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

ERL Upgrade Plans for the ARIEL e-Linac

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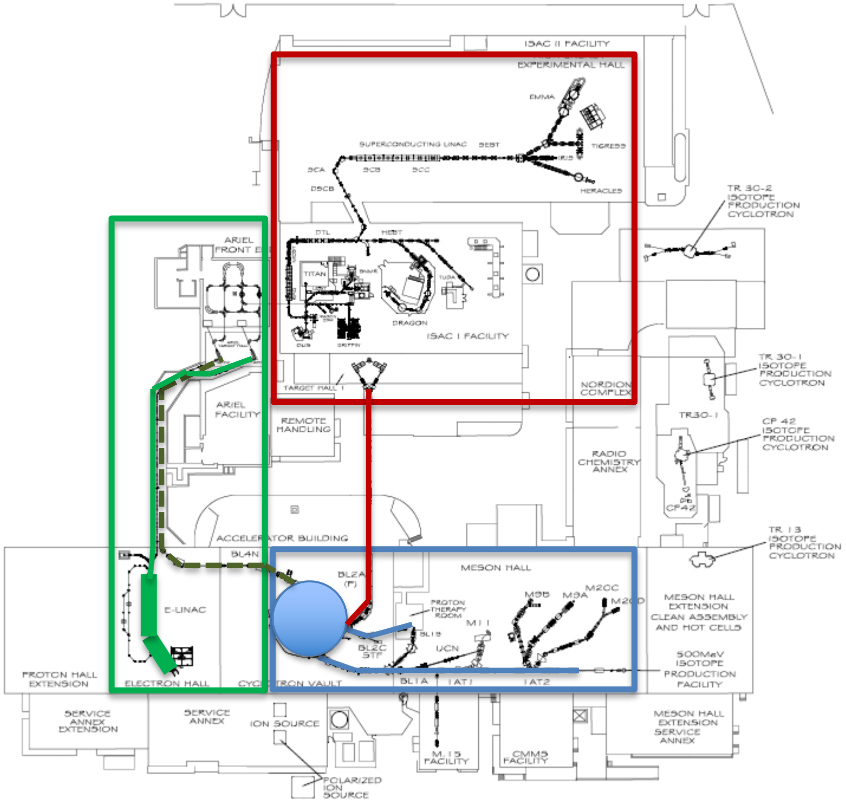
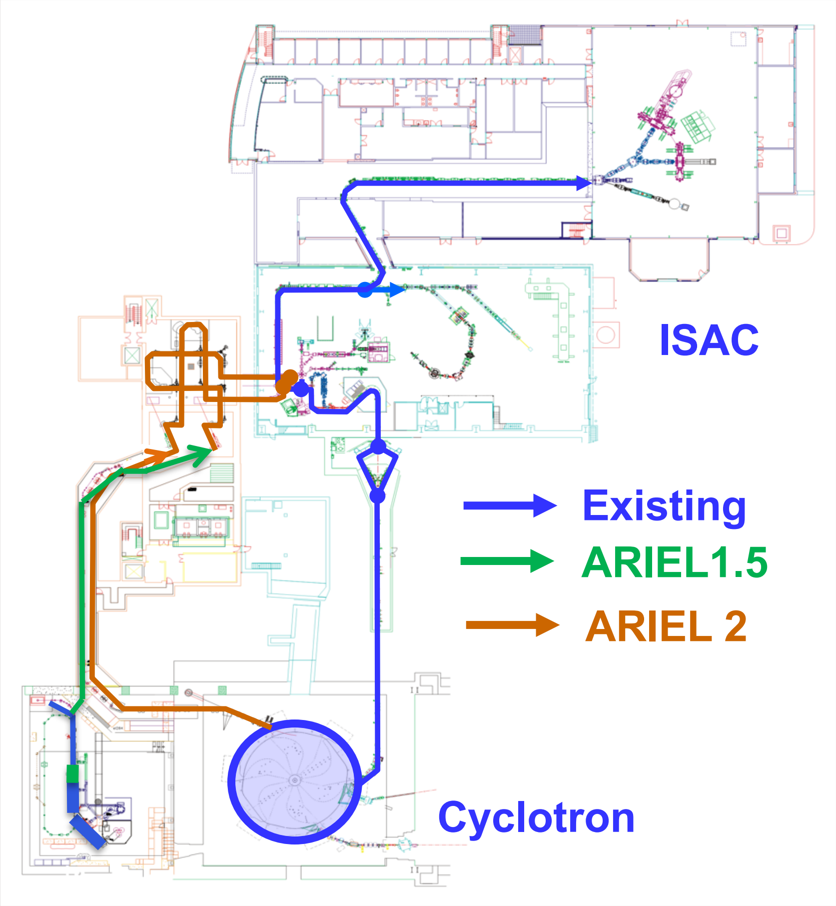
Contribution THICCC004

TRIUMF – in stages

- 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



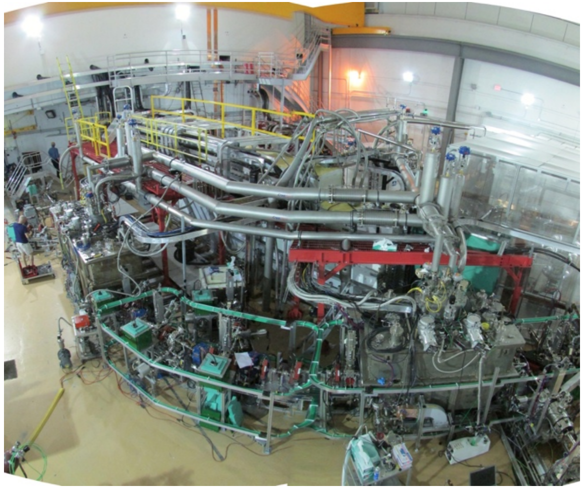
Advanced Rare IsotopE Laboratory - staging

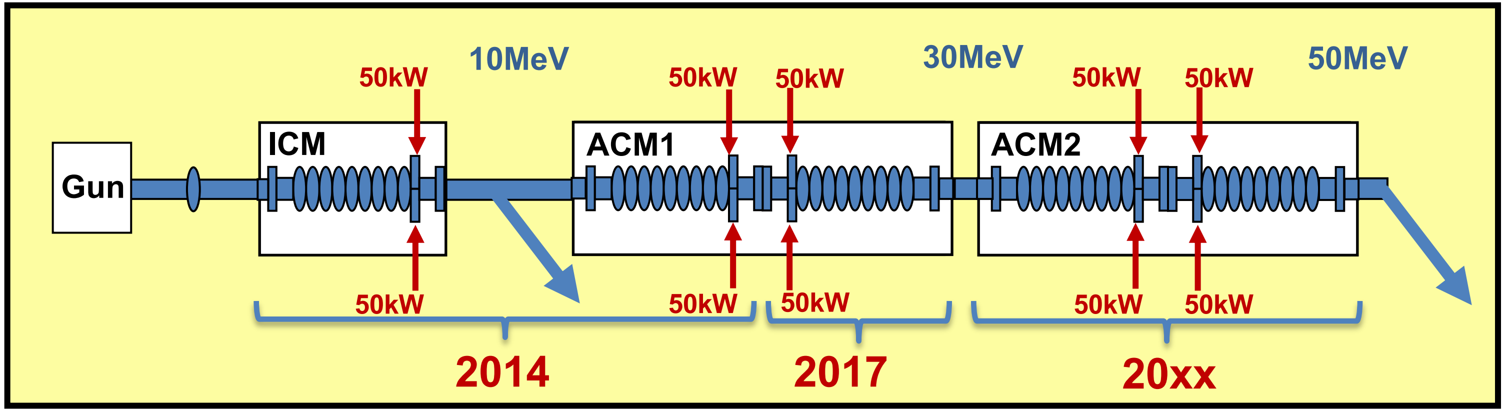


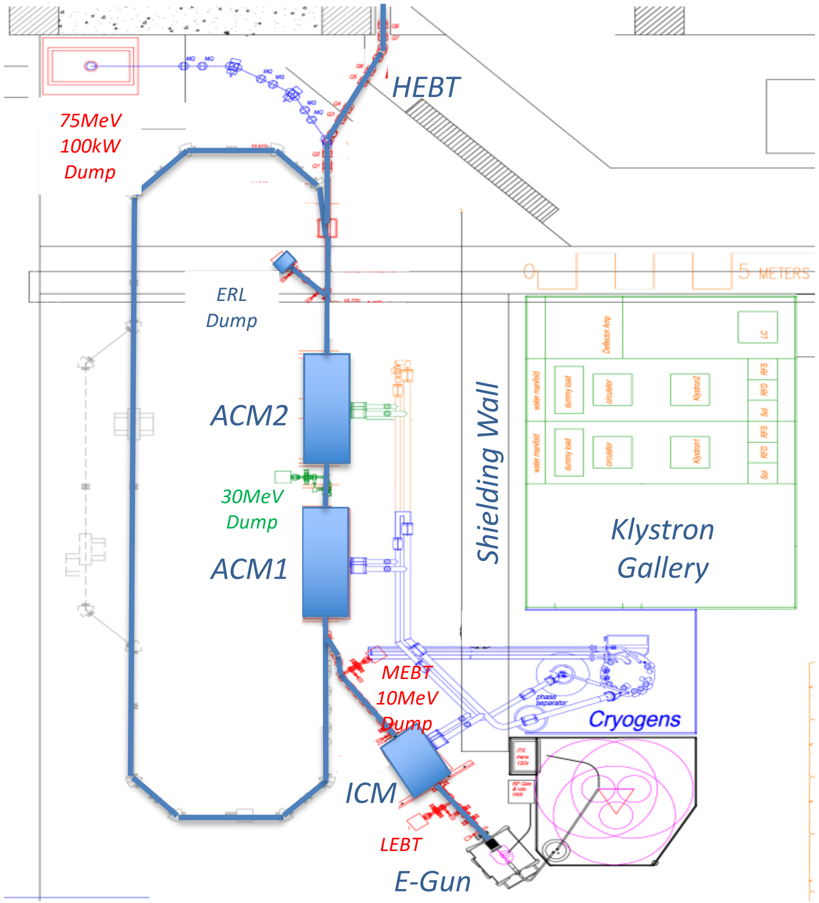
- ARIEL will triple the lab's RIB production by adding two new target stations resulting in up to three simultaneous ion beams
- ARIEL is staged
  - ARIEL-I
    - E-Linac demonstration at 23MeV (2 cavities) - 2014
  - ARIEL1.5
    - Complete e-Linac to 30-35MeV – third rf cavity added – 2017
    - Complete 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 (10mA)

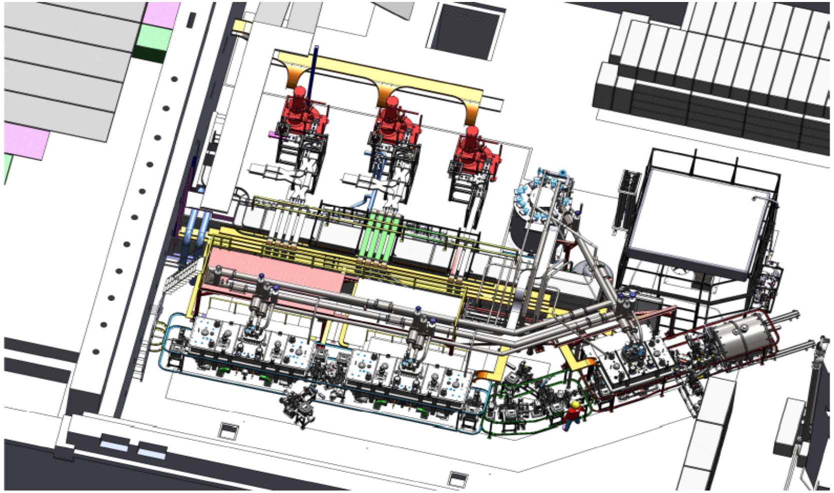
- Base-line design - five nine-cell cavities housed in three cryomodules – each cavity adds 10MeV (100kW)
- 23 MeV demonstrated from two cavities in 2014
- Install 30MeV capability in mid 2017 – in commissioning - ramp to 100kW in 2018
- 50MeV (10mA) capability foreseen pending funding (500kW)
- Bunch structure – 650MHz – macro-pulse established with e-gun rf – rep-rate is selectable from 0.1% to 100%



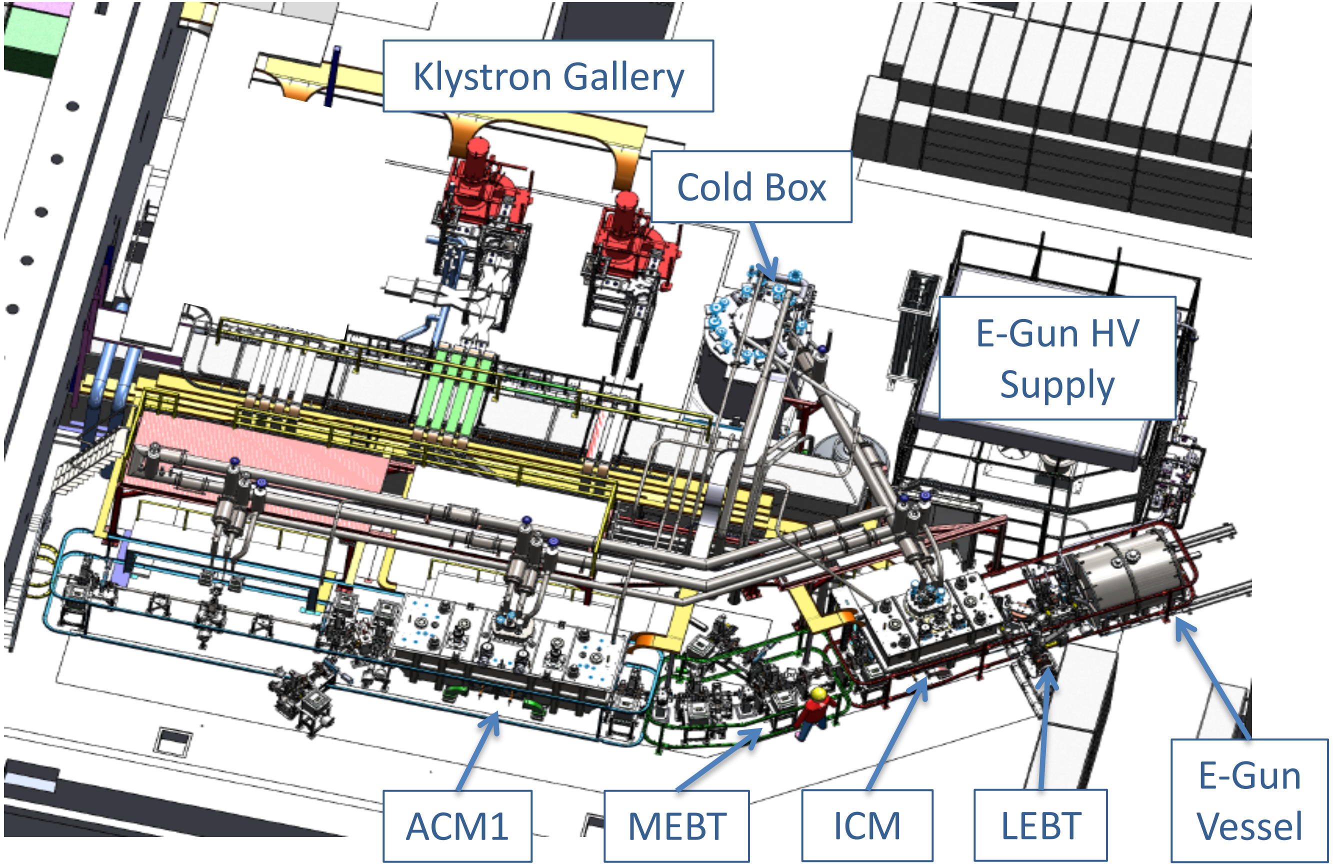




The linac is configured to allow a recirculating linac (RLA) for a multi-pass `energy doubler' mode or to operate as an energy recovery linac (ERL) for accelerator studies and applications



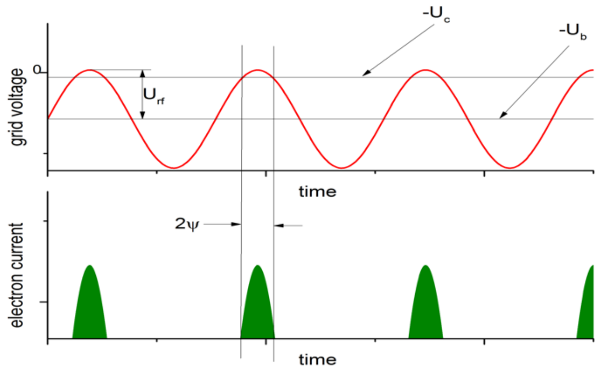
Accelerator Vault – existing configuration



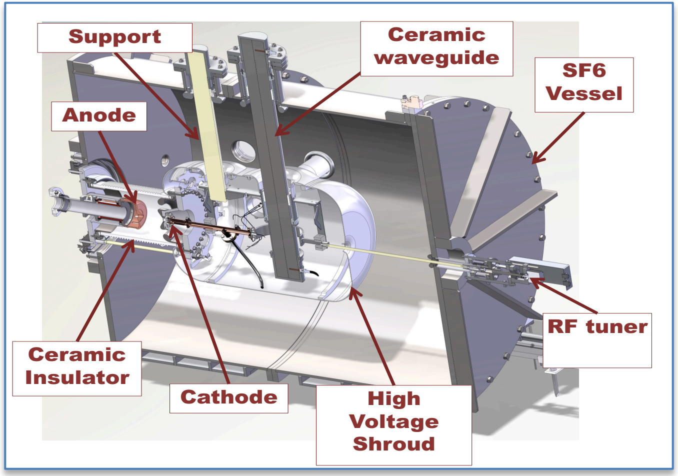
e-Linac Design and Status

Electron Gun

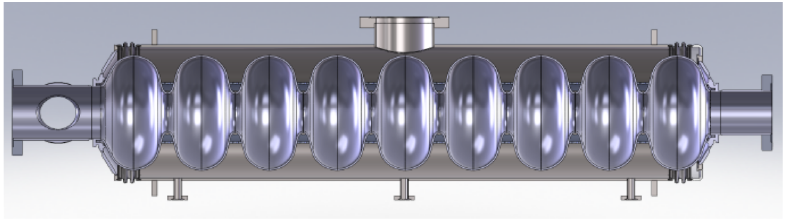
- Thermionic 300kV DC gun – cathode has a grid with DC supressing voltage and rf modulation that produces electron bunches at 650MHz
- Gun installed inside an SF6 vessel
- Rf delivered to the grid via a ceramic waveguide

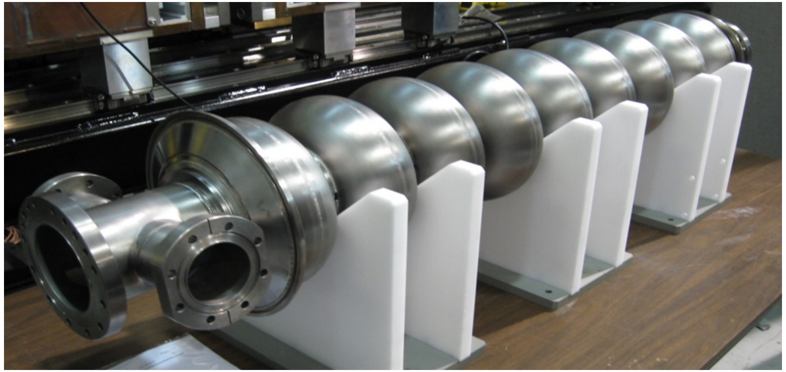


Parameter	Value
RF frequency	650MHz
Pulse length	$\pm 16^0$ (137ps)
Average current	10mA
Charge/bunch	15.4pC
Kinetic energy	300keV
Normalized emittance	5μm
Duty factor	0.01 to 100%



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



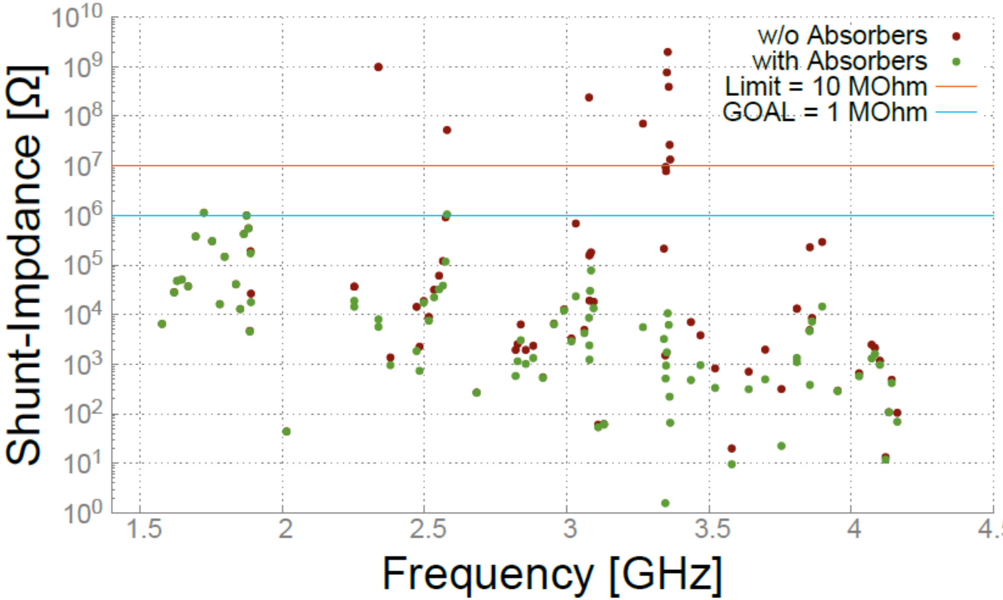


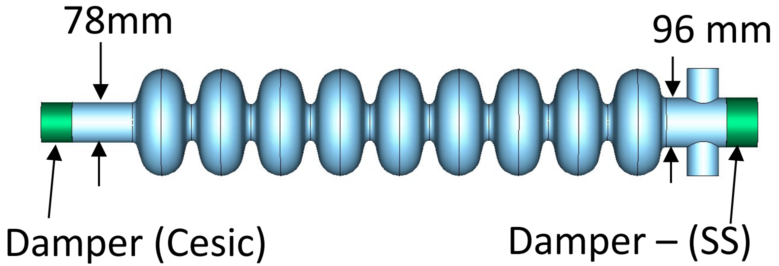
* P. Kolb, `The TRIUMF nine-cell SRF cavity for ARIEL', PhD thesis, University of British Columbia, DOI: 10.14288/1.0300057, April 2016.

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

HOM Damping

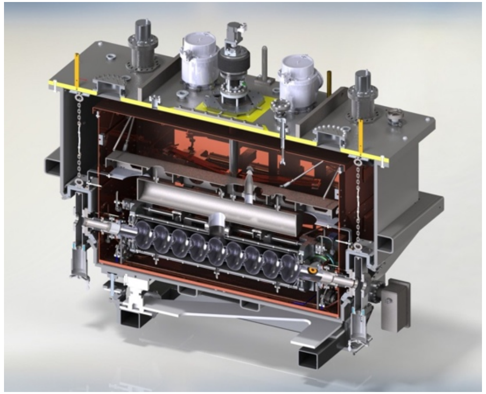
- To allow for a future ERL upgrade, BBU criteria set limits on the HOM dipole shunt impedance ($Rd/Q*Q_L$)
- Assuming a threshold current of 20 mA, beam dynamics calculations set a limit on dipole mode shunt impedance values of $Rd/Q*Q_L < 10^7\ \Omega$
- Estimation of fabrication errors combine to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





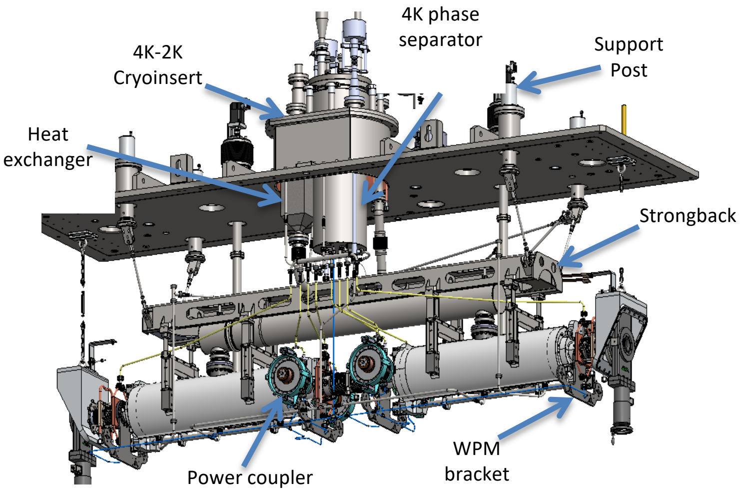
Houses

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



Features

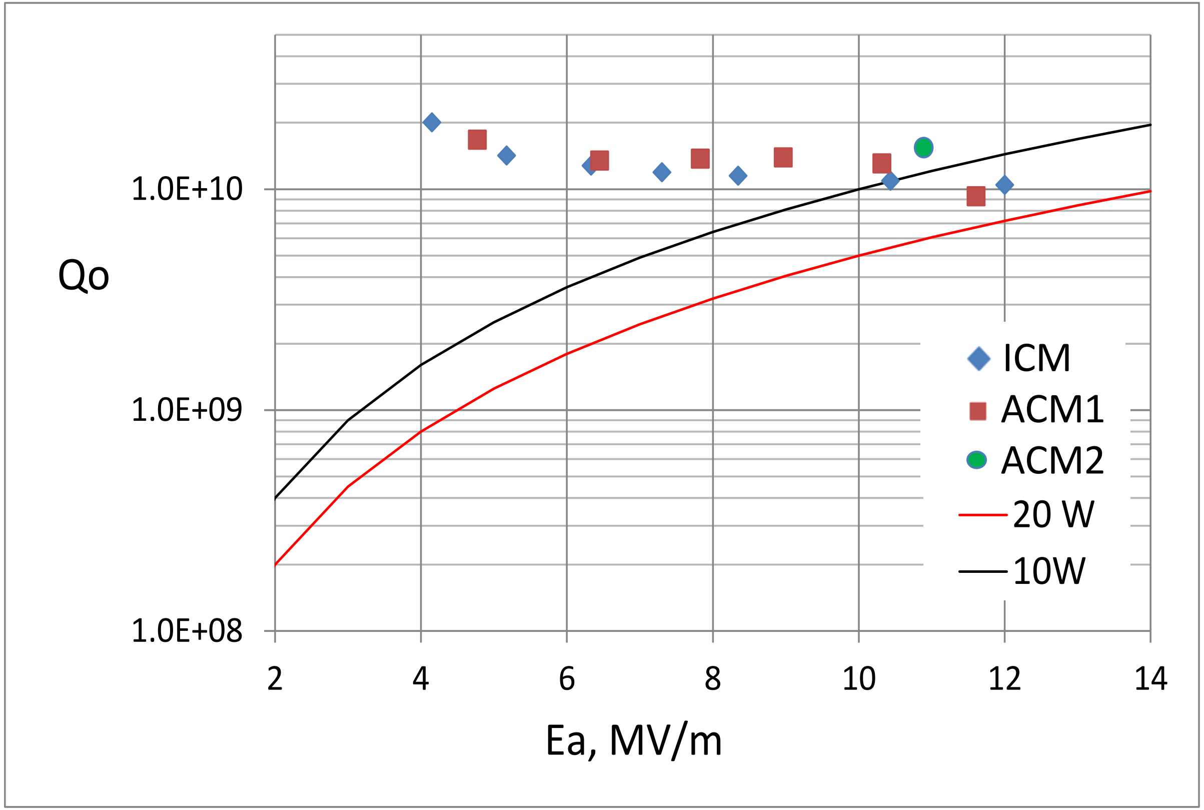
- 4K/2K heat exchanger with JT valve on board – allows standard 4K cold box
- scissor tuner with warm motor
- LN2 thermal shield – 4K thermal intercepts via syphon
- Two layers of mu-metal
- WPM alignment system



Cryomodule Cold test results

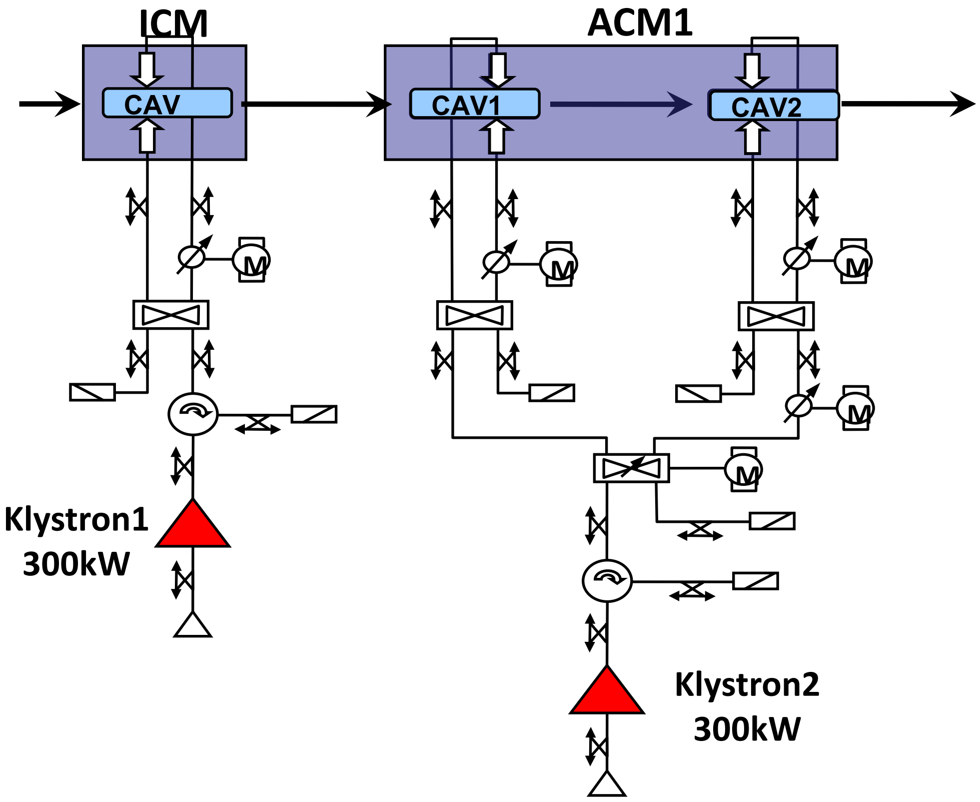
Parameter	ICM	ACM
4K static load	6.5	8.5
2K static load	5.5	11
77K static load	<130	<130
2K efficiency	86%	86%

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

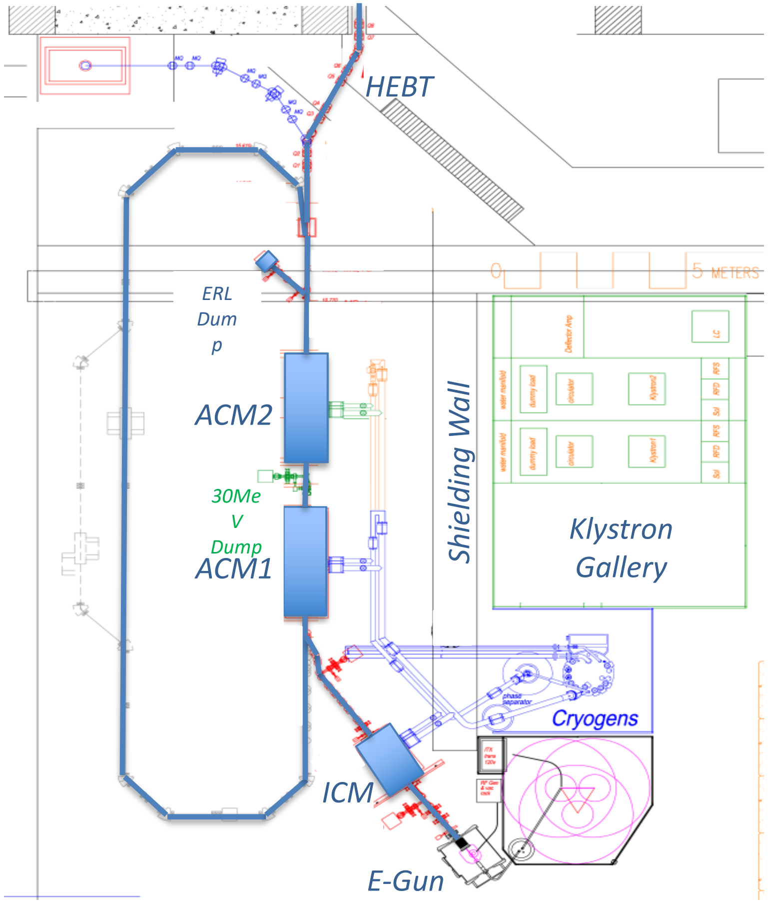


E-Linac RF Drive System

- There are two 300kW CPI klystrons – one for each cryomodule
- ACM1 – two cavities (two tuners) driven by one rf source in Vector Sum – stable operation demonstrated
- Each cavity turned on and tuned separately with SEL then combined in a single loop
- Working on Adaptive Feed Forward for compensation of beam loading in pulsed mode



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

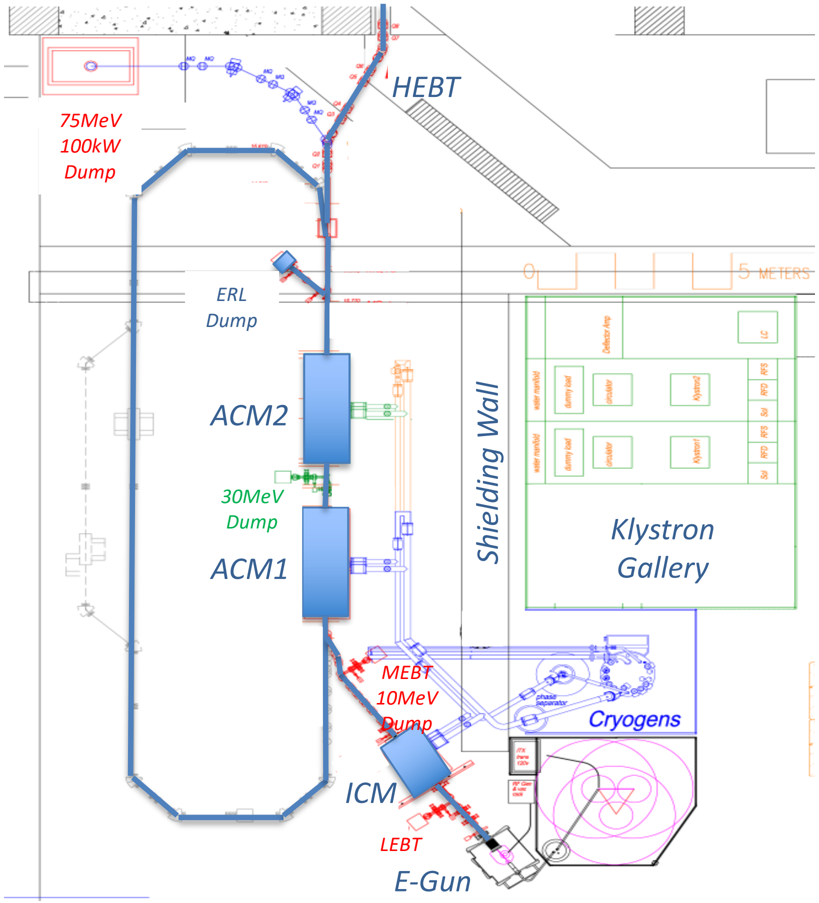
RLA applications:

- 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

Recirculating modes

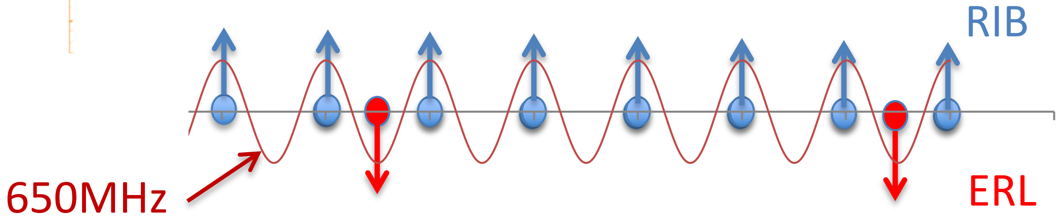


RLA

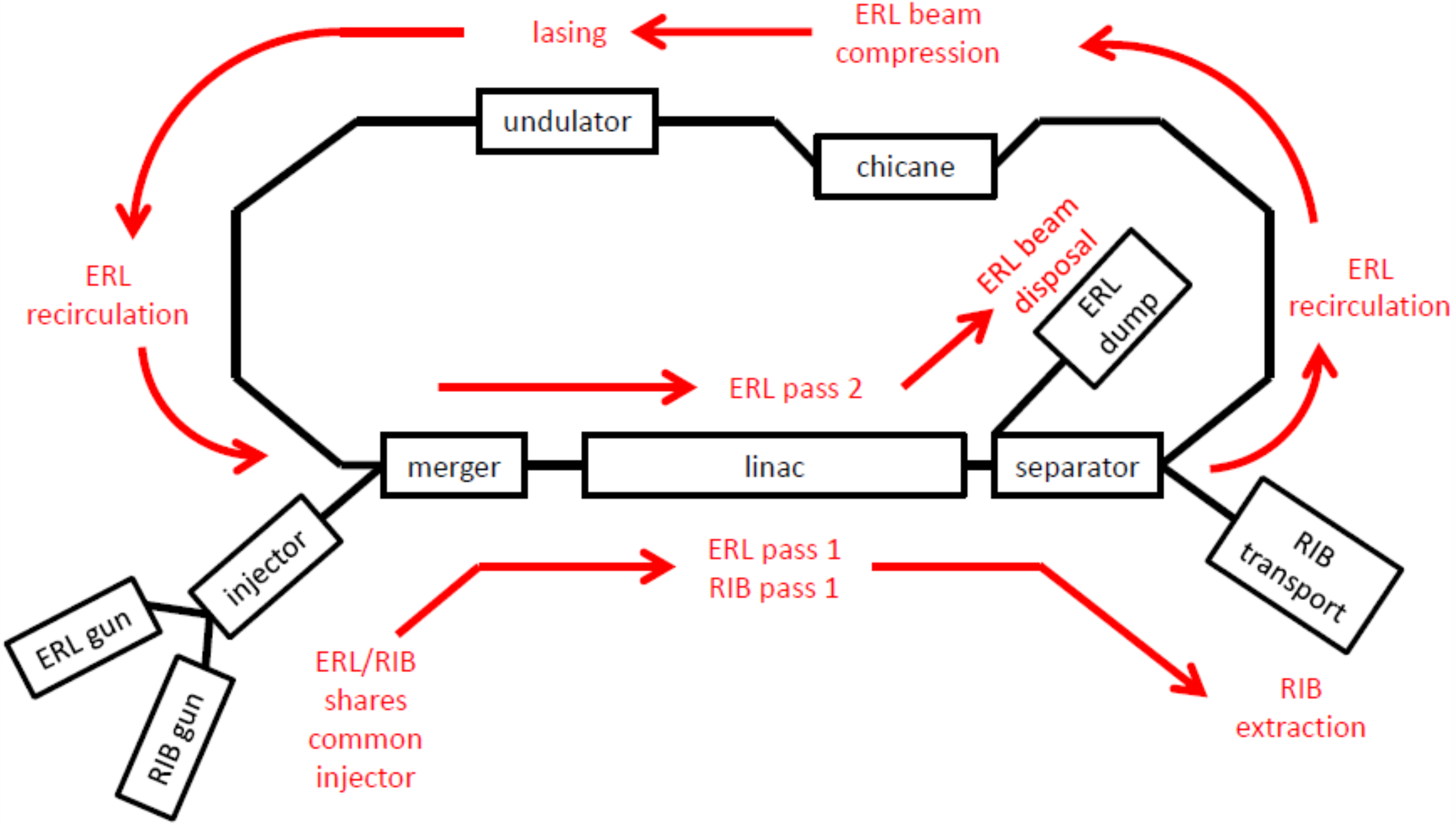
- Single user mode only
- Doubles beam loading so limits maximum beam intensity

ERL

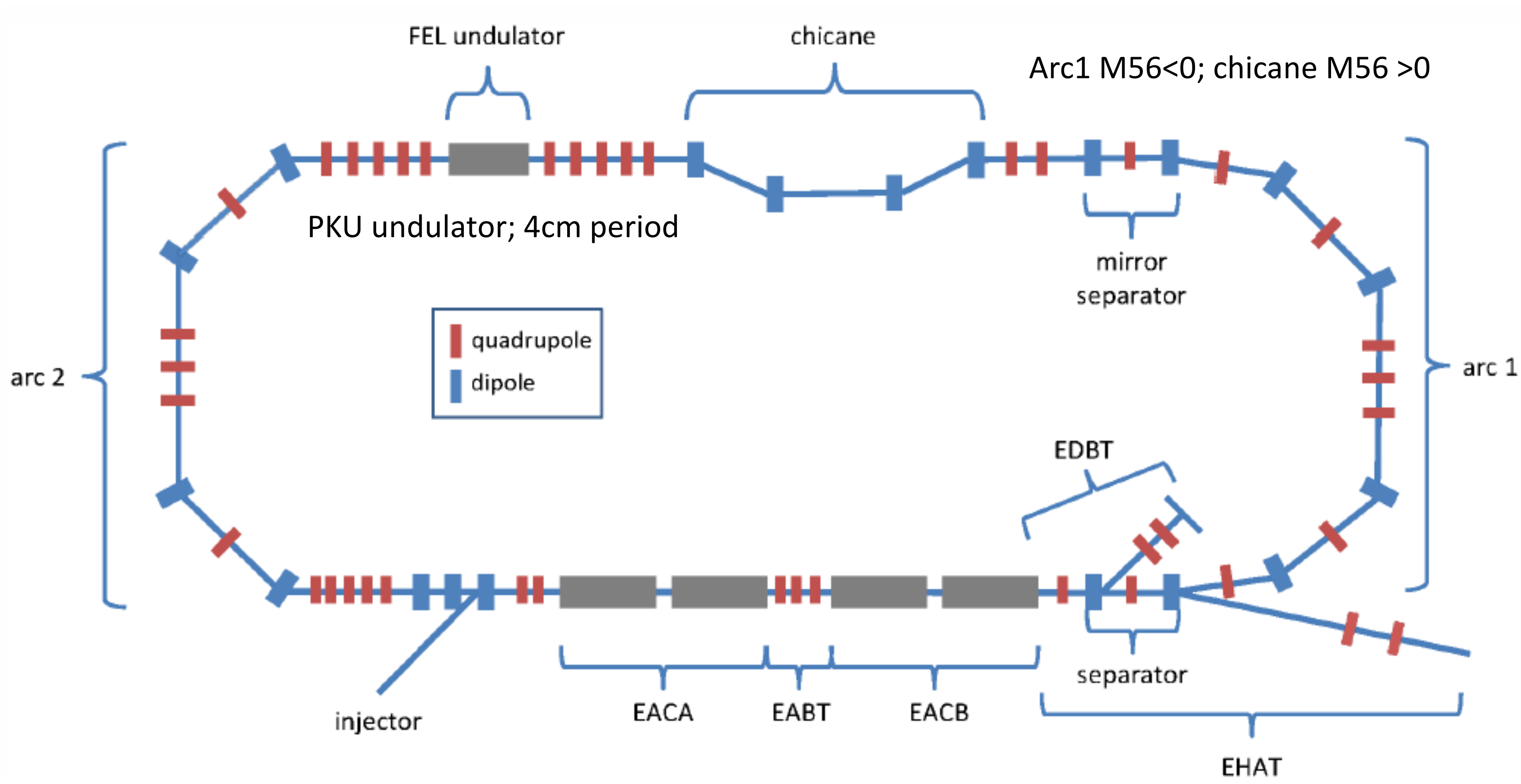
- Dual-use possible with two interleaved bunch trains into 1.3GHz buckets
- 650MHz pulse train - single pass acceleration for RIB production – low brightness
- 650MHz/n pulse train for ERL – high brightness
- 650MHz rf separator used to separate the beams



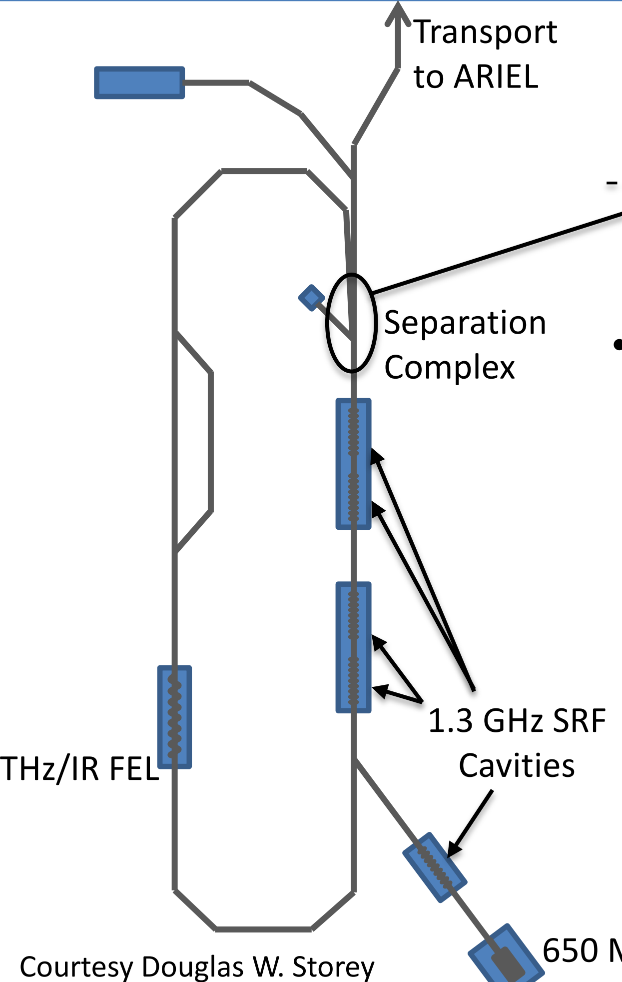
Overview of Dual Use ERL/Linac



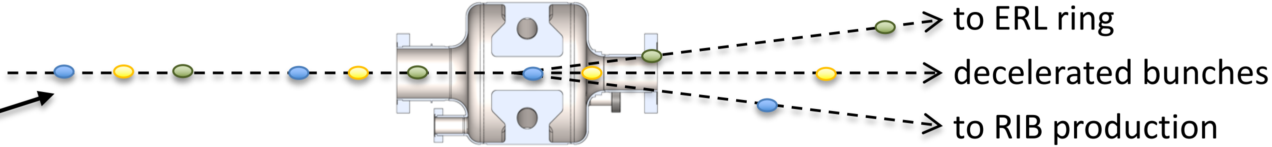
Initial ERL Layout (Chao, Gong)



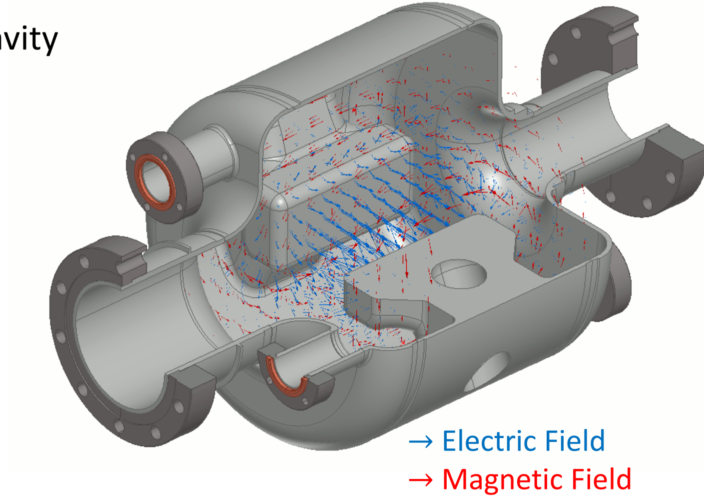
RF Separation of Interleaved Beams



Courtesy Douglas W. Storey

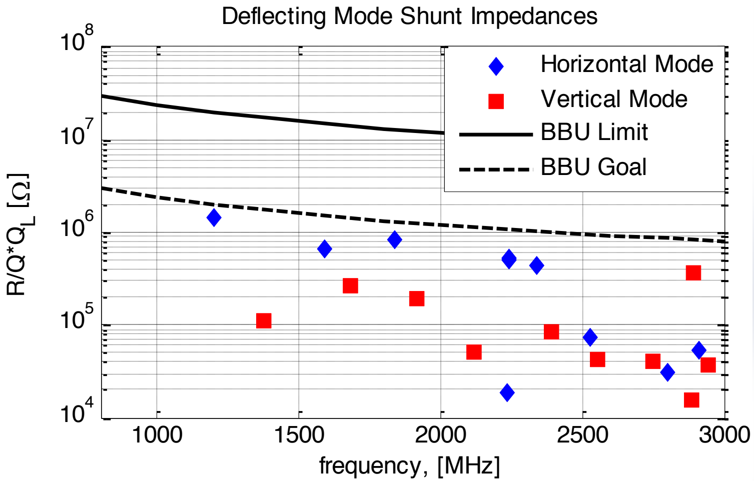


- Simultaneous beam delivery to both RIB production and an ERL/FEL requires RF separation of interleaved bunches
  - 650 MHz SRF deflecting mode cavity
  - Operates at 4 K
  - Provides 0.3 – 0.6 MV deflection
  - Shunt impedance of 625 Ω
  - Peak fields < 10 MV/m, 12 mT
  - 0.35 W power dissipation



- 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



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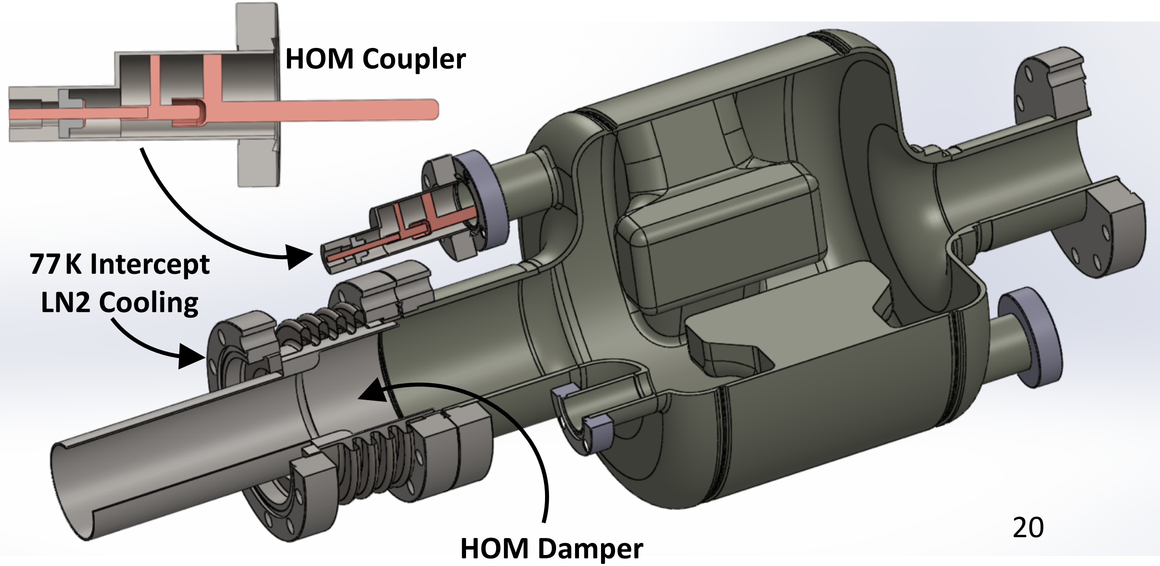
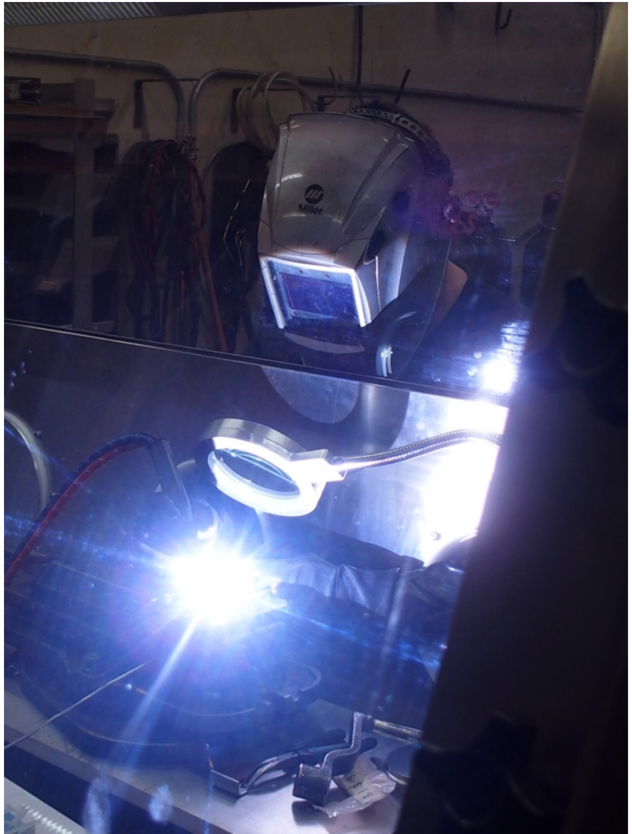


Fabrication of Separator Cavity

- 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



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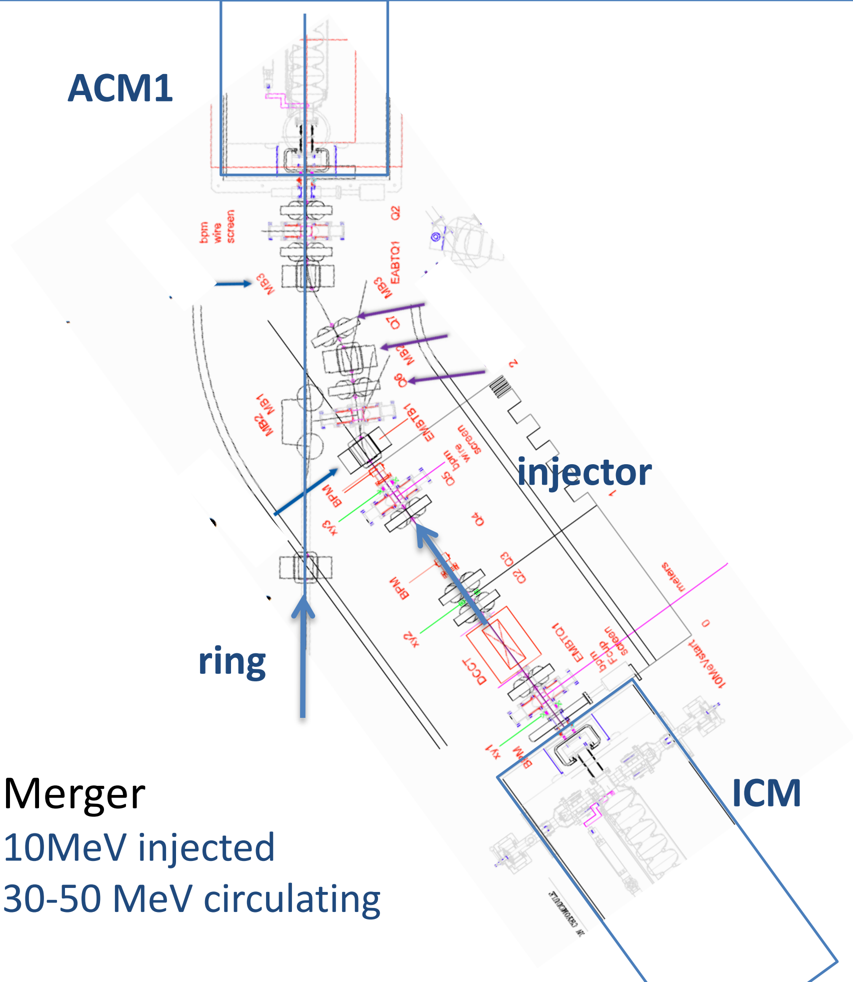
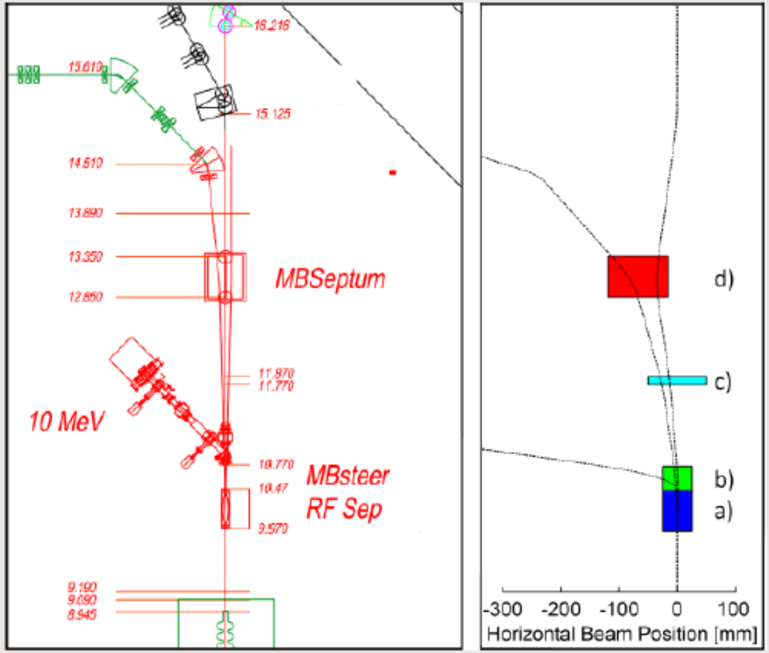
Merger and Separator Optics



Merger
10MeV injected
30-50 MeV circulating



a) RF separator cavity, b) dipole magnet, c) quadrupole, and d) septum

- THz radiation (0.3 to 20 THz), at the interface of electronics and photonics, is a frontier area for research in the physical sciences, biology, medicine.
- Accelerator-based THz sources with high peak and average power enable new applications.
- Two possibilities for linac-based THz sources:
    - Free Electron Lasers (FELs) => narrow-band THz
    - Coherent Synchrotron Radiation sources => broad-band THz
- **Require a high brightness photo-injector for the e-Linac**

IR FEL Parameters

Electron Beam Parameters		
Energy	MeV	30-50
RF frequency	GHz	1.3
Average current	mA	10
Charge per bunch	pC	77
Bunch rep freq.	MHz	130
Bunch length (rms)	ps	1
Energy spread (rms)	%	0.1
Output Light Parameters		
Wavelength range	µm	1-20
Micropulse energy	µJ	30
Laser power	kW	3-5

E-Linac as an X-ray Source via Compton Backscattering

Electron beam parameters

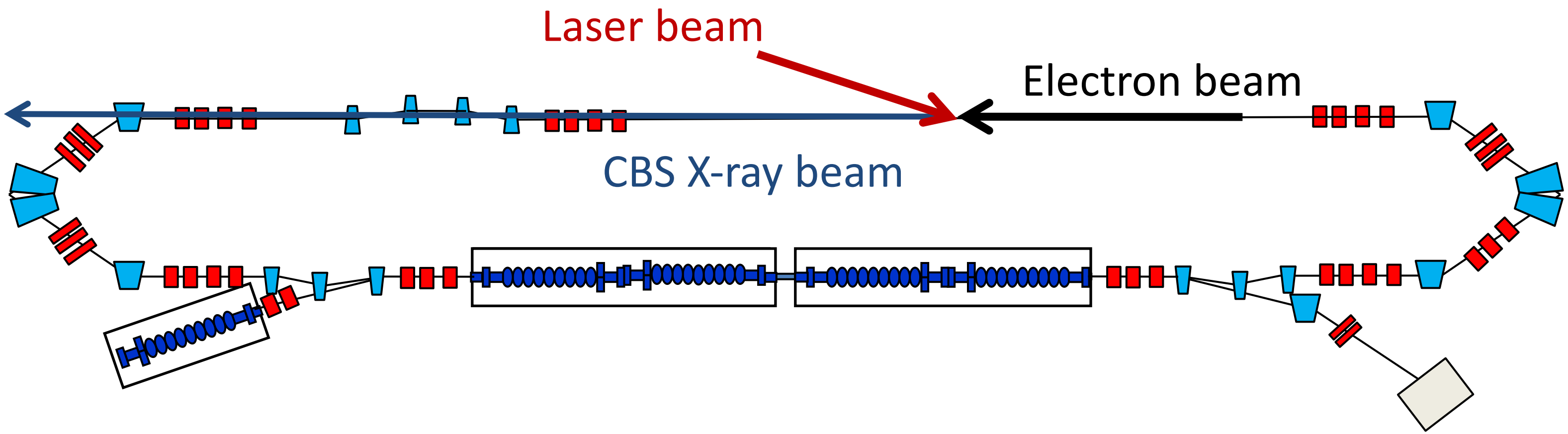
Energy 50 MeV
Beam current 13 mA
Bunch charge 100 pC
Norm. emittance (rms) 1 mm-mrad
Beam size 30 μm

Laser

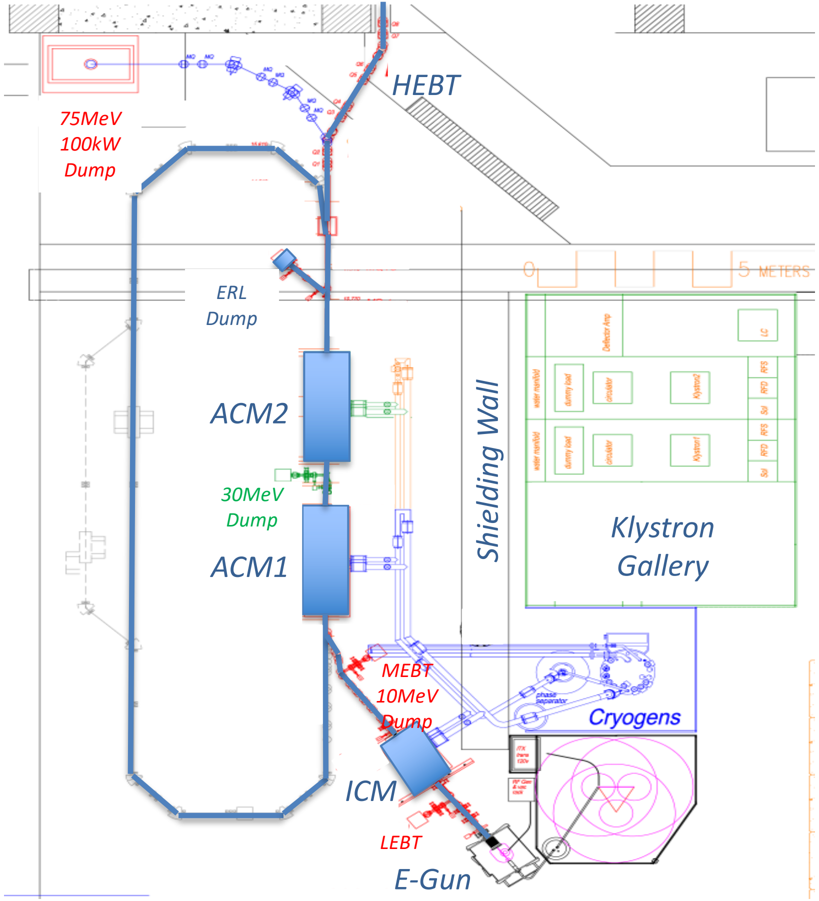
1.8 μJ, 1064 nm, 3 ps
Spot size 60 μm
Rep. rate 130 MHz
Cavity gain 3000

X-ray beam energy: E ~ 40 keV

X-ray flux: $N_X \sim 2.7 \times 10^{13}$ photons per second



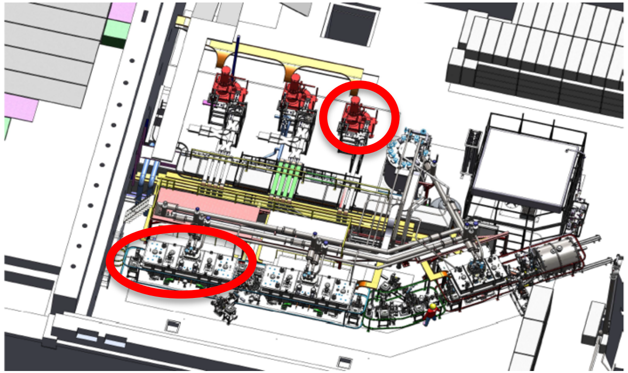
Required

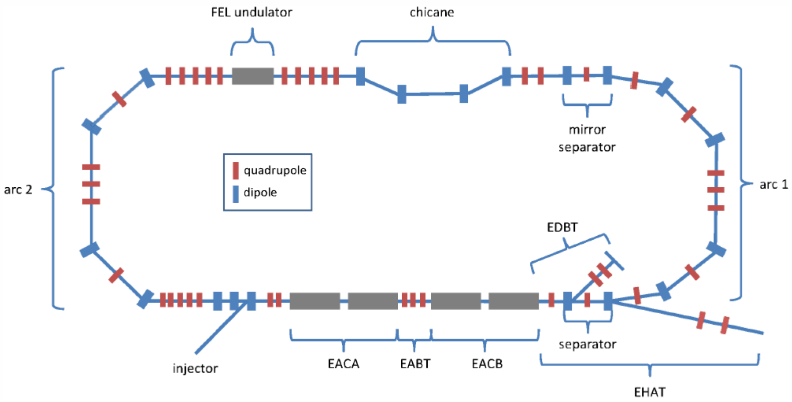


- ERL applications require a high brightness photo-gun – RIB production favours a low brightness beam
  - Will be difficult to find space for two guns
  - Can we produce low emittance and high emittance beams from the same gun
- Need to engage a user community to prioritize applications
- Need to optimize final parameter set – then detail budget and effort required

ARIEL e-Linac - Future

- E-Linac first operation
  - Commission linac at 30-35MeV (summer of 2017)
  - Ramp power to 100kW – 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





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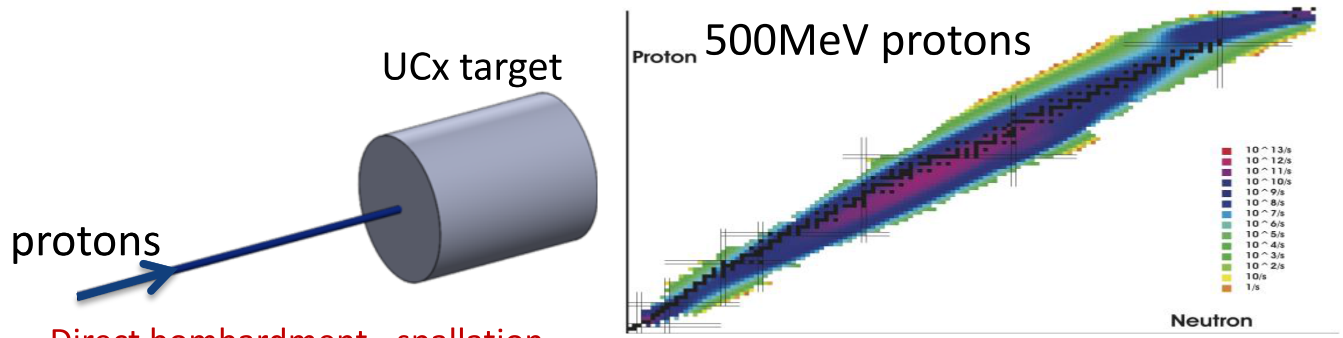
Electron vs proton driver

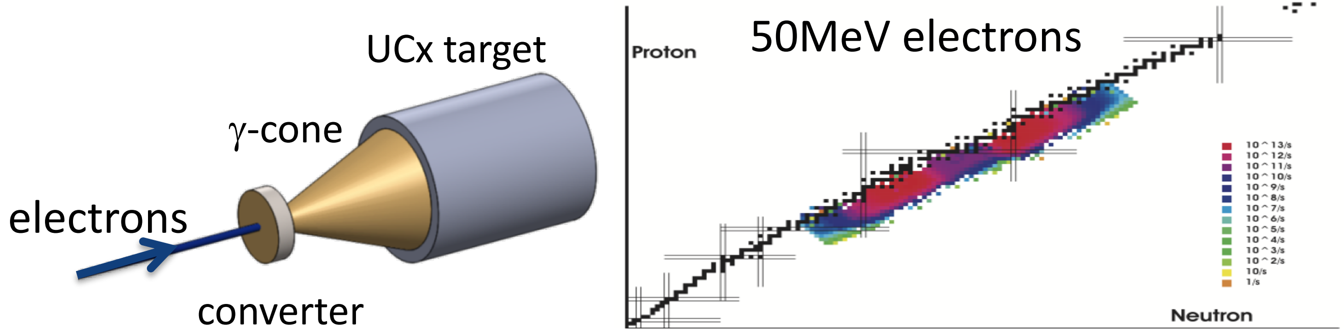
The electron linac driver complements the existing proton cyclotron driver

- Photofission yields high production of many neutron rich species with less isobaric contamination than spallation
- An energy of 50MeV is sufficient to saturate photo-fission production
- Electron photofission is used at ALTO (IPN Orsay) - much lower intensity – ARIEL is cutting edge



Direct bombardment - spallation, fragmentation, fission products

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



γ-cone produced in converter irradiates UCx target – fission products

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

Ring and Linac