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ARIEL Status

Multiplying TRIUMF's Radioisotope Science

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ARIEL Program Leader
Department Head, Targets and Ion Sources

TRIUMF Science Week
August 03, 2023

science week/23
Jul 31 - Aug 4

Discovery, accelerated

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Why Radioisotope Beams?

Discovery, accelerated

Periodic Table of the Elements

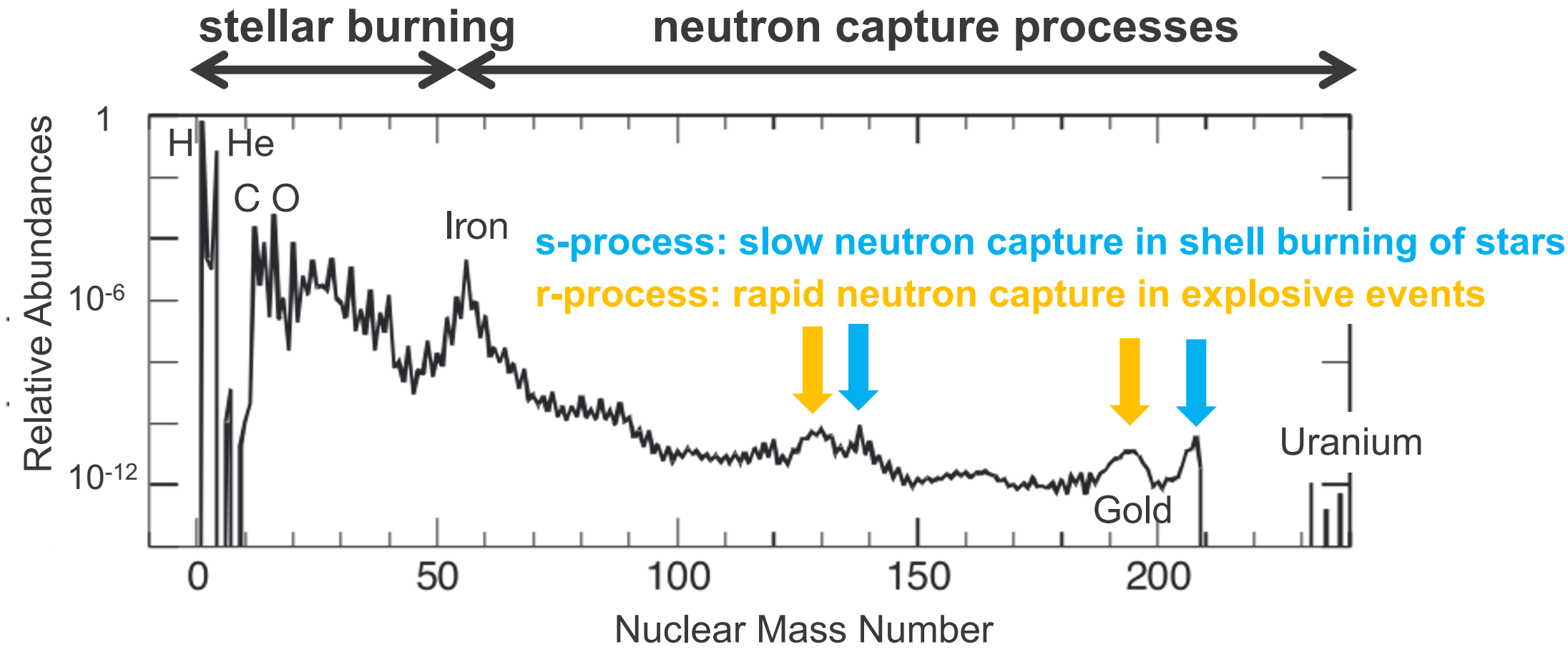
1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Atomic Number
Symbol
Name
Atomic Mass

Lanthanide Series	57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Alkali Metal | Alkaline Earth | Transition Metal | Basic Metal | Semimetal | Nonmetal | Halogen | Noble Gas | Lanthanide | Actinide

How are the elements made that make up our world?



Isotope Production Simulation in Neutron Star Merger

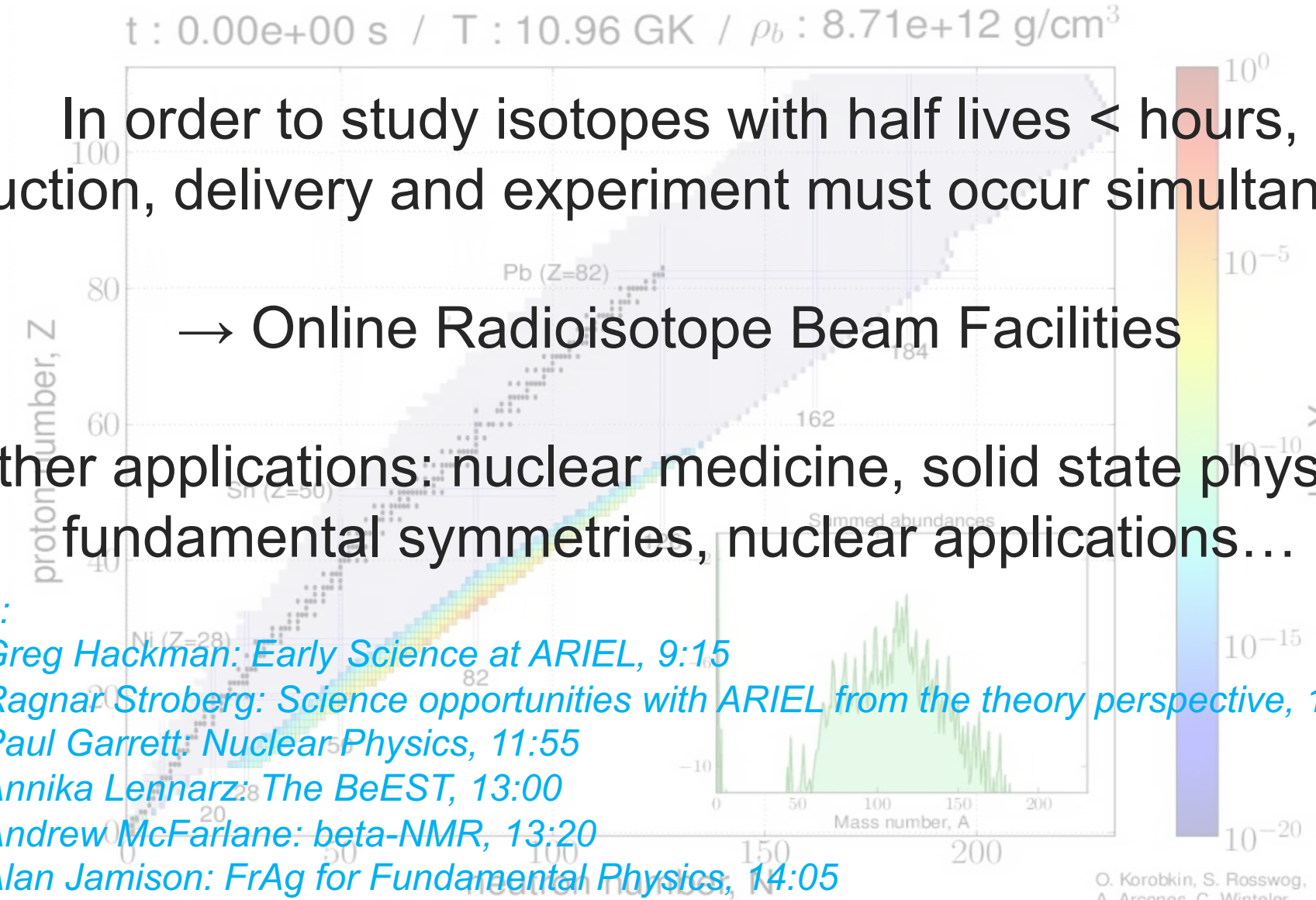
In order to study isotopes with half lives < hours, production, delivery and experiment must occur simultaneously

→ Online Radioisotope Beam Facilities

Other applications: nuclear medicine, solid state physics, fundamental symmetries, nuclear applications…

See:

- *Greg Hackman: Early Science at ARIEL, 9:15*
- *Ragnar Stroberg: Science opportunities with ARIEL from the theory perspective, 10:30*
- *Paul Garrett: Nuclear Physics, 11:55*
- *Annika Lennarz: The BeEST, 13:00*
- *Andrew McFarlane: beta-NMR, 13:20*
- *Alan Jamison: FrAg for Fundamental Physics, 14:05*



Discovery, accelerated

Radioisotope Beam Facilities World-Wide

Discovery, accelerated

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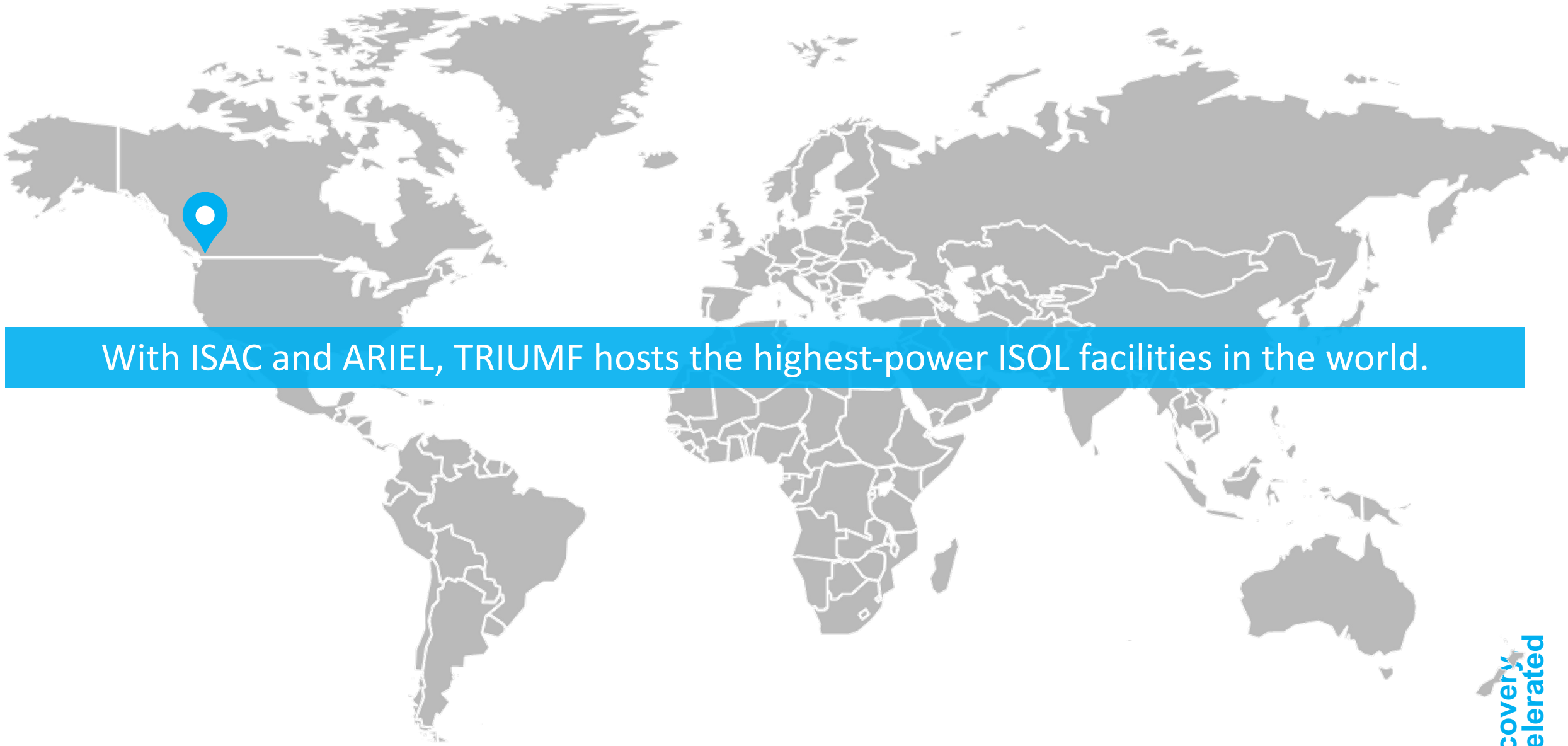
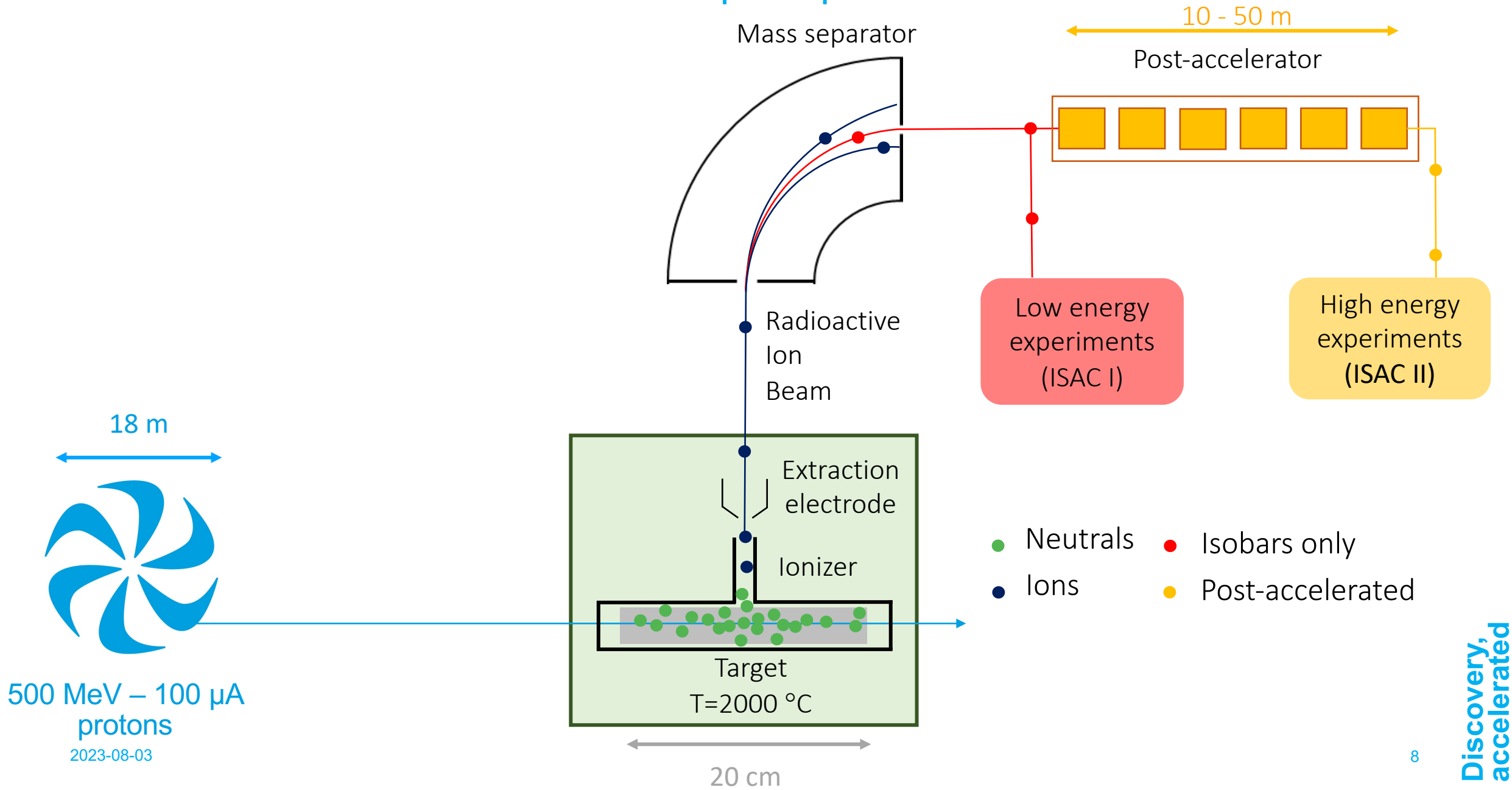


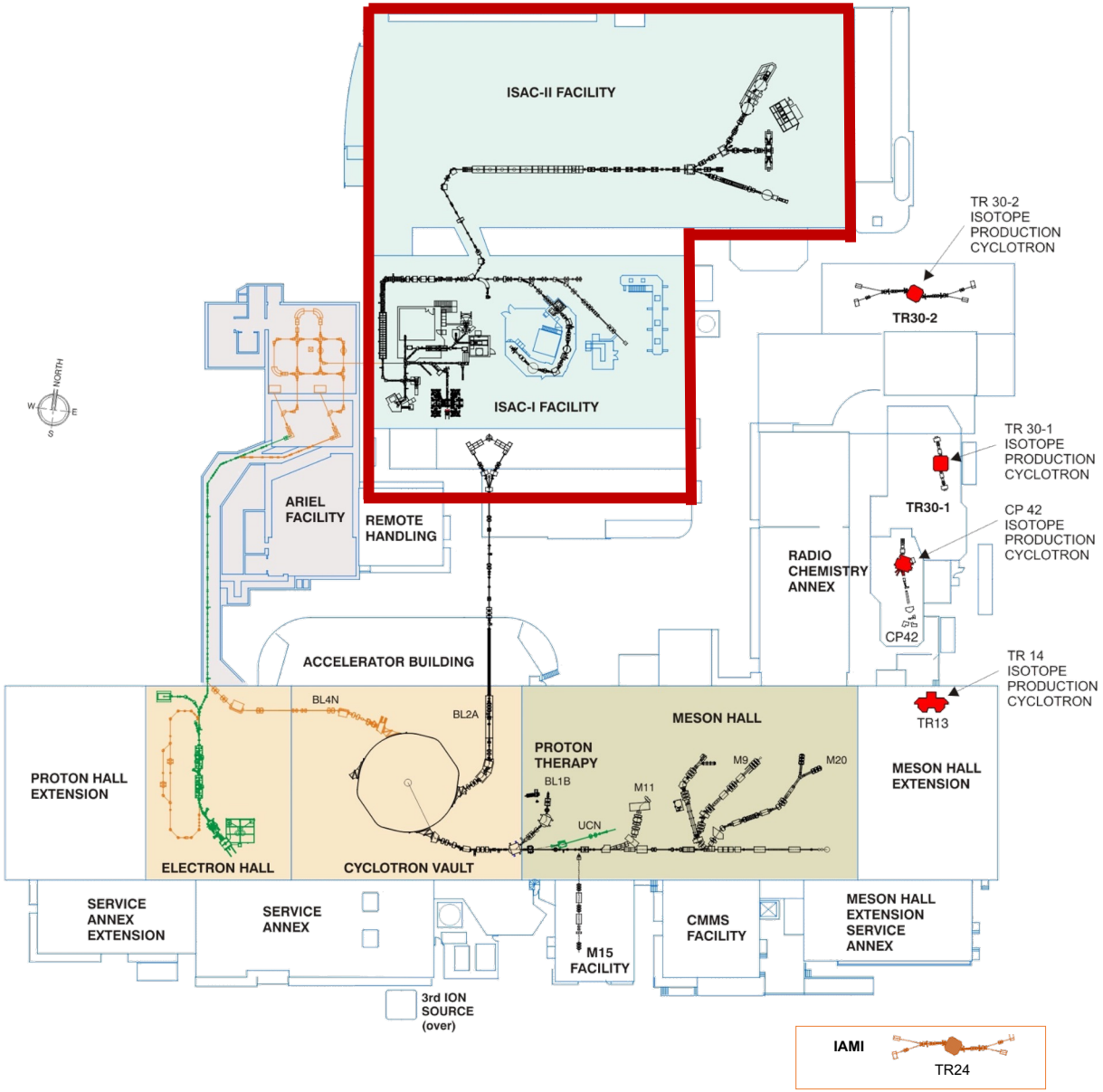
With ISAC and ARIEL, TRIUMF hosts the highest-power ISOL facilities in the world.

Discovery, accelerated

Isotope Separation Online for RIB Production



ISAC – The Highest-Power ISOL Facility



ISAC (Isotope Separator and Accelerator)

ISAC I:

- Low energy:
  <60 keV
- Medium Energy:
  0.15 - 1.7 MeV/u

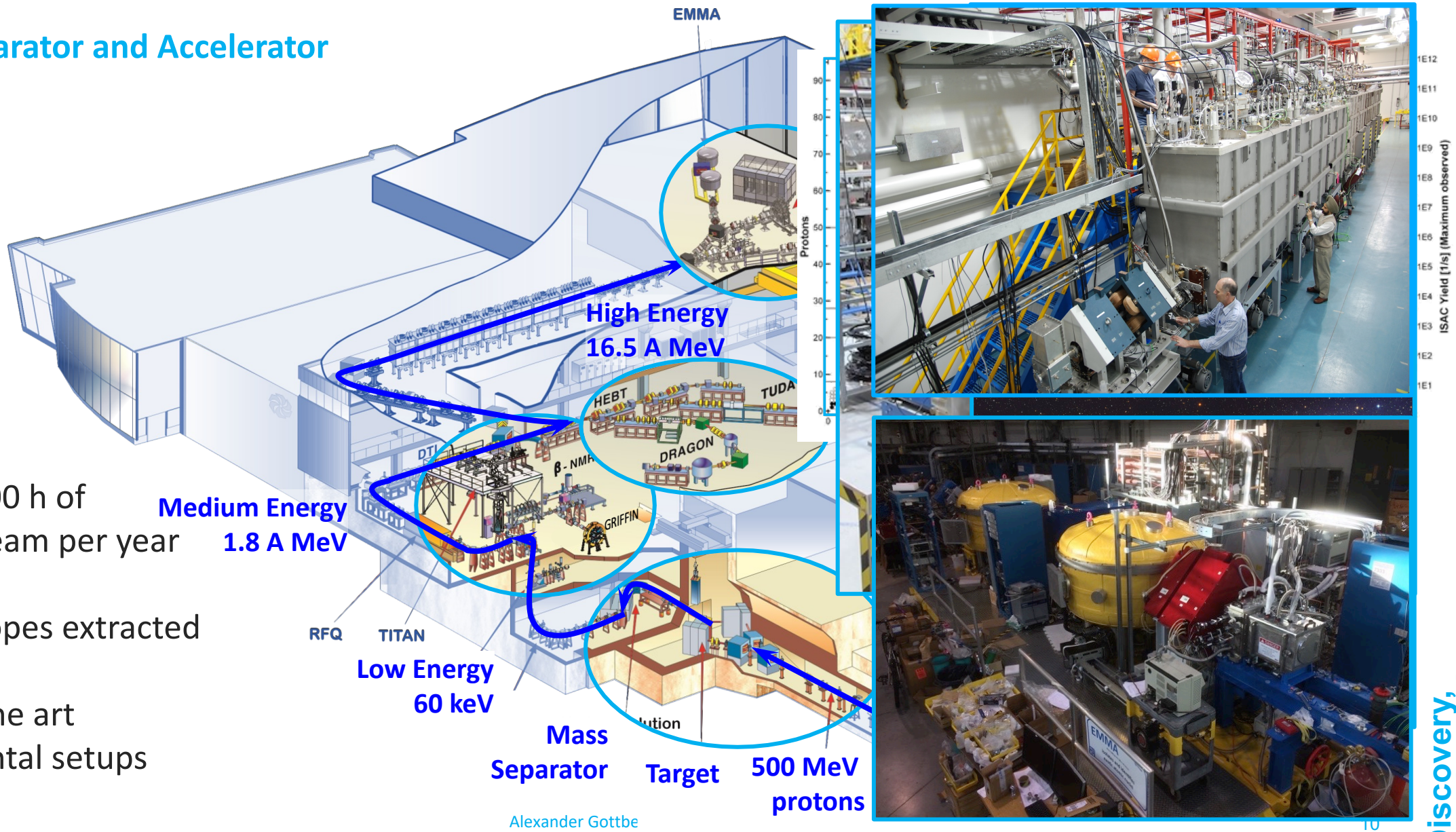
ISAC II:

- 6 - 15 MeV/u

Discovery, accelerated

ISAC – The Highest Power ISOL Facility in the World

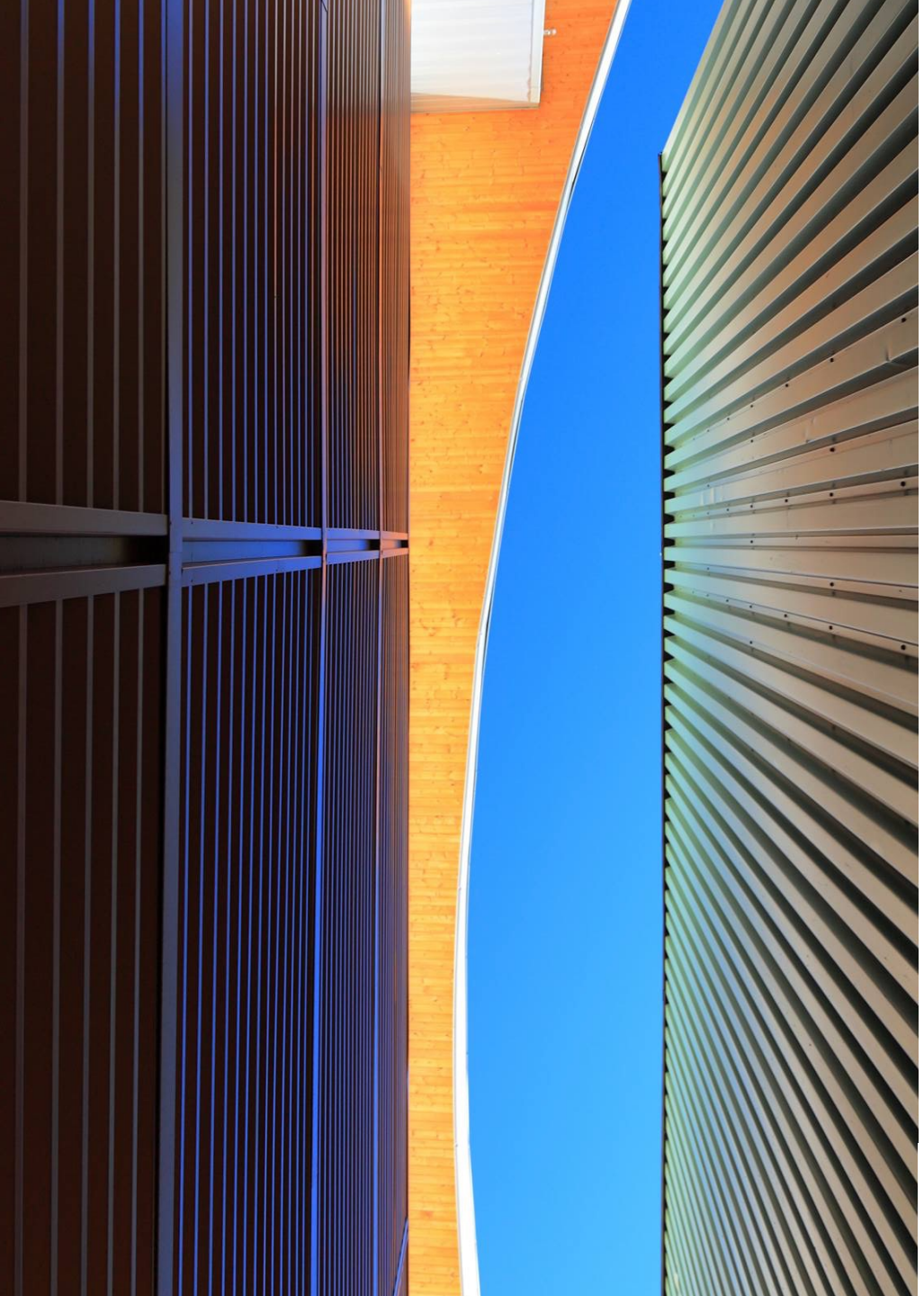
Isotope Separator and Accelerator since 1999



- About 3000 h of isotope beam per year
- >700 isotopes extracted
- State-of-the art experimental setups

Discovery, accelerated


ARIEL will triple TRIUMF's radioisotope beam science



Tripling TRIUMF ‘s Radioisotope Science Program

Advanced Radioisotope Laboratory (ARIEL)

- ARIEL-I (2012 - 2014)
  e-linac, beam tunnel, target building
- ARIEL-II (2017 - 2027)
  target stations, shielding, hot cells, RIB distribution
- CANREB (2014 - 2019)
  charge state breeding and purification for post-acceleration in ISAC II
- Therapeutic Isotopes (2020 - 2028)
  production and processing of medical isotopes at ARIEL proton target station

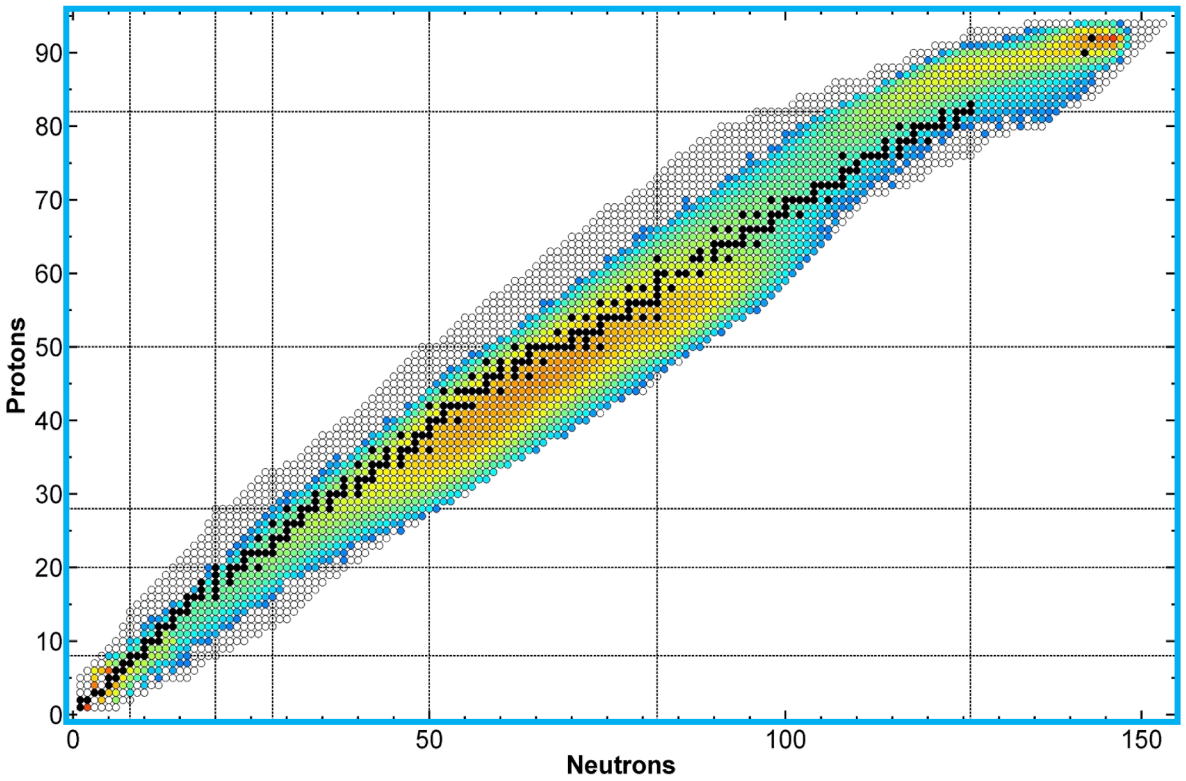
$200 million investment by federal and provincial governments; supported by 21 universities across Canada, about 700 FTE years total effort

Discovery, accelerated

An Independent Driver for TRIUMF's Rare Isotope Program

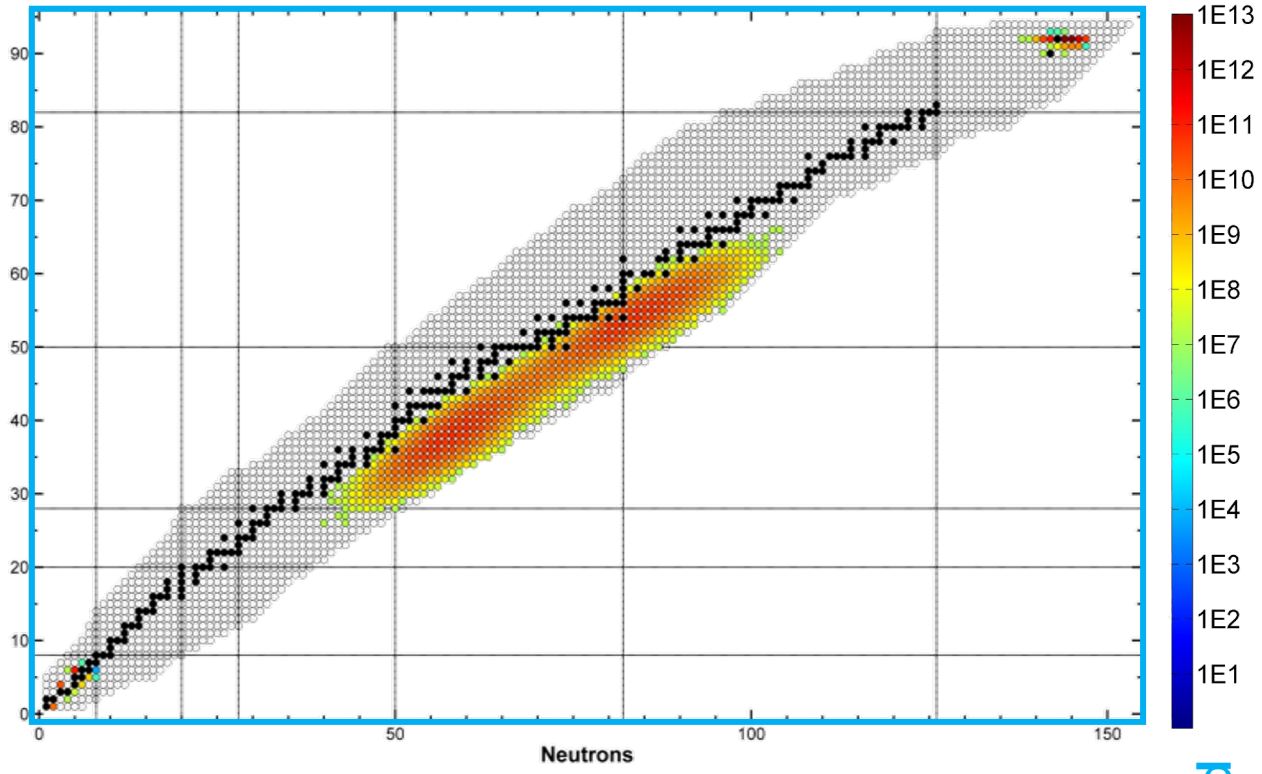
in-target production intensity from UC_x

500 MeV x 10 µA protons [1/s]



→ BL2A and BL4N (protons from main cyclotron)

30 MeV x 10 mA electrons [1/s]

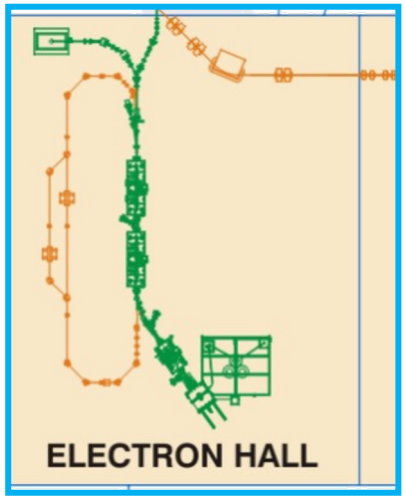


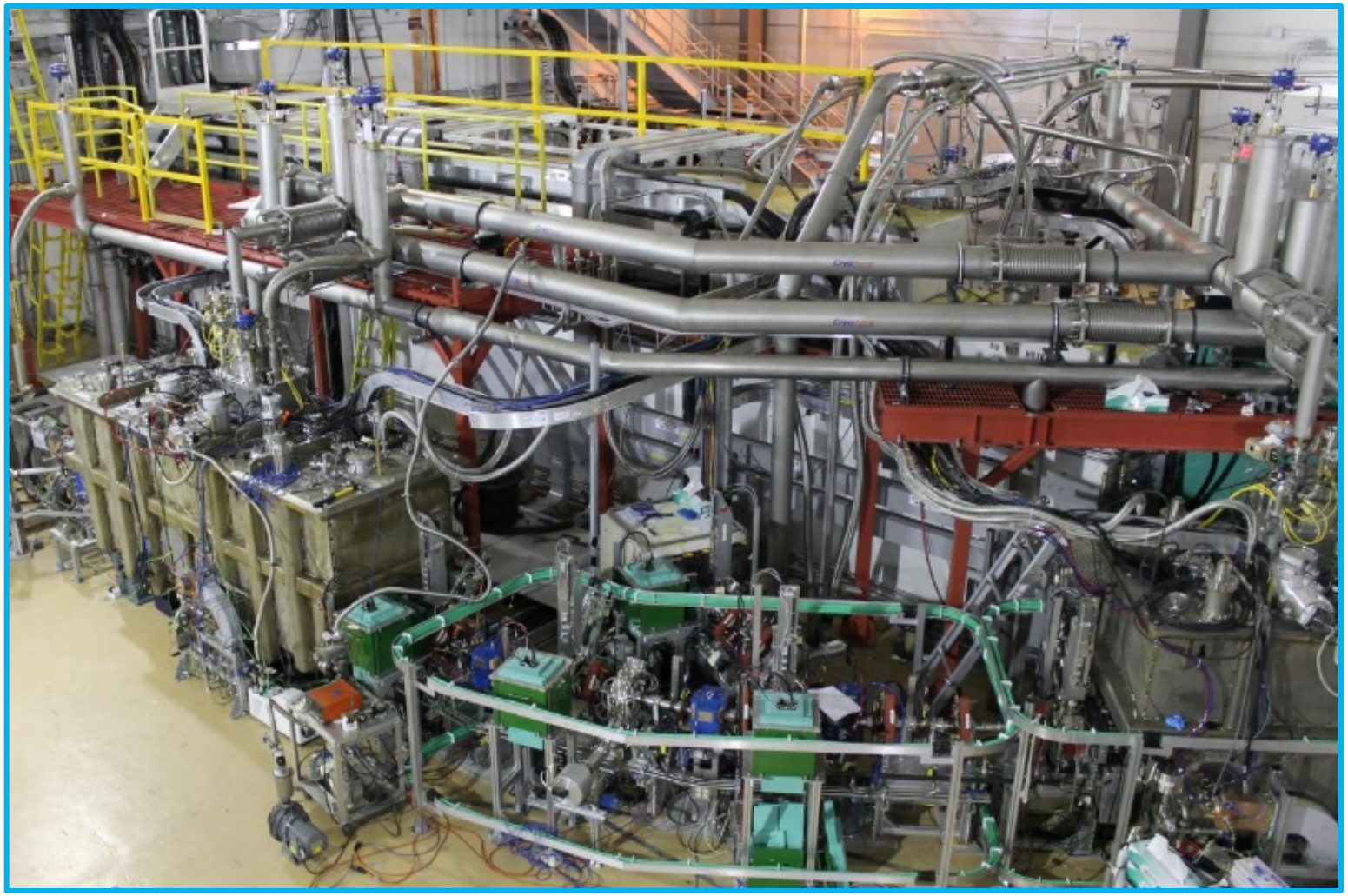
→ e-linac (30 MeV electrons)

Discovery, accelerated

ARIEL Electron Superconducting Linac

- Construction completed (ARIEL-I)
- Nominal beam (30 MeV, 10 kW) demonstrated
- Focus on reliability and beam power ramp-up

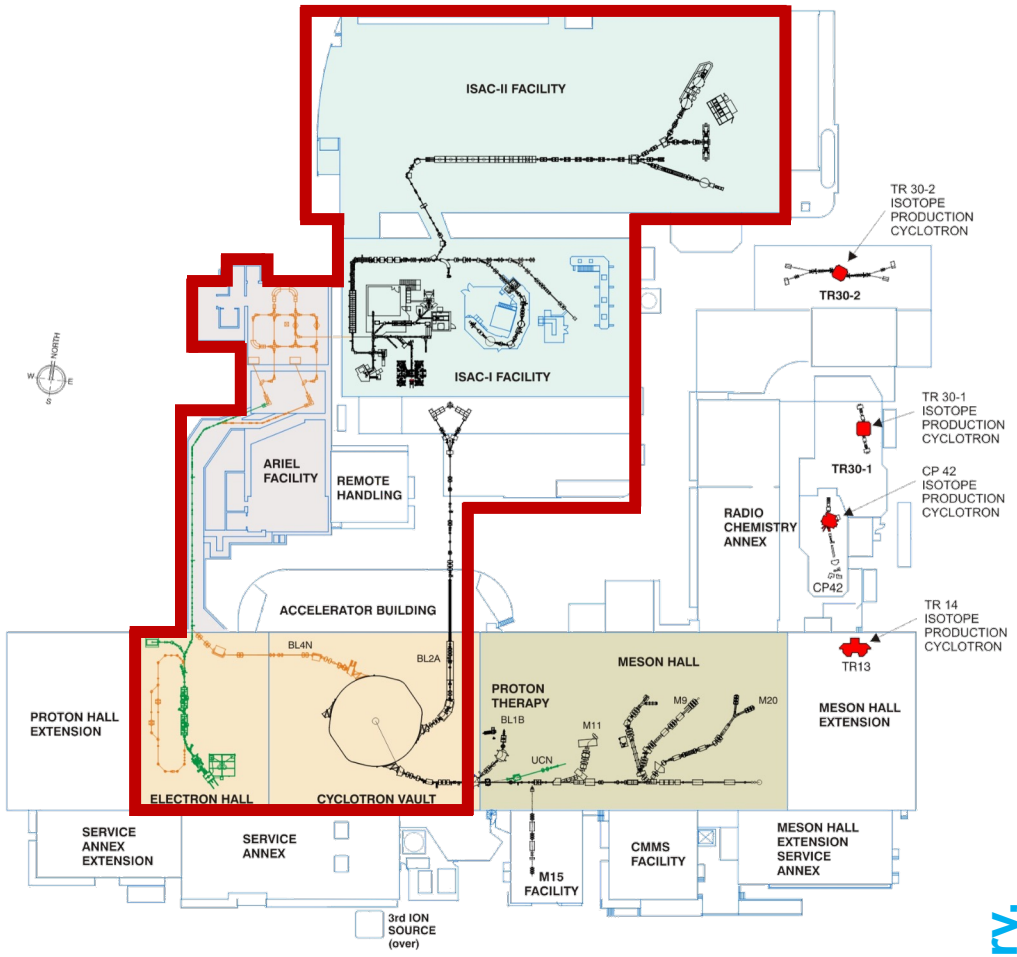




ARIEL Scope

ARIEL Ultimate Objectives:

- Two new radioisotope production target stations
  50 kW protons and 100 kW electrons
- Multi-user operation
  up to three simultaneous isotope beams (9000 RIB hours) delivered to the existing experimental facilities
- More efficient post acceleration
  electron beam ion source - charge state breeder, radiofrequency quadrupole, Nier-spectrometer and unique 1/20,000 resolution high-resolution mass separator.
- Medical Isotopes
  production and processing in proton target station beam dump

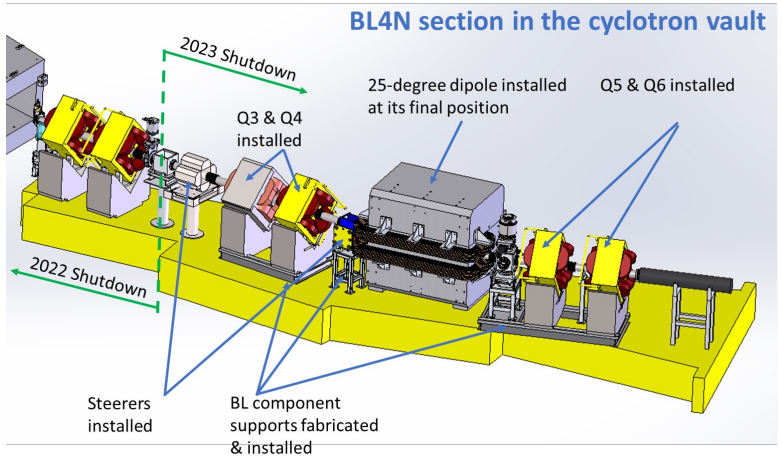


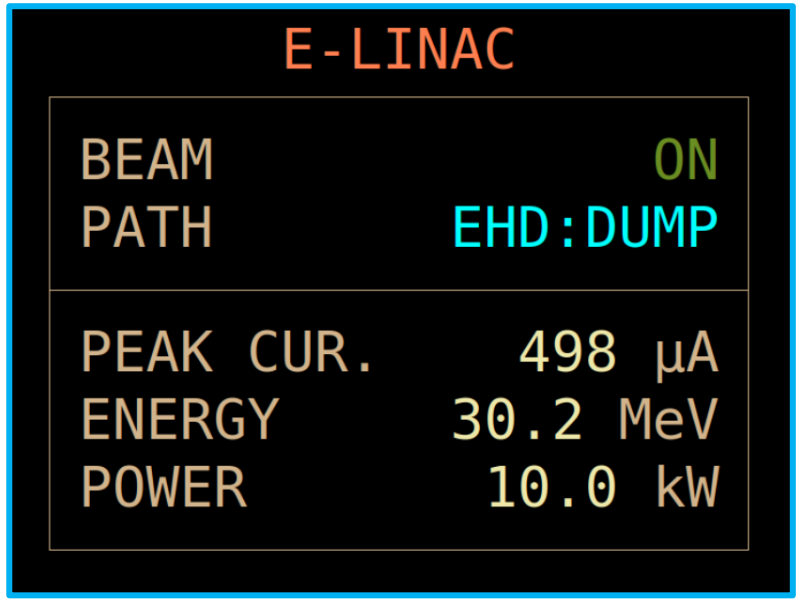

The ARIEL facility is taking shape!

Driver Accelerators for ARIEL

- e-linac towards high reliability and 100 kW beam power
  - 10 kW, 30 MeV beam demonstrated
  - R&D on particulate contamination, Plasma cleaning
  - Develop software tools to support beam ramp-up and high-power operation
  - Support science (DarkLight, FLASH, etc.)

- Primary proton beam line - BL4N
  - Extraction probe installed.
  - All vault section beamline section installed.
  - Proton beam with nominal energy (480 MeV) successfully extracted.

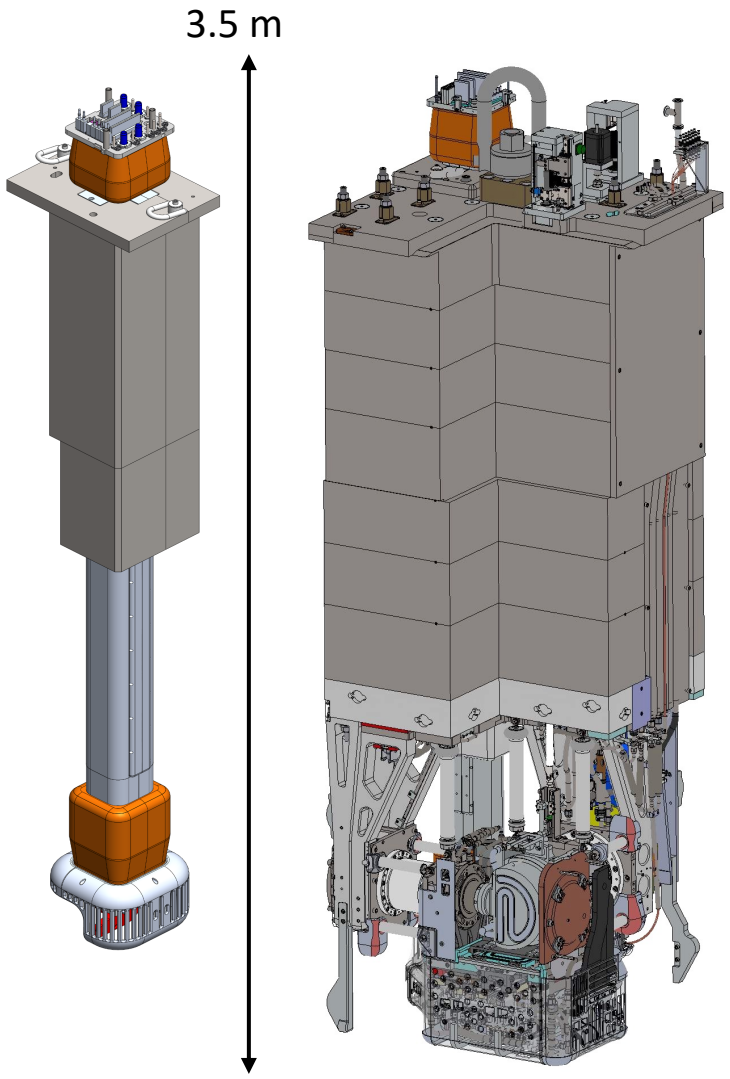




Discovery, accelerated

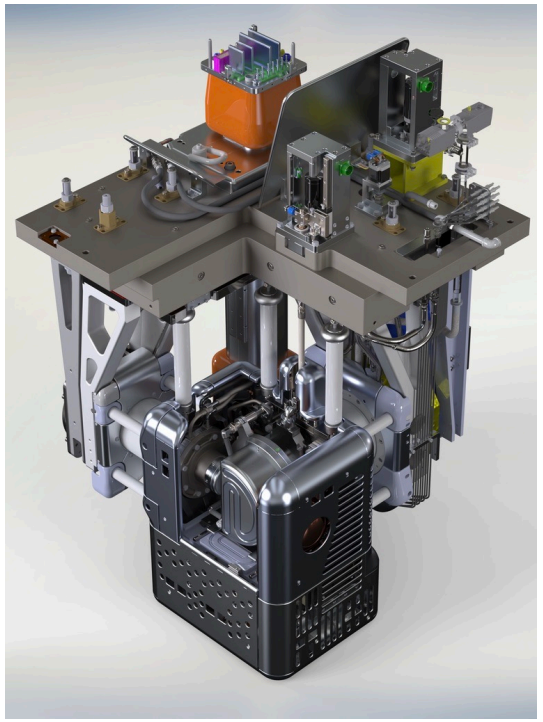
ARIEL Status: Target Station

- AETE (ARIEL Target Station East) targetry protype testing complete, technical risks retired.
- VECC collaboration: AETE Target/Ion Source Front End Prototype shipped
- Target Module front end & High Voltage Feedthrough (HVFT): Design & drawings nearing completion and parts being completed by machine shop and HVFT ordered.



HVFT

Target Module



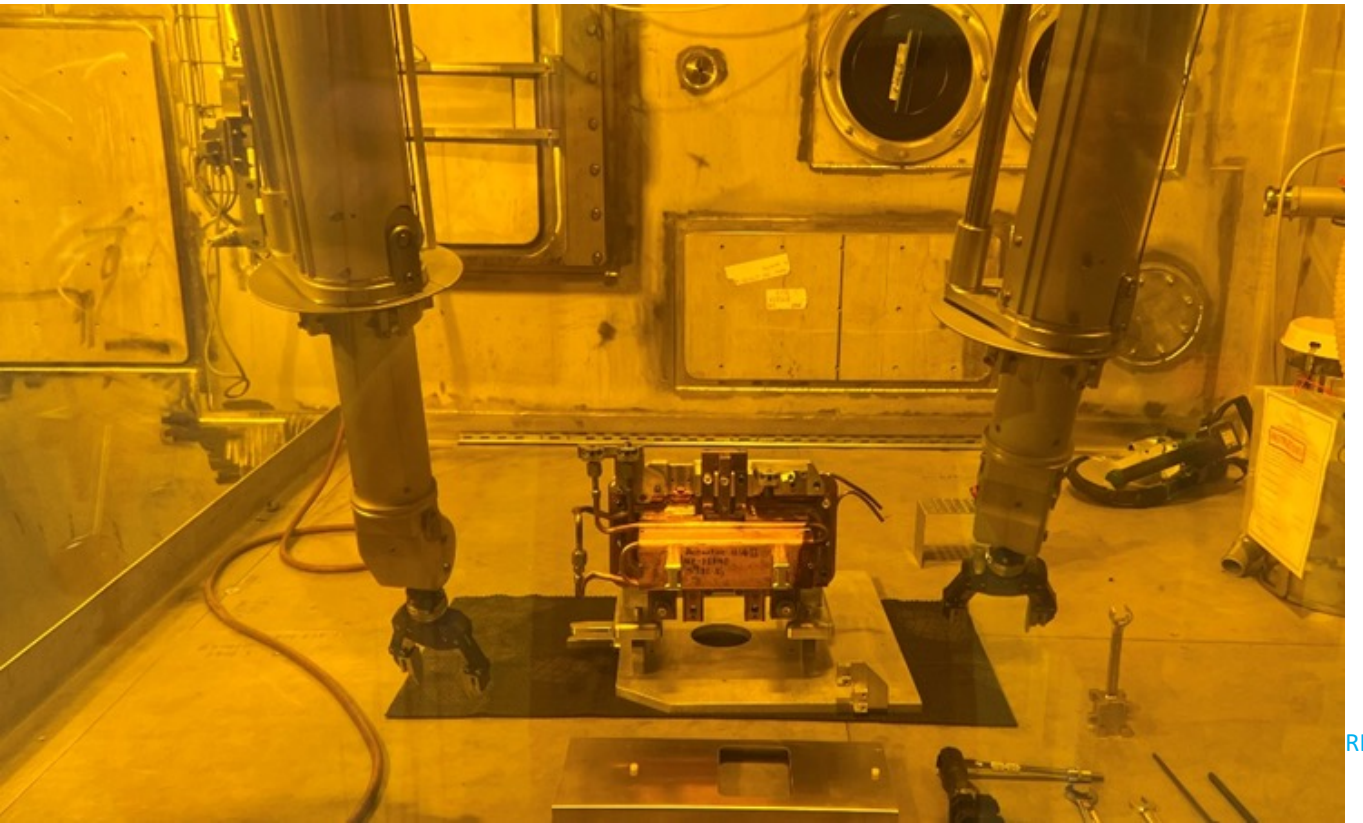
Target Ion Source Front End

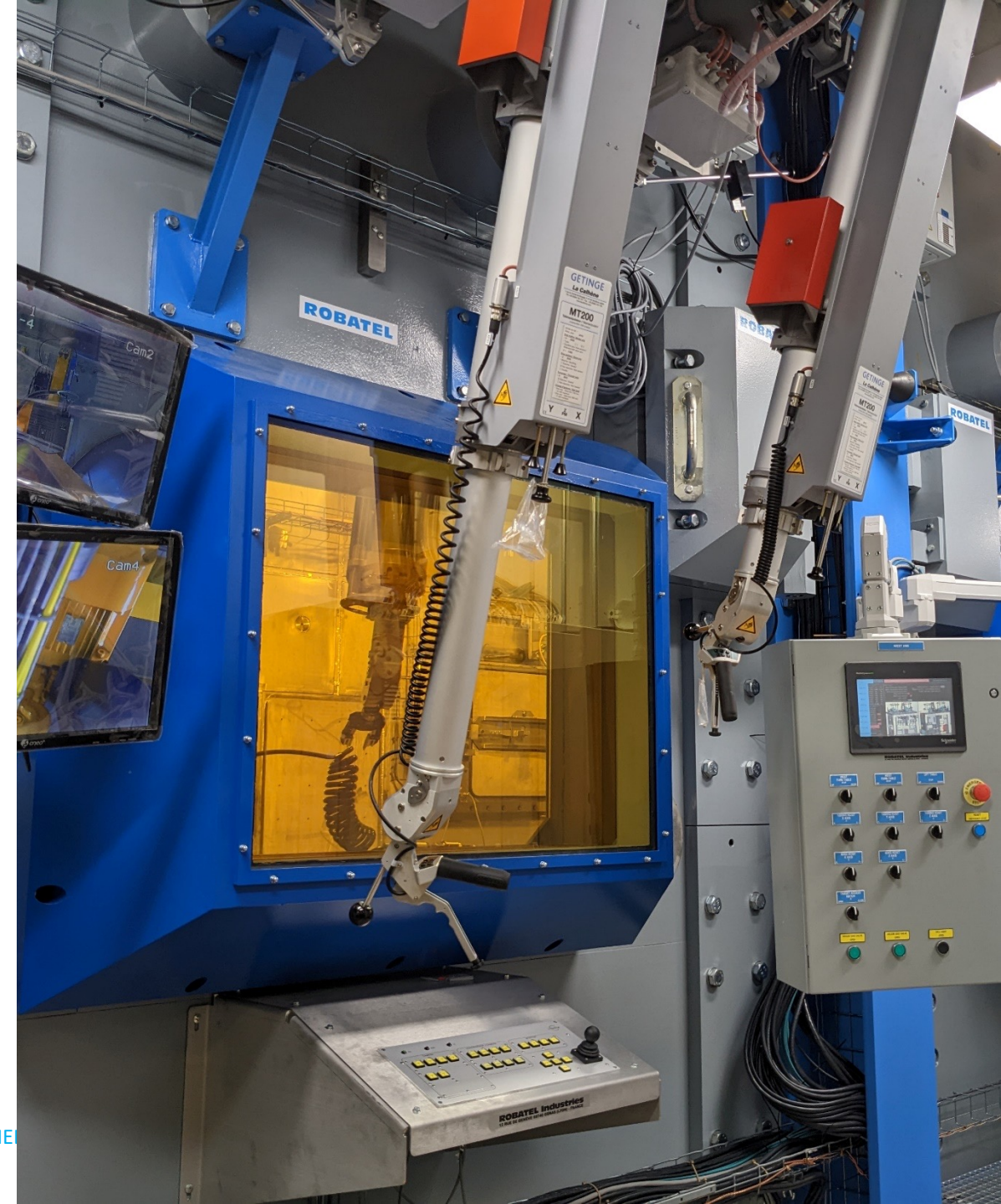
ARIEL Status: Target Hall Infrastructure

- Shielding construction ongoing and on time.
- Structural Supports for heavy ARIEL modules received and installation completed.

ARIEL Status: Hot Cell

- Largest single capital investment for the project.
- Hot cell installation completed!
- Prototyping ad training ongoing.

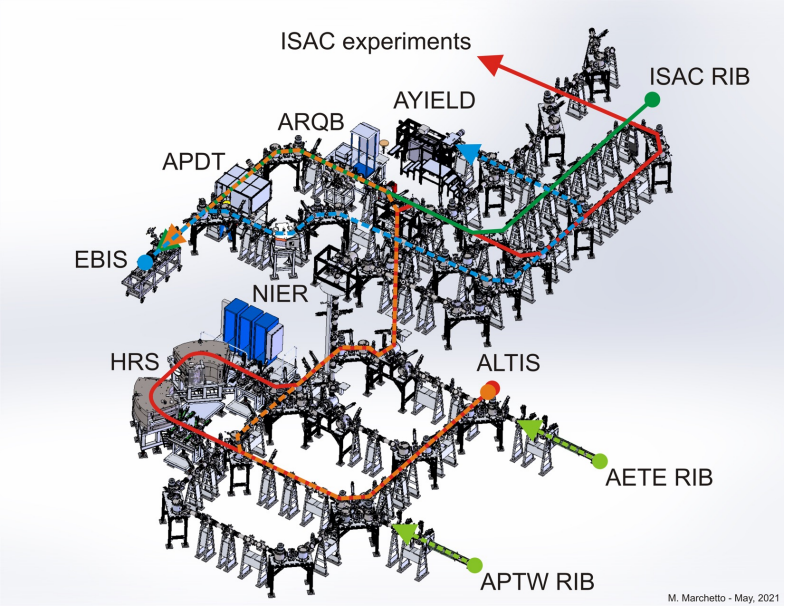




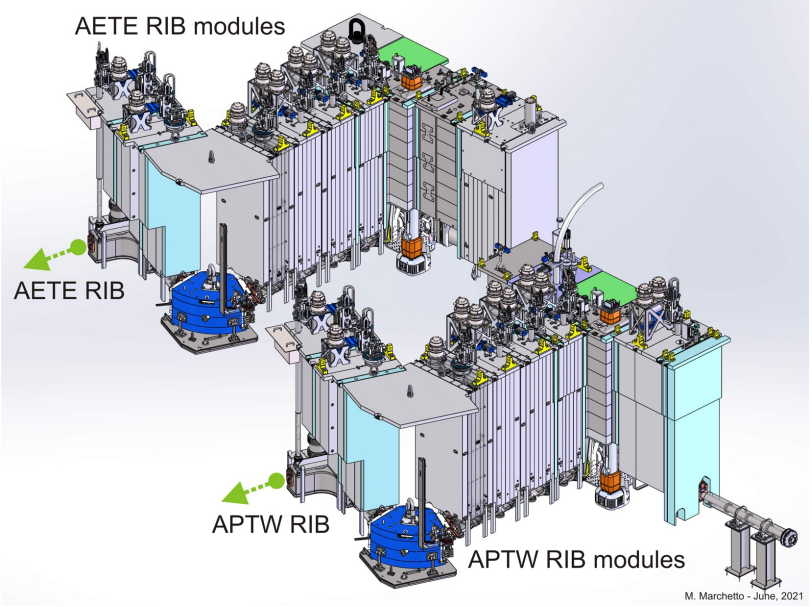
ARIEL Status: RIB (Transport) Modules

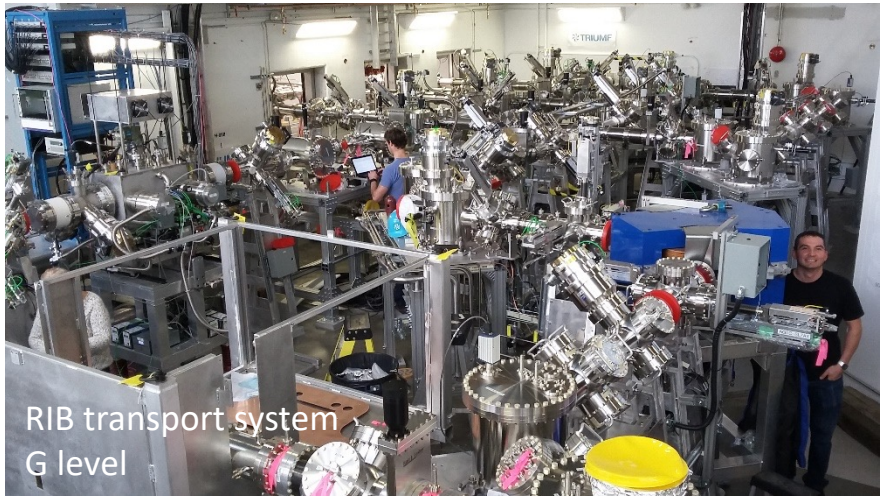
- RIB transport system outside the target hall (200 m of electrostatic beamline)
  >95% installed and commissioned
- RIB module vacuum chambers fabricated for VECC
- First RIB module vacuum dog-leg fabricated and assembled.
- RIB module steel shielding fabrication in progress!

Front-end outside the target hall

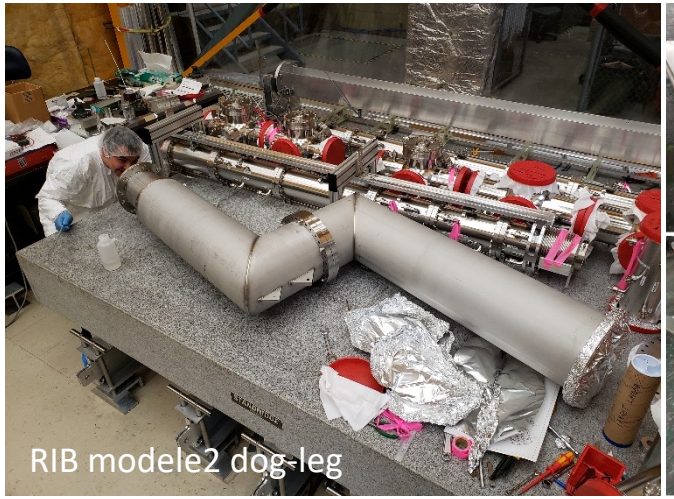


Front-end inside the target hall




RIB transport system
G level

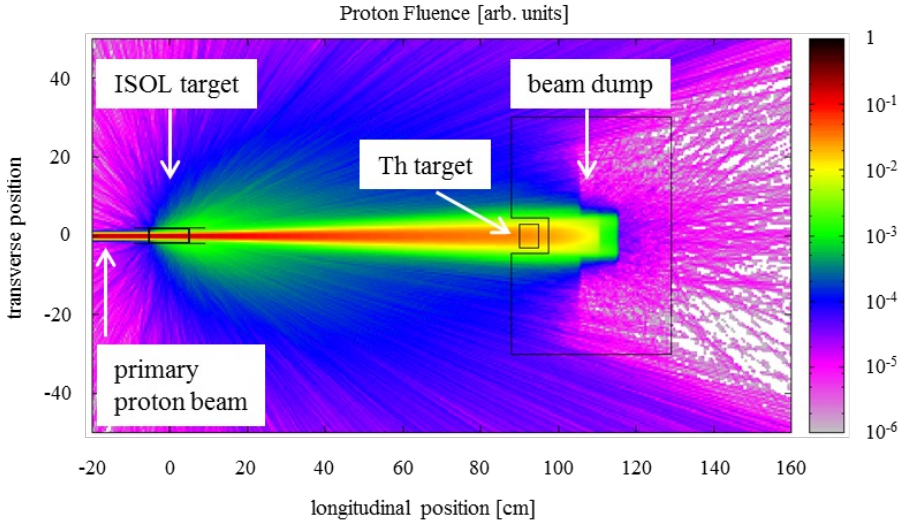

RIB module vacuum chambers


RIB modele2 dog-leg

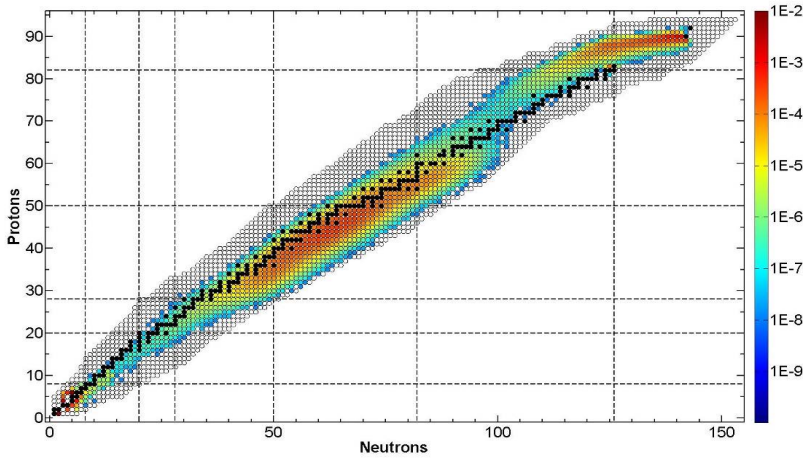

RIB module shields

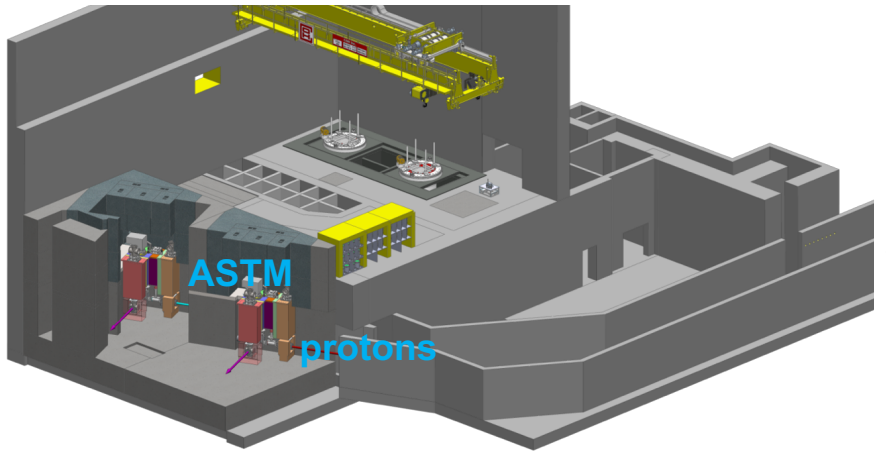
ARIEL Status: Medical Radioisotopes System Design Progressing

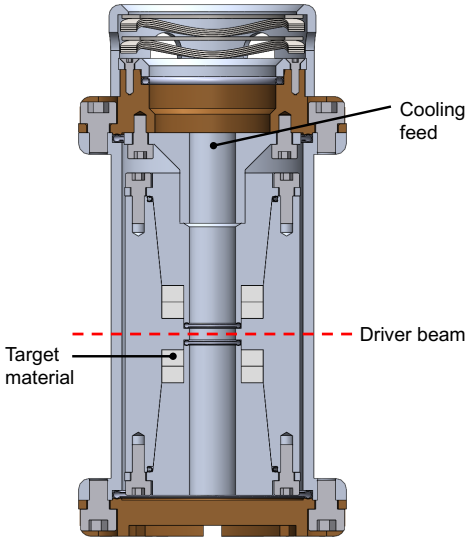
At 500 MeV (ISAC/ARIEL): ≤100 MeV stopped in target



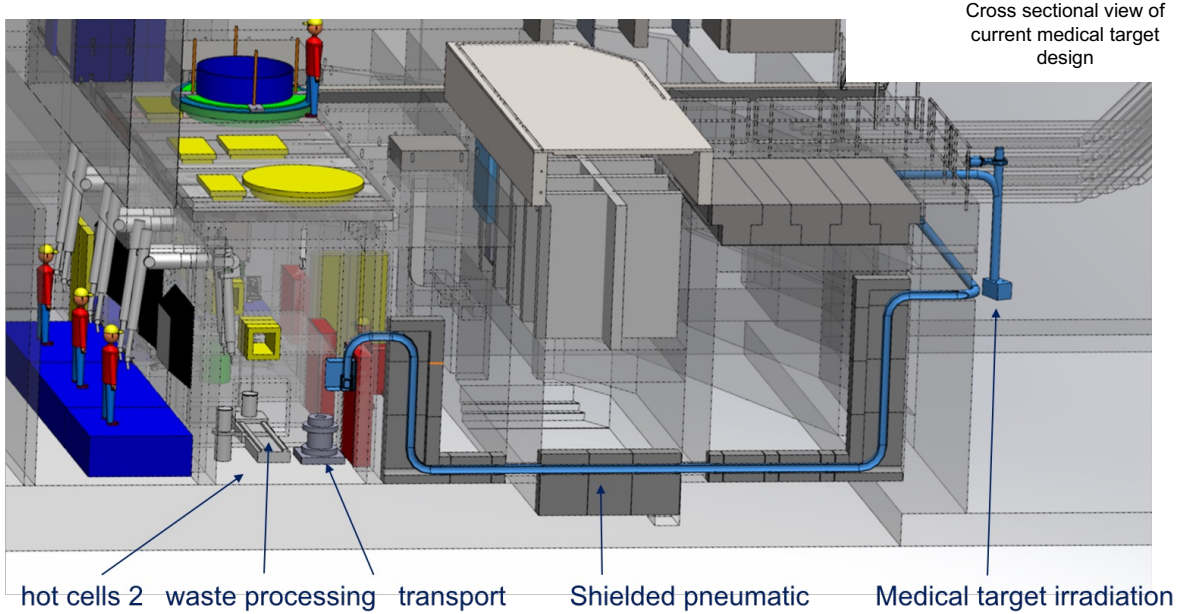
Hundreds of co-produced isotopes including;
^{225}Ra, ^{225}Ac, ^{224}Ra, ^{223}Ra, ^{213}Bi, ^{212}Pb, ^{212}Bi







Cross sectional view of current medical target design



Discovery, accelerated

ARIEL Project Completion

With approval of additional resources, TRIUMF has recently reaffirmed its commitment to complete the ARIEL CFI project within the next 5YP.

ARIEL CFI objectives:

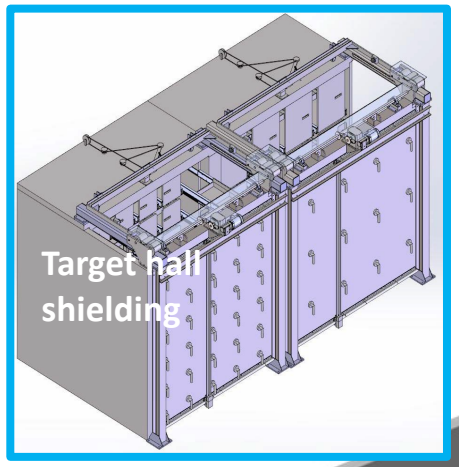
- ✓ ARIEL equipment maintenance Hot Cell (completed)
- ✓ CANREB beam line installation completed (completed)
- ✓ High mass Rare Isotope Beam from ISAC to ARIEL to ISAC (completed)
- ✓ ARIEL Electron Target East (AETE) design (completed)
- RIB from AETE at ~1 kW electron beam (2026)
- RIB from APTW at > 10 kW proton beam (2027)
- Therapeutic Isotopes (2028)

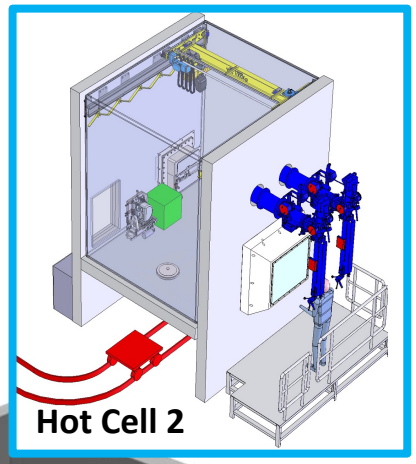
ARIEL Ramp Up

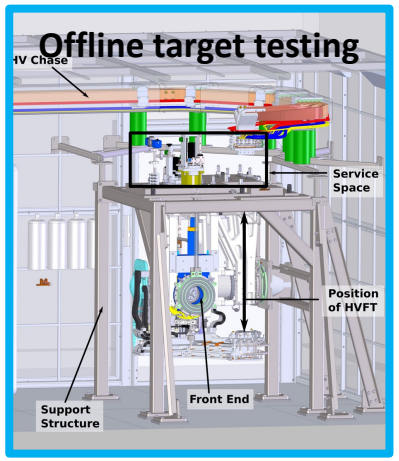
Required for the ramp up of operation to take full advantage of ARIEL over the next 5YP:

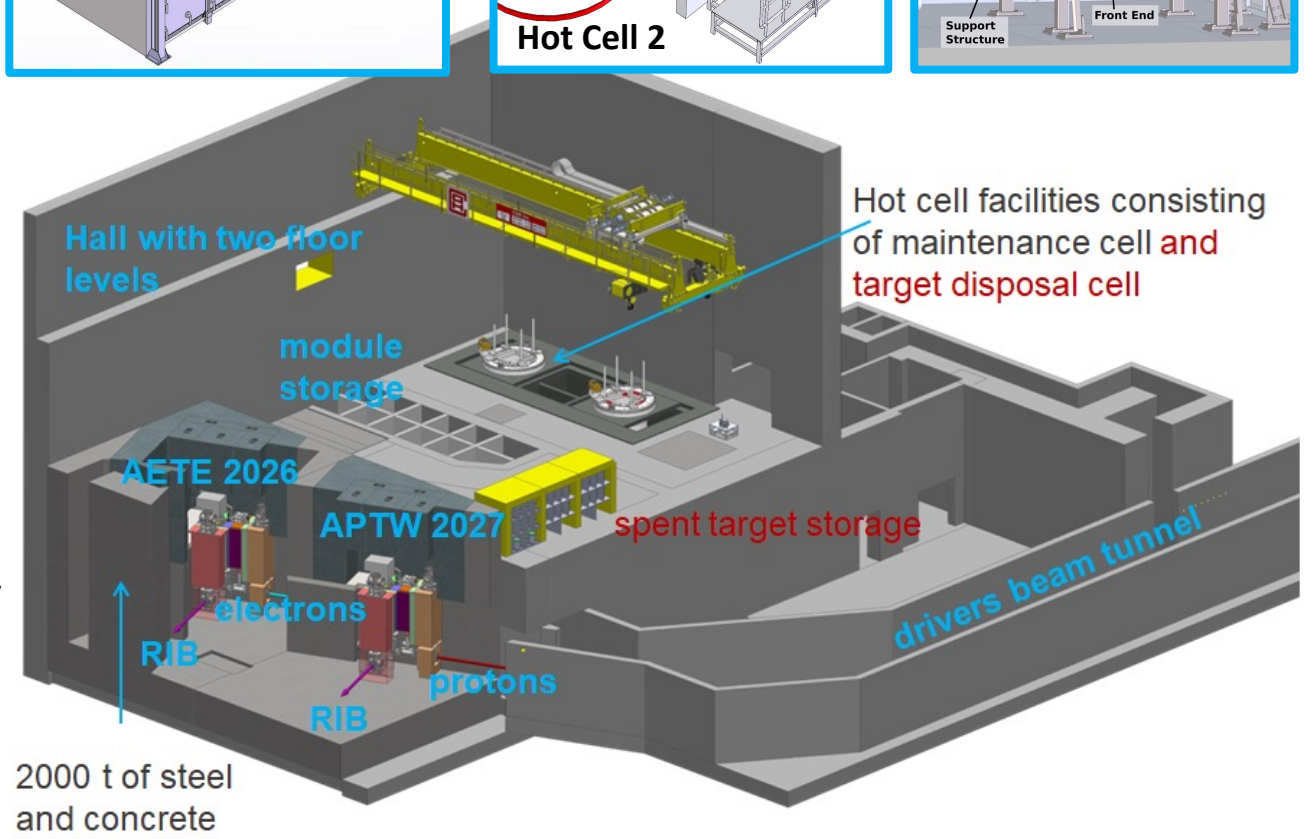
- Target production laboratories
- Dedicated target waste handling cell
- Target decay storage vault
- Offline target acceptance stand
- Resonant laser ion source for proton target station
- APTW proton beam raster system
- AETE power ramp-up from ~1 kW to >10 kW

Design goal of >10 kW electron beam power, 9000 hours beam time, 3 simultaneous RIBs. Only possible within the funding request of $450 M.









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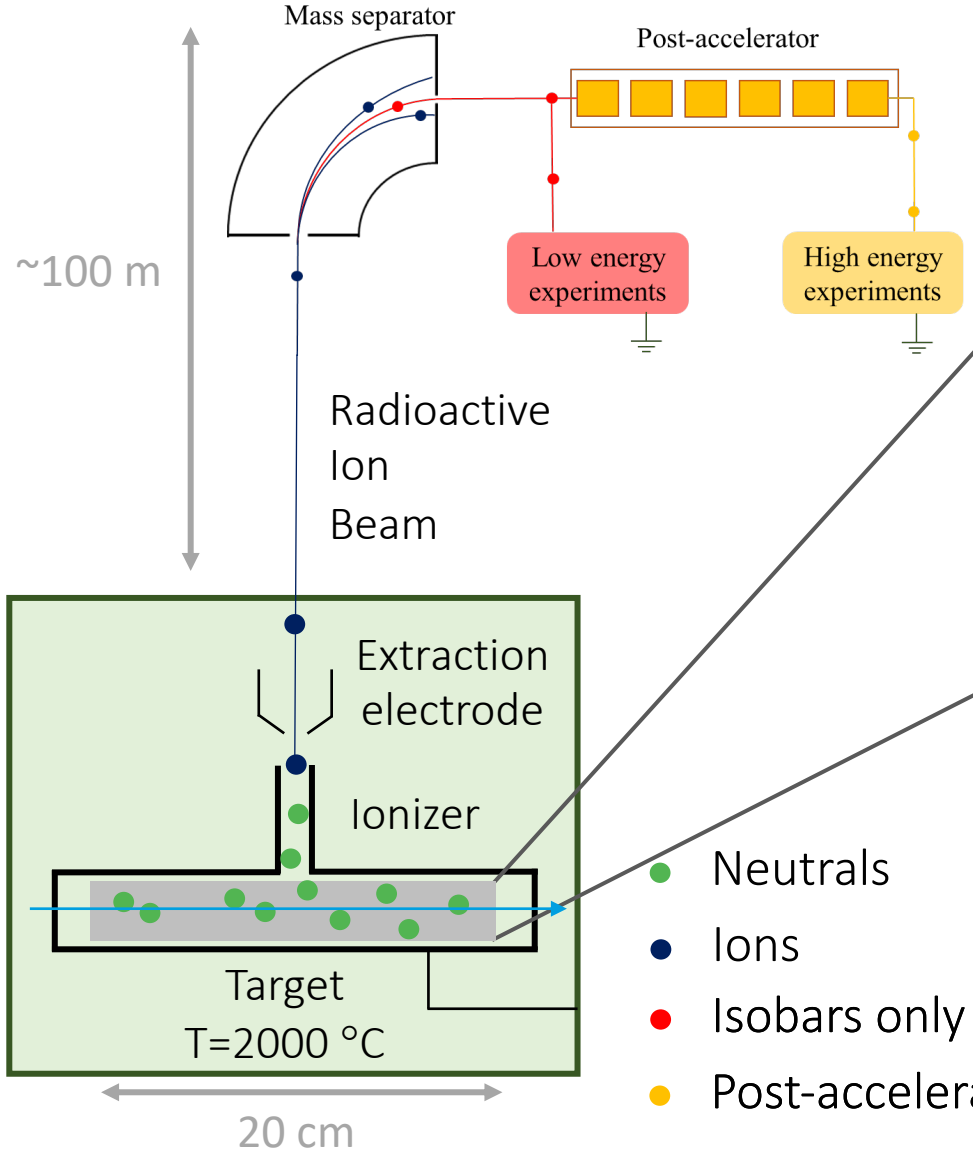
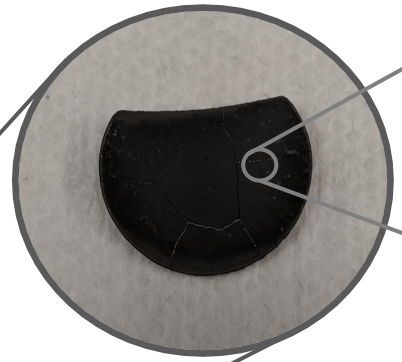
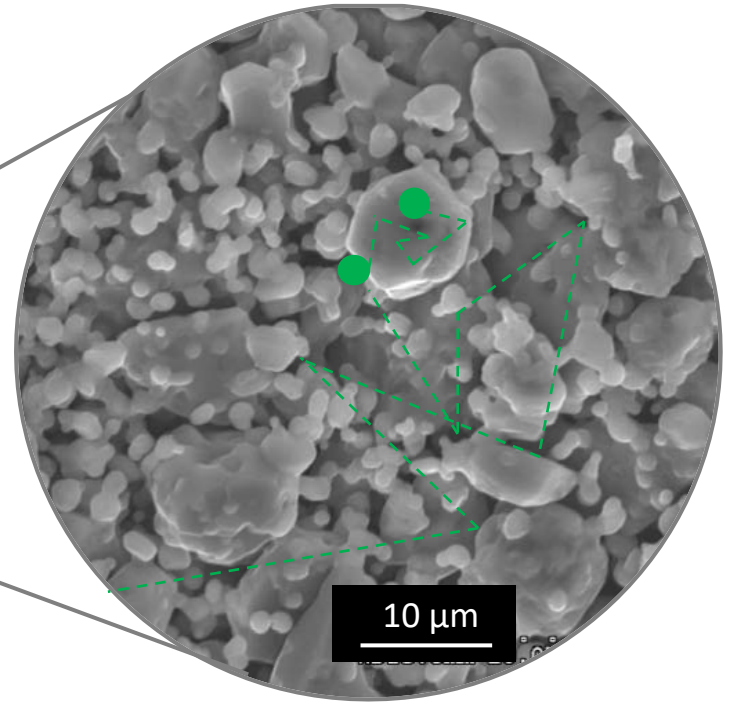
Beams from ARIEL

Discovery, accelerated

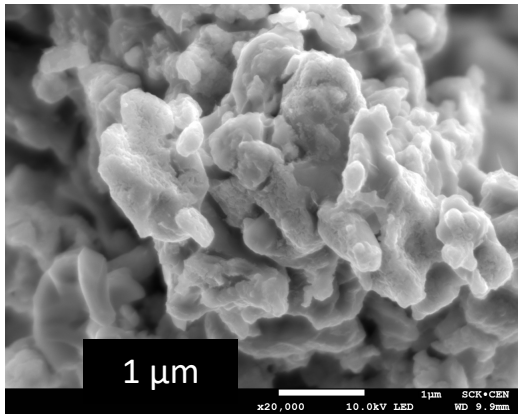
Release in ISOL Targets



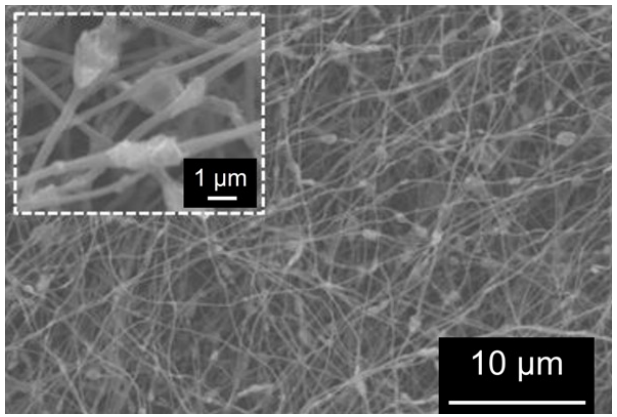




- Neutrals
- Ions
- Isobars only
- Post-accelerated



UC_x particle



nanometric-SiC

Discovery, accelerated

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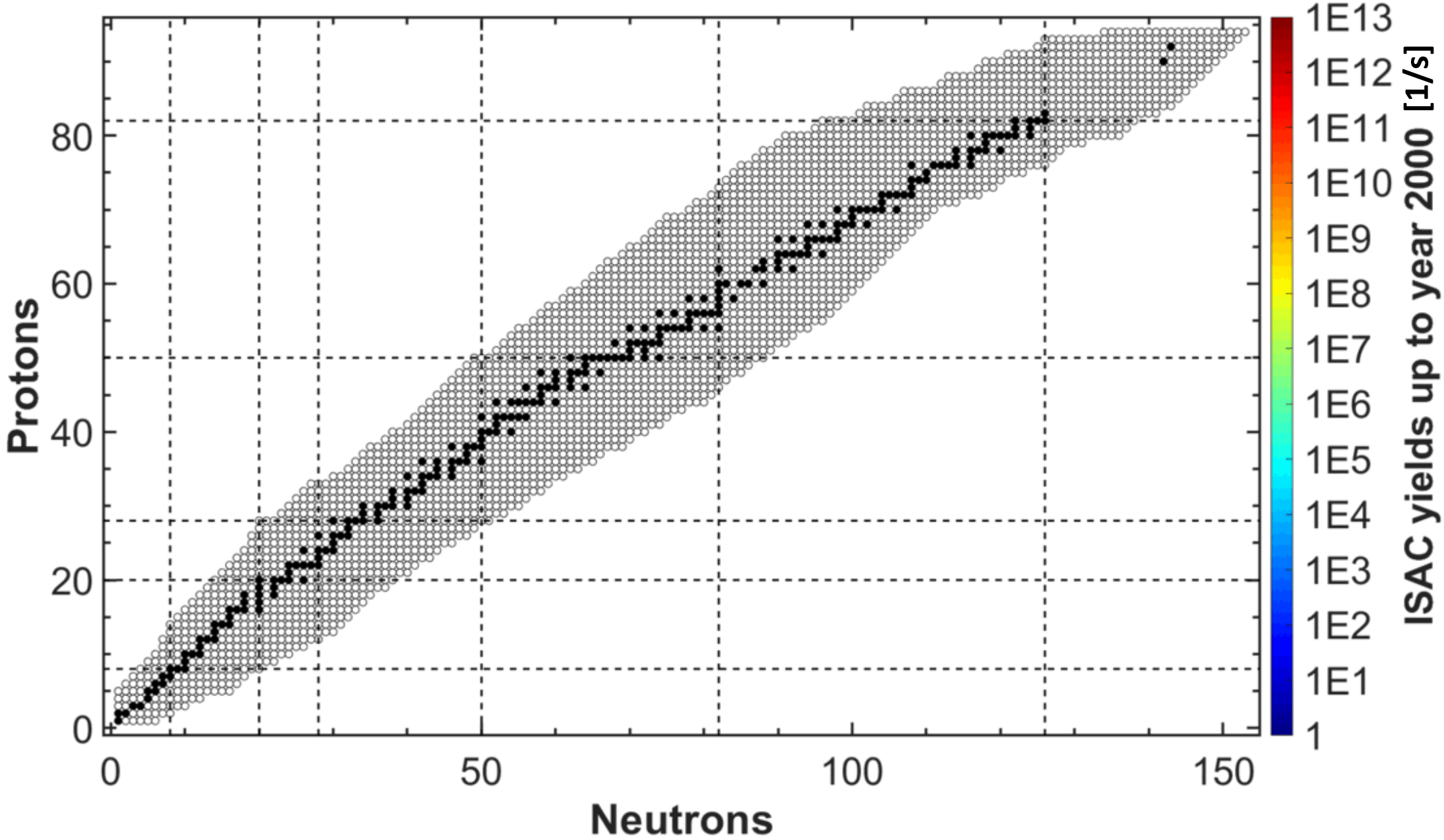
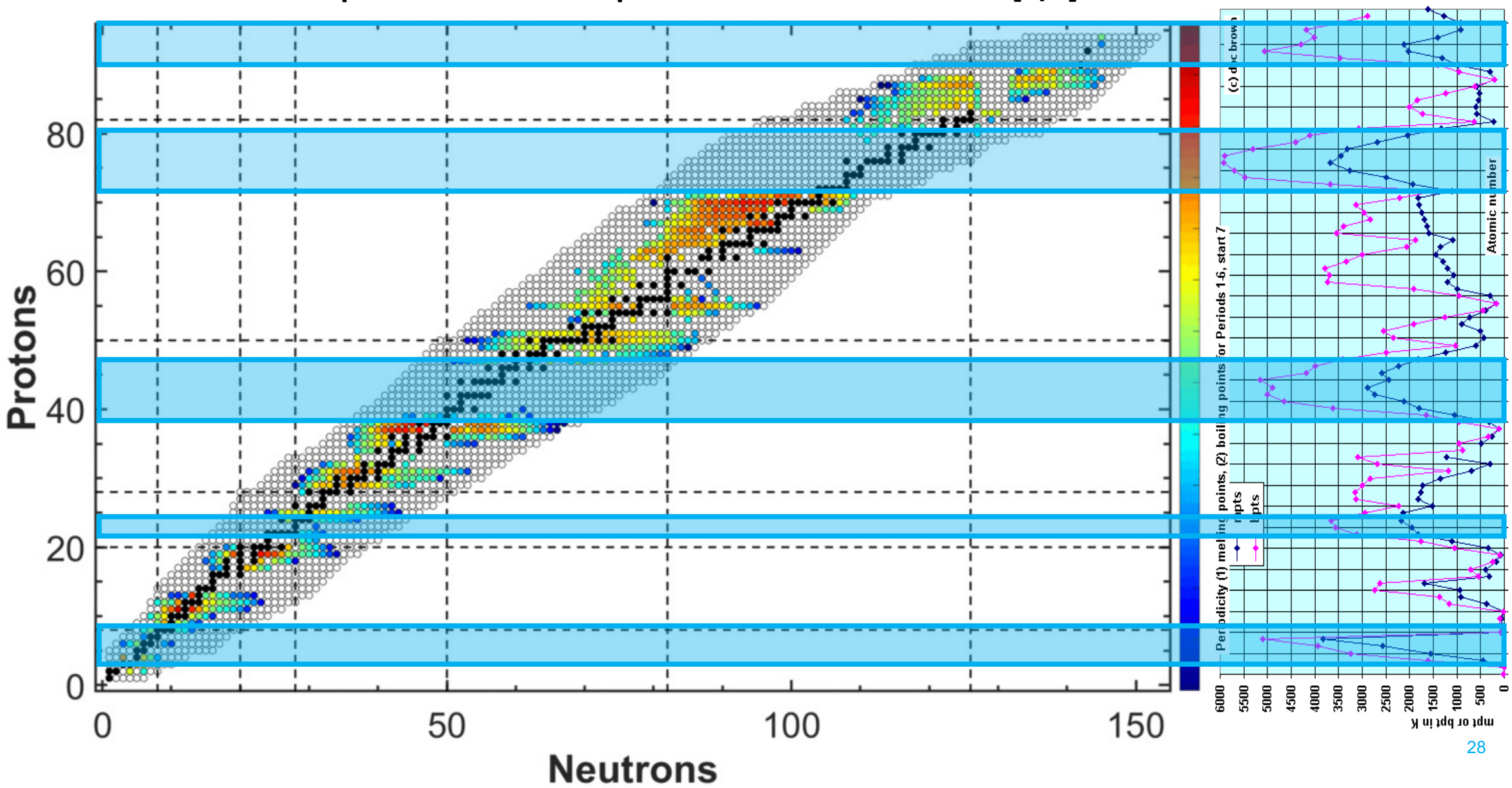
RIBs Availability from all ISAC Targets Over the Years



Discovery, accelerated

Origin of the Areas of Poor Isotope Release

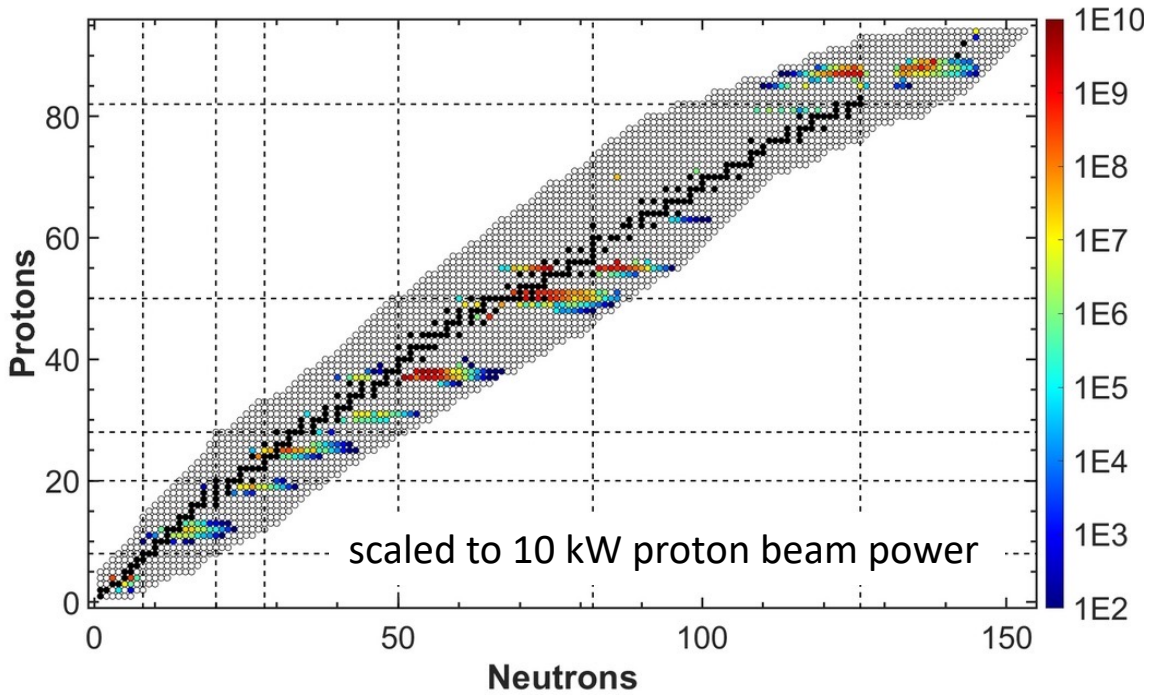
Experimental LE Isotope Rates at ISAC since 2000 [1/s]



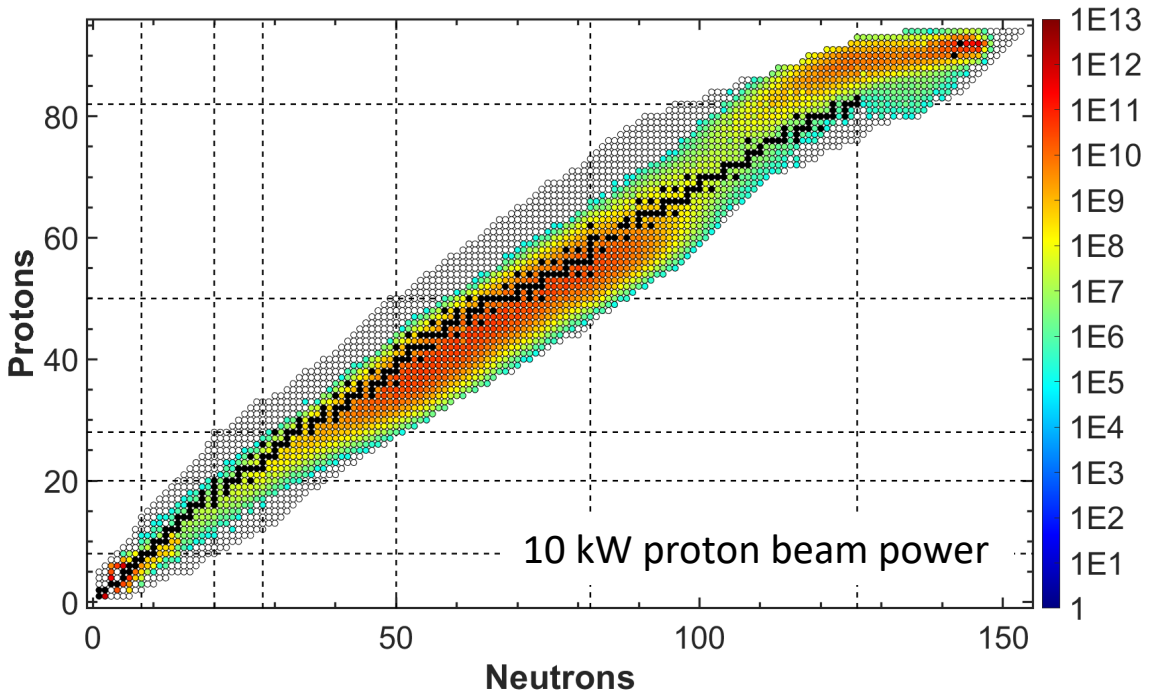
Discovery, accelerated

ISAC Isotope Extraction Efficiency

Average experimental ISAC LE isotope rates from UC_x [1/s]



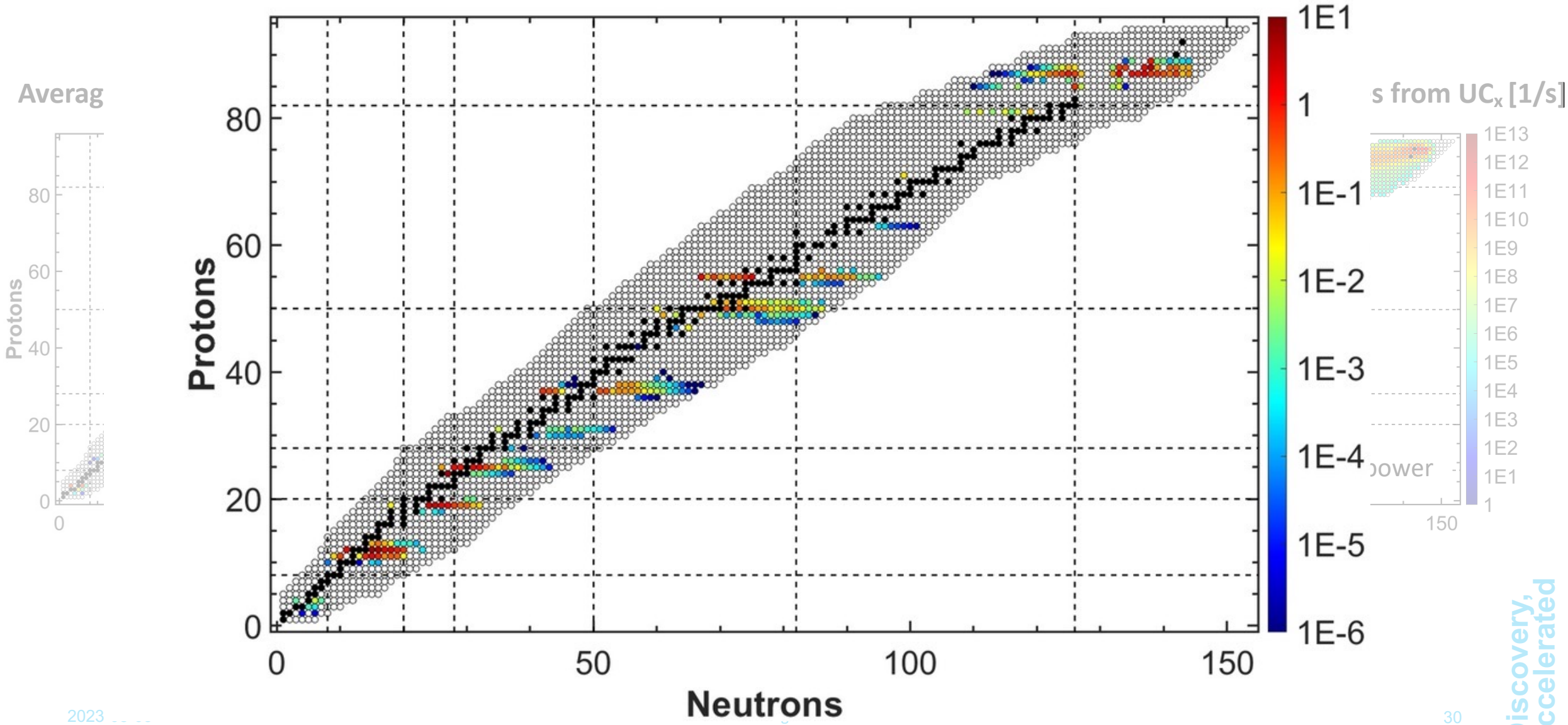
FLUKA ISAC in-target isotope production rates from UC_x [1/s]



Discovery, accelerated

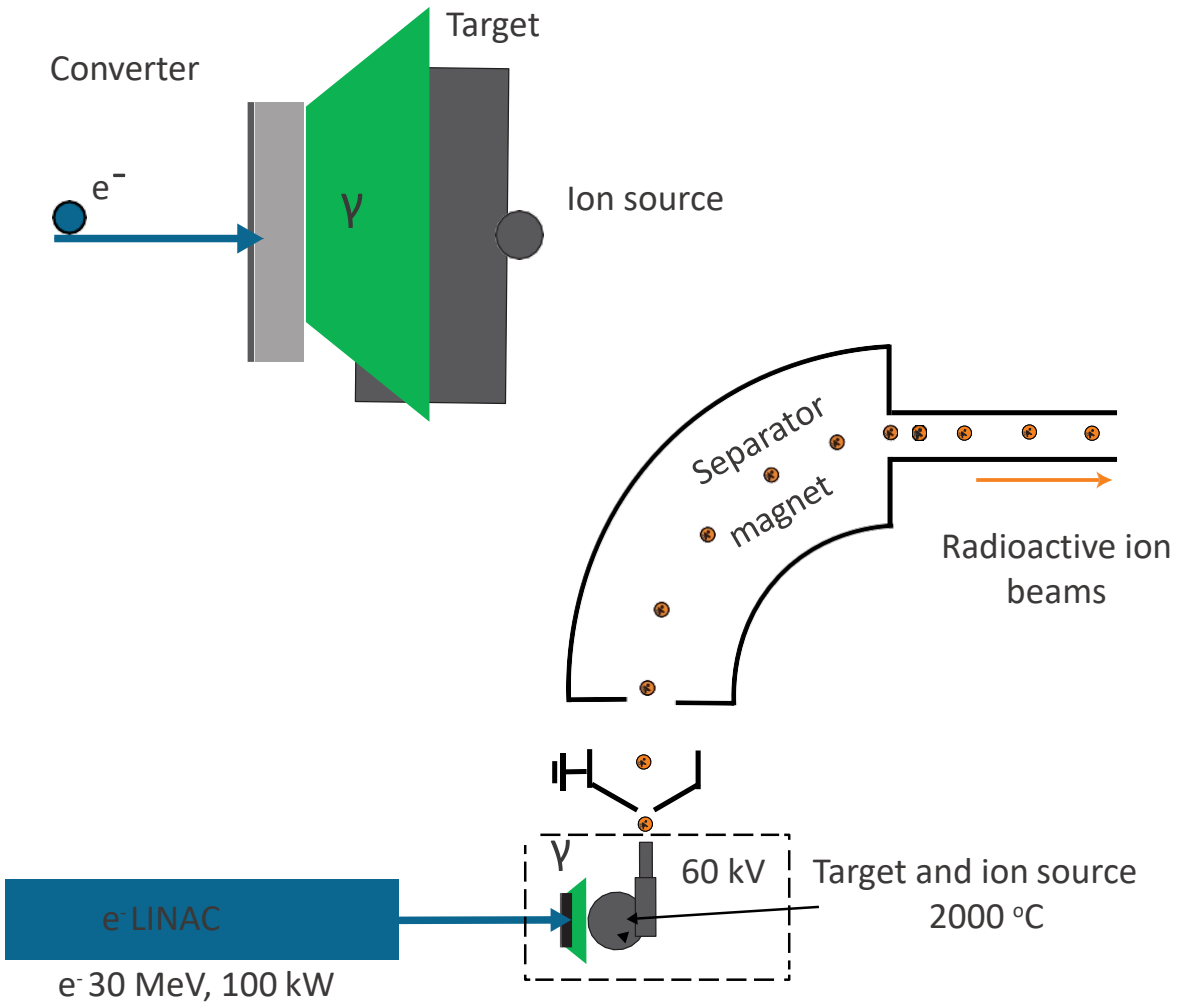
ISAC Isotope Extraction Efficiency

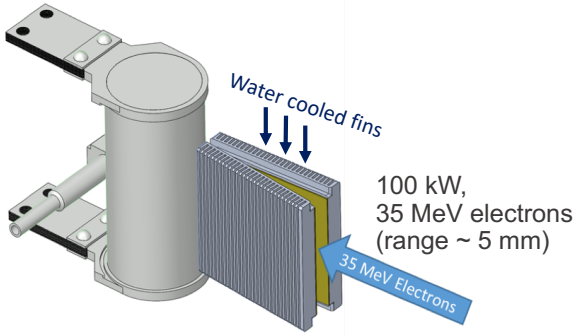
Average isotope extraction efficiencies from ISAC UC_x

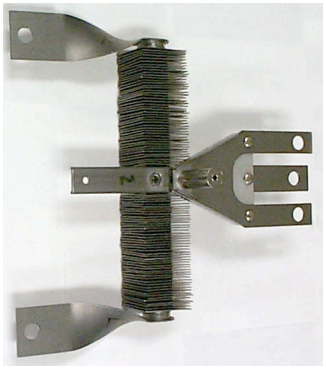


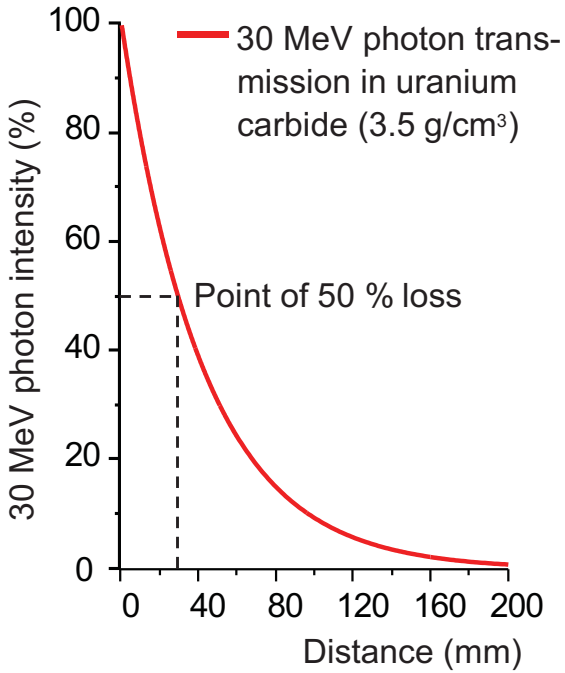
Discovery, accelerated

Electron-Driven ISOL Challenges

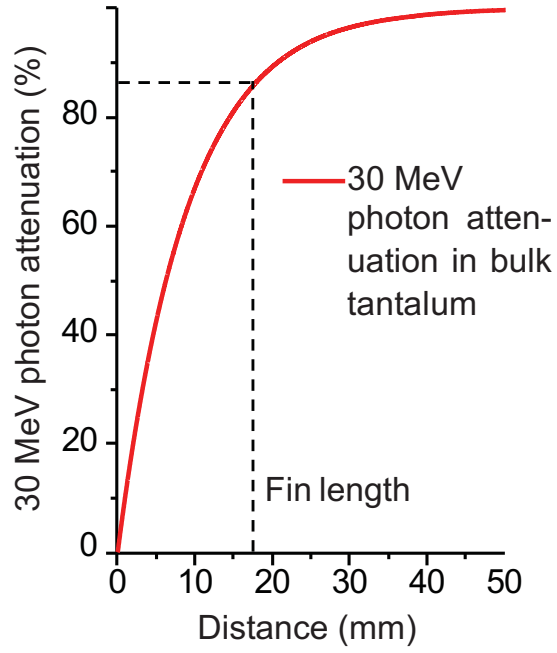








→ Thin target or
change of orientation

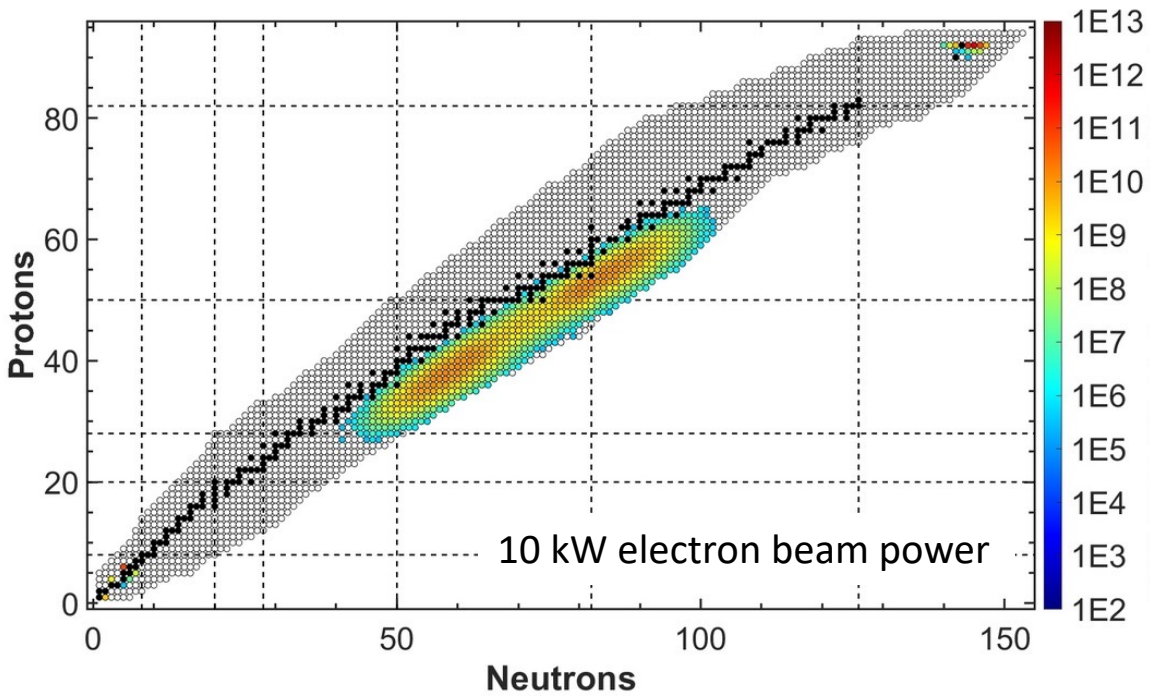


→ ISAC target geometry not
viable for AETE.

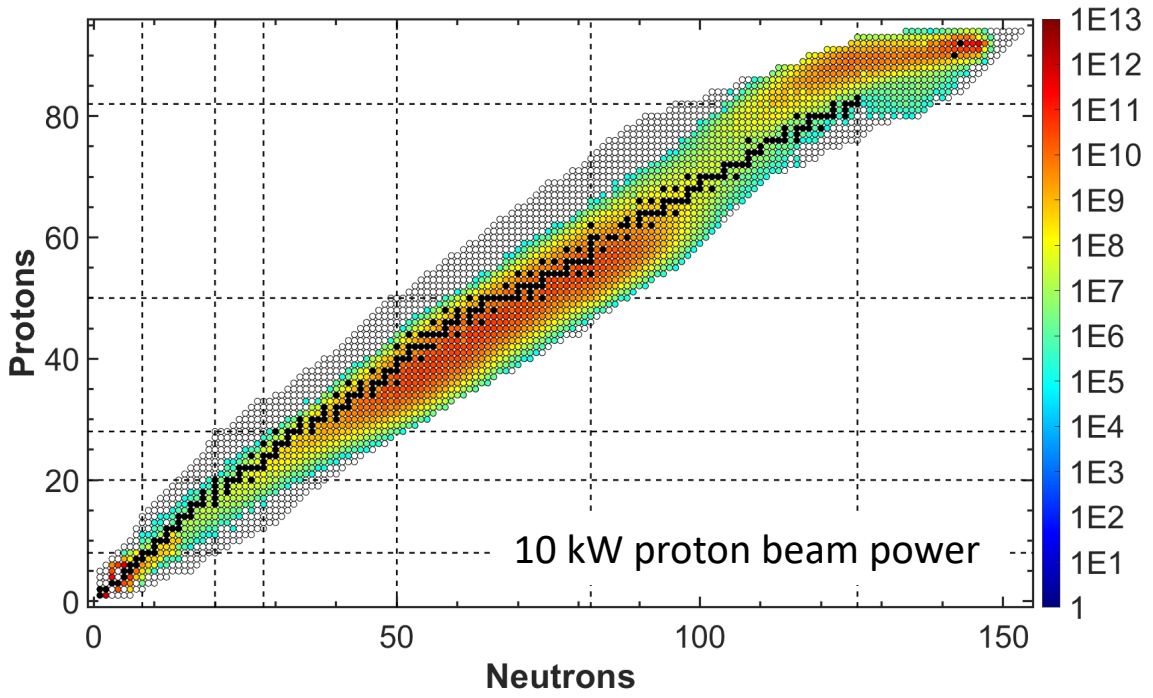
→ ISAC isotope extraction efficiencies not directly applicable to ARIEL AETE, but best assumption available…

Projecting ARIEL AETE Yields

FLUKA AETE in-target isotope production rates from UC_x [1/s]



FLUKA ISAC in-target isotope production rates from UC_x [1/s]



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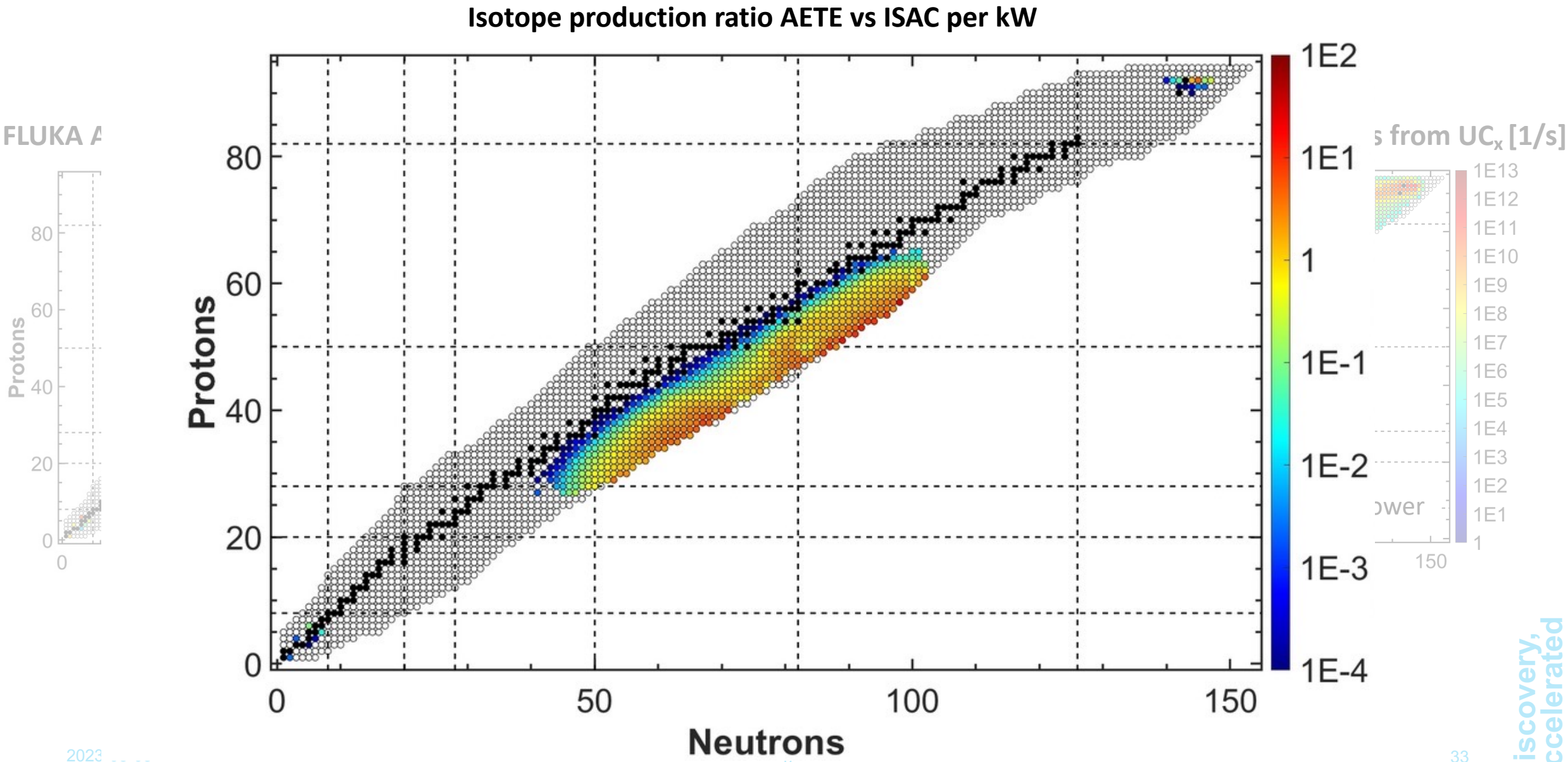
Projecting ARIEL AETE Yields



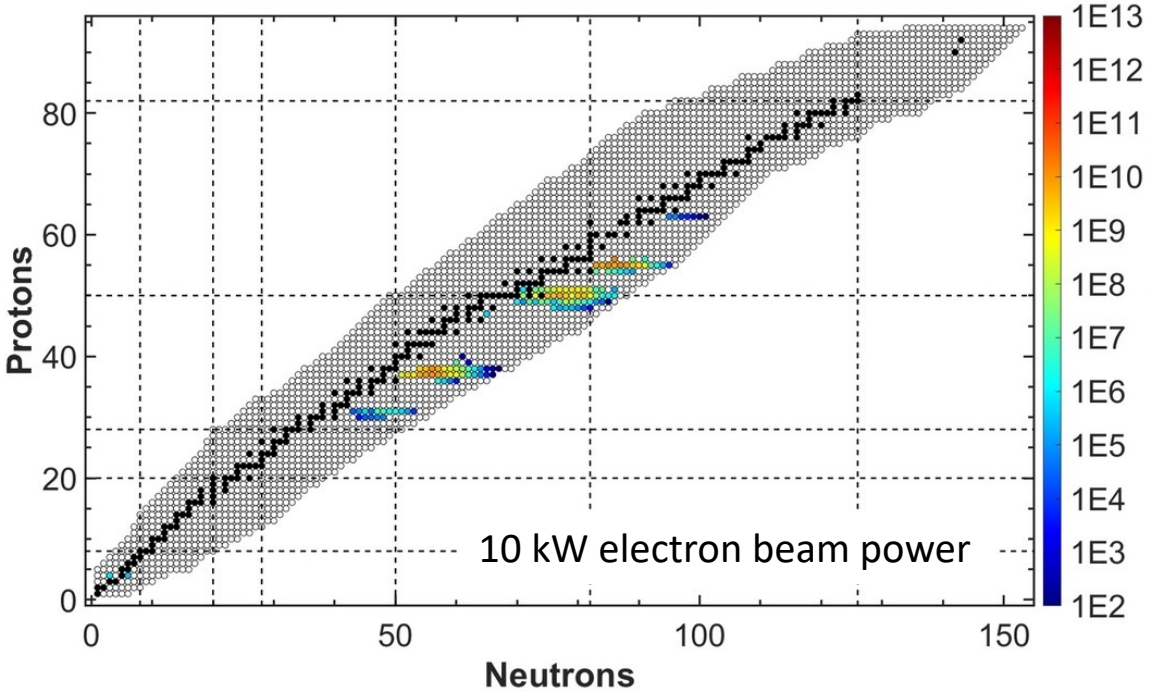
Discovery, accelerated

ARIEL AETE and APTW Projected Yields

Initial ARIEL AETE yields projected using measured ISAC-UC_x isotope extraction efficiencies

Differences in geometry and material microstructure will require confirmation and additional R&D

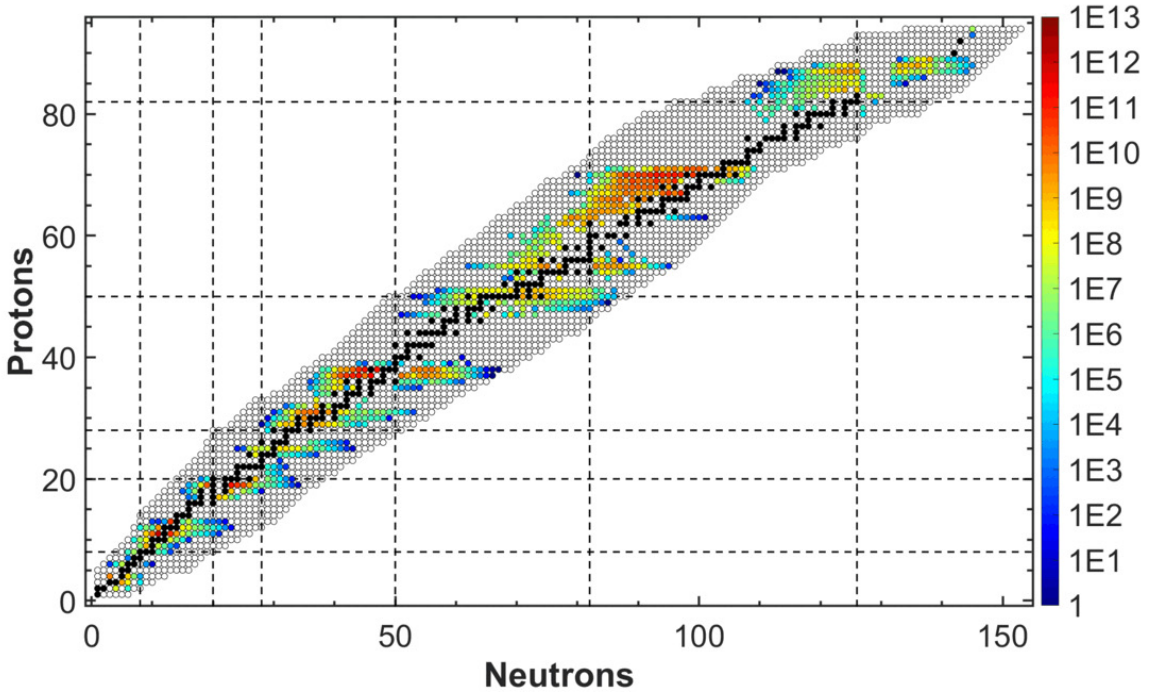
Projected LE Isotope Rates from AETE [1/s]



Initial ARIEL APTW yields will be comparable to current average ISAC yields

And: capabilities for new target materials, target ion source concepts, molecular beam formation, etc

Projected LE Isotope Rates from APTW [1/s]



→ *See Greg Hackman: Early Science at ARIEL, 9:15 am*


Recent accomplishments already nurture many science and international collaboration opportunities.

Hub for Training and R&D

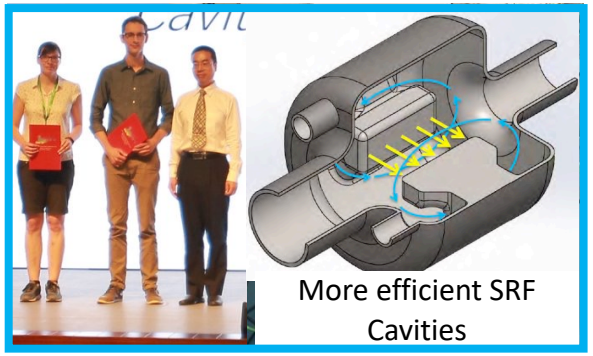
ARIEL is a platform for student projects across all disciplines (engineering, engineering, math, physics, graphics design, chemistry) and all levels (high school students, 30+ coop students, 8+ master students, 10+ PhD students, post-docs)

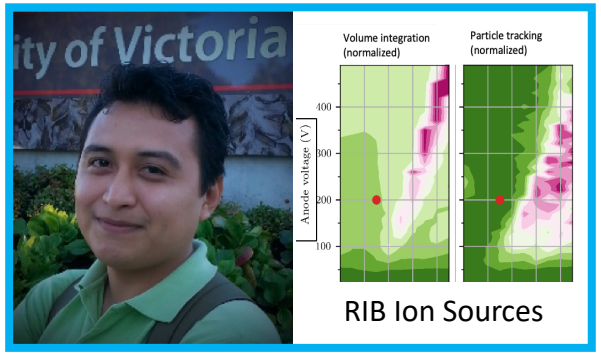
Example: The joint University of Victoria /TRIUMF accelerator research program

- 2 joint faculty positions,
- NSERC grant for student support in accelerator physics since 2011
  - 6 PhD, 4 MSc (6 international)
  - So far 1 PhD and 4 MSc theses finished
- One lecture taught by the adjunct faculty each year
- Research topics:
  - Beam physics and instrumentation (R. Baartman, T. Planche, O. Kester)
  - Superconducting RF (R. Laxdal, T. Junginger)
  - Ion Sources and Targets (A. Gottberg, T. Day Goodacre, O. Kester)

→ *See Tobias Junginger: Accelerator Physics and ARIEL, 10:55 am*

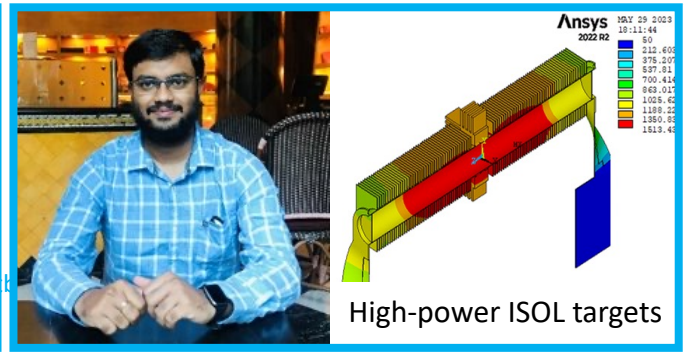
Material Radiation Damage


More efficient SRF Cavities

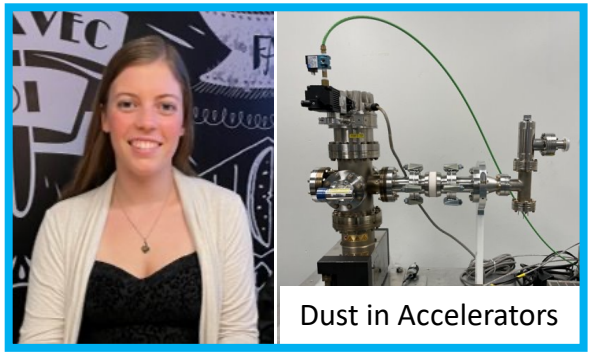


RIB Ion Sources

Target Materials



High-power ISOL targets


Dust in Accelerators

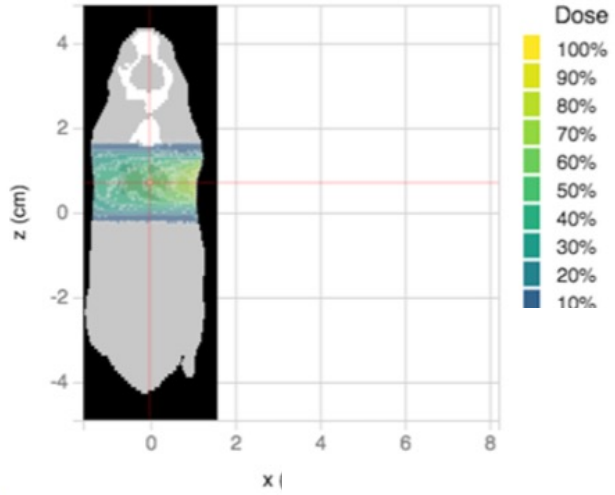
TRIUMF

→ *See Greg Hackman: Early Science at ARIEL, 9:15*

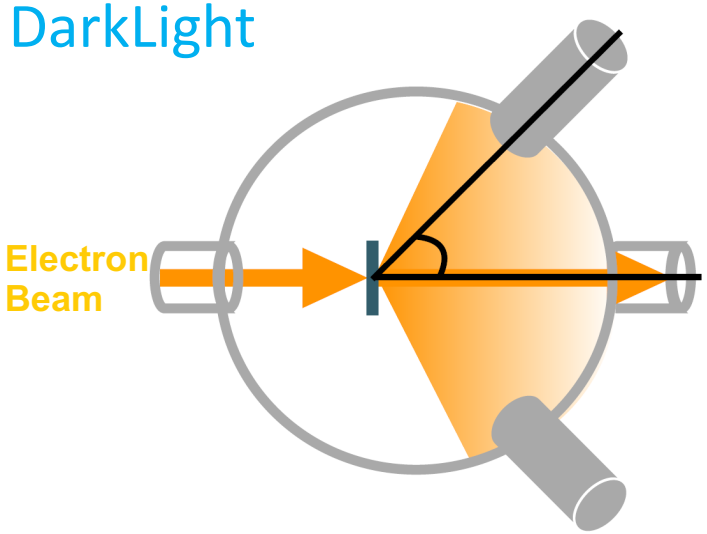
Early Science at the ARIEL e-linac

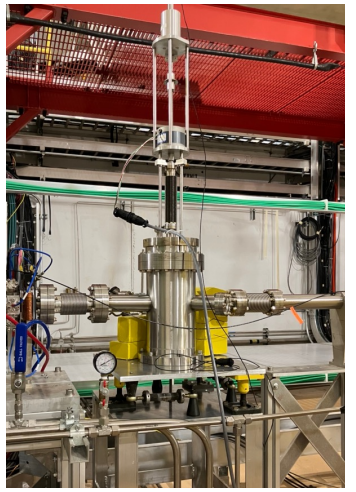
X-Ray FLASH Radiotherapy Research

Cancer radiotherapy with greatly reduced side effects

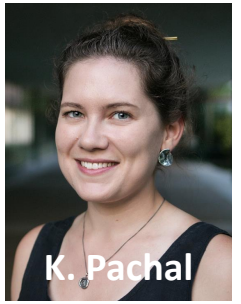


DarkLight





Search for dark matter



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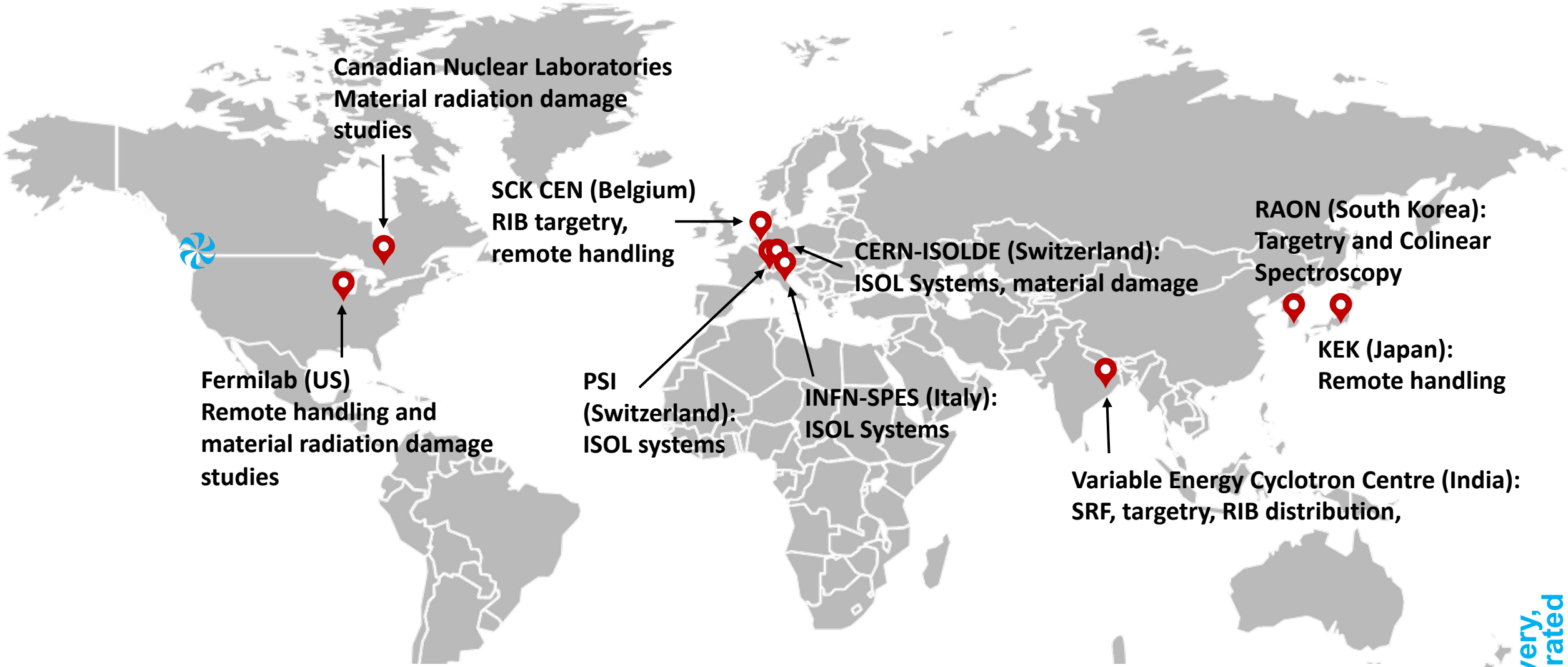
Saint Mary's University · Jefferson Lab · University of Manitoba · The University of Winnipeg Foundation · Hampton University · Arizona State University · Stony Brook University · Massachusetts Institute of Technology · JGU Johannes Gutenberg Universität Mainz · UBC · TRIUMF

Selected ARIEL Technology International Collaborations



→ See Arup Bandyopadhyay: TRIUMF/VECC collaboration towards ARIEL/ANURIB, 11:15 am

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Thank you
Merci

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