STATUS OF SUPERCONDUCTING ISAC-II AND ELINAC ACCELERATORS, AND SRF ACTIVITIES AT TRIUMF

V. Zvyagintsev, Z. Ang, K. Fong, T. Junginger, J. Keir, A. Koveshnikov, C. Laforge, D. Lang, R.E. Laxdal, Y. Ma, N. Muller, R. Nagimov, D.W. Storey, E. Thoeng, B. Waraich, Z. Yao, Q. Zheng

TRIUMF Canada's National Laboratory for Particle and Nuclear Physics,

Vancouver, BC V6T 2A3, Canada

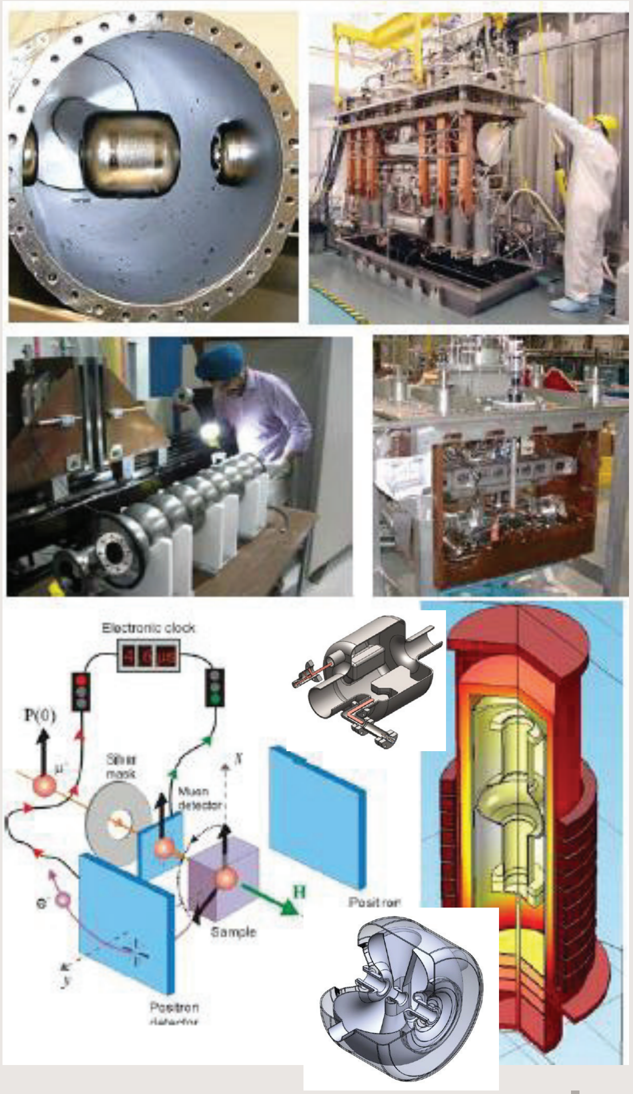
ABSTRACT

The development for superconducting accelerators has been started at TRIUMF in 2000. The main milestones and material implementations are: 2006 - commissioning of Phase-I of the heavy ion superconducting accelerator ISAC-II, 2010 - Phase-II, 2014 - commissioning of Phase-I of the superconducting electron linear accelerator eLinac. We are using the accumulated experience and resources for farther SRF development at TRIUMF and external projects VECC, RISP, FRIB and SLAC. TRIUMF is also running fundamental studies for SRF and educational program for universities. Status of Superconducting ISAC-II and eLinac accelerators and SRF development aspects, results and plans are discussed.

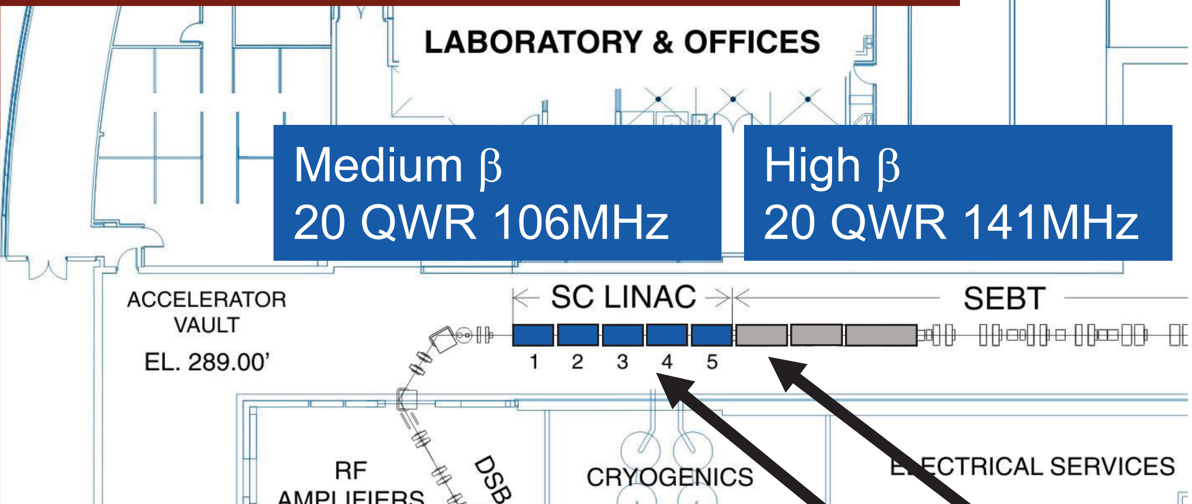
SRF2015 workshop was hosted by TRIUMF

Outline

- ISAC-II
  - Layout
  - Cavities
  - Operation
- eLinac
  - Introduction
  - Cavity
  - Cryomodules
  - RF System
  - Cryogenics
  - Commissioning
- SRF Developments and External Projects
  - RF Deflector Cavity for ERL eLinac
  - VECC: ICM2, IOT Transmitter
  - FRIB: Variable Test Coupler development and production
  - RISP: QWR and HWR unjacketed tests, RI QWR jacketed tests. Balloon Spoke Cavity Development.
  - uSR
  - Vertical EP, T-map, Induction oven
- Summary



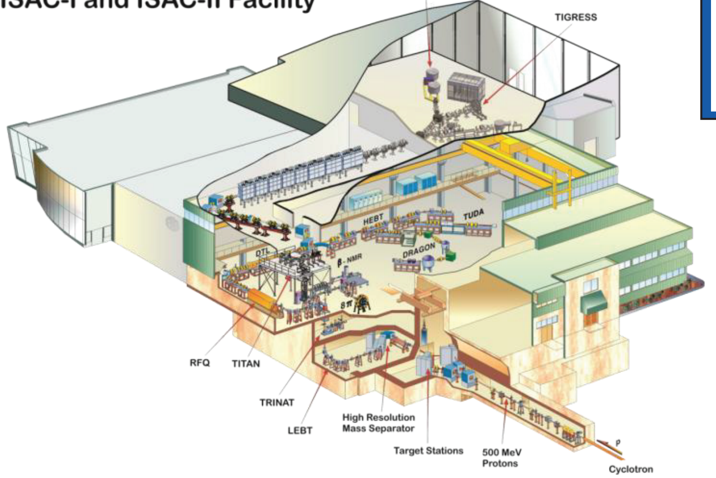
ISAC-II: Heavy Ion SC Linac



Medium β
20 QWR 106MHz

High β
20 QWR 141MHz

ISAC-I and ISAC-II Facility

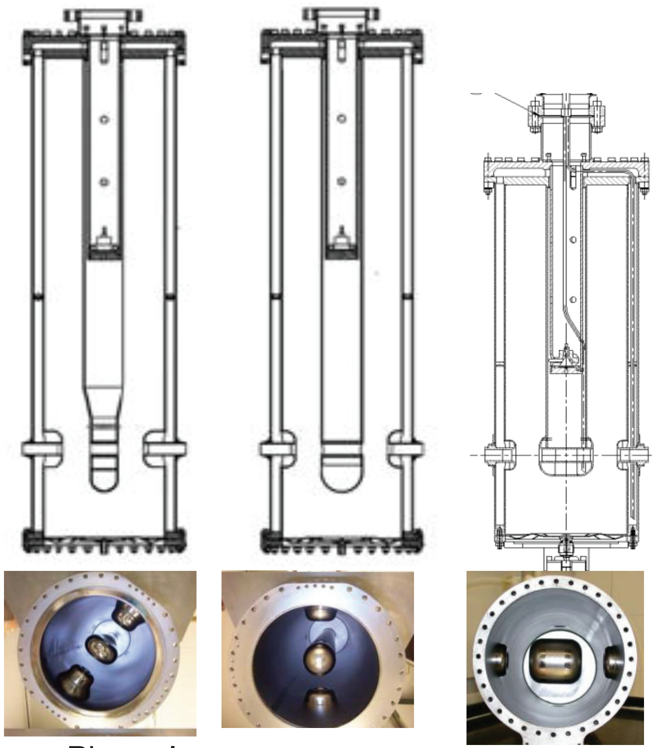


TRIUMF

Design goal for the final energy equivalent to acceleration of A/q=6 beam with input energy 1.5 MeV/u to 6.5MeV/u is achieved in 2010. ISAC-II supports a full physics program with both stable and radioactive beams being delivered. Stable beams of 16O5+, 15N4+, 20Ne5+ and radioactive beams (and their stable pilot beams) of 26Na, 26Al6+, (26Mg6+), 6He1+, (12C2+), 24Na5+, (24Mg5+), 11Li2+, (22Ne4+) including 74Br14+

TRIUMF

ISAC-II QWR Cavities

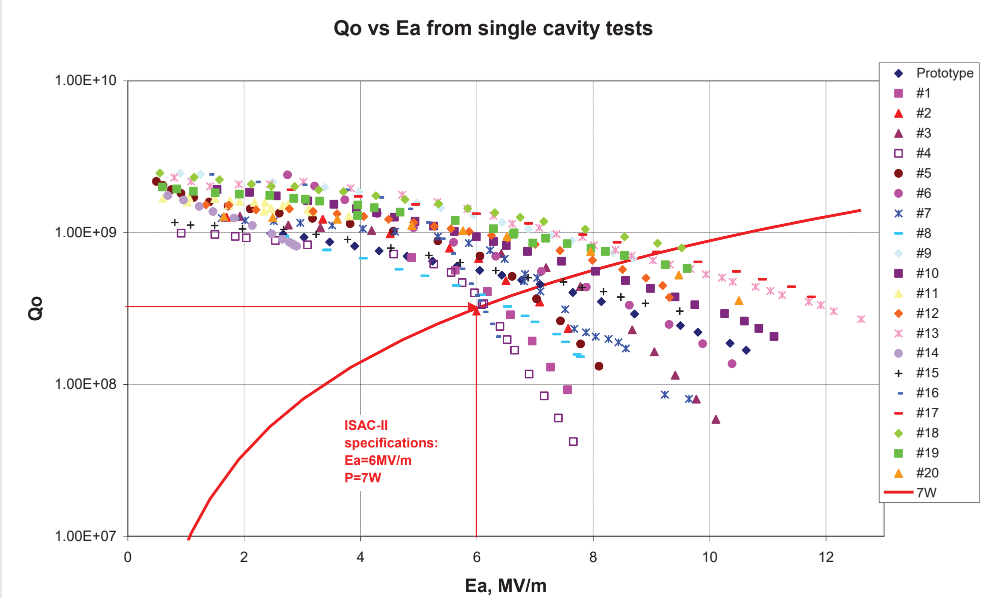


Phase-I
Zanon (Italy)

Phase-II
PAVAC (Canada)

	flat	round	donut
f(MHz)	106.080	106.080	141.440
RsQ(Ohm)	20.1	19.1	26.0
βo	0.064	0.075	0.112
TTFo	0.870	0.898	0.936
Ep/Ea	5.2	4.7	4.9
Bp/Ea(mT/(MV/m))	10.3	10.1	10.0
U/Ea2 (J/(MV/m)2)	0.100	0.094	0.067

All cavities are specified for CW operation at 7W power dissipation with acceleration voltage 1.08MV corresponding to 30MV/m electric and 60mT magnetic peak field.

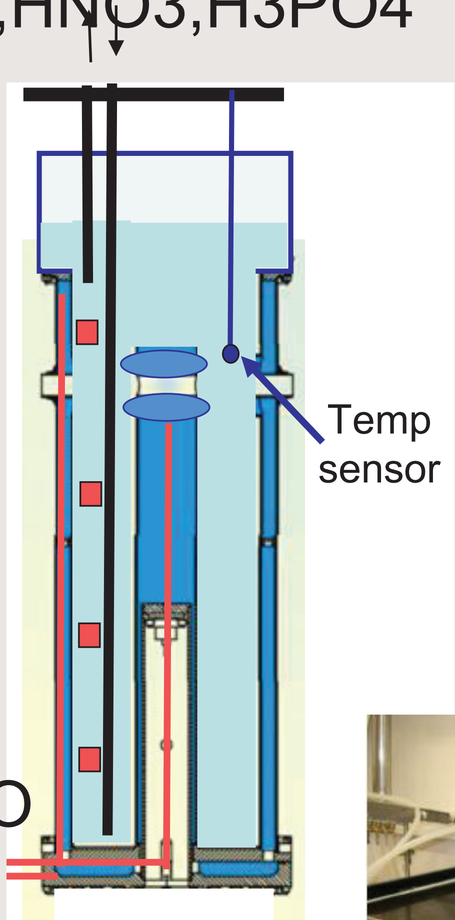


Cavity Production at PAVAC

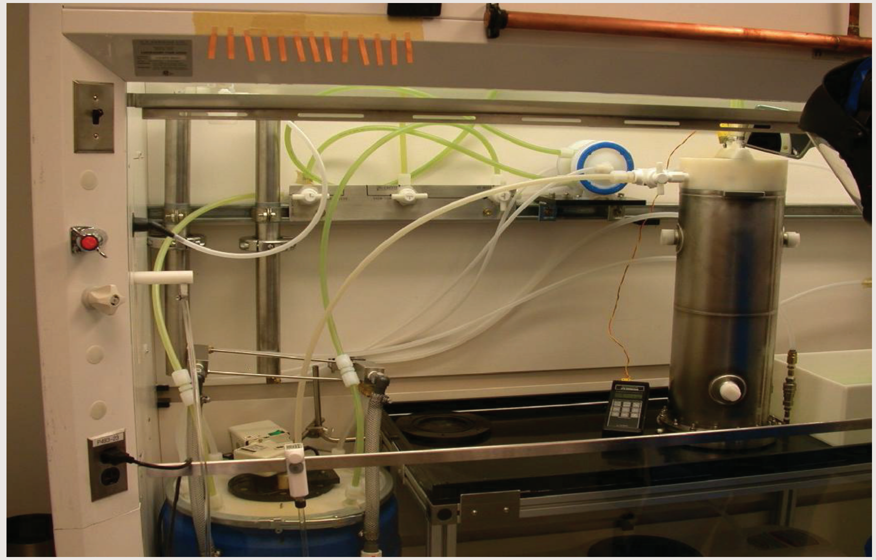
BCP Etching at TRIUMF

BCP 1:1:2

HF,HNO3,H3PO4



H_2O

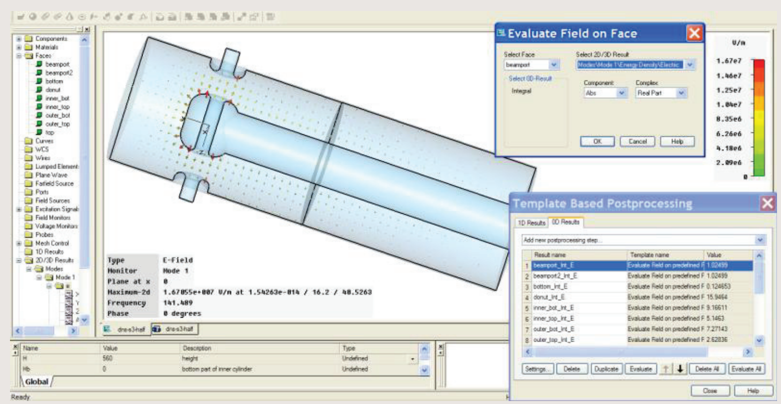


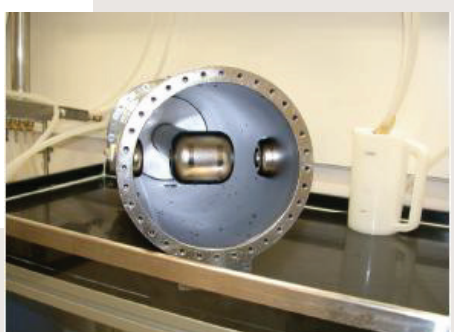
Pre-weld etching ~20um

$\sim 10^{0}$C

~1um/min

~100um etch





Differential etching for frequency compensation

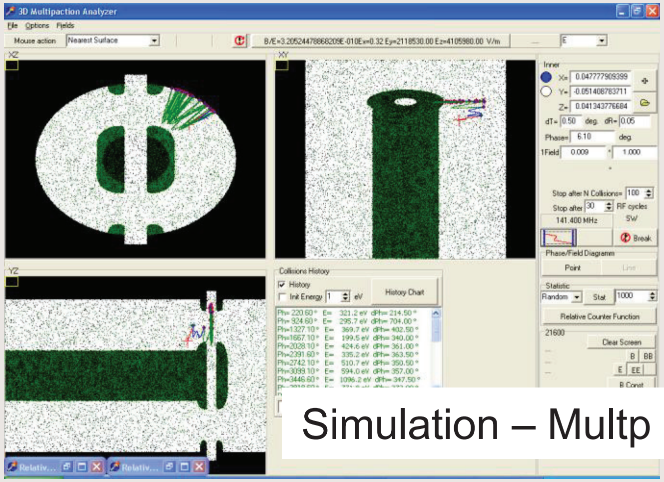
Differential sensitivity for ½

2 kHz/um for

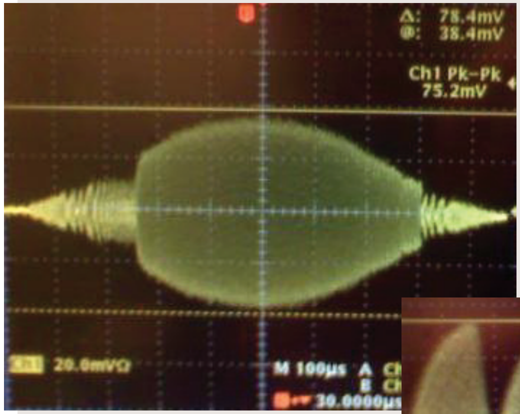
MULTIPACTING

We have MP only at start –
The strongest level is 3 order of magnitude less than operating level

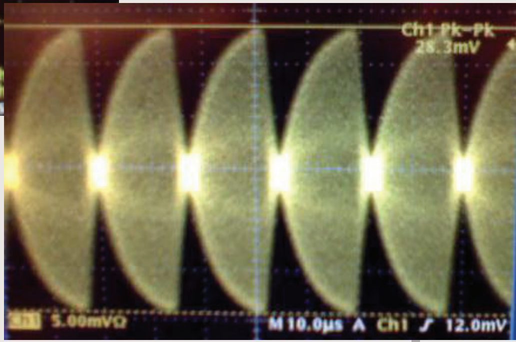
Simulation by MultP-M code		Measured
E_a, kV/m	Cavity region	E_a, kV/m
12.0 – 26.0	accelerating gap, donut – coax outer conductor	10 – 24
27.0 – 33.0	donut – coax outer conductor	28 – 33
35.0 – 54.0	coax line donut – end cap	42 – 50
58.0 – 193.0	donut – end cap	77 – 80



Simulation – Multp - MEPhI



Pulse conditioning

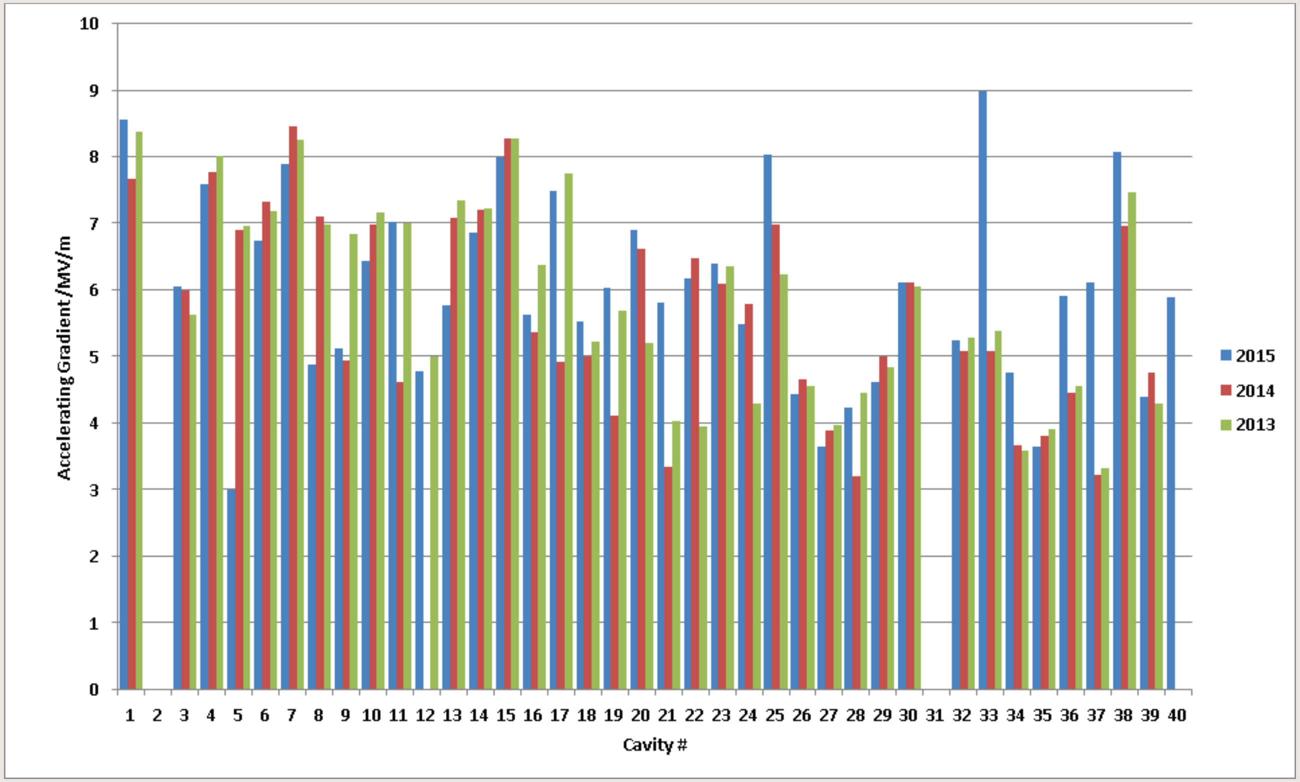


Most efficient
- Driven CW

M. Gusarova, M. Lalayan, N. Sobenin, V. Zvyagintsev, “Multipacting Simulation in ISAC-II Superconducting Cavities”, PAC’09, Vancouver, May 2009, FR5PFP076

Cavity Performance 2013-2015

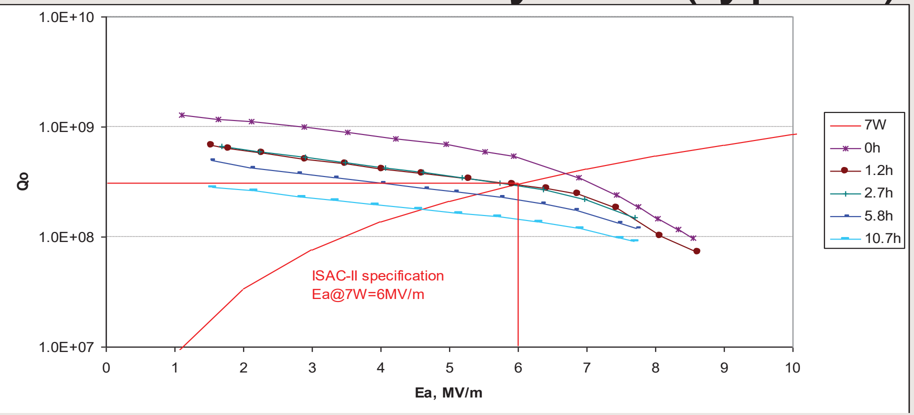
The linac cavities operate with an average gradient corresponding to a peak surface field of 32 MV/m for Phase-I and 28.5 MV/m – Phase-II without any discernible reduction in performance.



Less performance of Phase-II cavities:
-BCP 60um instead of 100um to mitigate risk of leak in welding
-Q-desease after 1h in 150-50K region while 10h for Phase –I cavities

Q-disease tests

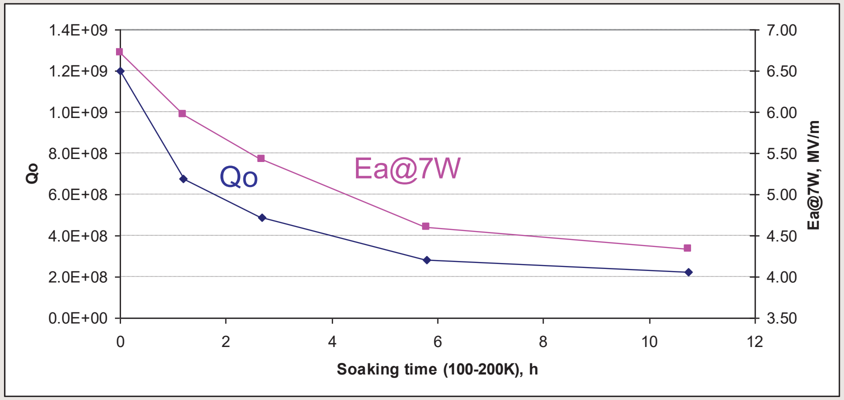
Phase-II cavity test (typical)



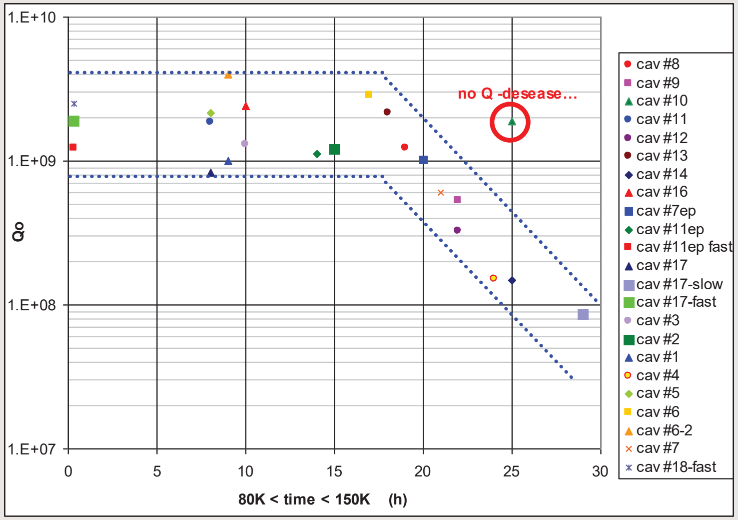
Q-disease data from cavity#21 test

time@100K hours	Qo	Ea@7W MV/m
0	1.2E+09	6.72
1.19	6.76E+08	5.97
2.69	4.91E+08	5.43
5.8	2.83E+08	4.60
10.73	2.26E+08	4.34

Soaking of H for rf surface with subsequent performance degradation when cavity in the range 100-200K



Phase-I cavities

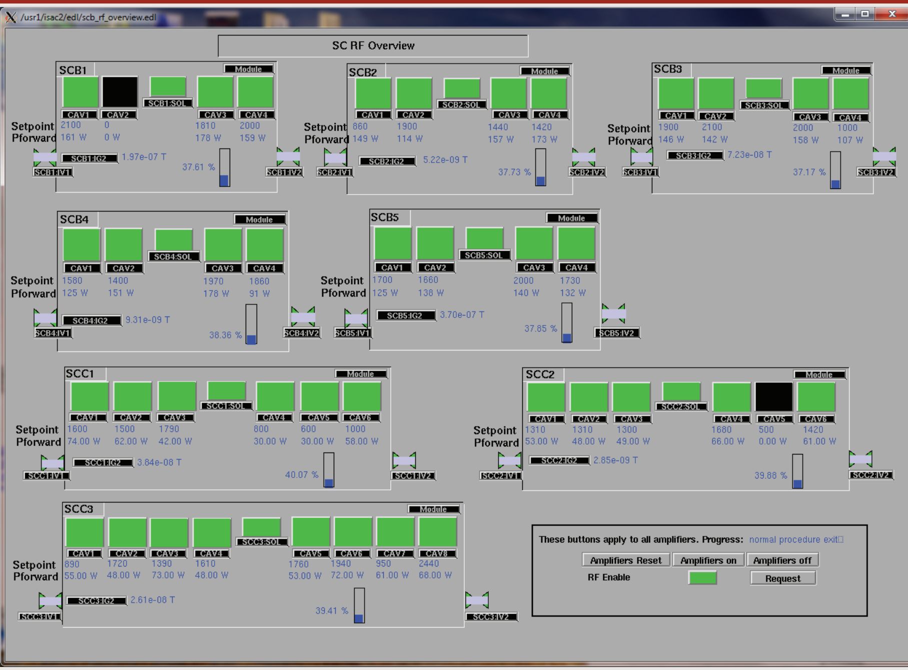


Significant degradation of Q even after 1h of soaking means big content of H in the material of Phase-II cavity (PAVAC)

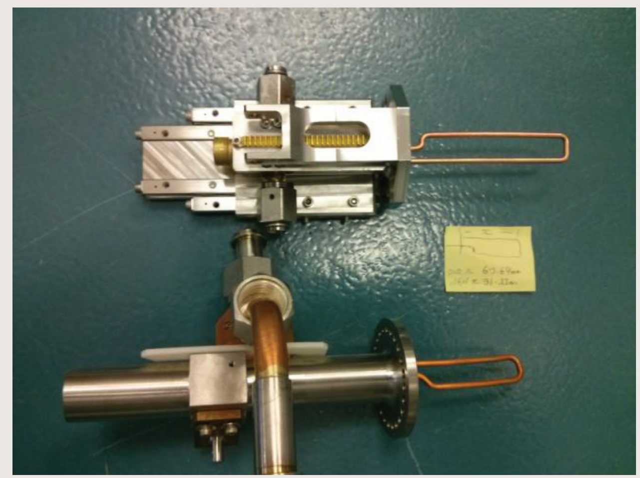
For Phase-I (Zanon) critical soaking time was 10h

TRIUMF

Cavities failures



Cavities failures don't stop operation. Since every cavity has an independent RF system, we can compensate the performance of the unavailable cavities by increasing the gradient in other cavities (at power dissipation >7W).



- Mechanical transmission failure
  - Bellows for - universal joints
  - Replace Phase-I to Phase-II couplers
- Cables failure due to RF glow discharge – 3/8” to ½” ANDREW – it's sufficient

Upgrades for ISAC-II

In a process

- Couplers
- Cables
- Phase-I tube to solid state RF amplifiers
- LLRF software upgrade

Future plans

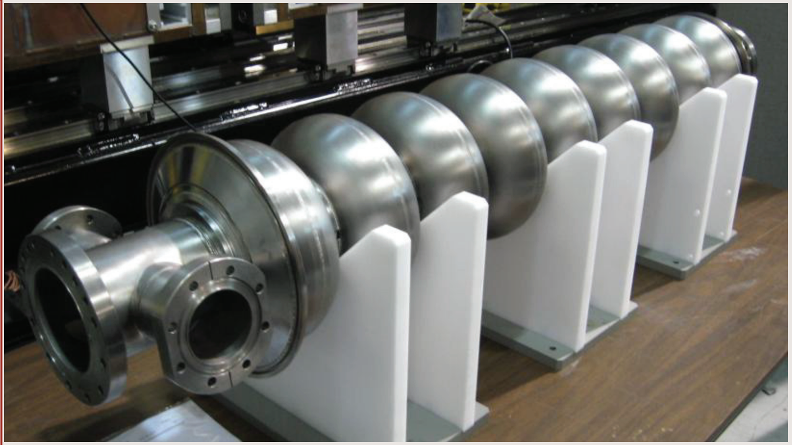
- Deagassing of Phase-II cavities to mitigate Q-desease

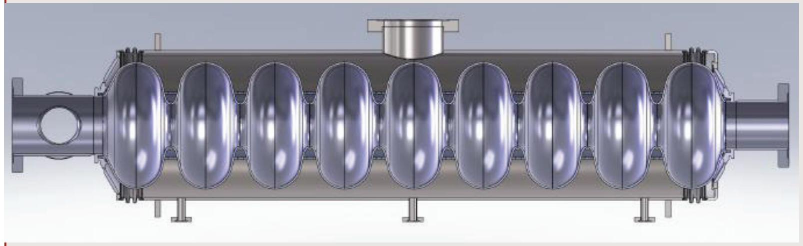
eLINAC

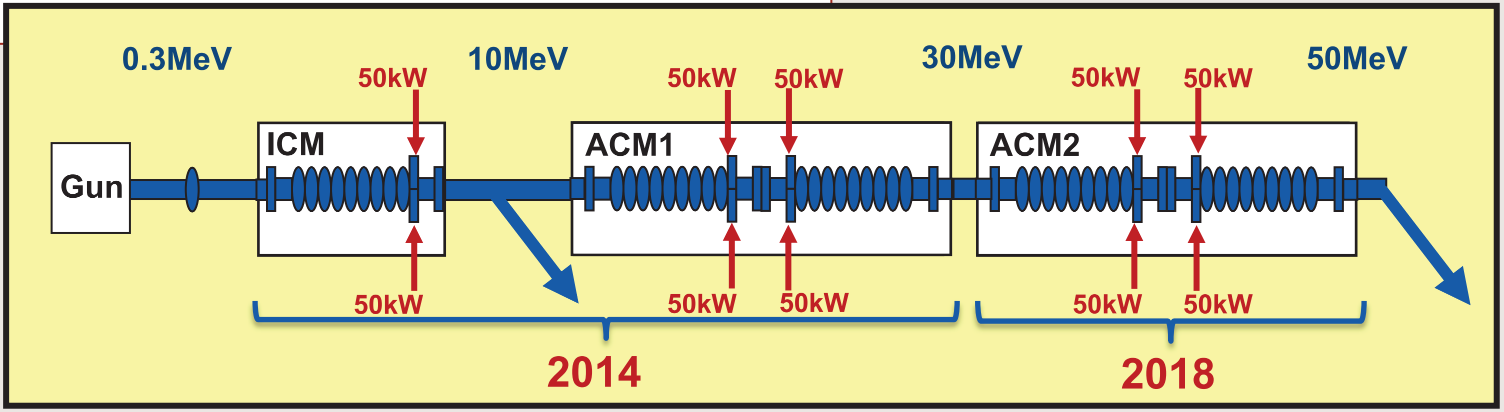
- The ARIEL project will allow an increase in the radioactive ion beam (RIB) hours with the addition of a new electron linac driver of 50 MeV (0.5 MW), a new proton line from the 500MeV cyclotron and new production target stations. Accelerated electrons can be used to generate RIBs via the photo-fission process. The electrons are stopped in a converter to generate bremsstrahlung photons for fission in actinide target material. An electron beam intensity and energy of 10 mA and 50 MeV is required for a fission rate of 10^{13} fissions/sec.

eLinac SRF Specifications

- The ARIEL E-Linac SRF specification – dominated by RF beam loading
  - 10mA at 50MeV - 0.5 MW CW
  - CPI 75kW VWP 3032 coupler to deliver 50kW CW -> 10 couplers
  - 2x 50kW couplers per cavity -> 5 cavities
  - 10MeV energy gain per cavity
  - 10W at 2K -> Qo=1e10
  - Reduce trapped HOMs
  - Large (90mm) single chimney sufficient for CW operation up to 50W
  - One cavity in ICM and 2 in ACM

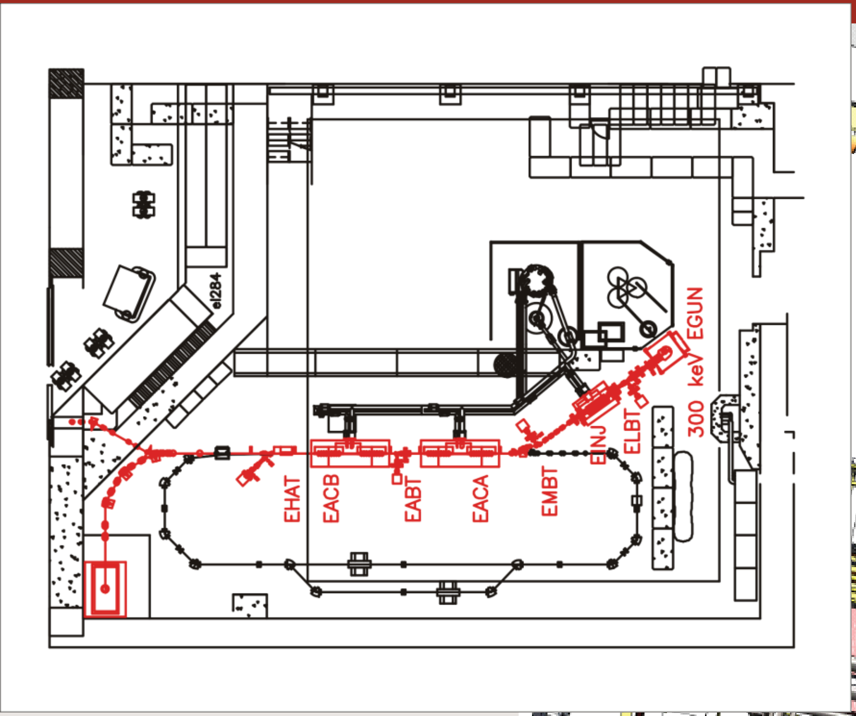


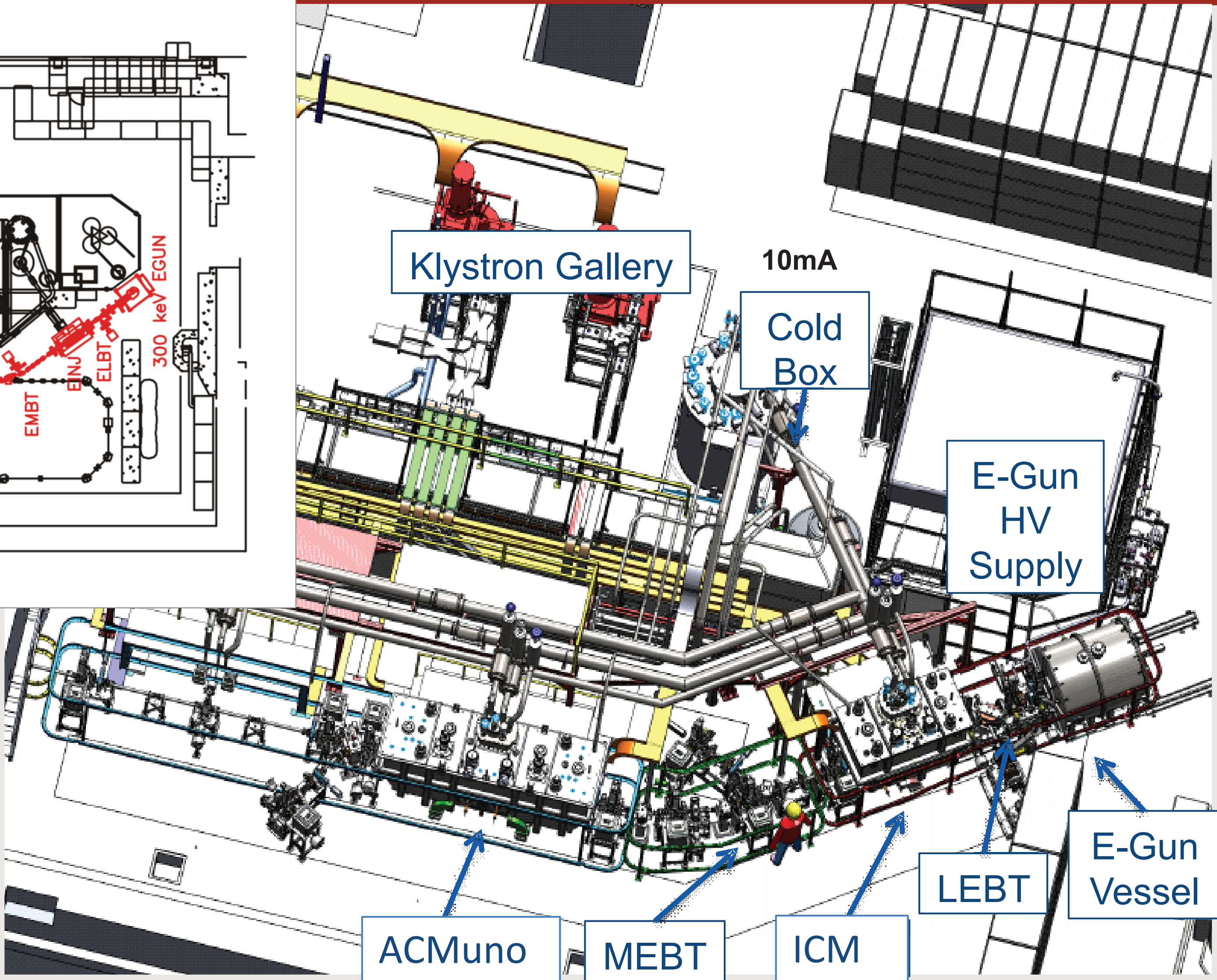




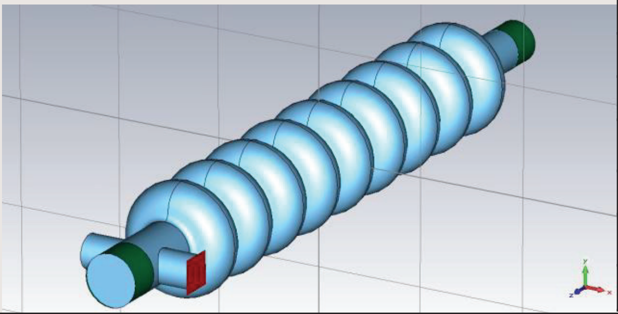
TRIUMF

E-Linac Accelerator Vault – Phase I

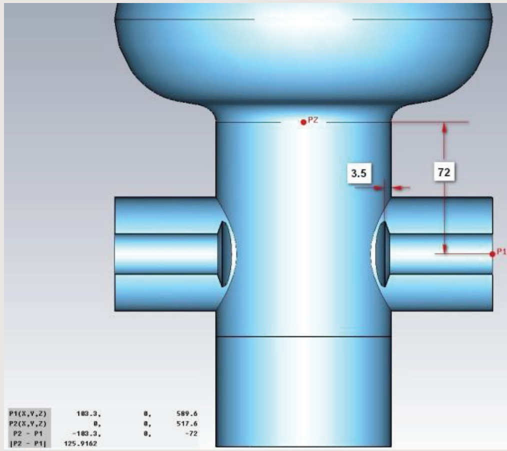




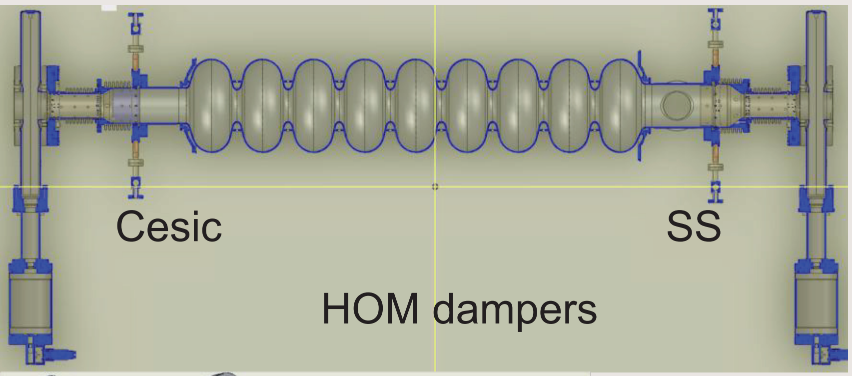
Cavity Design

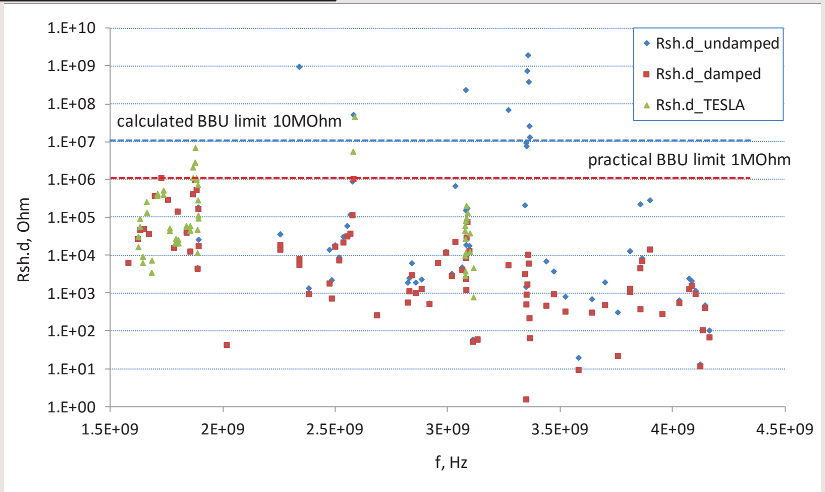


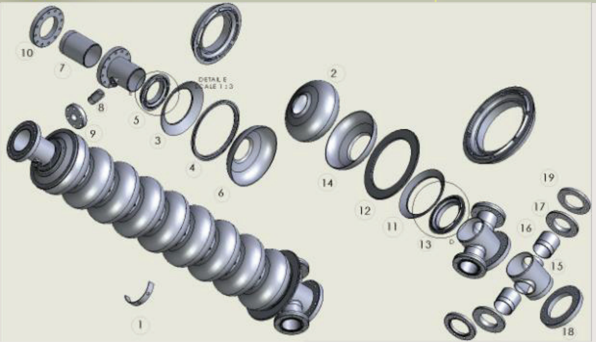
	TRIUMF	DESY	TRIUMF/DESY
Frequency [MHz]	1300	1300	-
R_{sh}/Q [Ohm]	1000	1030	3% less
Geometric factor G [Ohm]	290	270	7% more
E_p/E_a	2.1	2.0	5% more
B_p/E_a [mT/(MV/m)]	4.4	4.2	5% more
Cell coupling [%]	2.0	1.9	



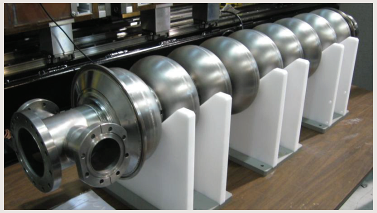
TRIUMF e-LINAC cavity is similar to 1.3GHz 9 cell DESY TESLA cavity. 2 symmetrically opposed 75kW CPI couplers



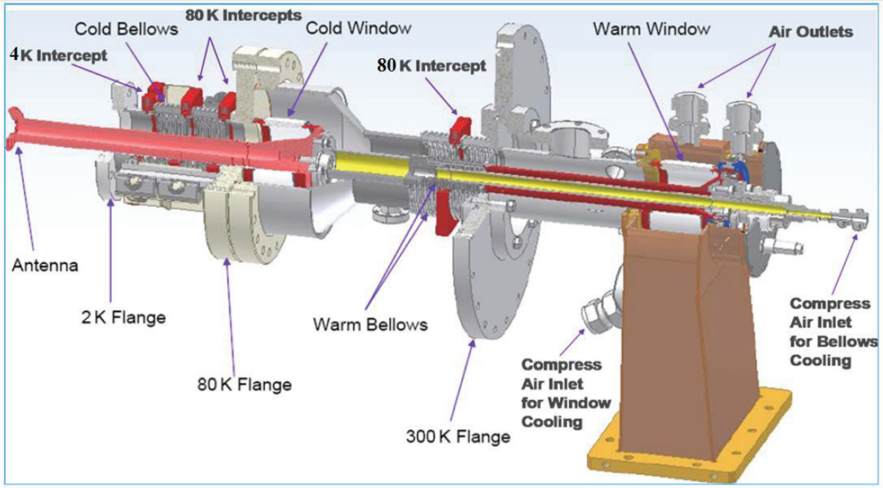




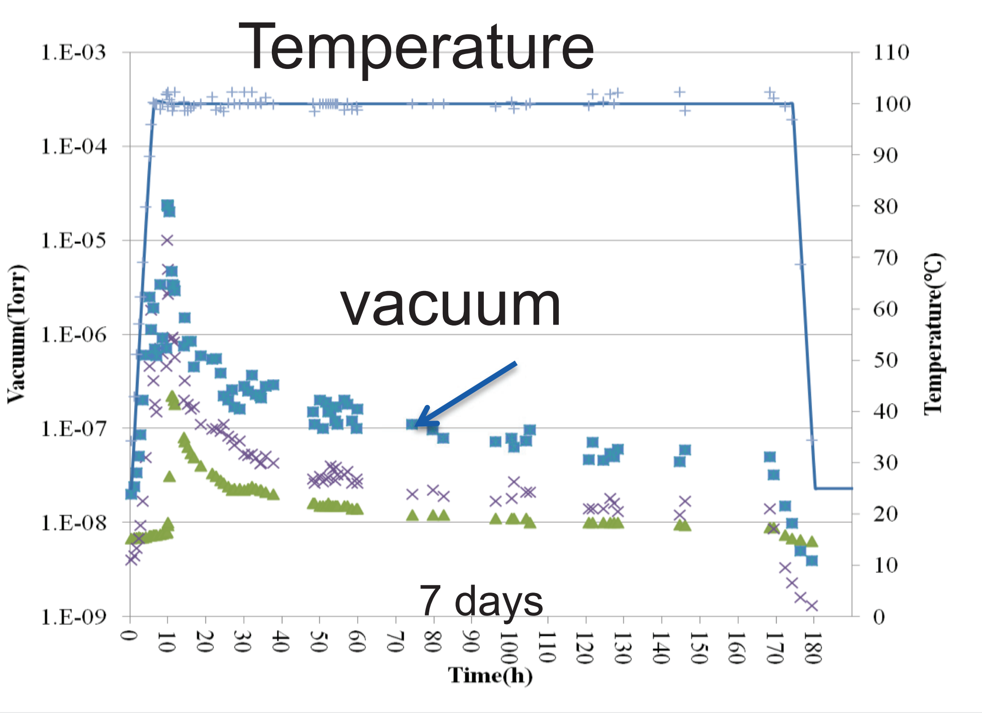
4 9-cell cavities fabricated at PAVAC



RF Power Couplers



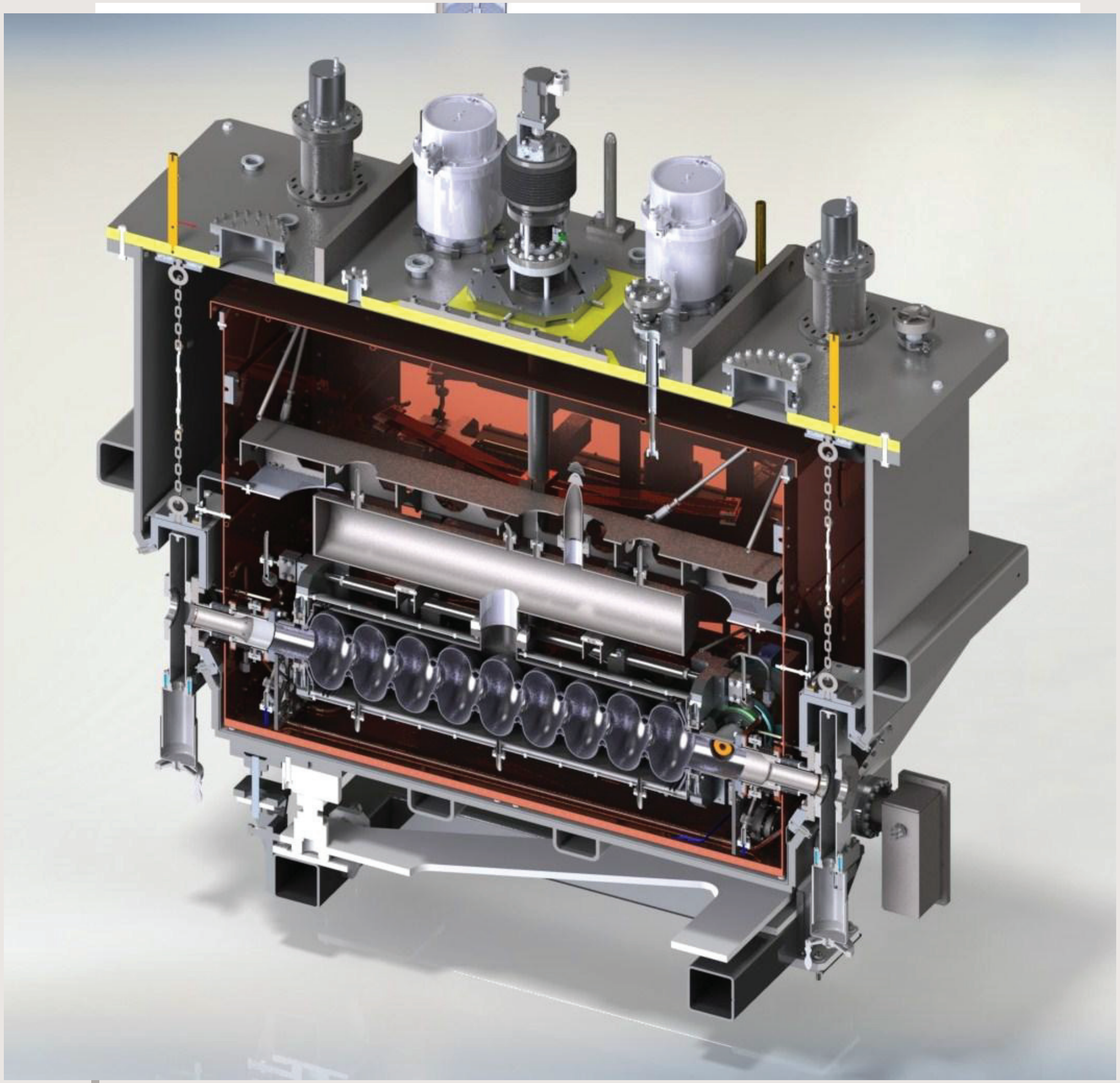
The CPI VWP 3032 75kW CW Coupler



Handling
Assembly in clean room
Keep sealed with filtered N2 gas

Baking
- 100C 7days
- 10C/hour
- N2 filtered gas flow to ‘warm’ assembly

Injector Cryomodule



Houses

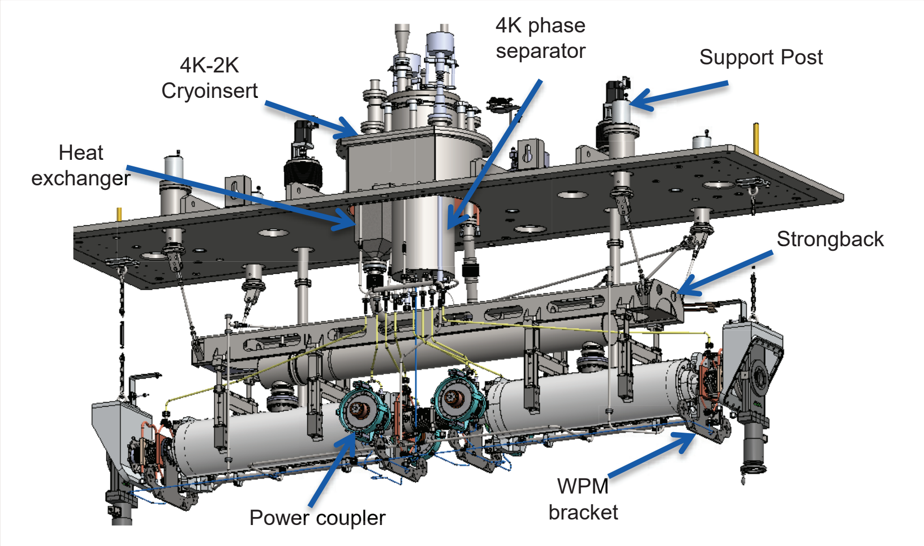
- one nine-cell 1.3GHz cavity
- Two 50kW power couplers

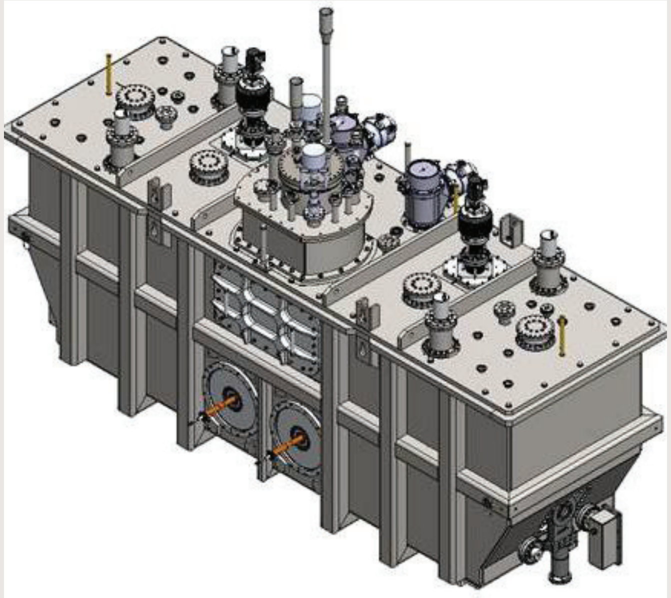
Features

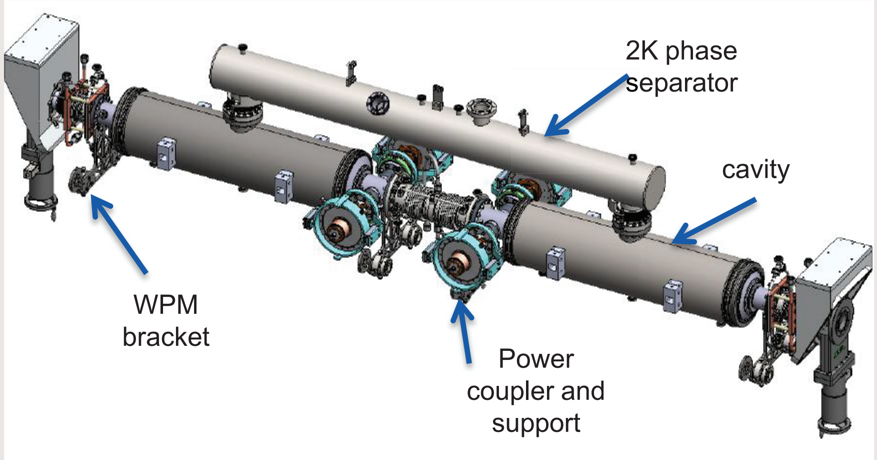
- 4K/2K insert with JT valve on board
- Scissor tuner with warm motor
- LN2 thermal shield – 4K thermal intercepts via syphon
- Two layers of mu-metal
- WPM alignment system

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

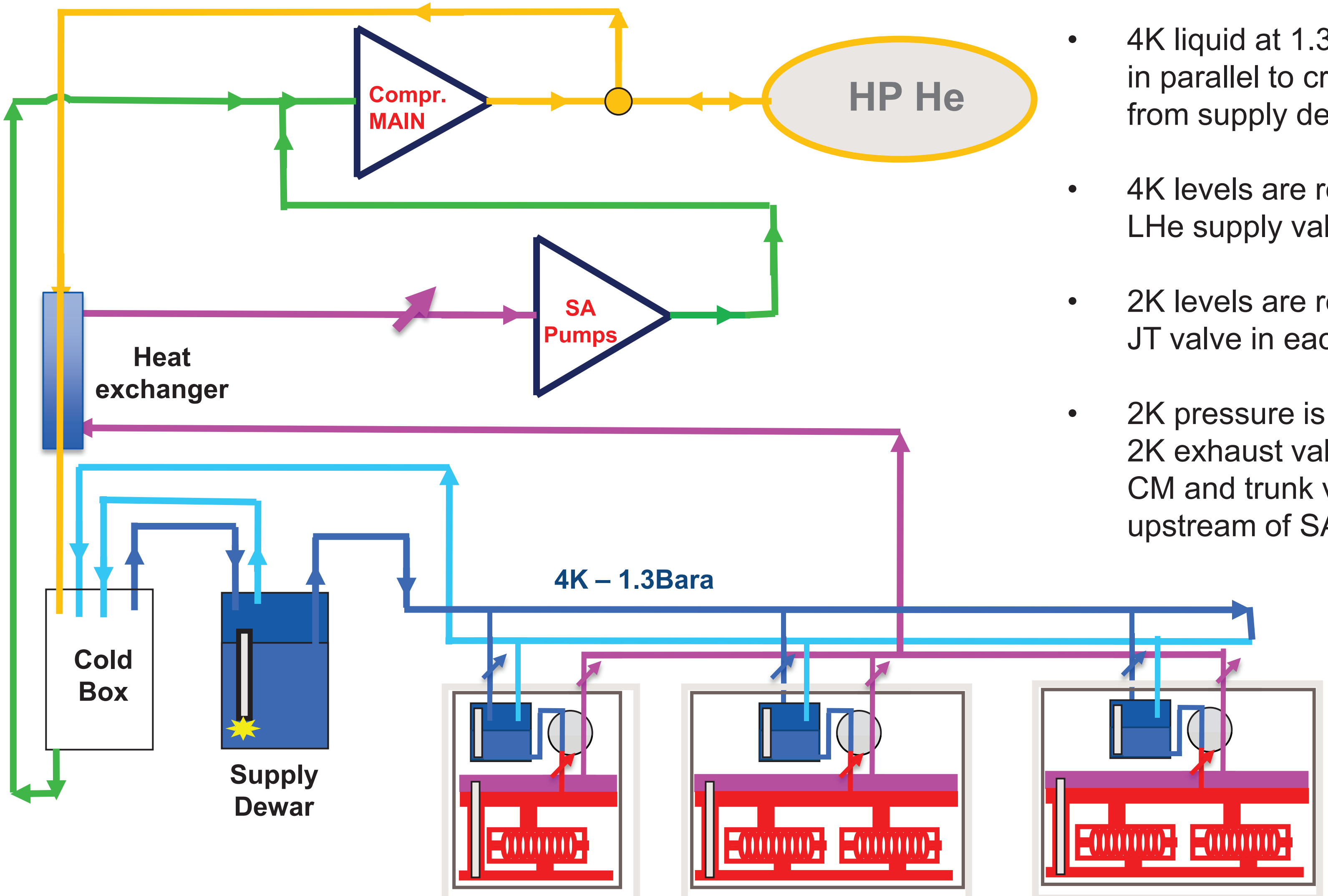






N. Muller, et al., "ARIEL e-Linac Cryomodule - Design and Performance", THPB115, SRF2015

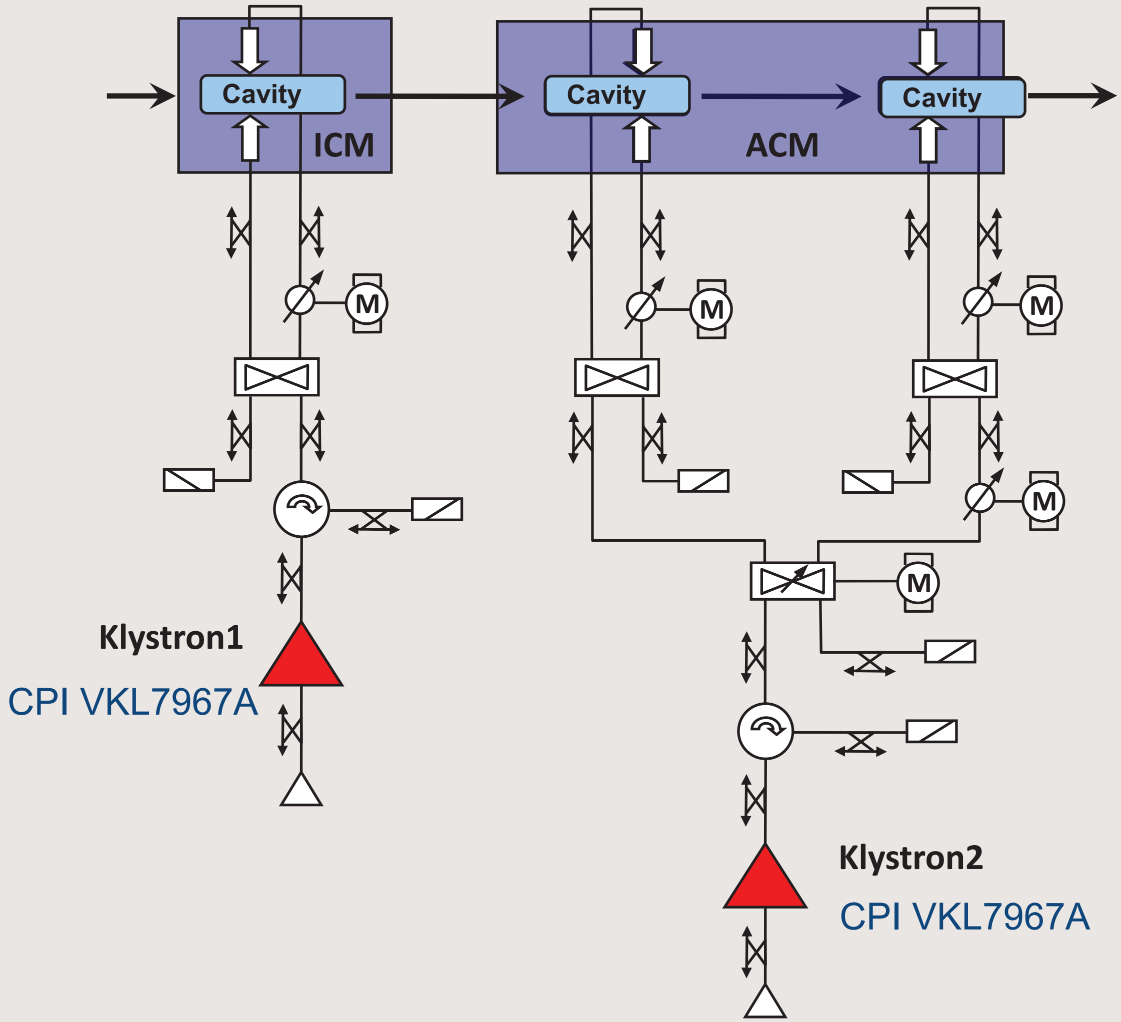
Cryogenics



- 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

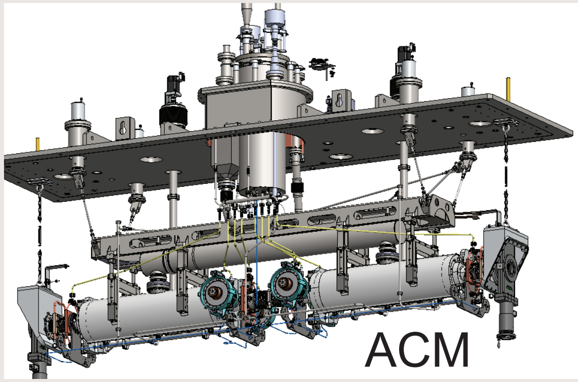
RF System Phase-I

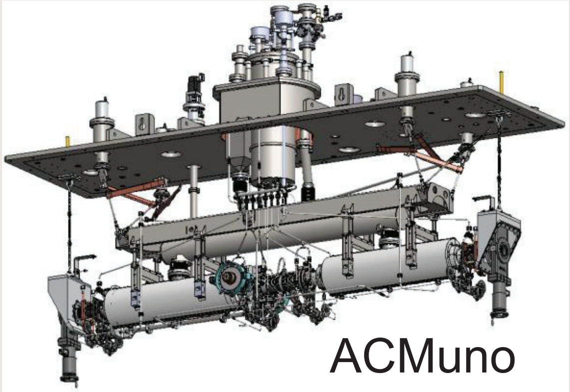
- For Phase I we specify two 290 kW CW CPI VKL7967A klystrons with 65 kV, 10 A DC AMPEGON power supply (KPS)
- In the future, for Phase II one of these klystrons will drive next cryomodule
- We are looking for a cost effective 1.3GHz power source at ~150kW for the ICM

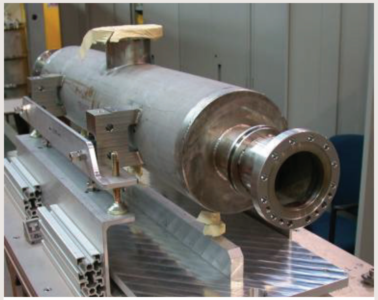


Cryomodule strategy

- Jacket and install ARIEL1 cavity in ICM
- Jacket and install ARIEL2 cavity in ACM together with a dummy cavity
- 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
- Installed the cryomodules for a combined beam test in Sept. 2014 – cryogenic engineering and funding milestone



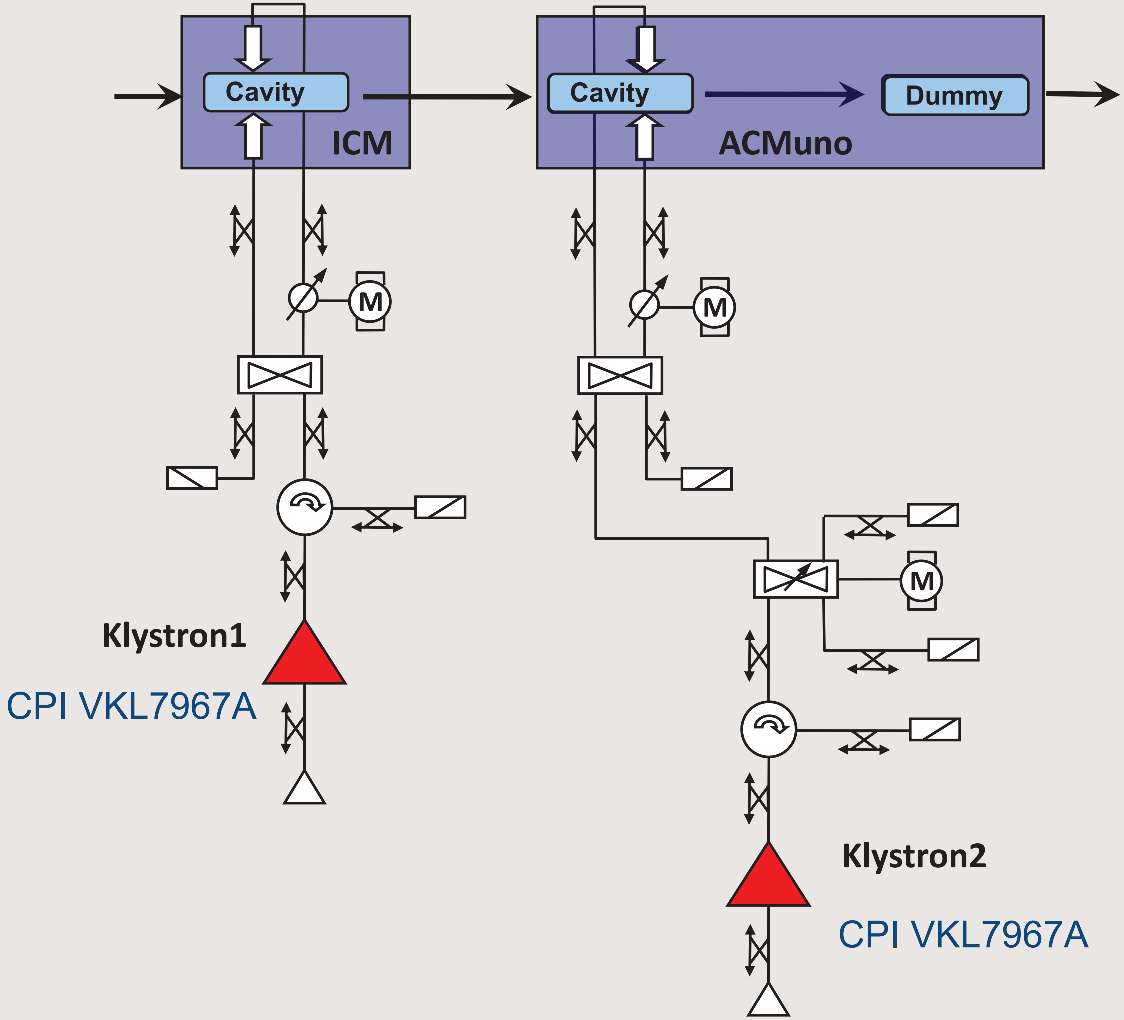



Dummy cavity

RF System Phase-I for Commissioning

RF System modification

- 'Dummy' waveguide branch of variable power divider has been terminated with RF load
- The variable power divider has been tuned for full transmission to the Cavity waveguide branch

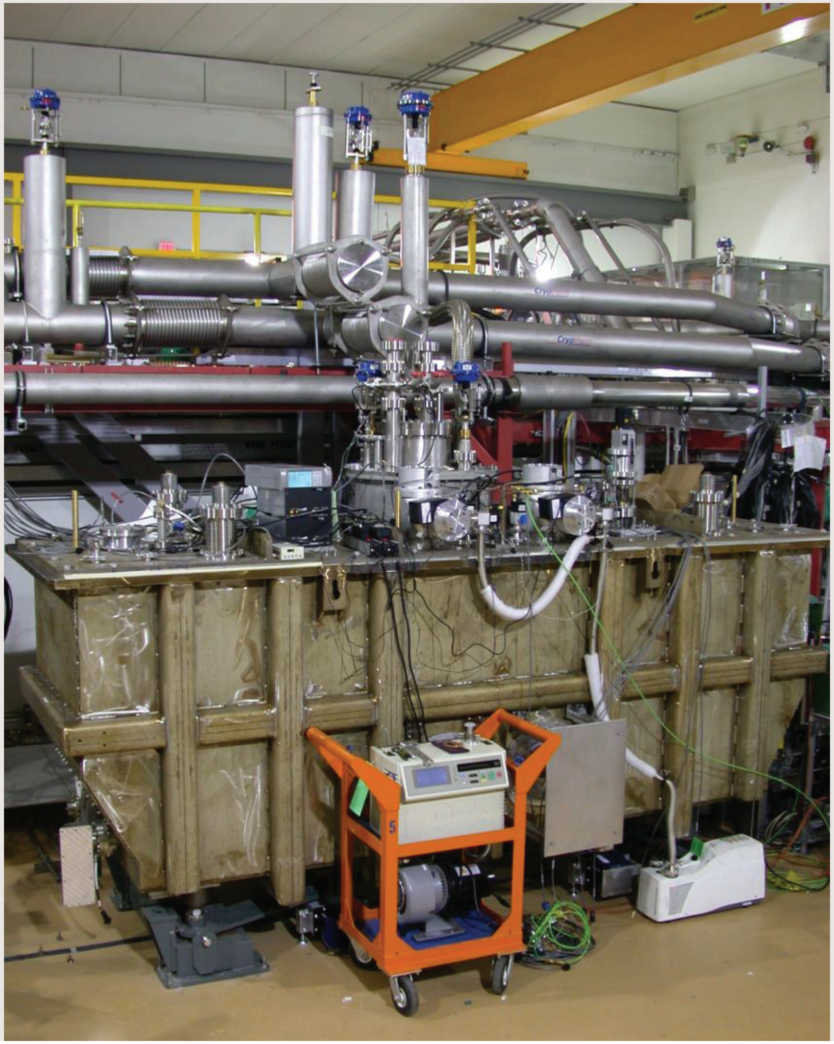


ICM and ACMuno Assembly

ICM top assembly

Assembly of both CMs proceeds through summer of 2014

ACMuno assembly



ACMuno – ready for cooldown Sept. 1

TRIUMF

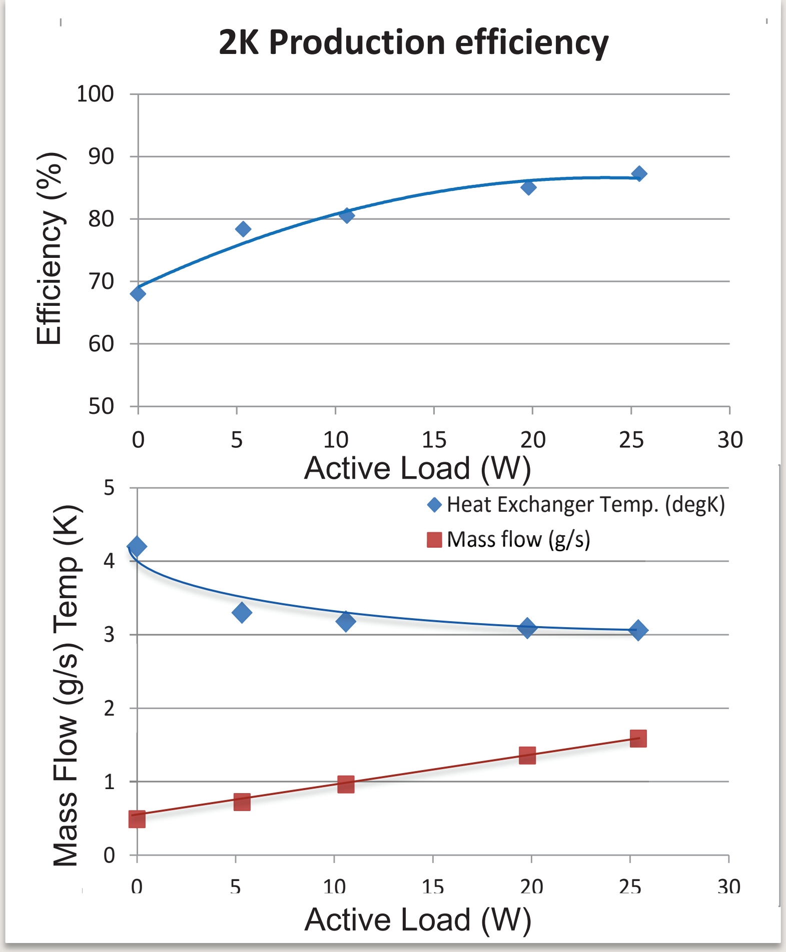
High Power RF Installation

- Installed
  - Two CPI 290kW CW 1.3GHz klystrons
  - Two 600kW 65kV klystron power supplies from Ampegon
- Each klystron reaches specification at the factory and tested at TRIUMF
- Delivered power into a cold cavity – 25kW pulsed and 18kW CW

ICM Cold test results

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

- ✓ Cryogenic engineering matches design expectations
- ✓ Syphon loop performance characterized – works well – optimized in off-line cryostat tests



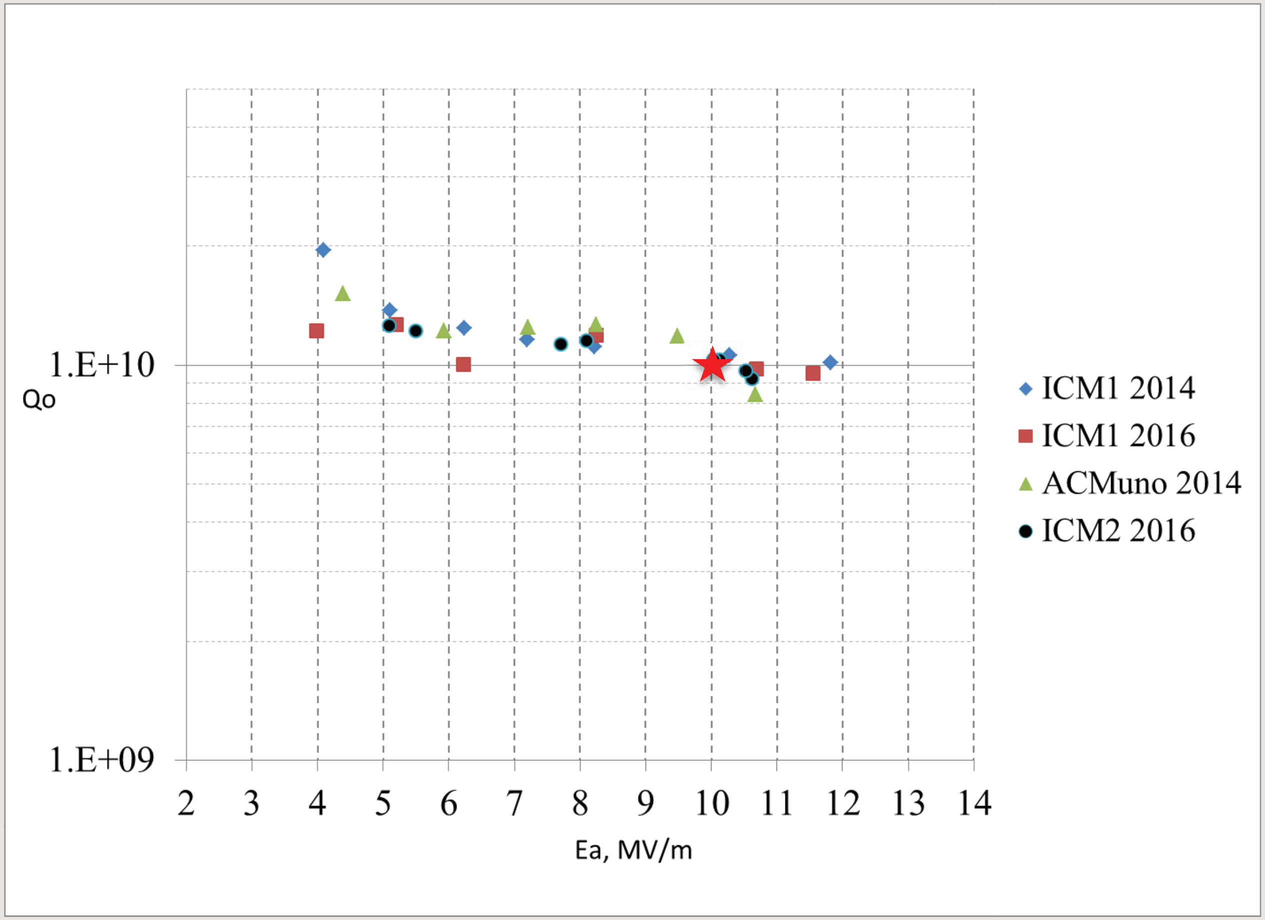
ACMuno First Cold test results

Parameter	Estimated	Measured
4K static load with syphon, W	7	6.4
2K static load, W	7	6.5
77K static load, W	100	TBD
2K production efficiency	82%	TBD

- ✓ Cryo-engineering looks good – static loads as expected – cooldown straightforward
- ✓ Initial RF tests – CW performance limited to 7MV/m and pulsed performance to 10MV/m by multipacting in couplers – no field emission to 10MV/m

A. Koveshnikov, et al., "Integration and Commissioning of the ARIEL e-Linac Cryogenic System at TRIUMF", ICEC-ICMC2014

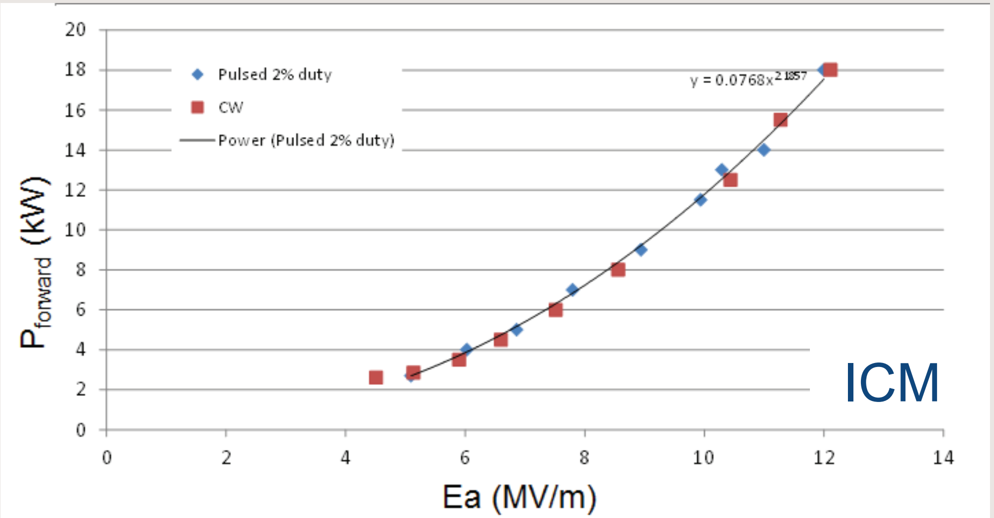
ICM, ICM2 and ACMuno Measured Q-values

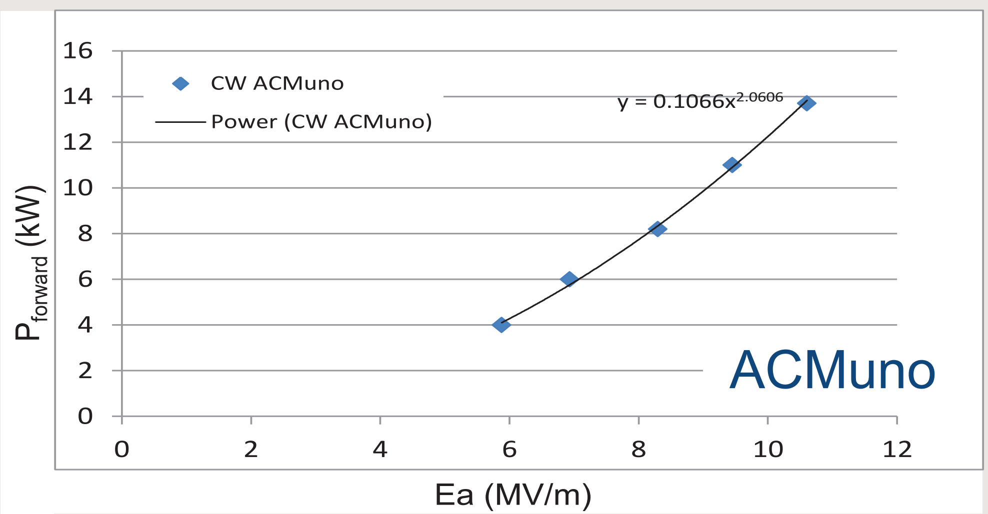


ARIEL cavities installed in ICM, ICM2 and ACMuno meets specification Qo=1e10 at Ea=10 MV/m

TRIUMF

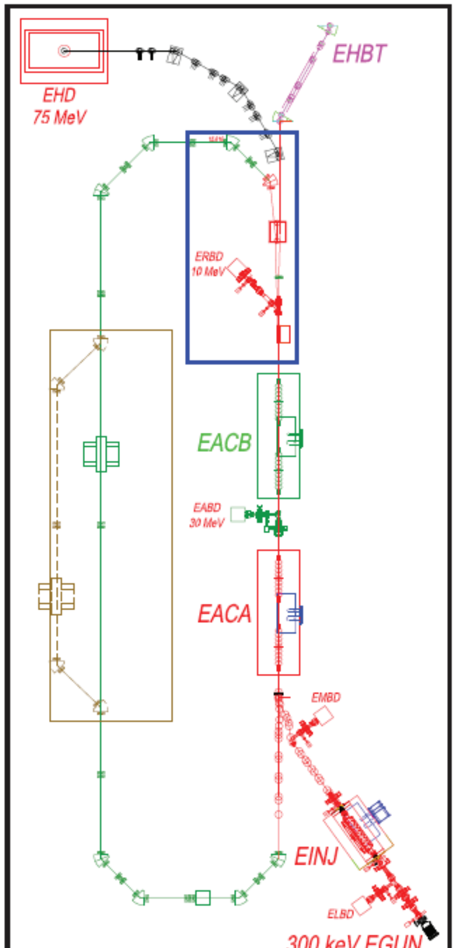
ICM and ACMuno gradient

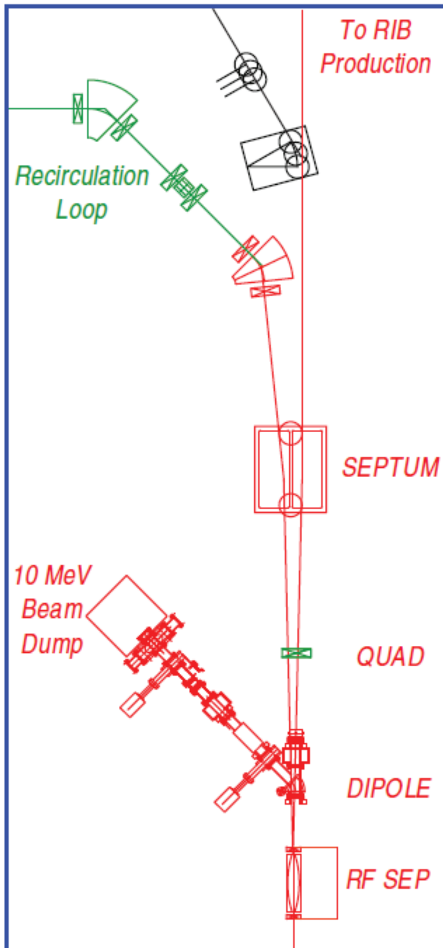




A SC RF DEFLECTING CAVITY FOR THE ARIEL e-LINAC SEPARATOR

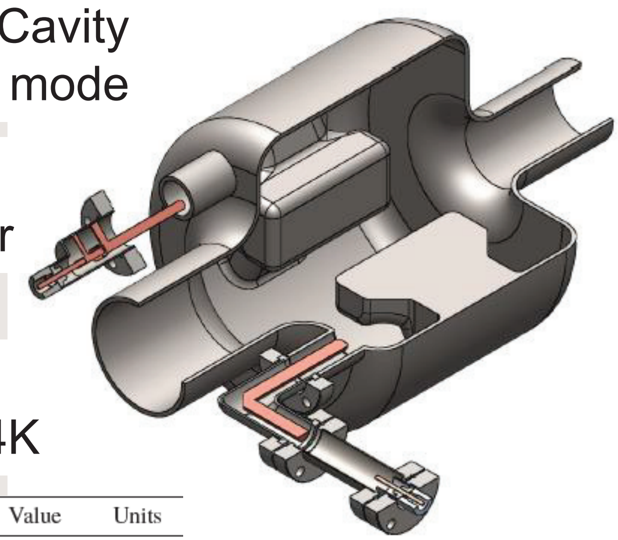
The future ERL extension of ARIEL e-Linac requires separating the bunches for either the ERL or RIB at the end of the linac at 650 MHz





RF Dipole Cavity
TE11-like mode

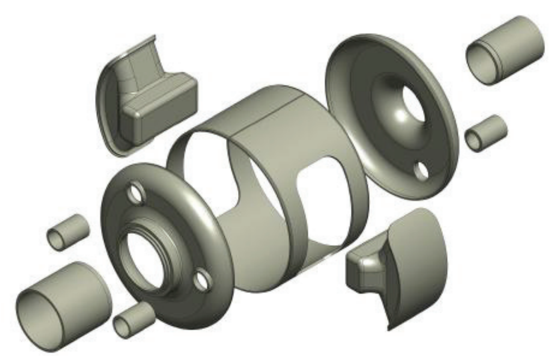
HOM
Dumper



RF Coupler

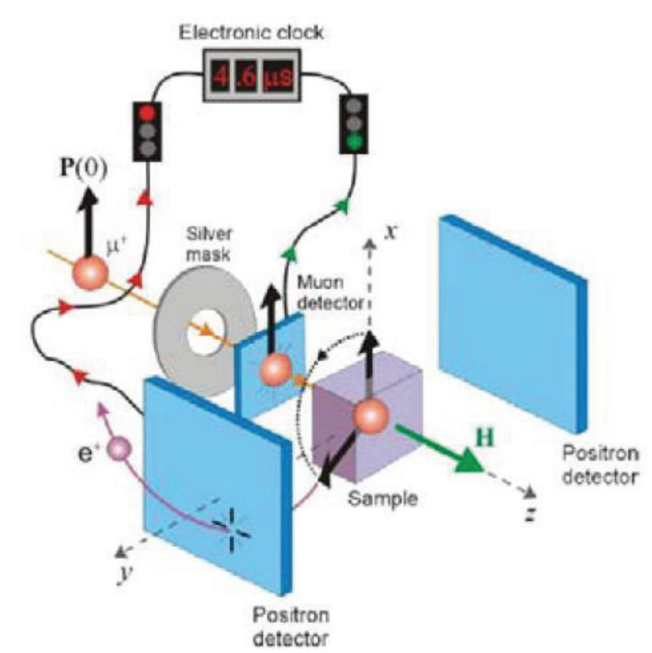
Vrf=0.3MV
Prf= 0.2W @ 4K

Parameter	Value	Units
Frequency of the operating mode	650	MHz
Frequency of the first HOM	935	MHz
Cavity length	177	mm
Cavity diameter	210	mm
Nominal (Max) cavity voltage, $V_\perp$	0.3 (0.6)	MV
Shunt Impedance, $R_\perp/Q$	625	Ω
Geometry Factor, G	99	Ω
$R_\perp R_s$	6.2×10^4	Ω^2
Peak electric field, E_p	9.5 (19)	MV/m
Peak magnetic field, B_p	12 (24)	mT

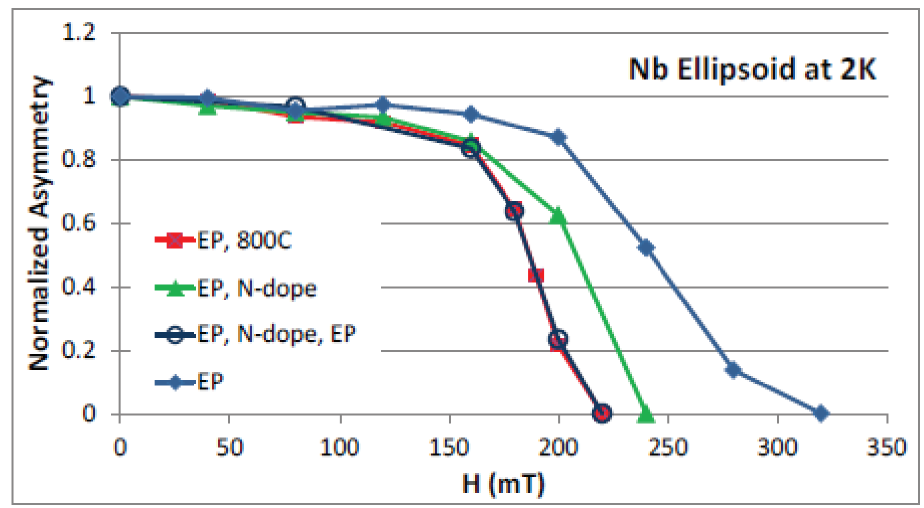


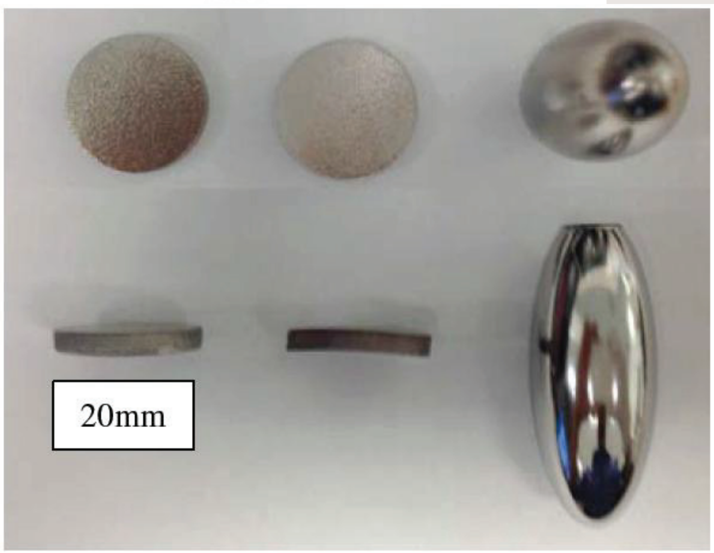
Cavity fabrication development for TRIUMF machine shop

CHARACTERIZATION OF SRF MATERIALS AT THE TRIUMF μSR FACILITY



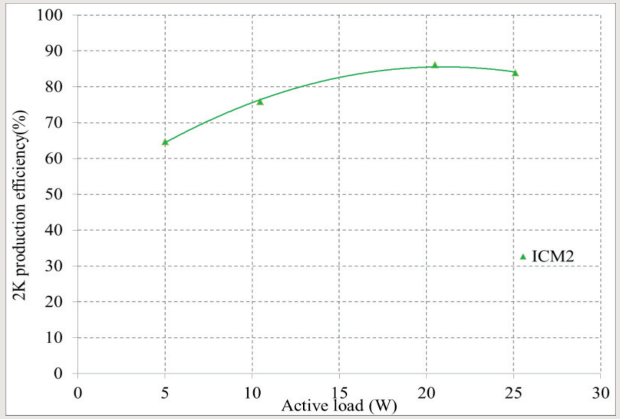
The method is using to characterize the sample superconducting state, particularly the transition from Meissner state to mixed state at different external magnetic field.





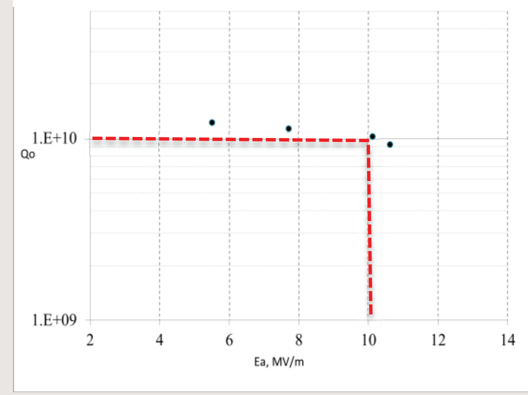
Since 2010 the SRF group at TRIUMF has been using the μSR technique to characterize materials and processing techniques typical for the SRF community using the TRIUMF surface muon beam

ICM2 Cryomodule for VECC

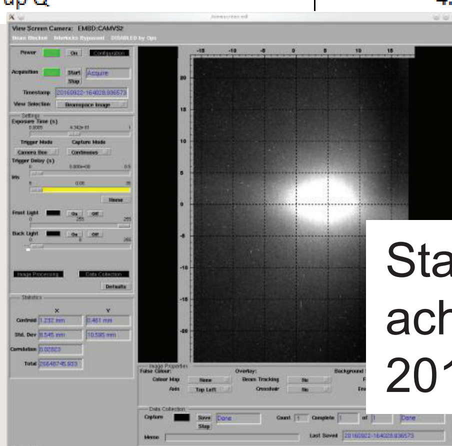


Production efficiency of 85% 2 K can be achieved

ICM2 meets specification of Qo=1e10 at Ea=10MV/m



Einj	MeV	0.3
Eout	MeV	**10.4**
Ea caculate by beam energy	MV/m	11.93714
Ppm	dBm	3.76
Ea caculate by pick up signal		11.09019
pick up Q		4.97E+10

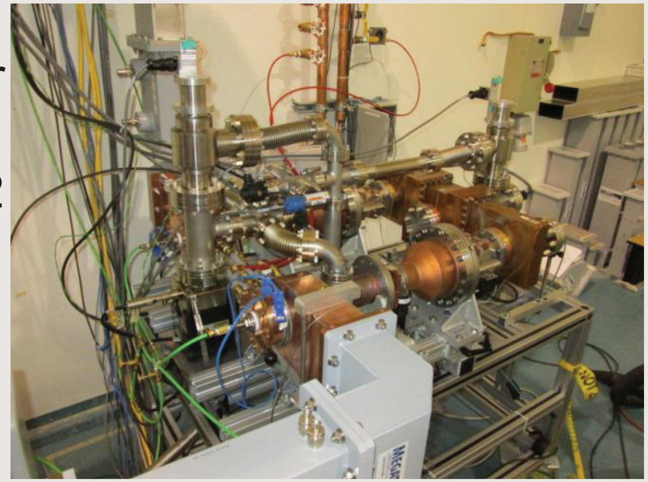


Copy of eLINAC Injector cryomodule ICM2 was made at TRIUMF for VECC project and successfully commissioned online in 2016

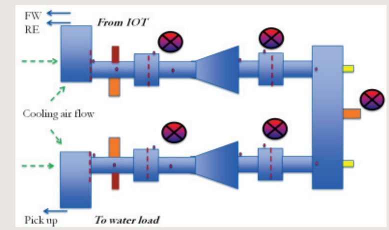
Stable operation at Ea=12MV/m was achieved during beam test in Sep 2016

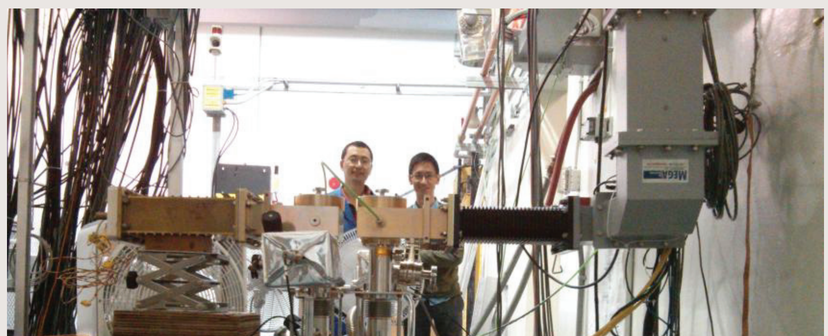
IOT Transmitter for VECC ICM

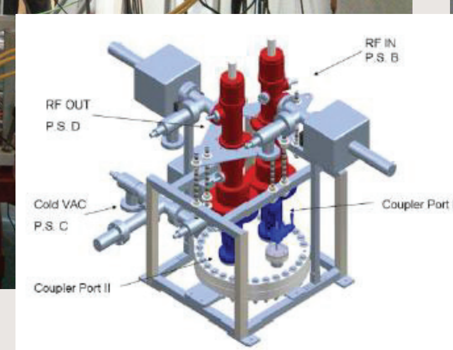
CPI IOT VKL 9130A 30kW CW 1.3GHz in Bruker Transmitter was Installed at TRIUMF in 2012



TRIUMF Power Coupler Test Station: 4 pairs of 50kW CPI VWP 3032 were conditioned





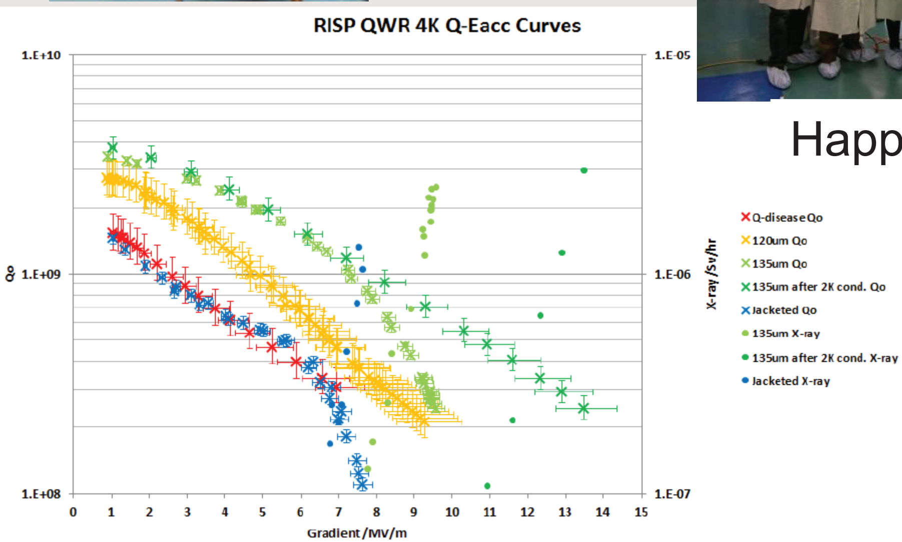


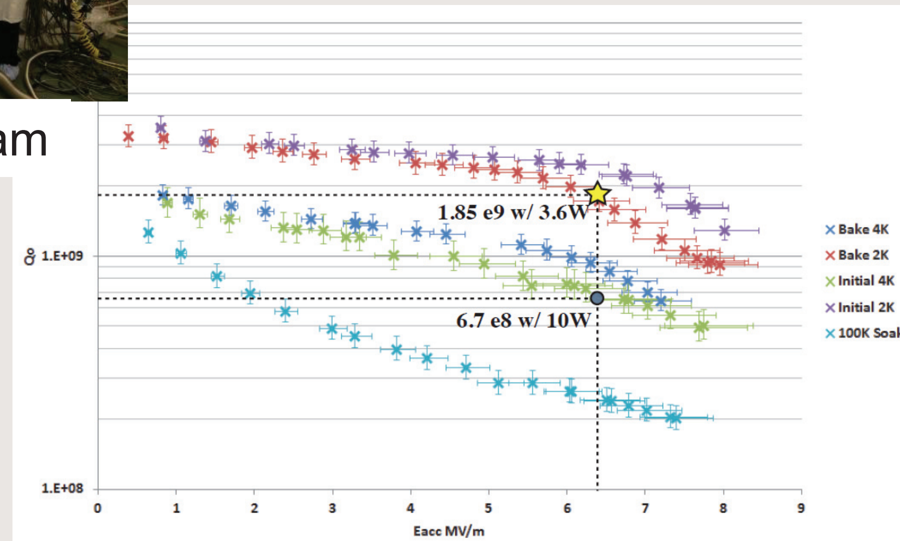
2 pairs of 4kW 1.3GHz couplers for SLAC LCLSII project were conditioned

Transmitter and IOT shipped to VECC (India) in July 2016

SRF tests of RISP QWRs and HWRs at TRIUMF

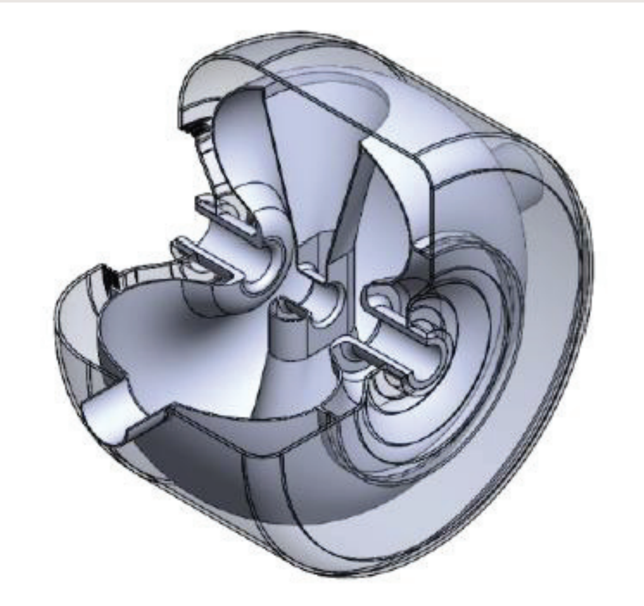
Happy Team



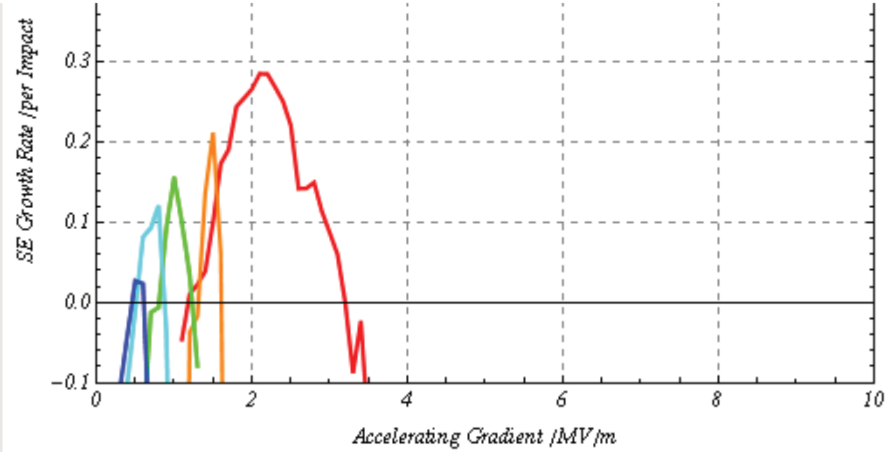


TRIUMF

BALLOON VARIANT OF SINGLE SPOKE RESONATOR FOR RISP



Ballon shape effectively suppresses the MP by moving barriers to lower field levels and narrowing them



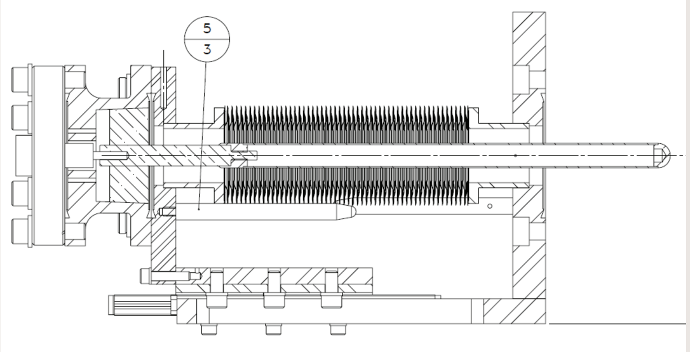
Parameters	Value	Units
Frequency	325	MHz
β_g	0.3	1
$L_{eff}=\beta\lambda$	0.277	m
E_p/E_{acc}	3.8	1
B_p/E_{acc}	6.1	mT/(MV/m)
R/Q	233	Ω
G	93	Ω

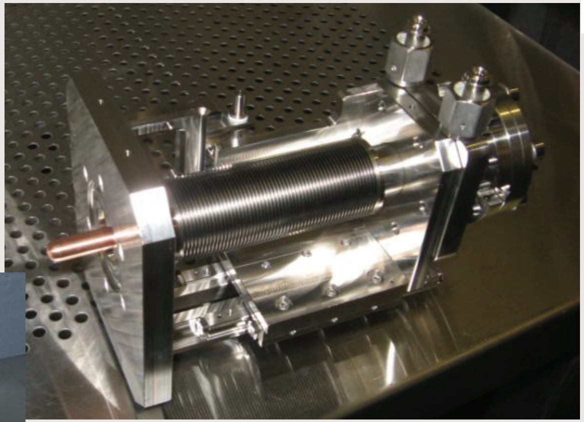
Parameters	Beam Tube	Value	Units
Stress @ 1bar	Fixed	35.9	Mpa
	Free	36.1	
df/dp	Fixed	-9.5	Hz/mbar
	Free	1.6	
LFD	Fixed	-1.9	$Hz/(MV/m)^2$
	Free	-10.9	
Tuning	N/A	444	kHz/mm
	N/A	18.2	kN/mm
	N/A	129.8	MPa/mm

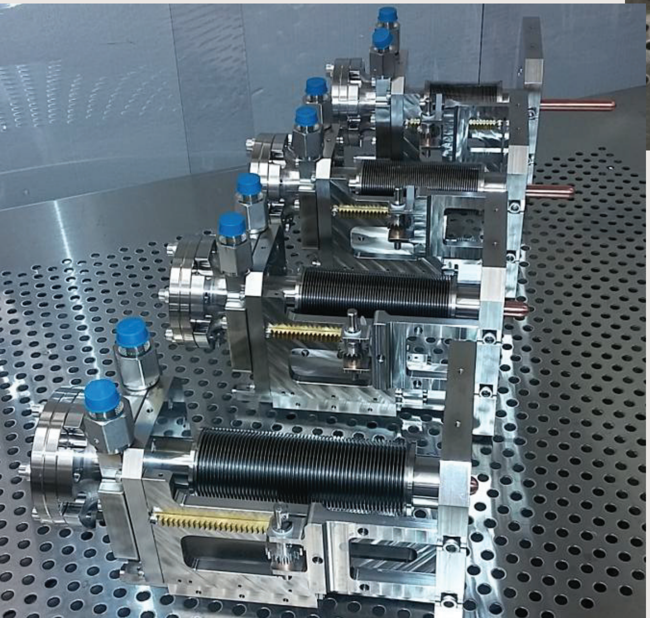
The cavity prototype fabrication is under preparation

Variable Test Couplers for FRIB

Variable test couplers were developed at TRIUMF for FRIB QWR and HWR SRF 2K-4K 'jacketed' tests
•100 W CW 500 W in pulse mode at DF=10%
•80-350 MHz
•50mm stroke
•Cooling with LN2

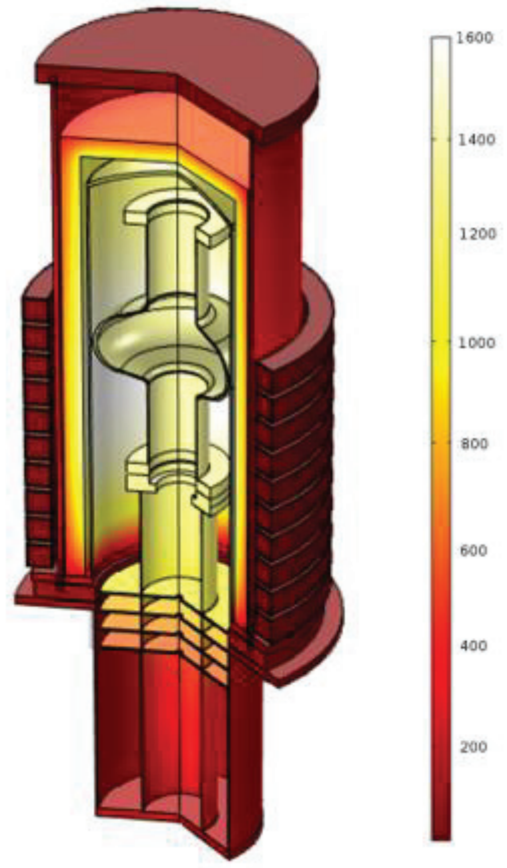




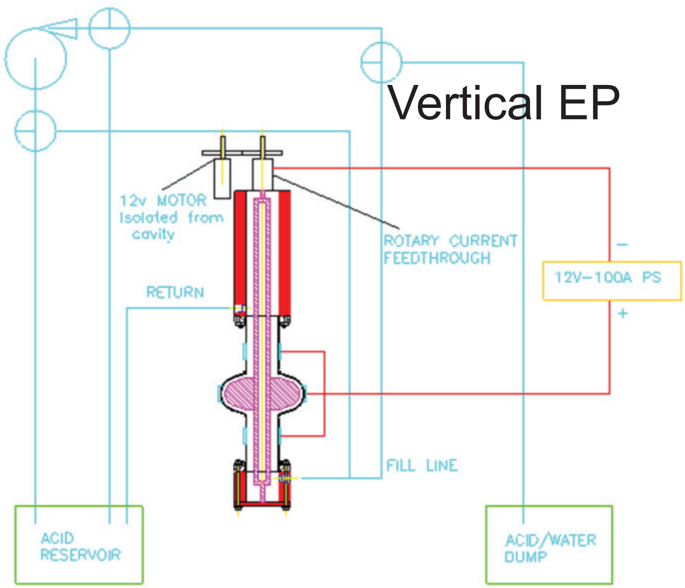


1st two Couplers were successfully used for FRIB cavities tests
2nd batch of 4 couplers was shipped to FRIB in Nov 2016

SRF Technology Developments

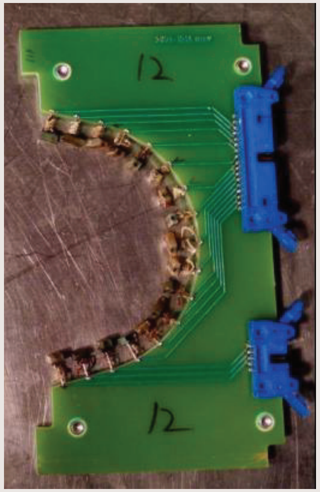


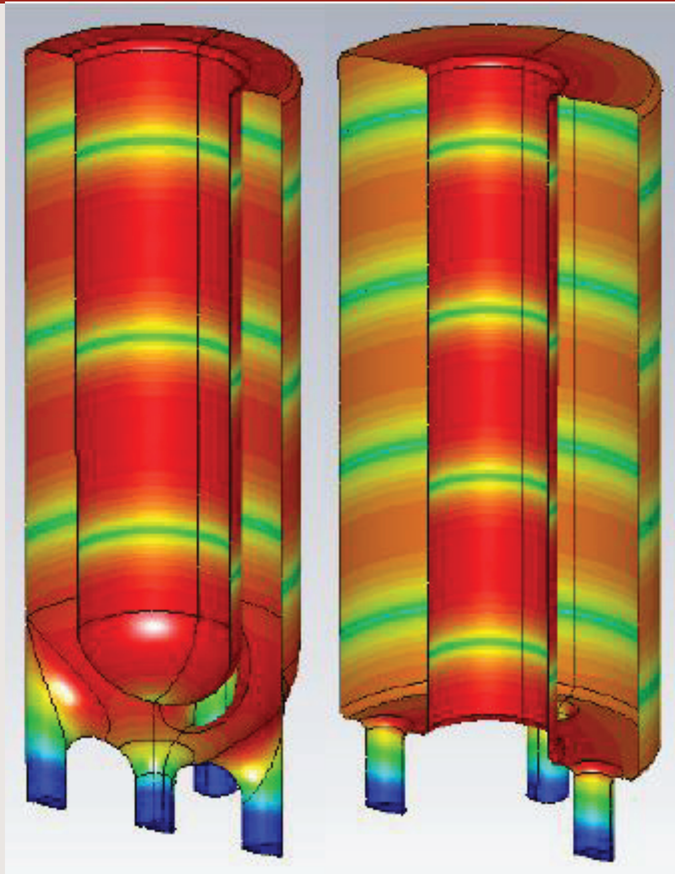
Induction Oven:
Degassing, N-doping



Vertical EP

T-map





Multimode test cavities

Summary

- ISAC-II is in 24/7 operation since 2006
- eLINAC phase-I of 1st stage consisting of 2 SC 9-cell cavities in ICM and ACMuno has been commissioned with 23 MeV beam test
  - 1st stage completion of ACM with 2nd cavity is expected in 2017
- eLINAC ICM2 has been fabricated and commissioned at TRIUMF
- TRIUMF is running SRF developments and uSR material study
- Work for External projects
- RISP
  - SRF tests of QWR and HWR prototypes – completed
  - Balloon Spoke cavity fabrication preparation is in a process
- FRIB
  - Couplers for QWR and HWR test – designed. 6 couplers delivered to MSU
- SLAC
  - 4 power couplers has been conditioned

TRIUMF

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

TRIUMF: Alberta | British Columbia | Calgary | Carleton | Guelph | Manitoba | McGill | McMaster | Montréal | Northern British Columbia | Queen's | Regina | Saint Mary's | Simon Fraser | Toronto | Victoria | Winnipeg | York

Thanks!

Owned and operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada
Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada