TRIUMF

Radioactive Ion Beams (RIB) at TRIUMF

Oliver Kester

Director, Accelerator Division

GSI Beschleunigerseminar

November 3, 2022

Discovery, accelerated

TRIUMF

Outline

- Introduction: TRIUMF
- Overview TRIUMF’s secondary particle production facilities
- Driver accelerators: Cyclotron and e-linac
- Production, preparation and post acceleration of rare isotope beams - ISAC
- The future of rare isotope science at TRIUMF - ARIEL

TRIUMF has five decades of experience in building a rich particle accelerator infrastructure that enables cutting-edge research while growing accelerator expertise.

Founded in 1968, the laboratory has delivered 50 years of science and innovation for Canada

Our mission is to serve as Canada’s Particle Accelerator Centre.

TRIUMF's Accelerator Division

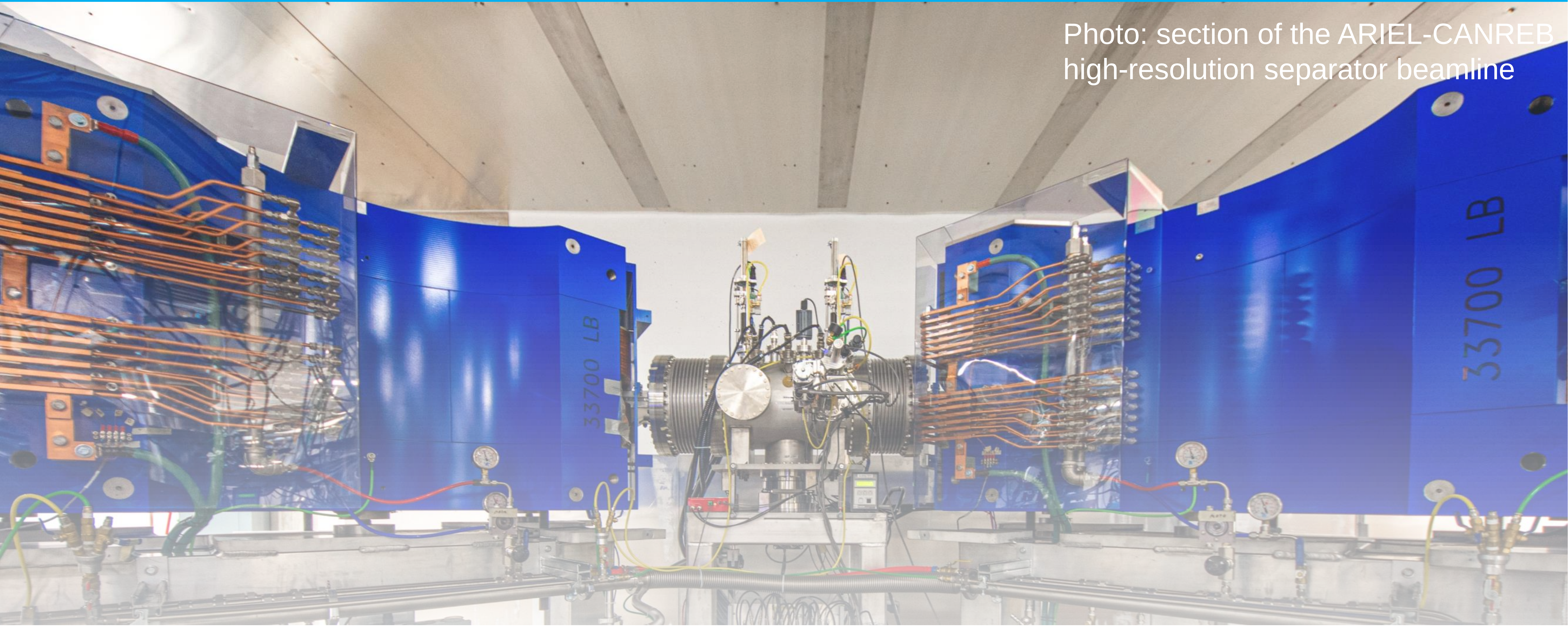


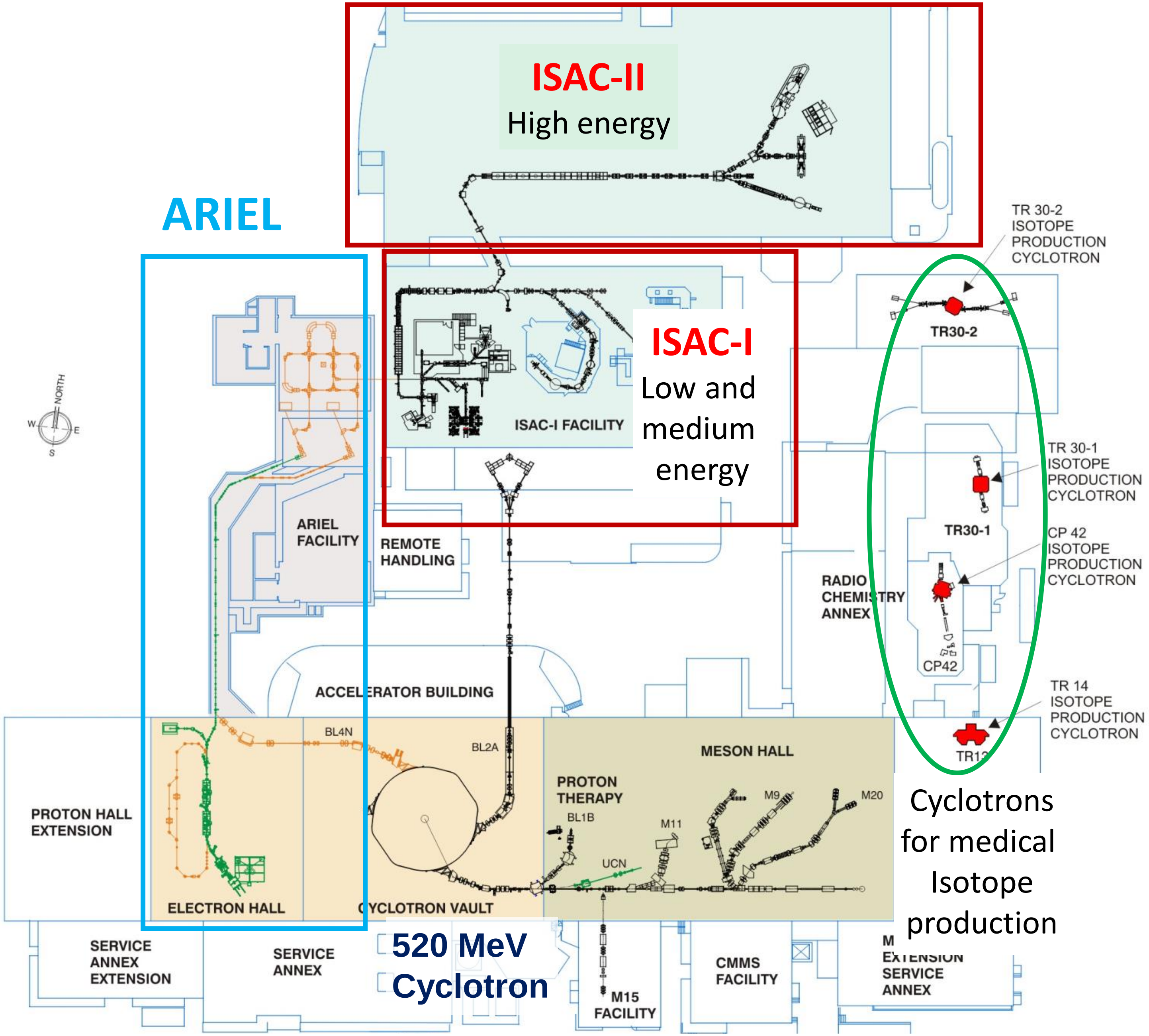
Photo: section of the ARIEL-CANREB high-resolution separator beamline

Our core mission: operate and develop TRIUMF's accelerator infrastructure and be a leader for accelerator science and technology in Canada.

To stay on top of the game: we leverage our infrastructure and expertise to pursue new technologies and new capabilities.

Overview TRIUMF’s secondary particle production facilities

TRIUMF accelerator complex



Primary beam driver:
Cyclotron, 520 MeV, H^-
Produces rare isotopes, neutrons and muons!

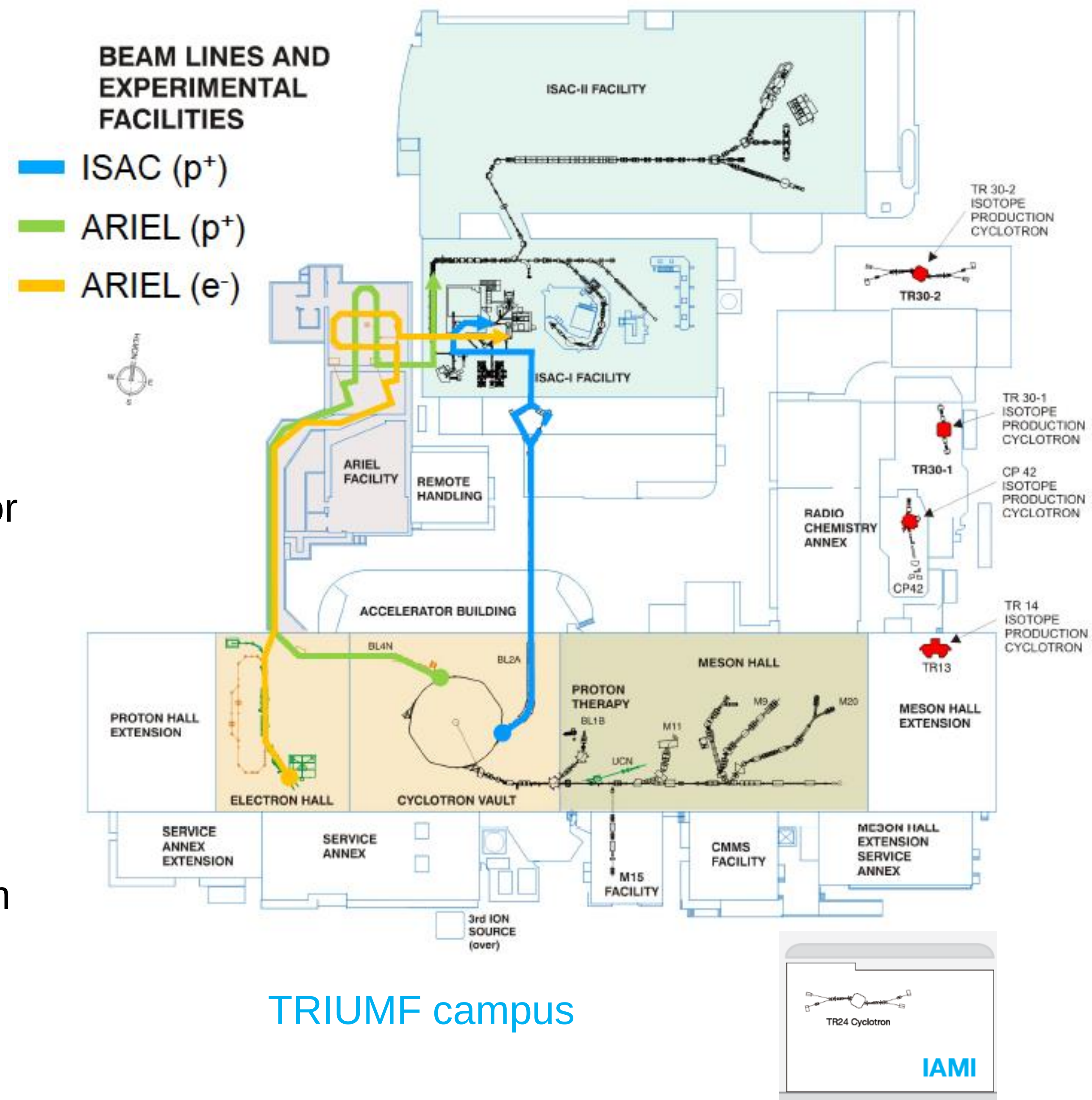
Isotope Separator and Accelerator facility - ISAC
Isotope Separator Online (ISOL) facility
ISAC-I: Normal conducting-linac, 0.15-1.8 MeV/u
ISAC-II: Superconducting-linac, 1.5-16.5 MeV/u

Advanced Rare Isotope Laboratory - ARIEL
Superconducting electron linac (e-linac)
30 MeV, 10 mA, cw

4 Cyclotrons for medical isotope production
(Soon a 5^{th} cyclotron a TR24 in the Institute for advanced Medical Isotope – IAMI)

ARIEL - TRIUMF's flagship project

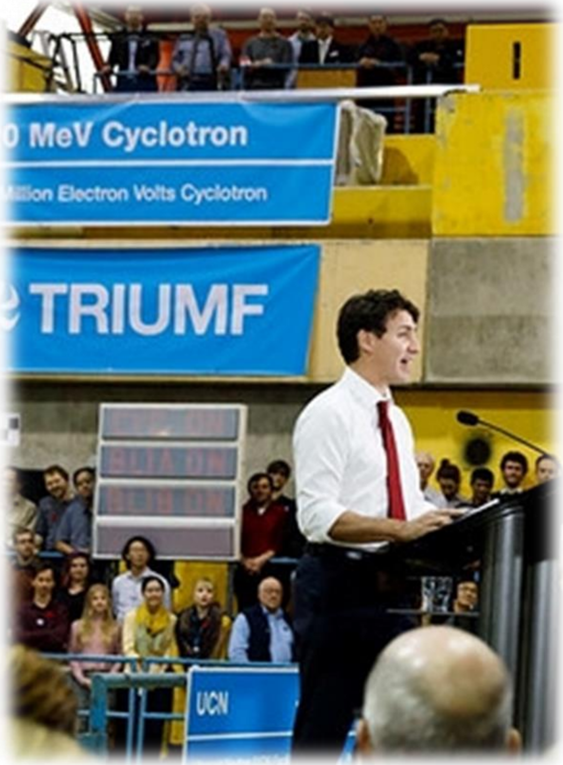
- Simultaneous RIB production from 3 targets
  - 50 kW existing ISAC proton target
  - 50kW new ARIEL proton target
  - 100kW new ARIEL electron target
- **ARIEL will triple ISAC's present rare isotope capabilities.**
- Multi-user capability with more and new isotopes for
  - Nuclear Structure and Dynamics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



TRIUMF campus

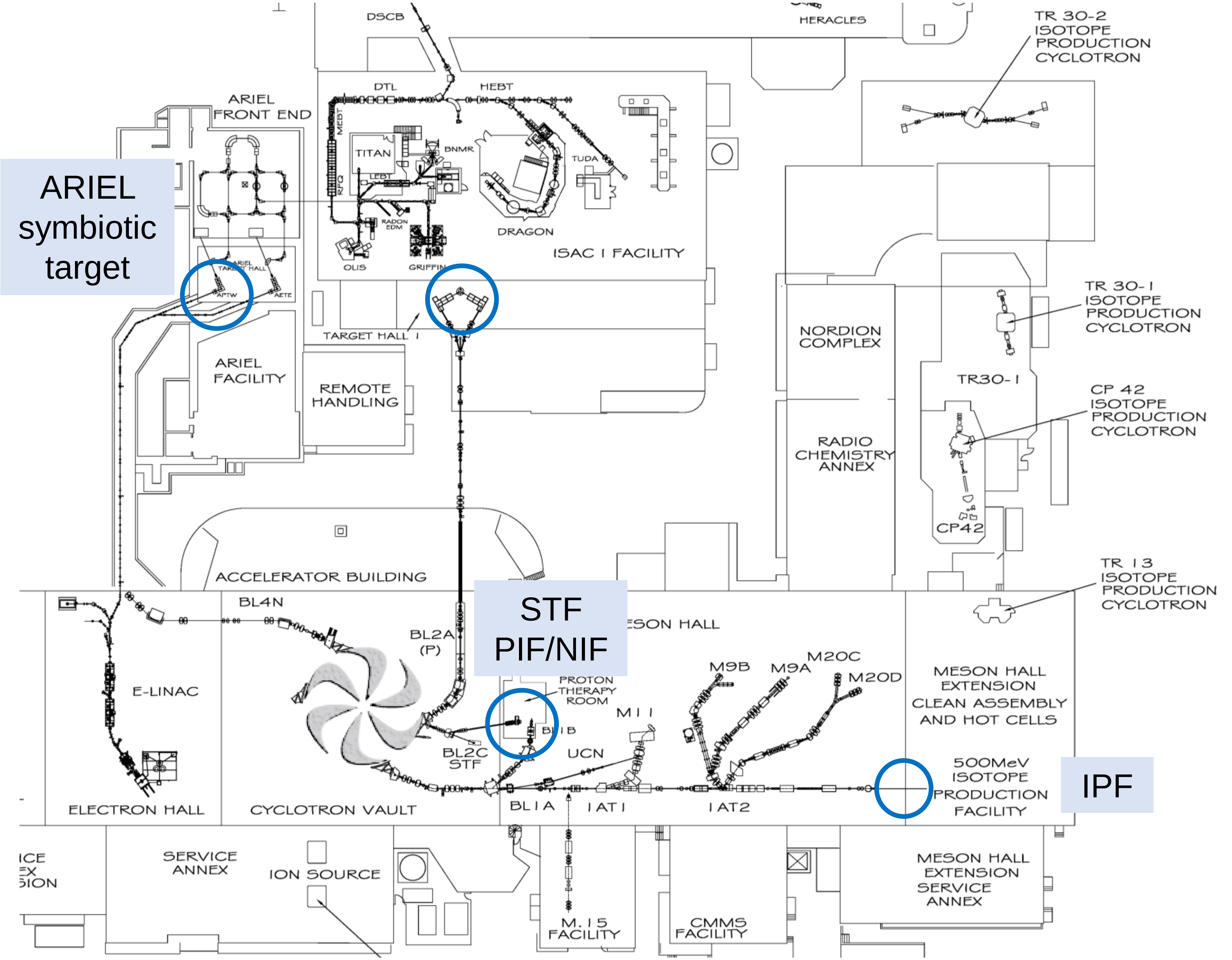
Institute for Advanced Medical Isotopes (IAMI)

- IAMI is a >$50M research and production facility
- IAMI will enable BC research into next-generation medical isotopes and radiopharmaceuticals.
- Located on the TRIUMF campus, IAMI will:
  - Provide provincial isotope security
  - Unlock development of next-generation cancer therapies
  - Enable clinical trials and cutting-edge medical research
  - Advance technological innovation and skills training
- Funding for IAMI was announced by Prime Minister Trudeau in Nov. 2018
- IAMI construction is completed; commissioning of the TR24 H- cyclotron is expected to begin end of this year.

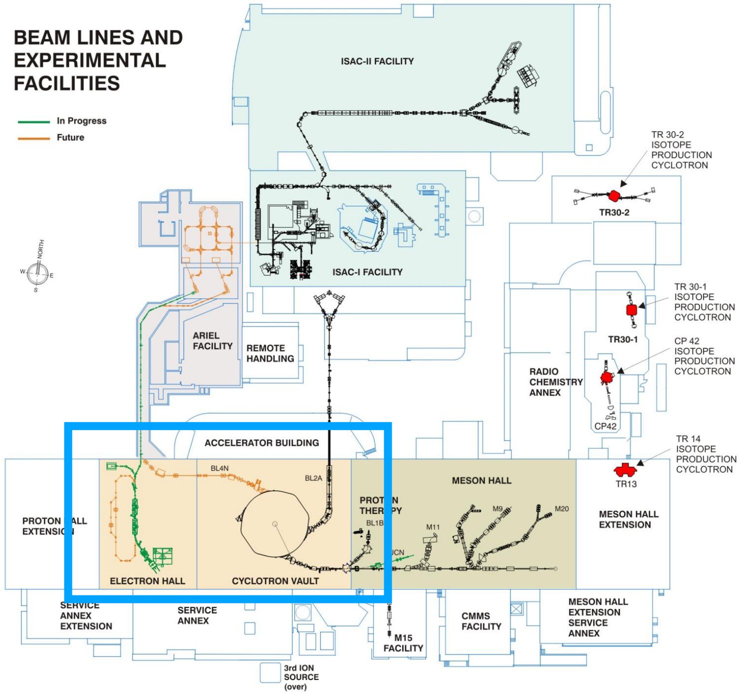


Overview of applications driven by the 520 MeV Cyclotron

- The 520 MeV cyclotron provides beam for medical isotope production (Nuclear Imaging & research on particle radiation therapy).
- Irradiation capabilities with protons and neutrons.
- Proton beams are delivered to
  - the Solid Targetstation Facility (STF) for Sr production [^{85}Rb(p,4n)^{82}Sr]
  - Isotope Production Facility (IPF)
  - Proton Irradiation Facility (PIF)
  - Neutron Irradiation Facility (NIF)
  - And in the future to the ARIEL Proton Target Station West (APTW) with the symbiotic medical target in the bam dump.

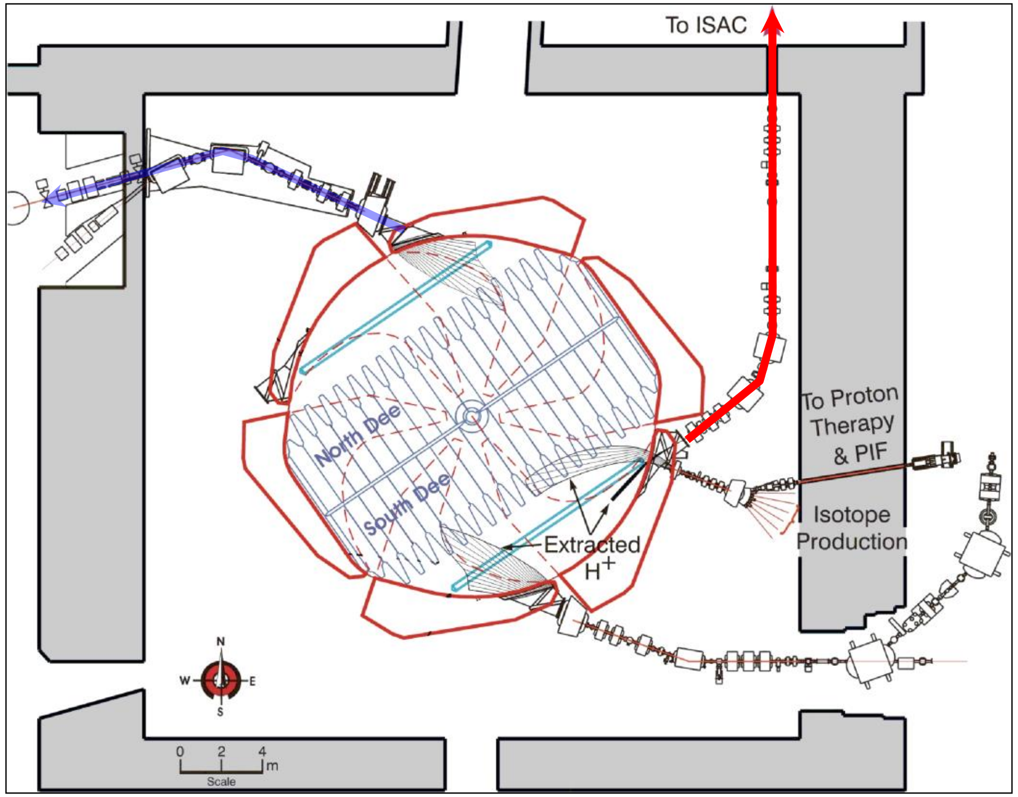


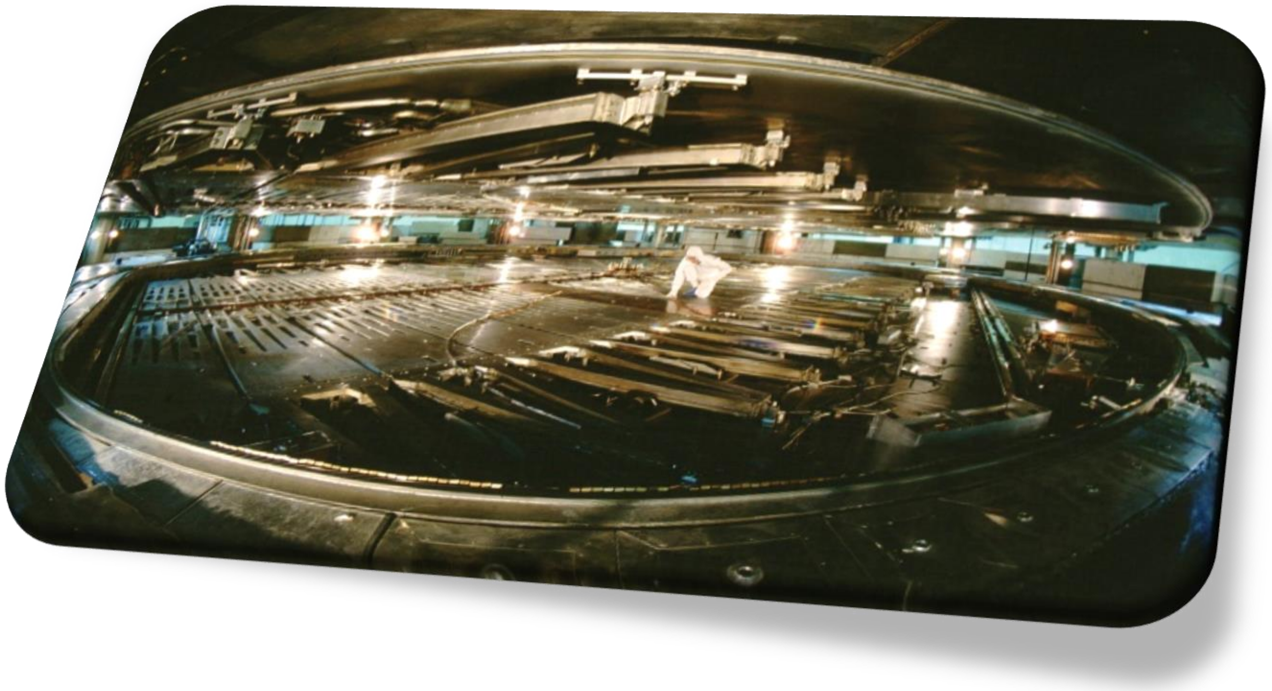
Driver accelerators – cyclotron and e-linac



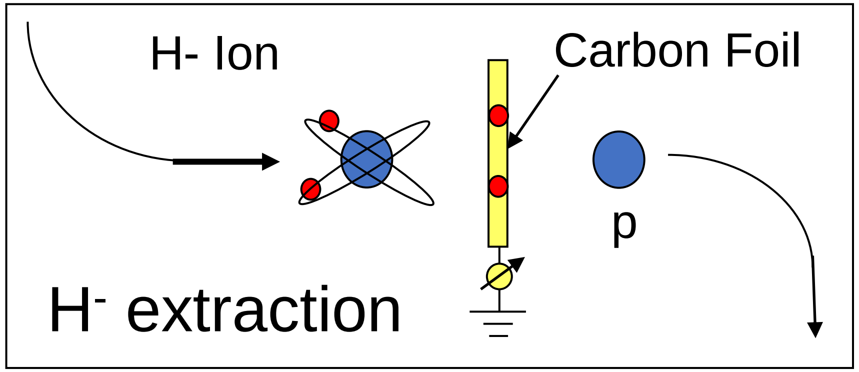
- Largest normal conducting Cyclotron in the world: D = 18 m
- Magnet weight: 4000 t, Coil current: 18500 A
- H- cyclotron (multiple extraction at different energies)
- 5500 hours of beam delivery per year

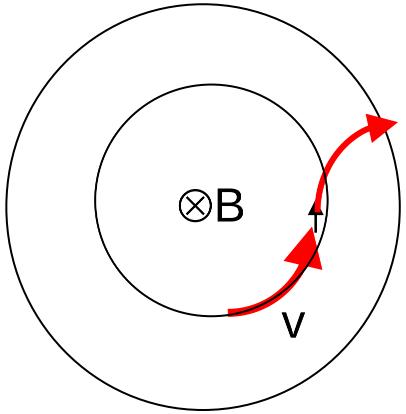
The 520 MeV H⁻-cyclotron





Proton beam energy can be varied between 70 and 480 MeV. Intensities up to 120 μA (>50 kW on target)





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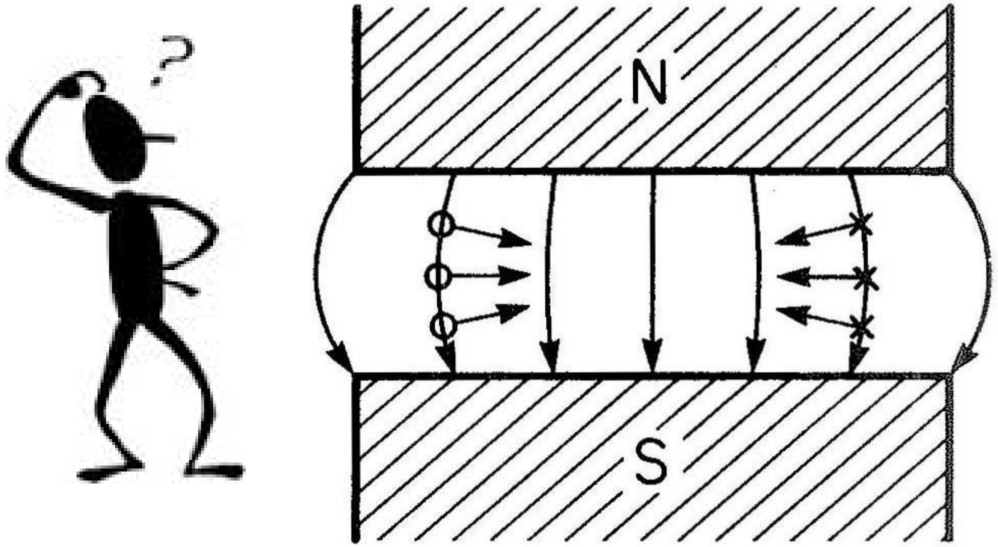
Limits of the classical cyclotron

Relativistic mass effect require a stronger magnetic field at the outside of the cyclotron that the particle stay in sync with the RF → isocyclotron

$$\omega_c = \frac{q}{\gamma \cdot m_0} B_z(r(\gamma)) = \frac{qB_0 \cdot \gamma}{\gamma \cdot m_0} = \frac{qB_0}{m_0}$$



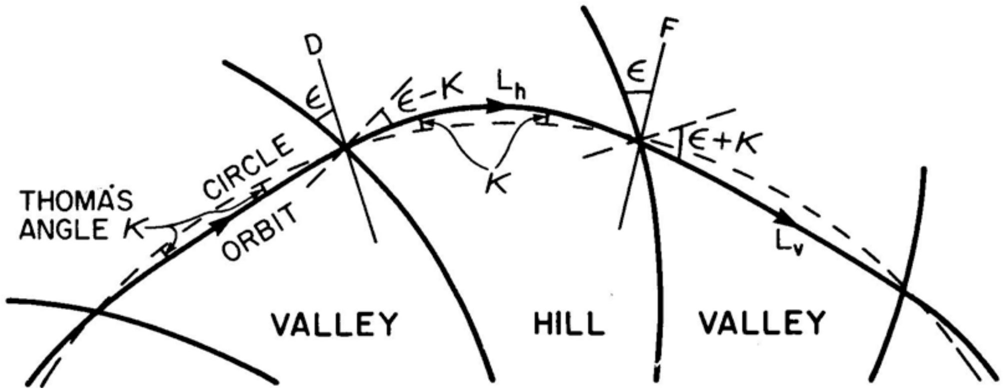
An outwardly-decreasing (negative-gradient) field ⇒ vertical focusing.
Positive axial focusing requires B decreasing with r → provided naturally by B fall-off towards pole edge.

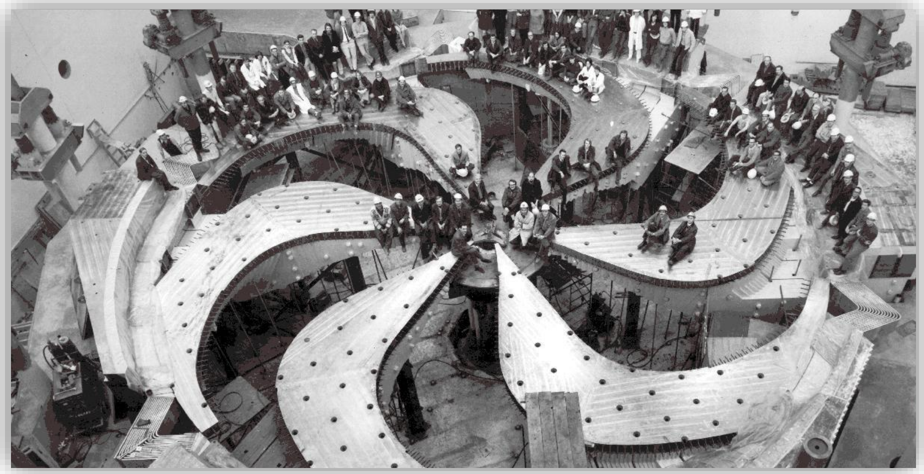
Solution to this problem:
The use of edge focusing to allow vertical focusing and stay isochronous.

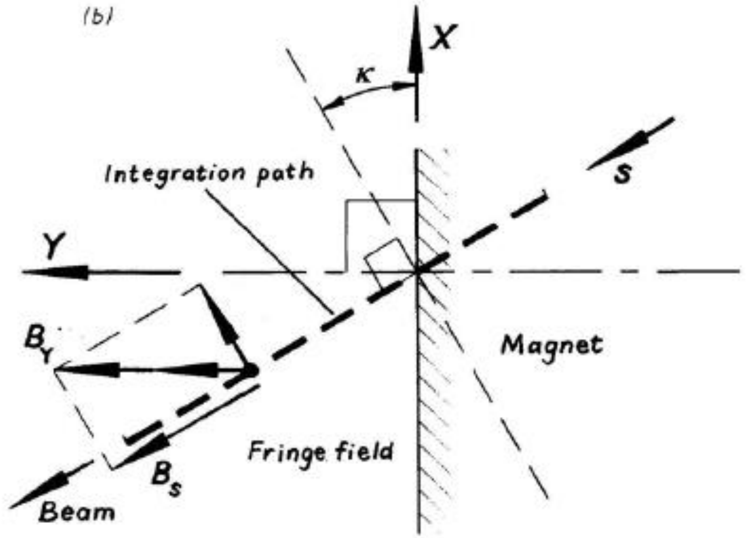
Edge focusing in the 520 MeV cyclotron

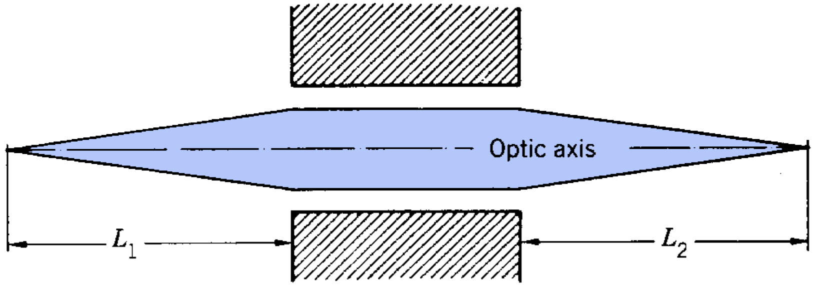
When a particle crosses a magnet end at an angle κ to the normal, longitudinal components of the fringe field B_y interact with velocity components v_x parallel to the edge, giving a vertical force!

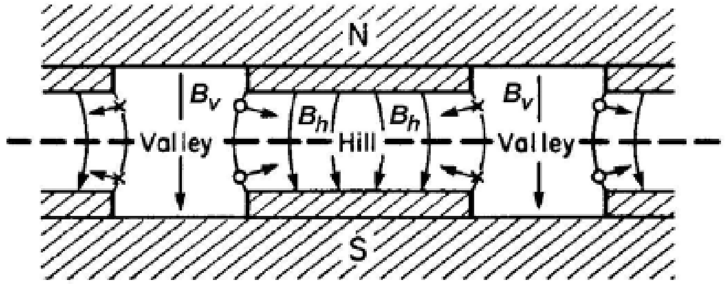
Kerst (1956) suggested using spiral sectors to increase the axial focusing







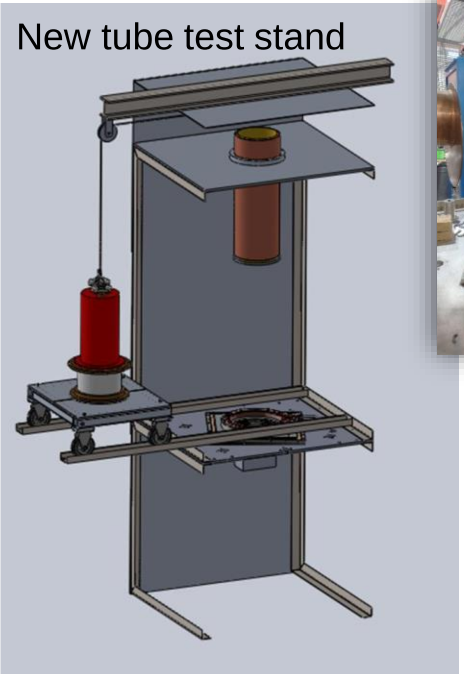


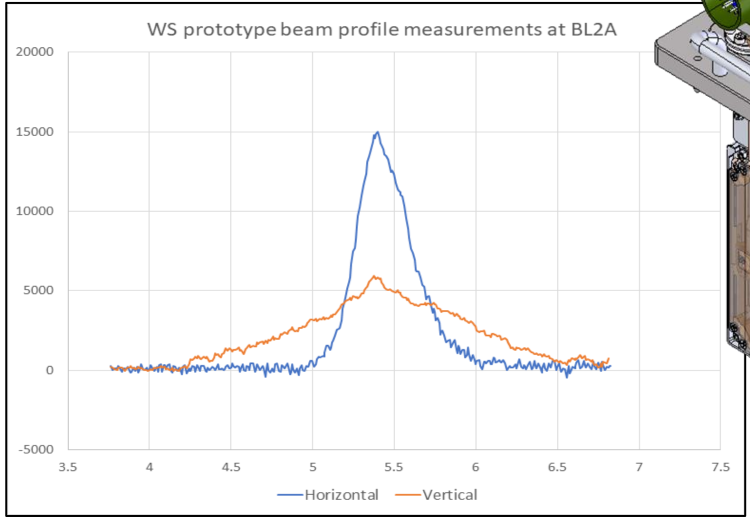


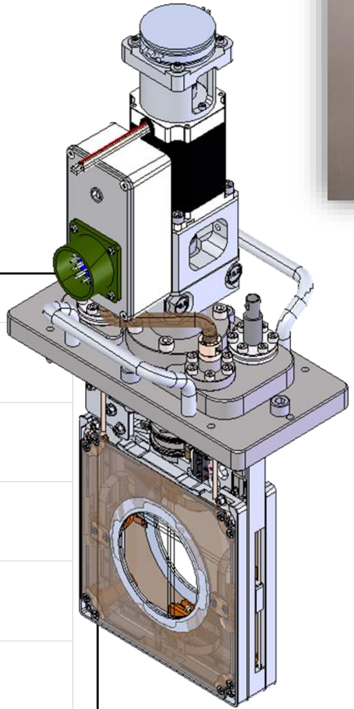
Significant cyclotron refurbishment program

TRIUMF is funding a significant refurbishment program addressing RF, vacuum, power supplies, upgrade of the control system, renewal of the cyclotron injector etc.

- BL1A power supplies replacement and prototyping of diagnostics with high dynamic range (nA to 250 μA)
- Cyclotron RF refurbishment - roadmap for 95 kV cyclotron gap voltage
  - New tubes and tube test stand is required for tube conditioning
  - New 0.8 MW dummy load for power amplifiers (250 kW each)
  - New digital LLRF



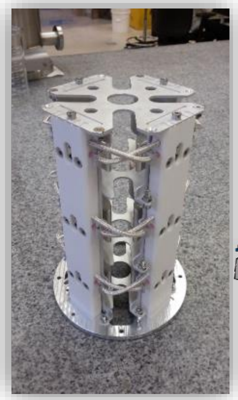


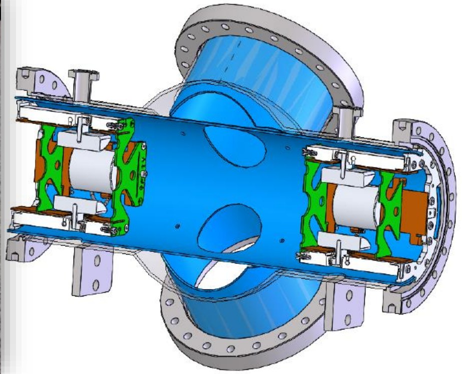


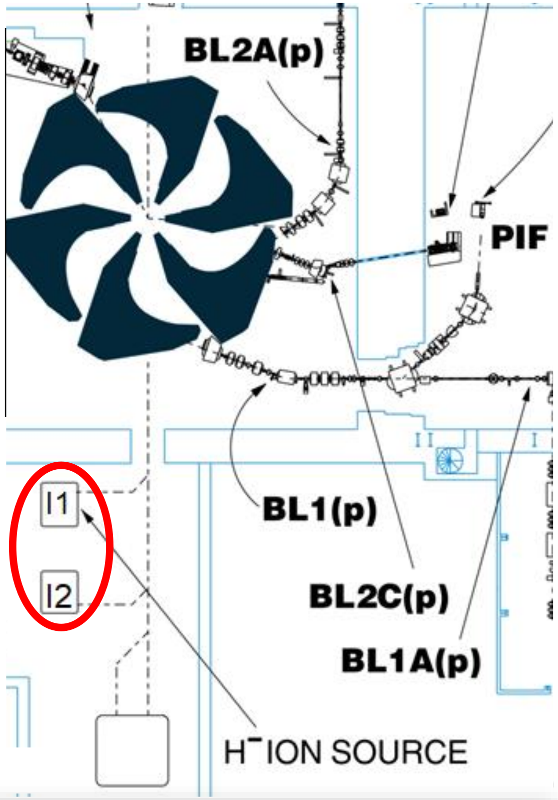
New high dynamic range diagnostics

Significant cyclotron refurbishment program

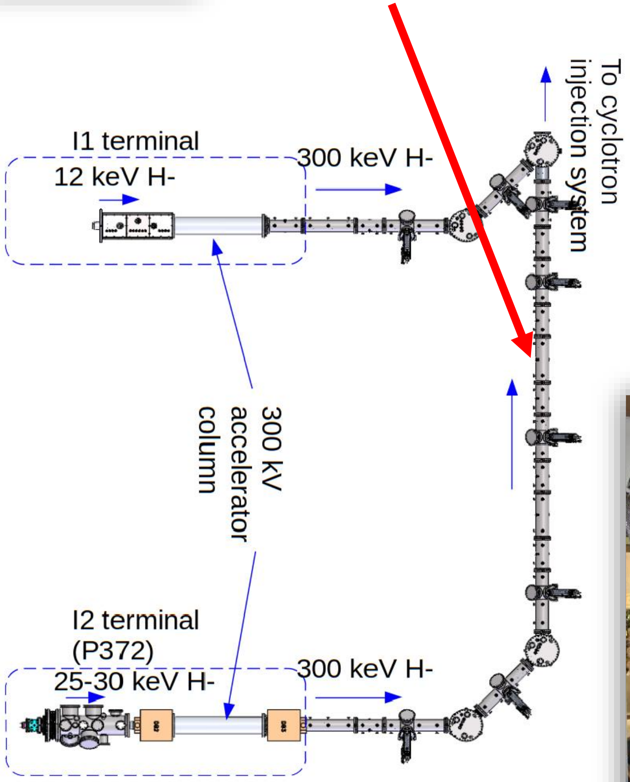
- Renewal of the horizontal part of the cyclotron injection beam line
  - Requires current feedback from skimmers and water-cooled collimators for machine protection
  - Mu-metal liners to shield from the cyclotron stray field
- Remote Handling infrastructure refurbishment
  - Extended ladder handling tool
  - Emergency trolley rescue winch
  - Bridge lift mechanism refurbishment





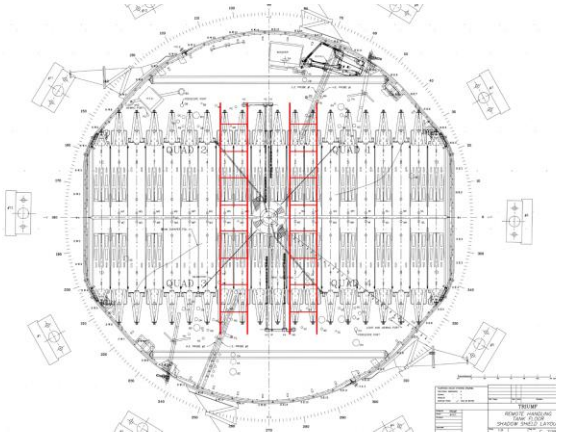


Extended Ladder Handling Tool



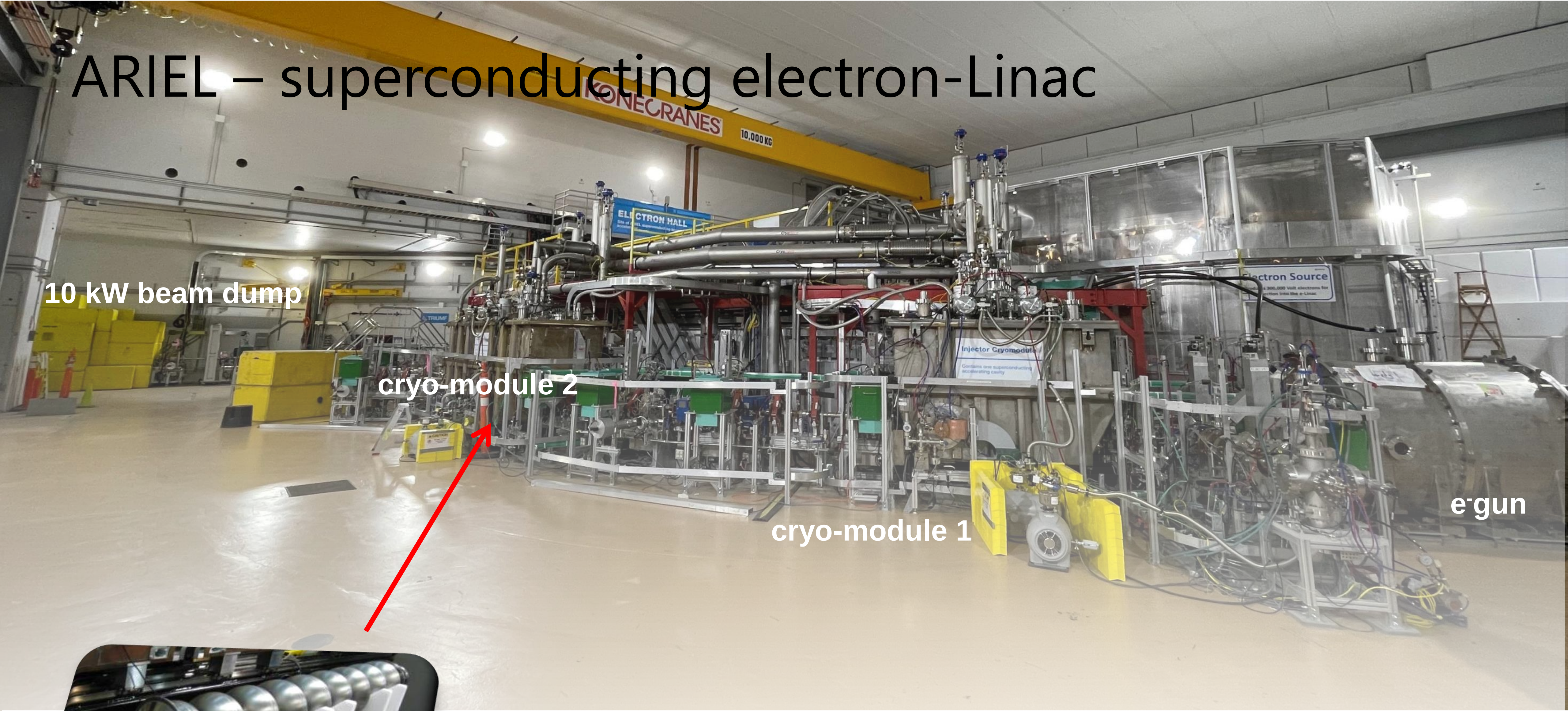
Extended Ladder Handling Tool

Ladder: ~6 m long, ~40 kg



Ladder position near centre post

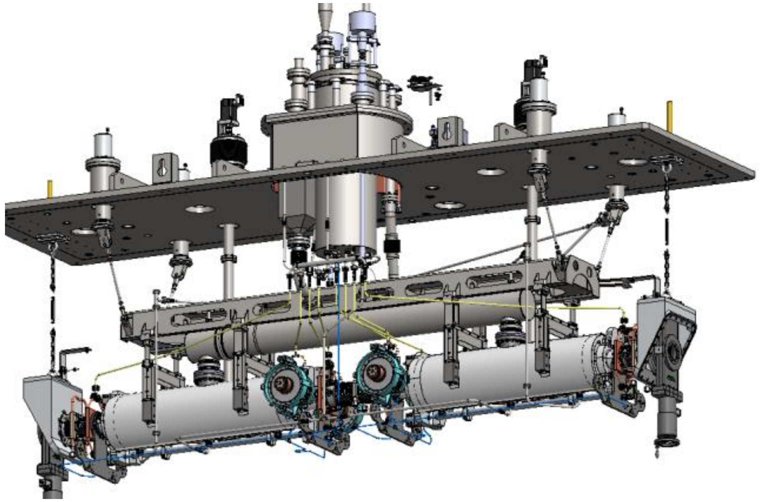
ARIEL – superconducting electron-Linac

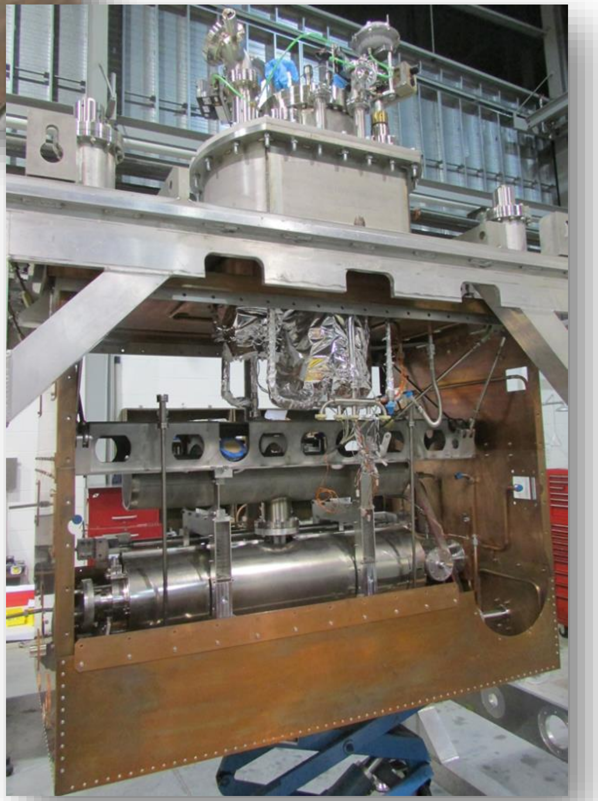


- E-gun delivers max. 10 mA at 300 keV beam
- The injector cryomodule (1) accelerates to 5-10 MeV
- The accelerator cryomodule (2) is equipped with two cavities and reaches max. 30 MeV.

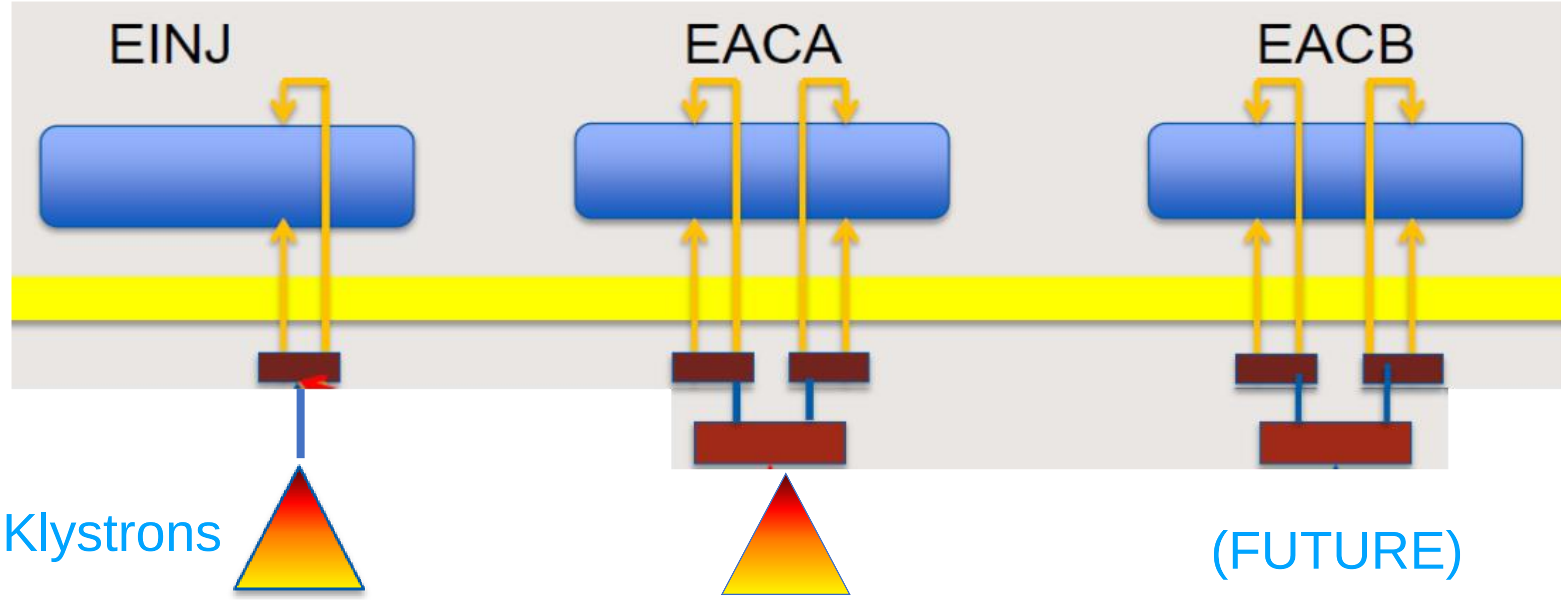
ARIEL – e-Linac modules

- Elliptical cavities, 1.3 GHz
- 9 cell, TESLA type
- 11 MV/m demonstrated





Singe cavity injection module



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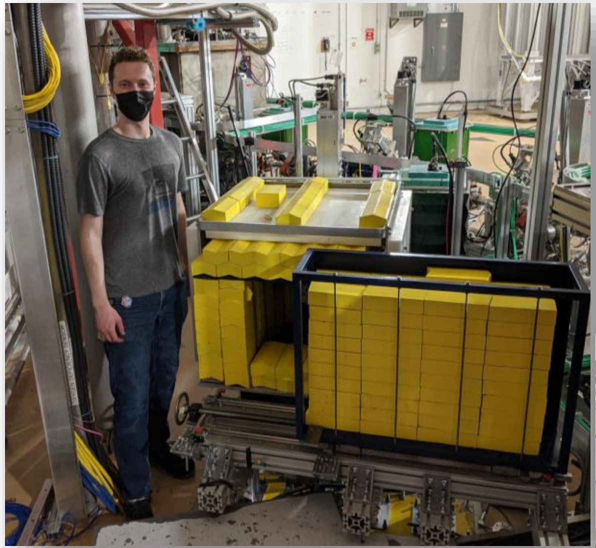
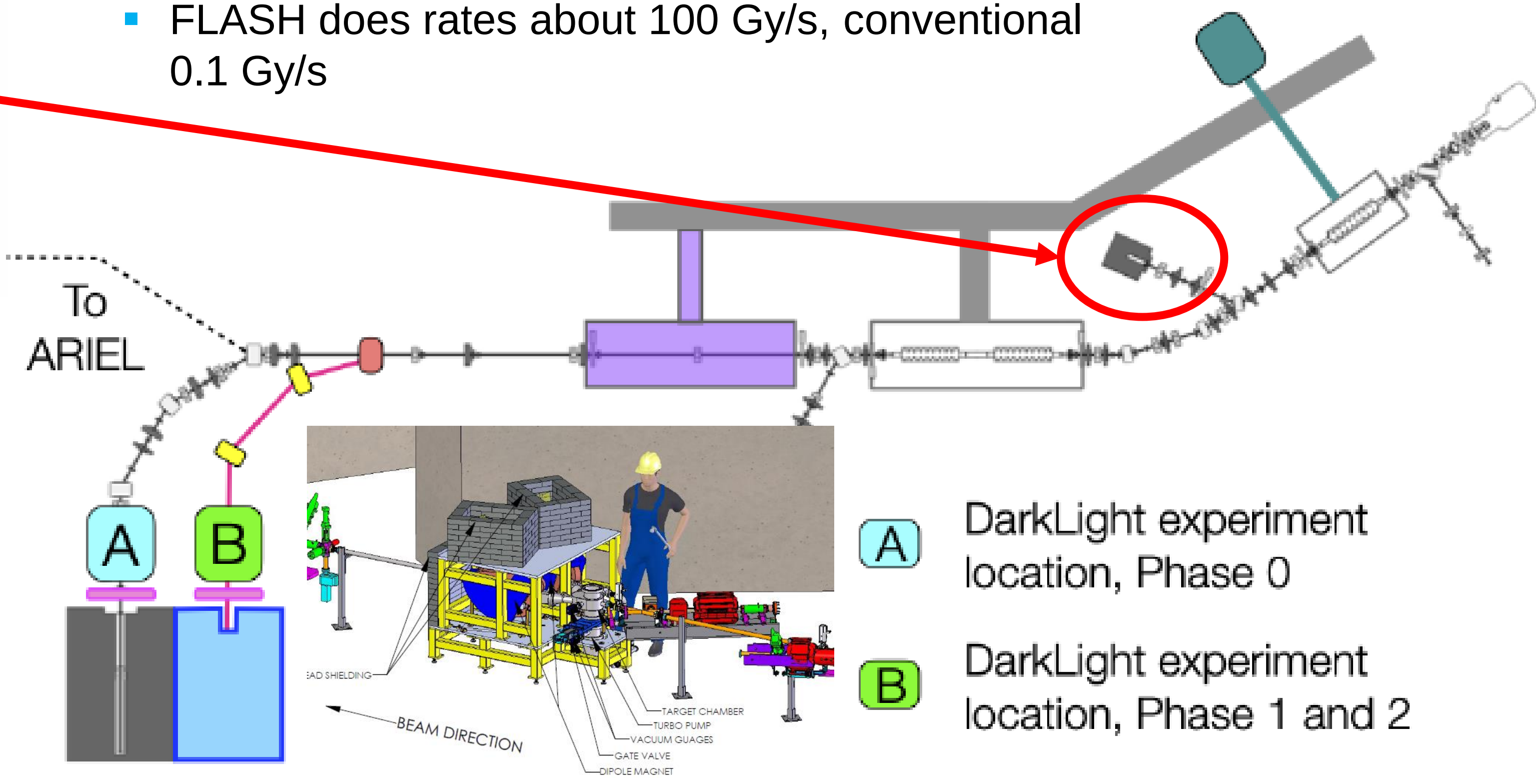
Early science supported by the ARIEL e-linac



PhD Nolen Esplen, UVic

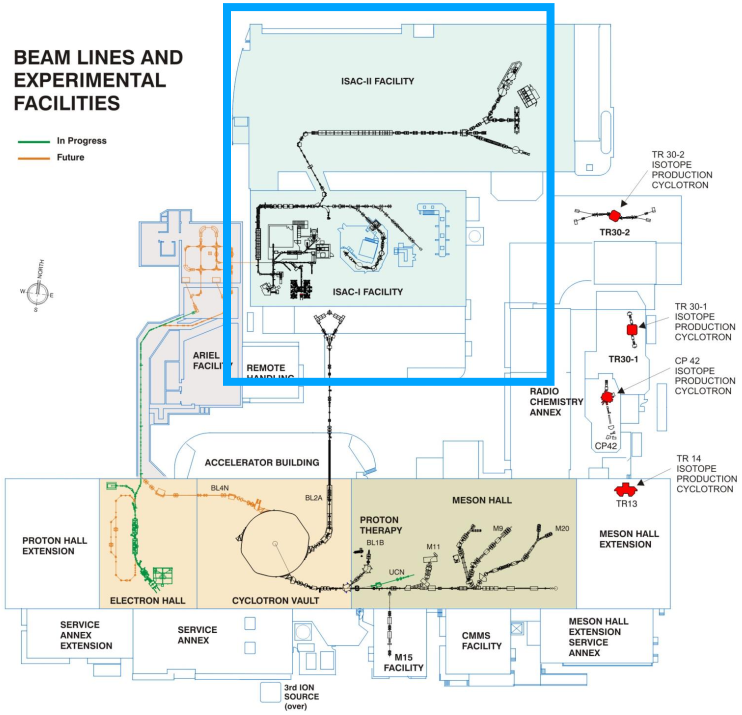
FLASH radiotherapy - involves the ultra-fast delivery of radiation treatment at dose rates several orders of magnitude greater than those currently in routine clinical practice.
It is enabled by the new ARIEL convertor technology:

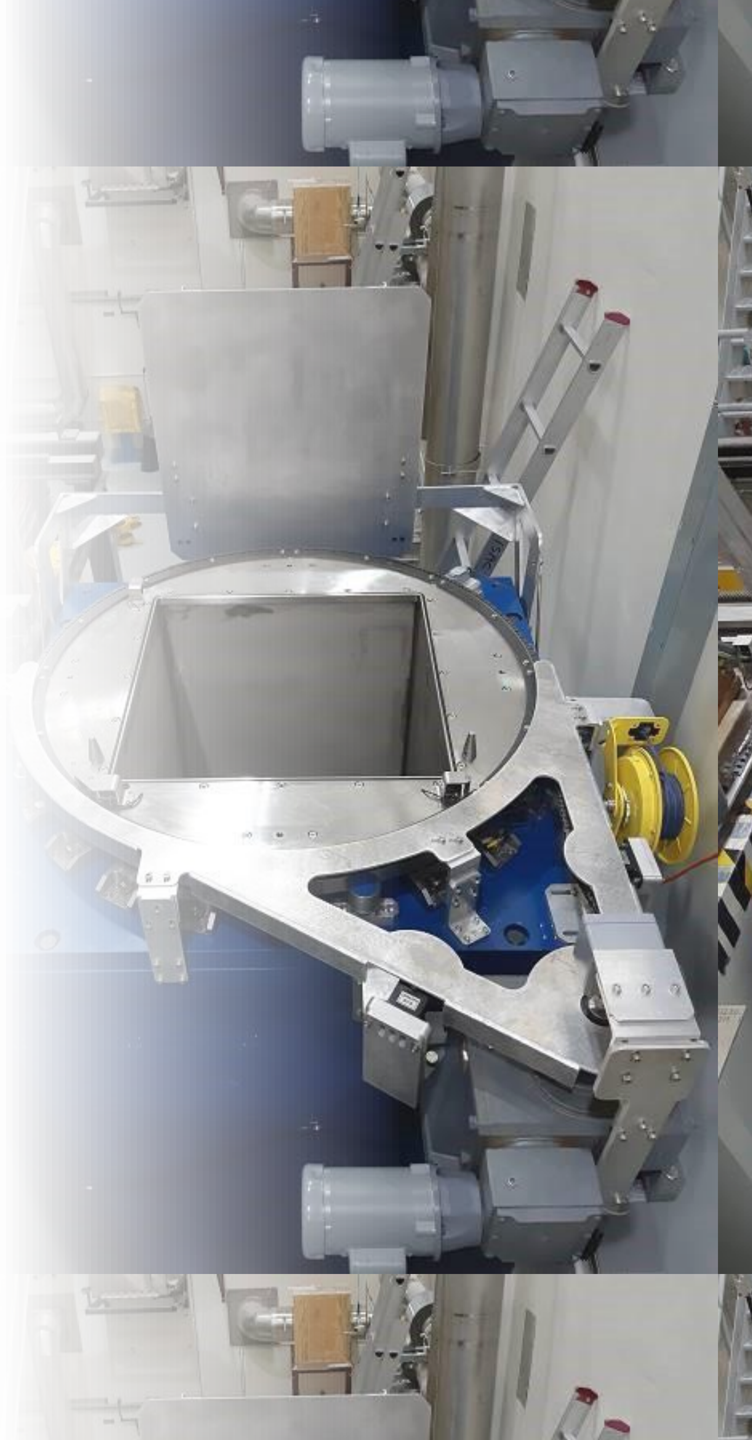
- Studies comparing response to identical dose deposited at FLASH and conventional rates in mouse, fruit fly and DNA completed
- FLASH does rates about 100 Gy/s, conventional 0.1 Gy/s



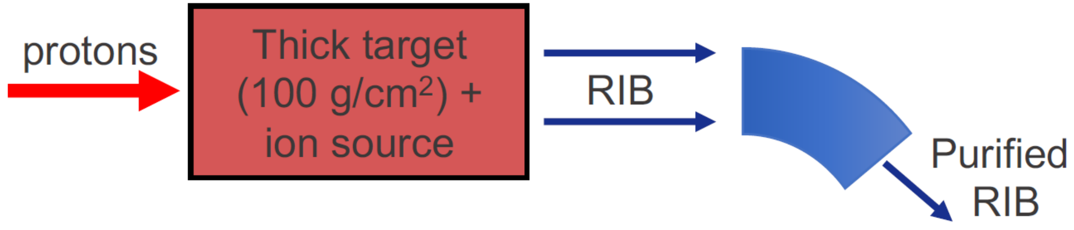
- Dark matter search – DARK LIGHT experiment looking for a 5th force (dark photons) at a low energy e-linac
  Experiment gets additional motivation from recent results from the muon g-2 experiment at FNAL
- First target test at 30 MeV and 10 nA
  test of radiation background, target foil integrity etc.

Production, preparation and post acceleration of rare isotope beams - ISAC

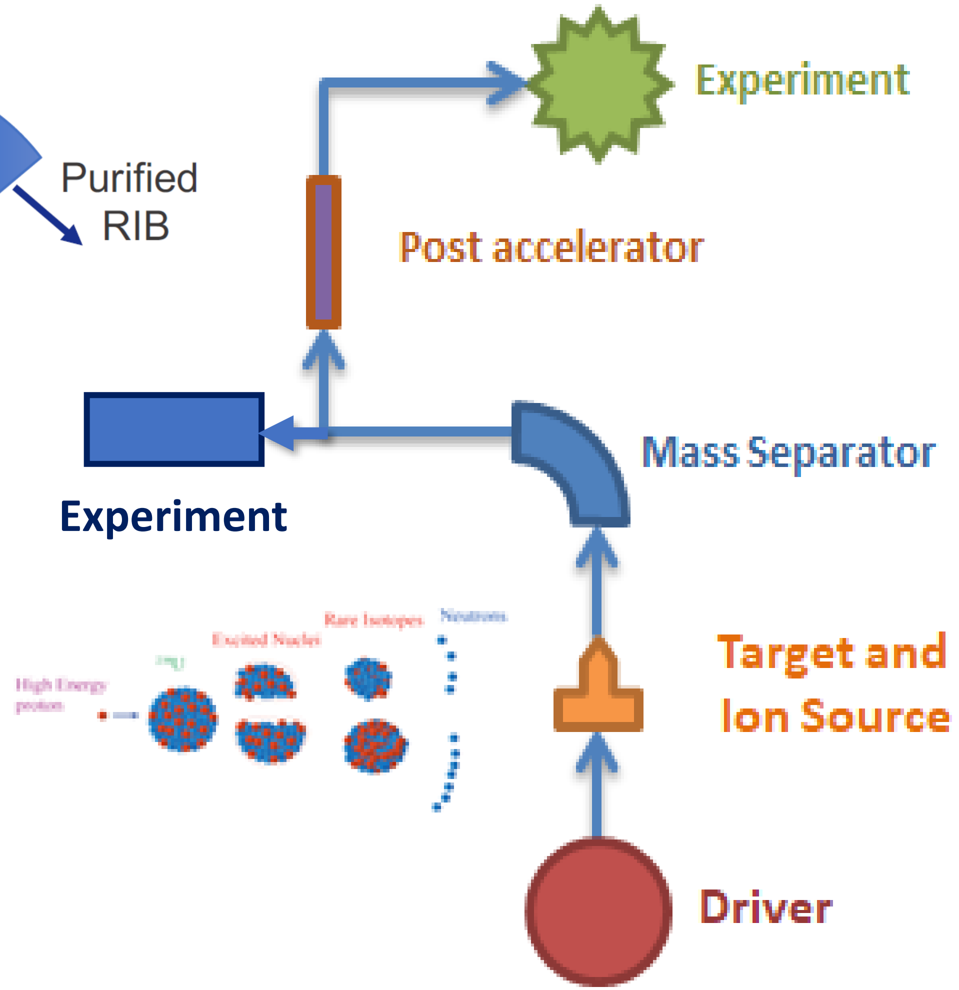


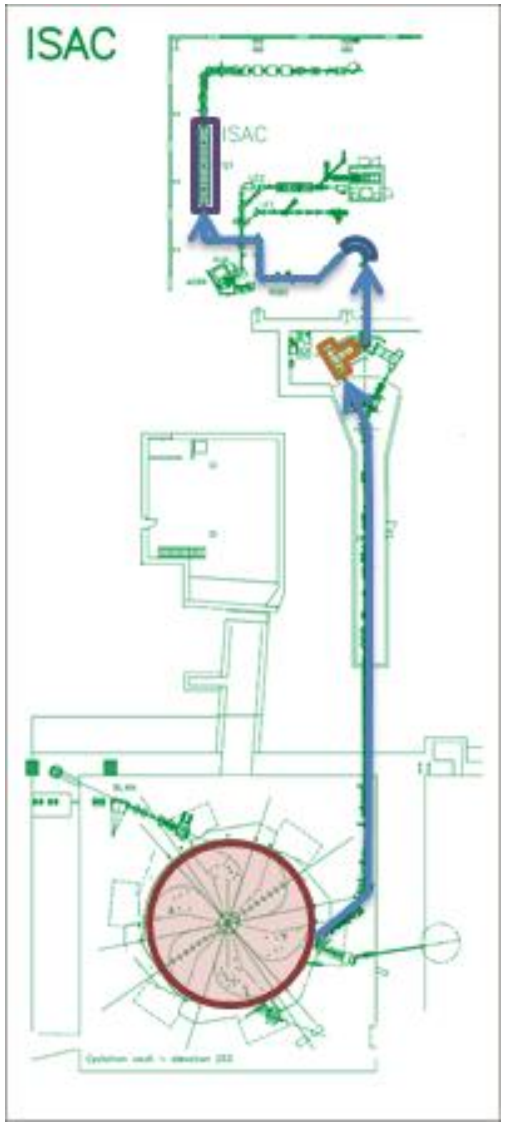


Isotope Separator Accelerator facility - ISAC at TRIUMF



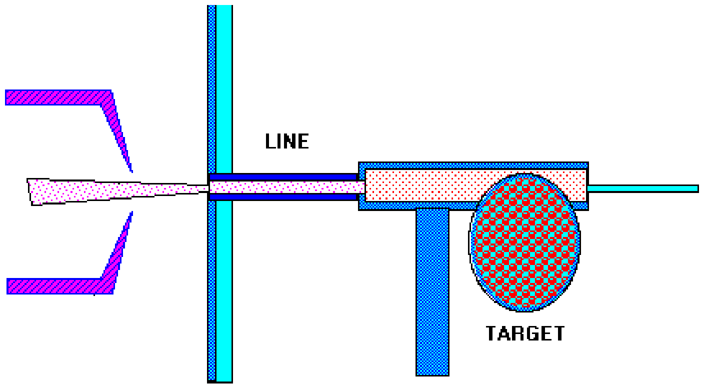
- Isotope Separation On-line (ISOL) facility for rare isotope beam (RIB) production
- High power proton beam (50 kW)
- Extracted ions are mass separated and either post-accelerated or delivered to low energy experiments directly.



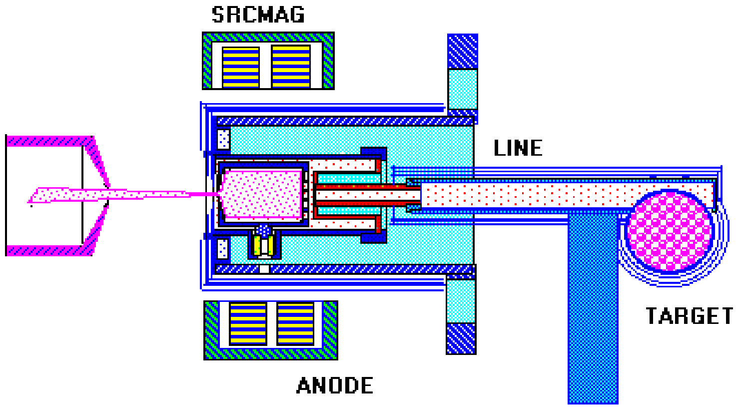


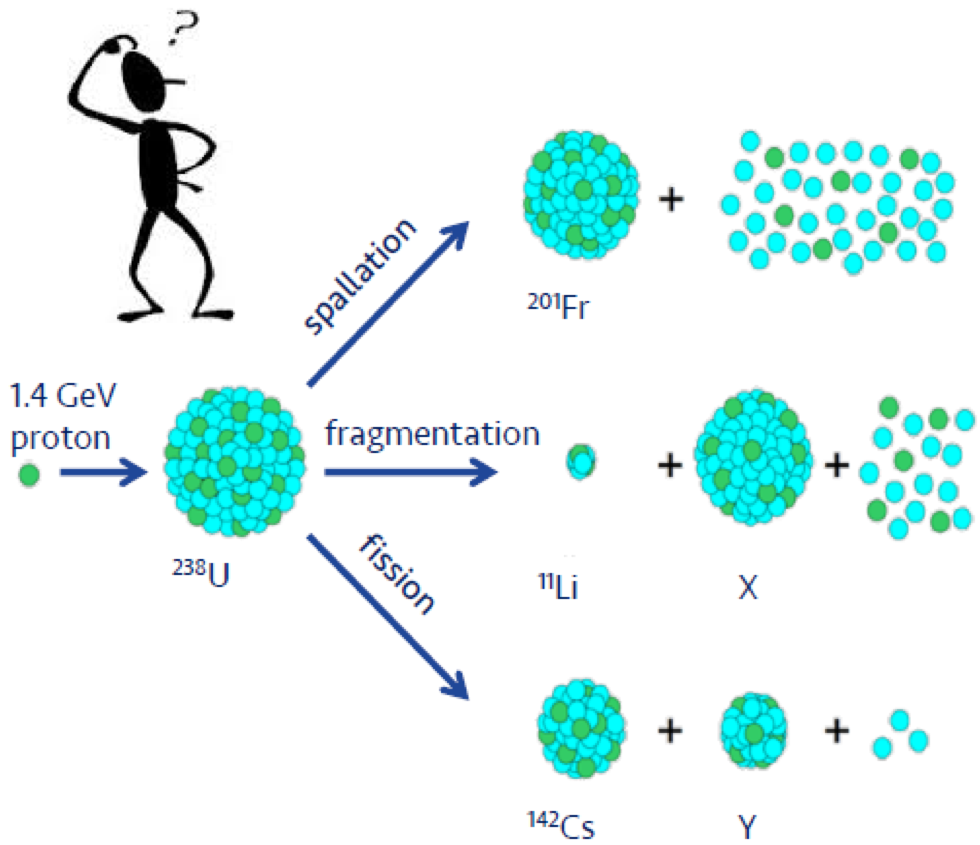
Target ion sources

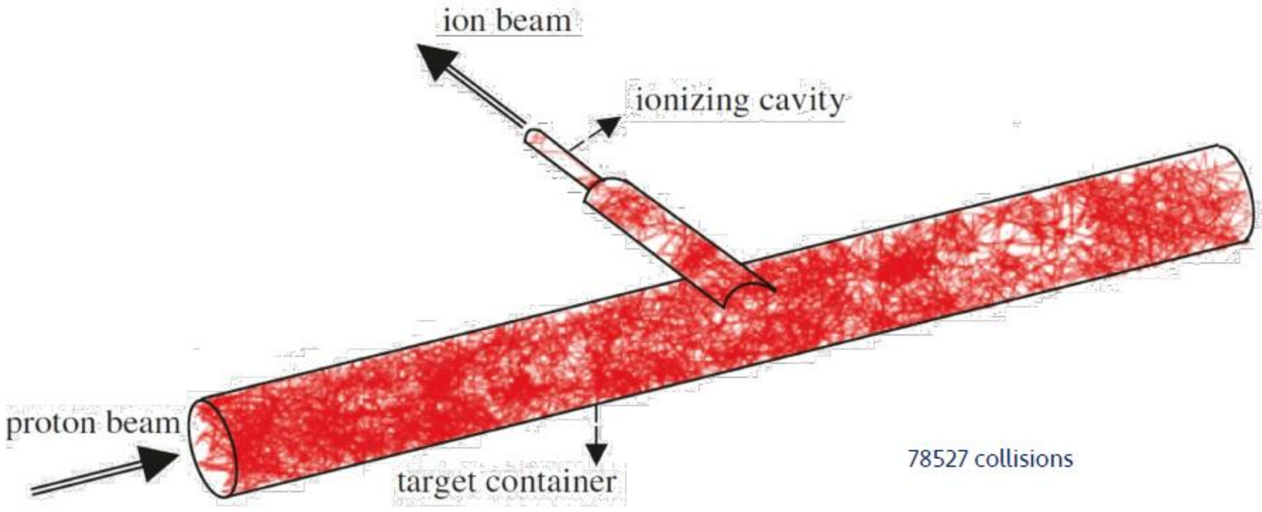
Surface ionisation



Plasma ion source

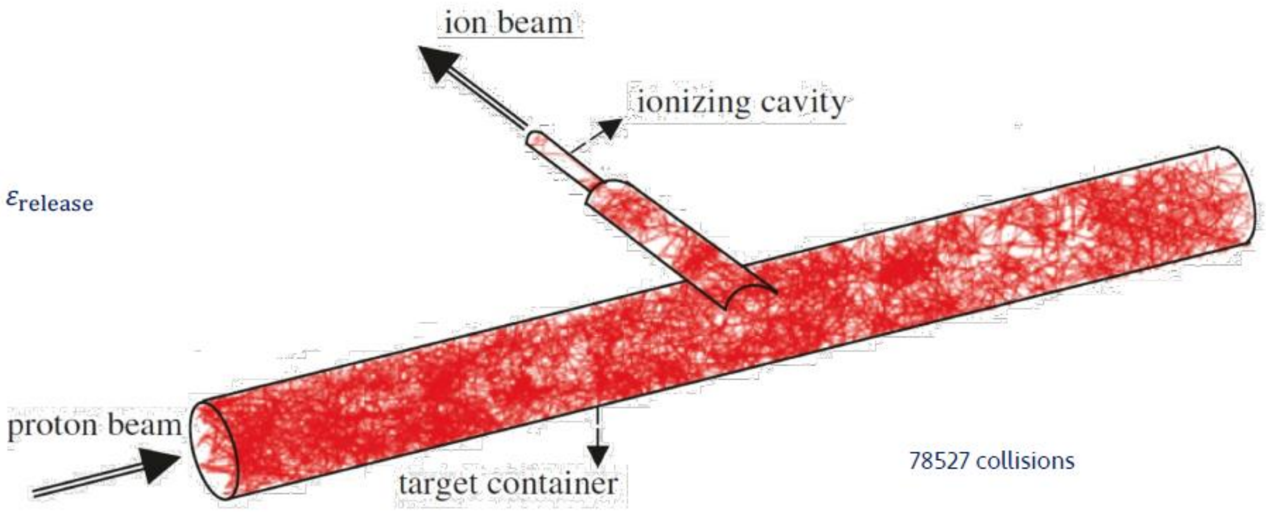




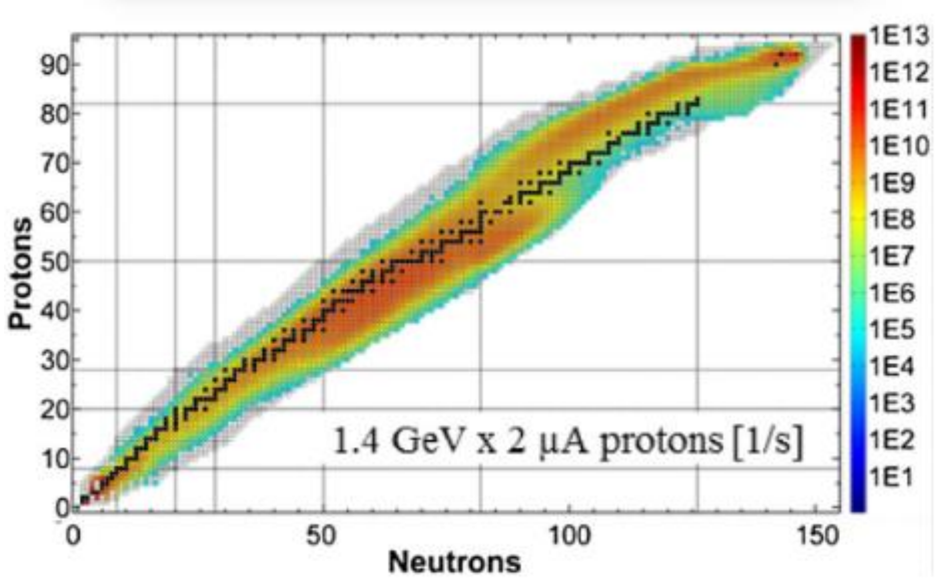


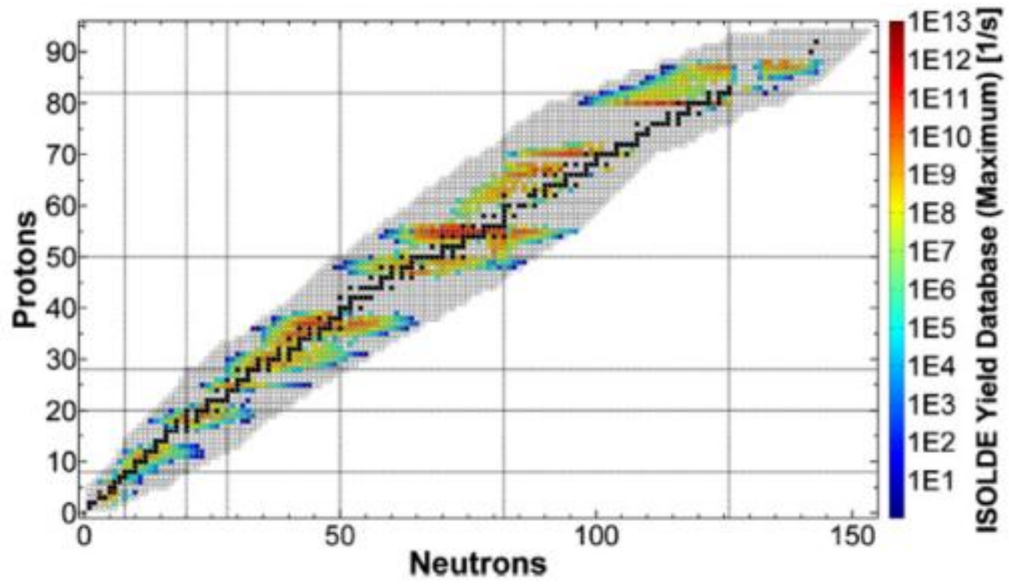
- Target and ion sources units, common is surface ionisation, laser ionisation and plasma ionisation
- Targets are heated up to high temperatures to support diffusion (random walk) of isotopes into the ionisation region

Isotope extraction

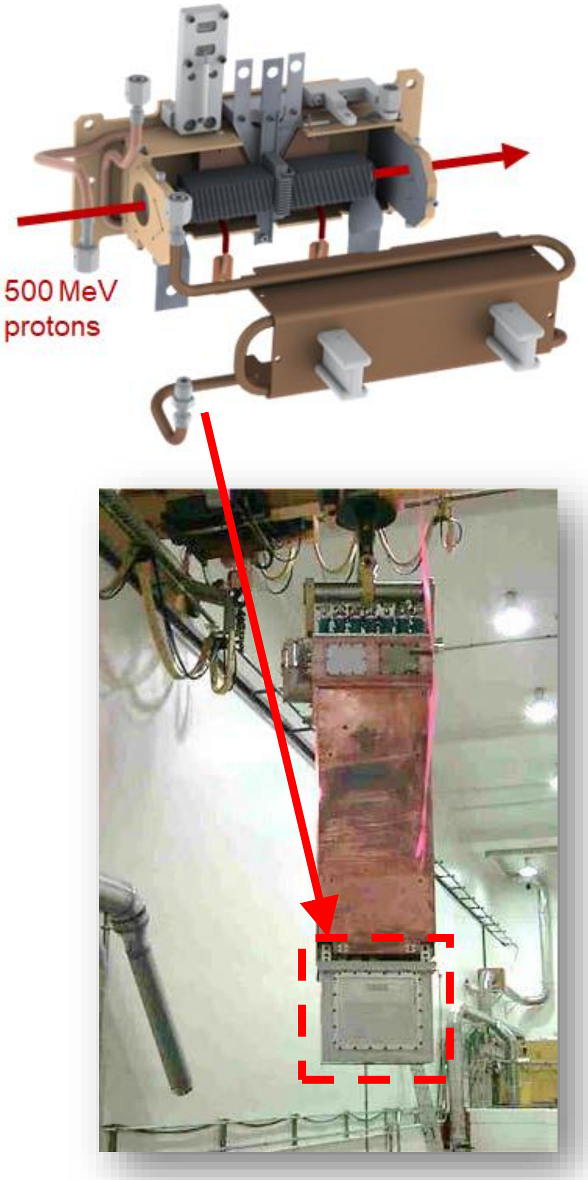


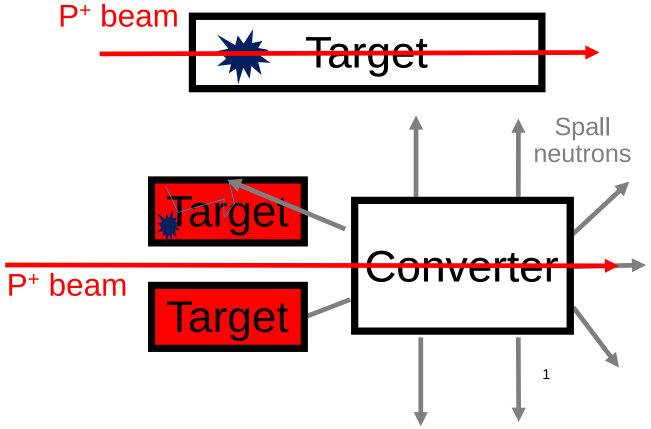
- Simulation of the path of one Ga atom produced in a Ta-foil target towards the ionizer (on the left)!
- Extraction times vary significantly between elements. Driven by volatility and in-target chemistry





Targets and Ion Sources program



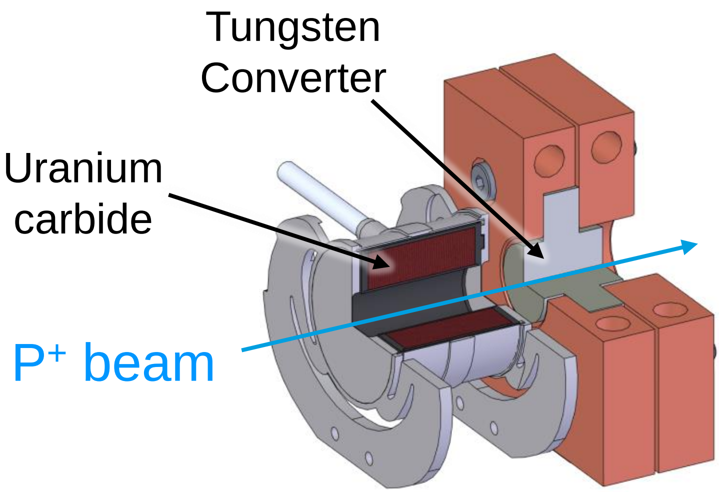


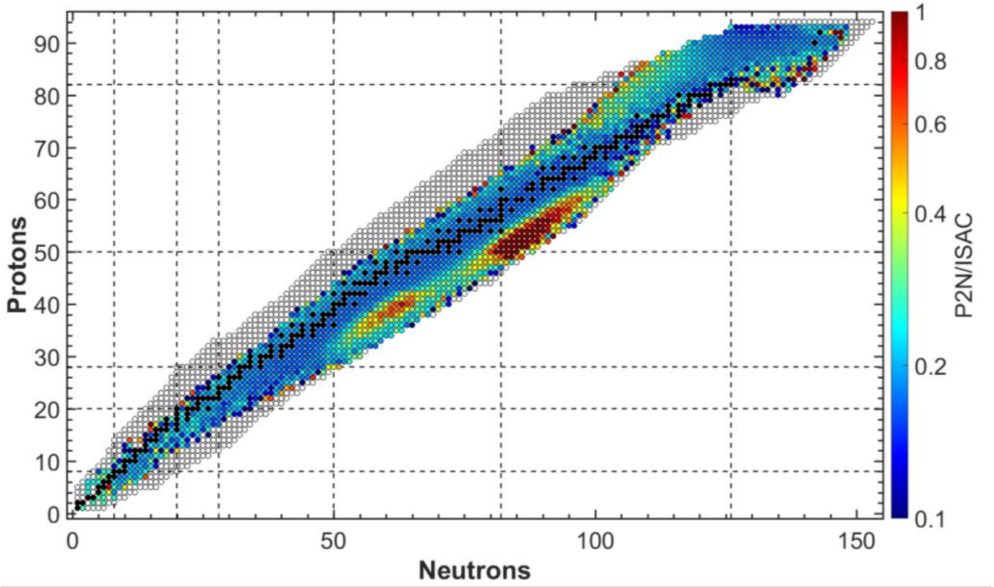
Proton-to-neutron converter target at ISAC

PhD Luca Egoriti, UBC

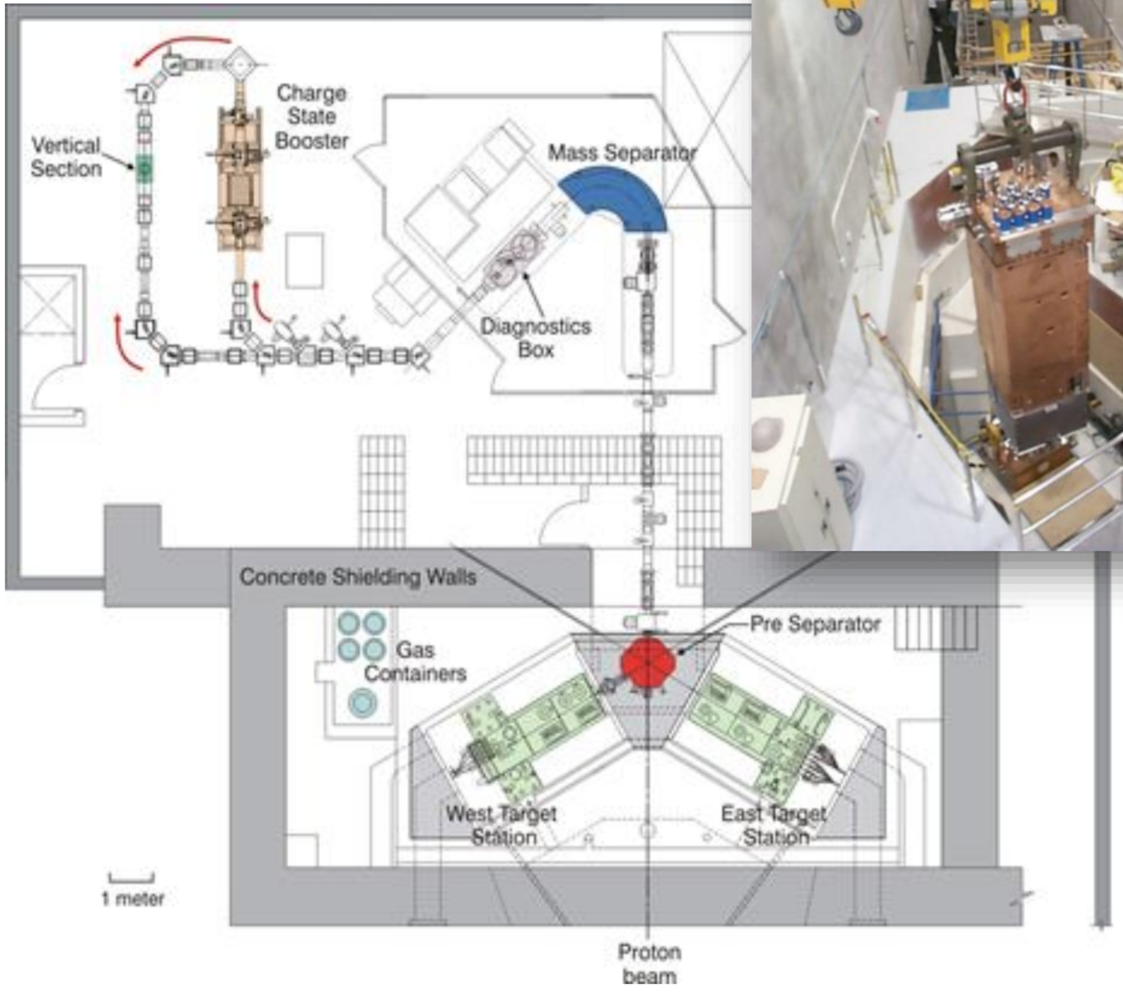
- Increasing purity of n-rich fission products through:
  - Isotope production mechanisms
  - Temperature control
- Tested in June 2021: Yield station and TITAN MR-ToF

new converter target



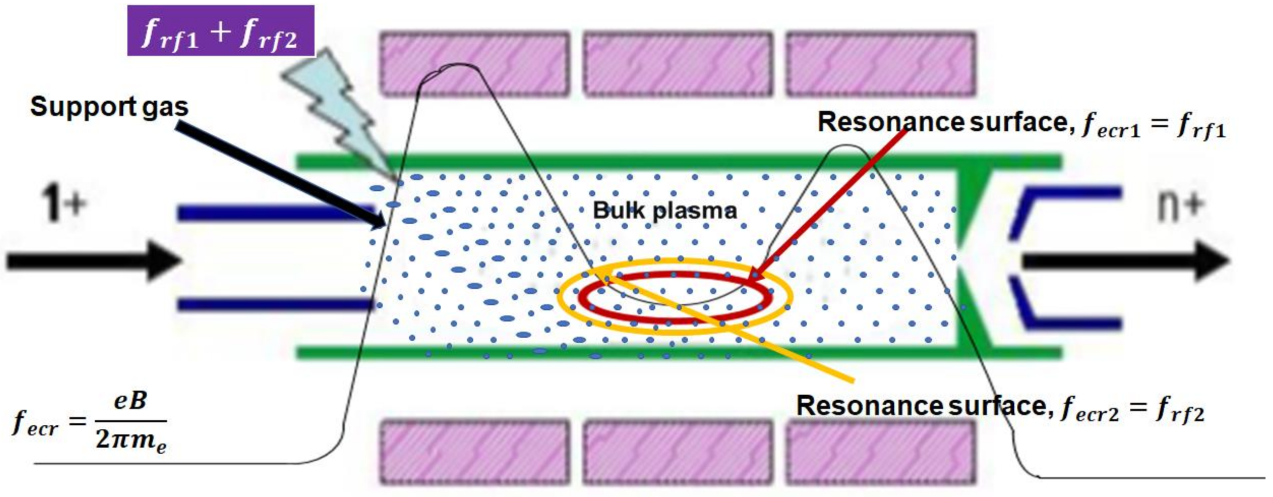


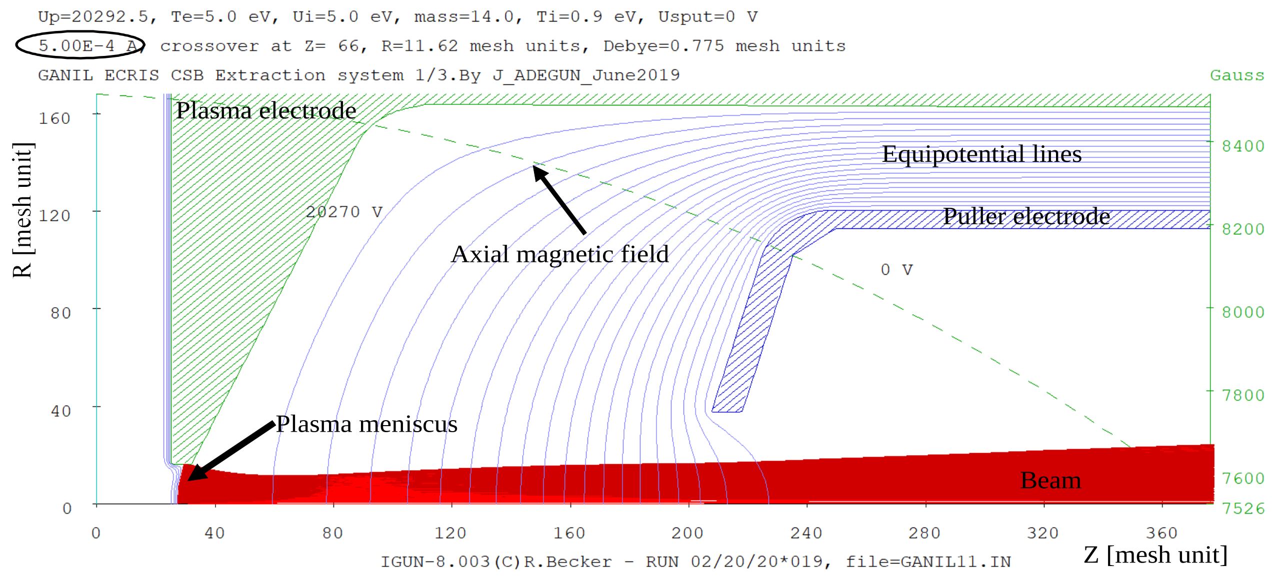
ISAC target stations and mass separator



- Two underground target stations with target modules located in a big vacuum tank!
- Proton beam sent to one of the target stations at the time.
- Common pre-separator inside the shielded area
- Mass separator on high voltage platform (typical operation resolving power 3000)
- Charge breeder (ECR type) for post acceleration.

Electron Cyclotron Resonance ion source (ECRIS) charge state breeder





- Resonant microwave plasma heating
- Electron energies – up to MeV via electron cyclotron resonance
- Magnetic confinement
- Higher frequency (14.5 GHz) B_{ecr} ~ f, Ion current ~ f^2

$$f_c = \frac{1}{2\pi}\frac{e}{m_e}B$$

- Increase of charge breeding efficiency by implementing

  two-frequency heating technique that provides two resonance zones

- Improving the beam properties by optimizing the extraction system
  - Simulations with the code IGUN©
  - Benchmarking with emittance measurements using beam tomography (quadrupole scans)

PhD Joseph Adegun, UVic

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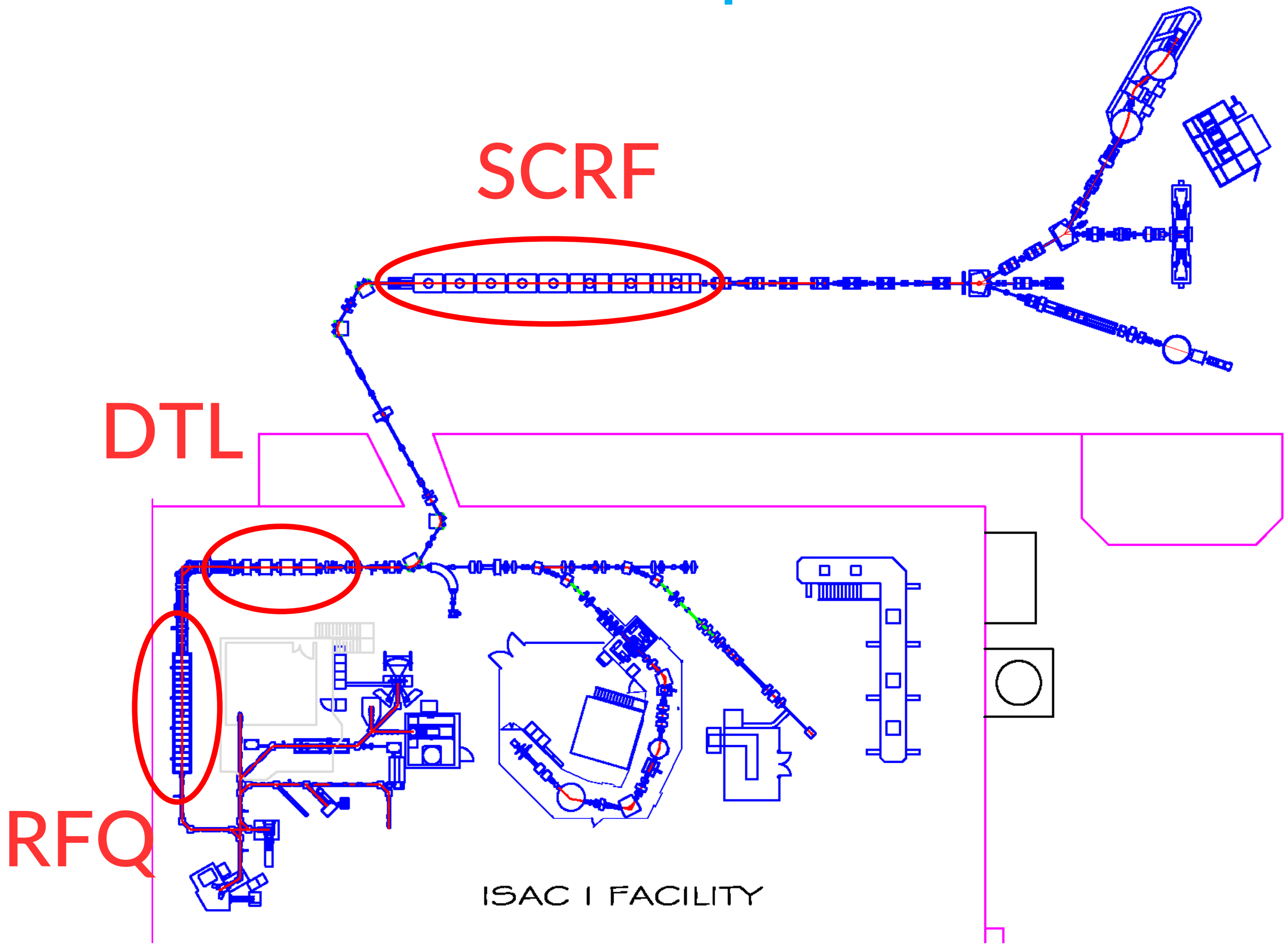
ISAC post-accelerator overview



The ISAC Accelerators

Three sequential accelerators, one of which is cryogenic:

The ISAC-radiofrequency quadrupole (RFQ)

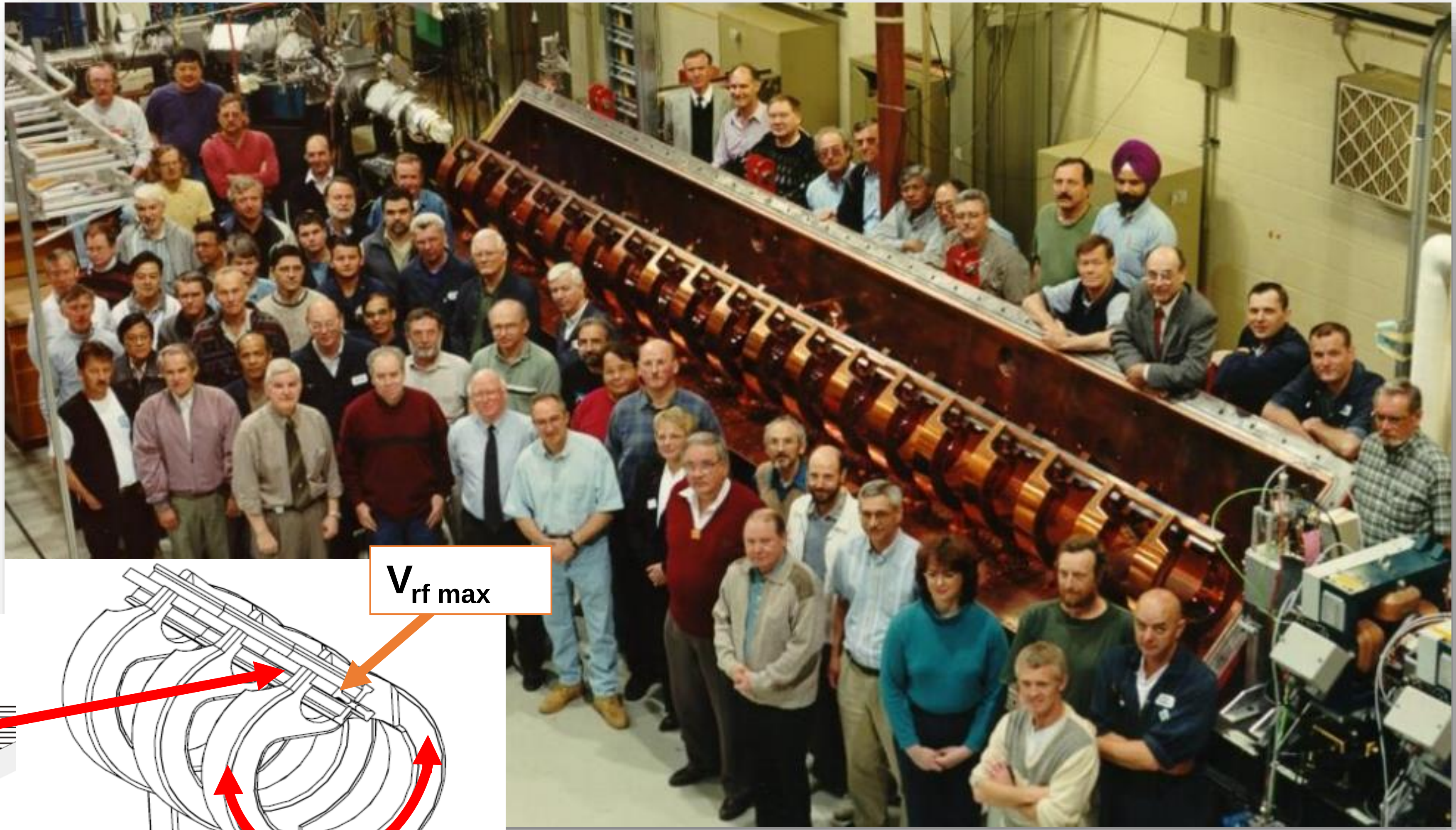
The 106 MHz Drift Tube Linac (DTL)

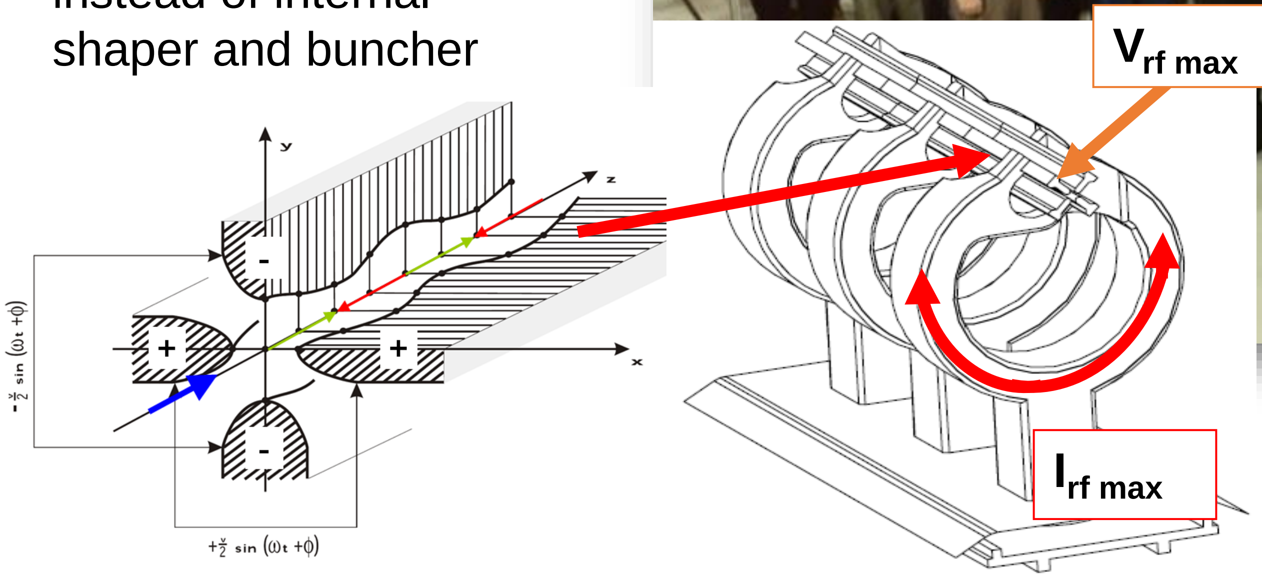
The 40-cavity superconducting rf linac (SCRF)

Both DTL and SCRF are fully **variable output energy** machines.

The ISAC Radiofrequency Quadrupole (RFQ

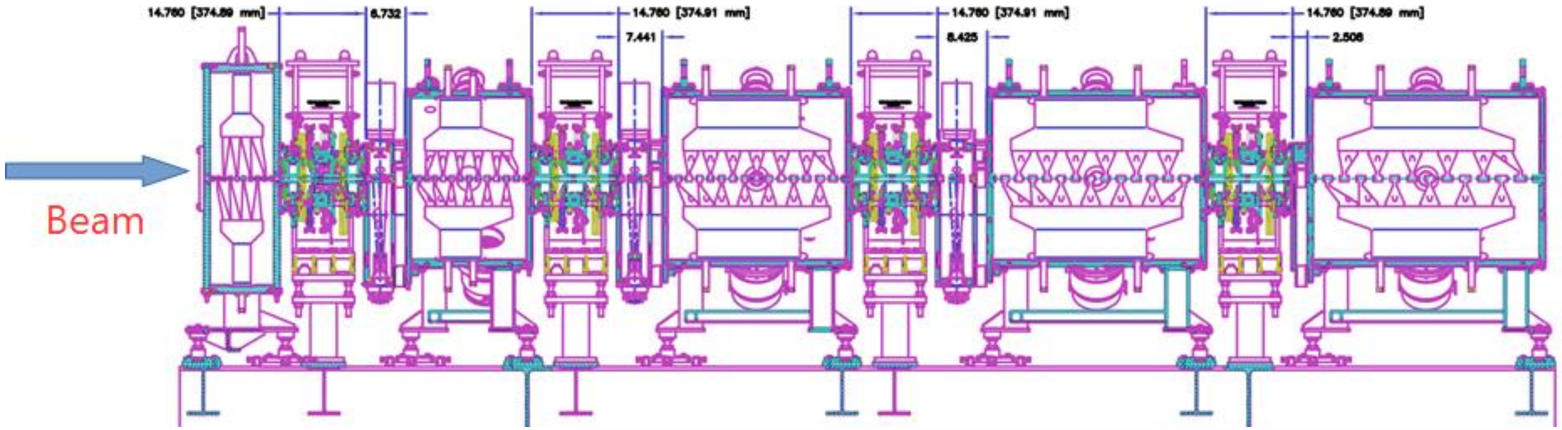
- 4-rod, Split ring structure 35 MHz
- 8m long, 85kW, 74kV peak voltage
- Provides up to 4.4MV of acceleration from 2keV/u to 150keV/u for masses A≤30
- uses external buncher instead of internal shaper and buncher

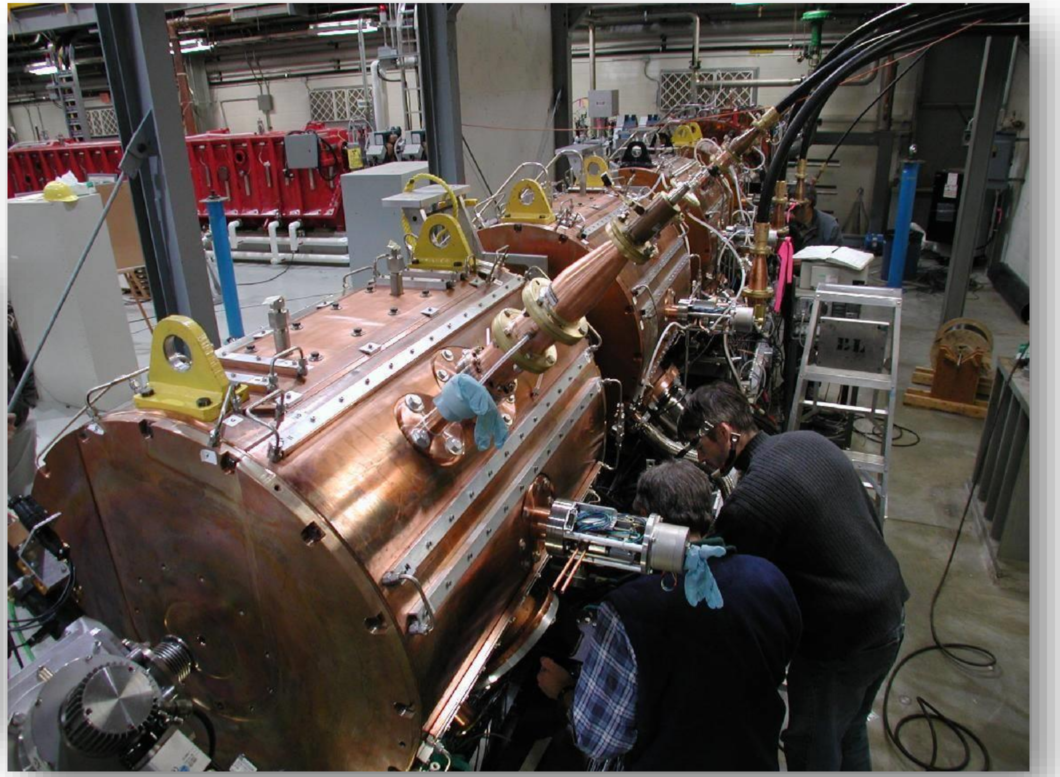




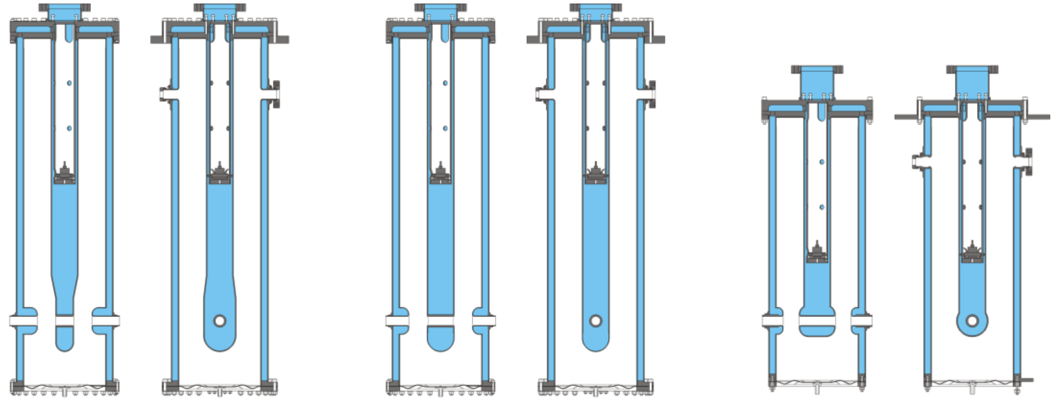
ISAC-I drift tube linac (DTL)

- 5 accelerating Interdigital H-type (IH) resonant cavities
- 3 bunchers to keep the particle bunches longitudinally focused
- Based on the “combined zero-degree synchronous particle structure (KONUS) beam dynamics design.





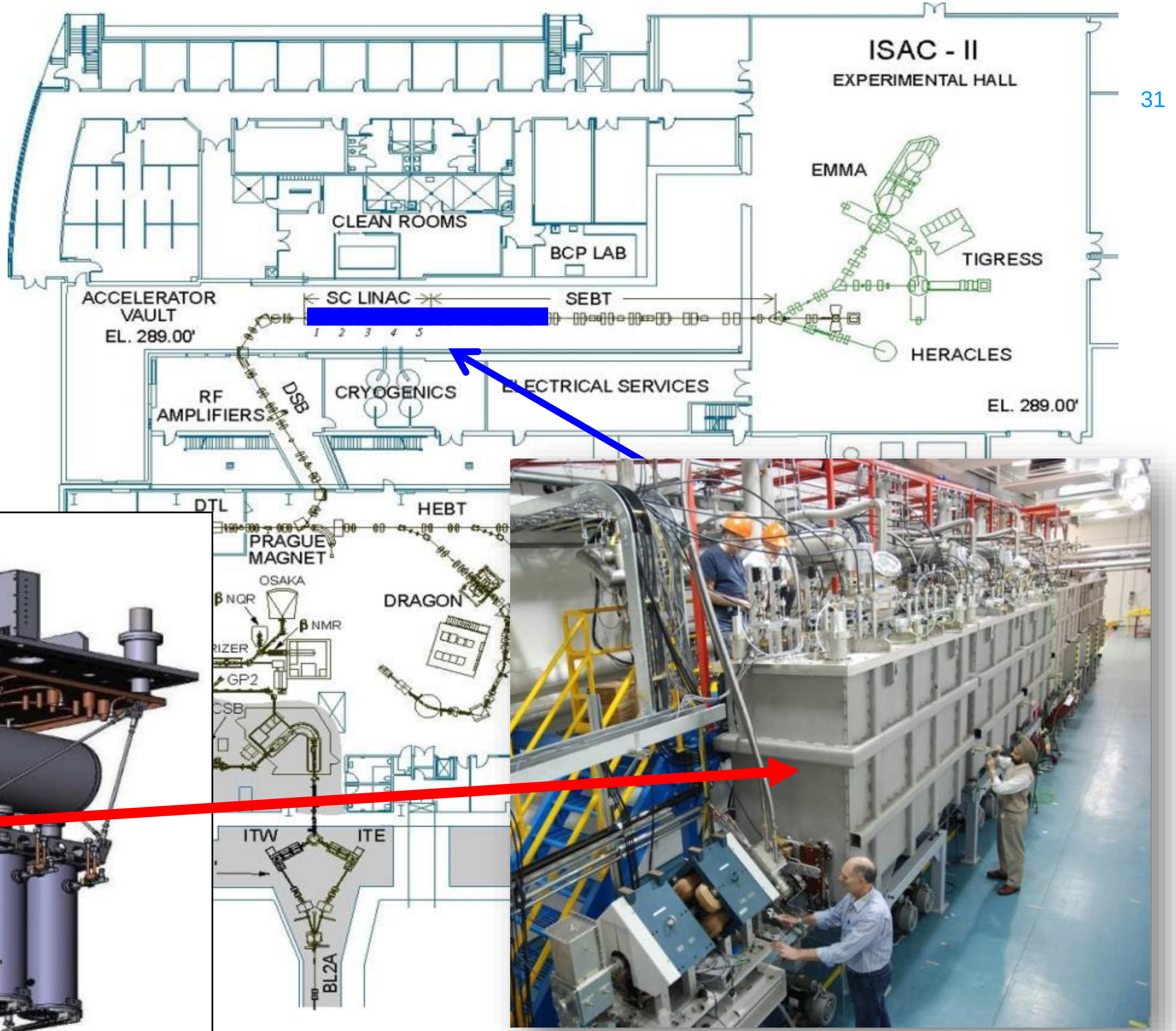
ISAC-II SRF linac

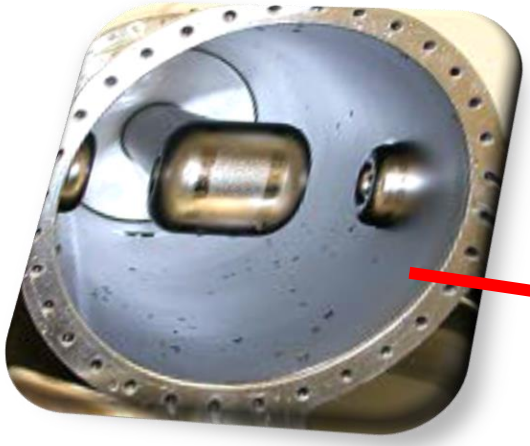


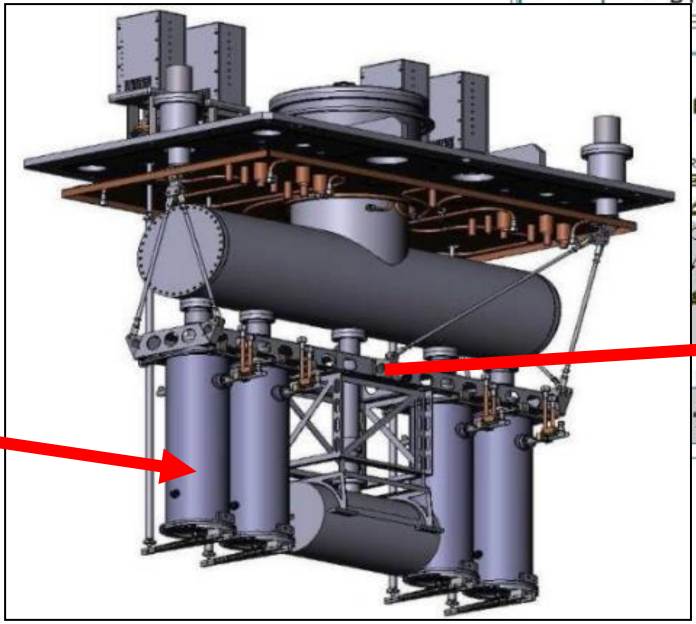
SCB low β (5.7%)
106.08 MHz

SCB medium β (7.1%)
106.08 MHz

SCC high β (11%)
106.08 MHz

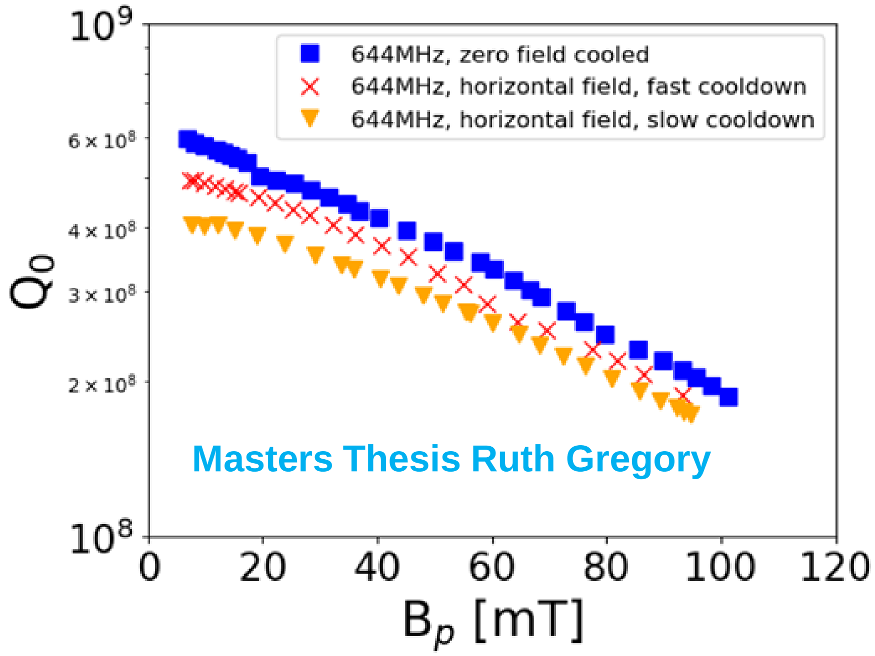


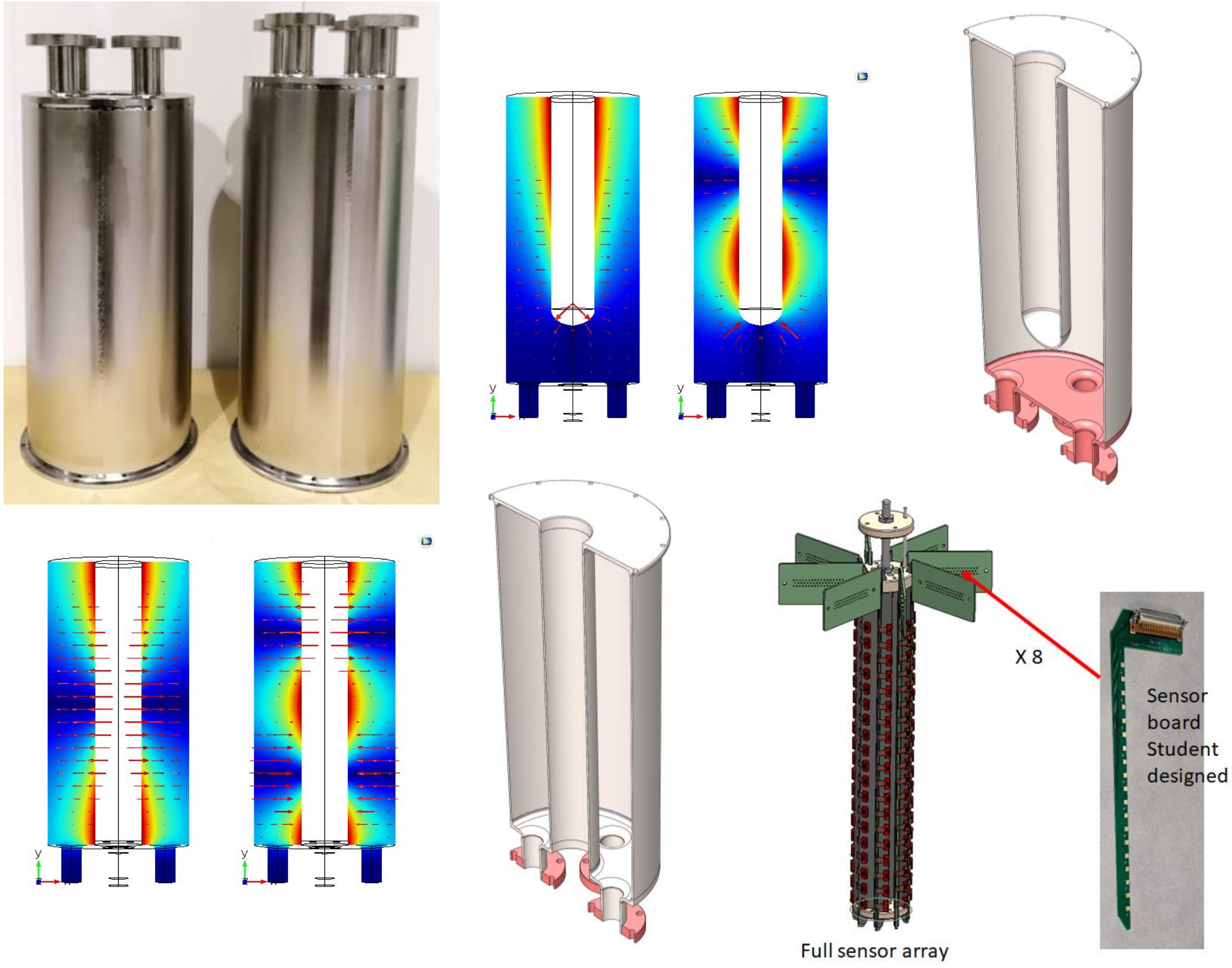




SRF research on coaxial cavities

- Testbed cavities with simplified geometry for new surface treatments.
- Excitation of different resonant modes to determine frequency dependence of the cavity performance.
- Using 3D Helmholtz coils, we transition the cavity into the superconducting state with different background fields → influence on the quality factor





Development of Temperature Mapping for Coaxial Cavities

- Sensor array to measure temperature distribution on the cavity surface
- Unique in the world – no one has done this for coaxial cavities before

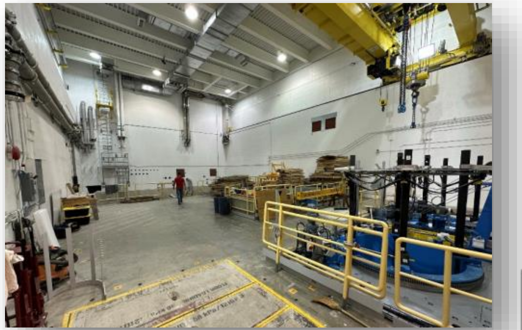
TRIUMF

The future of rare isotope science at TRIUMF - ARIEL

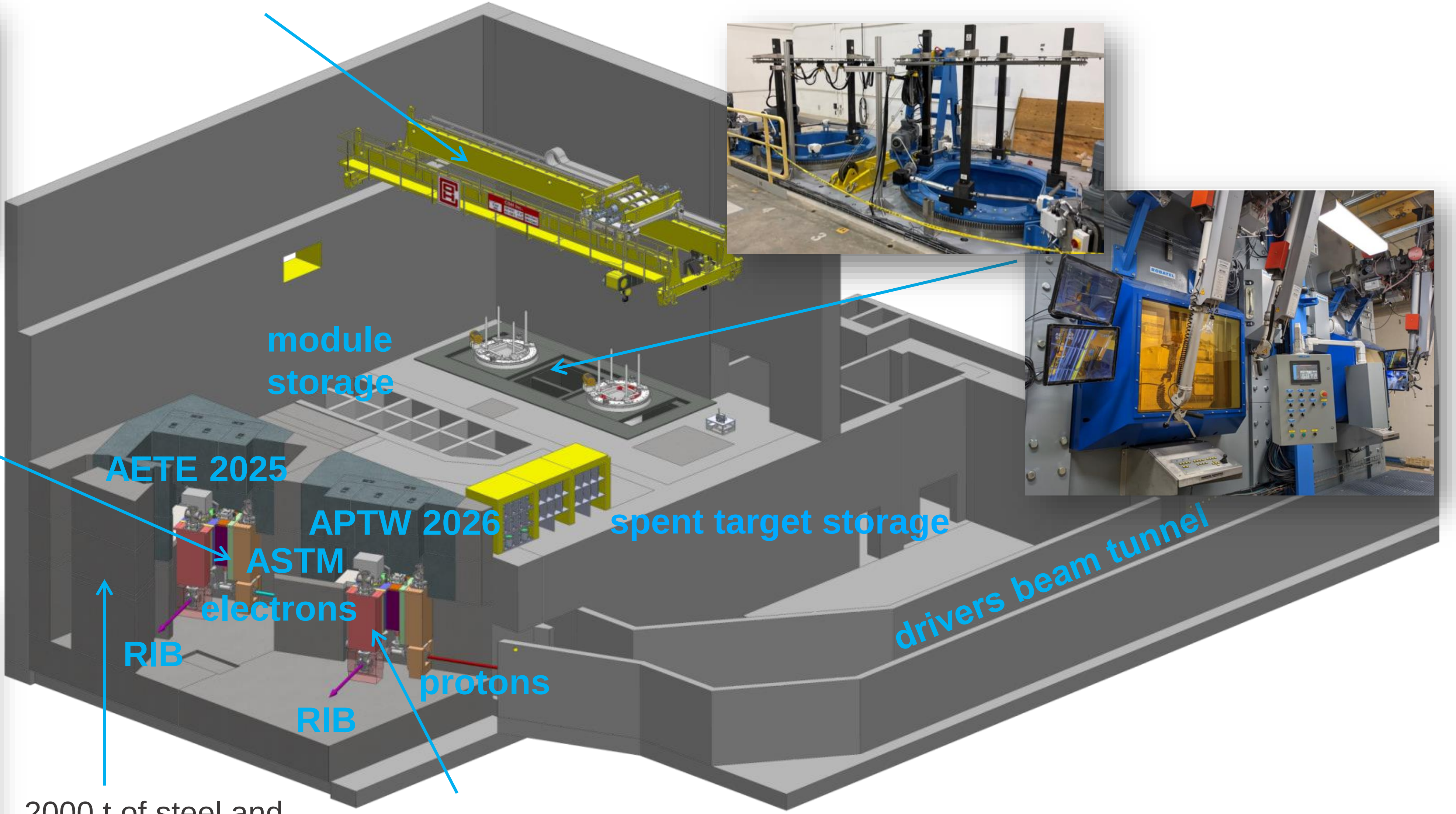
ARIEL Targetry Systems

Remote-controlled crane

Hot cell facilities



Symbiotic medical target in APTW beam dump

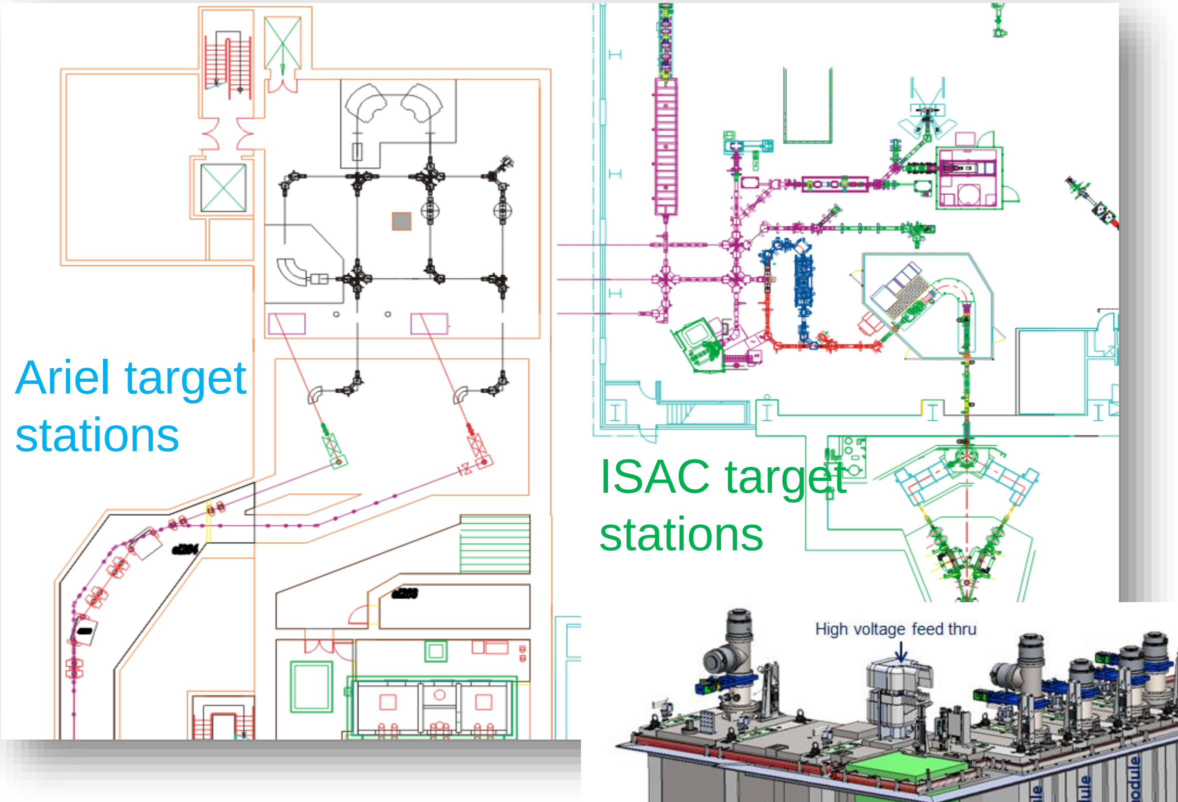


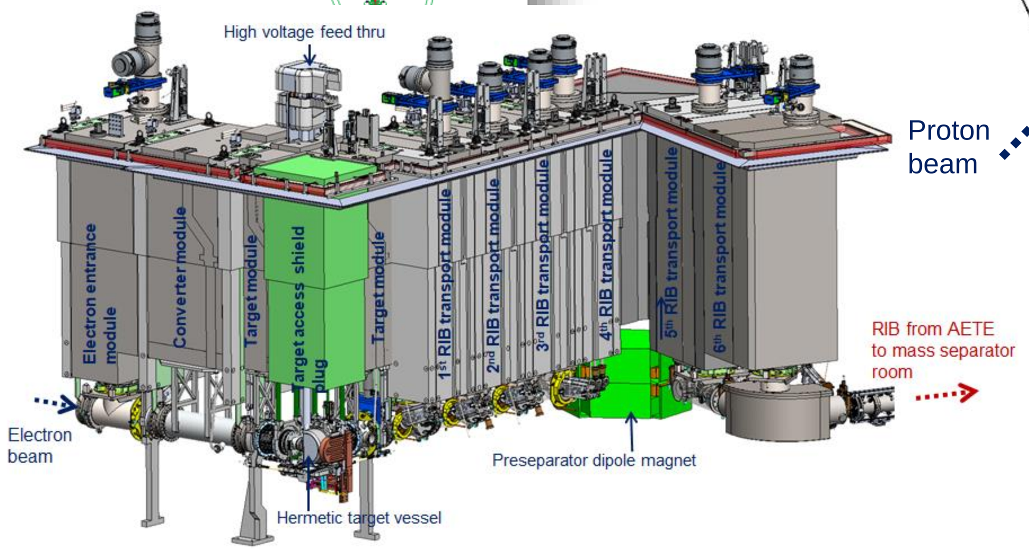
2000 t of steel and concrete

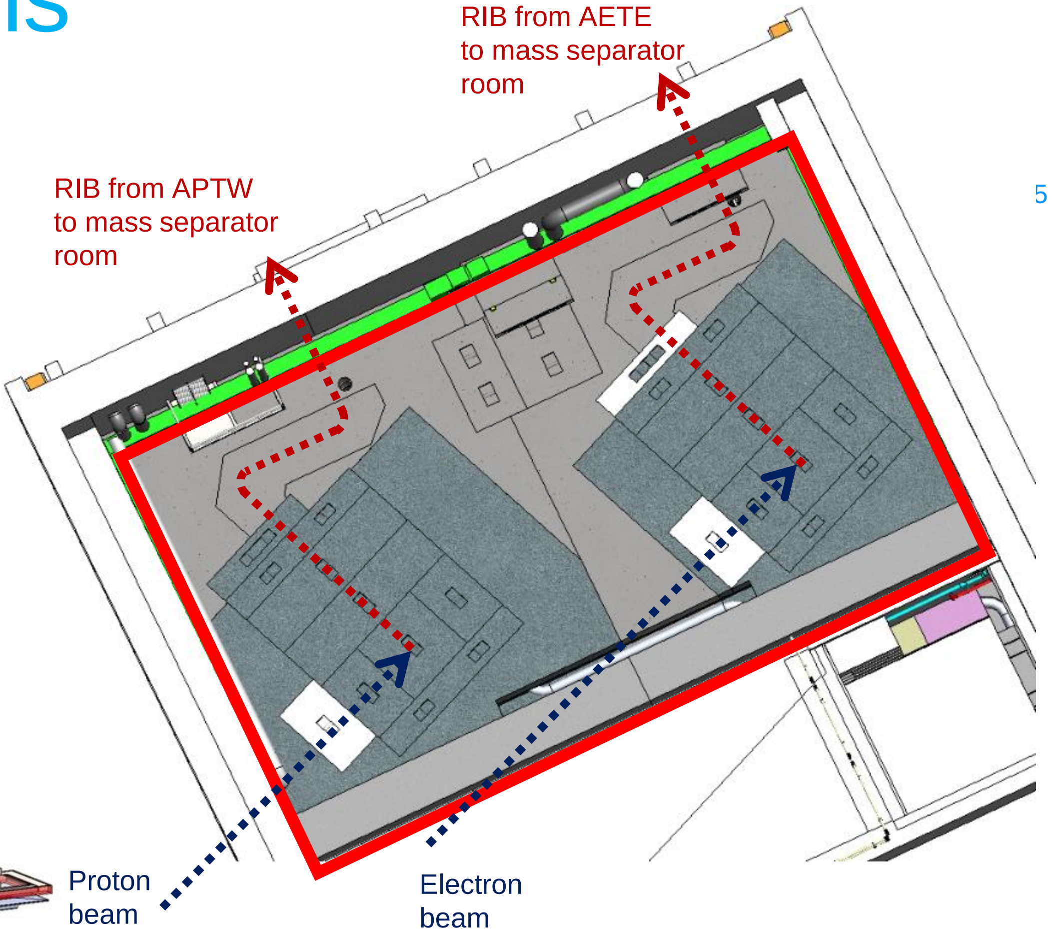
Modular RH high-power infrastructure

TRIUMF

ARIEL target stations



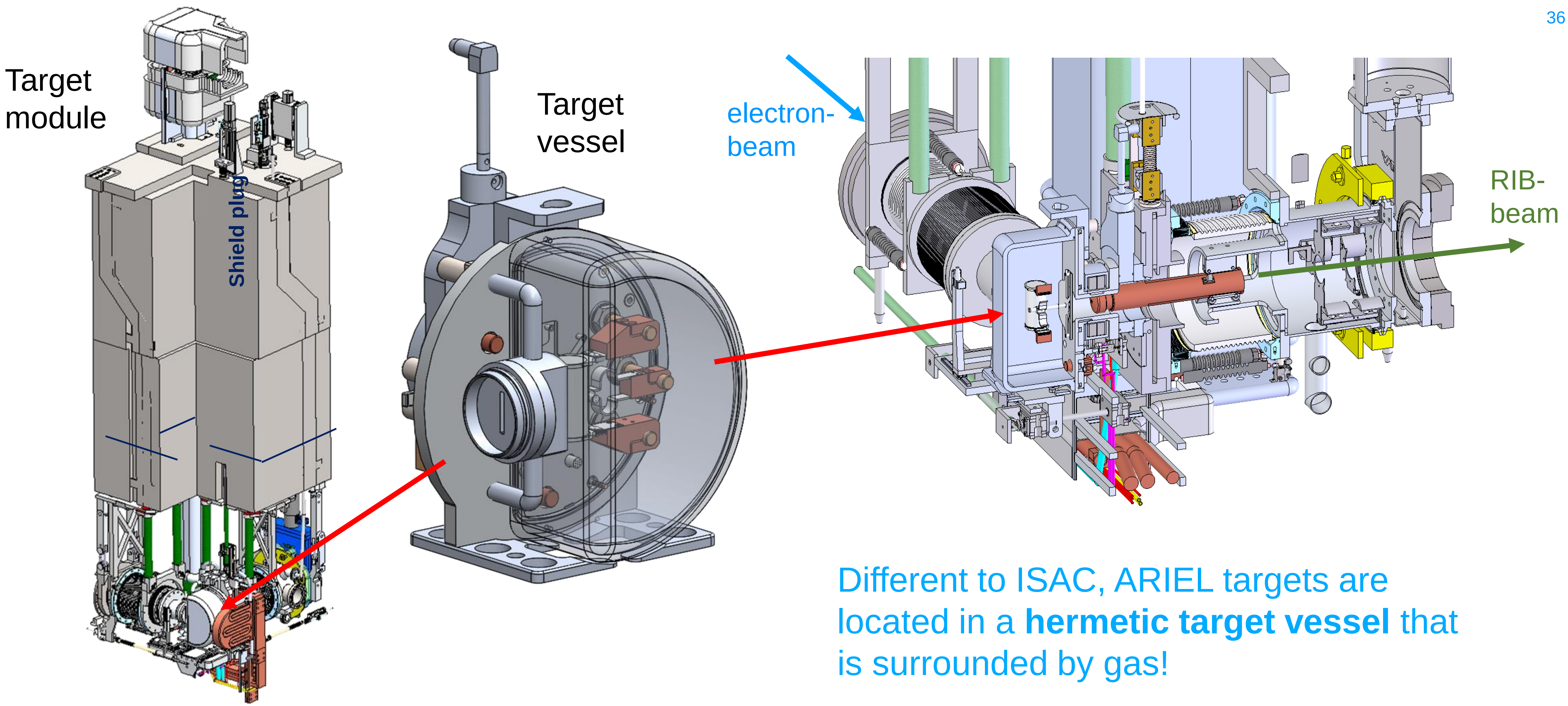




5

A target station comprises several modules, one of these is the target module (green).

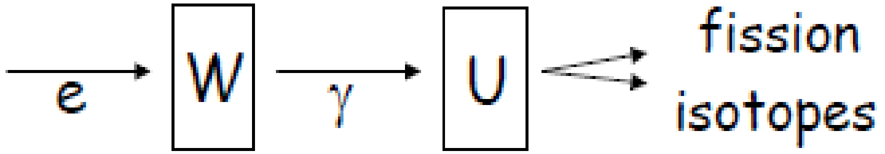
ARIEL target module and vessel

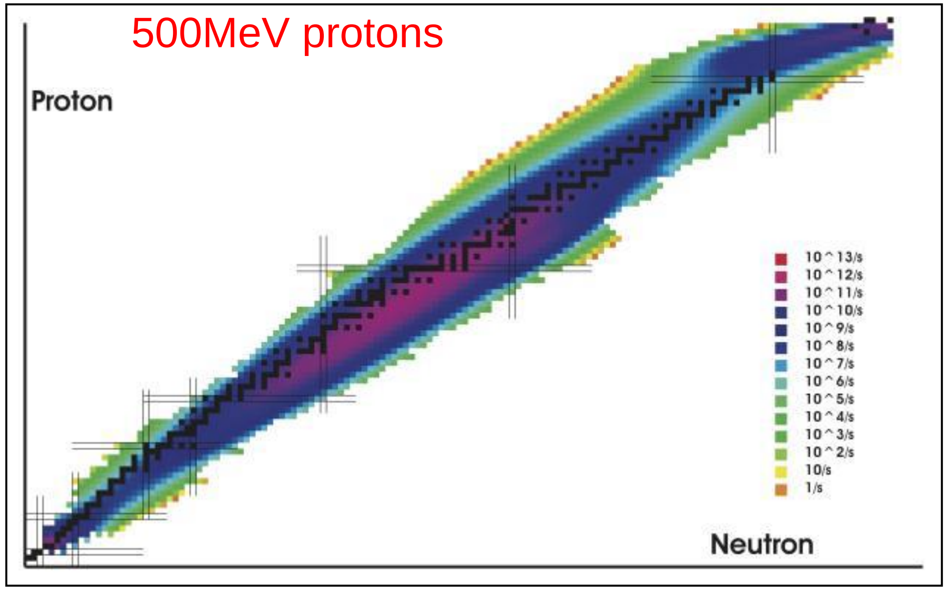


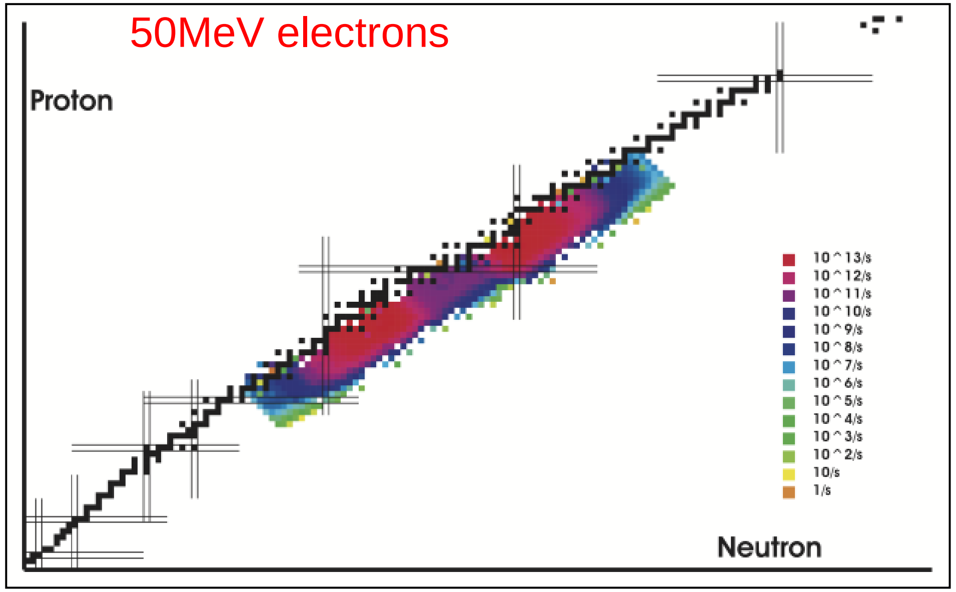
Different to ISAC, ARIEL targets are located in a **hermetic target vessel** that is surrounded by gas!

Production of RIBs with electron beams

- 10 mA of 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.
- An electron-to-gamma converter is required because the direct power deposition imposed by the 30 MeV electrons in a target is unsustainable.



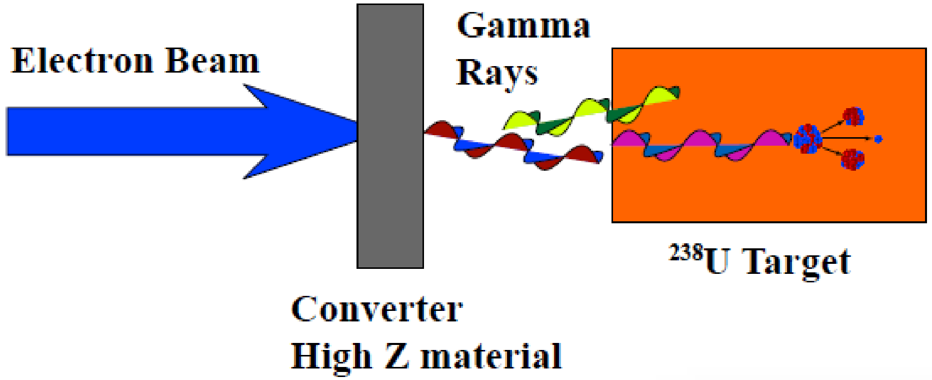


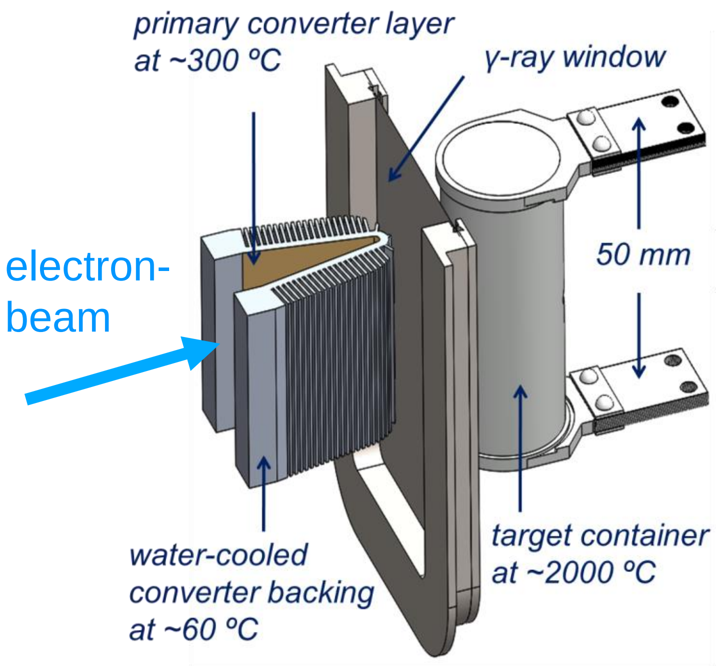


ARIEL electron target principles?

- An electron-to-gamma converter is required because the direct power deposition imposed by the 35 MeV electrons in a target would destroy the target.
- Converter made of high Z material, Au, W, Ta. Thickness ~ 3.5 mm.
- Electrons MUST be stopped in a low Z material 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!

Consequence: The electron beam needs to be scanned over a larger area and the resulting power is to be dissipated

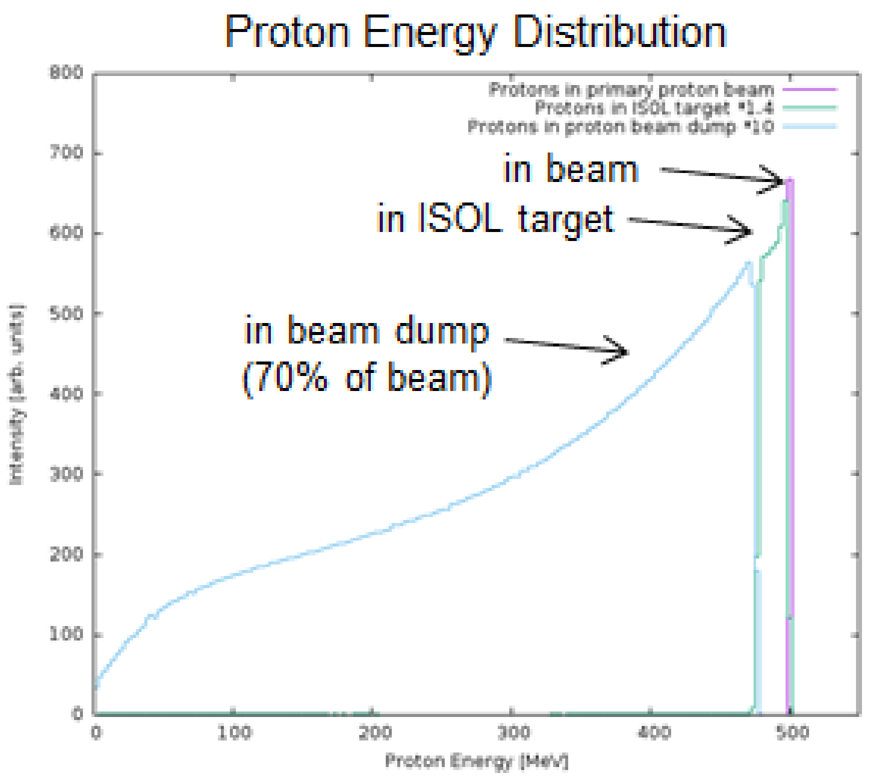


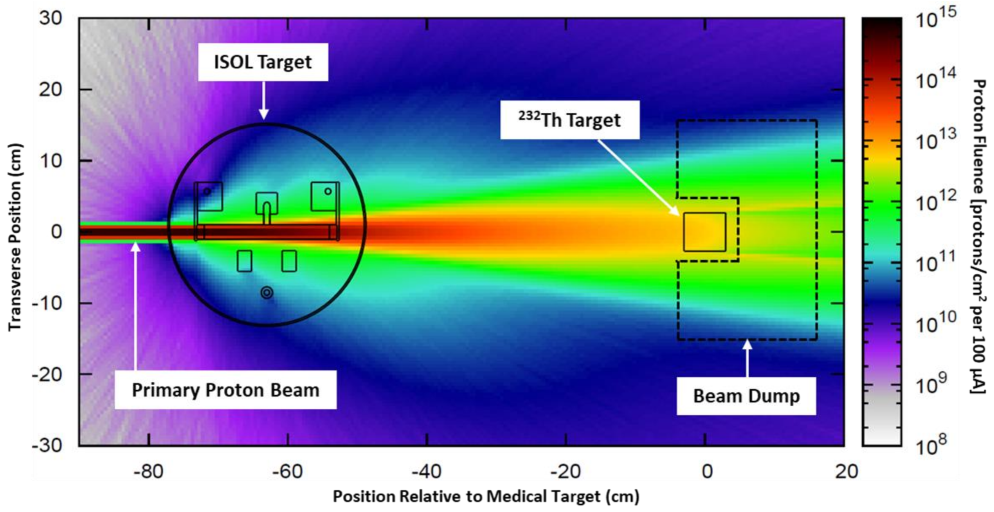


Symbiotic targets

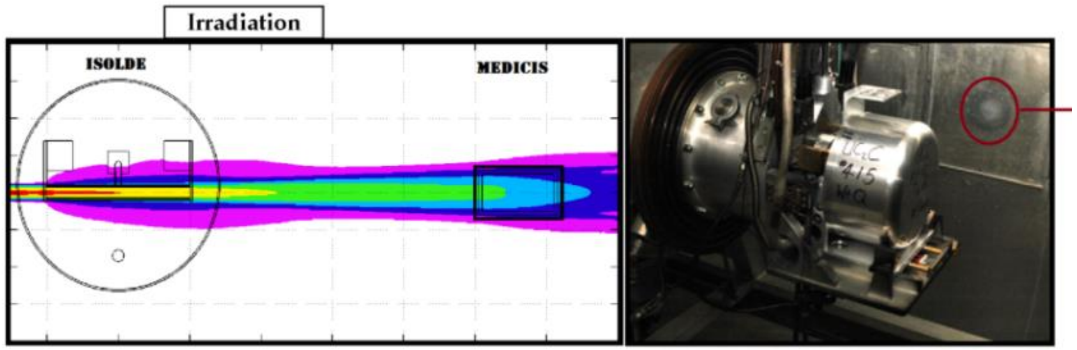
Symbiotic production of medical radionuclides

- Place symbiotic medical target in-between ISOL target and beam dump
- Pneumatic target delivery system from ARIEL hot cell complex to proton target station
- Independent operation from ISOL target
- up to 100 mCi of ^{225}Ac from ^{232}Th spallation



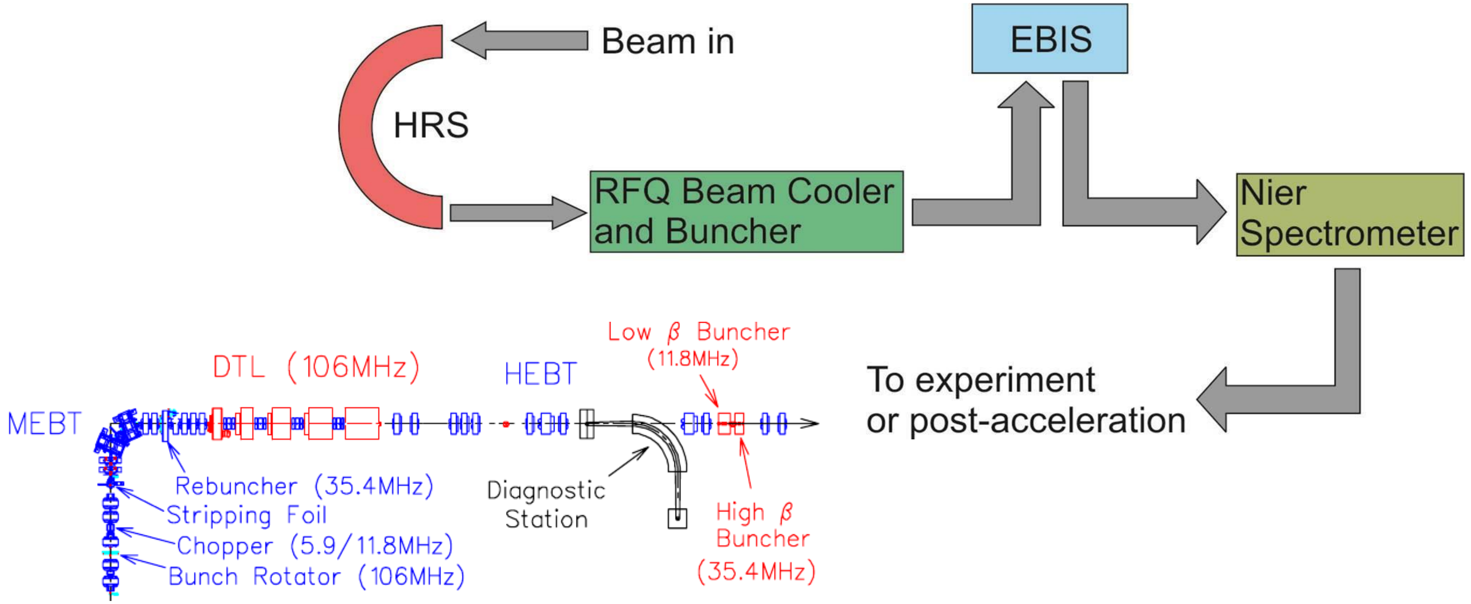


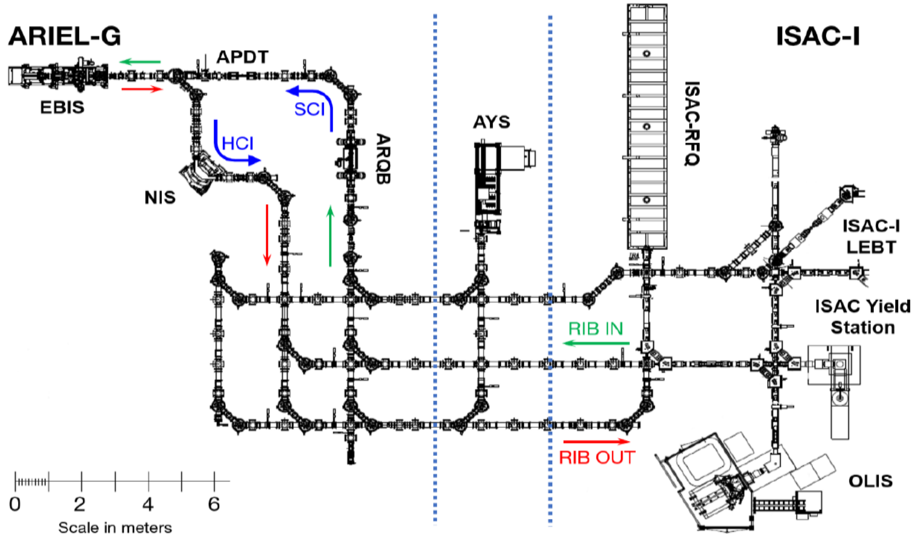
Examples are ARIEL and ISOLDE MEDICIS



CANadian Rare-isotope facility with Electron Beam ion source (CANREB) at TRIUMF

- CANREB consists of 200 m new RIB transport connecting ARIEL target stations to ISAC experimental areas.
- Gas filled Radio Frequency Quadrupole (RFQ) for beam quality improvement (cooling)
- Electron beam ion source (EBIS) charge state breeder with shortest breeding time (10 ms) and highest rep rate (100 Hz)!
- High Resolution mass Separator (HRS) M/ΔM = 20,000 for RIB beams





Create a diversified portfolio of isotopes for post-acceleration

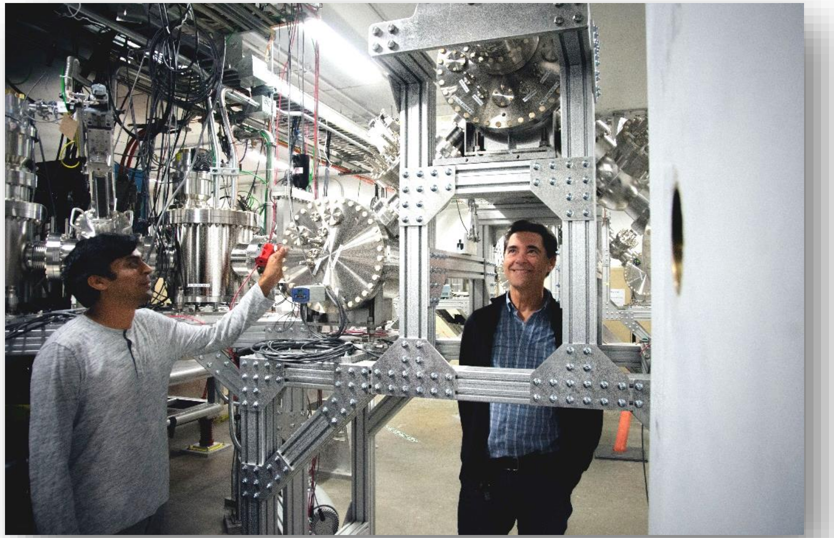
- *Short breeding times for short lived species*
- *High purity*
- *Higher mass range*

ARIEL-CANREB in pictures

Electron Beam Ion Source, Nier spectrometer, and beamlines

ISAC-ARIEL connection: RIB going both ways since May 2019

High-Resolution isotope Separator



Test ion source for commissioning

Discovery, accelerated

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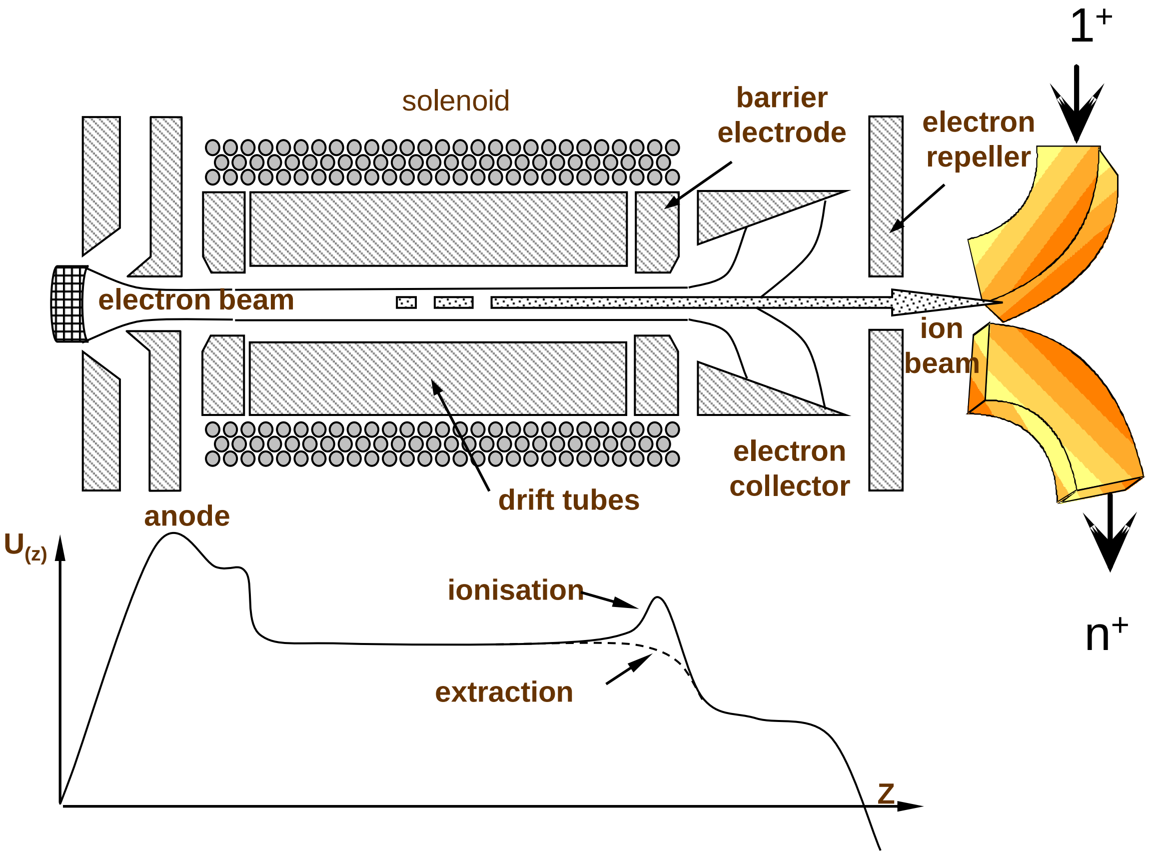
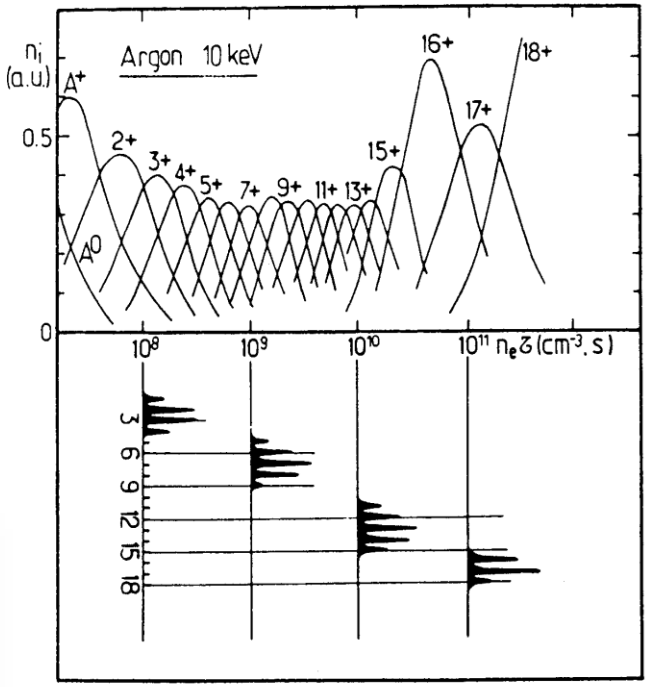
Electron Beam Ion Source/Trap (EBIS/T) charge state breeder



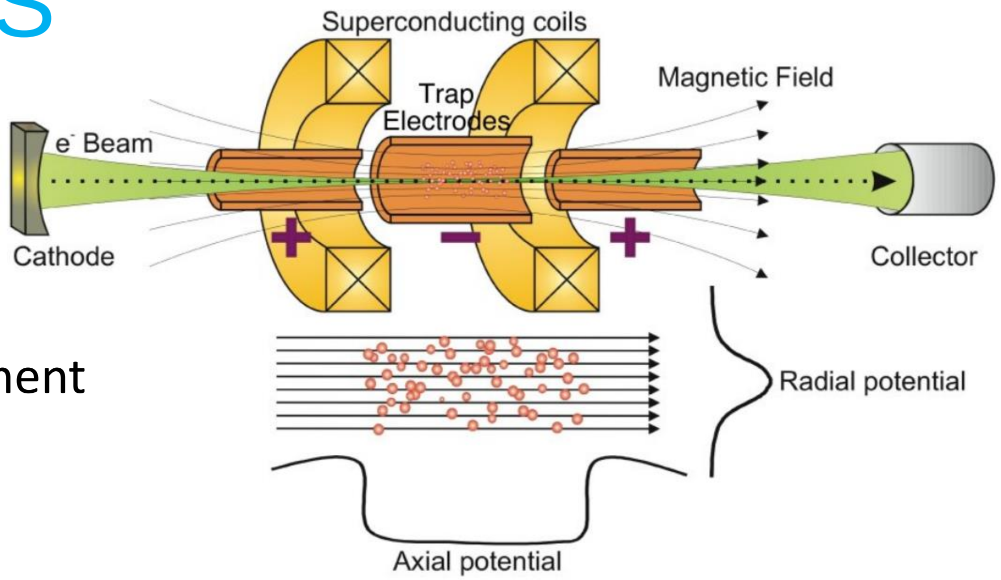
- Electrostatic confinement
- Intense electron beam (high current density, up to 10^4 A/cm^2)
- Tunable electron beam energy
- Storage capacity is proportional to trap length and electron current

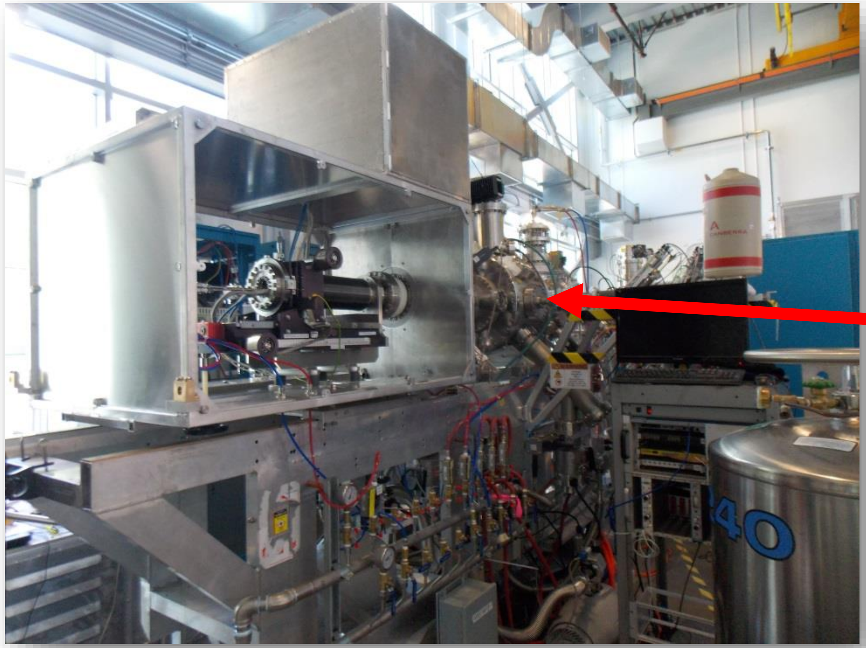


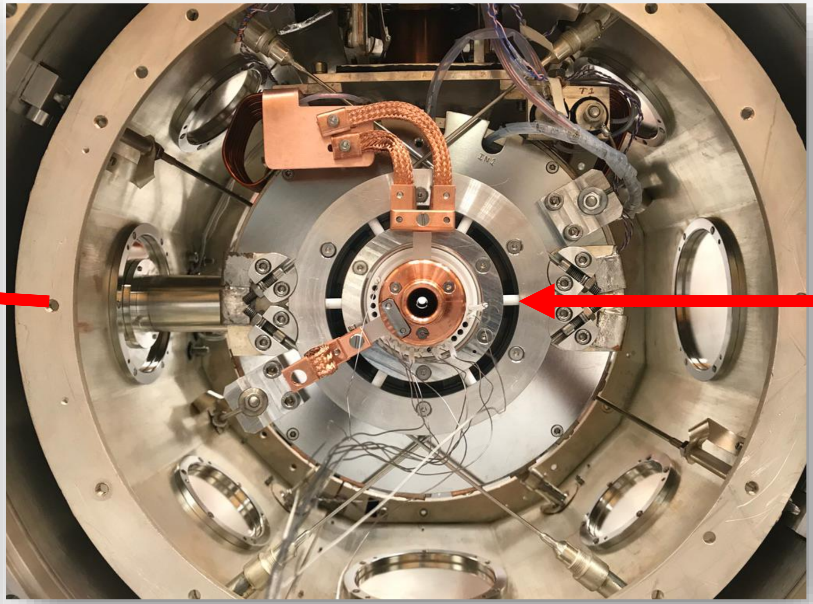
Charge development for stepwise ionisation

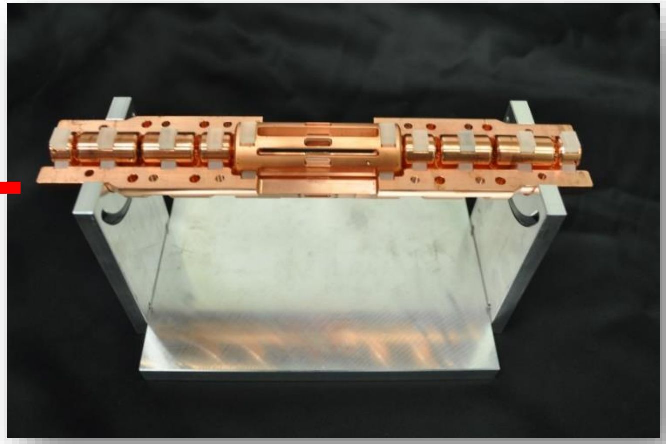
The CANREB EBIS

- 6T superconducting magnet in a Helmholtz coil set-up → Allows radial optical access to the trap
- Generate highly charges ions with A/Q < 7 within 10 ms
- Low rest gas background due to cryogenic (4 K) environment
- Operate 100 Hz repetition rate
- Designed for a 5 keV electron beam with a current of 1A



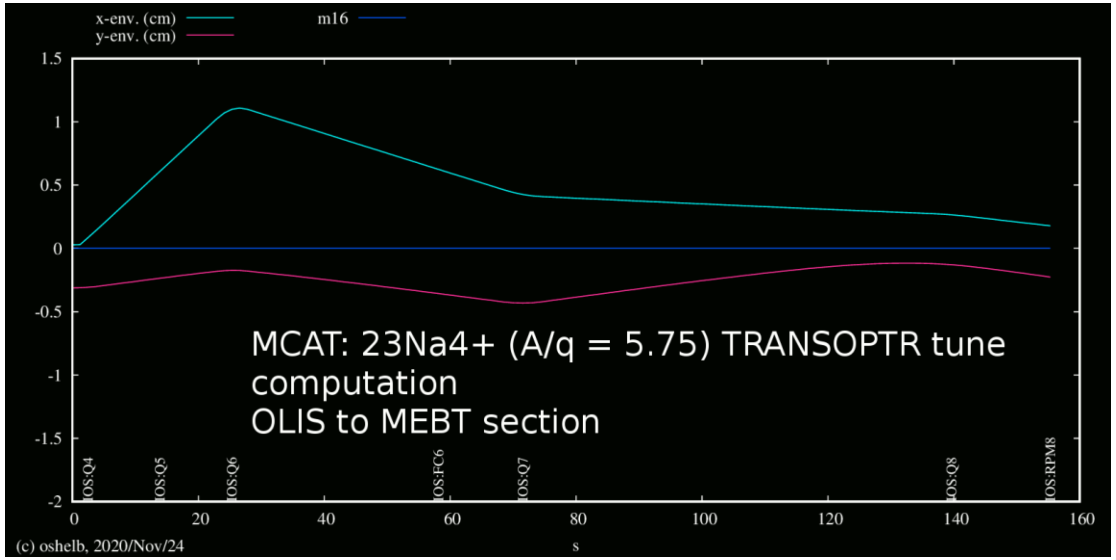




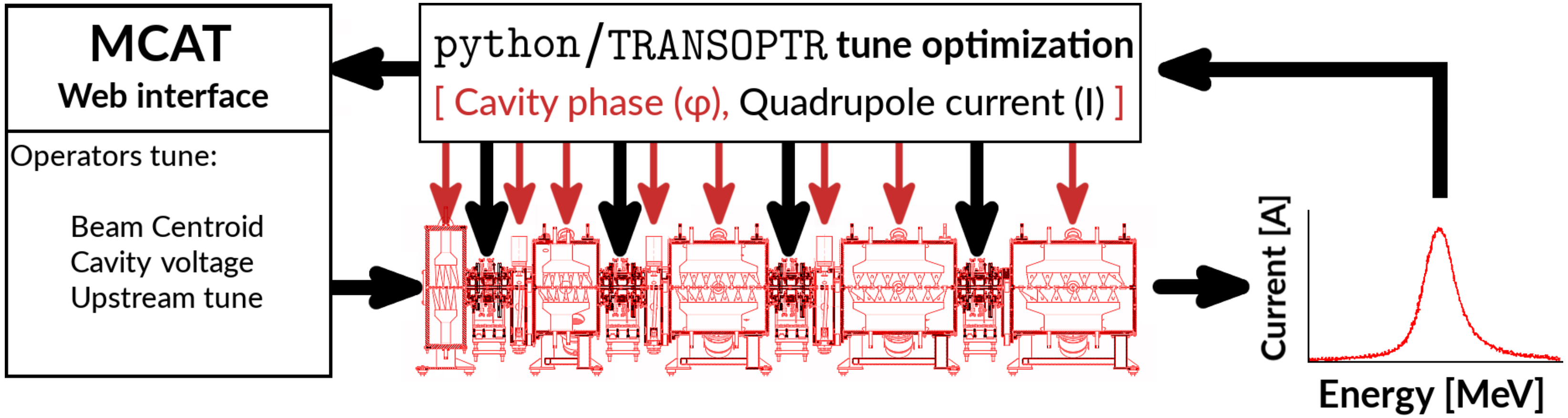


Beam physics: The future of beam development and delivery - Model coupled beam tuning

- A TRIUMF task force has developed a web-based framework and python interface to communicate with the accelerator control system for High-level applications (HLA).
- All of TRIUMF's accelerators and beamlines are planned to be integrated in model-based tuning using TRANSOPTR envelope code (R. Baartman).



- Emerged from HLA → Model Coupled Accelerator Tuning (MCAT) Coupled use of an envelope code in parallel to machine tuning, fed by on-line data. PhD of Olivier Shelbaya, UVic

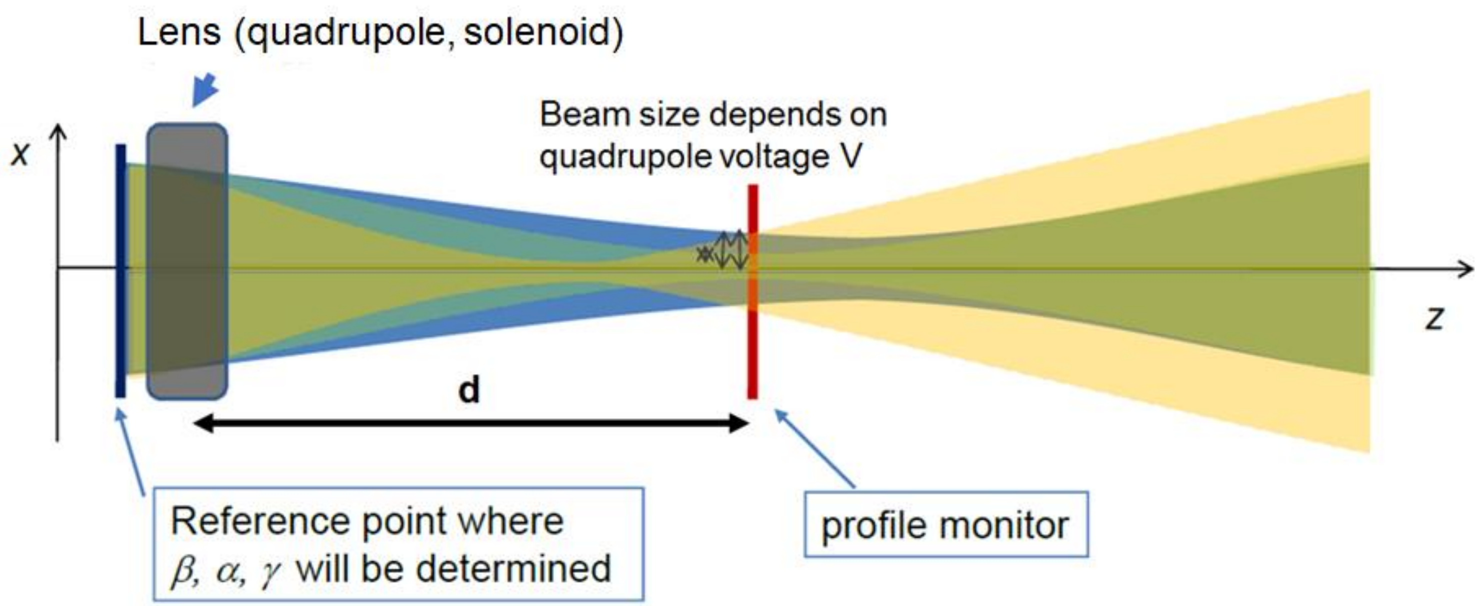


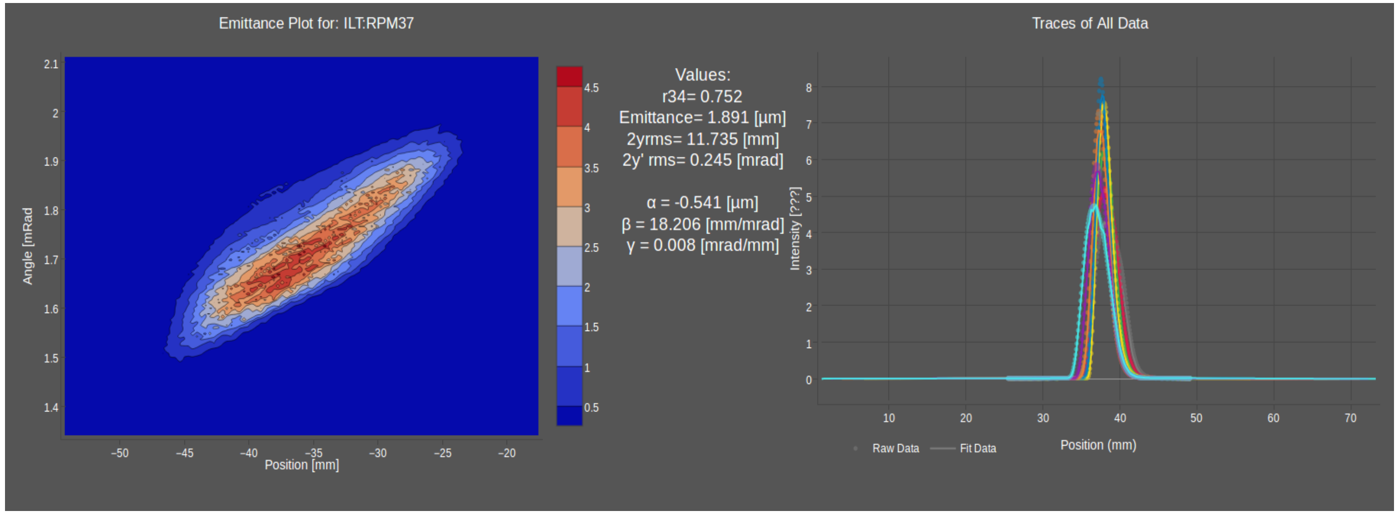
Beam Delivery – High Level Applications

One example of the HLAs is the determination of the beam emittance in certain positions of the accelerator.

Emittance tomography

- Reconstruction of beam 2D phase space (emittance) from series of 1D beam profiles (x, y)
- Useful where traditional emittance scanners are not installed.
- Automatic scanning of quadrupole voltage and profile measurements.





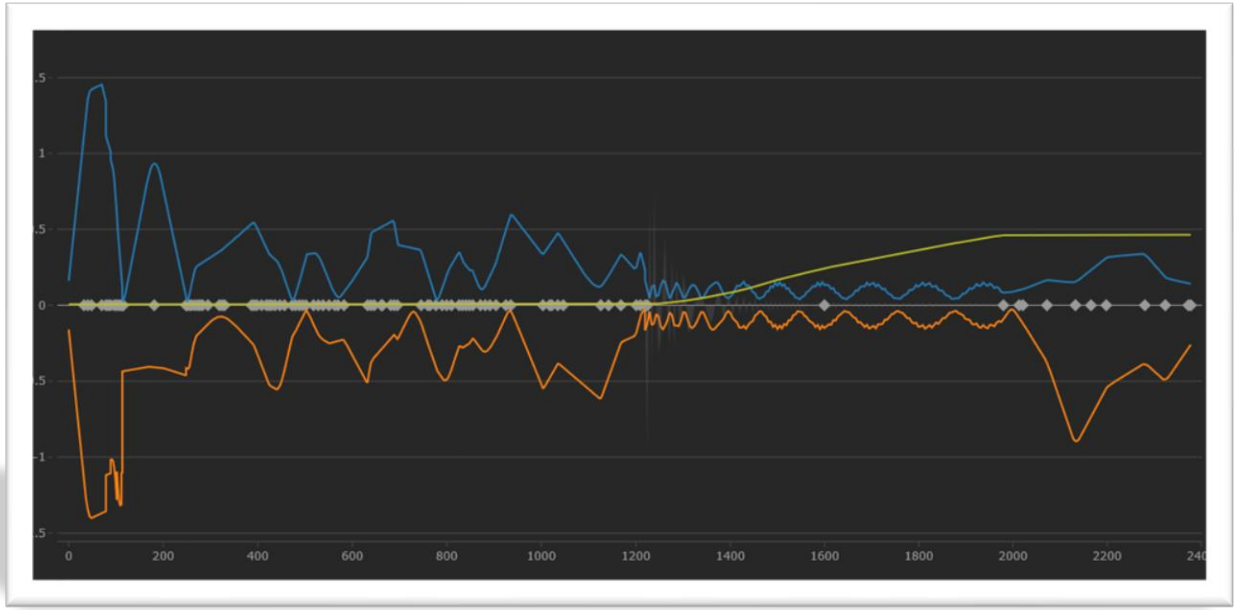
TRANSOPTR specifics

- TRANSOPTR treats as fully 6-dimensional beam envelope code all spacial dimensions in the same consistent way.

$$X = \left(x, P_x, y, P_y, z, P_z\right)^T \qquad (\text{note: } z = -\beta_0 c \Delta t \,,\, P_z = {\Delta E}/{\beta_0 c}) \quad \Rightarrow \quad \frac{dX}{ds} = \underline{F}(s) X$$

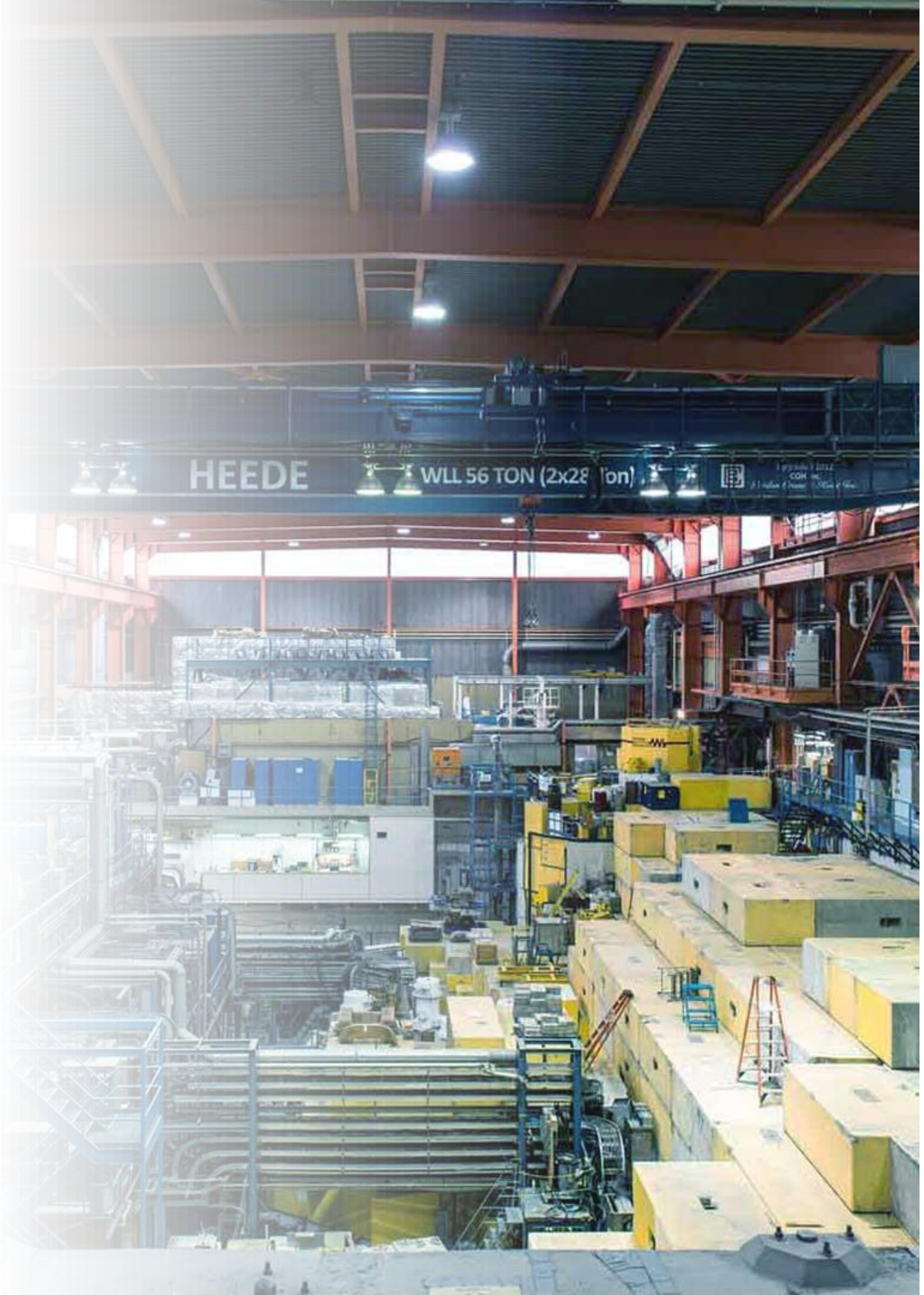
- F-matrix is determined by the second derivative of the Hamiltonian of the element
- Can treat all beam line elements, electrostatic and magnetic. The Radio Frequency Quadrupole accelerator was missing so far. This gap has recently been closed:
  O. Shelbaya, O. Kester and R. Baartman, Phys. Rev. Accel. Beams 22 (11) (2019) 114602

- TRANSOPTR computes the evolution of the statistical moments of a beam particle distribution as it interacts with various EM fields.



Conclusion

- Diverse, cohesive and constantly-evolving infrastructure that support excellence through technology, accelerator R&D, and Highly Qualified Personnel (HQP) training
- Strategic planning done hand in hand with our user's community ensured relevance:
  Proof when our international partners base their design on our infrastructures and TRIUMF-invented technologies.
- Canadian accelerator leadership and international collaborations are the cornerstone of TRIUMF's approach to attracting talents and developing new capabilities



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Thank you
Merci

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