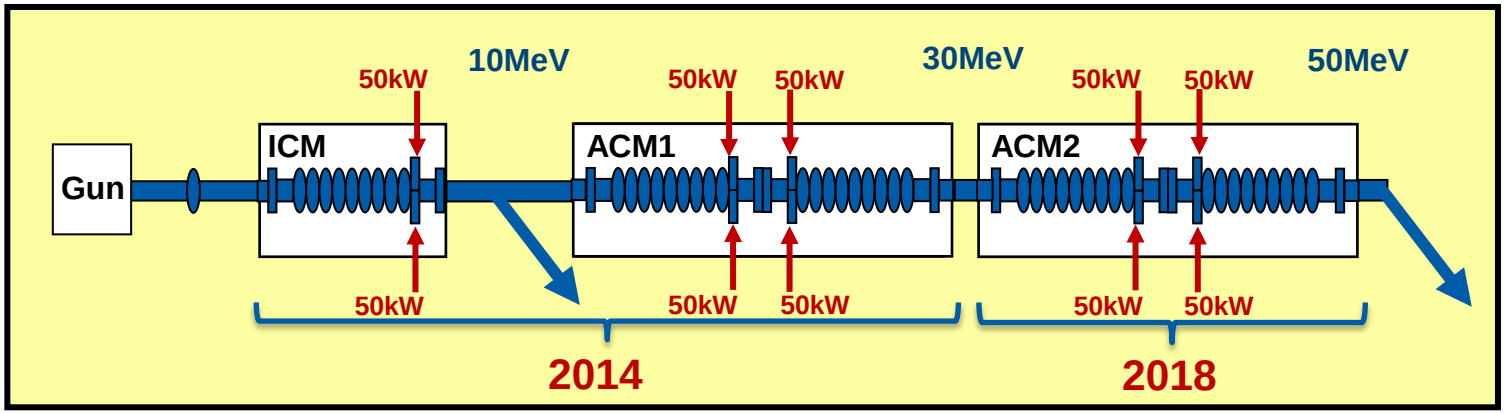
Calculated in-target production for 10 μA, 500 MeV protons incident on a 25 g/cm2 UCx target



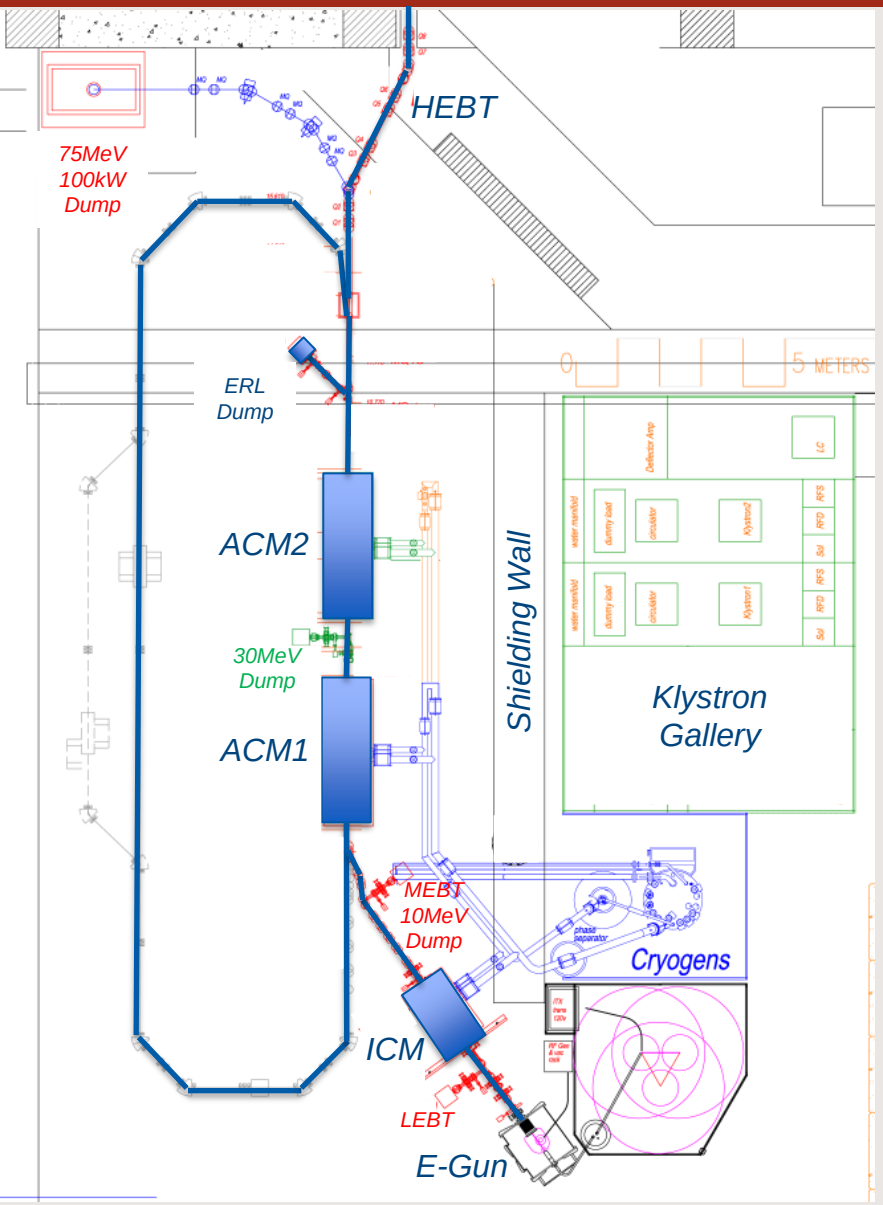
Calculated in-target production for 10 mA, 50 MeV electrons incident on a Hg converter and 15 g/cm2 UCx target

E-Linac Specifications

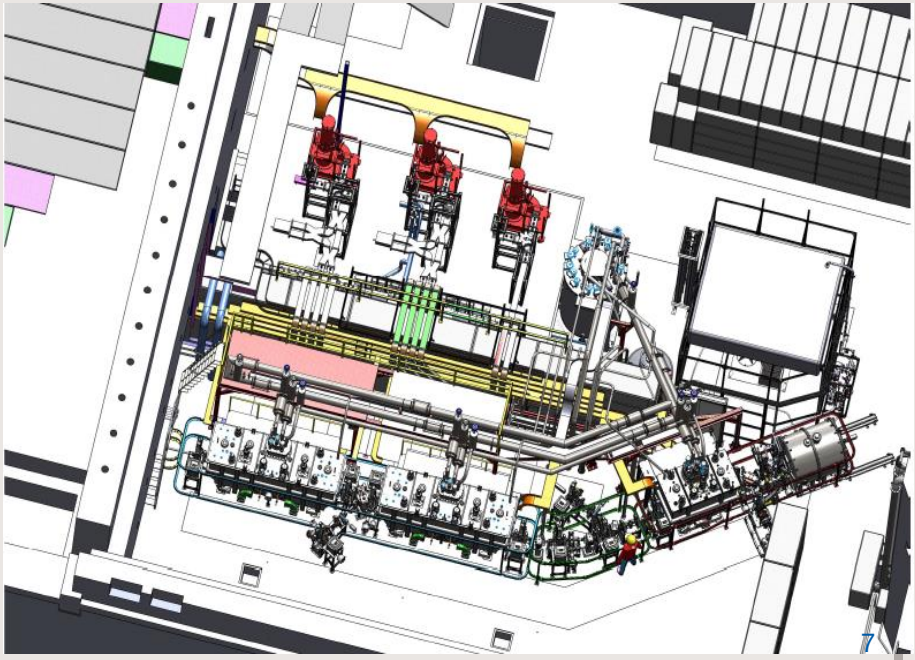
- The ARIEL E-Linac specification – dominated by rf beam loading
  - 10mA cw at 50MeV - 0.5 MW of beam power
  - Choose five cavities 100kW of beam loaded rf power per cavity
  - two couplers per cavity each rated for 50kW operation
  - Means 10MV energy gain per cavity
- Linac divided into three cryomodules
  - one Injector cryomodule (ICM) with one cavity
  - two Accelerator crymodules (ACM1, ACM2) with two cavities each
  - Installation is staged - Phase I – includes ICM and ACM1 for a required 25MeV/100kW demonstration by end of 2014



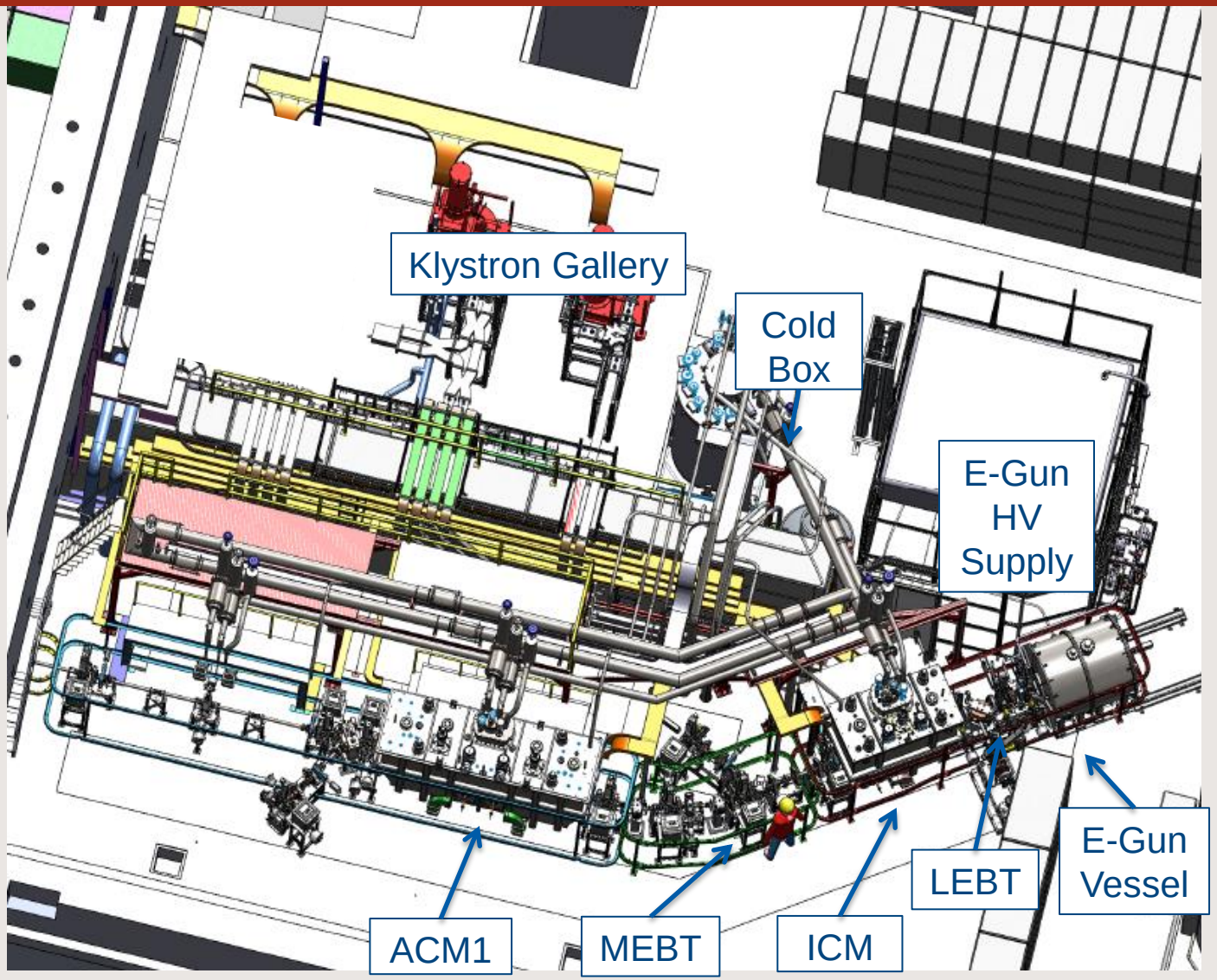
The ARIEL e-Linac as a recirculator



- The linac is configured to eventually allow a recirculating ring for a multi-pass `energy doubler' mode or to operate as an energy recovery linac for accelerator studies and applications



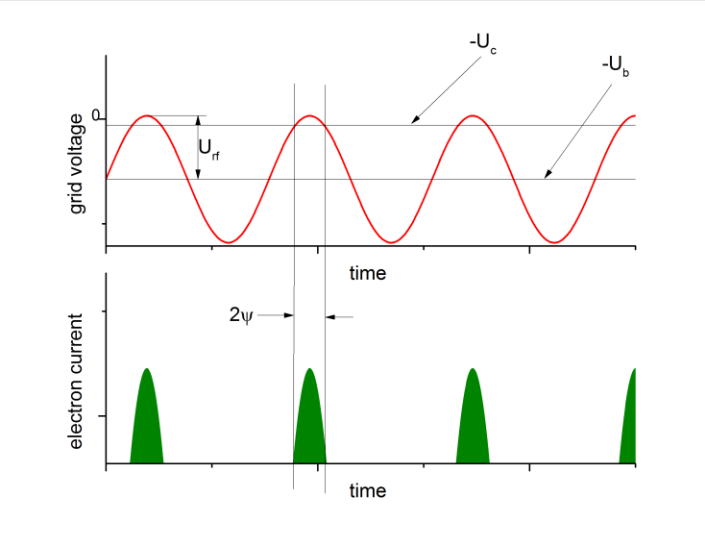
Accelerator Vault – Phase I



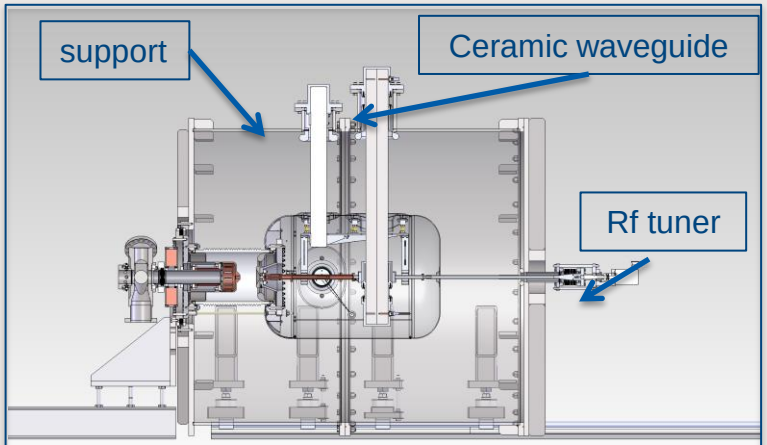
E-Linac Design

Electron Gun

- Thermionic 300kV DC gun – cathode has a grid with DC supressing voltage and rf modulation that produces electron bunches at rf frequency
- Gun installed inside an SF6 vessel
- Rf delivered to the grid via a ceramic waveguide



Parameter	Value
RF frequency	650MHz
Pulse length	$\pm 16^0$ (137ps)
Average current	10mA
Charge/bunch	15.4pC
Kinetic energy	300keV
Normalized emittance	5μm
Duty factor	0.01 to 100%

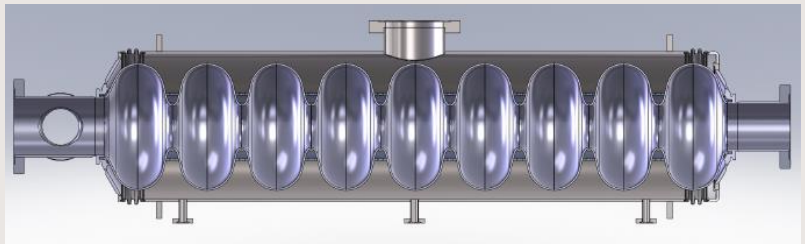


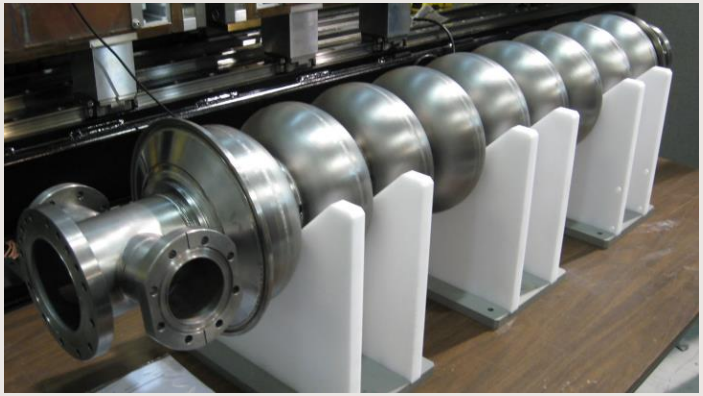
SF6 Vessel

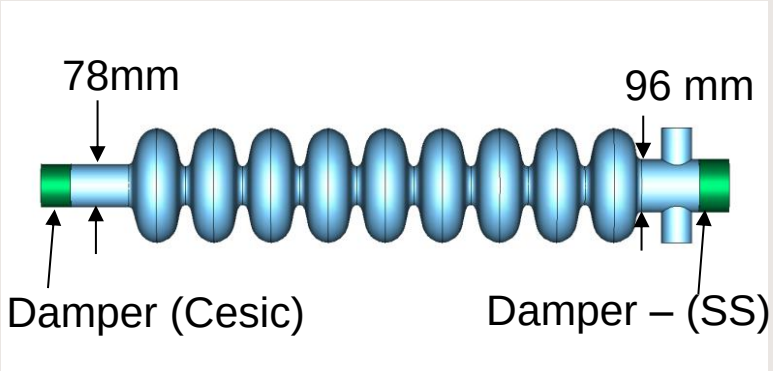
ARIEL cavities

- The ARIEL cavities
  - 1.3GHz nine-cell cavities
  - End groups modified to accommodate two 50kW couplers and to reduce trapped modes
  - Large (90mm) single chimney sufficient for cw operation up to 50W

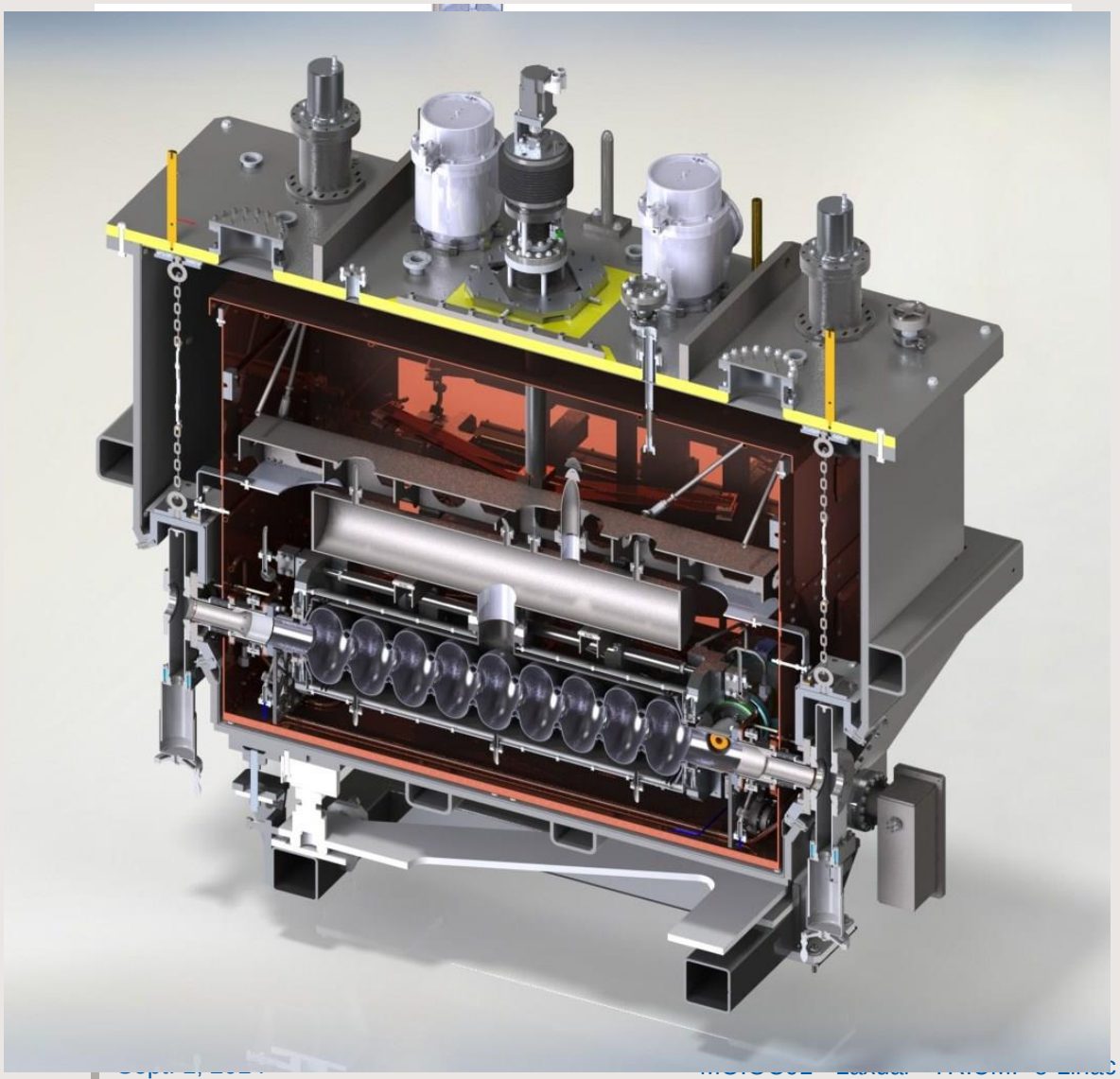
Parameter	Value
Active length (m)	1.038
RF frequency	1.3e9
R/Q (Ohms)	1000
Q_0	1e10
E_a (MV/m)	10
P_{cav} (W)	10
P_{beam} (kW)	100
Q_{ext}	1e6
Q_L*R_d/Q of HOM	<1e6







Injector Cryomodule



Houses

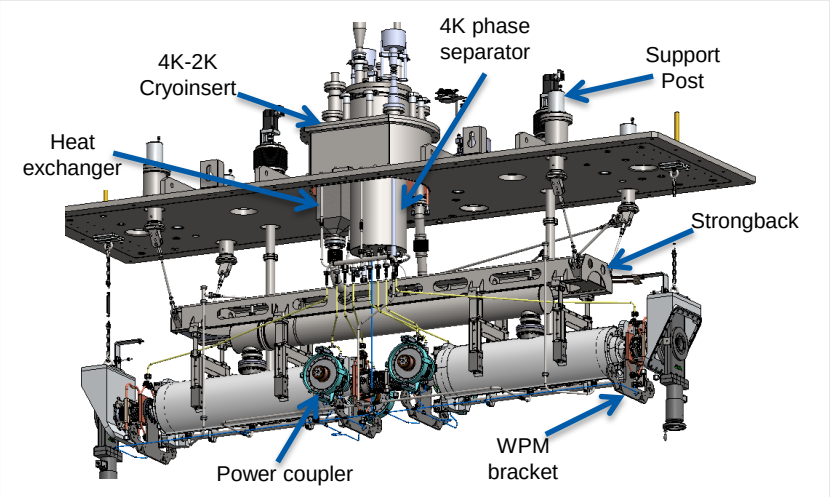
- one nine-cell 1.3GHz cavity
- Two 50kW power couplers

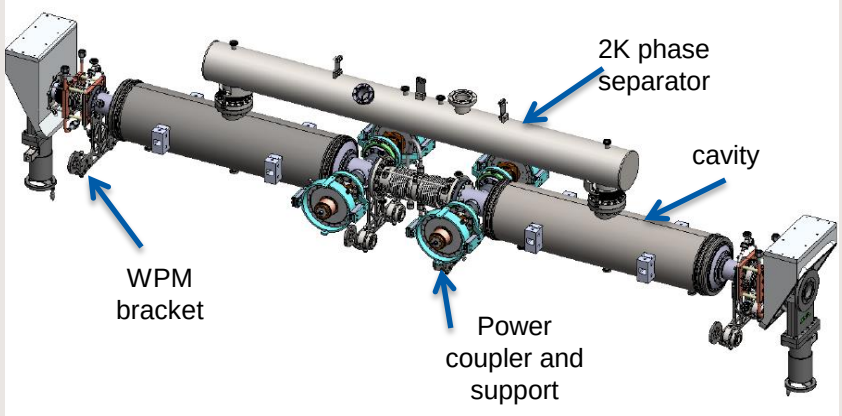
Features

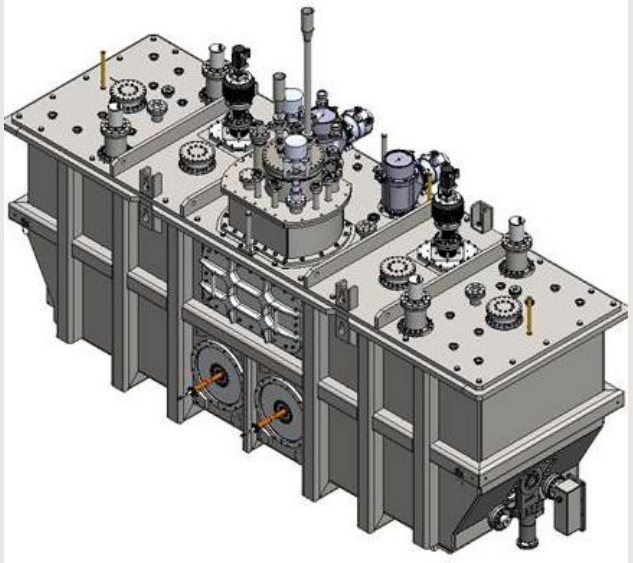
- 4K/2K heat exchanger with JT valve on board
- Scissor tuner with warm motor
- LN2 thermal shield – 4K thermal intercepts via syphon
- Two layers of mu-metal
- WPM alignment system

Accelerator Cryomodule

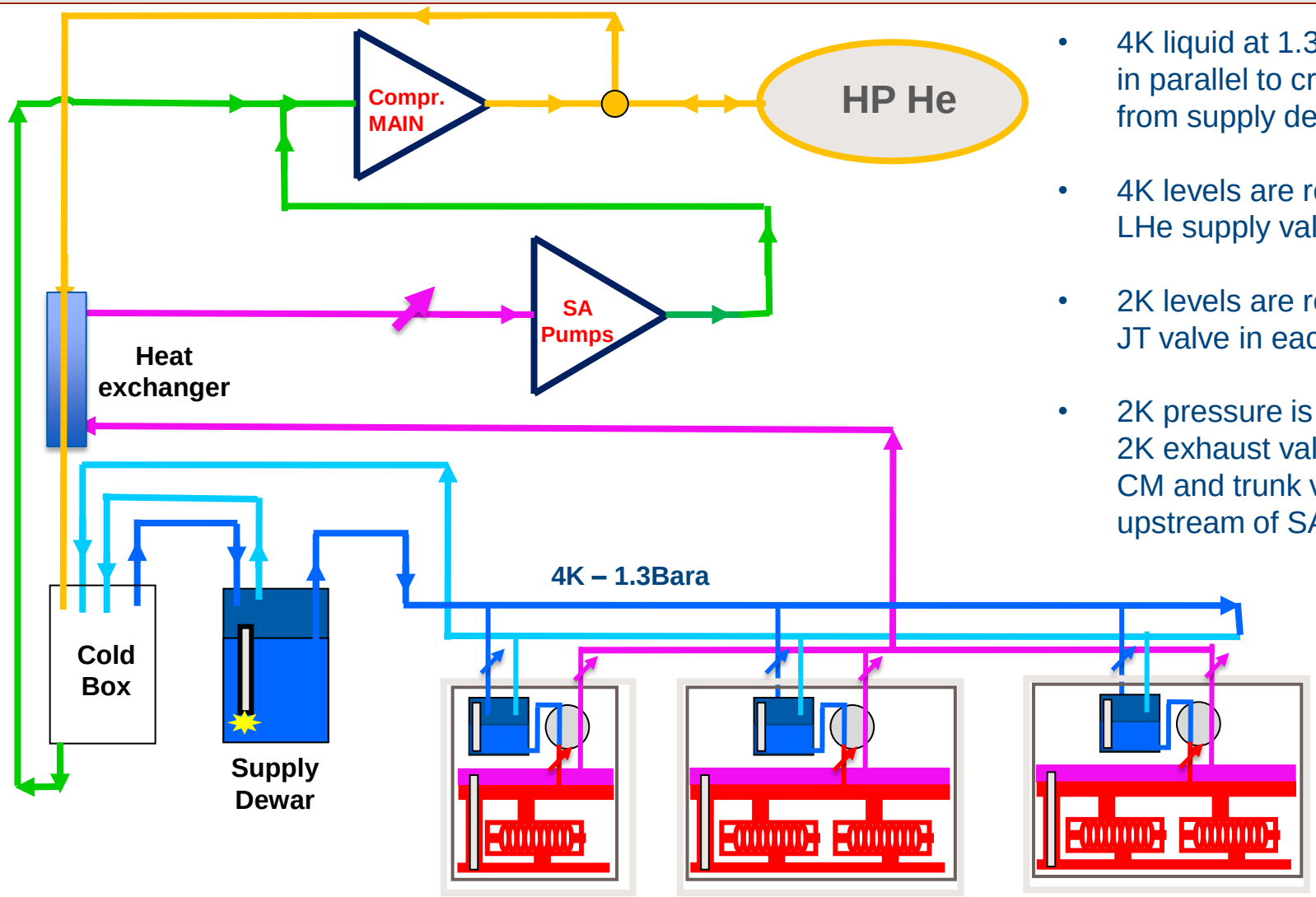
- The ACM uses same basic design as ICM but with two 1.3GHz nine cell cavities each with two 50kW power couplers
- There is one 4k/2k insert identical to the ICM
- Physical dimensions
  - L x H x W = 3.9 x 1.4 x 1.3 m
  - 9 tons







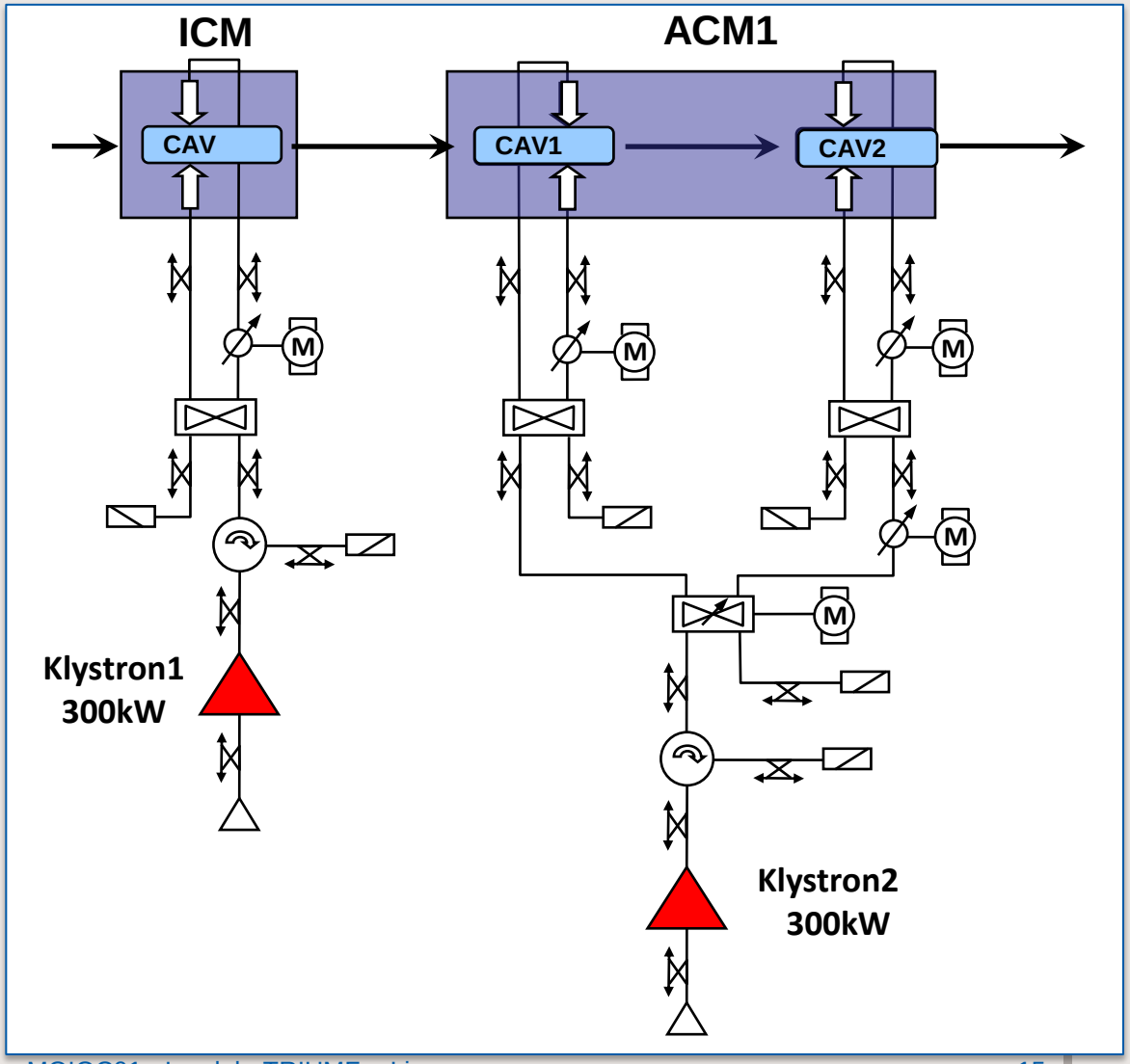
Cryogenics



- 4K liquid at 1.3 Bar delivered in parallel to cryomodules from supply dewar
- 4K levels are regulated by LHe supply valve
- 2K levels are regulated by JT valve in each CM
- 2K pressure is regulated by 2K exhaust valve on each CM and trunk valve upstream of SA pumps

E-Linac RF Drive System

- For Phase I we specify two 300kW klystrons – one for each cryomodule
- In the future one 300kW klystron will drive ACM2
- we are looking for a cost effective 1.3GHz power source at ~150kW for the ICM

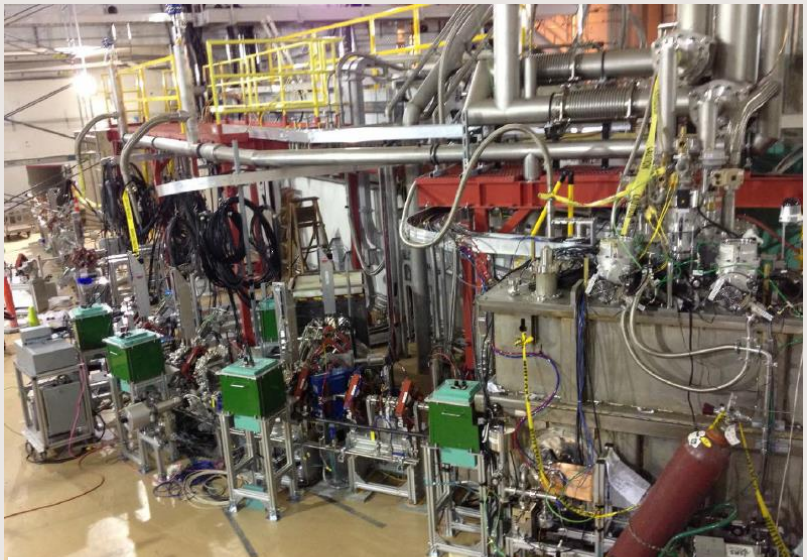


Status and Commissioning

Progress

- Progress in the last year
  - Cryogenics acceptance tests complete
  - E-Gun and LEBT installed and commissioned – MEBT installed
  - Two klystrons and HV supplies installed and commissioned
  - ICM assembled, installed and commissioned
  - ACM assembled and installed

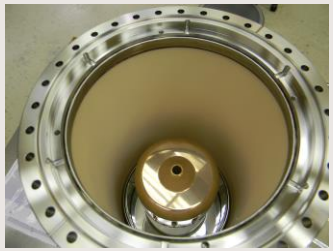
January 2014



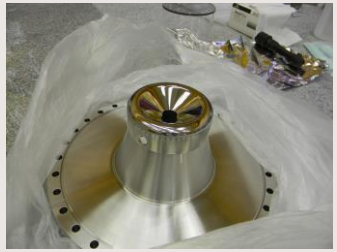
July 2014

Electron Gun Status

- The electron gun and LEBT were installed in February/March 2014
- Bias voltage of 325kV achieved
- 10mA cw achieved at 300kV
- Rf modulation with the ceramic waveguide a success
  - Macro pulsing demonstrated over a broad range
  - 100Hz-10kHz rep rates with duty factors from 0.01-100%
- Transverse and longitudinal phase space measured in LEBT



Cu-Be Anode



Ti Pierce Electrode

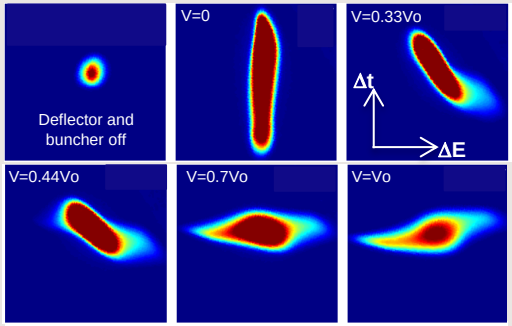
SF6 Vessel Installed

Ceramic Waveguide

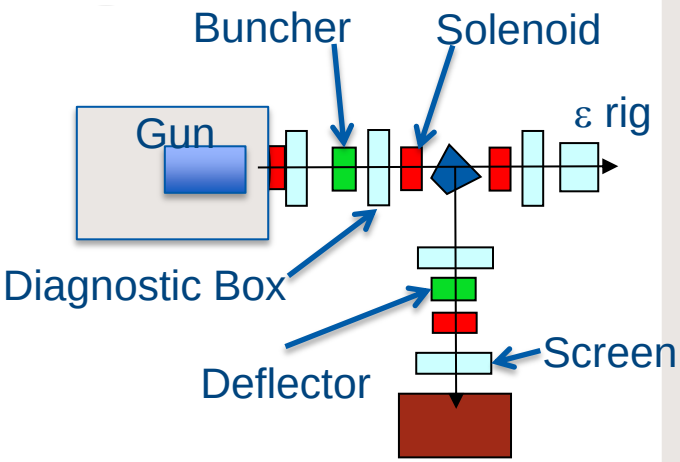
350 kV, 16 mA HVPS

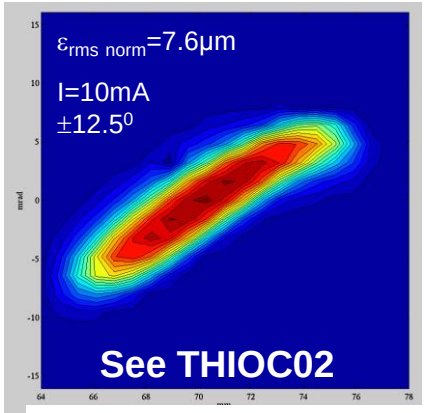
LEBT Diagnostics

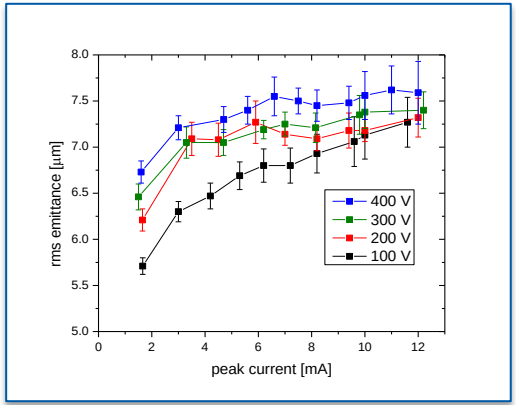
- LEBT includes an analyzing leg and diagnostics to characterize the gun emittance and set the matching for the ICM
- TM110 deflecting mode cavity and high power emittance rig

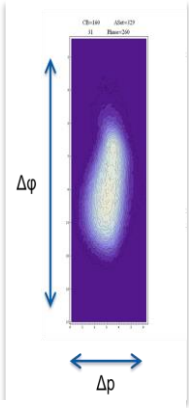


Screen images downstream of rf deflector show manipulation of longitudinal emittance with the buncher cavity at different voltages.

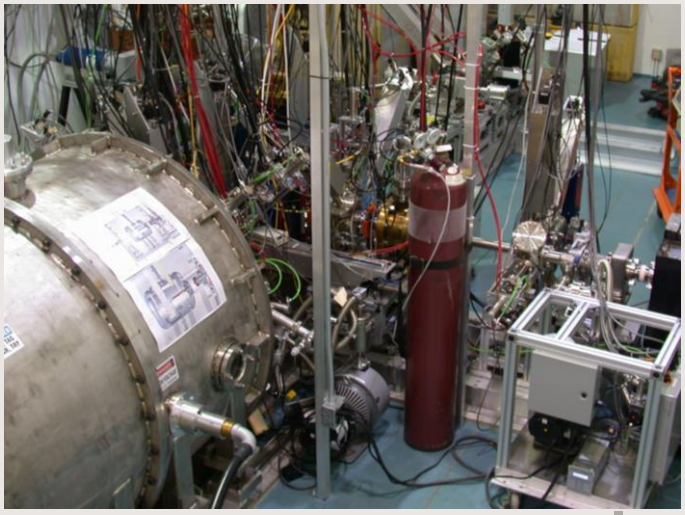






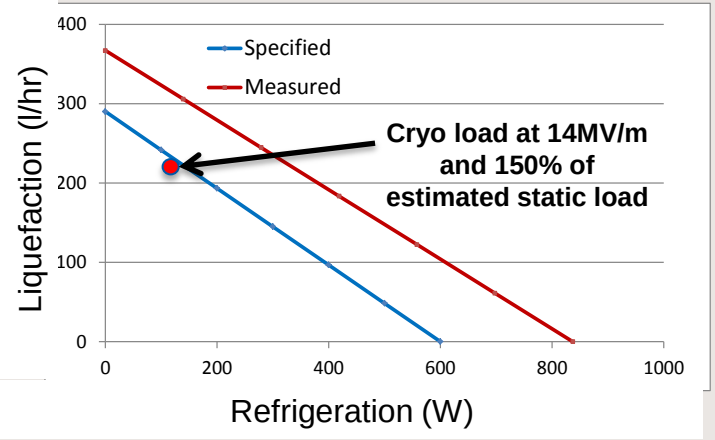


E-Gun transverse and longitudinal emittance measurements



Cryogenics installation

- 4K system
  - ALAT LL Cold Box, KAESER (FSD571SFC) main compressor (112g/s), Cryotherm - distribution
  - Acceptance tests (with LN2 pre-cooling) exceed all specifications with comfortable margins
- Sub-atmospheric pumping
  - Four Busch combi DS3010-He pumping units specified and installed (1.4g/s @ 24mBar each)



Parameter	Contract	Measured
Liquefaction	288 L/hr	367 L/hr
Refrigeration	600 W	837 W

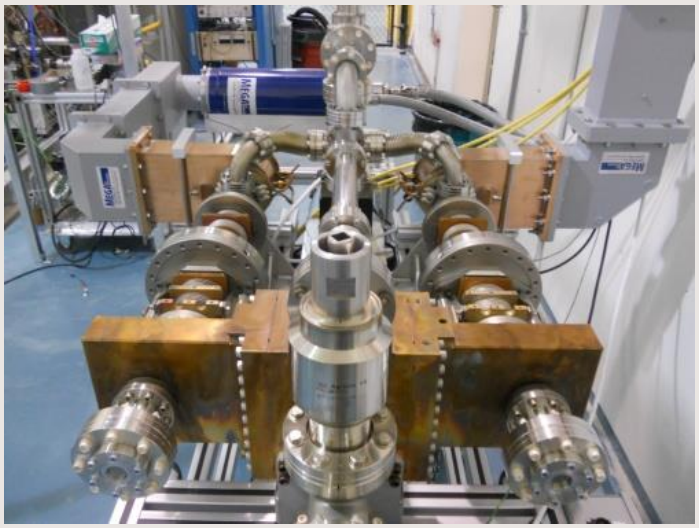
High Power RF Installation

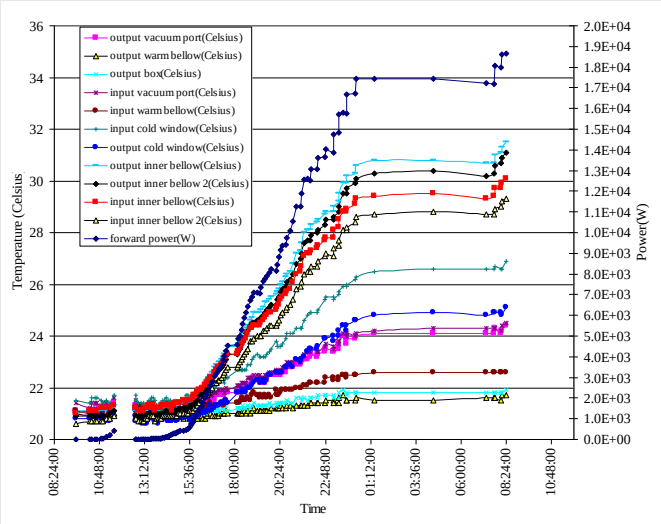
- Now installed
  - Two CPI 290kW cw 1.3GHz klystrons
  - Two 600kW 65kV klystron power supplies from Ampegon
- Each klystron reaches specification at the factory
- At TRIUMF – tests were limited by available load or circulator – one was operated to 250kW cw the other to 150kW cw
- Delivered a peak power of 25kW into a cold cavity at low duty factor

Power coupler conditioning

- Power coupler conditioning
  - Condition two couplers at once at room temperature using 30kW IOT
  - Two 50kW CPI couplers installed on waveguide box and power transmitted to a dummy load
- Preparation involves extended bakeout (five days) at 100C with N2 flowing
- RF conditioning in both TW (18kW cw) and SW mode (10kW pulsed) with adjustable short (five days)

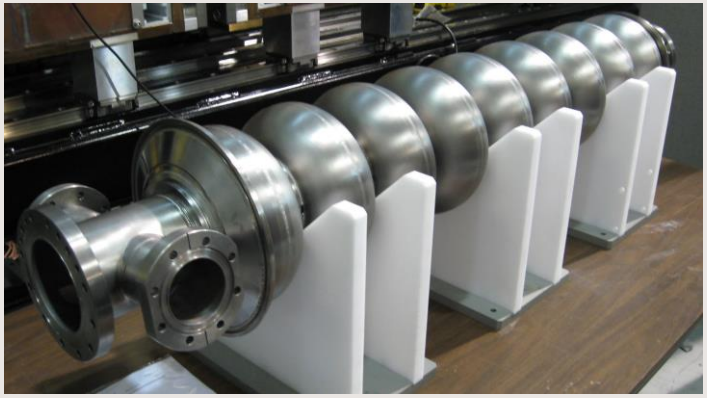
Conditioning Stand

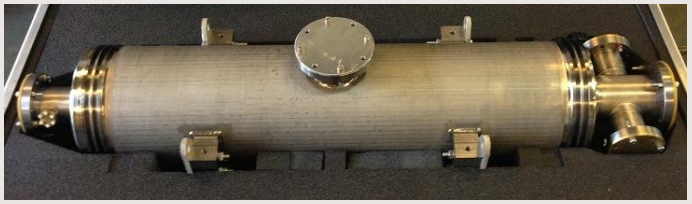


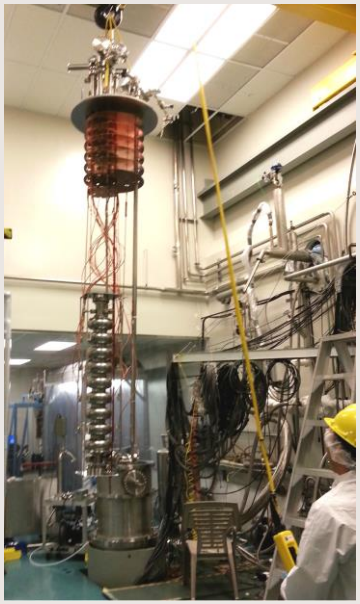


ARIEL Cavities - PAVAC

Cavity	Preparation	Status
ARIEL1	BCP120, Degas at FNAL	Installed in ICM1
ARIEL2	BCP, Degas at FNAL, 120Bake, HF rinse	Installed in ACMuno
ARIEL3	120micron BCP	Vertical test

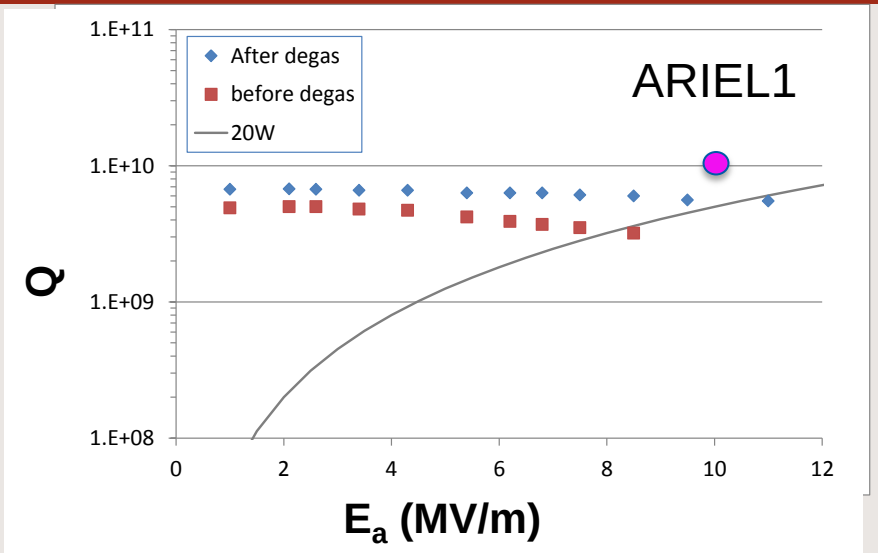


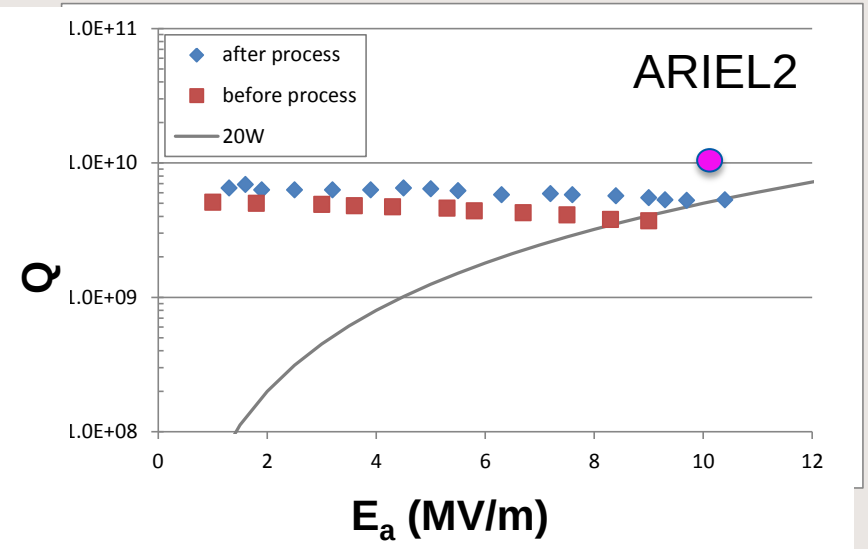




ARIEL Cavities

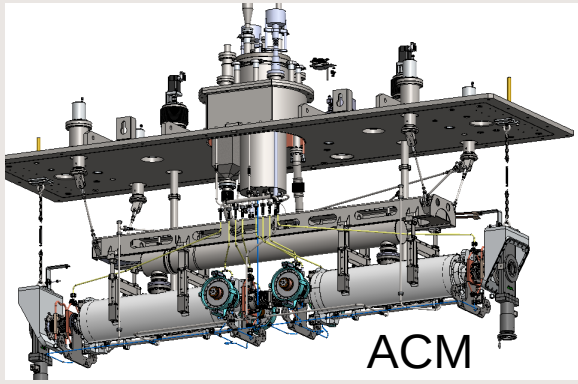
- Cavity vertical cold tests in ISAC-II before and after re-process
- Both cavities reach the specified gradient of 10MV/m but at Qo=6e9
- For Phase I we have lots of cryogenic power so derate specification to Qo=5e9
- Strategy is to utilize ARIEL1 and ARIEL2 to characterize the cryo-engineering of the cryomodules and use ARIEL3 to optimize the process.

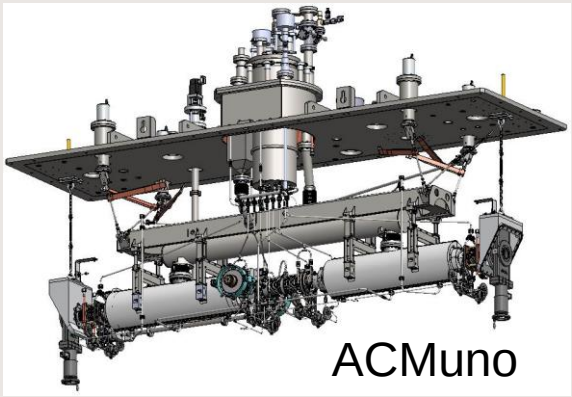


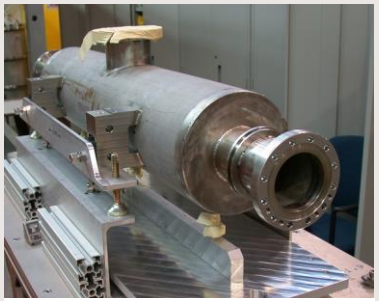


Cryomodule strategy

- Jacket and install ARIEL1 in ICM
- Jacket and install ARIEL2 and install in ACM together with a dummy cavity
  - We call the single cavity ACM configuration **ACMuno**
- ACMuno
  - Dummy cavity has all interface features including helium jacket and DC heater
  - All helium piping and beamline interconnects will be final
  - ACMuno allows a full cryogenics engineering test plus two cavity beam acceleration to 25MeV
- The goal is to install the cryomodules for a combined beam test in Sept. 2014 – cryogenic engineering and funding milestone







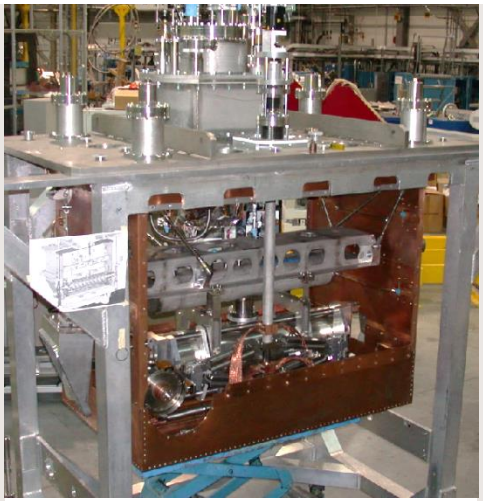
Dummy cavity

ICM Assembly

- Mock-up assembly of ICM used to test parts and procedures
- Final assembly (aided by lessons learned from mock-up) - completed in <1 month

Cavity hermetic unit (March 14, 2014)

ICM top assembly

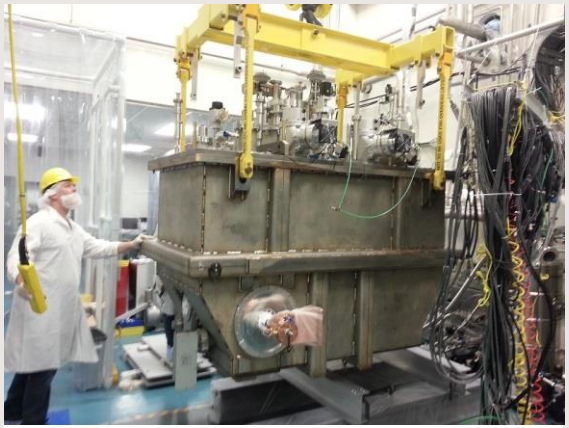


ICM mock-up – 2013

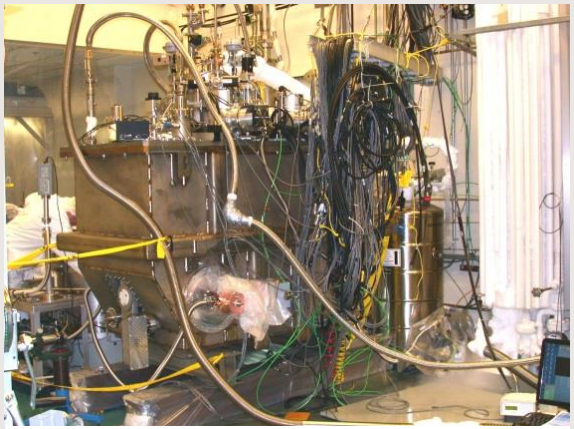
Top assembly into tank

ICM unit Complete (April 9, 2014)

ICM Cold test



ICM craned into position



ICM during cold test

Preparing cables and cryogenics

Cold test complete

- ICM delivered to cryogenic test area
- Established cool-down protocol, vacuum integrity and cryogenic performance
- Tested thermal syphon parameters
- Tuned couplers to Qext~$3x10^6$
- Established cold alignment

ICM Move (April 28)

ICM over ISAC-II

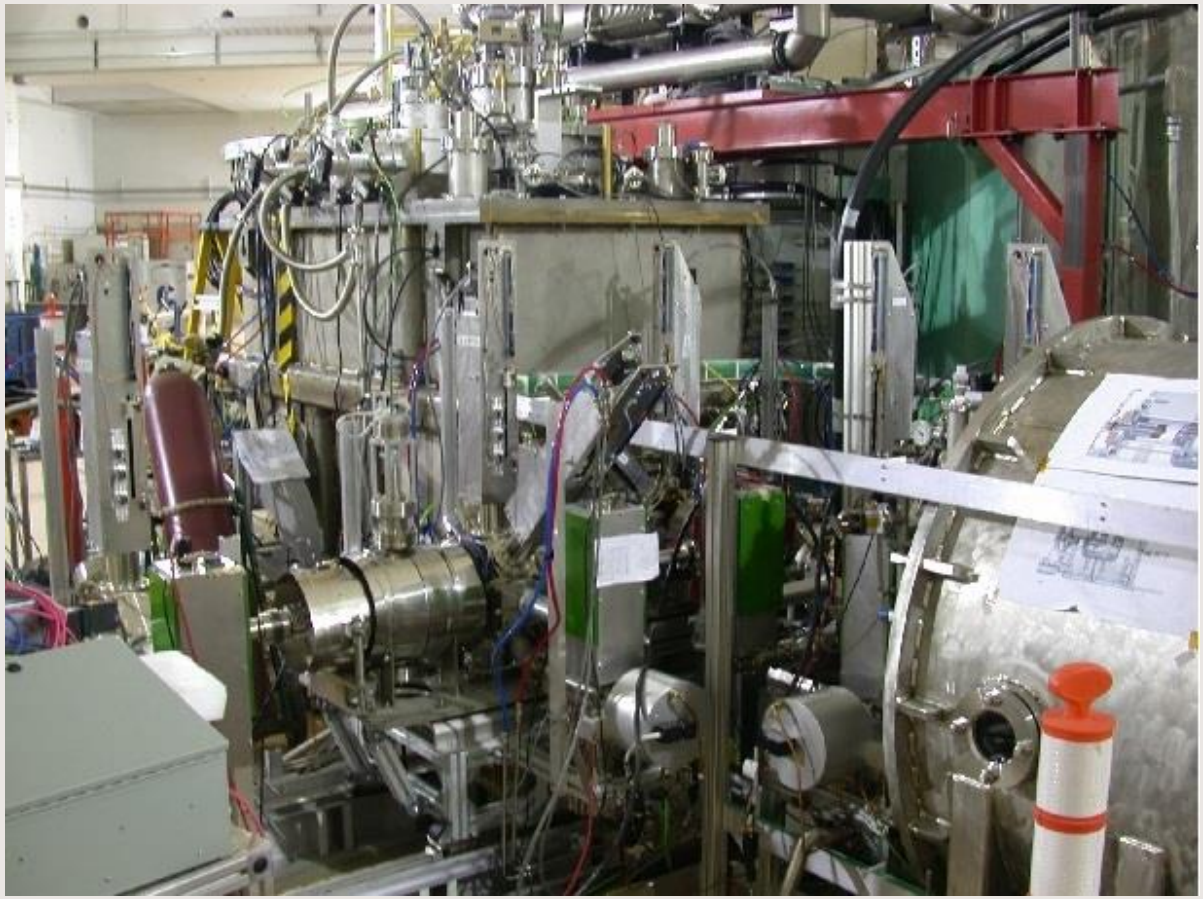
ICM on the move

Lowering ICM to the e-Hall

On April 28 the ICM was moved from the clean room, craned over ISAC-II hall, carted over to proton hall loading bay, craned down to e-hall and finally craned into position, six weeks after completion of the hermetic unit

ICM in position in the e-Hall

10MeV Beam Test – June 2014



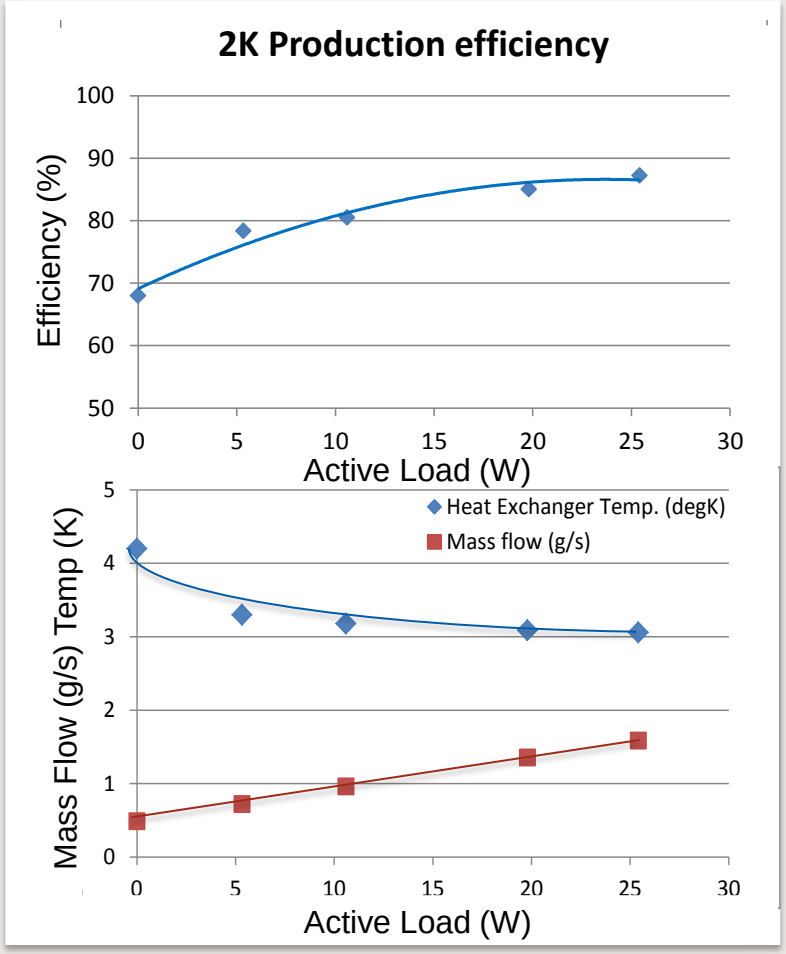
- 10MeV beam test was an integration test to validate cryogenics, HLRF, LLRF, e-Gun, LEBT, ICM engineering and synchronization
- The MEBT 10MeV analysing leg served as the destination for the accelerated beam

Cold test results

Parameter	Estimated	Measured
4K static load (no syphon)	2	3
4K static load with syphon	6	6.5
2K static load	5	5.5
77K static load	100	<130
2K production efficiency	82%	86%

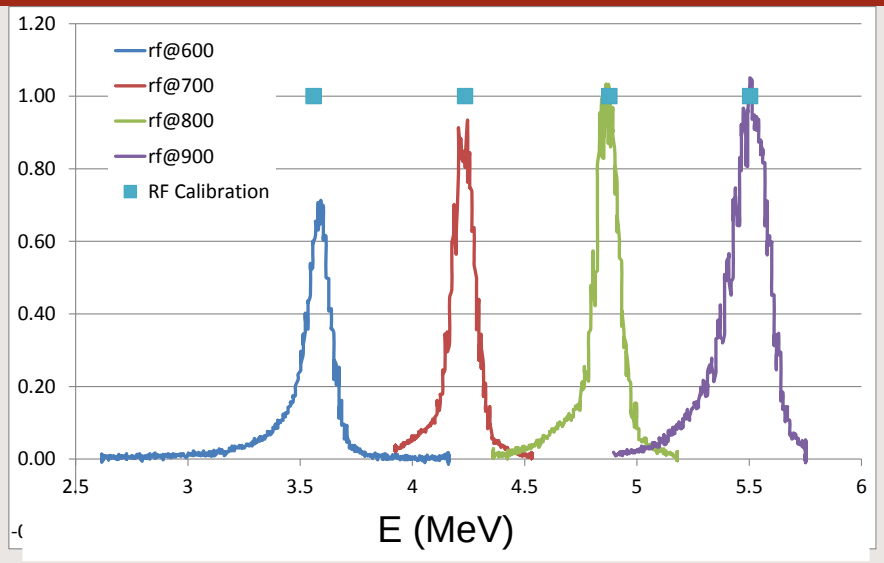
S nance characterized – w ed in off-line cryostat tests

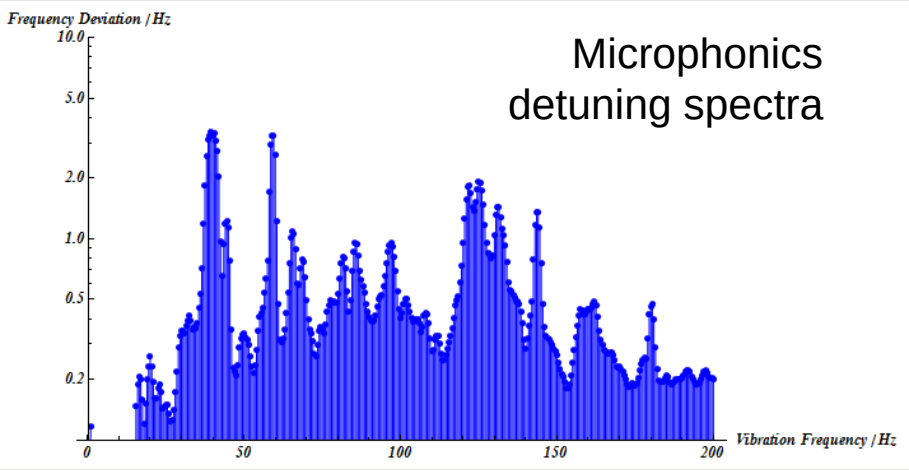
Early result – burst disk works!



ICM System Performance & Acceleration

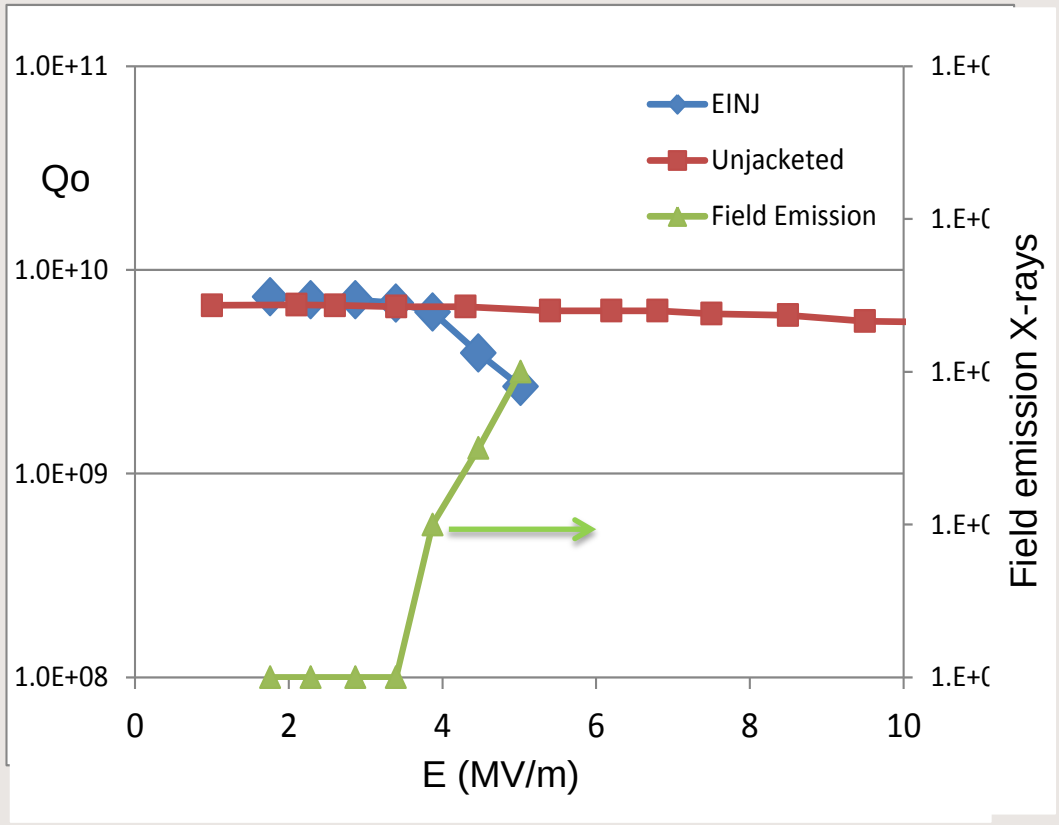
- All systems functional
  - HLRF, LLRF, tuner, power couplers
  - cavity phase lock is stable – couplers balance – rf protection in place
  - Confirmed tuning range – 400kHz
- Measured microphonics – very stable
- Successful acceleration achieved – confirms rf integration and calibration





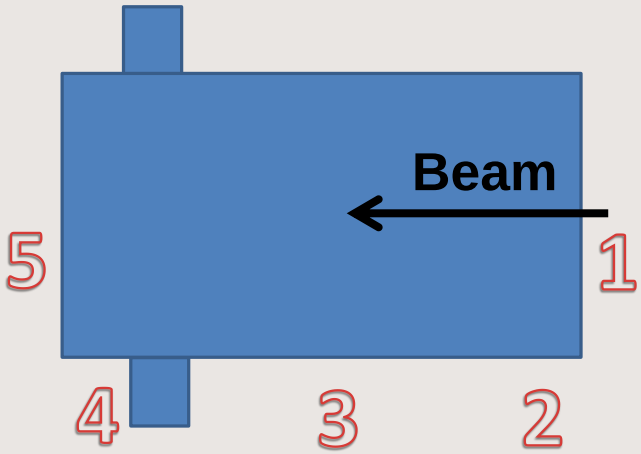
ICM Cavity Performance

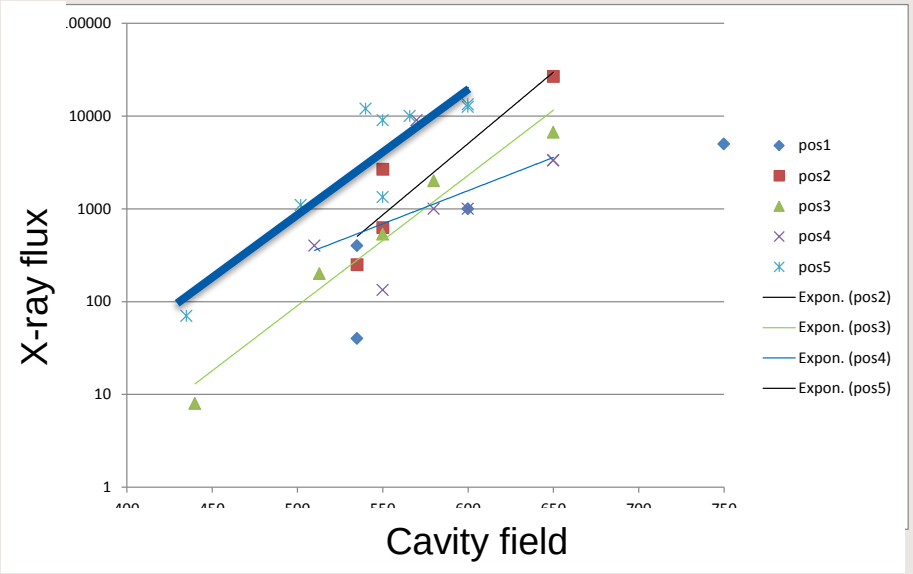
- Q_0 matches vertical test so magnetic field suppression is ok – fundamental is not loaded by the HOM dampers
- but …..
- gradient limited due to strong field emission
- Detective work ensued



Observations

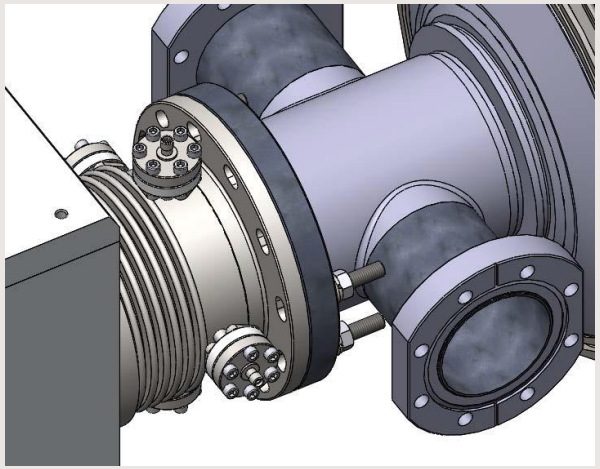
- Radiation measurements as a function of monitor position and rf set-point
- Results indicate that coupler end of the cavity is the most active by a factor of 5-10
- Further
  - Measurements of 7/9 and 8/9 fundamental modes suggest that quench is in the end groups
  - Temperature sensors on coupler side indicate some heating during quench

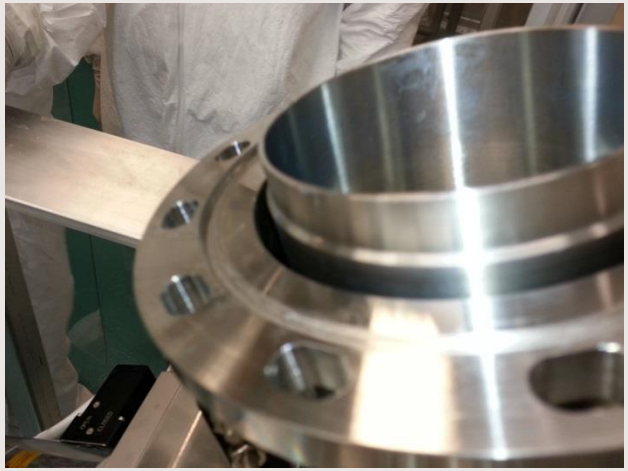


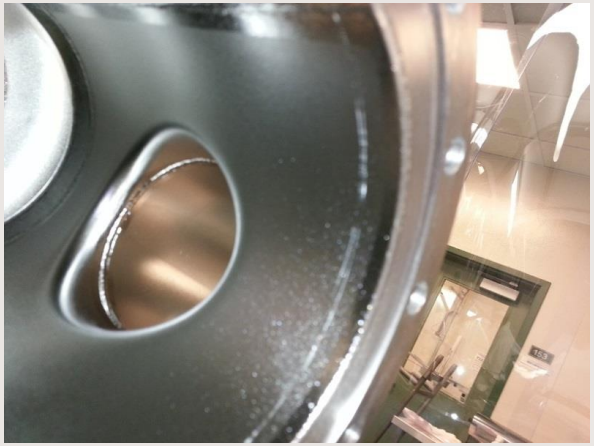


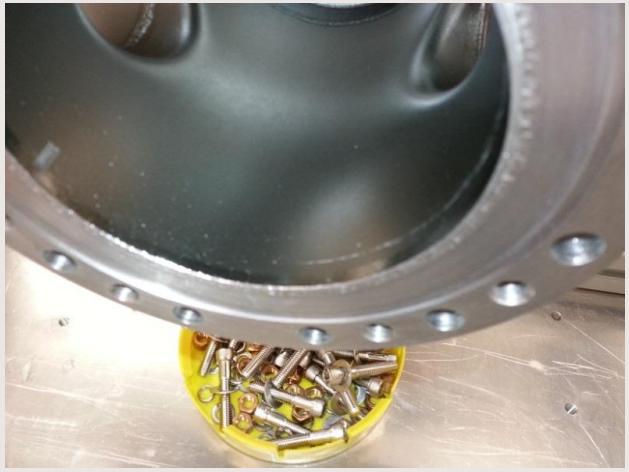
Stainless steel HOM damper – coupler side

- Took ICM off line for inspection
- Inspection revealed that the SS damper tube that fits inside the cavity at the coupler end touched down on the Nb cavity causing scoring and creating particulate
- Re-etched cavity and assembled with added support for HOM sub-assembly
- ICM is now in re-assembly and due on line in two weeks



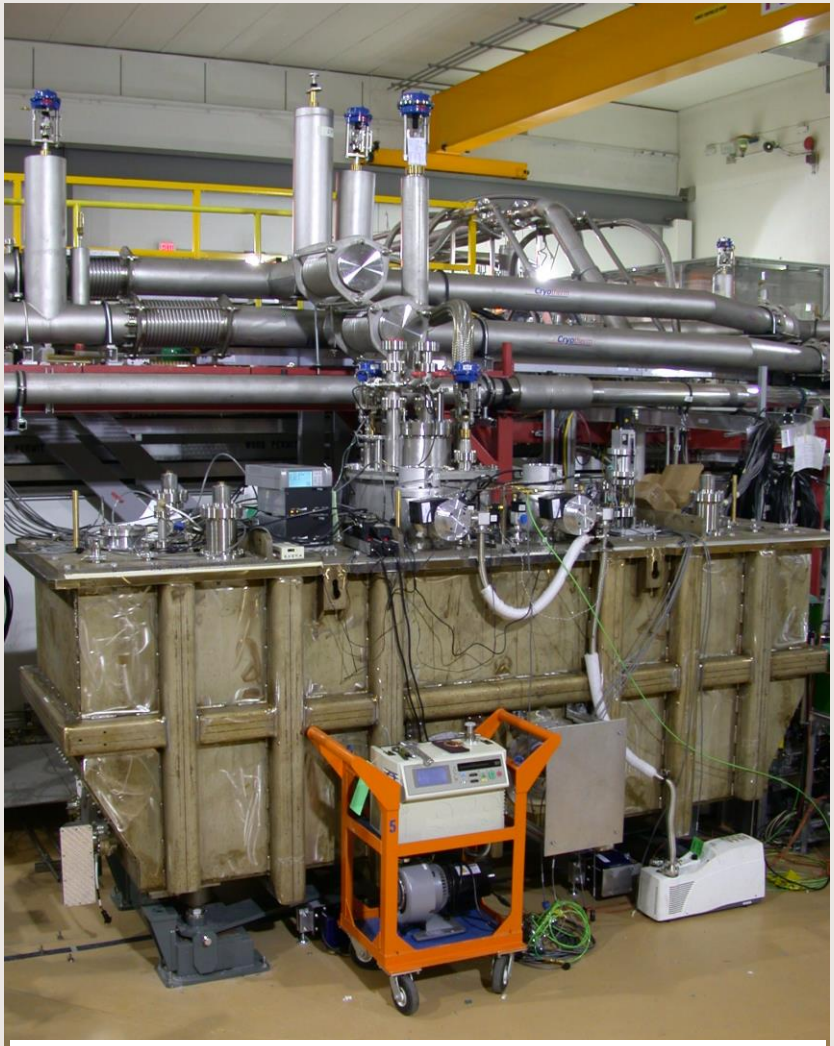






ACMuno

ACMuno assembly proceeds through June/July.

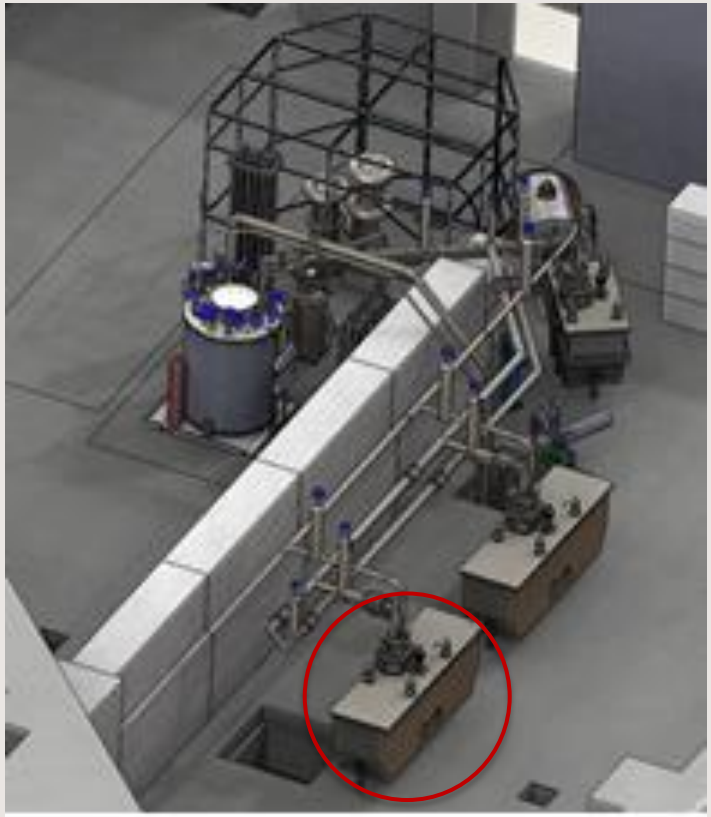


ACMuno – ready for cooldown!

Future

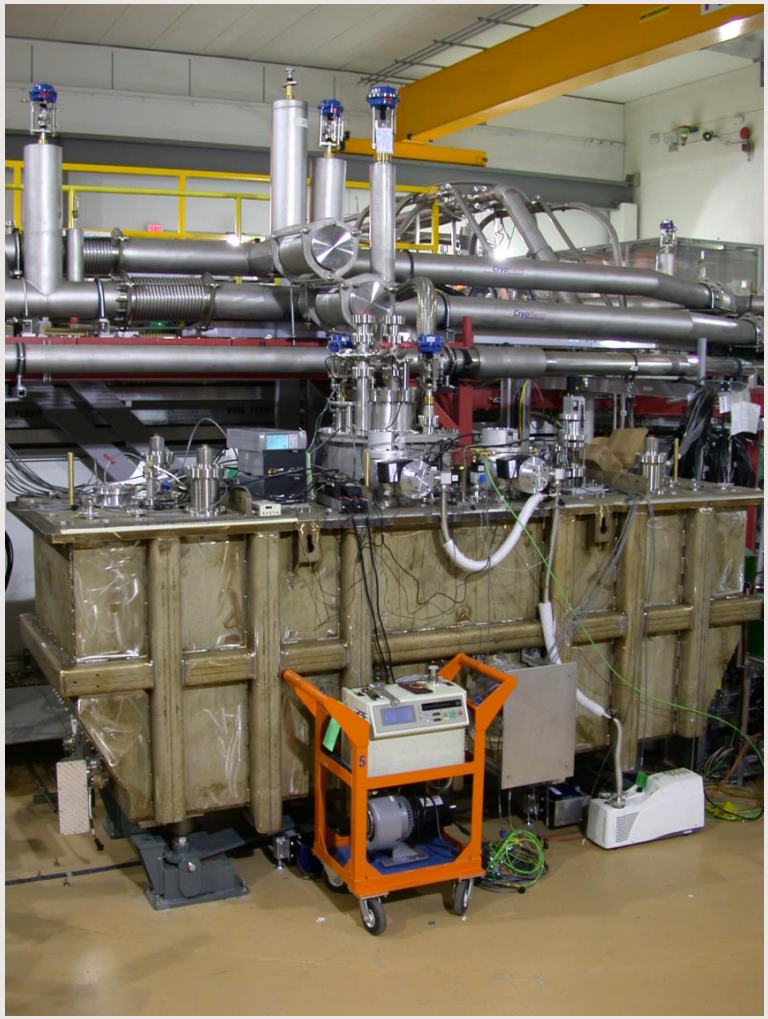
ARIEL e-Linac Completion

- Present to Dec. 2014
  - Continue beam tests at 25MeV up to 100kW
- Early 2015
  - Assemble a second ICM with ARIEL3 and test in e-Hall as part of a collaboration with VECC
  - Remove ACMuno and complete with ARIEL4
- 2018 – funding dependent
  - Complete second accelerating module (ACM2) to complete e-Linac
  - Fabricate, process and test two more cavities
  - Install 150kW RF system for ICM



Summary

- The ARIEL e-Linac initial phase is nearing completion
  - Cryogenic, rf and service installations complete
- The 300kV E-Gun has met specification
  - being used presently to commission the LEBT and MEBT
- The ICM initial cold tests demonstrated the cryo-engineering matches specifications
  - a problem with the coupler side damper tube reduced performance
- The ACMuno is on-line and cryogenic tests will begin this week
  - The second cavity will be added after the cryo-engineering is confirmed and initial beam commissioning with ICM and ACM is complete



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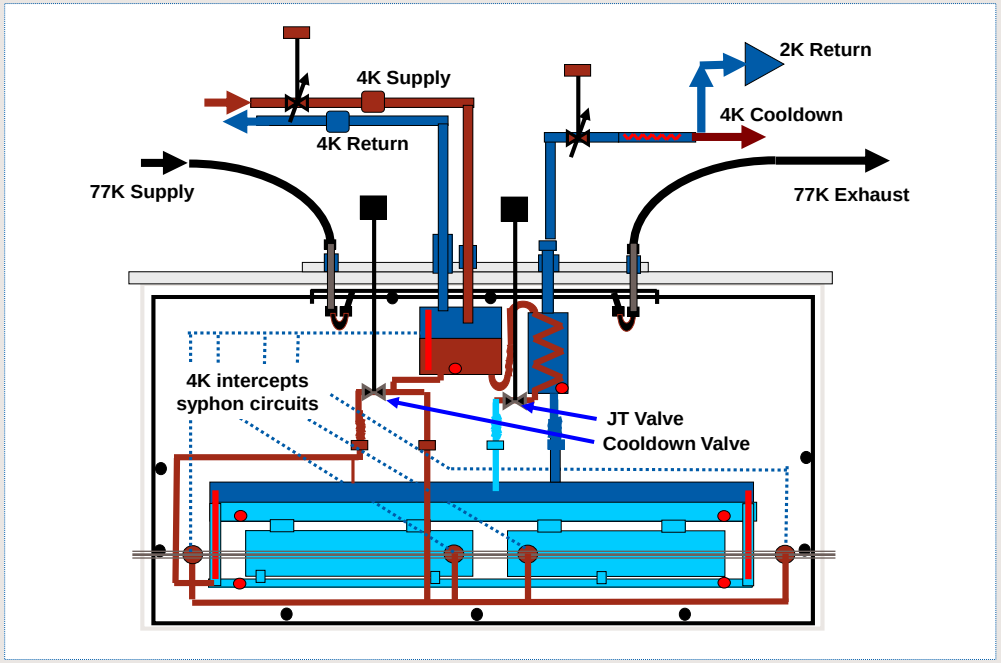
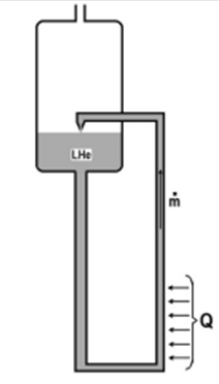
ICM / ACM Cryogenic Circuits

- 4K/2K insert designed to fit in a separate test cryostat prior to cryomodule assembly
- One 4K circuit feeds the heat exchanger and JT valve for 2K supply
- One 4K circuit feeds the bottom of the cold mass through a cooldown valve for initial cooling



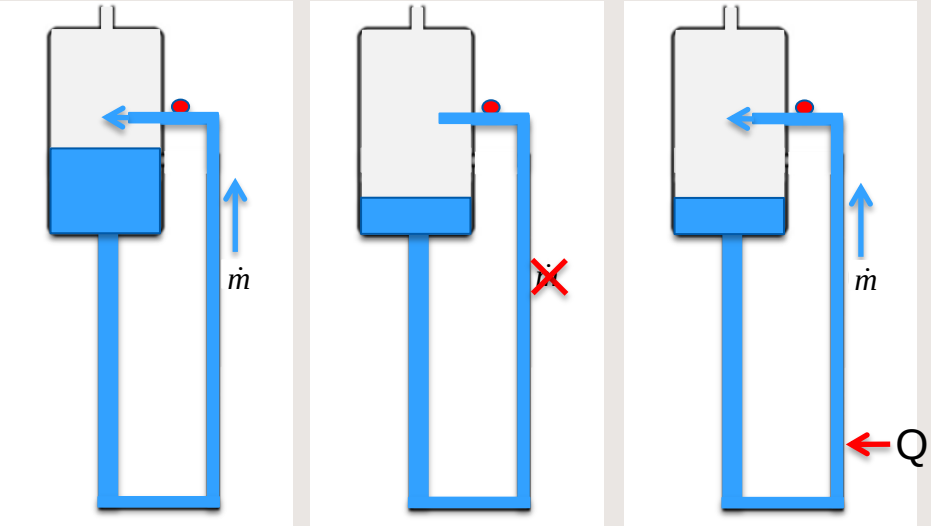
- One 4K circuit cools thermal intercepts via a self regulating thermal syphon circuit – flow is governed by the heat load and the LHe level in the 4K reservoir



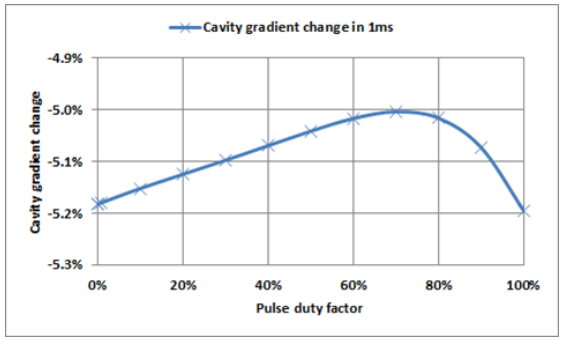
Syphon Loop

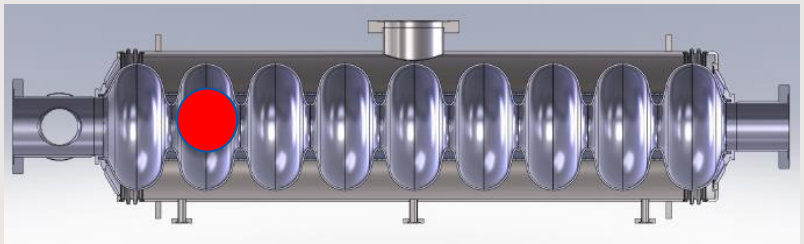
Syphon loop

- Demonstrated that the loop turns on and off depending on head pressure and heat load – self regulating
- Existence of flow is diagnosed by a temperature sensor on the return column
- Demonstrated that the heat load to 2K is effectively intercepted by syphon loop cooling
- Lesson learned – beware of creating convection in the 4K reservoir – heat source



RF Protection

- Need fast protection to kill the rf in case of rf transient
  - PMTs on couplers
  - Quench detection circuit
- Developed transient model for quench
  - COMSOL – quench zone analysis
  - Mathematica model used to study rf transients
  - Conclude that for all beam duty factors the cavity gradient gives the cleanest indication of a quench
- 



Typical operating regime

$$I = 10\text{mA}, E_a = 10\text{MV/m}, P_{beam} = 100\text{kW}, P_{cav} = 10\text{W}$$

$$b = \frac{P_{beam}}{P_{cav}} = 10000 \text{ and at } \varphi = 0\ \beta_{\text{opt}} \cong b = 10000$$

$$\text{so } Q_{\text{ext (opt)}} = \frac{Q_0}{\beta_{opt}} = 1\times10^6$$

Quench estimation : assume 25% of one cell

(ie $1/40$ of cavity) goes normal.

$$\text{So } P_{quench\ zone}\Big|_{SC} = \frac{10\text{W}}{40} = 0.25\text{W}$$

$$\rightarrow P_{quench\ zone}\Big|_{Normal} = 0.25\text{W} \times \frac{10\text{m}\Omega}{20\text{n}\Omega} = 100\text{kW}$$

Q_0 will go from 1e10 to 1e6

ie : The cavity will be matched (100J/msec)