TRIUMF

Secondary Particle Beam Production at TRIUMF

Development Vision

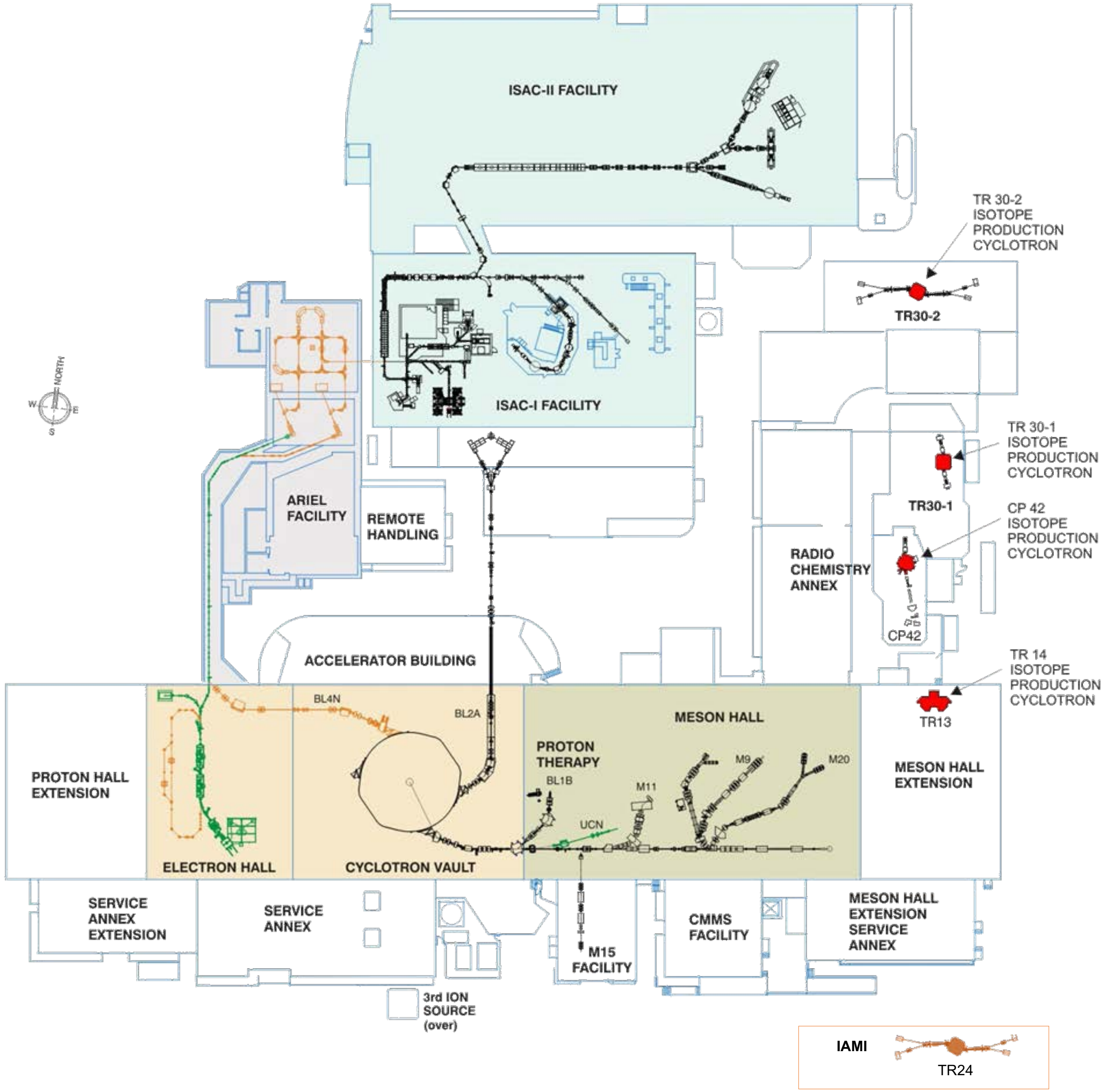
Alexander Gottberg
Department Head, Targets and Ion Sources

TRIUMF Science Week, August 20, 2020
Accelerators Session

Discovery, accelerated

TRIUMF

TRIUMF – A Fixed Target Laboratory



TRIUMF accelerators

- 520 MeV, 200 kW cyclotron
- 30 MeV, 100 kW e-linac
- Cyclotrons: TR30-1, TR30-2, TR14, TR24, CP42
- Heavy ion accelerators

520 MeV cyclotron
5500 proton hours annually to produce:

- ISOL RIB (50 kW protons)
- π and μ (60 kW)
- Medical isotopes (50 kW)
- Ultra-cold neutrons (20 kW)
- Proton therapy (50 W)

Discovery, accelerated

Accelerator target priorities for the next decade and beyond along TRIUMF's three critical dimensions

1. Science and Technology

2. People and Skills

3. Innovation and Collaboration

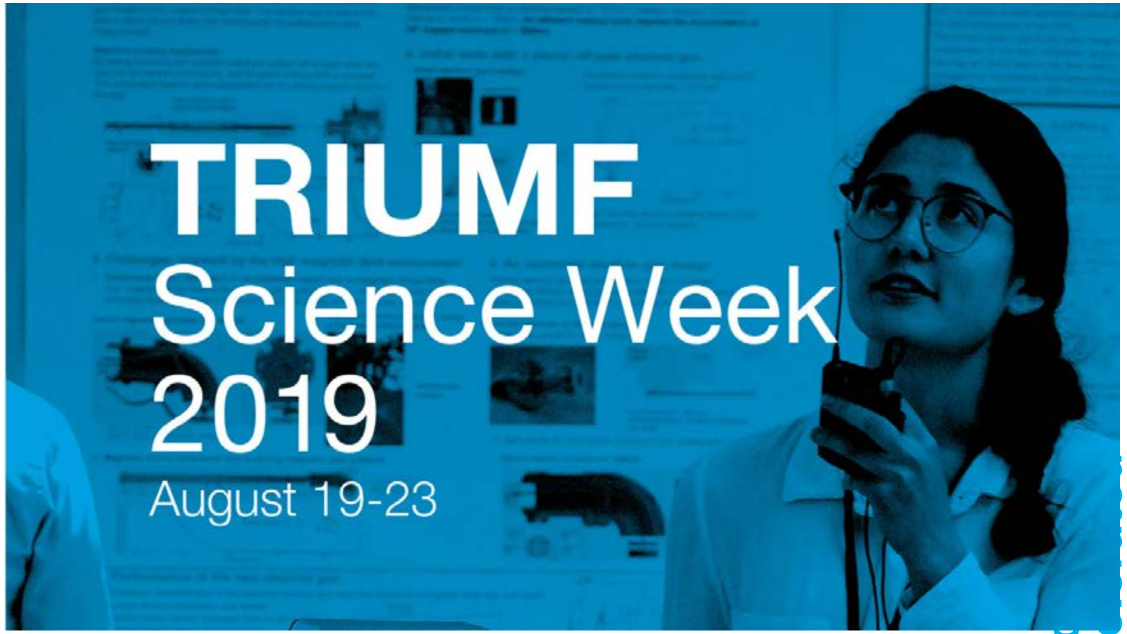
- **Capitalize, develop and exploit existing infrastructure**
  - Complete full scope of ARIEL
  - Ramp up electron beam power to 100 kW and fully exploit 50 kW proton potential
  - Increase RIB availability, intensity and purity through graduate student-level target/ion source development projects

- **Refurbish aging RH and targetry systems**
  - BL1 monuments and BL1 RH components, ISAC target hall, cyclotron RH, …

- **Sustainability and personnel dose reduction**
  - Develop and implement sustainable site-wide waste handling without increasing personnel radiation exposure
  - Develop full hands-off processes and technologies for all routine tasks at TRIUMF

- **Increase EDI awareness and contribute to building a strong, fair and transparent HQP training program**
  - Currently: 30% female – target: 50%,
  - Currently: 7 graduate students and PDFs – target: maintain level of program and diversity
  - Continue to promote target science and technology in student education (university courses, undergrad projects, student workshops)

- **Retain talent**
  - ARIEL's has been an excellent training platform and has attracted outstanding talents. Exciting projects to retain this talent are vastly available and need prioritization.
  - Maintain a flexible and versatile team



Innovation and Collaboration

- **Contribute to international projects and collaborations fostering TRIUMF's leadership in high-power targetry, RH and RIB technology, i.e.**
  - Neutron and neutrino production
  - High-power ISOL facilities under consideration or construction

- **Strengthen platforms for TRIUMF-internal exchange of target technology expertise**
  - World-leading expertise currently distributed over all TRIUMF divisions
  - Challenges and solutions are very similar and tools developed by different groups should be fully exploited to the benefit of all of TRIUMF

- **Realize small and medium size development opportunities towards novel accelerator target applications**
  - Medical (FLASH RT, radioisotope harvesting)
  - Irradiation services
  - Technology transfer

TRIUMF is internationally recognized for its leading role in remote handling, hot cell design and operation.

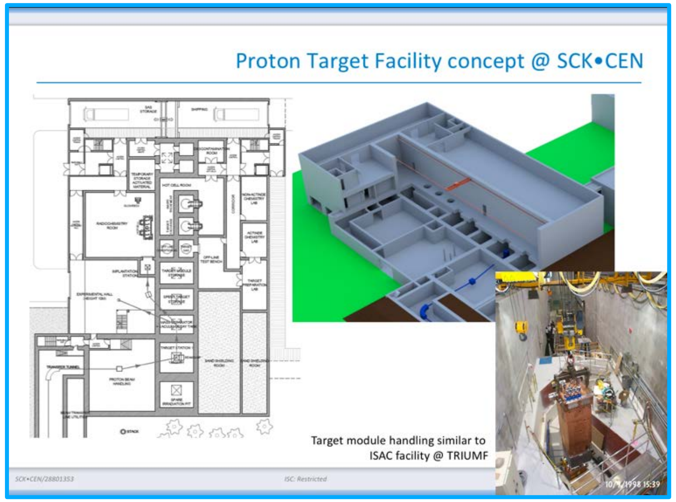
RH robotics development

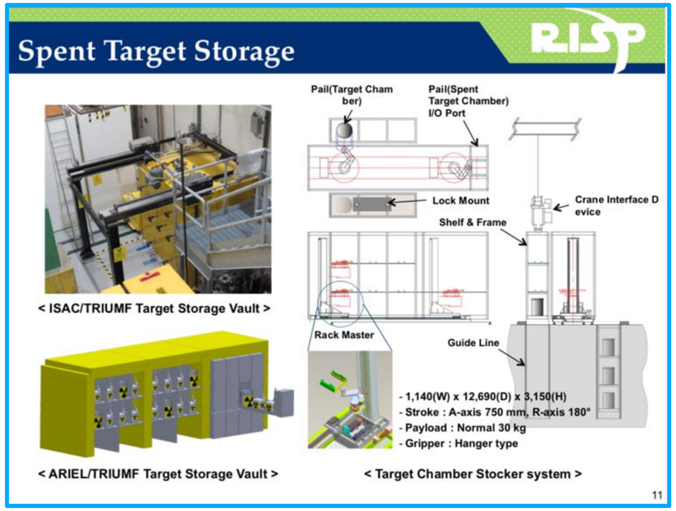
TRIUMF RH specialists assisting in T2K target repair

Remote handling vision

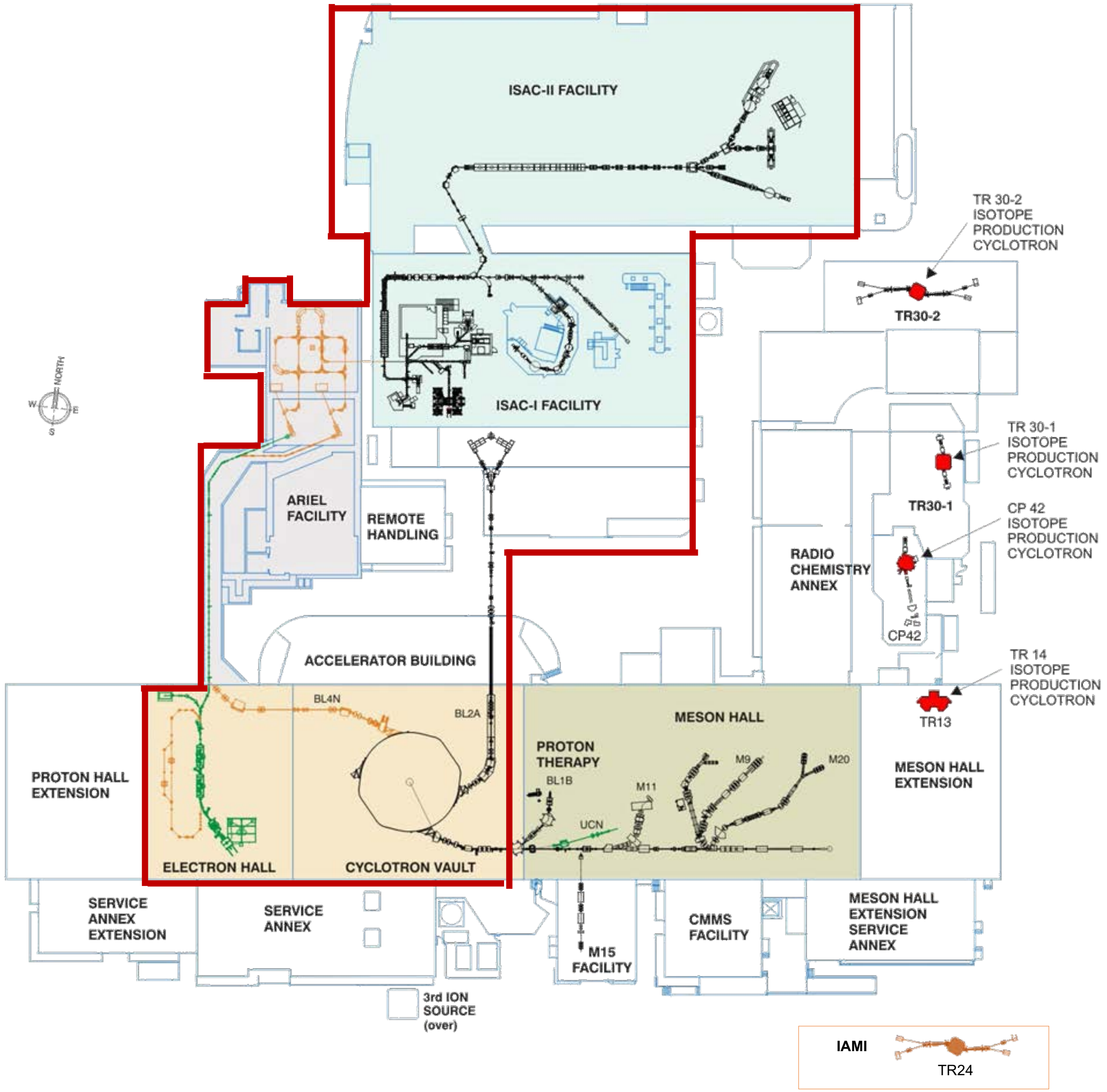
- Full hands-off control of all routine RH activities
  ➔ reduction of dose and inefficiencies
- Strengthen international collaborations and develop technology for Canada and the world
- Reinforce world leadership in RH

Examples of international designs based on TRIUMF RH:





TRIUMF's RIB Factory



ISAC RIB Production (since 1995)
- 2 target stations
- Highest power ISOL driver with 50 kW 500 MeV protons

ARIEL RIB production (in progress)
- Two new ISOL target stations
- First high-power electron driver with 100 kW, 30MeV (2021)
- High-power proton driver with 50 kW 500 MeV (2023)

ISAC/ARIEL experimental areas
- Low energy ≤ 60 kV
- Medium energy ≤ 1.8 MeV/u
- High energy ≤ 16.5 MeV/u

With ARIEL, TRIUMF will host the largest RIB production complex in the world.

Discovery, accelerated

ISAC - The North American ISOL Facility

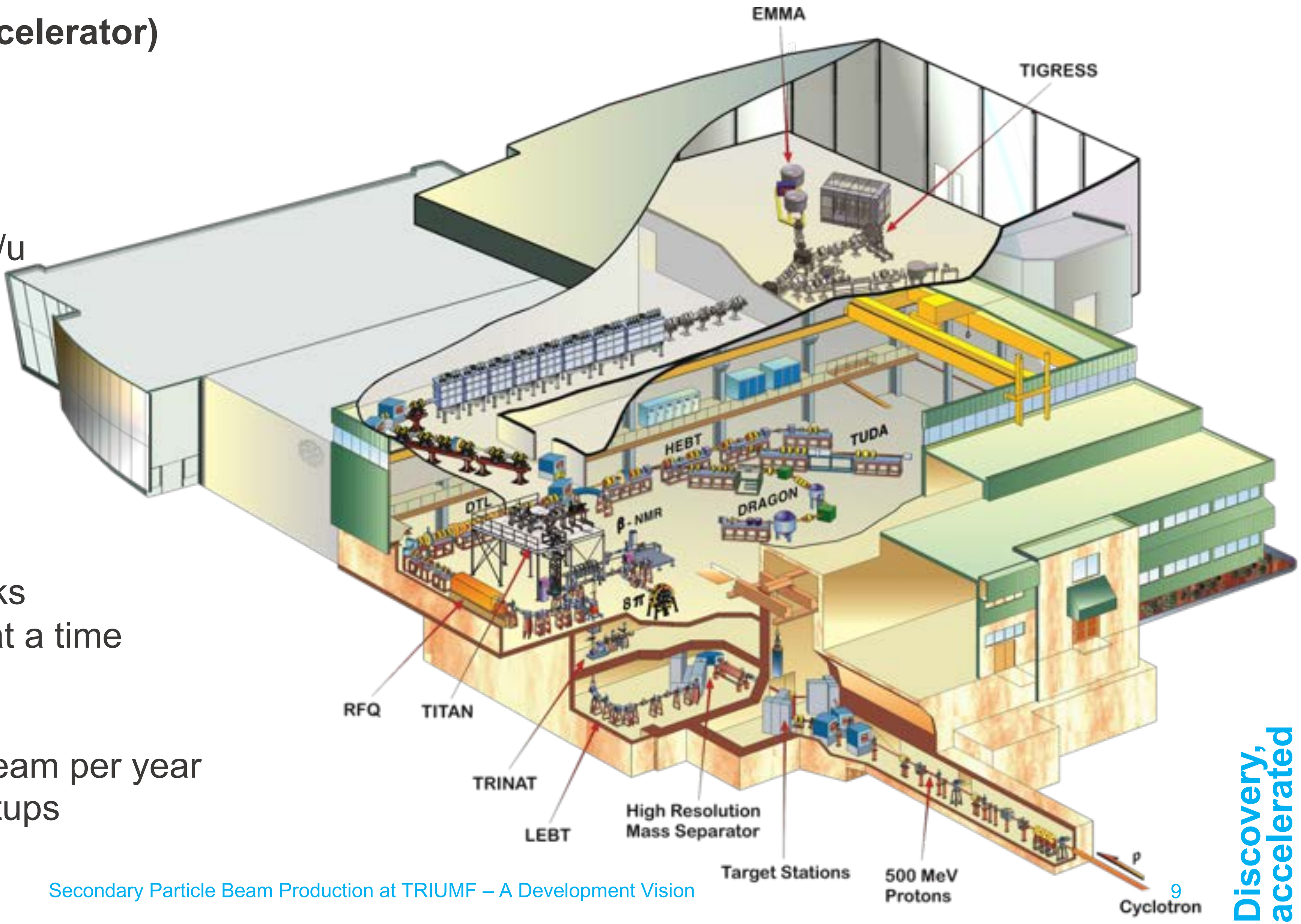
ISAC (Isotope Separator and Accelerator)

ISAC I:
- Low energy: <60 keV
- Medium Energy: 0.15 – 1.8 MeV/u

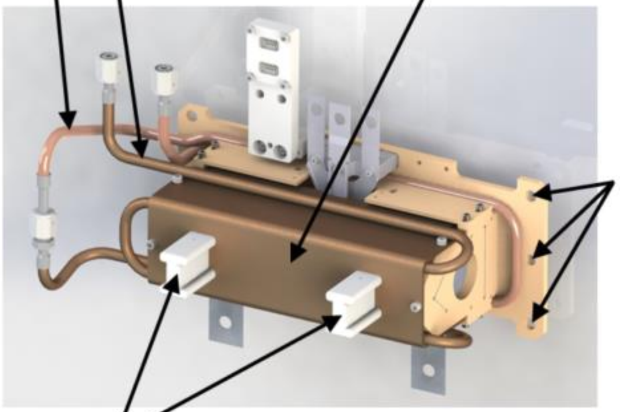
ISAC II:
- 5 – 16.5 MeV/u

- Target exchange every 2-5 weeks
- Operation of one target station at a time

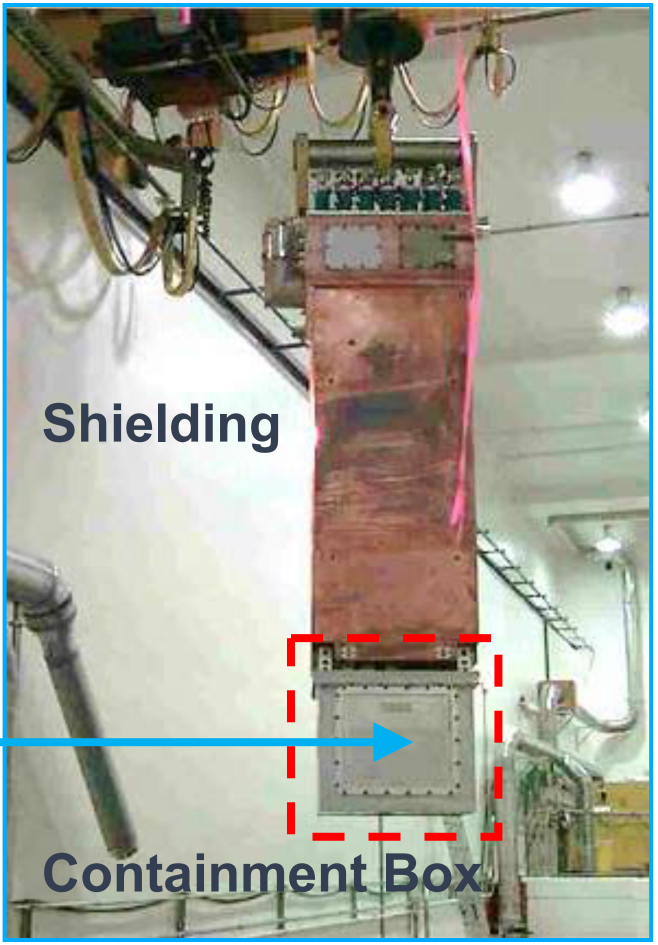
- 700 isotopes extracted
- > 3000 h of high intensity RIB beam per year
- State-of-the art experimental setups



ISAC – World Highest Power ISOL Target Systems



Target assembly mounted in the Target Module containment box



ISAC Target module hanging from remote handling crane

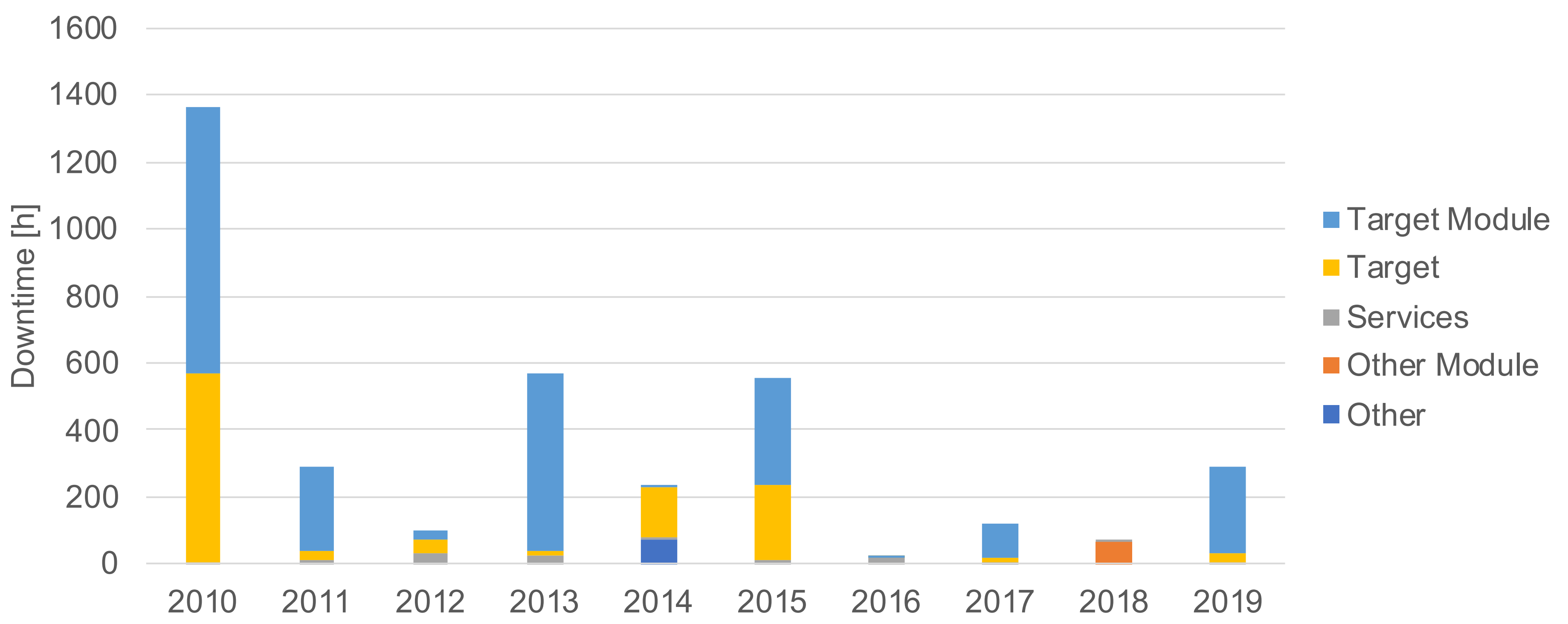
ISAC is at the forefront of RIB science.

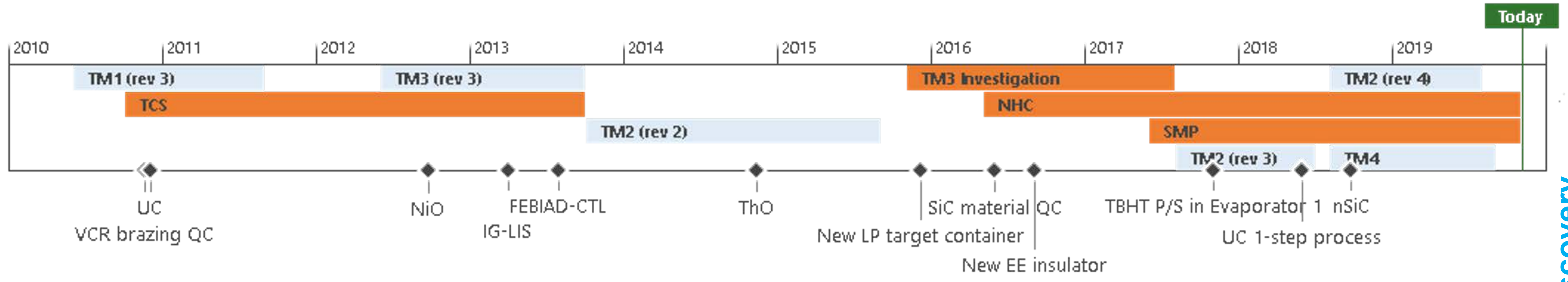
Goal:
ISAC/ARIEL as the global leader in ISOL facilities

Requires
- completion of ARIEL
- ISAC refurbishment for efficient, reliable operation
- continued development of exotic beams

Targets and ion sources reliability:
- Improved ISAC target system reliability
- Establish full ISAC functionality
- Increased operational efficiency

Performance Statistics 2010 – 2019





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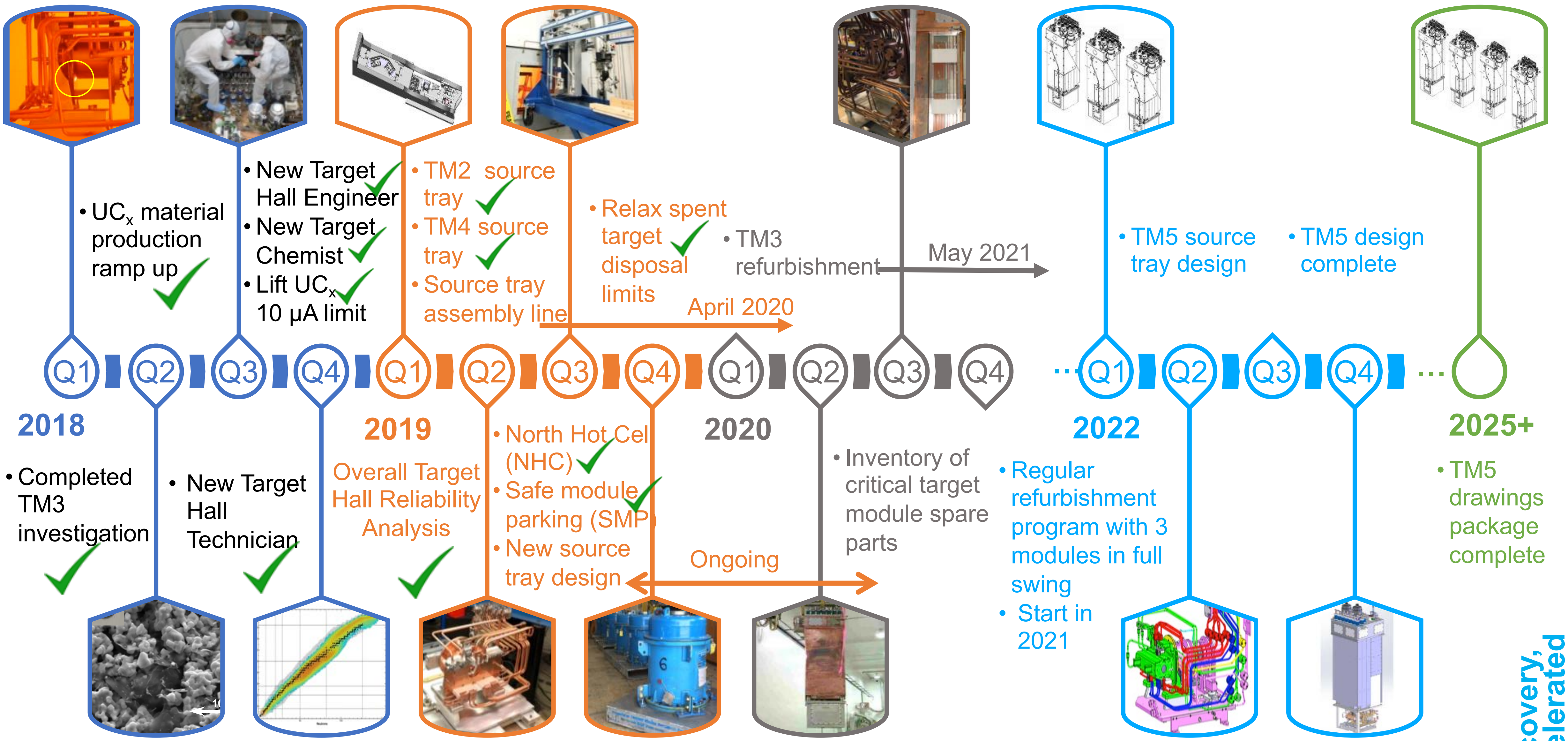
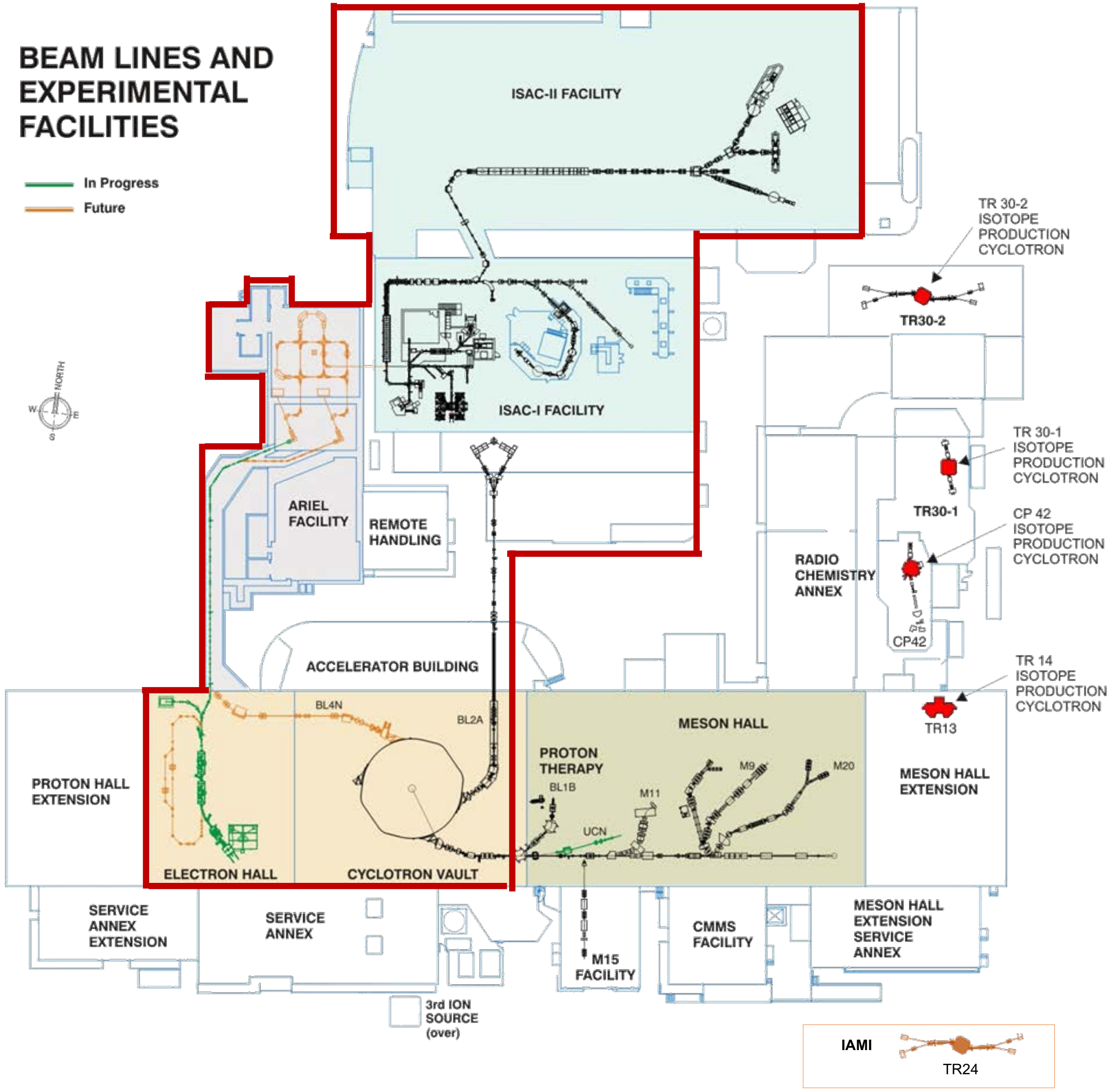
ISAC Target Infrastructure Refurbishment Timeline



The ARIEL Revolution



ARIEL:

Additional driver beams and ISOL target stations for three times more RIB (>9000 h).

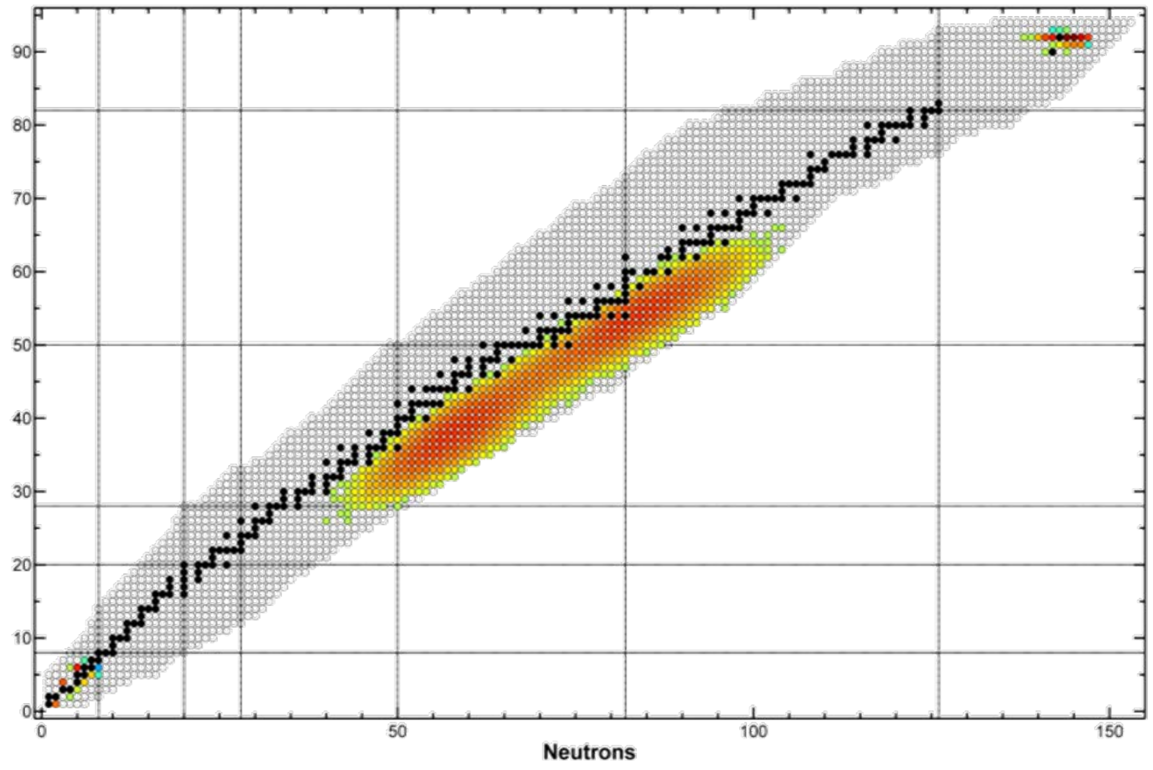
ARIEL vision:

- Complete ARIEL CFI Project
- Complete full ARIEL scope
- Operational ramp-up
- Reach full operational efficiency, reliability, capability
- Establish full power operation 100 kW electrons, 50 kW protons
- Deliver 9000 RIB h / year according to user demand

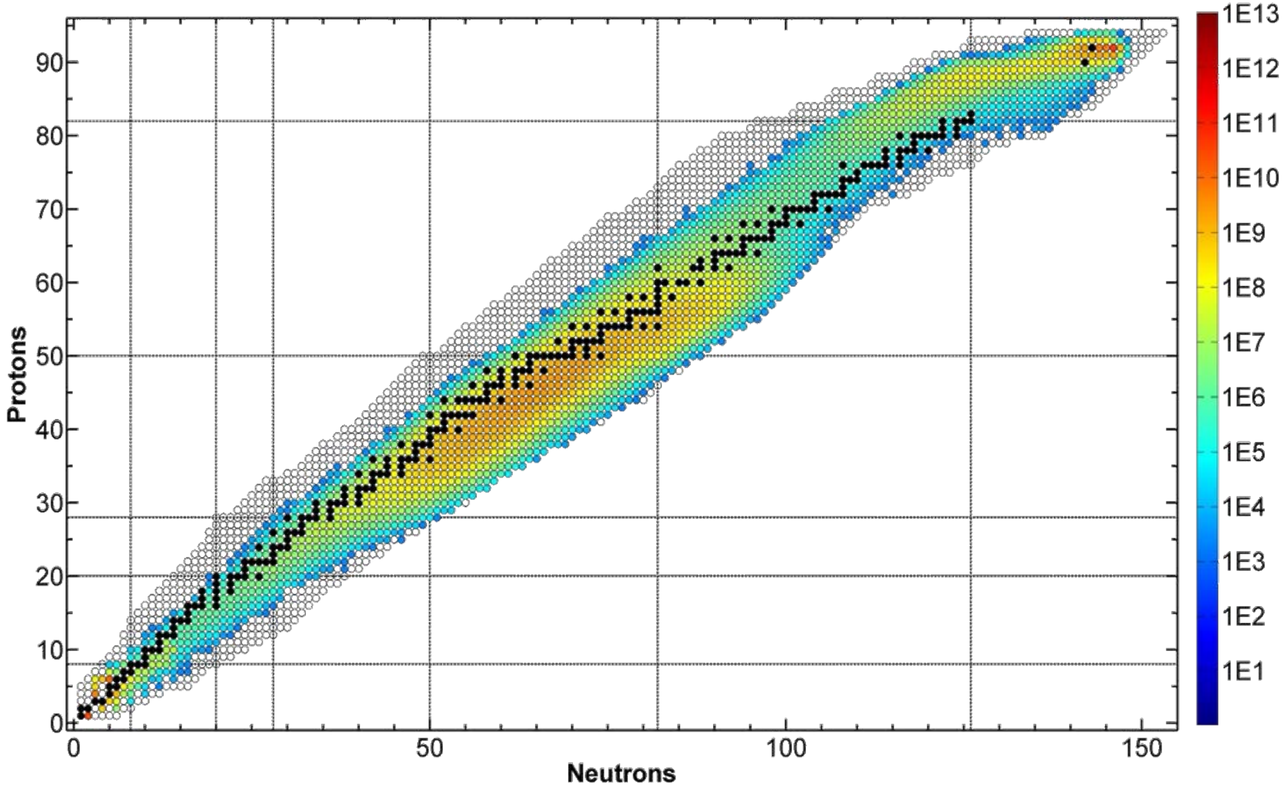
Tripling TRIUMF's RIB program

production intensity from $^{238}UC_x$

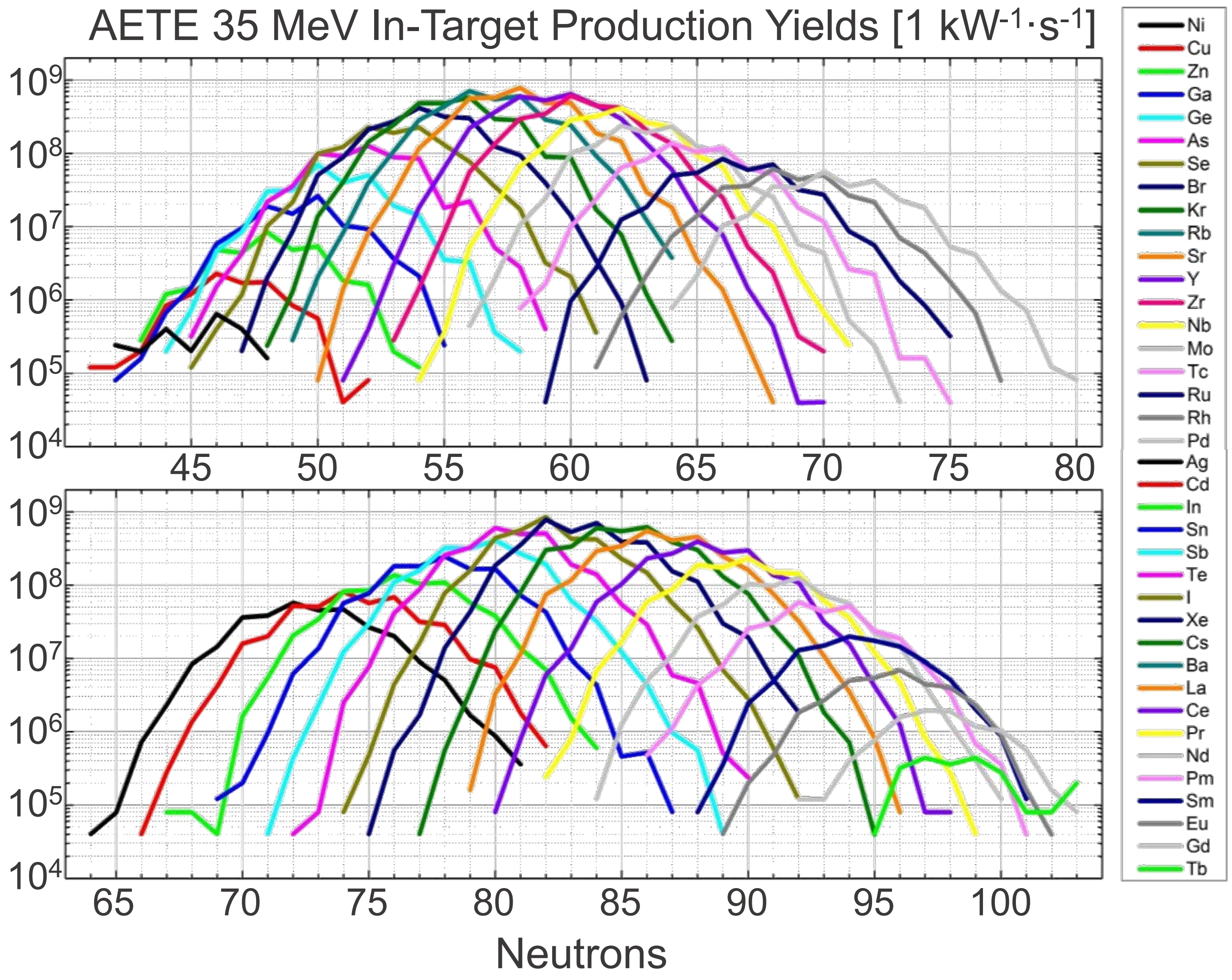
35 MeV x 10 mA (350 kW) electrons [1/s]



500 MeV x 10 μA protons [1/s]



Isotope production at ARIEL



In-target production rates

35 MeV electrons on UC_x (per kW · s):	
^{78}Ni:	$1 \cdot 10^4$
^{98}Kr:	$8 \cdot 10^6$
^{100}Rb:	$1 \cdot 10^7$
^{98}Sr:	$5 \cdot 10^8$
^{132}Sn:	$5 \cdot 10^7$
^{146}Xe:	$2 \cdot 10^6$
^{144}Ba:	$5 \cdot 10^8$
^{150}Cs:	$4 \cdot 10^4$

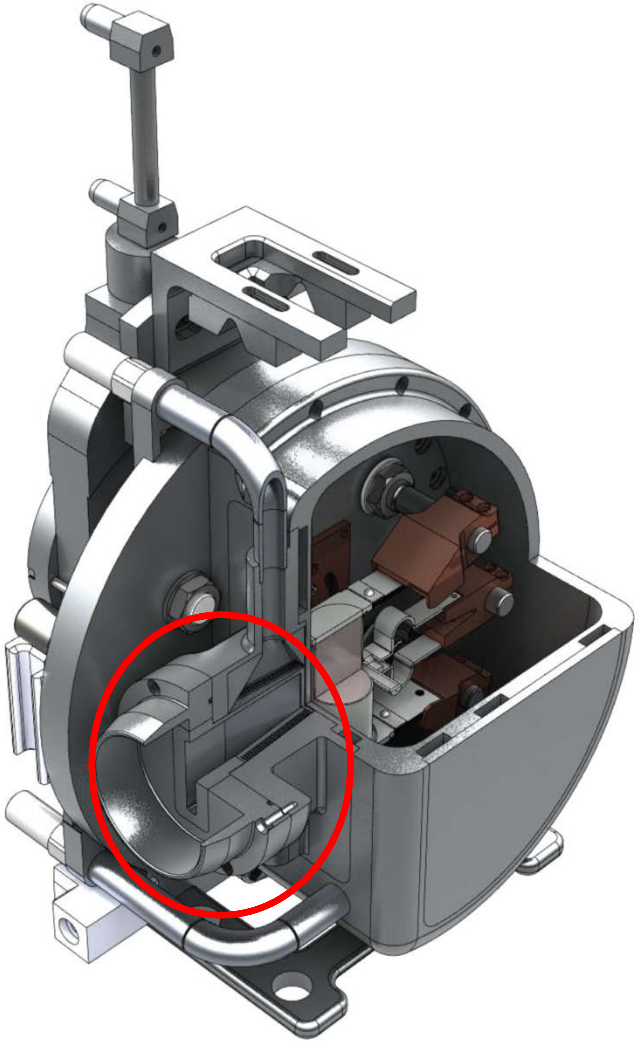
500 MeV protons on UC_x (per 10 μA · s):	
^{78}Ni:	$2 \cdot 10^6$
^{98}Kr:	$1 \cdot 10^8$
^{100}Rb:	$9 \cdot 10^7$
^{98}Sr:	$1 \cdot 10^{10}$
^{132}Sn:	$5 \cdot 10^9$
^{146}Xe:	$1 \cdot 10^7$
^{144}Ba:	$2 \cdot 10^{10}$
^{150}Cs:	$5 \cdot 10^5$

Driver beam power ramp-up required to achieve competitive isotope production rates

Two-step process of electron-induced RIB production

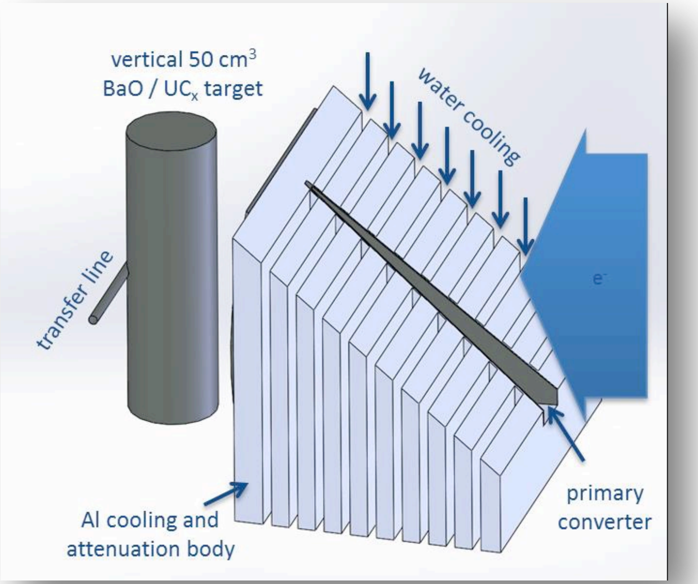
1. Conversion of electron beam into bremsstrahlung gamma rays

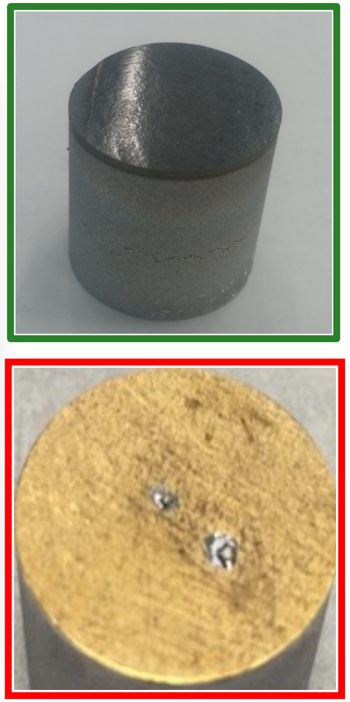
- e-γ converter stops majority of incident electrons in the range of mm
- About 30% of power is deposited in converter assembly

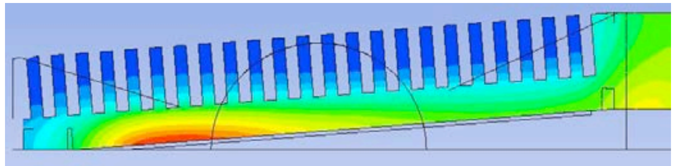


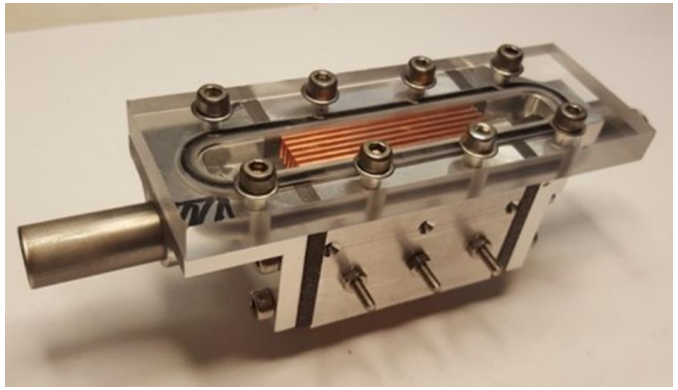
1. Conversion of electron beam into bremsstrahlung gamma rays

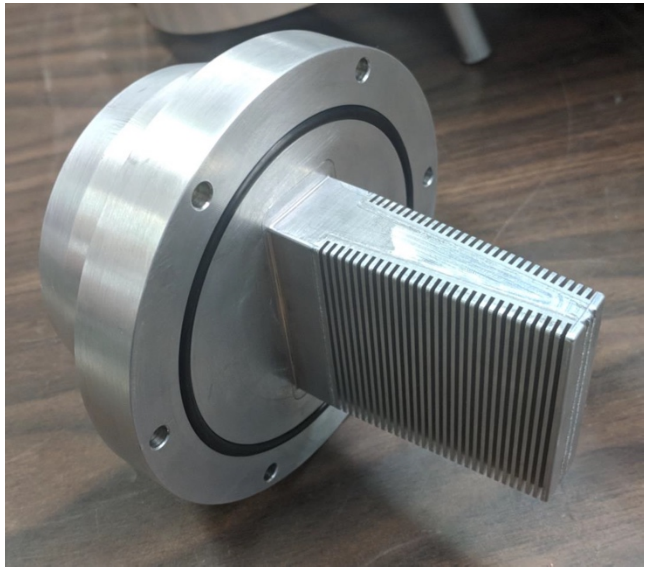
Early concept	Solving the material challenge with irradiation tests	Thermo-mechanical realization	Working prototype
2015	2017	2018	2019



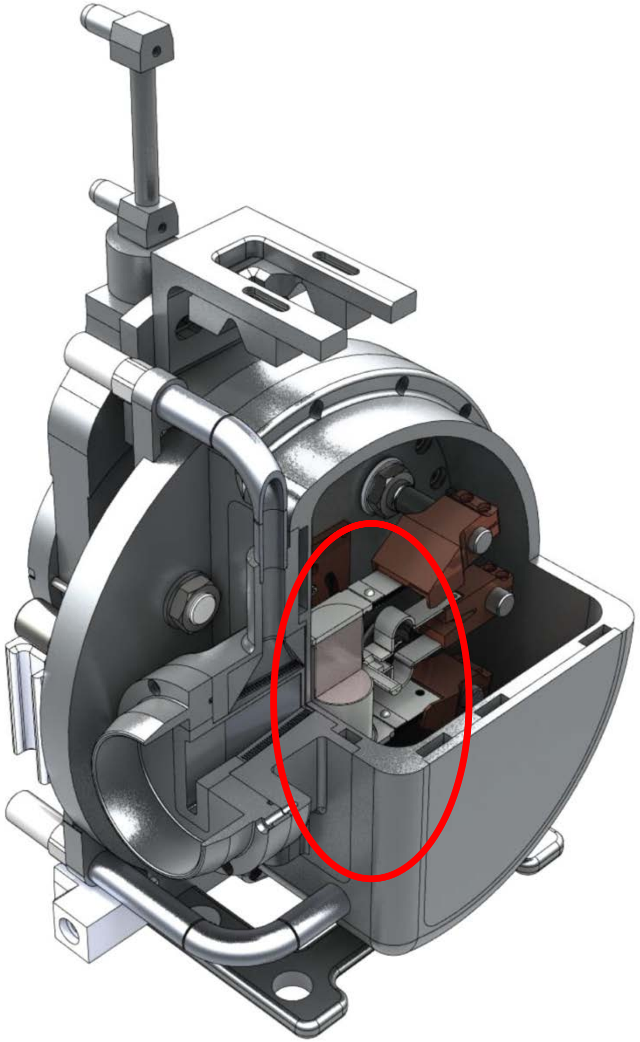






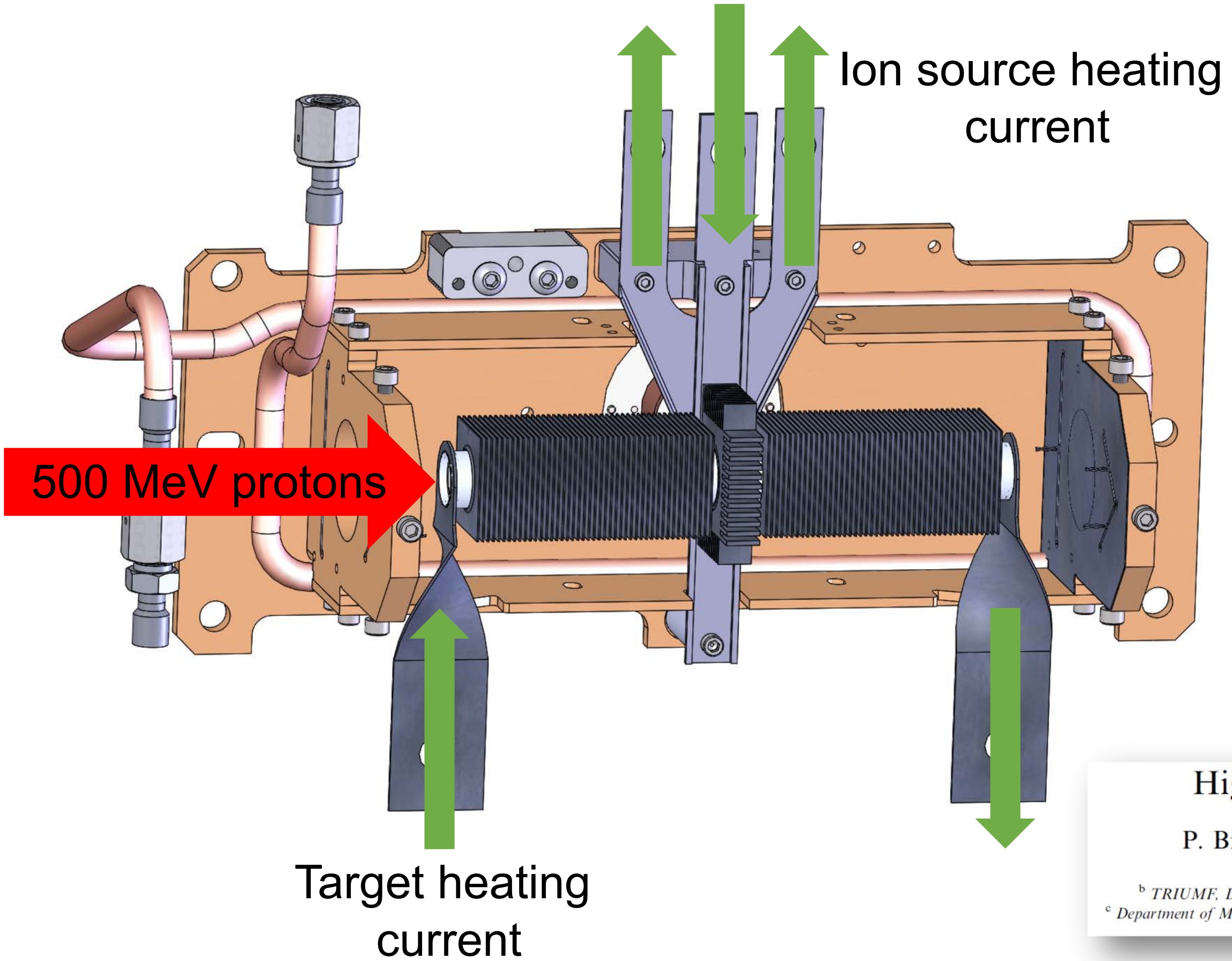


1. Conversion of electron beam into bremsstrahlung gamma rays
2. Electron-induced RI production and power removal from target container



- High-energy gammas are converted to e^{+}-e^{-} pairs causing heat generation inside the target material
- About 35% of power is deposited in target

ISAC is world leading in high-power ISOL RIB production



Accepts a 500 MeV, 50 kW proton beam

Effective emissivity ≈0.9

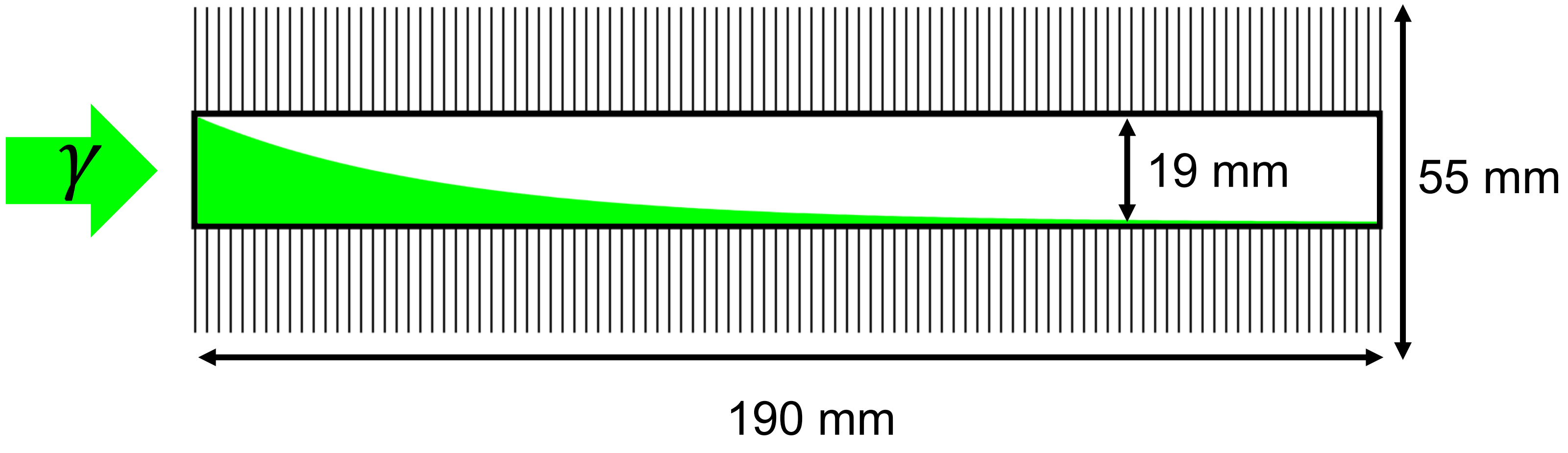
High power target developments at ISAC

P. Bricault [a,*], M. Dombsky [a], A. Dowling [b], M. Lane [c]

[a] TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, Canada V6T 2A3
[b] TRIUMF, Department of Physics & Astronomy, University of Victoria, Victoria, BC, Canada V8W 3P6
[c] Department of Metals & Materials Engineering, University of British Columbia, Vancouver, BC, Canada V6T 1Z4

ARIEL electron station target containers

ISAC style

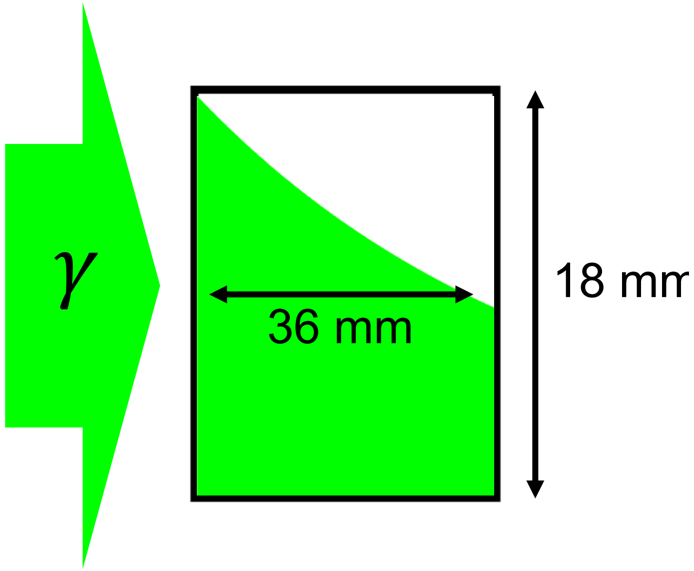


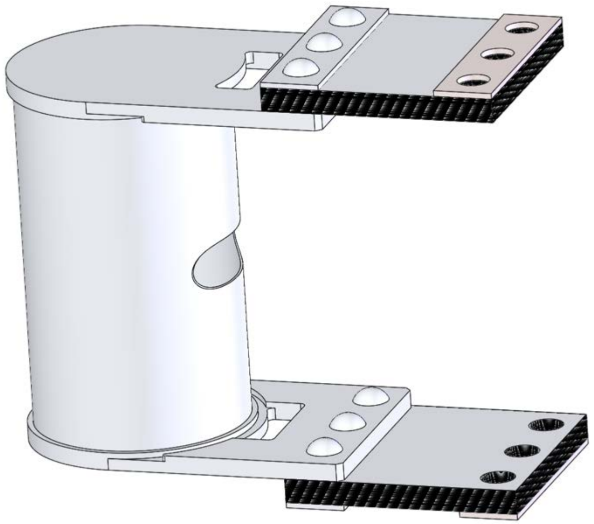
ARIEL electron station

At 100 kW, we deposit about triple the heat inside of the target as compared to ISAC

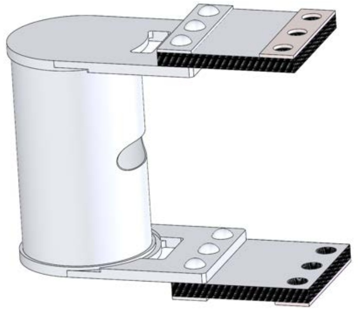
Remaining challenges:

- Heat conduction from target material into container
- Heat removal from target container





ARIEL electron station target containers

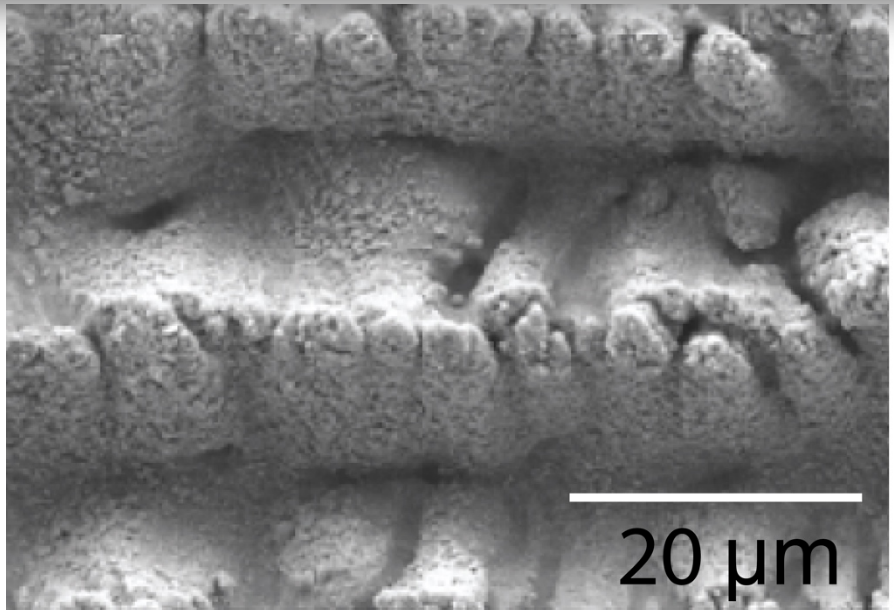


Using fins causes additional heat deposition by gammas and heating rather than cooling

Two potential solutions identified for an emissivity of ~0.9:

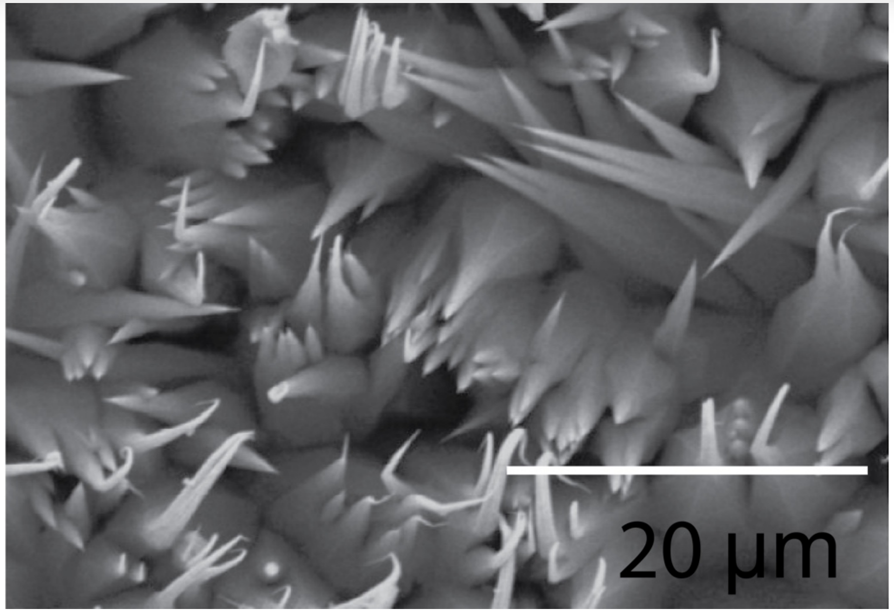
Blackening of metals using femtosecond fiber laser

Huan Huang,* Lih-Mei Yang, Shuang Bai, and Jian Liu
PolarOnyx, Inc. 2526 Qume Drive, Suite 17 & 18, San Jose, California 94538, USA



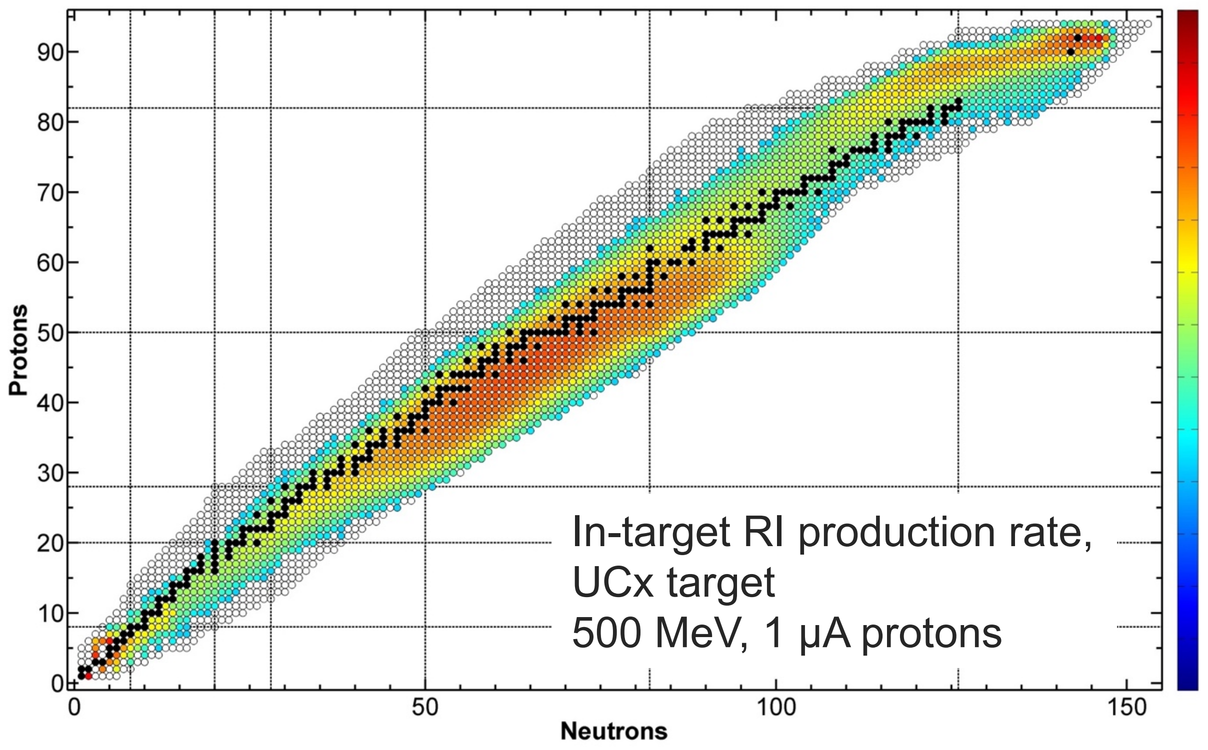
Efficiency and behavior of textured high emissivity metallic coatings at high temperature

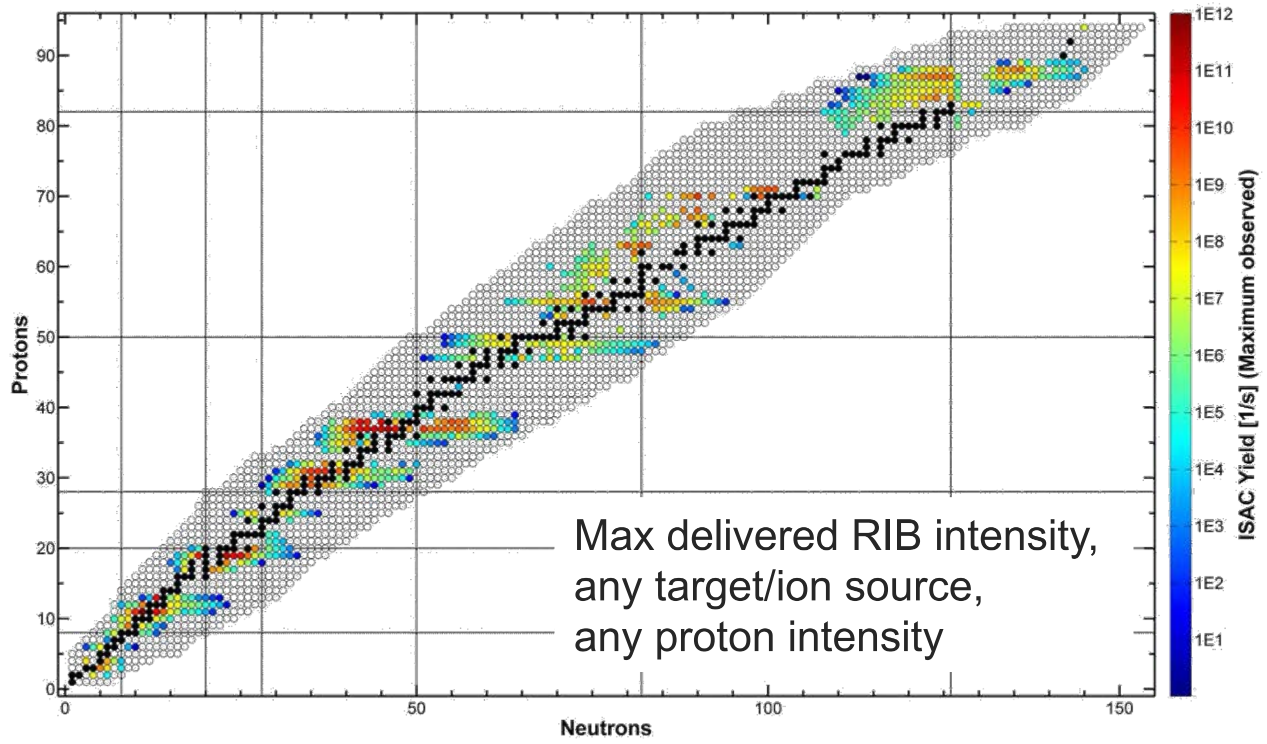
E. Brodu [a,b], M. Balat-Pichelin [a,*], J.L. Sans [a], M.D. Freeman [b], J.C. Kasper [b]
[a] *Laboratoire Procédés, Matériaux et Energie Solaire, PROMES-CNRS, 7 rue du Four Solaire, 66120 FONT-ROMEU ODEILLO, France*
[b] *Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*



Experimental Realities

Extraction times vary significantly between elements. Driven by volatility and in-target chemistry.





RIB Intensity

$$I_{\mathrm{RIB}} = \varepsilon \cdot I_{prod} = \varepsilon \cdot \int_{\mathrm{target}} \sigma(E)\, N_{\mathrm{target}}(l)\, I_{\mathrm{primary}}(l)\, dl$$

I_{RIB} - rare ion beam intensity [s^{-2}]
ε - overall efficiency
I_{prod} - pruduction rate of a reaction product[s^{-2}]
σ - reaction cross−section [barn = 10^{-24} cm^2]
N_{target} - target atoms per exposed area [cm^{-2}]
$I_{primary}$ - primary beam intensity

$$\varepsilon = \underbrace{\varepsilon_{\mathrm{release}} \cdot \varepsilon_{\mathrm{ionization}}}_{\text{typically } 10^{-3} \text{ to } 10^{-8} \text{ !!!}} \cdot \underbrace{\varepsilon_{\mathrm{transport}} \cdot \varepsilon_{\mathrm{cool-bunch}} \cdot \varepsilon_{\mathrm{breeding}} \cdot \varepsilon_{\mathrm{post-accel}}}_{\text{typically } 5\% \text{ to } 90\%}$$

Almost every beam that can be produced can be developed for RIB through PhD-type projects.

Required: Close exchange with user community (proposals and LOIs but also frequent consultation and direct communication)

Desired: Joint projects between RIB target group and user groups for targeted RIB production development

RIB Target and Ion Source Development Vision:

- Continuously maintain target and ion source development projects
- Foster already strong user engagement in development projects
- Fully capitalize vast additional development capabilities at ARIEL
  (increased beam time, target, ion source transfer line and operational flexibility)

ISAC Laser Applications

Resonant laser ionization is most versatile system for RIB delivery.

- 37 elements routinely laser ionized
- New ionization schemes every year
- Operation > 2000 h per year

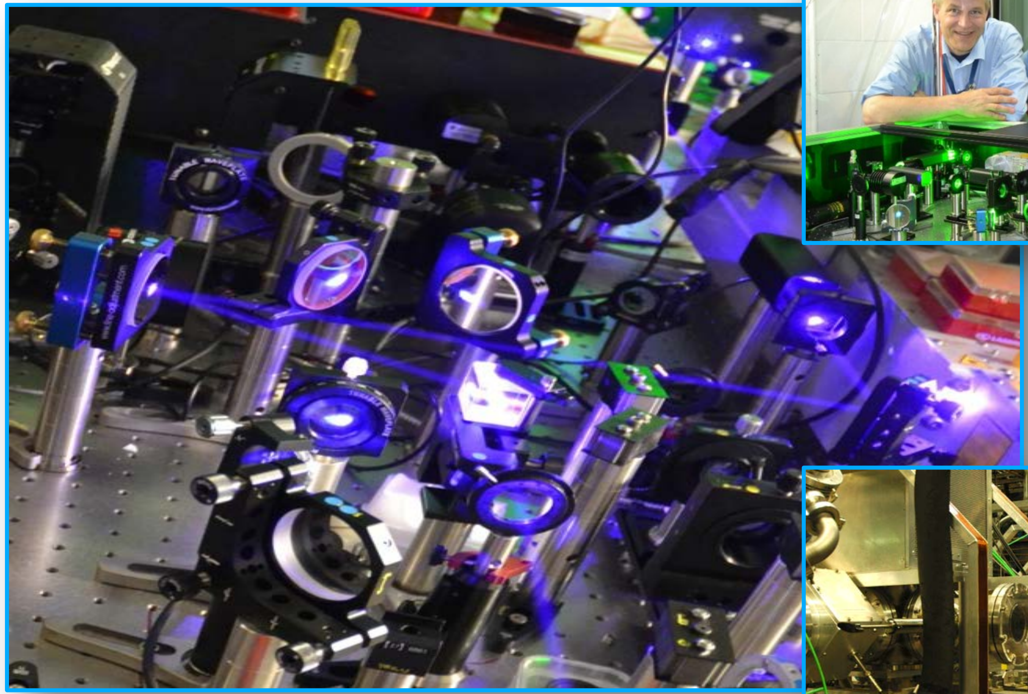
Operation of the only routine delivery of spin-polarized radioisotope beams world-wide.

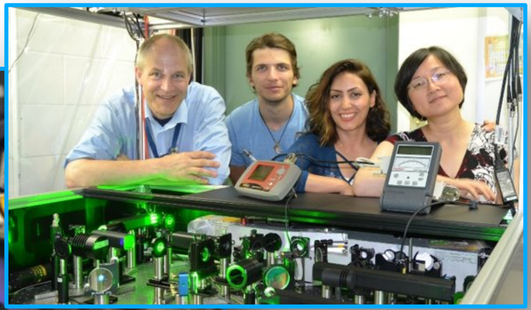
- β-NMR, collinear laser spectroscopy
- New polarization schemes every year
- Supporting POLARIS realiziation

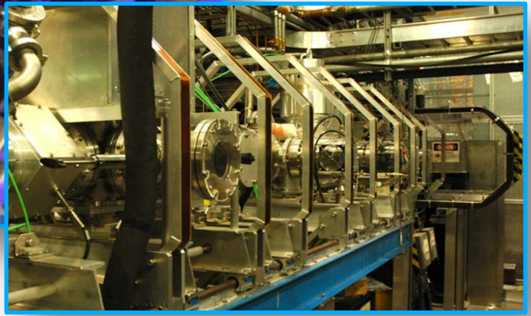
ARIEL/ISAC: 70% RILIS ionization of 3 beams

Requirements

- Faster laser frequency changes
- Faster laser beam transport setup
- Maintain reliability







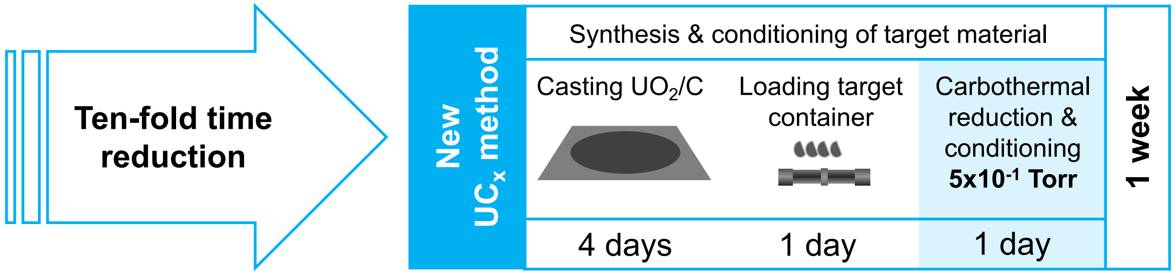
Laser applications vision

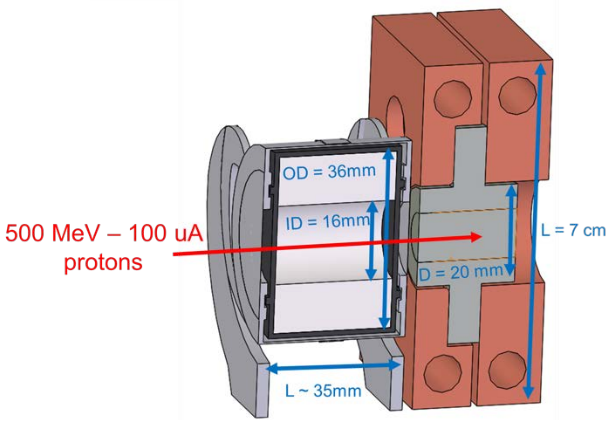
- Strengthen TRIUMF's dominance in RIB laser applications
- Improved operational efficiency
- Increased development capabilities
- Maintain strong international student program

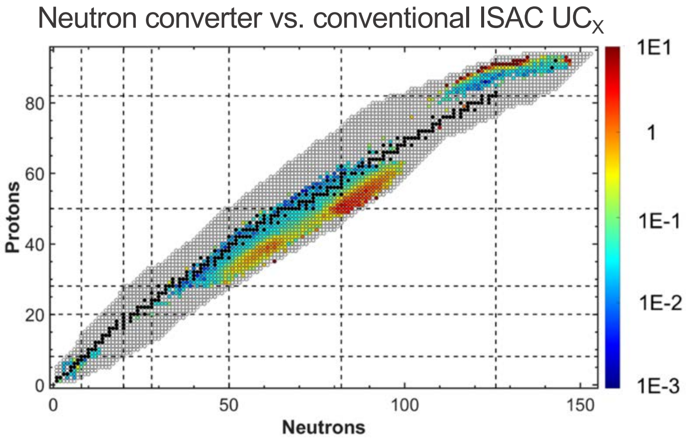
Example TIS Student Projects

all projects are aligned with service mission and international accelerator research interest

Ph.D. Luca Egoriti (UBC)
High-power electron-to-gamma and proton-to-neutron converters for intense and pure RIB
L. Egoriti, et al., Proc. 9th Int. Particle Accelerator Conf., 3917-3920 (2018)





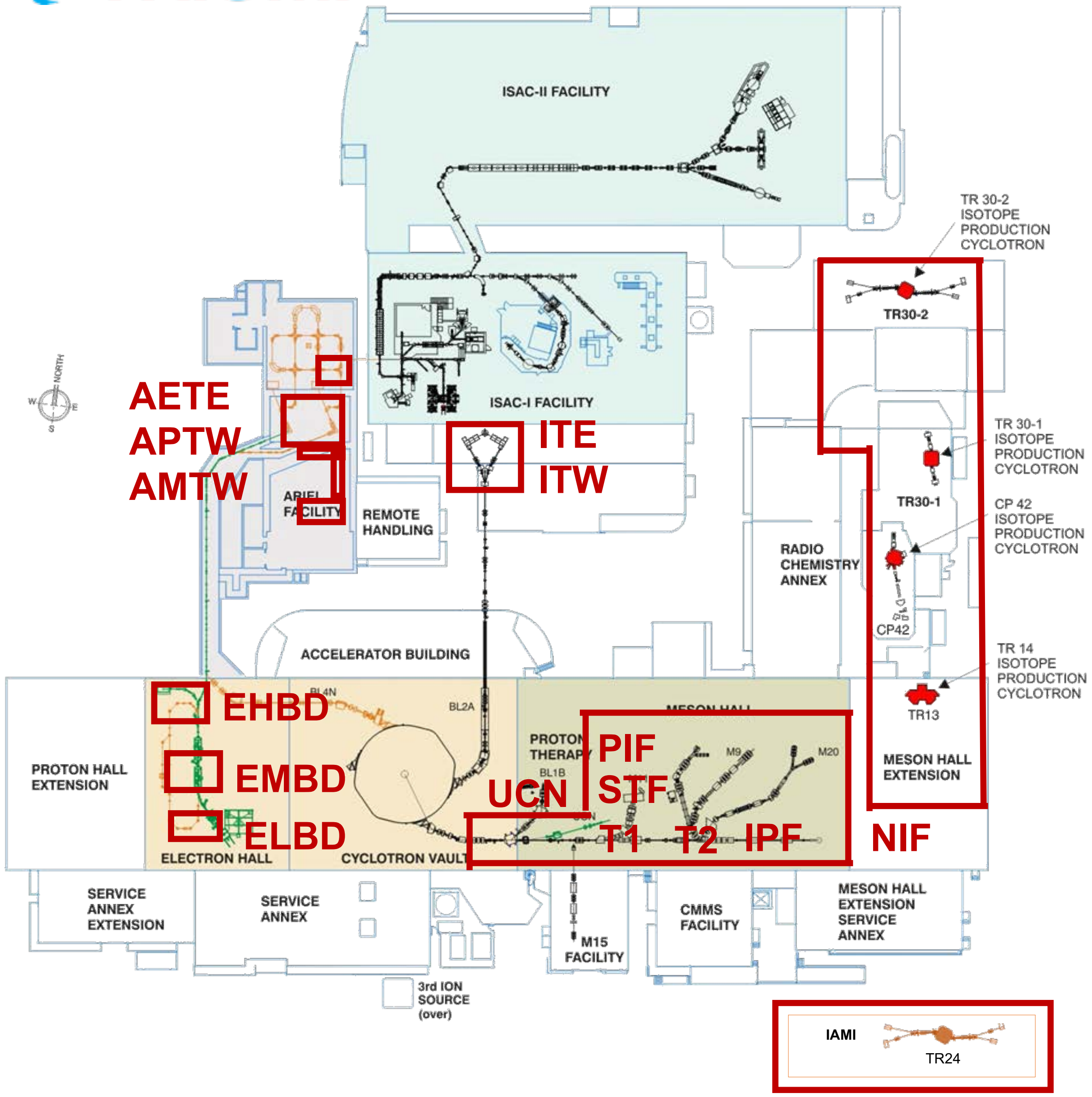


Ph.D. Marla Cervantes (UVic)
Novel Actinide Target Materials for the Production Short-Lived RI
M. S. Cervantes, et al., Proc. 9th Int. Particle Accelerator Conf., 4990-4991 (2018)

Highly Qualified Personnel (HQP) vision:

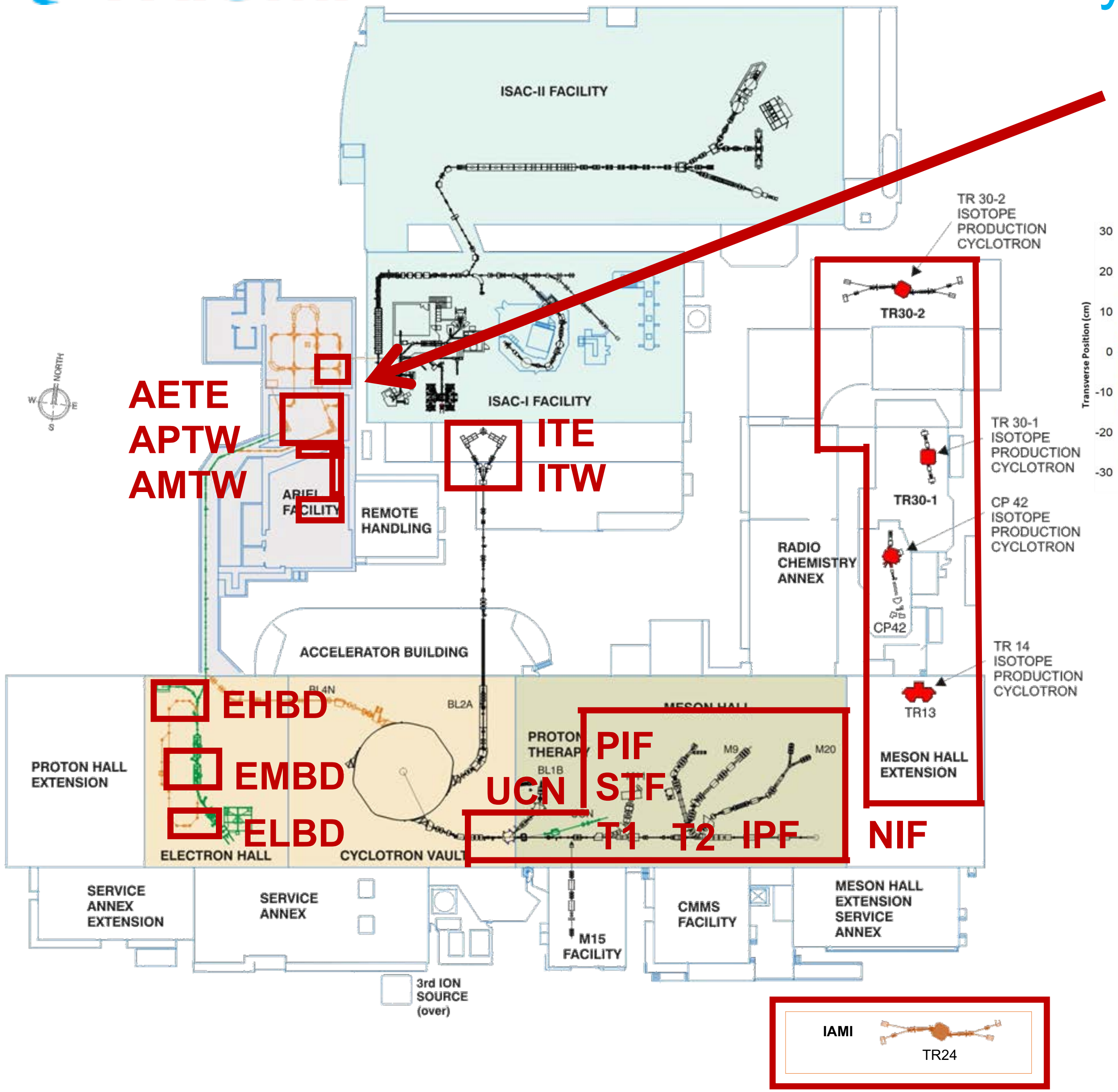
- Maintain student projects with Canadian Universities
- Strengthen international partnerships to the benefit of TRIUMF and accelerator science in Canada
- Maintain wide spectrum of professional development opportunities
- Retain HQP

But there are many more target applications at TRIUMF…

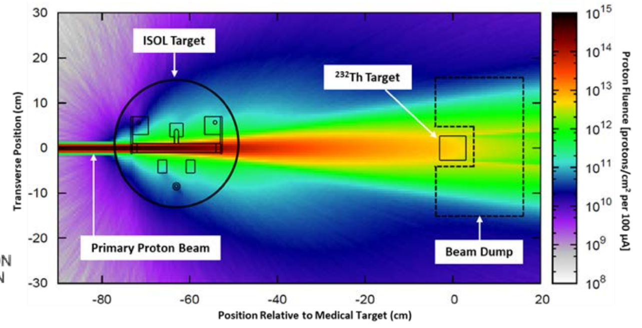


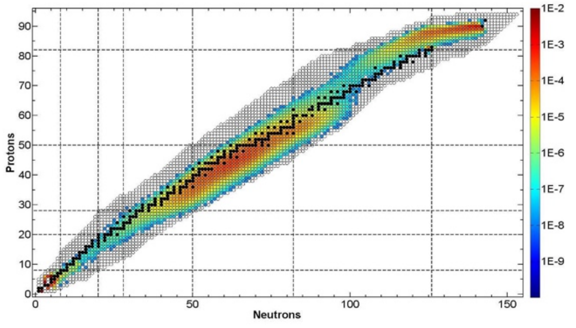
Discovery, accelerated

But there are many more target applications at TRIUMF…

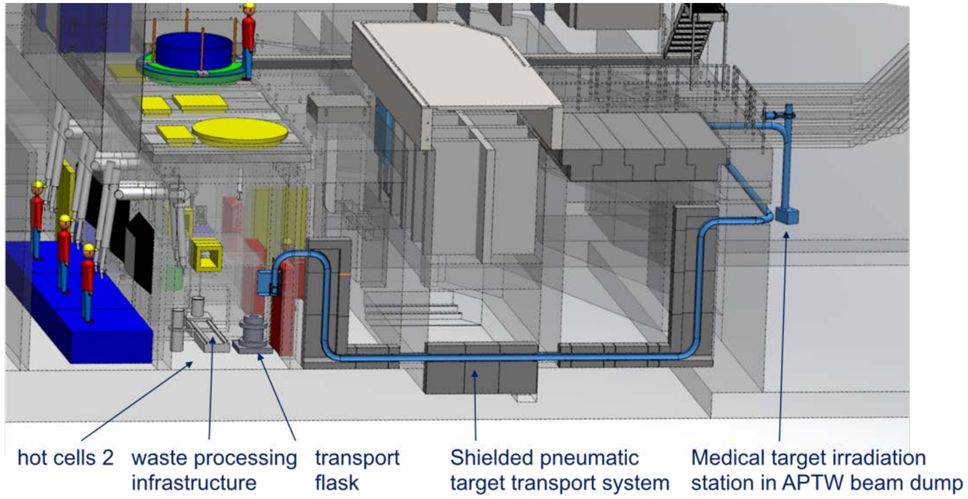


Example 1:
The use of the ARIEL proton station waste beam for rare medical isotope production





Hundreds of co-produced isotopes including;
^{225}Ra, **^{225}Ac**, ^{224}Ra, ^{223}Ra, ^{213}Bi, ^{212}Pb, ^{212}Bi



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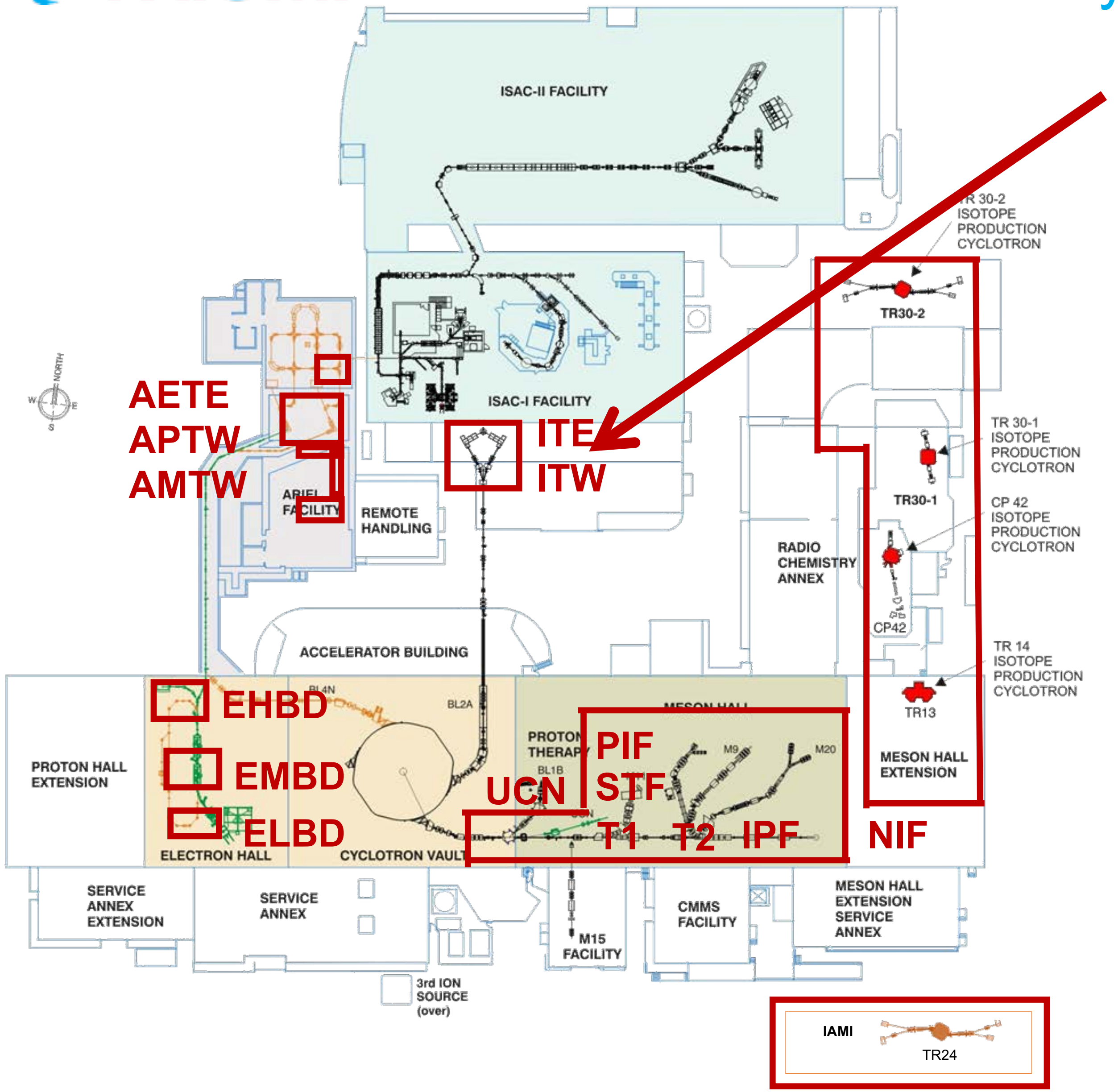
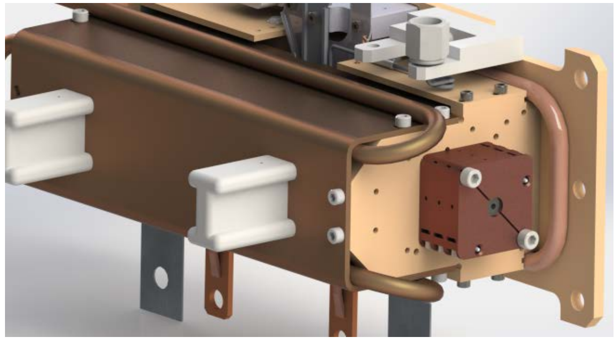
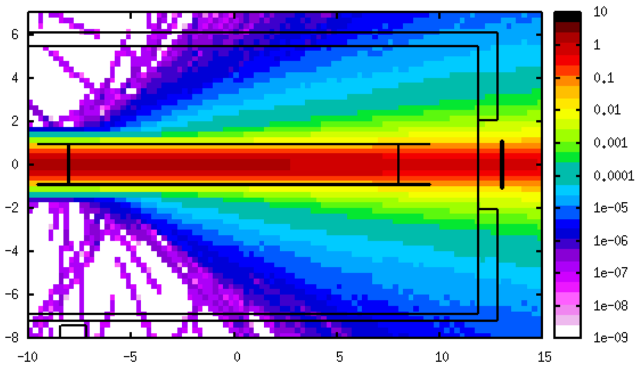
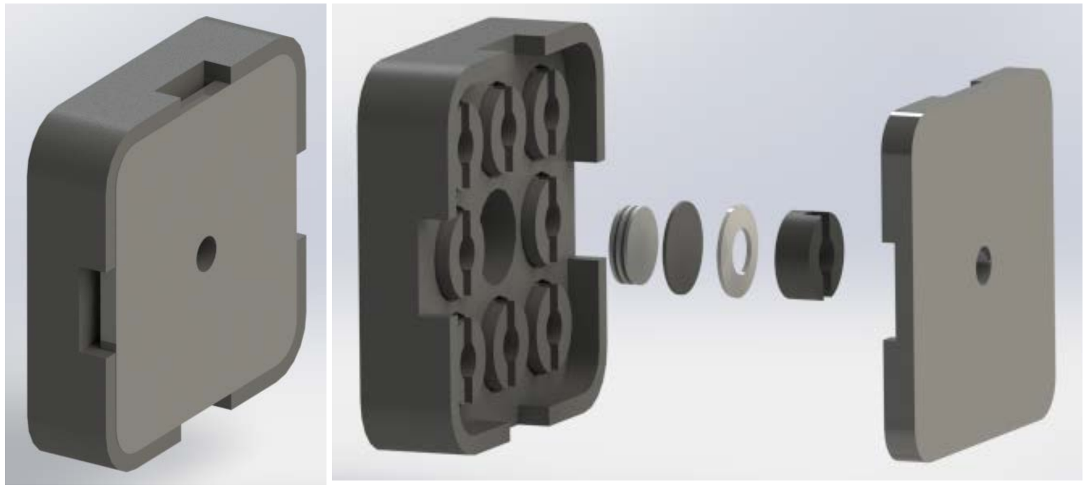


Example 2:

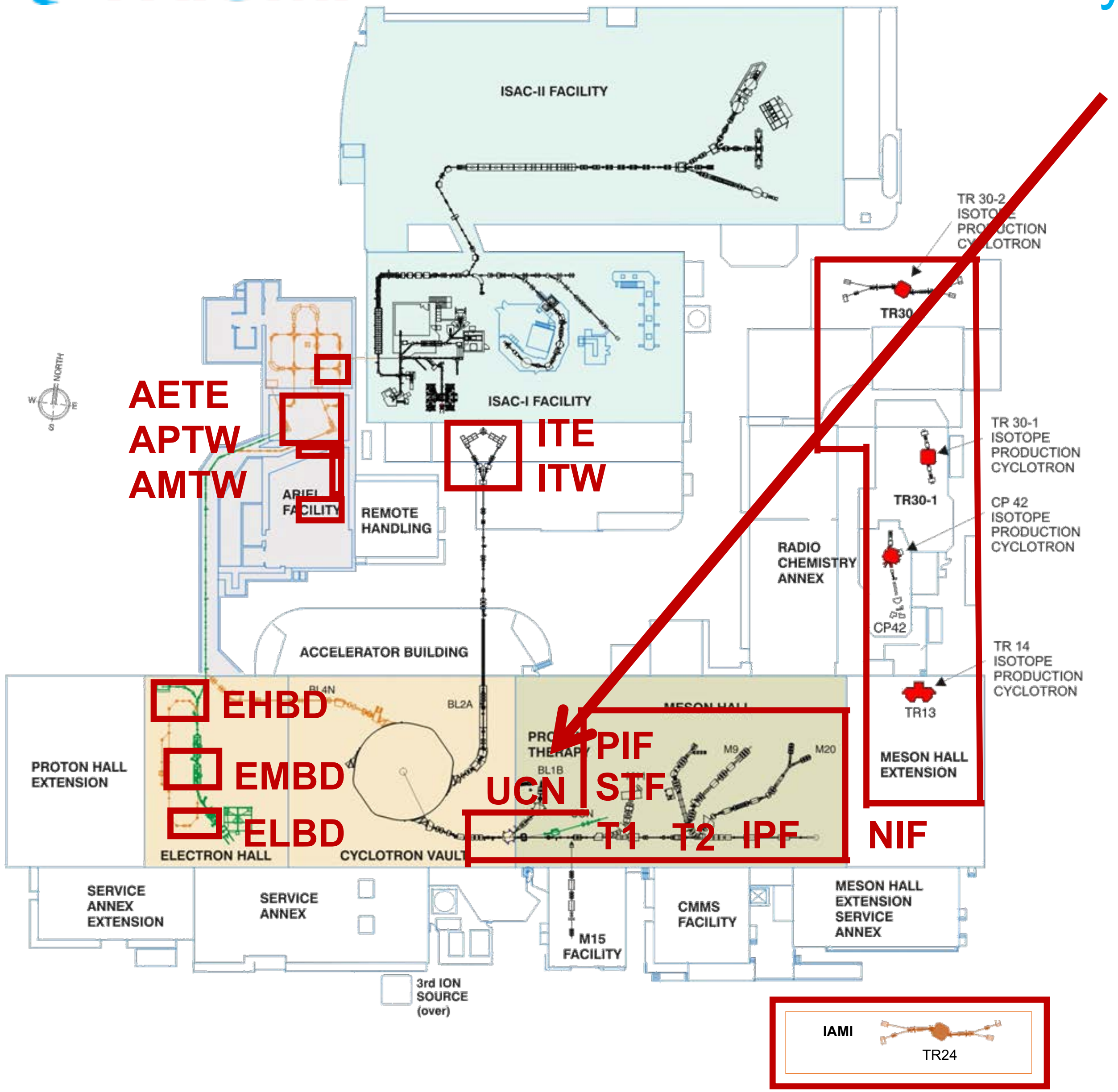
The use of the ISAC waste beam for studies of radiation damage in materials or isotope harvesting



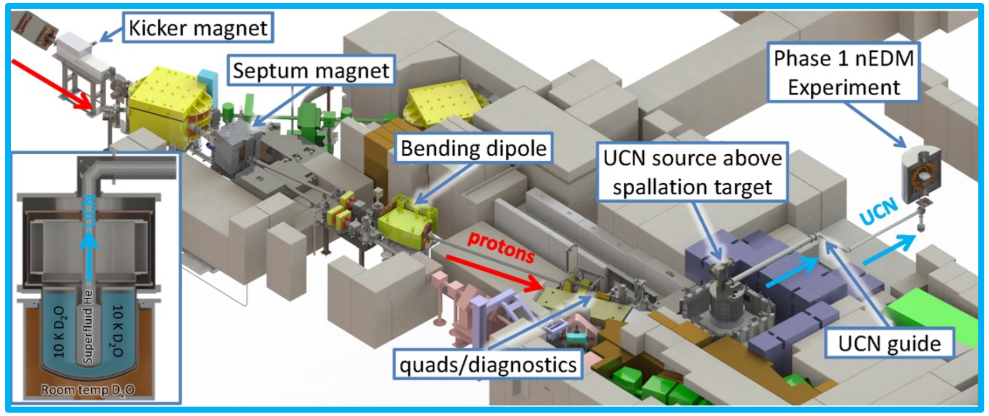


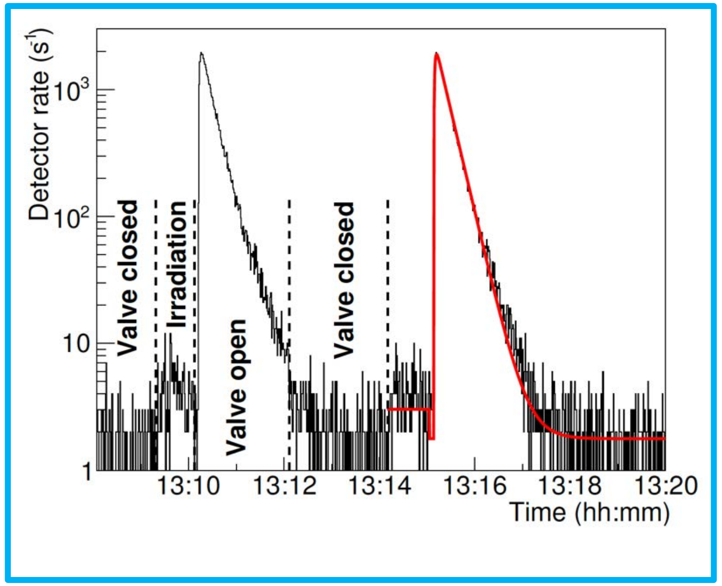


But there are many more target applications at TRIUMF…



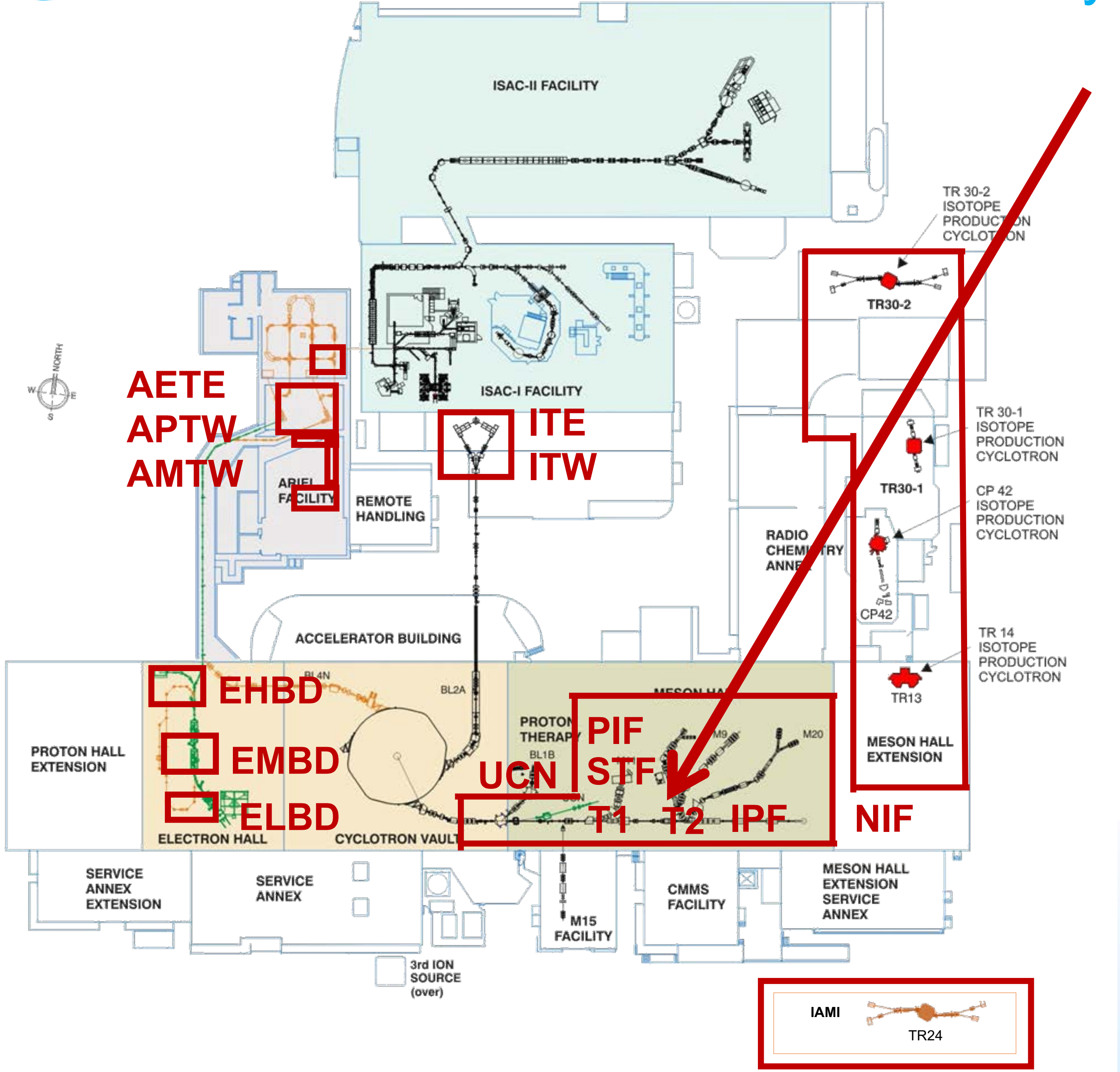
Example 3:
Spallation target for ultra cold neutron production



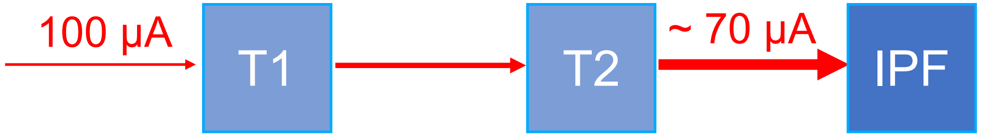


Discovery, accelerated

But there are many more target applications at TRIUMF…



Example 4:
Muons from T1 and T2



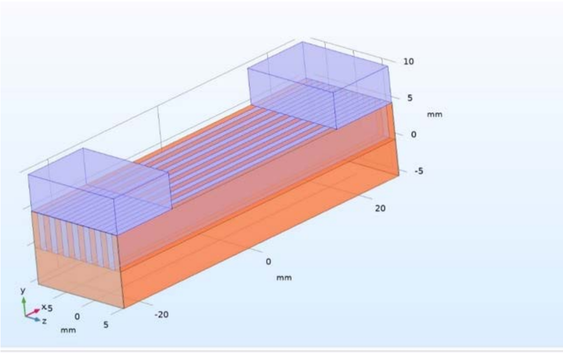
Proposal:

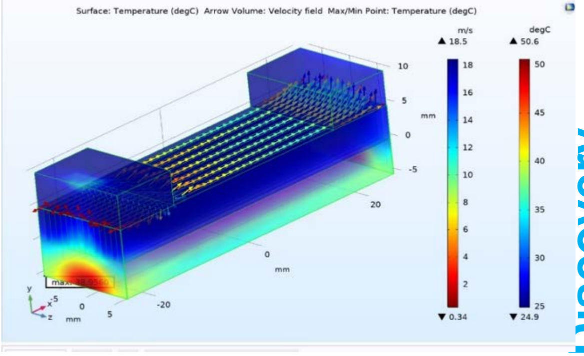
Replace 5 cm Be with 3.5 cm CVD diamond

➔ Enhanced cooling performance

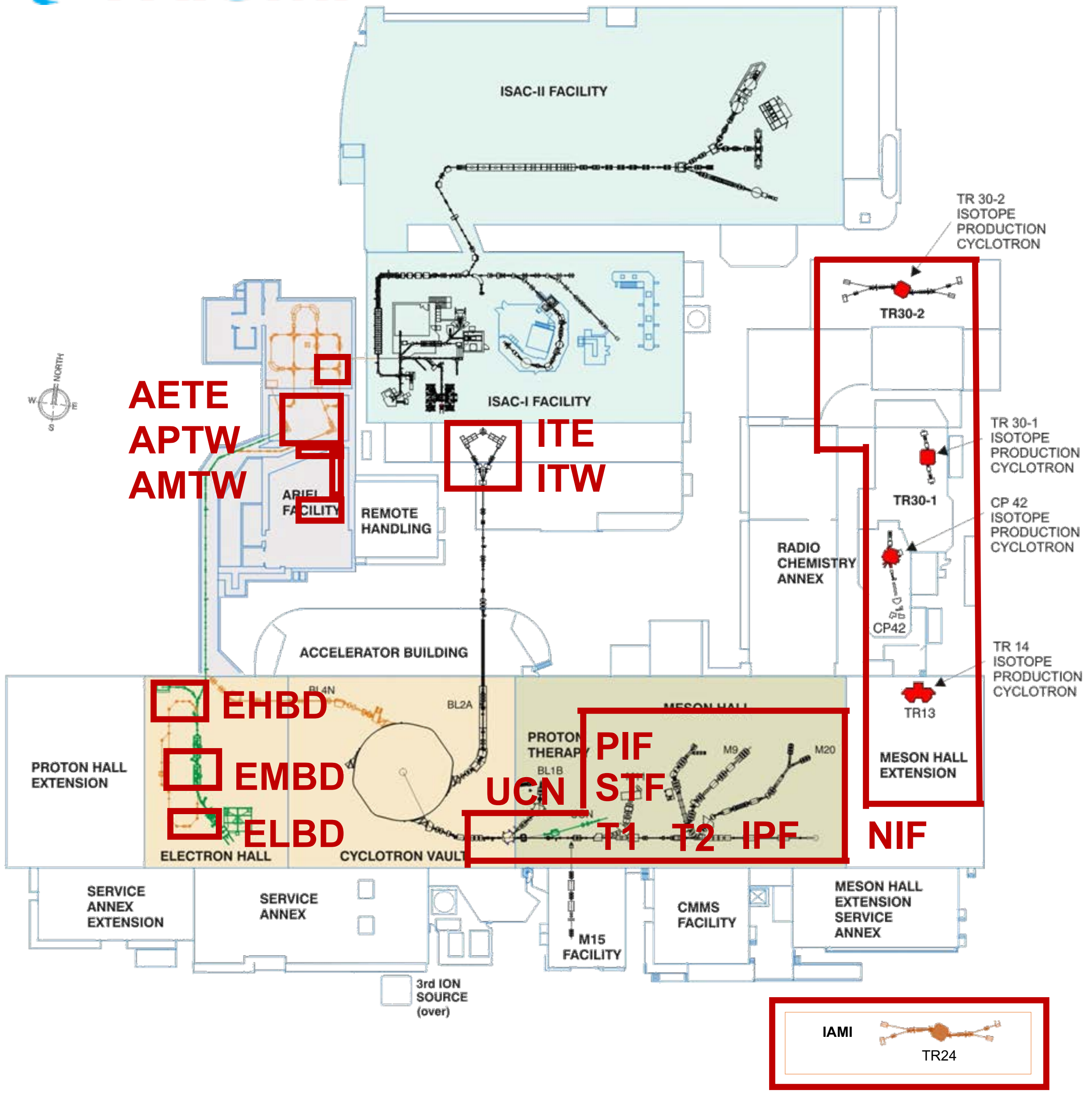
➔ Enhanced muon production

(see presentation by S. Kreitzman)





But there are many more target applications at TRIUMF…



And many many more…

- Twin (gallium + rubdium) target at STF
- Gas and liquid targets at TR13, TR30-1, TR30-2, CP42
- IAMI and ARTMS targets
- Isotope harvesting from expired targets and beam dumps
- Beam dump technology at ISAC, ARIEL, NIF
- …

Vision for distributed target technology expertise

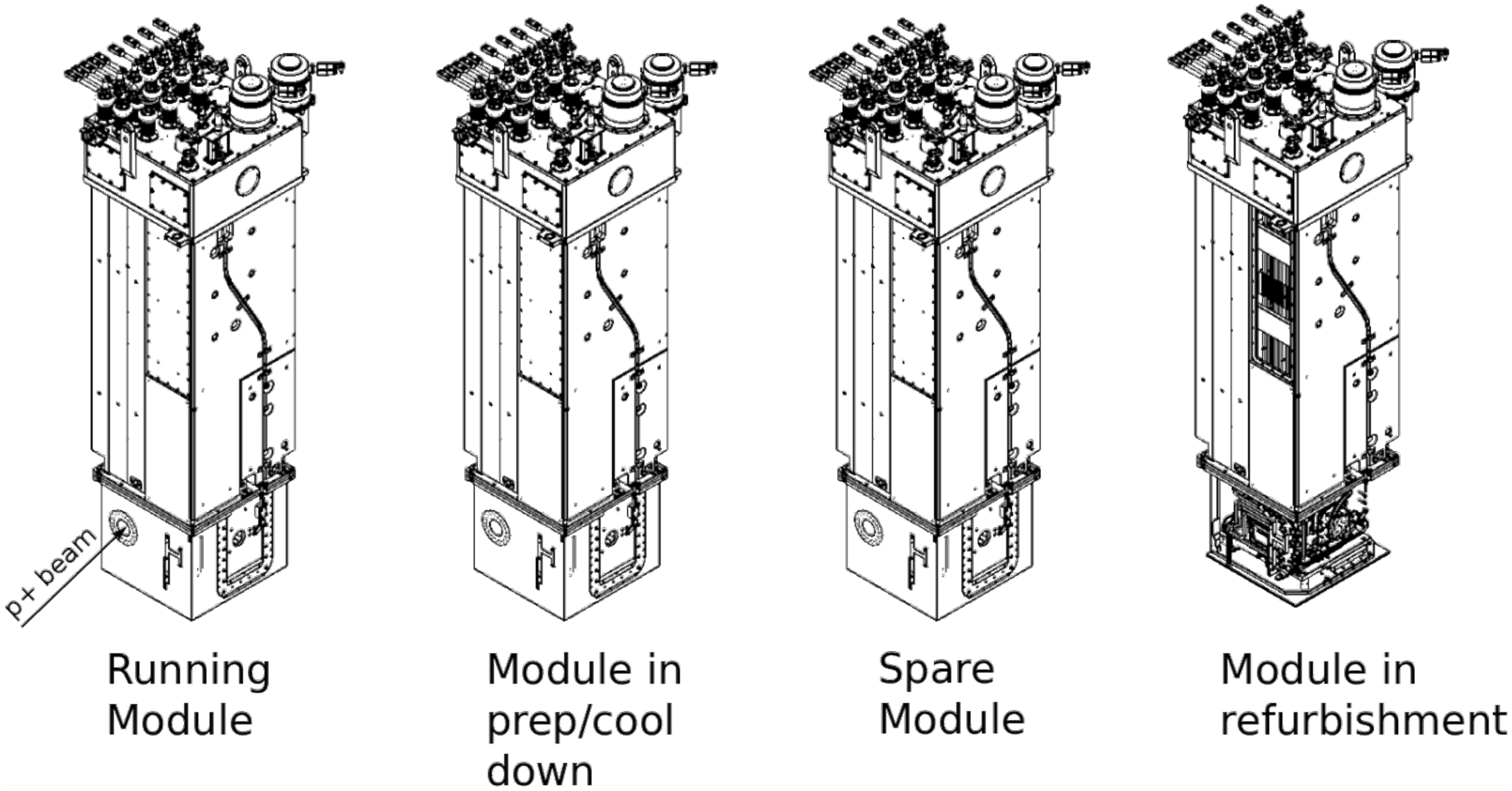
- Continue and intensify internal collaborations
- Establish platforms for sharing and developing ideas
  (i.e. target technology seminars, consultation in design reviews, common projects)
- Optimize development capabilities
- Share resources, tools, expertise

TRIUMF

Thank you!
Merci!

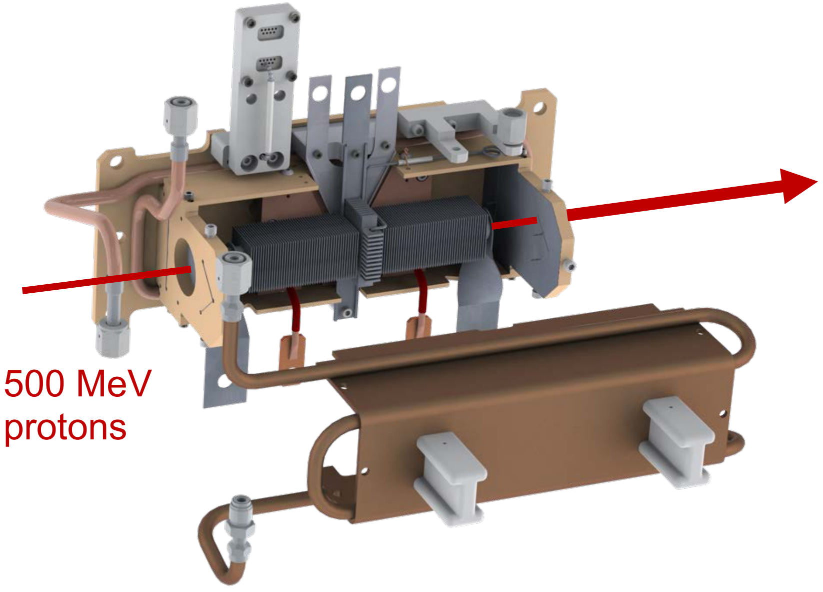
Ultimate Target Module Vision

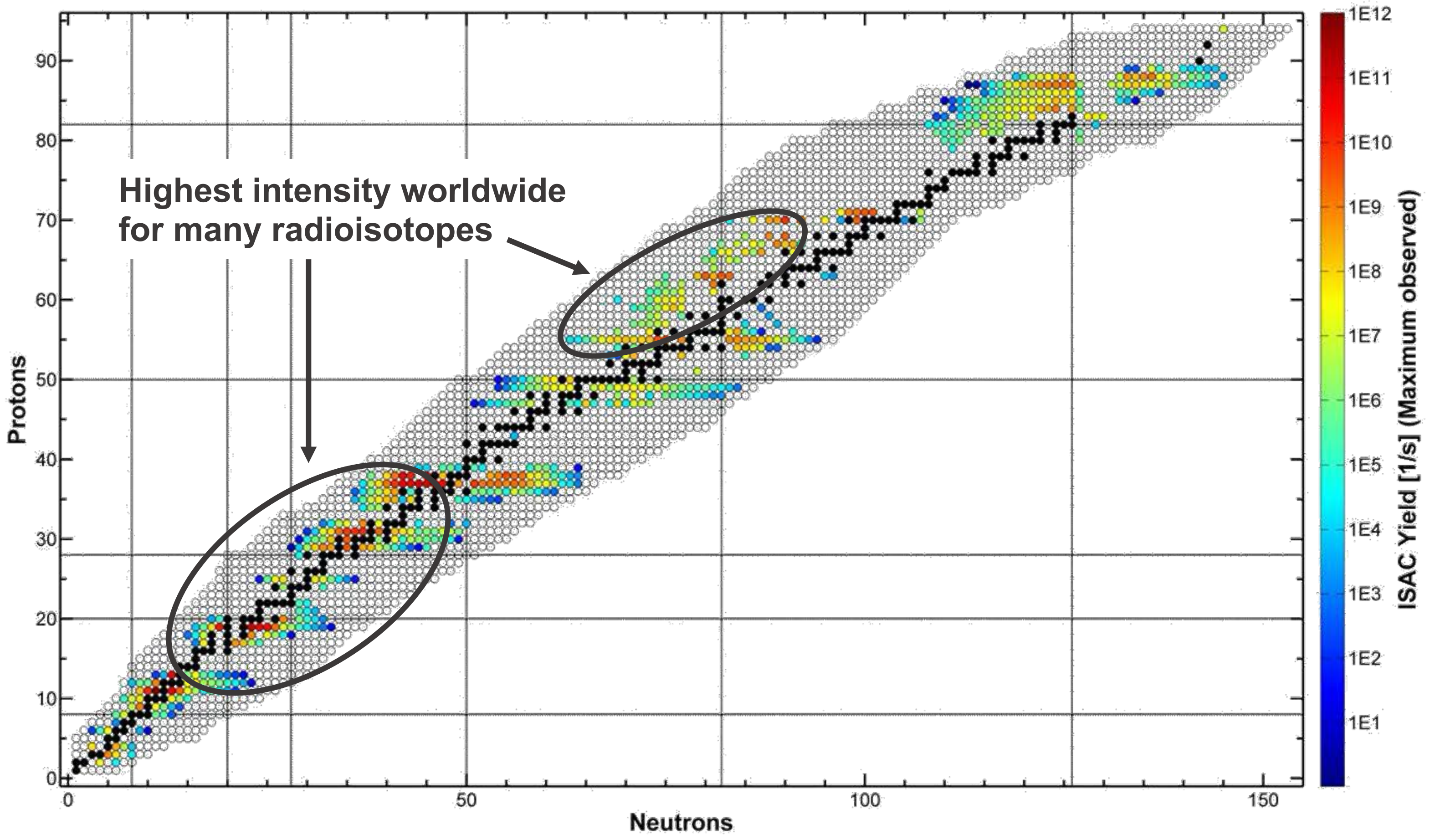
Four operating target modules required for reliable and sustainable operation of two ISAC target stations.



Constant upgrades and two-module operation with a spare module in reserve for emergencies

ISAC Radioisotope Beams Since 1998





Target materials:
- UC_x
- UO_2
- ThO
- Nb
- Ta
- TaC
- NiO
- ZrC
- TiC
- SiC

Variable beam power

Variable transfer lines

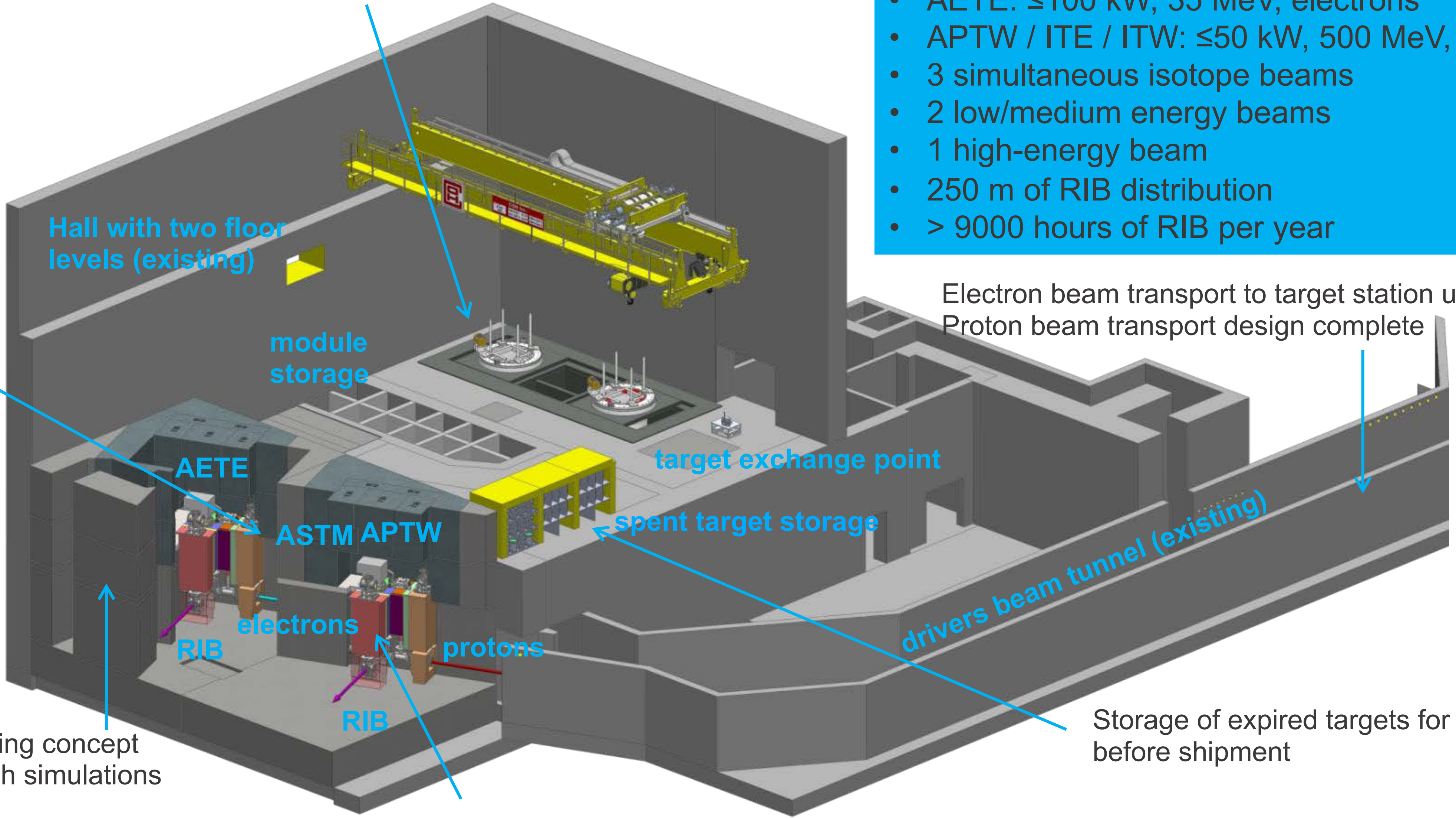
Ion sources:
- surface
- resonant laser
- FEBIAD
- IG-LIS

Targets and ion sources vision:
- **Improved ISAC target system reliability**
- **Increased operational efficiency**

ARIEL Target Systems

- AETE: ≤100 kW, 35 MeV, electrons
- APTW / ITE / ITW: ≤50 kW, 500 MeV, protons
- 3 simultaneous isotope beams
- 2 low/medium energy beams
- 1 high-energy beam
- 250 m of RIB distribution
- > 9000 hours of RIB per year

Hot cell facilities
- contract awarded for 2/3 hot cells,
- funding approved for remaining cell



Symbiotic medical target in APTW beam dump

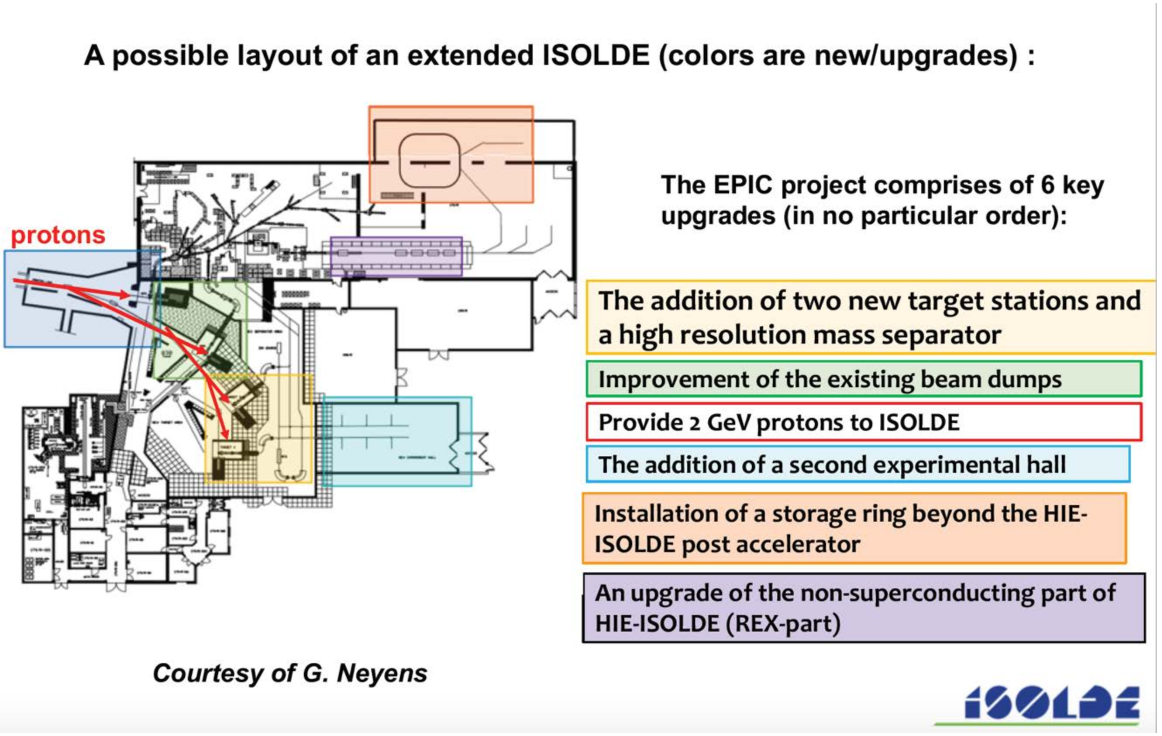
Electron beam transport to target station under construction
Proton beam transport design complete

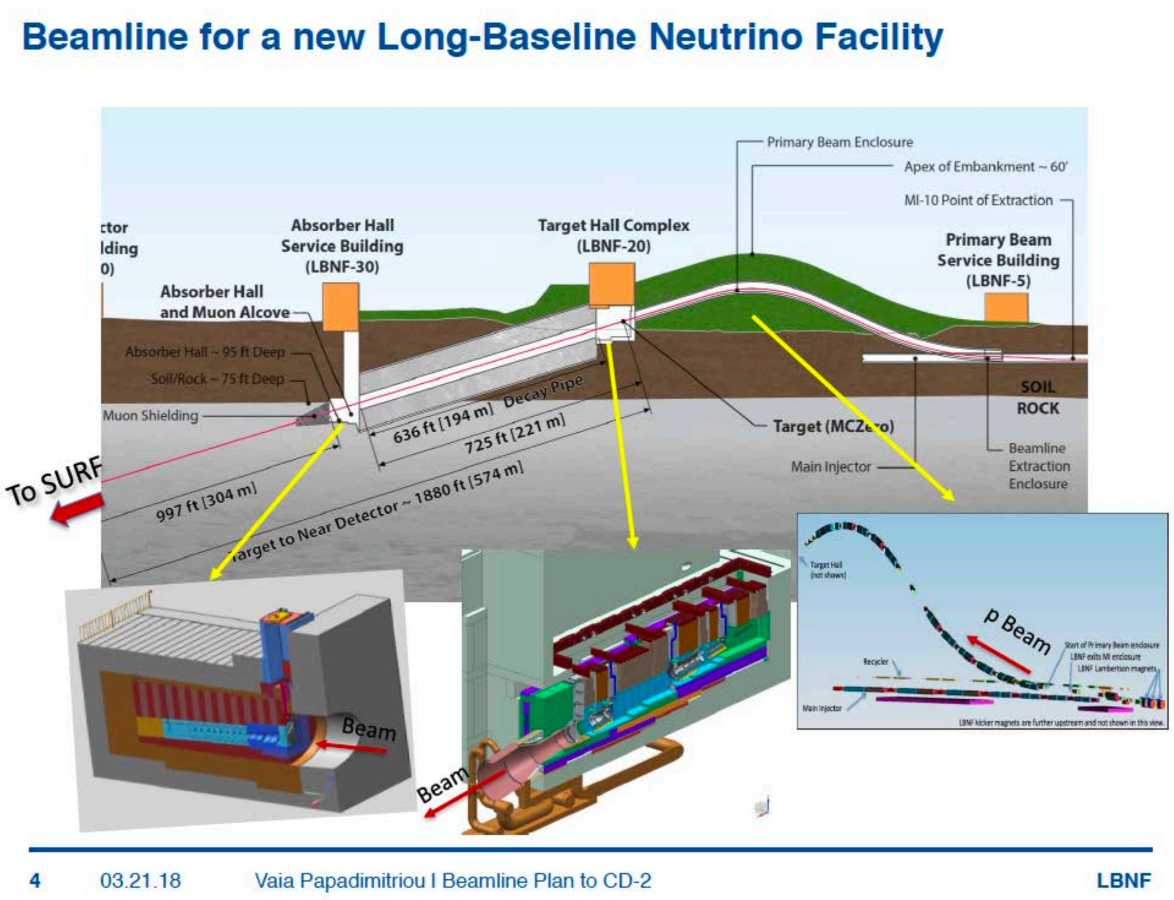
Target pit shielding concept validated through simulations

Storage of expired targets for 3 years before shipment

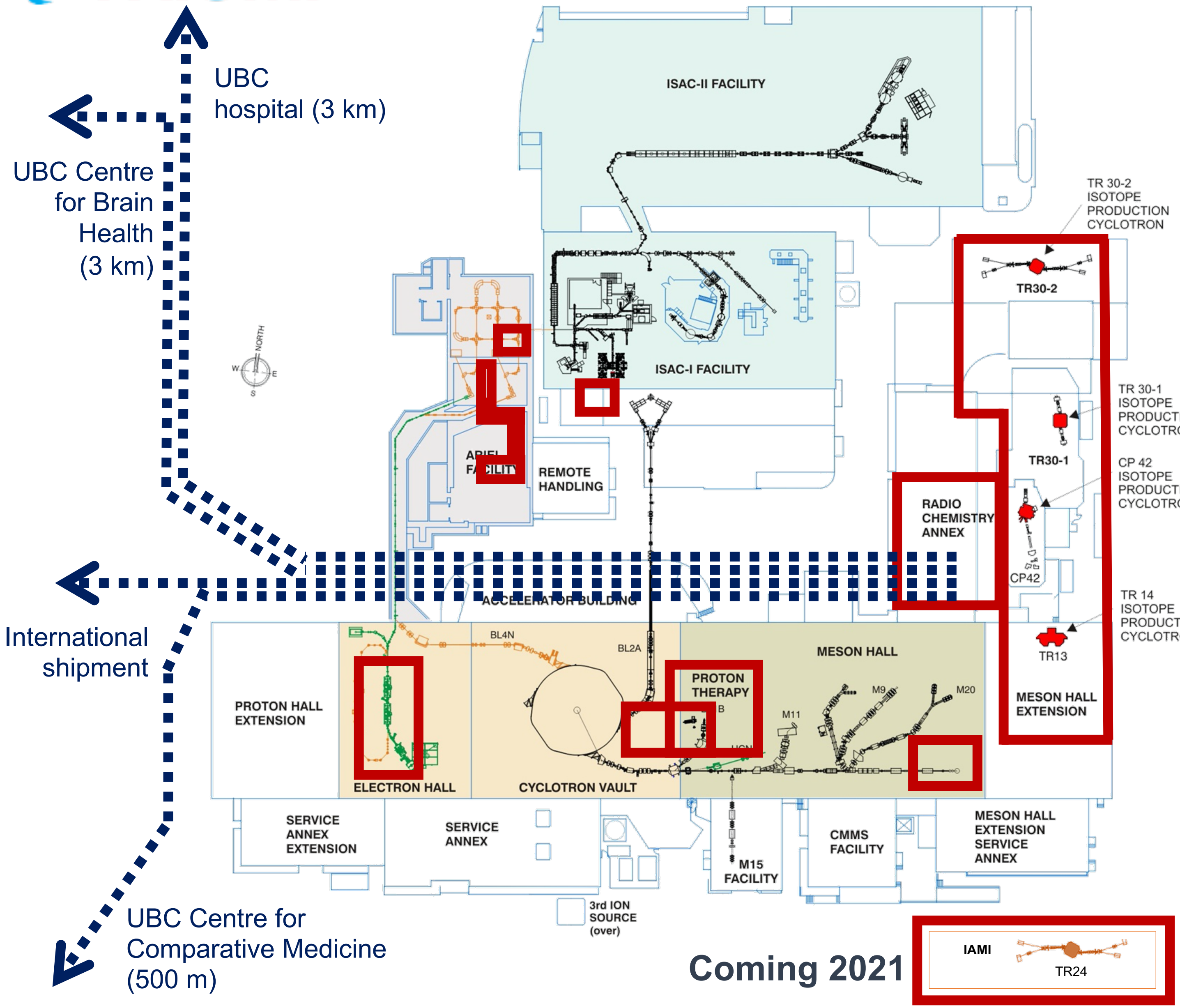
All beam-critical components with life-time < 30 years are modular and serviceable in hot cell facility

Collaborations as a platform for new facility development





TRIUMF's Medical Isotope Factory



Five H⁻ medical cyclotrons

- TR30-1, TR30-2, CP42, 250 μA – 1 mA (solid, liquid and gas targets)
  - Operated by ATG for BWXT
  - 2M doses annually
  - ^{103}Pd, ^{111}In, ^{123}I, others…
- TR13, >1 mA (solid, liquid and gas targets)
  - ^{11}C, ^{18}F, ^{44}Sc, ^{64}Cu, others…
- TR24, 5 mA (gas, solid, liquid targets)
  - Future for IAMI

Protons from 90-500 MeV, 300 μA cyclotron

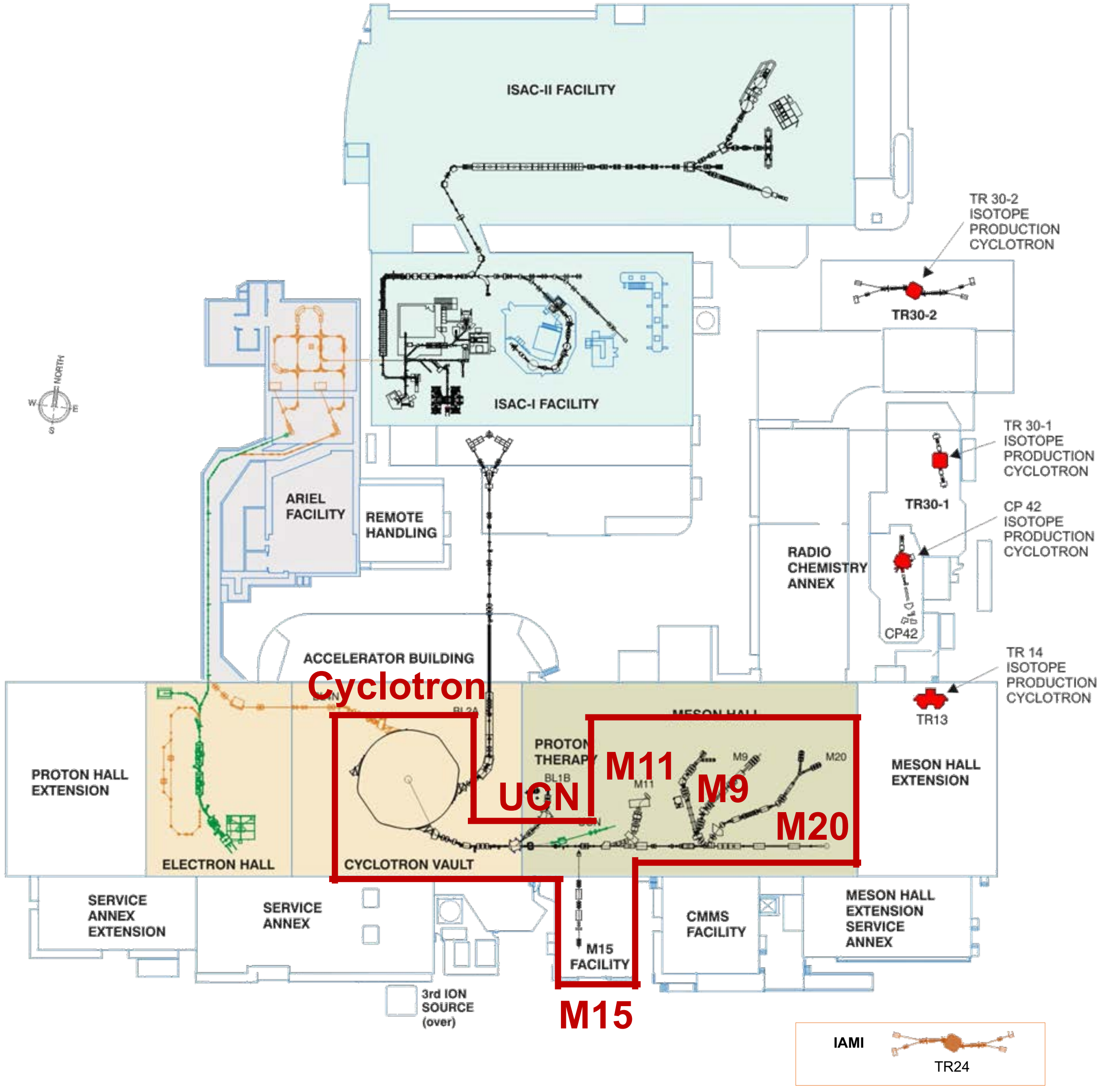
- ^{82}Sr / ^{82}Rb production
- ^{111}Ag, ^{212}Pb, ^{225}Ac production
- Exotic medical isotope R&D, fission and spallation with optional isotope separation

Electrons from 35 MeV, 10 mA linac

- Preclinical combined FLASH and microbeam radiotherapy

TRIUMF

TRIUMF's Proton, Neutron, Pion, Muon Programs



Beamline 1

- Four secondary channels from two production targets
  - Pions, muons for material and fundamental science
- UCN (Ultra Cold Neutrons) for nEDM measurement

Challenges

- High power targets,
- High intensity beam delivery
- Remote Handling service