Accelerator R&D at TRIUMF

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Deputy Director, Accelerator Division

FRIB Seminar

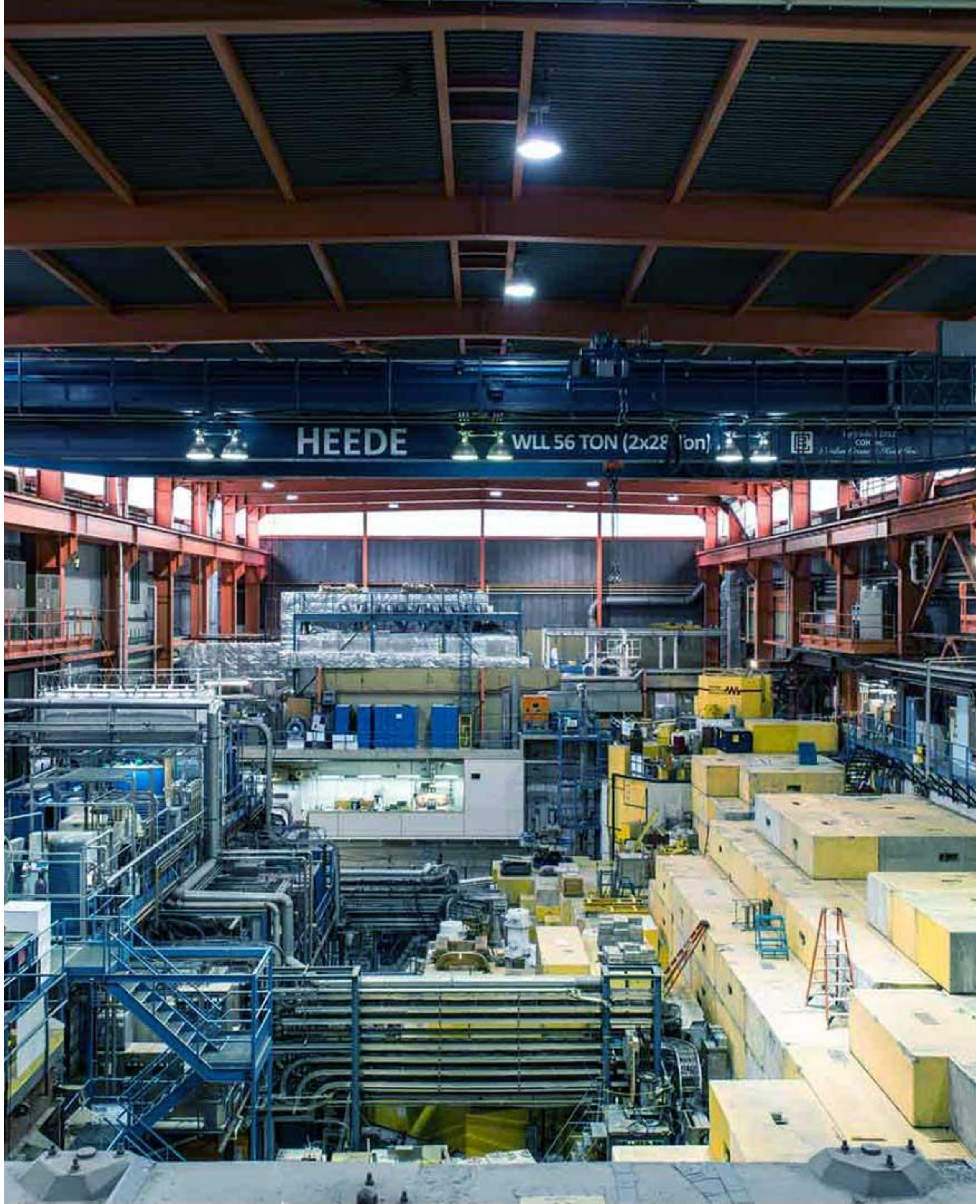
May 22, 2025

Topics:

- TRIUMF Accelerator Division
- TRIUMF Five Year Plan
- Core competencies
- Accelerator Science program
- Selected R&D

Discovery, accelerated

TRIUMF Accelerator Division



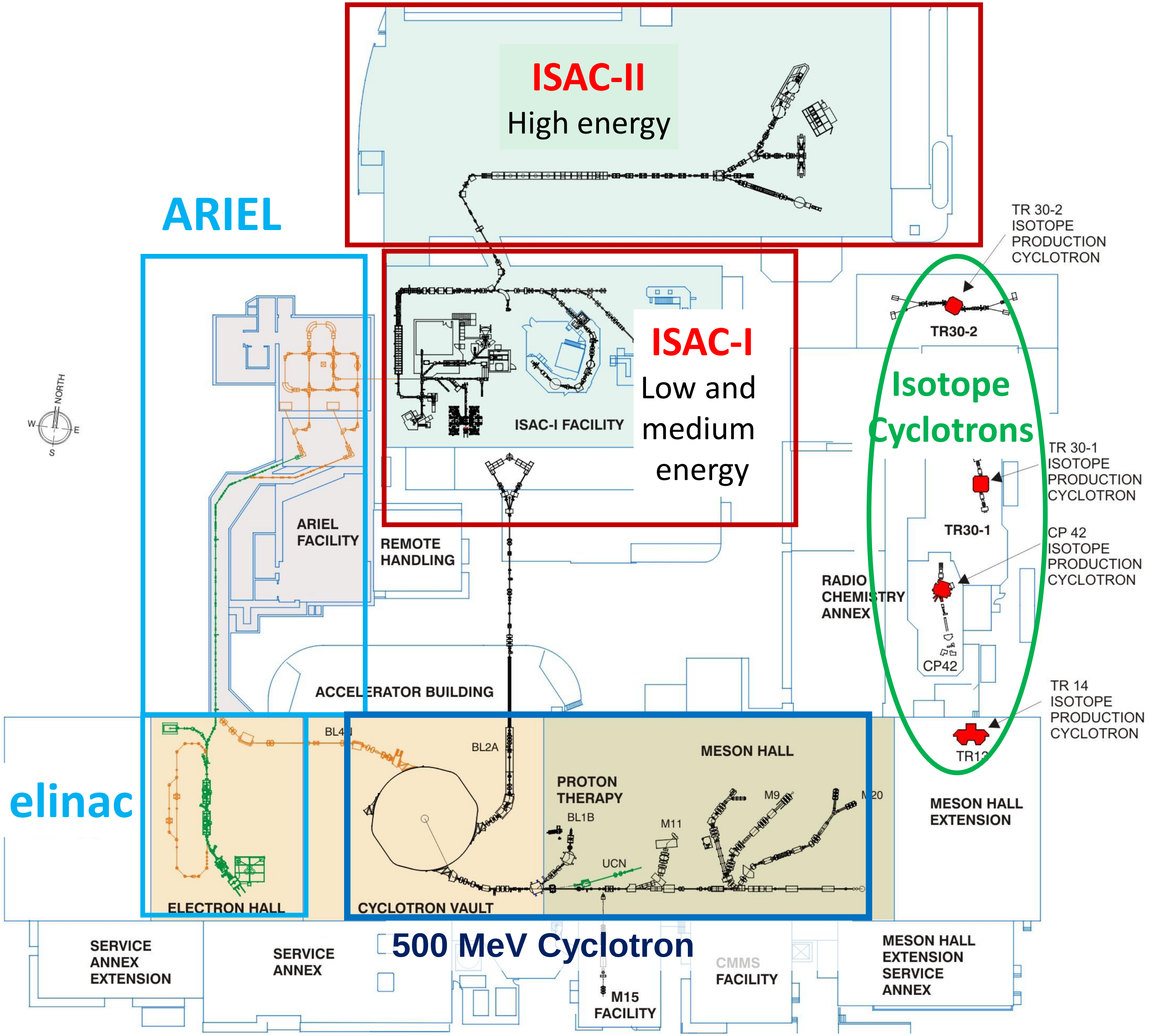
Discovery, accelerated

TRIUMF is Canada's **particle accelerator** centre

TRIUMF has five decades of experience in building a rich particle accelerator infrastructure that nurtures cutting-edge research.

ACC division mission statement

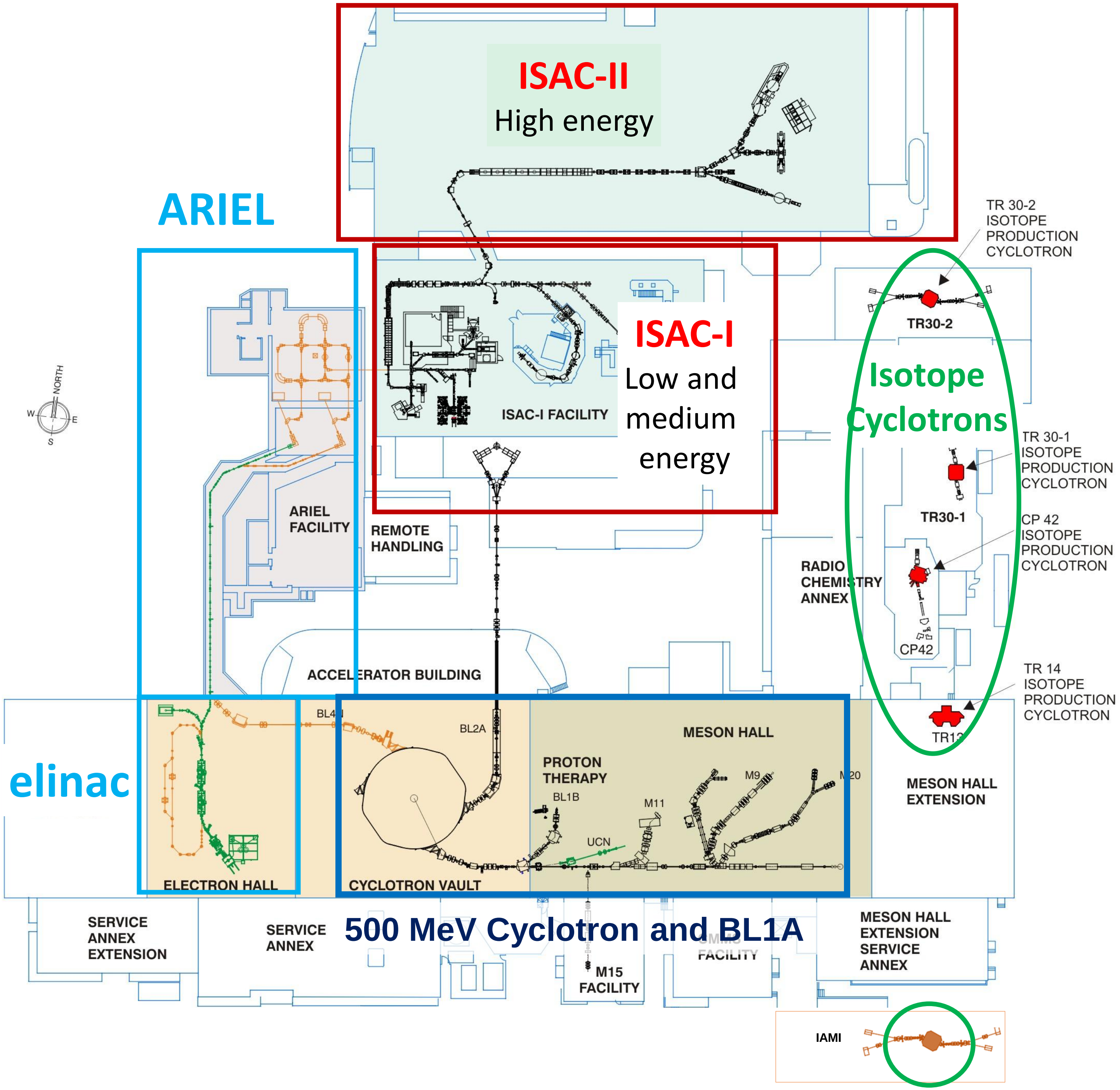
- The TRUMF accelerator division safely operates the TRIUMF accelerator complex with high performance and availability.
- We develop and implement new accelerator facilities and related technologies to support world class science nationally and internationally.
- We lead accelerator physics research in Canada and foster TRIUMF’s position at the forefront of accelerator science.
- We advance our core competencies and transfer our knowledge to industry for the benefit of society.
- We leverage infrastructure and expertise to provide world class training of young researchers in accelerator physics and engineering.



This mission is reflected in the wide variety of accelerator technologies that populate the campus.

Our strategy is to use internal projects and external collaborations as springboards to expand core competencies or gain new ones.

Rather than import technology, we typically develop it, accumulating a broad expertise within a relatively small lab.



TRIUMF accelerator complex

Primary beam driver (1974):

500 MeV Cyclotron, 300 μA, H^-
Produces rare isotopes, neutrons and muons

Isotope Separator and Accelerator facility – ISAC (1996)

- ISAC-I: Normal conducting-linac
  - 0.15-1.8 MeV/u (2000)
- ISAC-II: Superconducting-linac
  - 1.5-16.5 MeV/u (2006)

Advanced Rare Isotope Laboratory – ARIEL (in progress)

- Superconducting electron linac
  - 30 MeV, 10 mA, cw (2019)

4 (+1) Cyclotrons for medical isotope production – TR30 and TR13 designed by TRIUMF

Update: Structure of the ACC Division

Director
ACCELERATOR DIVISION
O. Kester

Deputy Director
R. Laxdal

Administrative Assistant
P. Dela Zilwa

145 staff members (including post doctoral fellows)
+34 staff members in ATG
+15+2 graduate students (2 among staff)

Responsible for:

Accelerator Operations
J. Aoki

- Accelerator Operation Driver and RIB accelerators
- Operation Life Science Division cyclotrons

Accelerator Systems
Y. Bylinski

- Vacuum
- Cryogenics
- Power Convertors
- Beam Instrumentation
- Accelerator Engineering Physics and Beam lines

Applied Technology Group (ATG)
Y. Hosepyan

- Operations of Medical cyclotrons for BWXT
- Operation of the Solid State Facility (STF) and Isotope Production Facility (IPF)

Beam Physics & Delivery
T. Planche

- Beam optics simulations
- Beam line and accelerator design
- Beam Delivery
- ARIEL e-linac
- Automatic Beam Tuning and machine learning for beam tuning

RF / SRF
R. Laxdal

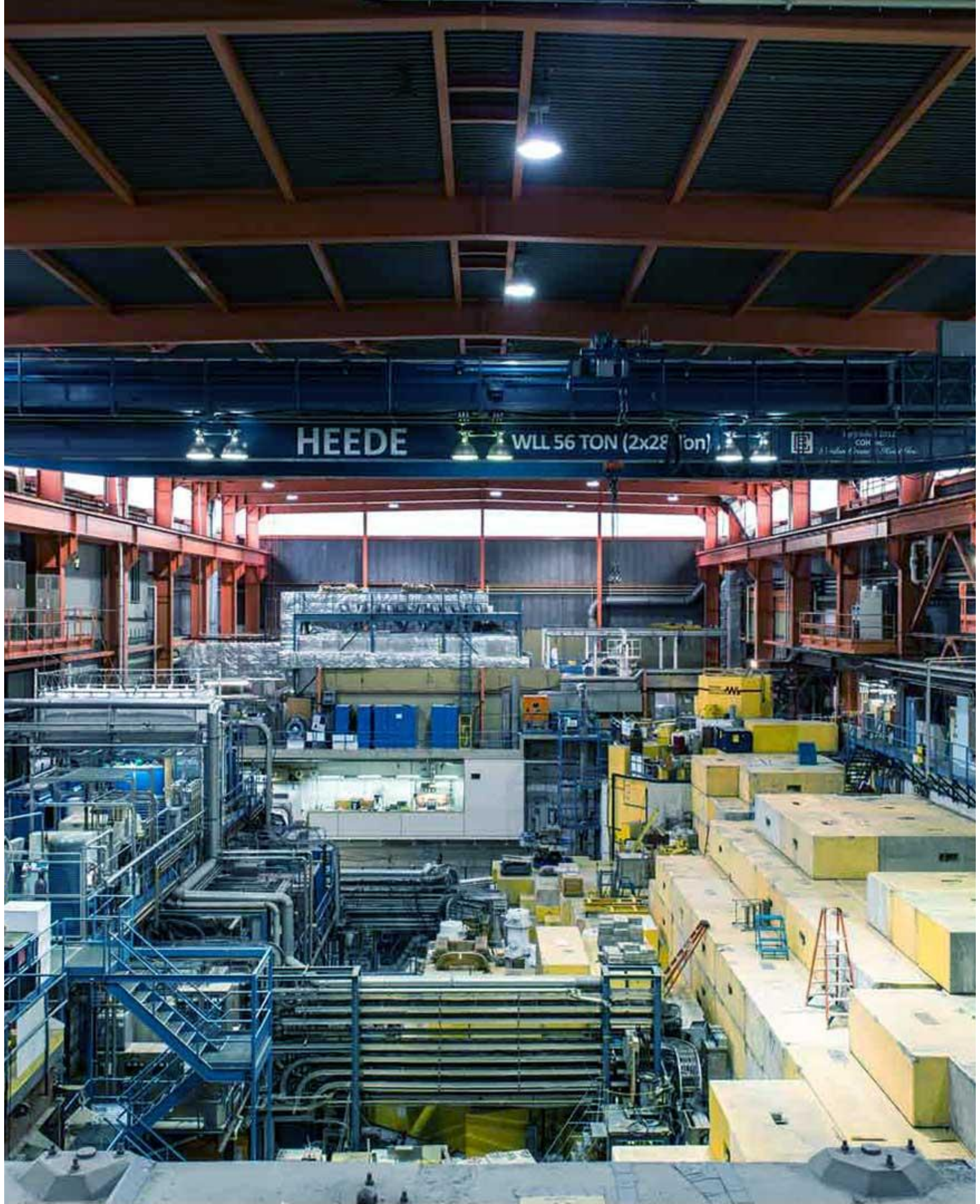
- High Power RF
- Low Level RF
- Superconducting RF
- Cavities

Targets and Ion Sources
A. Gottberg

- Laser Application
- High Power Target systems
- Remote Handling
- Target and target station technology development

TRIUMF

TRIUMF Five Year Plan (2025-2030)



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TRIUMF Implementation Plan - Core Deliverables

Deliver science from the Advanced Rare Isotope Laboratory (ARIEL)

1. Deliver 5000 hours of radioactive isotope beam to ISAC by the 2029 operational year
2. Ensure ARIEL is ready for Gate-4A (*CD-4*) by 2027

Complete and operate the Institute for Advanced Medical Isotopes (IAMI)

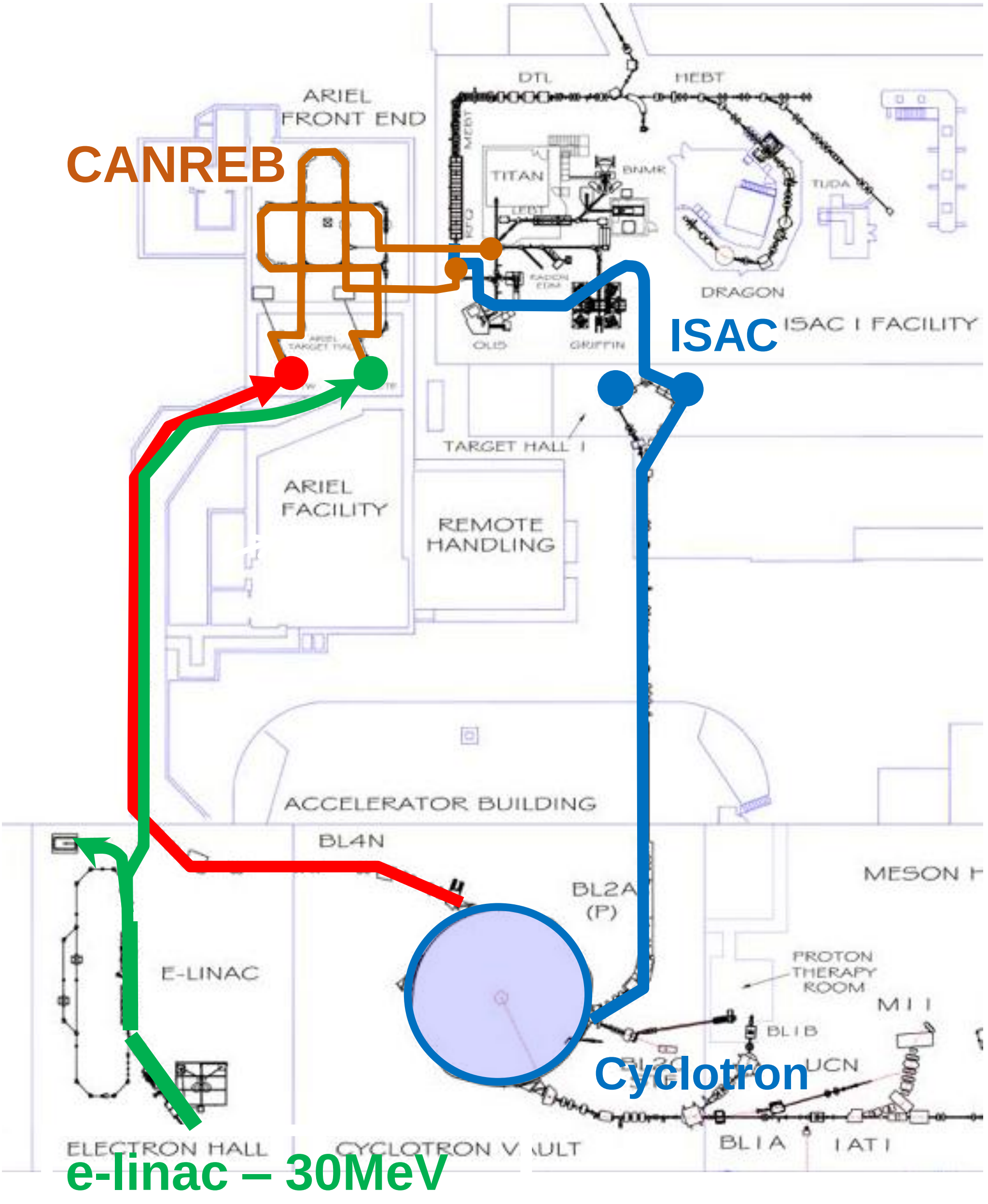
3. Initial operations of the IAMI facility in 2025

Refurbish key infrastructure and systems

4. Replacement of key components of Beamline 1A, supporting material sciences and isotope production

TRIUMF-5Y-Implementation-Plan-2025-2030.pdf

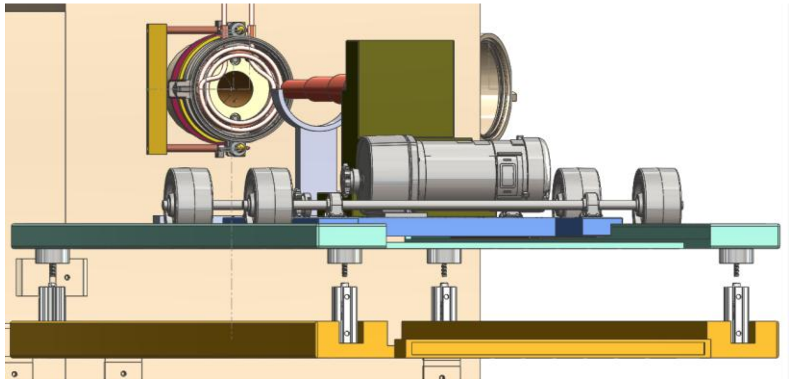
Adding new capabilities - ARIEL



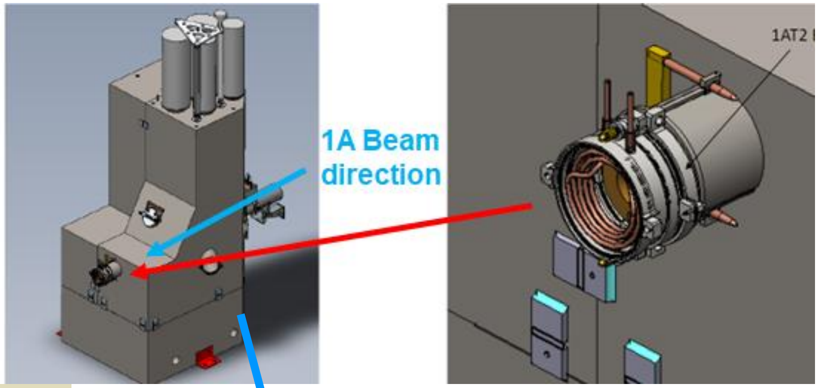
- Present: ISAC 500MeV - 50kW ISOL facility
- ARIEL
  - Two new target stations
    - APTW – 500MeV - 50kW protons
    - AETE – 30MeV - 100kW electrons
  - 30MeV superconducting electron linac and beamline with 100kW beam power cw
  - New 500MeV beamline from the cyclotron (50kW beam power)
  - Beam switchyard and separator
    - HRS (high resolution separator) - 20000
    - CANREB EBIS charge breeder
  - Plus medical target irradiation
  - Goal – delivery of three simultaneous ISOL RIBs to ISAC users

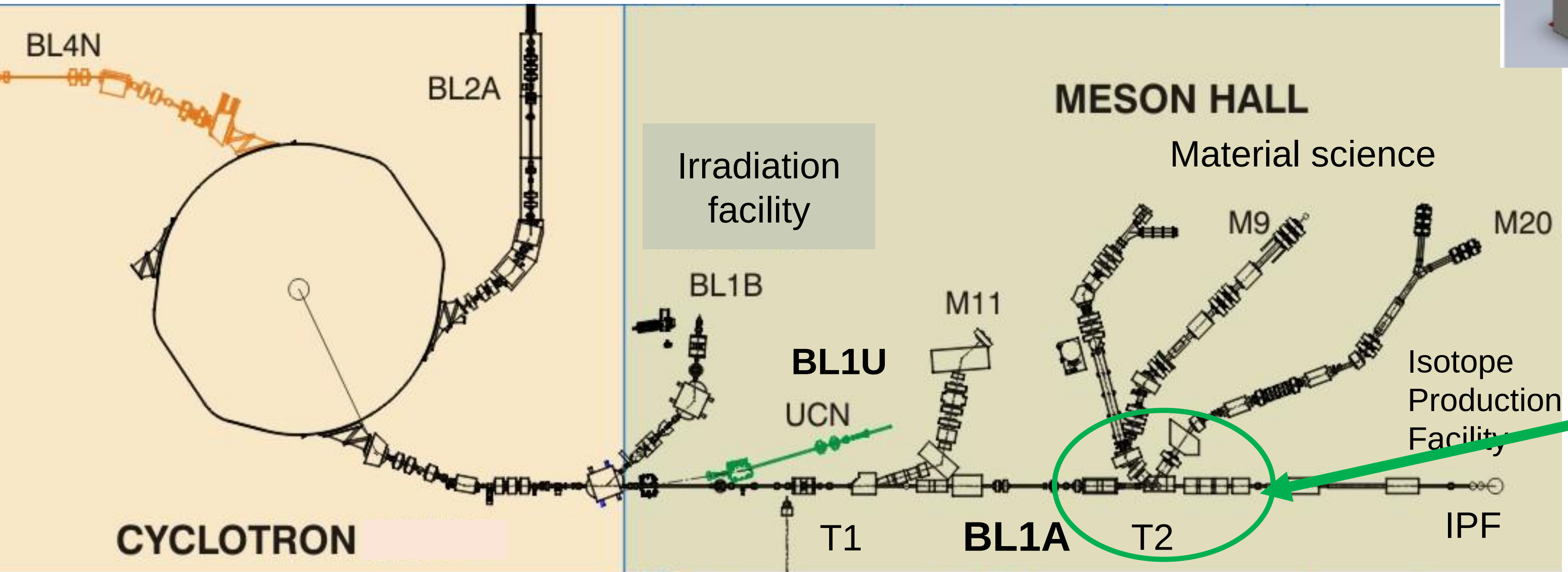
Refurbishment of BL1A

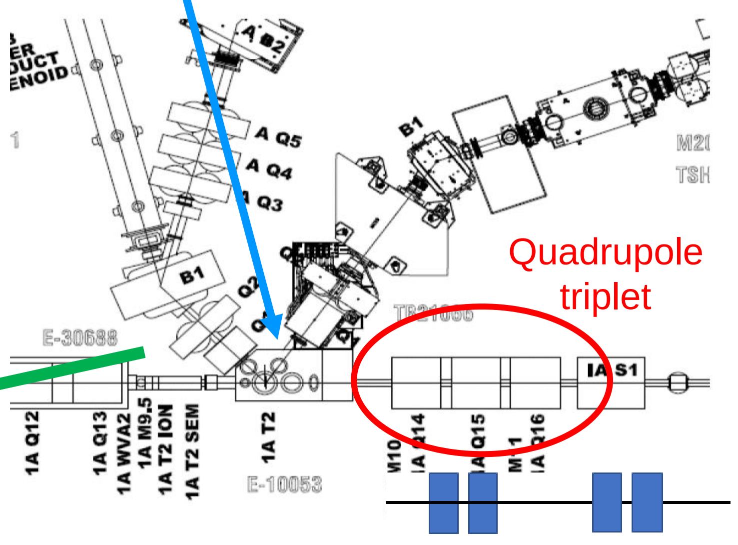
- The BL1A is one of the major high intensity proton beamlines feeding the T1 and T2 meson production targets (material science) and UCN (ultra-cold neutrons) – requires refurbishment after 50 years operation to restore reliable beam operation and enhance functionality of BL1A
  - Revision of the beam optics, alignment and vacuum integrity
  - Replacement of the collimator at T2 and the replacement of the quadrupole triplet downstream of T2



Collimator



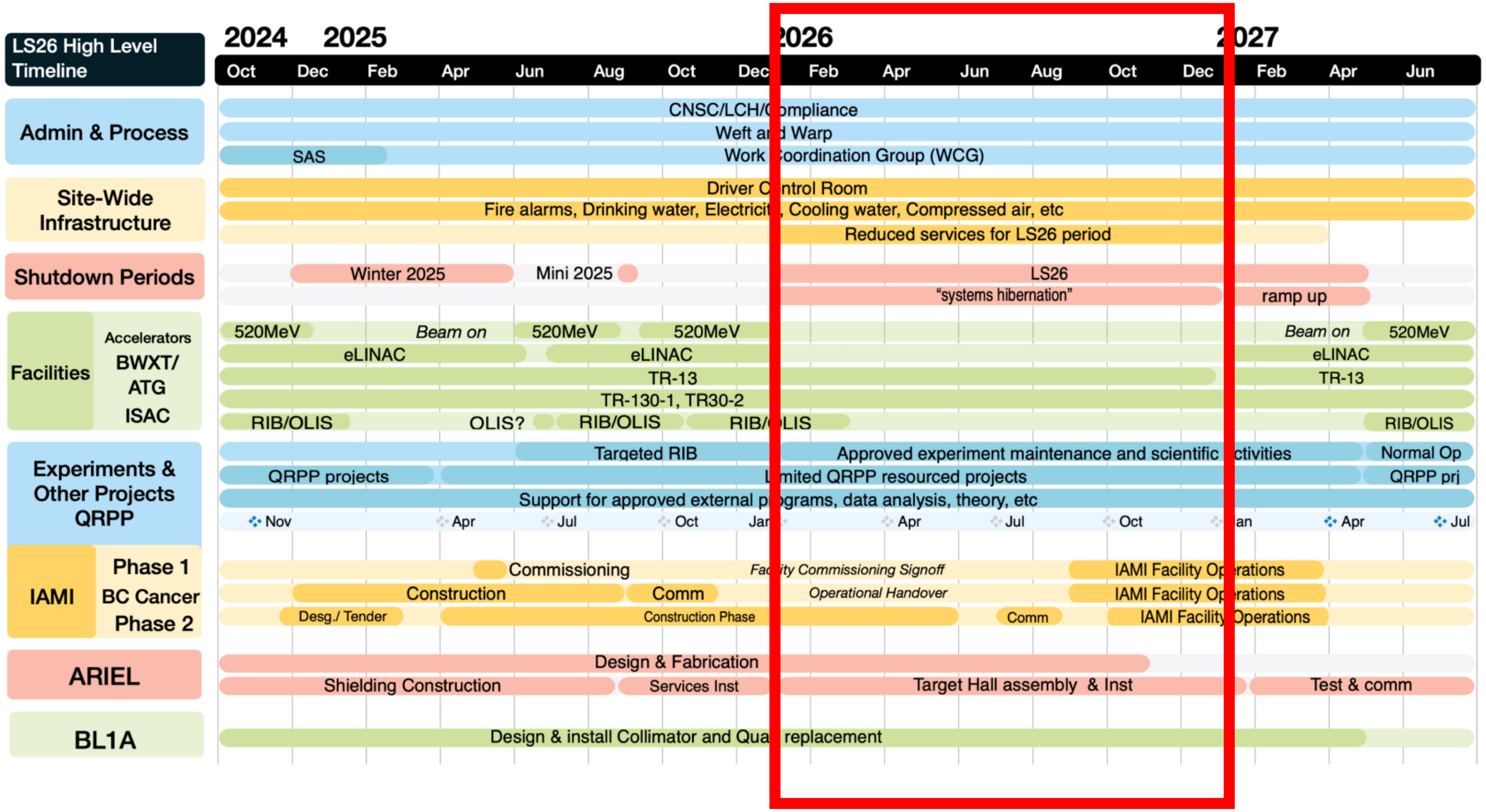




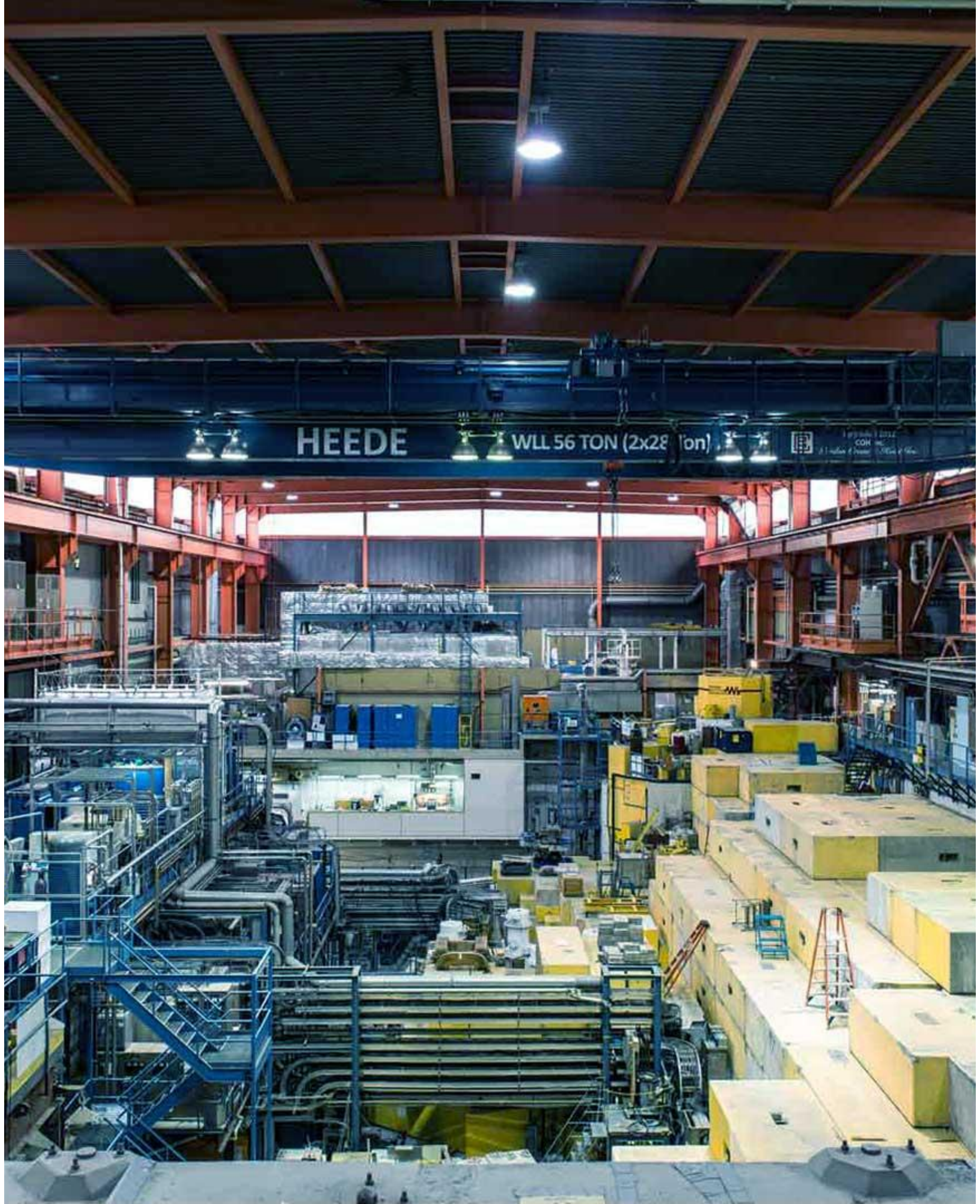
TRIUMF

Long shutdown 2026 (LS26)

- A key feature of the FYP is the shutdown of accelerators and beam delivery for CY2026
- The goal of SD26 is to free resources to enable the completion of the core deliverables of the Implementation Plan
  - ARIEL
  - IAMI
  - BL1A



ARIEL Status



Discovery,
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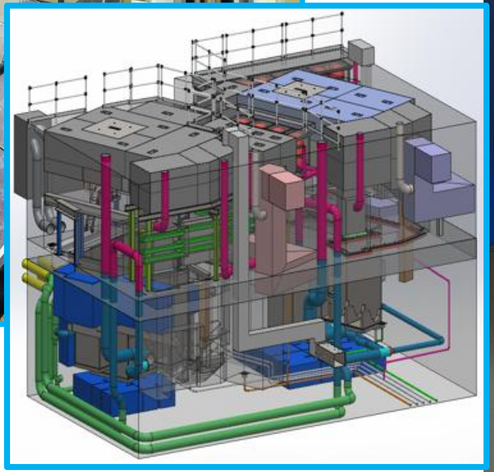
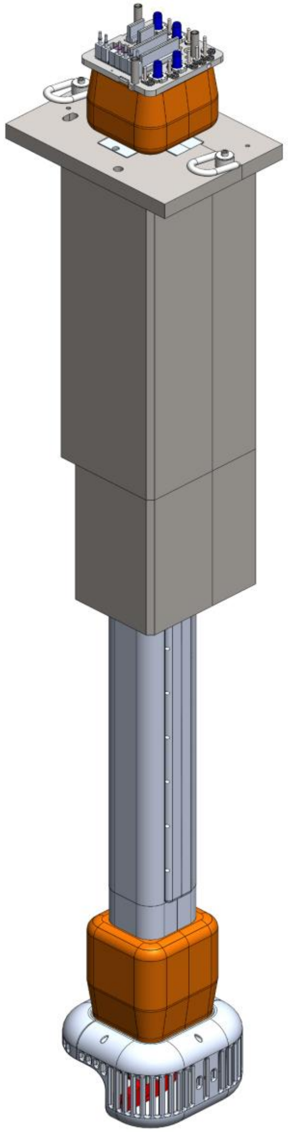
ARIEL Infrastructure

- Target hall shielding and embedded services well advanced
    - last fixed shielding installation in progress
- Hot cell installation completed.

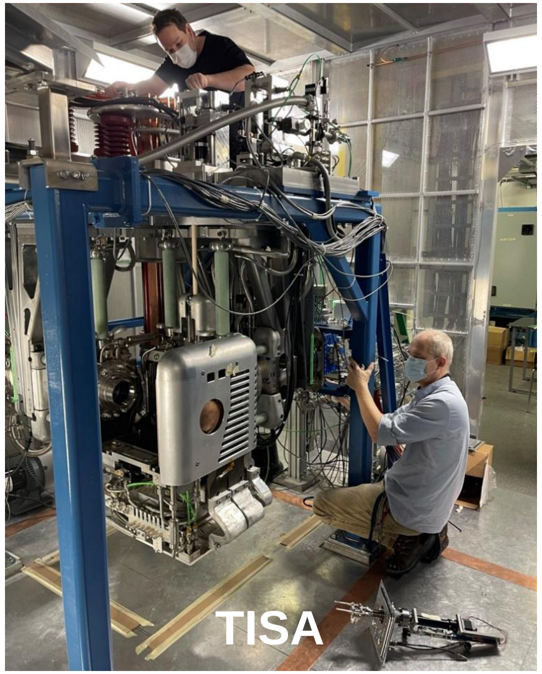


ARIEL status: Target Station

- AETE (ARIEL Electron Target Station East) targetry prototype testing complete (TISA), technical risks retired.
- Hermetic target vessel assembly completed – first target
- APTW Target Ion Source Front End assembly complete and placed into hot cell for remote handling validation tests.
- High voltage feedthrough (HVFT) prototyped successfully
  - Brings services from top of the shielding plug to target vessel at 60kV
  - first series article fabricated and being potted at the vendor

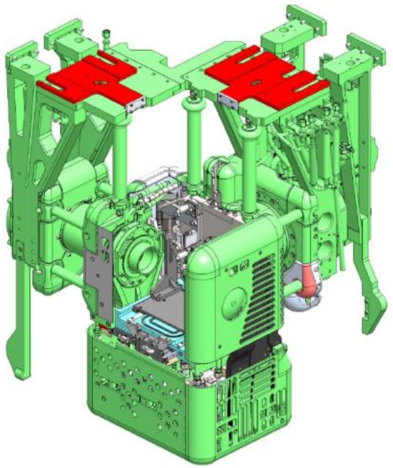


High voltage feedthrough



TISA

Hermetic target vessel

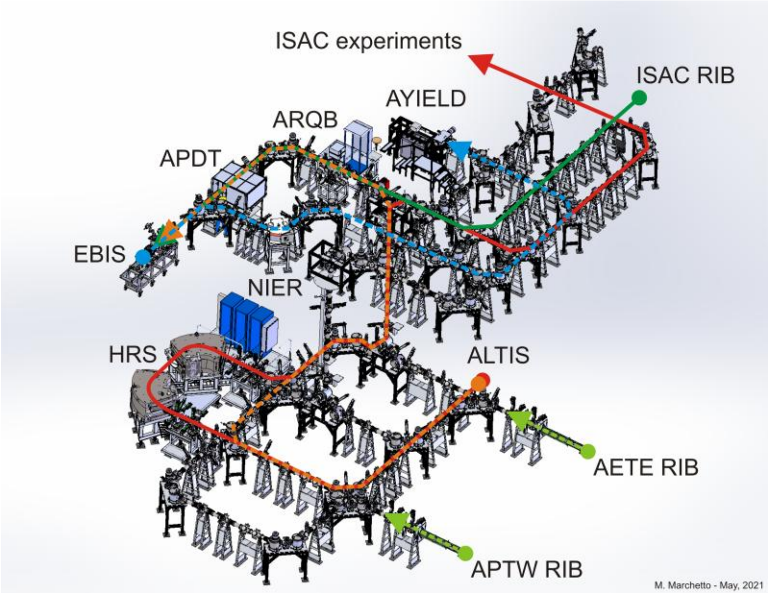


Front end in Hot cell

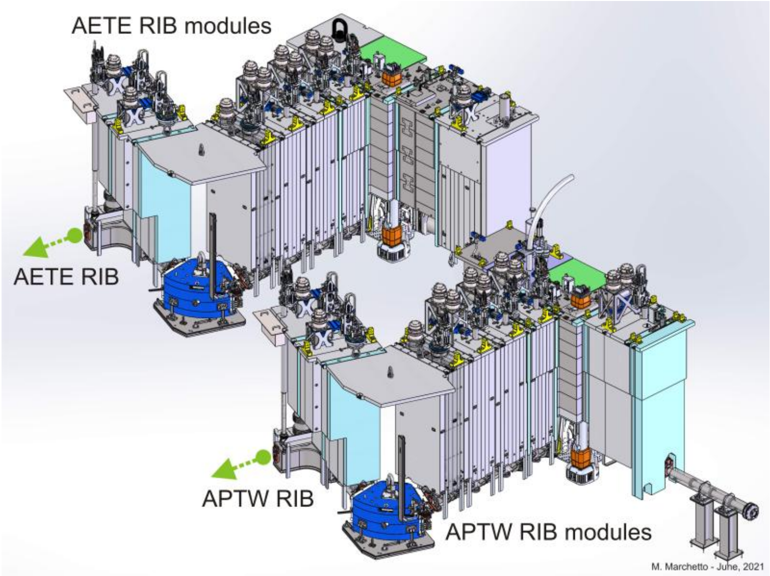
ARIEL RIB Transport

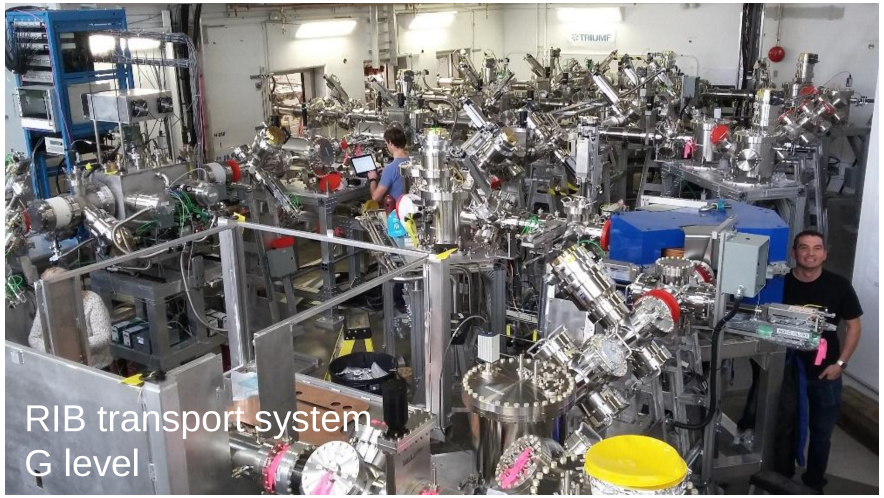
- RIB transport from ARIEL target hall to ISAC (200 m of electrostatic beamline) – 95% installed and commissioned
- Target hall RIB line in production
- Flexible layout enables 3 simultaneous RIB's delivery: 2 simultaneous ARIEL beams + ISAC beam
- Includes:
  - High resolution spectrometer (installed)
  - Charge breeding: EBIS (installed)
  - Yield station (installed)

Front-end outside the target hall

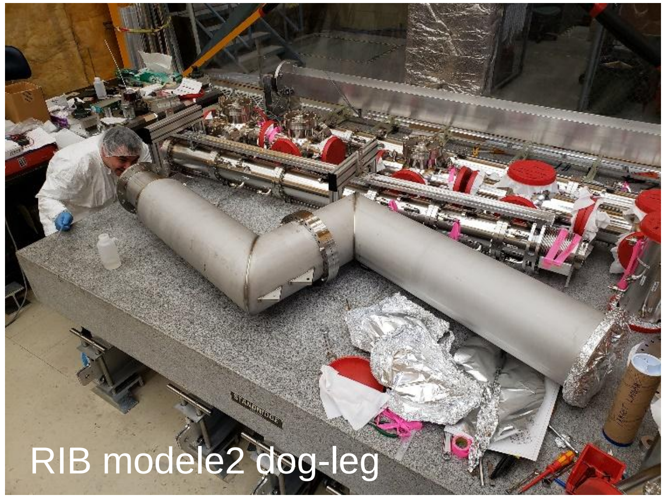


Front-end inside the target hall




RIB transport system G level

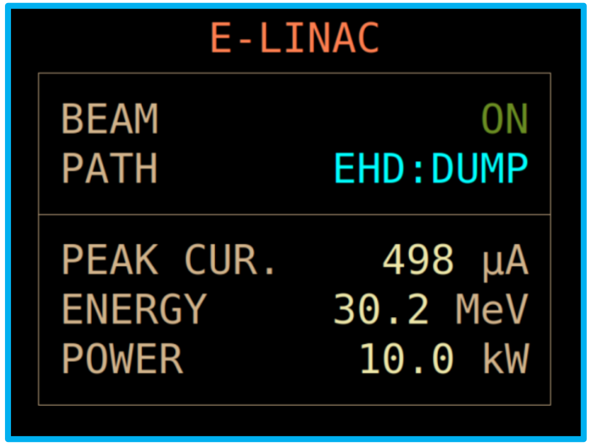

RIB module vacuum chambers

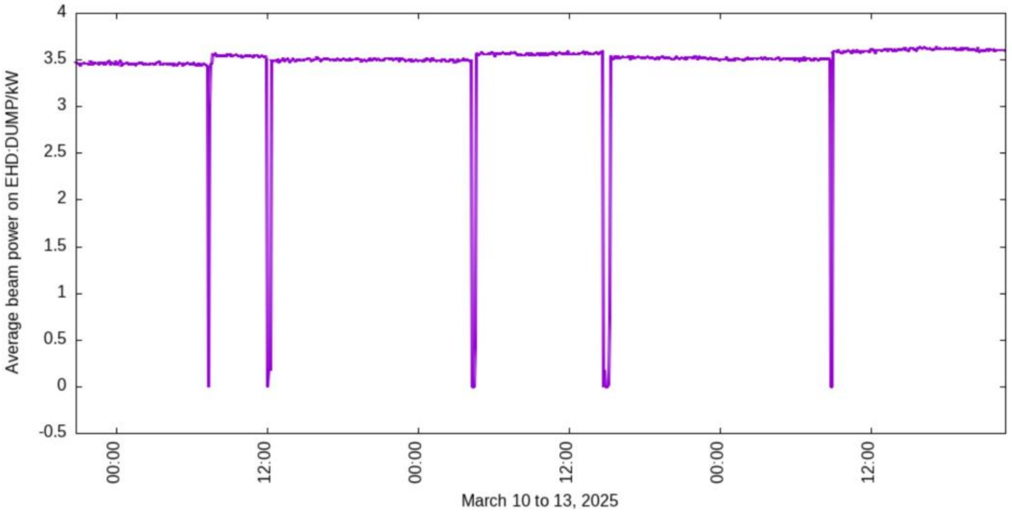

RIB modele2 dog-leg


RIB module shields

Driver accelerators for ARIEL

- e-Linac development has concentrated on reliability and operability
  - 10kW and 30MeV demonstrated
  - 3-day continuous run at 98% availability
  - Adding software tools to support operational mode

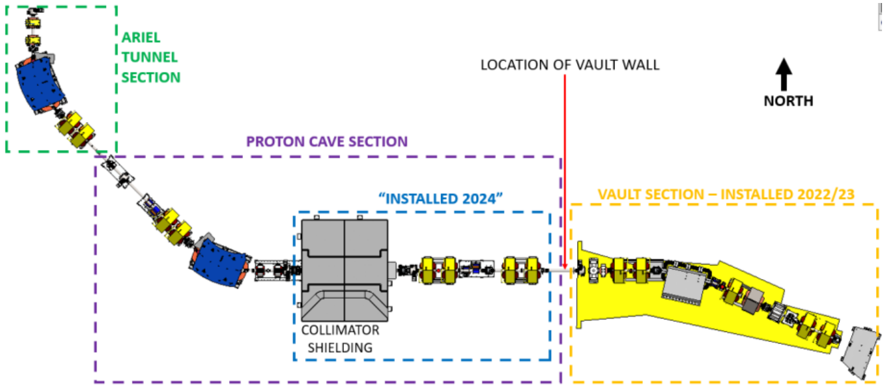




E-Linac 3-day continuous operation

- Primary proton beamline – BL4N
  - Extraction probe installed in cyclotron and beam extracted at low power
  - E-W section of beamline installed from cyclotron to tunnel

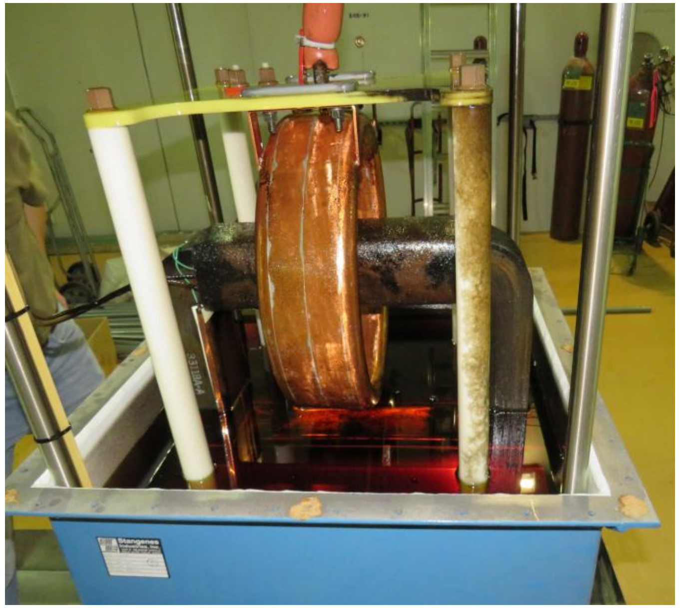
BL4N Collimator



BL4N E-W section installed

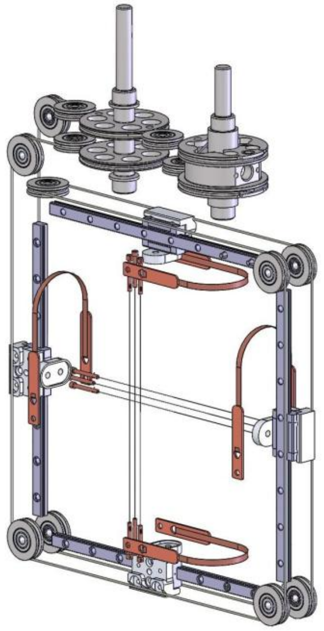
E-Gun biased to 300kV

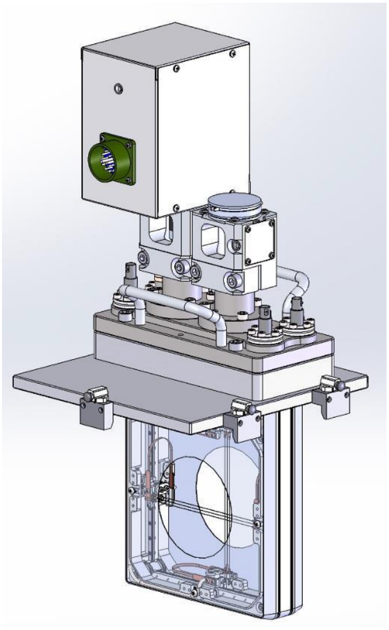
- Issues with original isolation transformer
- Replaced with hydro-turbine from Canyon Pico Hydro Turbine System (Washington)
  - designed for powering off-grid cabins
  - Turbine/generator assembly generates power from flow rate and head (pressure differential)

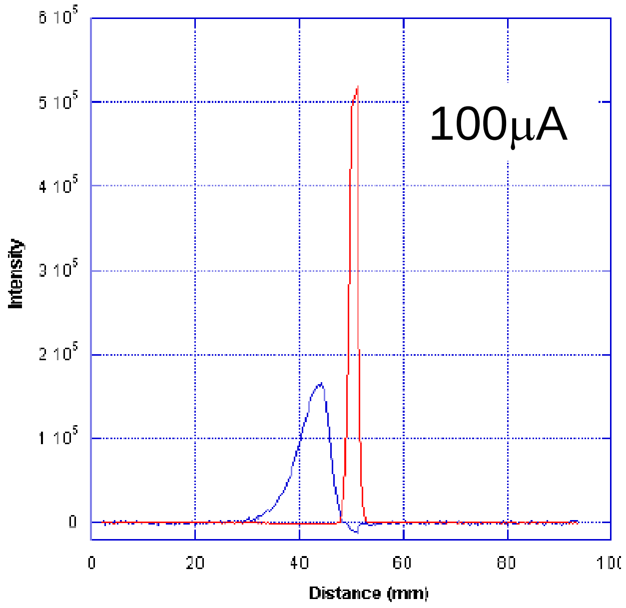


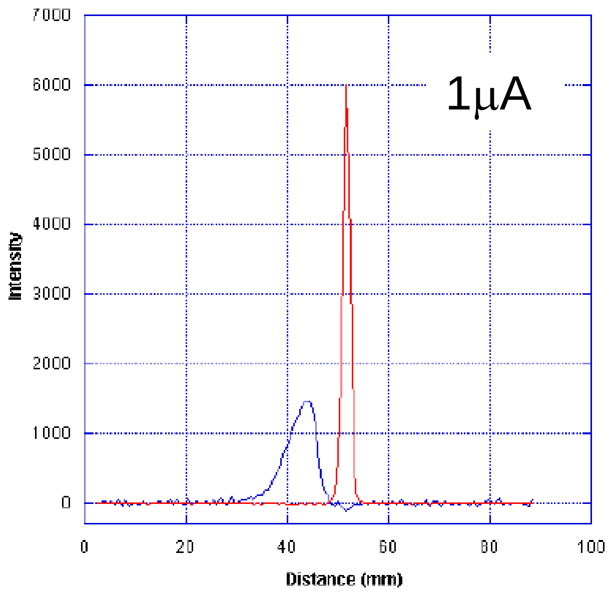
Proton line profile monitor

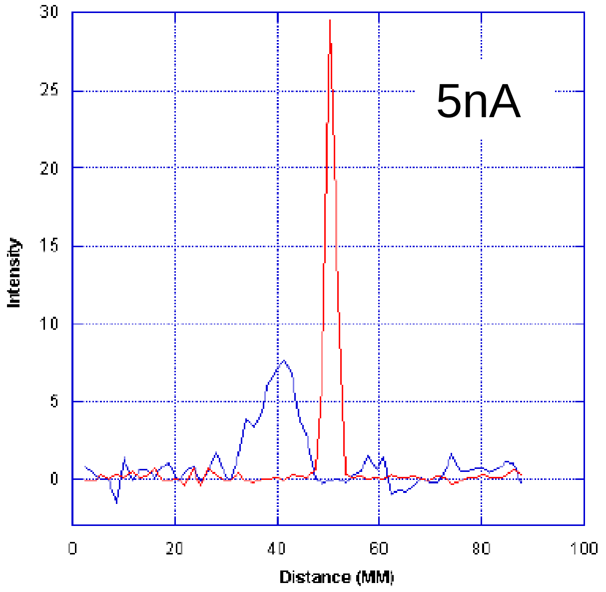
- Profile monitor with wide dynamic range successfully tested
- For deployment in proton beamlines
- 50micron Ti wires







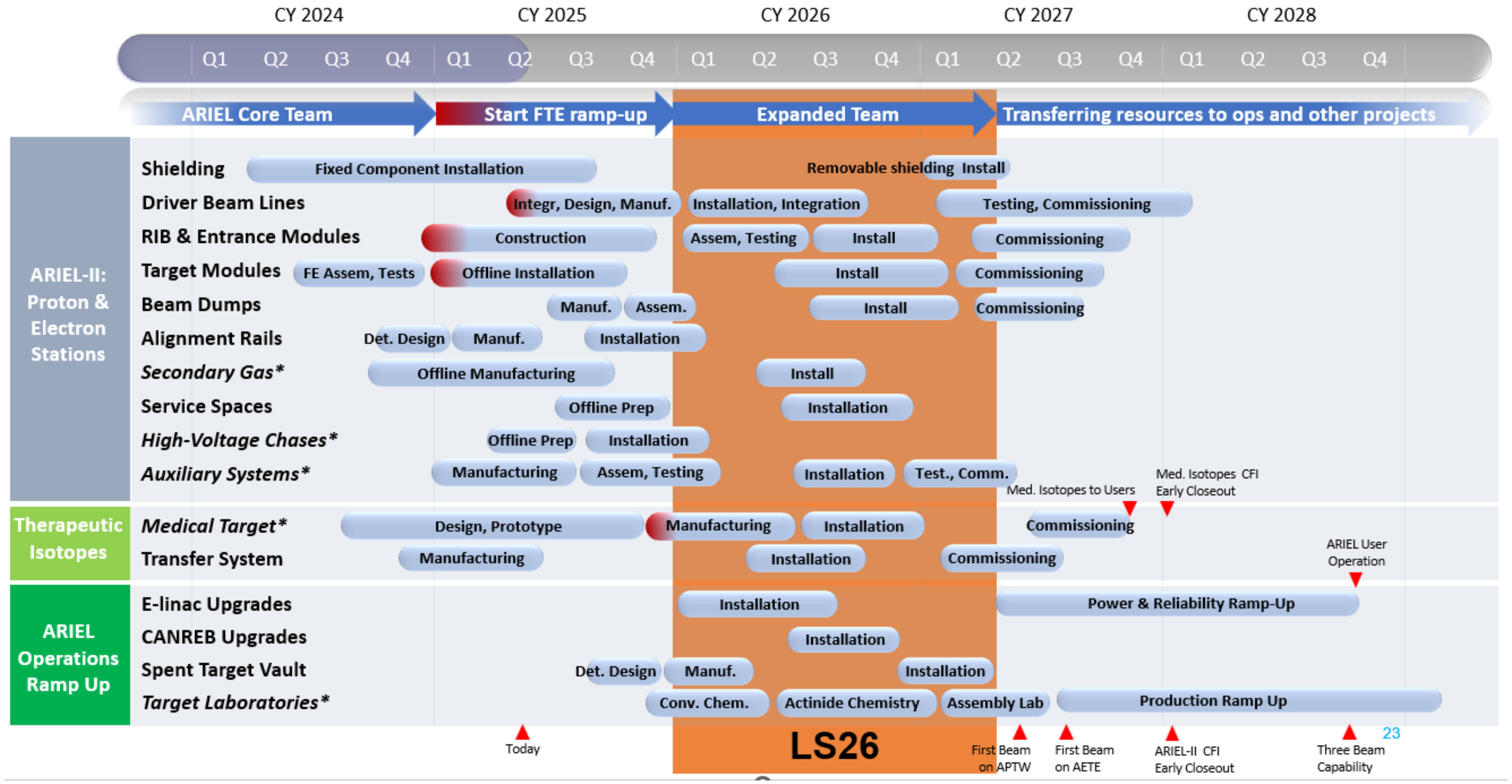




ARIEL Milestones

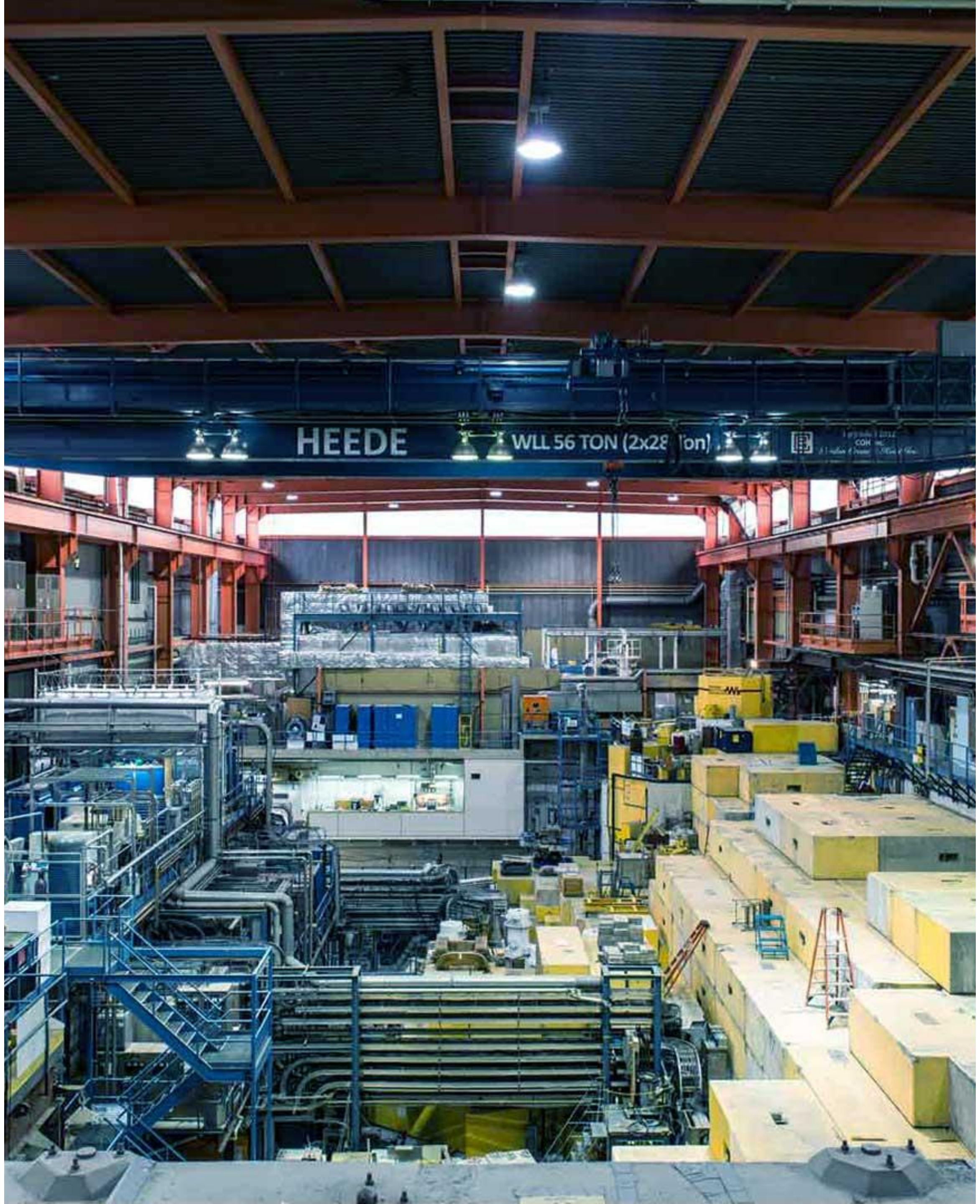
- SD2026 allows us to install the proton and electron target areas equipment together with commissioning in 2027
- Commissioning will be interleaved with TRIUMF operation
- ARIEL user operation starting in 2028

Milestone	Calendar quarter
First beam on APTW	Q2 2027
First beam on AETE	Q3 2027
ARIEL project early completion	Q1 2028
ARIEL user operation	Q4 2028



TRIUMF

Accelerator Developments



TRIUMF Accelerator Development and Research

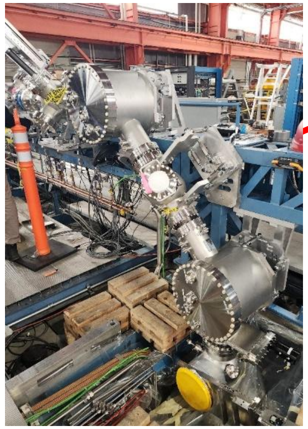
Areas of activities:

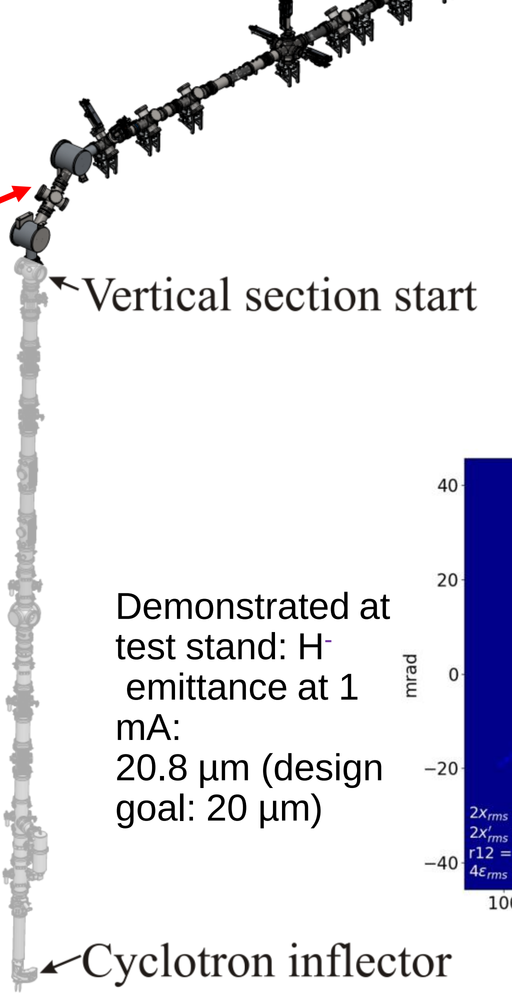
- ✓ Capacity increase via design and construction of new accelerator systems (ARIEL, CANREB)
- ▪ Operation, refurbishment and upgrade of the TRIUMF accelerator complex for efficient operation in the ARIEL era
  - ✓ Refurbished BL1A – replace aging infrastructure and mitigate operational risk
  - ▪ Cyclotron beam intensity increase to 400 μA capability (upgraded source and injection beamline)
- ▪ Domestic and international accelerator projects (THz, CANS, SCK (ISOL), HL-LHC, EIC …)
- ▪ Accelerator research and development (focused on TRIUMF core competencies)
  - ▪ beam physics
  - ▪ secondary particle production
  - ▪ SRF/RF technologies and research

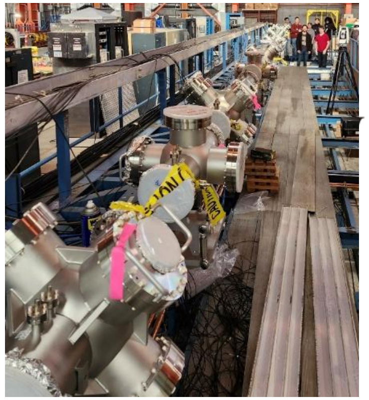
Reducing operational risk and increasing cyclotron beam intensity – Ion Source Injection System upgrade

Replacement of cyclotron horizontal injection beamline

- Cyclotron horizontal injection beamline and new Multi-harmonic buncher
- Replaces 50 year old injection line for improved reliability maintainability and high current capability
- Being commissioned



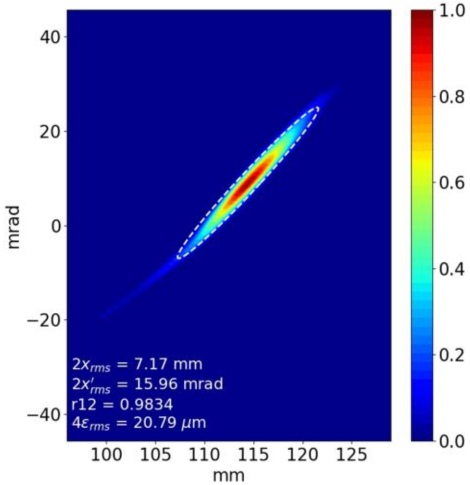


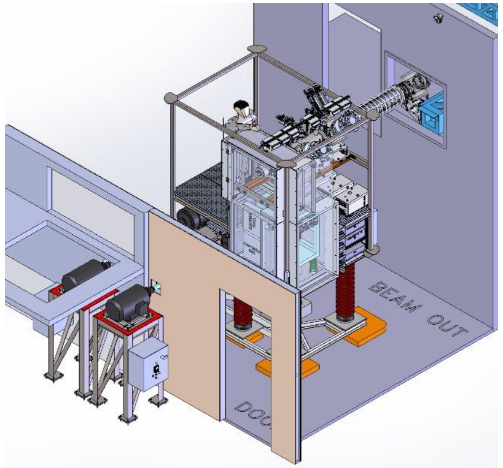


2nd H- ion source

- Add new high intensity H- source
- Increase output current for ARIEL operation
- Provided redundancy in operation
- 90% complete

Demonstrated at test stand: H^- emittance at 1 mA:
20.8 μm (design goal: 20 μm)

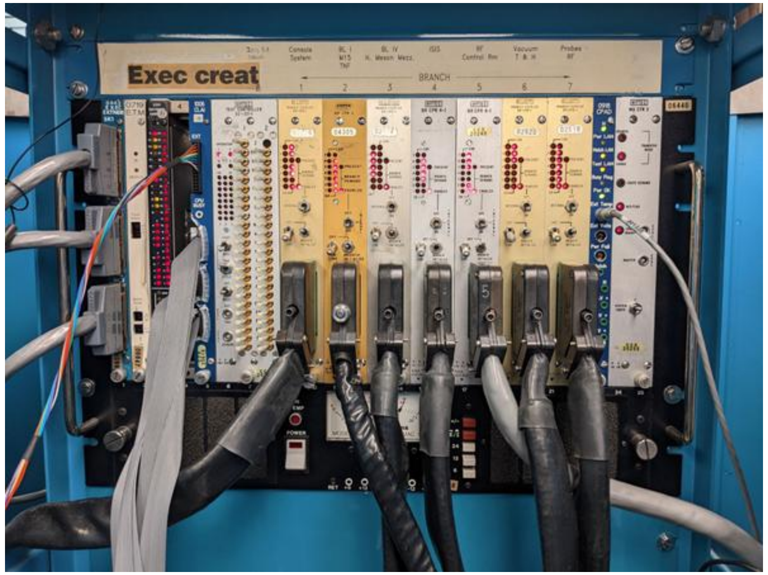




TRIUMF Cyclotron Control System Upgrade – reduce operational risk

Cyclotron Control System (CCS) upgrade

- Replace legacy CCS CAMAC executive crates with in-house built hardware running EPICS.
- remove controls hardware to make room for future TRIUMF Control Centre.
- Eliminate risk of executive crate failure that could cause months of downtime due to the scarcity of replacement parts.



Status and plans:

- **Mitigation:** In 2025 we plan to engage multiple external vendors for an assessment and cost estimate for project completion.
- **Timeline:** LS2026 will provide us with an opportunity to make significant progress, with the goal to relocate or remove the CCS CAMAC executive crate by 2028 a required step to allow implementation of the TRIUMF Control Centre (TCC) project.

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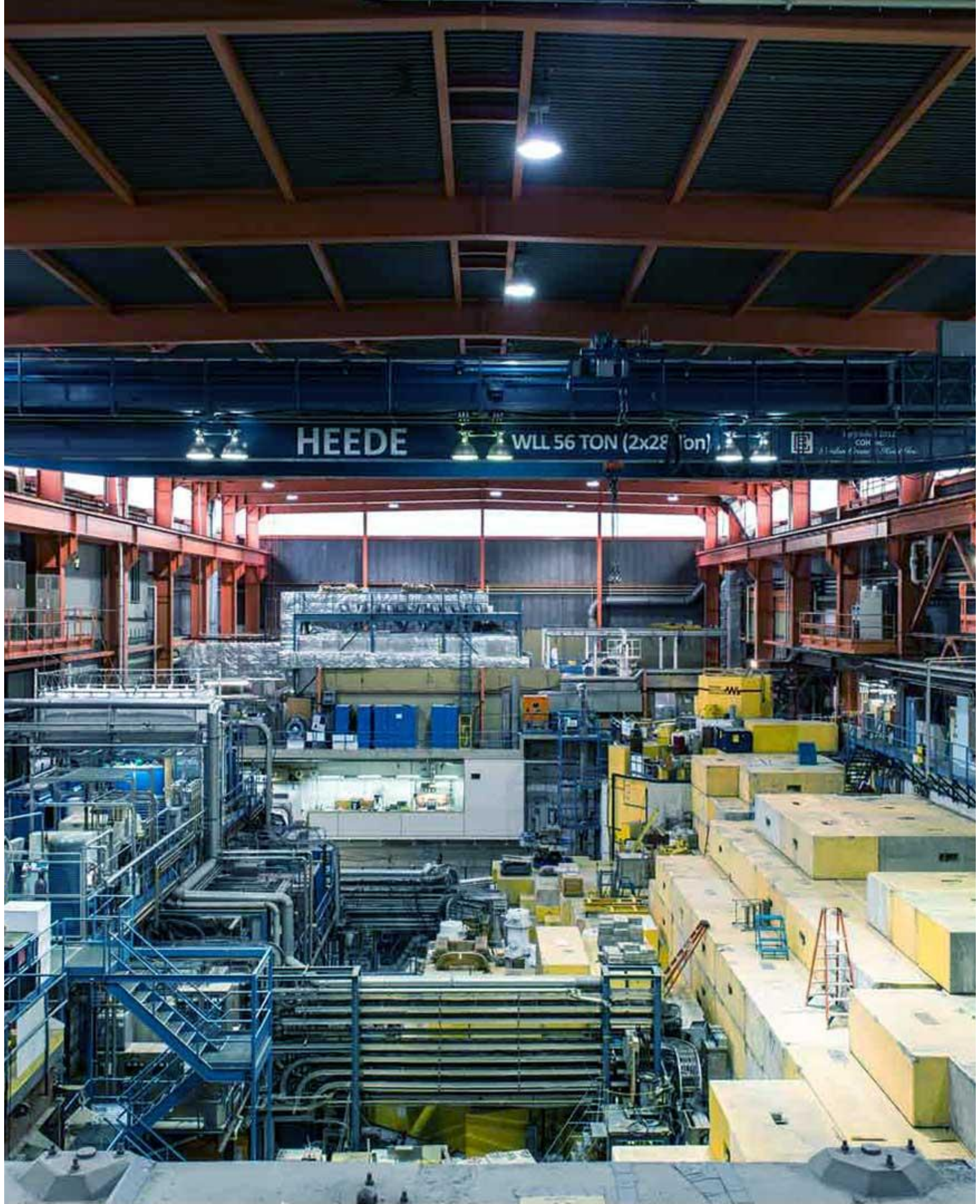
Domestic collaborations

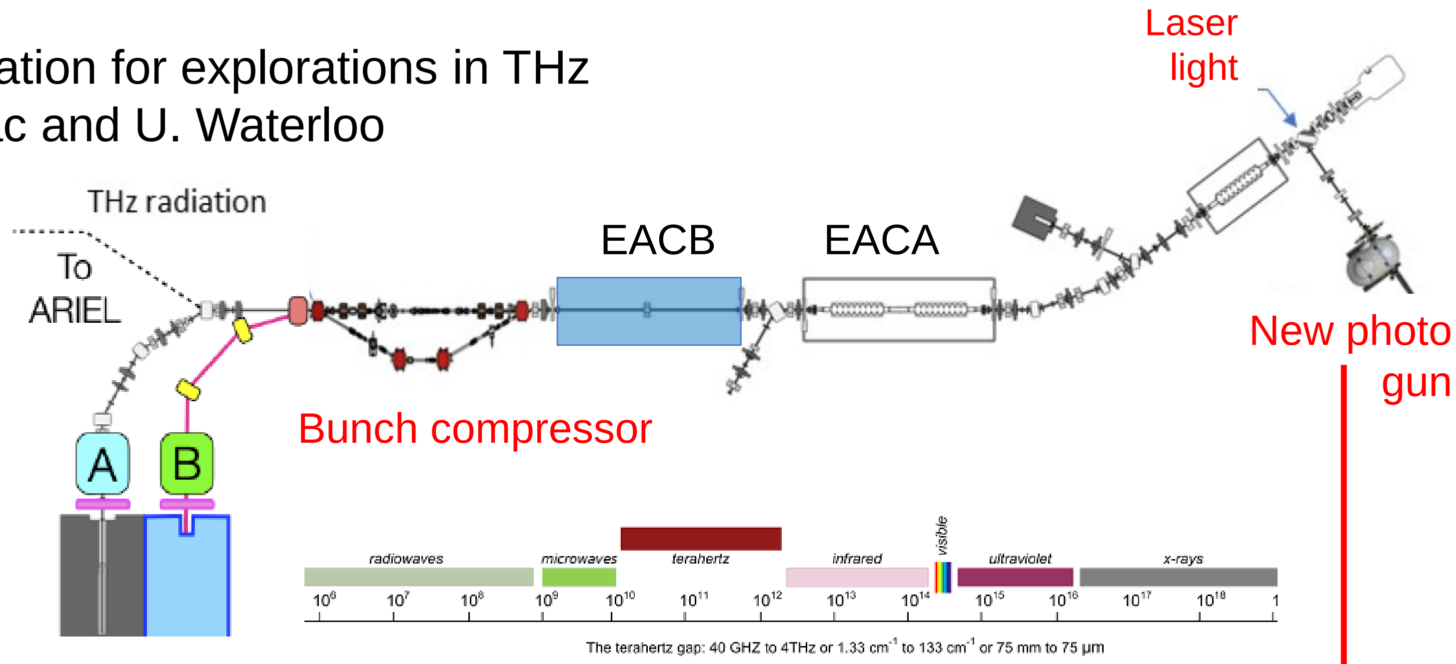


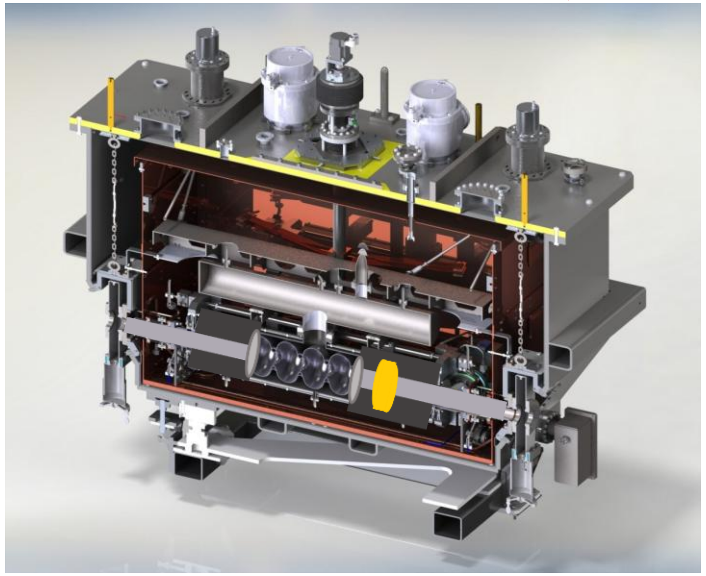
Discovery, accelerated

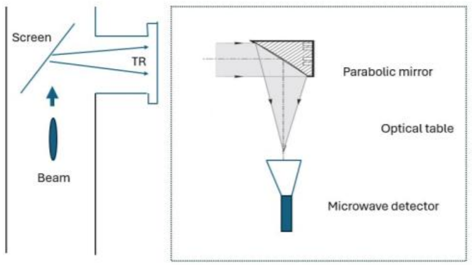
THz radiation project @ e-Linac

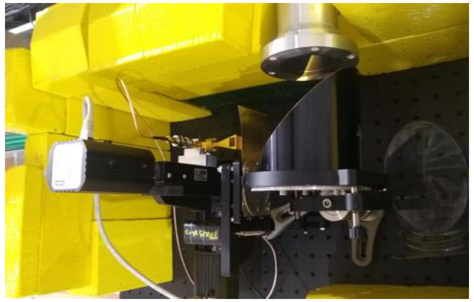
TRIUMF is partnering with a Canadian collaboration for explorations in THz radiation -> new installations planned for e-Linac and U. Waterloo

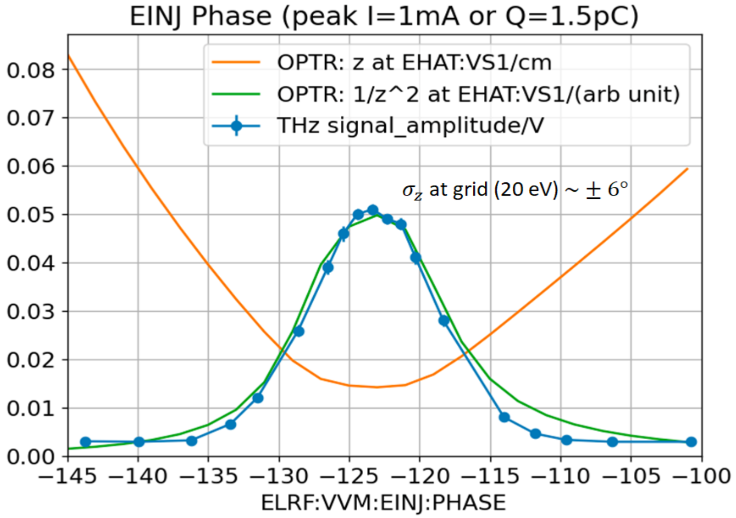
- **Scope:**
  - SRF high brightness photo-gun
  - Clean room for the photo-gun laser system on top of the e-hall
  - Bunch compressor chicane
- **Progress:**
  - First THz radiation detected at the ARIEL e-linac in November 2024 → great diagnostics tool for longitudinal beam parameter – quadratic dependence of signal on the bunch length





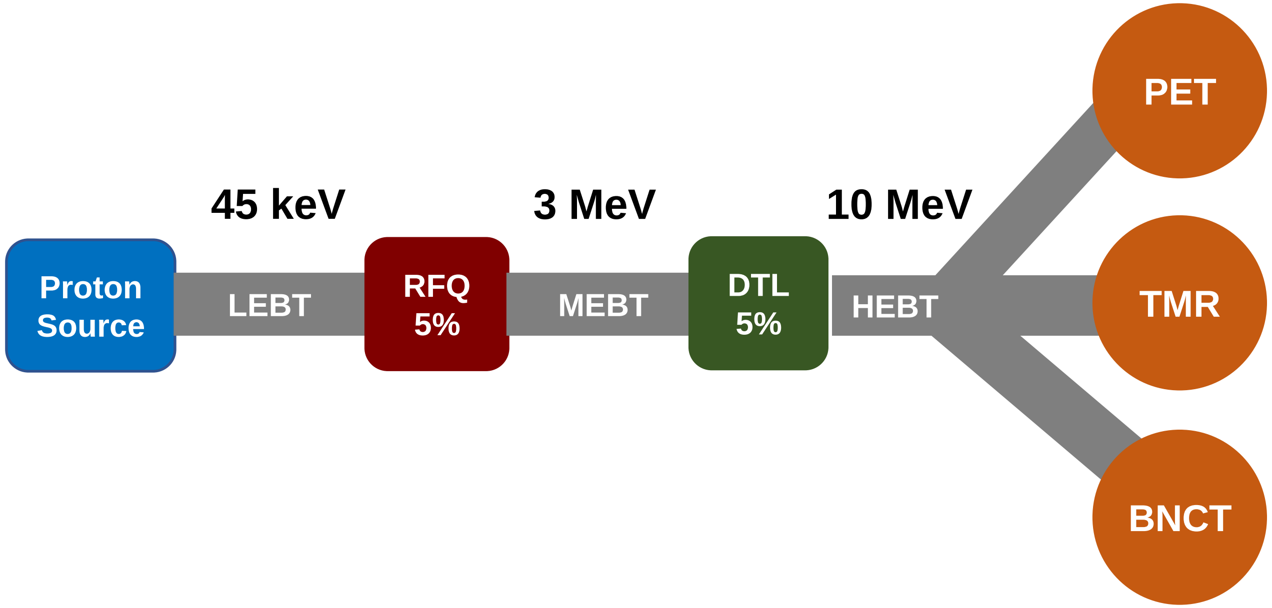






Compact Accelerator Based Neutron Sources

PC-CANS is a proposal for a high intensity pulsed neutron source at U. Windsor – TRIUMF is leading the linac and target design effort in support of the Canadian neutron community



Goals:

1. Neutrons for Science (cold and thermal)
2. Neutrons for BNCT (epithermal)
3. Protons for 18F for PET

Station	Energy (MeV)	I_{ave} (μA)	DF (%)	P_{ave} (kW)	I_{peak} (mA)	P_{peak} (kW)
Neutron	10	200	5	2	4	40
18F	10	100	5	1	2	20
BNCT	10	200	5	2	4	40
Stage 2 totals	10	500	5	5	10	100
Stage 3 totals	10	1000	5	10	20	200

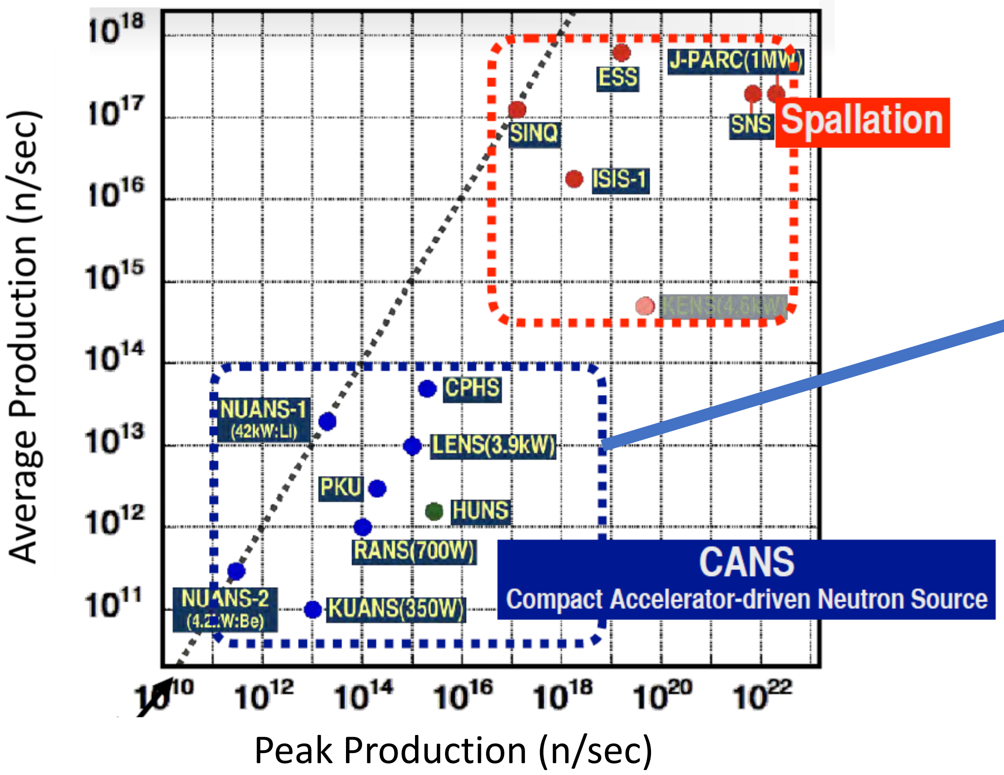
Status:

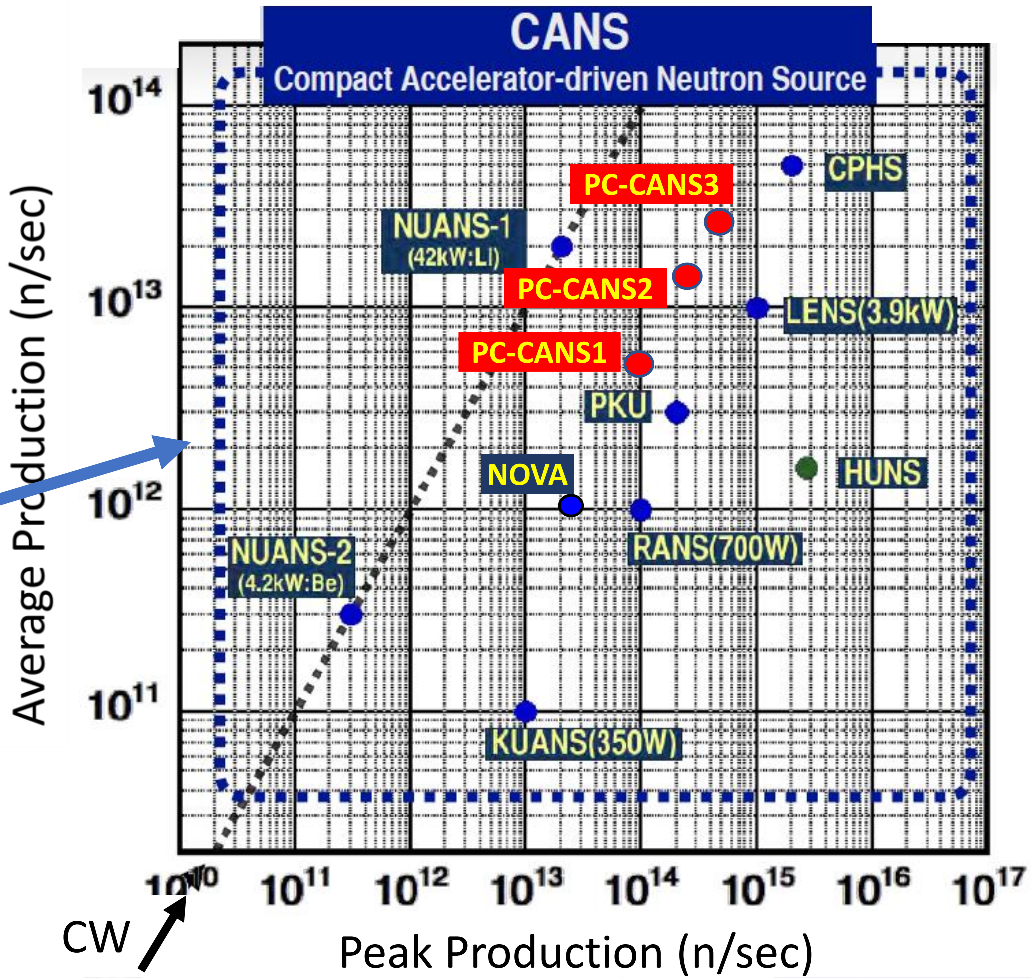
- Conceptual design released
- Plan is to prepare a detailed technical proposal supported by external funding for a future funding opportunity
- Linac studies including beam quality analysis, RF design, detailed costing are continuing

[1] PC-CANS CDR, TRIUMF internal document, R. Laxdal editor, (2022)
[2] R. Laxdal, et al., Journal of Neutron Research **23**99-117, (2021).

Staged PC-CANS Performance – evolving target capabilities

- Stage 1 – shared (I_{ave} / I_{peak} =200μA/4mA – 2kW)
- Stage 2 – dedicated (I_{ave} / I_{peak} =500μA/10mA – 5kW)
- Stage 3 – upgrade (I_{ave} / I_{peak} =1mA/20mA – 10kW)



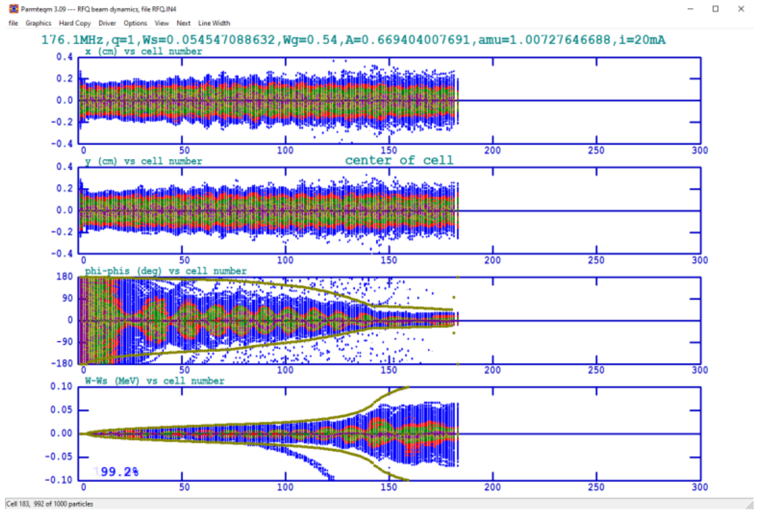


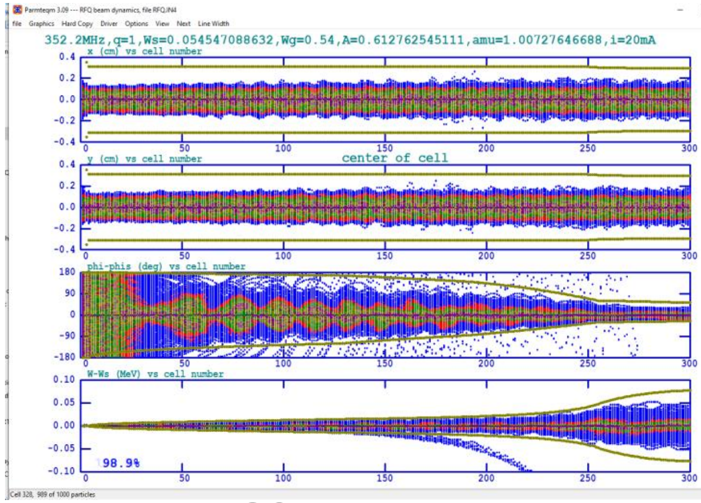
RFQ variants:

Two variants considered each giving 99% transmission for 20mA beam current from 45 keV to 3MeV as simulated in PARMTEQ:

- Each optimized for same Kilpatrick and minimized length
- 176 MHz
  - Subharmonic of DTL frequency
  - RF structure – typically 4-rod
  - Increased longitudinal emittance
- 352 MHz
  - DTL frequency
  - RF structure – typically 4-vane
  - Shorter with improved output emittance
- DTL studies preformed assuming 352MHz RFQ

Parameters	176.1 MHz RFQ	352.2 MHz RFQ
Beam species	H+	H+
Injection energy (MeV)	0.045	0.045
Output energy (MeV)	3	3
Resonant frequency (MHz)	176.1	352.2
Peak beam current (mA)	20	20
Inter-vane voltage (kV)	130	78.3
Cavity length (m)	3.6	3.2
minimum aperture a (cm)	0.38	0.19
Ratio r_V/r_0	0.85	0.85
Maximum surface field (MV/m)	26.1 (1.8 Kp)	34.0 (1.8 Kp)
Input ε_t (n,rms)(cm.mrad)	0.025	0.025
Output ε_t (n,rms)(cm.mrad)	0.029	0.026
Output ε_l (n,rms)(MeV-deg (352))	0.238	0.135
Transmission (%)	99.2%	99 %
Number of cells	181	326
RF power loss (peak kW) - est	396	369

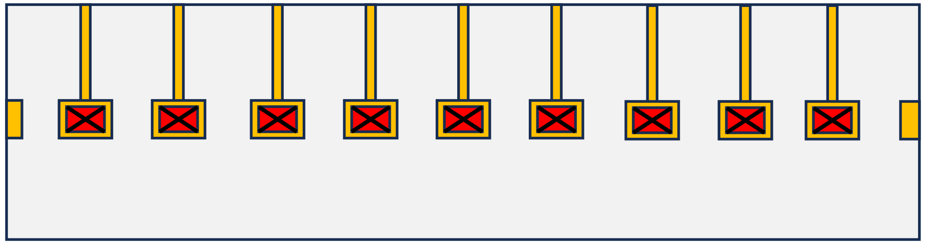




DTL variants:

Alvarez:

- TM010 mode with βλ between gaps
- Transverse focusing by quad magnets in drift tubes
- Longitudinal focusing with rf phase at -25 degrees

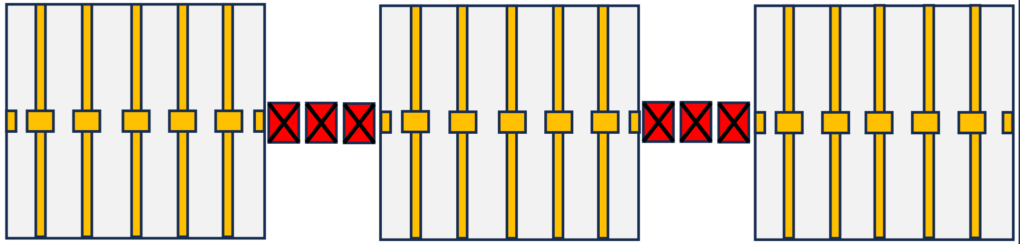


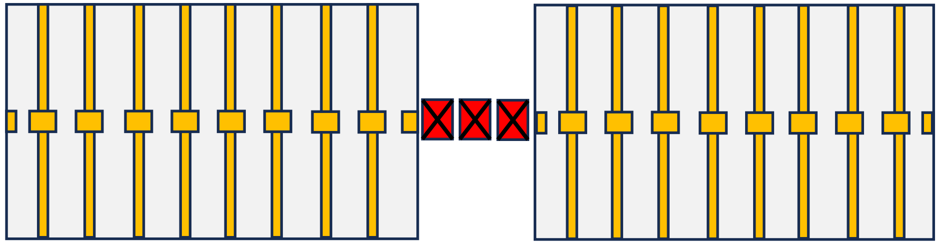
H-mode:

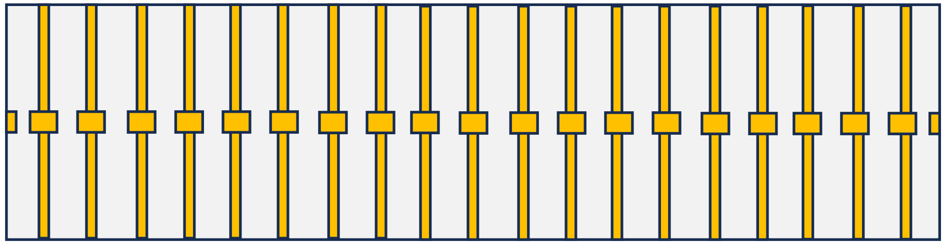
- TE11 (IH) or TE21 (CH) mode with βλ/2 between gaps

Choice of beam dynamics

- Negative synchronous phase
  - Periodic Transverse focusing by quad magnets between accelerating tanks
  - Longitudinal focusing with rf phase at -25 degrees
- KONUS dynamics
  - Periodic Transverse focusing by quad magnets between accelerating tanks
  - Acceleration at 0 deg and periodic Longitudinal focusing at -60 deg
- Alternate phase focusing (APF)
  - Transverse and Longitudinal focusing with varying rf phase along the length







DTL Study

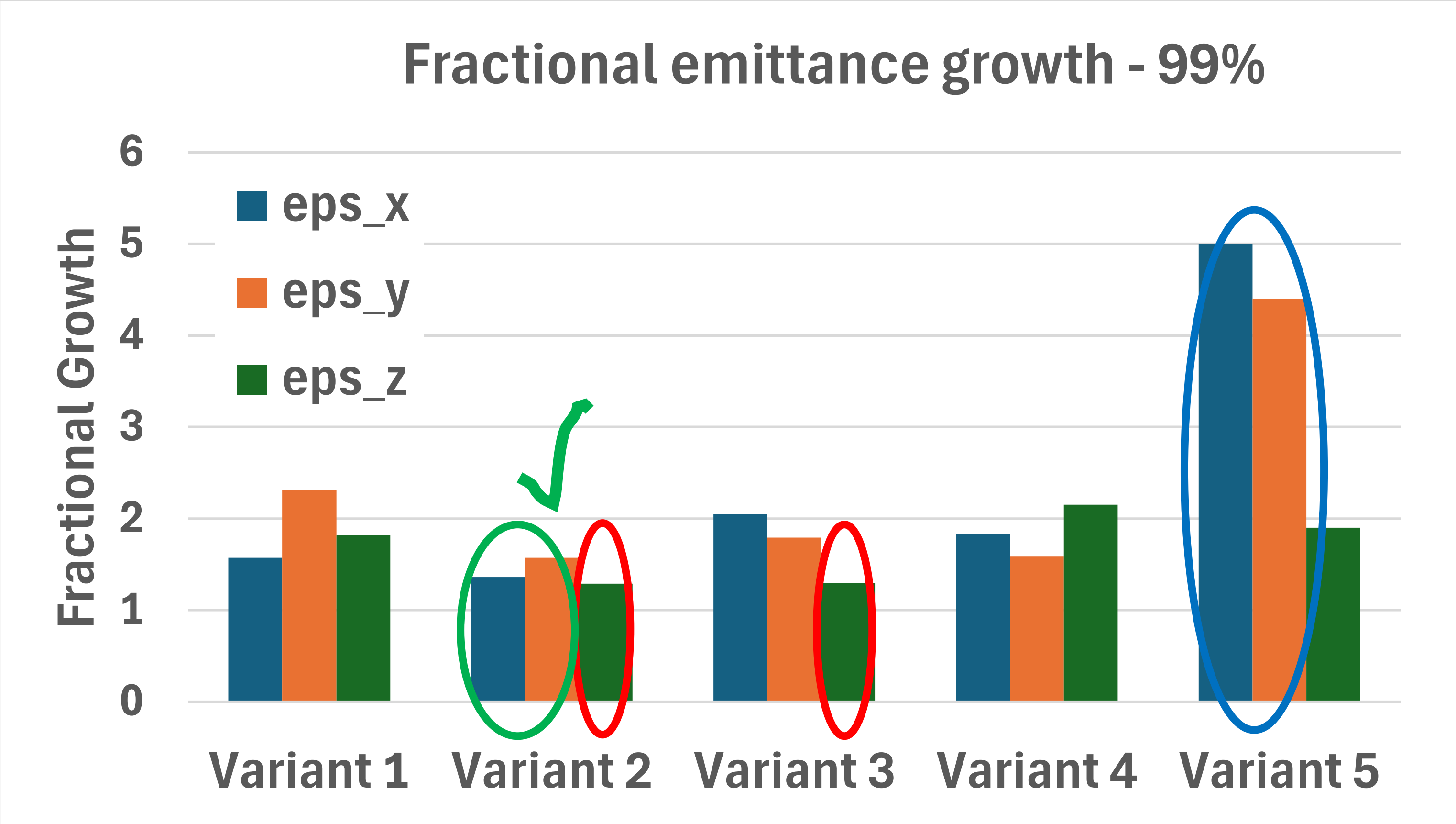
Each variant is Modeled in LANA and PARMILA

- Establish 100% transmission with good quality
- Calculate emittance growth for RMS and 99% contours
- Estimate longitudinal and transverse acceptance

Parameter	Variant 1	Variant2	Variant3	Variant4	Variant5
Type	Alvarez/ No MEBT	Alvarez/ MEBT	CH-KONUS / MEBT	CH-DTL/ MEBT	CH-APF/ MEBT
Tanks	1	1	2	3	1
Drift tubes	25	25	12,15	13,10,14	46
Eo (MV/m)	3.4	3.4	6.6	5	6.7
Synch. Phase φ_s	-30	-30	0, -60, 0	-28, -27, -28	varying
Length (m)	2.6	3.4	2.6	3.5	3.1

Summary plot – emittance growth 99%

- All variants give reasonable results with 100% transmission in all cases
- Alvarez with MEBT (Variant 2), KONUS (Variant 3) have the smallest longitudinal emittance growth.
- The smallest transverse emittance growth is with the Alvarez with MEBT (Variant 2)
- The largest transverse growth is from the APF (Variant 5)
- The longitudinal and transverse acceptance is largest for Variant 2 (Alvarez with MEBT)

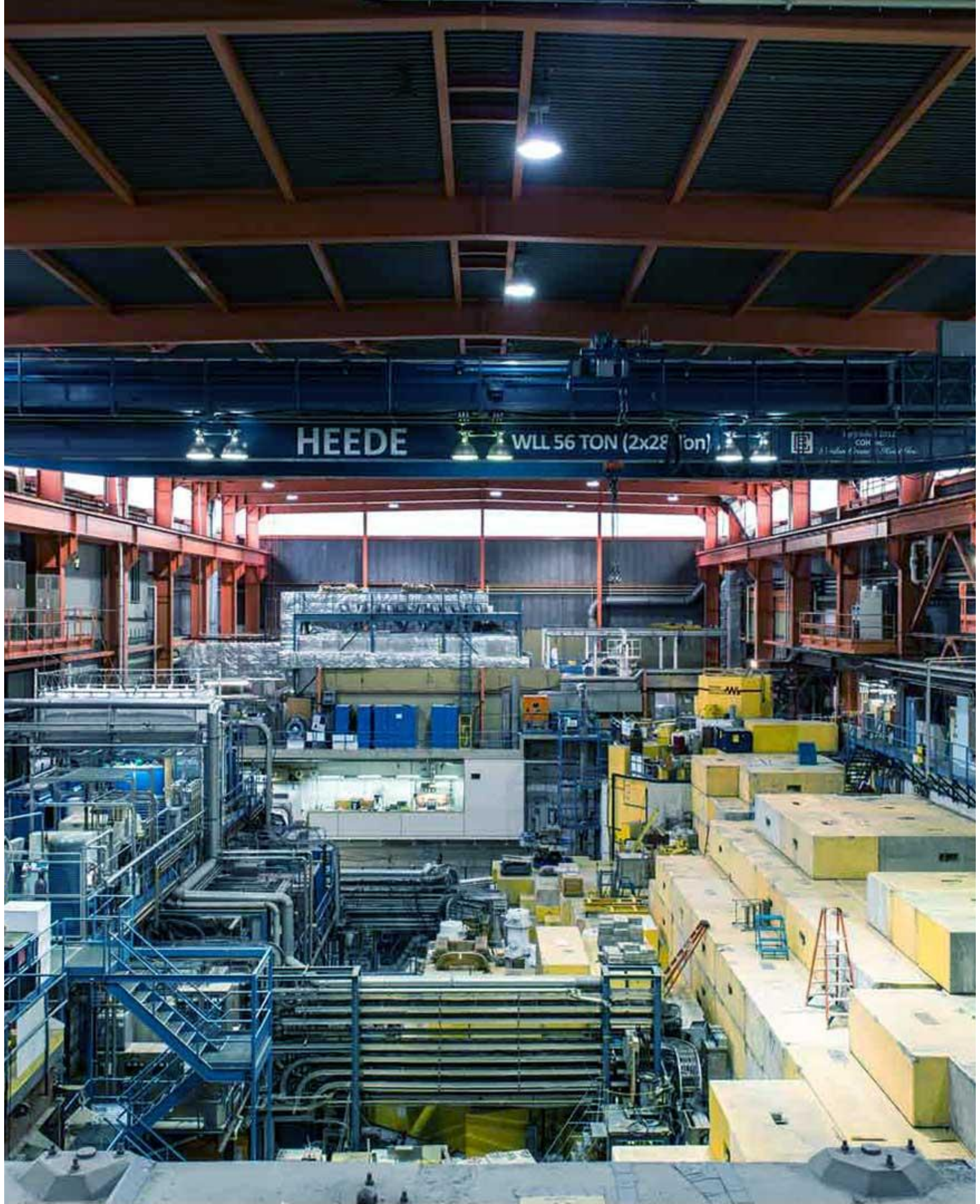


Alvarez No MEBT	Alvarez 4Q MEBT	CH-KONUS	CH-5MV-3Tank	CH-6.7MV-APF

https://accelconf.web.cern.ch/linac2022/papers/fr1aa05.pdf

TRIUMF

International collaborations



Discovery, accelerated

TRIUMF

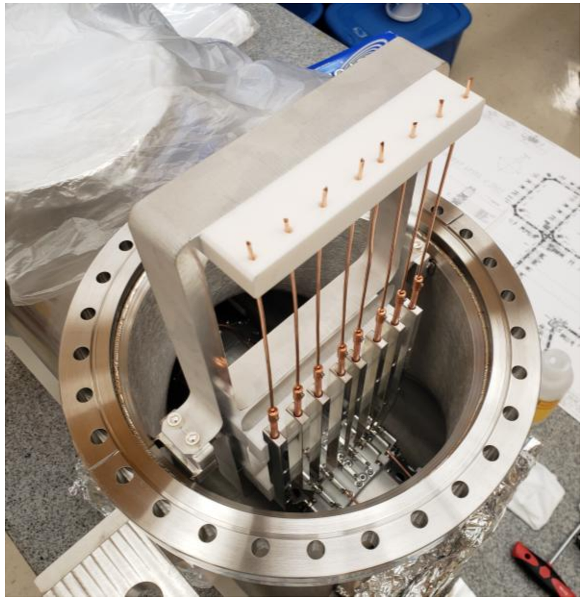
VECC Deliverables-> India

- TRIUMF and VECC (Kolkata) have had an active collaboration since 2008
- As part of the collaboration TRIUMF has completed and shipped three major deliverables to India in 2023
  - 110 MHz SRF cryomodule – shipped January 2023
  - TISA Front end – prototype ARIEL target module – May 2023
  - RIE – radioactive ion extraction beamline – Nov. 2023

Quarter-wave Resonator Heavy Ion Cryomodule

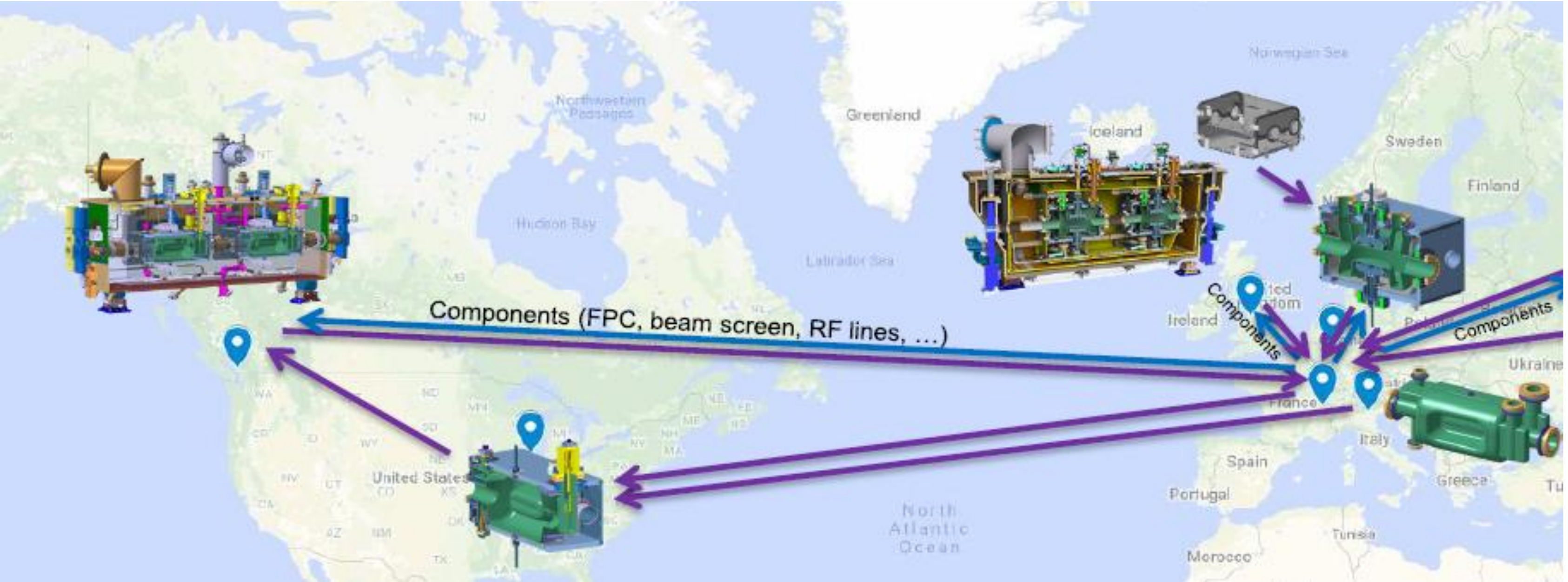
TISA Front end

RIB module - HV feed lines



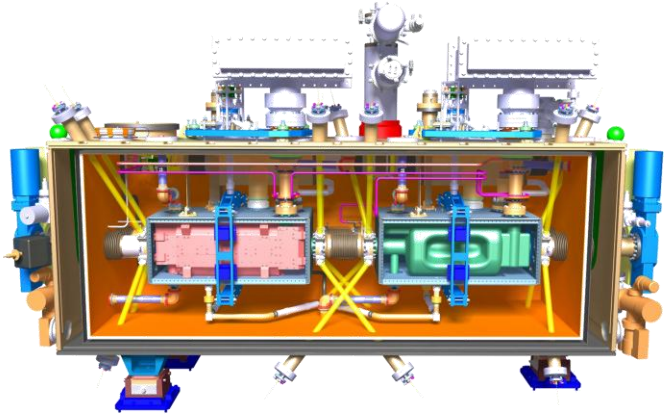
RIB beamline pre-separator

TRIUMF and Hi-Lumi at CERN



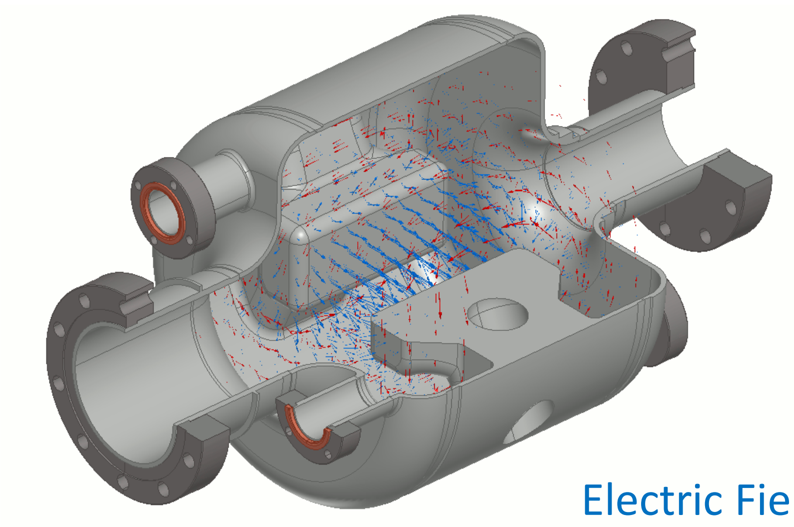
The Hi-Luminosity project at CERN includes the installation of vertically deflecting (DQW) and horizontally deflecting (RFD) crab cavities upstream and downstream of CMS and ATLAS respectively

TRIUMF is part of global collaboration (CERN, USA, UK) that will deliver 5 RFD Crab Cavity modules as a Canadian contribution to Hi-Lumi

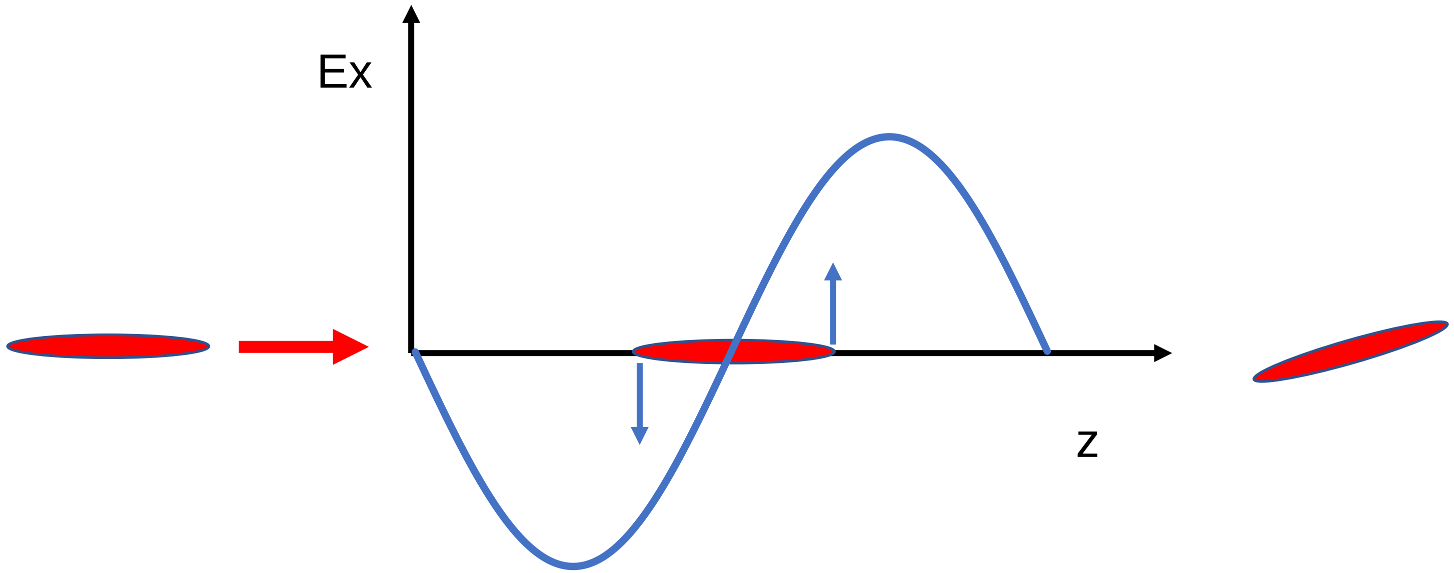


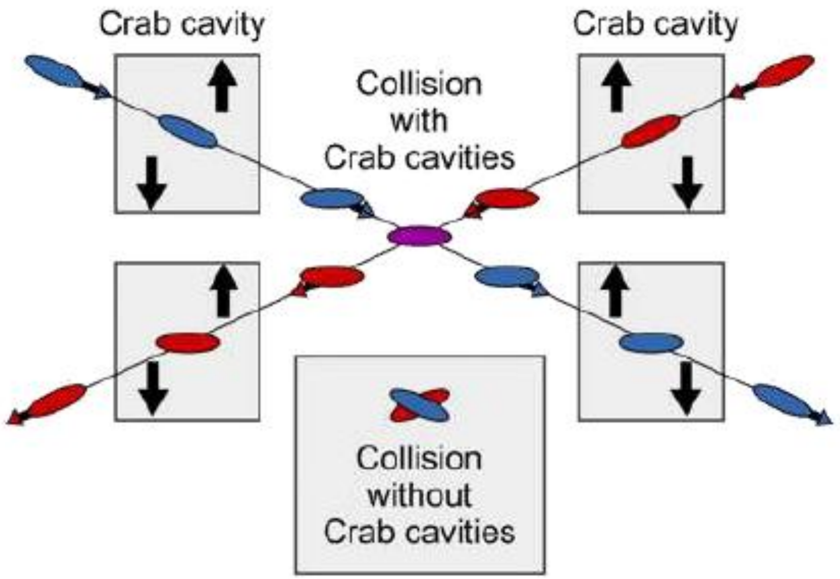
`Crabbing' the beam

- The RF Dipole cavities produce time varying electric fields that deflect the beam transversely
- The beam bunches are synchronized such that the head and tail of the bunch are deflected in opposite directions
- The beam is skewed with respect to the direction of travel counteracting the finite crossing angle of the two beams



Electric Field →
Magnetic Field →





HL-LHC Cryomodule Project - Status

Scope: Assemble 5 crab cavity CMs (with 10 cavities) and deliver 4 CMs before July 2028 for installation in the LHC during CERN's LS3 for the Hi-Lumi upgrade

Milestone #1:

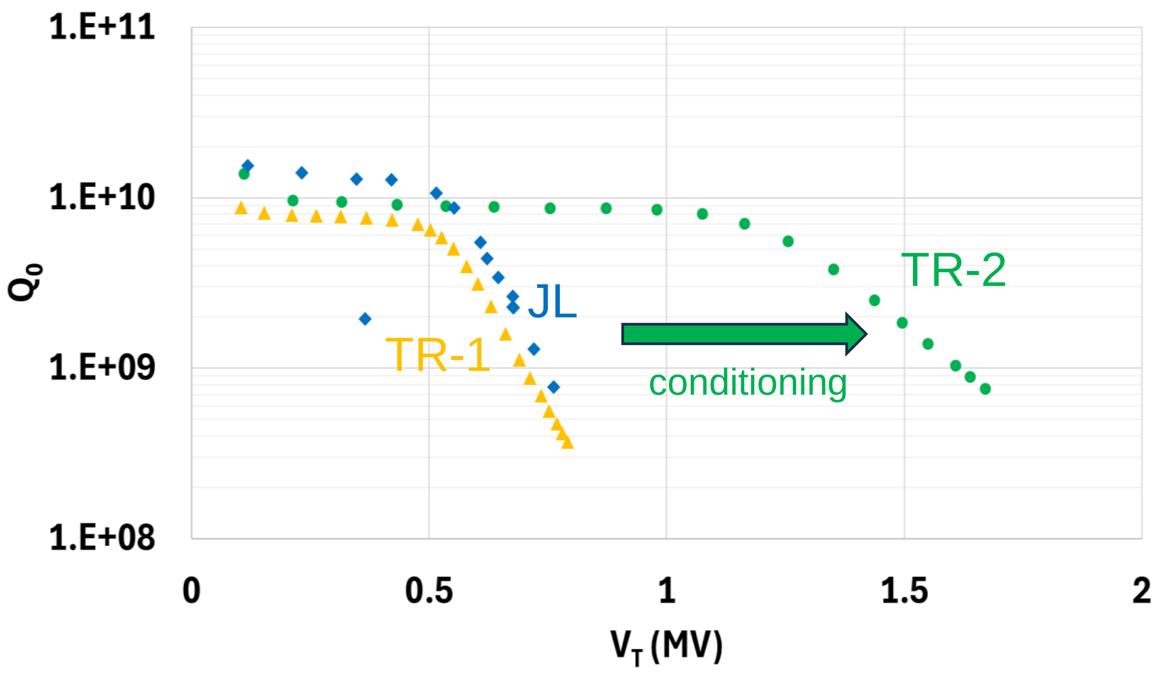
- ✓ **All money has been committed, and parts will be received before June 30, as required by the funding agreement**
  - 5M$ of hardware ordered and invoiced over the last year
  - Major procurements completed for infrastructure and cryomodules

Milestone #2

- ✓ **New clean room installed and in final commissioning**

Milestone #3

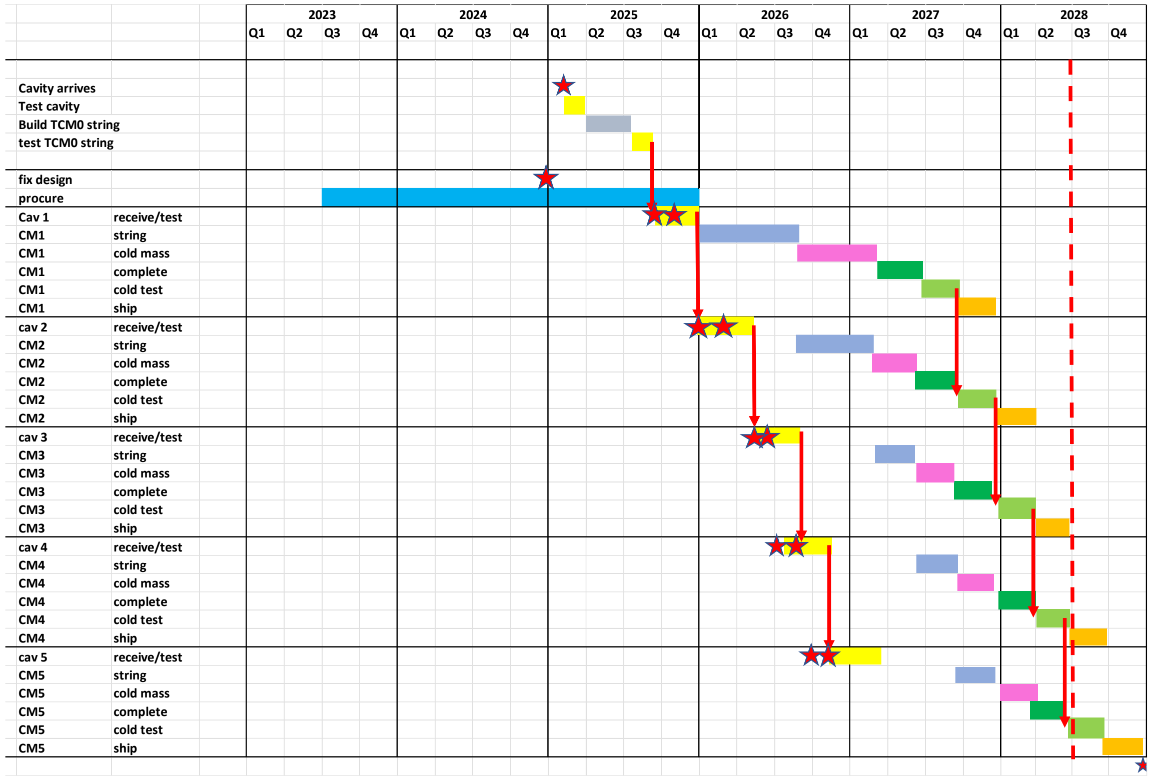
- ✓ **First prototype RFD cavity received from JLab and requalification test completed – all new test infrastructure confirmed**



PRJ_455 HL-LHC Cryomodule Project

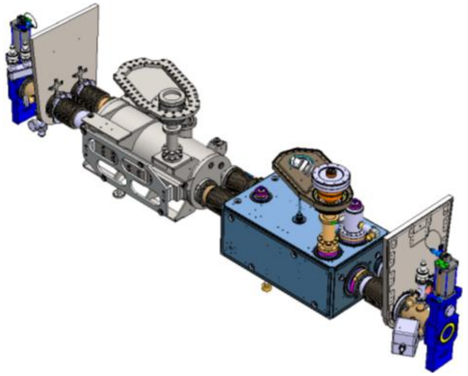
Schedule

- Critical path runs through delivery of first two series cavities from US partners – delayed to fall 2025
- All other cavities off critical path presently – require cavity cryogenic qualification in 2026
- Goal is to complete string assembly and top assembly of TCM1 in 2026 in order to verify parts and procedures for series assembly in 2027/28



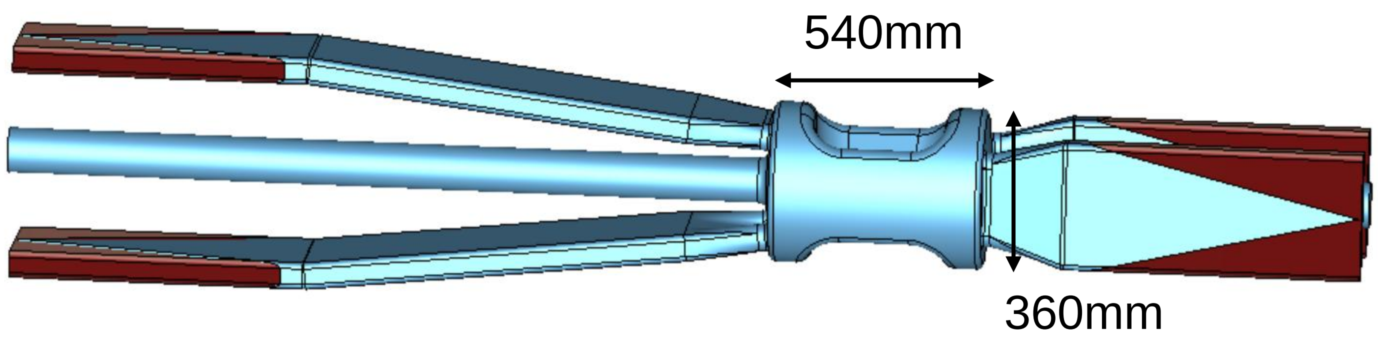
Milestones - 2025

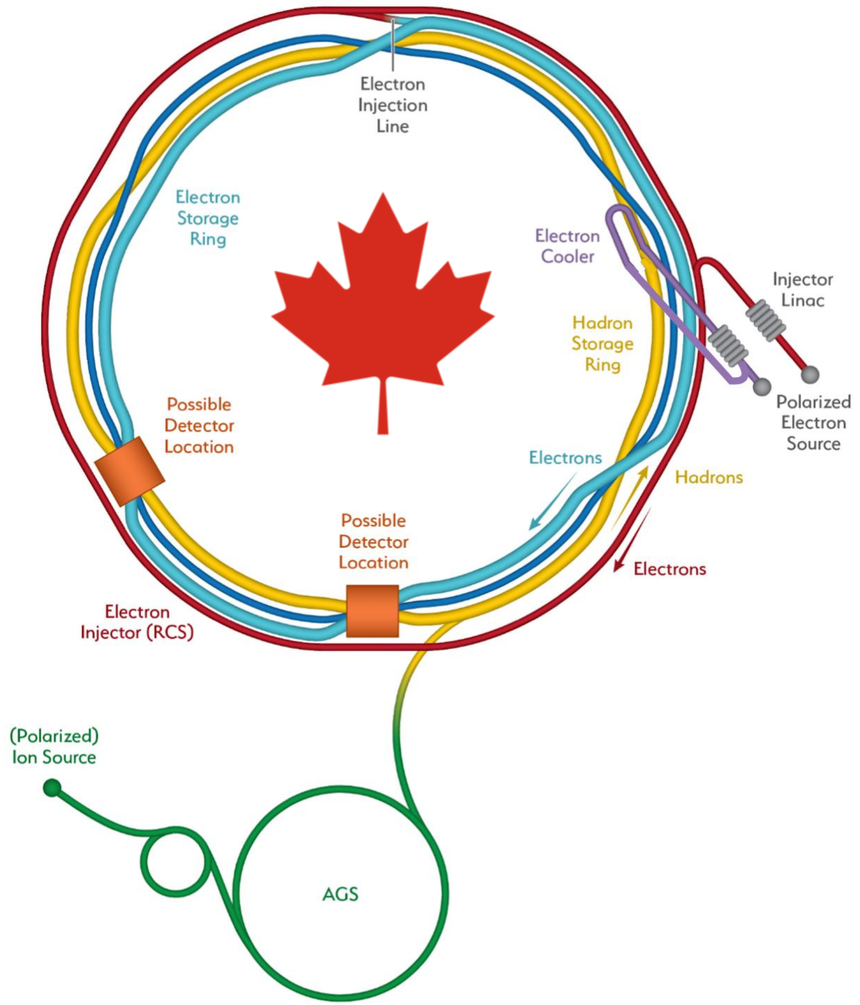
- Assemble TCM0 string -> May - Aug
  - Parts in hand – tooling and procedures in preparation
- Requalify TC0 -> Aug
- Rinse and retest TC0 –> Sept
- Receive cavities TC1,2, qualify and prepare to assemble TCM1 string - Fall
- TCM1 string assembly – starts Dec 2025



Electron-Ion Collider

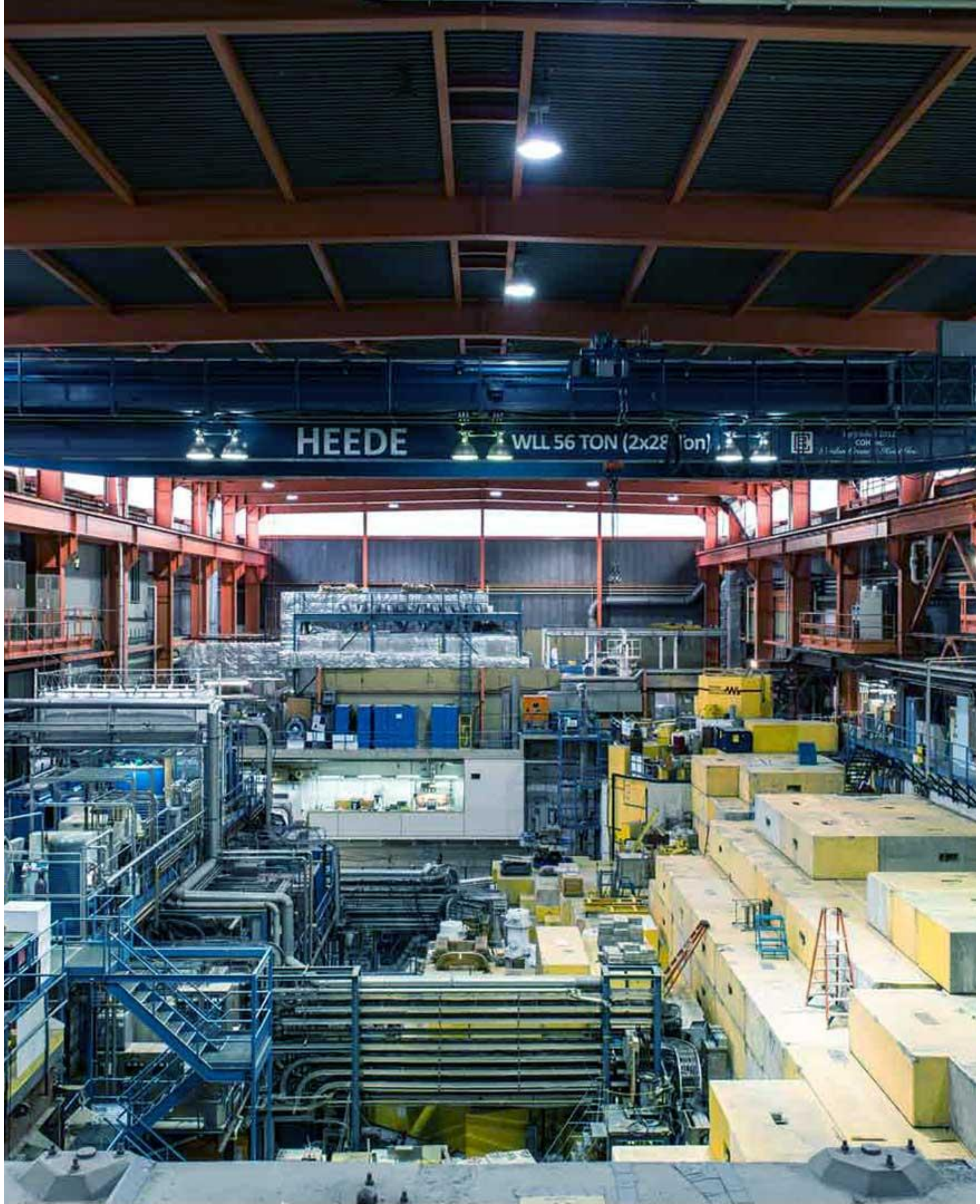
- TRIUMF in partnership with EIC-Canada is seeking Canadian funding to support in-kind contributions.
- TRIUMFs SRF group started work on the design of the 394MHz crab cavity required for both hadron and electron rings – similar size to HL-LHC 400MHz crab cavity
- Challenging HOM design due to high beam current





TRIUMF

Student focused research

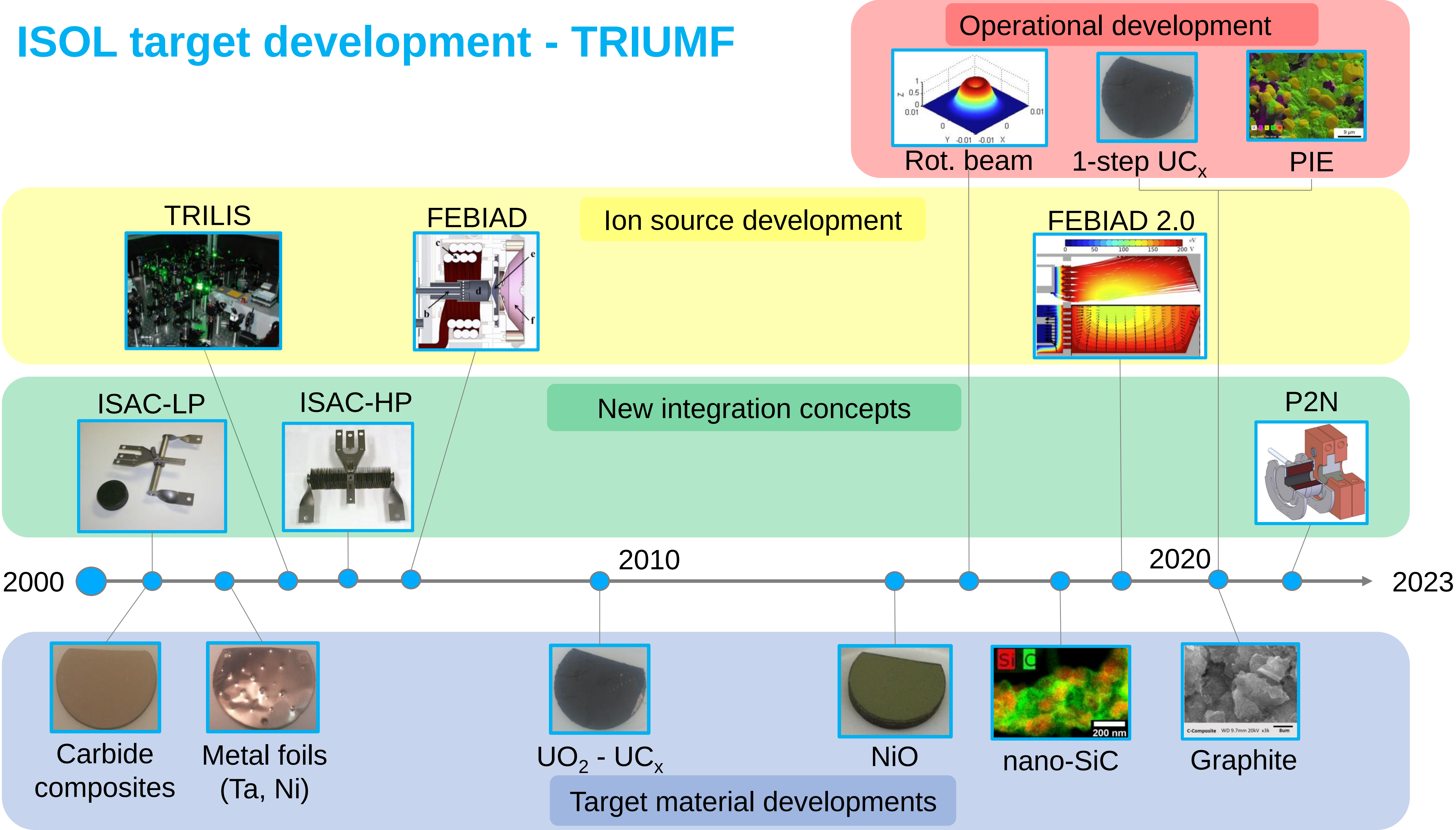


Discovery, accelerated

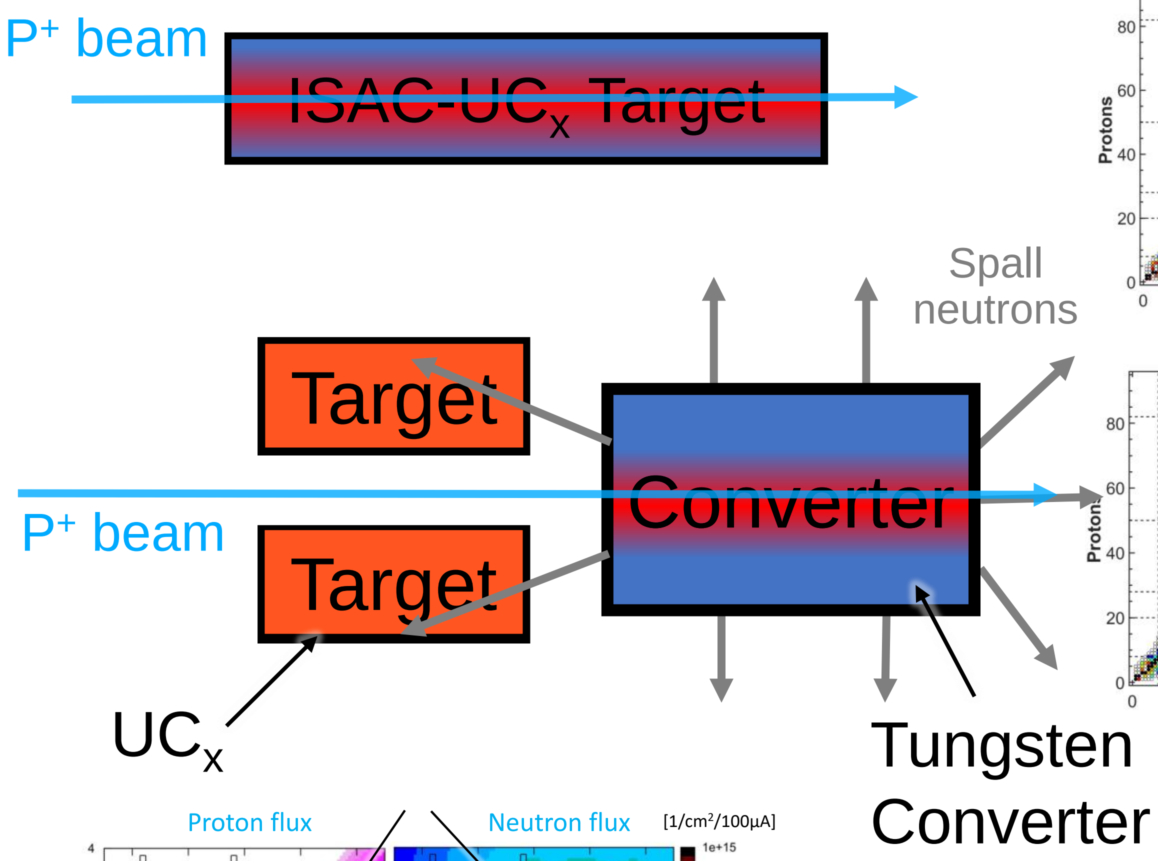
Accelerator Physics Training

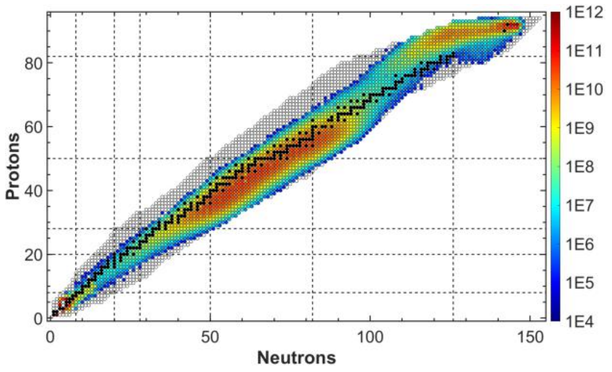
- We leverage infrastructure, projects and expertise to provide world class training of young researchers in accelerator physics and engineering.
- Student focussed research and development (leverages TRIUMF core competencies)
  - beam physics
  - secondary particle production
  - SRF/RF technologies and research
- Accelerator Division researchers tag-team a hybrid course in accelerator physics once a year through UBC and UVic
  - ~15 students take the course each year

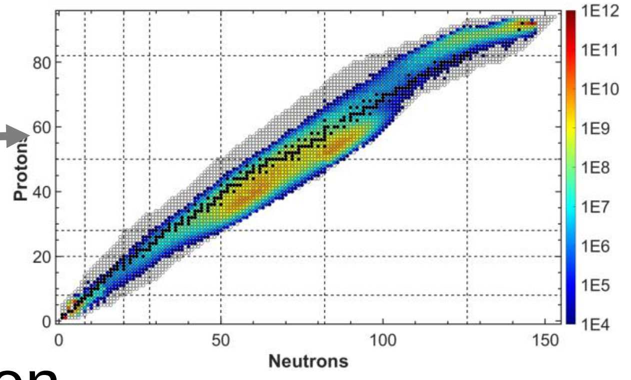
ISOL target development - TRIUMF

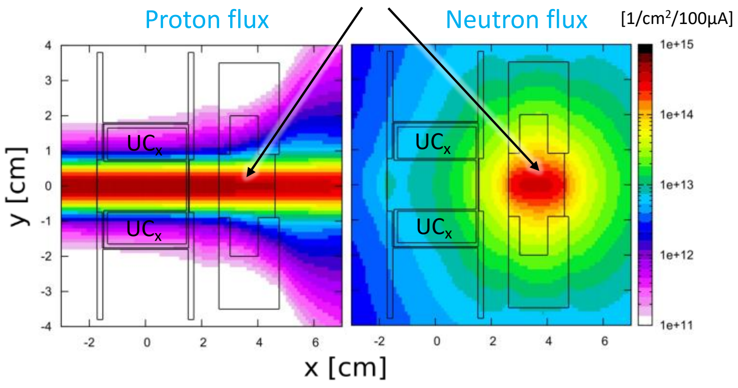


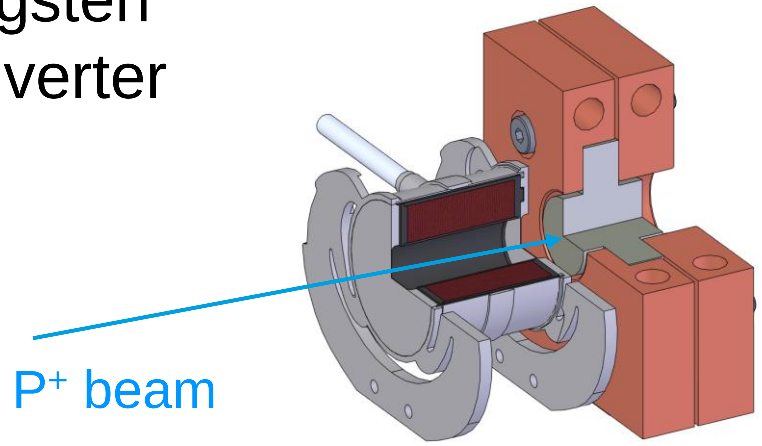
Conventional ISAC vs Converter targets









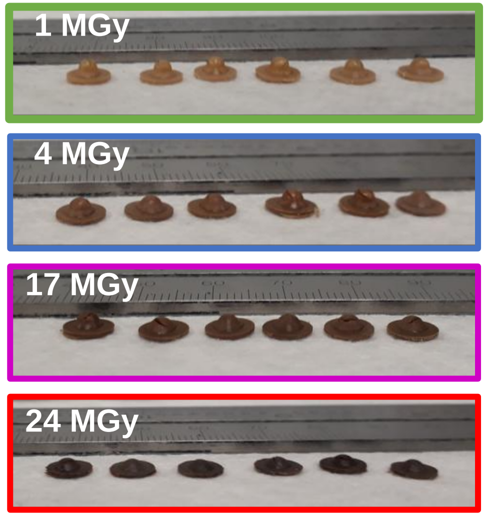


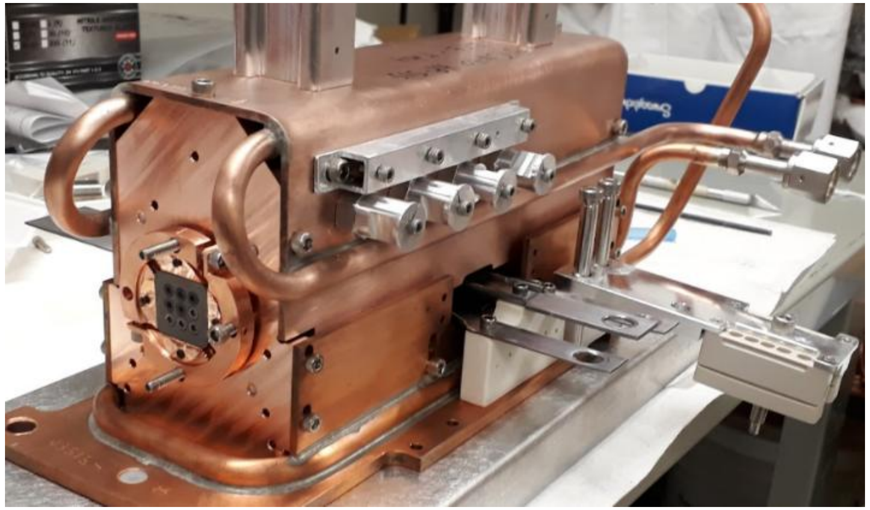
- Typical ISOL targets produce radioactive isotopes by spallation through direct bombardment of thick targets
- Converter targets protons produce neutrons in a thick tungsten converter that fission in a neighbouring actinide target
- Produce cleaner neutron rich species compared to spallation production

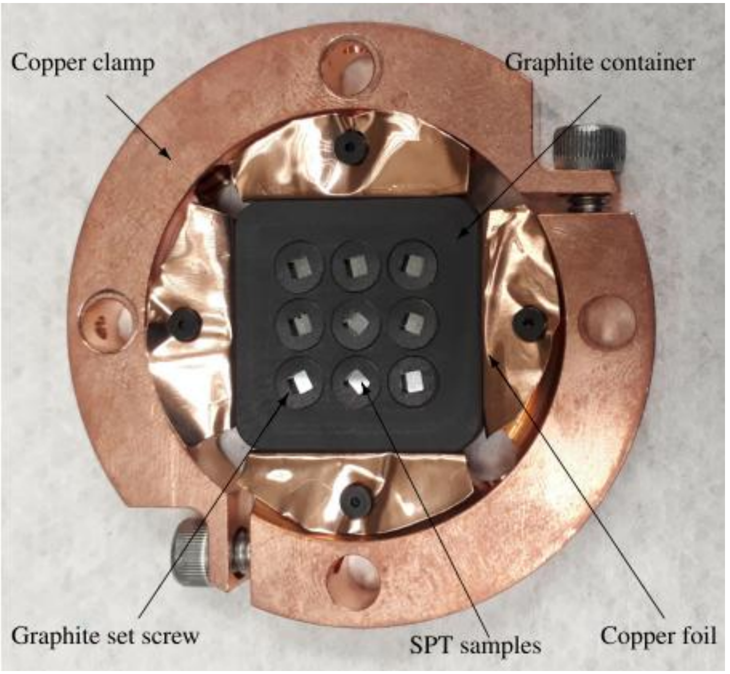
Irradiation of accelerator materials:

- Secondary irradiation using sample mounted on ISAC target-ion source units
- PEEK irradiation and Al AM plus beam windows
- C-seal style peek seals were irradiated to doses near 200MGy before leaking (improved approx. x2 rad. resistance vs. previous version)
- Upstream irradiation of CuCrZr beam window material for Ariel

Irradiation damage studies – example: PEEK
Tensile and fracture properties

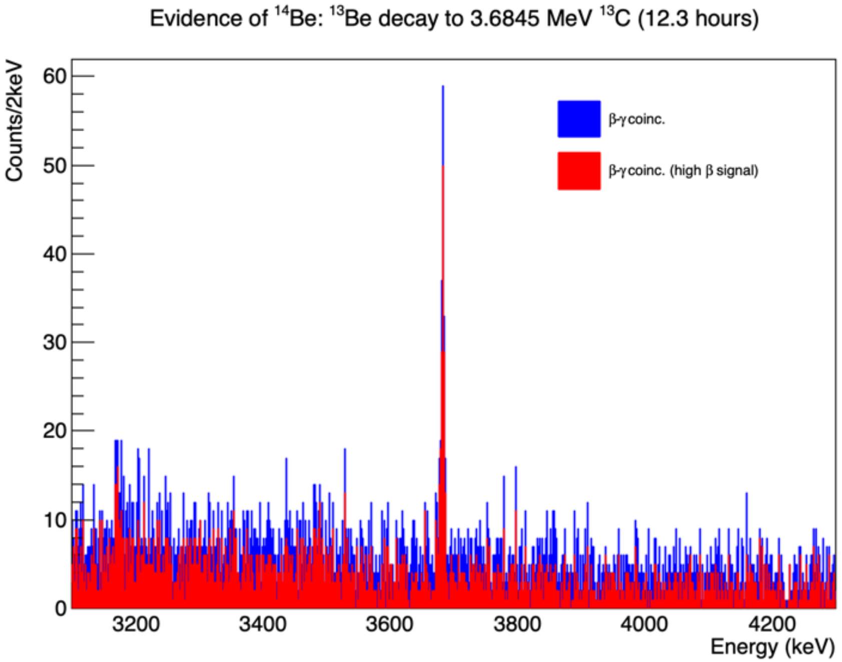






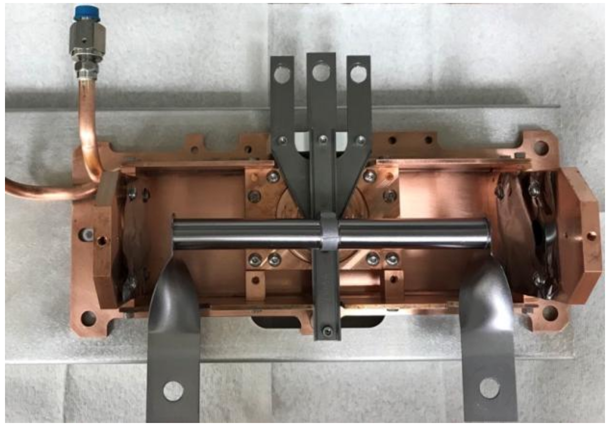
F. Boix Pamies and A. Gottberg, Secondary irradiation for radiation damage studies and isotope harvesting PRAB 27, 123001 (2024)

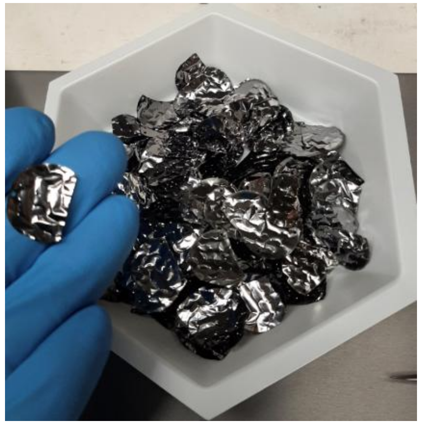
Extraction of short-lived isotopes from Low Power Tantalum ISOL Targets

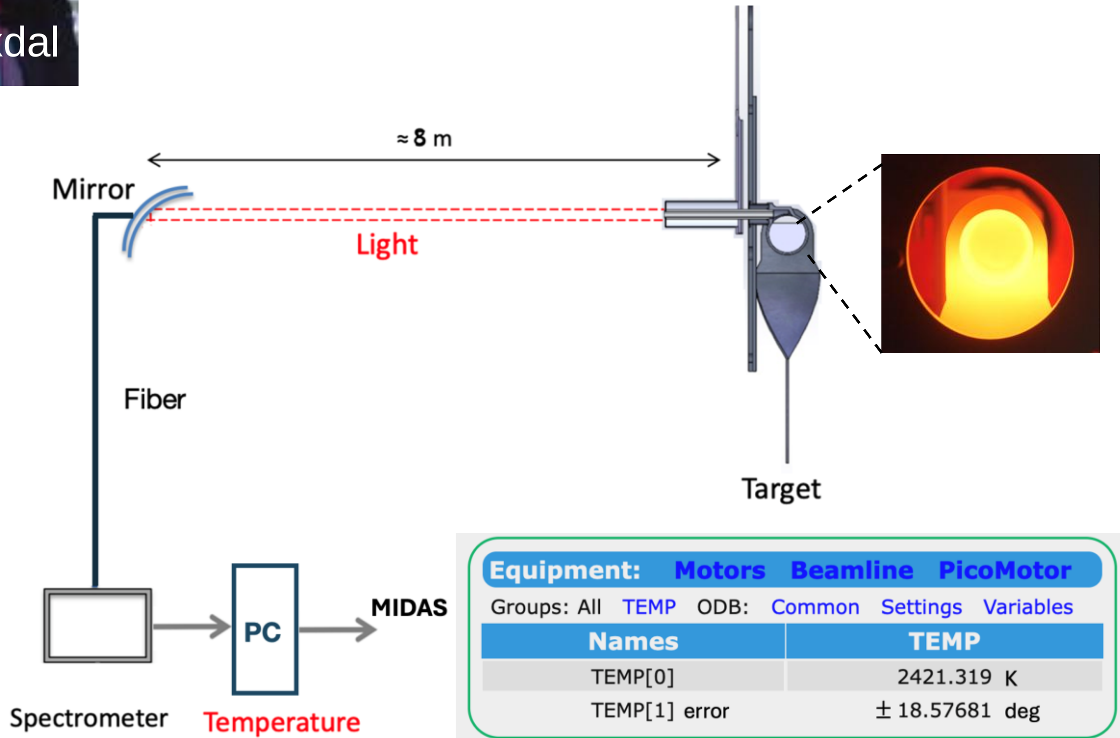


New Low Power Tantalum target design:
- built with 470 tantalum foils: 10 µm thick -> 40% of the standard target thickness - better release of short lived species
- approved for maximum operating rotating proton beam: 95 µA

Produced:
^{14}Be first time at TRIUMF, detected at GRIFFIN
^{12}Be tripled the previous record: 18,000 ions/s
^{11}Li high yields

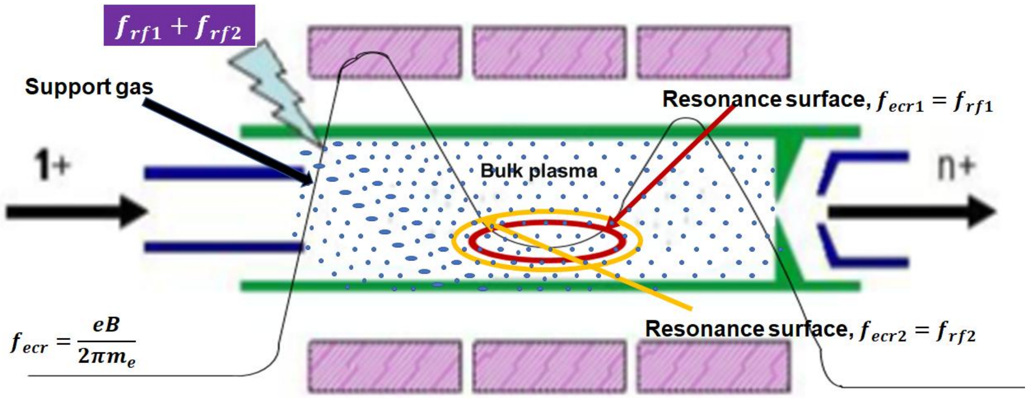


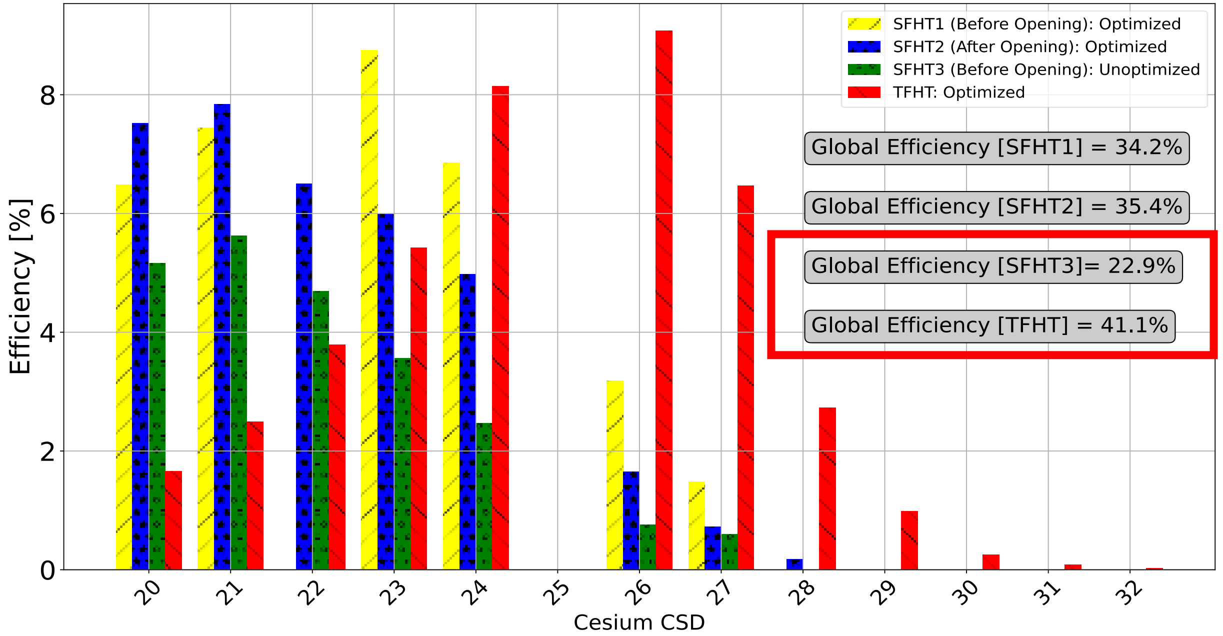




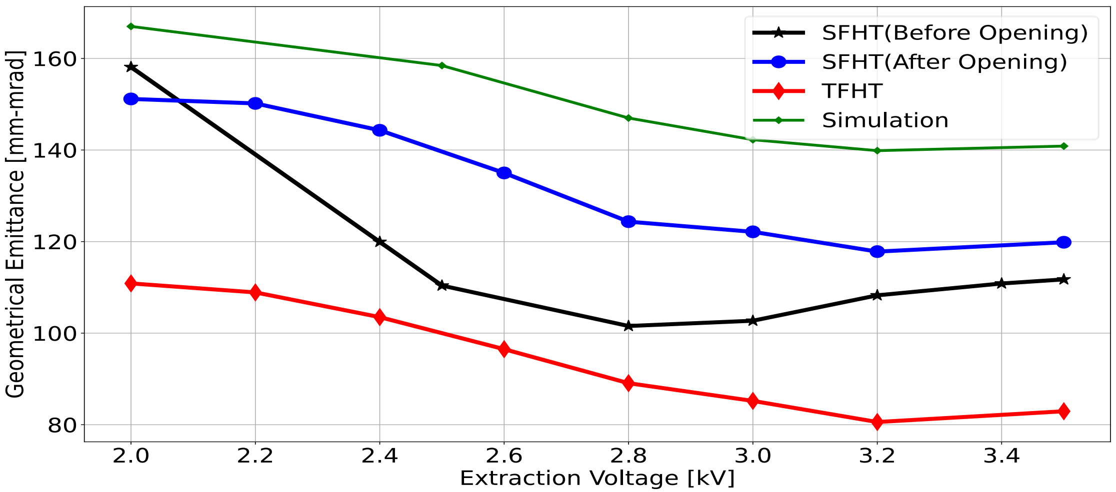
New optical diagnostic for target temperature:
- allows for Yield – Temperature target analysis
- method suitable for measurements in **radiation** environment
- displays target temperature in **real time**: MIDAS & EPICS

ECR Charge State Booster (CSB) improvements





- The CSB is a 14.5 GHz Electron Cyclotron Resonance Ion Sources (ECRIS) that uses microwave plasma heating and magnetic confinement to produce highly charges ions.
- Increase of charge breeding efficiency by implementing two-frequency heating near 14GHz (TFHT) → provides two resonance heating zones
- Optimized all beam transport, ion extraction system and the charge state separator via detailed modeling and benchmarking via beam tests.

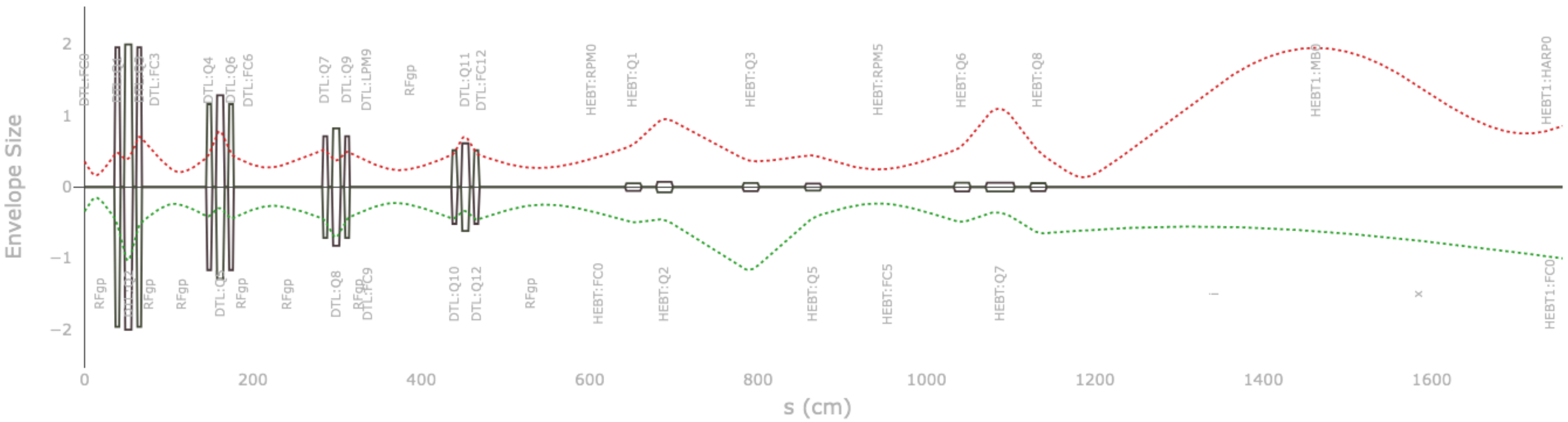


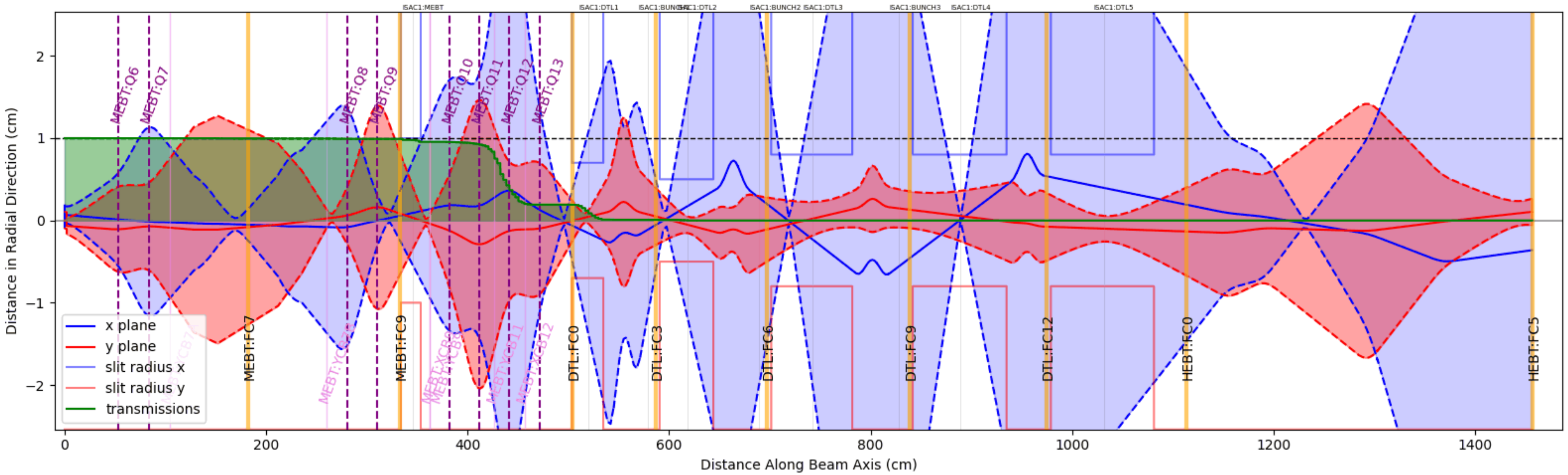
Beam physics – MCAT for beam tuning in ISAC

Developing tools to significantly reduce manual tuning as we prepare for the ARIEL era.

Model Coupled Accelerator Tuning (MCAT) – new tool for aiding tuning in ISAC

Bayesian optimization also being developed in ISAC





STEP: 0

'MEBT:Q6': 9.75

'MEBT:Q7': 14.44

'MEBT:Q8': 17.94

'MEBT:Q9': 23.43

'MEBT:Q10': 8.95

'MEBT:Q11': 21.43

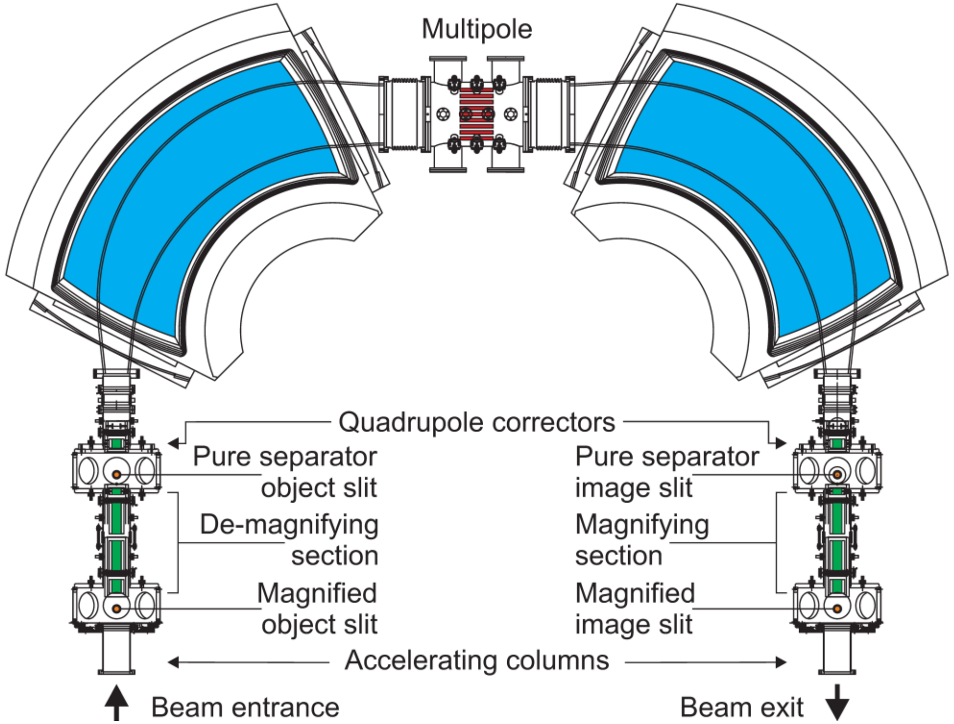
'MEBT:Q12': 21.86

'MEBT:Q13': 12.01

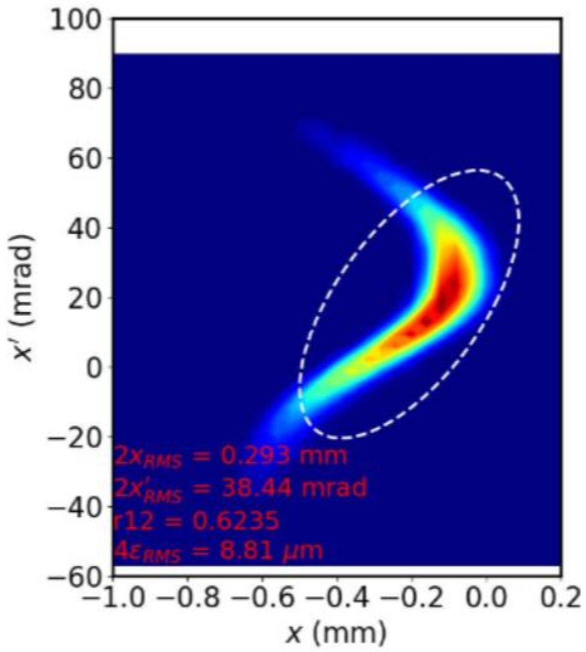
TRANSMISSION: 0.0

Beam Physics - High Res. Spectrometer

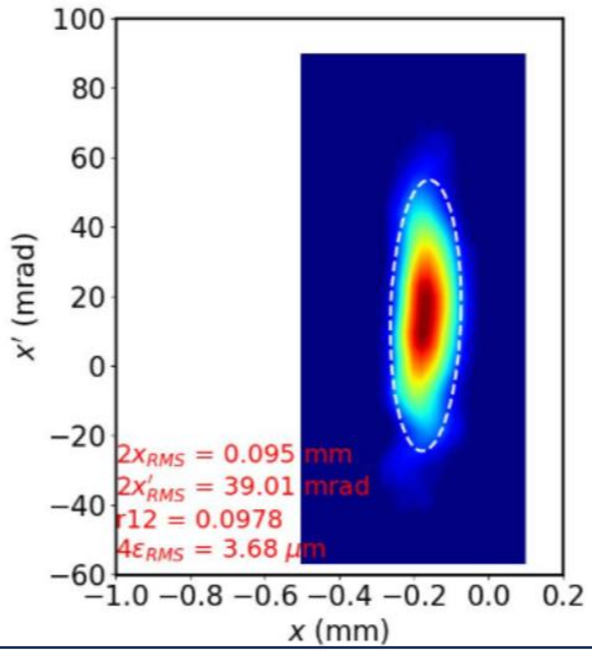
- Two 90-degree dipole design
- Electrostatic Multi-pole corrector between dipoles
- ΔM/M=1/16000 resolution tune demonstrated with high transmission



Latest commissioning results



Emittance at exit slit before multipole correction



Emittance at exit slit after multipole correction

SRF Developments

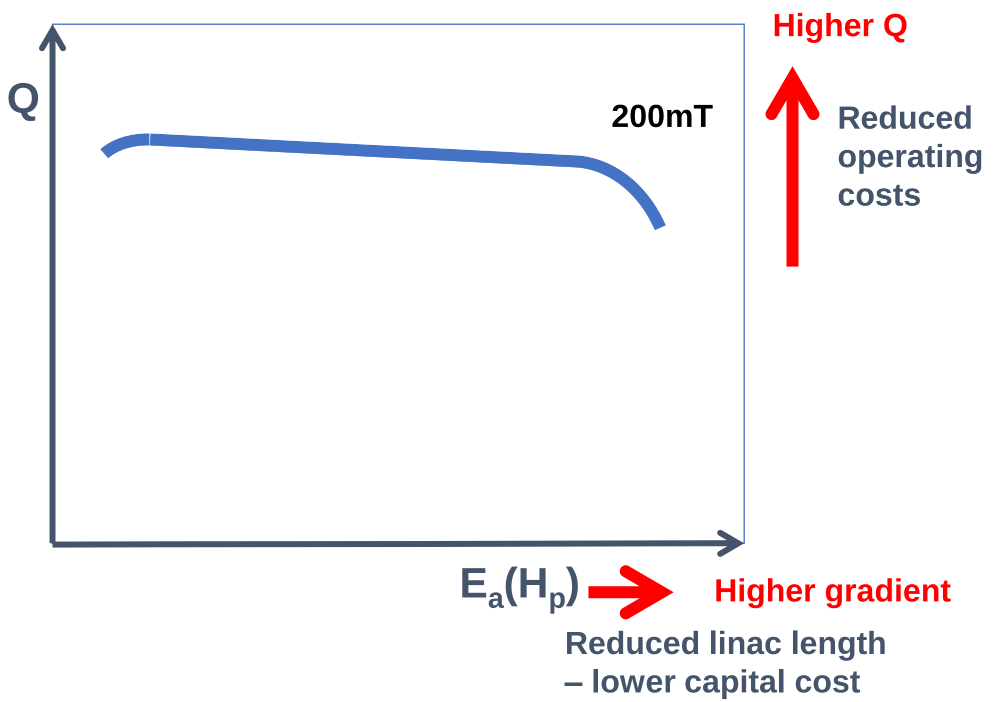
Global push to improve performance by increasing achievable gradient and quality factor

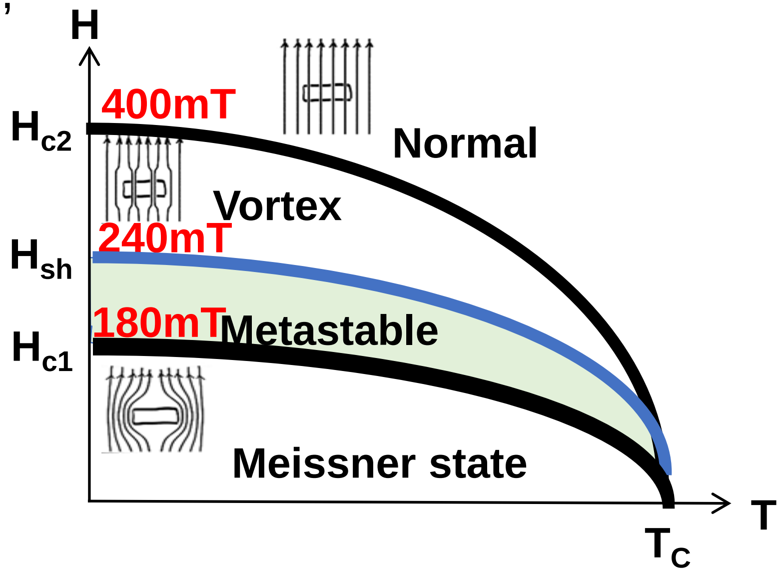
High G

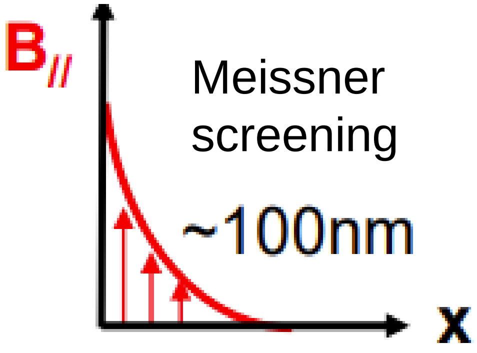
- Intrinsic limits – peak magnetic field until vortex penetration
  - Need materials that can maintain the Meissner state to high rf fields -> new materials, new treatments
- Extrinsic limit – Field emission – clean assembly, particle migration, plasma cleaning

High Q

- Intrinsic limit – BCS resistance -> heat treatments (doping)
- Extrinsic limit – magnetic flux trapping, Q-disease -> magnetic shielding, cooldown dynamics, hydrogen degassing

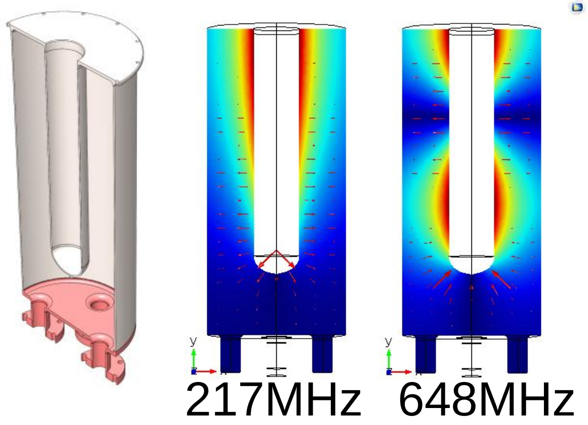


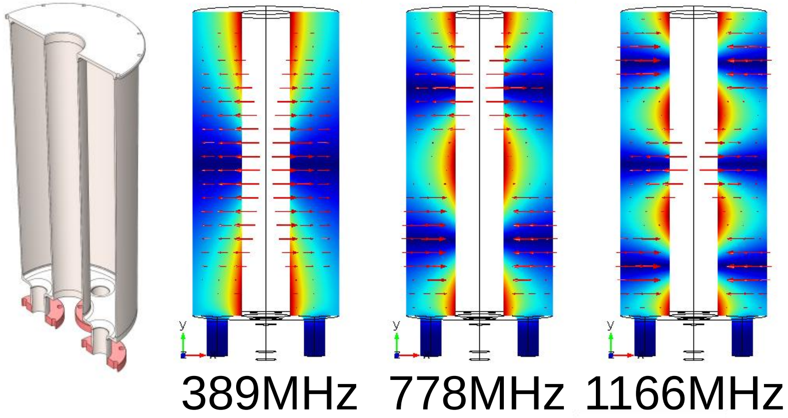




Coaxial Cavities for SRF Research

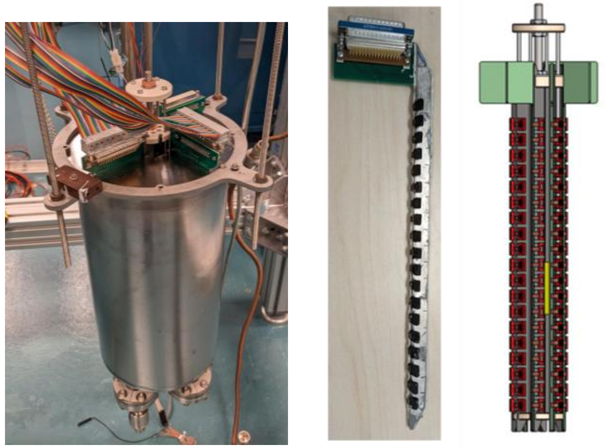
- TRIUMF has designed and built two research cavities – QWR and HWR
- Cavities allow excitation of different resonant modes → rf frequency dependence to cavity performance.
- Induction furnace for customized heat treatments in coaxial cavities
- T-map diagnostic for coaxial cavities
- Three axis Helmholtz coil for trapped flux studies
- Research explorations:
  - Can surface treatment gains at high frequency in elliptical cavities translate to lower frequency coaxial cavities





Induction furnace

Helmholtz coil



T-map diagnostic

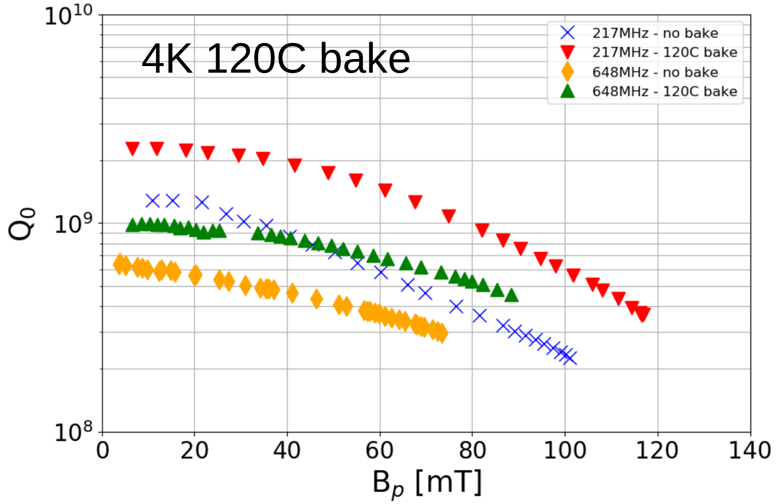
Infrastructure to support coaxial student program

- **Research questions:**
  - **Field dependence:** How does the field dependence of the rf surface resistance depend on frequency and surface treatment
  - **Heat treatments:** Can surface treatment gains at high frequency in elliptical cavities translate to lower frequency coaxial cavities

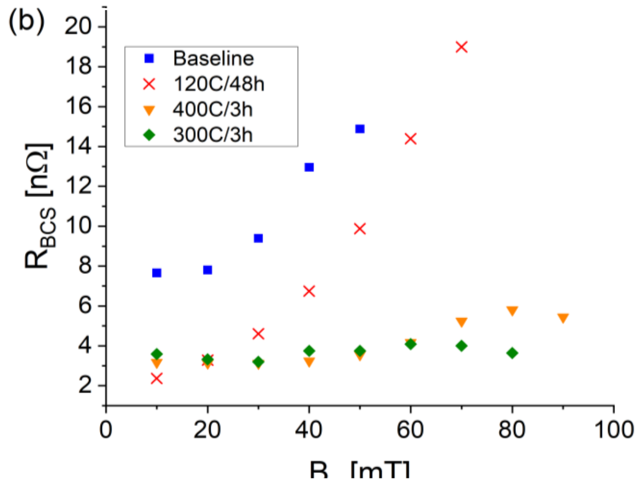
  [Phys. Rev. Accel. Beams 23, 122001](#)
  [Front. Electron. Mater, 08 October 2023, Sec. Superconducting Materials](#)

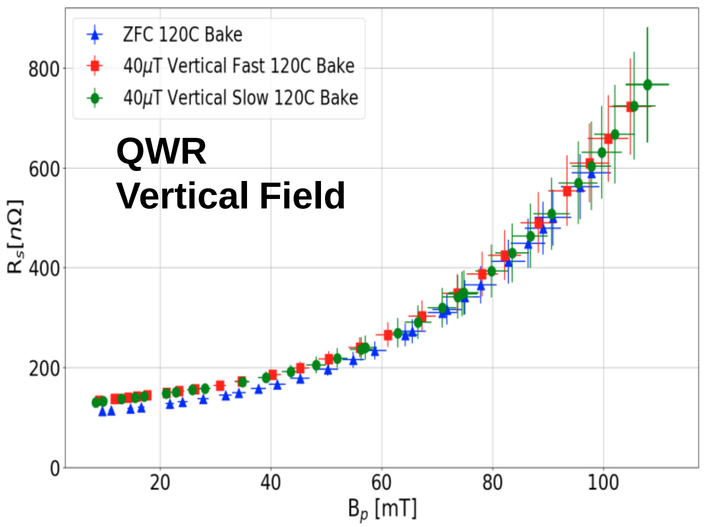
  - **Magnetic flux trapping findings:** Cavity shape (QWR vs HWR), flux direction (vertical vs horizontal, cooldown speed (fast vs slow) all affect impact of background flux

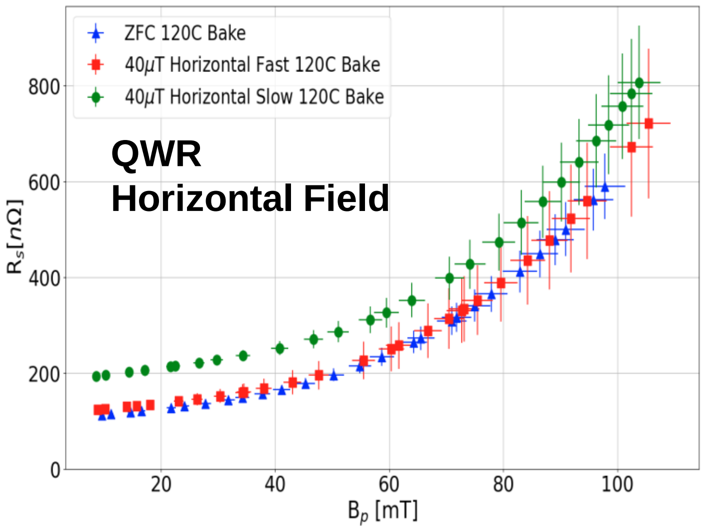
  https://accelconf.web.cern.ch/srf2023/papers/mopmb023.pdf - Ruth Gregory MSc UVic



2K – mid-T bake – 1166MHz







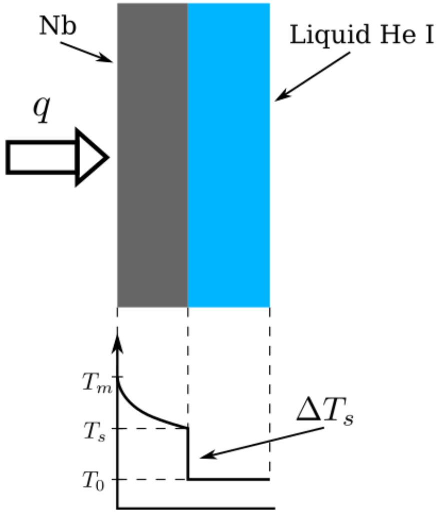
Modelling thermal feedback in surface resistance studies on coaxial SRF cavities

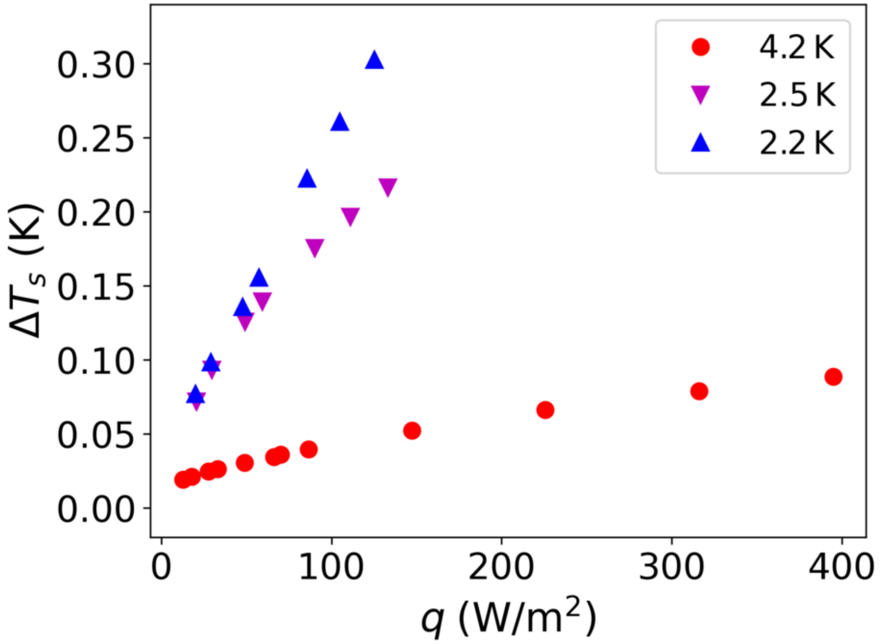
The superconducting rf surface resistance is highly dependent on the surface temperature

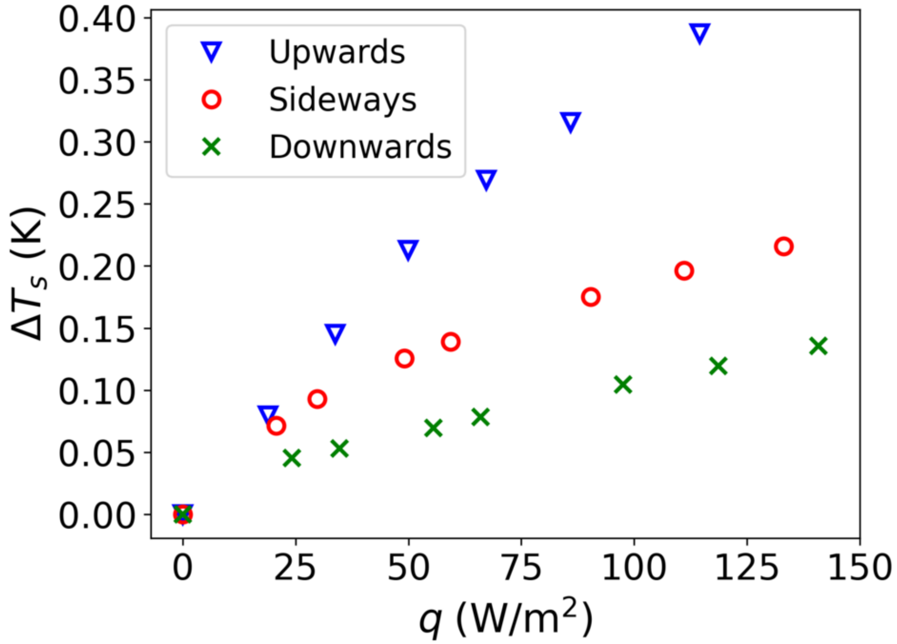
Question: Do thermal gradients across the cavity wall impact performance?

Experimental data was taken to measure heat transfer across Niobium at cryogenic temperature to help us understand the role of thermal conductance in SRF performance.

Efficiency of heat transfer is both temperature and geometry dependent

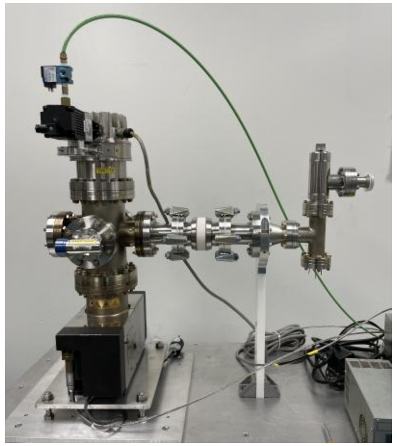






M. McMullin, et al, Thermal feedback in coaxial superconducting radio frequency cavities , PRAB 27, 092001 (2024)

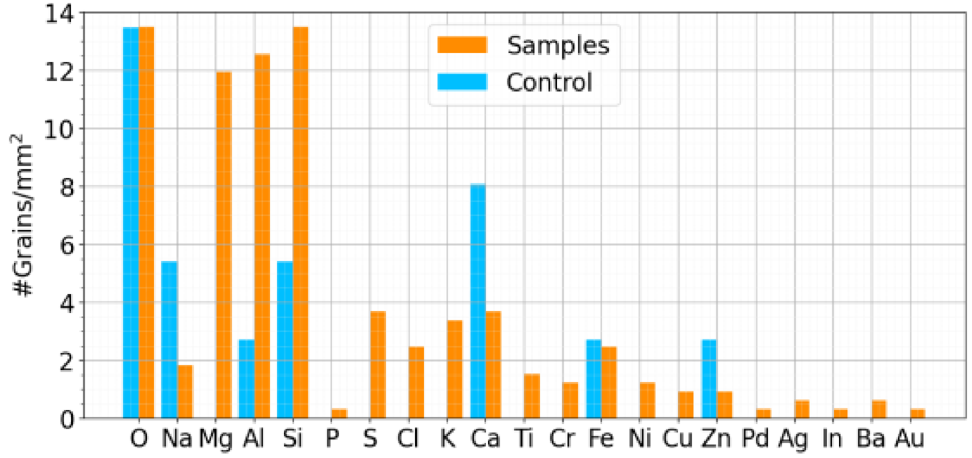
Attacking field emission in SRF cavities



Particle migration test centre

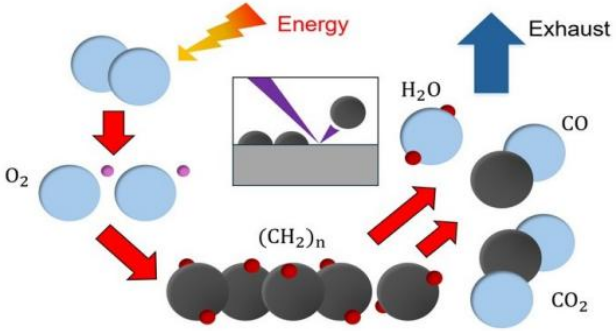
Dust migration Aveen Mahon (PhD, UVic)

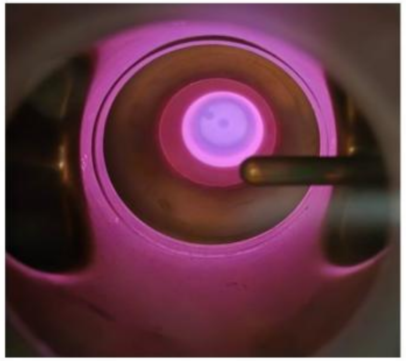
- developing methods to suppress dust migration from beamlines to SRF cavities – samples of dust analyzed to try to understand the source

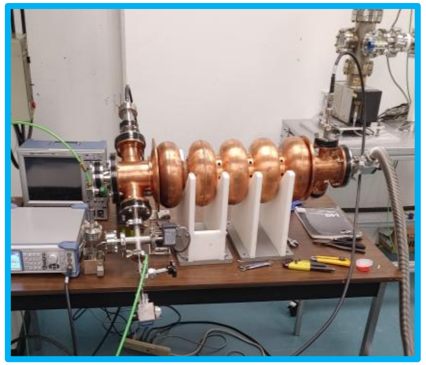


Plasma conditioning Daniel Hedji (MSc, UVic)

- developing RF cavity cleaning methods that can be done in-situ to improve cavity performance without disassembly



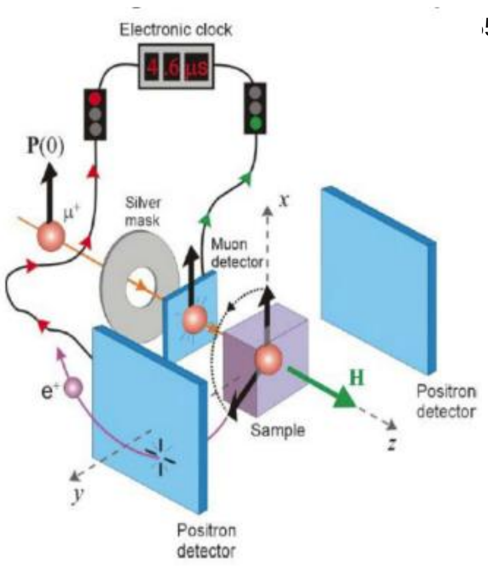


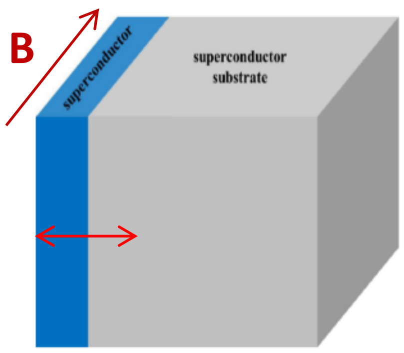


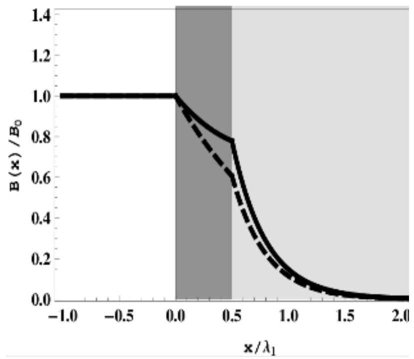
Aveen and Daniel were top prize winners at the student poster competition at Linac 2024

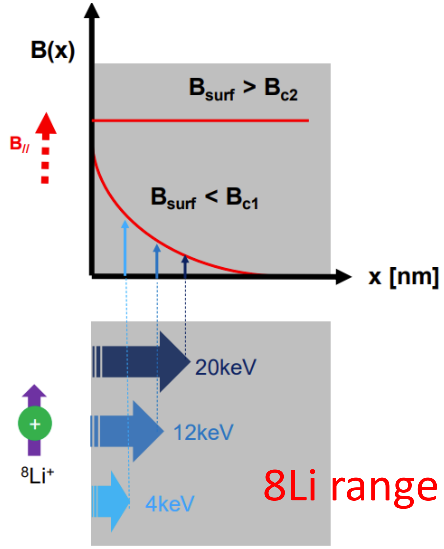
Material Probes of magnetic response – μSR & β-NMR

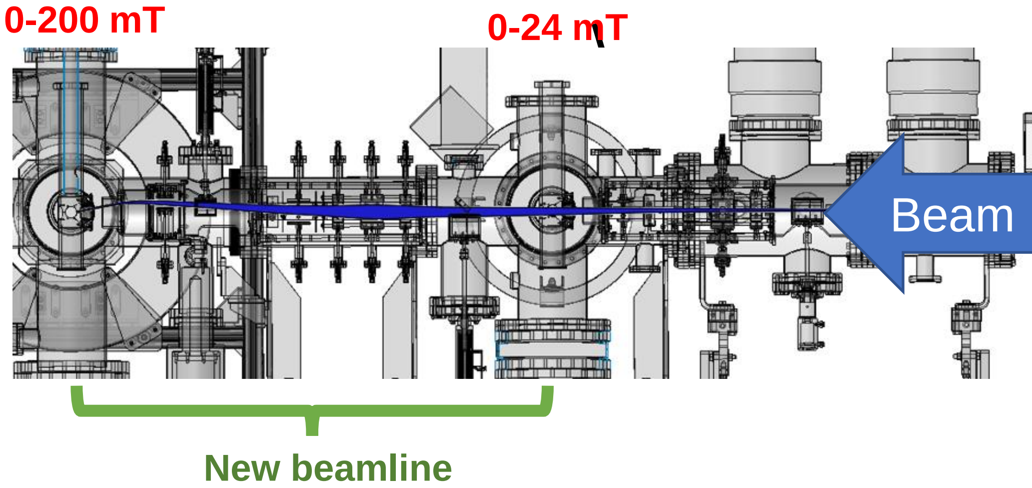
- TRIUMF has two world class material science probes in μSR and β-NMR – utilize the beta-decay of a beam of polarized muons or 8Li ions respectively as probes of local magnetism
- TRIUMF μSR -> bulk probe (100μm depth) - Allow measurements of the on-set of flux penetration from an applied DC magnetic field
- Beta-NMR – surface probe measuring magnetic field in first 100nm with depth profiling – allows measurement of London penetration depth
- **TRIUMF has recently installed and commissioned a new spectrometer capable of applying a parallel field of 200mT (near Hc1 for Niobium).**
- **Unique facility to diagnose new treatments (doping) and new layered structures**











[Frontiers | SRF material research using muon spin rotation and beta-detected nuclear magnetic resonance](), T. Junginger, R. Laxdal , W. MacFarlane and A. Suter, Frontiers in Electronic Materials – Jan 2024

Measurement of Meissner screening profile at beta-SRF

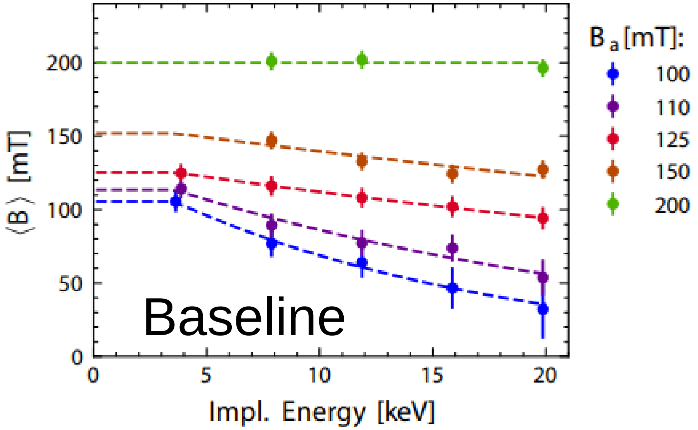
- `β-SRF' - Unique facility in the world for depth profiling materials in parallel magnetic fields up to 200mT – SRF regime – critical field of Nb

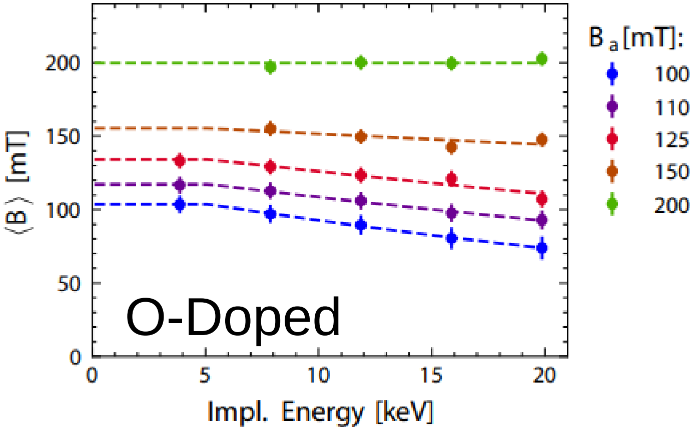
[E. Thoeng et al, A new high parallel-field spectrometer at TRIUMF's β-NMR facility | Review of Scientific Instruments | AIP Publishing](), *Rev. Sci. Instrum.* 94, 023305 (2023)

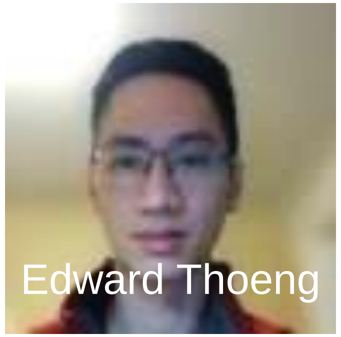
[E. Thoeng et al, Depth-resolved characterization of Meissner screening breakdown in surface treated niobium | *Scientific Reports*]() **volume 14**, Article number: 21487 (2024)

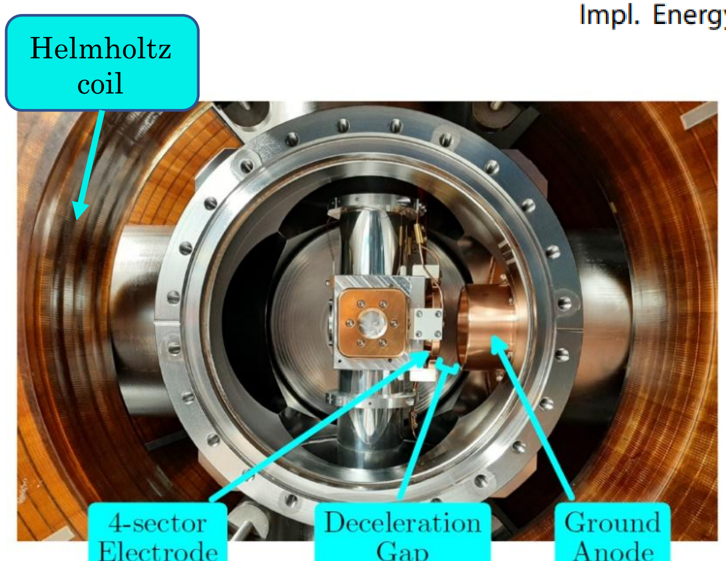
First results show Meissner screening in two samples as a function of applied field:

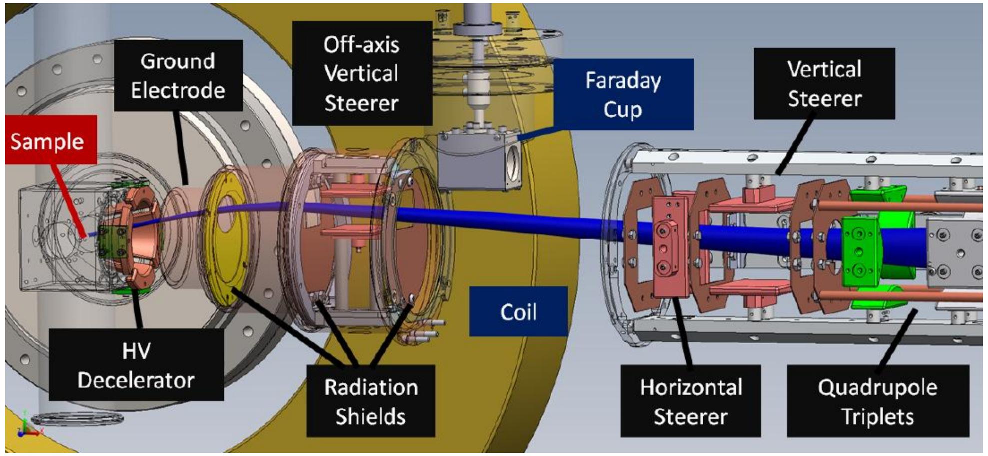
- Clear difference in screening profile between the two samples
  - $\lambda_{baseline}$ = 40nm and λ_{doped} = 130nm











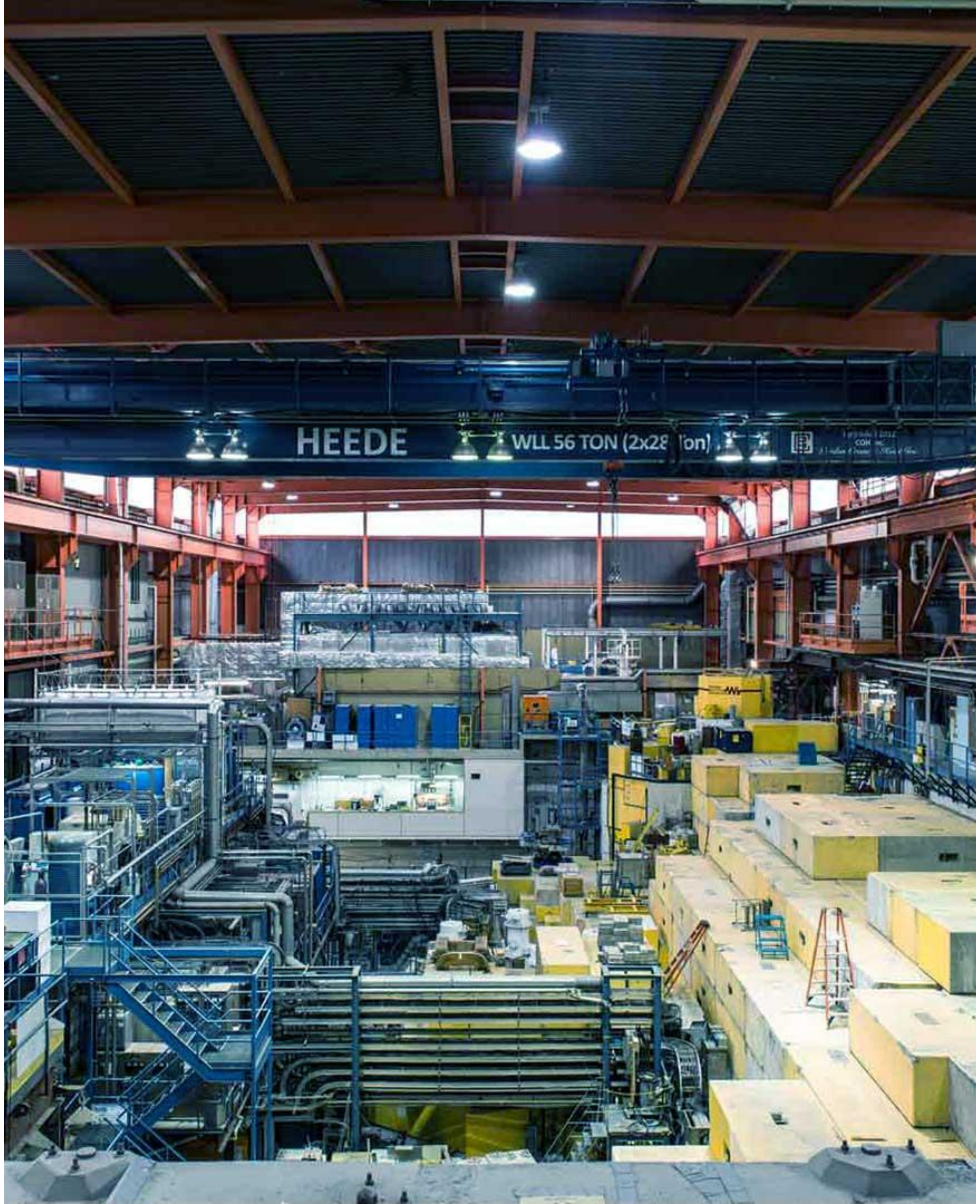
Summary

- The TRIUMF Accelerator Division goal is to complete ARIEL and BL1A in SD2026 as part of the deliverables for the Five Year Plan
- Other opportunistic developments will be completed to prepare for operation in the ARIEL era
- Domestic and international collaborations like THz and Hi-Lumi will continue as allowed by available resources
- An active student program advances understanding around the three core competences of SRF, beam physics and ISOL technology
- There are many synergies between FRIB and TRIUMF
    - SRF (coaxial cavities, SRF guns), RIBs, diagnostics, remote handling, beam physics, high power targets, radiation damage to materials, …

TRIUMF

Thank you
Merci

Questions?



Discovery, accelerated

Scale of Operations

HIGHLY QUALIFIED PERSONNEL

~ 600 staff[1]

> 200 students & postdoctoral researchers[2]

1000+ scientist & researcher visits per year

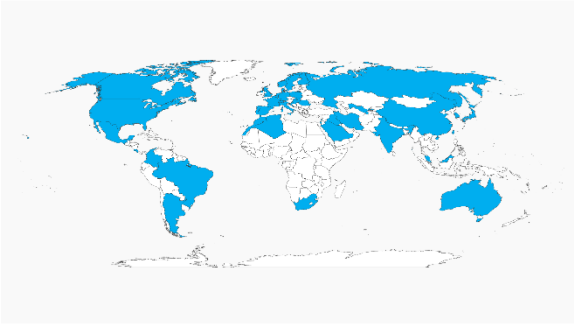
KNOWLEDGE

~80% of Canada's subatomic physics research involves TRIUMF

INTERNATIONAL ENGAGEMENT

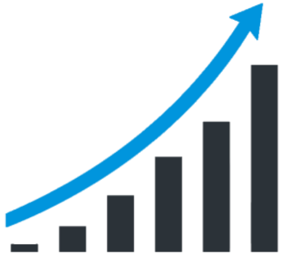
75 international agreements & partnerships

Visitors from over 40 countries



BUSINESS

Generated nearly $500M in economic activity from 2018 – 2022



1 – Total across funding sources
2 – Includes external students and post-docs

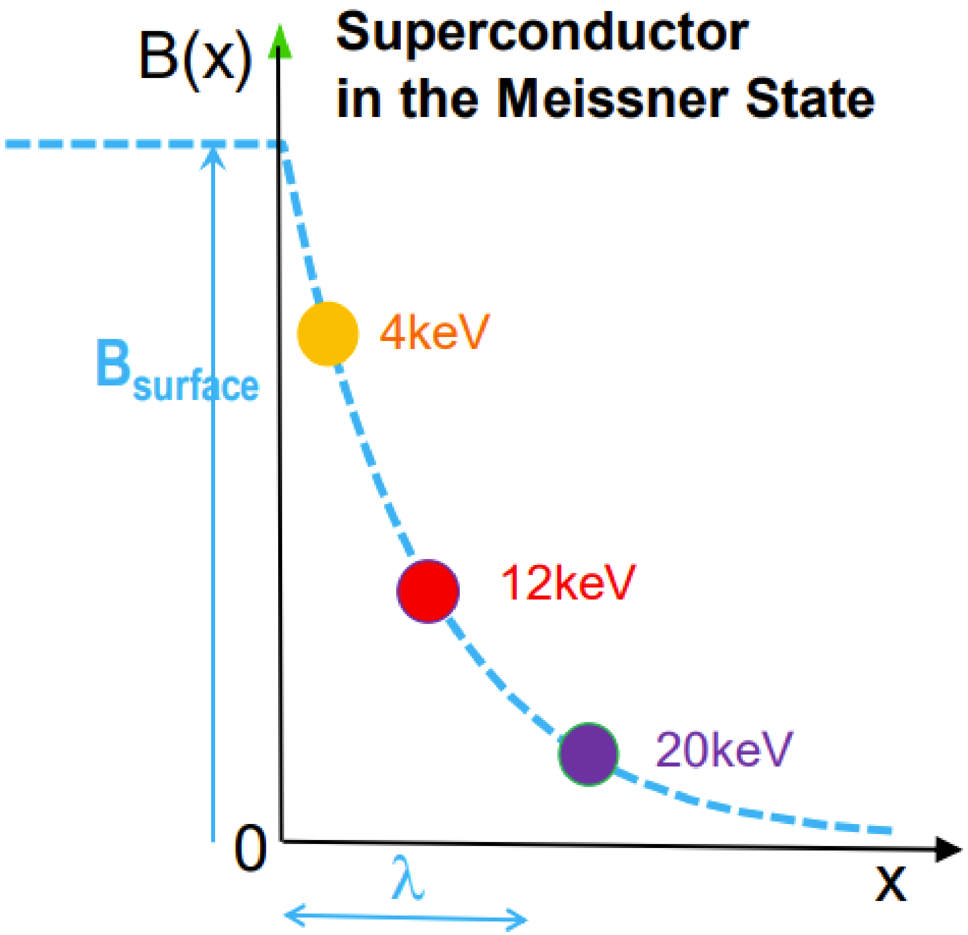
Our multidisciplinary community drives leading-edge research that delivers impact in science, medicine, and industry, positioning Canada as a world leader.

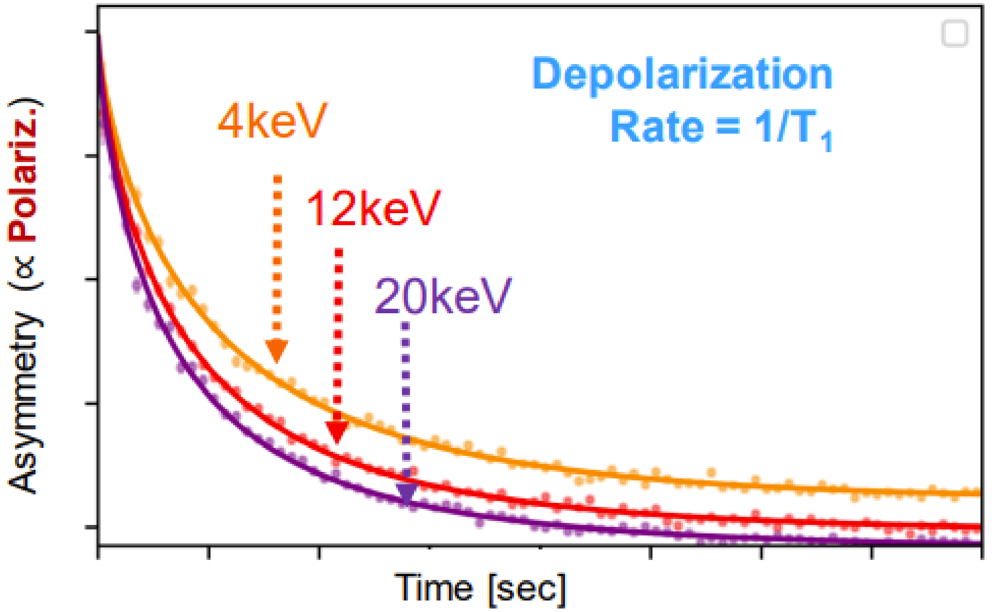
- *University of Alberta*
- *University of British Columbia*
- *University of Calgary*
- *Carleton University*
- *University of Guelph*
- *University of Manitoba*
- *McGill University*
- *McMaster University*
- *Université de Montréal*
- *University of Northern BC*
- *Queen's University*
- *University of Regina*
- *Saint Mary's University*
- *Université de Sherbrooke*
- *Simon Fraser University*
- *University of Toronto*
- *University of Victoria*
- *University of Waterloo*
- *Western University*
- *University of Winnipeg*
- *York University*

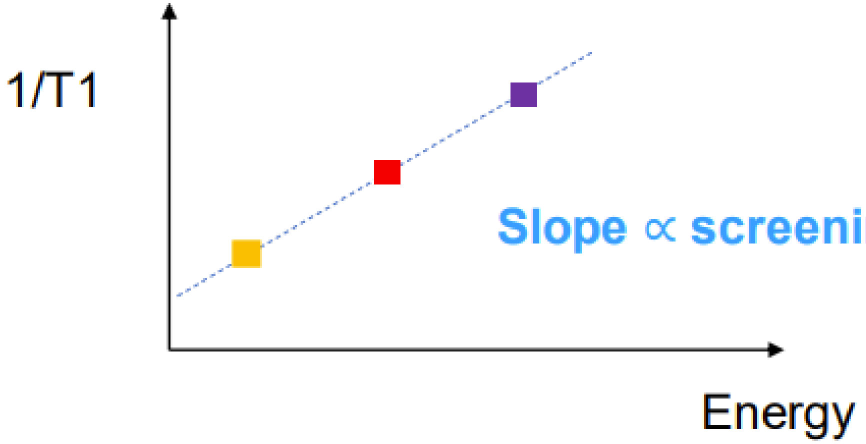
Discovery, accelerated

TRIUMF

Local Field: Spin-Lattice-Relaxation







$$\frac{1}{T1} = \frac{a}{b + \langle B_{loc} \rangle^2}$$