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

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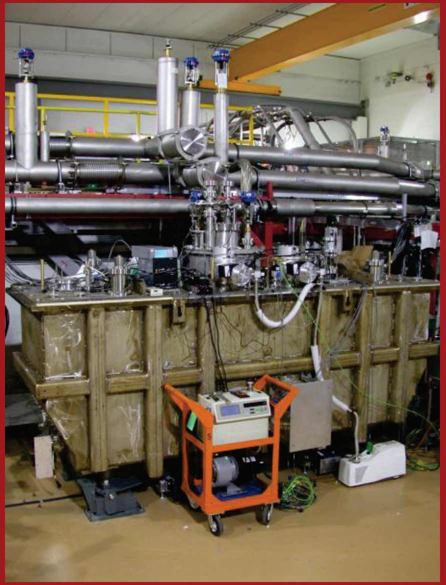
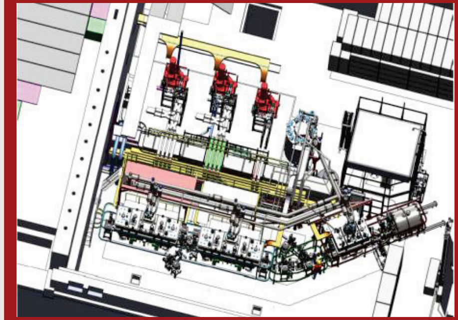
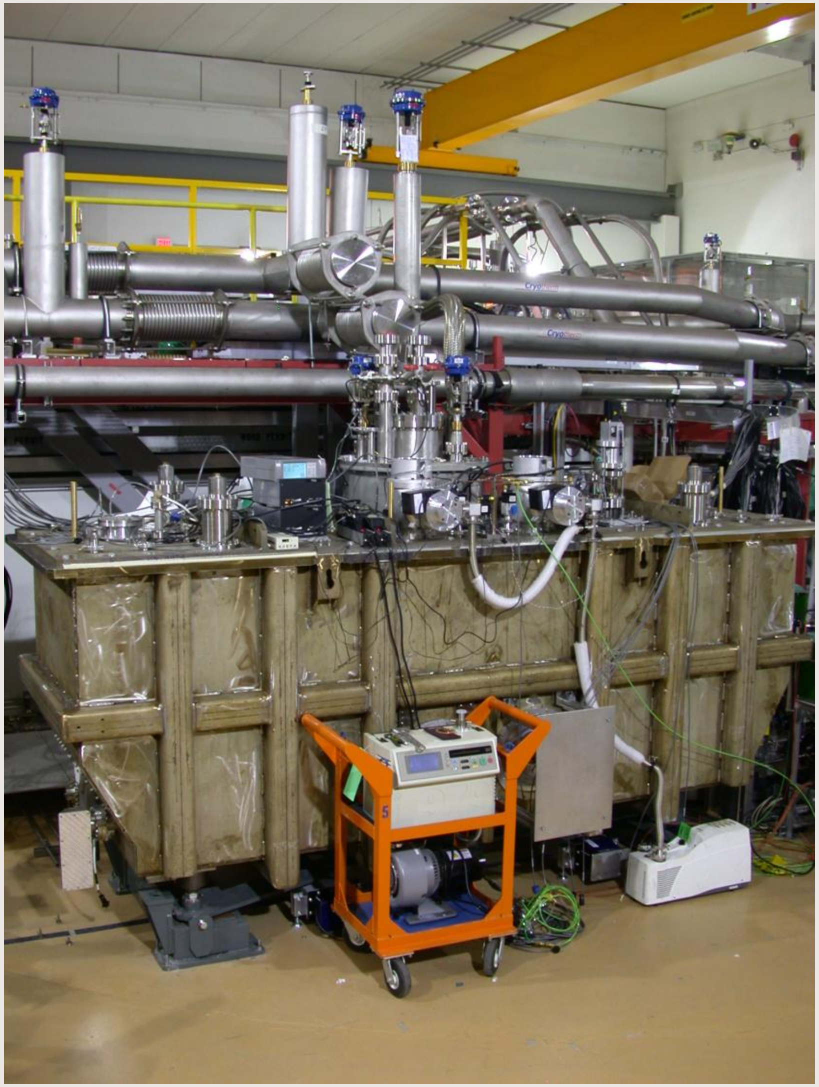




Outline

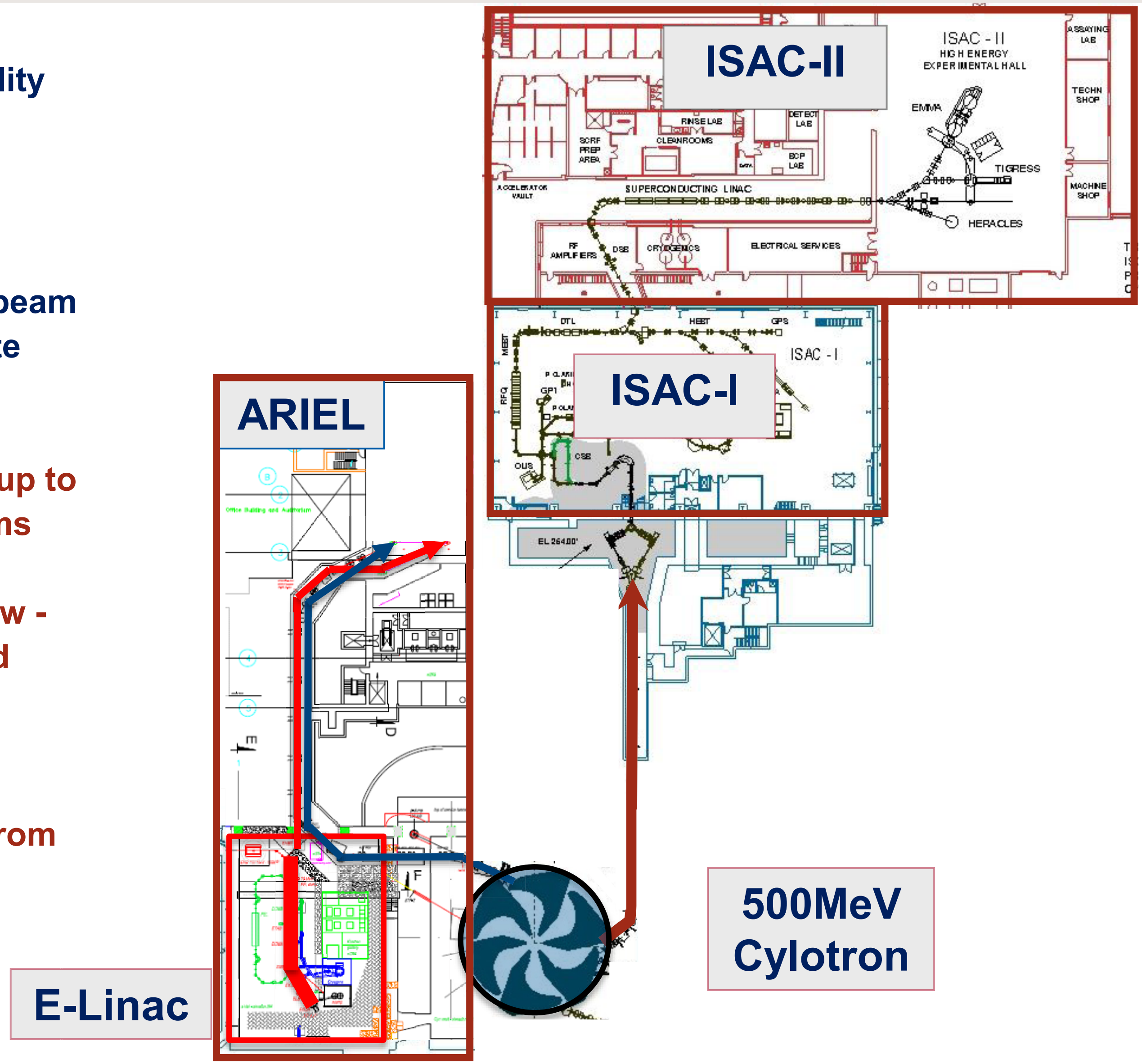
- ARIEL Project
  - E-Linac Specification
- E-Linac design
  - Major components
- Status and commissioning results
- Future plans



ARIEL and the e-Linac

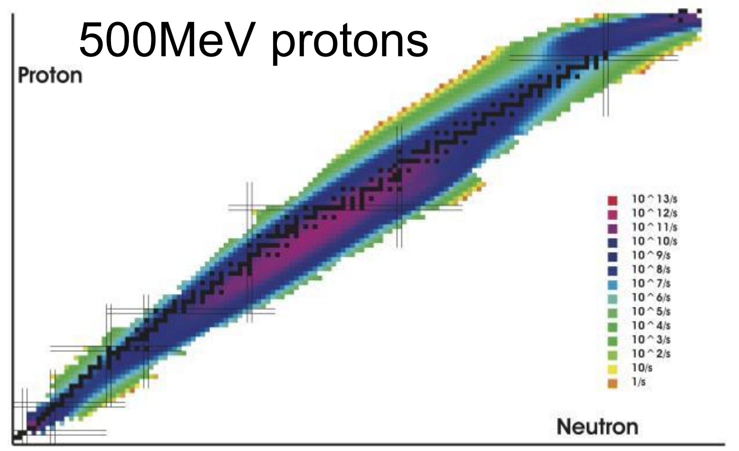
ARIEL Project (2010-2020)

- •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

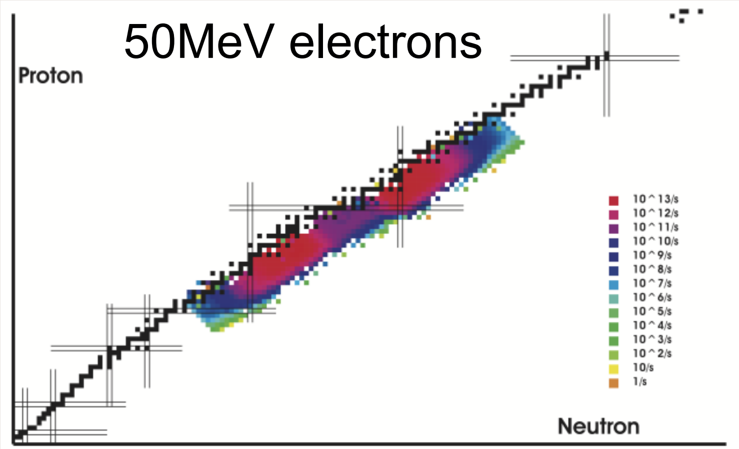


Why electrons? Why 50MeV?

- 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



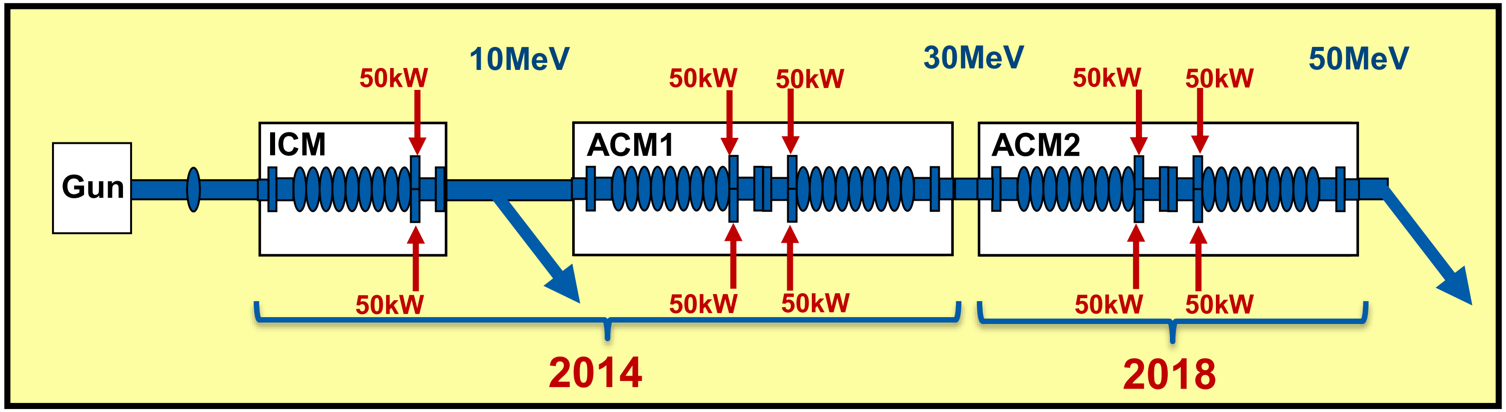
Calculated in-target production for 10 μA, 500 MeV protons incident on a 25 g/cm2 UCx target



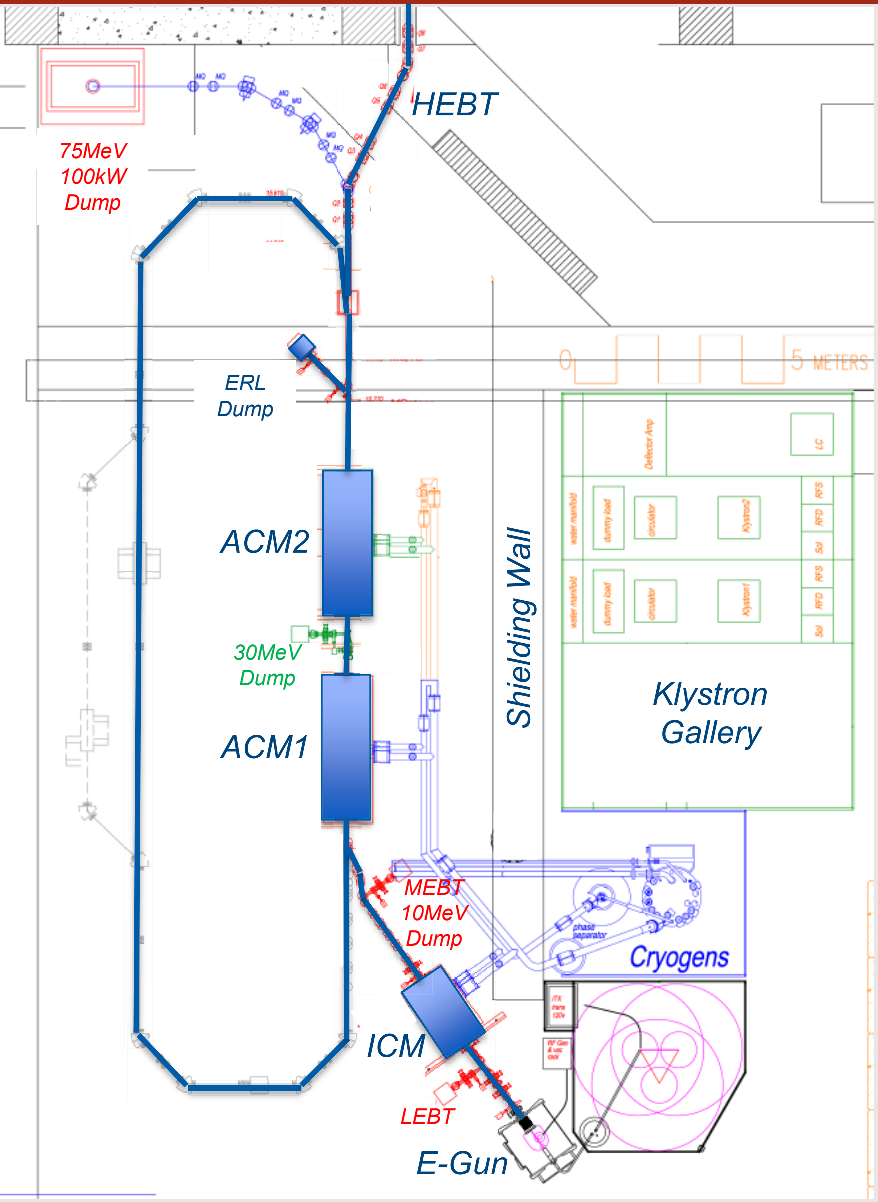
Calculated in-target production for 10 mA, 50 MeV electrons incident on a Hg converter and 15 g/cm2 UCx target

E-Linac Specifications

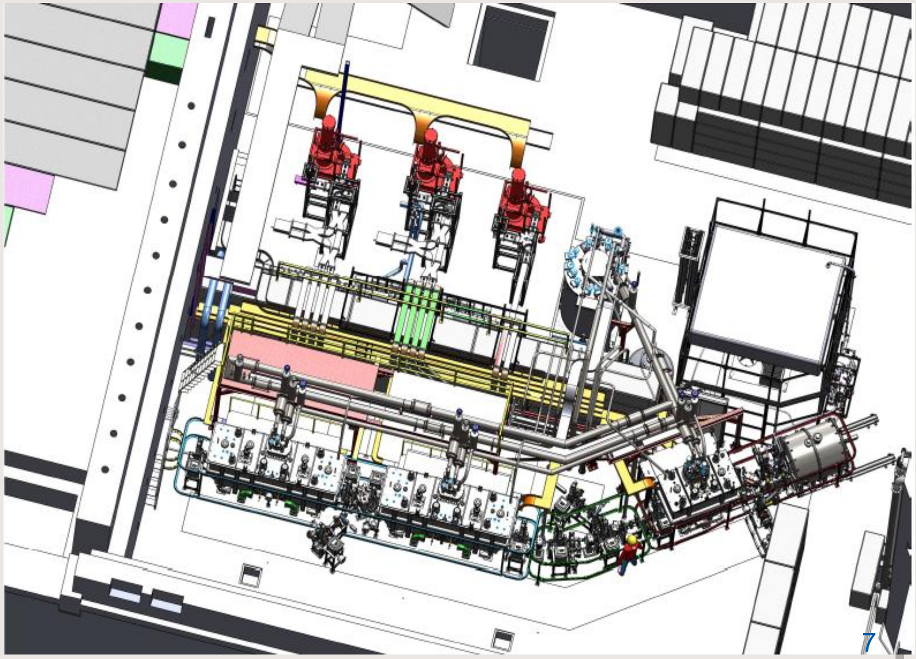
- The ARIEL E-Linac specification – dominated by rf beam loading
  - 10mA cw at 50MeV - 0.5 MW of beam power
  - Choose five cavities 100kW of beam loaded rf power per cavity
  - two couplers per cavity each rated for 50kW operation
  - Means 10MV energy gain per cavity
- Linac divided into three cryomodules
  - 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



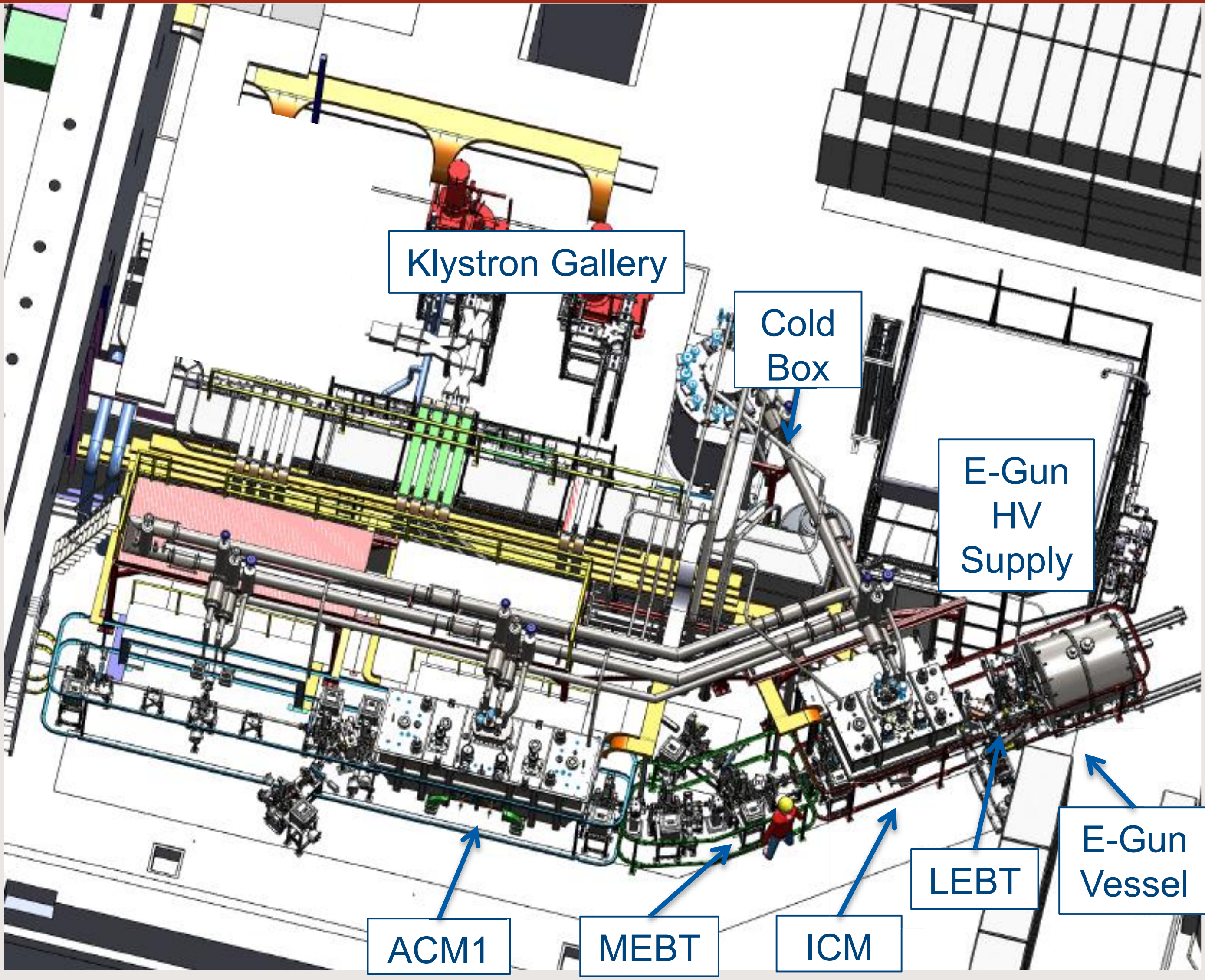
The ARIEL e-Linac as a recirculator



- 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



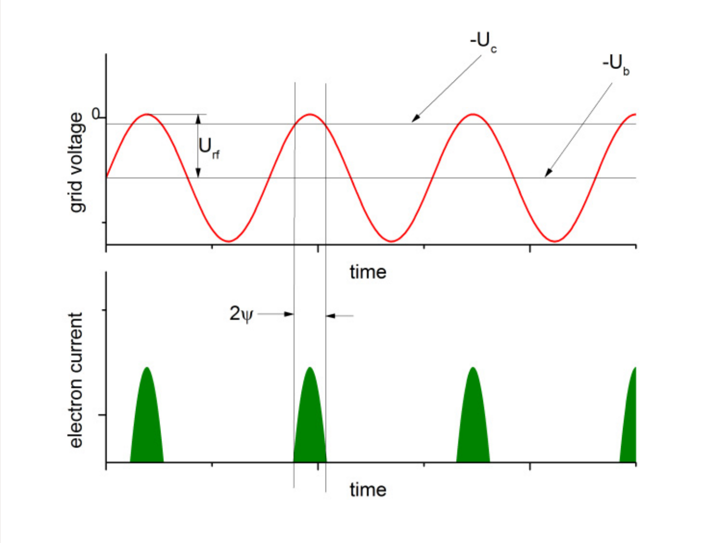
Accelerator Vault – Phase I



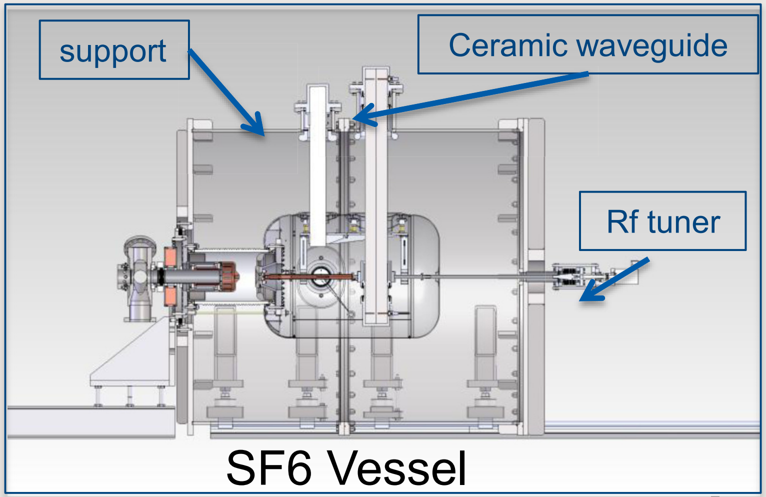
E-Linac Design

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



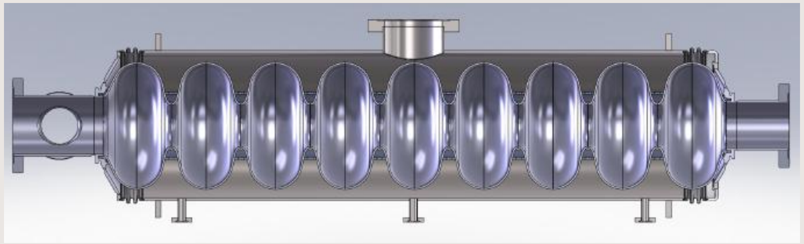
Parameter	Value
RF frequency	650MHz
Pulse length	$\pm 16^0$ (137ps)
Average current	10mA
Charge/bunch	15.4pC
Kinetic energy	300keV
Normalized emittance	5μm
Duty factor	0.01 to 100%

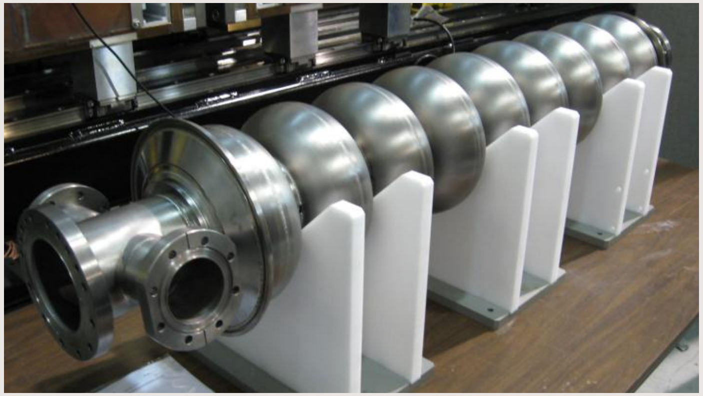


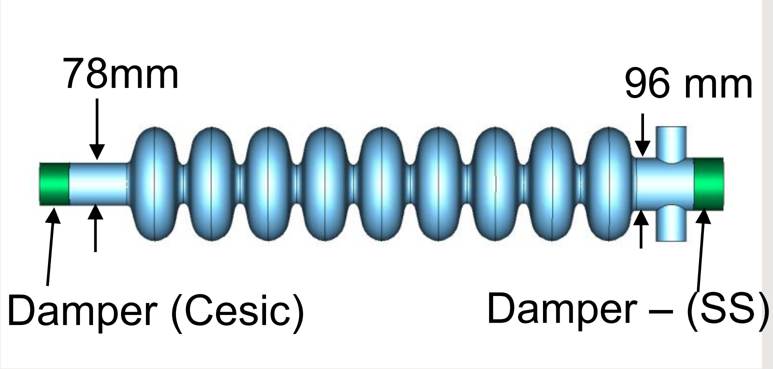
ARIEL cavities

- 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

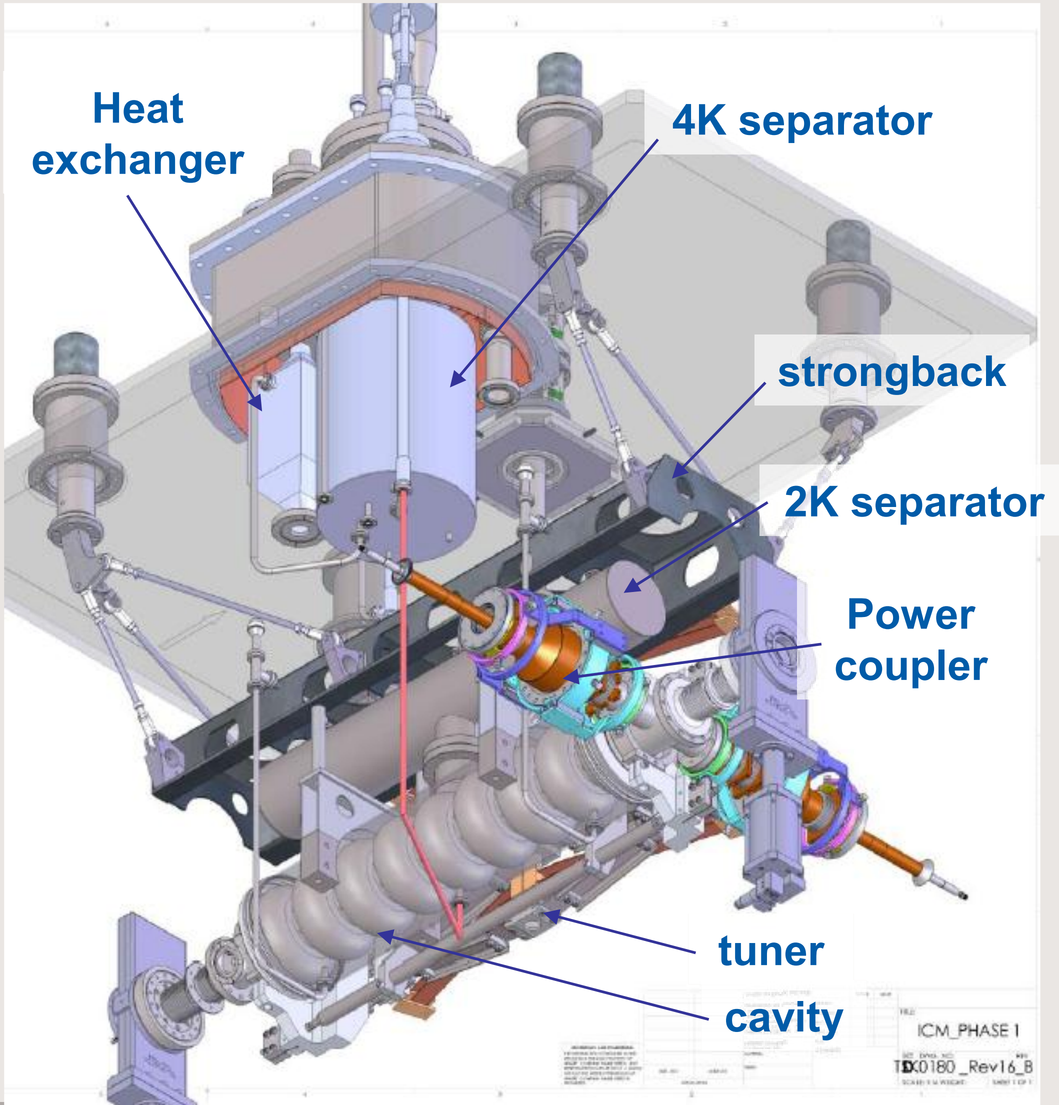
Parameter	Value
Active length (m)	1.038
RF frequency	1.3e9
R/Q (Ohms)	1000
Q_0	1e10
E_a (MV/m)	10
P_{cav} (W)	10
P_{beam} (kW)	100
Q_{ext}	1e6
Q_L*R_d/Q of HOM	<1e6







Injector Cryomodule



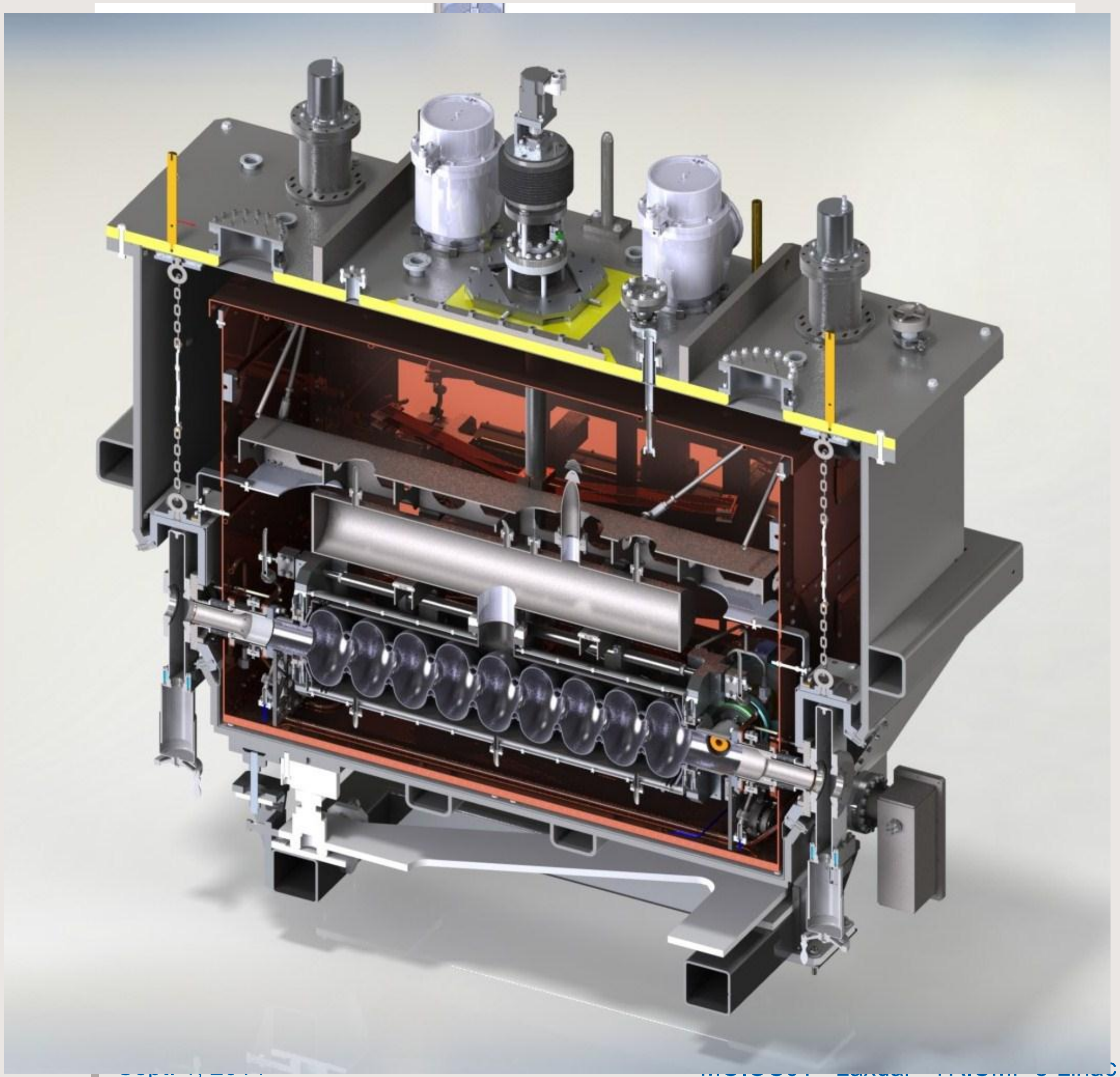
Houses

- •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

Injector Cryomodule



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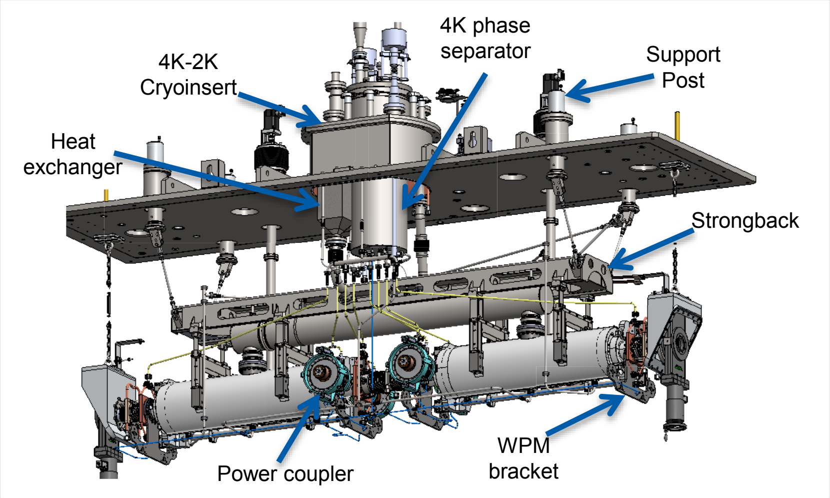
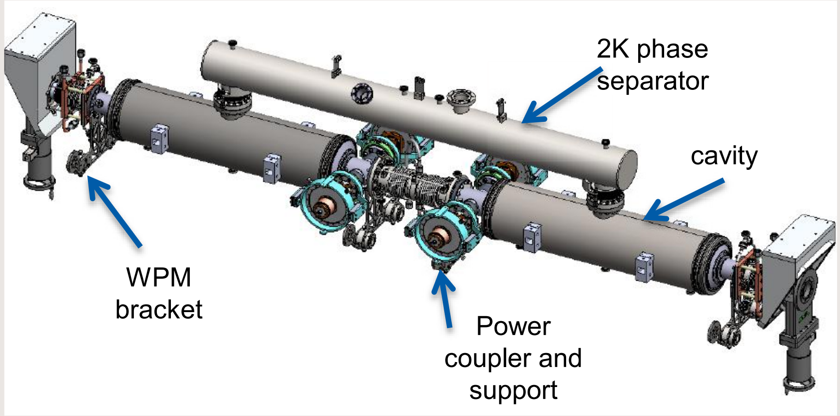
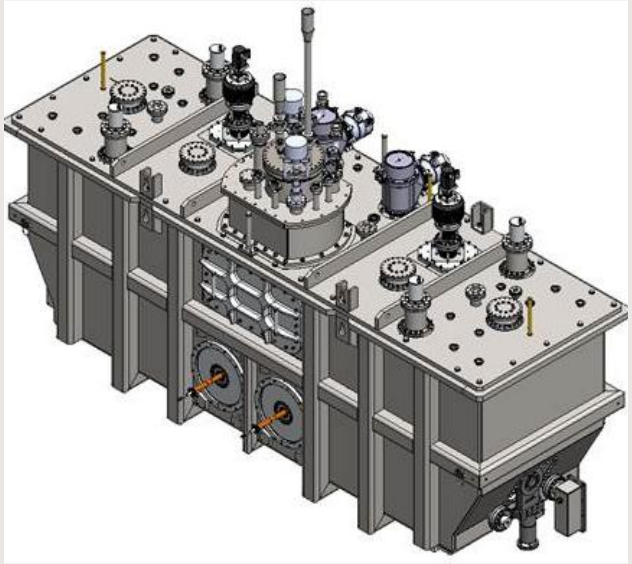
Accelerator Cryomodule

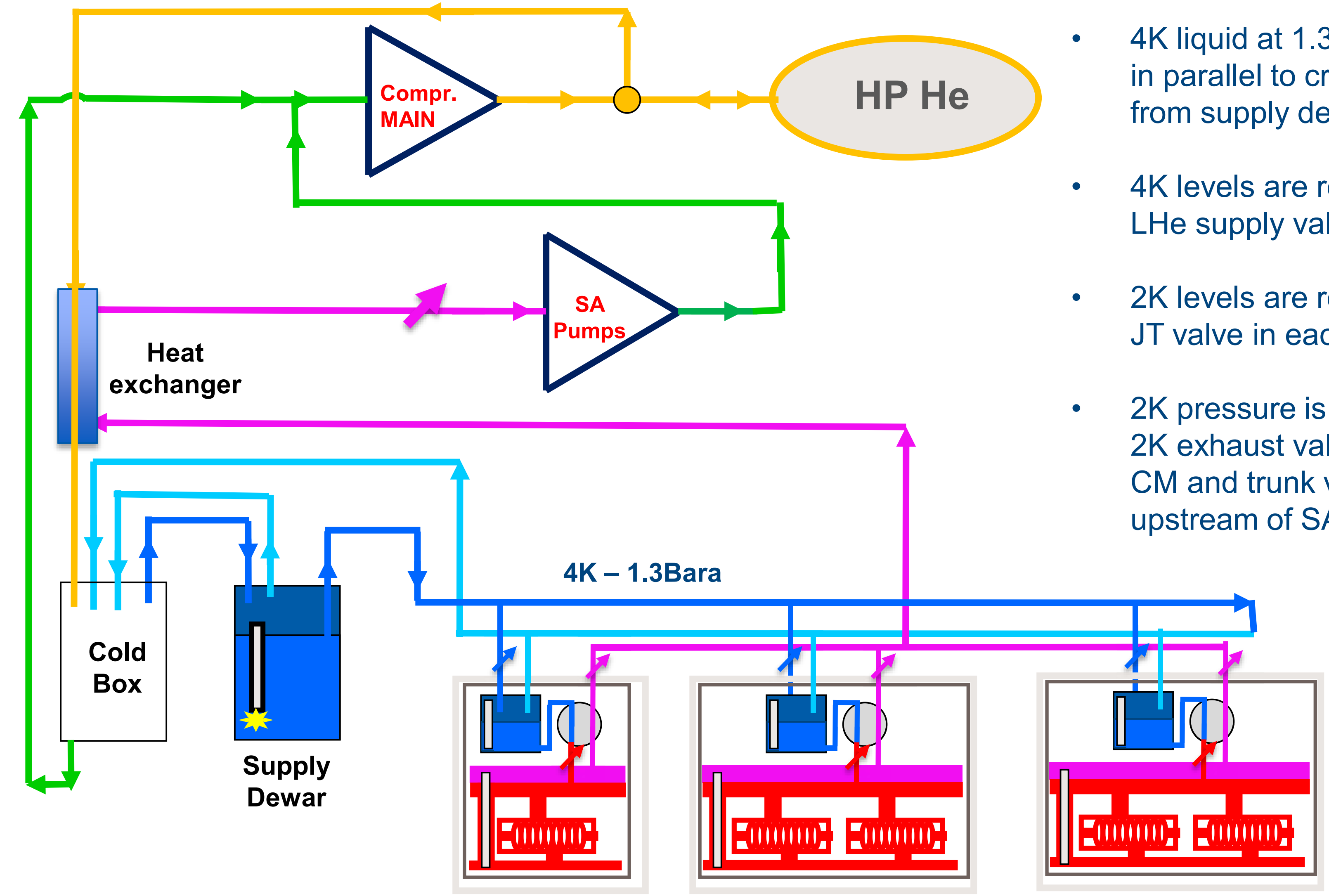
- The ACM uses same basic design as ICM but with two 1.3GHz nine cell cavities each with two 50kW power couplers
- There is one 4k/2k insert identical to the ICM
- Physical dimensions
  - L x H x W = 3.9 x 1.4 x 1.3 m
  - 9 tons







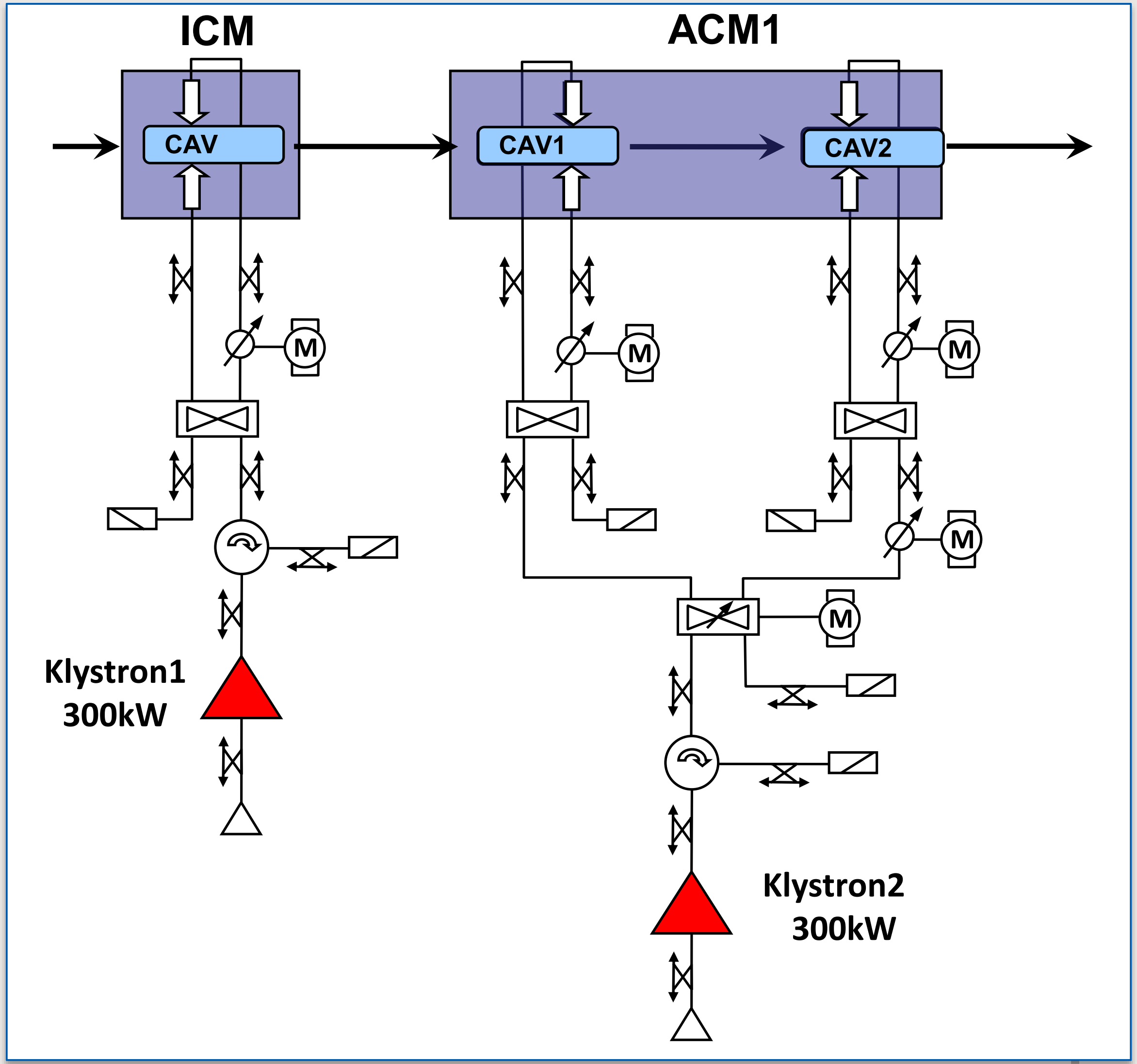
Cryogenics



- 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

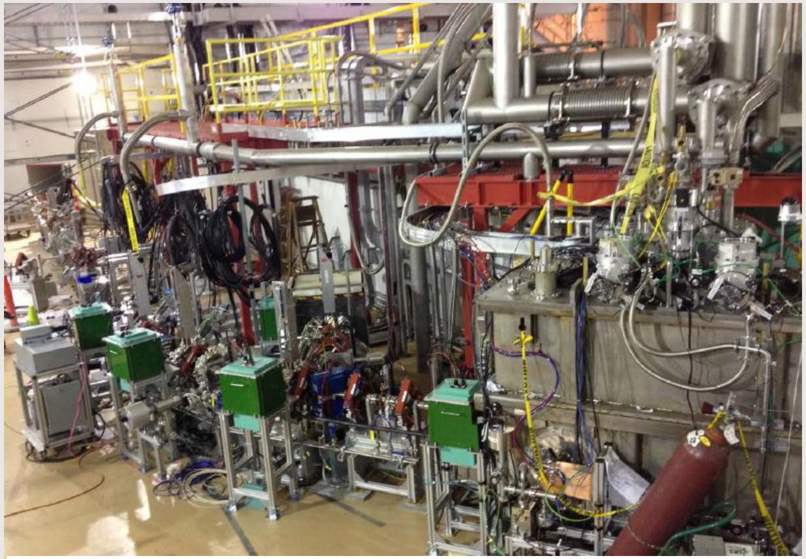


Status and Commissioning

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

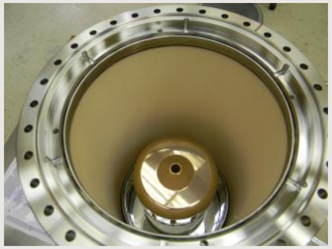
January 2014



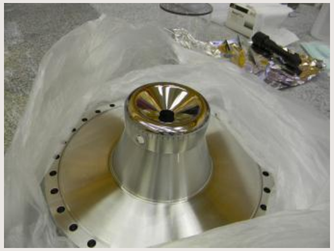
July 2014

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

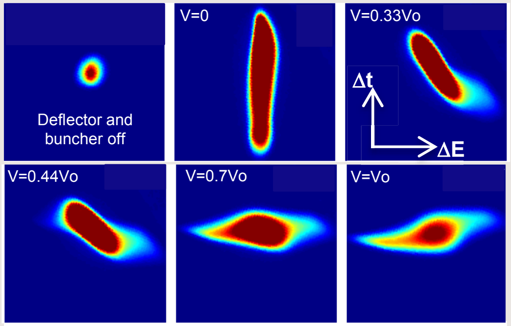
SF6 Vessel Installed

Ceramic Waveguide

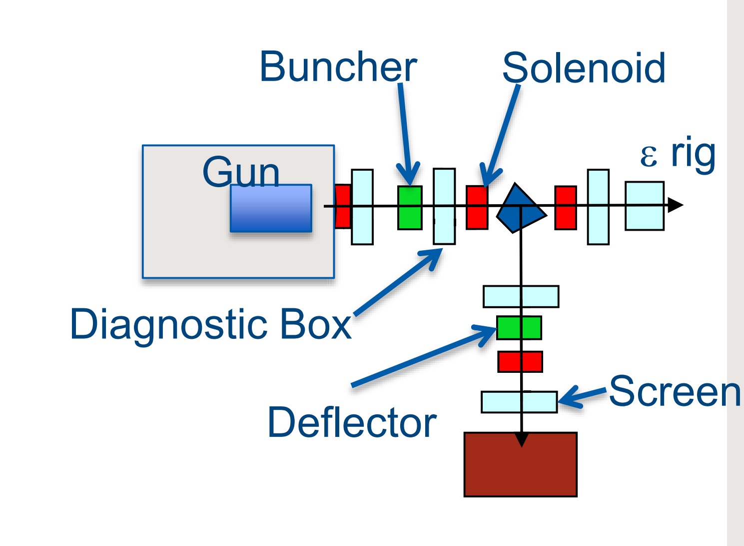
350 kV, 16 mA HVPS

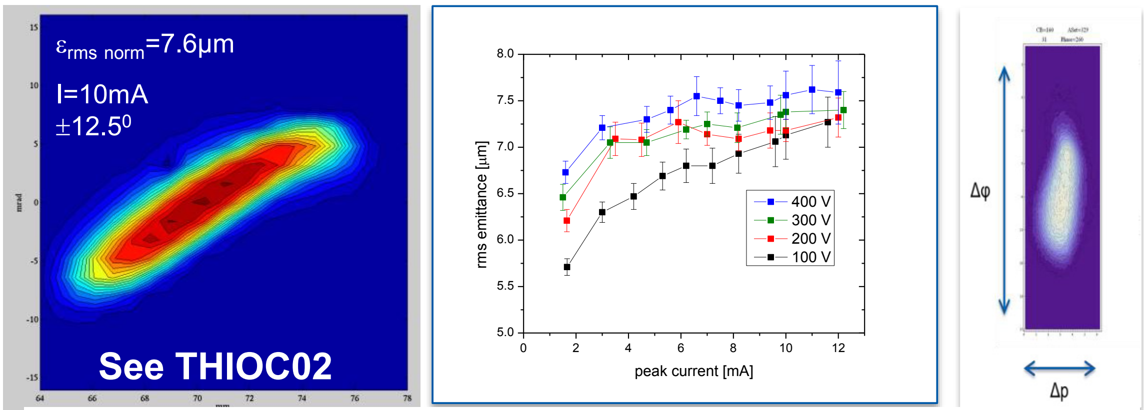
LEBT Diagnostics

- 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

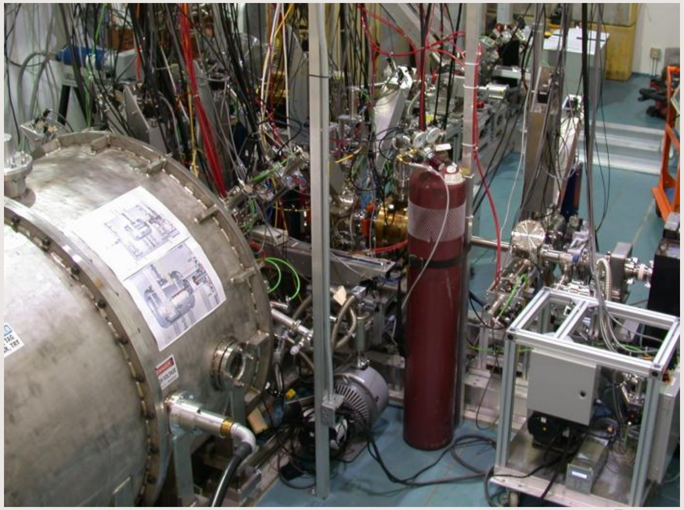


Screen images downstream of rf deflector show manipulation of longitudinal emittance with the buncher cavity at different voltages.



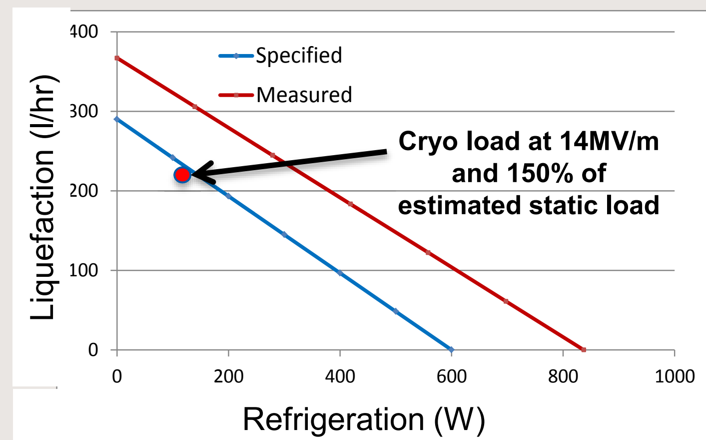


E-Gun transverse and longitudinal emittance measurements



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

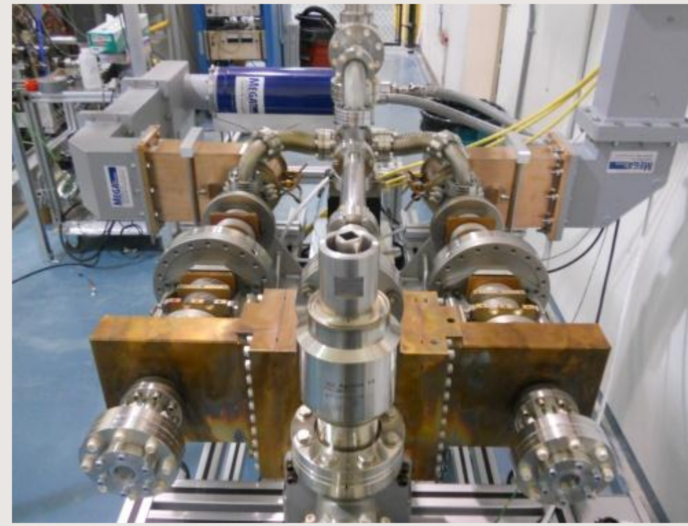
High Power RF Installation

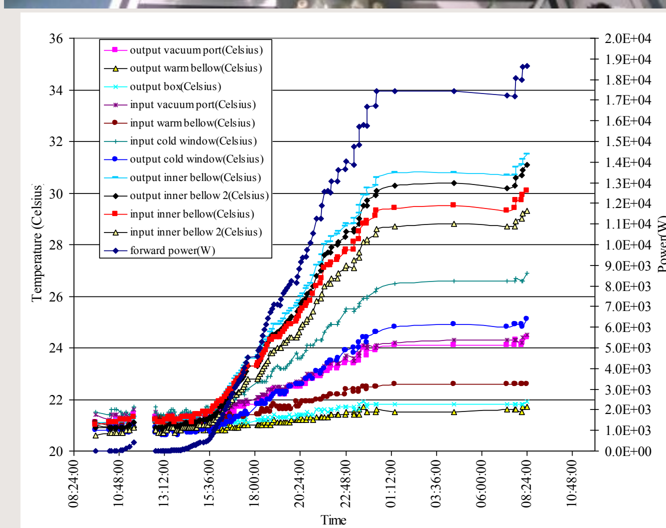
- Now installed
  - Two CPI 290kW cw 1.3GHz klystrons
  - Two 600kW 65kV klystron power supplies from Ampegon
- Each klystron reaches specification at the factory
- At TRIUMF – tests were limited by available load or circulator – one was operated to 250kW cw the other to 150kW cw
- Delivered a peak power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

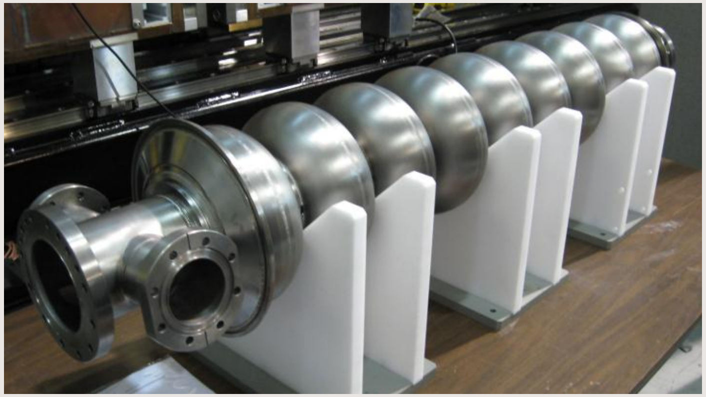
Conditioning Stand

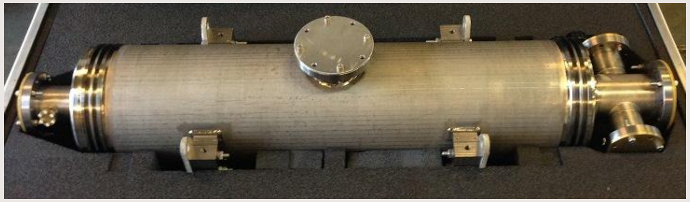


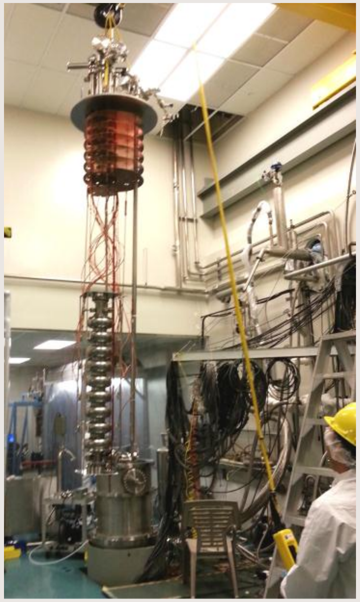


ARIEL Cavities - PAVAC

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

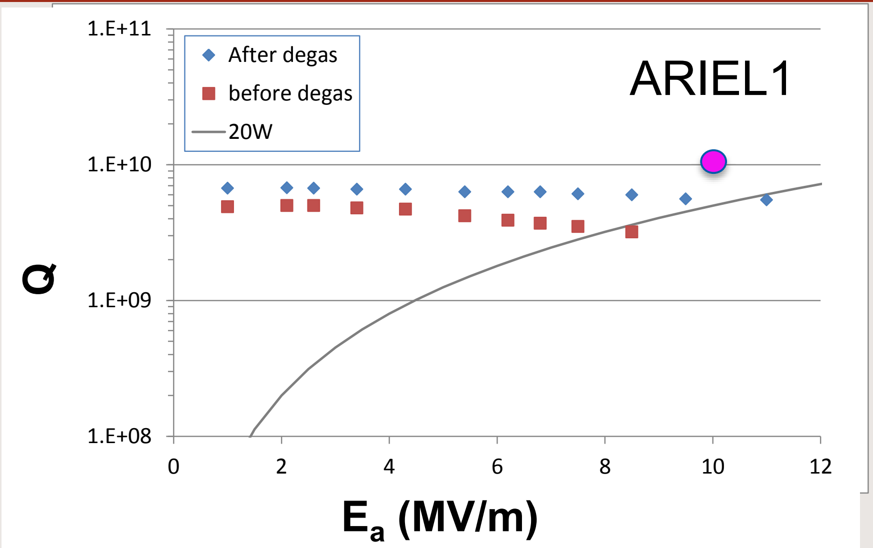


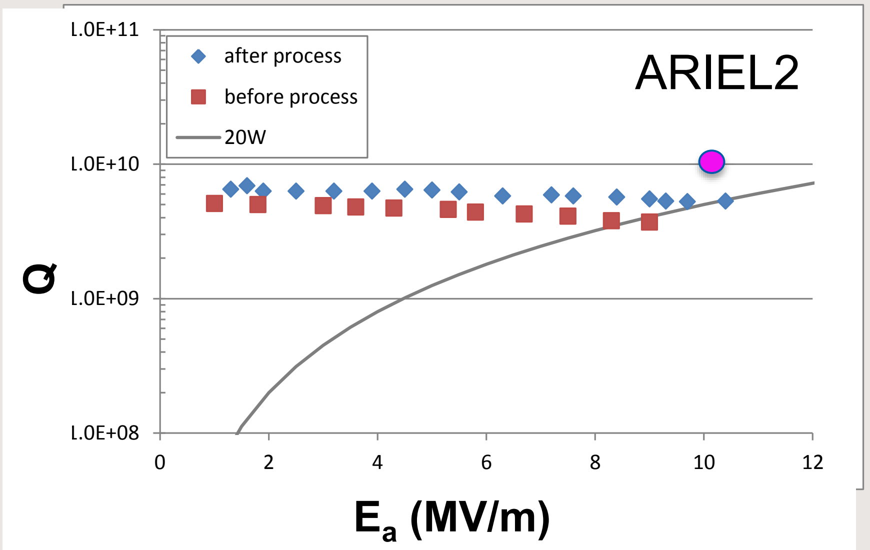




ARIEL Cavities

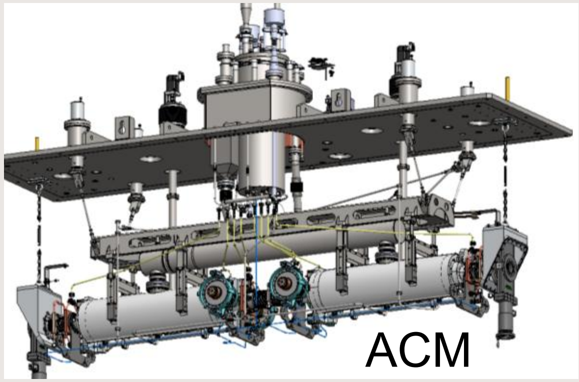
- Cavity vertical cold tests in ISAC-II before and after re-process
- Both cavities reach the specified gradient of 10MV/m but at Qo=6e9
- For Phase I we have lots of cryogenic power so derate specification to Qo=5e9
- Strategy is to utilize ARIEL1 and ARIEL2 to characterize the cryo-engineering of the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

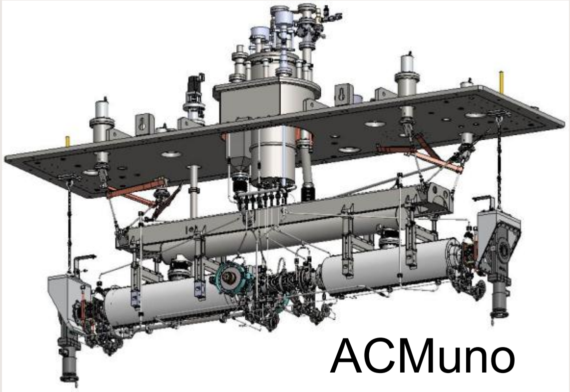


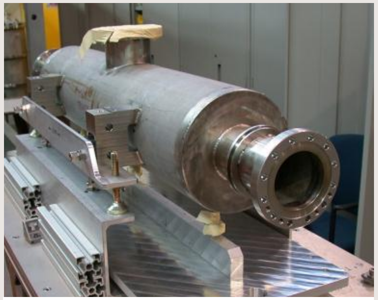


Cryomodule strategy

- 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

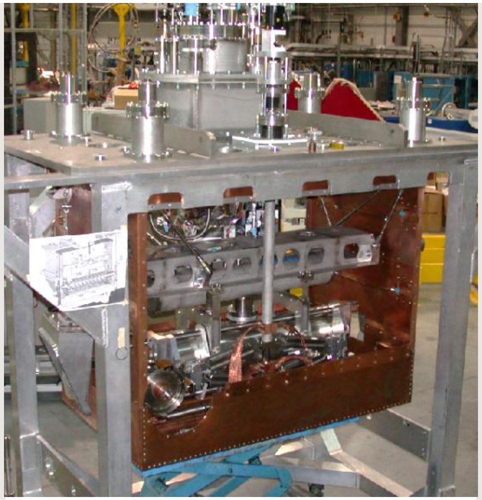

ACM


ACMuno

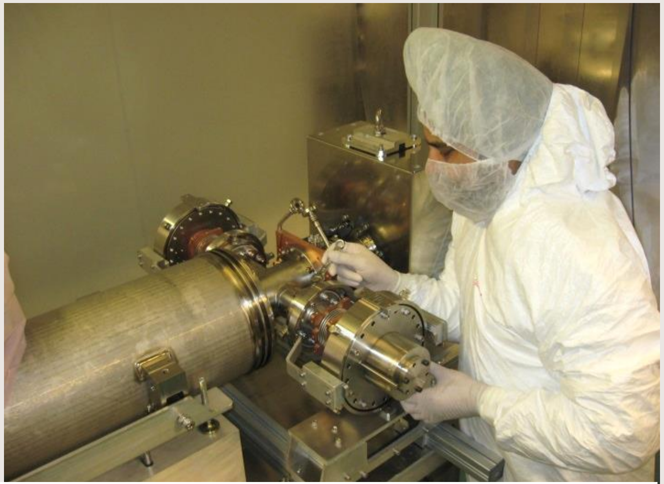

Dummy cavity

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



ICM mock-up – 2013



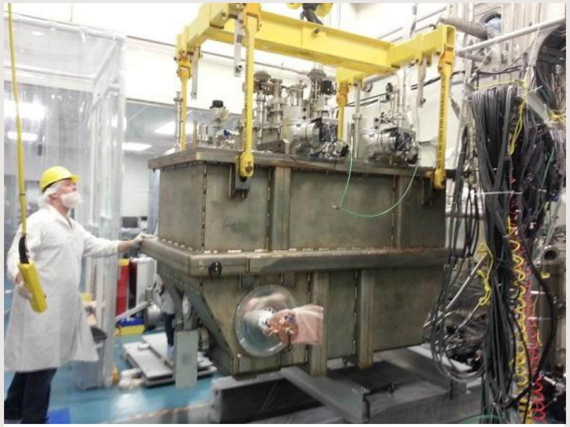
Cavity hermetic unit (March 14, 2014)

ICM top assembly

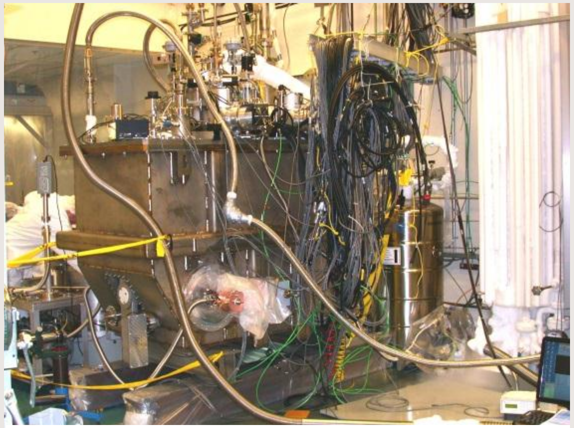
Top assembly into tank

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

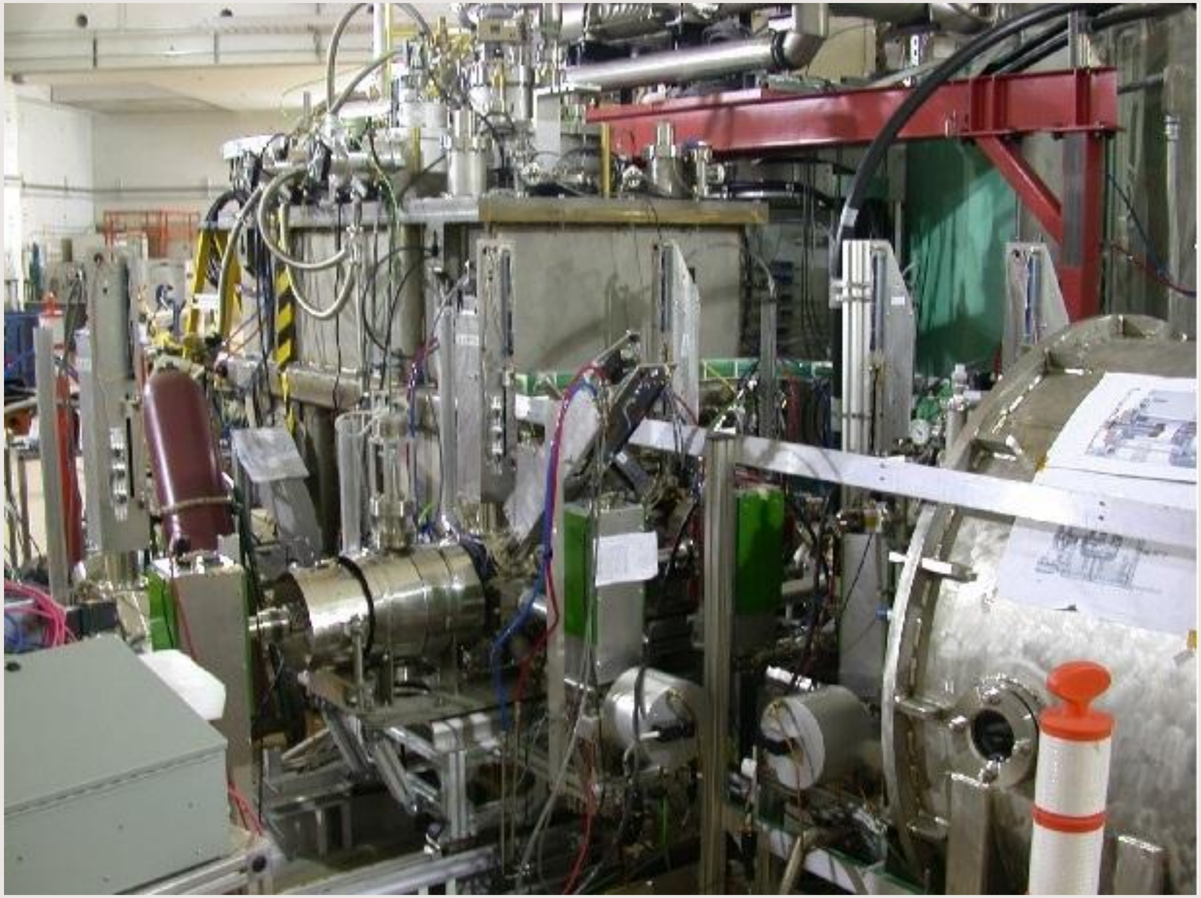
ICM on the move

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

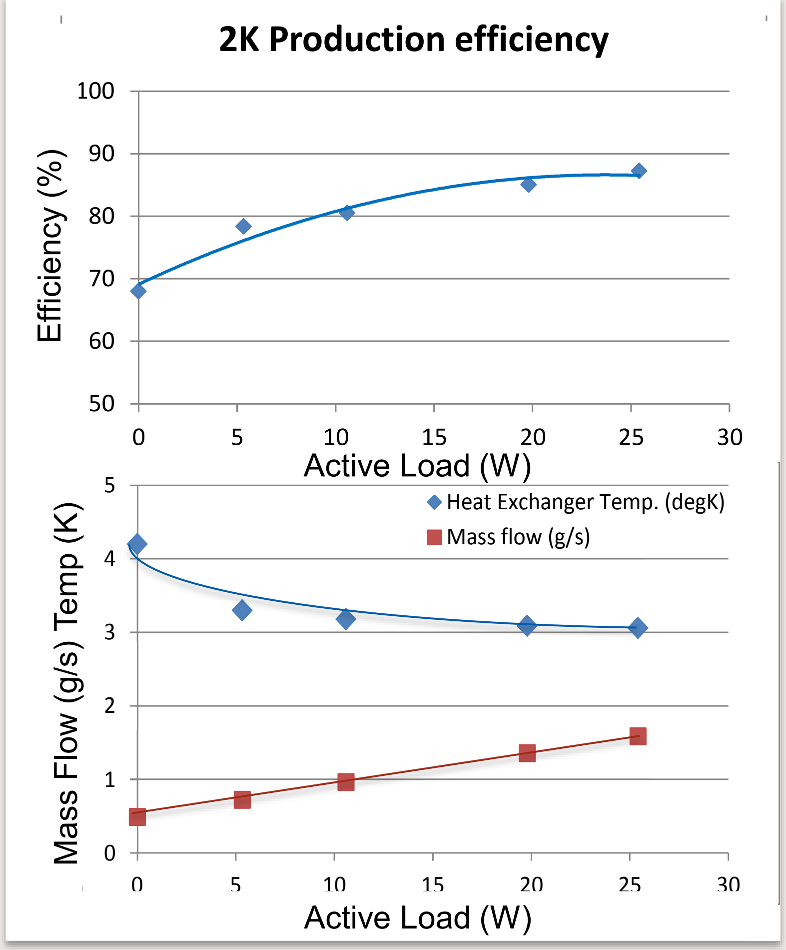


- 10MeV beam test was an integration test to validate cryogenics, HLRF, LLRF, e-Gun, LEBT, ICM engineering and synchronization
- The MEBT 10MeV analysing leg served as the destination for the accelerated beam

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%

Syphon loop performance characterized – works well – optimized in off-line cryostat tests



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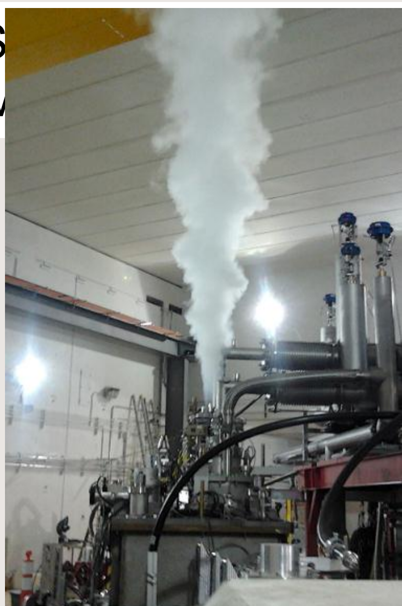
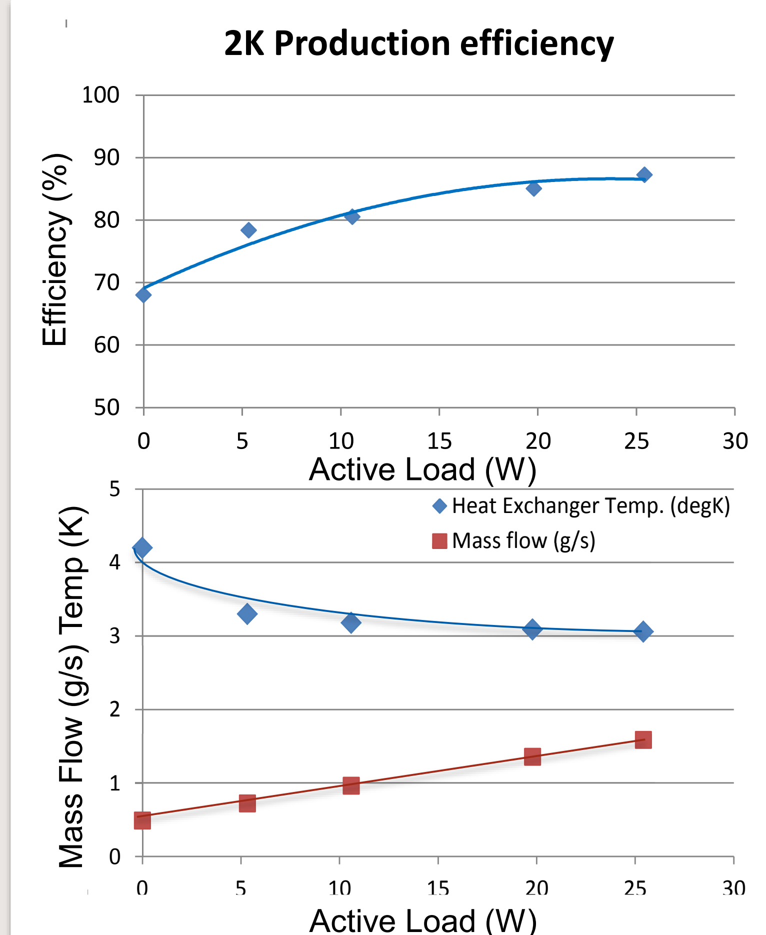
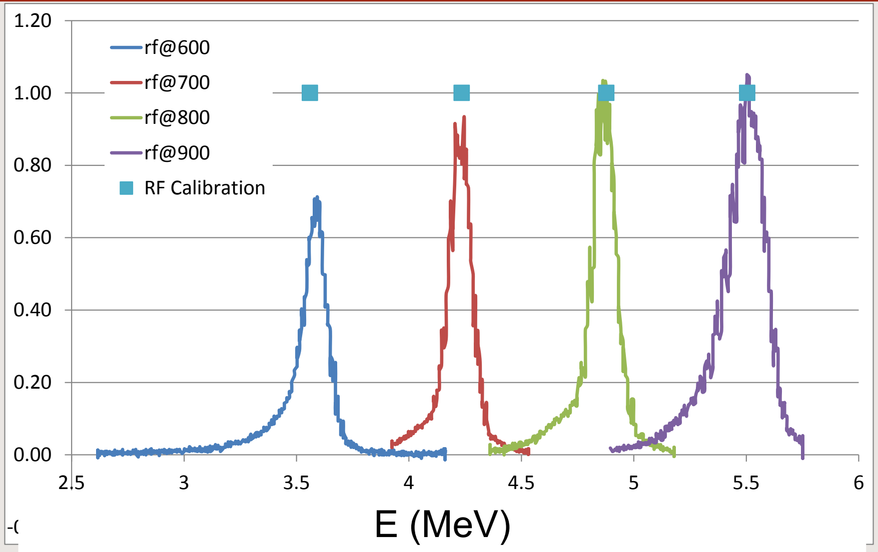


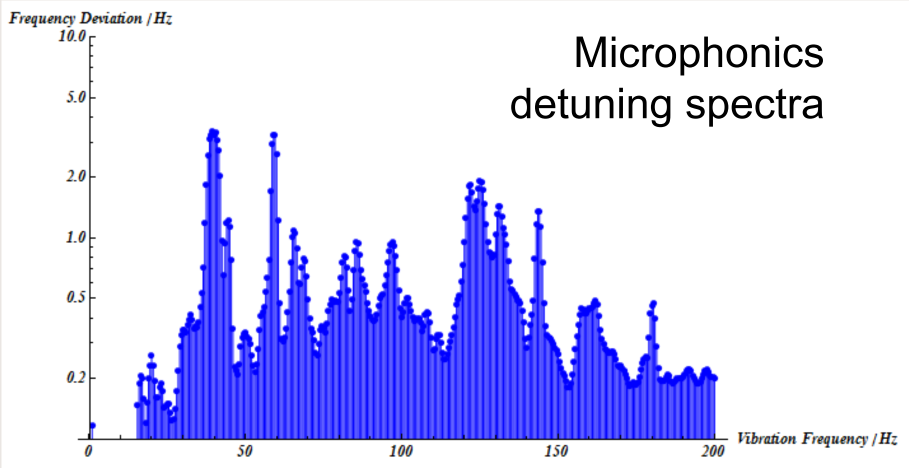
Early result – burst disk works!



ICM System Performance & Acceleration

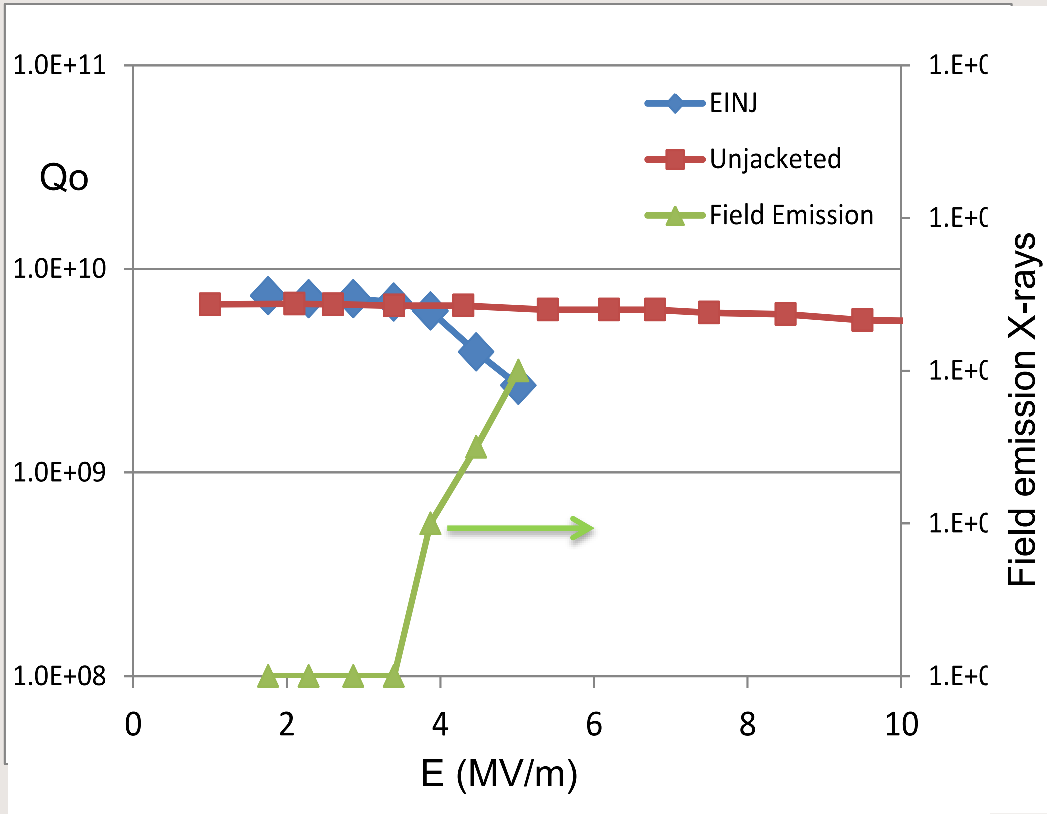
- All systems functional
  - HLRF, LLRF, tuner, power couplers
  - cavity phase lock is stable – couplers balance – rf protection in place
  - Confirmed tuning range – 400kHz
- Measured microphonics – very stable
- Successful acceleration achieved – confirms rf integration and calibration





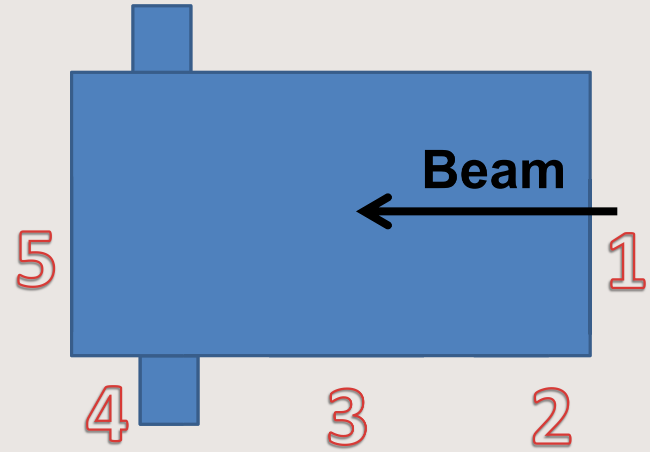
ICM Cavity Performance

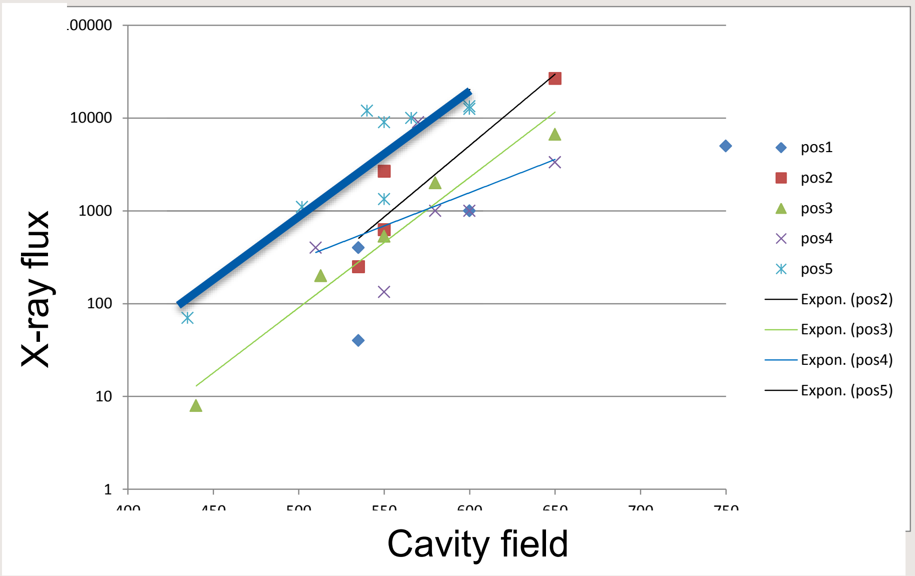
- Q_0 matches vertical test so magnetic field suppression is ok – fundamental is not loaded by the HOM dampers
- but …..
- gradient limited due to strong field emission
- Detective work ensued



Observations

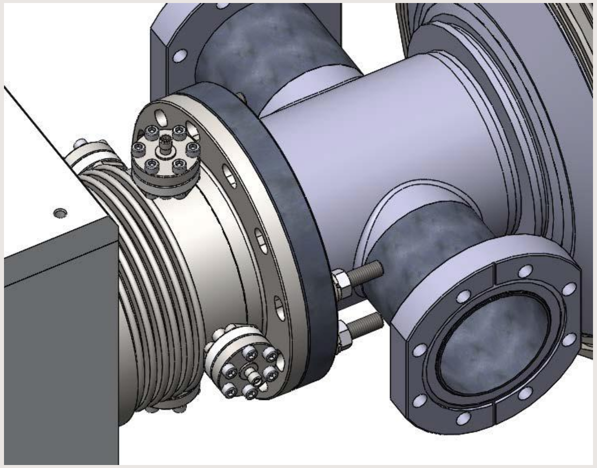
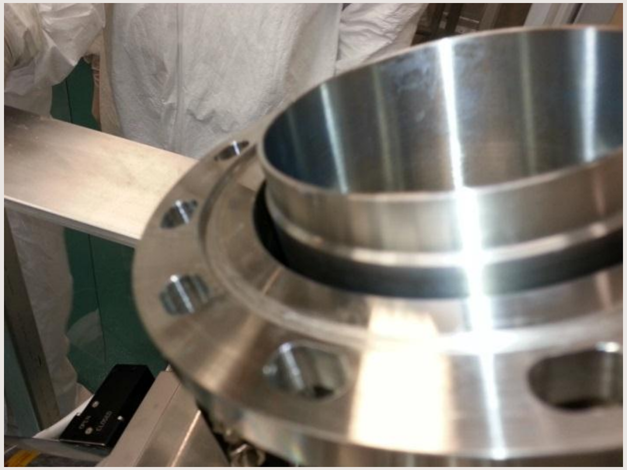
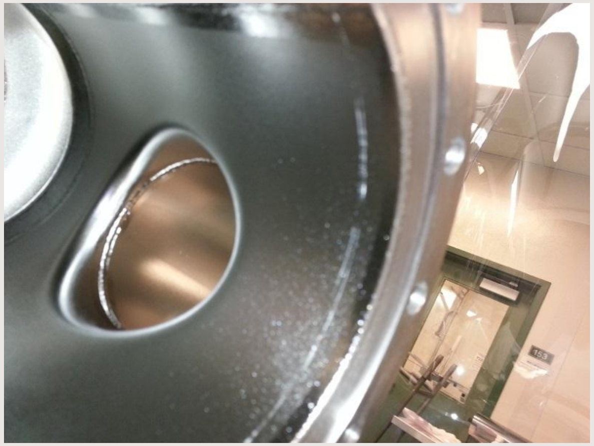
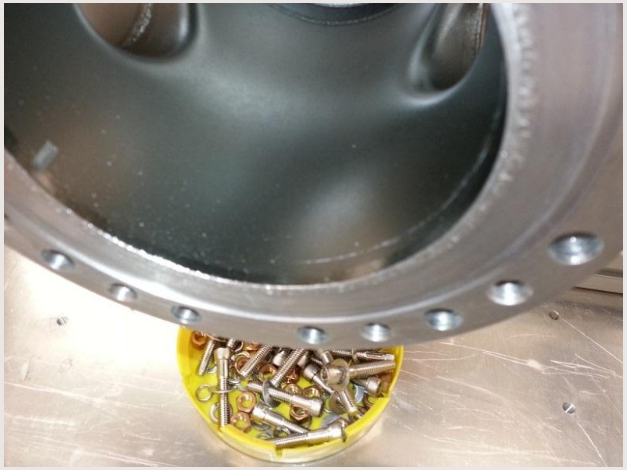
- Radiation measurements as a function of monitor position and rf set-point
- Results indicate that coupler end of the cavity is the most active by a factor of 5-10
- Further
  - Measurements of 7/9 and 8/9 fundamental modes suggest that quench is in the end groups
  - Temperature sensors on coupler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





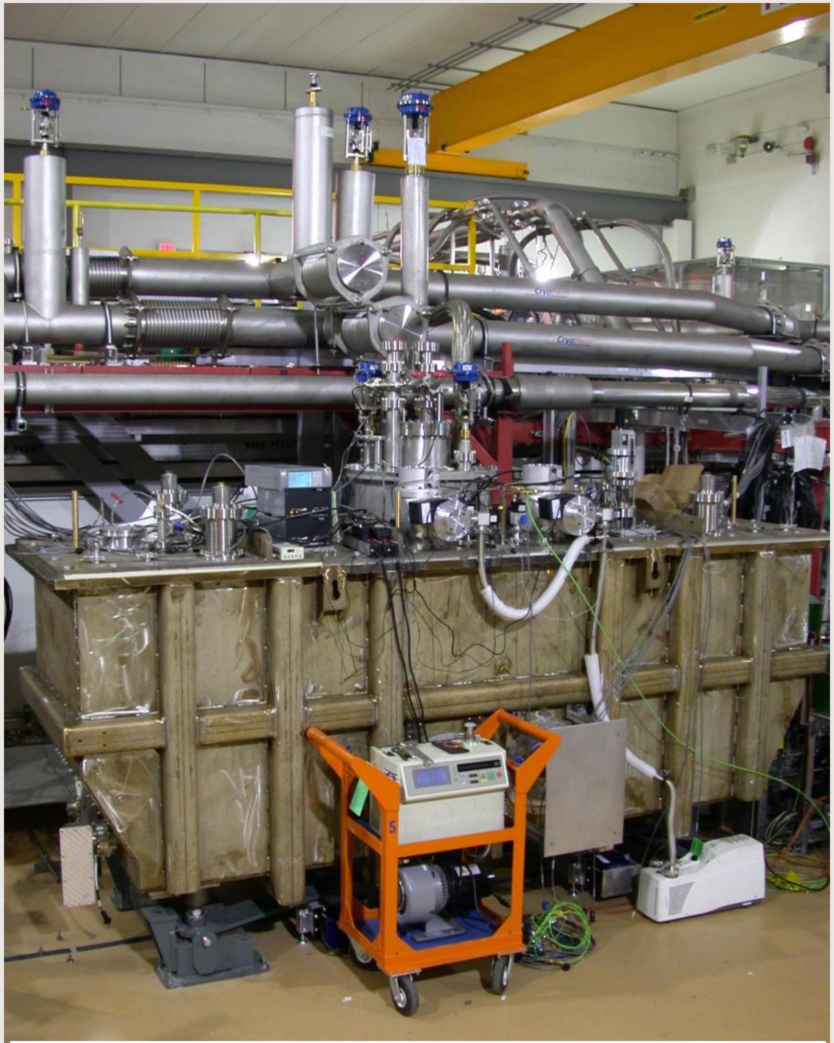
Stainless steel HOM damper – coupler side

- 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.

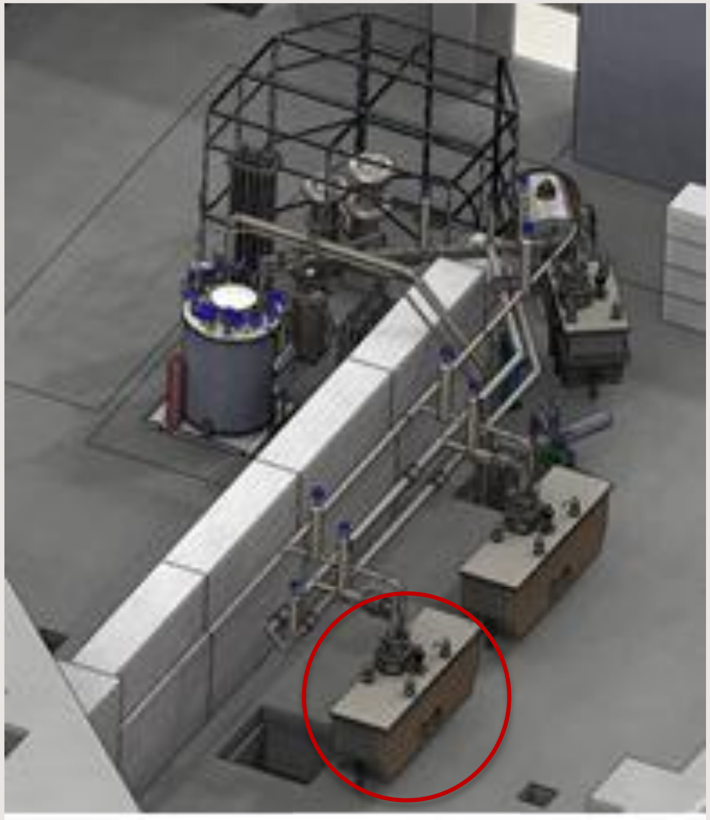


ACMuno – ready for cooldown!

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

Thanks, Merci

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