Case study: The Super-conducting ARIEL electron linac at TRIUMF

Oliver Kester

Director, Accelerator Division

IAS Saskatoon

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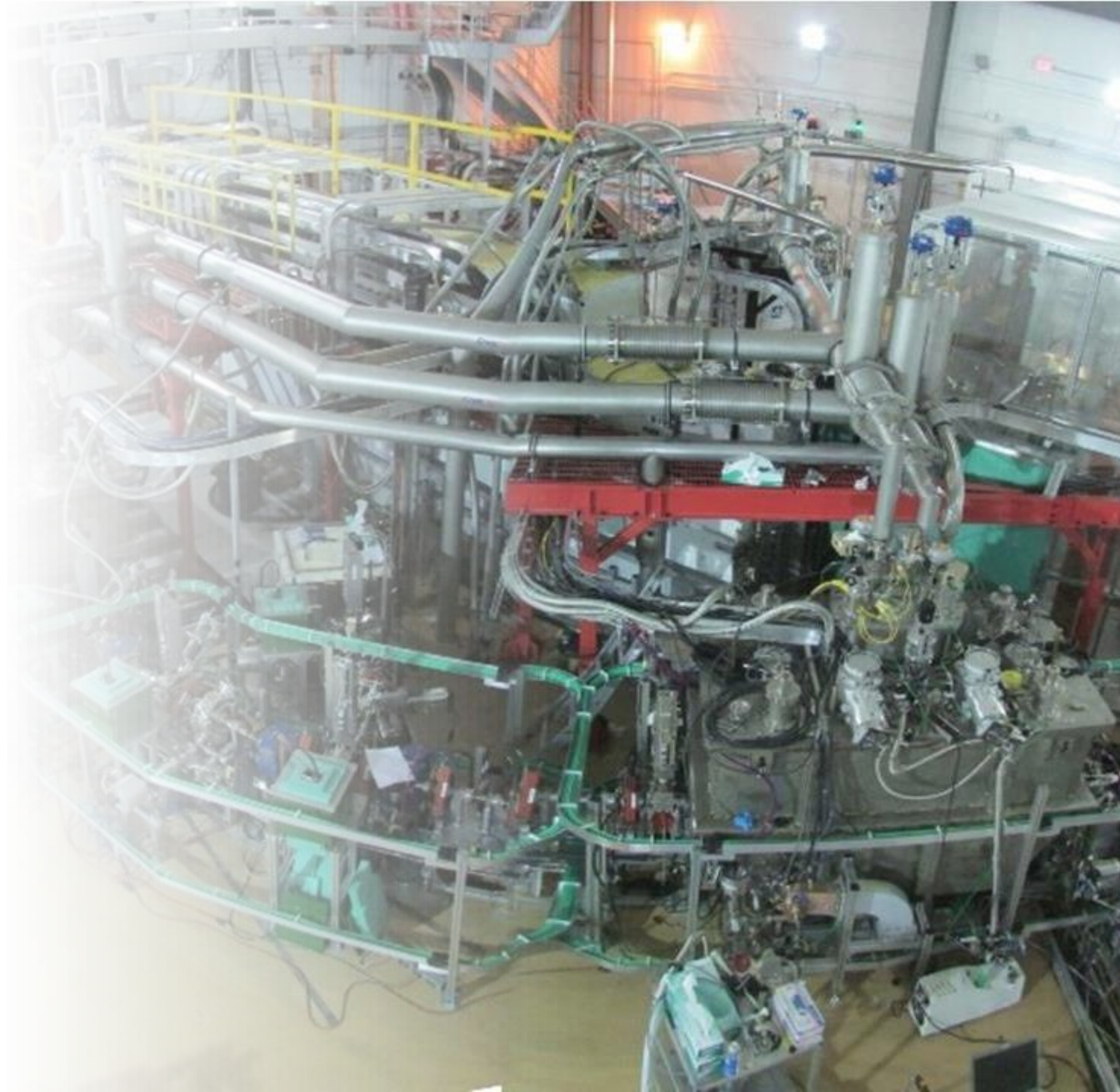
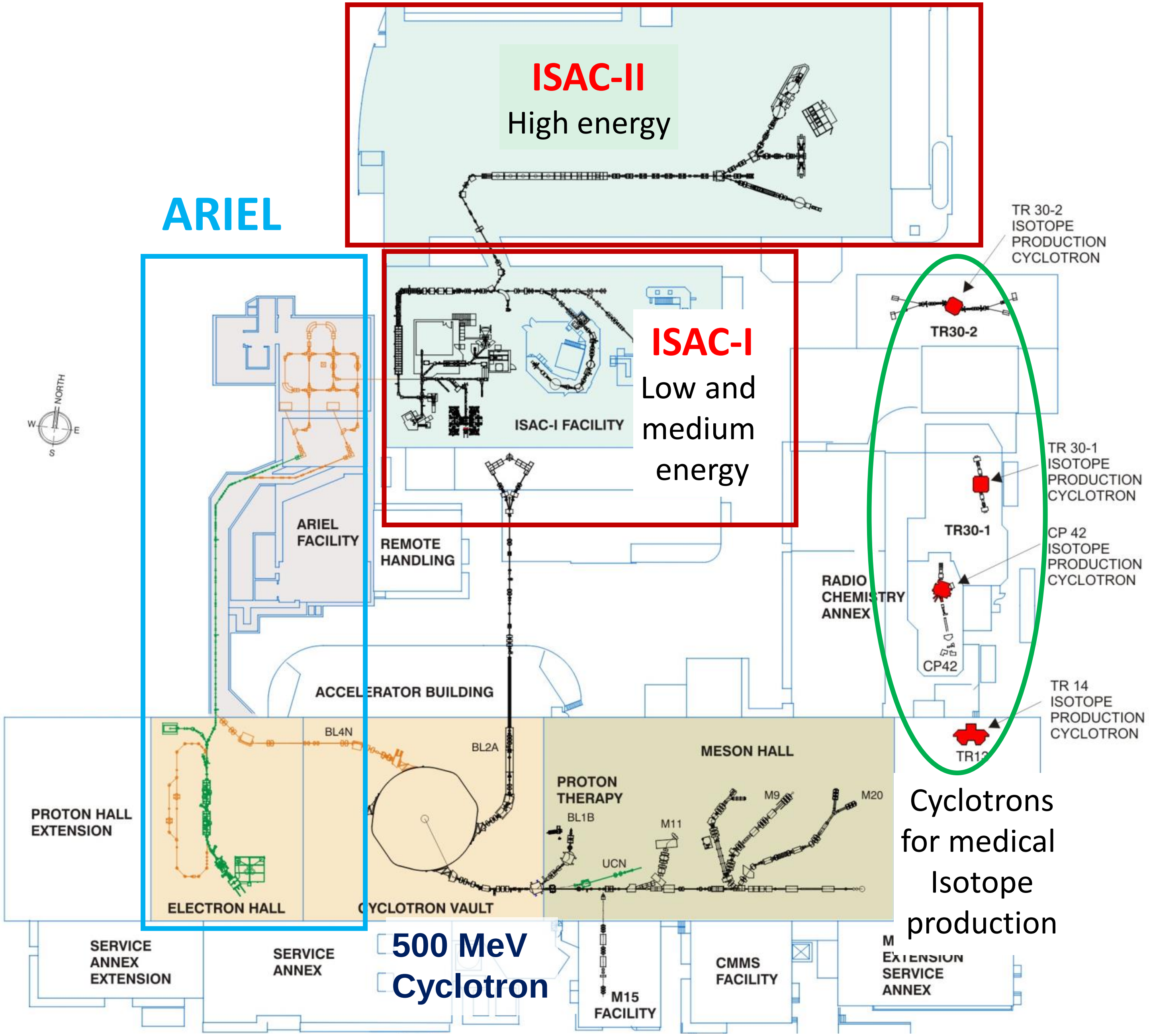
Outline

- Overview: The TRIUMF accelerator complex
- Production of rare isotopes with beam from the e-linac
- The TRIUMF superconducting ARIEL electron linac (e-linac)
- e-linac operation and future perspectives



TRIUMF accelerator complex



Primary beam driver:

Cyclotron, 520 MeV, H^-

Produces rare isotopes, neutrons and muons!

Isotope Separator and Accelerator facility - ISAC

Isotope Separator Online (ISOL) facility

ISAC-I: Normal conducting-linac, 0.15-1.5 MeV/u

ISAC-II: Superconducting-linac, 5-15 MeV/u

Advanced Rare Isotope Laboratory - ARIEL

Superconducting electron linac

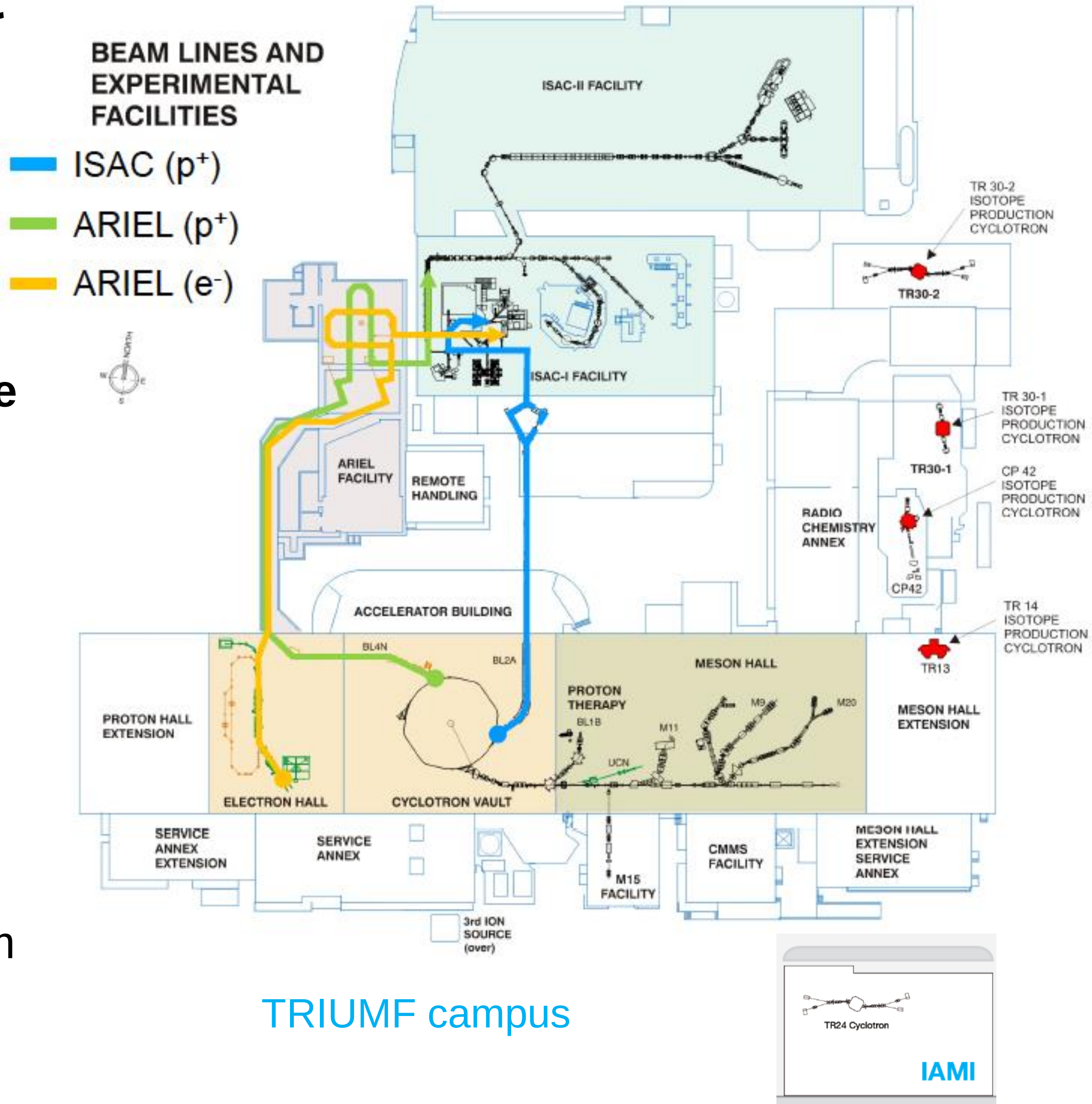
30 MeV, 10 mA, cw

4 Cyclotrons for medical isotope production

(Soon a 5th cyclotron a TR24 in the Institute for advanced Medical Isotope – IAMI)

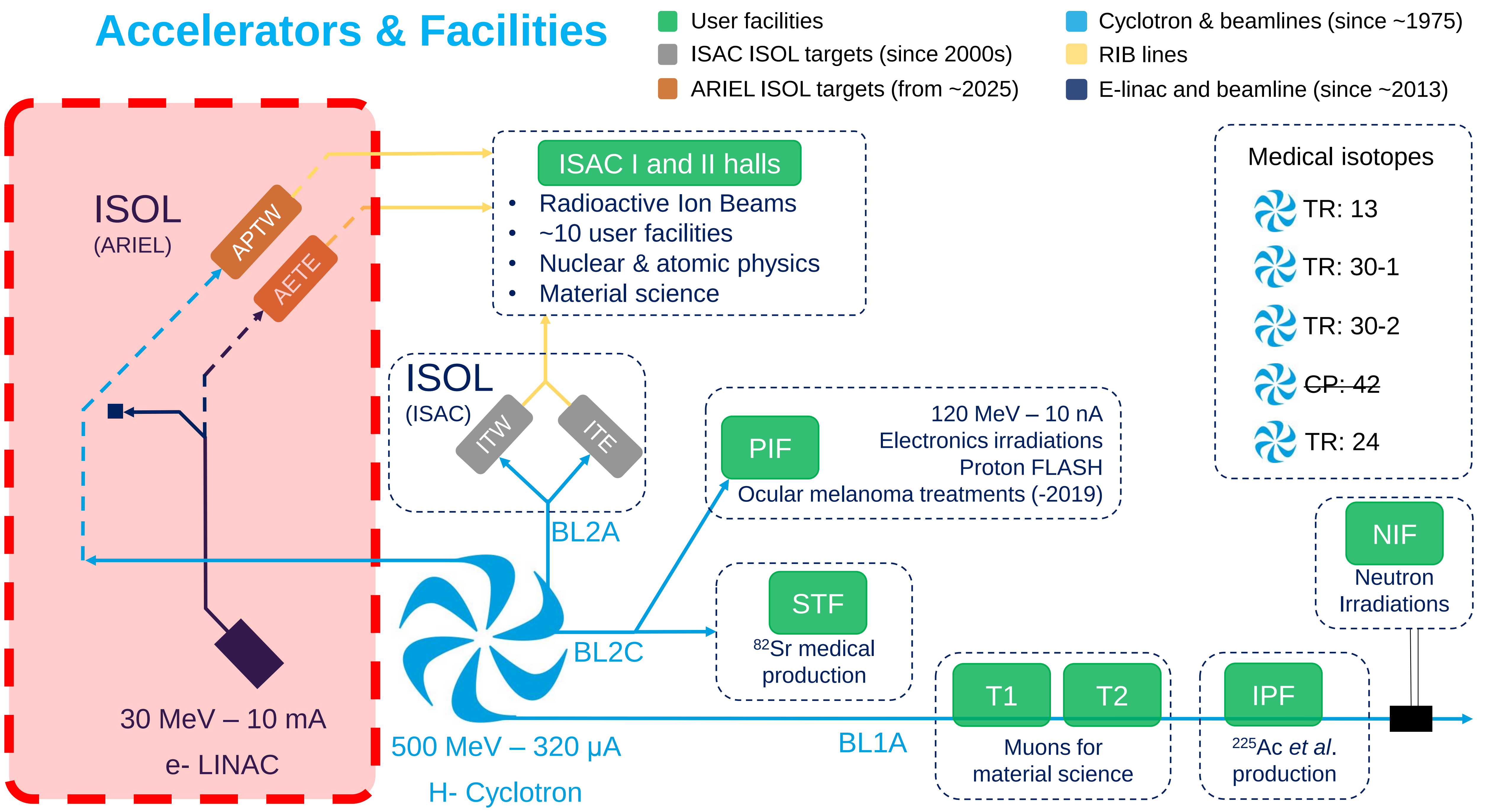
ARIEL - TRIUMF's flagship project

- Simultaneous RIB production from 3 targets
  - 50 kW existing ISAC proton target
  - 50kW new ARIEL proton target
  - 100kW new ARIEL electron target
- **ARIEL will triple ISAC's present rare isotope capabilities.**
- Multi-user capability with more and new isotopes for
  - Nuclear Structure and Dynamics
  - Nuclear Astrophysics
  - Fundamental Symmetries
  - Materials Science
  - Life Sciences
- Unique beam preparation and transport system (CANadian Rare isotope facility with Electron Beam ion source - CANREB)

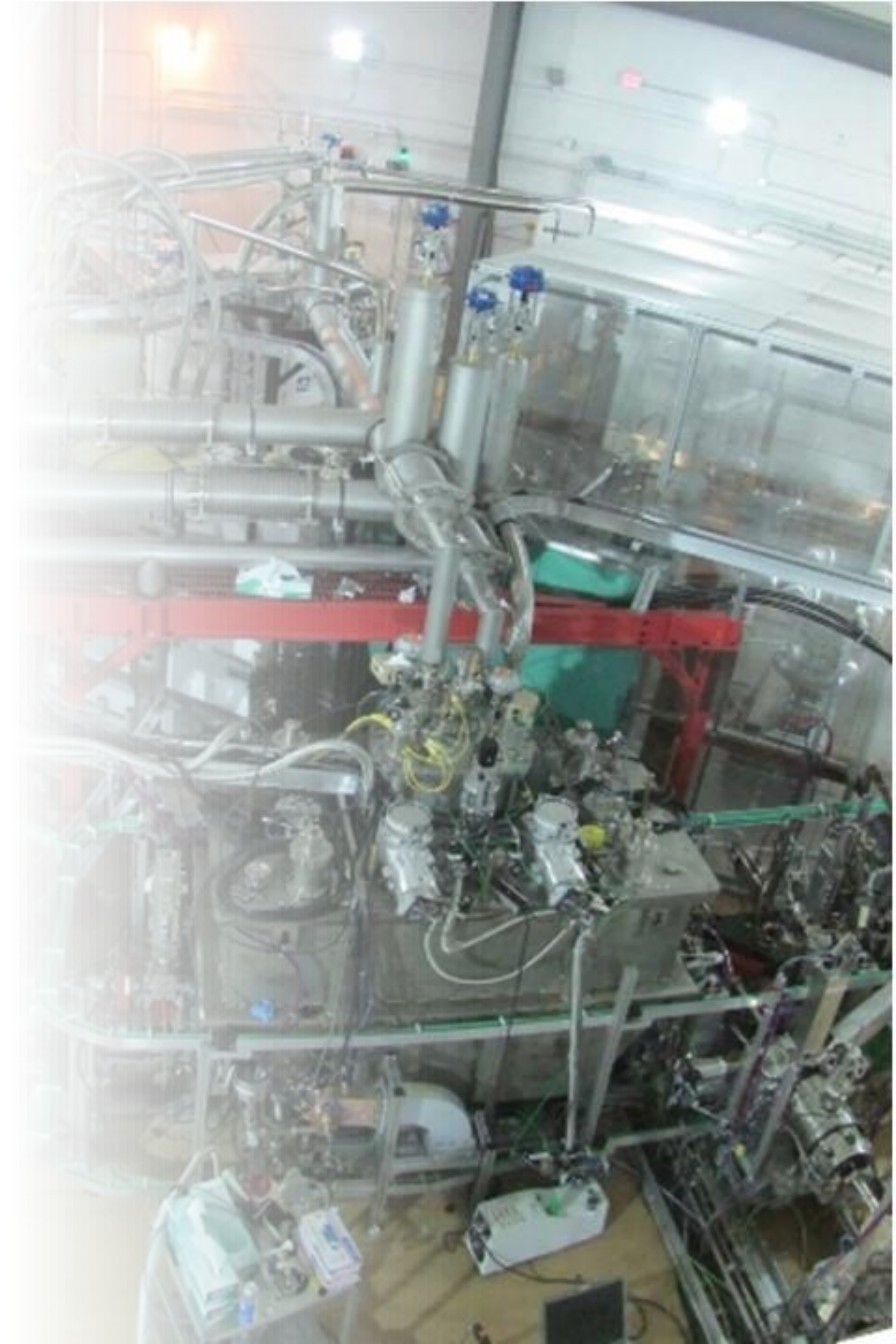


TRIUMF campus

Accelerators & Facilities

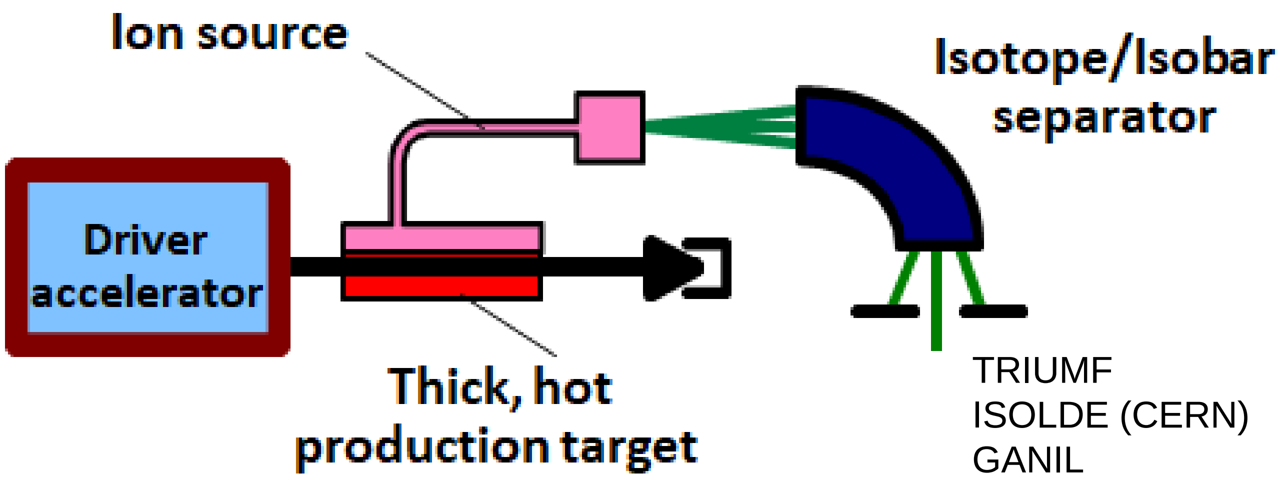


Production of rare isotopes with beam from the e-linac



Rare isotope production

Ion Separation OnLine (ISOL)



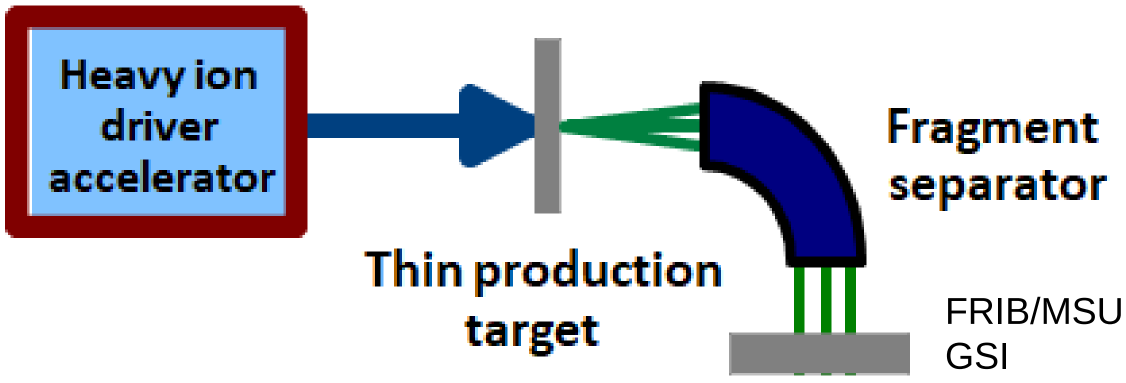
TRIUMF
ISOLDE (CERN)
GANIL

Typical driver accelerators:

- Synchrotrons
- Cyclotrons
- **Linear accelerators (Linacs)**

→ Isotopes produced from target nuclei!

Projectile Fragmentation (PF)



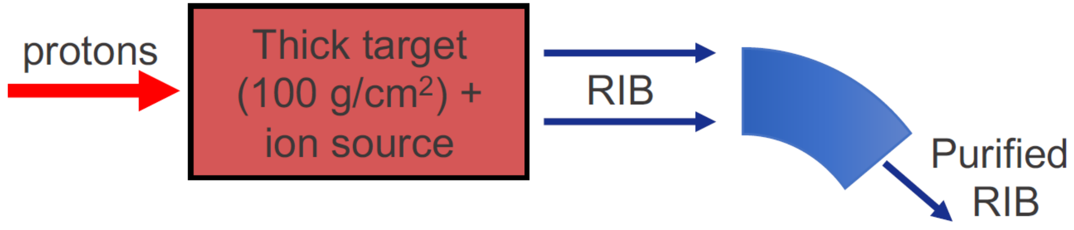
FRIB/MSU
GSI
RIKEN

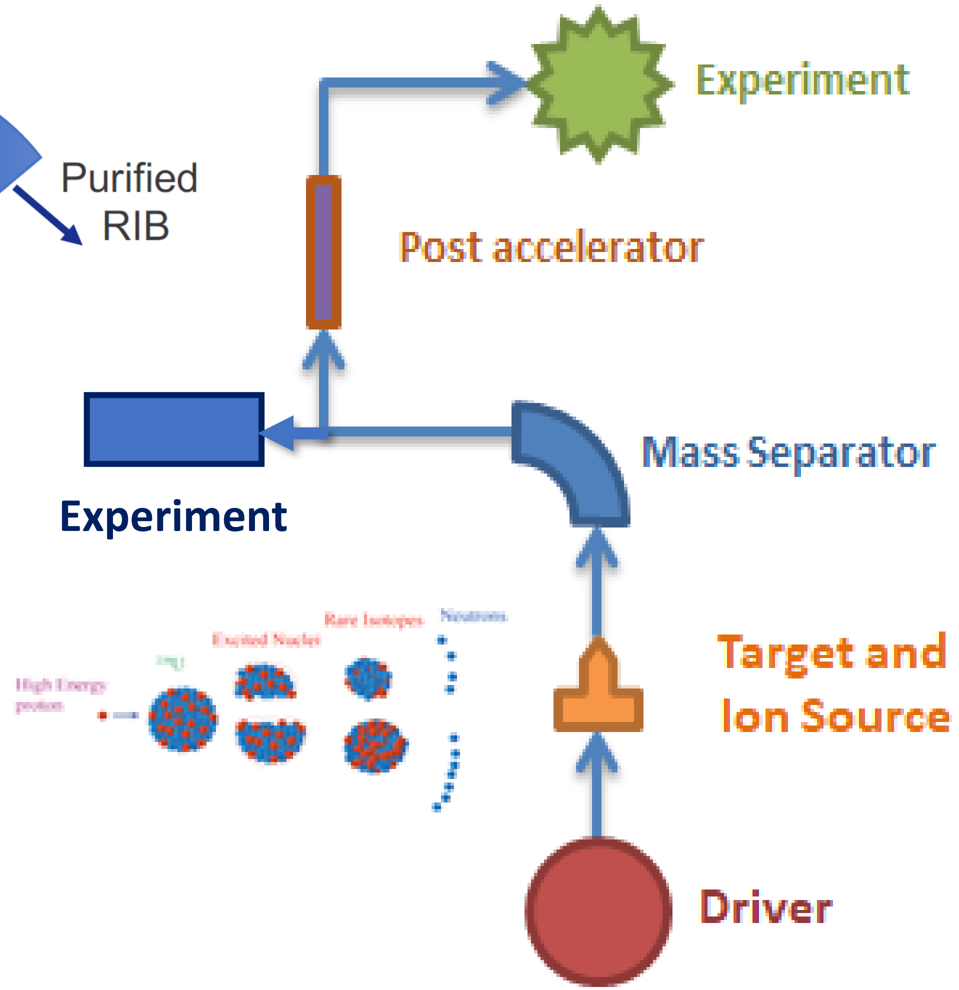
Typical driver accelerators:

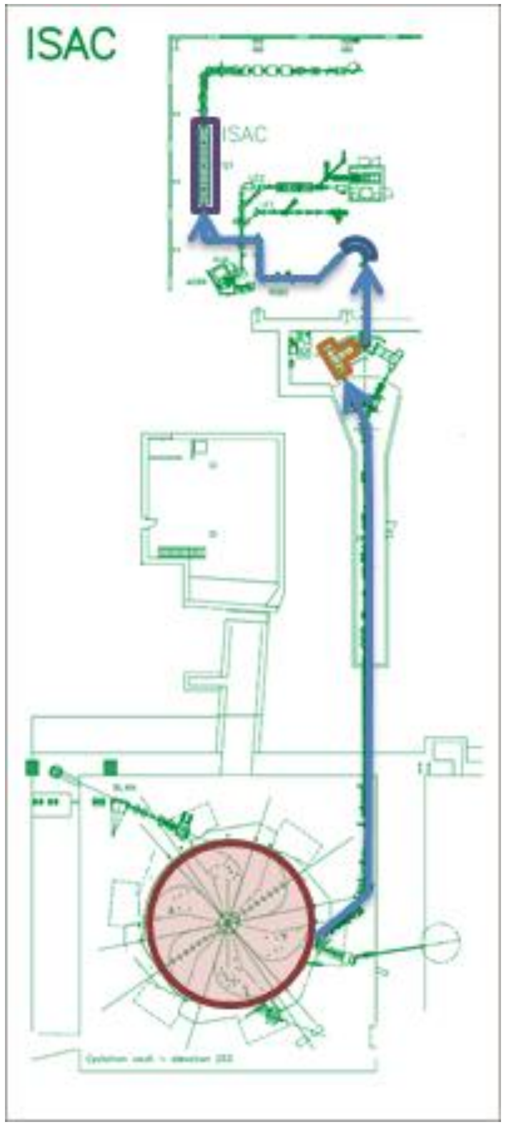
- Synchrotrons
- Cyclotrons
- Heavy Ion Linacs

→ Isotopes produced from the projectiles!

Isotope Separator Accelerator facility - ISAC at TRIUMF

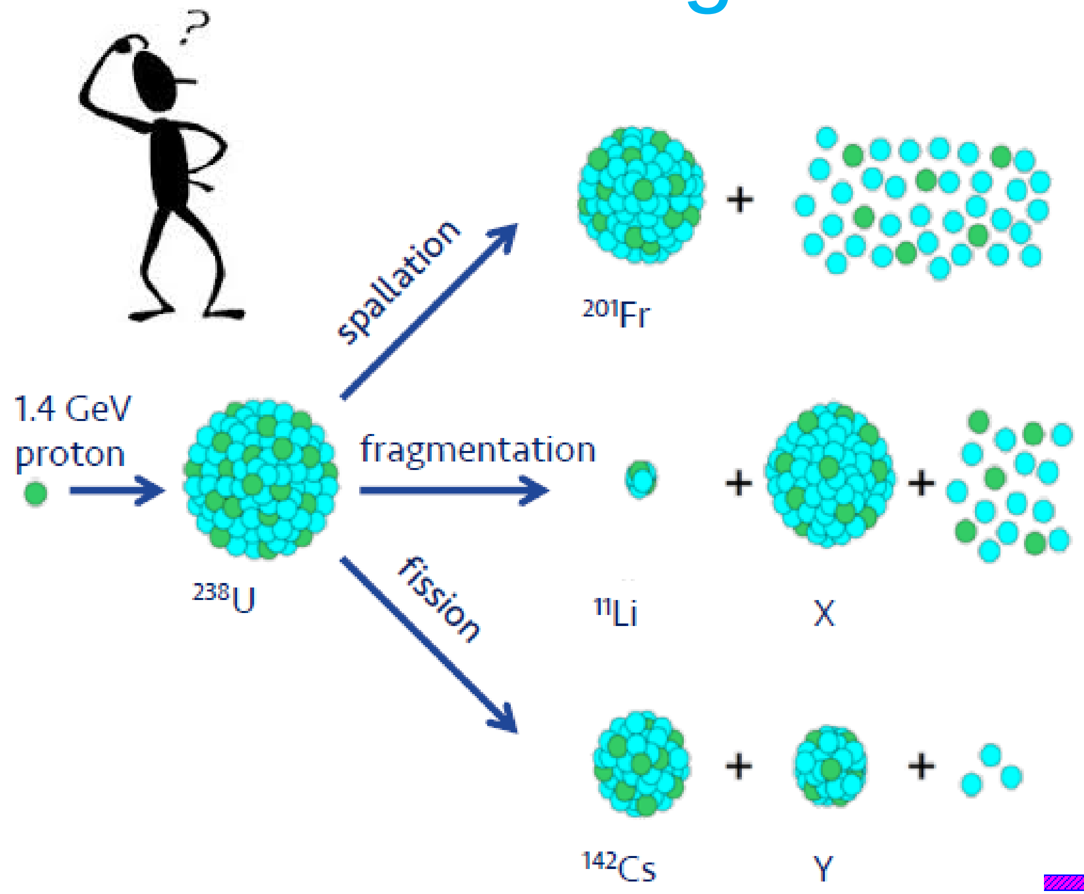






- Isotope Separation On-line (ISOL) facility for rare isotope beam (RIB) production
- High power proton beam (50 kW)
- Extracted ions are mass separated and either post-accelerated or delivered to low energy experiments directly.

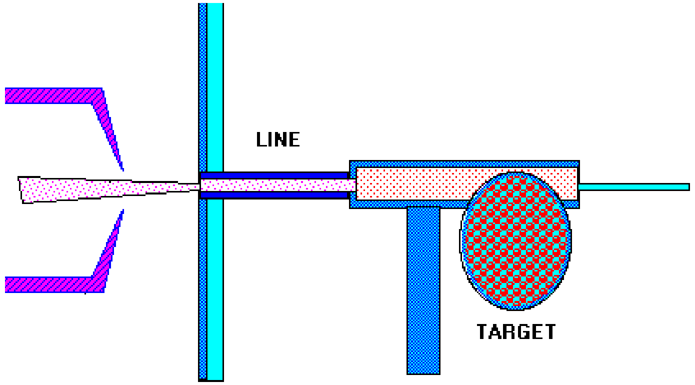
Target ion sources



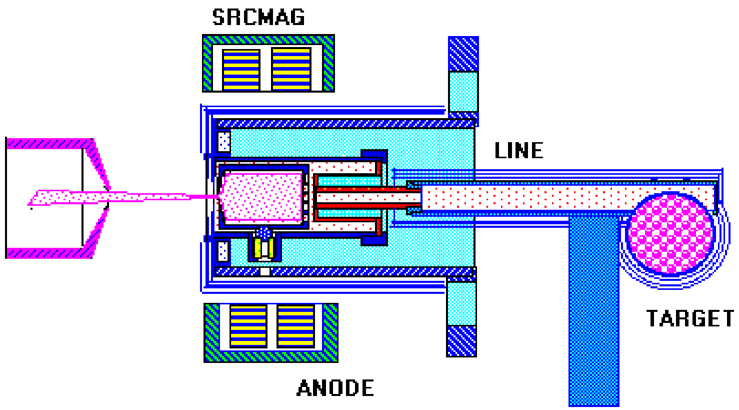
- Rare isotopes are generated by nuclear reactions of the projectile nuclei
- Target and ion sources units, common is surface ionisation, laser ionisation and plasma ionisation

Targets are heated up to high temperatures to support diffusion (random walk) of isotopes into the ionisation region

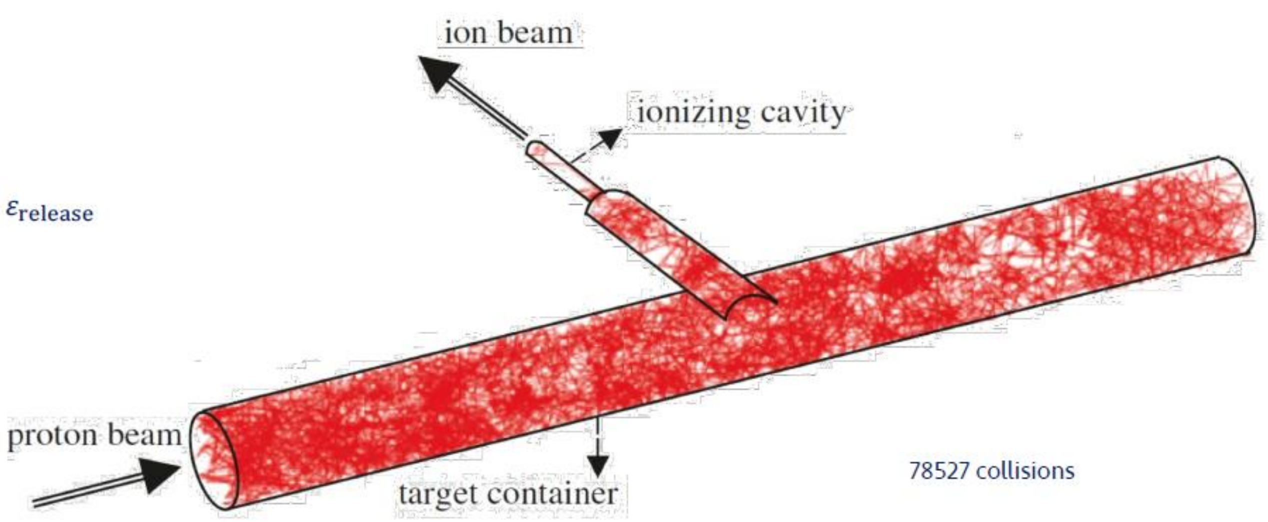
Surface ionisation



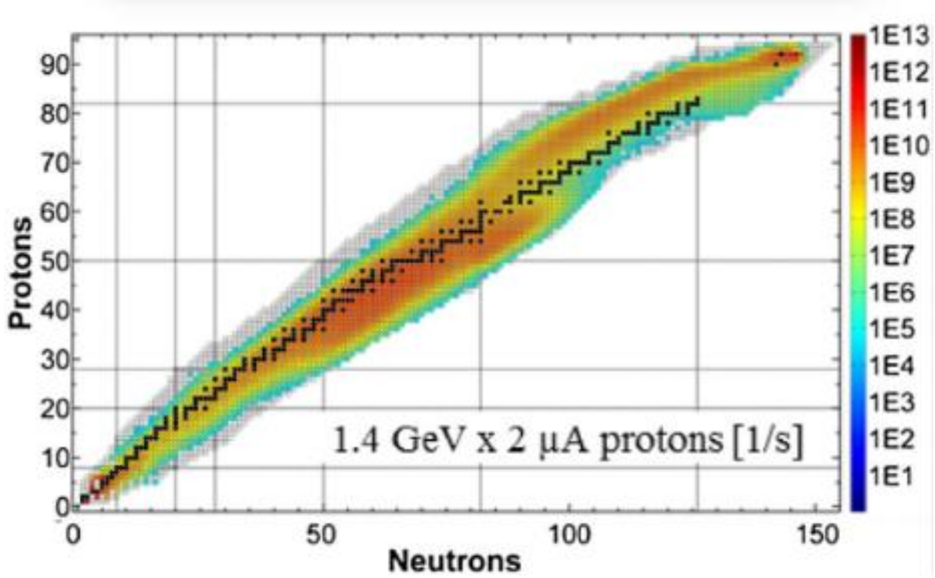
Plasma ion source

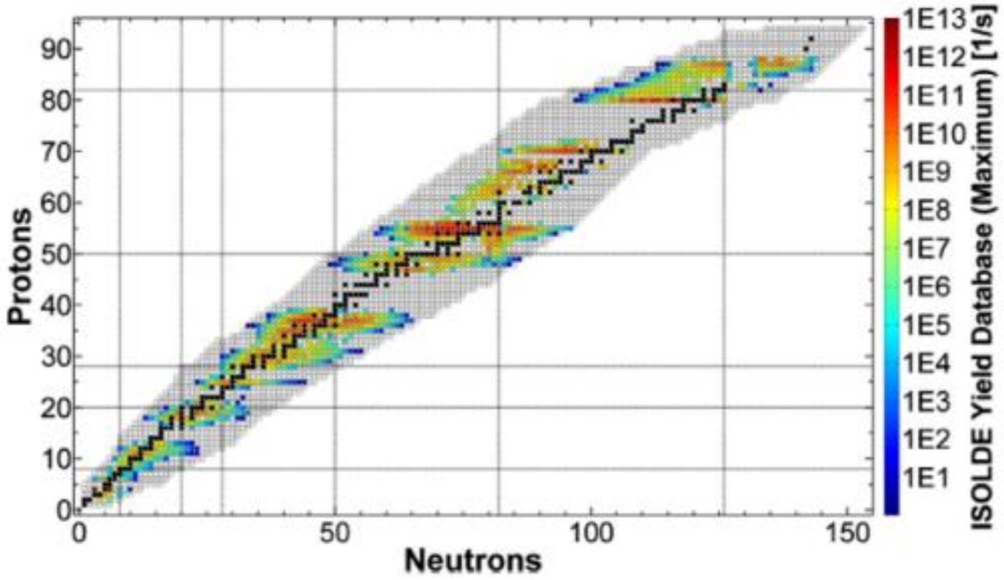


Isotope extraction



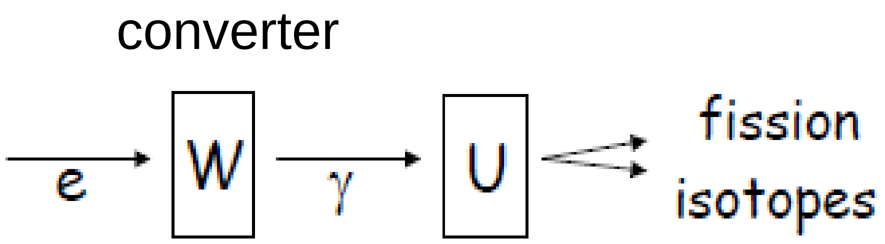
- Simulation of the path of one Ga atom produced in a Ta-foil target towards the ionizer (on the left)!
- Extraction times vary significantly between elements. Driven by volatility and in-target chemistry

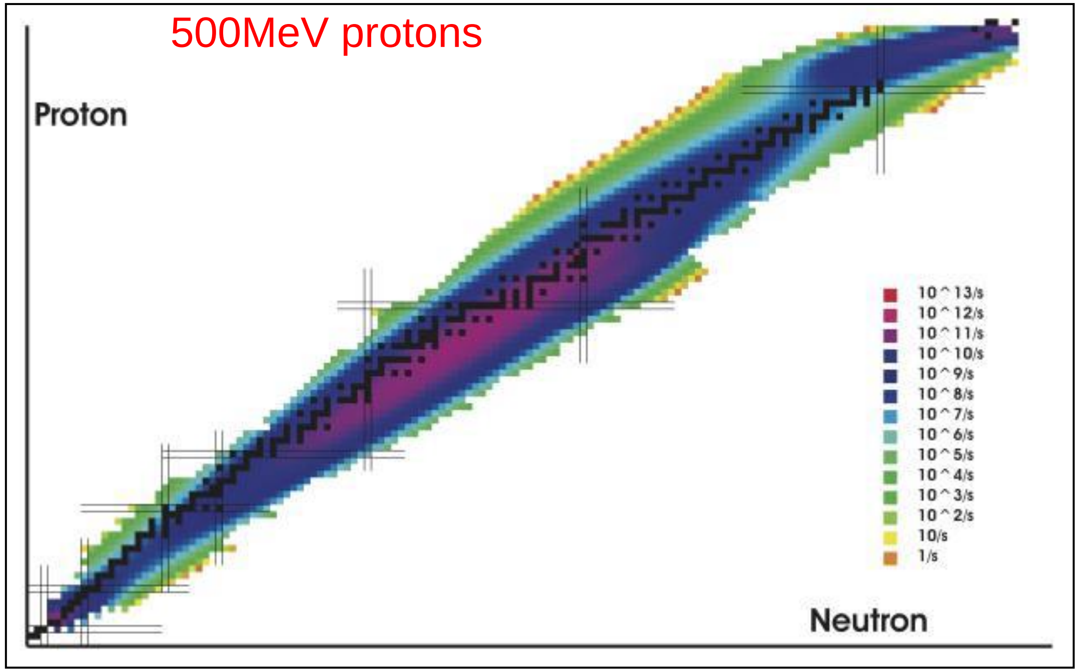


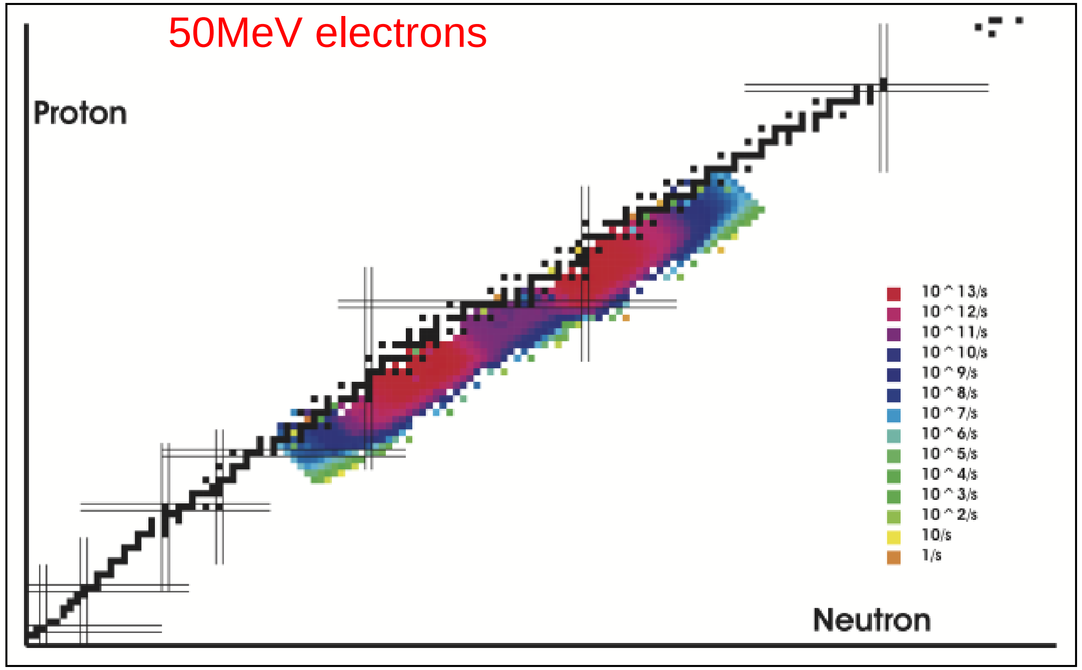


Production of RIBs with electron beams

- An electron-to-gamma converter is required because the direct power deposition imposed by the 30 – 50 MeV electrons would melt the target and is unsustainable.
- 30-50 MeV electrons from the superconducting e-linac (via the photo fission process) yielding a range of isotopes not available from proton reactions and higher beam purity.



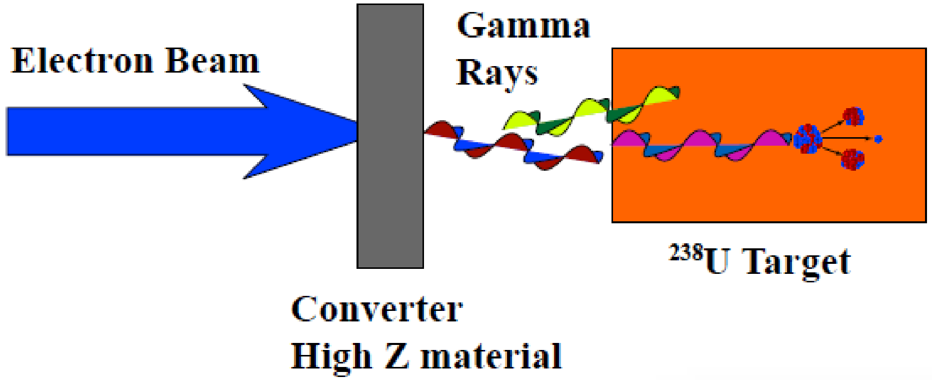


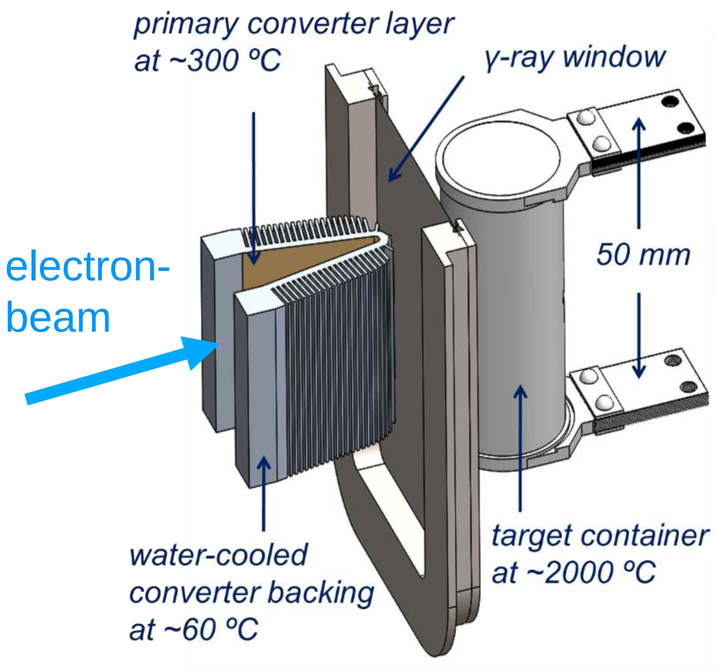


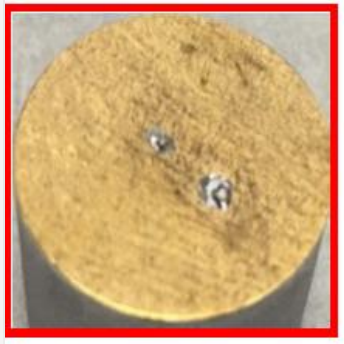
ARIEL electron target principles?

- Converter made of high Z material, Au, W, Ta. Thickness ~ 3.5 mm.
- Electrons MUST be stopped in a low Z material like Al.
- The e-linac delivers 100 kW electron beam with FWHM ≈ 1 mm → 1 MW/cm^3 power density inside of the converter, which is unsustainable!
- Converter target material tests with Ta and Au performed and feasibility demonstrated with Ta.

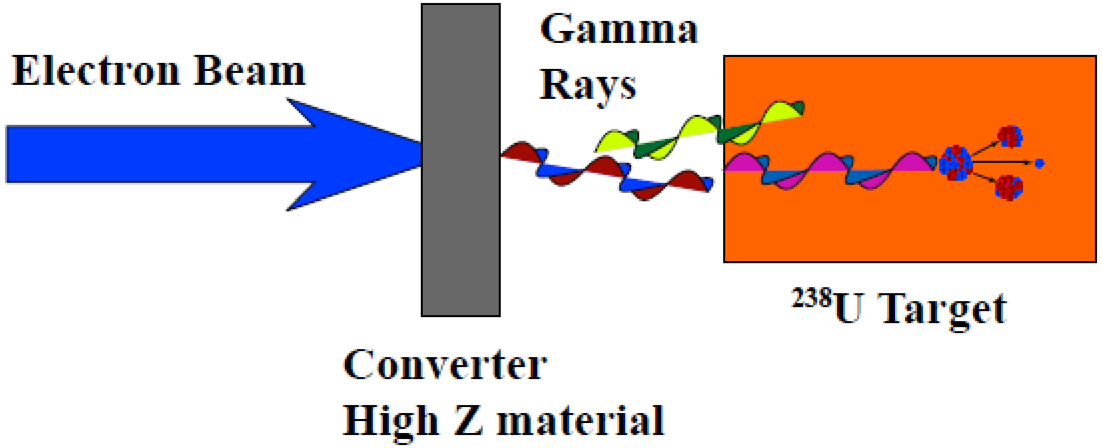
Consequence:
The electron beam will be scanned over a larger area to dissipate the beam power.

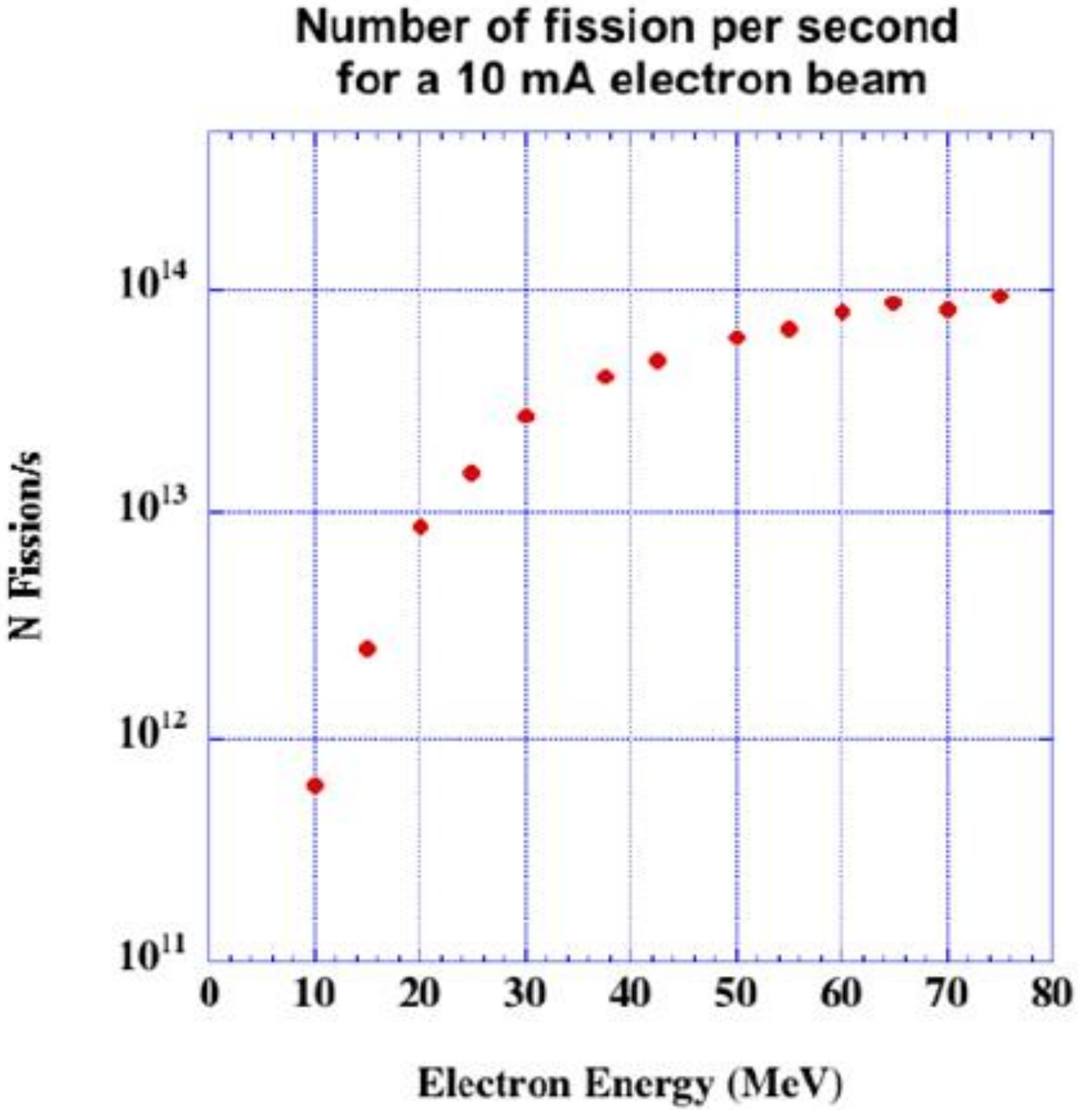






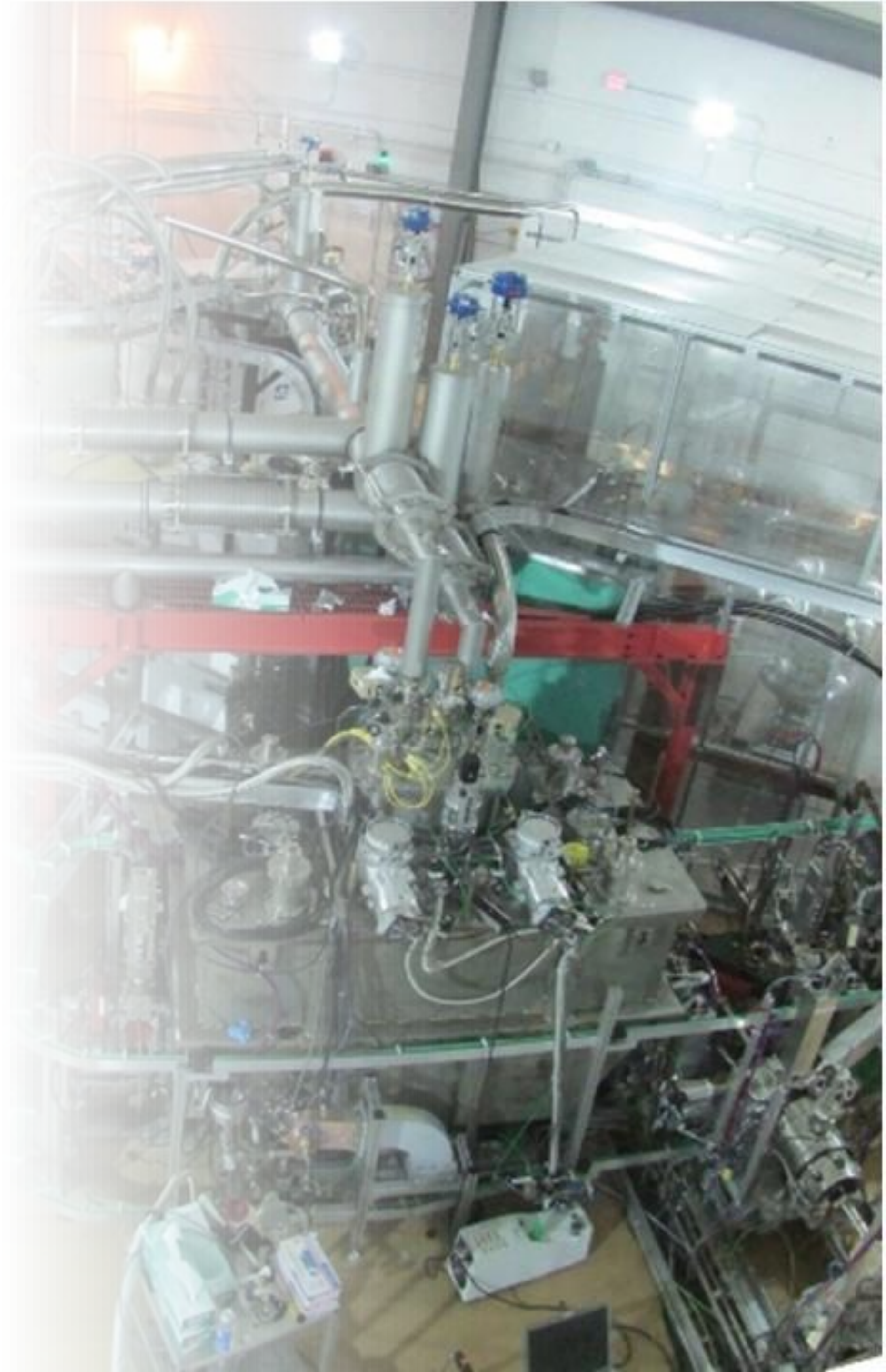
Required electron beam energy



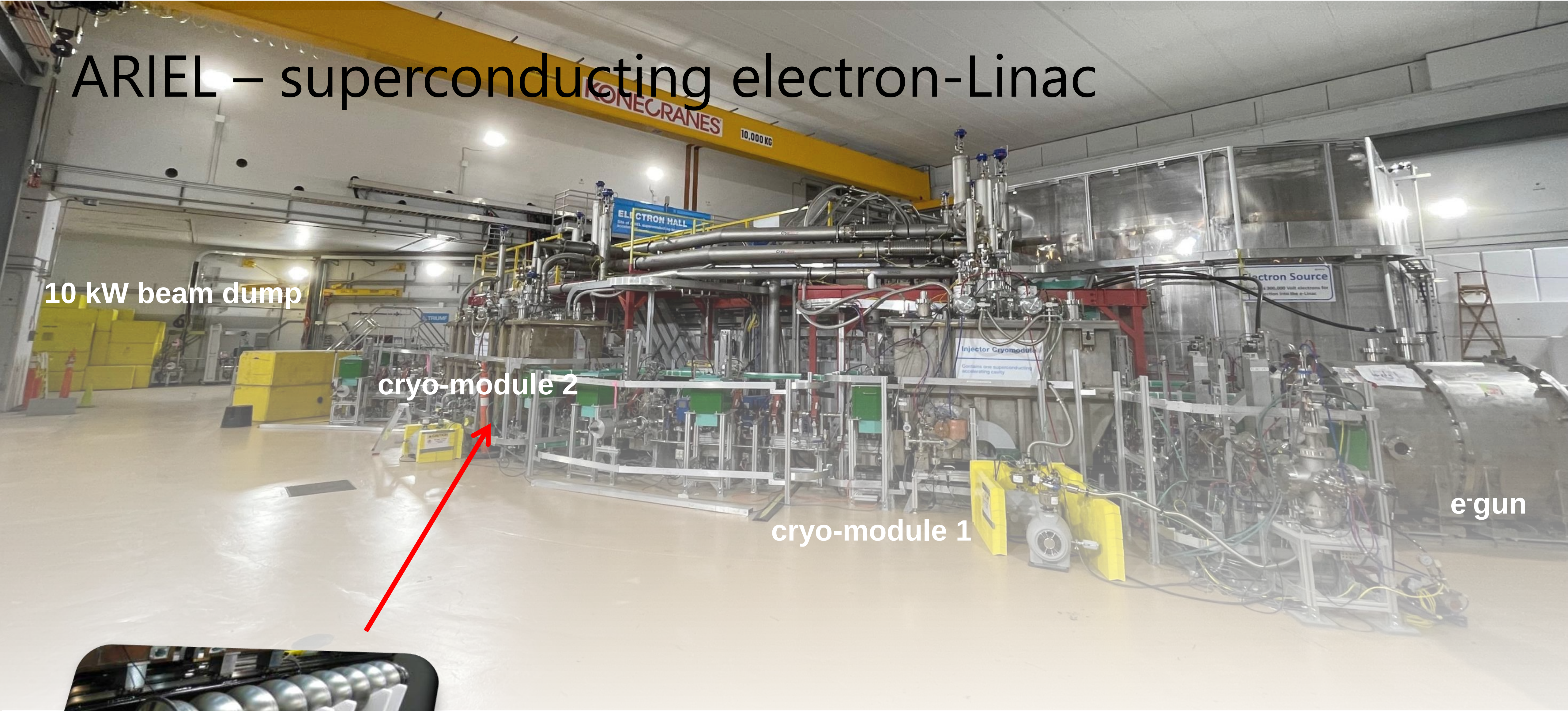


- Production rate increase is significant below 30 MeV, but reduced between 30 and 50 MeV
- 50 MeV does provide a smaller γ-cone angle, less heating of the target station material.

The TRIUMF superconducting ARIEL electron linac (e-linac)



ARIEL – superconducting electron-Linac



- E-gun delivers max. 10 mA at 300 keV beam
- The injector cryomodule (1) accelerates to 5-10 MeV
- The accelerator cryomodule (2) is equipped with two cavities and reaches max. 30 MeV.

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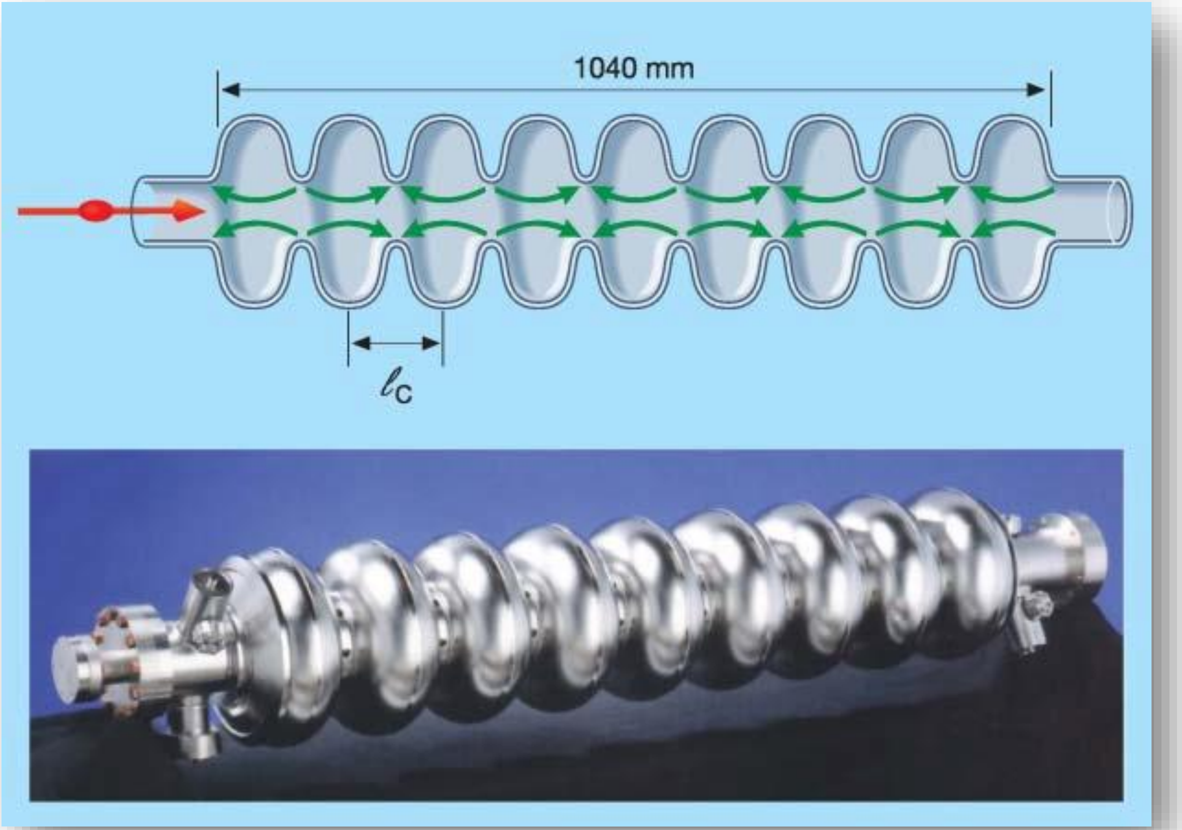
Electron Linacs

As an electron's speed v → c (β=1), the speed of light, at relatively low energies (~500 keV), the gap and pillbox cavity size can be kept constant for the higher energies.

E-linacs are then built from identical sections and cavities → optimized elliptical cavities.

For higher energies and cw-operation the 1.3 GHz nine cell elliptical niobium cavity (TESLA type cavity) is the dominant cavity for SRF electron linacs (FLASH linac and the European XFEL at DESY in Hamburg).

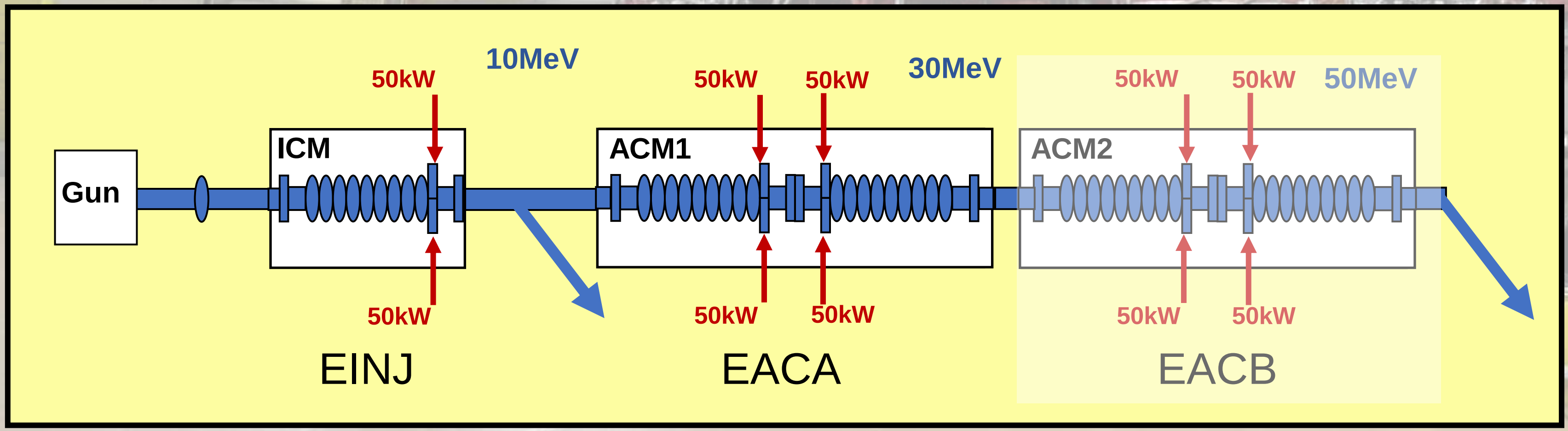


TESLA (Tera-Electronvolt energy Superconducting Linear Accelerator)

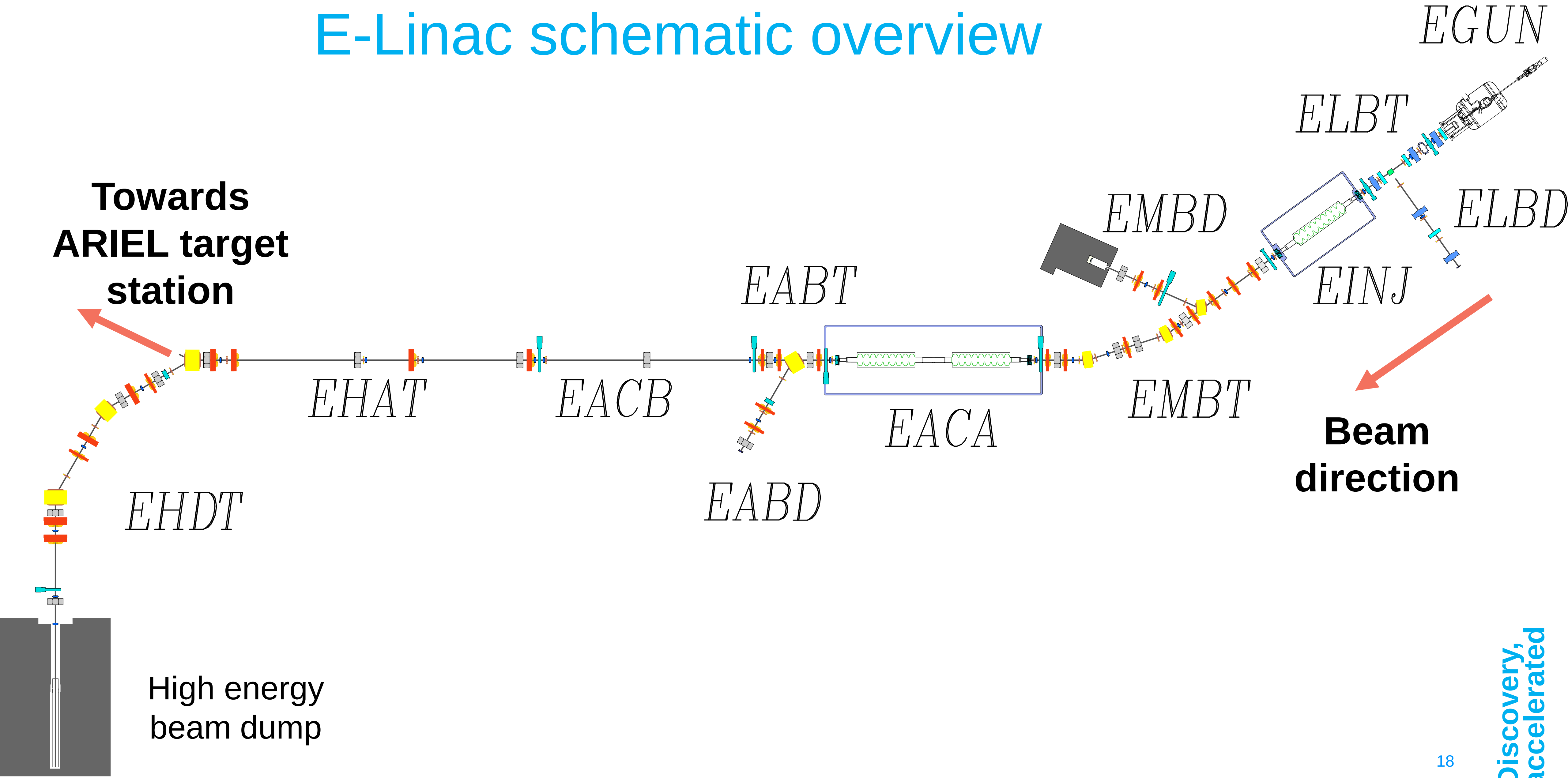
E-linac design parameter

1.3 GHz SRF Electron Linac (10 mA)

- Base-line design - five nine-cell cavities housed in three cryomodules. Each cavity adds about 10 MeV (100 kW at full current)
- Installed 30 MeV capability , which will provide 100 kW on the ARIEL electron target station.
- 50 MeV (10 mA) capability foreseen for the future with a second cryomodule (500 kW beam power at full current)
- Bunch structure – 650 MHz – macro-pulse established with e-gun rf – rep-rate is selectable from 0.1% to 100% (variable duty cycle)



E-Linac schematic overview



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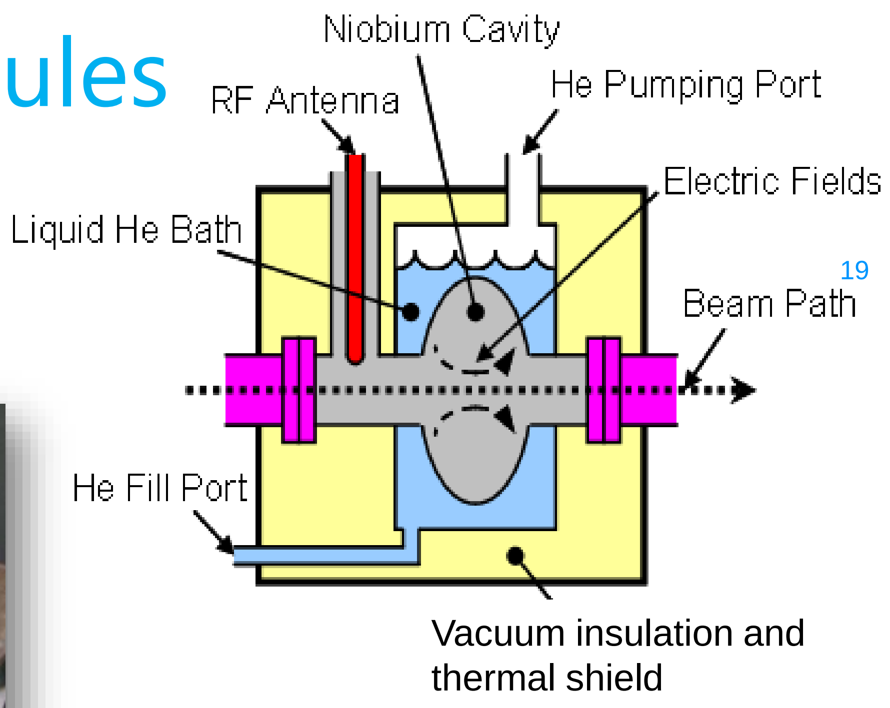
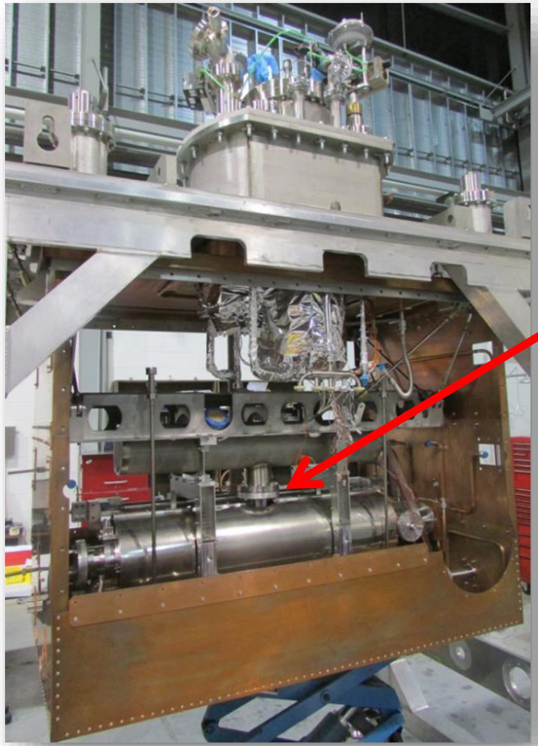
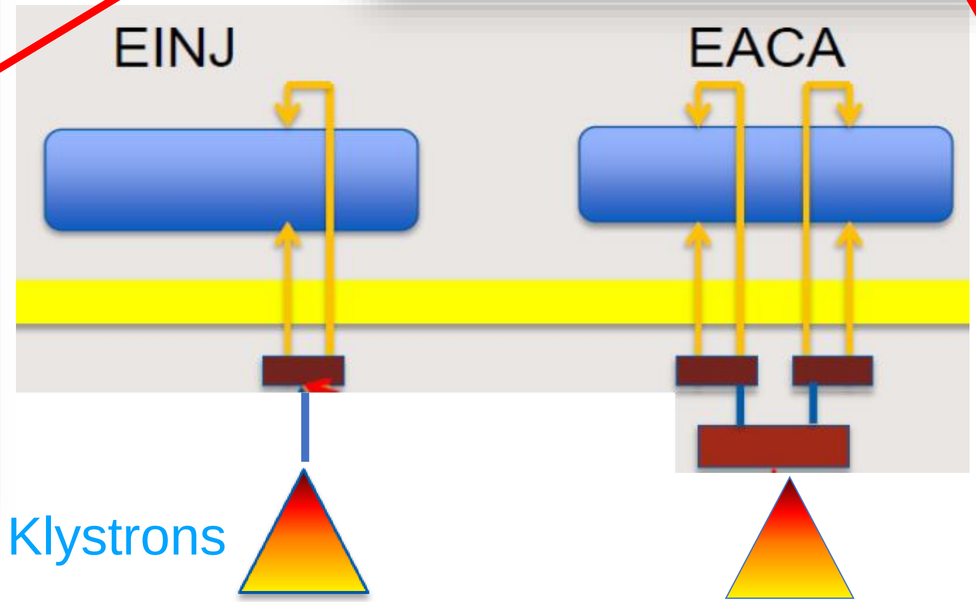
ARIEL – e-Linac cryomodules

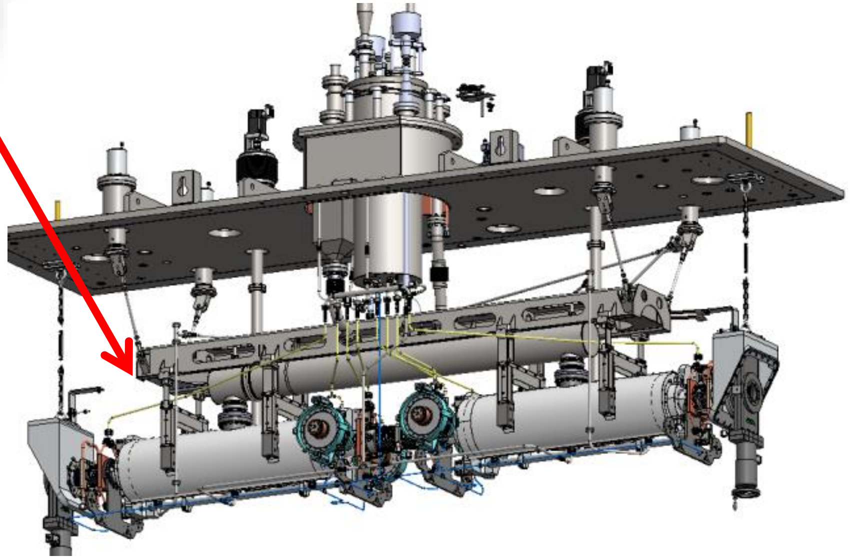
- One single cavity injector cryomodule and one double cavity acceleration cryomodule
- 4 K cryogenics supply and sub-atmospheric pumping to provide 2K He to the cavities.





Singe cavity injection module

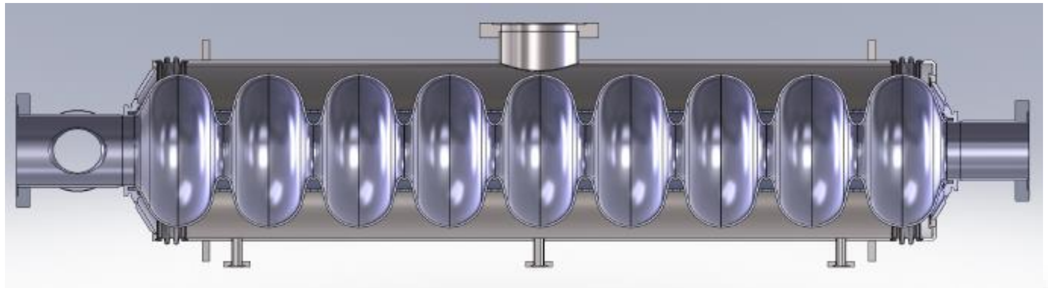


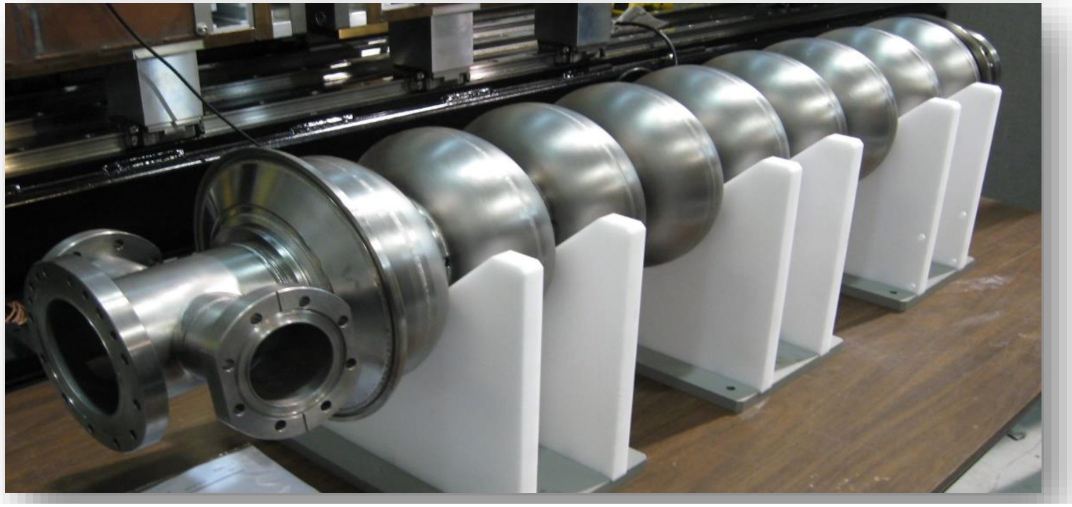


Dual cavity acceleration module

1.3 GHz nine-cell elliptical cavities not the original TESLA type 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.

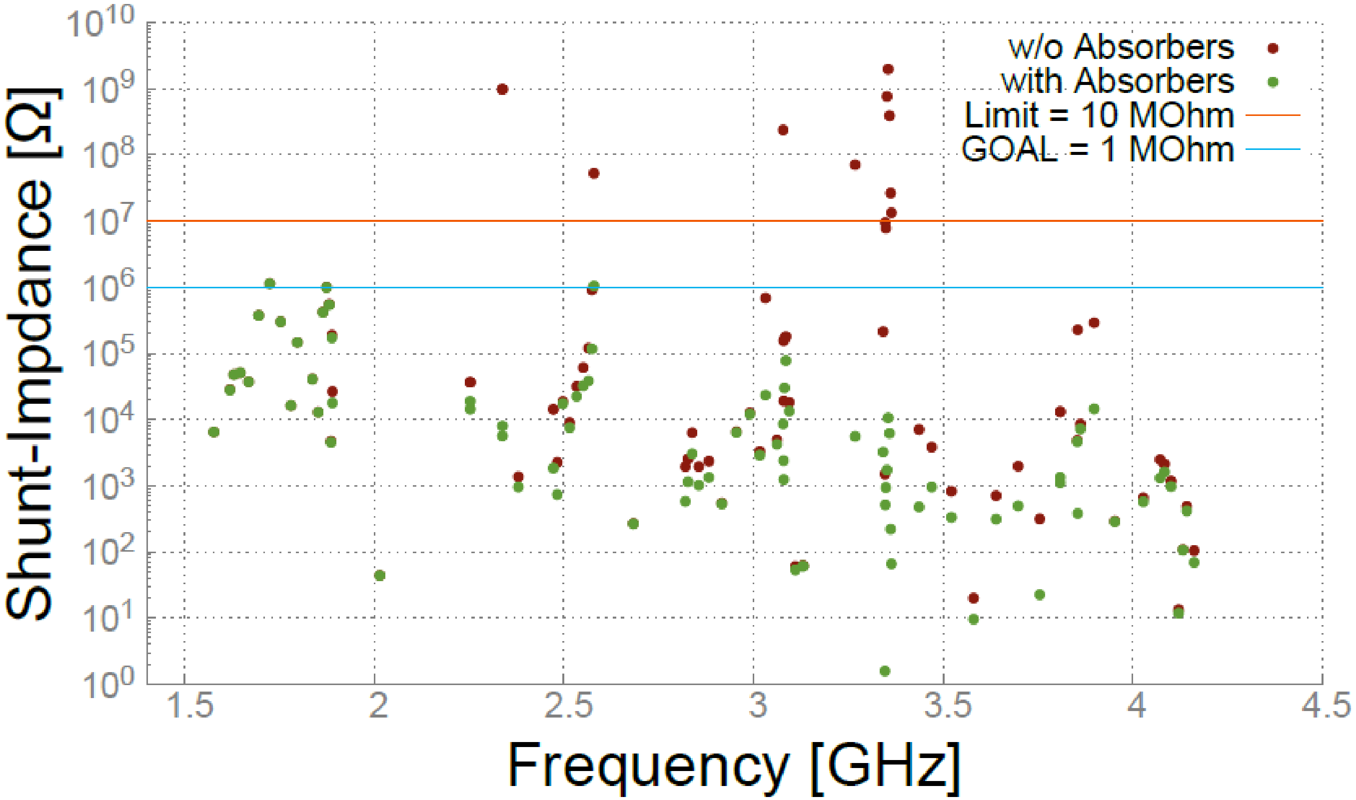
Typical gradients of the cavities for cw application are 16 MV/m (LCLS-II) and 23.5 MV/m for pulsed (XFEL)

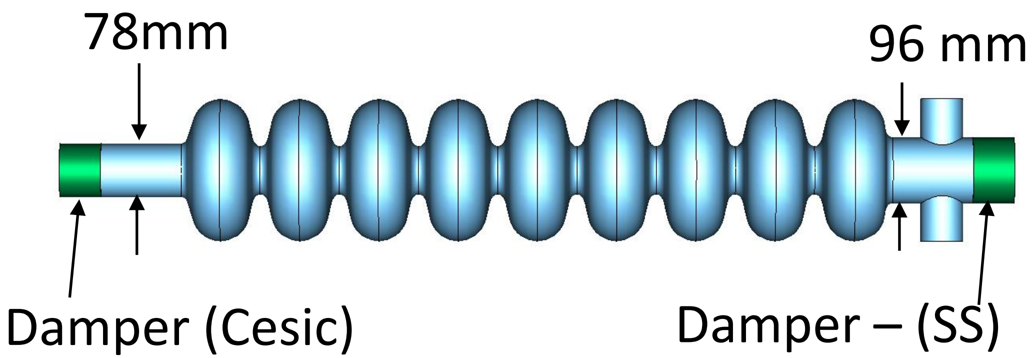
Parameter	Value
Active length (m)	1.038
RF frequency	$1.3 \cdot 10^9$
R/Q (Ohms)	1000
Q_0	10^{10}
E_a (MV/m)	10
P_{cav} (W)	10
P_{beam} (kW)	100
Q_{ext}	10^6

See Bob Laxdal's lecture on SRF cavities

Higher order mode (HOM) Damping

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





The e-linac Injector Cryomodule (ICM)

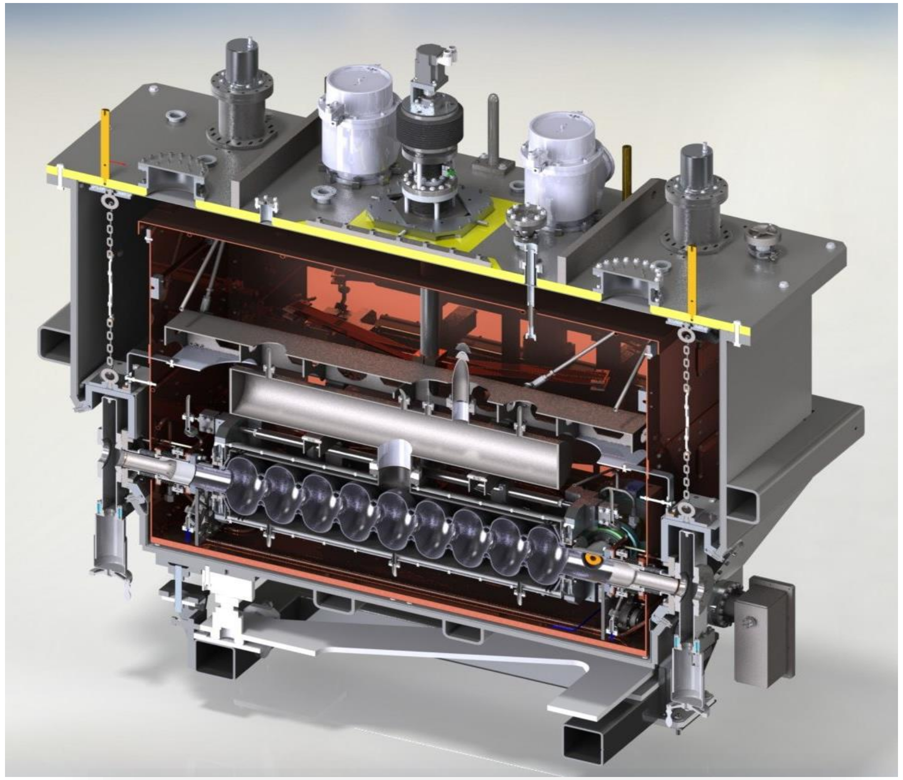
Houses

- One nine-cell 1.3 GHz cavity
- Two 50kW power couplers
- HOM coaxial passive dampers

Features

- 4K / 2K heat exchanger with a Joule Thomson (JT) valve on board – allows standard 4K cold box
- Scissor tuner with warm motor
- LN_2 thermal shield – 4K thermal intercepts via syphon
- Two layers of mu-metal
- 'Wire Position Monitor' alignment system

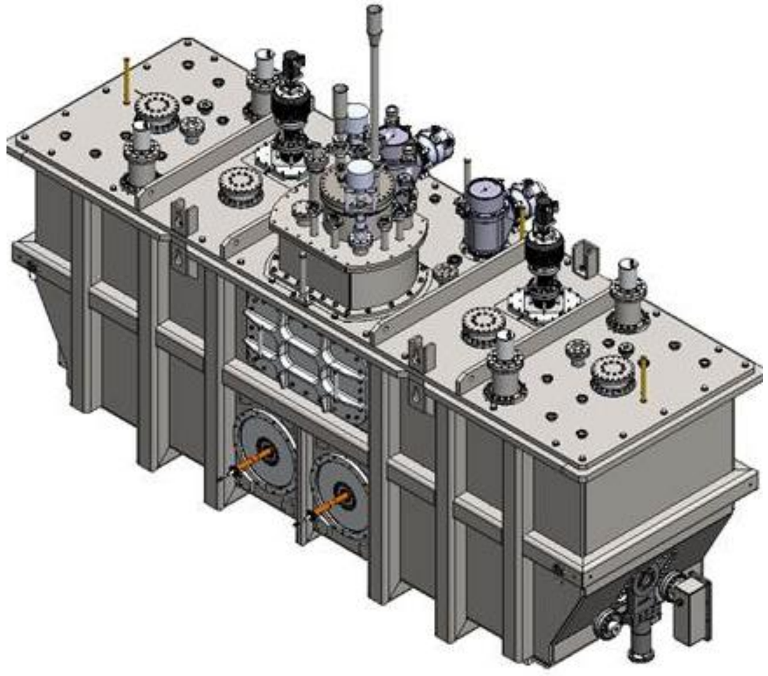
See Nusair Hasan's lecture on cryostat technology

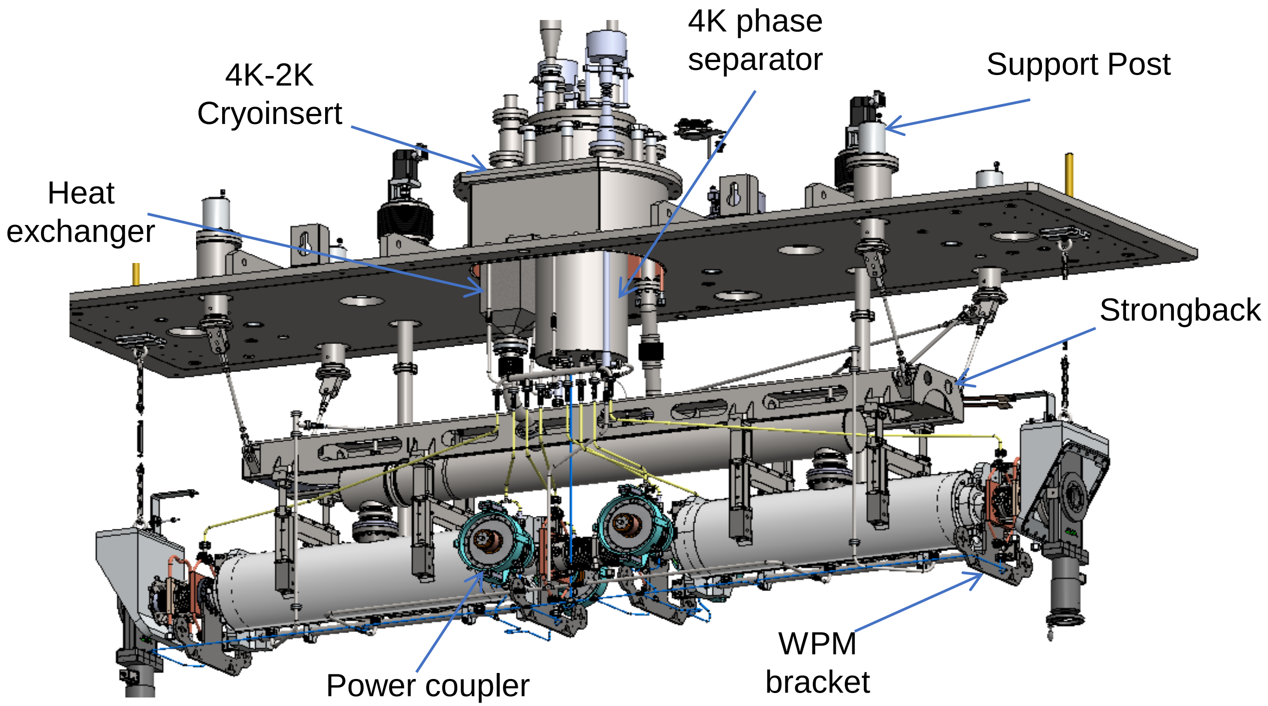


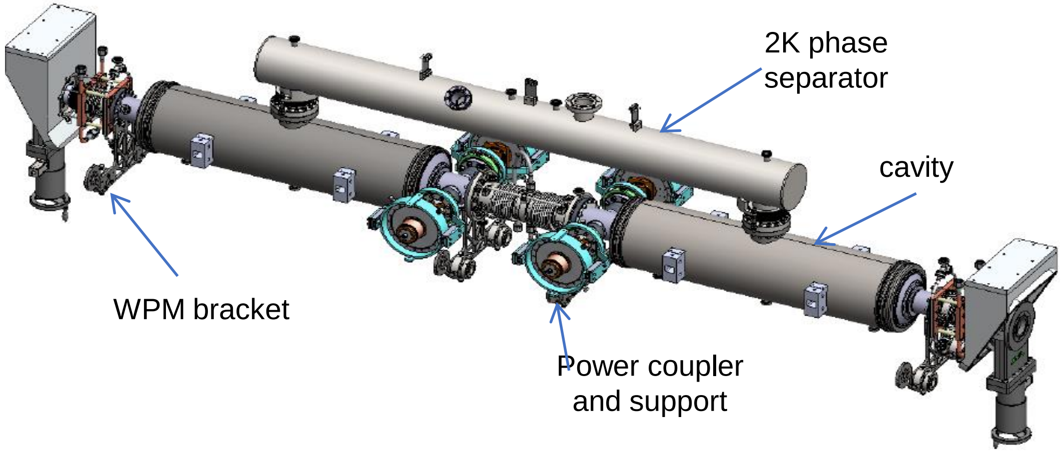
Discovery, accelerated

Accelerator Cryomodule (ACM)

- 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 Injector Cryomodule (ICM)
- Physical dimensions
  - L x H x W = 3.9 x 1.4 x 1.3 m, 9 tons

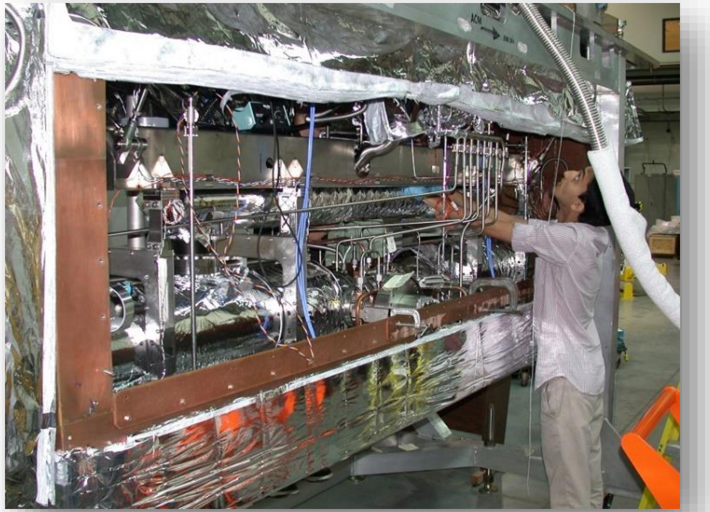






ACM assembly

String assembly

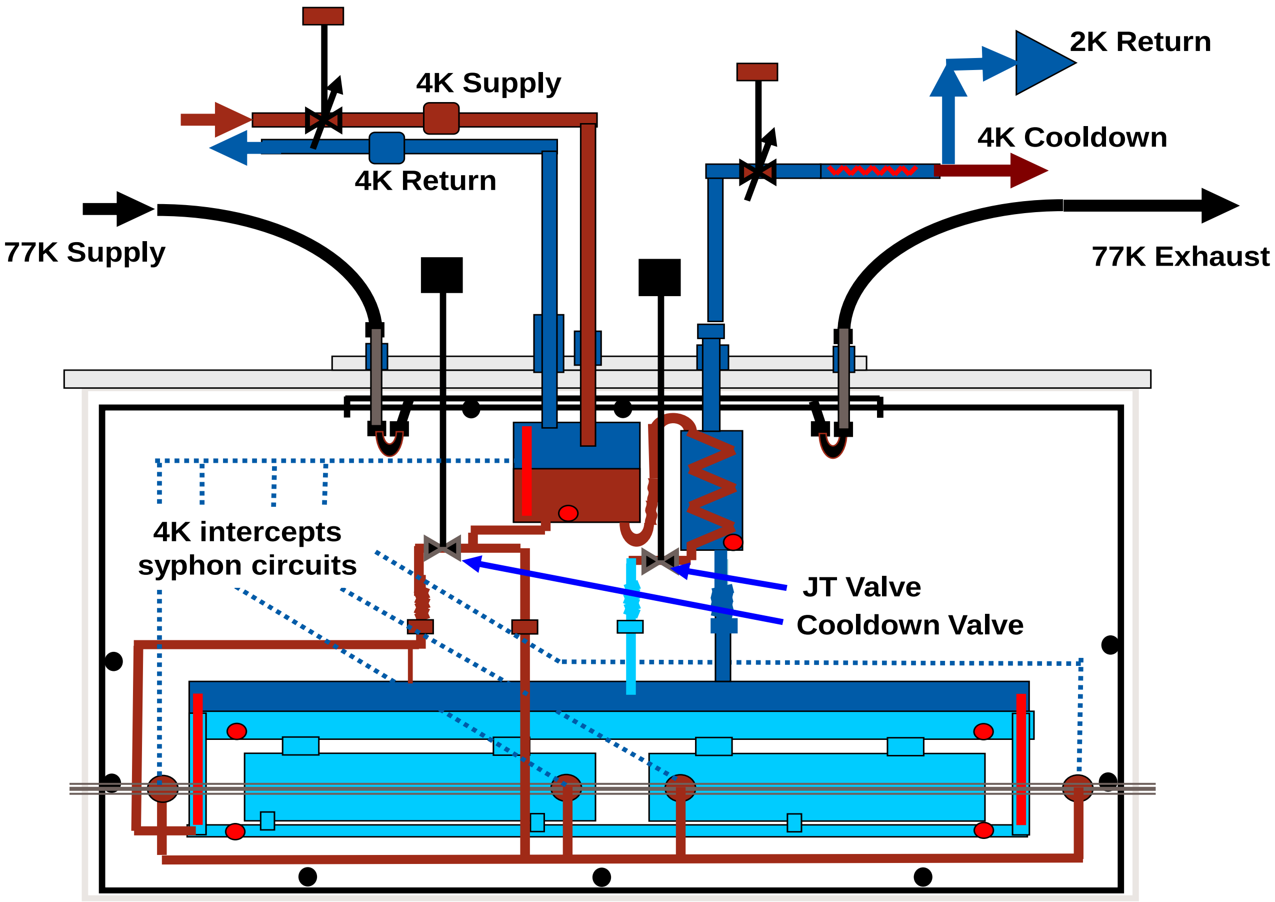


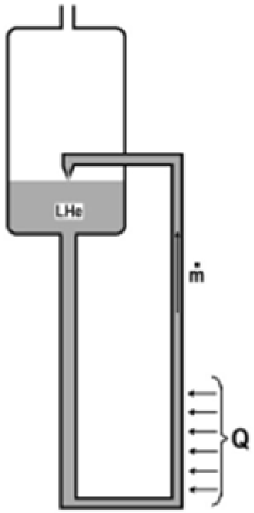
ACM – ready for cooldown!

ICM / ACM Cryogenic Circuits

- 4K/2K insert designed to fit in a separate test cryostat prior to cryomodule assembly
- One 4K circuit feeds the heat exchanger and JT valve for 2K supply
- One 4K circuit feeds the bottom of the cold mass through a cooldown valve for initial cooling

Concerning 2K refrigeration see lectures on cryogenics systems.

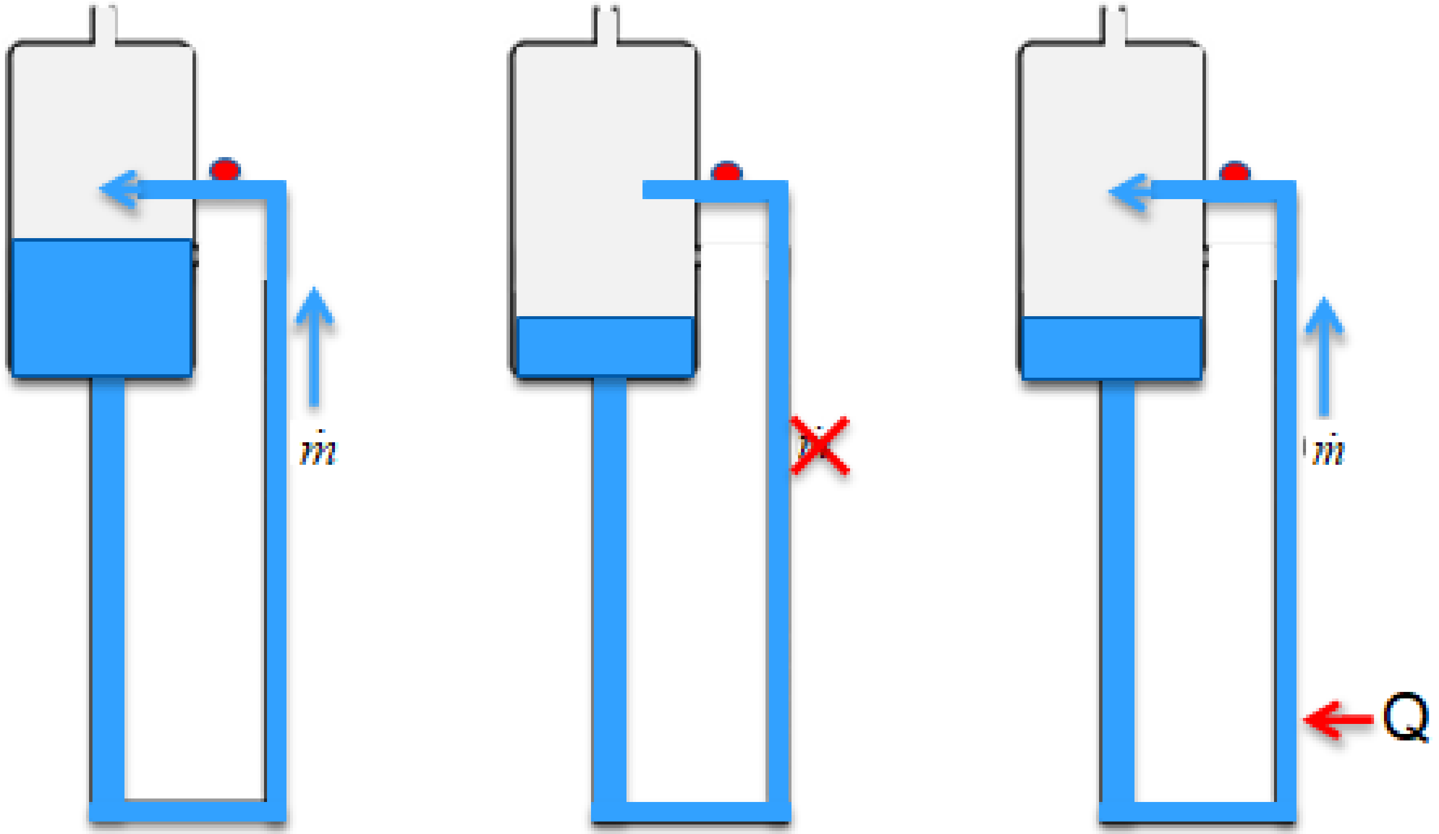




One 4K circuit cools thermal intercepts for beam pipes and couplers via a self-regulating thermosyphon circuit – flow is governed by the heat load and the LHe level in the 4K reservoir

Syphon Loop explained

- Demonstrated that the loop turns on and off depending on head pressure and heat load – self regulating
- Existence of flow is diagnosed by a temperature sensor on the return column
- Demonstrated that the heat load to 2K is effectively intercepted by syphon loop cooling, but the design of the return line is important.



- Lesson learned – beware of creating convection in the 4K reservoir – heat source!

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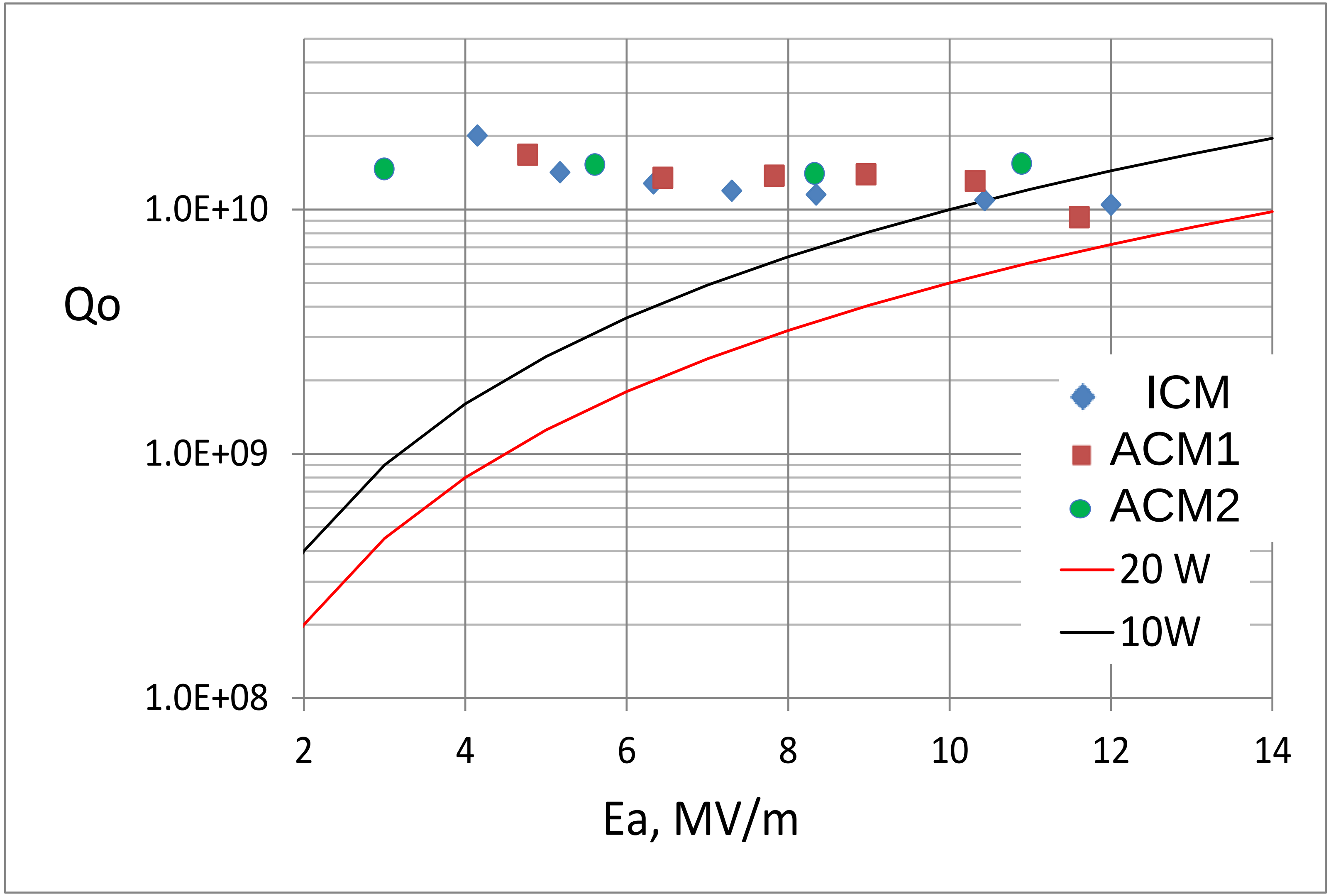
Cryomodule Cold test results

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

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

✓Cavities meet specification



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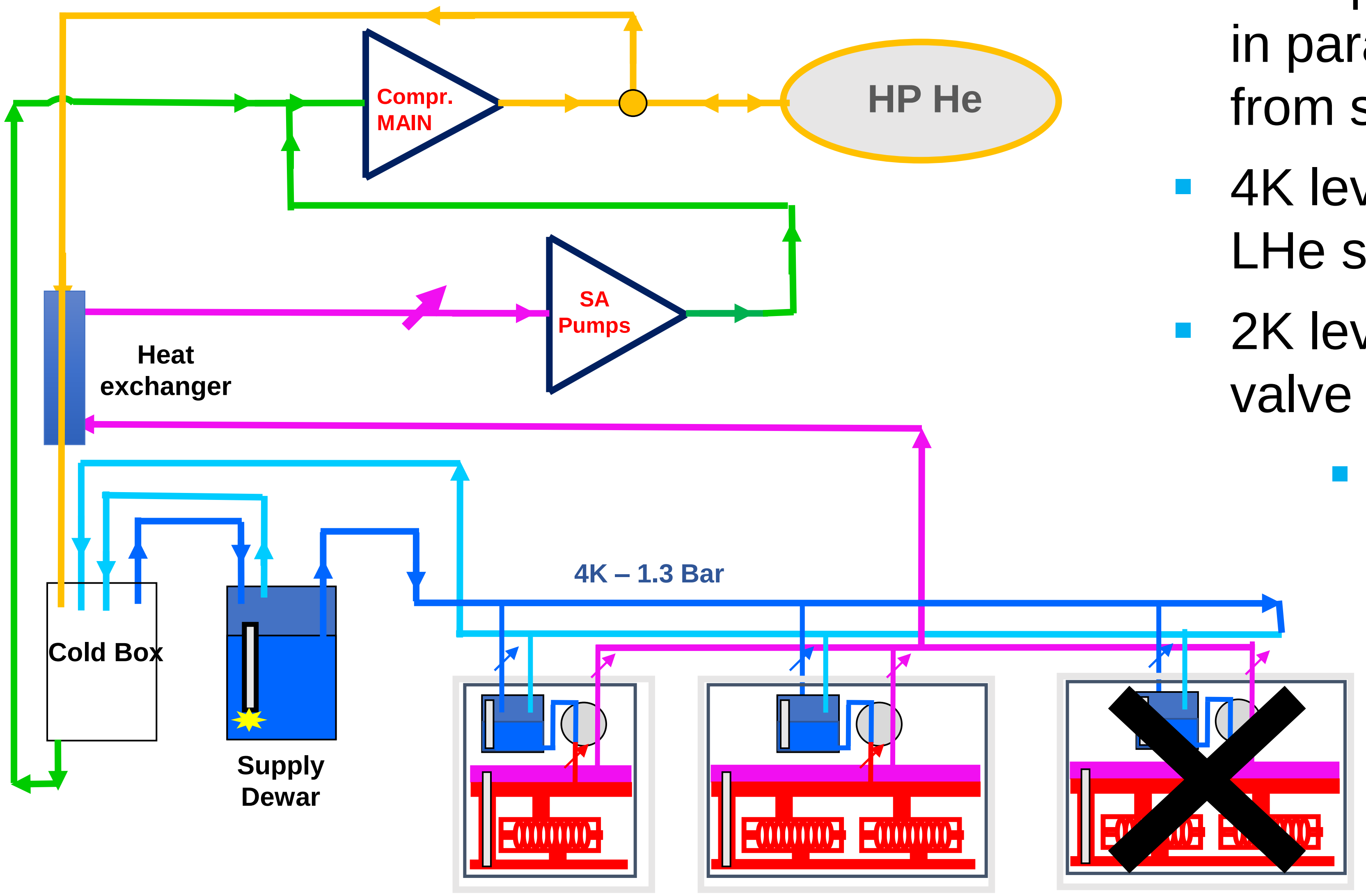
E-linac Cryogenics



- 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.

Discovery, accelerated

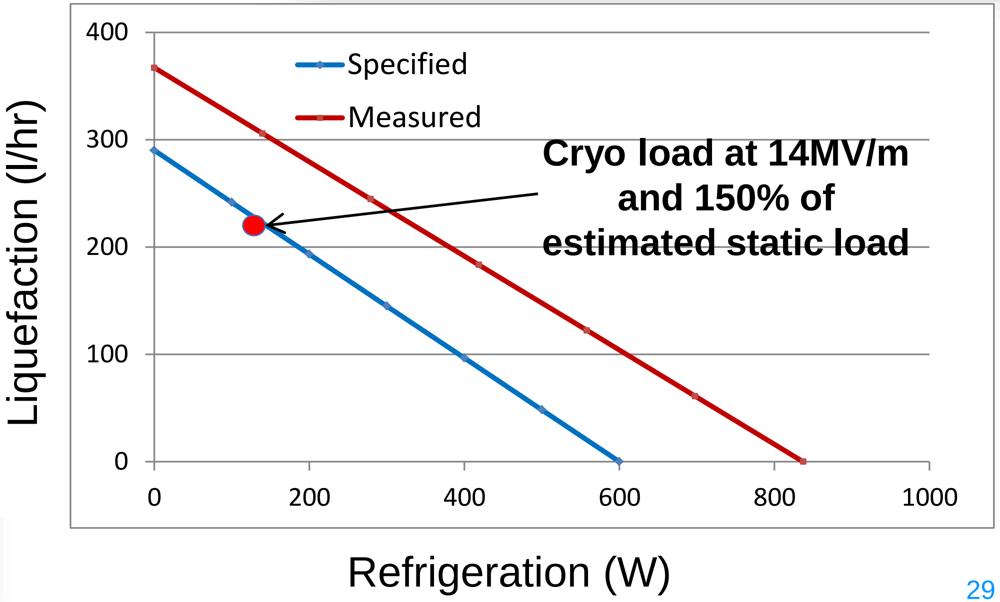
Cryogenics installation

- 4K system
  - ALAT LL Cold Box, KAESER (FSD571SFC) main compressor (112g/s), Cryotherm - distribution
  - Acceptance tests (with LN2 pre-cooling) did exceed all specifications with comfortable margins

Parameter	Contract	Measured
Liquefaction	288 L/hr	367 L/hr
Refrigeration	600 W	837 W

- Sub-atmospheric pumping

  Four Busch combi DS3010-He pumping units specified and installed:
  (1.4g/s @ 24mBar each)



Discovery, accelerated

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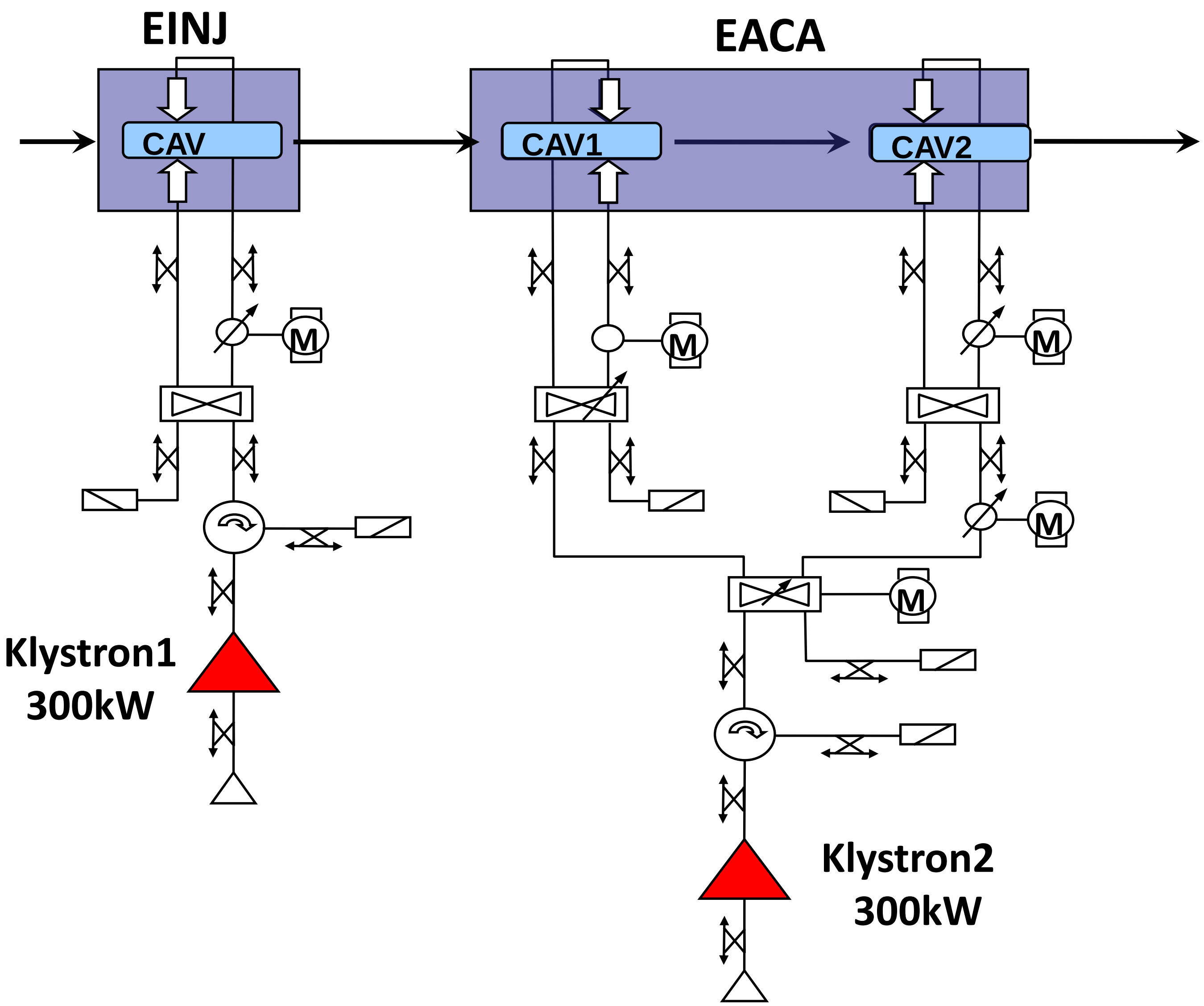
E-Linac RF Drive System

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



Di
accelerated

TRIUMF

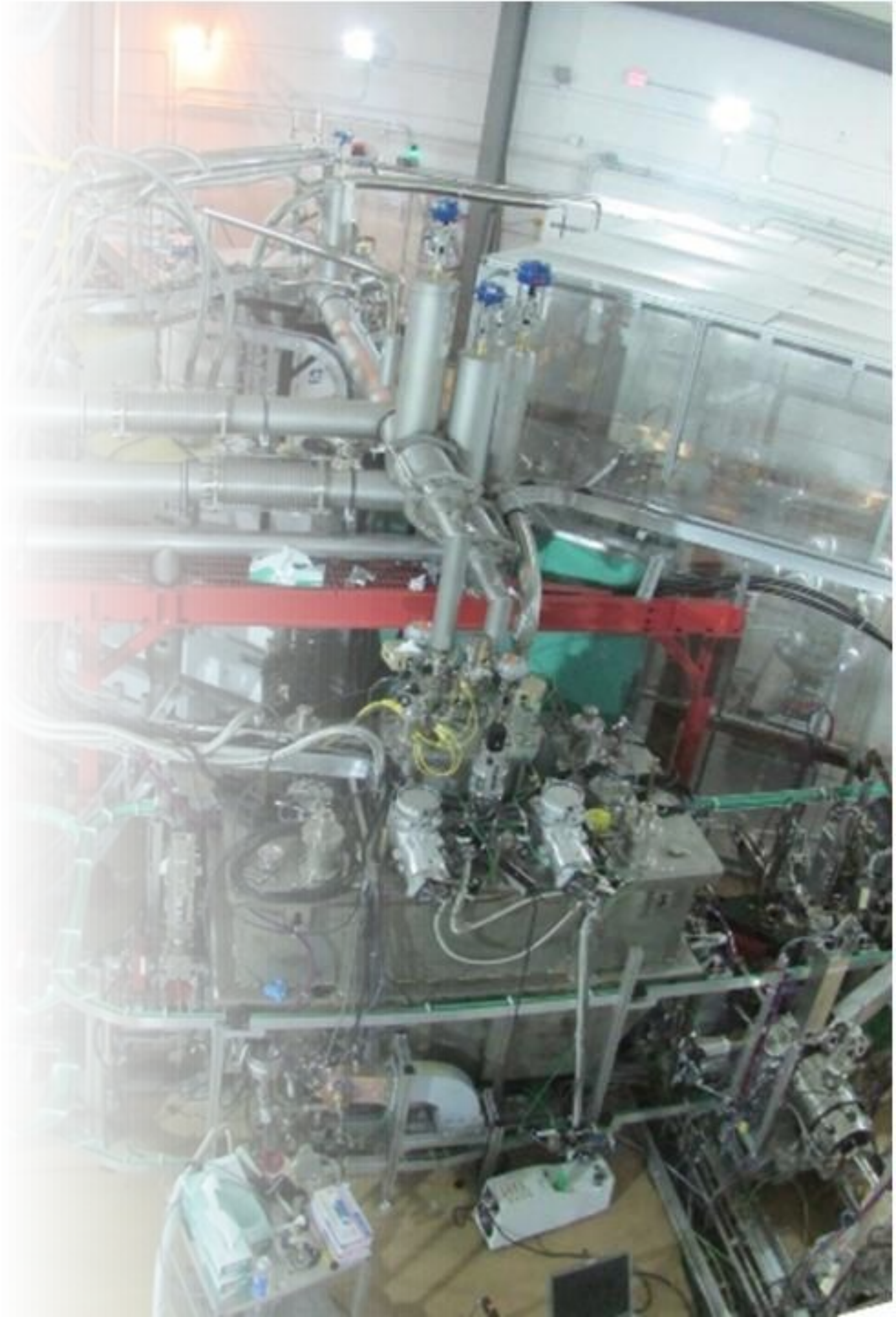
High Power RF Installation

- Now installed
  - Two CPI 290 kW cw 1.3GHz klystrons
  - Two 600 kW klystron power supplies from Ampegon
- Each klystron reaches specification at the factory and were tested at TRIUMF with available loads or circulators
- Now in operation since commissioning started and part of the reliability improvement program
- It’s planned to procure a 130 kW SSA for the injector cryomodule and make the klystron available as backup and later for the second accelerator cryomodule.

Discovery, accelerated

TRIUMF

e-linac operation and future perspectives



High-Power Commissioning Timelines

31 MeV at low beam power

30 MeV at 10 kW

Dec. 2019

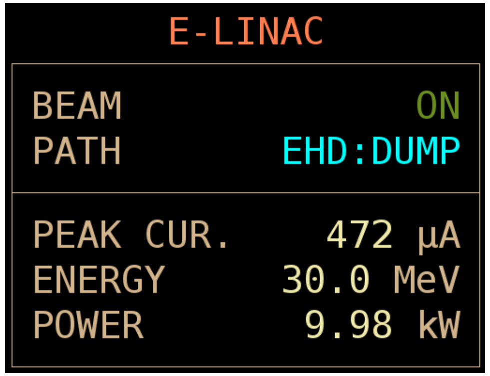
Feb. 2020

Dec. 2020

Sep. 2021

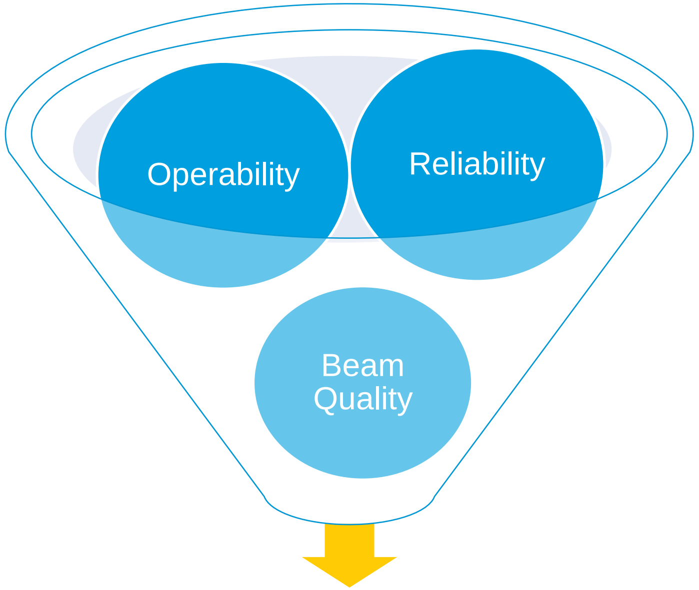
1 kW 7 MeV

26 MeV at 1 kW



September 13th

Roadmap after 30 MeV @ 10 kW



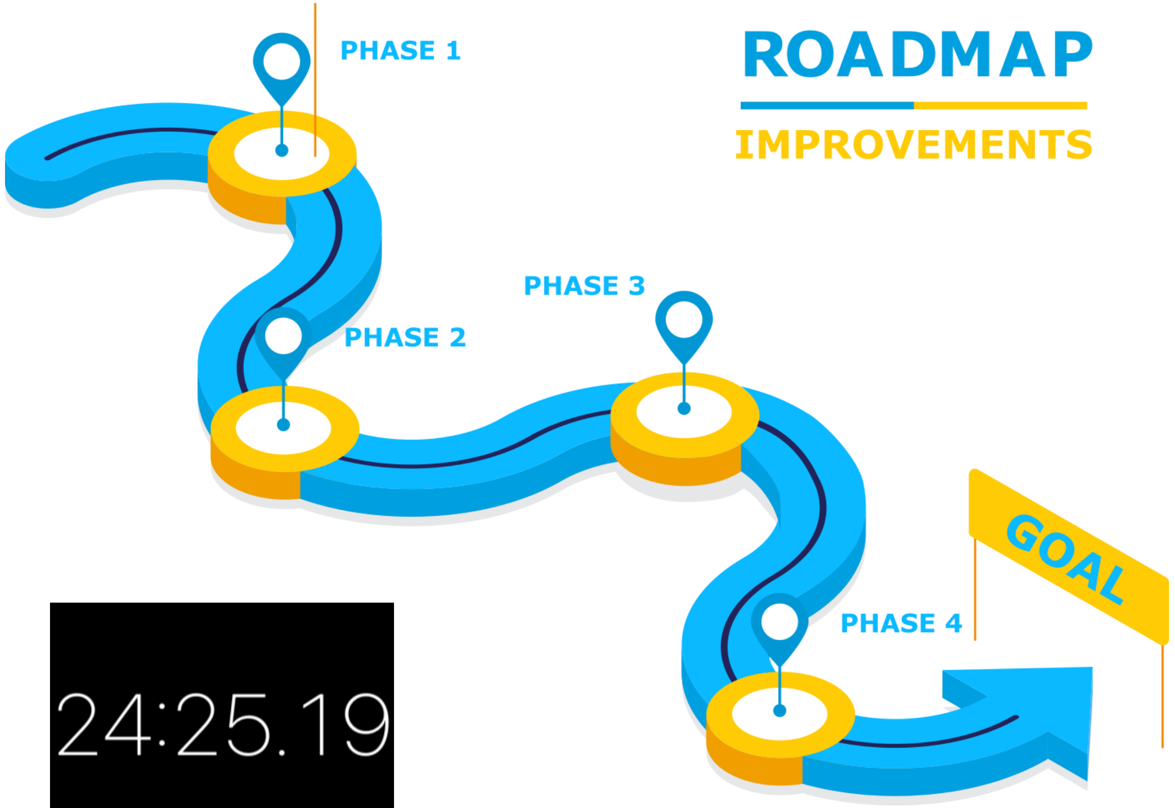
GOAL

PHASE 1: Startup in less than 30 min:
From lock up to beam ON.

PHASE 2: 8-hour continuous beam delivery.

PHASE 3: Energy stability better than 0.1%.

PHASE 4: 3-day continuous beam delivery.



Prep for FLASH irradiation

FLASH irradiation research

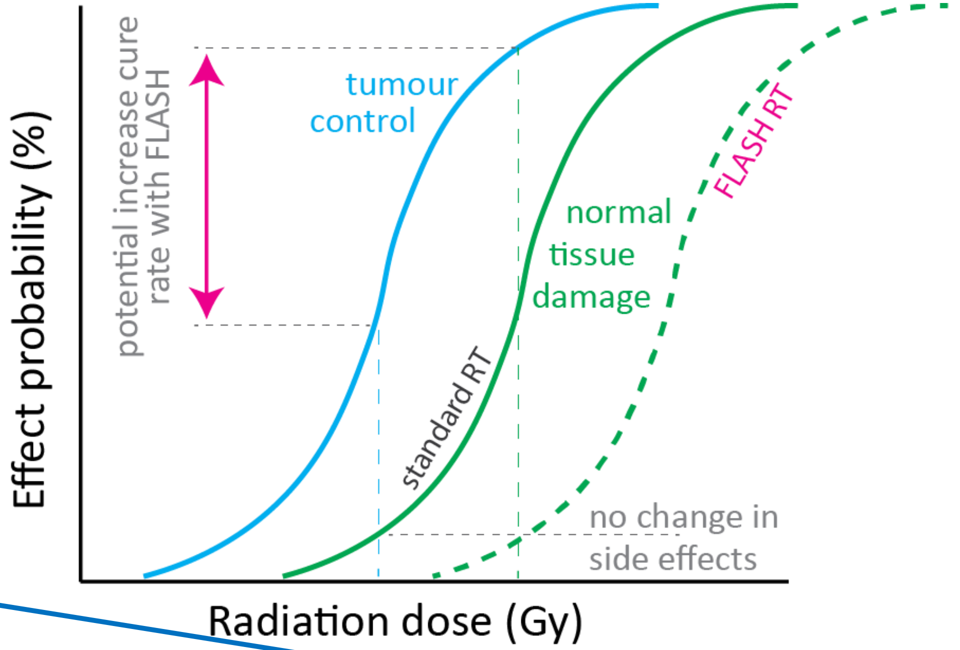
Conventional dose rate ~ 0.03 Gy/s

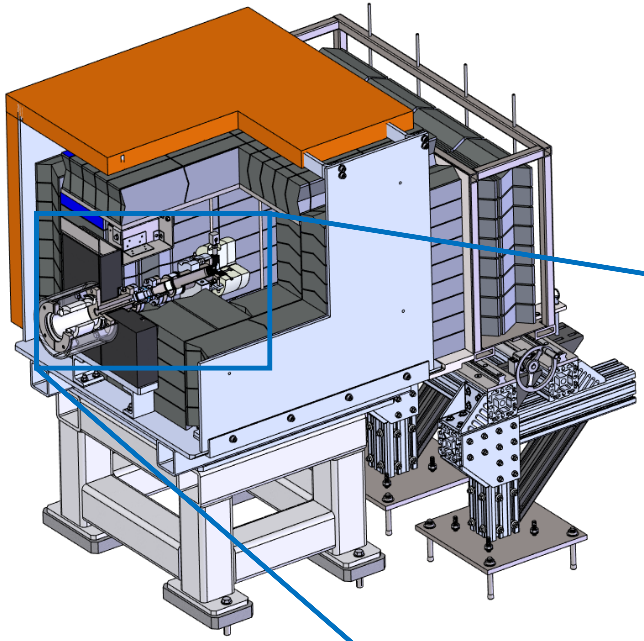
- In 20 – 30 fractions to affect all cell cycle phases, and to reach the hypoxic centre of a tumour

FLASH dose rate < 40 Gy/s

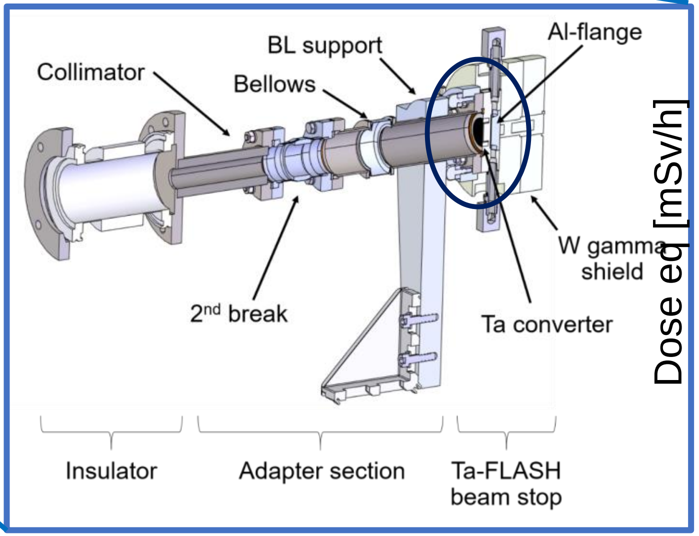
- Lower toxicity in healthy tissue but same tumour control
- Oxygen – depletion hypothesis, healthy tissue becomes basically hypoxic
- Uses the γ-conversion, but for high dose rates, convertor will be removed.

Increase therapeutic index by protecting healthy tissue

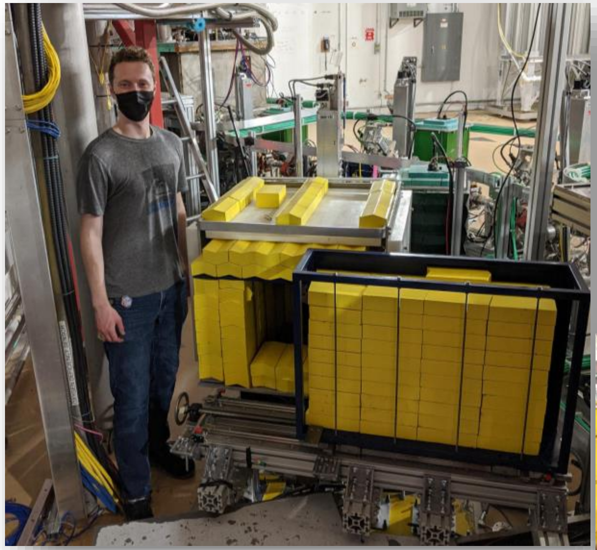




Structure + shielding



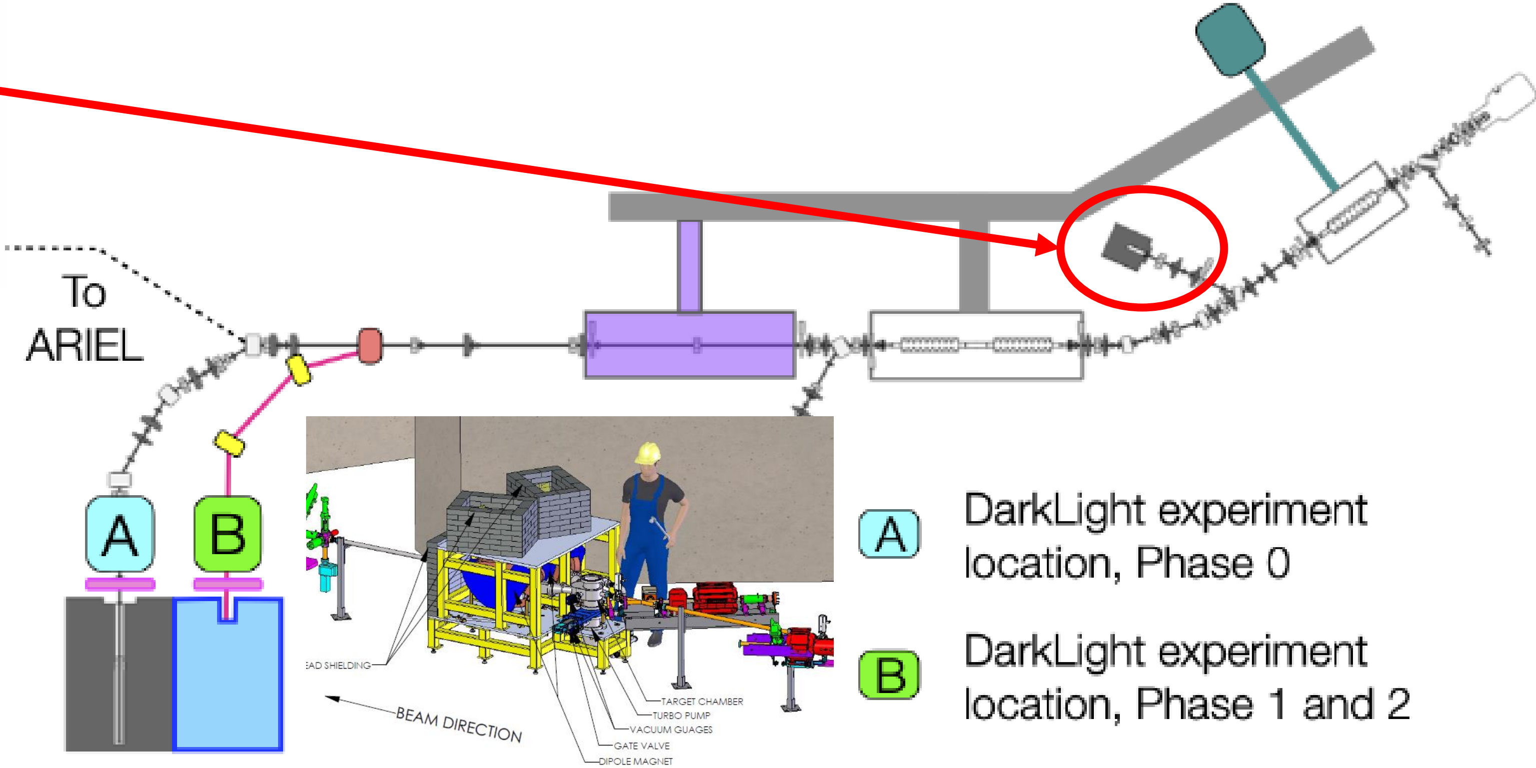
Early science supported by the ARIEL e-linac



PhD Nolen Esplen, UVic

FLASH irradiation test involve the ultra-fast delivery of radiation. It is enabled by the new ARIEL convertor technology:

- Studies comparing response to identical dose deposited with FLASH and conventional rates in mice, fruit flies and DNA samples have been completed.
- FLASH does rates about 100 Gy/s, conventional 0.1 Gy/s



- Dark matter search – DARK LIGHT experiment looking for a 5th force (dark photons) at a low energy e-linac
- First target test at 30 MeV and 10 nA completed
  → test of radiation background, target foil integrity etc.

DARKLIGHT - Detecting A Resonance Kinematically with eLectrons Incident on a Gaseous Hydrogen Target

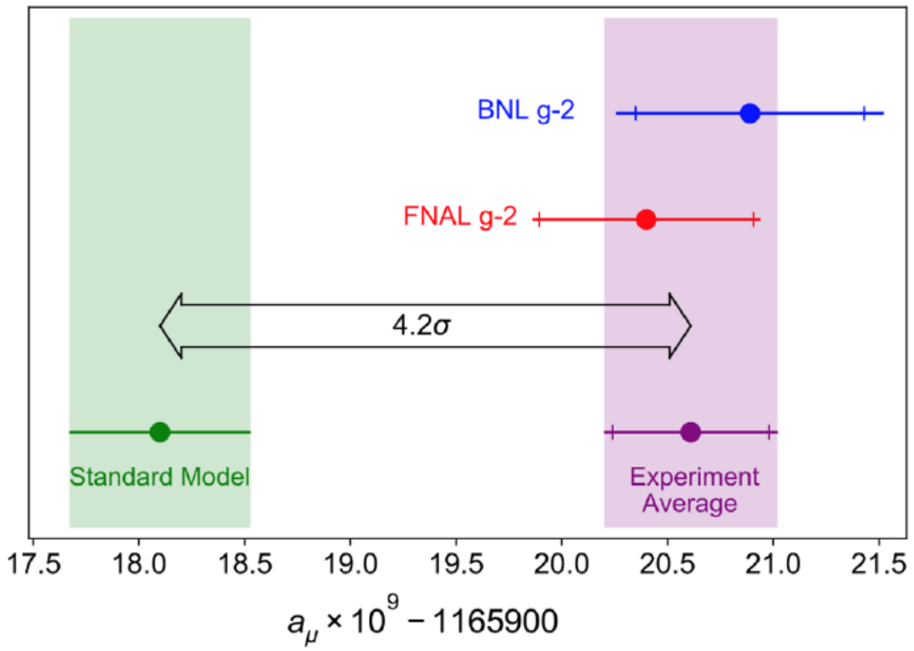
- Impetus for searches for a new massive, dark photon
  → recent astrophysical observations and measurements of the anomalous magnetic moment of the muon and the Standard Model expectation → g-2 experiment at Fermilab

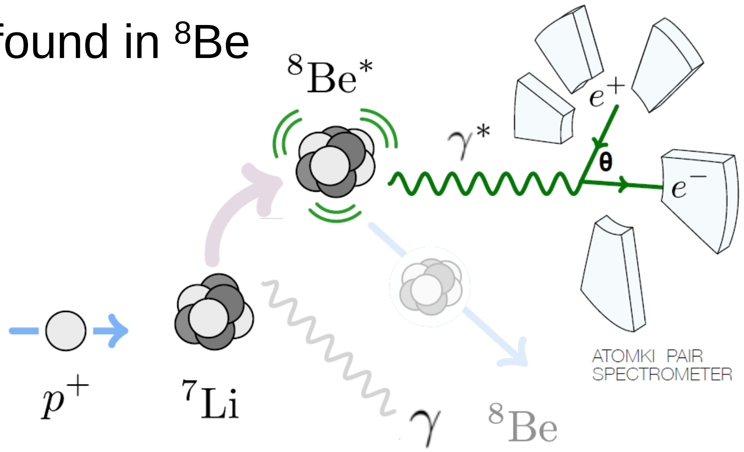
- The DarkLight experiment has been designed to search for evidence of dark matter particle in electron scattering from a hydrogen gas target, originally at Jlab, USA.
  Now will be adopted to lower electron beam energies (<100 MeV) as the expected resonance is expected in the invariant mass region around 17 MeV.

- 17 MeV is motivated by the Atomki anomaly found in ^{8}Be
  - ^{7}Li(p,γ)^{8}Be - two highly energetic states, decay to the ground state via E/M
  - Measurements of e$^\pm$ pairs from internal conversion reveal a signal at 17 MeV.
  - New results on ^{3}H(p; γ)^{4}He

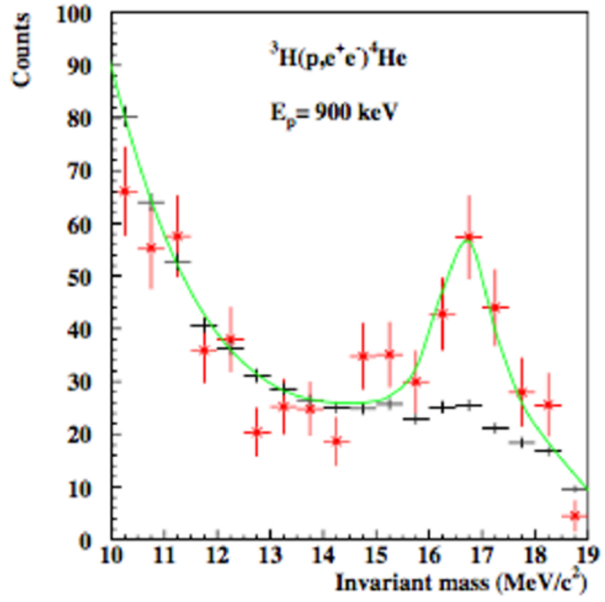
  Therefore, measurements of this "X17" at an electron accelerator.

Muon g-2 Discrepancy

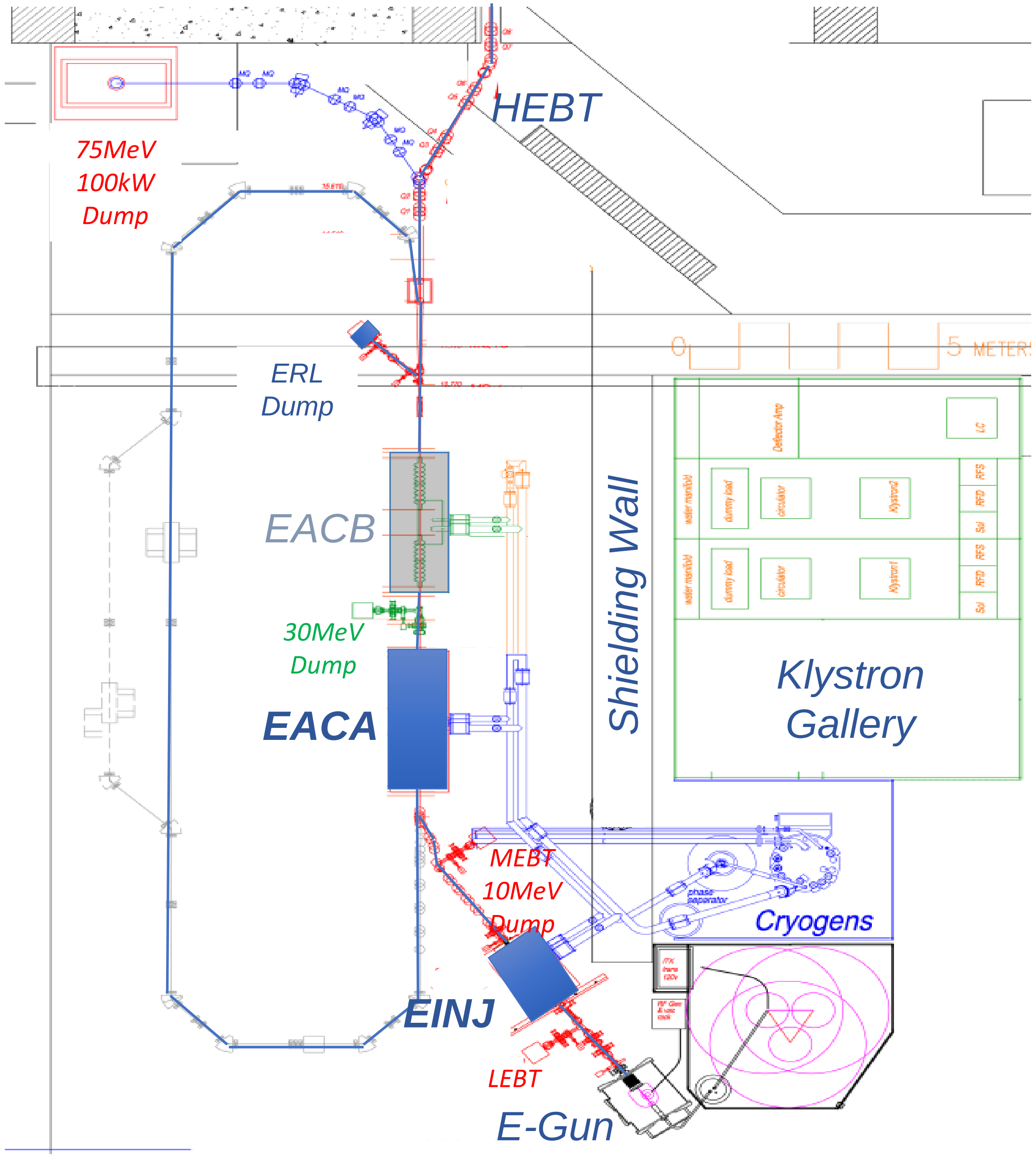




X17 in 4He and 8Be

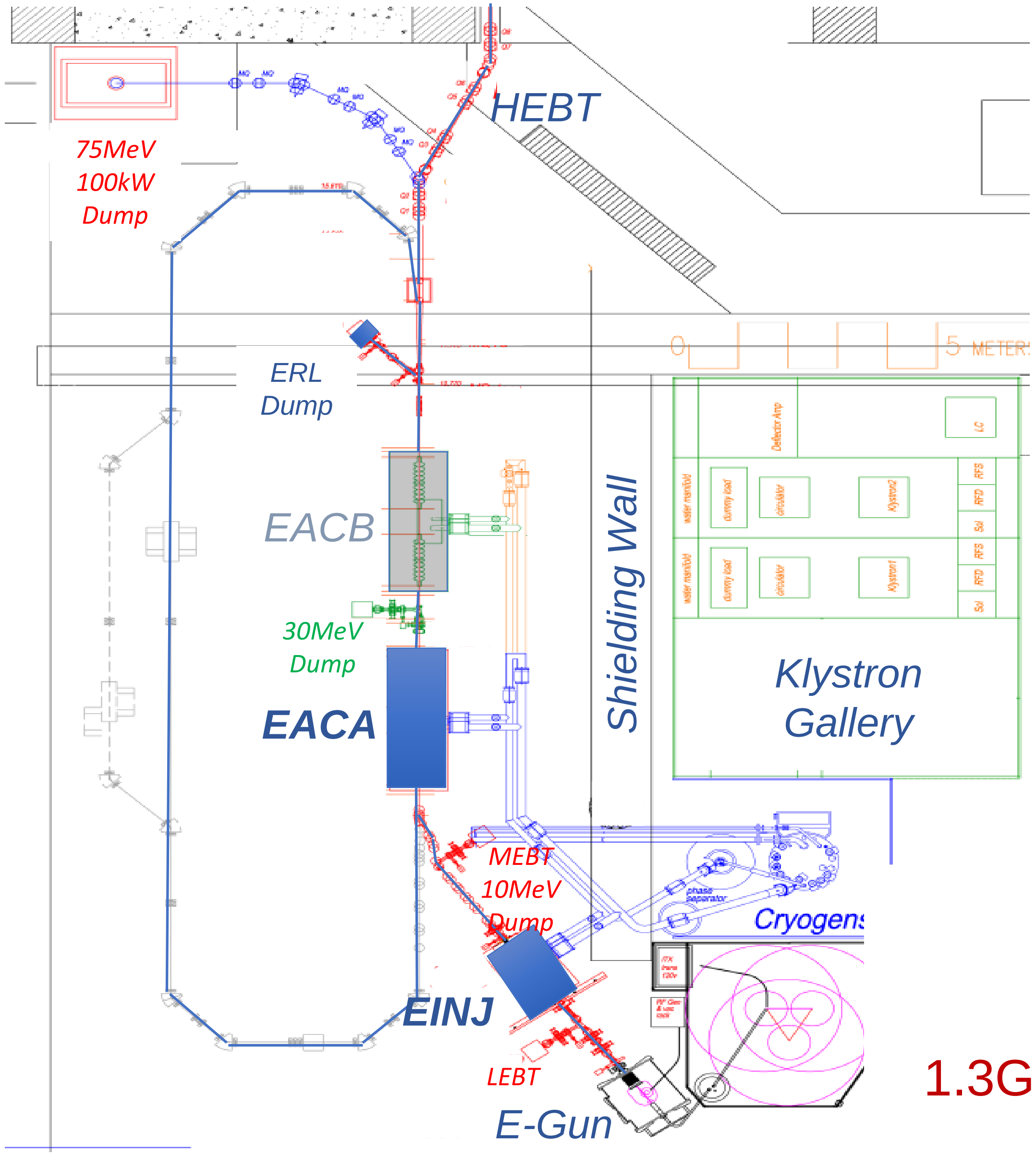


The ARIEL e-Linac as a re-circulator



- The linac is configured to allow a recirculating linac (RLA) for a multi-pass `energy doubler’ mode
  → can reach 50 MeV required for DARKLIGHT
- or to operate as an energy recovery linac (ERL) for accelerator studies and applications (high energy beam cooling, BBU limits etc.)

Recirculating modes

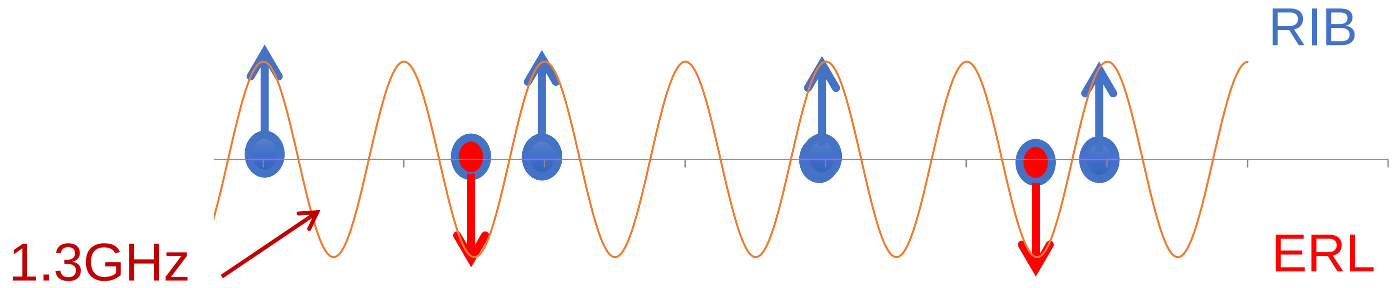


Re-circulation (energy doubler)

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

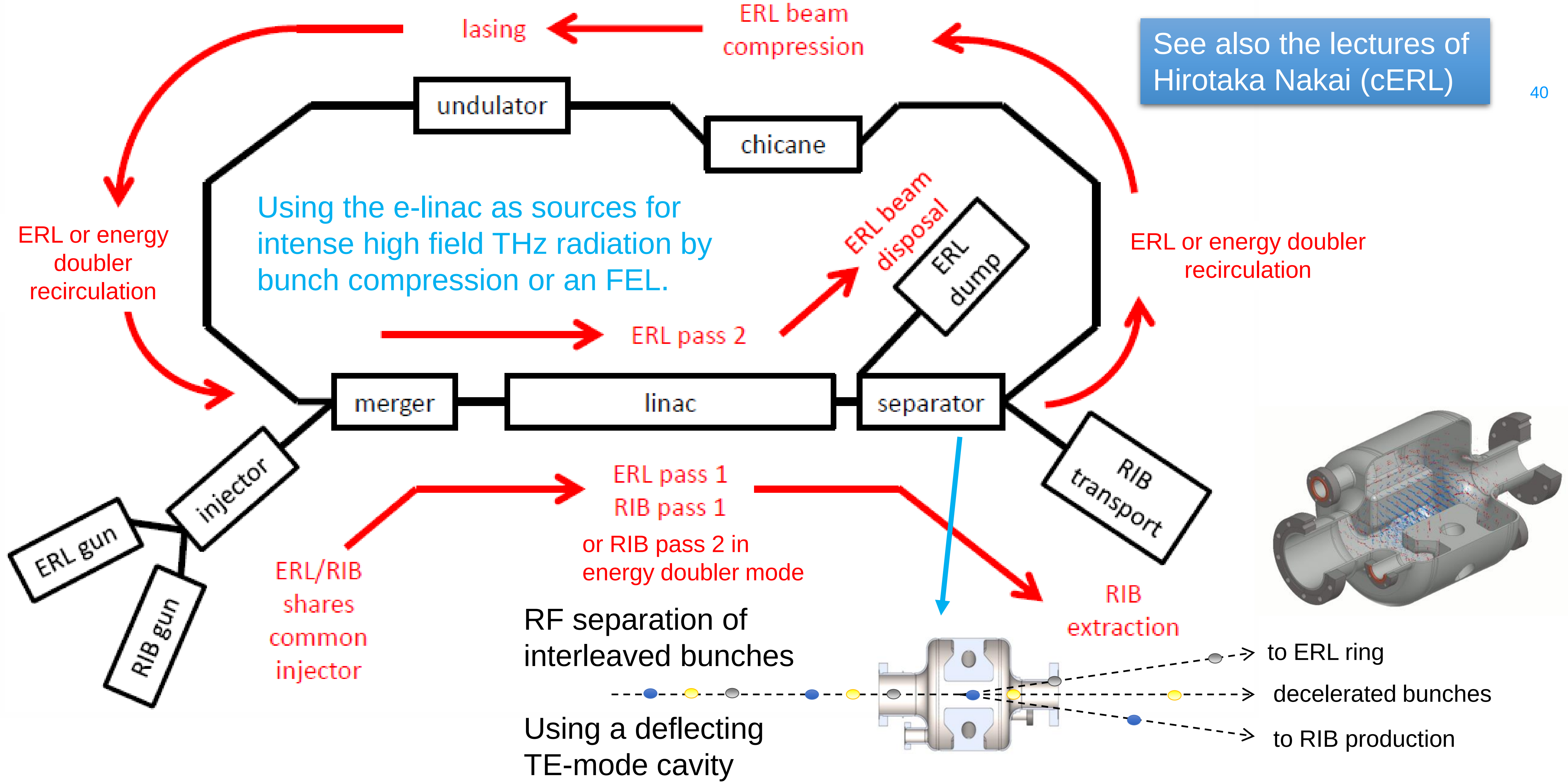
Energy Recovery LINAC (ERL)

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



Future dual use ERL/Linac

See also the lectures of Hirotaka Nakai (cERL)



Thanks for your attention!

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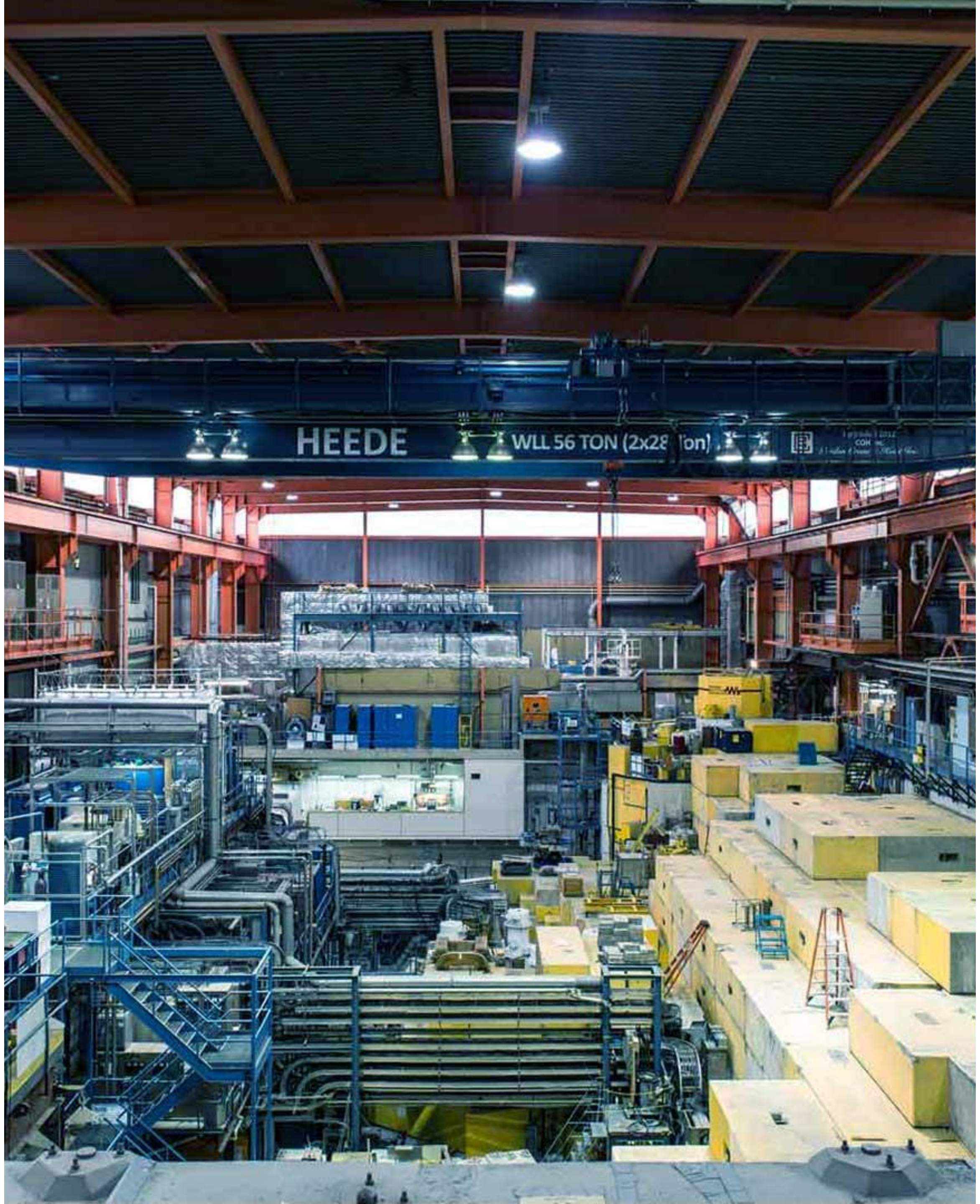
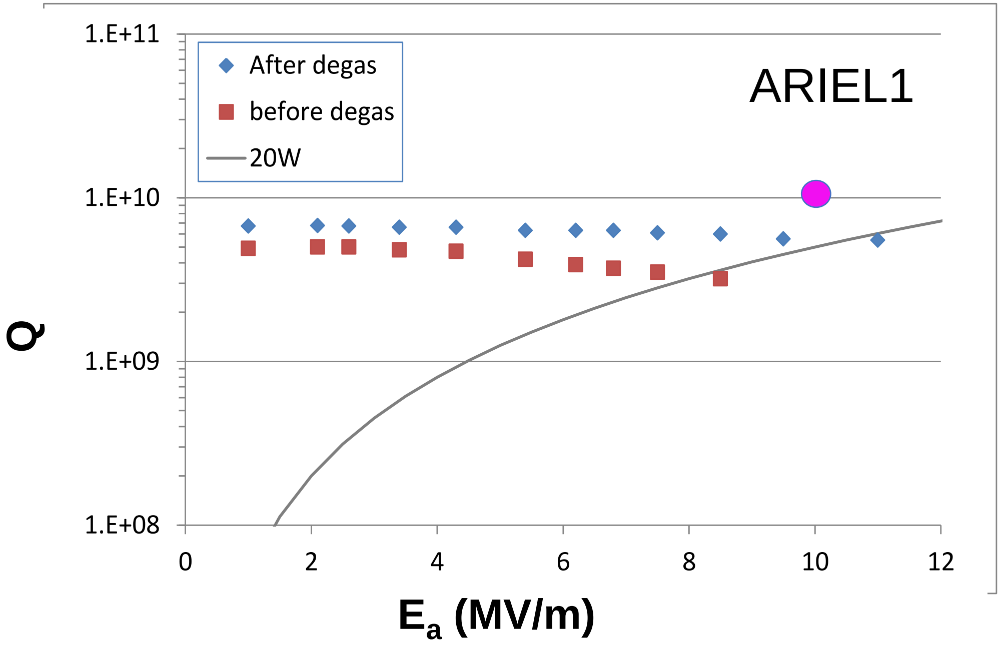


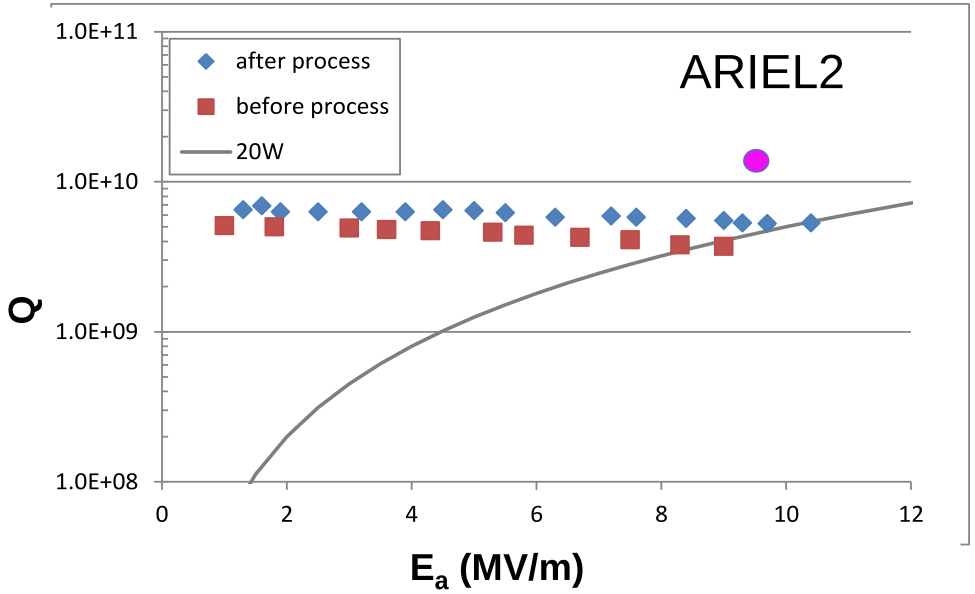
Discovery, accelerated

Additional slides

ARIEL linac cavities

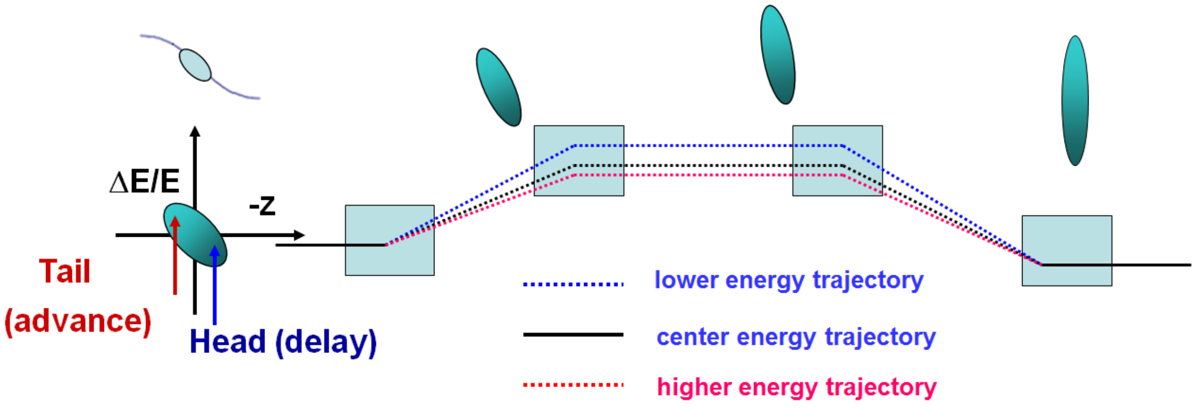
- Cavity vertical cold tests in ISAC-II before and after re-process
- Both cavities reach the specified gradient of 10 MV/m but at $Q_o = 6 \cdot 10^9$
- For Phase I we have lots of cryogenic power so derate specification to $Q_o = 5 \cdot 10^9$
- Strategy was to utilize ARIEL1 and ARIEL2 to characterize the cryo-engineering of the cryomodules and use ARIEL3 to optimize the process.

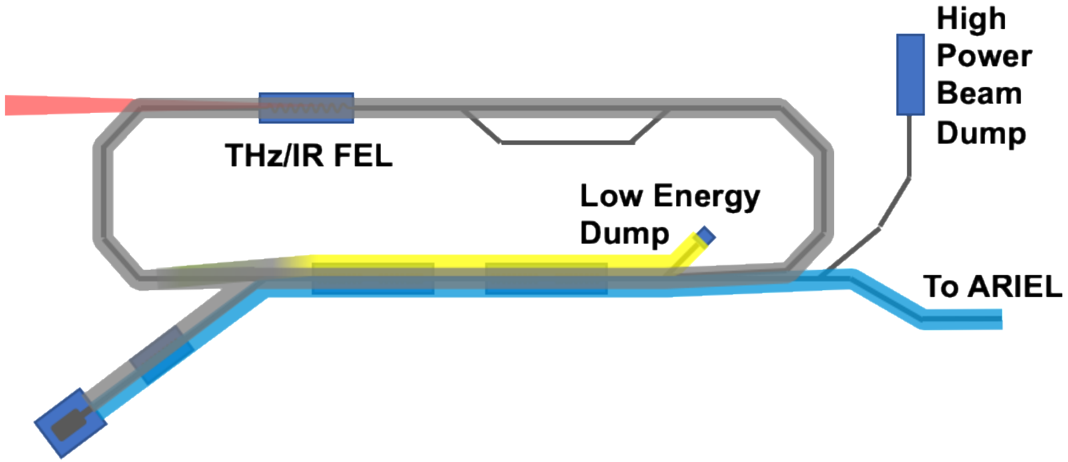




Using the e-linac to generate THz radiation Infrastructure for photon science community

- Using the e-linac as sources for intense high field THz radiation by bunch compression or an FEL.
- Terahertz region is now receiving increasing attention due to the progress in developing powerful radiation sources based on lasers and electron accelerators.
  → e-linac can produce THz radiation with extreme high electric field for pump-probe experiments.
- The IR and THz frequency region of spectra is widely used for research in physical, chemical, biological, material and life sciences as well as industrial applications.





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