TRIUMF

High-Power Targets for Radioisotope Beam Production

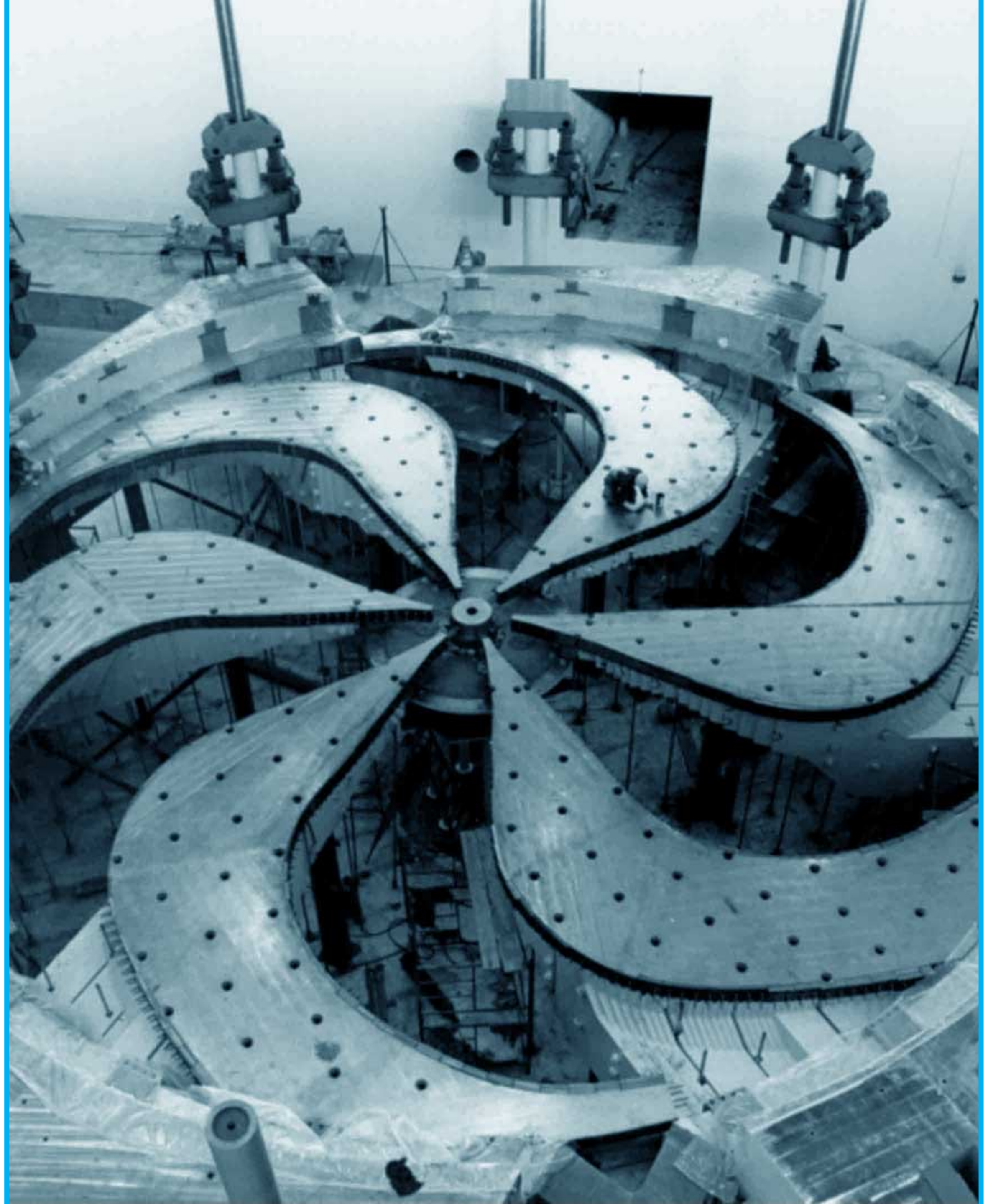
Alexander Gottberg

Department Head, Targets and Ion Sources

Professor of Physics, University of Victoria

September 28, 2022

INTDS 2022, Paul Scherrer Institut



Discovery, accelerated

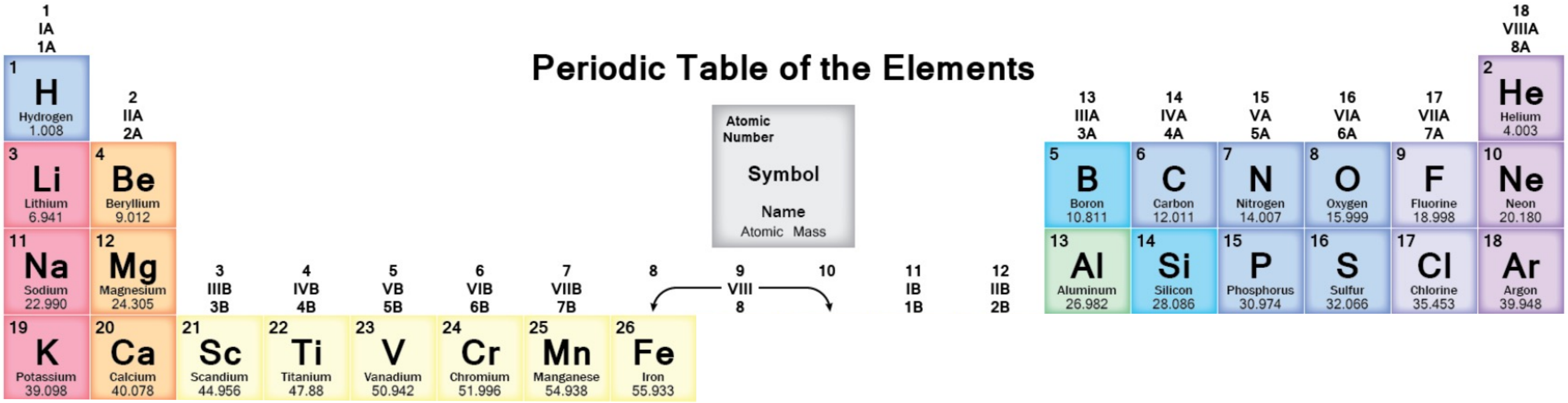
Periodic Table of the Elements

Atomic Number
Symbol
Name
Atomic Mass

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

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



Most nuclear properties of stable isotopes and long-lived radioisotopes known (half lives, binding energy, nuclear reaction cross sections)

→ nucleosynthesis during stellar burning of elements up to iron understood

Periodic Table of the Elements

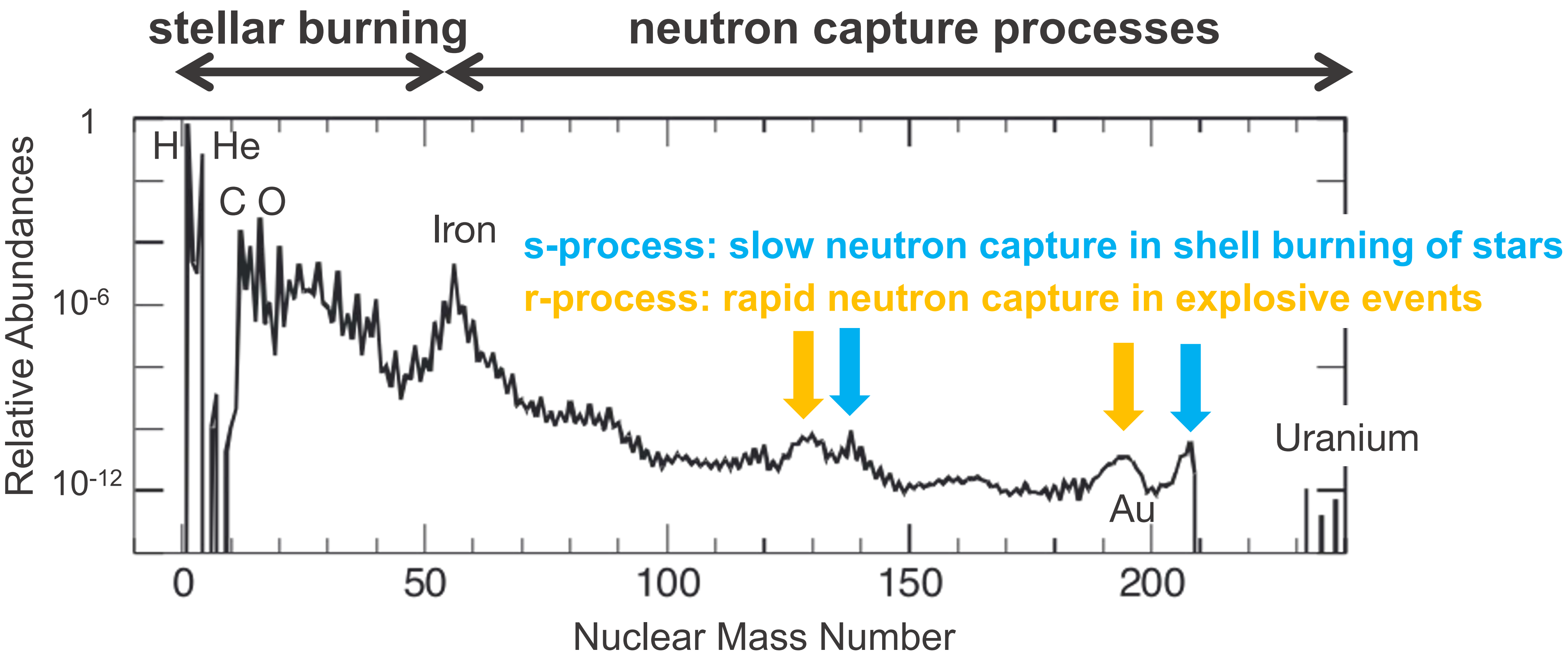
Atomic Number
Symbol
Name
Atomic Mass

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

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]

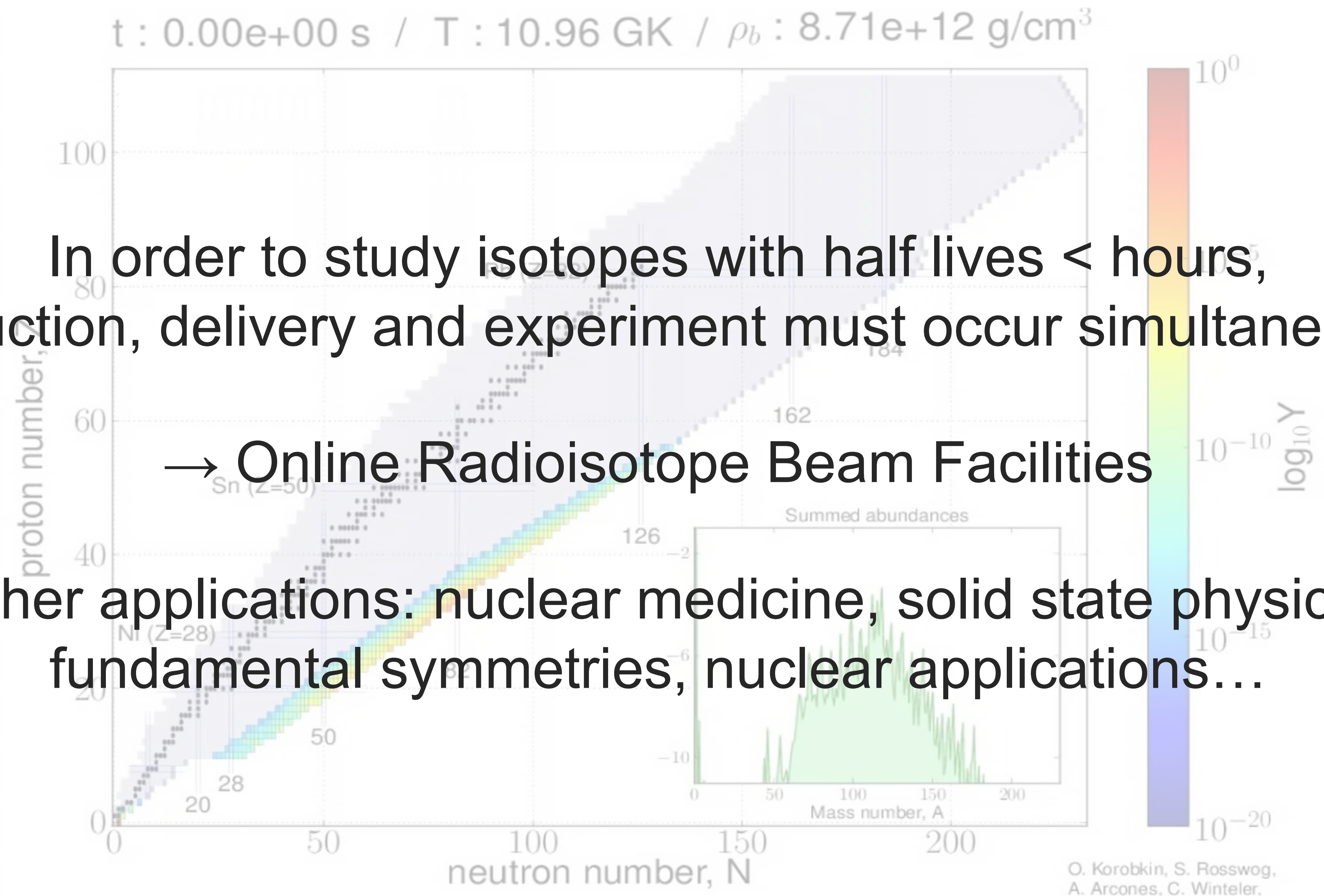
Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide

How are the elements made that make up our world?



Discovery, accelerated

Isotope Production Simulation in Neutron Star Merger



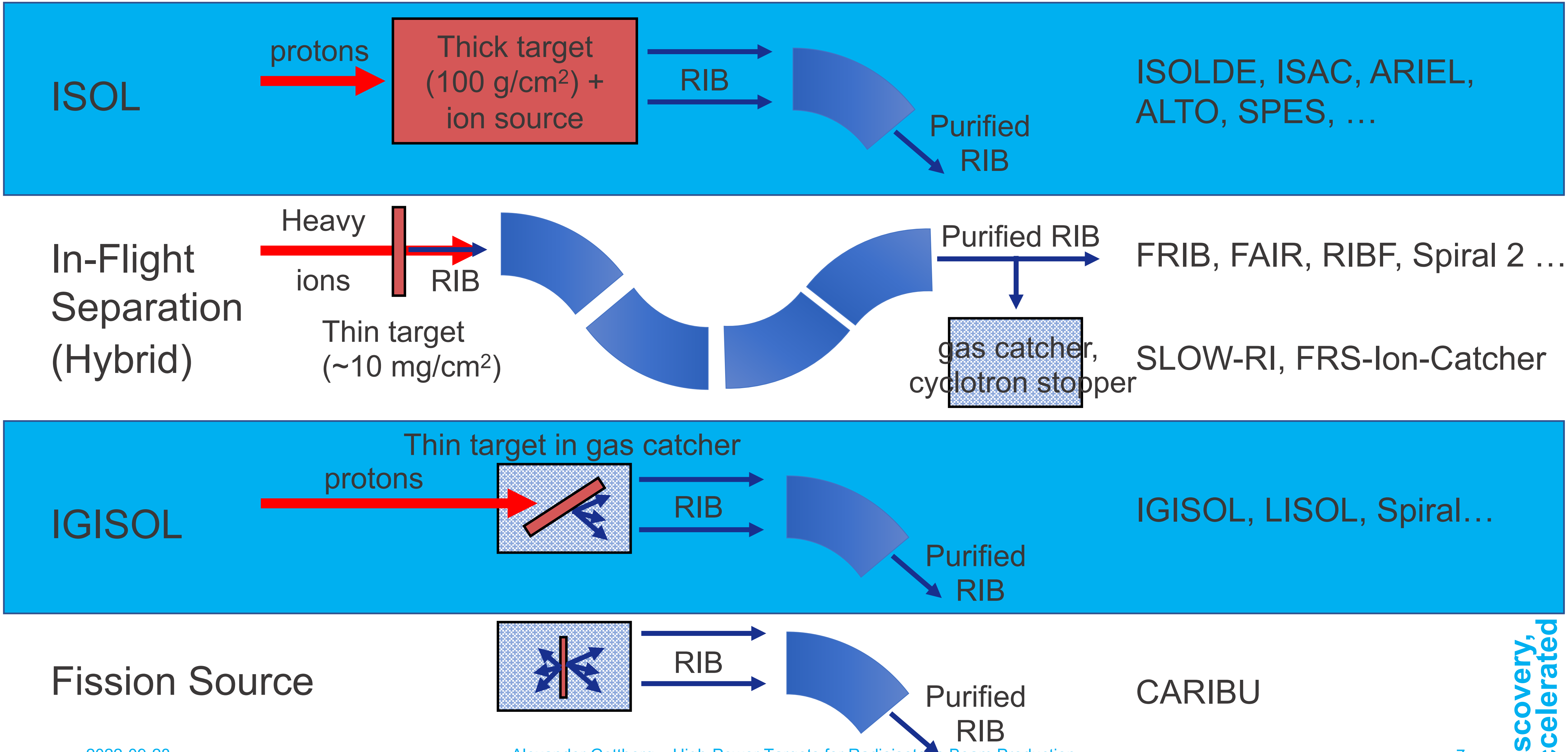
O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379

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…

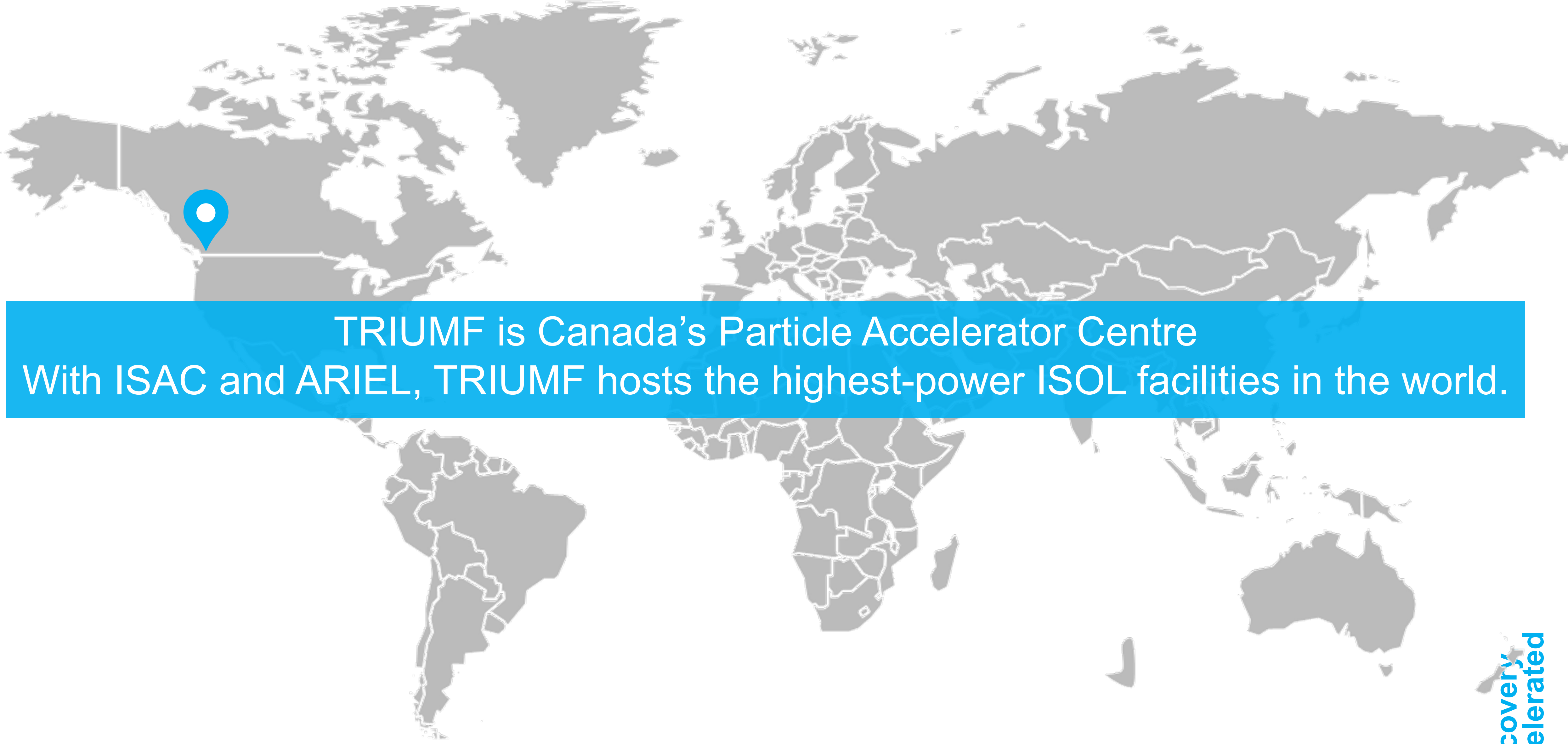
Versions of Radioactive Ion Beam Production



Radioisotope Beam Facilities World-Wide

Discovery accelerated

TRIUMF



TRIUMF is Canada’s Particle Accelerator Centre

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

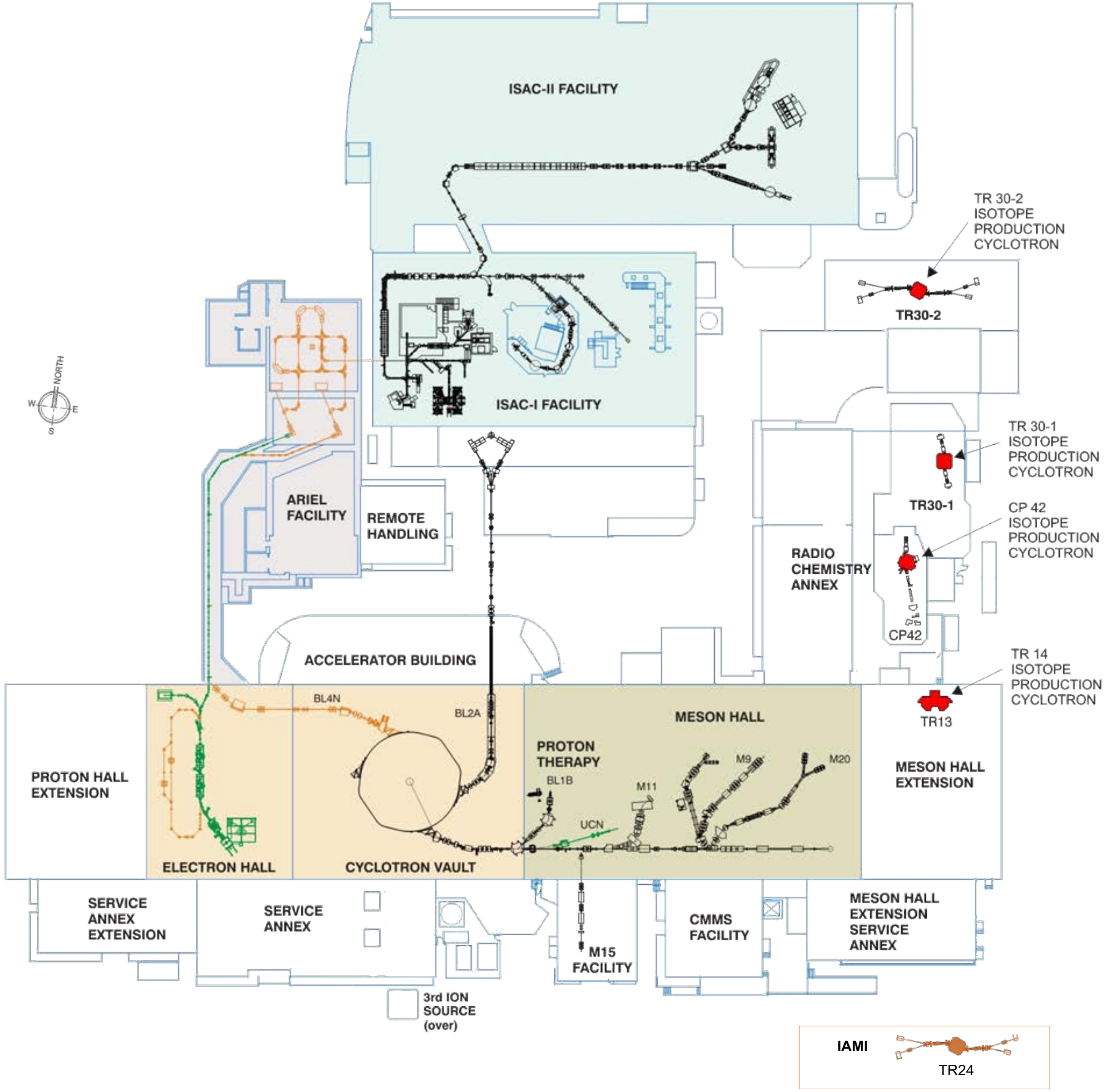
Discovery, accelerated

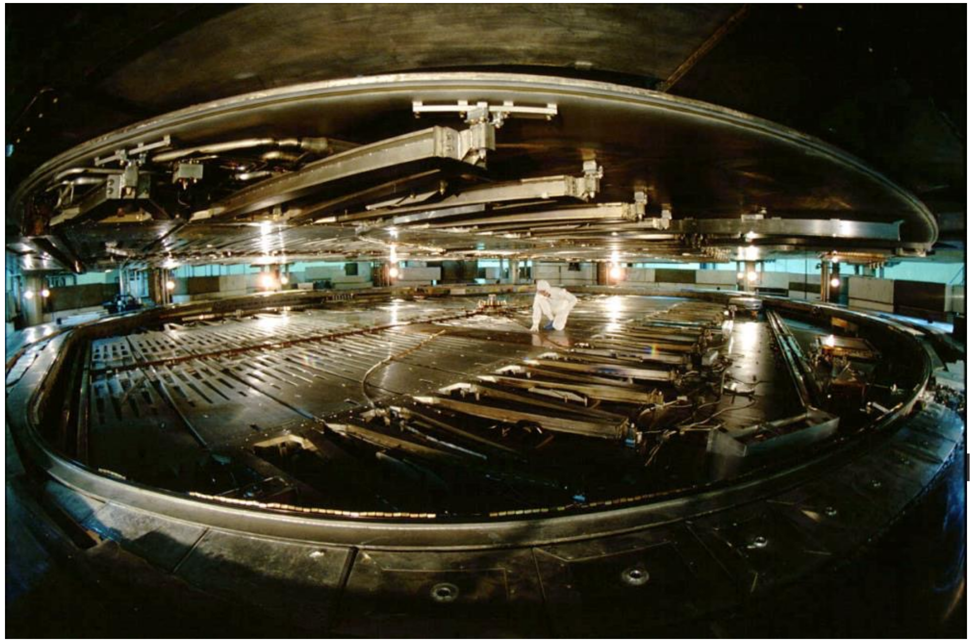
TRIUMF has five decades of experience in building a rich particle accelerator infrastructure that enables cutting-edge multidisciplinary research while growing accelerator expertise.

TRIUMF

TRIUMF

Primary and Secondary Particle Accelerators at TRIUMF





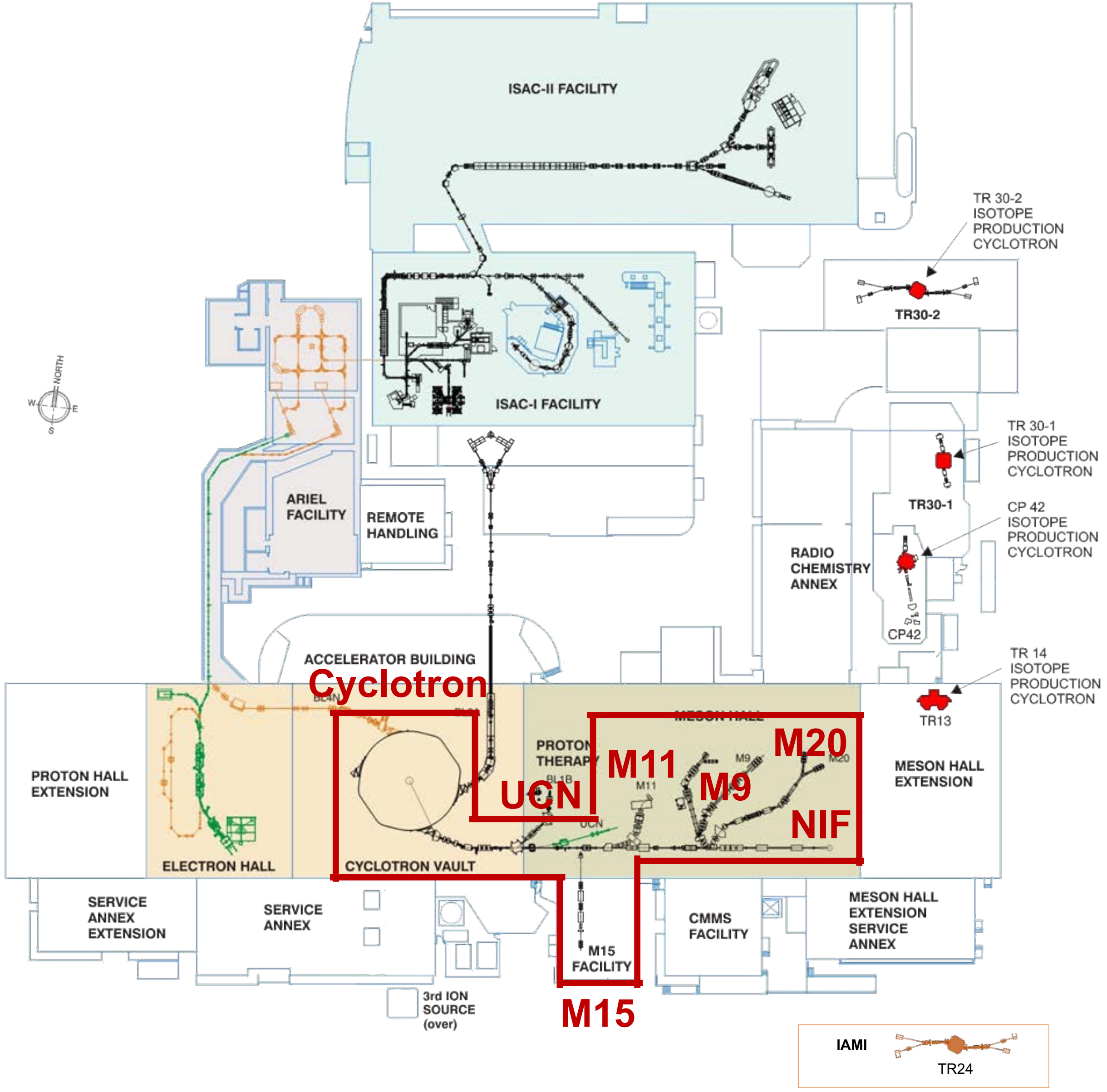
520 MeV H^- cyclotron
5500 hours per year:

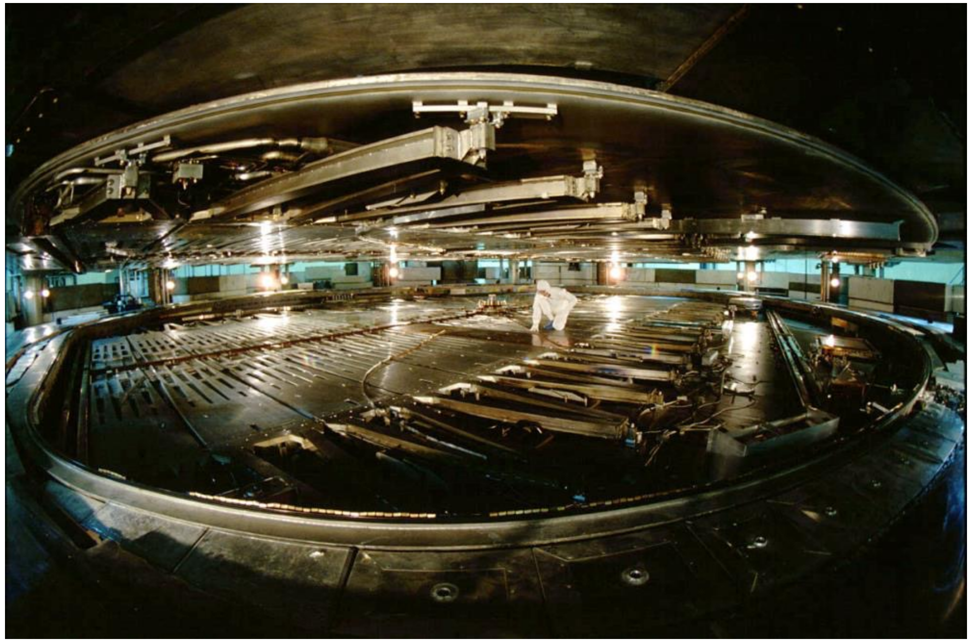
- ISOL RIB (50 kW protons)
- π and μ (60 kW)
- Medical isotopes (50 kW)
- Ultra-cold neutrons (20 kW)
- Proton therapy studies (50 W)

Discovery, accelerated

TRIUMF

TRIUMF's Proton, Neutron, Pion, Muon Programs





Beamline 1

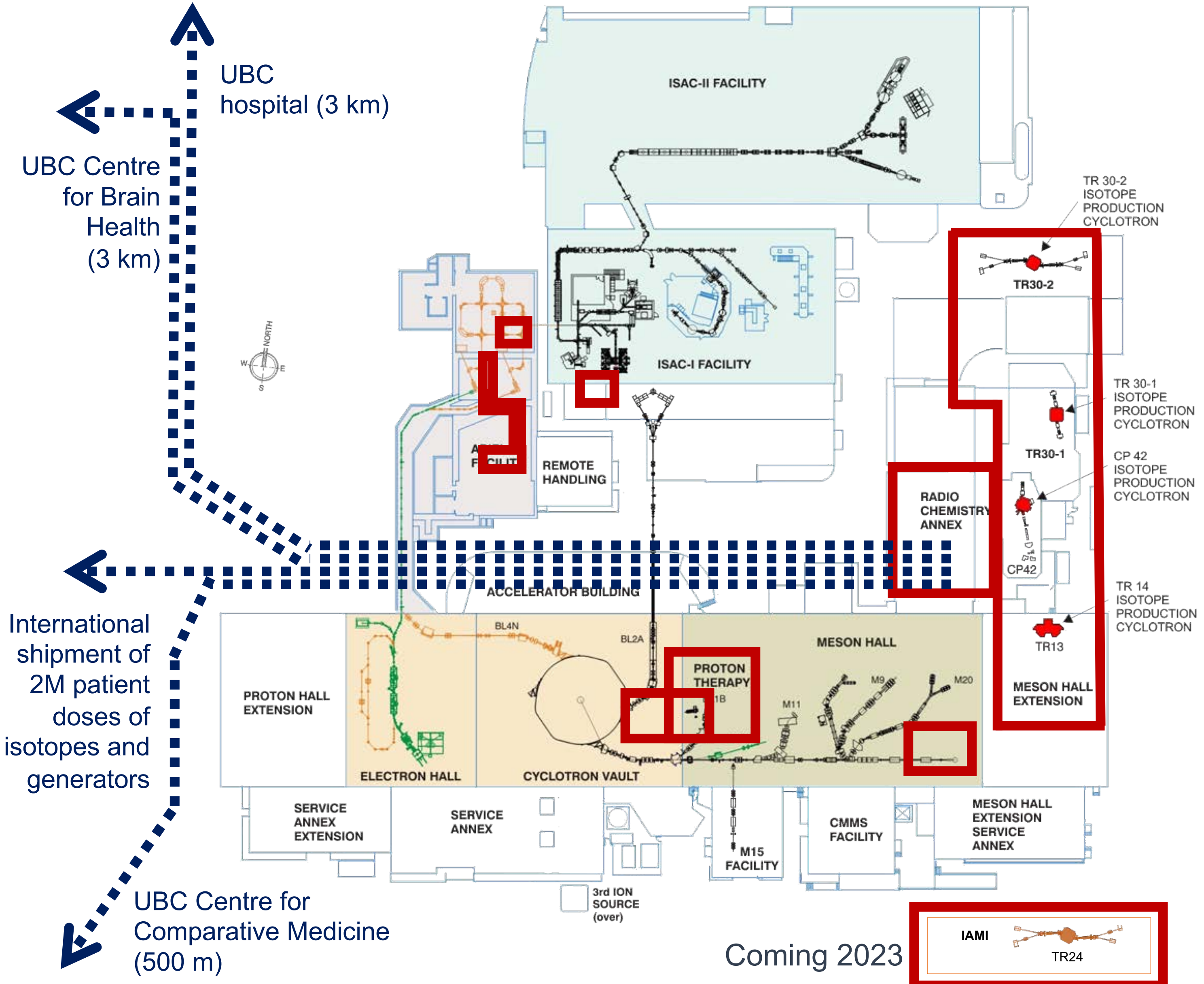
Nine secondary channels

- UCN (Ultra Cold Neutrons) for nEDM measurement
- Pions, muons for material and fundamental science
- Neutrons for electronics irradiations services

Discovery, accelerated

TRIUMF

TRIUMF’s Medical Isotope Factory



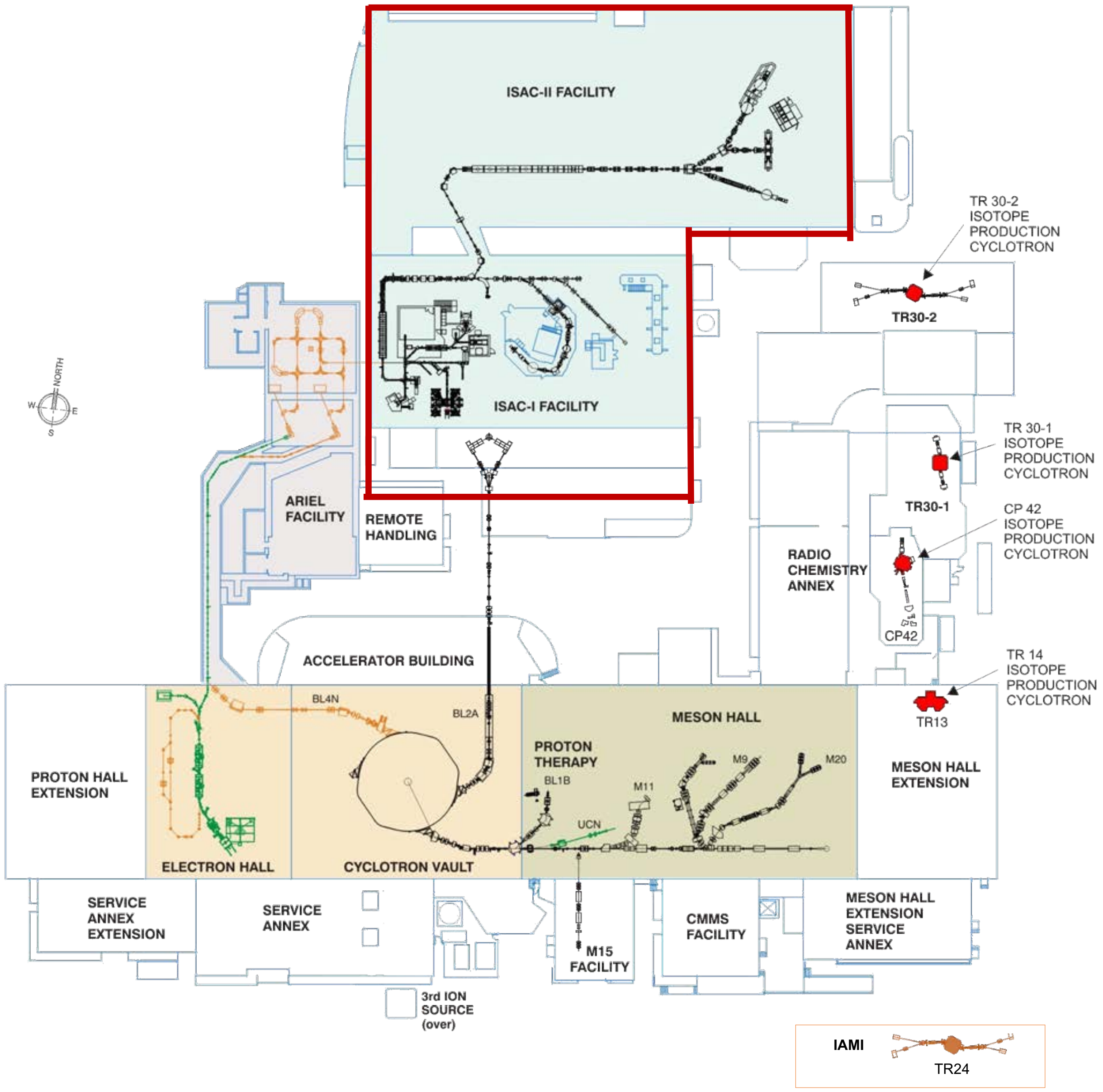
Five H$^-$ medical cyclotrons

- 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, <100 μA (solid, liquid and gas targets)
  - ^{11}C, ^{18}F, ^{64}Cu, ^{68}Ga, others…
- TR24, 1 mA (gas, solid, liquid targets)
  - Future for IAMI

Protons from 90-500 MeV, 300 μA cyclotron

- ^{82}Sr / ^{82}Rb production
- ^{212}Pb, ^{213}Bi, ^{225}Ac production
- Exotic medical isotope R&D, fission and spallation with optional isotope separation

ISAC – High-Power ISOL Facility



ISAC (Isotope Separator and Accelerator) since 1999

ISAC I:

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

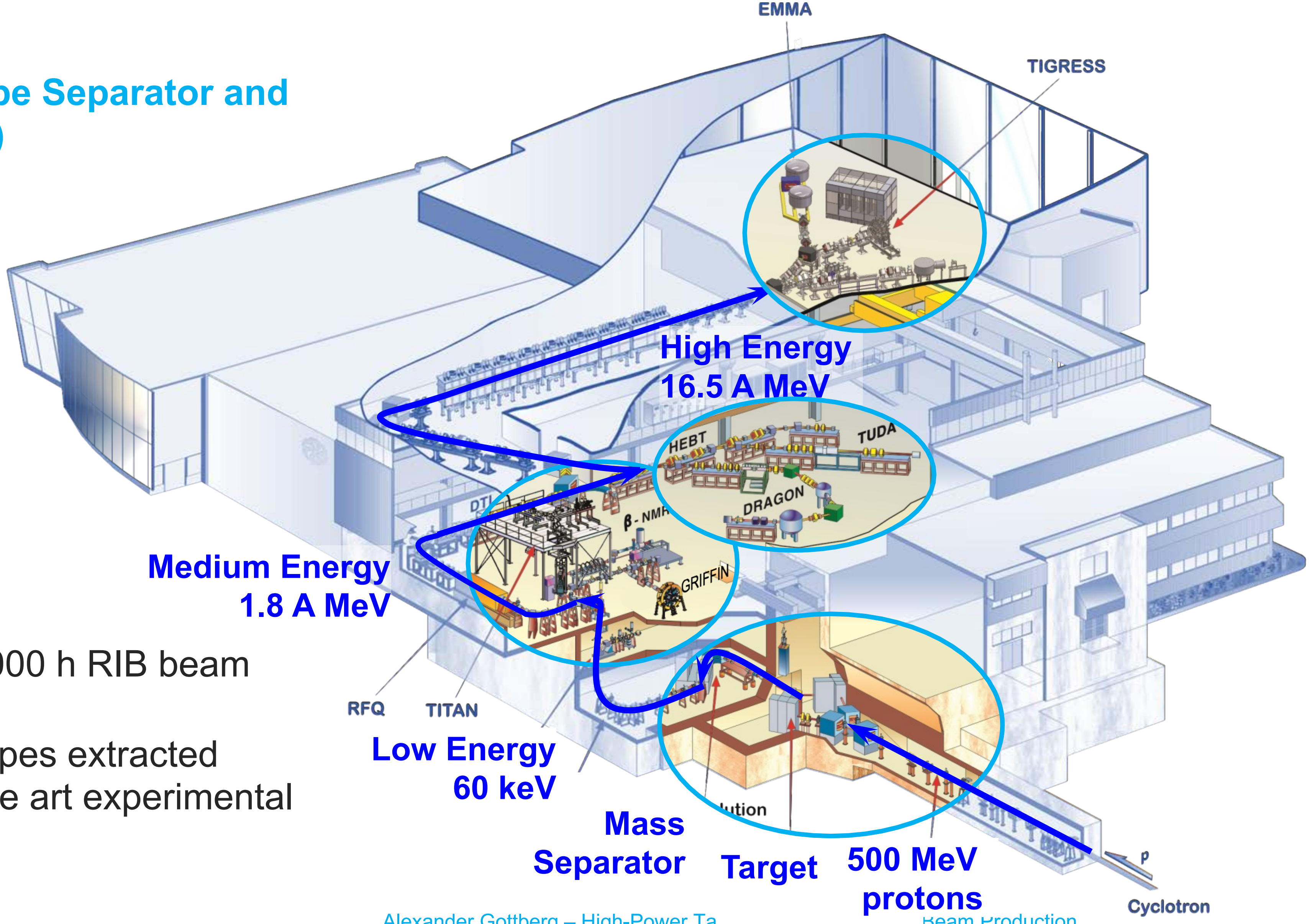
ISAC II:

- 6 - 15 MeV/u

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

ISAC – The Highest Power ISOL Facility in the World

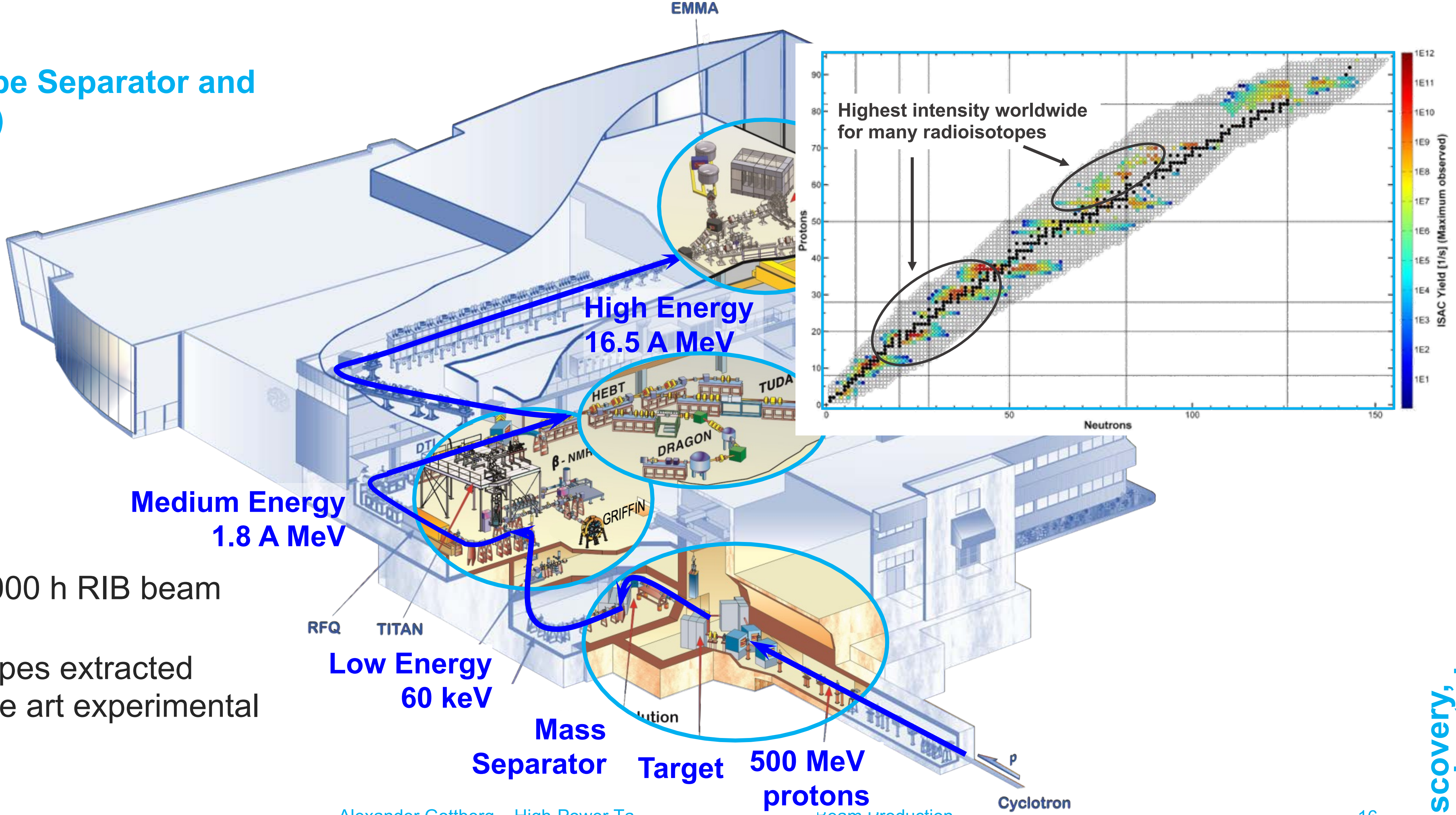
ISAC (Isotope Separator and Accelerator) since 1995



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

ISAC – The Highest Power ISOL Facility in the World

ISAC (Isotope Separator and Accelerator) since 1995

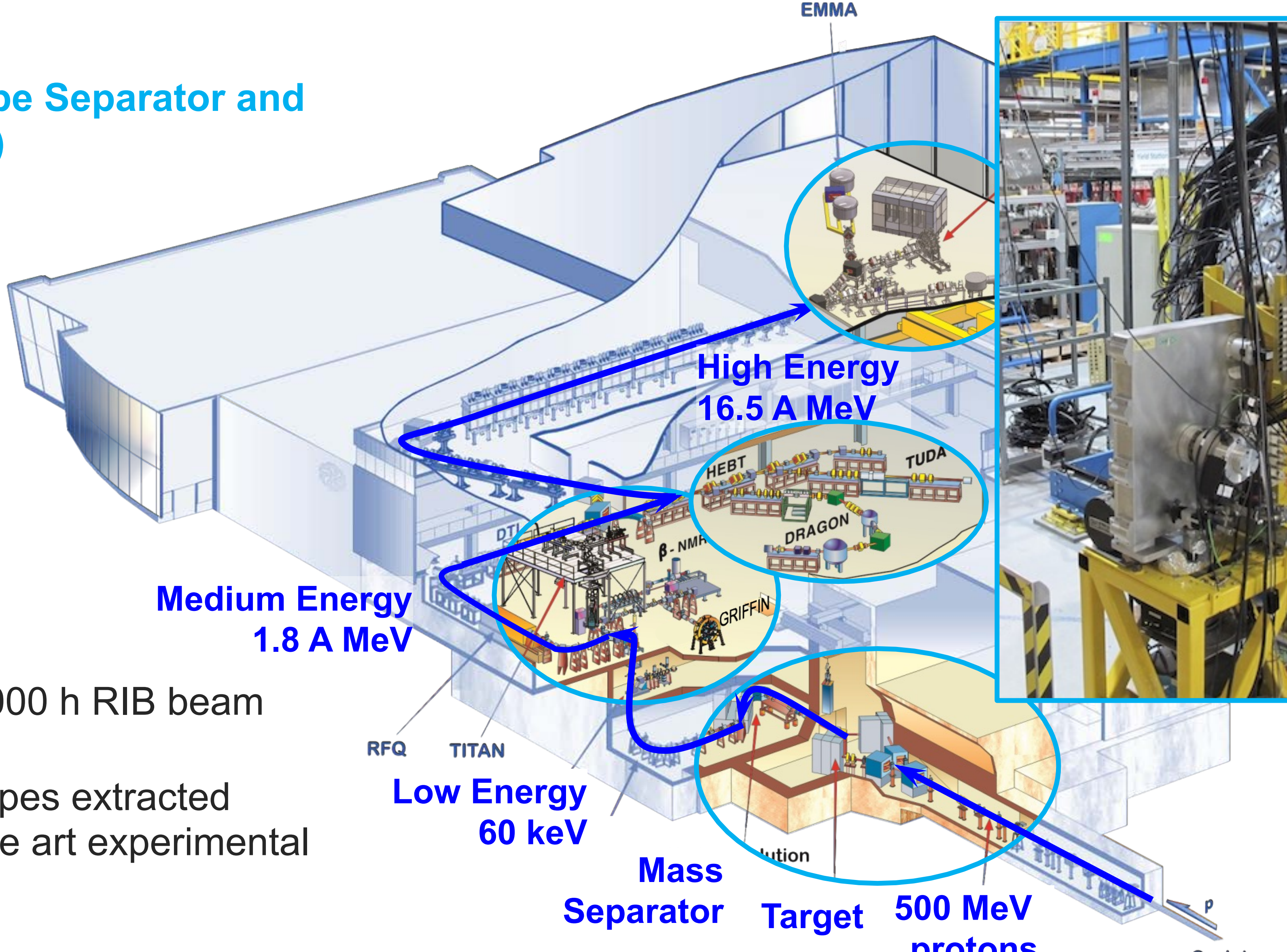


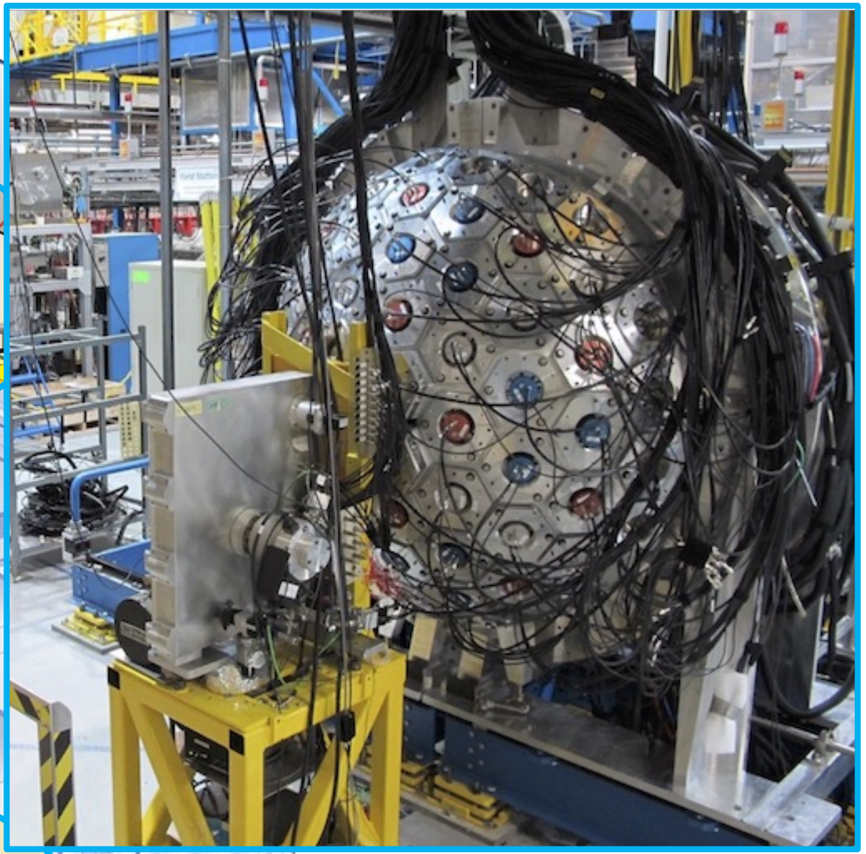
- Approx. 3000 h RIB beam per year
- >700 isotopes extracted
- State-of-the art experimental setups

Discovery, accelerated

ISAC – The Highest Power ISOL Facility in the World

ISAC (Isotope Separator and Accelerator)
since 1995

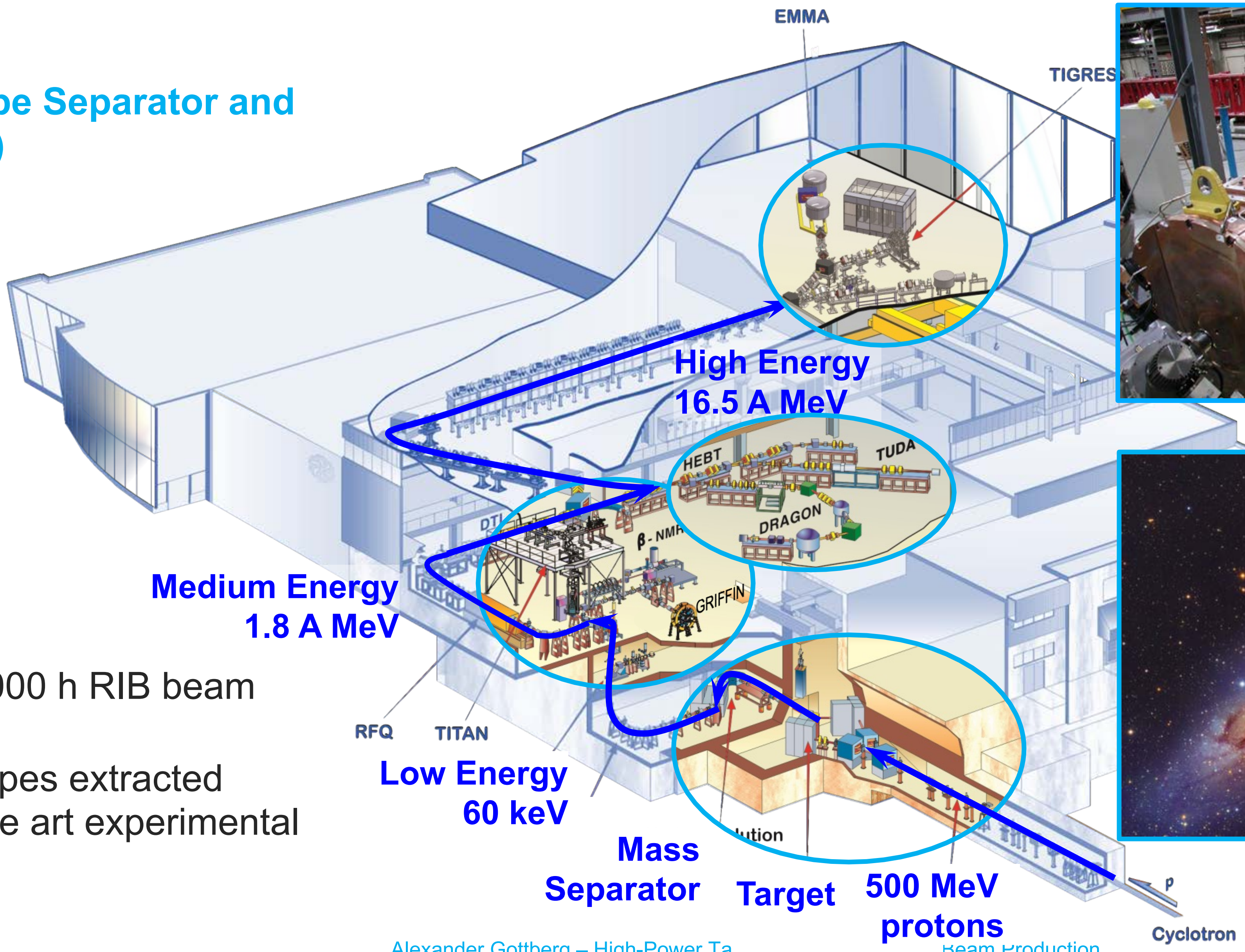


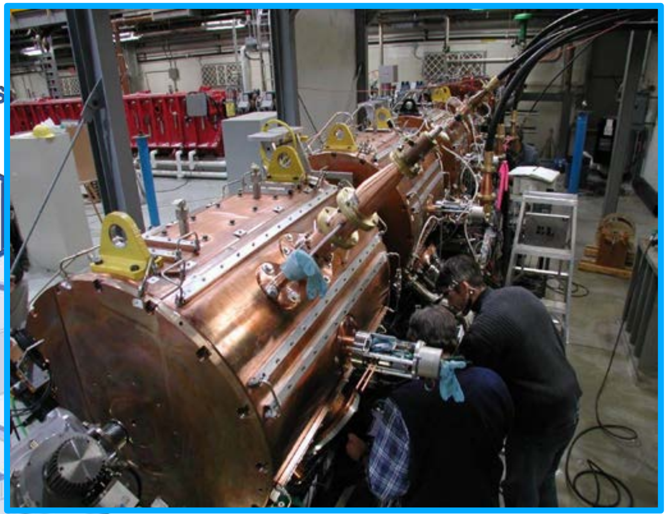


- Approx. 3000 h RIB beam per year
- >700 isotopes extracted
- State-of-the art experimental setups

ISAC – The Highest Power ISOL Facility in the World

ISAC (Isotope Separator and Accelerator) since 1995



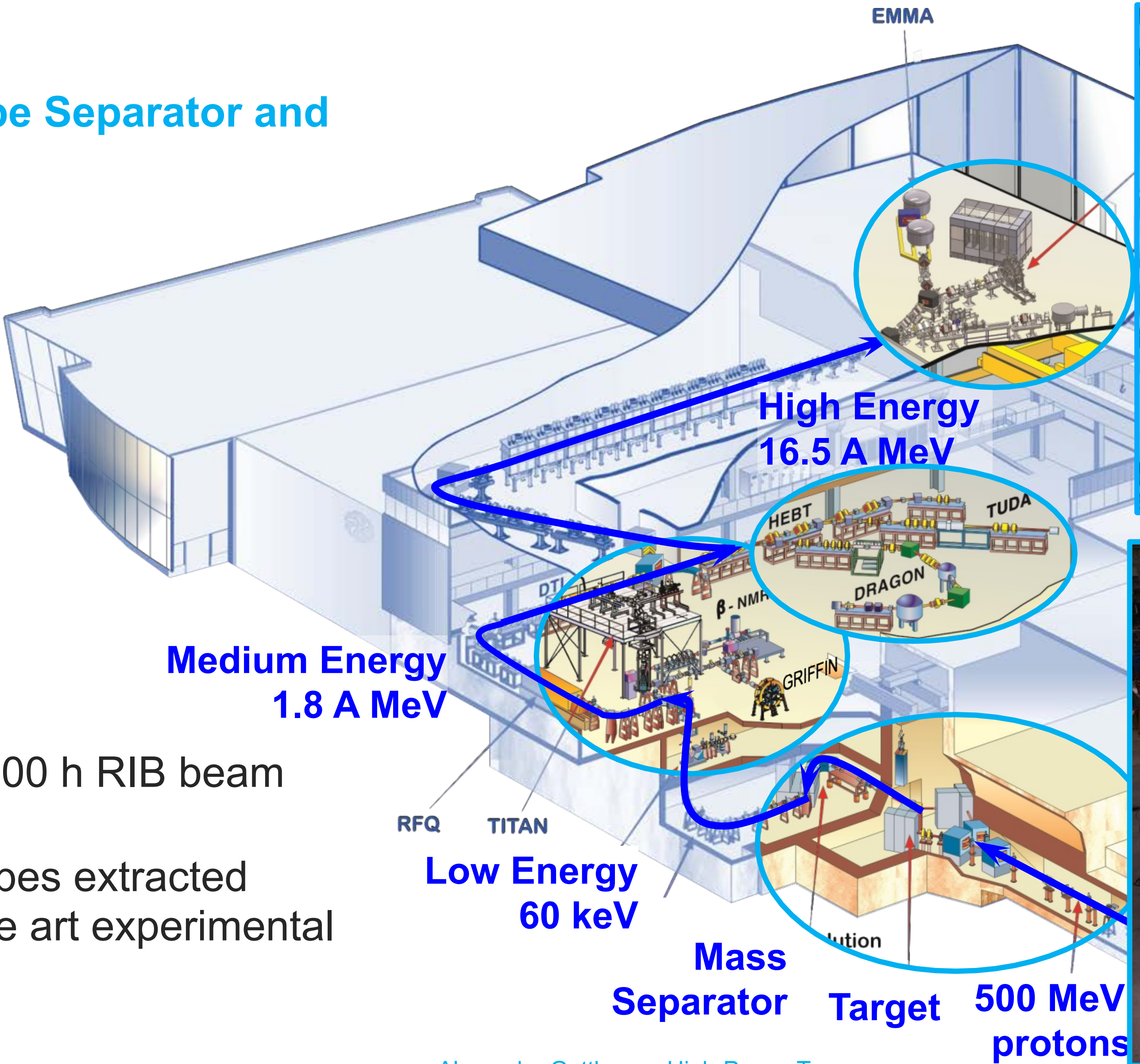


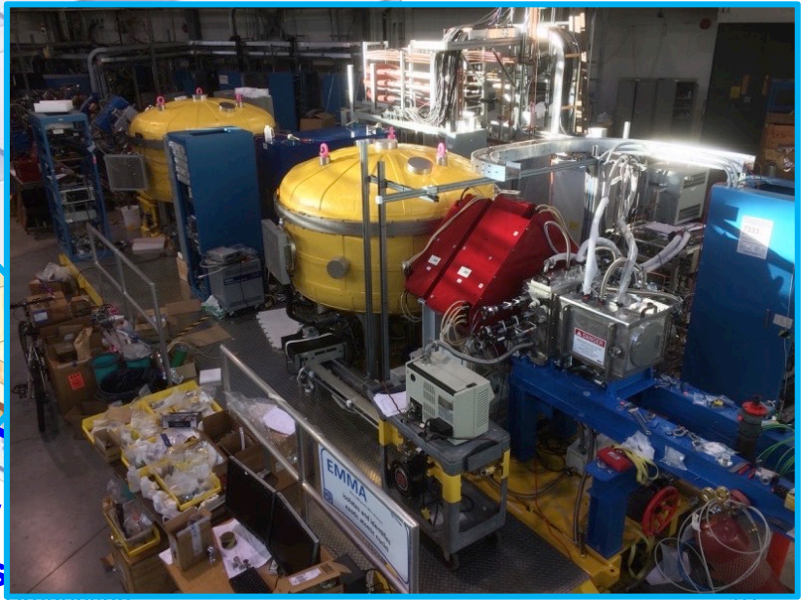
- Approx. 3000 h RIB beam per year
- >700 isotopes extracted
- State-of-the art experimental setups

Discovery, accelerated

ISAC – The Highest Power ISOL Facility in the World

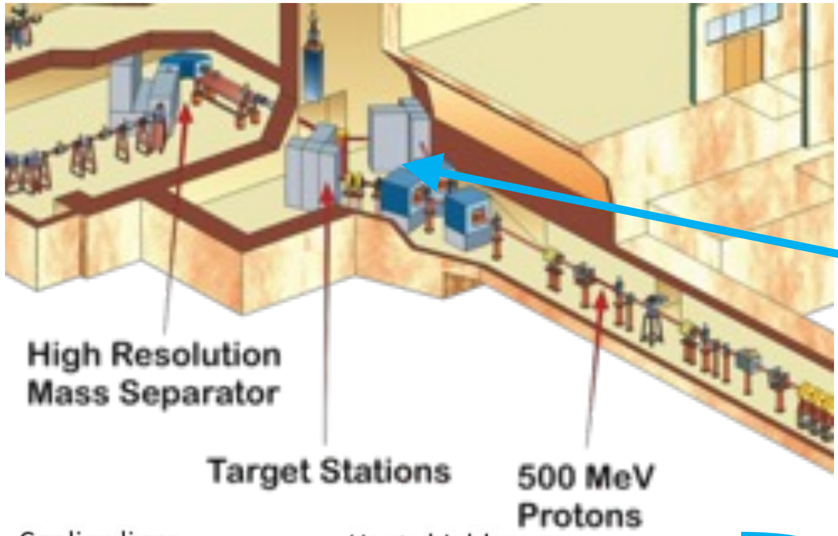
ISAC (Isotope Separator and Accelerator) since 1995

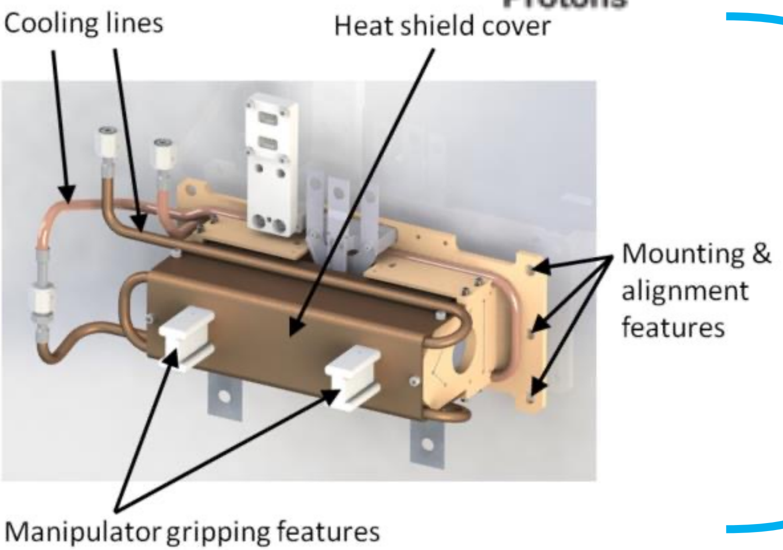




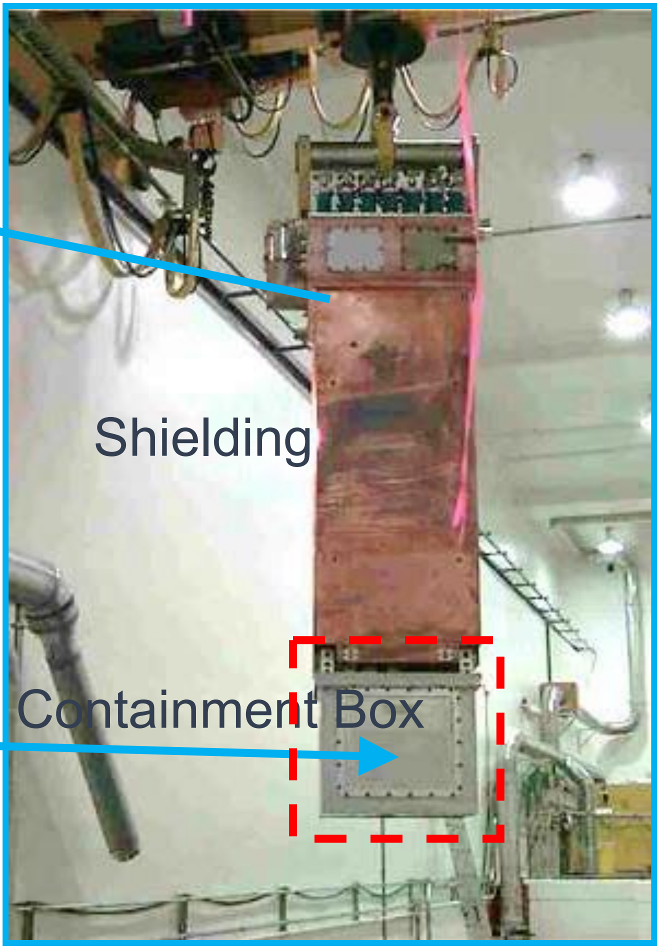
- Approx. 3000 h RIB beam per year
- >700 isotopes extracted
- State-of-the art experimental setups

ISAC Target Stations / Target Modules

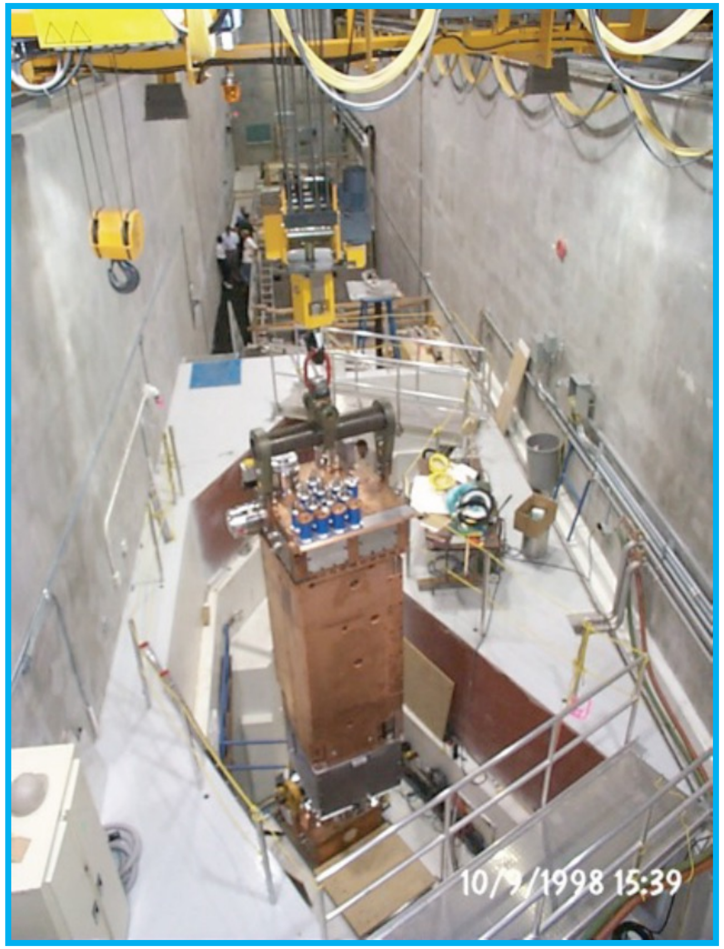




Target assembly is mounted on the extraction Front End in the Target Module containment box

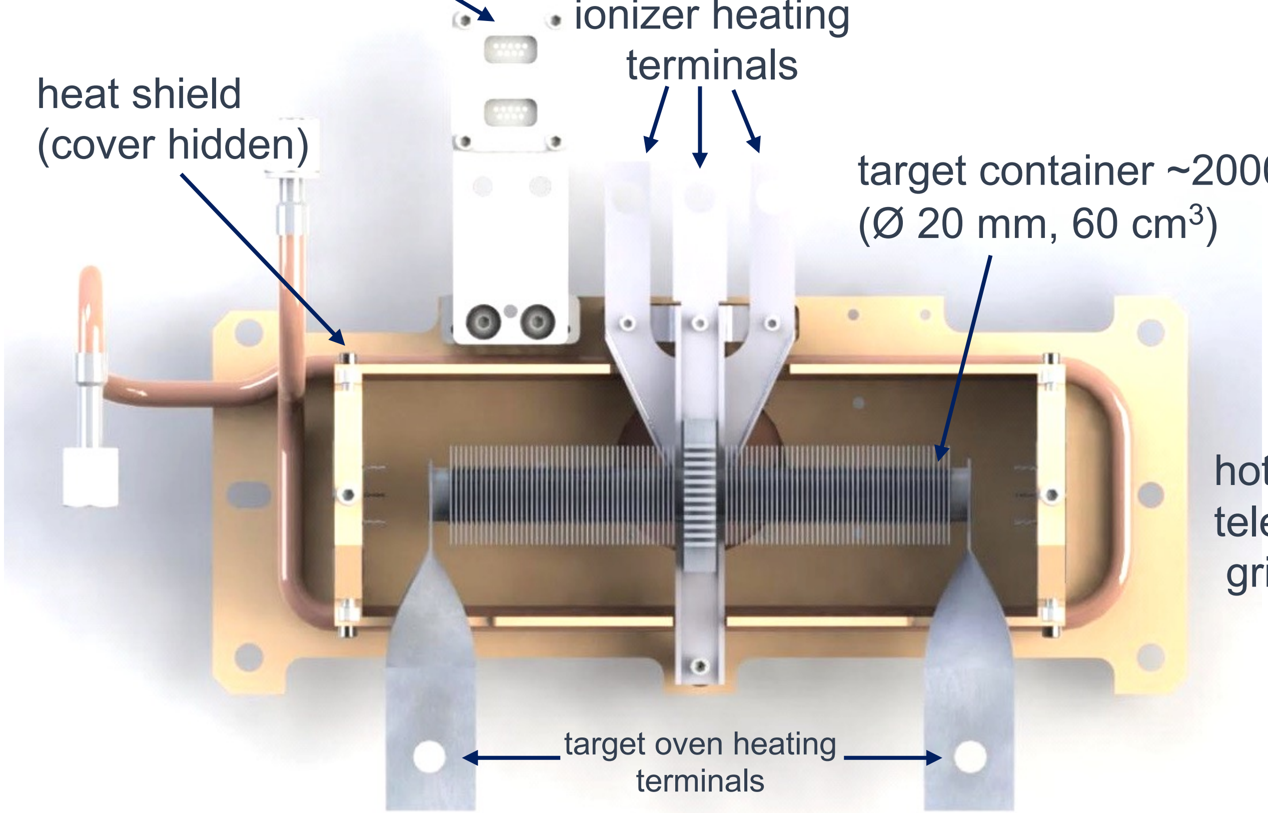


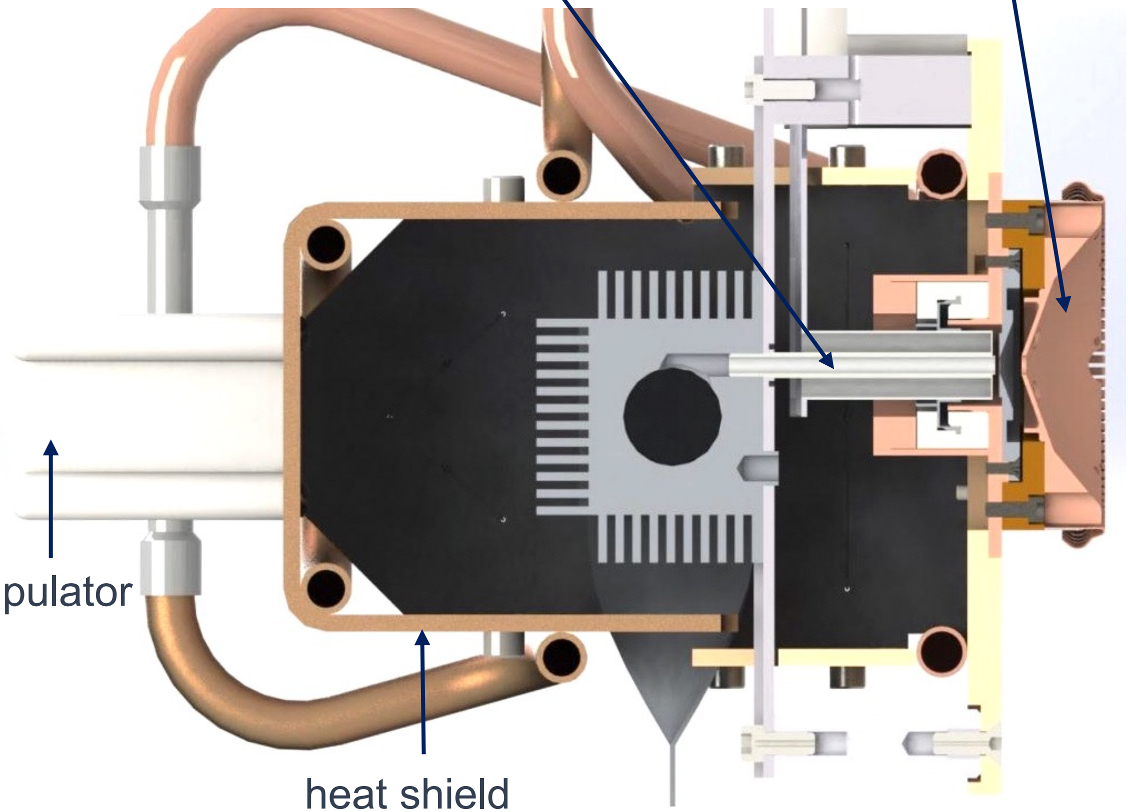
ISAC Target module hanging from remote handling crane



Target module transport to target station

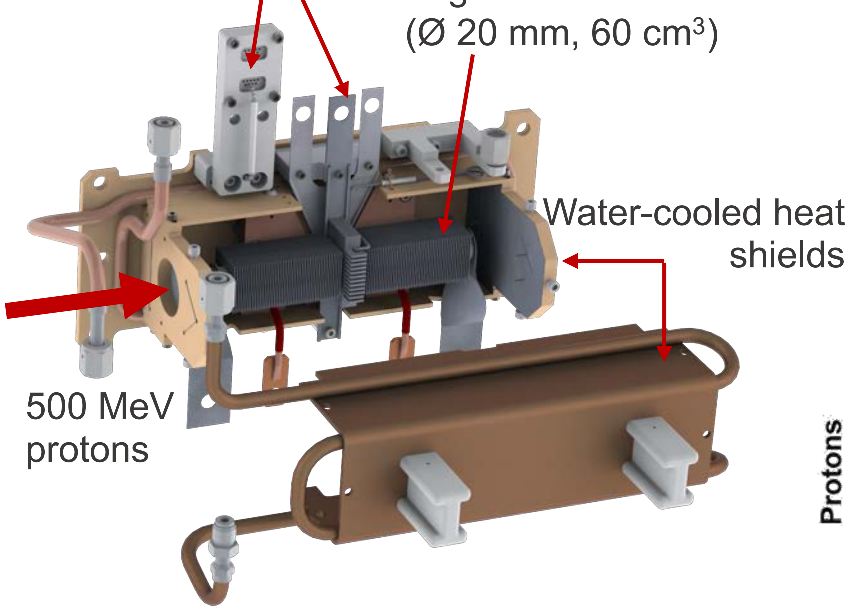
ISAC 50 kW Target Assembly

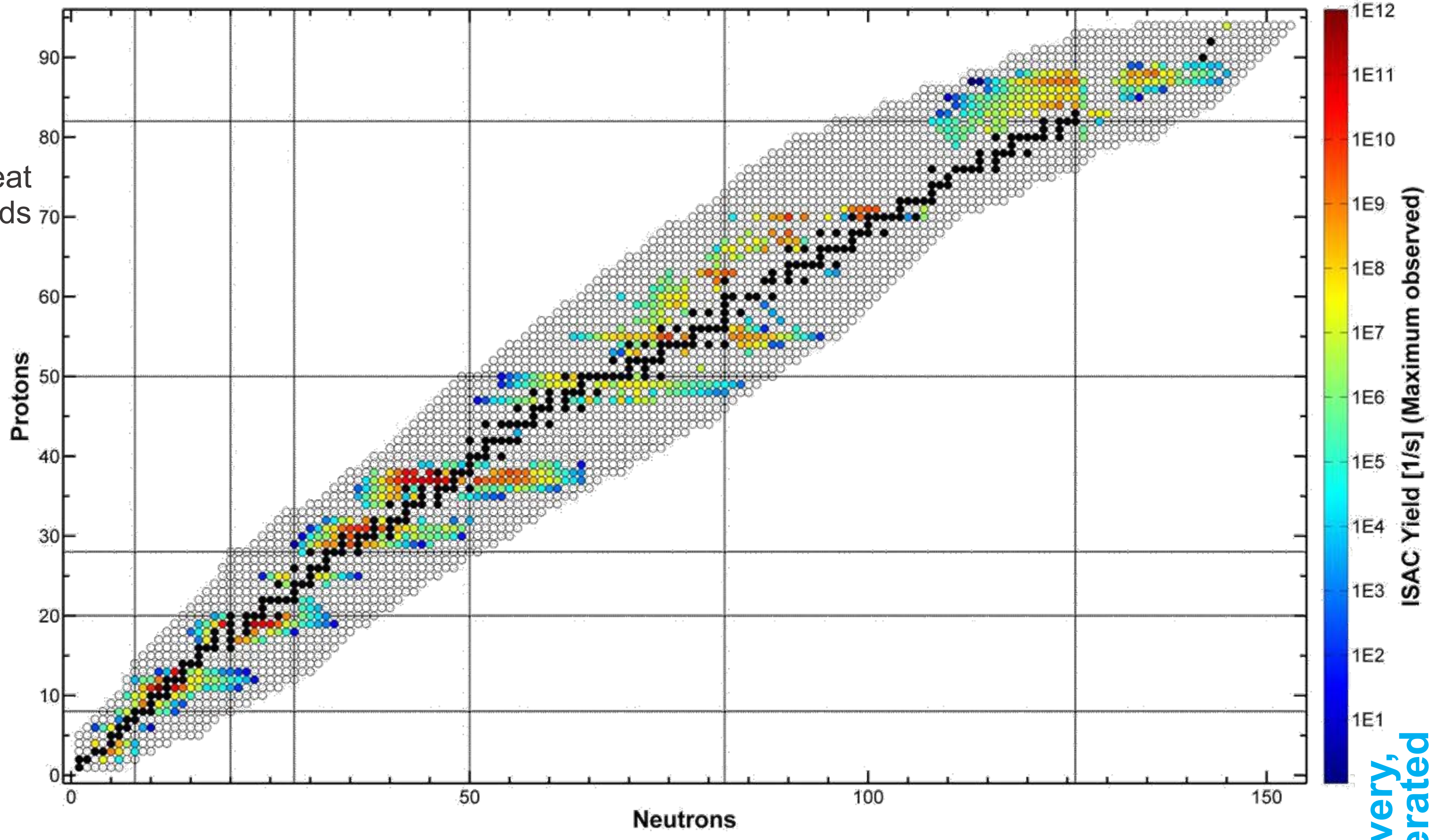




diffusion bonded Ta fins
→ radiative cooling of up to 13 kW
→ 50 kW proton irradiation

ISAC Radioisotope Beams Since 1998





ion sources:

- surface
- resonant lasers
- FEBIAD
- IG-LIS

target materials:

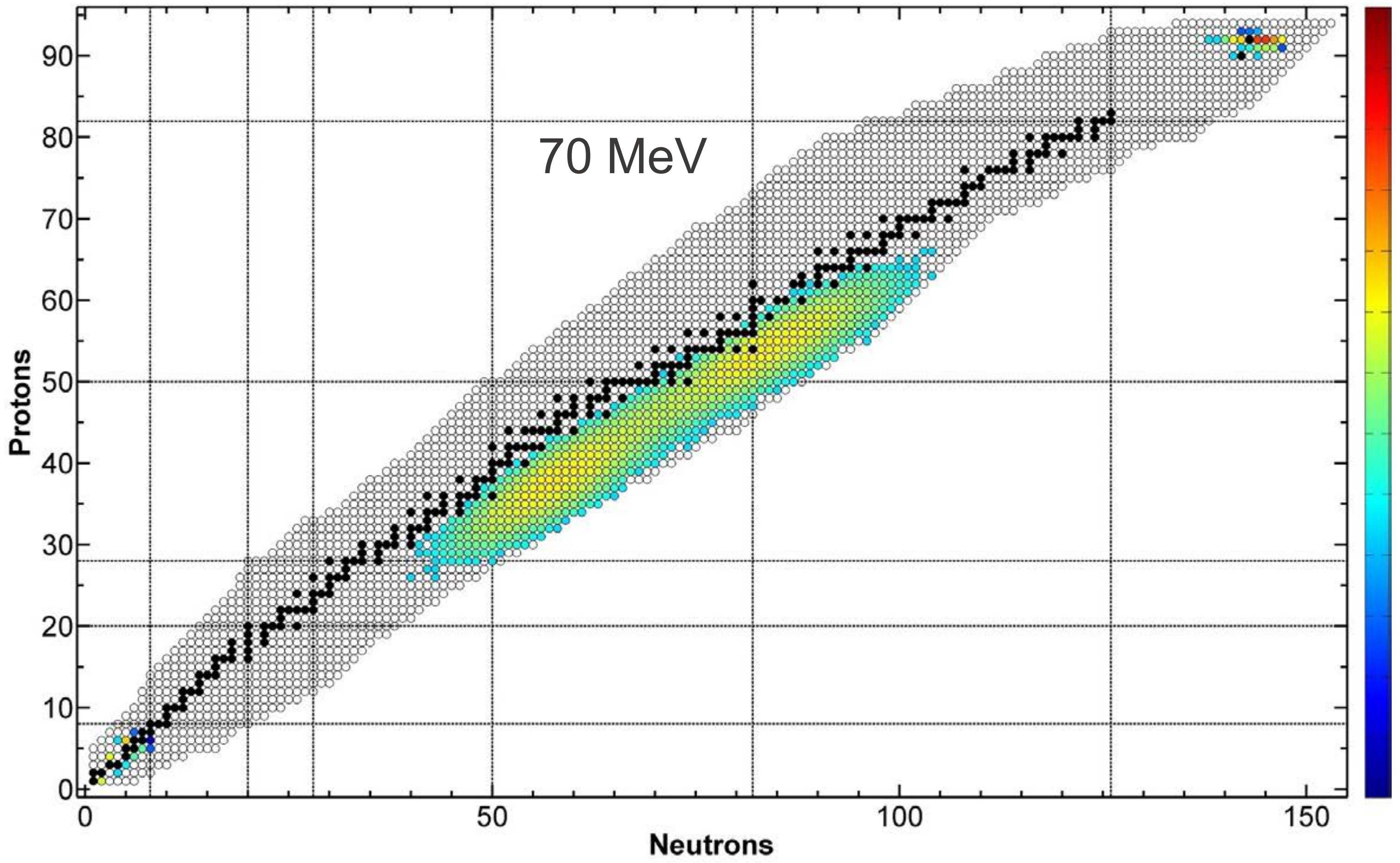
- UC_x
- UO_2
- ThO
- Nb
- Ta
- TaC
- NiO
- ZrC
- TiC
- SiC

Pushing the Power Boundaries

ISOL Fission Facilities

Most new and planned high-power ISOL facilities are using low-energy accelerators, thin targets and low energy fission in actinide targets as baseline

- INFN-SPES: 70 MeV protons
- IBS-RISP: 70 MeV protons
- iThemba-LERIB: 70 MeV protons
- SCK CEN-PTF: 100 MeV protons
- VECC-ANURIB: 35 MeV electrons
- IPNO-ALTO: 50 MeV electrons and 18 MeV deuterons
- CIEA-BRIF: 100 MeV protons
- …

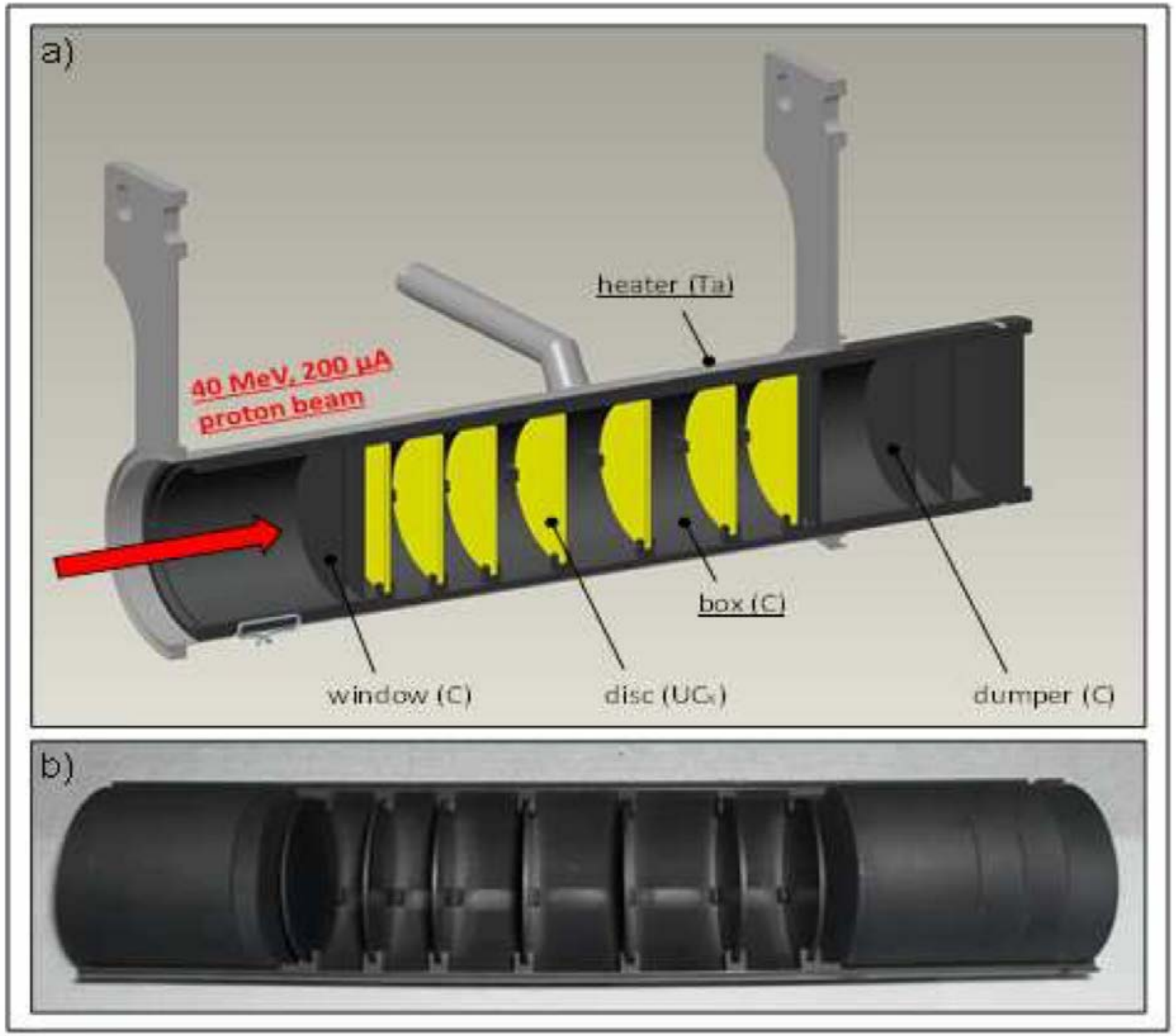


Discovery, accelerated

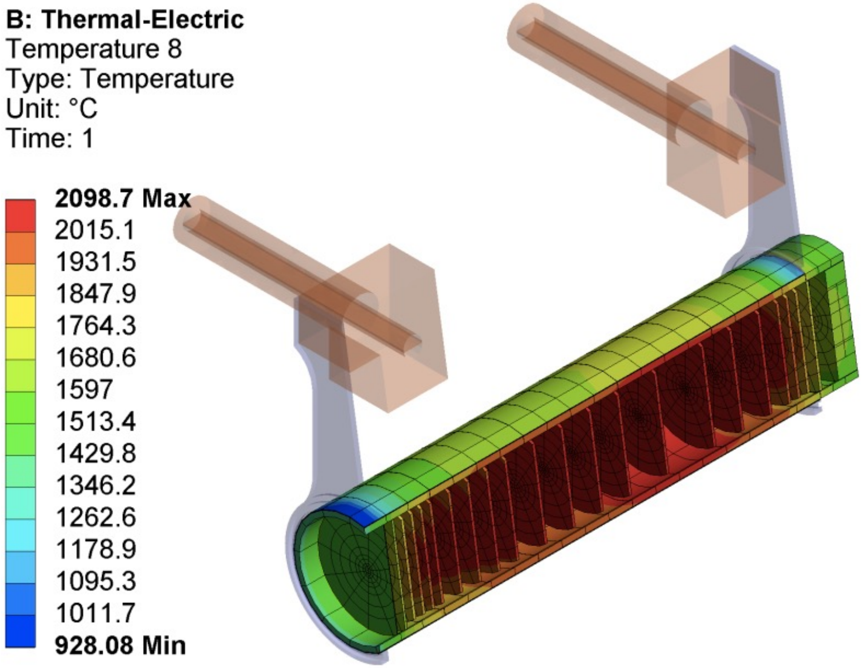
TRIUMF

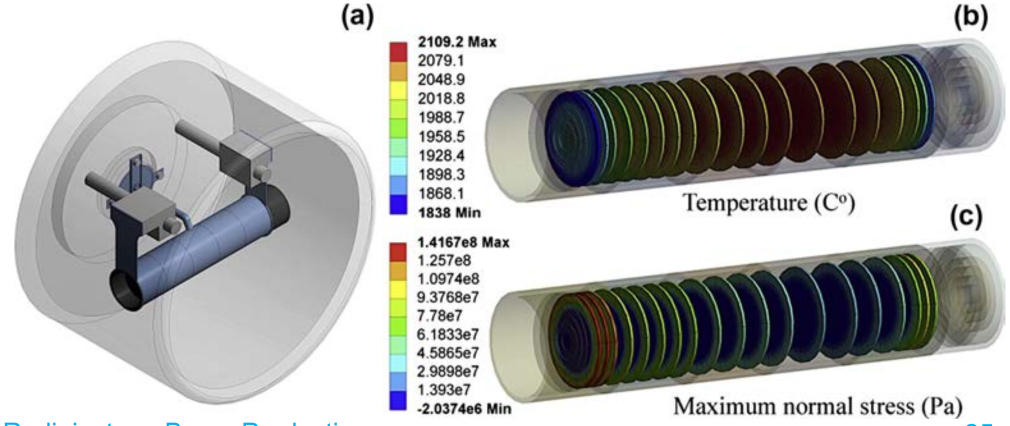
Beam Power Management in Low-Energy ISOL Targets

INFN – SPES

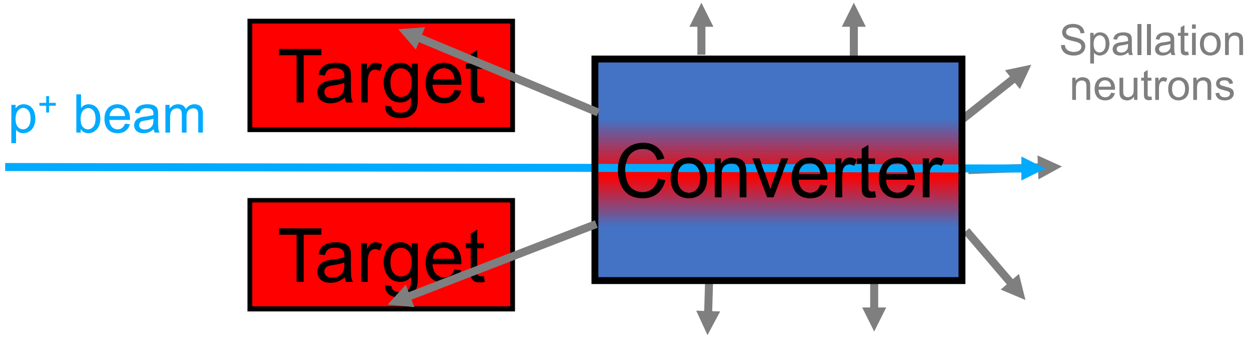


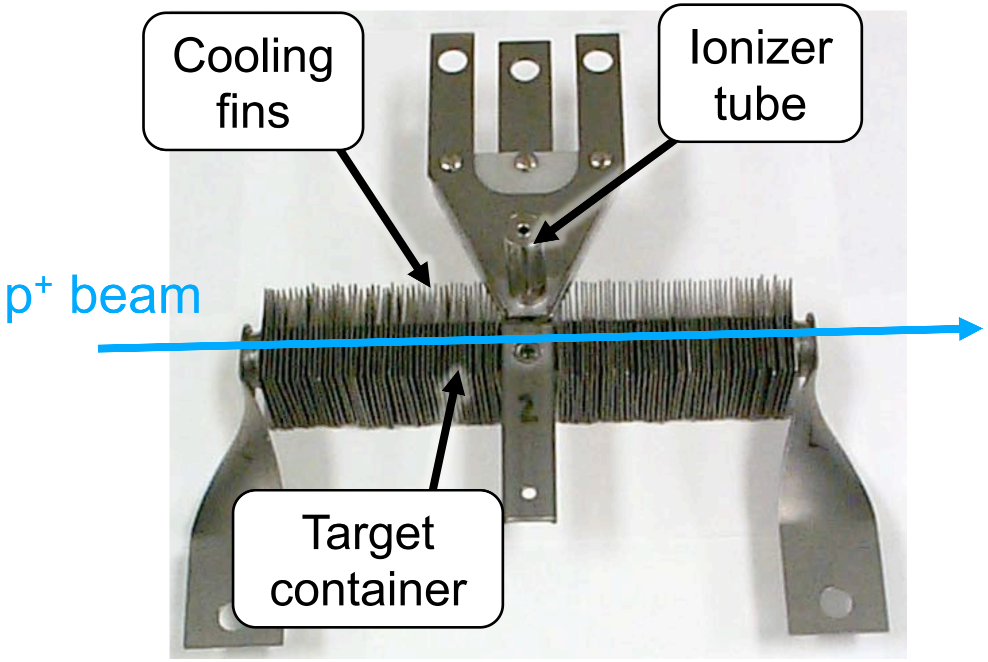
IBS – RISP

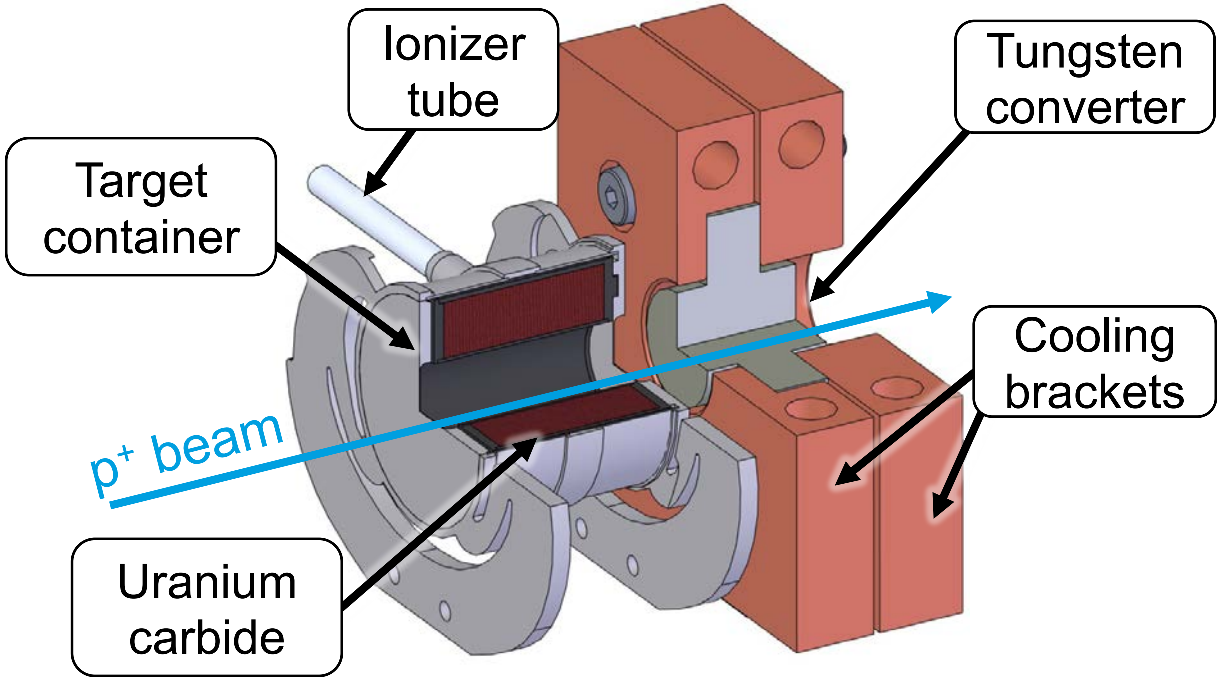




Beam Power Management in High-Energy ISOL Targets







- Target heating: Ohmic + beam
- Max I_p: 40 – 100 μA (500 MeV)
- Limited by target thermal performance

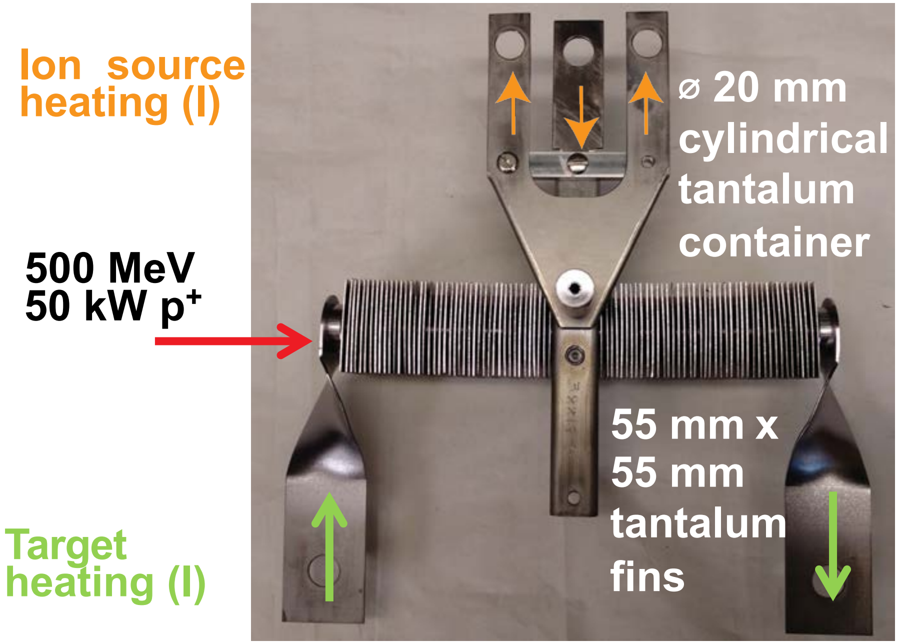
- Target heating: Ohmic only
- Max I_p: 100 μA
- No temperature gradients

ISAC – High-Power ISOL Target Material Development

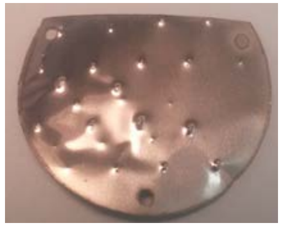
500 MeV, up to 100 μA proton driver beams

Tantalum fins increase the effective emissivity to ~0.9.

High-power (50 kW) target design



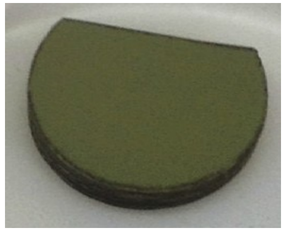
Combination of porous materials for optimized release of short-lived radioisotopes on backing foils for high conductive heat transfer into tantalum container



2000: Tantalum or niobium foils

2008: SiC_x, TiC, ZrC_x cast onto graphite foils

2013: UC_x cast onto exfoliated graphite foils



2015: NiO cast onto niobium foils

Experimental Realities

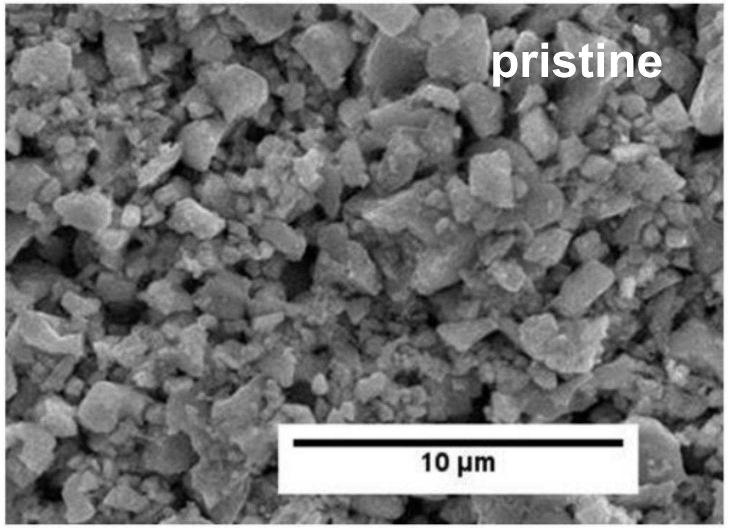
Isotope beam intensity depends on:

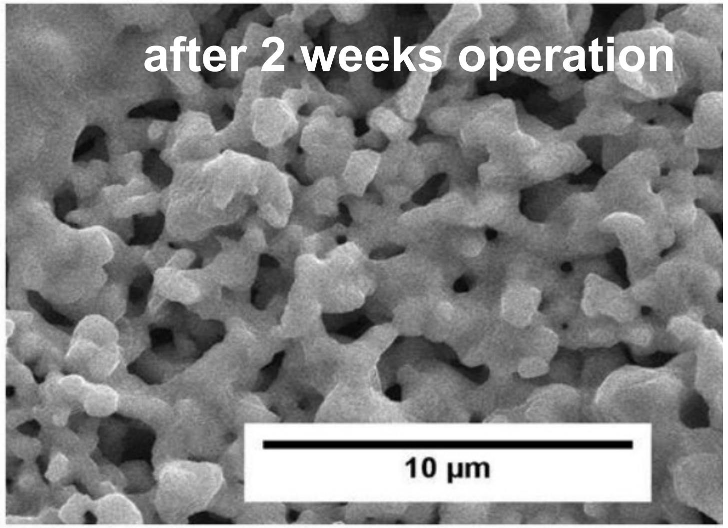
- Nuclear production cross section
- Target thickness
- Ionization efficiency
- Radioisotope release efficiency ⟵ as low as 10^{-6} !

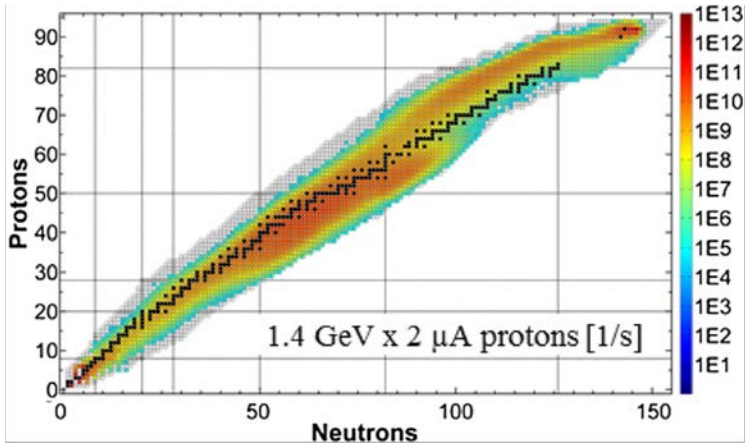
Release efficiency depends on:

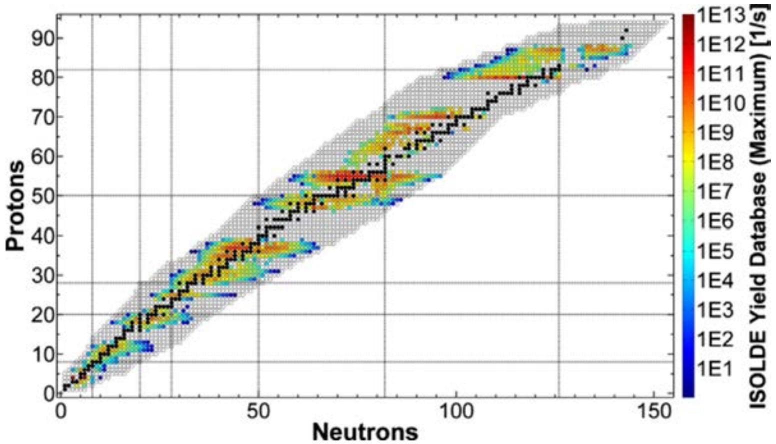
- Temperature and temperature distribution
- Microstructure
- In-target chemistry

ISAC ZrC target material

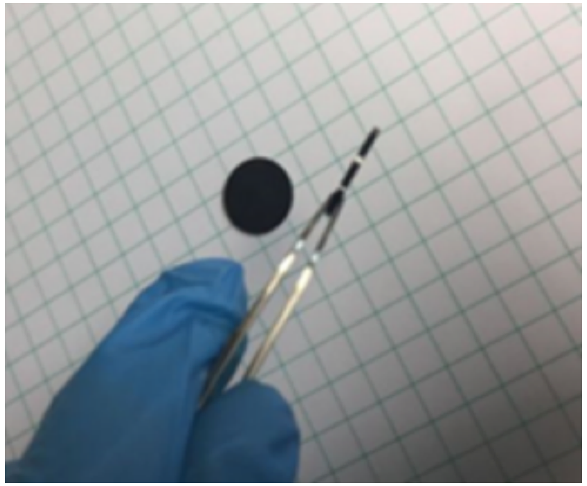


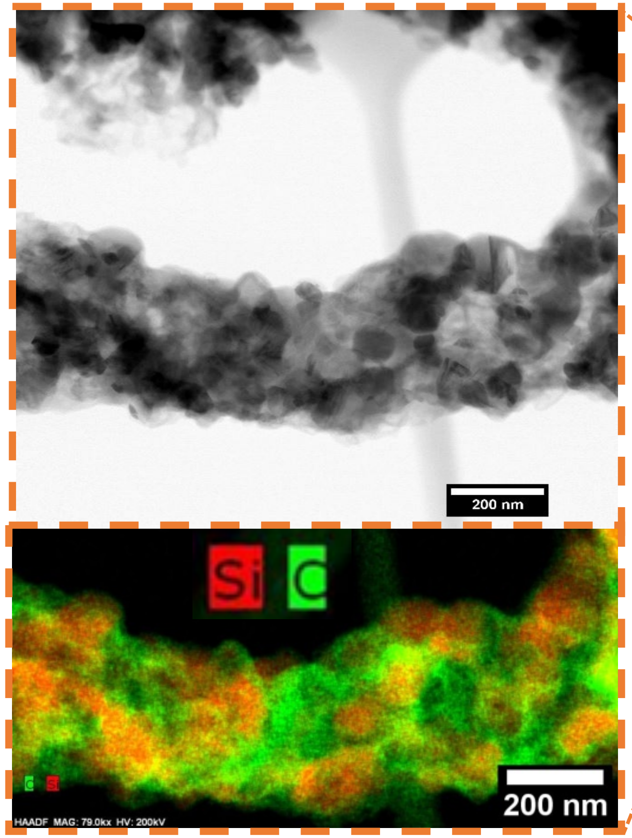


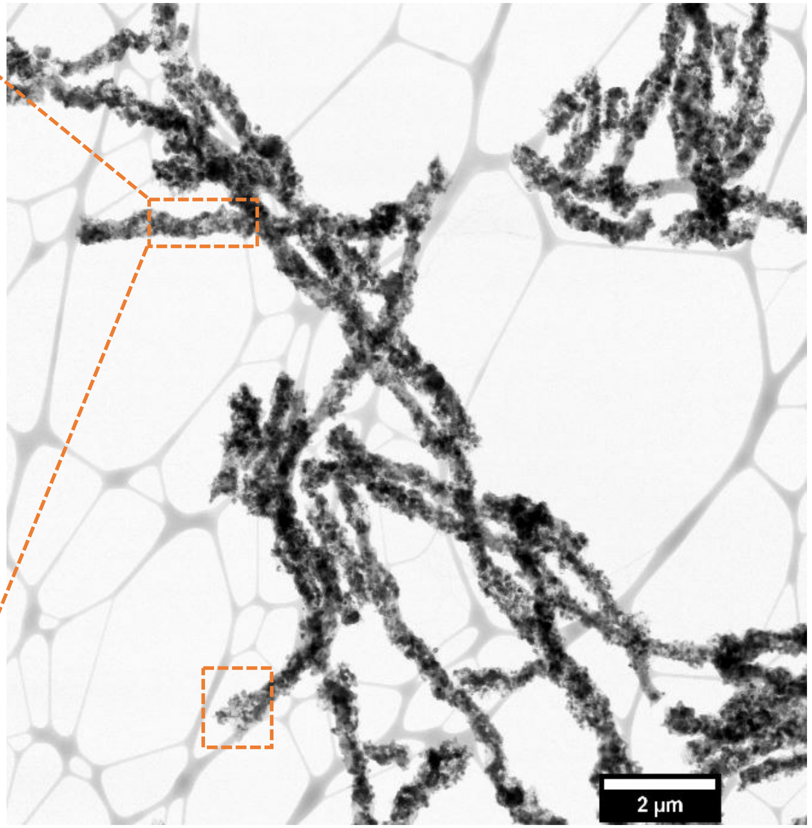




Engineered Target Materials – Example: Electro Spun SiC Nanofibres







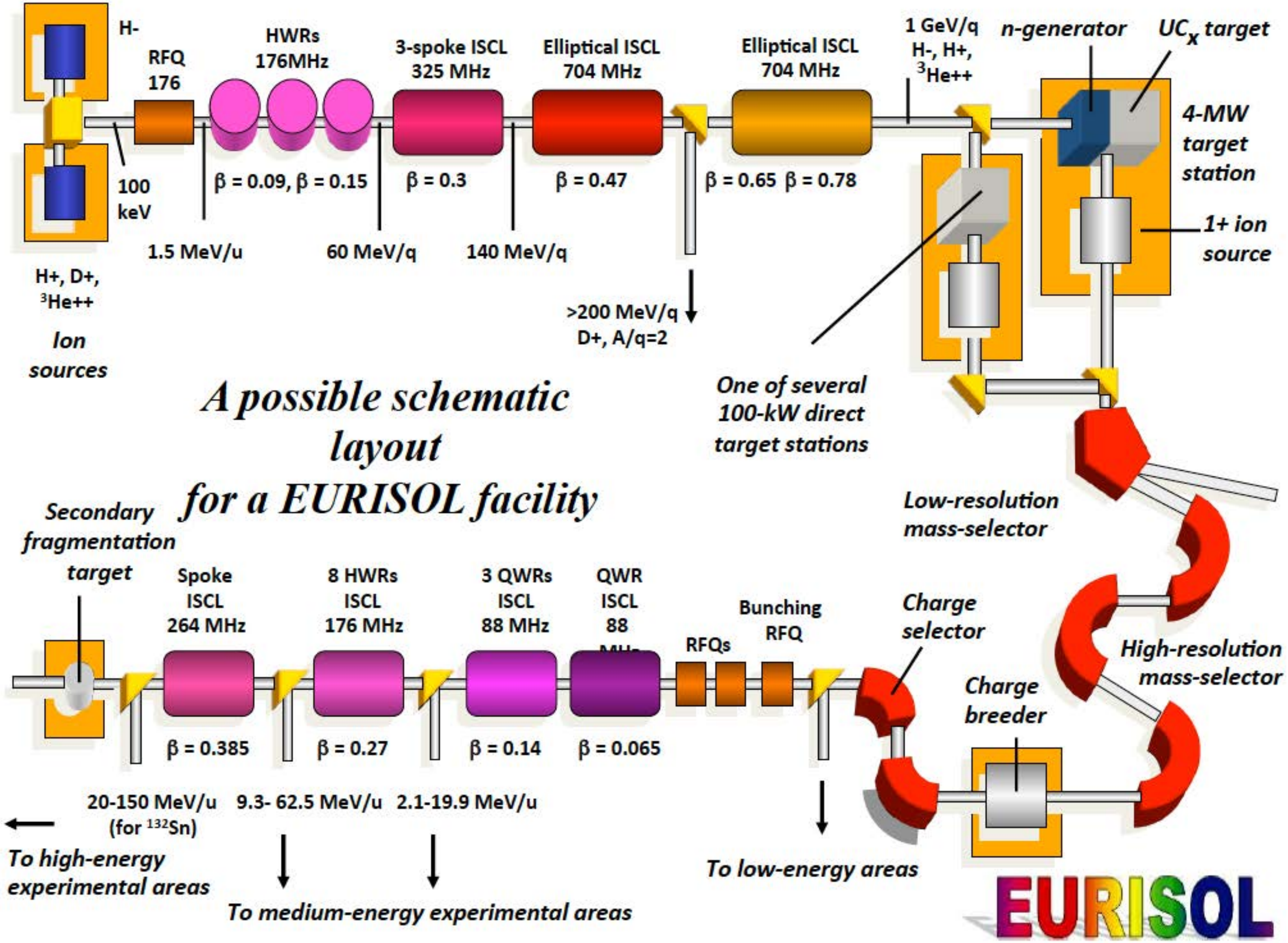
Goal:
- Reduction of particle size, increase of open porosity
- Nanometric stabilization in refractory carbon fibre backbone
- Increased yield of exotic diffusion limited isotopes

Status:
- Target operated for 15 days at 55 µA
- Stable operation, no signs of material degradation

Discovery, accelerated

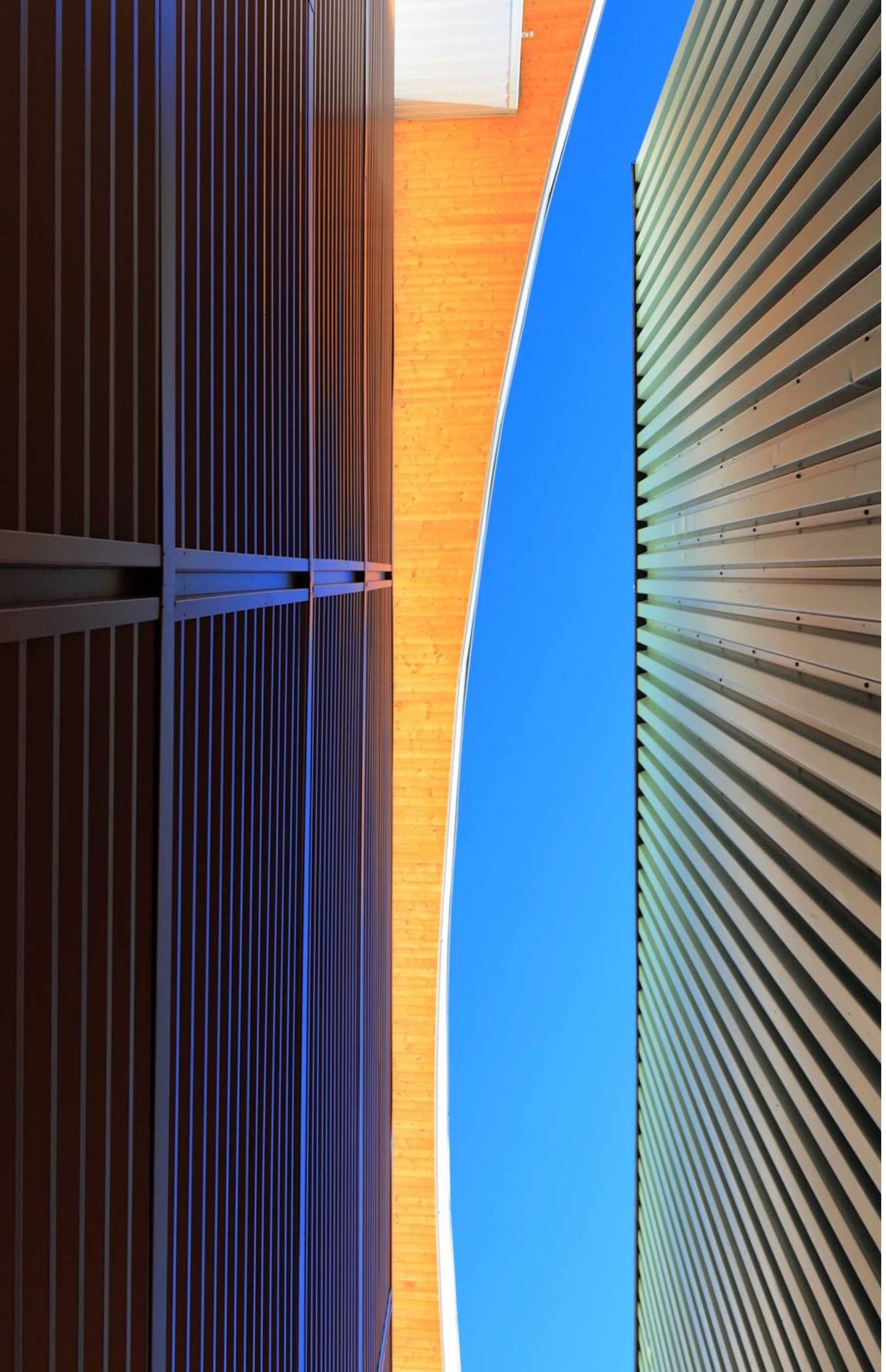
Translation Into a Multi-User High-Power RIB Facility

EURISOL

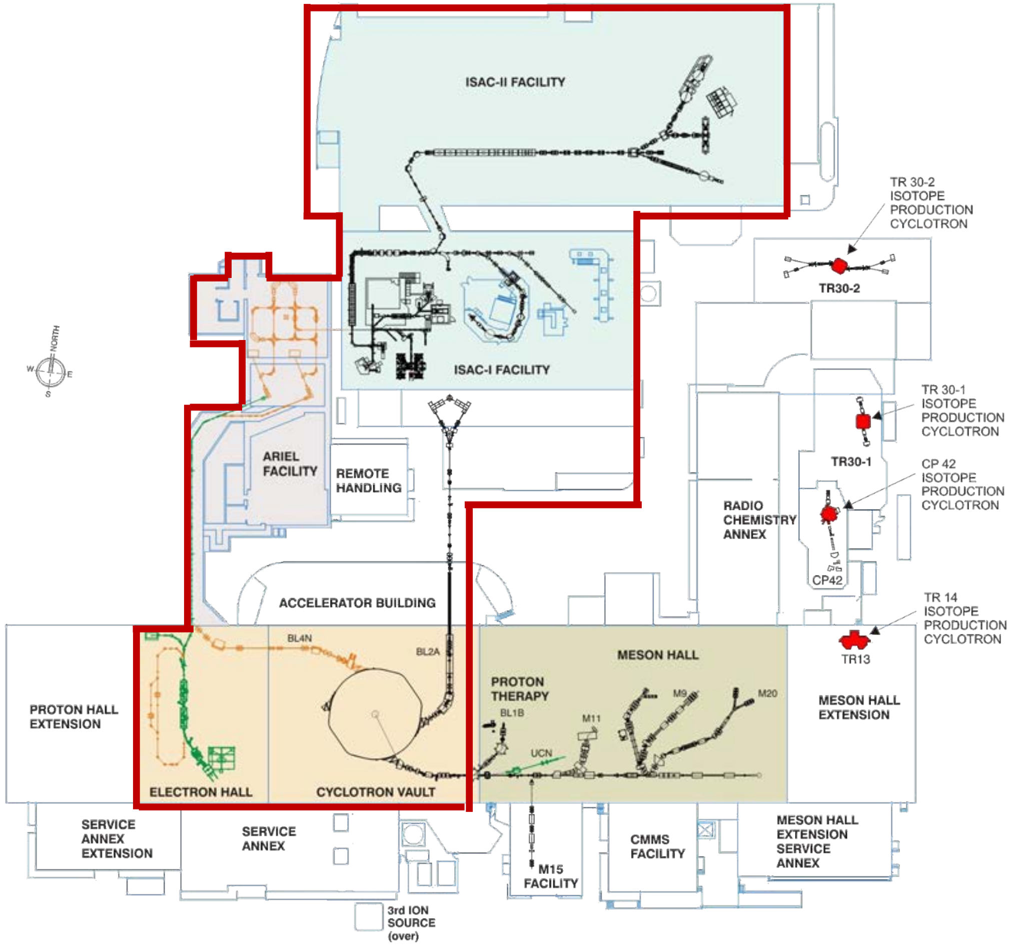


EURISOL DS:

- 1-2 GeV proton driver
- 1 high power (4 MW) indirect (Hg proton-to-neutron converter) UC_x target station
- 2-4 ‘low power’ (100 kW) target stations
- Post acceleration to up to 150 MeV/u
- Experimental areas:
  - ~ 60 keV
  - ~ 20 MeV/u
  - ~ 60 MeV/u
  - ~ 150 MeV/u
- Secondary target for RIB fragmentation



Tripling TRIUMF's Radioisotope Output
Advanced Radioisotope Laboratory - ARIEL



Discovery, accelerated

TRIUMF

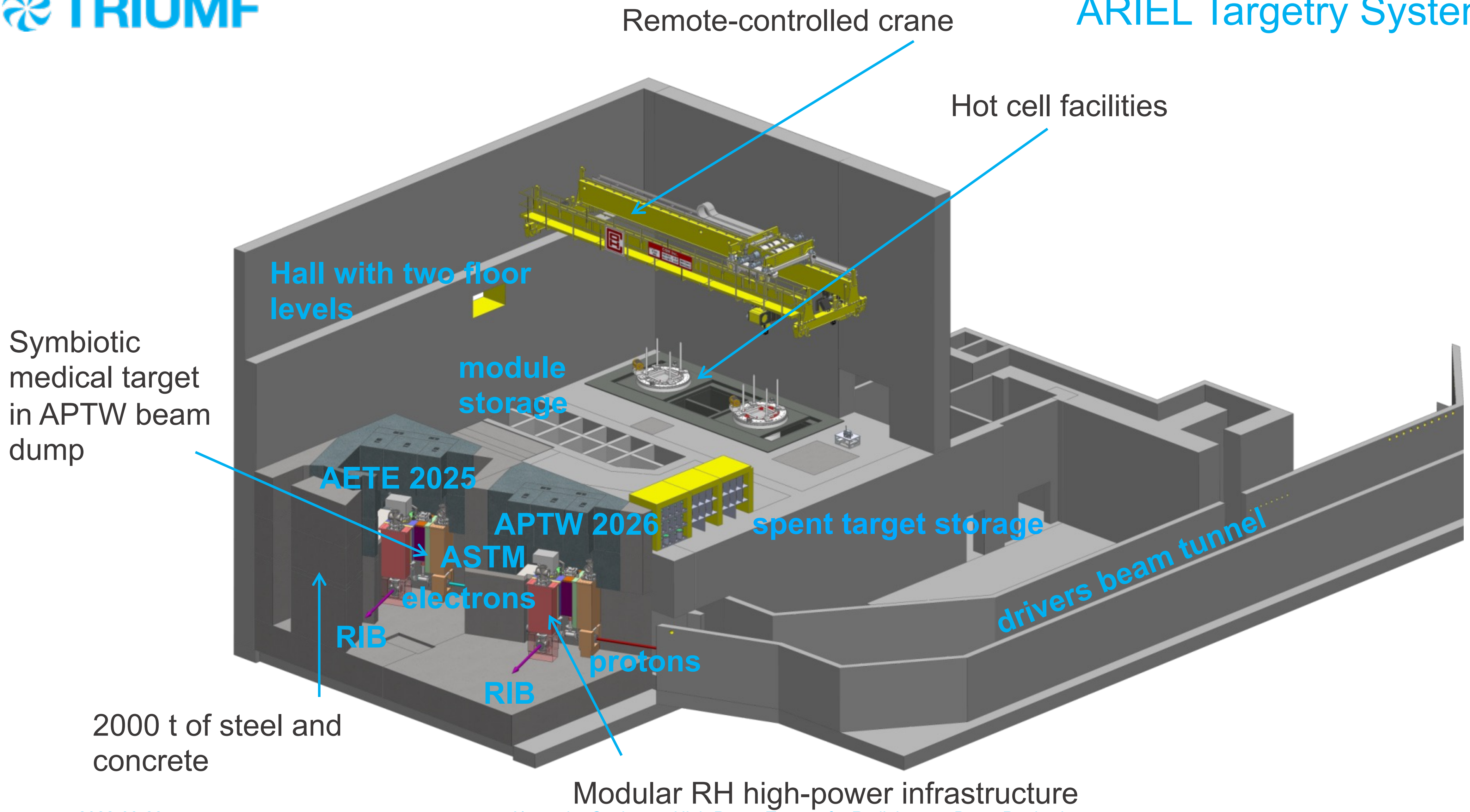
Technology Cherry Picking for a Modern High-Power Multi-User ISOL Facility

ARIEL top level scope and technical concept is informed by a systematic analysis of developments, lessons learned, strengths and weaknesses of RIB facilities worldwide.

ARIEL Objectives:

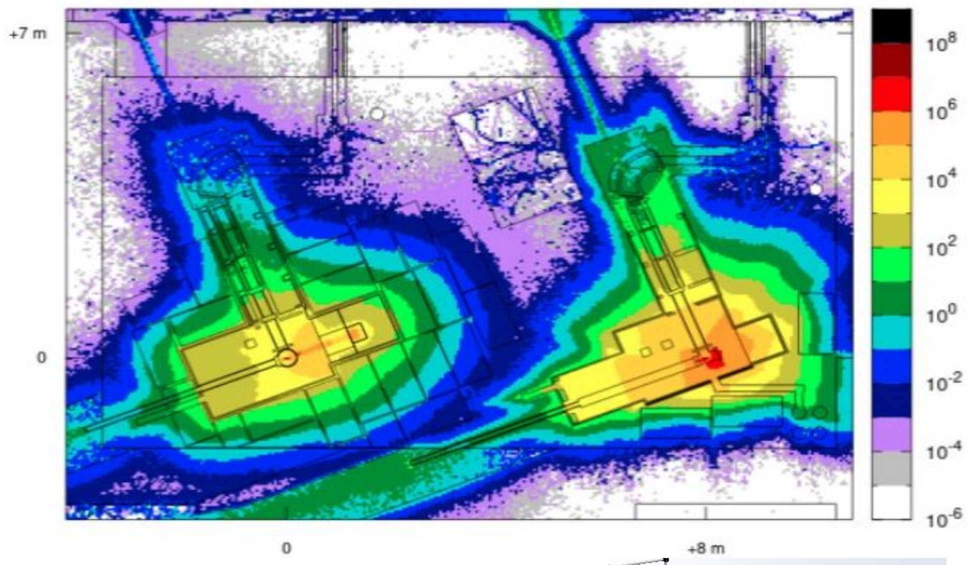
- Accept high-power proton (50 kW) and electron (100 kW) beam
- Multiply RIB capacity and introduce multi-user operation
- Reduce downtime and increase reliability
- Improve safety and long-term operability
- Generate development opportunities
- Gain operational efficiencies while increasing operational flexibility

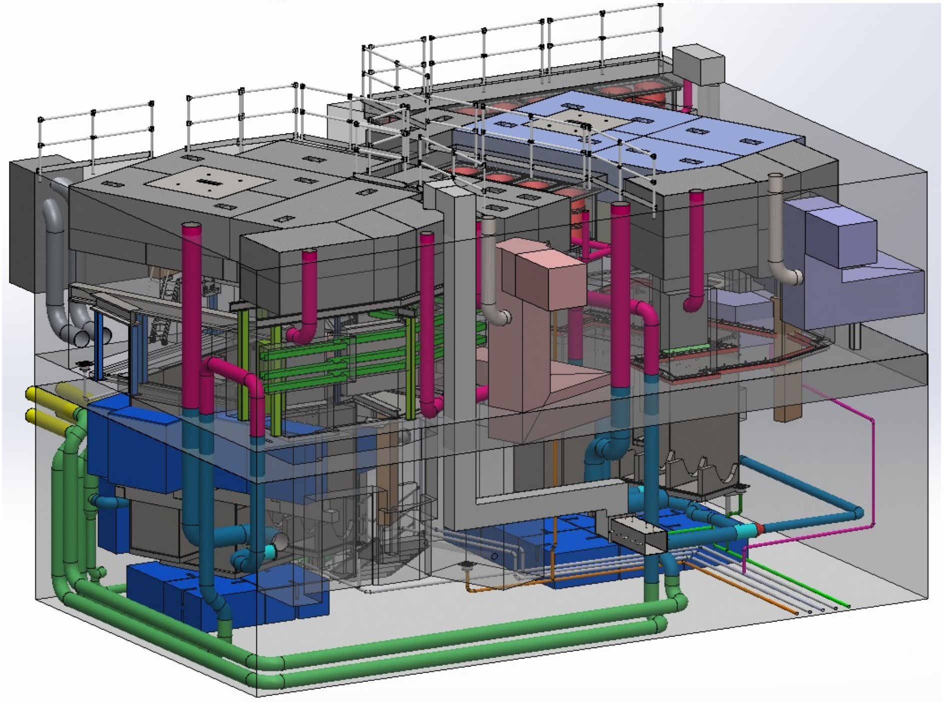
ARIEL Targetry Systems



Target Pit Shielding and Assembly Design

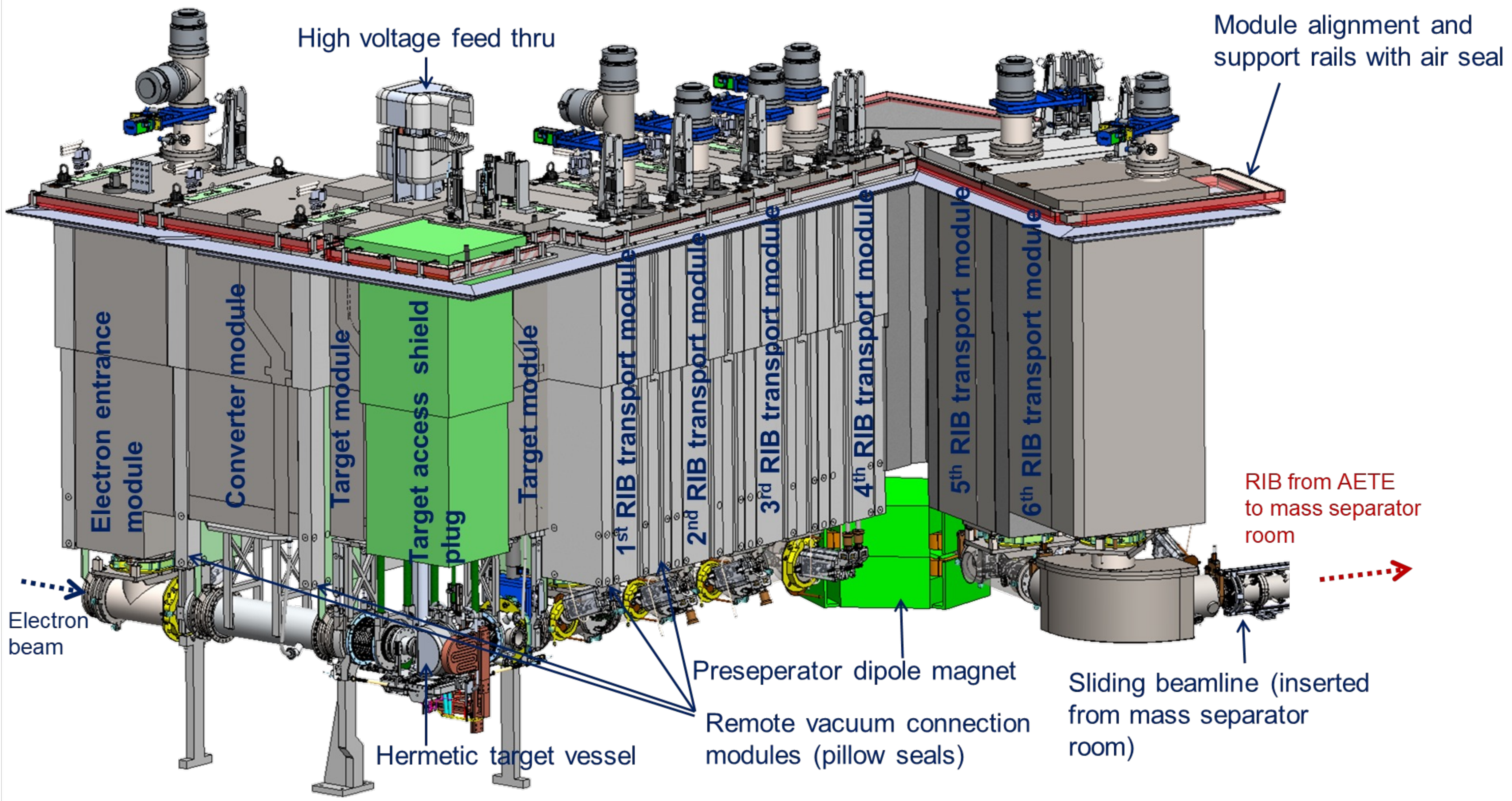
- Compact shielding envelope around the targets is time-consuming and cost intensive
- Iterative simulation-based co-development with service and handling design.
- 4 years and about 20 major simulation and design iterations before design freeze and build.





Discovery, accelerated

Proven Modular Design Paradigm for Target Station



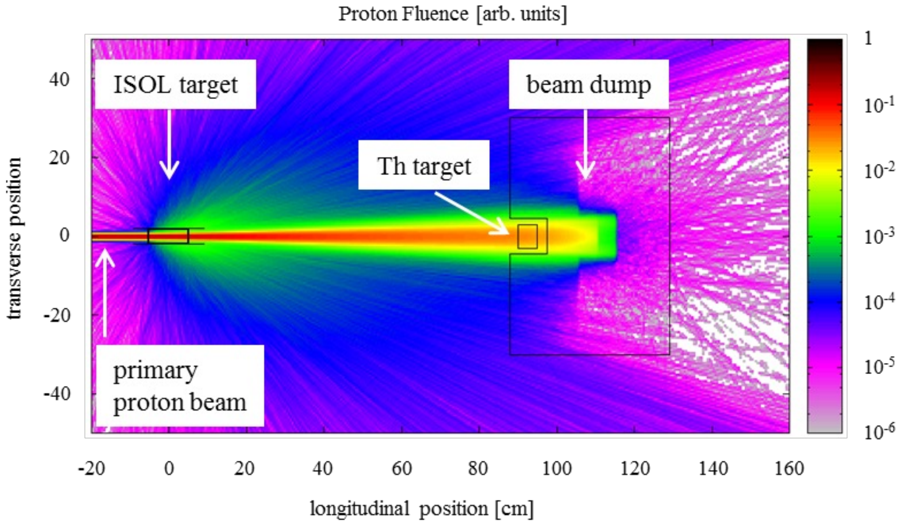
Discovery, accelerated

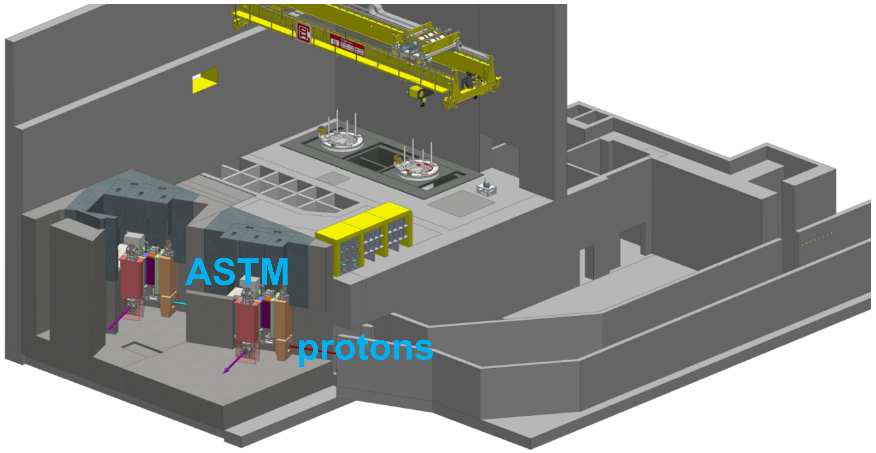
TRIUMF

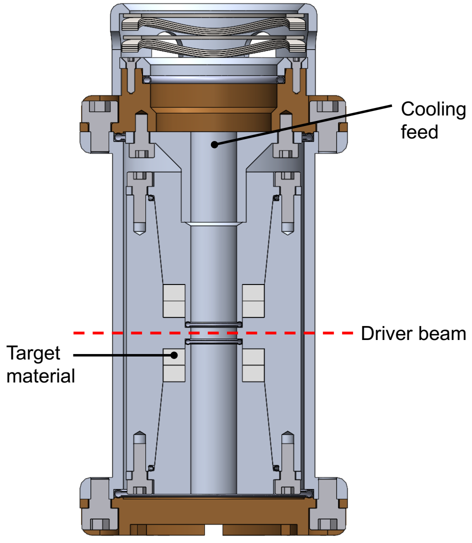
The Use of the Parasitic Beam

Use of Parasitic Beam – Medical Radioisotopes

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

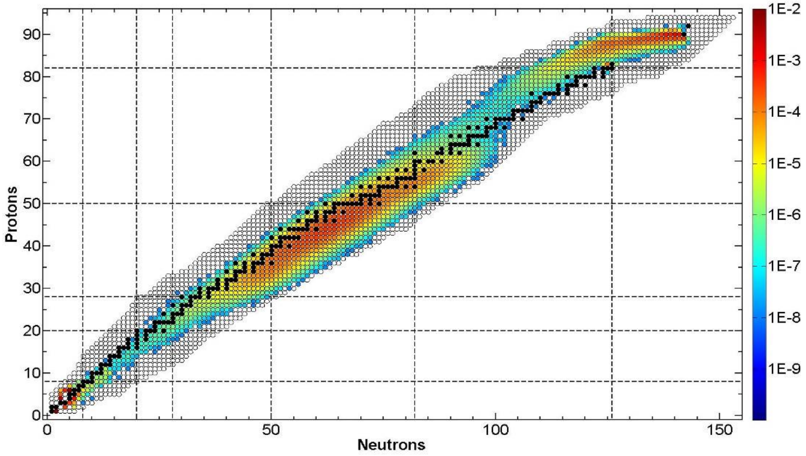


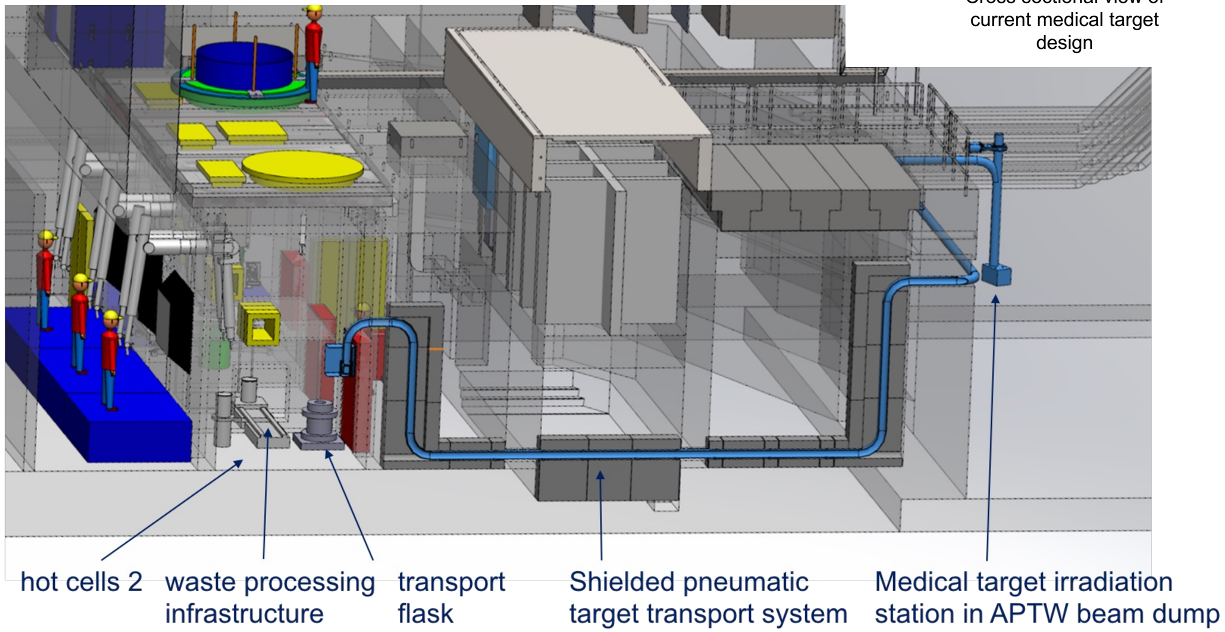




Cross sectional view of current medical target design

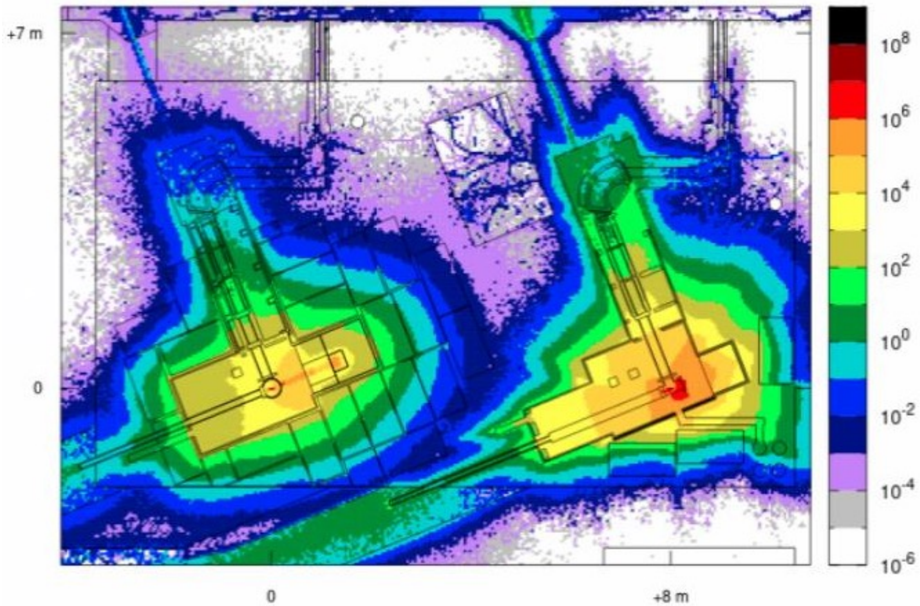
Hundreds of co-produced isotopes including; ^{225}Ra, ^{225}Ac, ^{224}Ra, ^{223}Ra, ^{213}Bi, ^{212}Pb, ^{212}Bi



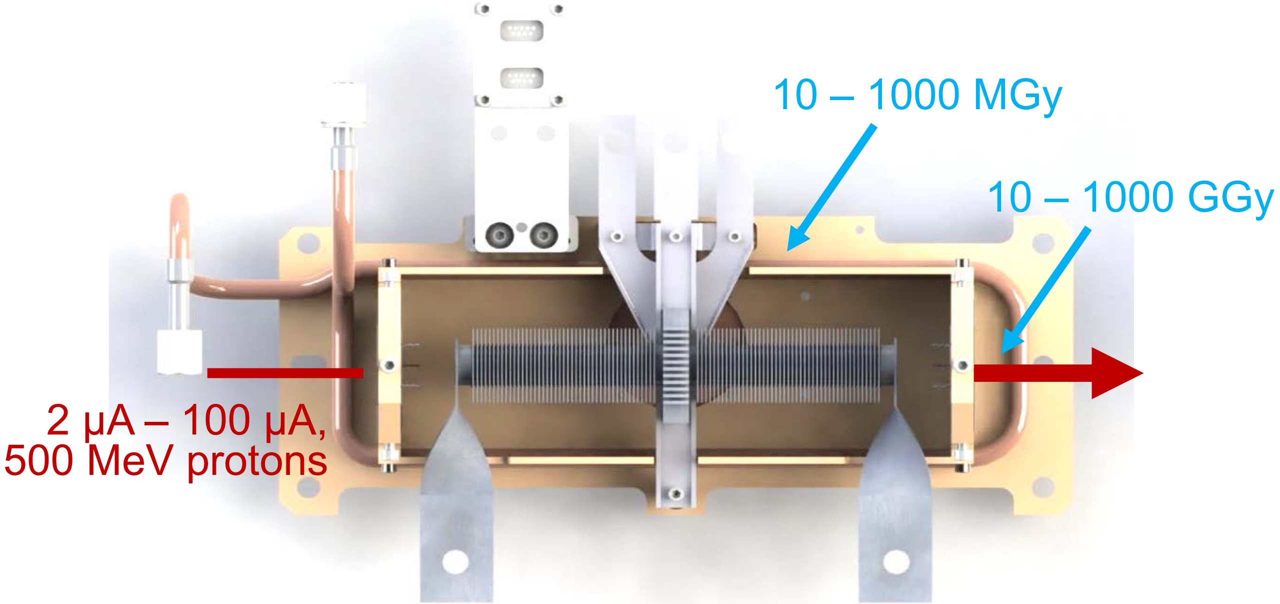


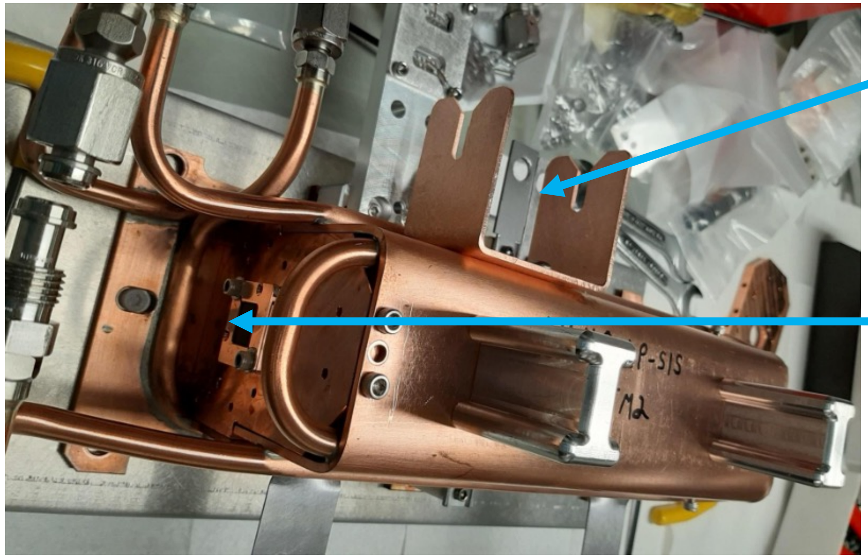
Use of Parasitic Beam – Radiation Damage in Materials

Dose rates at ARIEL target: up to several GGy/h



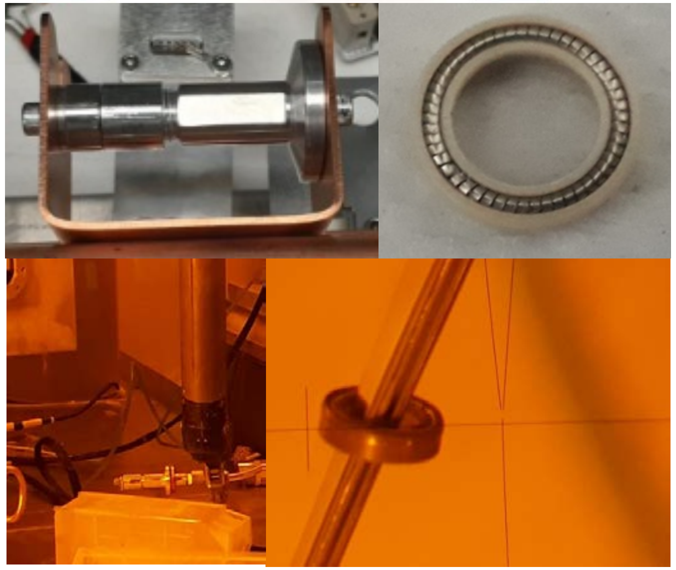
Parasitic material testing at ISAC





Scattered beam material studies (seals, greases, insulators)

In-beam material studies (beam windows, targets, beam dumps)



Example: spring loaded PEEK seal leak tests after 60 MGy

Thank you
Merci

www.triumf.ca

Follow us **@TRIUMFLab**

Discovery, accelerated