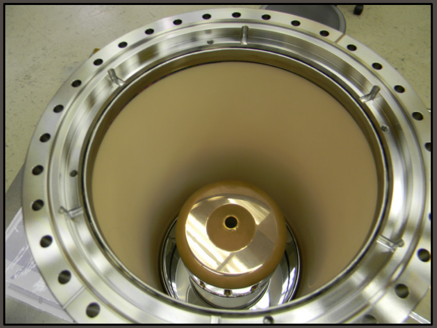
TRIUMF

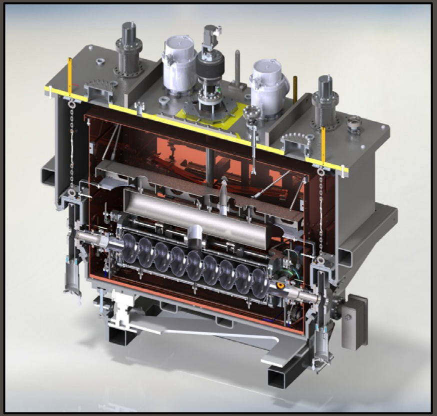
Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

Commissioning and Operation of the ARIEL Electron Linac at TRIUMF

On behalf of the e-linac commissioning team

Marco Marchetto | TRIUMF





OUTLINE

- RIB production at TRIUMF
  - ISAC
  - ARIEL
- Elinac
  - design
  - installation
  - commissioning
  - challenges
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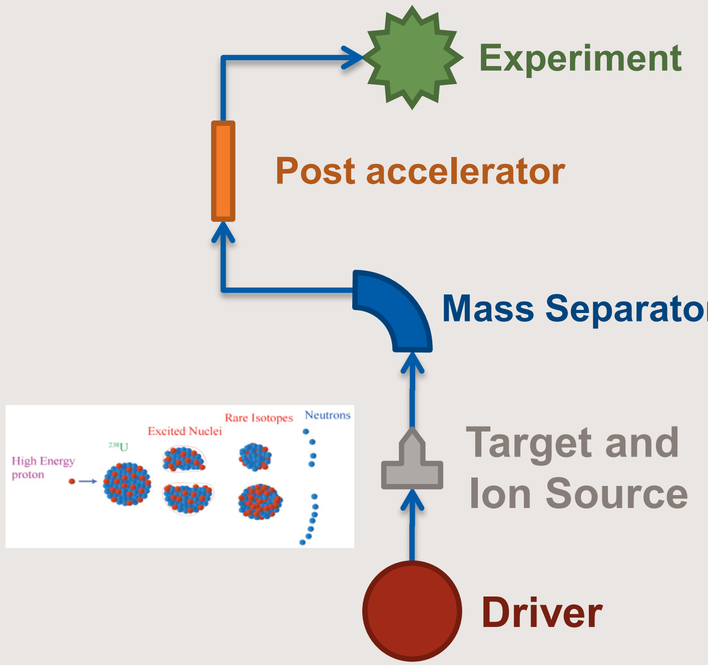
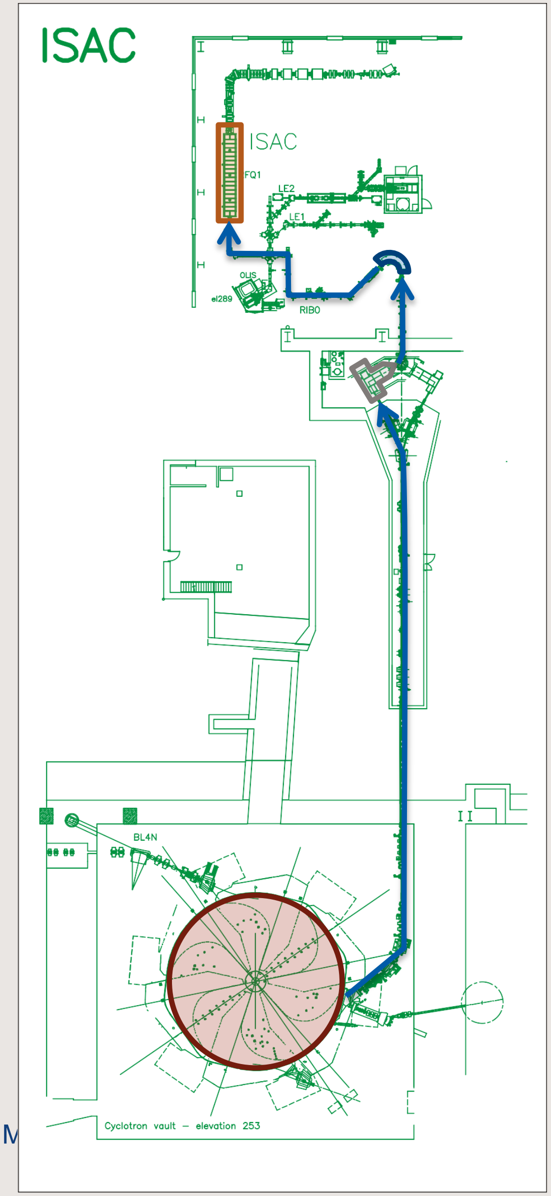
ISAC RIB production

- Isotope Separation On Line (ISOL) facility for rare isotope beam (RIB) production

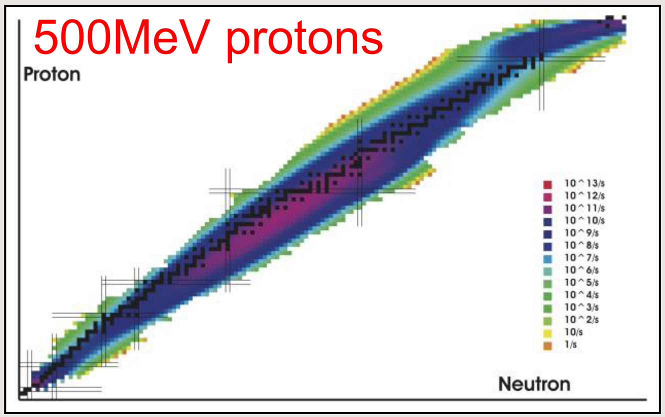


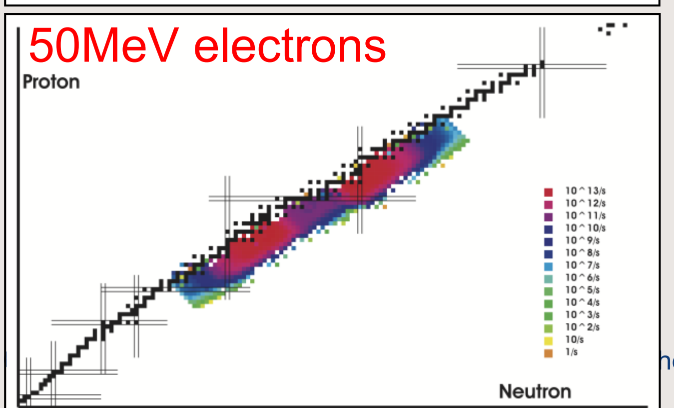
- Highest power driver beam: 500 MeV proton up to 100 μA (**50 kW**) from the TRIUMF cyclotron
- Most intense radioactive beam of certain species: **^{11}Li yield at 2.2·10^{4} ions/s** with 65 μA (April 2015).

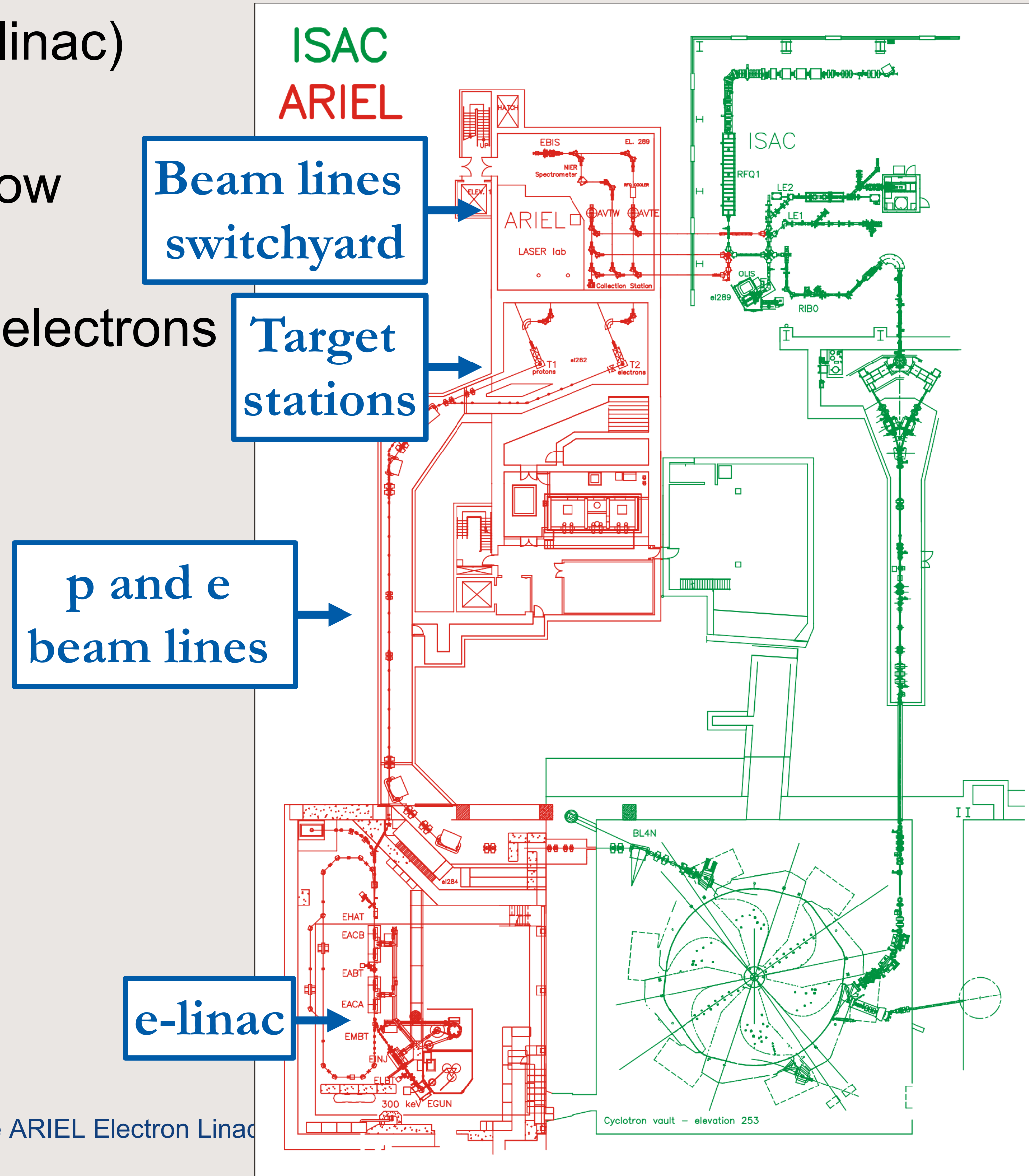


ARIEL RIB production

- New driver: the electron linac (e-linac) complementary to the cyclotron
- **Photofission** production yields low isobaric contamination
- Two target stations: protons and electrons

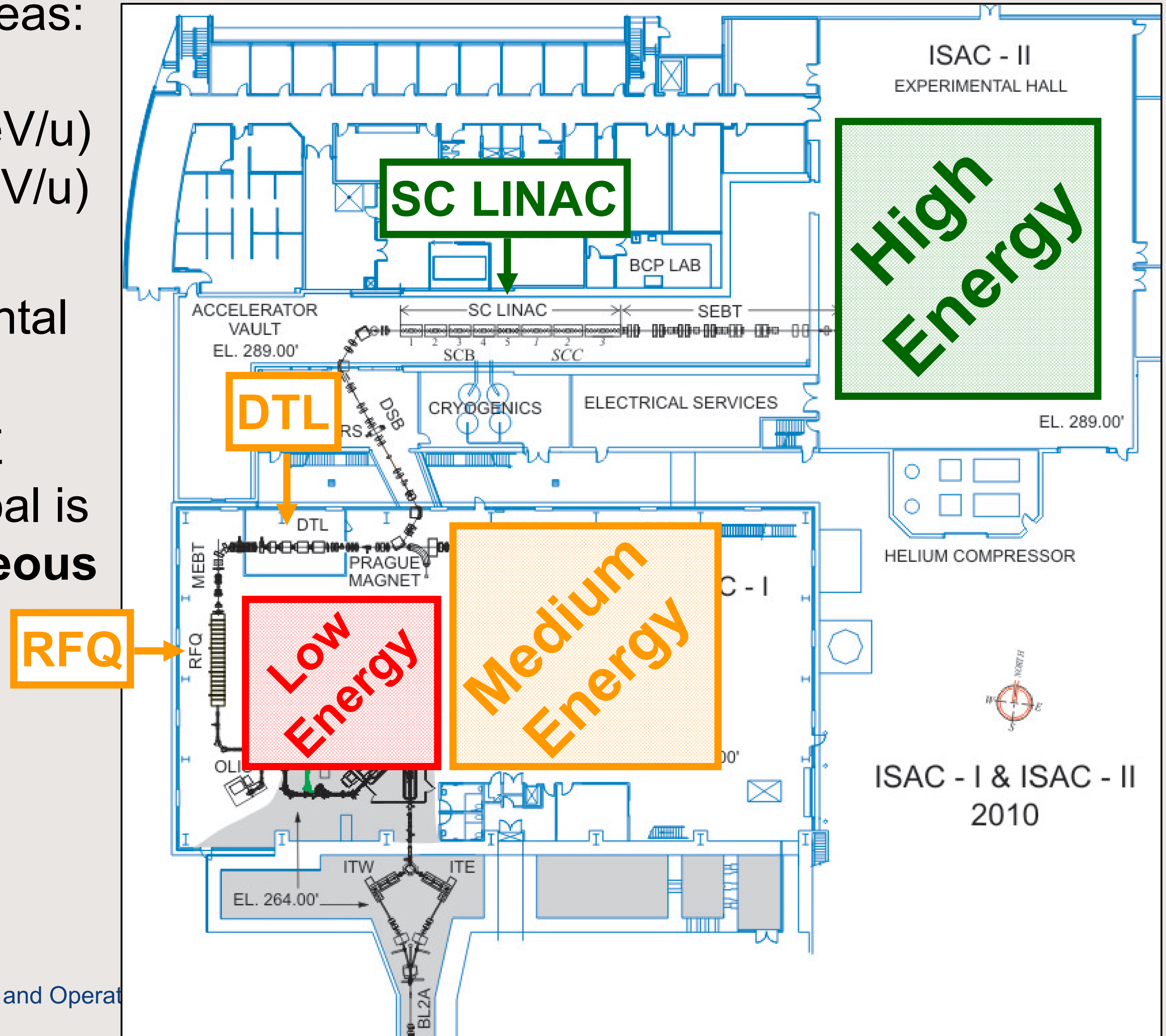






ISAC Experimental facilities

- Three experimental areas: **low** (up to 60 KeV), **medium** (up to 1.5 MeV/u) and **high** (up to 18 MeV/u) energy
- 1 RIB for 15 experimental stations
- Advance Rare IsotopE Laboratory (ARIEL) goal is to provide **3 simultaneous RIB**



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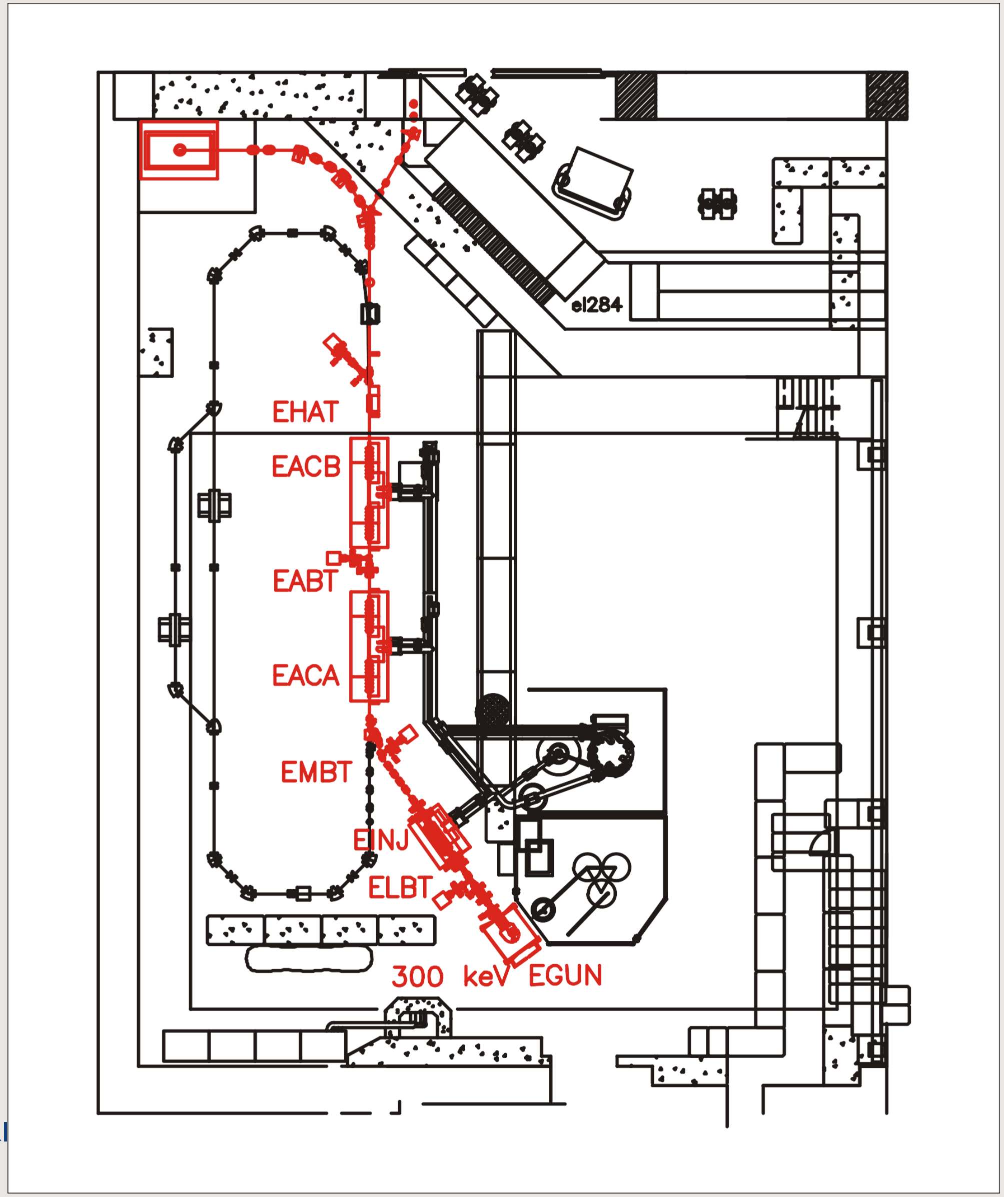
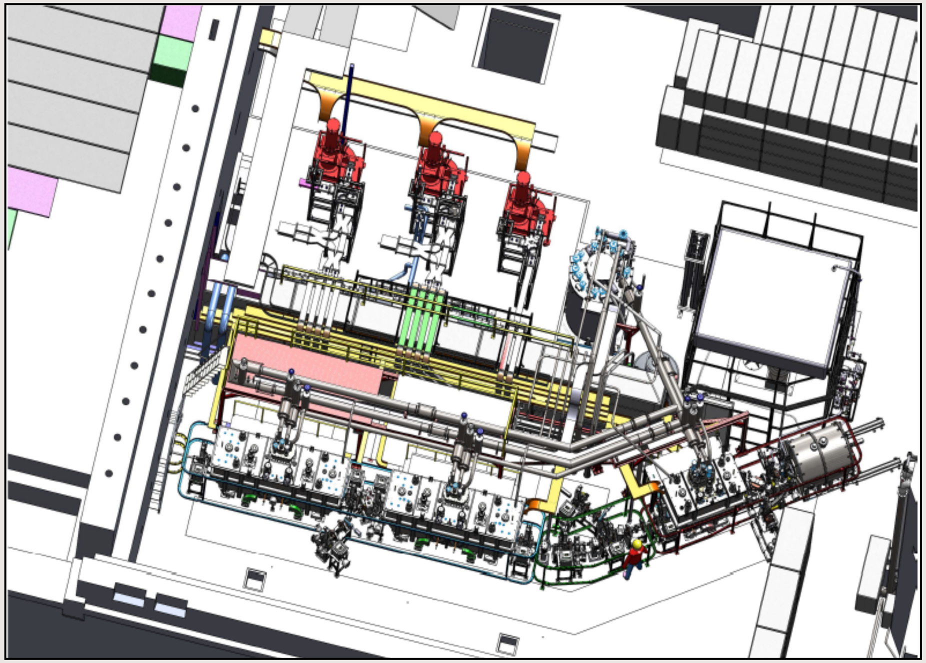
ARIEL e-linac

- Located in the refurbished proton experimental hall (now e-hall)
- 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



E-linac main parameters

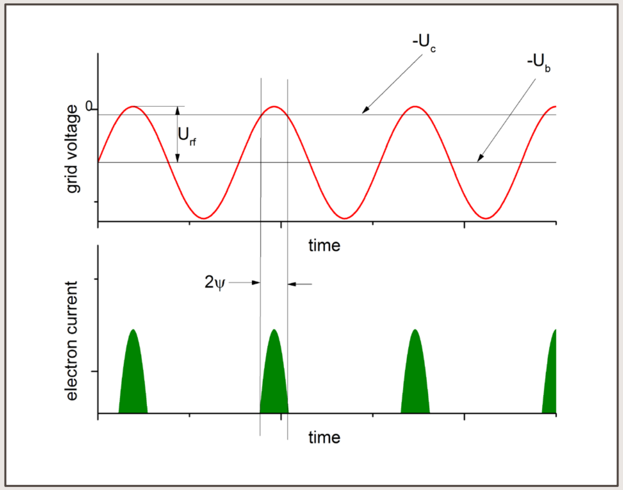
- The ARIEL E-Linac specification
  - 10mA cw at 50MeV - **0.5 MW** of beam power
  - five cavities 100kW of beam loaded rf power per cavity
  - two couplers per cavity each rated for 50kW operation
  - 10MV energy gain per cavity
- Linac divided into three cryomodules
  - one Injector cryomodule (ICM) 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 (demonstrated September 2014)



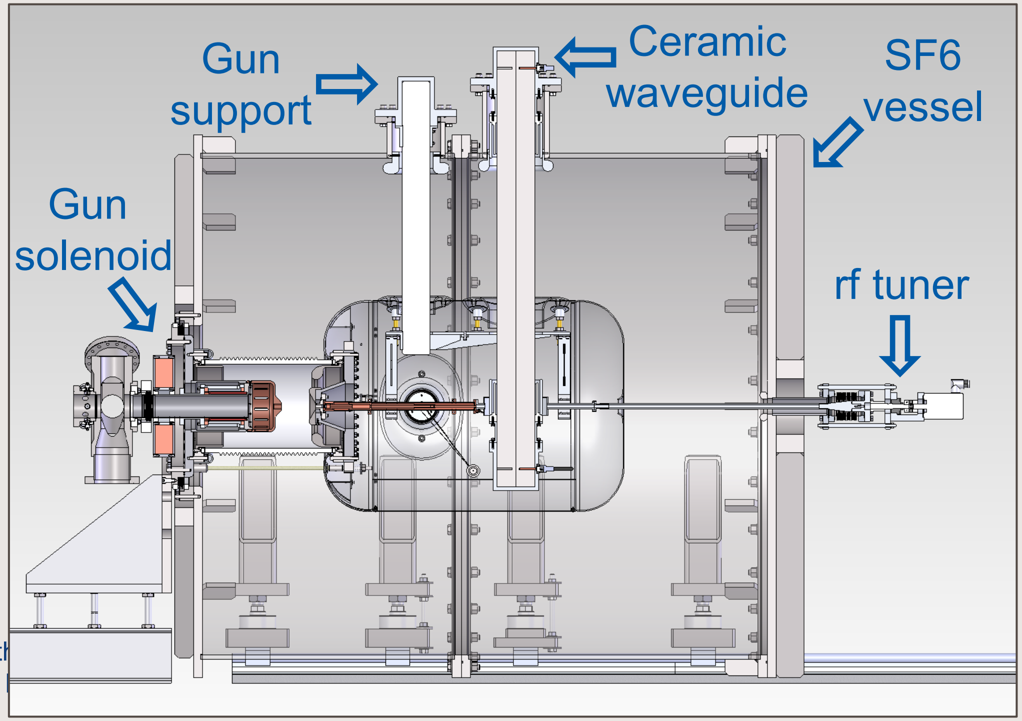
Courtesy of Bob Laxdal

Electron Gun

- Thermionic **300kV** DC gun: cathode has a grid with DC supressing voltage (up to 400V) 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



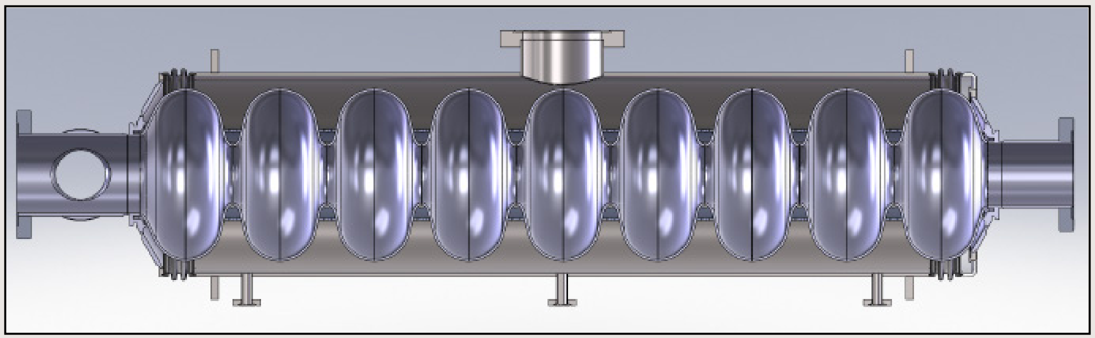
Parameter	Value
RF frequency	650MHz
Pulse length	±16⁰ (137ps)
Average current	10mA
Charge/bunch	15.4pC
Kinetic energy	300keV
Normalized emittance	5μm
Duty factor	0.01 to 100%

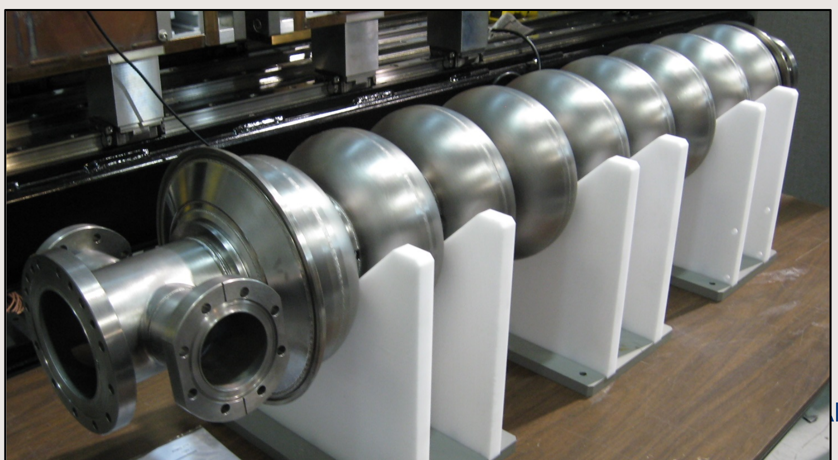


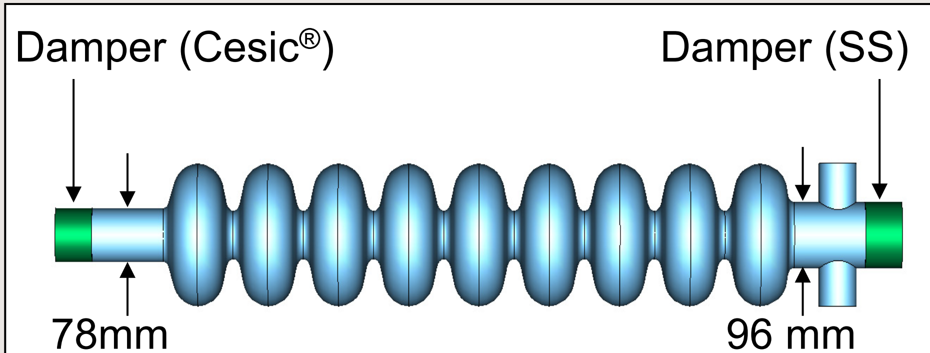
ARIEL cavities

- **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 (GHz)	1.3
R/Q (Ohms)	1000
Q_0	$1 \cdot 10^{10}$
E_a (MV/m)	10
P_{cav} (W)	10
P_{beam} (kW)	100
Q_{ext}	$1 \cdot 10^{6}$
Q_L*R_d/Q of HOM	$<1 \cdot 10^{6}$



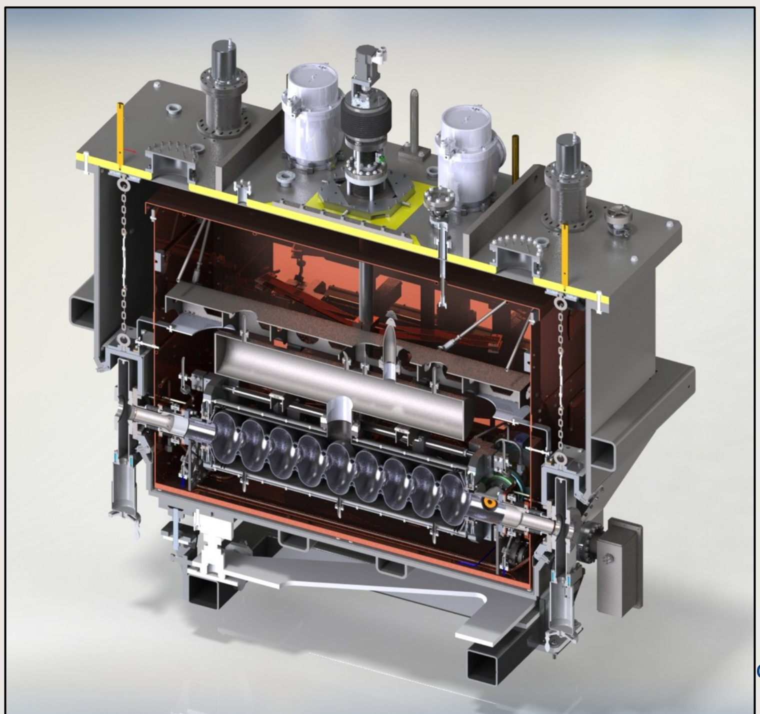


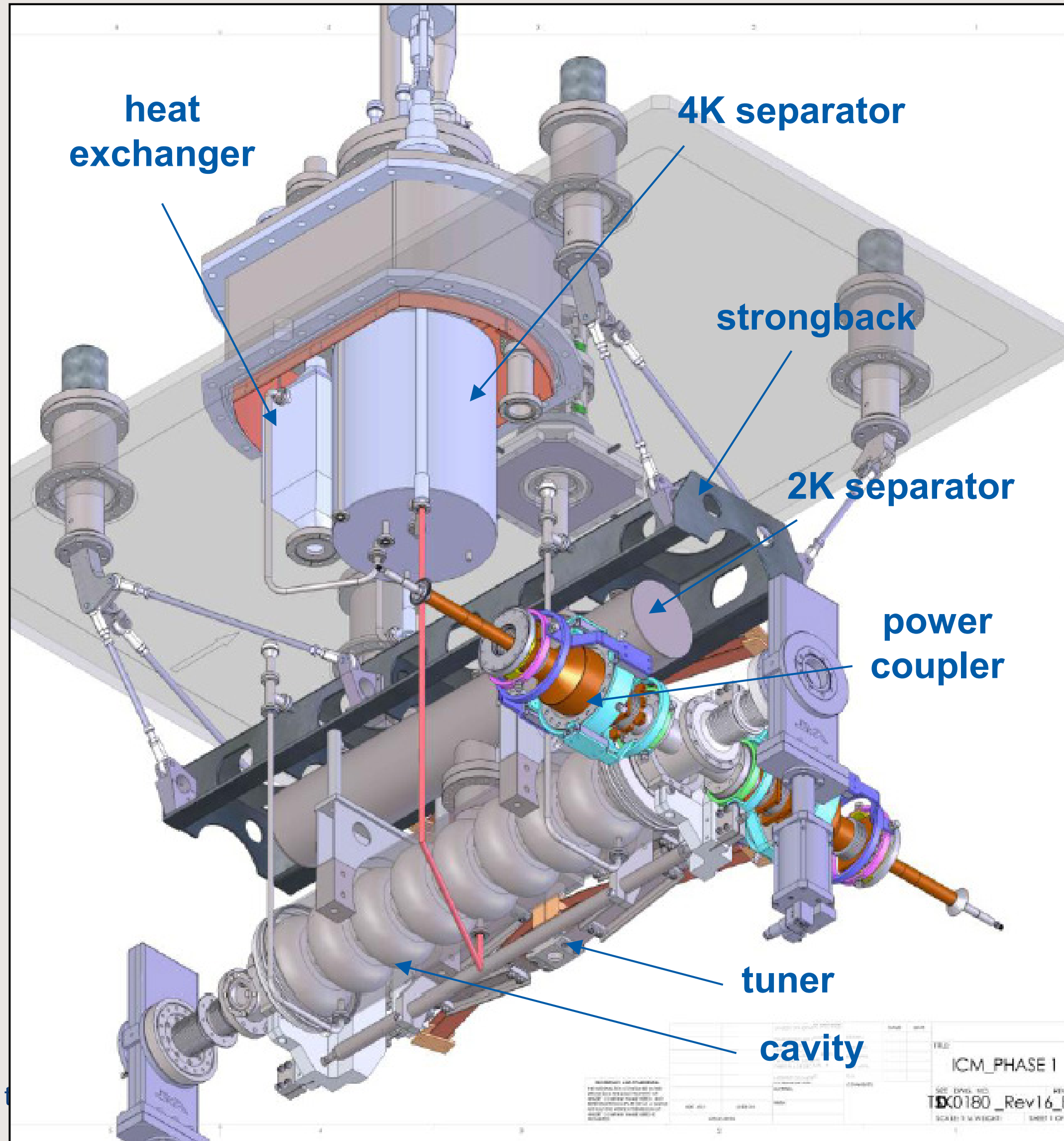


[3] P. Kolb, et al: Cold tests of HOM absorber material for the ARIEL eLINAC at TRIUMF, http://dx.doi.org/10.1016/j.nima.2013.05.031.

Injector cryomodule

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





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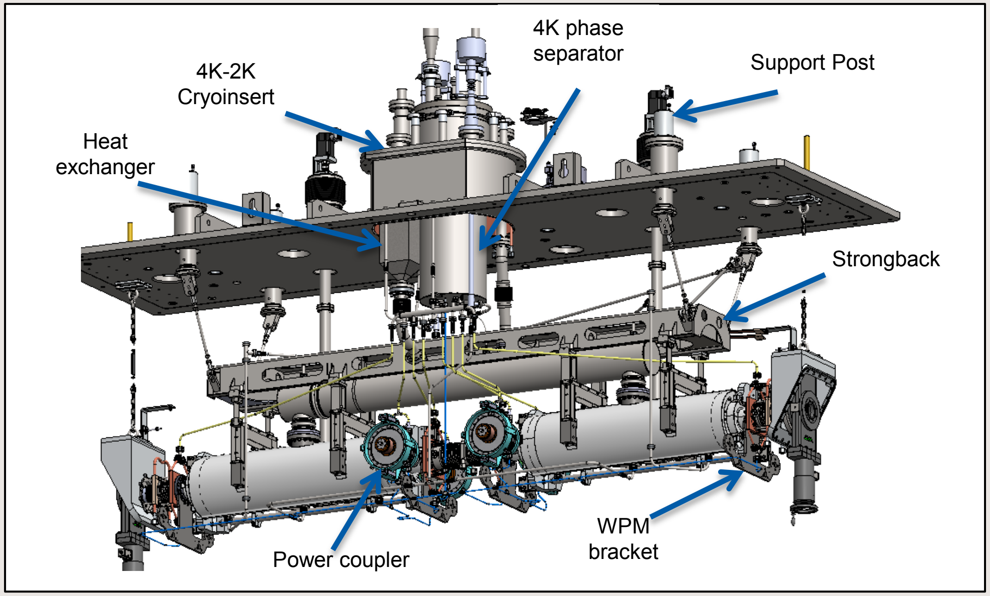
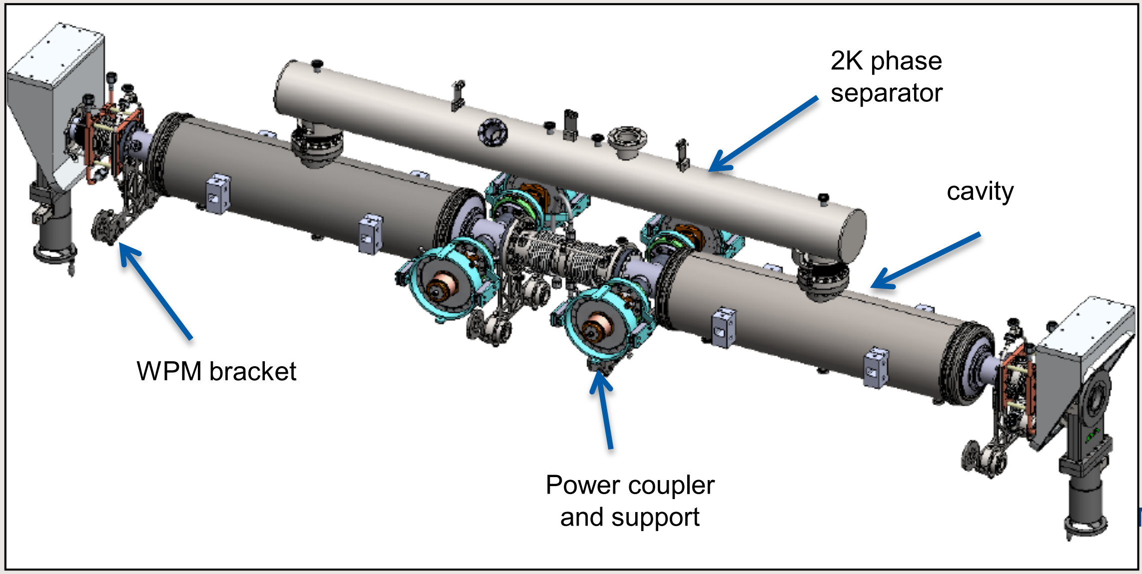
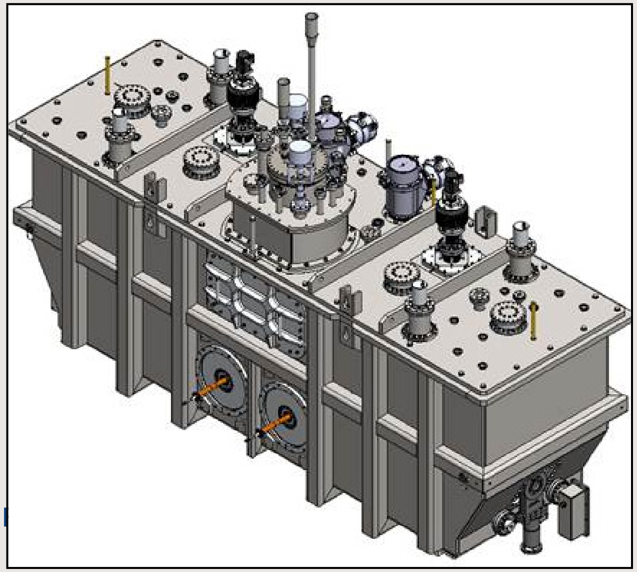
Accelerator cryomodule

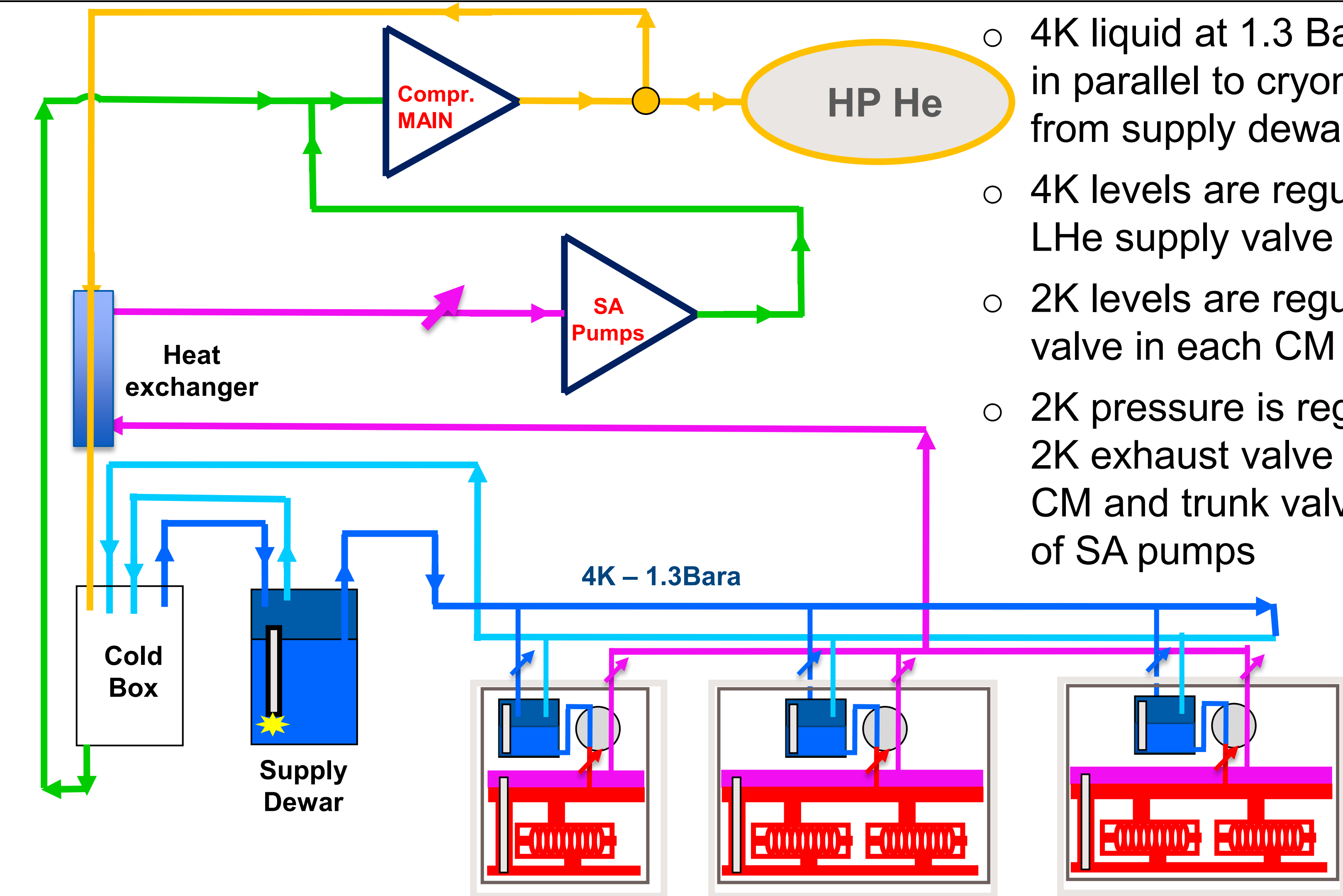
- The ACM uses same basic design as ICM but with two 1.3GHz nine cell cavities each with two 50kW power couplers
- There is one 4k/2k insert identical to the ICM
- Dimension: 3.9 x 1.4 x 1.3 m
- Weight: 9 tons







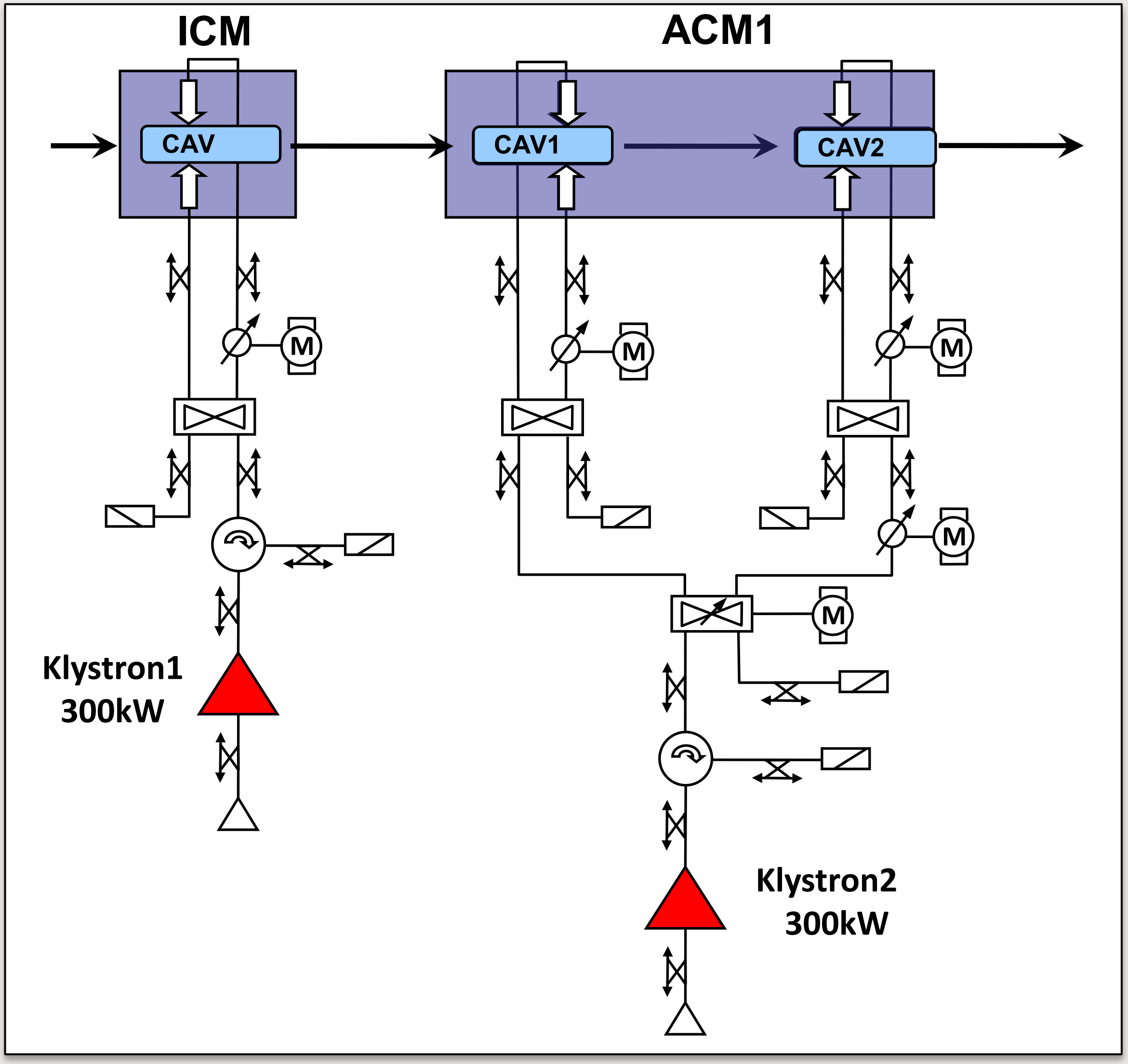
Cryogenics



- 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



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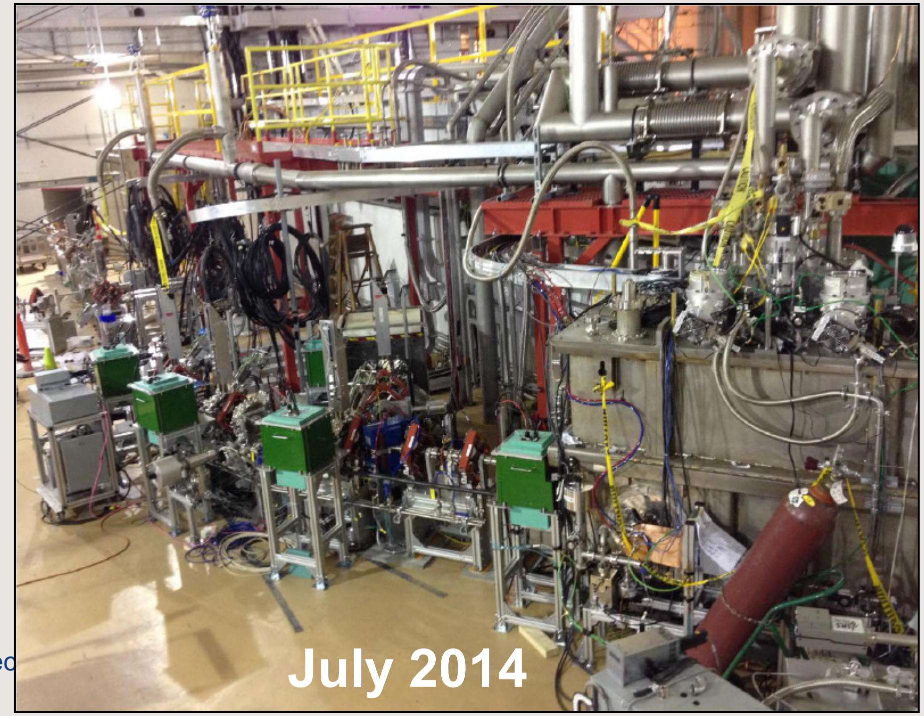
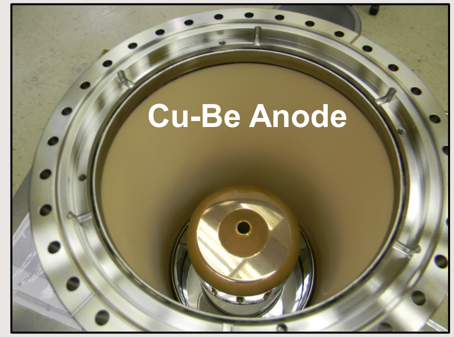
Installation in 2014

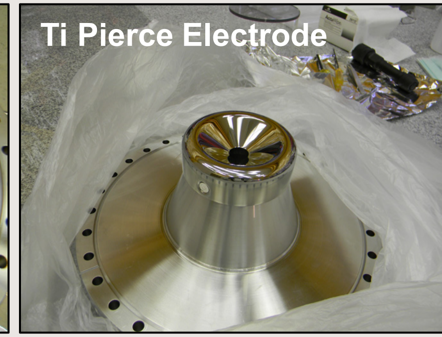
- **Interleaved installation** (day shift) **and commissioning** (night shift) in order to meet deadline
- Cryogenics acceptance tests complete
- E-Gun, LEBT and MEBT installed and commissioned
- Two klystrons and HV supplies installed and commissioned
- ICM assembled, installed and commissioned
- ACM assembled, installed and commissioned



Electron Gun Status

- The electron gun and LEBT were installed in February/March 2014
- Bias voltage of 325kV achieved
- 10mA cw achieved at 300kV
- Successful rf modulation with the ceramic waveguide
  - 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

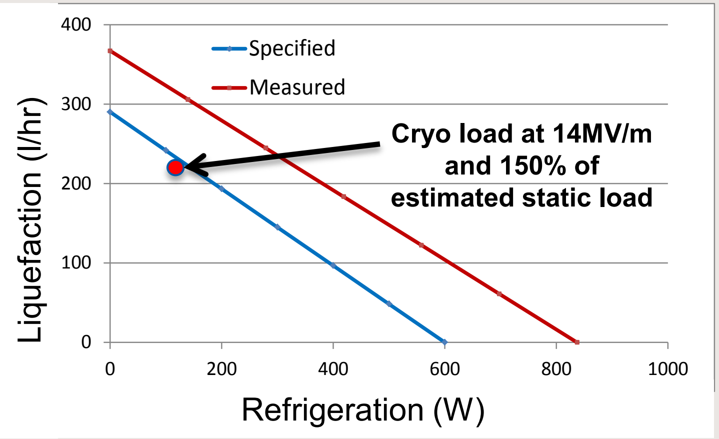




Cryogenics installation

- 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

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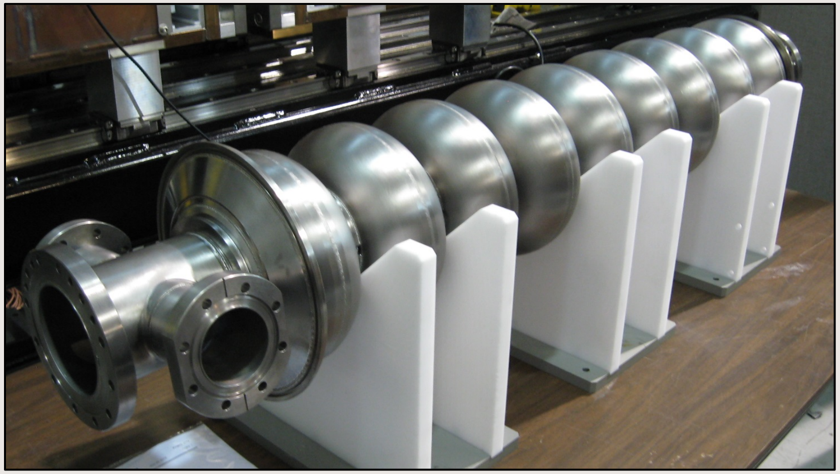
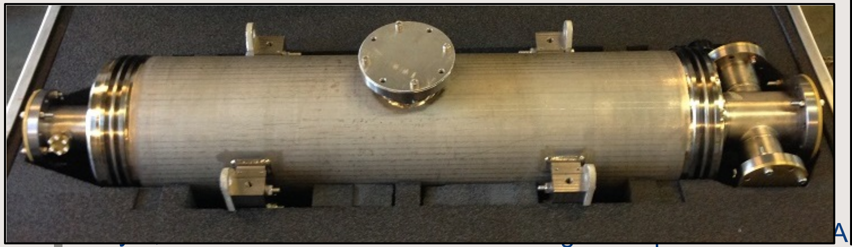
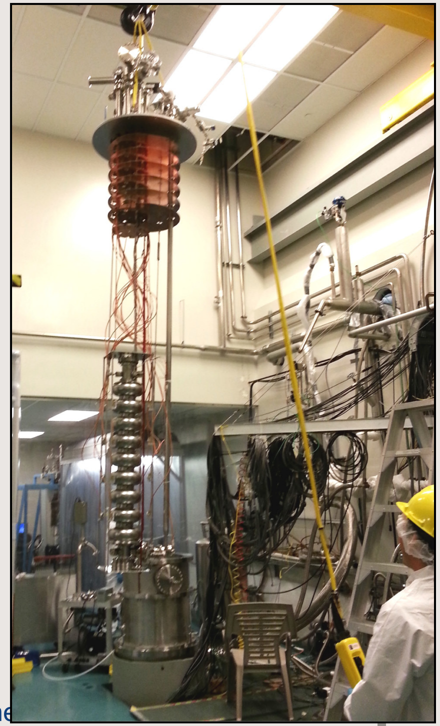
ARIEL Cavities - PAVAC

Cavity	Preparation	Status
ARIEL1	BCP120, Degas at FNAL, BCP20	Installed in ICM1
ARIEL2	BCP, Degas at FNAL, 120Bake, HF rinse BCP20	Installed in ACM1
ARIEL3	BCP120, Degas, BCP20	Ready for testing

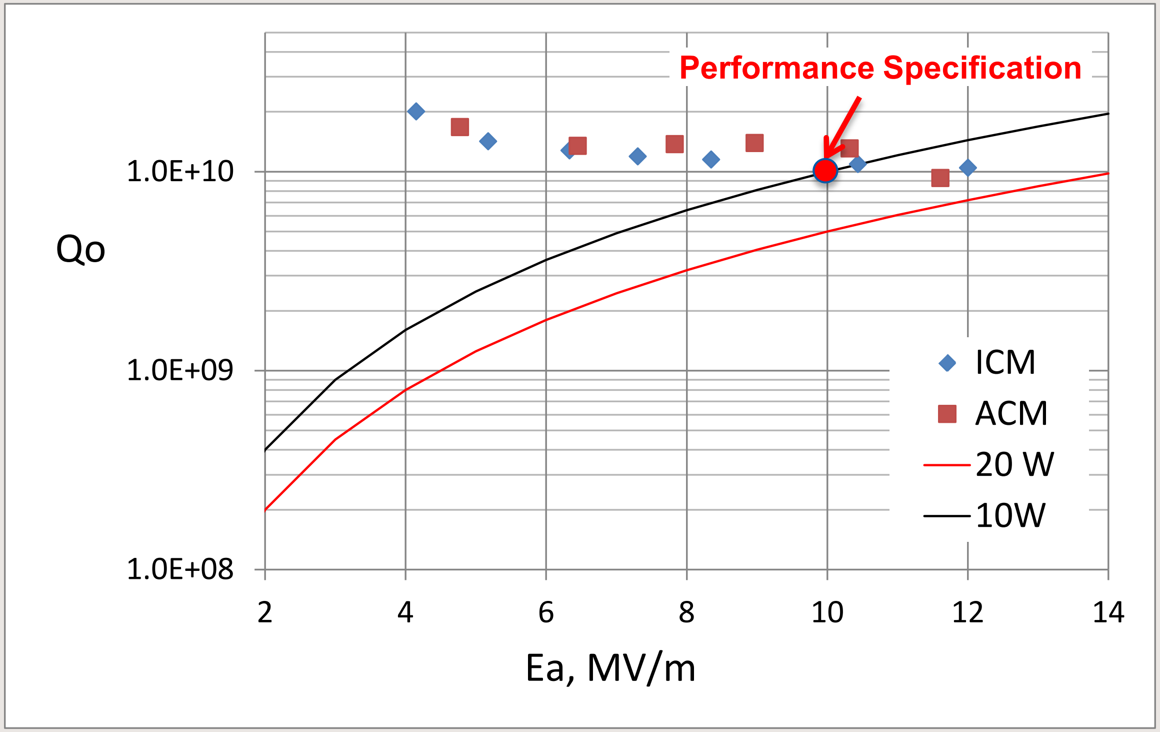






ARIEL Cavities

Both ARIEL1 and ARIEL2 meet specifications (limit is in the coupler conditioning)



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ICM Assembly

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

Cavity hermetic unit (March 14, 2014)

ICM top assembly

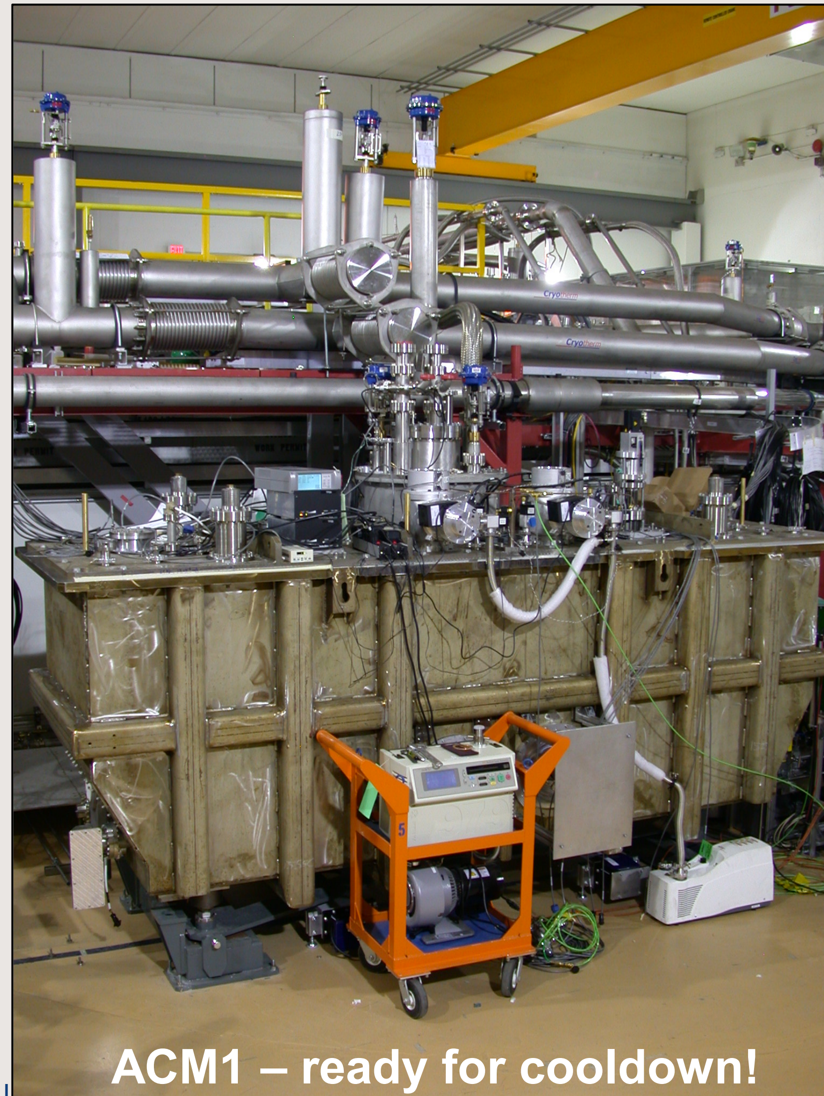
ICM mock-up – 2013

Top assembly into tank

ICM unit Complete (April 9, 2014)

ACM1

- ACM1 assembly proceeds through June/July 2014
- Only one cavity installed to allow early testing of cryomodule



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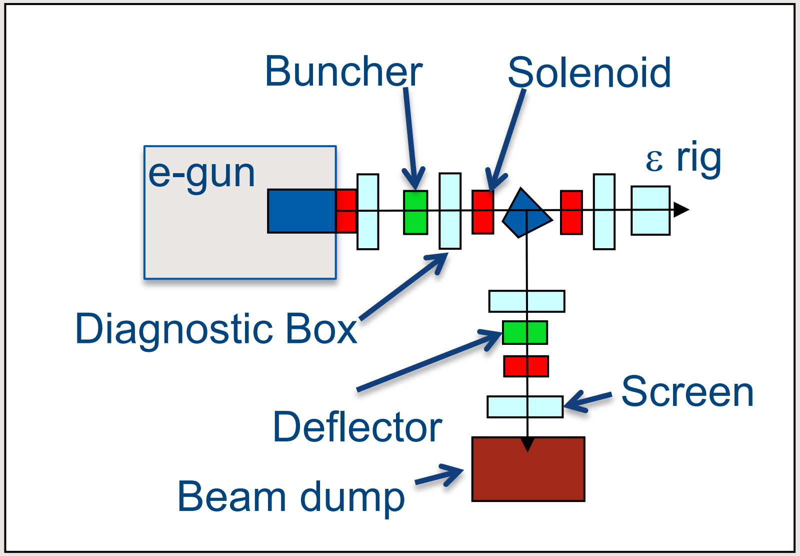
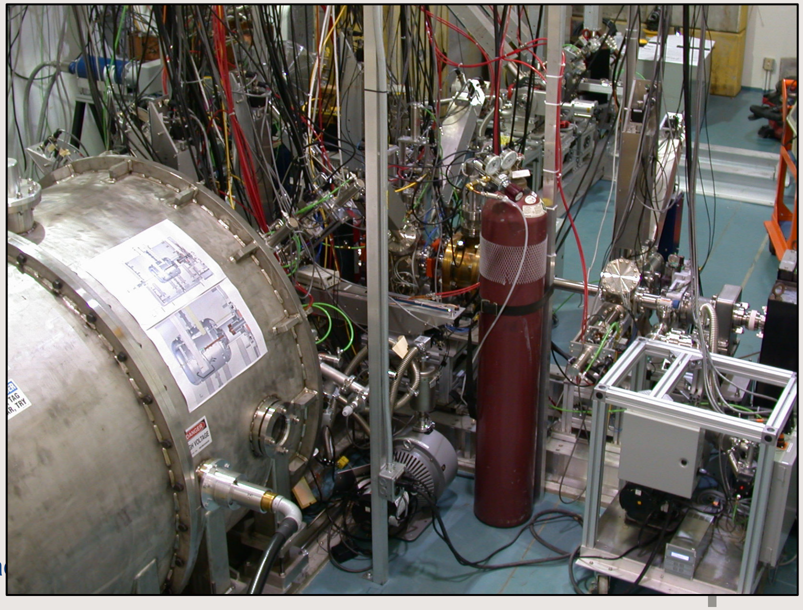
Beam lines

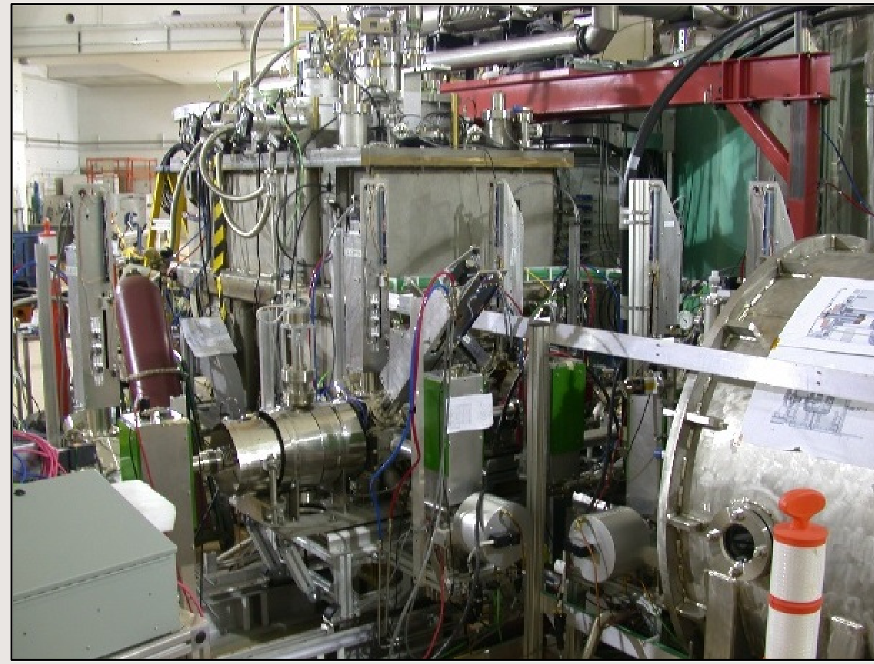
- The current e-linac low energy transport line (ELBT) was installed in the ISAC-II vault to conduct early test while the final site (e-hall) was being prepared
- Beam line components include:
  - Optics: solenoid (for the low energy part), quadrupole (for the medium and high energy) and steerers
  - Diagnostic: view screen, faraday cup, analysing magnet, emittance rig.
  - RF devices: buncher, deflector and cryomodules (ICM and ACM)
- Equipment is commissioned first without beam: e-Gun, rf cryomodules, cryogenic, magnets, diagnostic, etc.





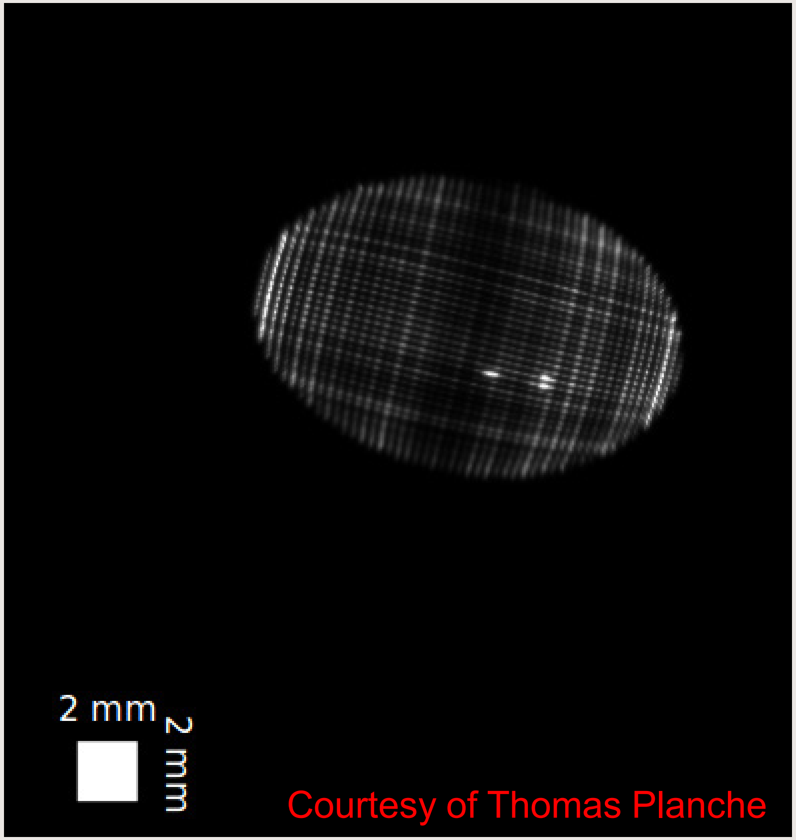
Beam commissioning

- e-Gun:
  - transverse emittance
  - beam output: current, bunch length, duty factor
- Optics:
  - calculated value of the optics elements based on beam dynamics simulation and magnet measurements are applied
  - beam profiles at screen location and transmission are used as performance parameters
- Acceleration system:
  - final energy is the main performance criteria



Transverse emittance

- The beam image (real space) at the location of the first view screen (EGUN:VS0) is represented on the side picture
- To recreate the transverse phase space at this location we used tomographic reconstruction
- Several images of the beam at low intensity are taken at the second screen location (ELBT:VS2) for different setting of the solenoids (ELBT:SOL1 and ELBT:SOL2).



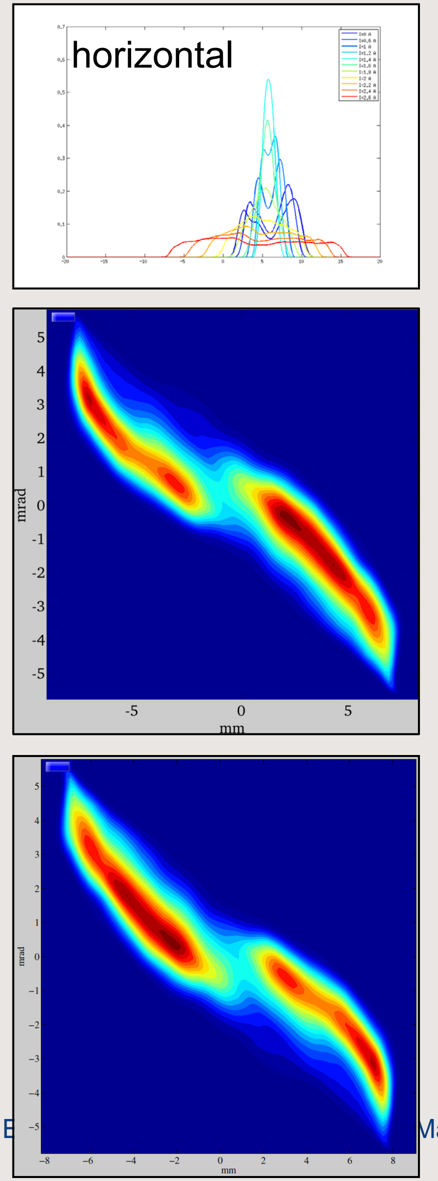
Emittance tomography reconstruction

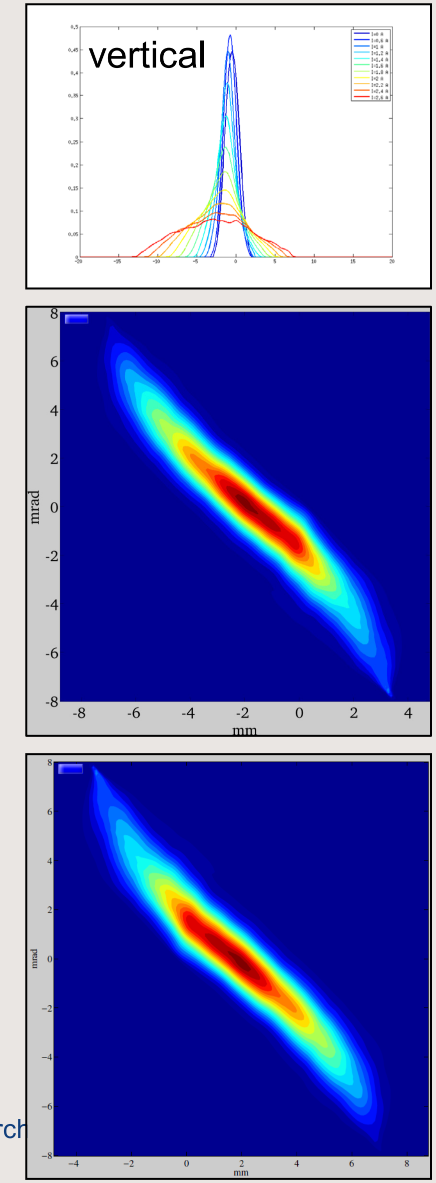
SOL1 data:

- ε_{rms}= 5 μm horizontal
- ε_{rms}= 3 μm vertical

SOL2 data:

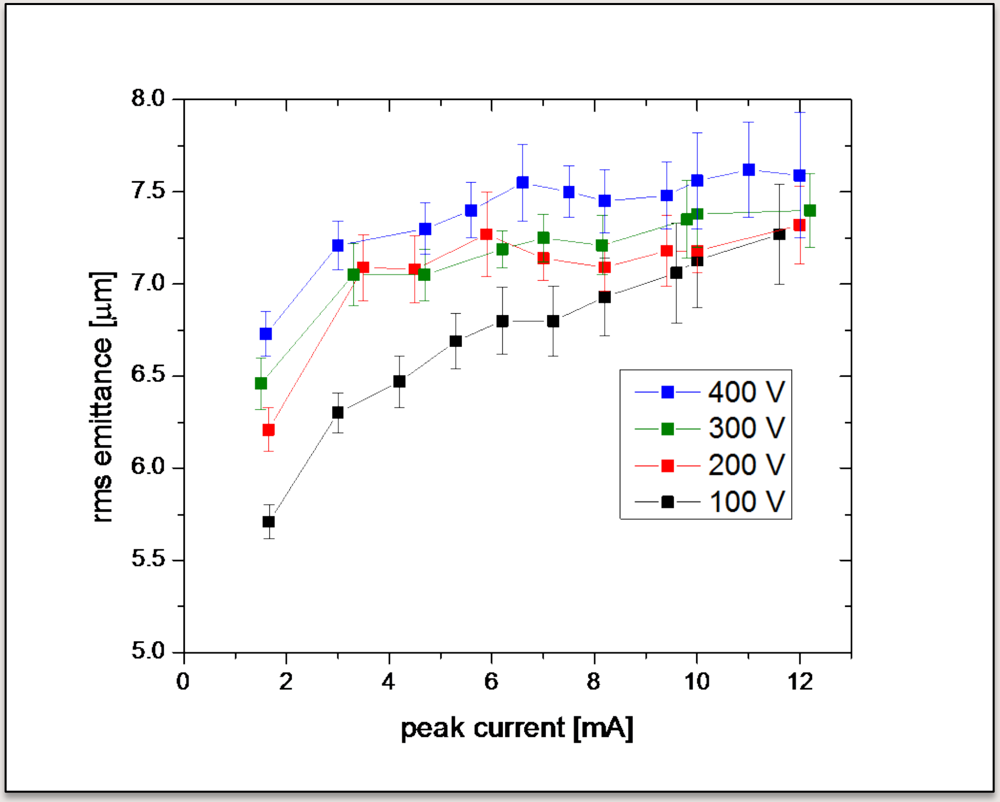
- ε_{rms}= 5 μm horizontal
- ε_{rms}= 3 μm vertical

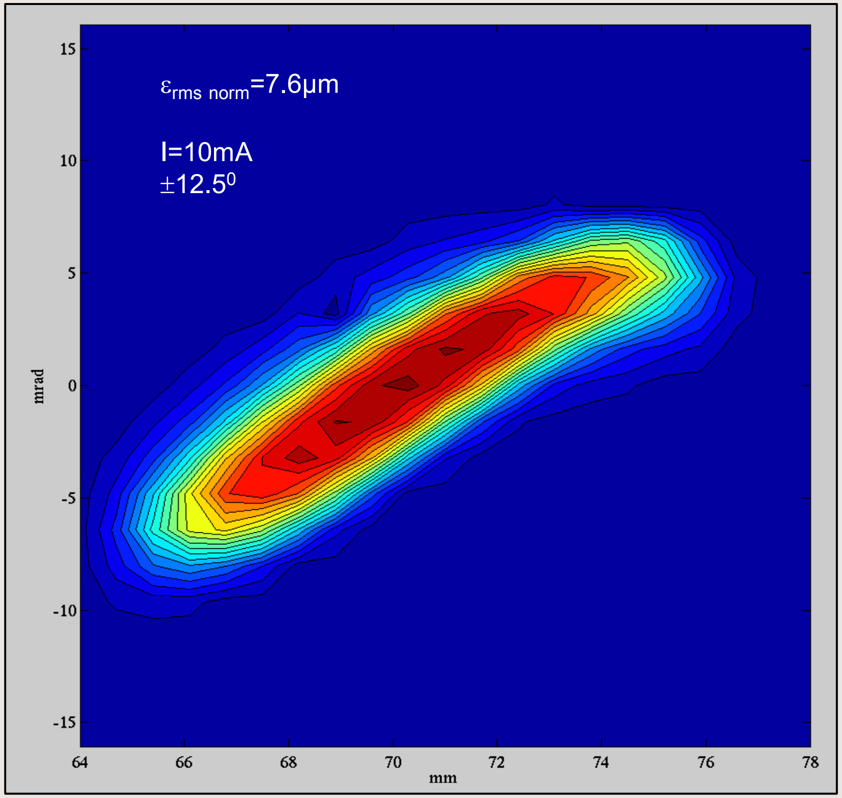




Emittance measurement

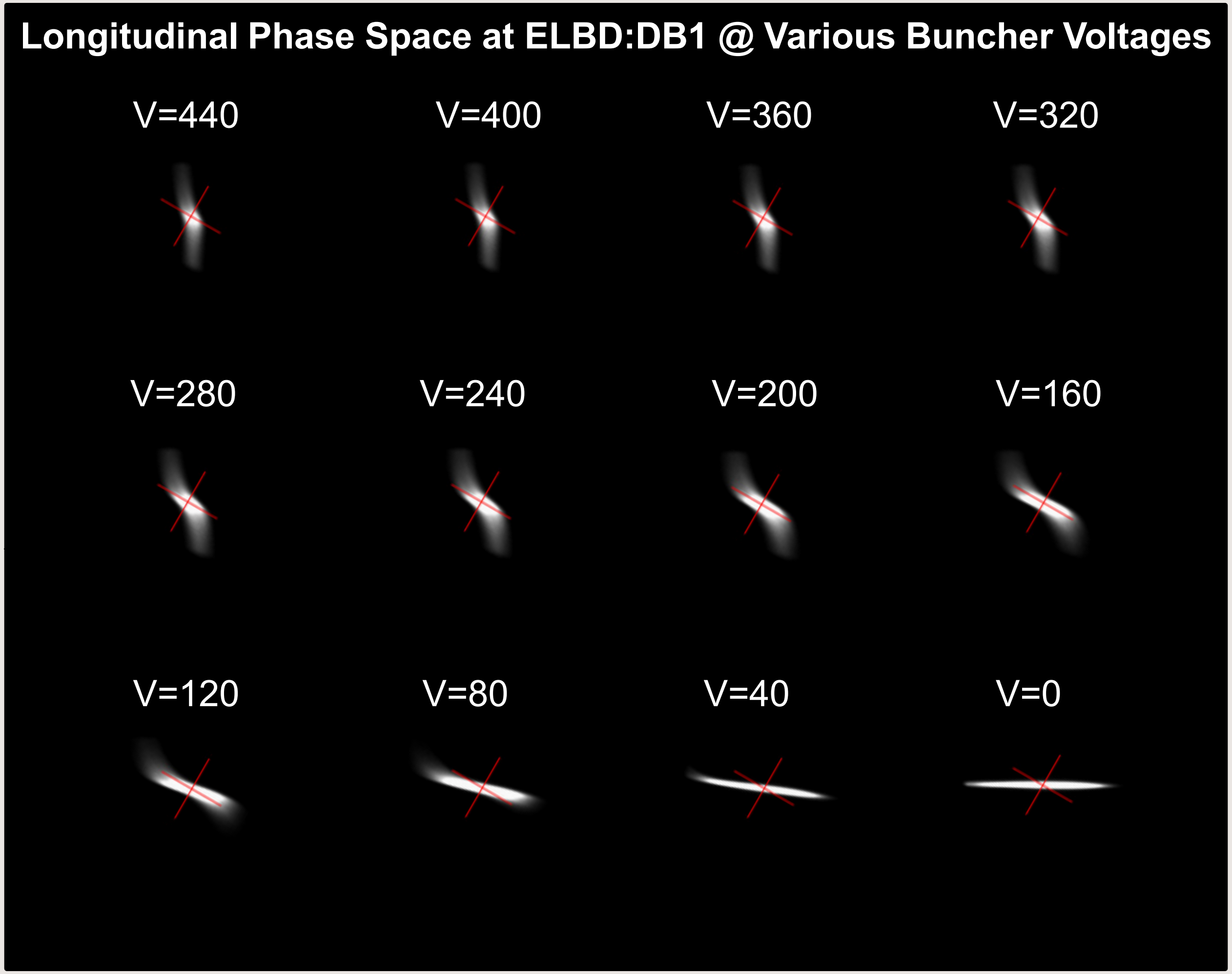
Reconstructed emittance is consistent with the early measurements done at the ISAC-II test area





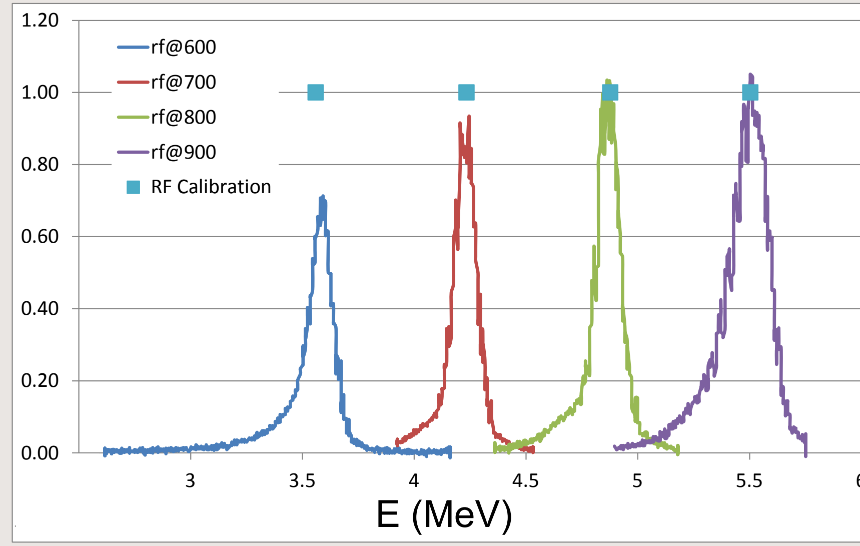
Deflector cavity

TM110 deflecting mode cavity to measure the longitudinal phase space and tuning the ELBT buncher



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
- Successful acceleration achieved confirms rf integration and calibration
- Initial energy out the injector cryomodule: 5.5 MeV
- Final Injector energy: 12 MeV
- ACM1 energy: **23 MeV** (with a single cavity)



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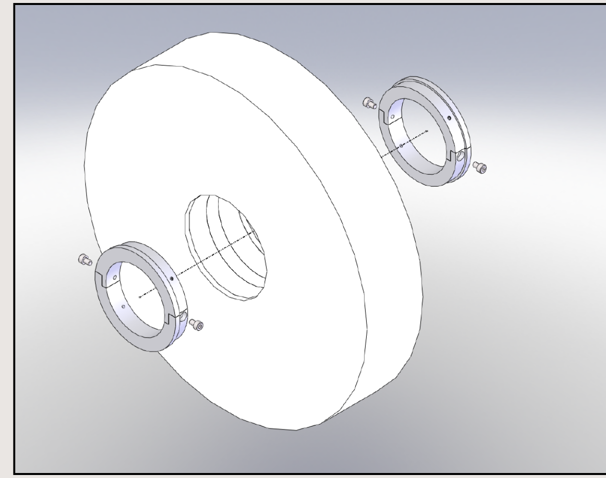
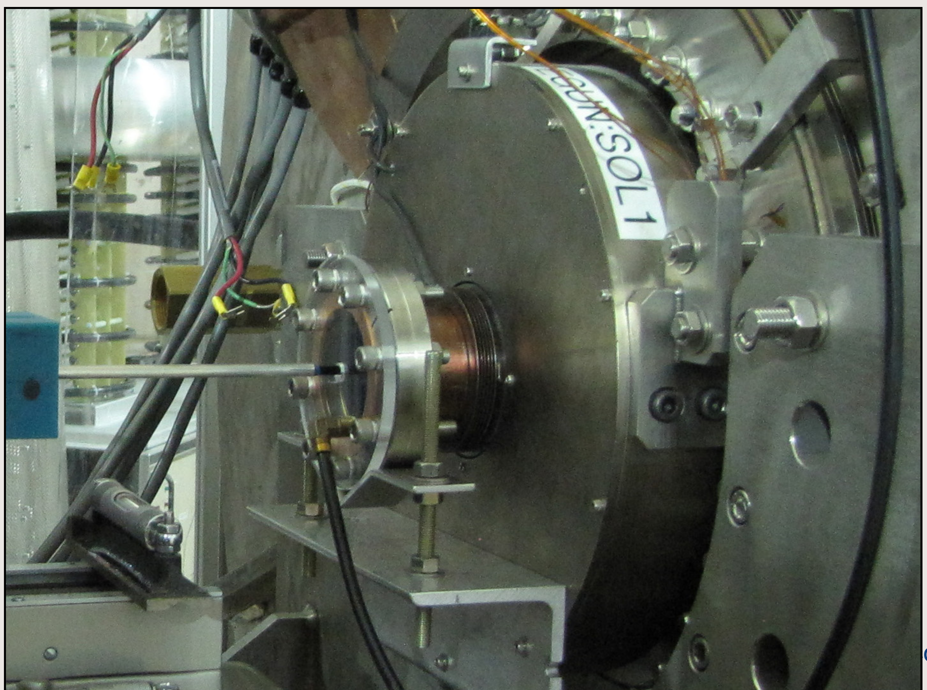
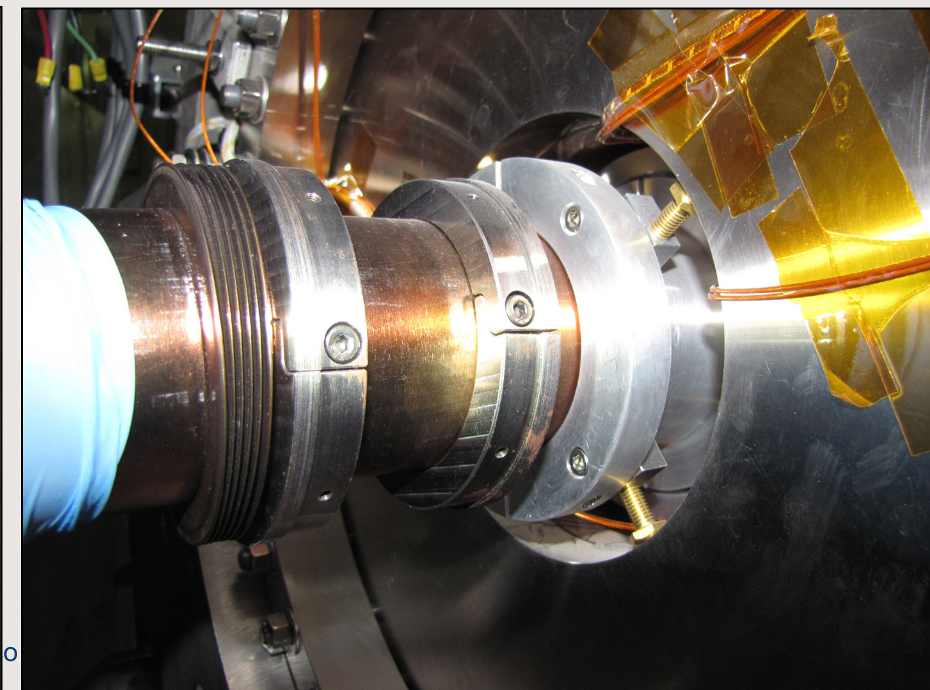
Egun solenoid

- Design specifications
  - ID 3.5 inches OD <12 inches
  - $\int Bdl \approx 4770\ G\ cm$
  - Fall off at $\pm$15 cm <50 G
- Mechanical constraints doesn't allow for water cooled solenoid
- Field clamp necessary to produced required field

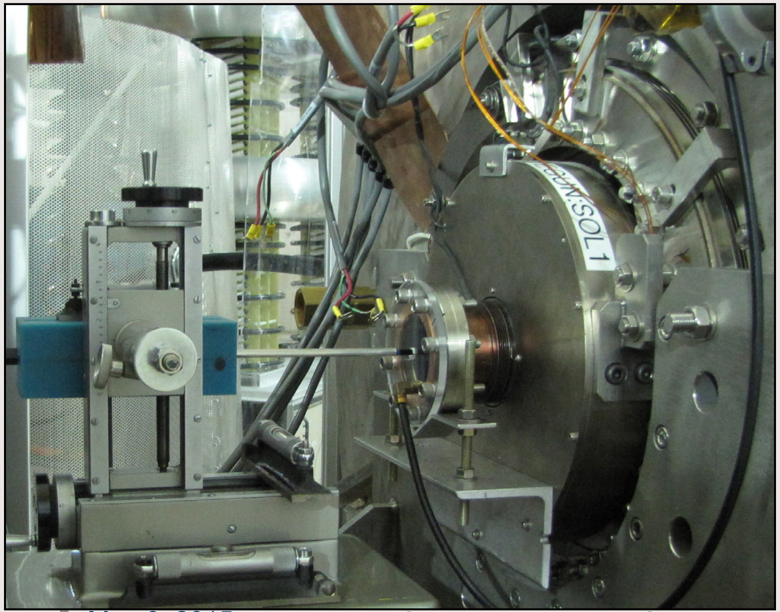


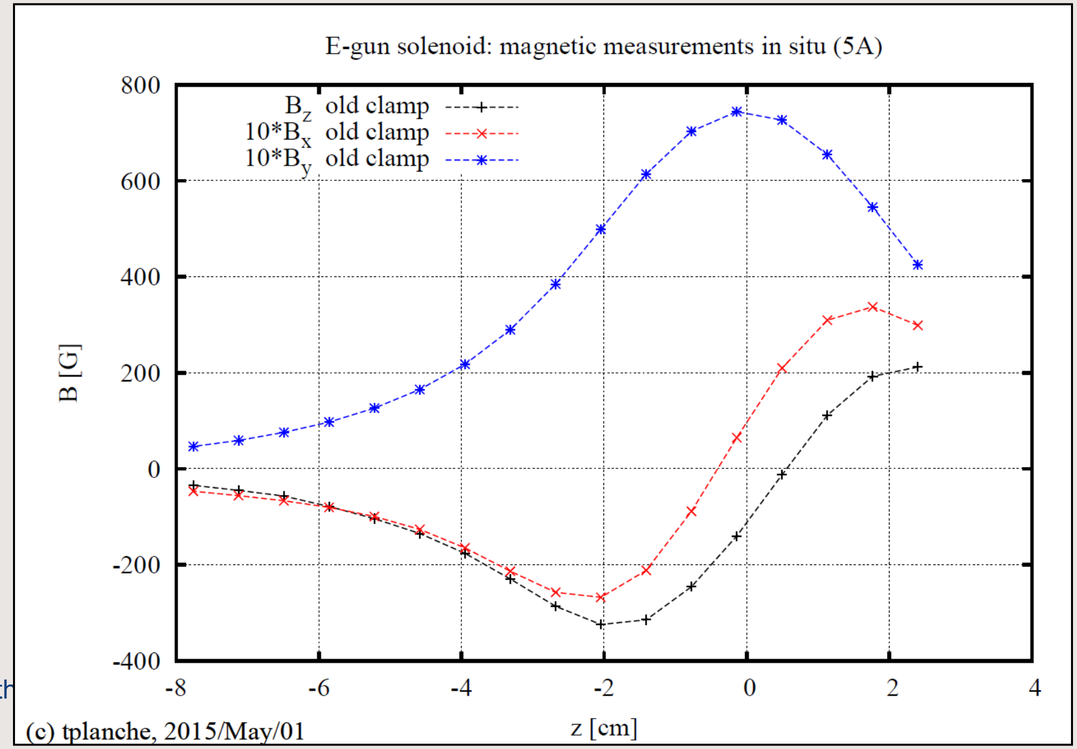




Egun solenoid asymmetric field

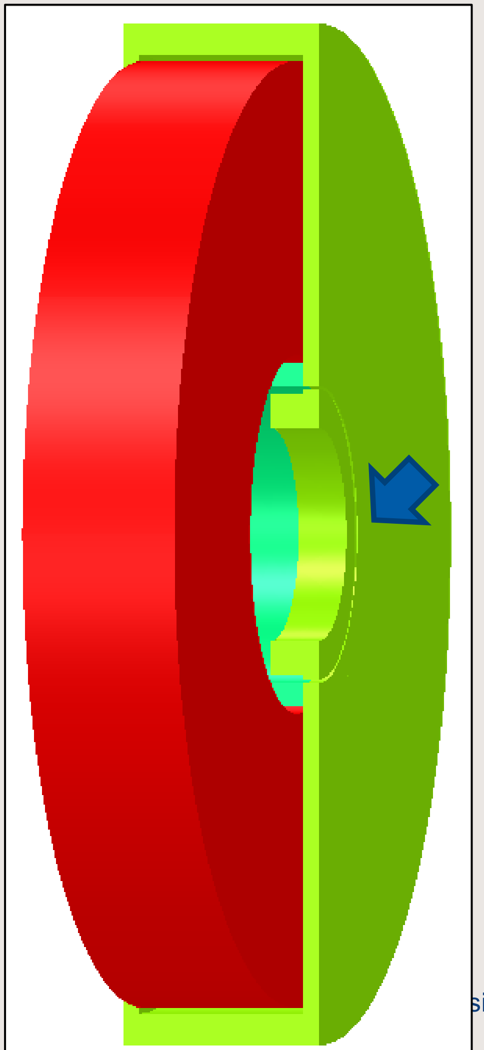
- Egun solenoid steered the beam aligned on axis
- Asymmetric beam shape when changing solenoid strength
- In situ measurement show asymmetric field
- Simulated solenoid displacement and/or tilt with respect to the clamps without reproducing the transverse kick



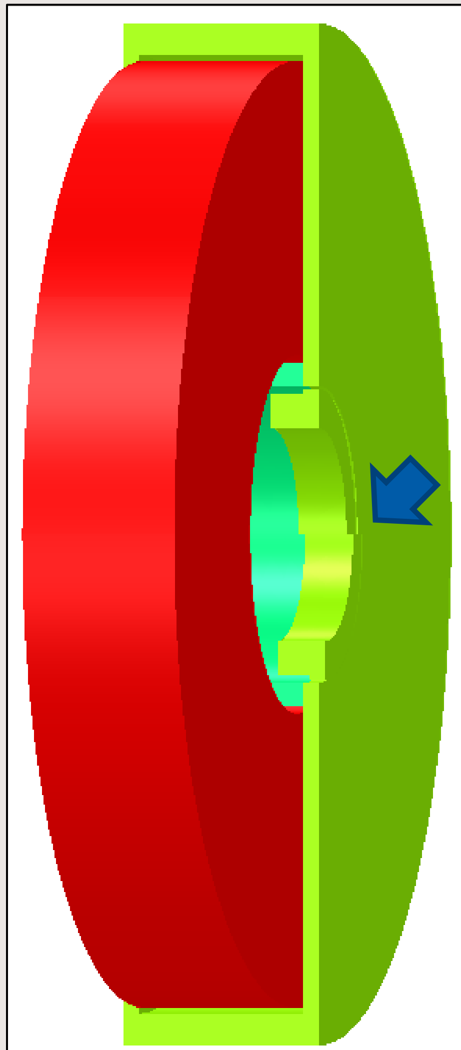


Egun solenoid – field clamps re-design

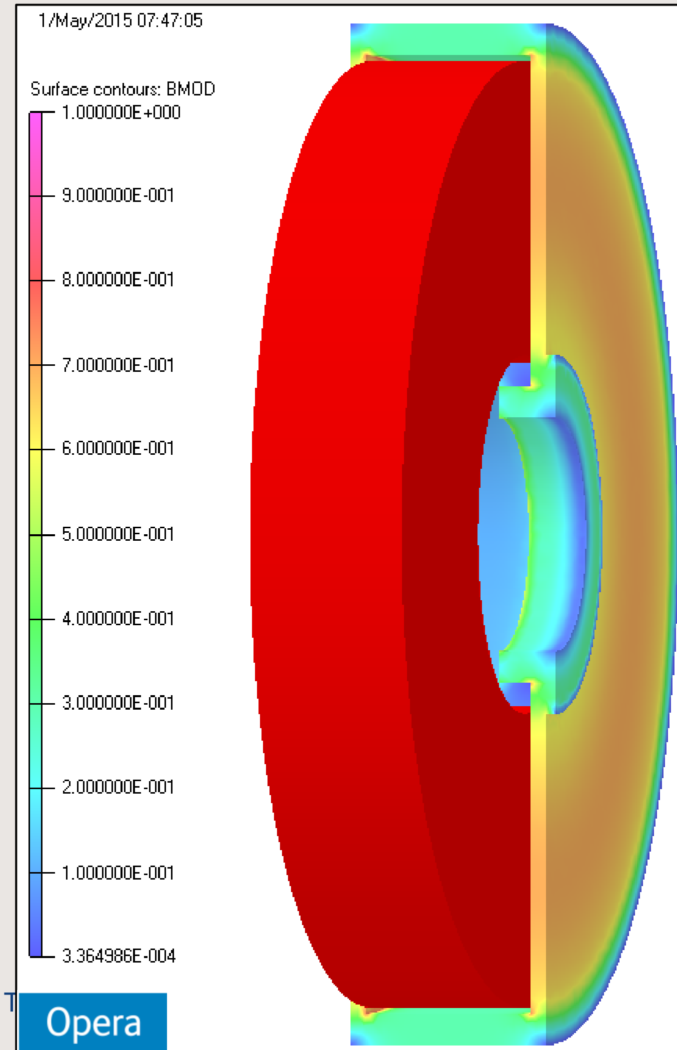
Original design



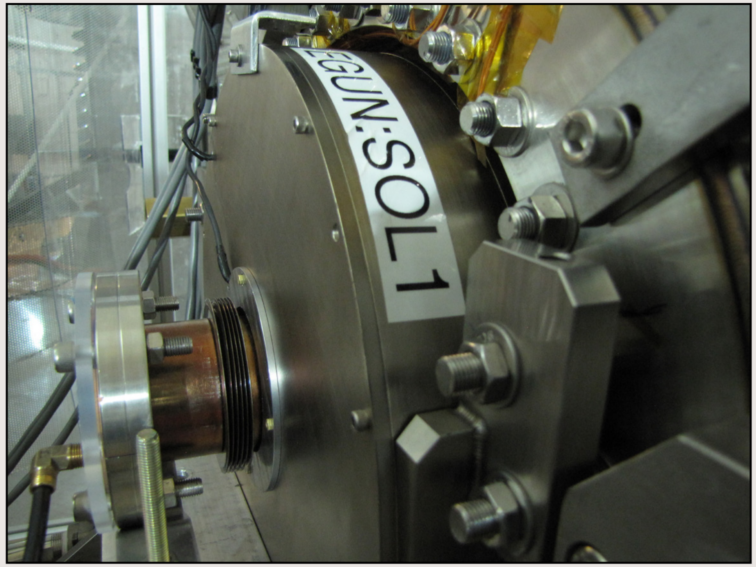
Displaced clamp

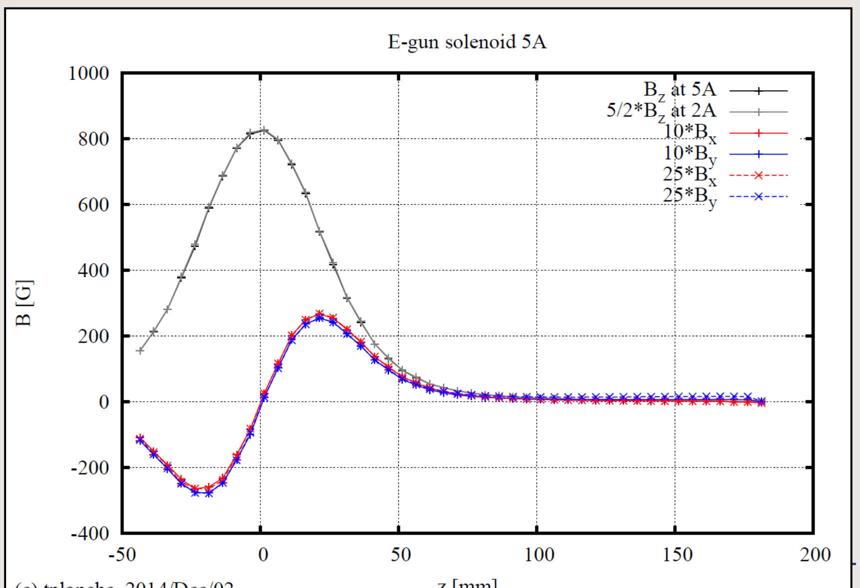


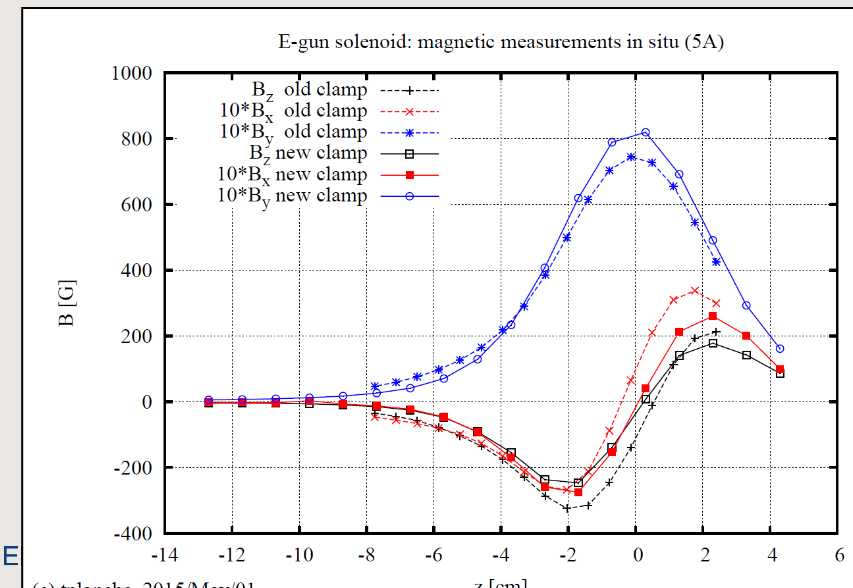
New design



Egun solenoid new design







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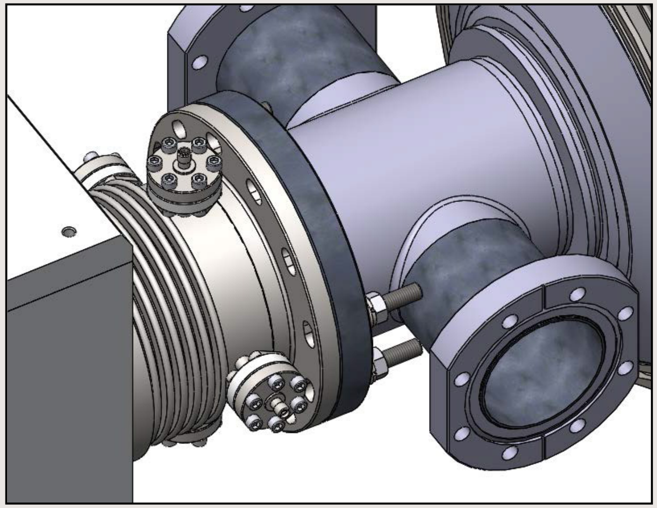
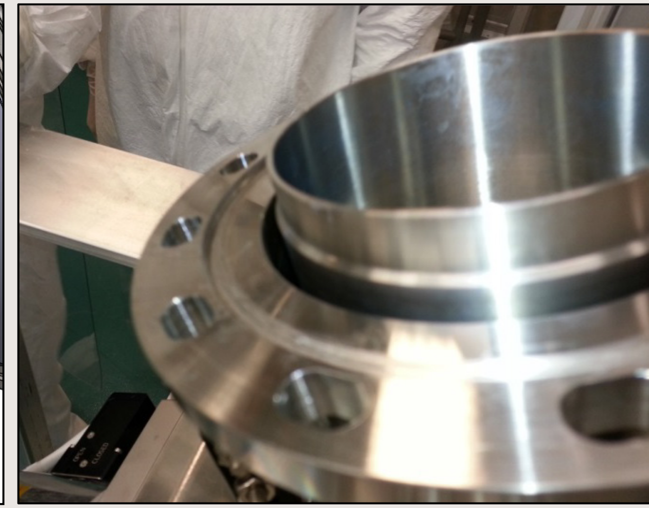
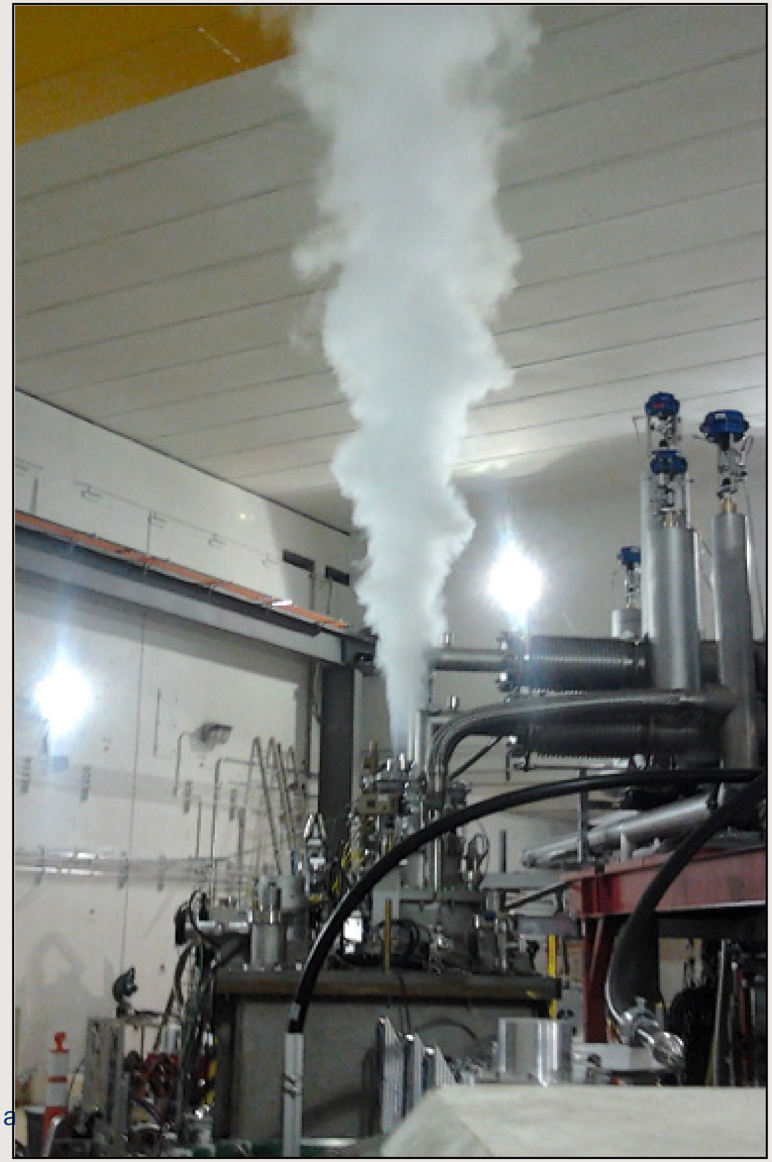
Stainless steel HOM damper – coupler side

- Field emission was limiting the gradient (just 5.5 MeV)
- 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

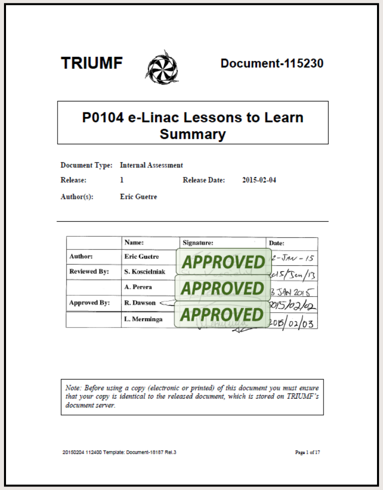
Cold test

- Early result: burst disk works!
- Lesson learned: not necessary to test the burst disk
- Real lesson learned: do not operate without the proper interlock in place



Challenges

- Internal workshop on "what went well" and "what went wrong"
- Quality management document analyzing human resources, communications, documentation, schedule, procurement and cost
- Internally we tend to focus more on what went wrong to keep optimizing our performances but …
- Overall **everything went very well**:
  - adapt infrastructure for 1.3GHz high beta SRF technology
  - design 300kV DC electron gun
  - design new 2K cryomodule
  - equipment meet specifications
  - delivered quality hardware on a very tight schedule set by project funding
  - the whole lab (accelerator, engineering, science, nuclear medicine and administration division) engaged
  - Installation and commissioning completed while running full science program



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P0104 e-Linac Lessons to Learn Summary

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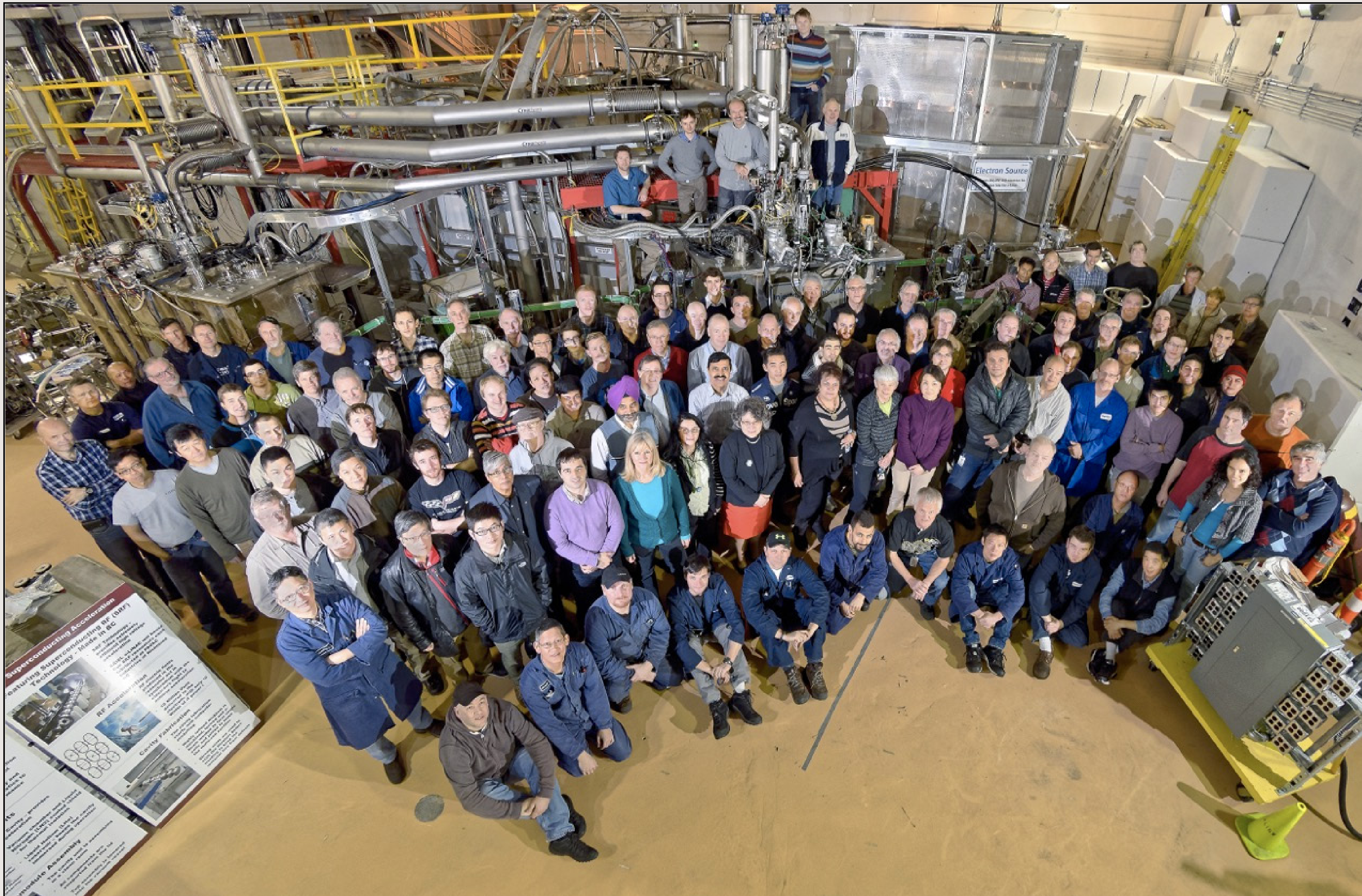
OUTLINE

- RIB production at TRIUMF
  - ISAC
  - ARIEL
- Elinac
  - design
  - installation
  - commissioning
  - challenges
- Summary

Summary

- Early stage of commissioning demonstrates that the e-linac equipment **meets performance goals**
- The e-gun is performing reliably and providing the beam quality expected
- Installed cavities meet performance specification and cryomodules exhibit robust engineering also within specification
- The beam optics shows good agreement with simulation even though it still needs to be fully characterized in order to increase the beam power
- Refined training and safety procedures to be implemented before resuming commissioning
- e-linac is a **tremendous success** delivered on a challenging schedule
- TRIUMF has now high intensity protons and electrons, stable and radioactive heavy ions, cyclotron, room temp heavy ion linac, low and high beta superconducting linac technology all under one roof

e-linac team



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Thank you!
Merci

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