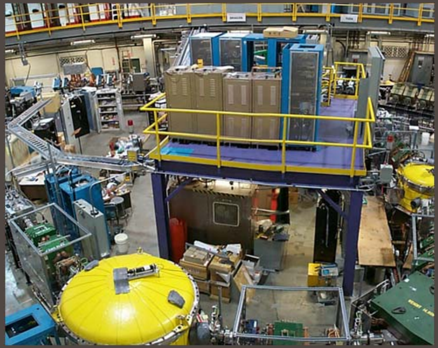
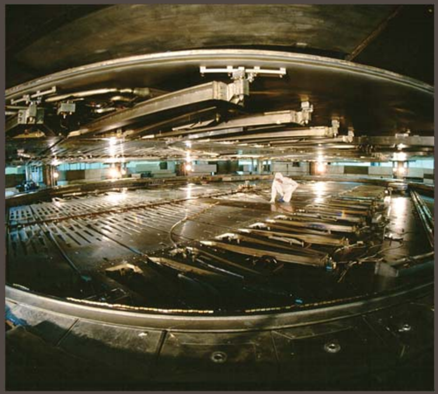
Critical Technologies and Future Directions in High Intensity ISOL RIB Production



Pierre Bricault | Head Target/Ion Source | TRIUMF



Outline of the Talk

- ISOL Method to Produce Rare Isotope Beams, (RIB)
- Physics with RIB
- How it is done?
- Increasing RIB intensity
  - Issues
    - Target & Ion source for high power ISOL RIB production
  - Improving Reliability
  - CSB
- Future Directions of ISOL RIB

ISAC at TRIUMF

Driver:

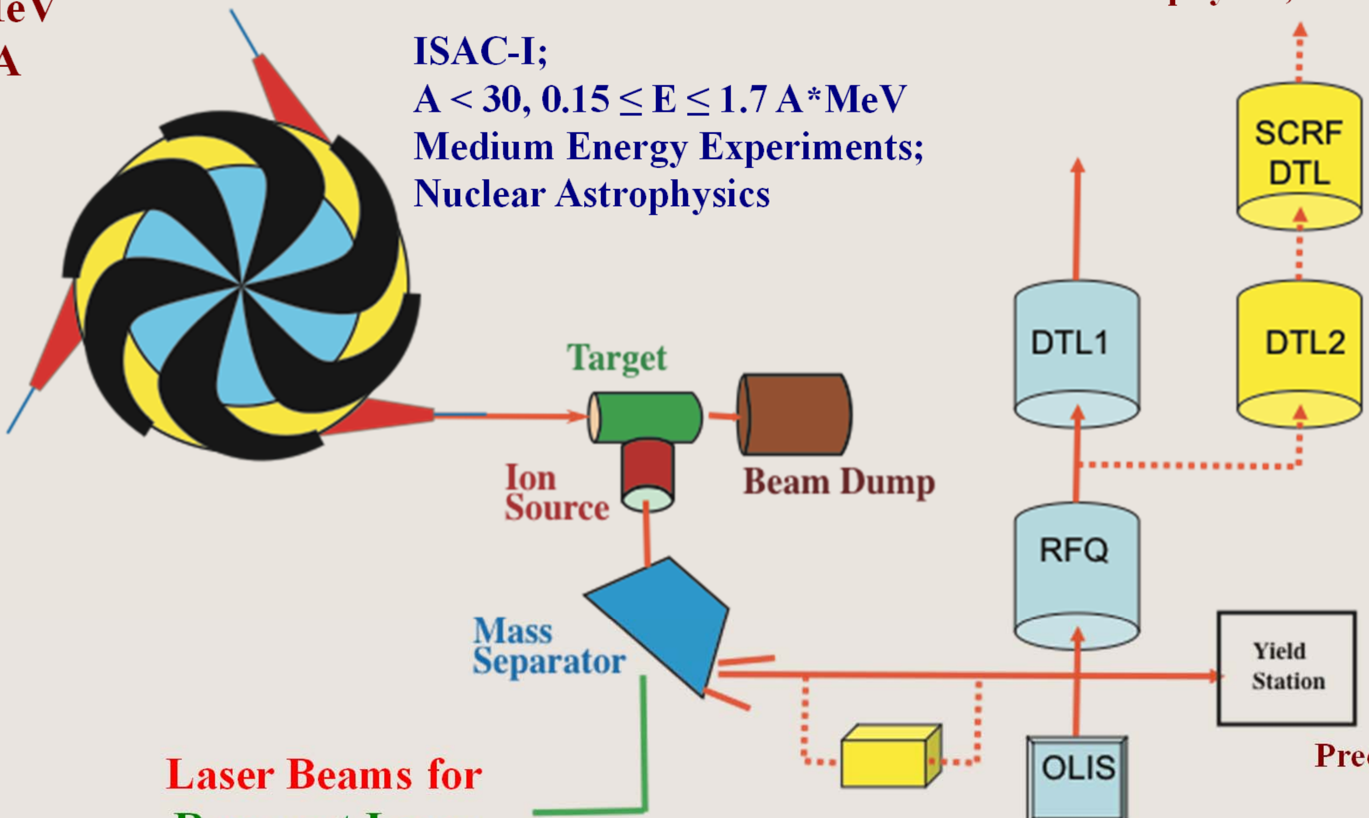
Cyclotron H^-

500 MeV

100 µA

ISAC-I;
A < 30, 0.15 ≤ E ≤ 1.7 A*MeV
Medium Energy Experiments;
Nuclear Astrophysics

ISAC-II; A ≤ 150, 1.0 ≤ E ≤ 15 A*MeV
High Energy Experiments;
Nuclear Structure, Nuclear
Astrophysics, Nuclear Reactions



Low Energy
Experiments;
Neutral Atoms Trap,
Mass Measurements,
Gamma Spectroscopy,
Laser Spectroscopy,
Precise Decay Measurements

Laser Beams for
Resonant Laser
Ion Source

Charge State Breeder

Off-Line Ion Source

ISOL Method

Driver:

Cyclotron H^-

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High Energy Experiments;
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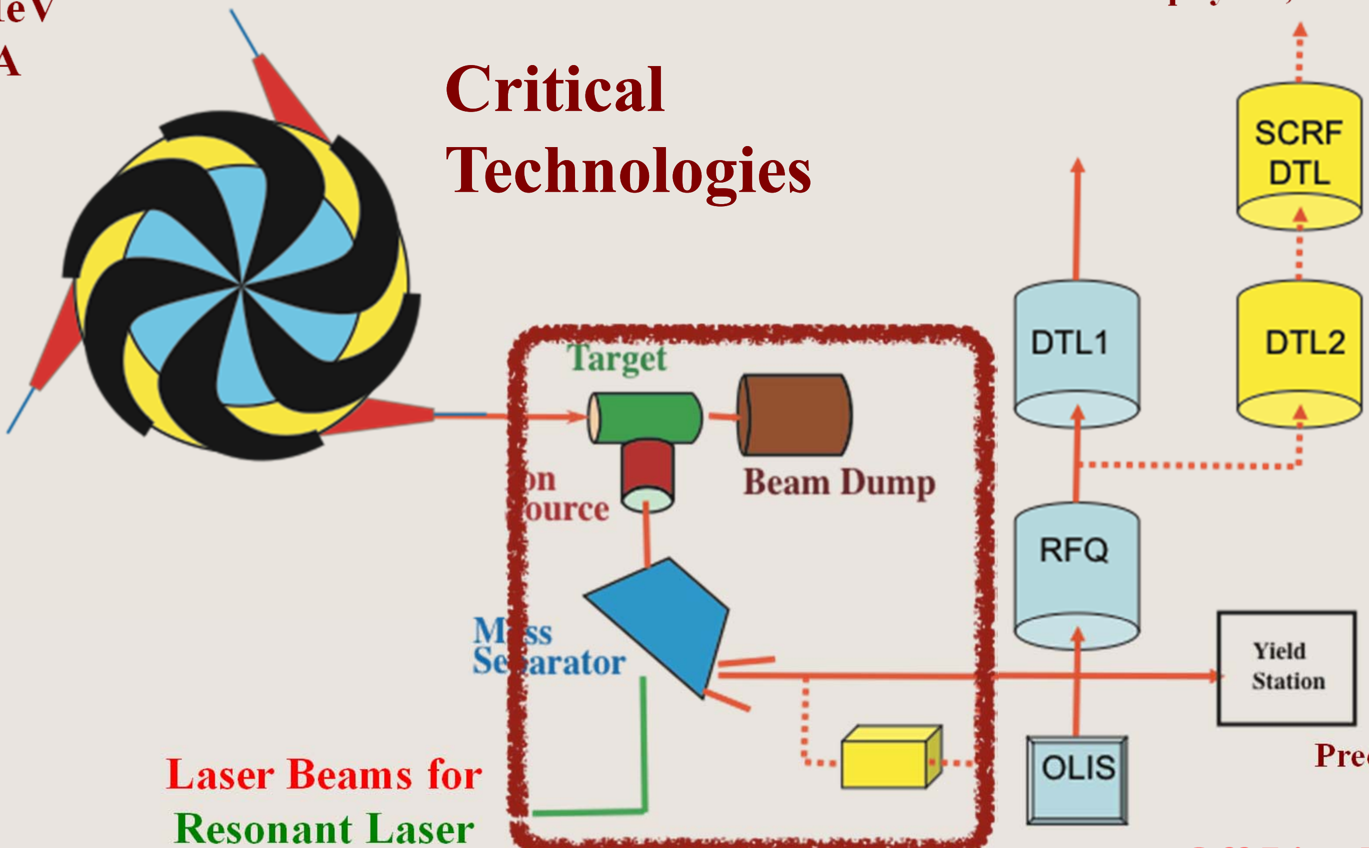
Critical Technologies



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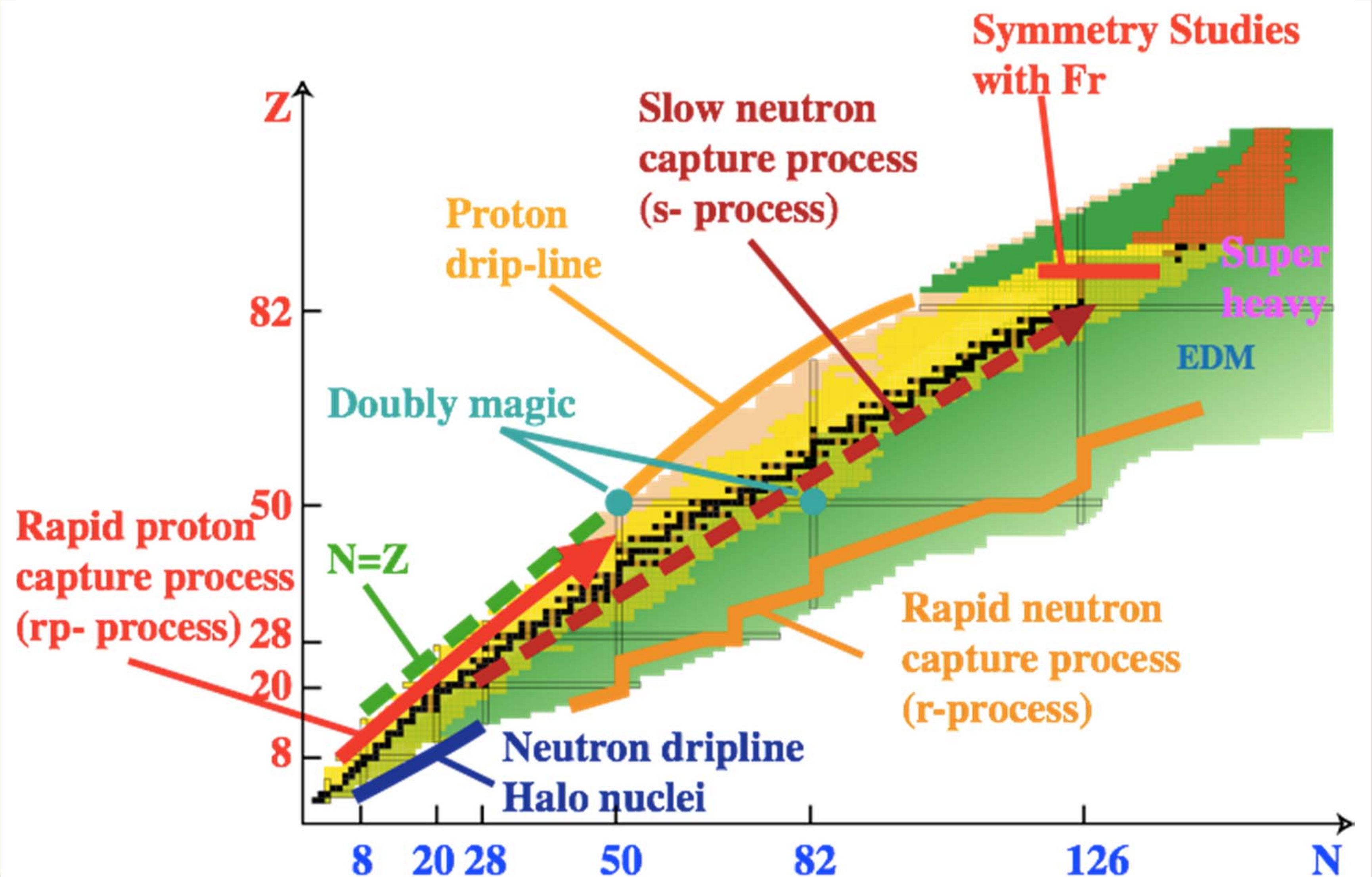
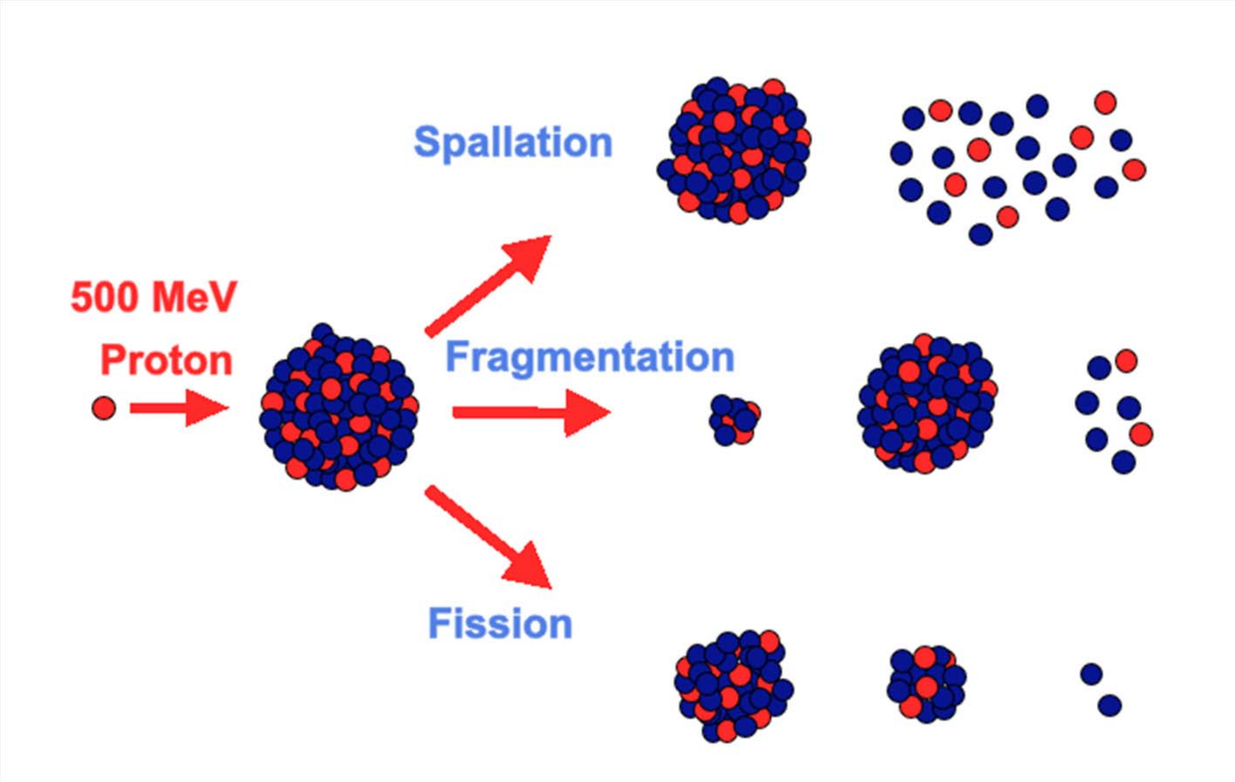
Physics with RIB

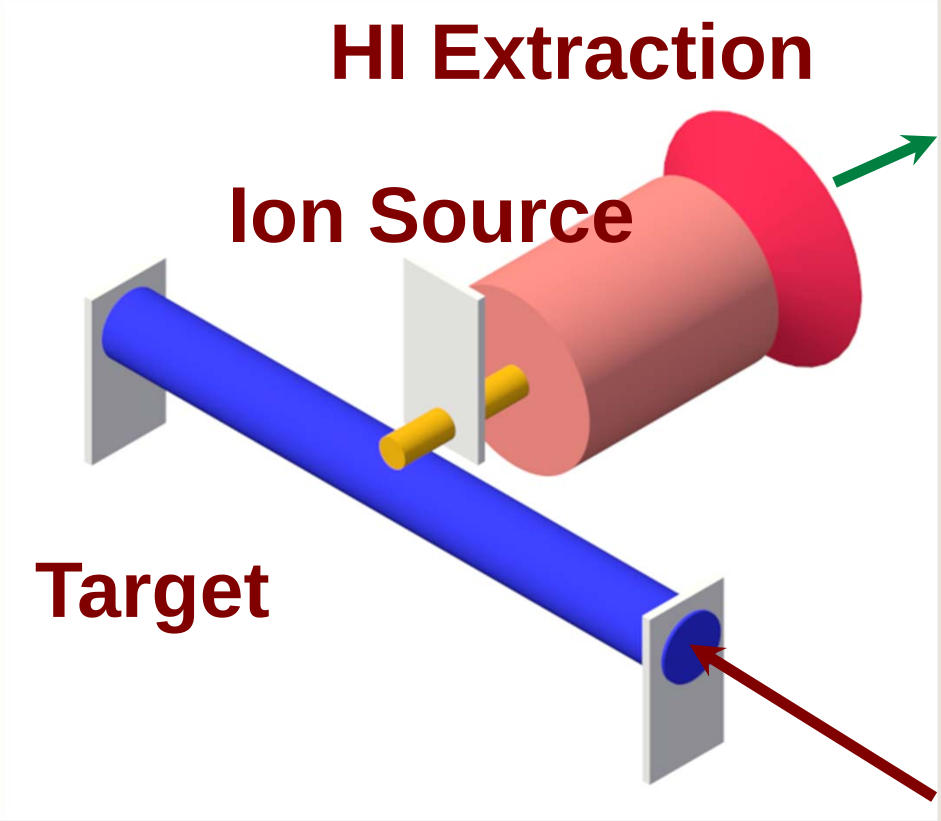


RI Production Reaction Mechanisms



- Spallation: products distribution peaks few mass units lighter than target.
  - Neutron deficient
- Fragmentation: product N/Z ratio reflects the target ratio.
  - Neutron rich.
- Induced fission into roughly equivalent mass products.
  - Medium range masse region

ISOL Concept



Rare Isotope Beam

Proton Beam

- This method involves the interaction of light ion beam onto a thick high-Z target material,
- The fragments are imbedded into the bulk of the target material.

ISOL RIB Method

- The rare atoms diffuse out of the target material matrix, => Diffusion process, ε_D.
- Then they effuse out of the "target oven" to the ion source, => Effusion process, ε_E.
- The rare isotope are then ionized in the ion source, => Ionization process, ε_I.

  - $Y = \Phi\ \sigma\ (N_A/A)\ \tau\ \varepsilon_D\ \varepsilon_E\ \varepsilon_I.$

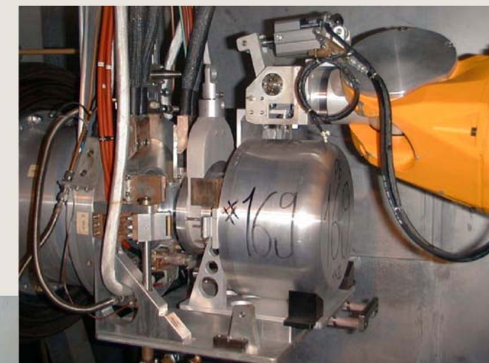
- High yield can be obtained by increasing:
  - the proton beam intensity, Φ
  - improving the release efficiency, $\varepsilon_D\ \varepsilon_E$
  - improving ionization efficiency, ε_I.

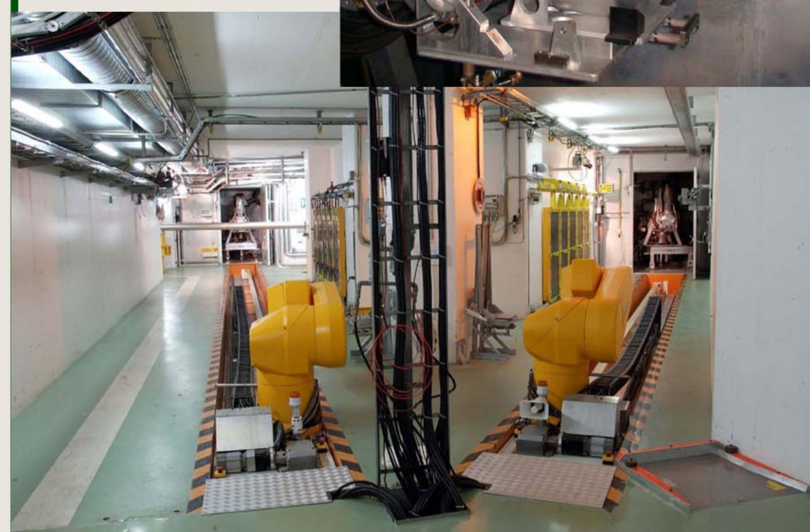
ISAC technologies

- Because ISAC is capable of using 50 kW proton beam on ISOL target we have developed a target station quite different than the one in used at ISOLDE/CERN and HRIBF at Oak Ridge for example.
- High Radiation Dose
  - all non radiation hard material are shielded behind steel and concrete shielding plug.
  - Target/ion source at bottom of a steel shielding plug
  - Use an overhead crane to transfer the Target Module from the Target Station to Hot-cell for target exchange

ISAC Remote Handling Technology

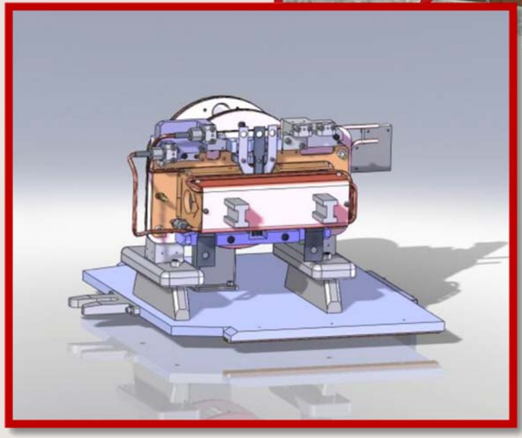
ISAC/TRIUMF	ISOLDE/CERN
Proton CW: 500 MeV Φ ~ 100 μA	**Proton Pulsed: 1.4 GeV** Φ ~ 2μA

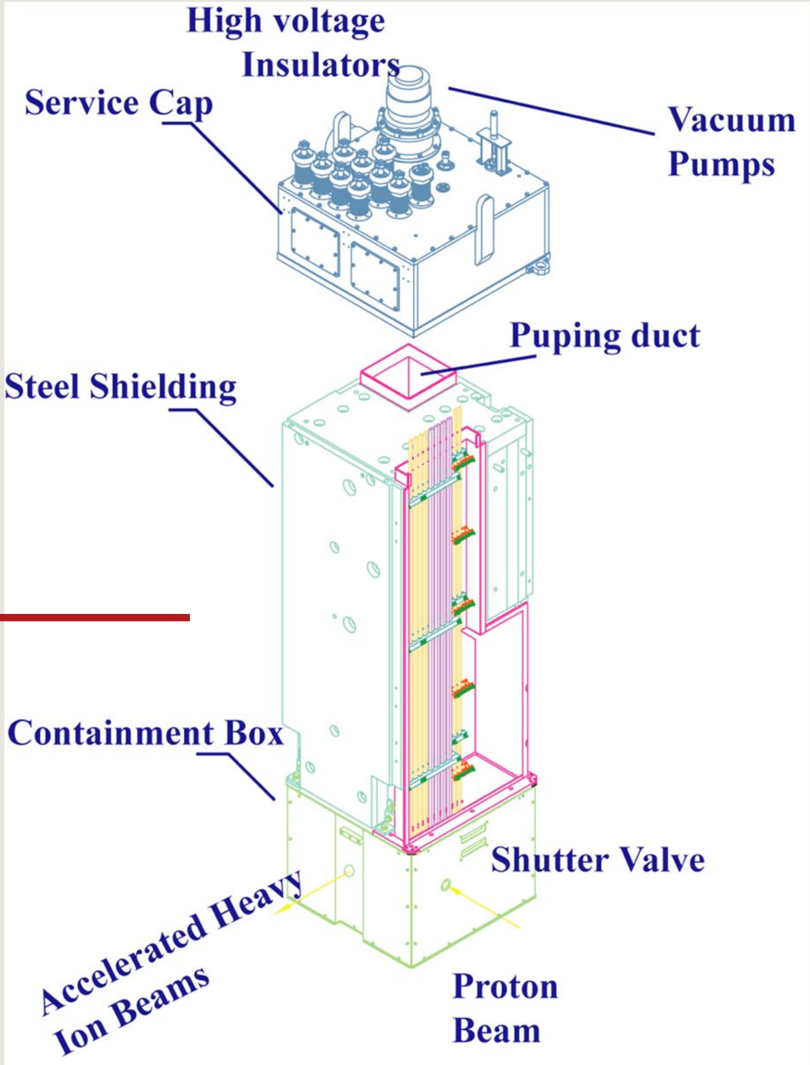




ISAC Facility, Technologies

- Target module





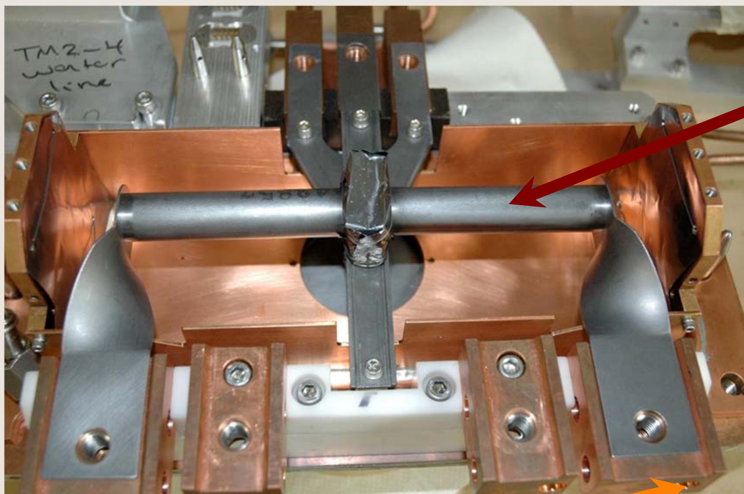
High Intensity ISOL RIB

1. High power target container capable of removing the power to the surrounding heat shield, then to cooling circuit.
2. Need target material capable of sustaining high power deposition in target

- Target assembly can be described as consisting of two parts:
  - the target material itself,
  - the target container.
- ISAC High Power target can dissipate up to 25 kW.

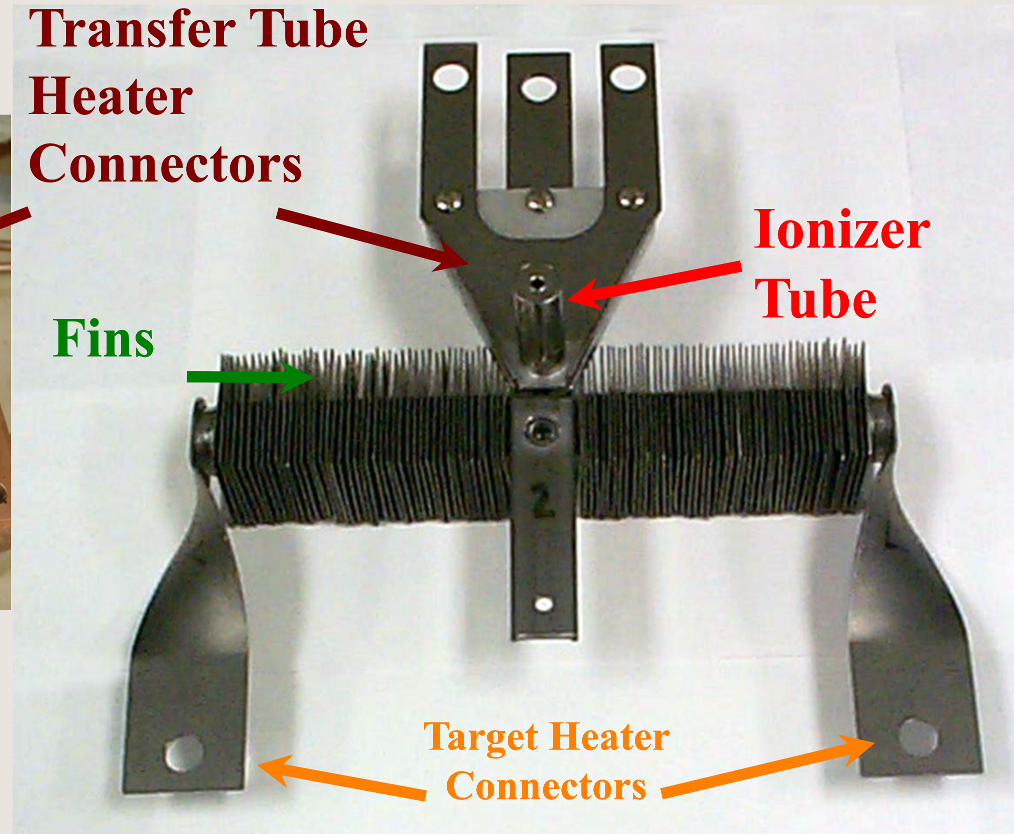
1) ISAC "Target Ovens"

Normal Target



$I_{Proton} \leq 40\ \mu A$

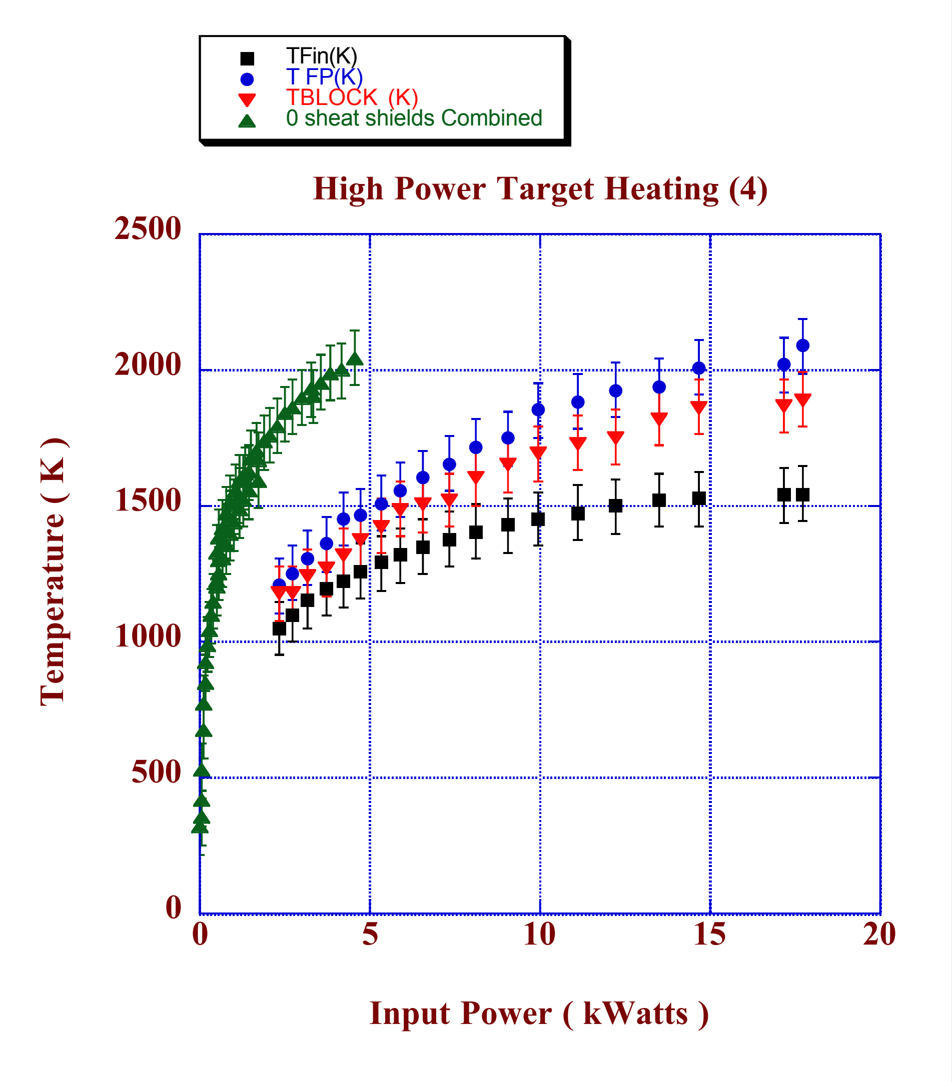
High Power Target



$55 \leq I_{Proton} \leq 100\ \mu A$

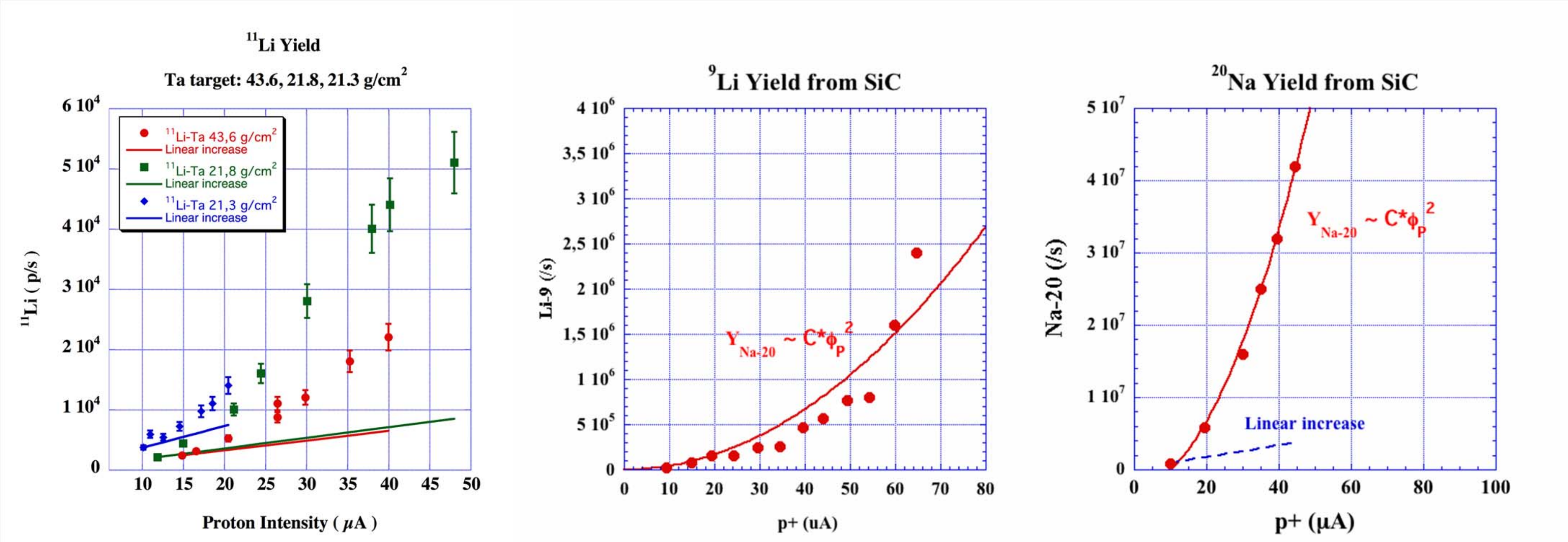
High Power Target

- Low power target oven can dissipate up to 5 kW of beam deposition power.
- The high power target oven has fins attached to the Ta tube and can dissipate up to 20 kW beam power.
- How do we compare with other,
  - ISOLDE/CERN, 1 kW,
  - SPIRAL/GANIL, 1 kW,
  - HRIBF/Oak Ridge, 500 W

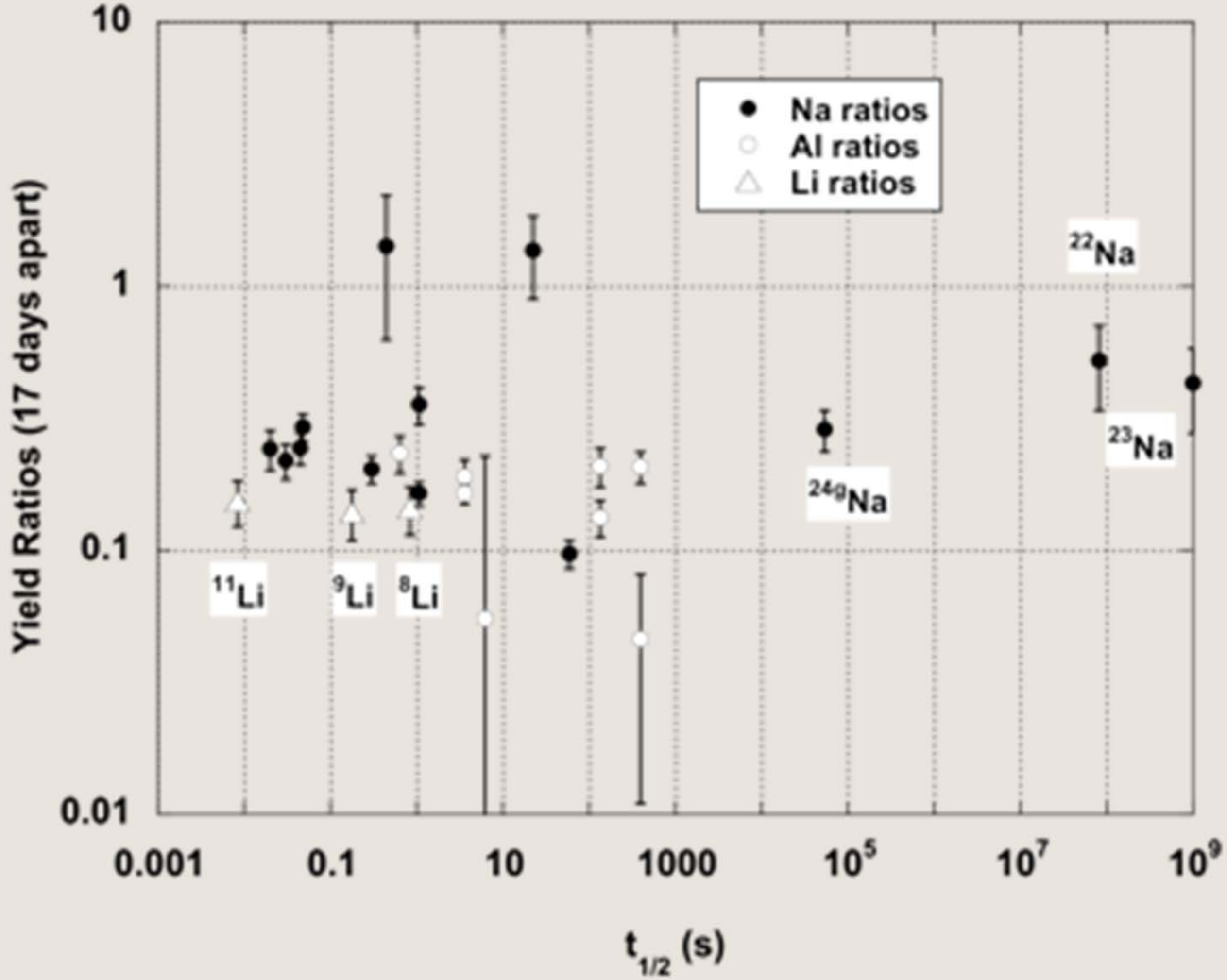


Radiation Enhanced Diffusion

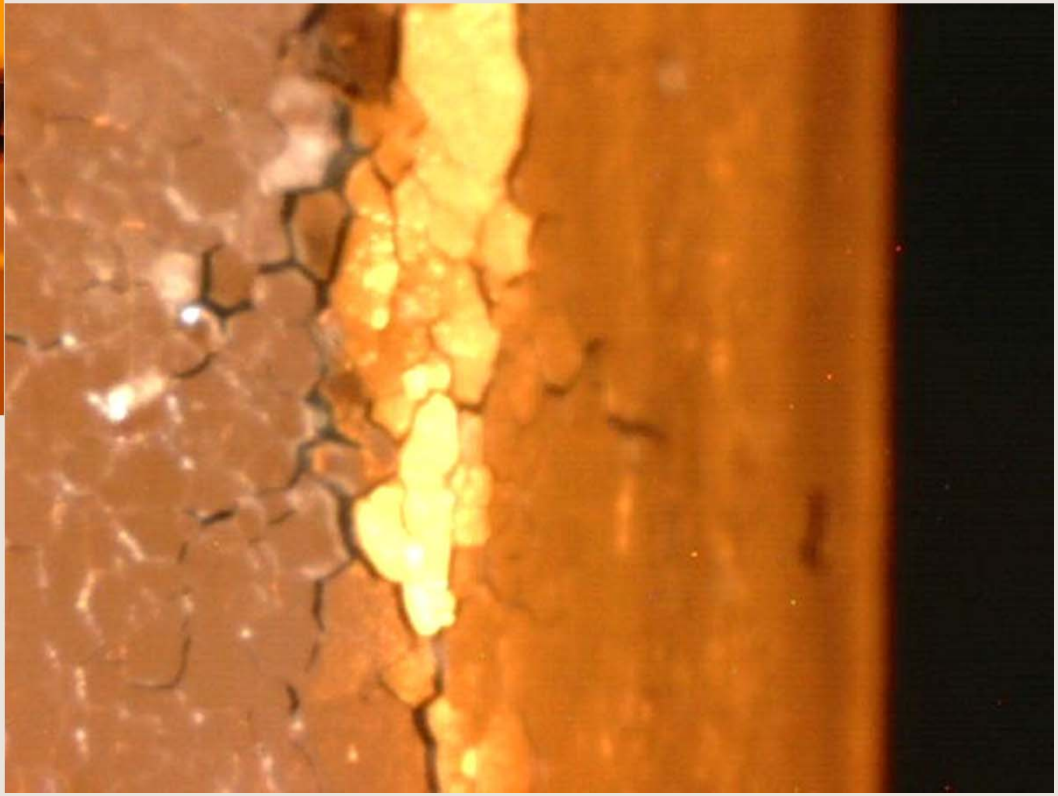
- Perhaps the most striking result of operating at higher proton beam currents has been the observation of radiation enhanced diffusion (RED).



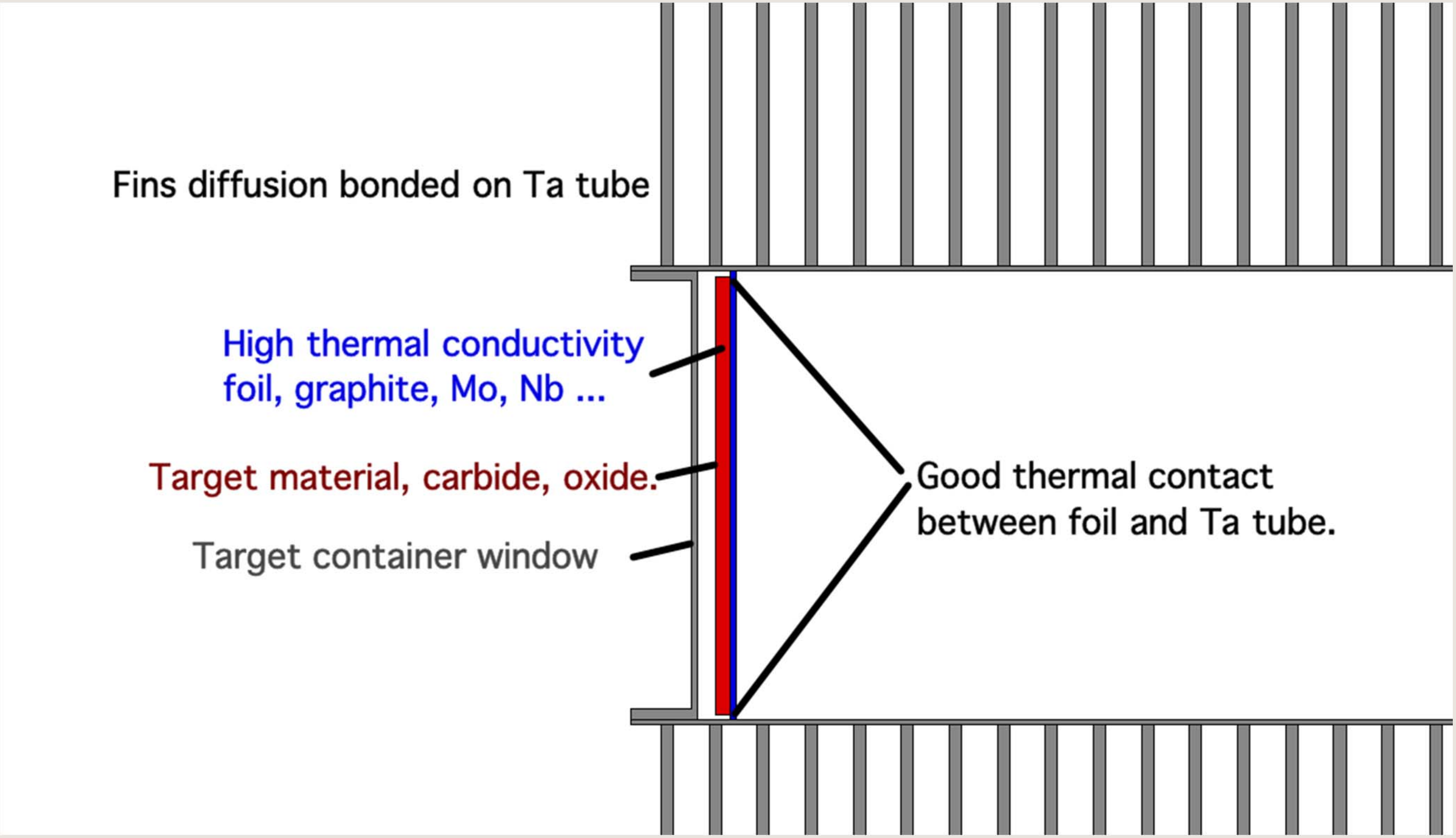
Yield ratios showing performance degradation



Target Oven Damage

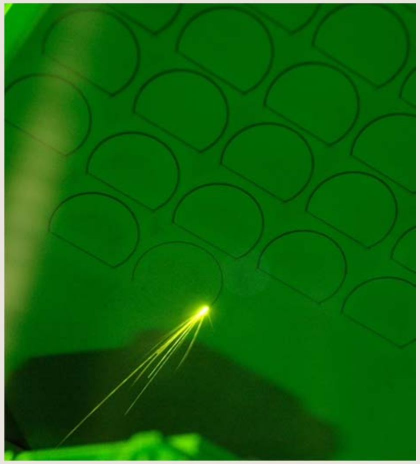


2) High Power Target Material, composite



High Power Target Material Fabrication

- The ceramic powder suspended in a solvent, which contains dissolved polymers that favor the powder dispersion. This mixture in suspension is poured into a mold or onto a backing foil and then allowed to dry.
- The dried slip cast, which contains the ceramic powder particulates and the polymers, is easily cut into the desired shape using LASER cutting.
- These carbide ceramics can be used up to 40 µA. However, due to their relatively low thermal conductivity compared to metal foils, it is necessary to increase the effective thermal conductivity of the carbide ceramics in order to operate targets at higher beam intensity.
- We have developed a technique allowing us to pour the ceramic powders and polymers onto an exfoliated graphite foil. These composite carbide targets are capable of dissipating very high power. The ceramic layer is typically 0.25 mm thick, while the graphite layer is around 0.13 mm thick.



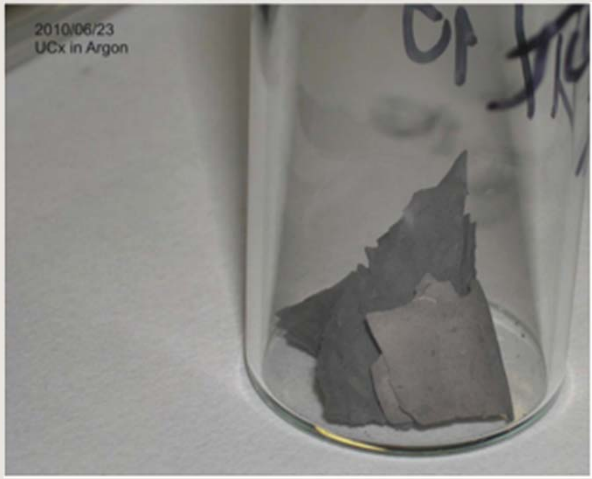
UCx as Target Material

- Advantage:
- Good thermal conductivity, compared to UO_2
- Low vapour pressure at high temperatures

- Concerns:
- Exothermic oxidation
  - Operation safety
- Long-term stability after use
  - Storage of irradiated targets

Fabrication of UCx

- UC_x was produced by from UO_2 + graphite,
- Using a ball mill machine they are ground to fine power in a plasticiser solution,
- Carbonization is done under vacuum,
- The resulting sheet is milled in a plasticiser solution again,
- The solution is then cast onto a graphite foil
- Target disks are then cut from the “green” cast.
- Target disks are then load into the target container for thermal conditioning under vacuum.



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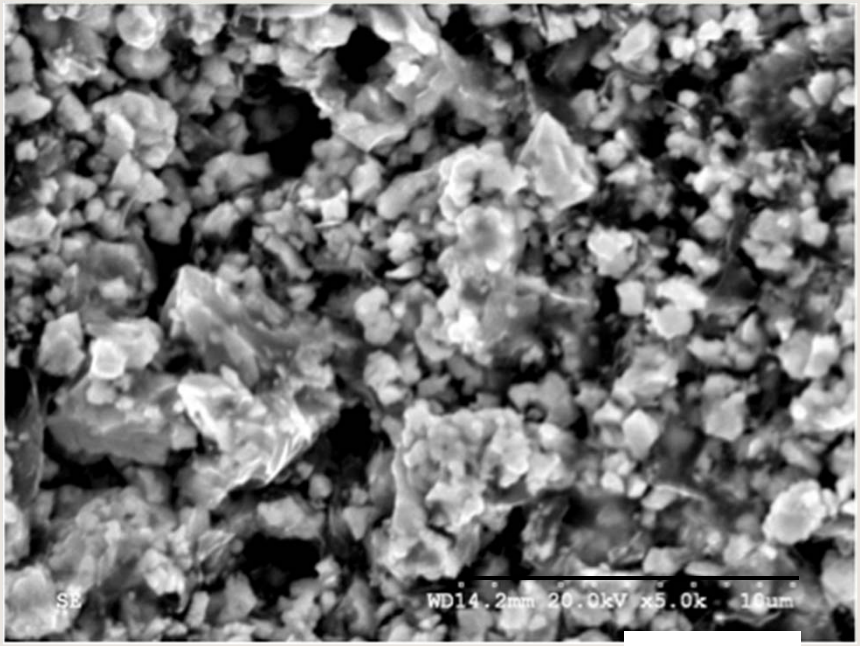
Test Chemical Stability of UCx

- Test the chemical reactivity in air
  - Exposure of raw and sintered UC_x to air for different periods of time.
- Chemical reactivity in air at higher temperatures
  - Heating the raw and sintered UC_x up to 400 degree Celcius.
- Chemical reactivity in water
  - Exposure of the raw and sintered UC_x to water.
- All these tests show that the UCx material is quite stable and can be used safely within the ISAC operating conditions

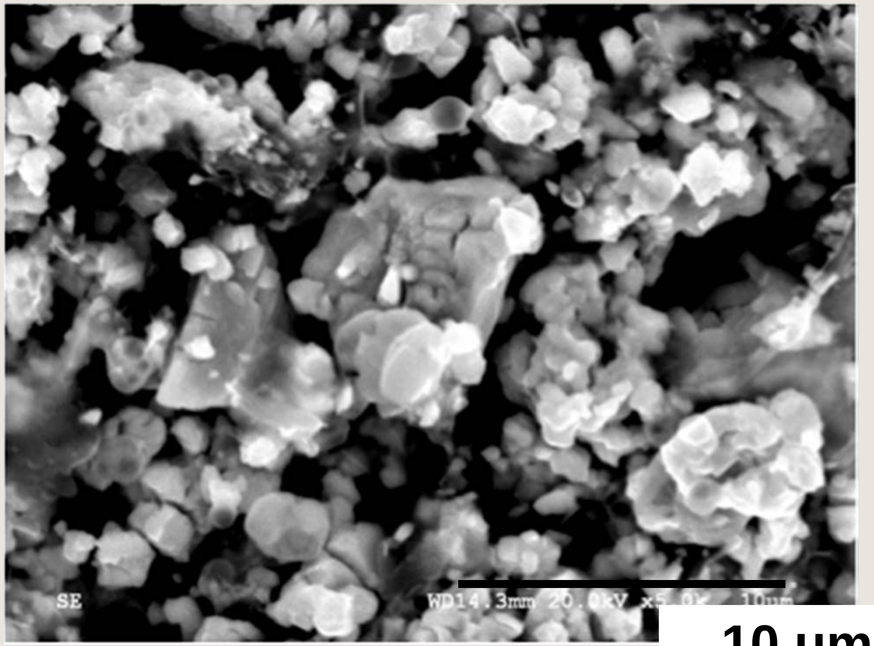
SEM of "raw" and sintered UC_x



10 um

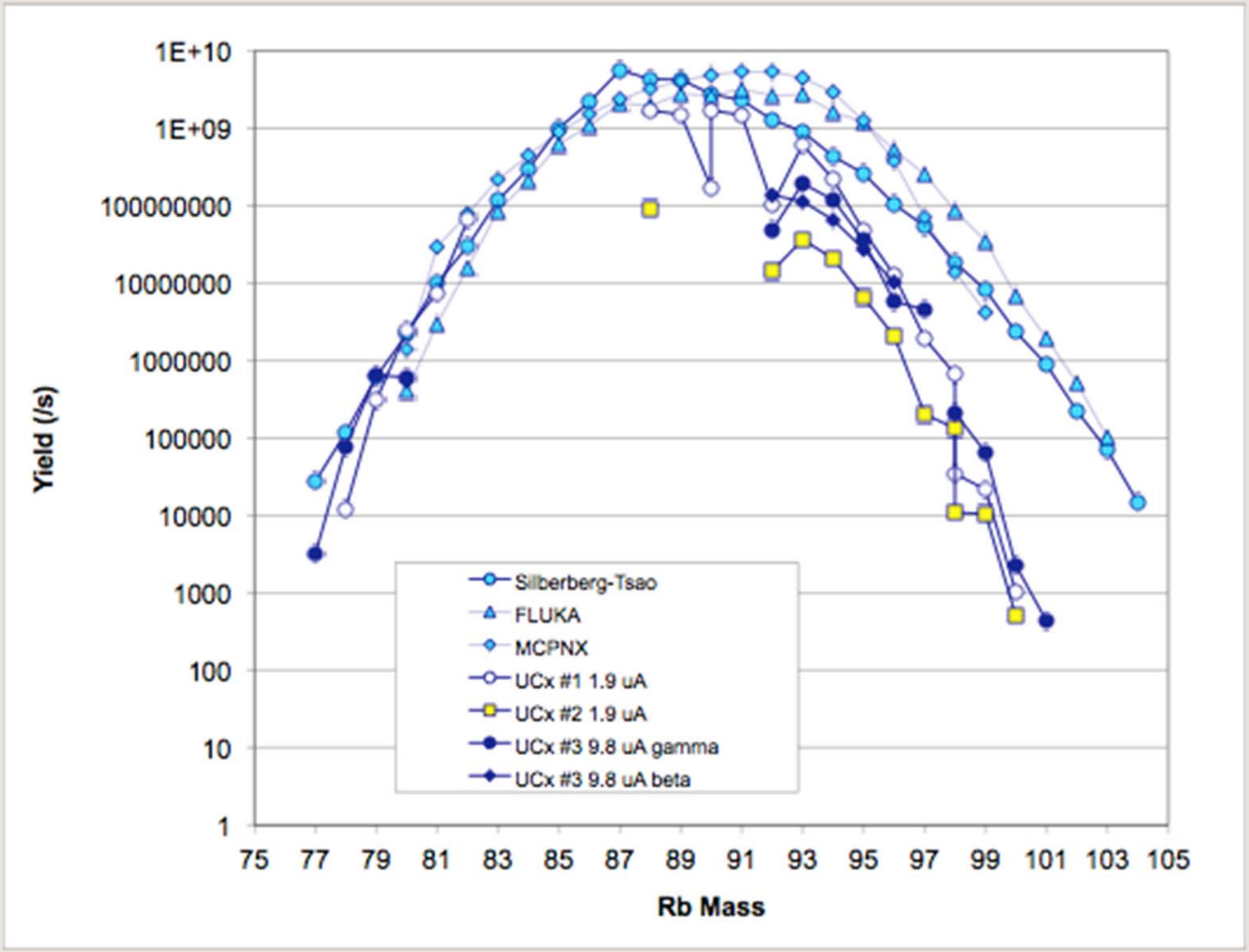
"raw" UC_x

Sintered UC_x



10 um

10 µA proton on UCx target



Release properties of ISOL target material

- The release efficiency of rare isotopes is not the same for all elements. This play in our advantage by improving the selectivity or to our disadvantage by not releasing the element we want.
- The requirement for fast release of short-lived rare isotopes species from the target material involves operating the target/ion source at high temperature and require stable temperature.
- The target must be a refractory material having a low vapor pressure at elevated temperature to avoid vaporization of the target material.
  - refractory metal foils, Ta, Nb, ...
  - refractory carbide discs, SiC, TiC, ZrC, TaC,...
  - refractory oxide, Al_2O_3,UO_2 ...
- => need of R&D.

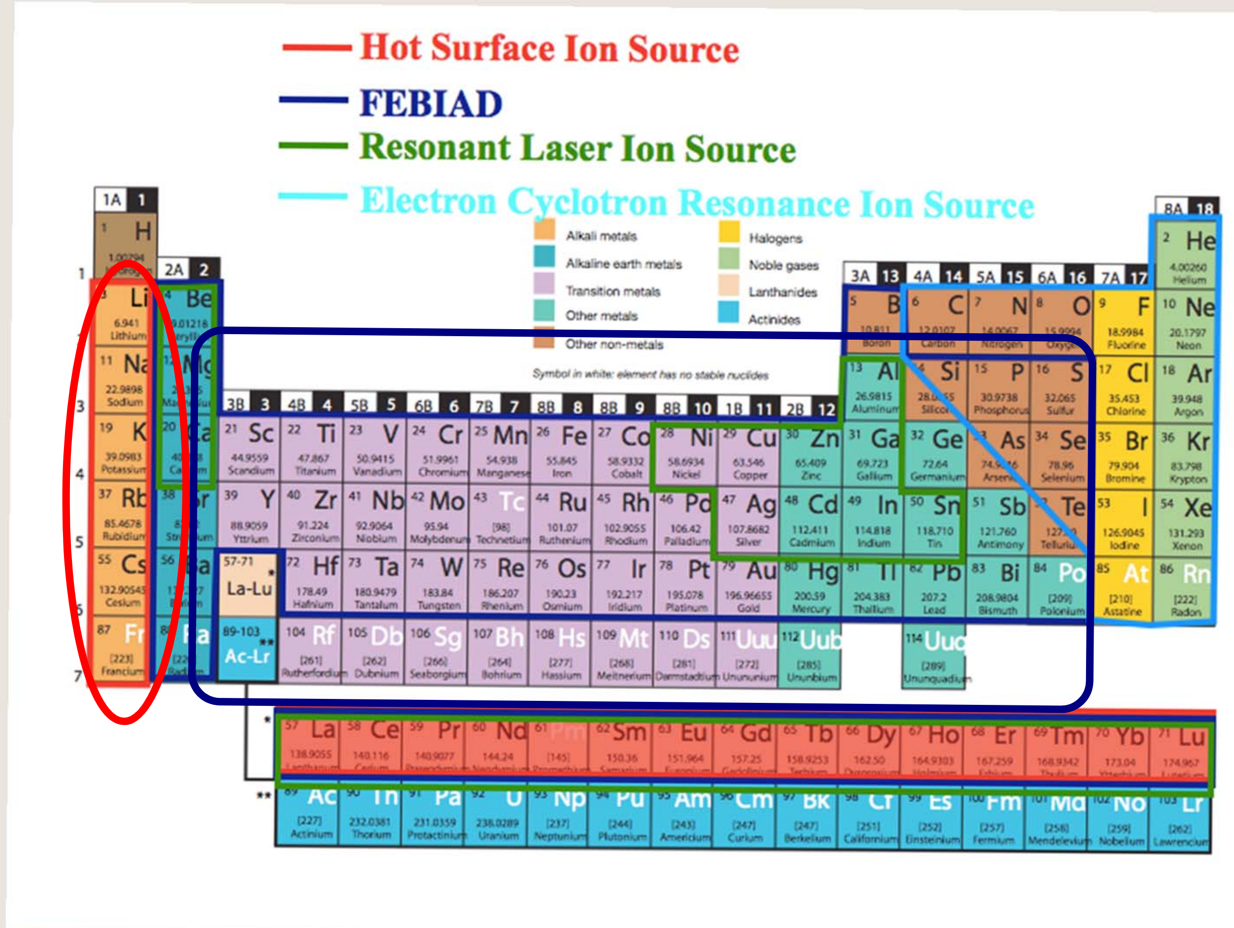
Ion Source Operation Domain

- There is *no universal* ion source for on-line application,
- We must develop ion source for each group of elements;

Hot Surface IS

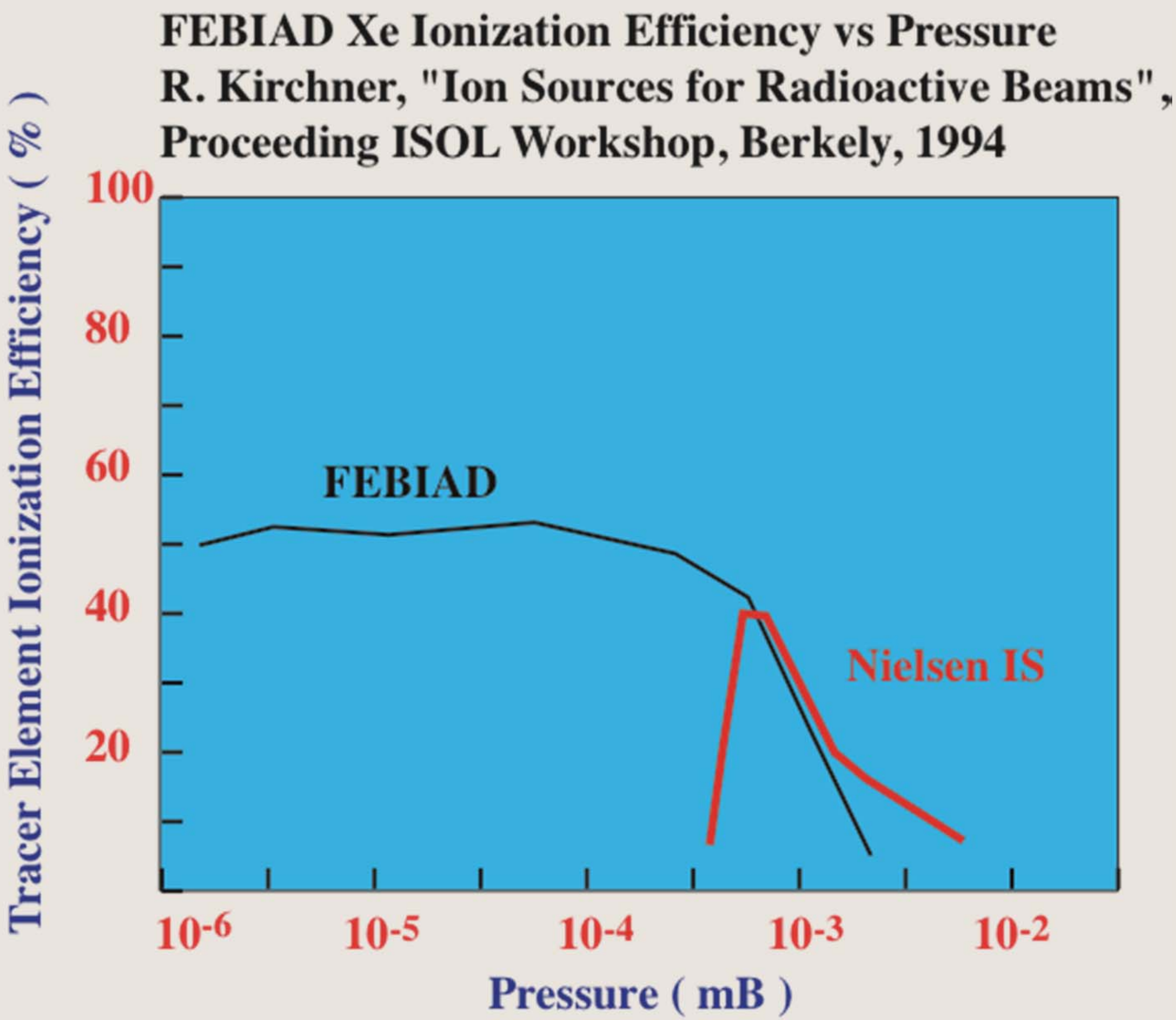
LASER IS

Negative IS



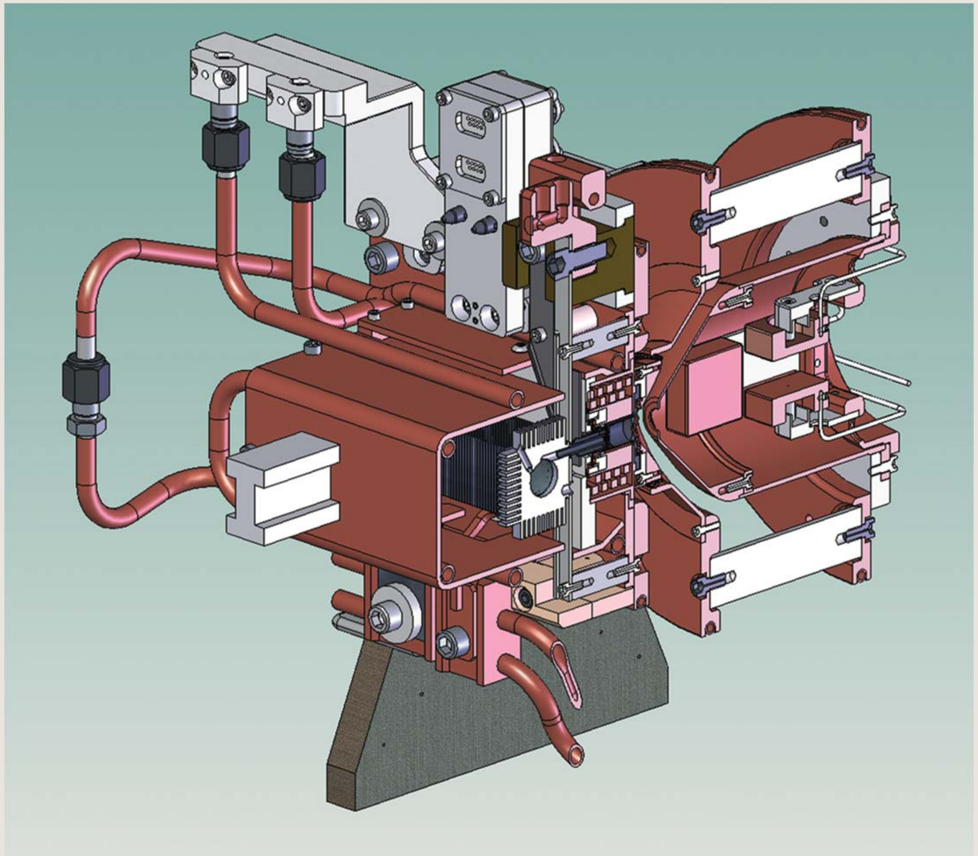
Plasma Ion Source; Electron impact, ECR ion sourc

FEBIAD Ion Source



Hot Plasma Ion Source, FEBIAD

- FEBIAD ion source, it is a hot plasma ion source,
- It was used for TUDA $^{18}F(p,\alpha)^{15}O$ experiment,
- We operated the FEBIAD combined with a high power composite target such as SiC/gr, TiC/gr, ZrC/gr at 70 μA.



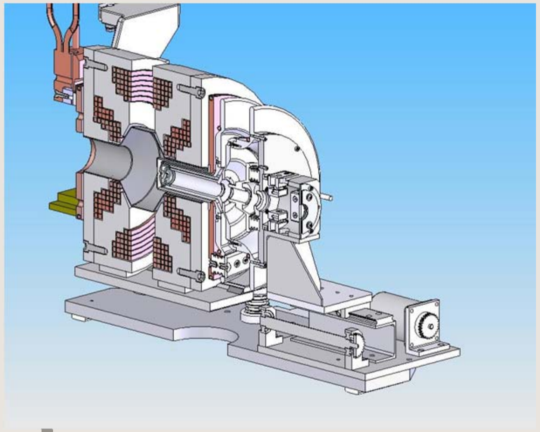
FEBIAD Ion Source, section view.

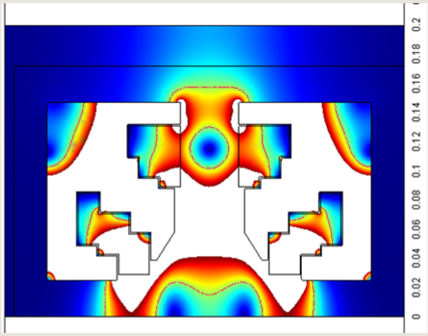
High performance ECR Ion Source

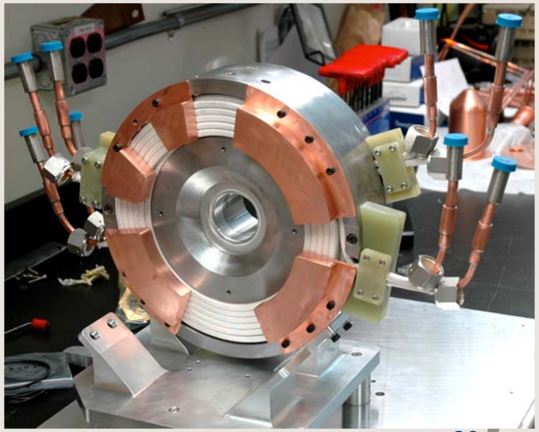
- Radiation resistant ECRIS for mono charged ions.
  - No permanent magnets
- High level of confinement, using 4 coils arrangement
- Tests were done to measure ionization efficiency

Element	I Eff %
F	72
Ne	48
Kr	48*
Xe	40*

*** higher charge state are produced.**







RIB Charge Breeding

- The physics with RIB in the intermediate mass range, $60 < A < 150$ requires efficient acceleration of the RIB.
- Need Charge Breeding to reduce A/q below 7.
- So far we observed large contamination from Fe, Ni, Cr ions coming from material inside the CSB.
  - Coating of the plasma chamber
  - and machining the injection and extraction electrode with pure Al reduces the Fe, Ni and Cr in our beam output spectrum.
- Test under way with RIB.

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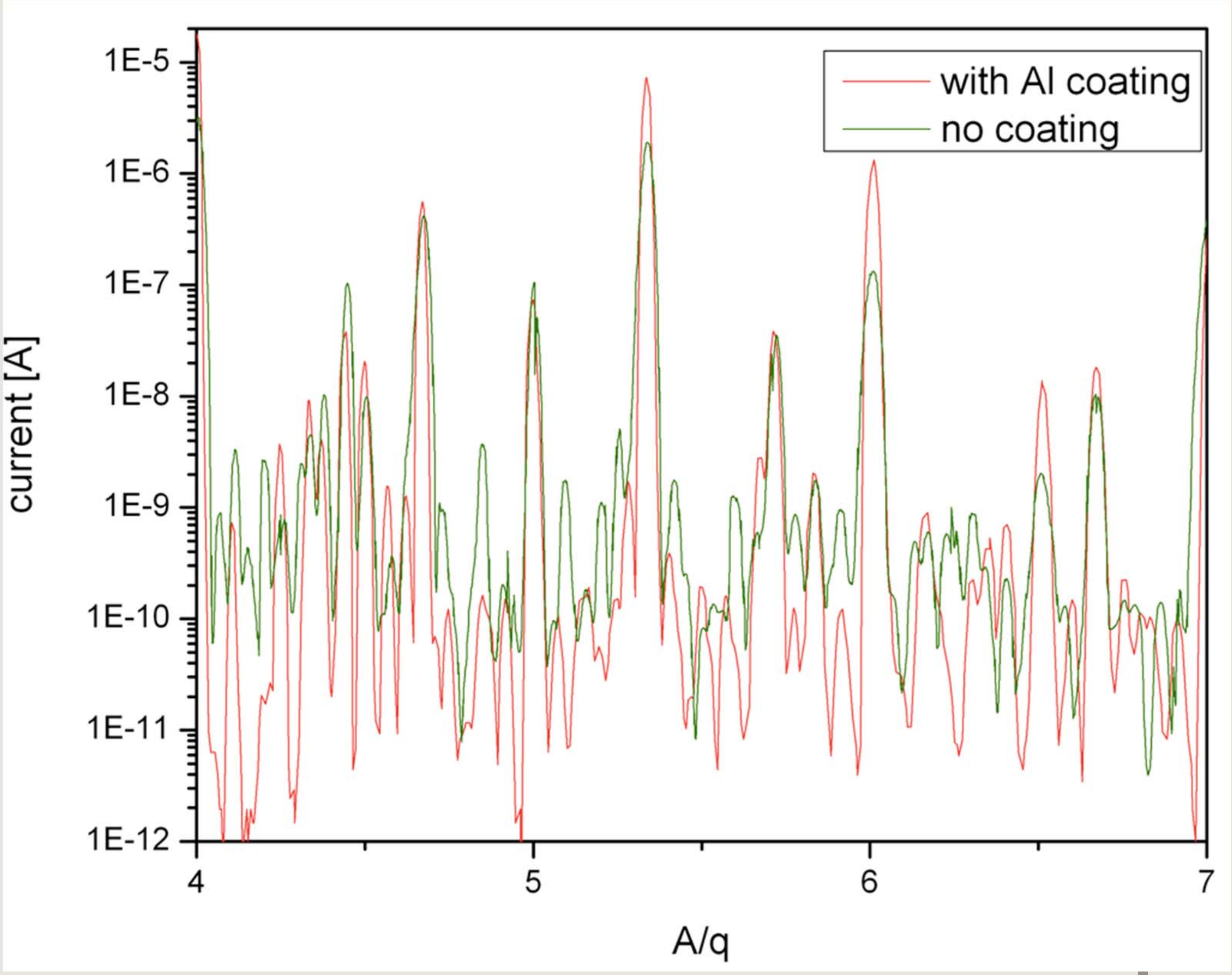
RIB Charge Breeding

- Al coating reduces contaminants from Fe, Ni, Cr ions.



Reliability Issues

- Targets have to operate in high radiation dose environment making repair and maintenance extremely difficult and challenging.
  - Need high reliability
    - To guaranty beam time to users
    - RIB repeatability, to maximize beam time,
    - Minimize dose for repair and maintenance,

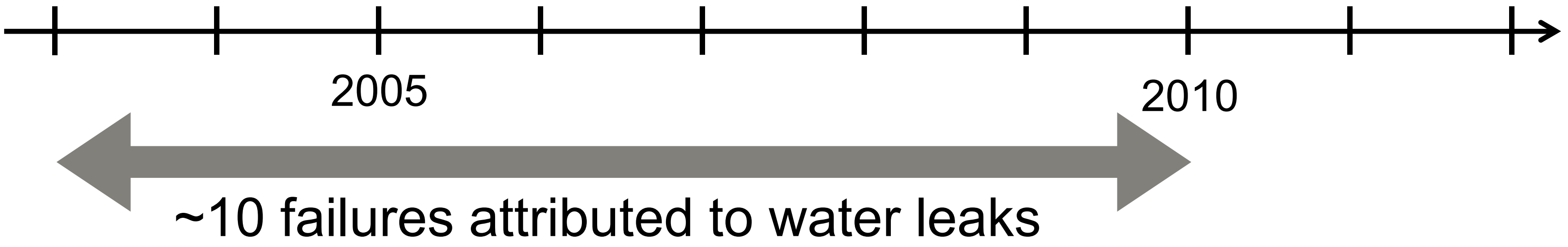
Failure Mode & Effect Analysis

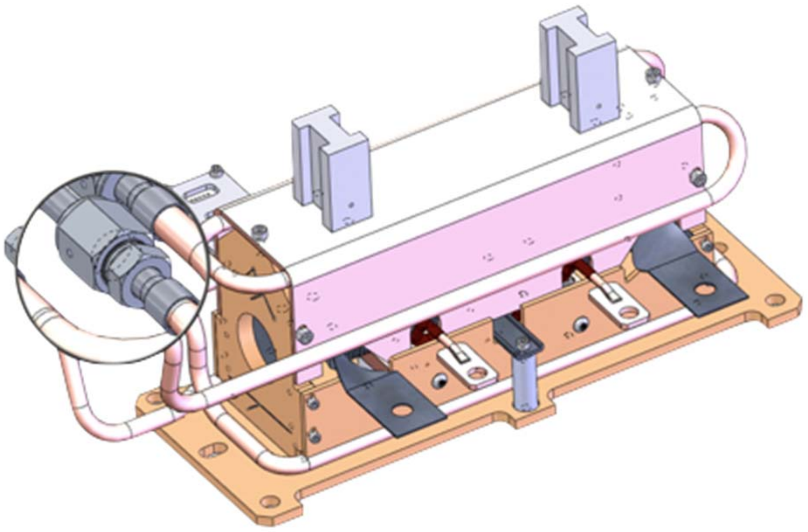
- **Designs and processes have been analyzed to improve the Target/ion source reliability**
- **FMEA is used in product development in manufacturing industries for example, where it helps to identify potential failure modes based on experience.**
- **To help focusing on the critical failure mode(s) it is important to come up with some sort of rating of the risk.**

Item/ function	Potential Failure Mode	Potential Effects of Failure	Potential Cause(s)	Severity (S)	Occurrence (O)	Current Control	Ease of Detection (D)	Risk Priority Number (RPN)	Critical Character Y/N	Recommended Actions, ECO number	Responsibility and Target Date for Completion	Action Taken

- **Help to prepare for next generation of RIB facility.**

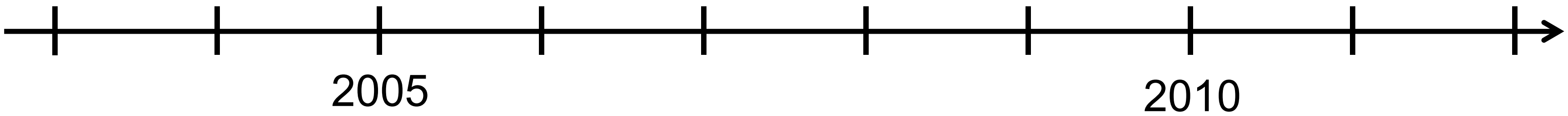
VCR connection



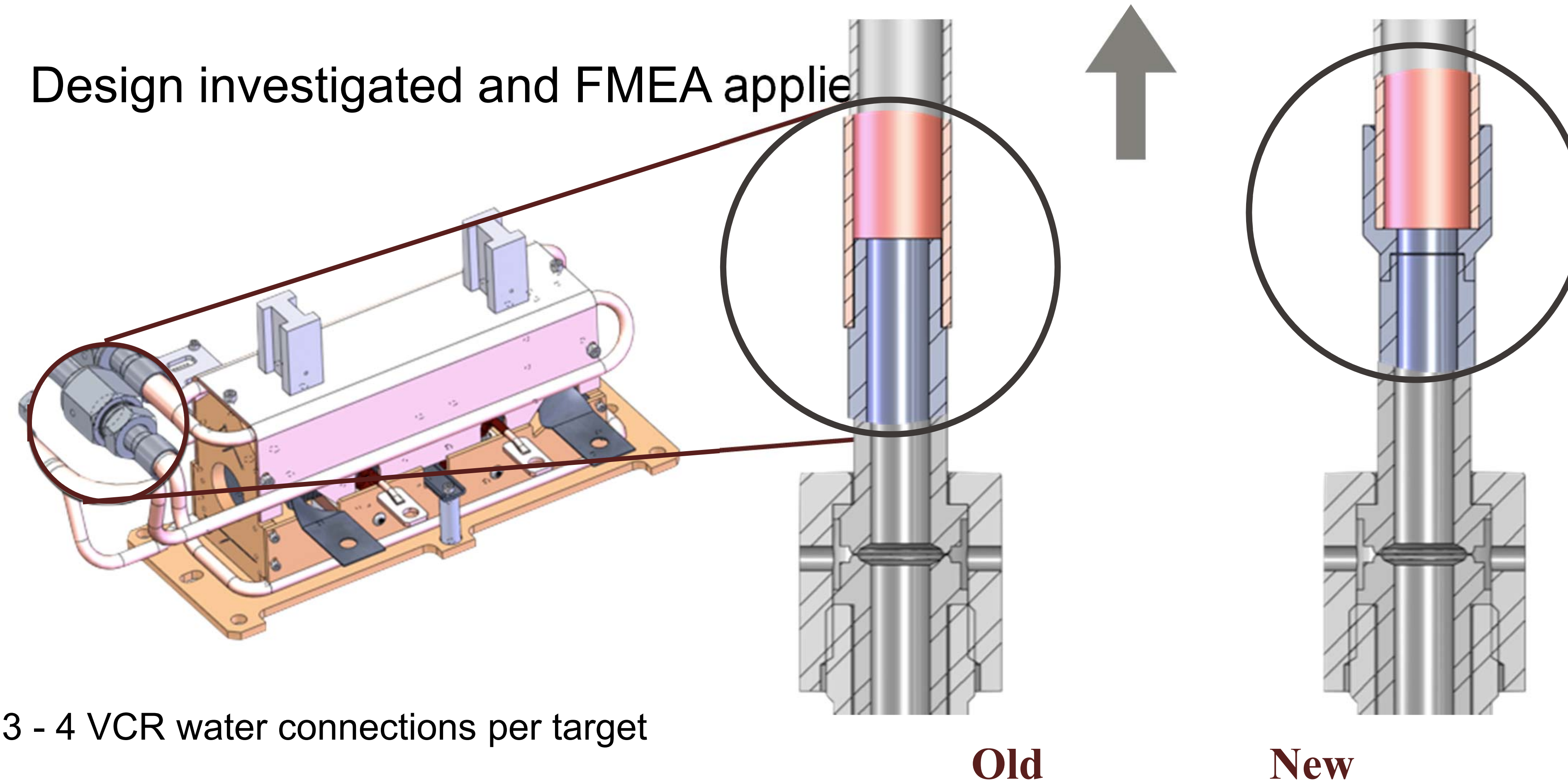


3 - 4 VCR water connections per target

VCR connection



Design investigated and FMEA applie

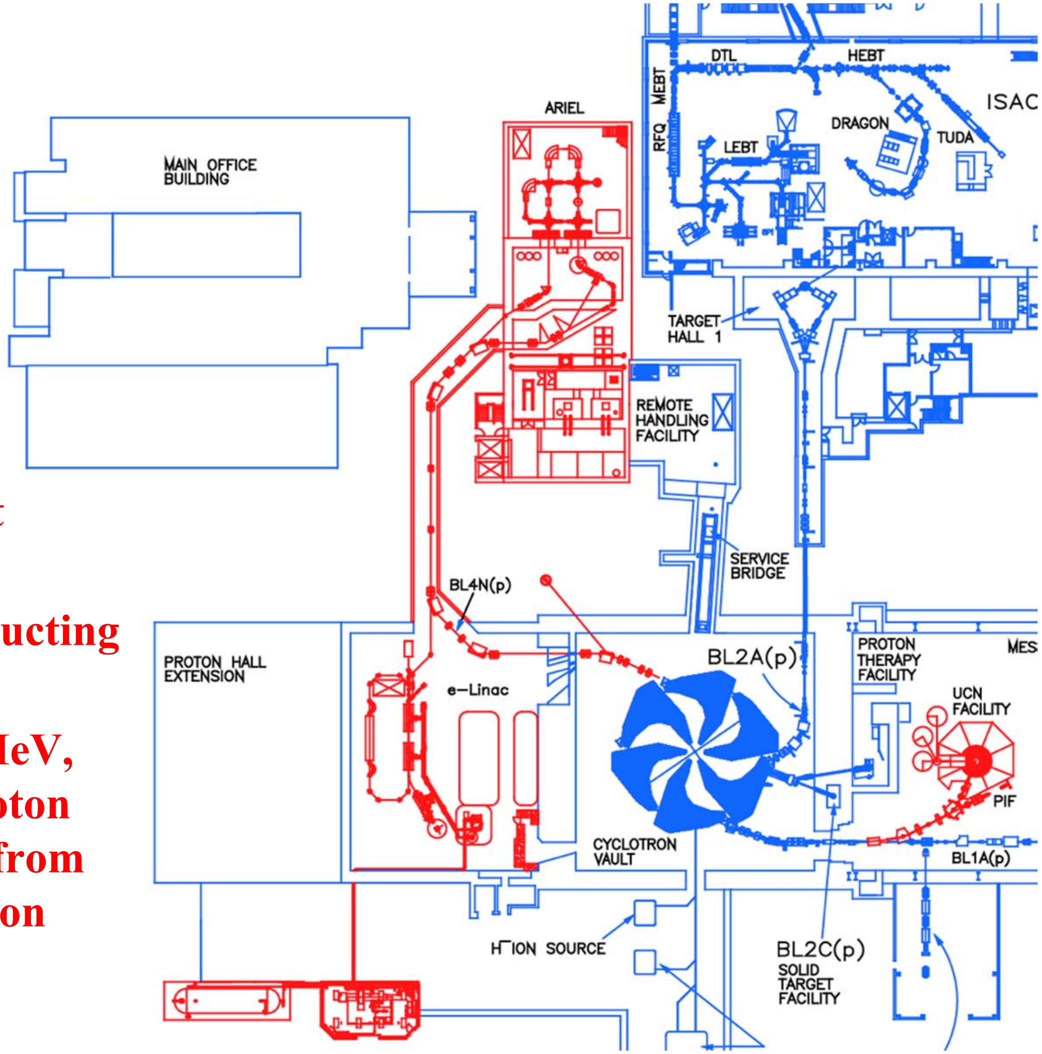


3 - 4 VCR water connections per target

Future Directions

- There is a long list of new proposals and projects with the goal to increase the RIB intensity; SPIRAL-II, ARIEL, KoRIA, CARIF, EURISOL
- Neutrons and Gammas to induced fission:
  - Neutrons are produced from ^{2}H on graphite converter in the case of SPIRAL-II,
  - Neutron from spallation or high flux nuclear reactor.
  - Gammas from high intensity electron LINAC

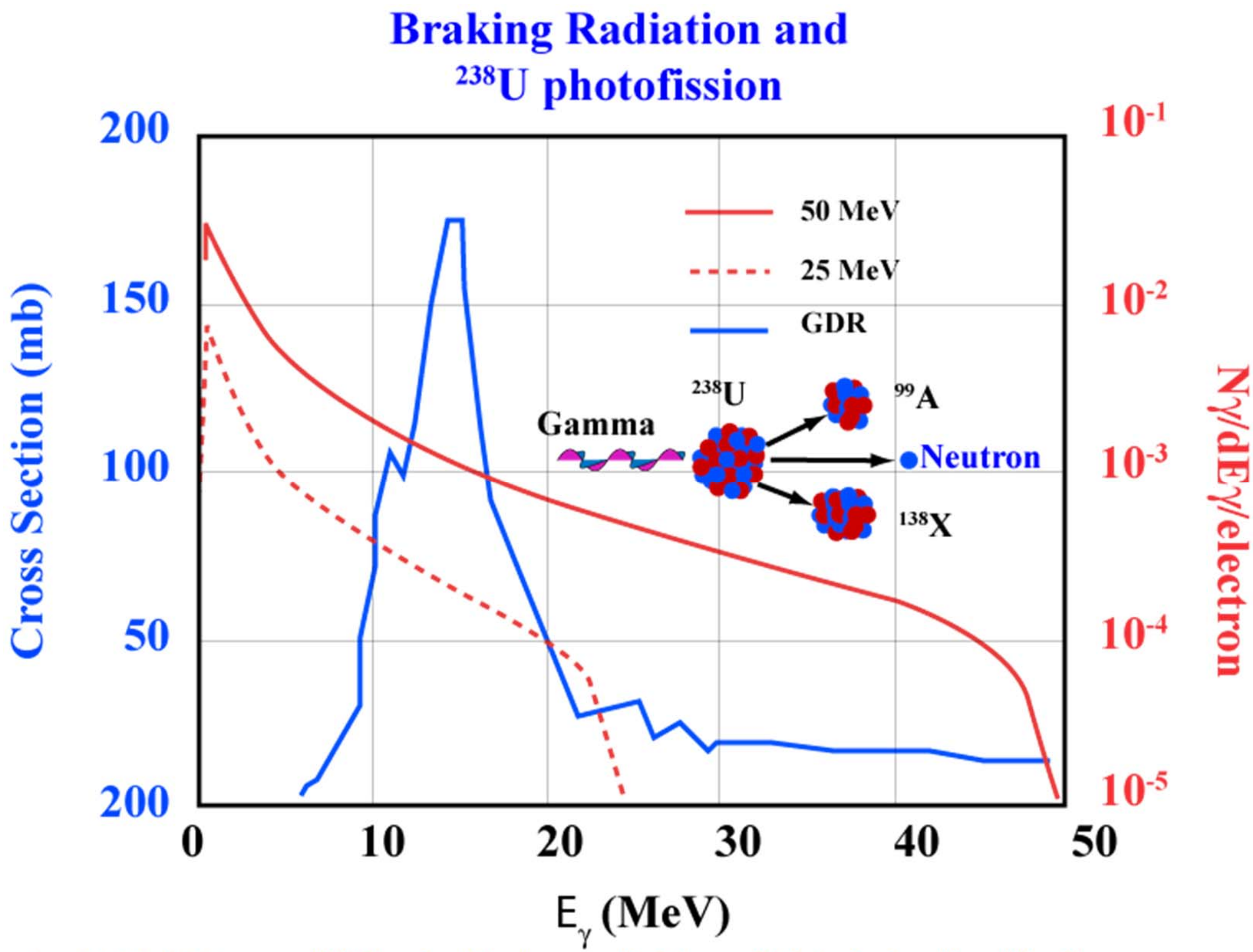
More RI Beams To Users



ISAC RI beam Facility is one user only.
Back log is important

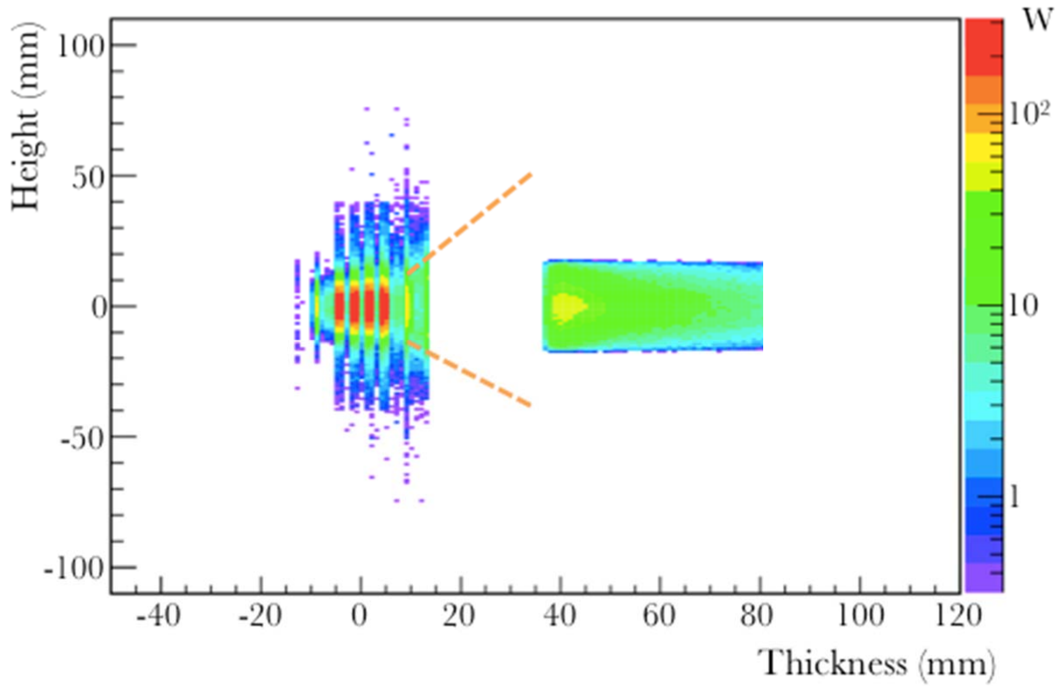
- **ARIEL project**
  - **Electron Superconducting LINAC**
  - **New 500 MeV, 200 µA proton beam line from H- Cyclotron**

Characteristics of the induced photo-fission



100 kW converter

- Simulation using GEANT4 shows that 96% of the gamma are within a 10º cone
- Power distribution for a 100 kW beam onto Ta converter and UC_2 target



- **37 kW in converter**
- **22 kW in Target**

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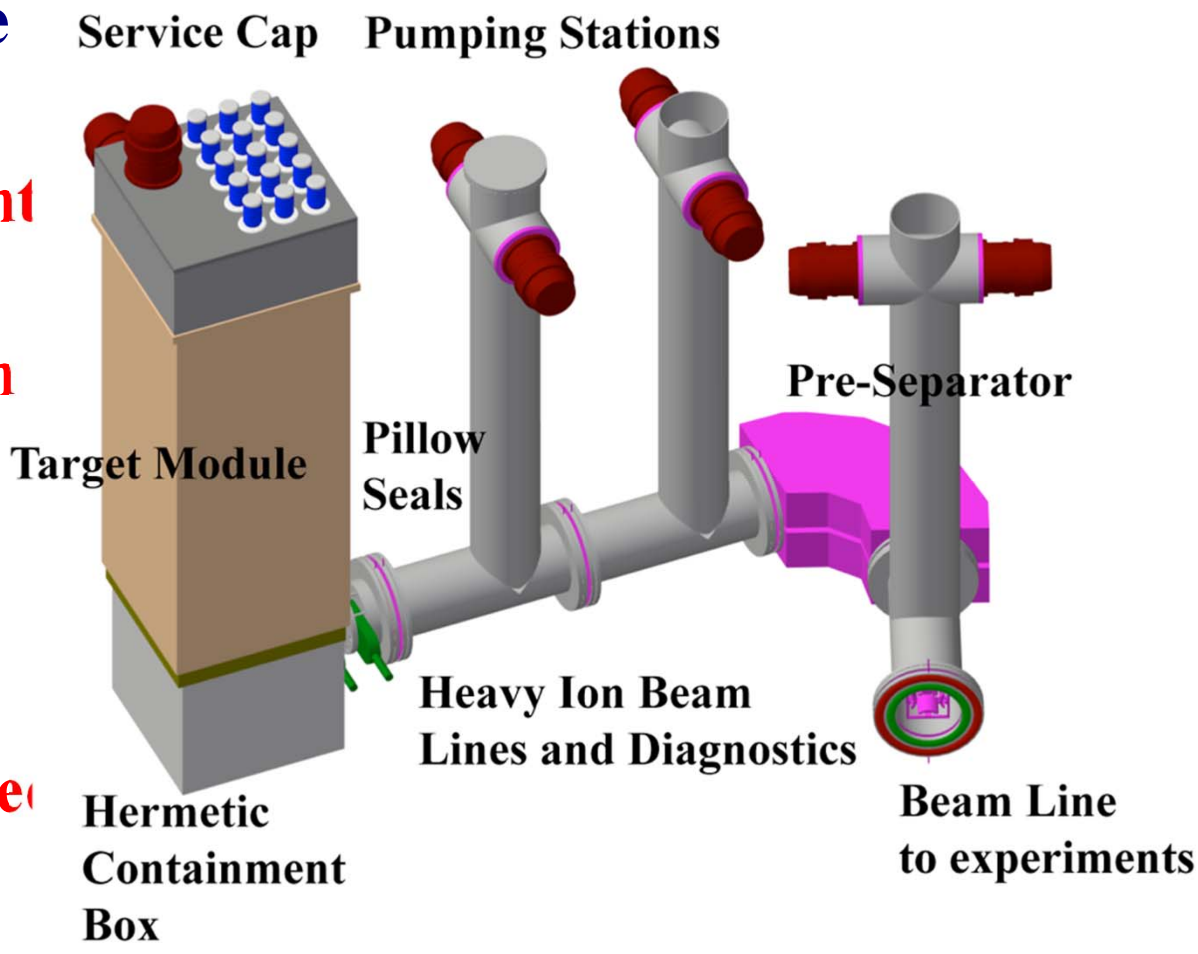
500 kW converter

- **For beam power above 150 kW we cannot apply the static target solution for a converter.**
- **Options for a ½ MW converter**
  - **Water-cooled rotating wheel**
  - **Liquid metal converter**
- **Power distribution, 274 kW in converter, 75 kW in Target**

ARIEL/TRIUMF Target Station Concept

- Uses Target Module similar as for ISAC
  - Sealed containment box.
  - Simplified vacuum system.
  - Quick disconnect vacuum envelope using pillow seals technique developed for T2K.



Critical Technologies for Higher ISOL RIB Intensity

1) Target material has to be capable of sustaining high power deposition from the driver beam,
   - Refractory foils target, Ta, Nb ... operate at 100 µA, corresponding to 50 kW proton beam power
   - Composite target developed at ISAC/TRIUMF have high thermal conductivity
     - Carbide targets, SiC, TiC, ZrC, UC on Graphite foil are operating in the range of 70 to 80 µA proton
     - Oxide targets, NiO, Al_2O_3 on Nb or Ta foil run at 20 to 35 µA

Critical Technologies for Higher ISOL RIB Intensity

2) Target container capable of dissipating the power from the target material to the heat-shield and cooling system.
   - To limit target damage the driven beam has to have limited beam trips, T > 5 sec.
3) Ion Source capable of operating efficiently in a wide pressure range
4) Bridge the gap between species available with ISOL method. Force non volatile species into more volatile molecular form. F by adding Al , Al by adding F, -> AlF Sn by adding S -> SnS, etc.

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Critical Technologies for Higher ISOL RIB Intensity

5) The Target/ ion source is operating in a very high radiation field. It is imperative to have high reliability. Failure Mode and Effects Analysis of the Design and Process is a necessary tool to identify the criticality of the components and processes.

6) To RIB need for a large fraction of the physics required Charge Breeding.

- Higher breeding efficiency
- Higher beam purity, need to reduce stable contaminants

Future Directions

New facilities are proposing to use neutrons and photons beam to induce fission from U target.

- **The optimum goal is to reach 10^{15} to 10^{16} f/s. To achieve reliable operation these targets have to be made with target material capable of sustaining high power deposition in target and high thermal conductivity.**
- **Development of composite UCx and high power target is critical for the success these facilities.**
- **For example in the ARIEL project it even more critical to have high conductivity target material because of the high power deposited by the photon. They mainly convert into e-e+ pair. We will have to dissipate 75 kW in the UCx target.**

Thank you! Merci!

- Friedhelm Ames
- Marik Dombsky
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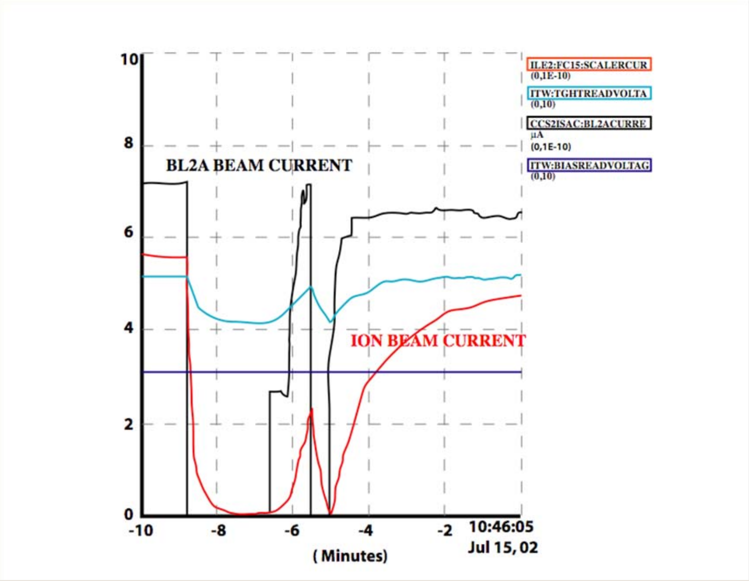
- Bevan Moss
- John Wong
- Rick Maharaj
- Aurelia Laxdal
- Donald Jackson
- Maico della Valle
- Francis Labrecque

TRIUMF

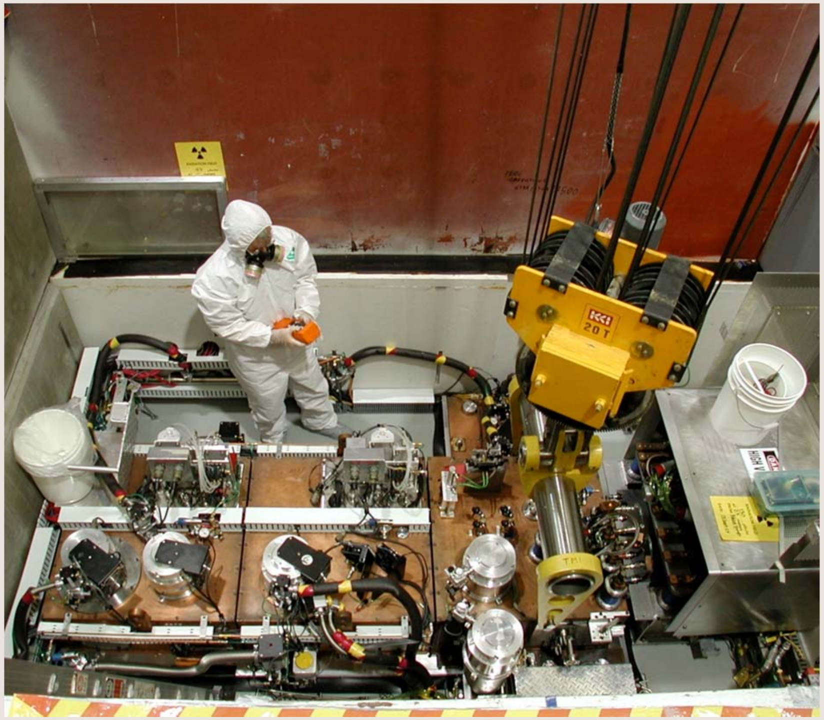
Driver Beam Stability

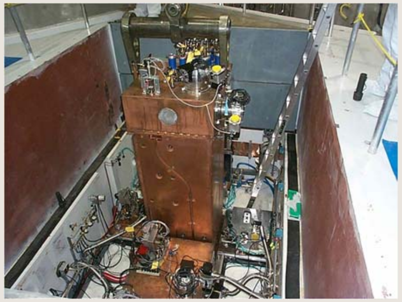
- Above 40 µA we are relaying on the proton beam to heat the target
- The target cooling occurs within seconds. The impurities which diffuse to grain boundaries freeze out. Micro cracks appear, which become larger every time the target cool down.
- It is imperative to limit beam trip > 5 sec.

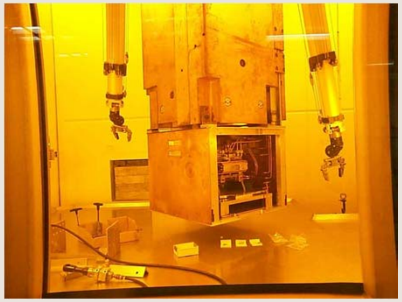


Target Exchange Process

- Hands On target module connection and disconnection
  - Need one week cool-down after beam off before starting services disconnection
- Target exchange takes from 3 to 4 weeks requiring proton beam off periods, ~ 200 H.
- The overall process limit RIB development due to large overhead require by the target exchange
  - Create schedule issue for RIB development





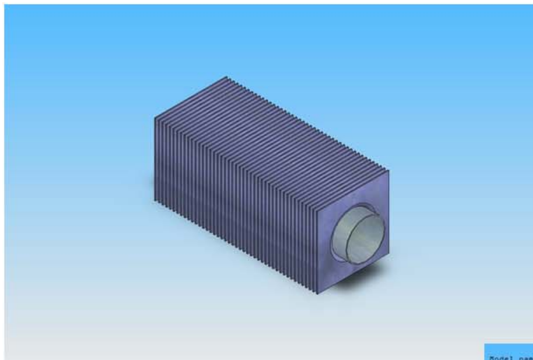


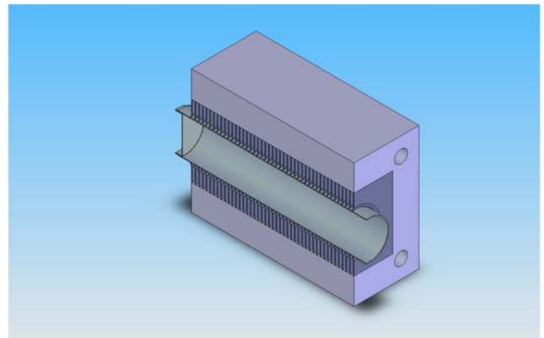
ARIEL Project

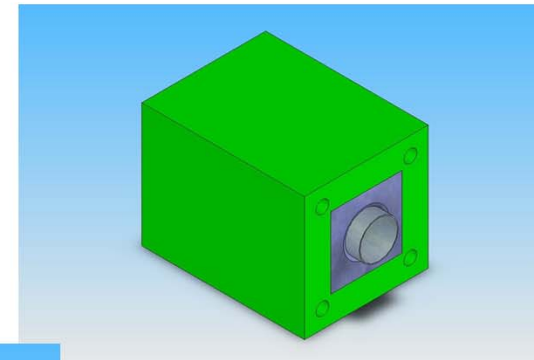
- ARIEL project phase 1,
  - TRIUMF received funding for electron superconducting LINAC through a the Canadian Foundation for Innovation,
  - and British Columbia government allocated $30.7 M for the building as matching funds.
- Phase 2
  - 100 kW target for photo-fission of ^{238}U.
- Phase 3
  - proton beam line to a second target station,
  - 500 kW for photo-fission.

Cooling High Power Target

- **Cooling concept for P ~ 30 - 60 kW**







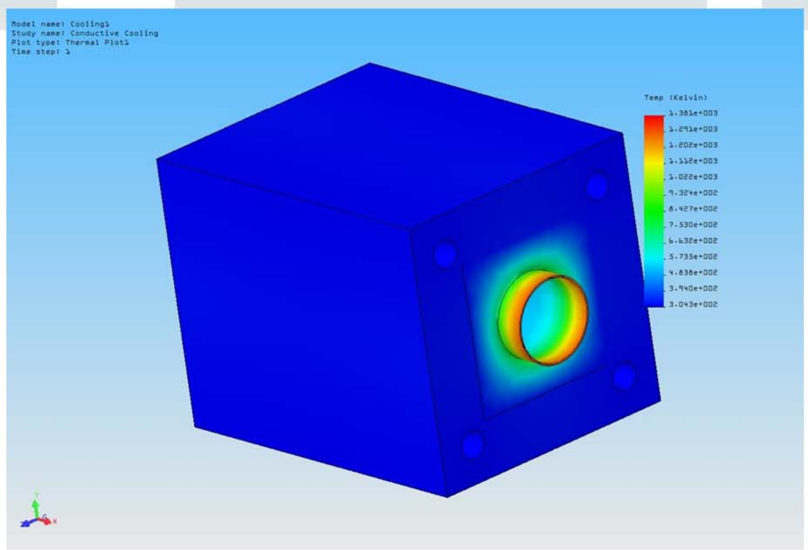
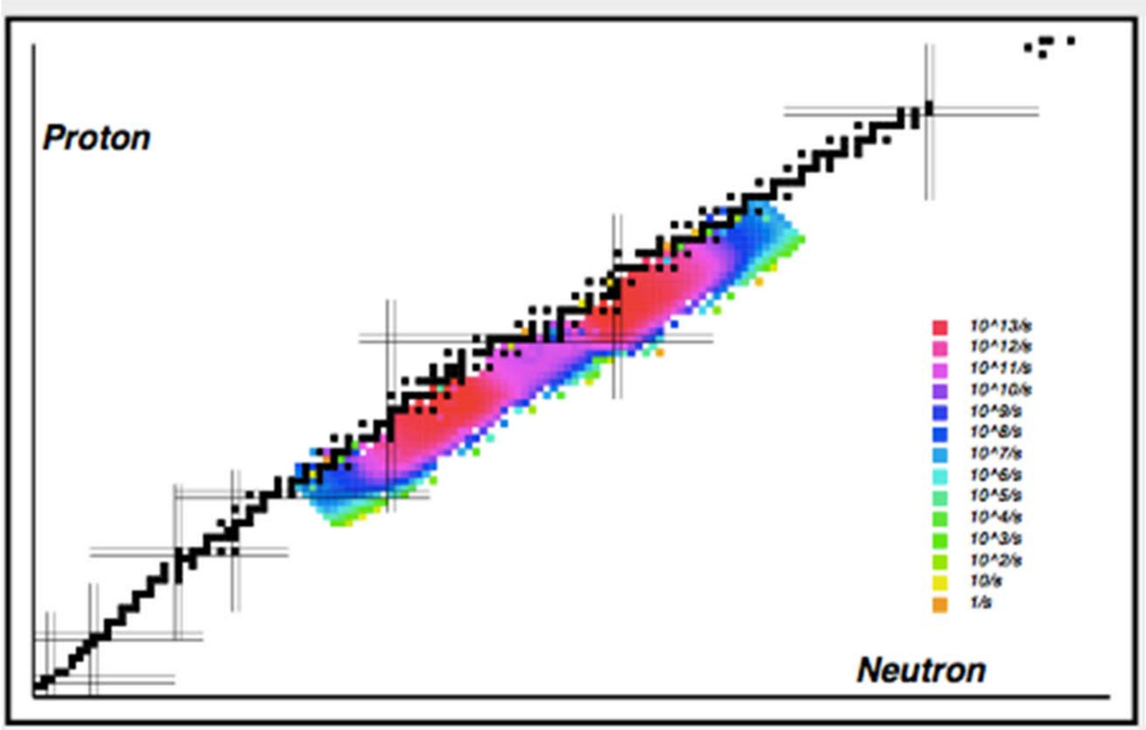


Photo-fission yield

- **Use GEANT4[1] and FLUKA[2] to simulate the photo-fission.**
  - **50 MeV,100 kW yield to ~ $1x10^{13}$ photo-fissions/s.**



1) Geant4 Developments and Applications, J. Allison et al., IEEE Transactions on Nuclear Science **53** No. 1 (2006) 270-278
Geant4 - A Simulation Toolkit, S. Agostinelli et al., Nuclear Instruments and Methods **A** 506 (2003) 250-303
2) Copyright Italian National Institute for Nuclear Physics (INFN) and European Organization for Nuclear Research (CERN)("the FLUKA copyright holders"), 1989-2007.

New Proton Beam Line

- **Second proton beam line, BL4N, to be installed by 2014.**
- **This new beam line will allow to operate ISAC target up to 200 µA with the exception of actinide target, which will be limited to 10 µA to be within TRIUMF release limits.**