TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

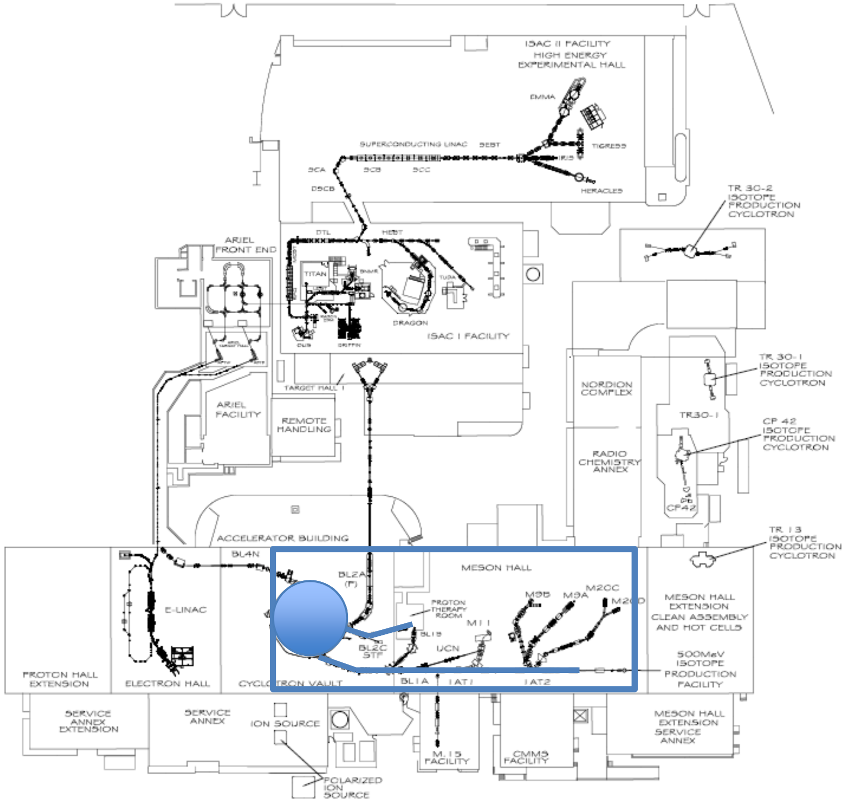
The 30MeV Stage of the ARIEL e-Linac

Bob Laxdal, Z. Ang, T. Au, K. Fong, O.K. Kester, S. Koscielniak, A. Koveshnikov, M. Laverty, Y. Ma, D.W. Storey, E. Thoeng, Z. Yao, Q. Zheng, V. Zvyagintsev (TRIUMF, Vancouver, Canada)

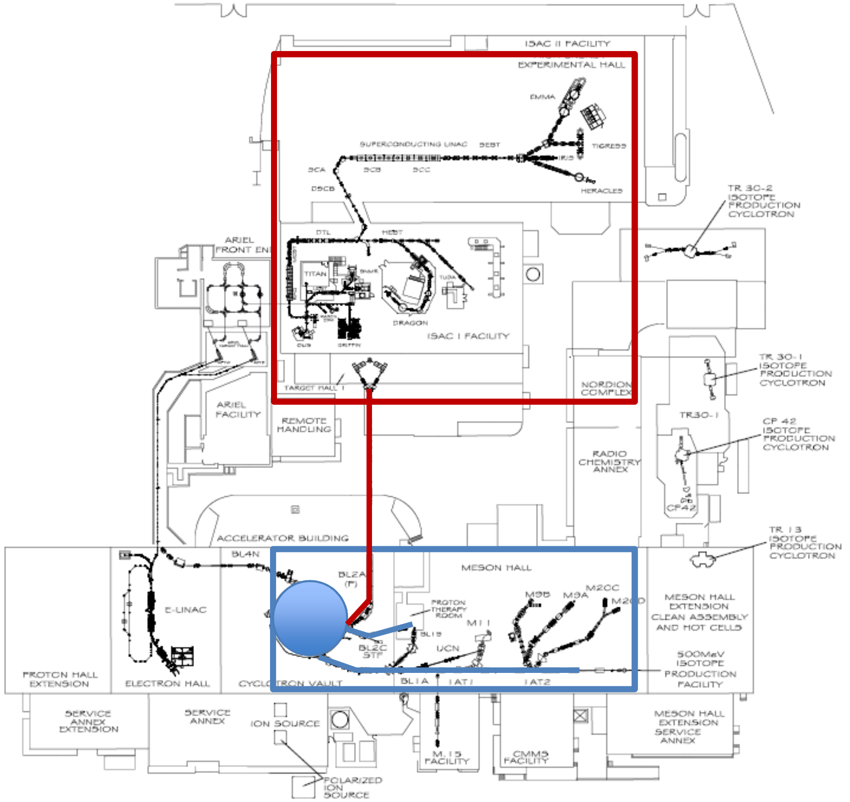
July 17, 2017

Contribution MOXA03

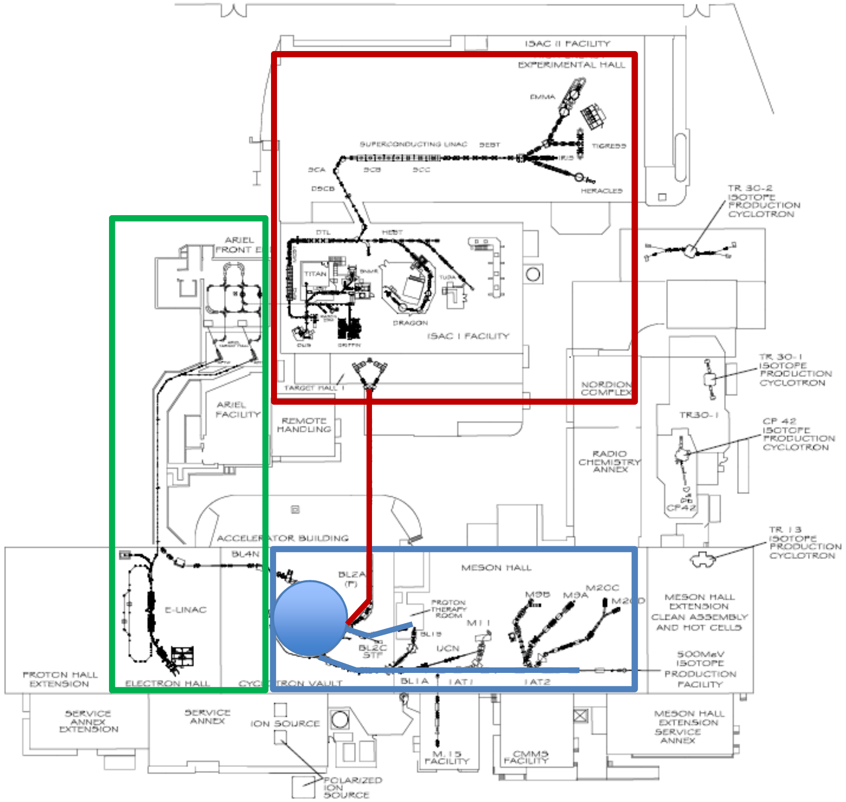
- 500MeV cyclotron since 1974
  - ~300μA distributed to multiple beamlines



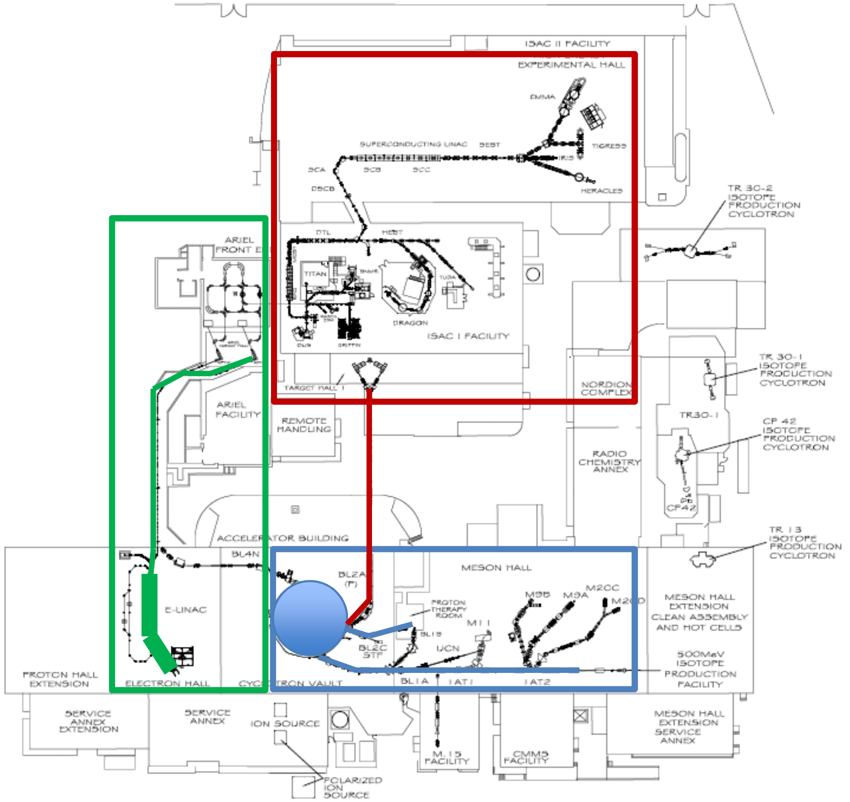
- 500MeV cyclotron since 1974
  - ~300μA distributed to multiple beamlines
- ISAC since 1995
  - Radioactive ion beam (RIB) facility
  - Driven by 500MeV protons from cyclotron



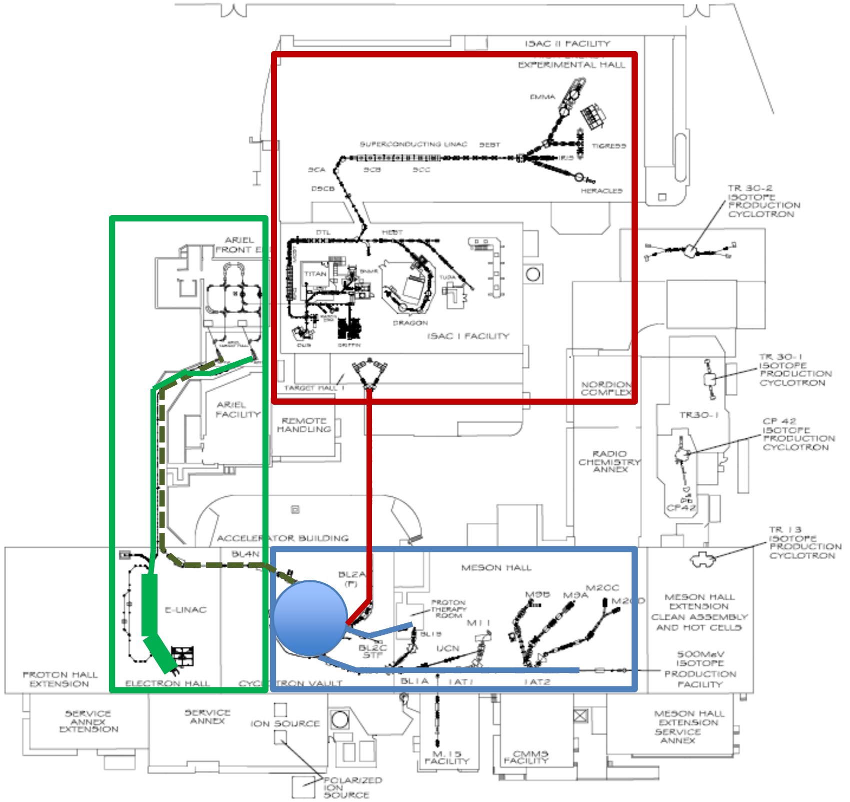
- 500MeV cyclotron since 1974
  - ~300μA distributed to multiple beamlines
- ISAC since 1995
  - Radioactive ion beam (RIB) facility
  - Driven by 500MeV protons from cyclotron
- ARIEL in progress (2010-2023)



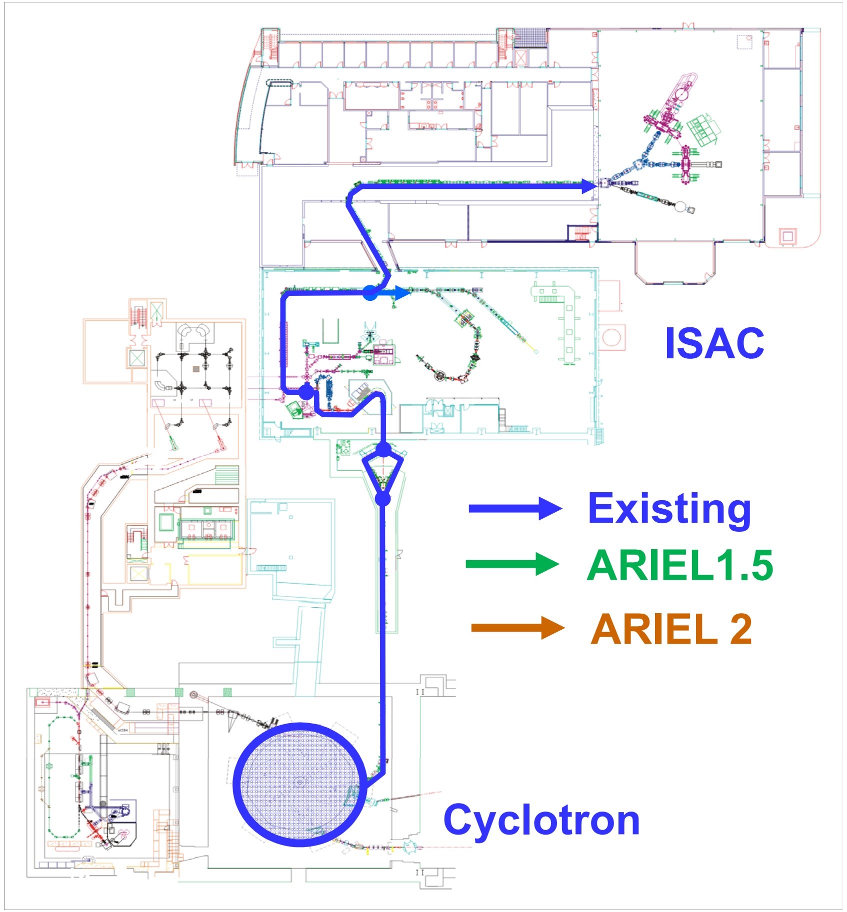
- 500MeV cyclotron since 1974
  - ~300μA distributed to multiple beamlines
- ISAC since 1995
  - Radioactive ion beam (RIB) facility
  - Driven by 500MeV protons from cyclotron
- ARIEL in progress (2010-2023)
  - e-Linac being commissioned – demonstrator beam in 2014
    - Will drive RIB production in new ARIEL target area (e-line in progress)



- 500MeV cyclotron since 1974
  - ~300μA distributed to multiple beamlines
- ISAC since 1995
  - Radioactive ion beam (RIB) facility
  - Driven by 500MeV protons from cyclotron
- ARIEL in progress (2010-2023)
  - e-Linac being commissioned – demonstrator beam in 2014
    - Will drive RIB production in new ARIEL target area (e-line in progress)
  - BL4N proton line
    - Will drive second ARIEL RIB production target

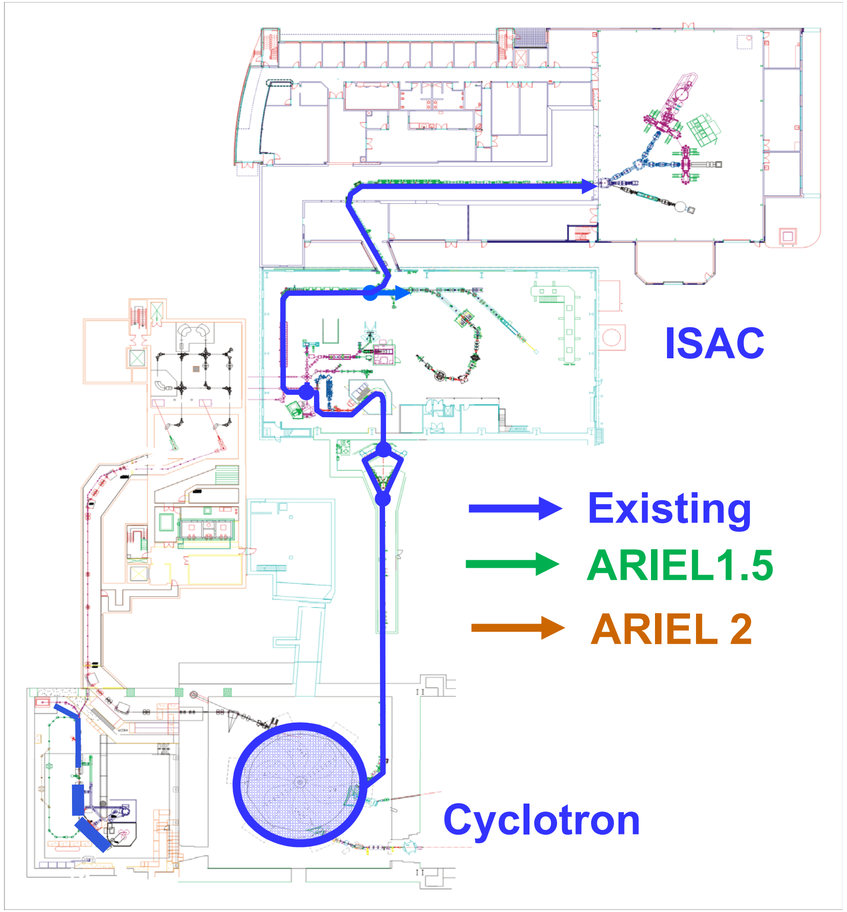


Advanced Rare IsotopE Laboratory - staging



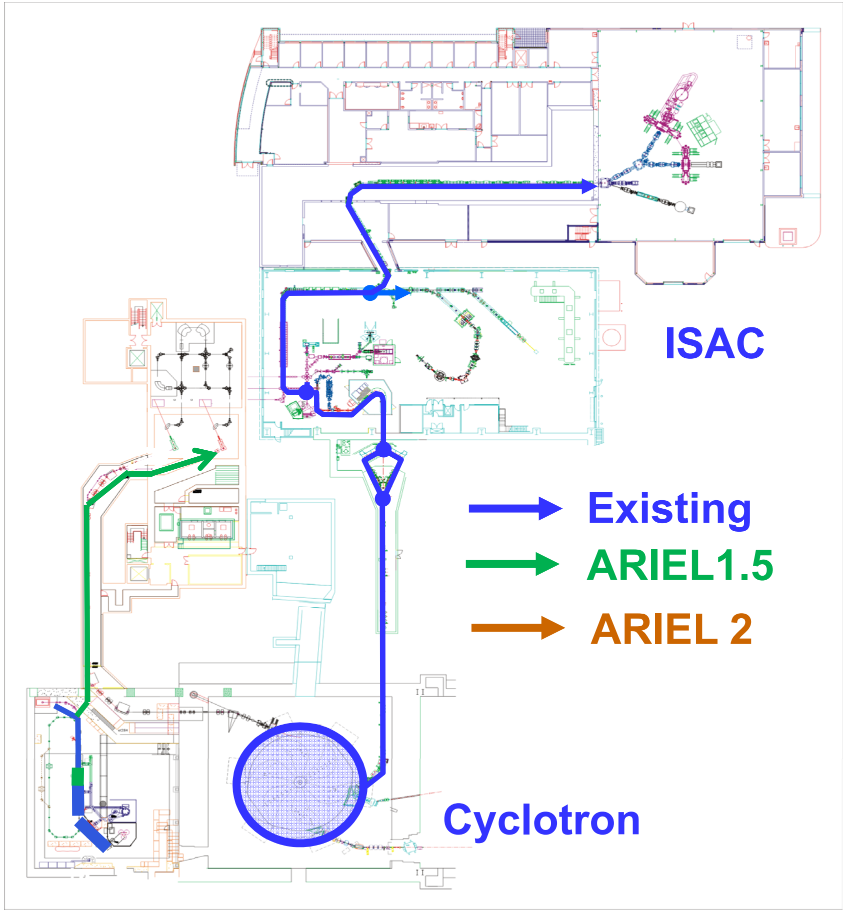
- ARIEL will triple the lab's RIB production by adding two new target stations resulting in up to three simultaneous ion beams
- ARIEL is staged
  - ARIEL-I

Advanced Rare IsotopE Laboratory - staging



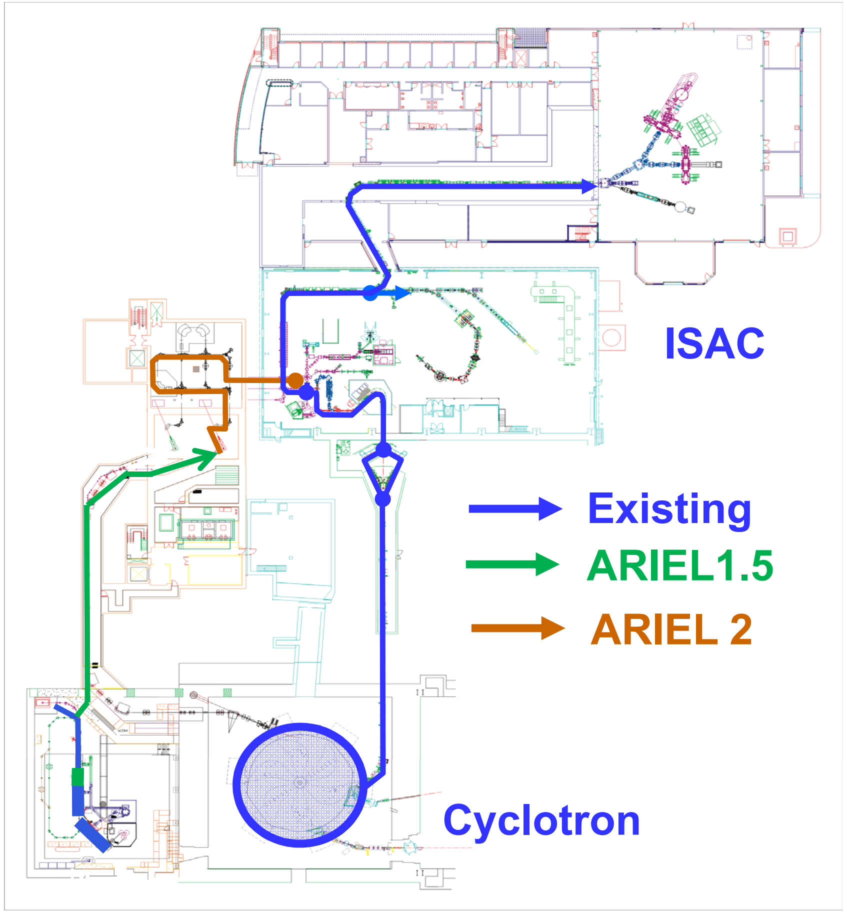
- ARIEL will triple the lab's RIB production by adding two new target stations resulting in up to three simultaneous ion beams
- ARIEL is staged
  - ARIEL-I
    - E-Linac demonstration at 23MeV (2 cavities) - 2014

Advanced Rare IsotopE Laboratory - staging



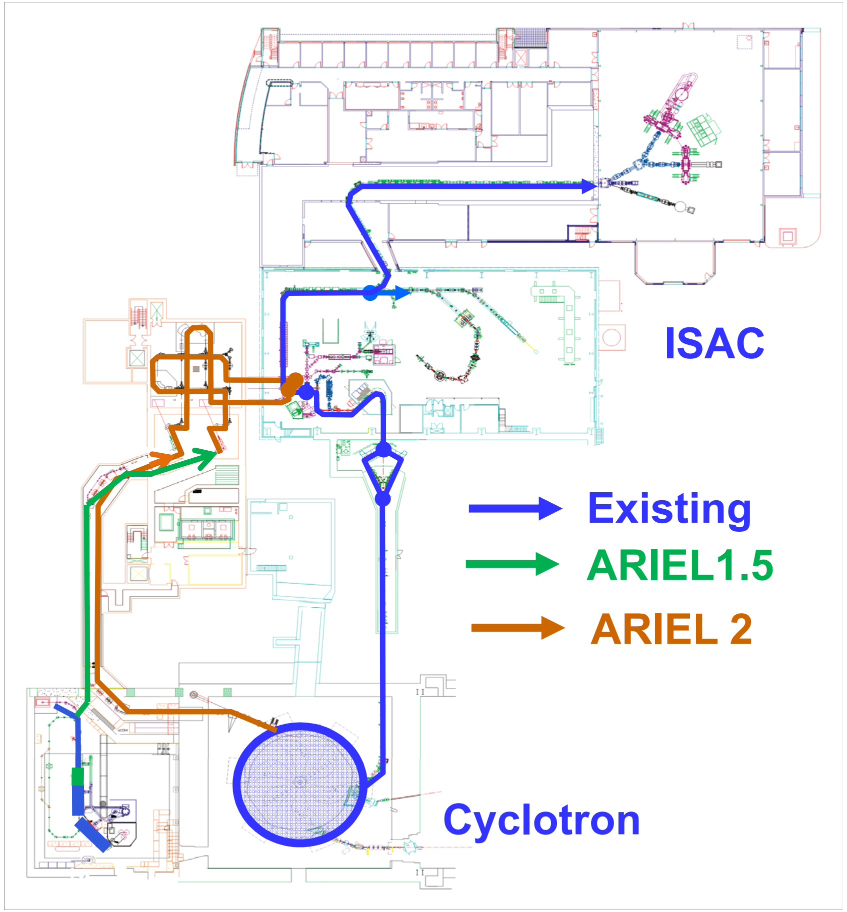
- ARIEL will triple the lab's RIB production by adding two new target stations resulting in up to three simultaneous ion beams
- ARIEL is staged
  - ARIEL-I
    - E-Linac demonstration at 23MeV (2 cavities) - 2014
  - ARIEL1.5
    - Complete e-Linac to 30-35MeV – third rf cavity added – 2017
    - Complete e-beamline – 2018
  - ARIEL-II

Advanced Rare IsotopE Laboratory - staging



- ARIEL will triple the lab's RIB production by adding two new target stations resulting in up to three simultaneous ion beams
- ARIEL is staged
  - ARIEL-I
    - E-Linac demonstration at 23MeV (2 cavities) - 2014
  - ARIEL1.5
    - Complete e-Linac to 30-35MeV – third rf cavity added – 2017
    - Complete e-beamline – 2018
  - ARIEL-II
    - Install electron target station (AETE) and RIB lines - 2019

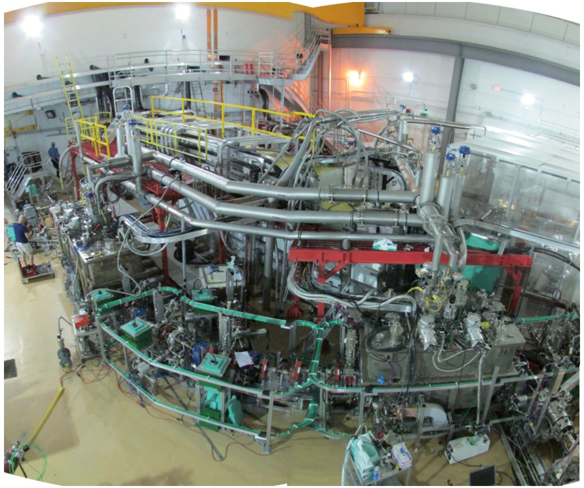
Advanced Rare IsotopE Laboratory - staging

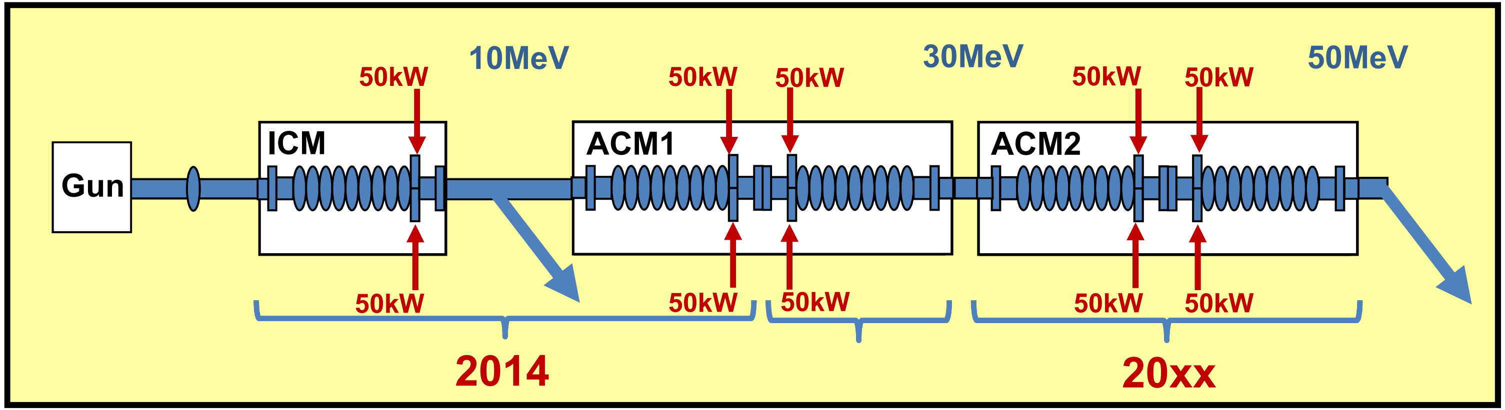


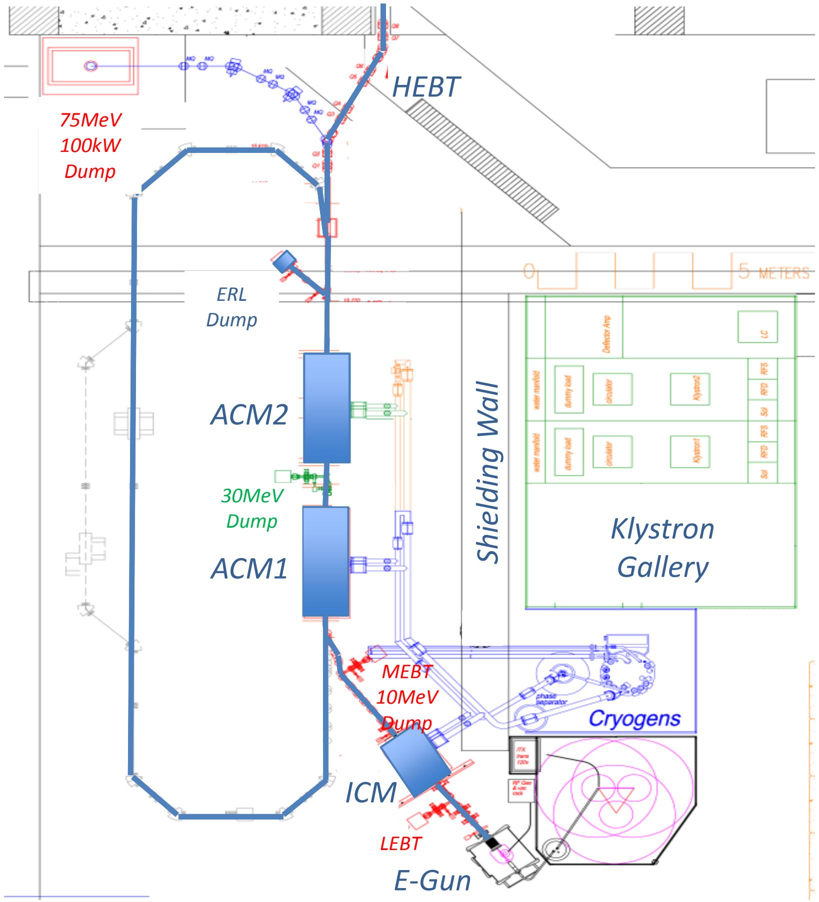
- ARIEL will triple the lab's RIB production by adding two new target stations resulting in up to three simultaneous ion beams
- ARIEL is staged
  - ARIEL-I
    - E-Linac demonstration at 23MeV (2 cavities) - 2014
  - ARIEL1.5
    - Complete e-Linac to 30-35MeV – third rf cavity added – 2017
    - Complete e-beamline – 2018
  - ARIEL-II
    - Install electron target station (AETE) and RIB lines - 2019
    - Install BL4N proton beamline, proton target station (APTW) and RIB lines - 2022

1.3GHz SRF Electron Linac (baseline 50MeV/10mA)

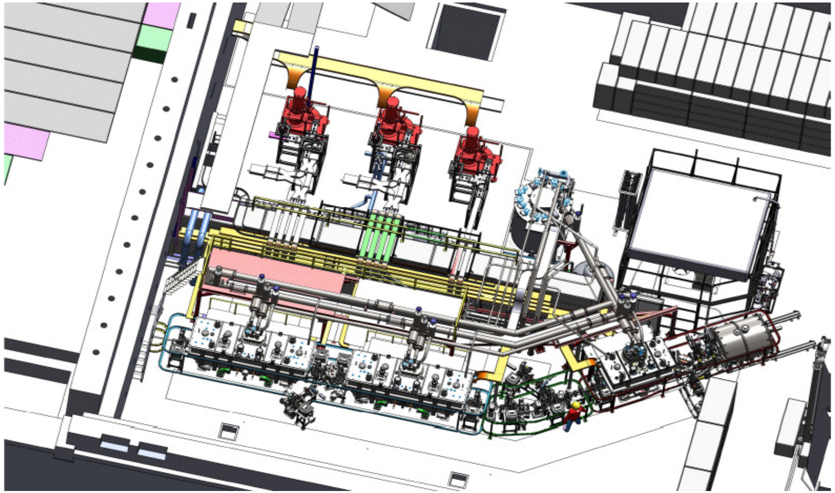
- Base-line design - five nine-cell cavities housed in three cryomodules – each cavity adds 10MeV (100kW)
- 23 MeV demonstrated from two cavities in 2014 with only one cavity in ACM1 - `ACMuno configuration'
- Install 30MeV capability in mid 2017 – in commissioning - ramp to 10kW in 2018 – limited by dump
- Bunch structure – 650MHz – macro-pulse established with e-gun rf – rep-rate is selectable from 0.1% to 100%



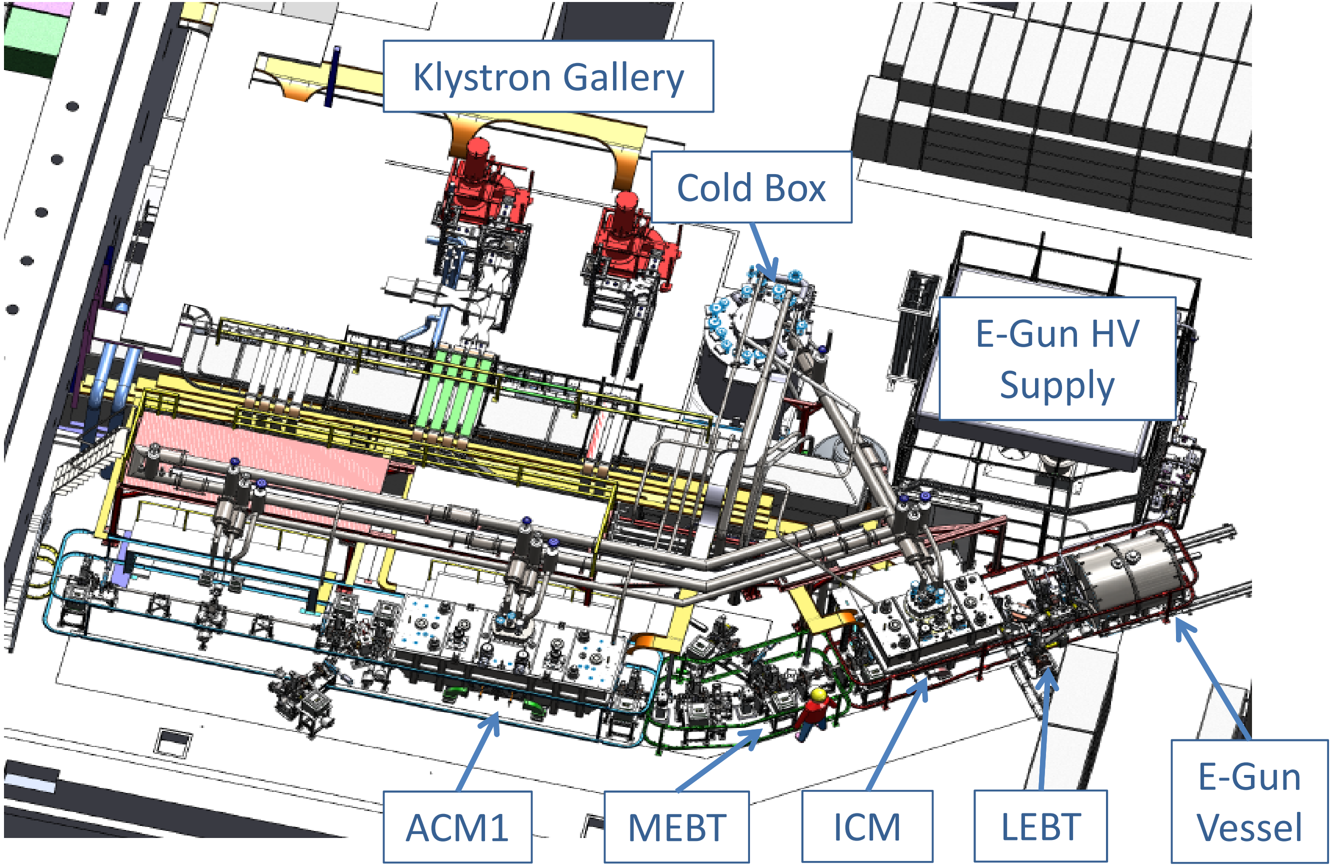




The linac is configured to allow a recirculating linac (RLA) for a multi-pass `energy doubler’ mode or to operate as an energy recovery linac (ERL) for accelerator studies and applications



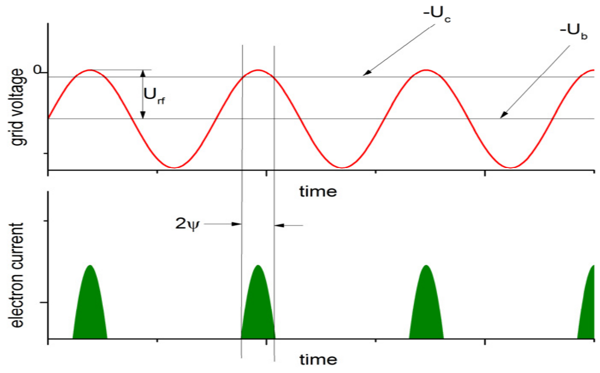
Accelerator Vault – existing configuration



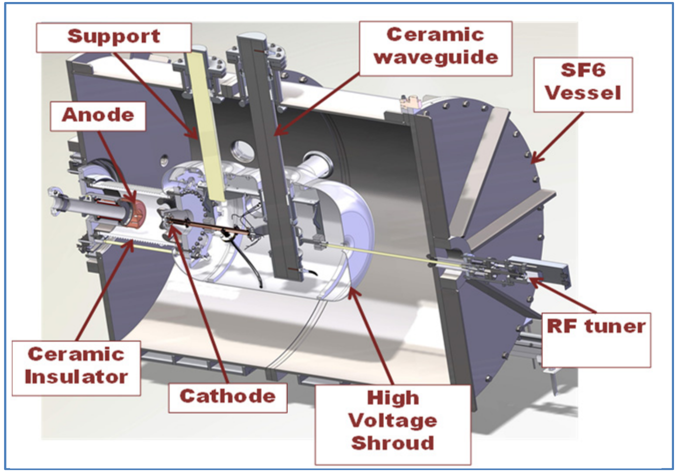
e-Linac Design and Status

Electron Gun

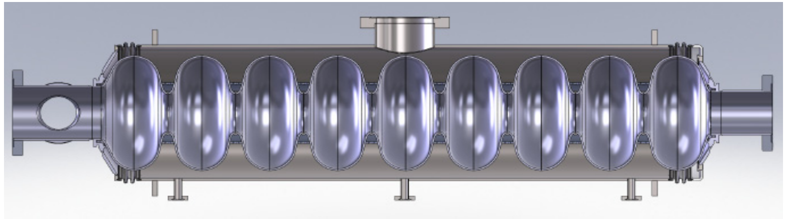
- Thermionic 300kV DC gun – cathode has a grid with DC supressing voltage and rf modulation that produces electron bunches at 650MHz
- Gun installed inside an SF6 vessel
- Rf delivered to the grid via a ceramic waveguide

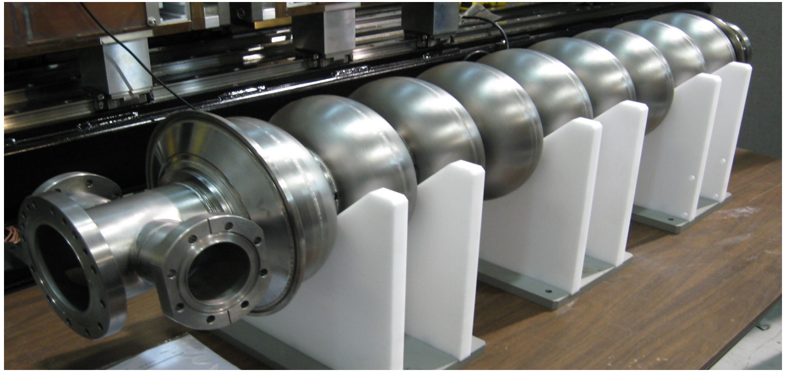


Parameter	Value
RF frequency	650MHz
Pulse length	±16^0 (137ps)
Average current	10mA
Charge/bunch	15.4pC
Kinetic energy	300keV
Normalized emittance	5μm
Duty factor	0.01 to 100%



- 1.3GHz nine-cell elliptical cavities
- End groups modified to accommodate two 50kW couplers and to reduce trapped modes

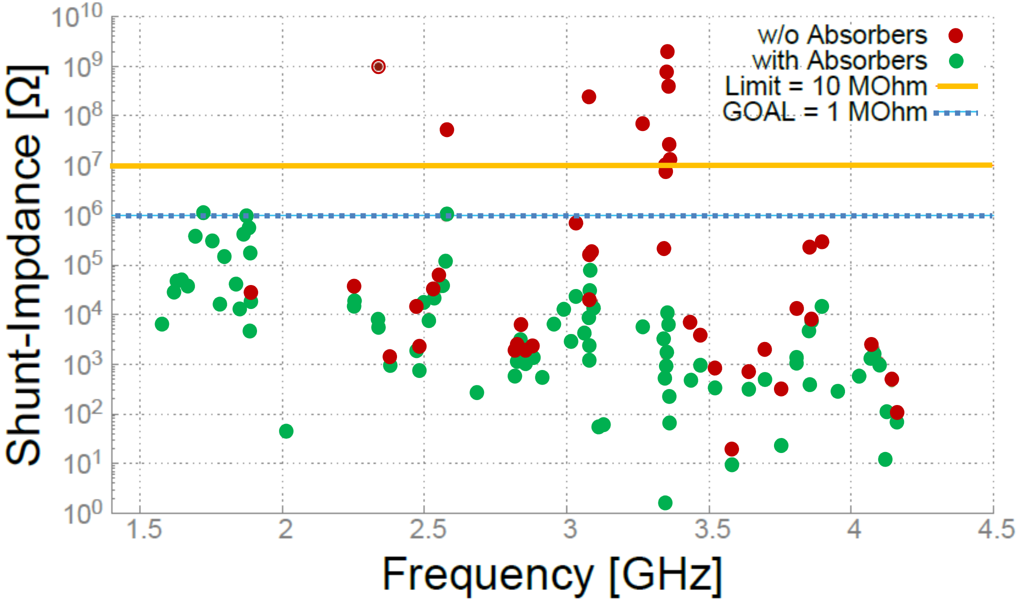


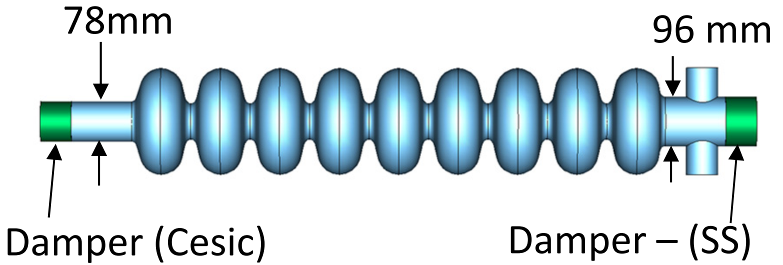


* P. Kolb, `The TRIUMF nine-cell SRF cavity for ARIEL', PhD thesis, University of British Columbia, DOI: 10.14288/1.0300057, April 2016.

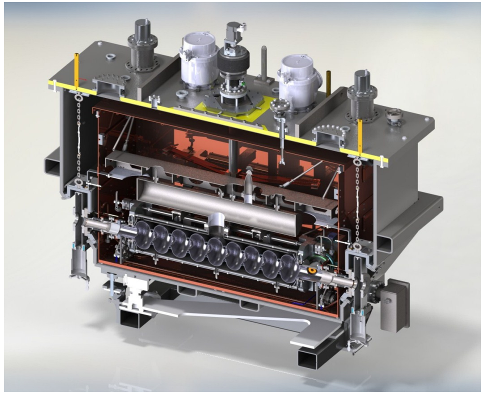
Parameter	Value
Active length (m)	1.038
RF frequency	1.3e9
R/Q (Ohms)	1000
Q_0	1e10
E_a (MV/m)	10
P_{cav} (W)	10
P_{beam} (kW)	100
Q_{ext}	1e6
Q_L*R_d/Q of HOM	<1e6

- To allow for a future ERL upgrade, BBU criteria set limits on the HOM dipole shunt impedance (R_d/Q^*Q_L)
- Assuming a threshold current of 20 mA, beam dynamics calculations set a limit on dipole mode shunt impedance values of $R_d/Q^*Q_L < 10^7\ \Omega$
- Estimation of fabrication errors combine to set a lower limit of $R_d/Q^*Q_L < 10^6\ \Omega$
- CESIC and SS passive coaxial dampers used to suppress HOMs to <BBU limit up to 4GHz





ARIEL Cryomodules

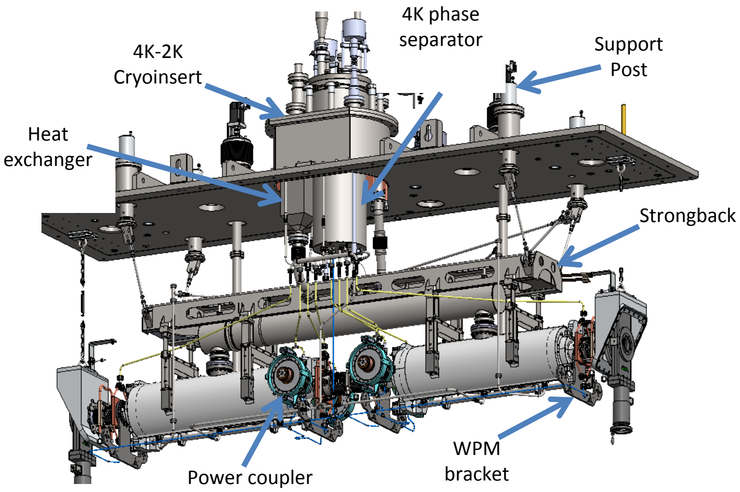


Houses

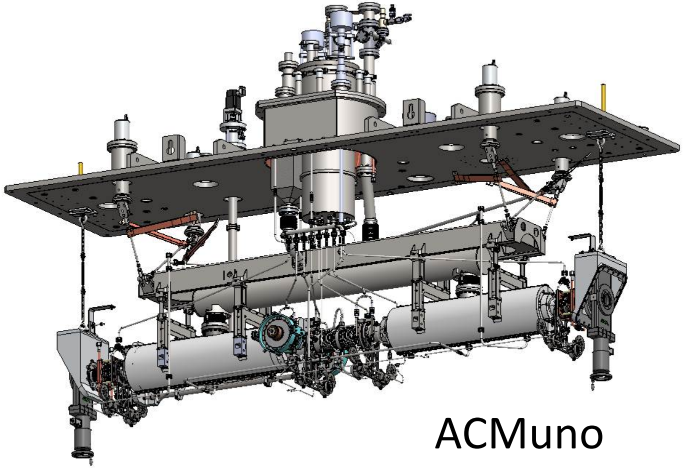
- One/two nine-cell 1.3GHz cavity
- Two/four 50kW power couplers
- HOM coaxial dampers

Features

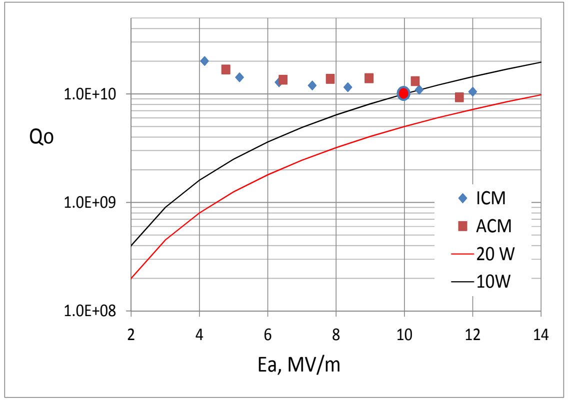
- 4K/2K heat exchanger with JT valve on board – allows standard 4K cold box
- scissor tuner with warm motor
- LN2 thermal shield – 4K thermal intercepts via syphon
- Two layers of mu-metal
- WPM alignment system



- Demonstration configuration
  - Installed one cavity in ICM and one cavity in ACM - `ACMuno' configuration
  - A dummy cavity is placed in the second position
- ACMuno
  - ACMuno allows a full cryogenics engineering test plus two cavity beam acceleration to 23MeV
  - cryogenic engineering and funding milestone
- Aug. 2016 – ACMuno → ACMduo initiated



ACMuno

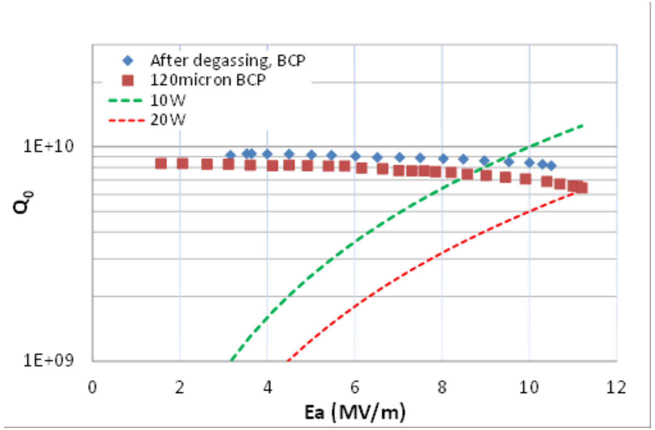


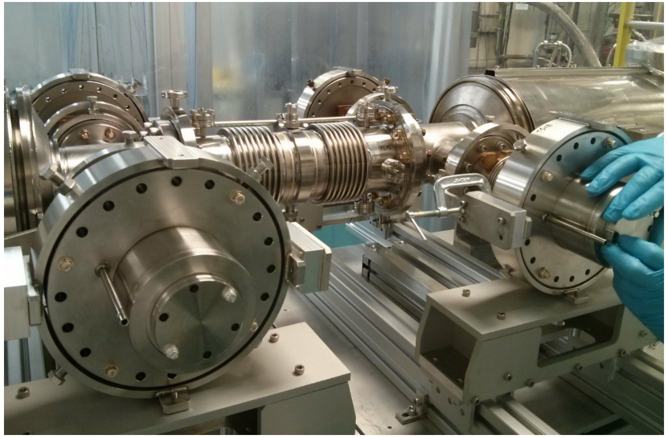
ACMuno → ACMduo

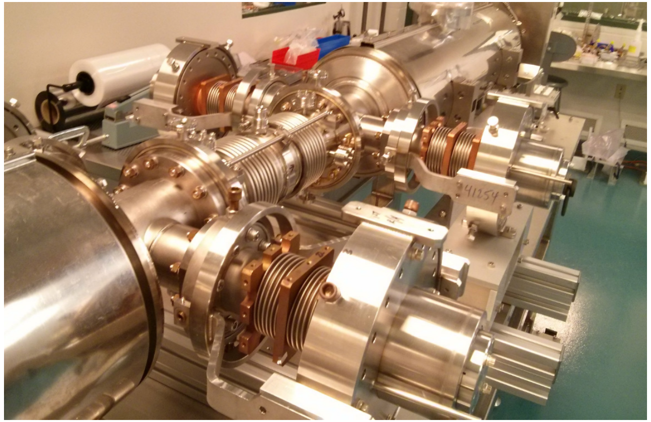
Initiated swap from ACMuno to ACM duo in Aug. 2016

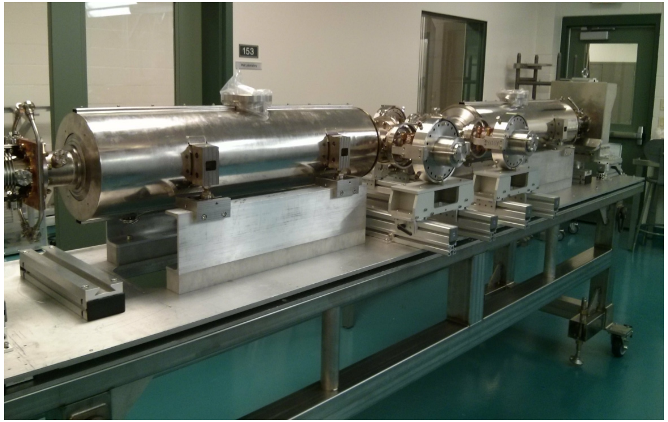
Cryomodule moved to ISAC-II assembly area and disassembled

Third cavity prepared and the hermetic unit cleaned, and re-assembled in the clean room in Dec. 2016

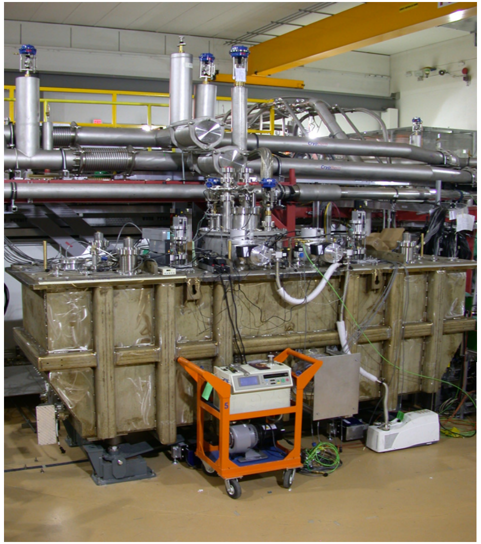








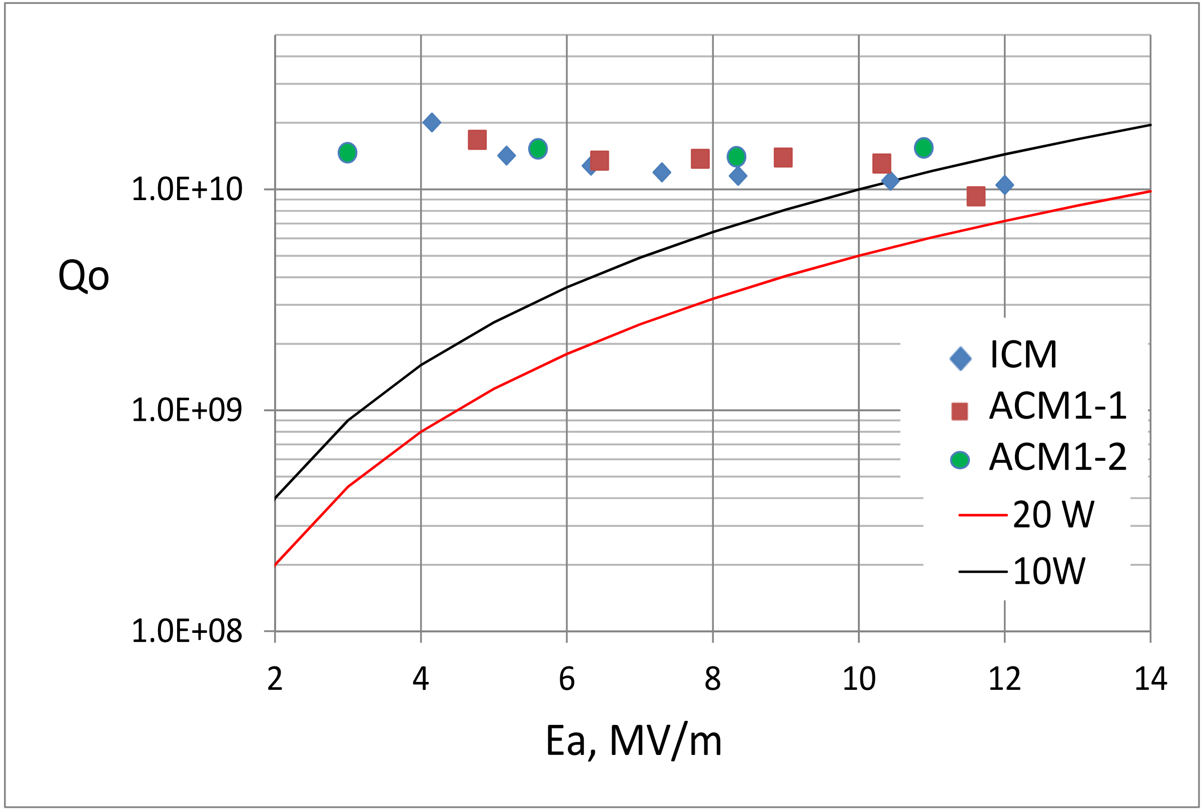
Hermetic unit re-installed on cold mass top assembly and the cryomodule (now ACMduo) was moved to the e-hall March 2017 for installation in April 2017



Cryomodule Cold test results

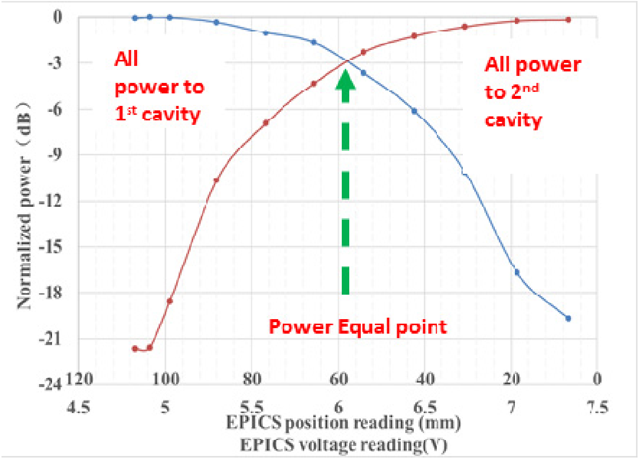
Parameter	ICM	ACMduo
4K static load	6.5	8.5
2K static load	5.5	11
2K efficiency	86%	86%

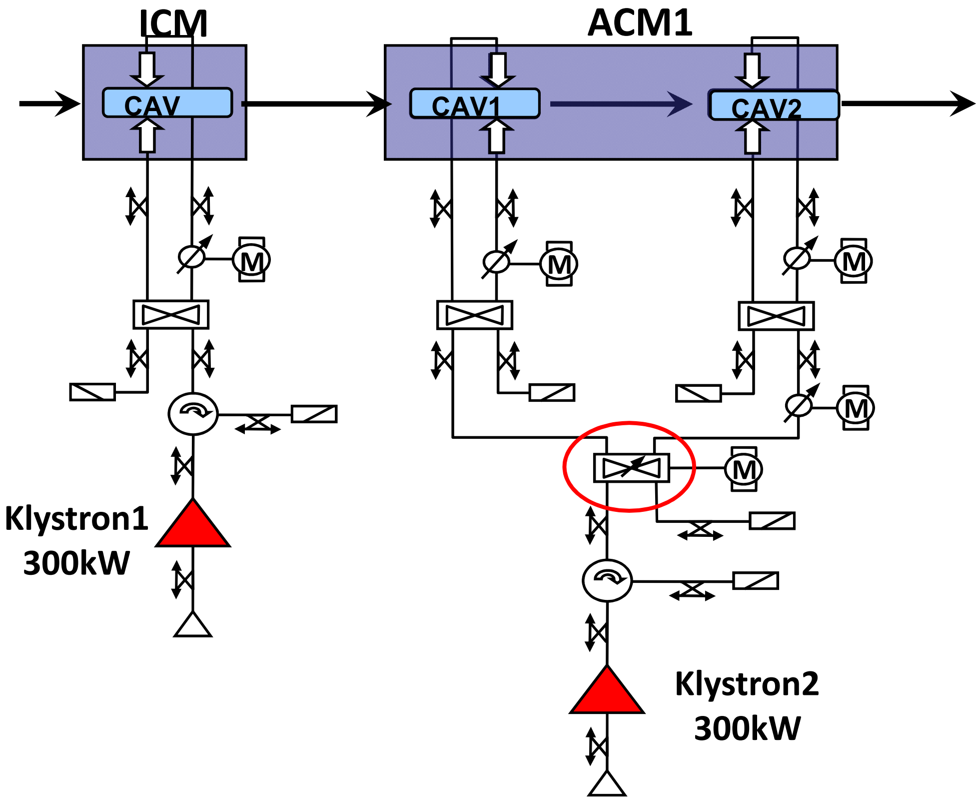
- ✓ Cavities meet specification
- ✓ Cryogenic engineering matches design expectations
- ✓ 2K production efficiency 86%
- ✓ Syphon loop performance characterized



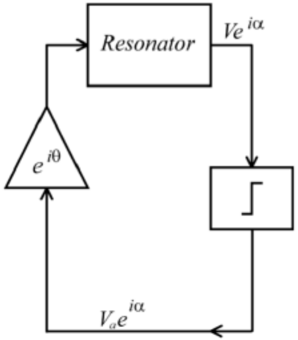
MOPB105 Thermosyphon Cooling Loops for ARIEL Cryomodules – Y. Ma

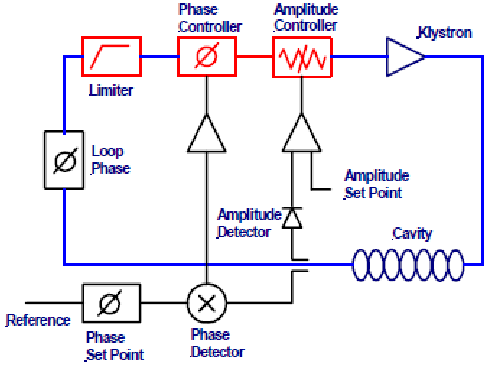
- The RF system for the e-Linac utilizes two 300kW klystrons – each source driving one module
- A power divider is used to divide the power to each cavity and to power each cavity independently during start-up





- TRIUMF has a history of using self-excited loop for LLRF – one source per cavity
- In SEL mode there is no frequency seeking required as the SEL tracks the resonant frequency - π-mode is selected using a band pass filter and an adjustable delay line

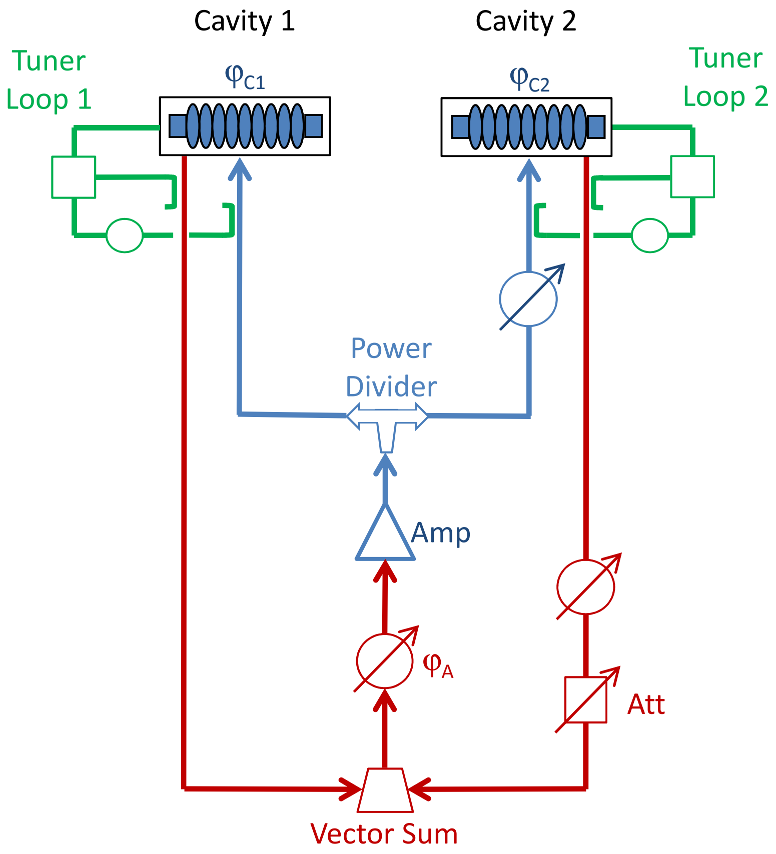




[3] J. R. Delayen, "Phase And Amplitude Stabilization of Superconducting Resonators", PhD Thesis, California Institute of Technology, 1978.

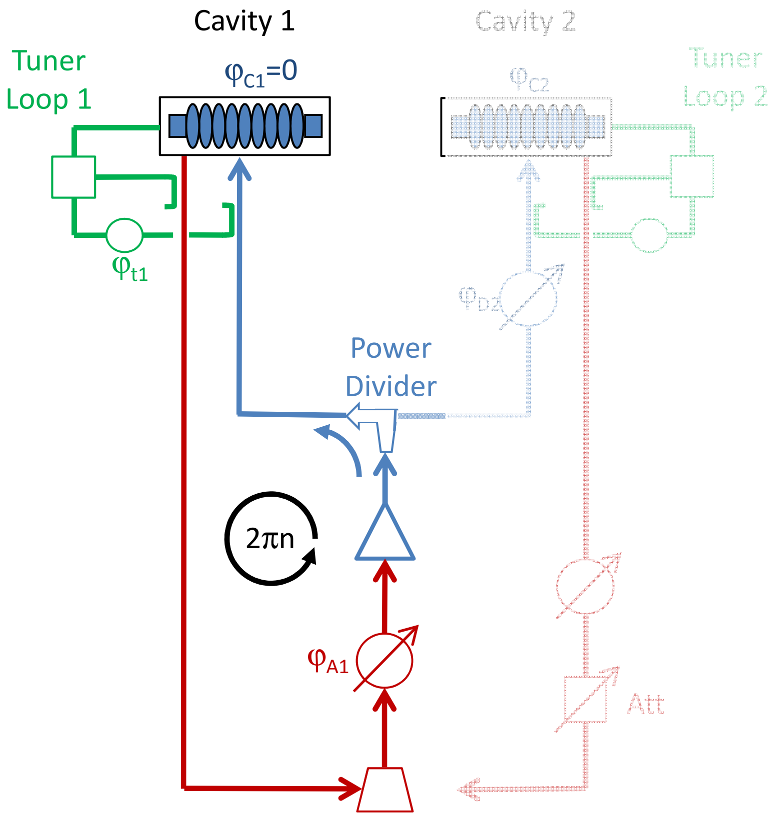
ACMduo – LLRF – Self-Excited Loop (SEL)

- TRIUMF has a history of using self-excited loop for LLRF – one source per cavity
- In SEL mode there is no frequency seeking required as the SEL tracks the resonant frequency - π-mode is selected using a band pass filter and an adjustable delay line
- ACMduo – two cavities – two tuners – one source – stable SEL demonstrated in Vector Sum

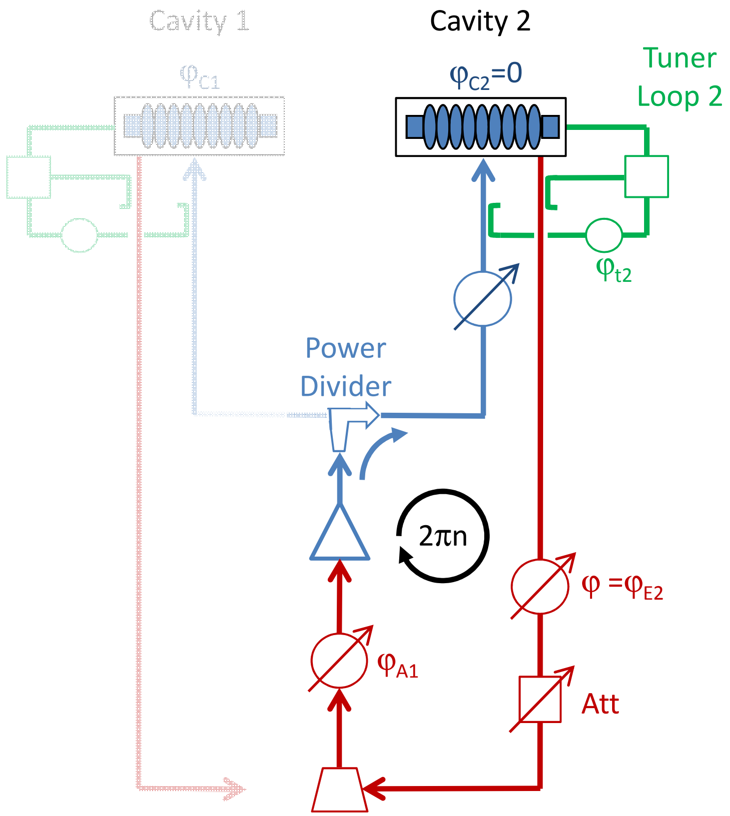


ACMduo – LLRF – Self-Excited Loop (SEL)

- TRIUMF has a history of using self-excited loop for LLRF – one source per cavity
- In SEL mode there is no frequency seeking required as the SEL tracks the resonant frequency - π-mode is selected using a band pass filter and an adjustable delay line
- ACMduo – two cavities – two tuners – one source – stable SEL demonstrated in Vector Sum
- Each cavity is turned on and tuned separately with SEL then combined in a single loop

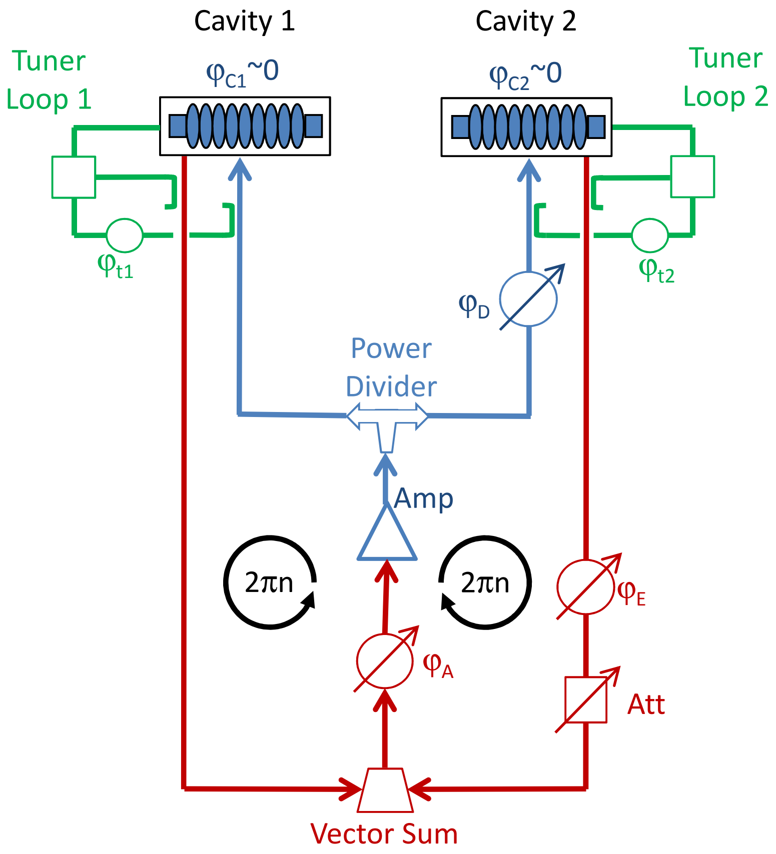


- TRIUMF has a history of using self-excited loop for LLRF – one source per cavity
- In SEL mode there is no frequency seeking required as the SEL tracks the resonant frequency - π-mode is selected using a band pass filter and an adjustable delay line
- ACMduo – two cavities – two tuners – one source – stable SEL demonstrated in Vector Sum
- Each cavity is turned on and tuned separately with SEL then combined in a single loop

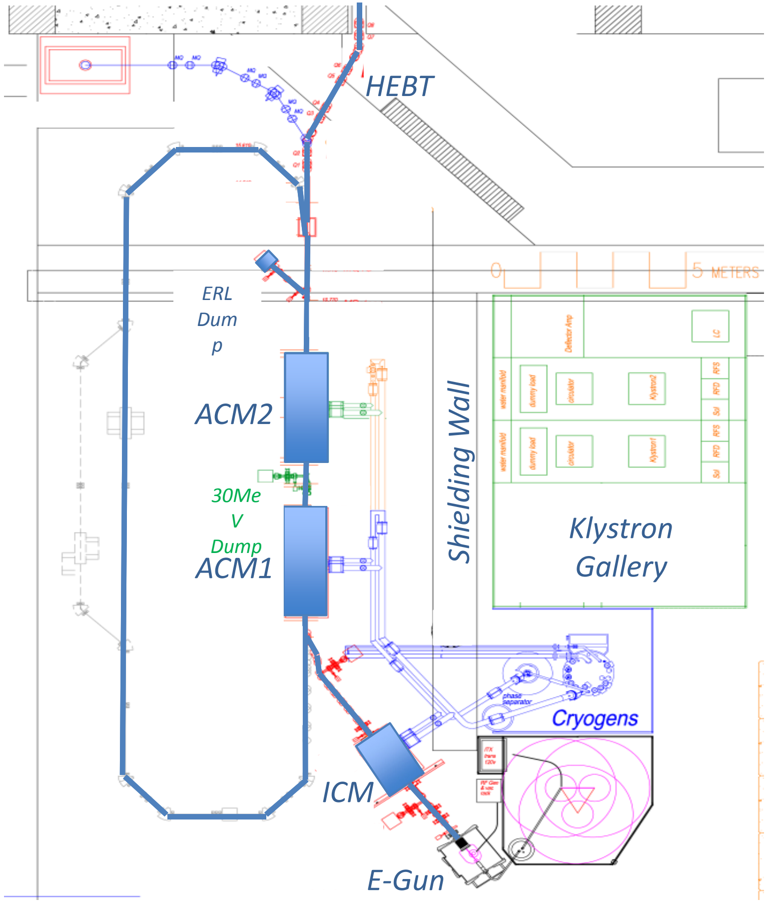


ACMduo – LLRF – Self-Excited Loop (SEL)

- TRIUMF has a history of using self-excited loop for LLRF – one source per cavity
- In SEL mode there is no frequency seeking required as the SEL tracks the resonant frequency - π-mode is selected using a band pass filter and an adjustable delay line
- ACMduo – two cavities – two tuners – one source – stable SEL demonstrated in Vector Sum
- Each cavity is turned on and tuned separately with SEL then combined in a single loop
- Developing Adaptive Feed Forward for compensation of beam loading in when beam is pulsed



e-Linac with re-circulation



Beyond 2020 – proposing a ring to operate as a recirculating linac (RLA) (energy doubler) or as an energy recovery linac (ERL) for accelerator studies and applications

RLA applications:

- Increase energy for RIB production

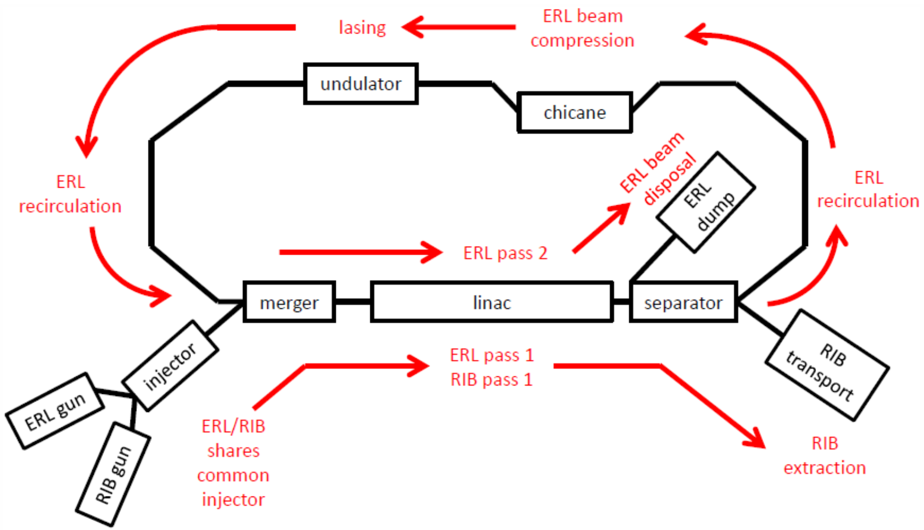
ERL Applications:

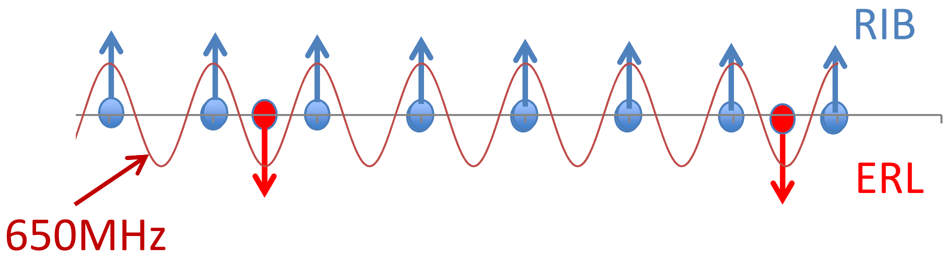
- Infra-red and Ultra-violet Free Electron Lasers
- Intense THz radiation source (FEL and/or Coherent Synchrotron Radiation (CSR))
- Compton backscattering source of X-rays

Overview of Dual Use ERL/Linac

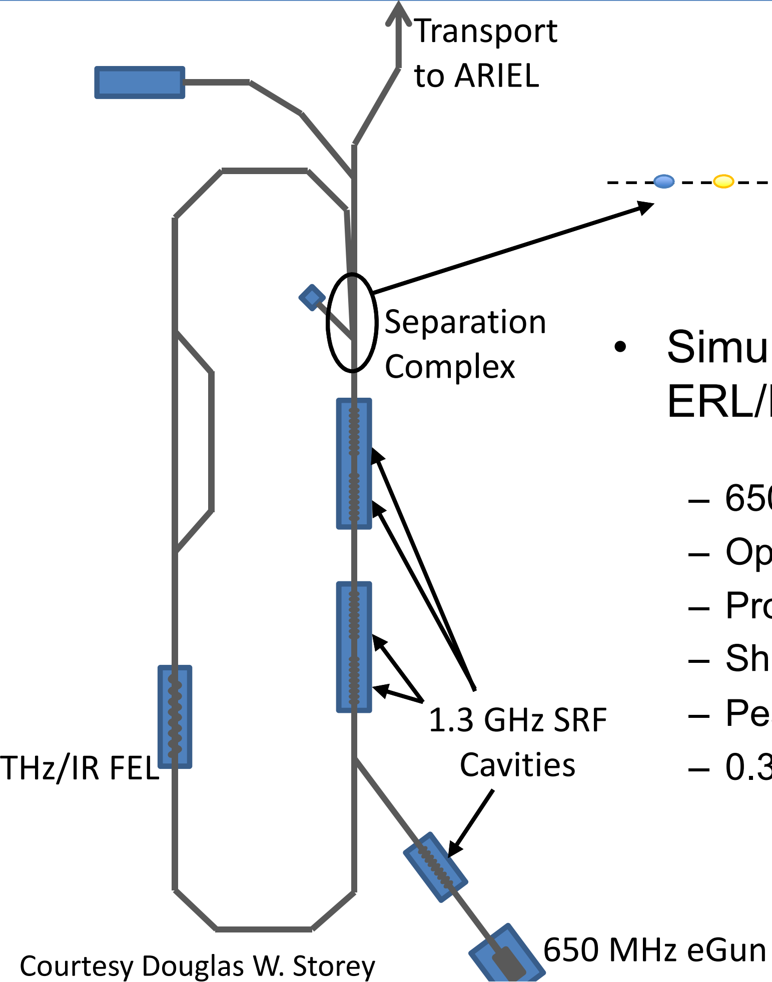
ERL

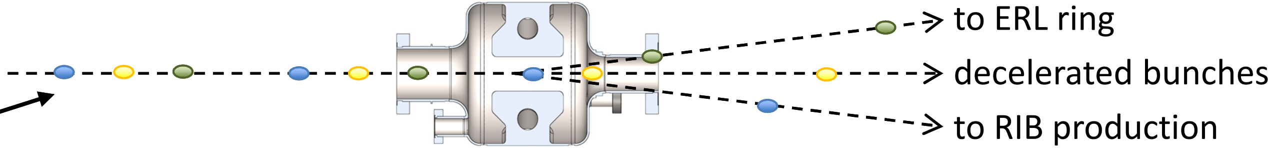
- Dual-use possible with two interleaved bunch trains into 1.3GHz buckets
- 650MHz pulse train - single pass acceleration for RIB production – low brightness
- 650MHz/n pulse train for ERL – high brightness
- 650MHz rf separator used to separate the beams



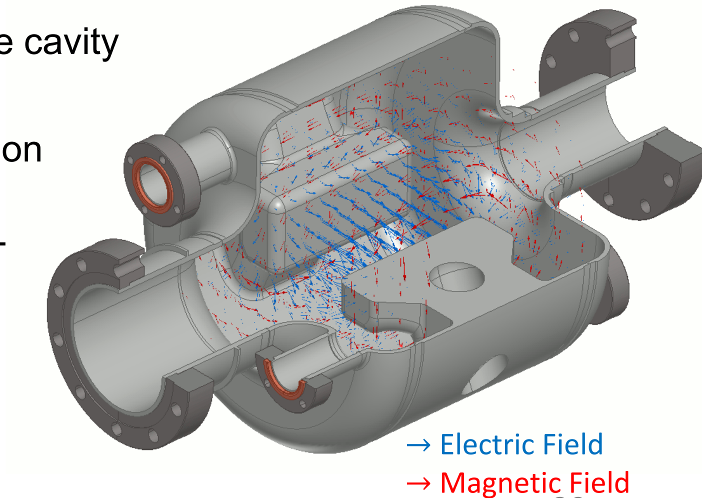


RF Separation of Interleaved Beams





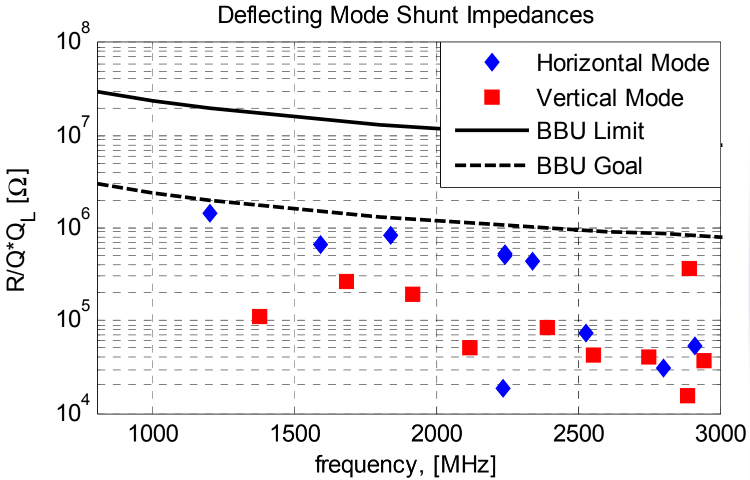
- Simultaneous beam delivery to both RIB production and an ERL/FEL requires RF separation of interleaved bunches
  - 650 MHz SRF deflecting mode cavity
  - Operates at 4 K
  - Provides 0.3 – 0.6 MV deflection
  - Shunt impedance of 625 Ω
  - Peak fields < 10 MV/m, 12 mT
  - 0.35 W power dissipation



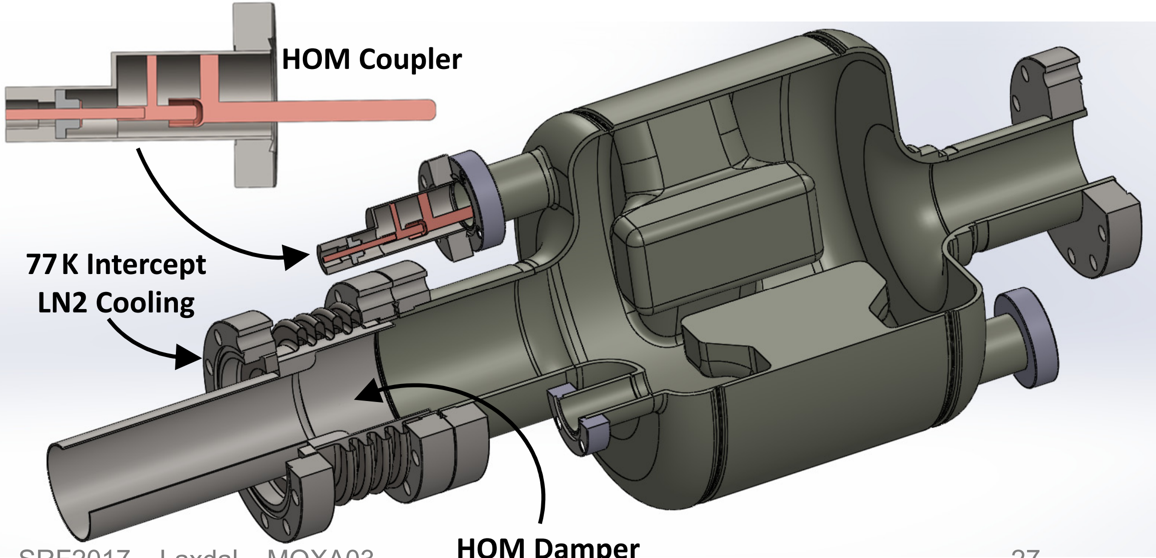
HOM Damping Strategy

- Damping of Higher Order Modes is important due to high current CW beam
- Two types of HOM dampers used:
  - HOM Coupler: antenna with 650 MHz filter
  - HOM Damper: resistive coaxial beam pipe insert, cooled by LN2
- Modes damped to below goal imposed by multi-pass Beam Break-Up

Cu model

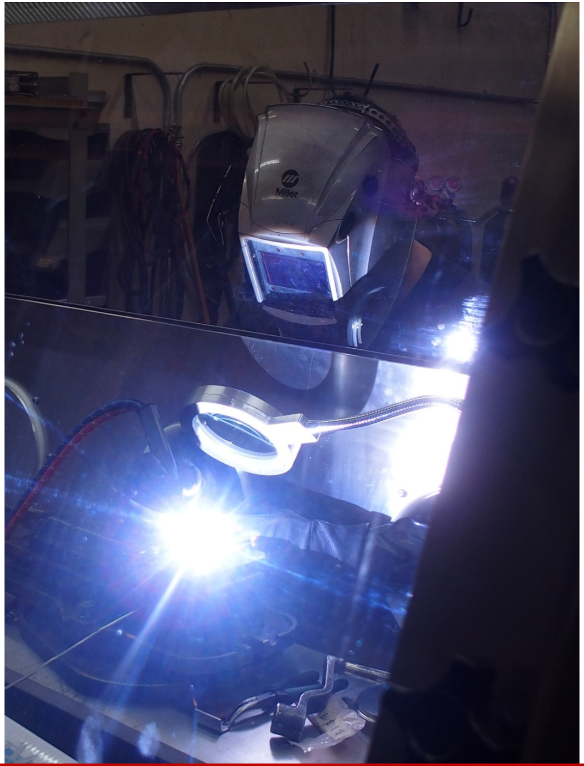


Courtesy Douglas W. Storey



Fabrication of Separator Cavity

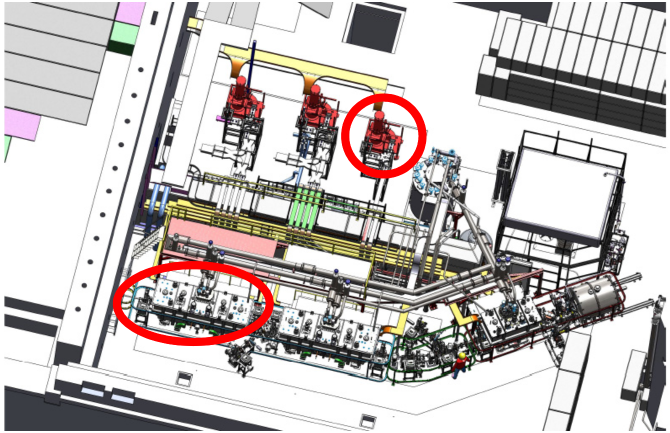
- Due to low performance specs, fabrication methods include some alternative techniques:
  - Machining from bulk *reactor grade* Niobium
    - RRR of 45 compared to usual ~300
  - Tungsten Inert Gas (TIG) welding
    - Developed as an alternative to electron beam welding

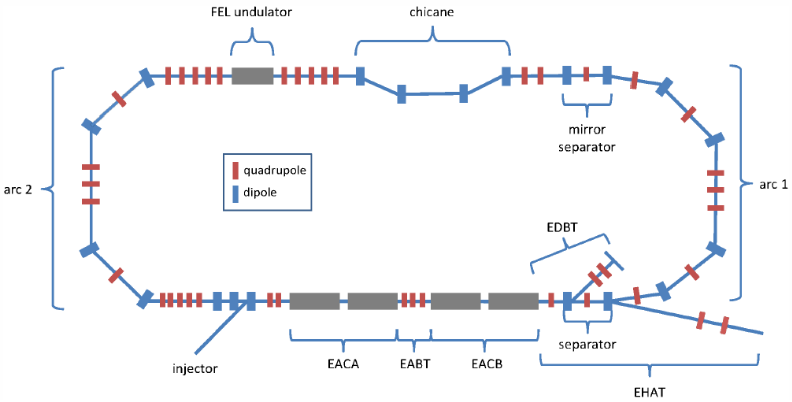


TUPB063 Fabrication and Test Results of a SRF Deflecting Cavity for the ARIEL eLinac – D.W. Storey

Courtesy Douglas W. Storey

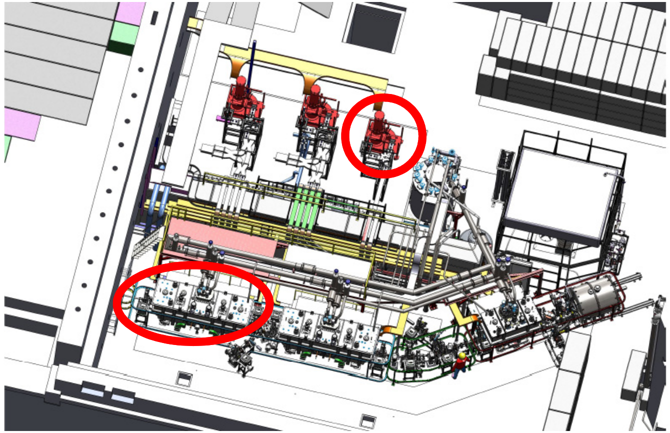
- E-Linac first operation
  - Commission linac at 30-35MeV (summer of 2017)
  - Ramp power to 10kW – 2018
  - First beam on ARIEL target 2019
- TRIUMF is now in the planning phase for the next five year funding cycle starting in 2020
- Projects being discussed include a second accelerating module to complete the linac to the original specification and the addition of a circulation ring to enable ERL R&D and applications

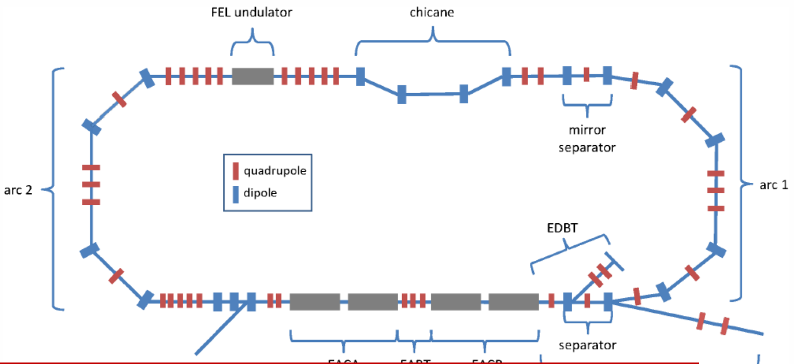




ARIEL e-Linac – Future

- E-Linac first operation
  - Commission linac at 30-35MeV (summer of 2017)
  - Ramp power to 10kW – 2018
  - First beam on ARIEL target 2019
- TRIUMF is now in the planning phase for the next five year funding cycle starting in 2020
- Projects being discussed include a second accelerating module to complete the linac to the original specification and the addition of a circulation ring to enable ERL R&D and applications





Wanted : SRF Post-doc – see me or apply on-line at TRIUMF Human Resources

Papers from TRIUMF at SRF2017

MOPB042 The TRIUMF/VECC Injector Cryomodule Performance – Y. Ma

MOPB105 Thermosyphon Cooling Loops for ARIEL Cryomodules – Y. Ma

TUPB063 Fabrication and Test Results of a SRF Deflecting Cavity for the ARIEL eLinac – D.W. Storey

TUPB064 Operating Experience on Cavity Performance of ISAC-II Superconducting Heavy Ion Linac, Z. Yao

TUPB065 Design of Multi-frequency Coaxial Test Resonators – Z. Yao

WEXA05 Dirty layers, Bi-layers and Multi-layers: Insights from Muon Spin Rotation Experiments – T. Junginger

THXA02 Fabrication and Testing of Balloon Single Spoke Resonator – Z. Yao

Clint Laforge – SRF Cryomodule Technician and long time TRIUMF colleague and friend passed away last week after a prolonged illness.

We are thinking of Clint today.

Canada’s national laboratory for particle and nuclear physics and accelerator-based science

Thank you!
Merci!

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

Follow us at TRIUMFLab