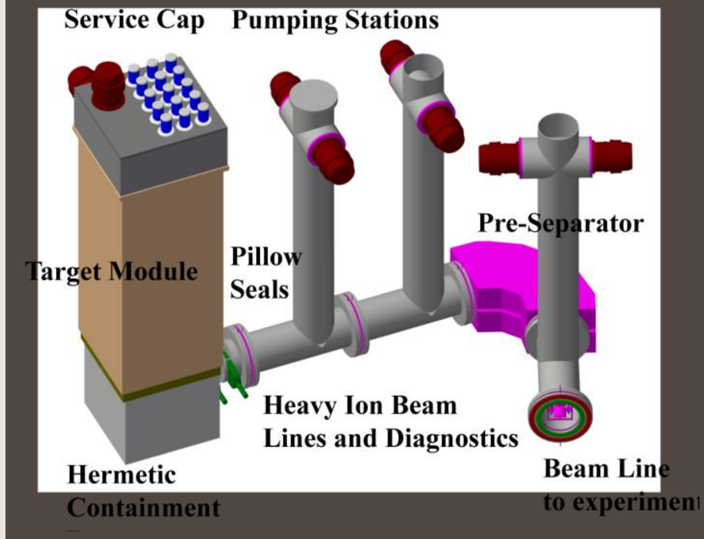
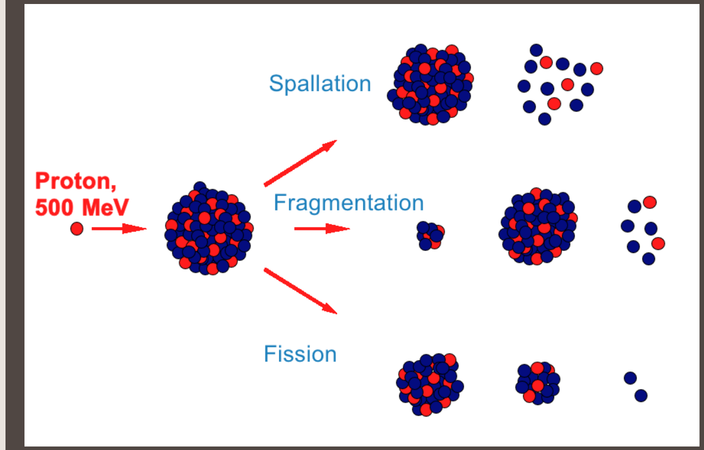
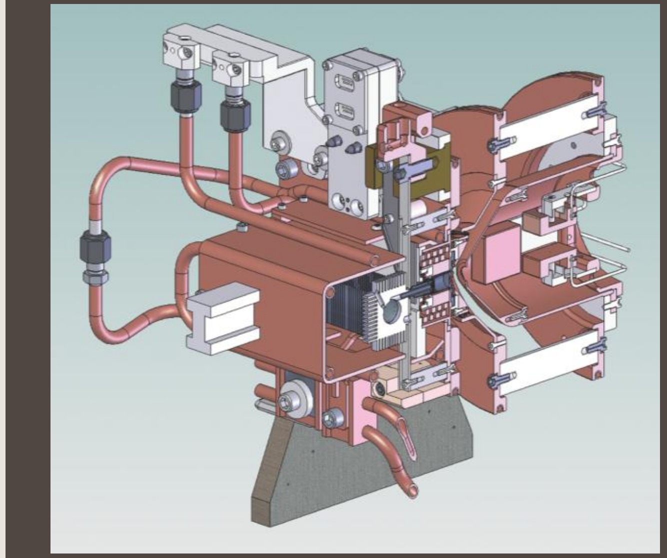
# Frontier Technologies and Future Directions in High Intensity ISOL RIB Production

**Pierre Bricault**
**Head Target/Ion Source Dept.| TRIUMF**
**HIAT12, June 18, 2012, Chicago**





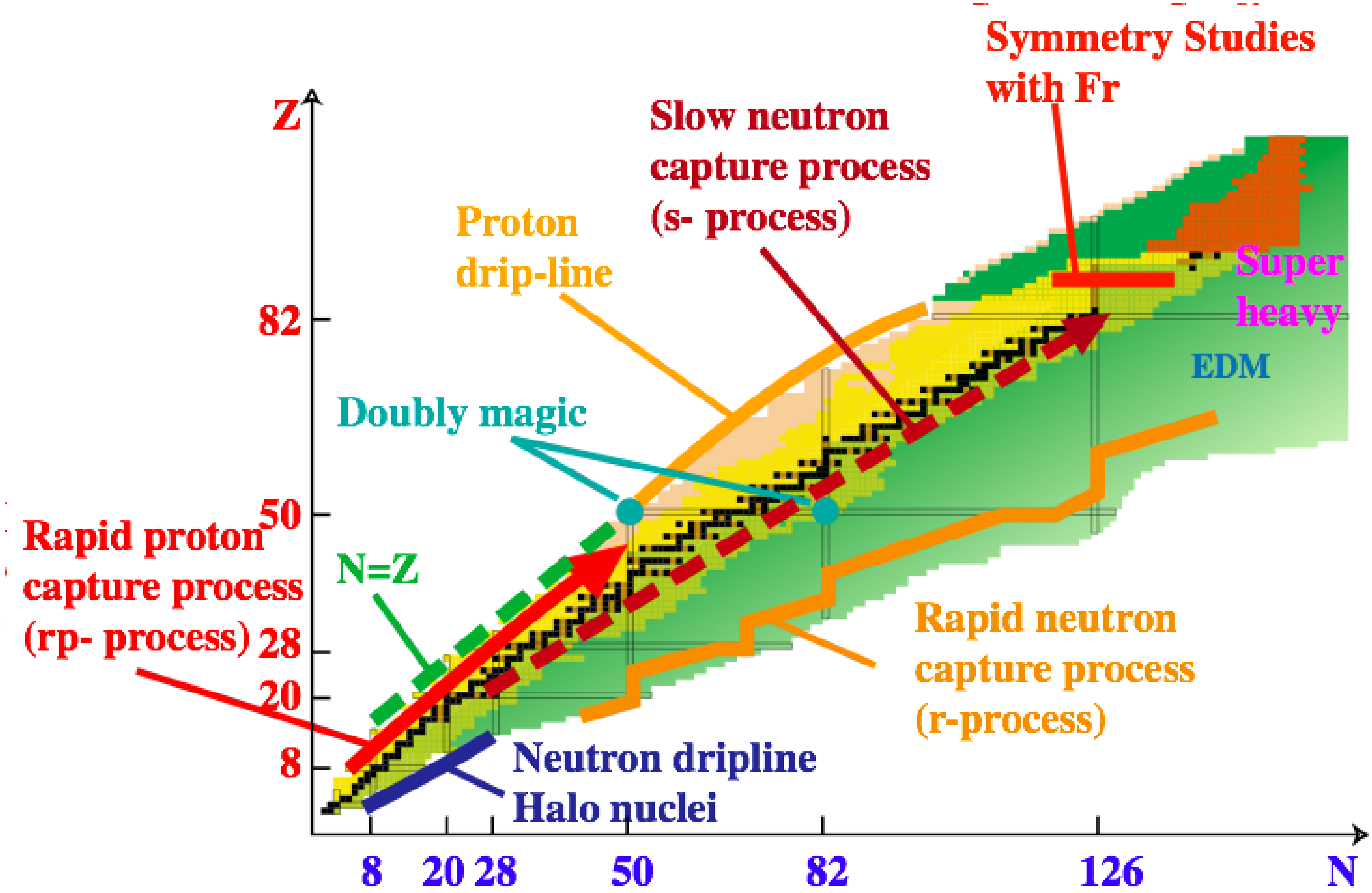


# Outline of the Talk

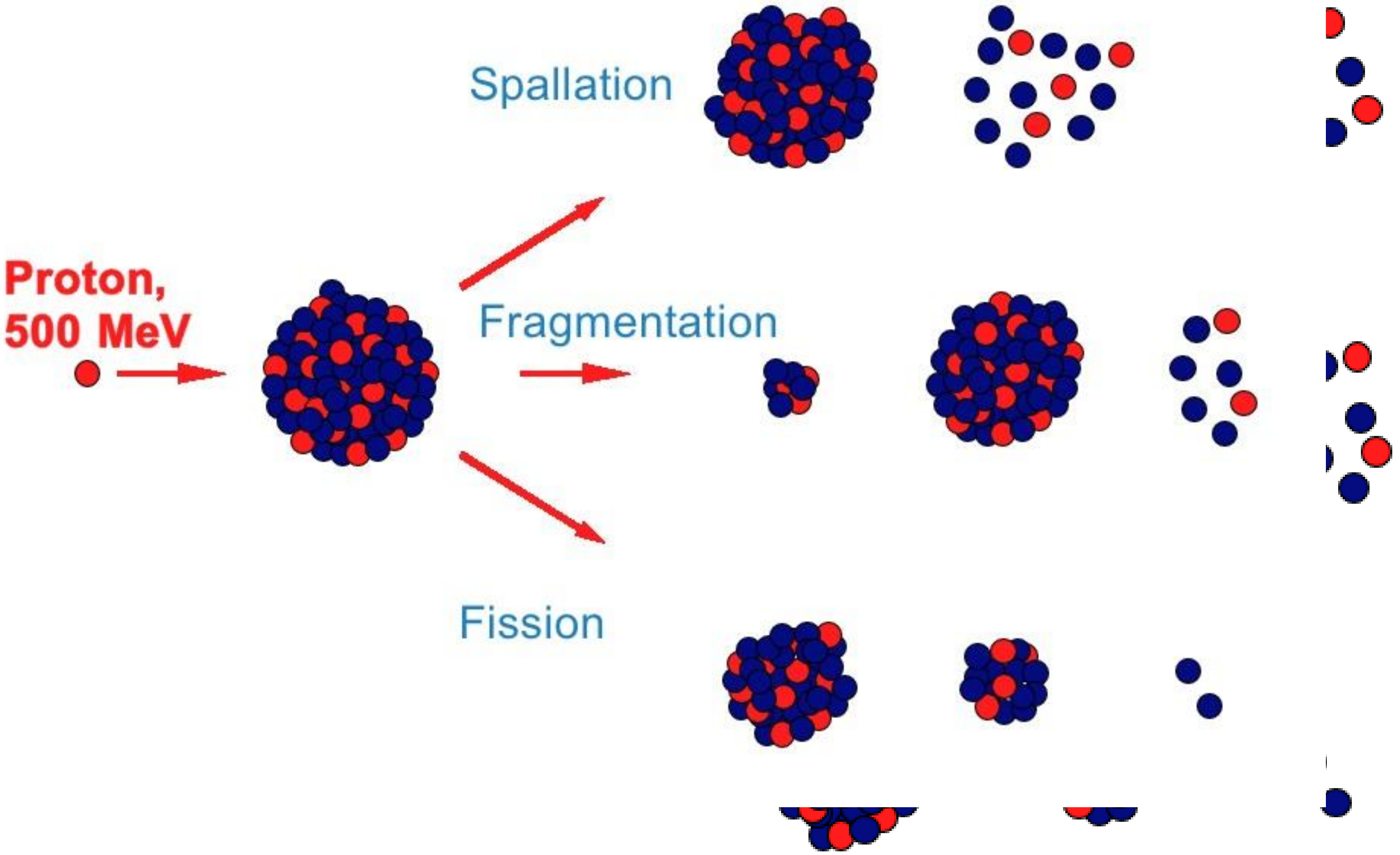
- ISOL Method to Produce High Intensity Rare Isotope Beams, (RIB)
- Increasing RIB intensity
  - Issues
    - Target & Ion source for high power ISOL RIB production
  - Improving Reliability => New Generation of Target Station for High Power Beam
- Future Directions of ISOL RIB

TRIUMF

# Physics with RIB

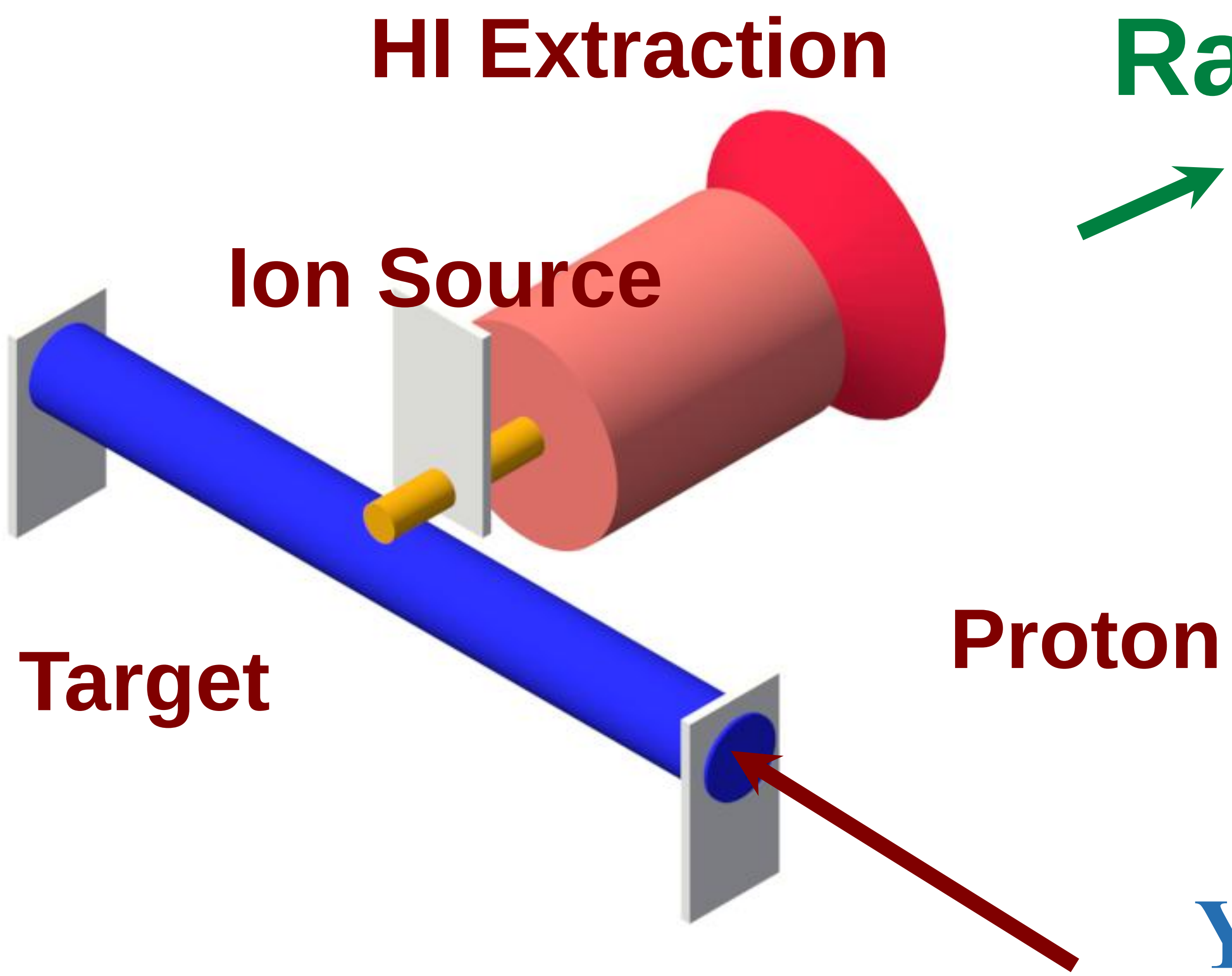


# RI Production Reaction Mechanisms



- Spallation: products distribution peaks few
  ass units lighter than
  rget.
  Neutron deficient
  agmentation: product
  Z ratio reflects the
  rget ratio.
  Neutron rich.
  duced fission into
  ughly equivalent mass
  products.
- Medium range masse region

# ISOL Concept



- 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.

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

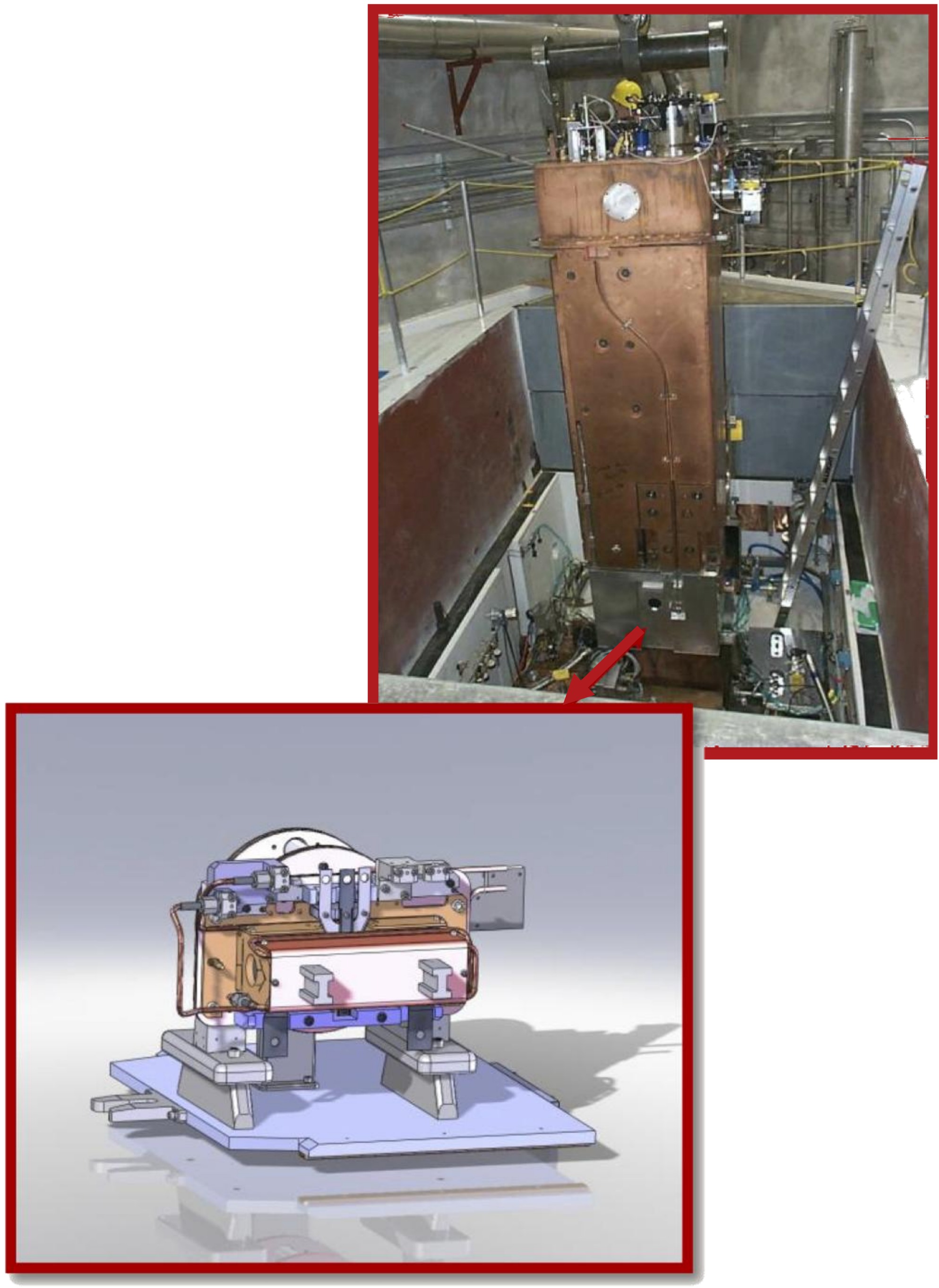
- High yield can be obtained by increasing:
  - the proton beam intensity, $\Phi$
  - improving the release efficiency, $\varepsilon_D \, \varepsilon_E$
  - improving ionization efficiency, $\varepsilon_I$.

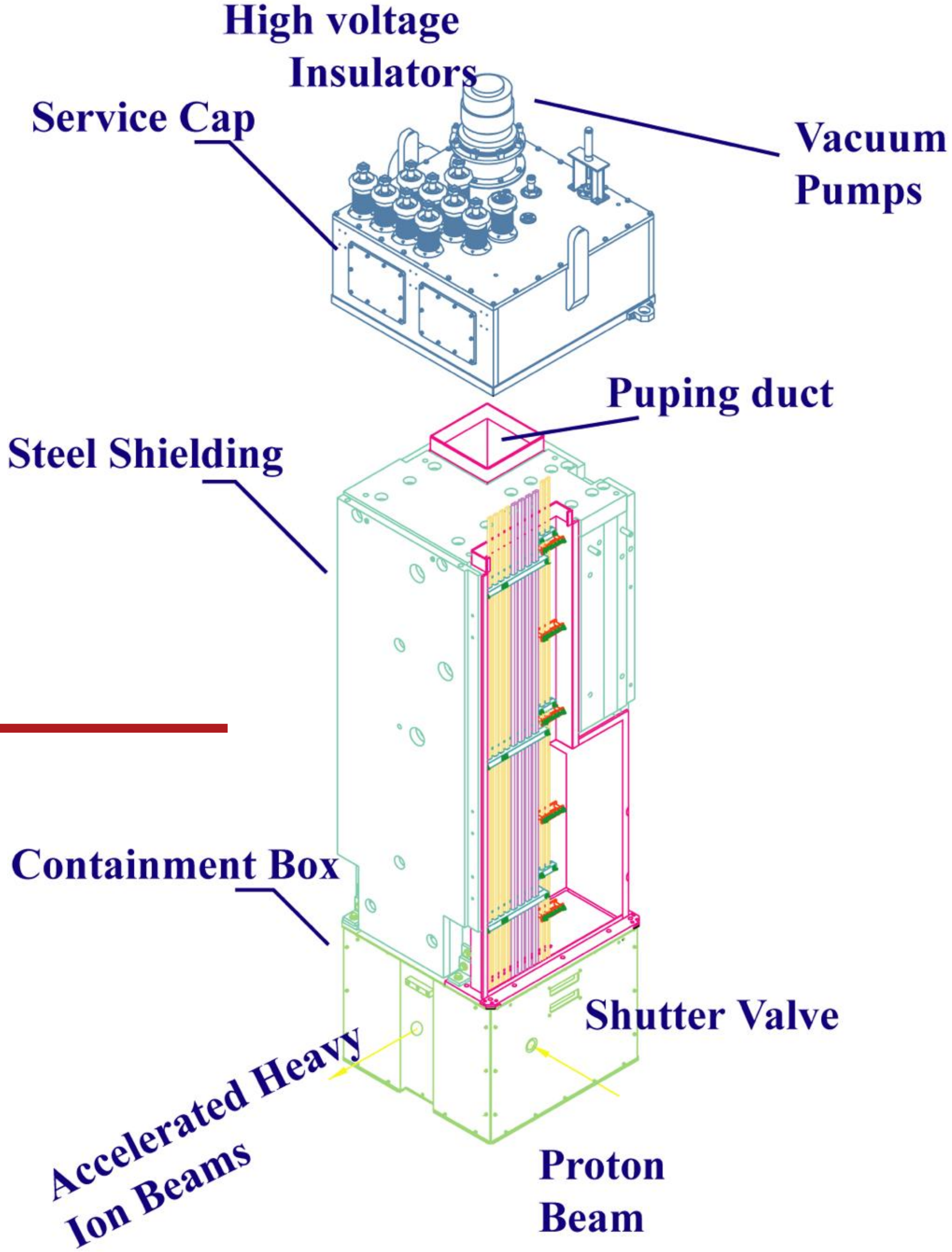
# ISAC Remote Handling Technology

| ISAC/TRIUMF | ISOLDE/CERN |
|---|---|
| **Proton CW: 500 MeV**<br>Φ ~ 100 µA | **Proton Pulsed: 1.4 GeV**<br>Φ ~ 2µA |

# ISAC Facility, Technologies

- **Target module**





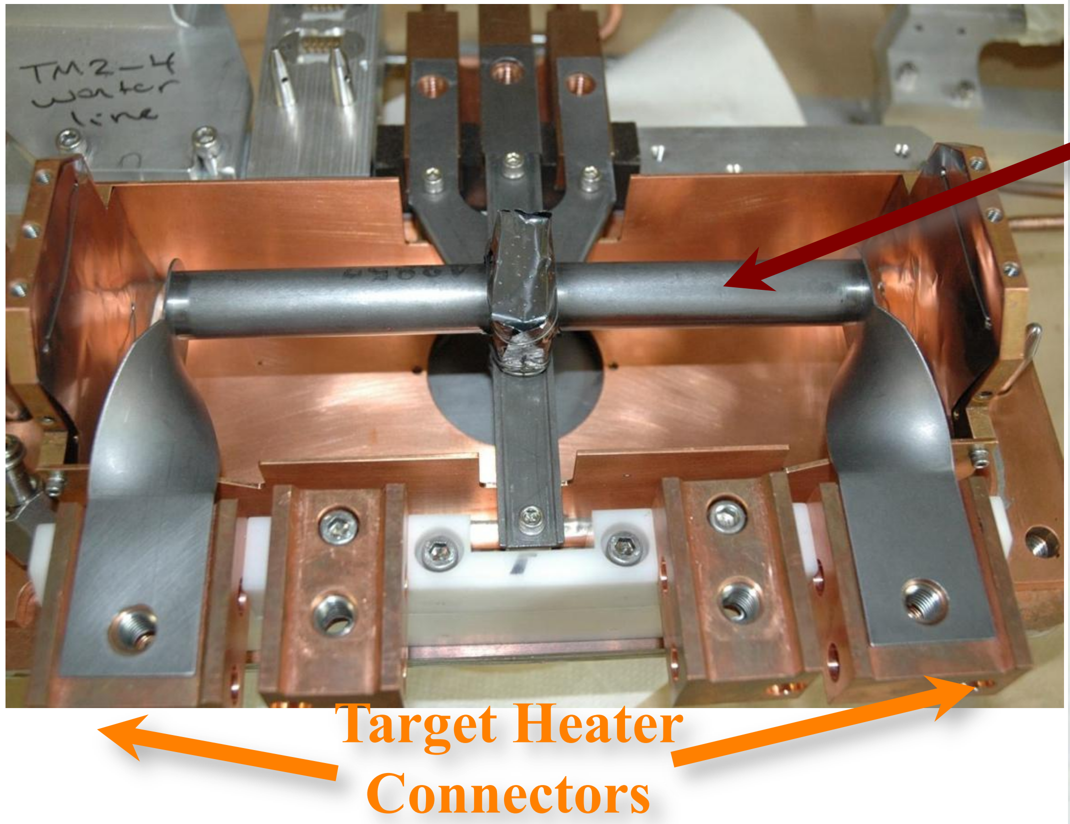
# High Intensity ISOL RIB

- **Target assembly can be described as consisting of two parts:**
  - **the target material itself,**
  - **the target container.**
- **High power target container capable of removing the power to the surrounding heat shield, then to cooling circuit.**
- **Need target material capable of sustaining high power deposition in target**
- ***Need to solve both issues before increasing driver beam power on target.***

TRIUMF

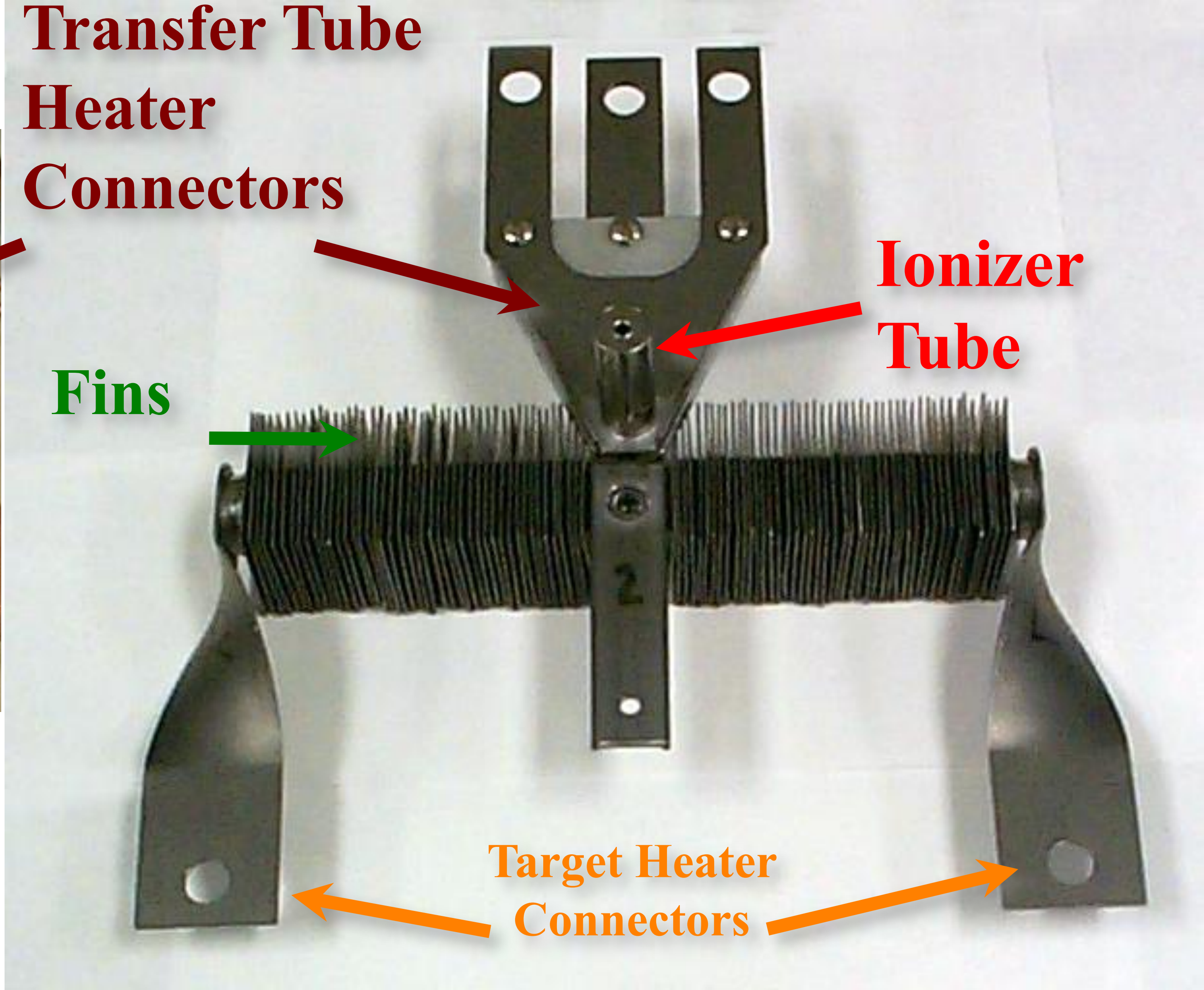
# 1) ISAC “Target Ovens”

## Normal Target



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

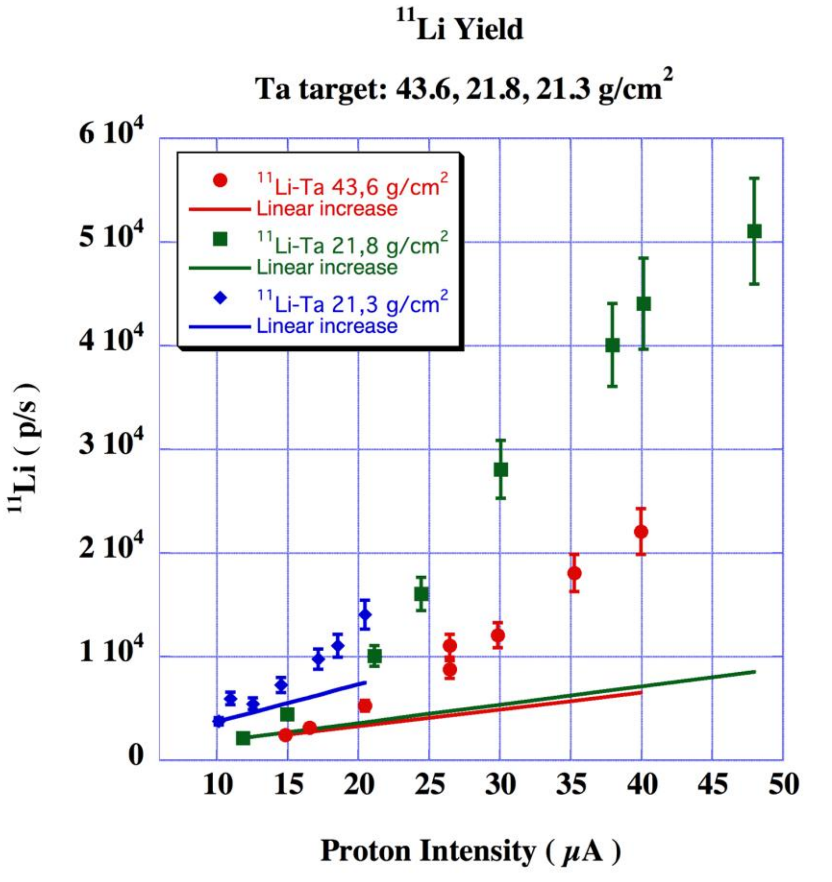
## High Power Target



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

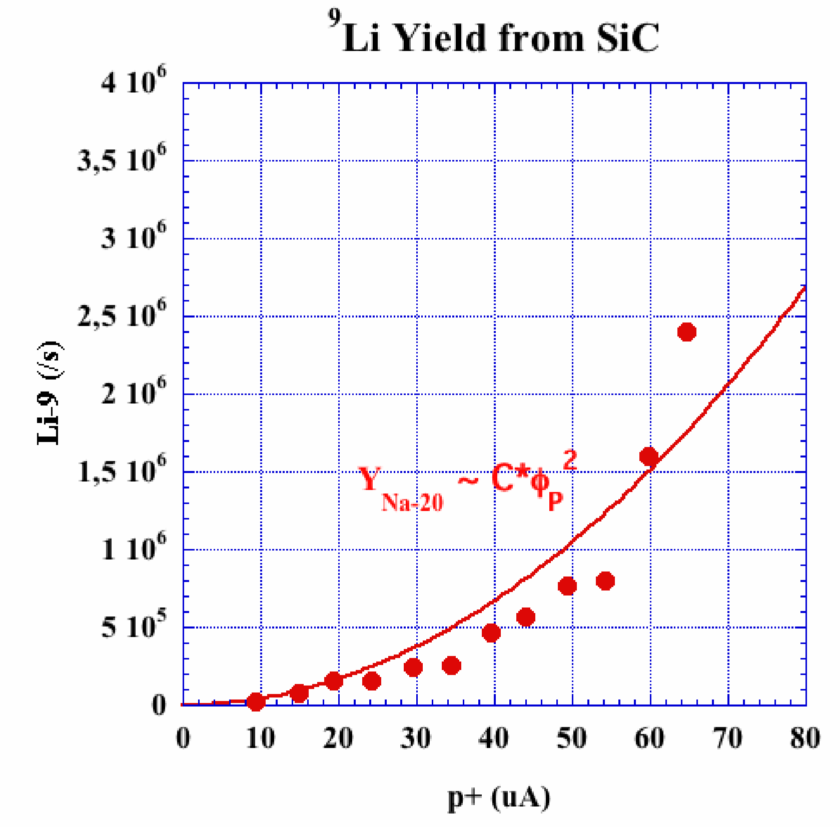
# Radiation Enhanced Diffusion

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

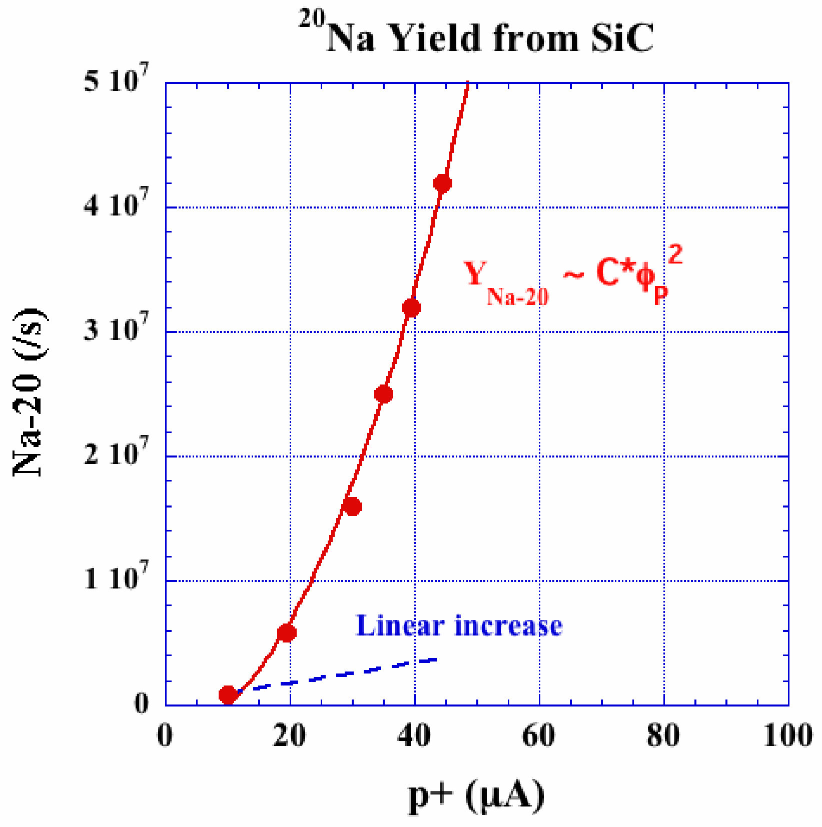


$^{11}$Li Yield

Ta target: 43.6, 21.8, 21.3 g/cm$^2$

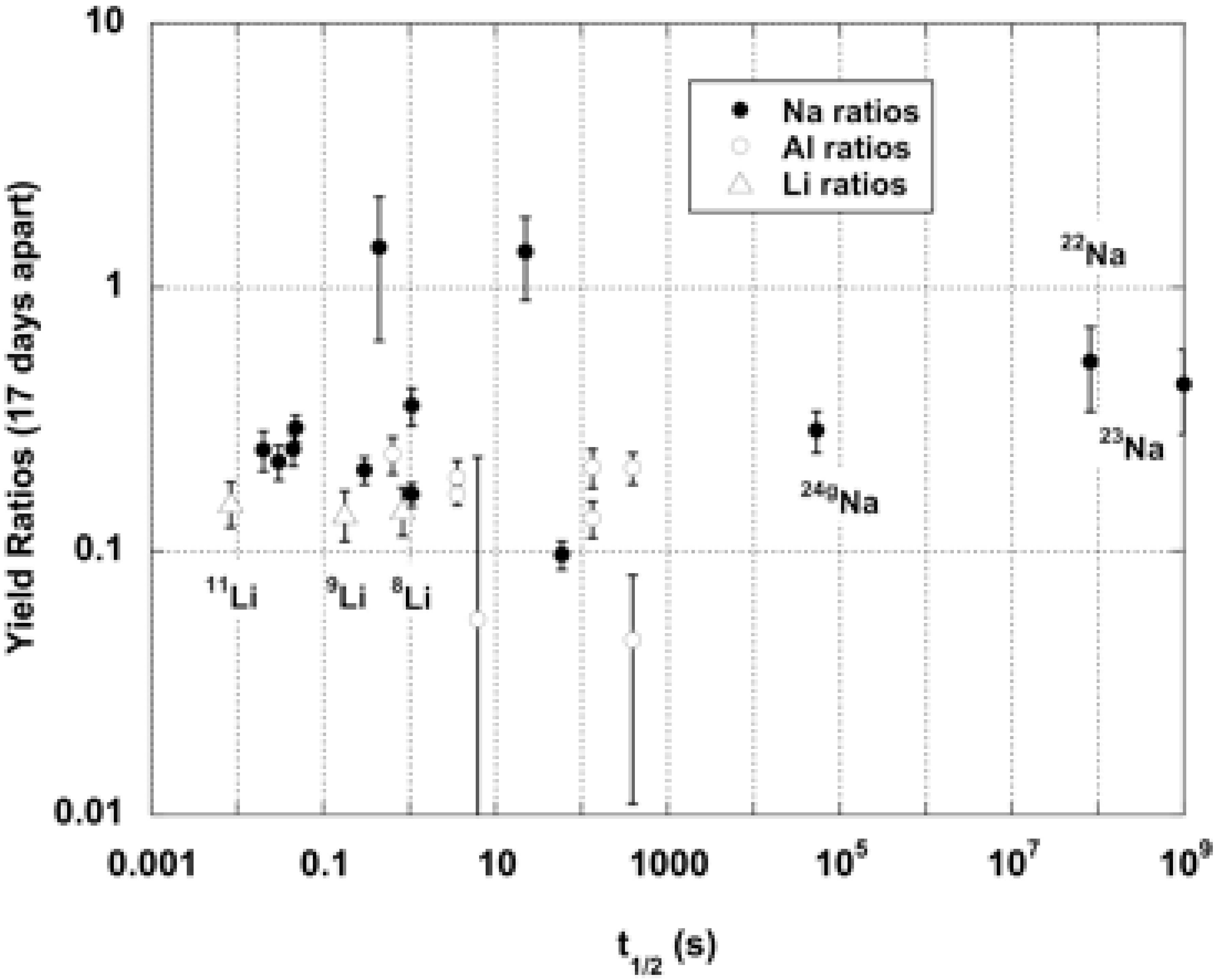


$^9$Li Yield from SiC

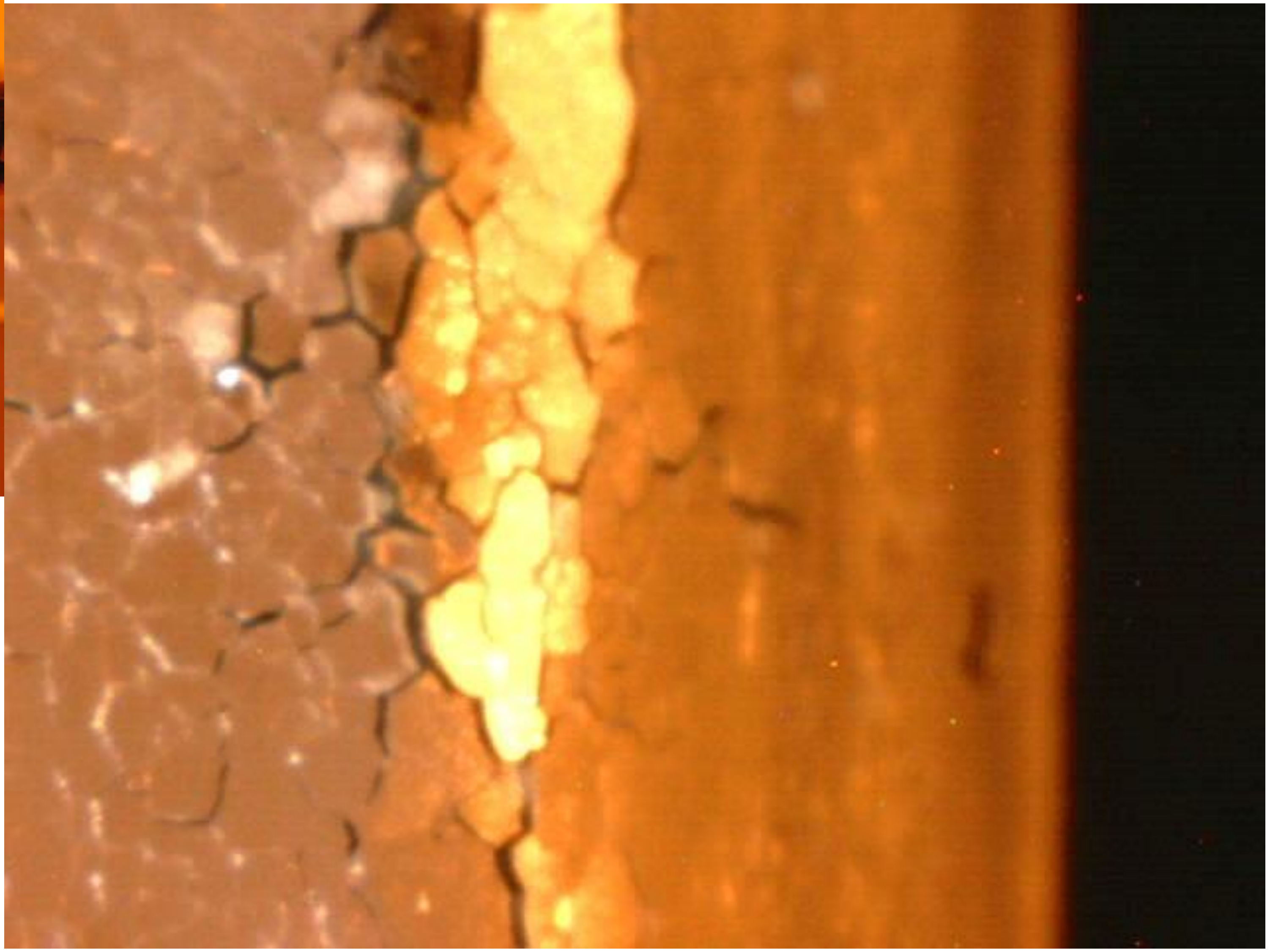


$^{20}$Na Yield from SiC

# Yield ratios showing performance degradation

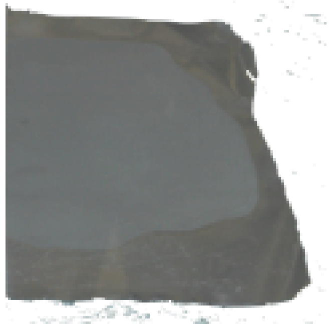


# Target Oven Damage

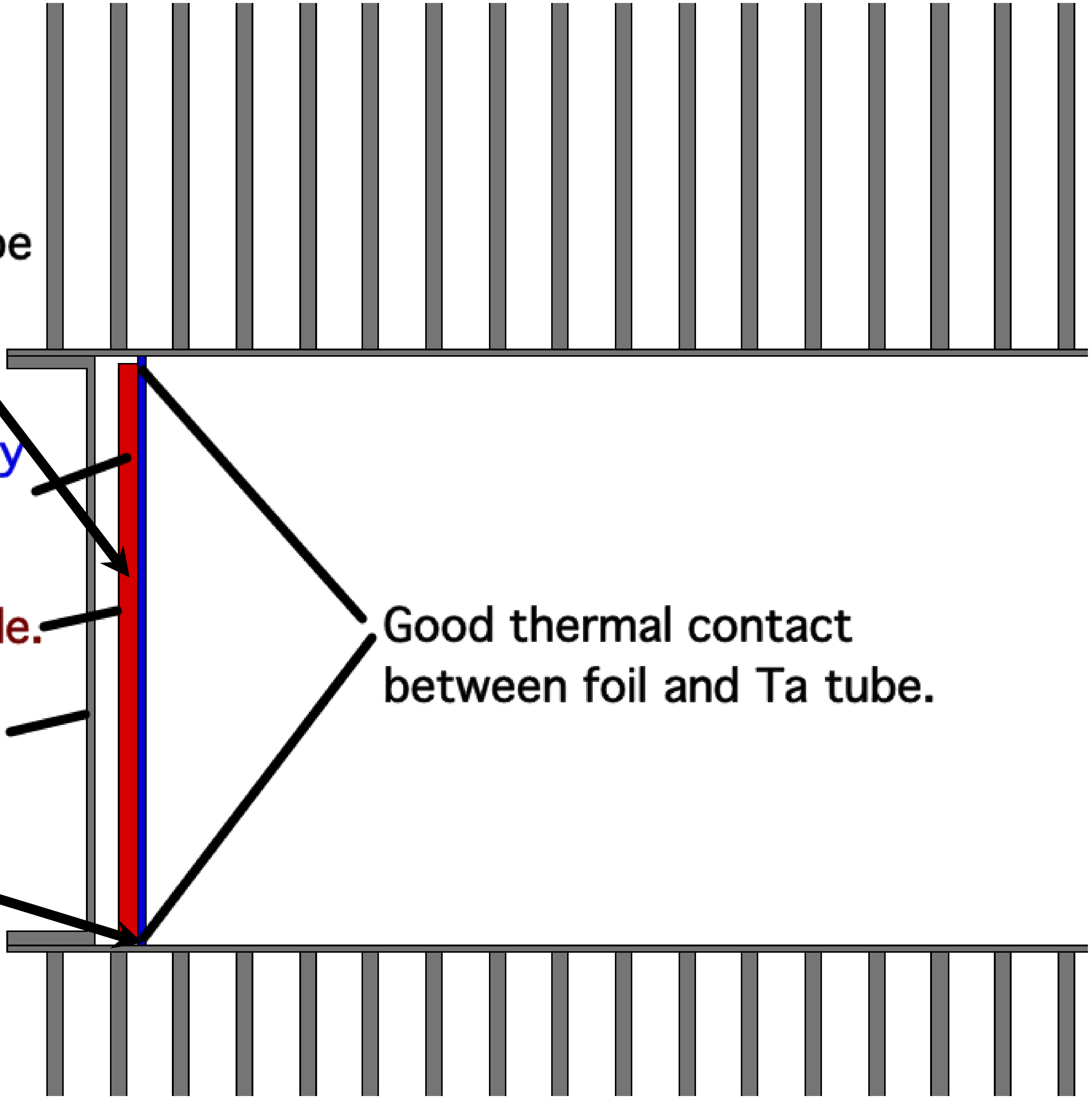


# 2) High Power Target Material, composite

**Ceramic slip cast**



Fins diffusion bonded on Ta tube



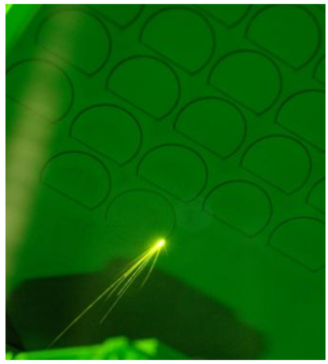
High thermal conductivity foil, graphite, Mo, Nb ...

Target material, carbide, oxide.

Target container window

Good thermal contact between foil and Ta tube.

**Laser cutting the Ceramic slip cast for a good contact**



# UCx as High Power Target Material

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

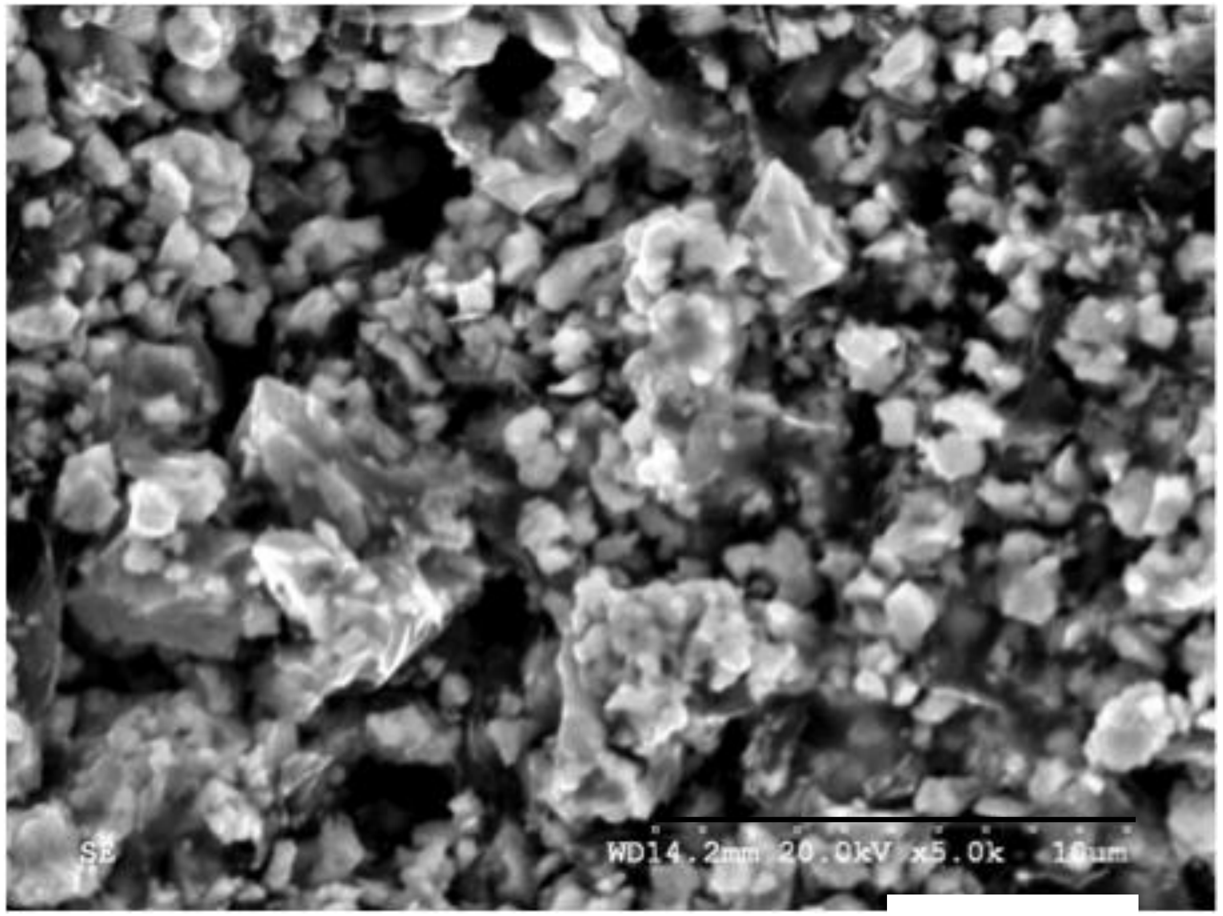
- **Concerns:**
  - Exothermic oxidation
    - Operation safety
  - Long-term stability after use
    - Storage of irradiated targets

TRIUMF

# 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

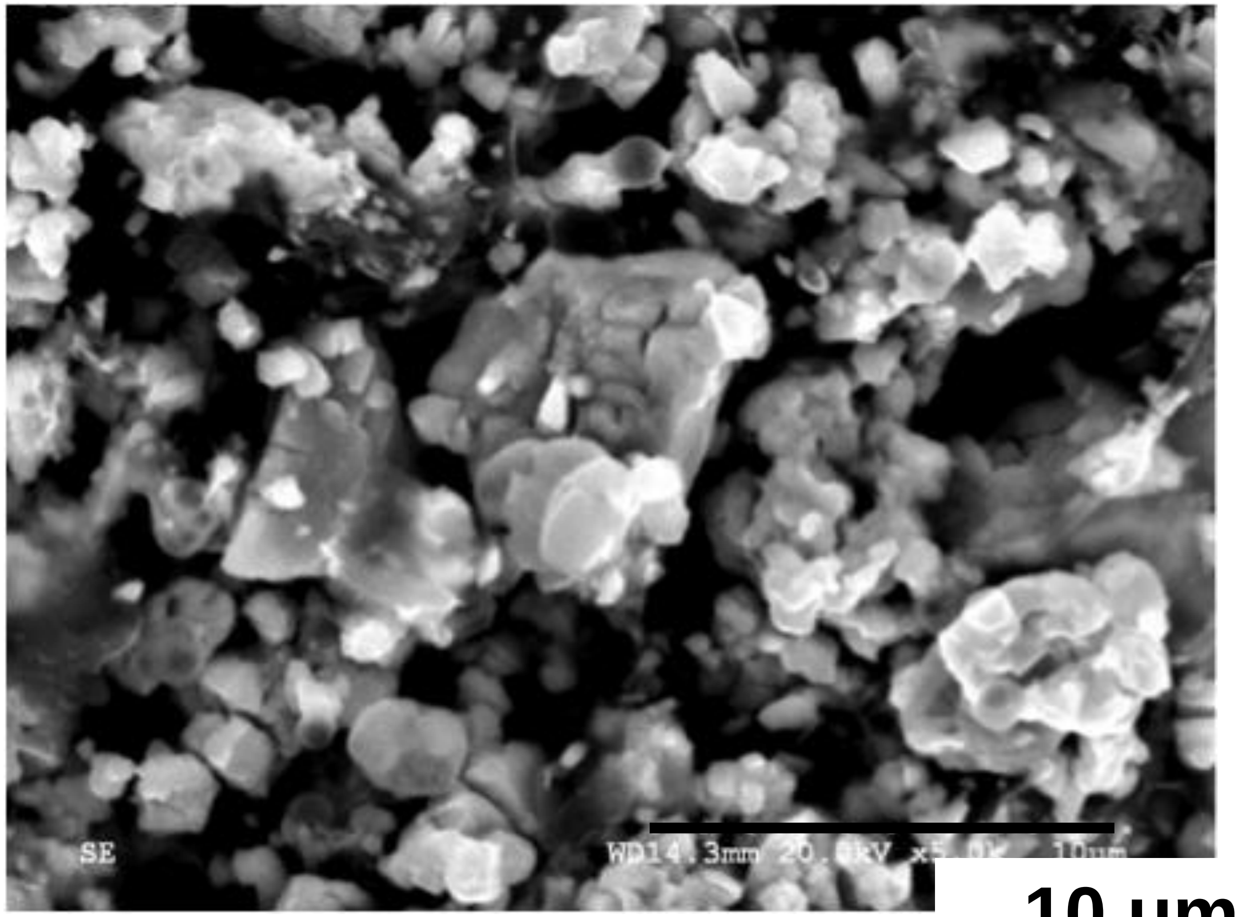
# SEM of “raw” and sintered UC$_x$



“raw” UC$_x$

**10 um**

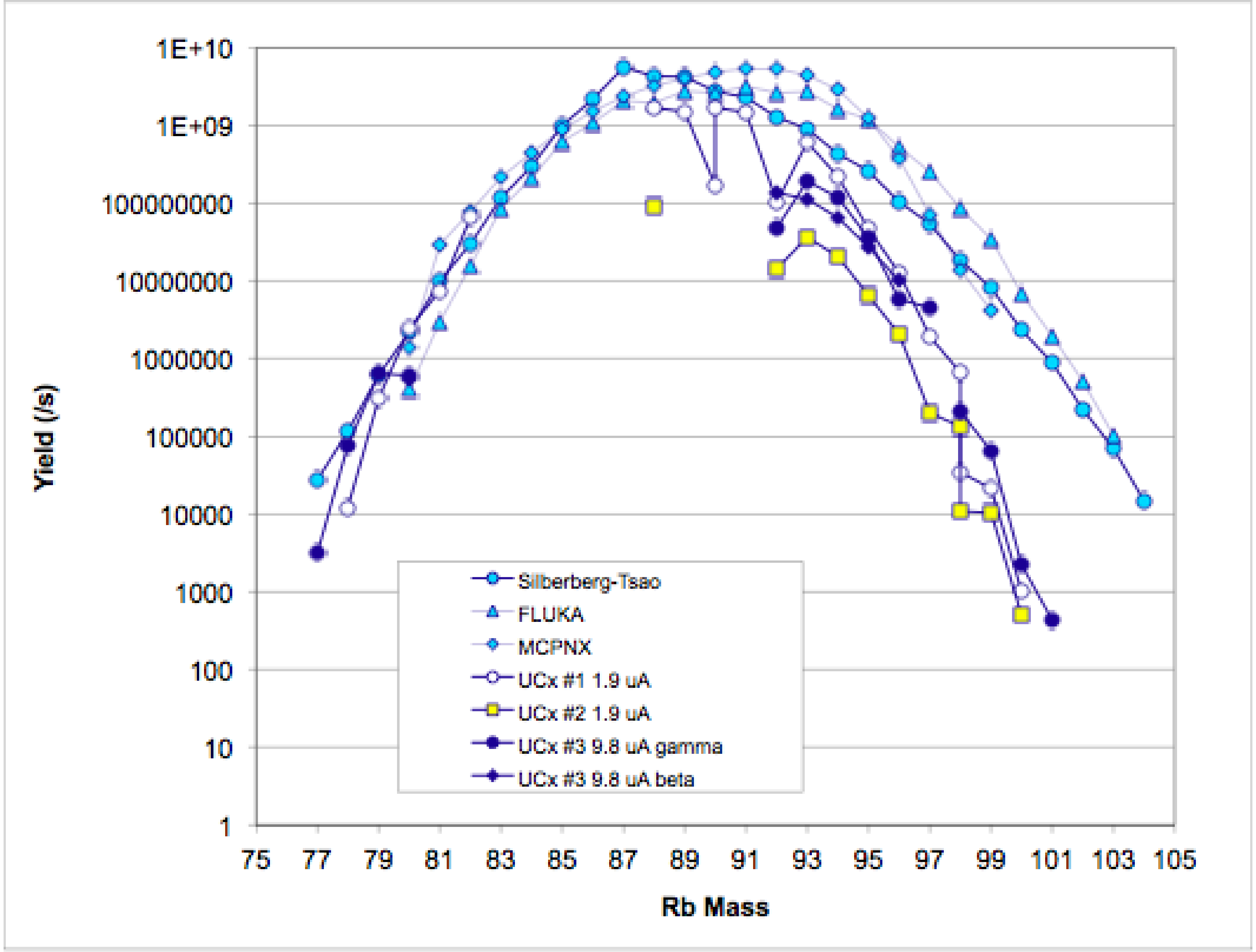
Sintered UC$_x$



**10 um**

TRIUMF

# 10 µA proton on UCx target

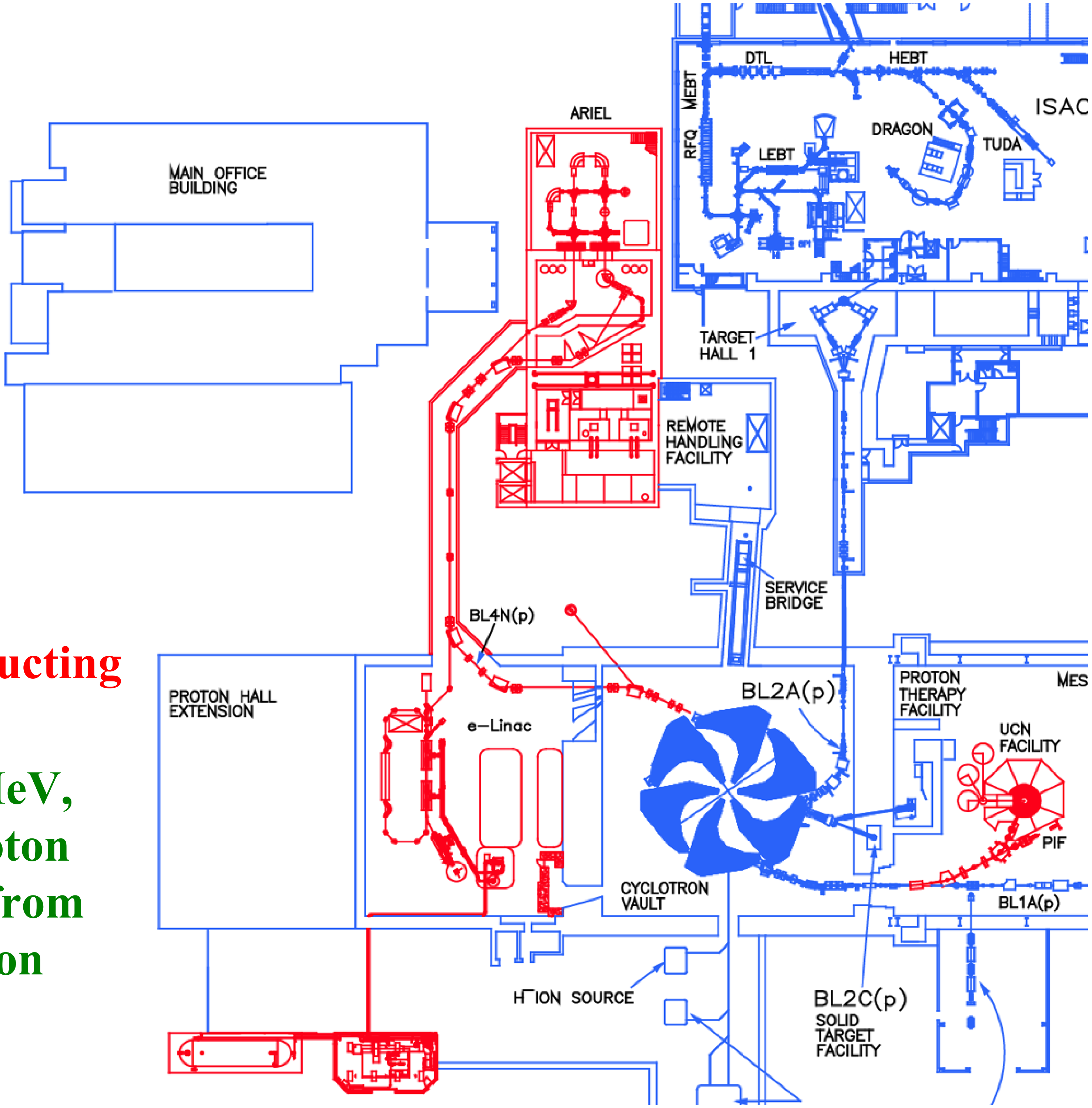


# Future Directions

- 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

TRIUMF

# More RI Beams To Users

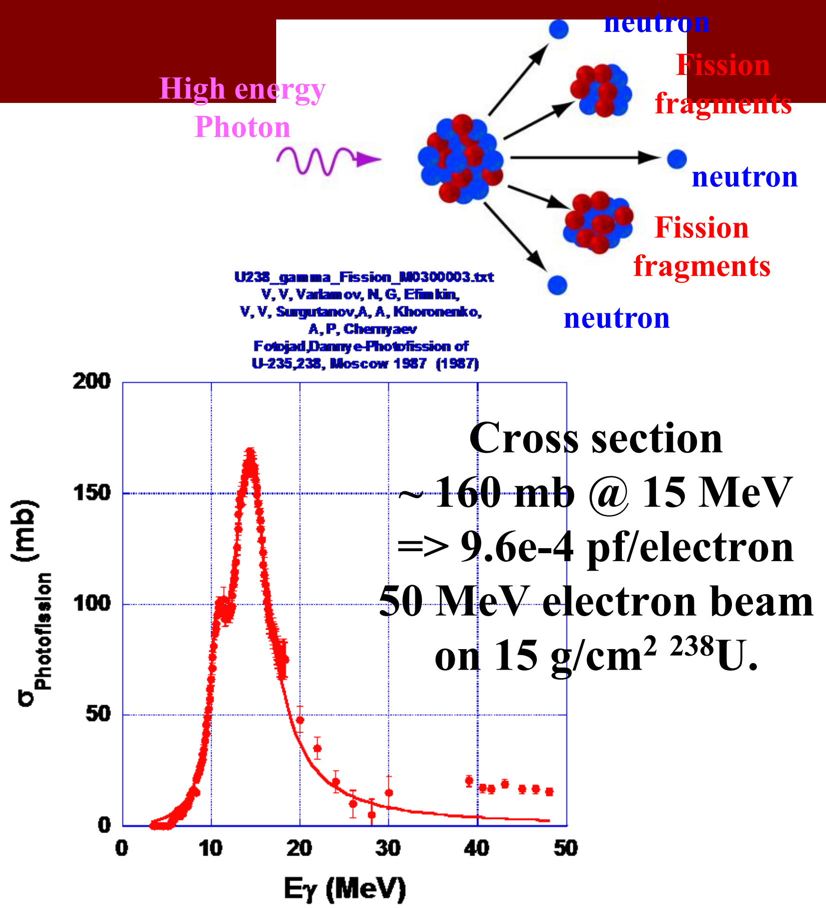


**ISAC RI beam Facility is one user only. Back log is important**

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

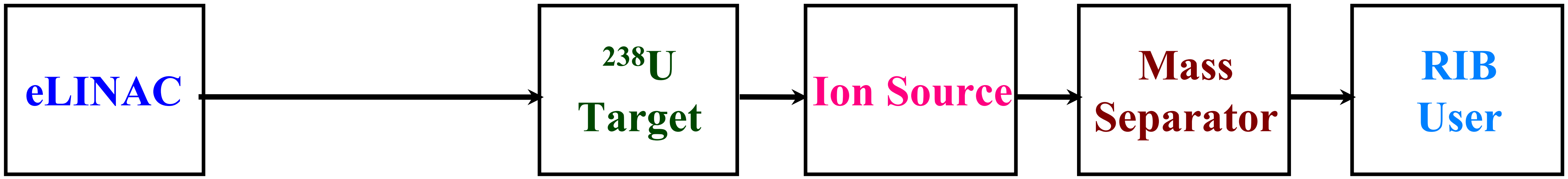
# eLINAC photofission

| Item | Value | Units |
|---|---|---|
| Electron energy | 50 | MeV |
| Total power | 500 | kW |
| Electron current | 10.00 | mA |
| Target, $UC_2$ | 15 | g/cm$^2$ |

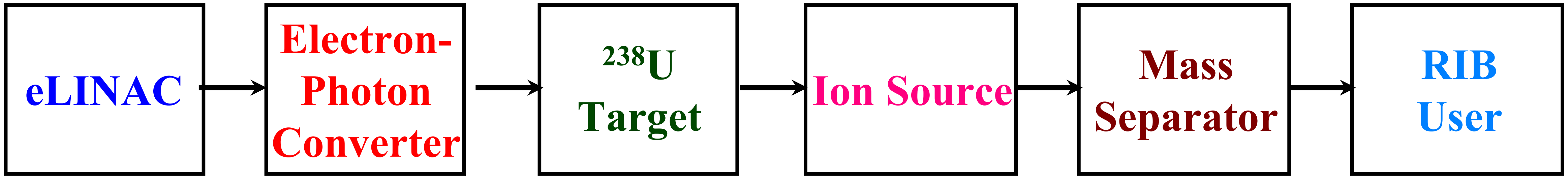


Cross section
~ 160 mb @ 15 MeV
=> 9.6e-4 pf/electron
50 MeV electron beam
on 15 g/cm$^2$ $^{238}$U.

## Low electron beam power < 15 kW

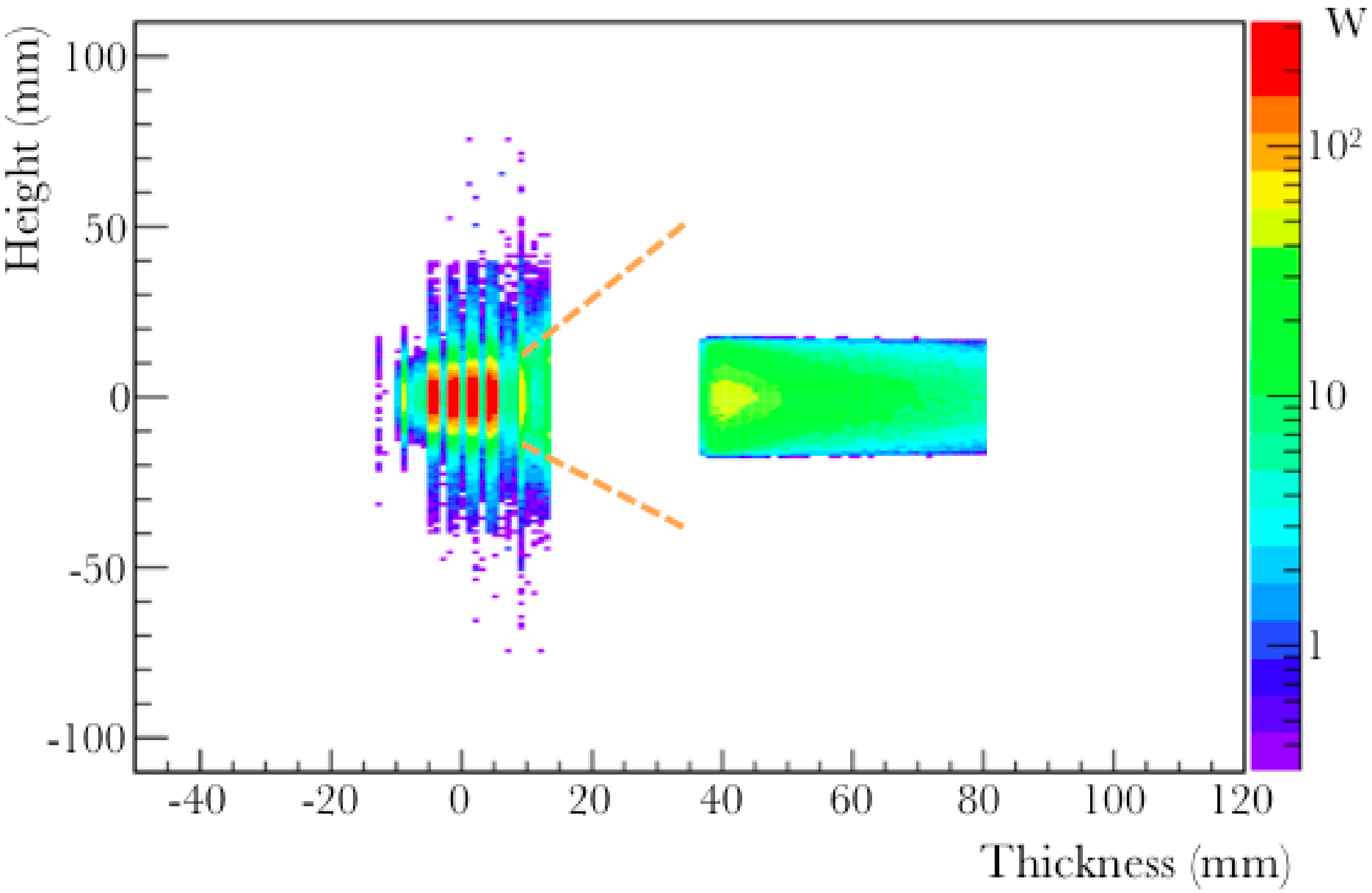


## High electron beam power > 25 kW



# 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**

**This is possible to accomplish with present target design.**

# 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
- Simulation shows the following
  - Power distribution,
    - 274 kW in converter,
    - 75 kW in Target!
  - No easy solution for cooling the target.

# Design Failure Mode & Effect Analysis

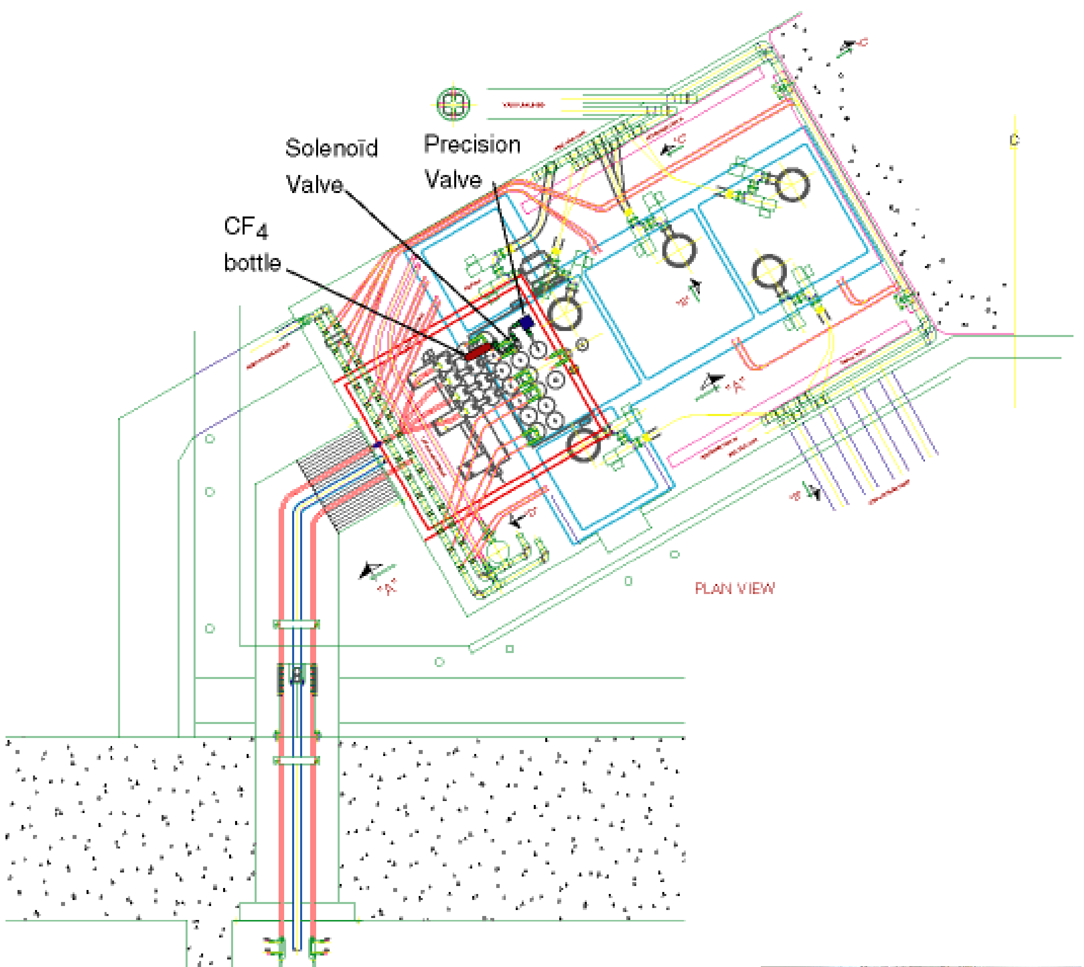
- Designs and processes have been analyzed to build the next generation of target stations
- FMEA is used in product development in manufacturing industries for example, where it helps to identify potential failure modes based on experience.
- To help focusing on the critical failure mode(s) it is important 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 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|

# Analysis of ISAC Technologies

- **Advantages**
  - All non radiation resistant components and materials are located behind shielding, in a low radiation field,
    - reduces maintenance and personnel exposure.
  - This approach allow us to operate ISAC routinely at the design proton beam intensity, 100 µA or 50 kW on target.
  - Two stage mass separator system proof to work well to limit contamination spread in beam lines.

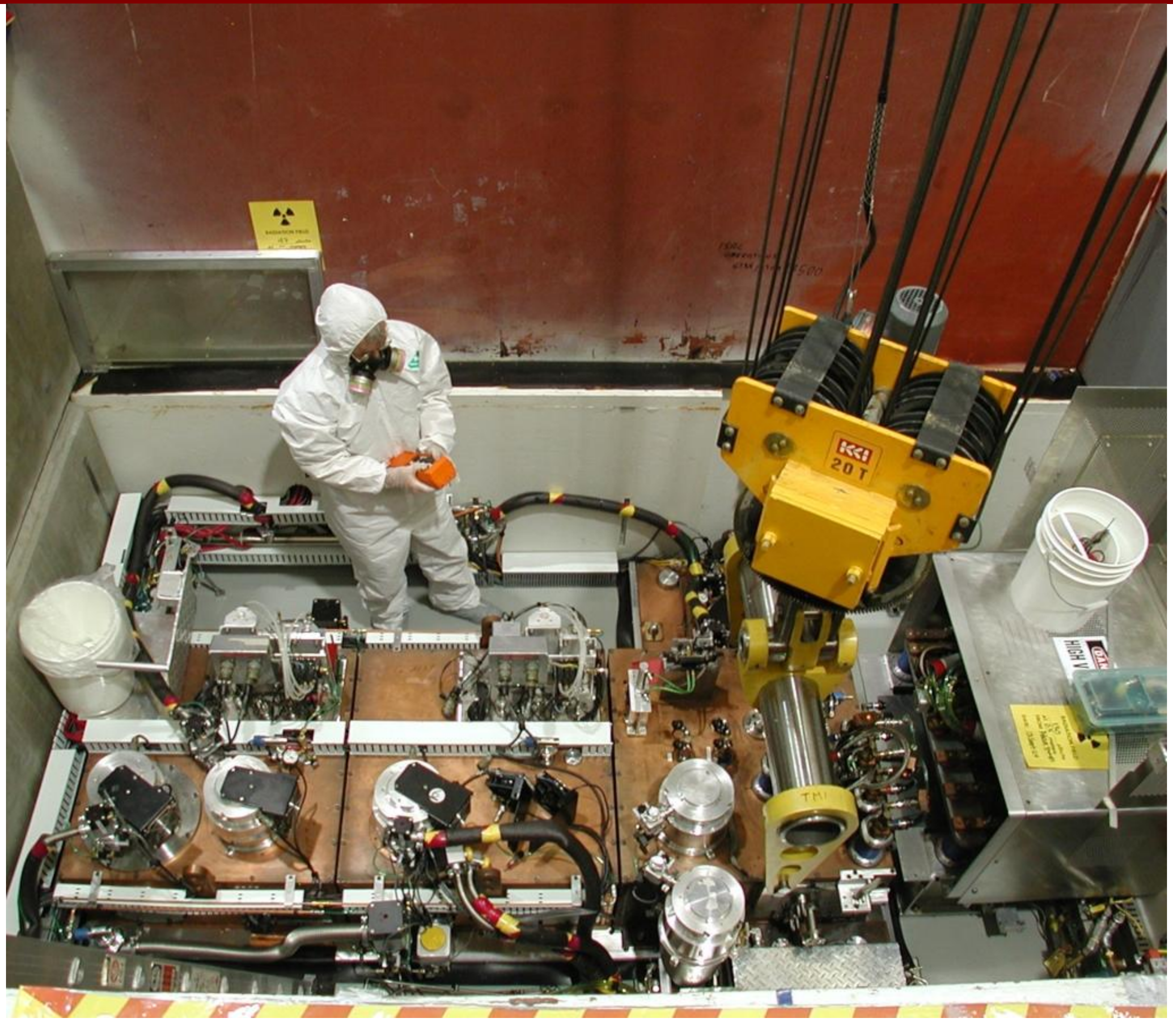
Target station top view



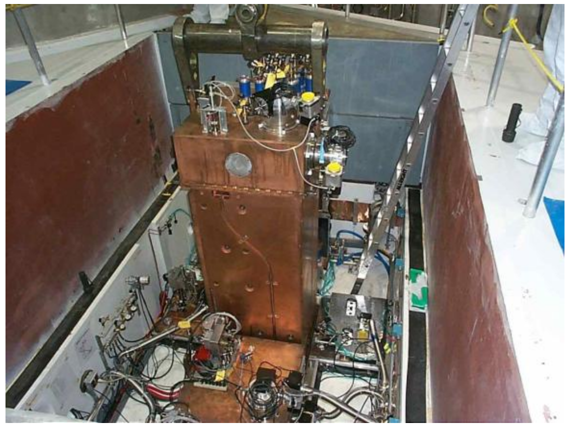
# Evaluation of the ISAC technology

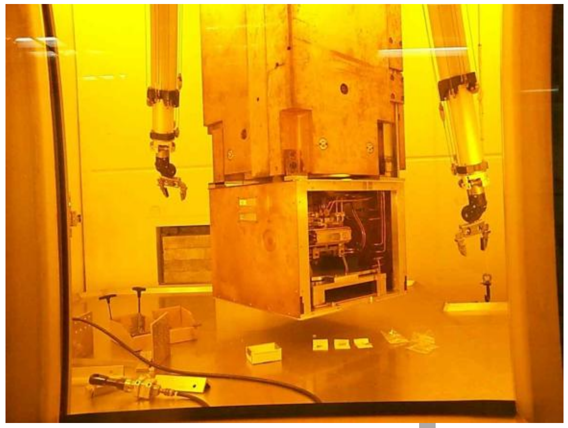
- Issues with the actual ISAC target station,

1. Actual confinement box housing the target is not hermetic.
    - It creates difficulties when operating air sensitive target material such as $LaC_2$ and $UC_2$.
    - The target/ion source cannot be pre-conditioned off-line, delay the operation of the new target on-line,
2. Hand on connection and disconnection of the target services,
    - We have to let the target cool-down before disconnecting services.
3. Target exchange takes from 3 to 5 weeks, it requires proton beam off periods for installation for the operating target.
4. Limited RIB development due to the overhead to change target/ion source assembly.



Target module



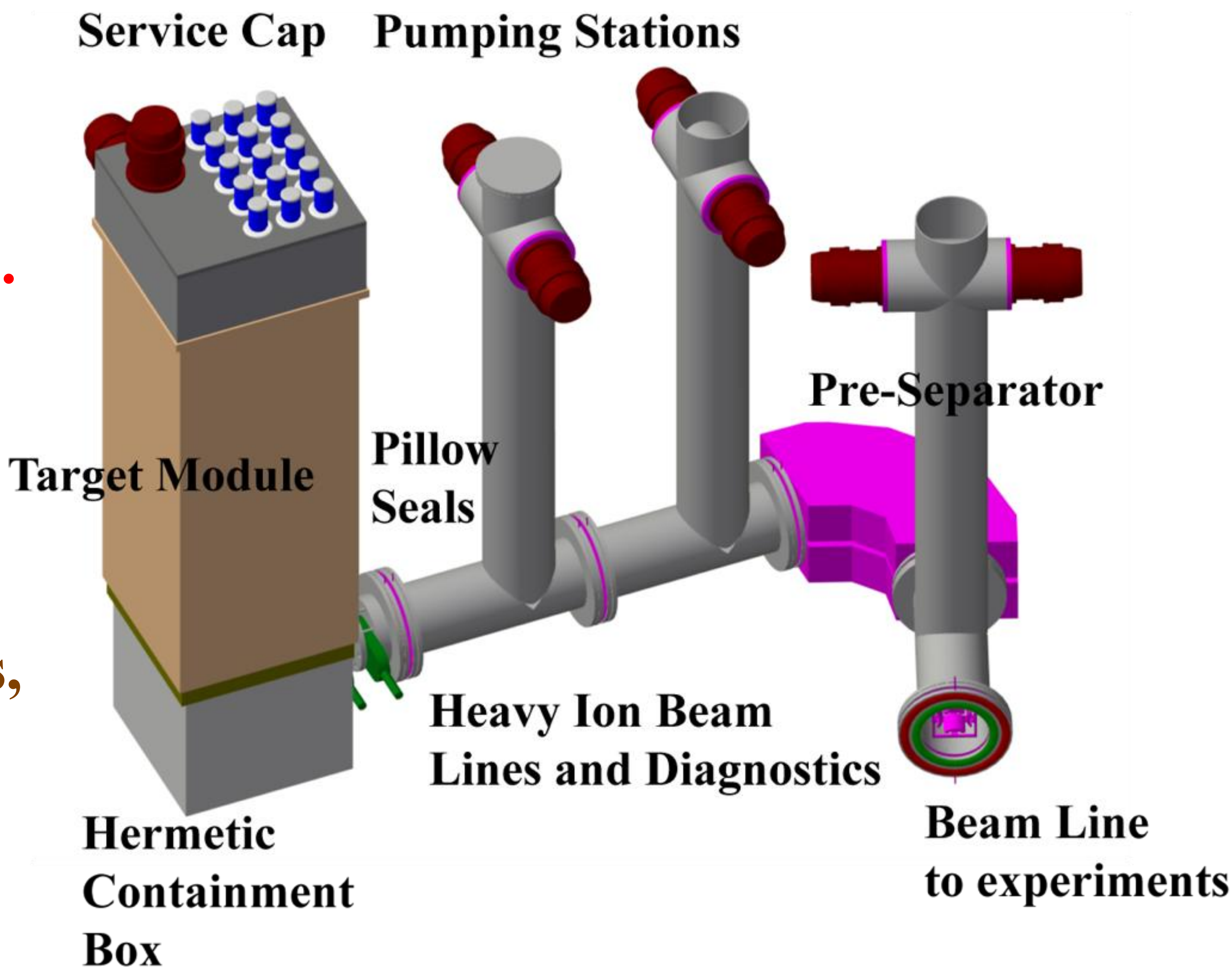


# Solution

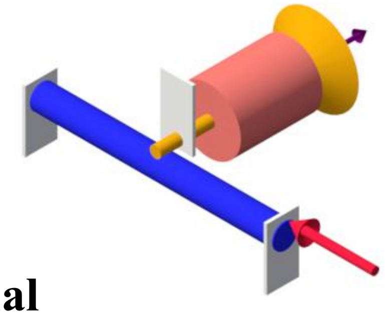
- **Target should be inside a completely sealed containment box,**
  - **Will simplify the target handling,**
  - **Will limit the risk of spreading contamination,**
- **Having an hermetic containment box will allow us to prepare the target/ion source before on-line operation,**
  - **Will allow high voltage conditioning,**
  - **Will allow target conditioning.**
- **We will implement a system to connect the target/ion-source services remotely, => faster turn around,**
  - **Technology exists at CERN-ISOLDE, Oak-Ridge, GANIL.**

# ARIEL/TRIUMF Target Station Concept

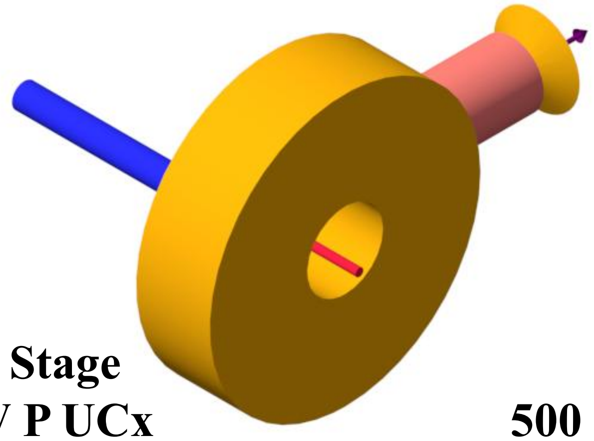
- **Uses Target Module similar as for ISAC**
  - **Sealed containment box.**
  - **Simplified vacuum system.**
  - **Quick disconnect vacuum joints**
    - **Pillow seal technique developed for T2K,**
      - **Leak rate ~ $10^{-8}$ Pa $m^3/s$, too large. Need improvement**
    - ***new vacuum joint development required.***



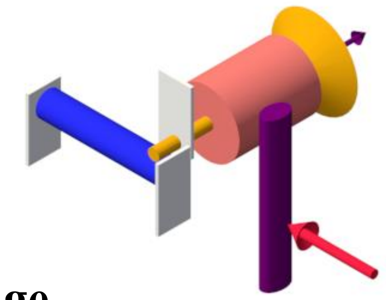
# Comparison



Actual
5 kW P UCx



Two Stage
50 kW P UCx



Two Stage
500 kW electron UCx

| Nucleus | 5 kW proton | 50 KW proton two-stage | 500 kW electron two-stage |
|---|---|---|---|
| Ni-72 | 3.80E+08 | 2.00E+08 | 8.00E+07 |
| Zn-78 | 1.40E+09 | 3.40E+09 | 8.90E+08 |
| Kr-91 | 5.30E+10 | 2.30E+11 | 2.70E+11 |
| Kr-94 | 1.30E+10 | 1.30E+11 | 6.70E+10 |
| Rb-97 | 7.40E+09 | 1.10E+11 | 1.90E+10 |
| Sn-132 | 1.10E+10 | 2.50E+10 | 1.50E+11 |
| Sn-134 | 1.00E+09 | 2.40E+09 | 1.30E+10 |
| Xe-142 | 1.10E+10 | 5.20E+10 | 1.20E+11 |
| Xe-144 | 1.00E+09 | 7.90E+09 | 9.50E+09 |
| Cs-144 | 6.80E+09 | 6.00E+10 | 7.70E+10 |
| Cs-146 | 5.00E+07 | 9.20E+08 | 9.80E+09 |

# 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/Ni, $Al_2O_3$ on Nb foil run at 35 µA instead of 2 - 3 µA maximum.

# 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.

# 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

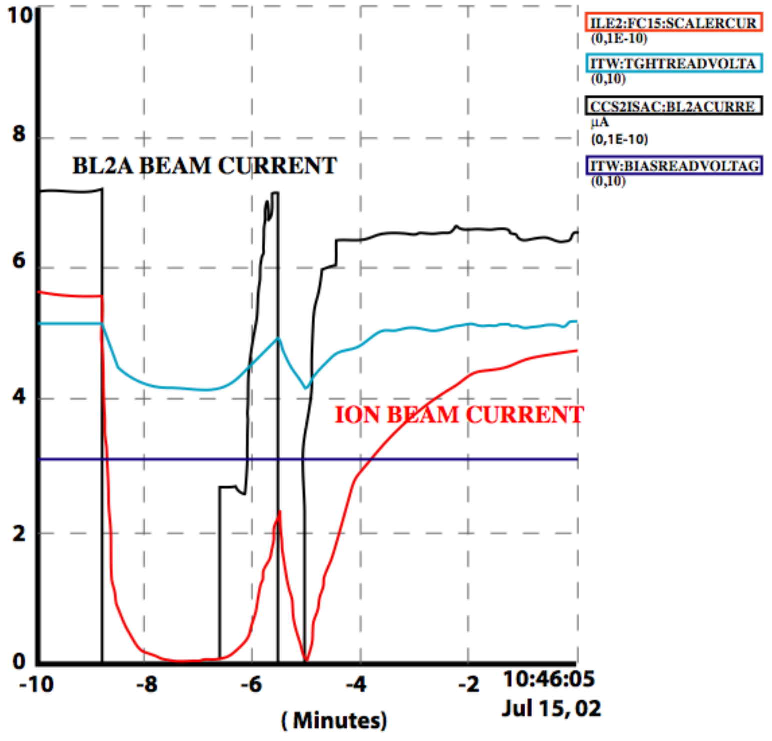
- New facilities are proposing to use neutrons and photons beam to induce fission from U target.
- The optimum goal is to reach $10^{15}$ f/s and above. To achieve reliable operation these targets have to be made with target material capable of sustaining high power deposition in target and high thermal 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.
- For 500 kW electron beam we will have to dissipate 75 kW in the UCx target.

# Thank you! Merci!

- Friedhelm Ames
- Marik Dombsky
- Jens Lassen
- Phil Levy
- Grant Minor
- Bevan Moss
- John Wong
- Rick Maharaj
- Aurelia Laxdal
- Donald Jackson
- Maico della Valle
- Francis Labrecque
- Nikita Bernier
- Mina Nozar

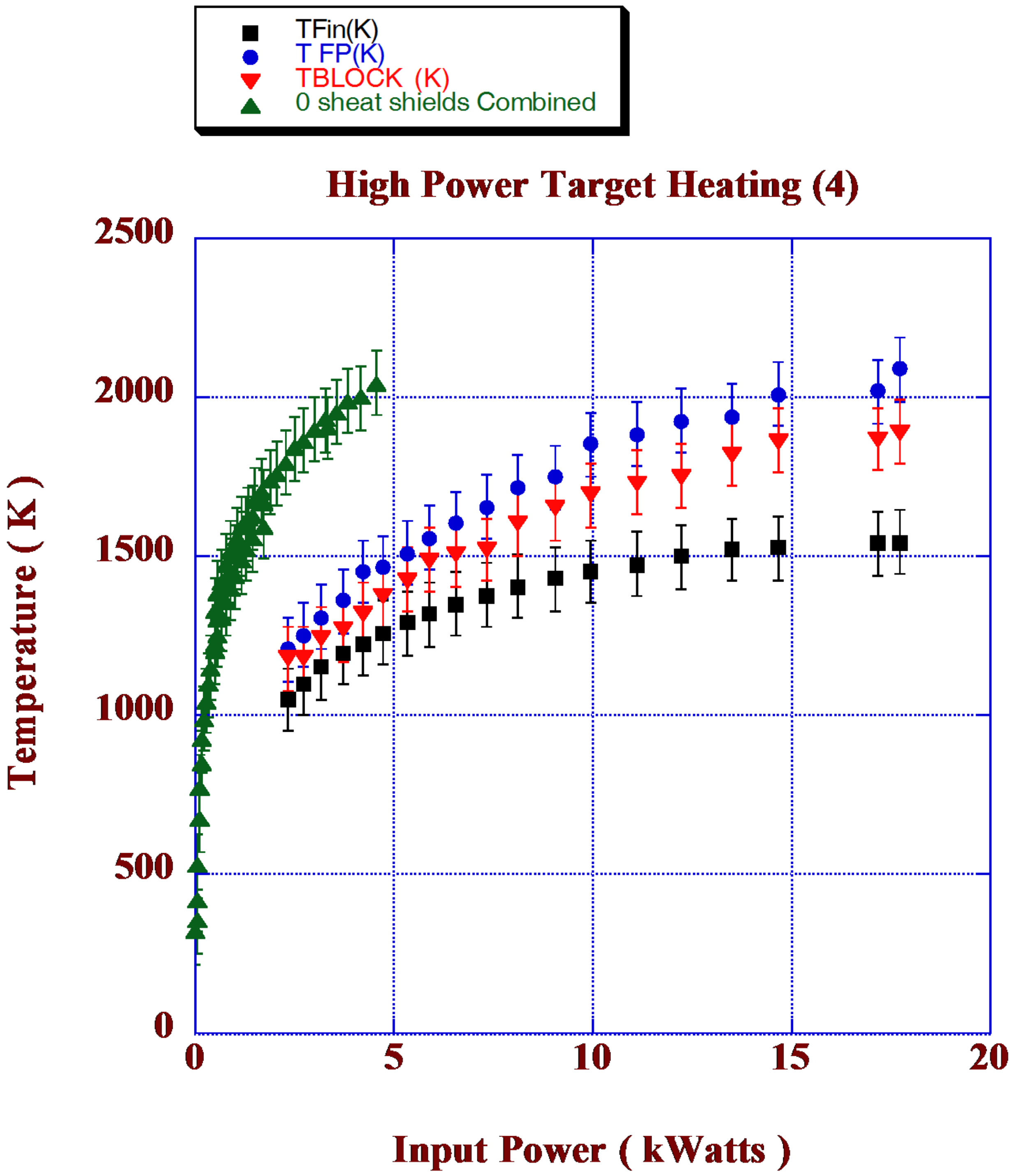
# Driver Beam Stability

- 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.



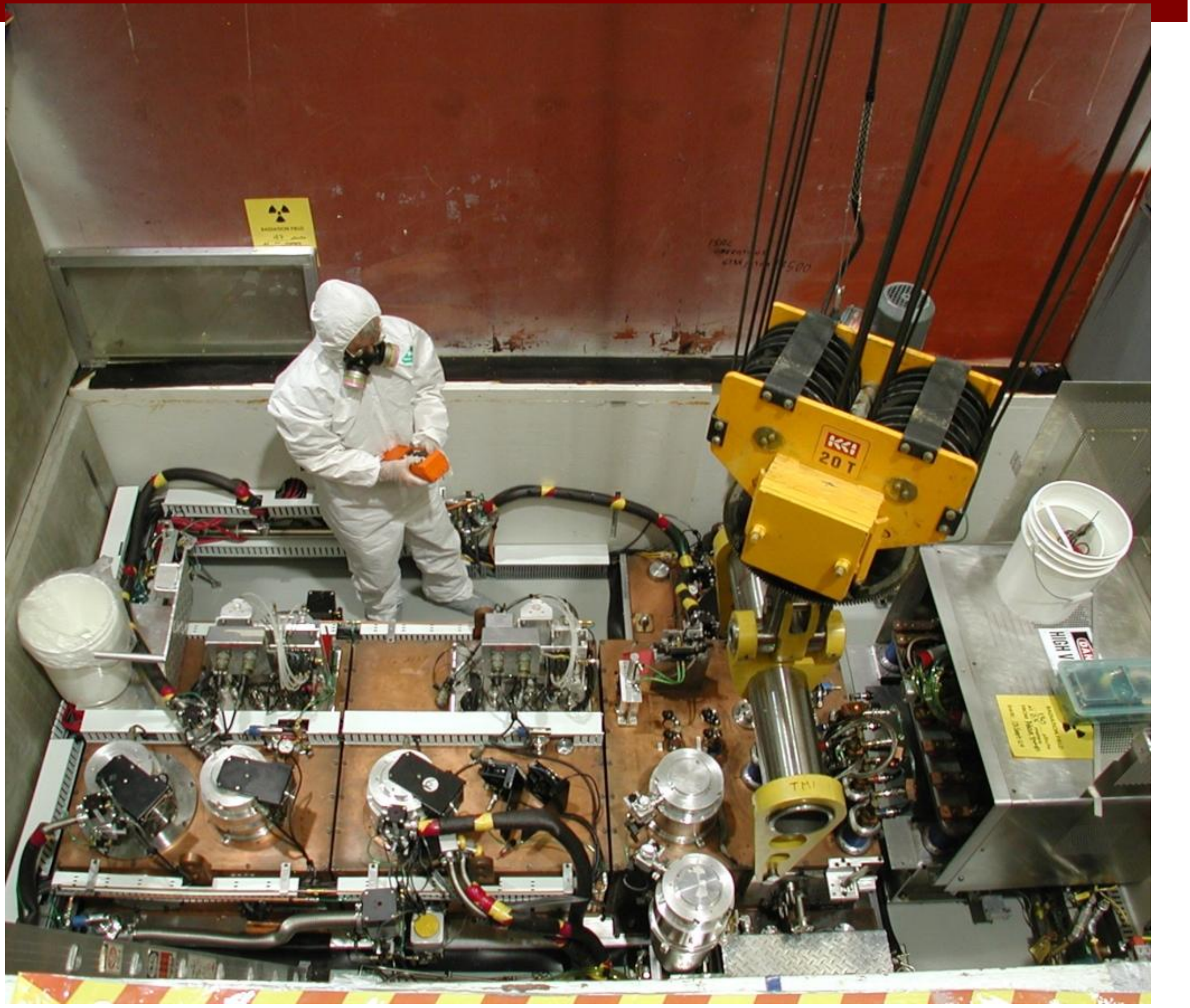
# High Power Target

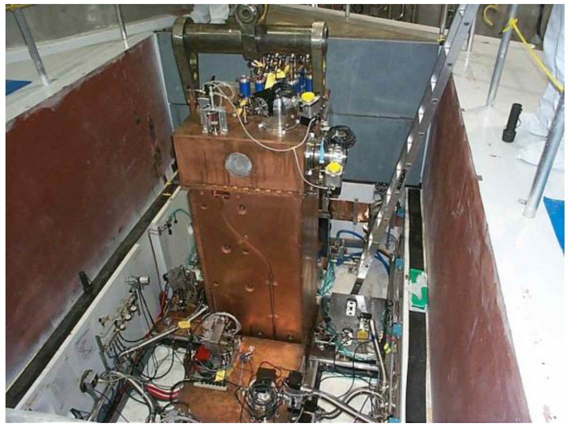
- Low power target oven can dissipate up to 5 kW of beam deposition power.
- The high power target oven ha fins attached to the Ta tube an can dissipate up to 20 kW bear power.
- How do we compare with othe
  - ISOLDE/CERN, 1 kW,
  - SPIRAL/GANIL, 1 kW,
  - HRIBF/Oak Ridge, 500 V

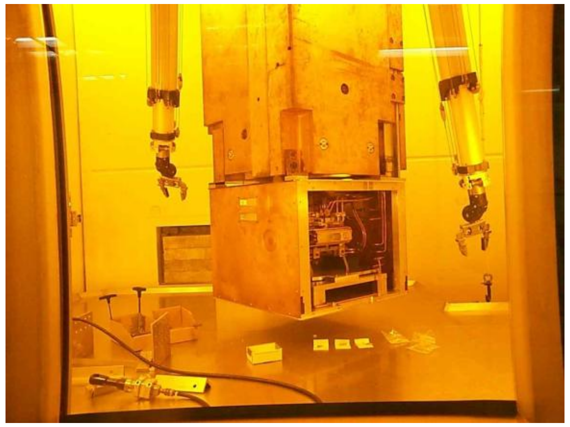


# Target Exchange Process

- **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**





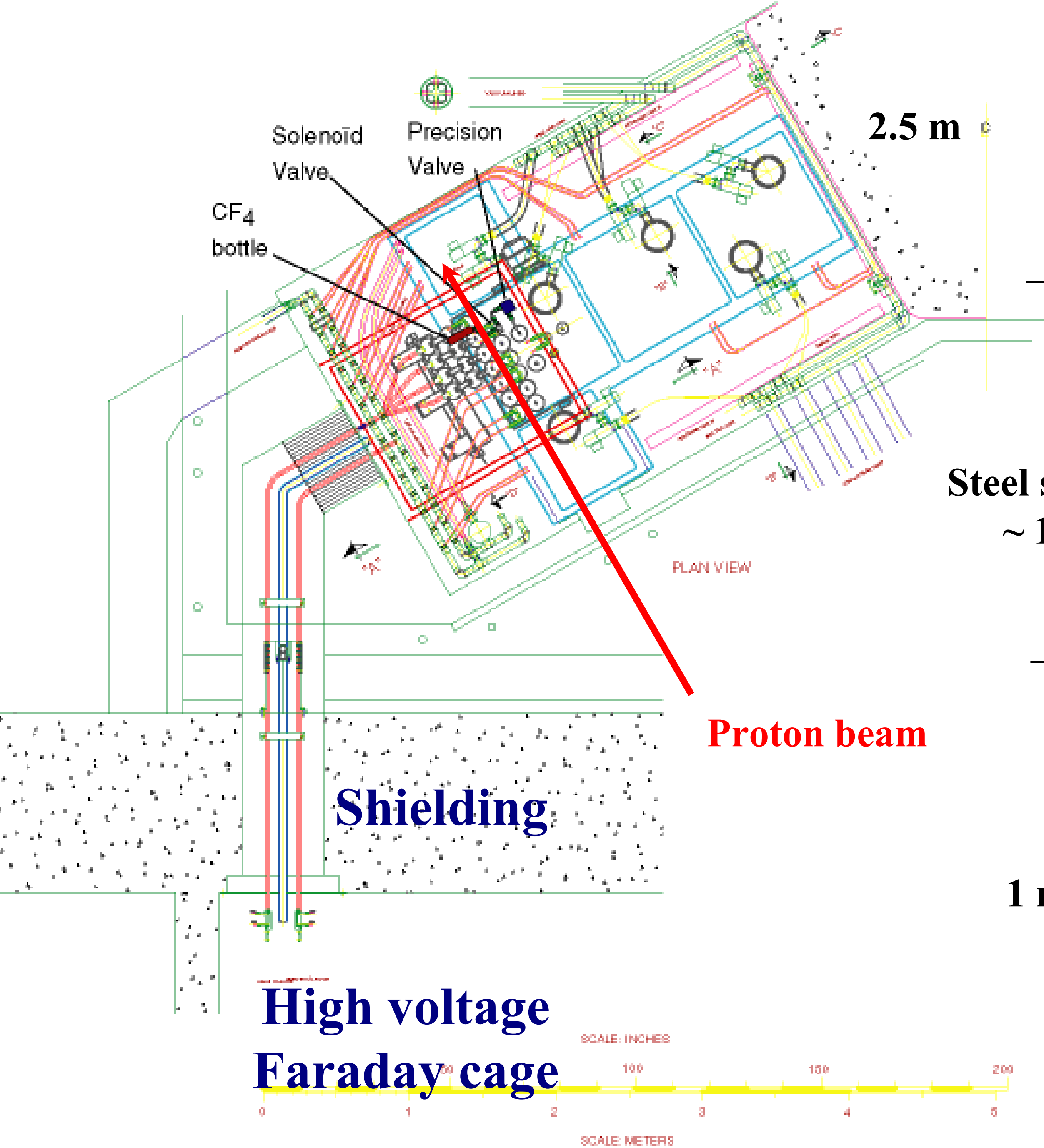


# ARIEL Project

- 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.

# ISAC target stations

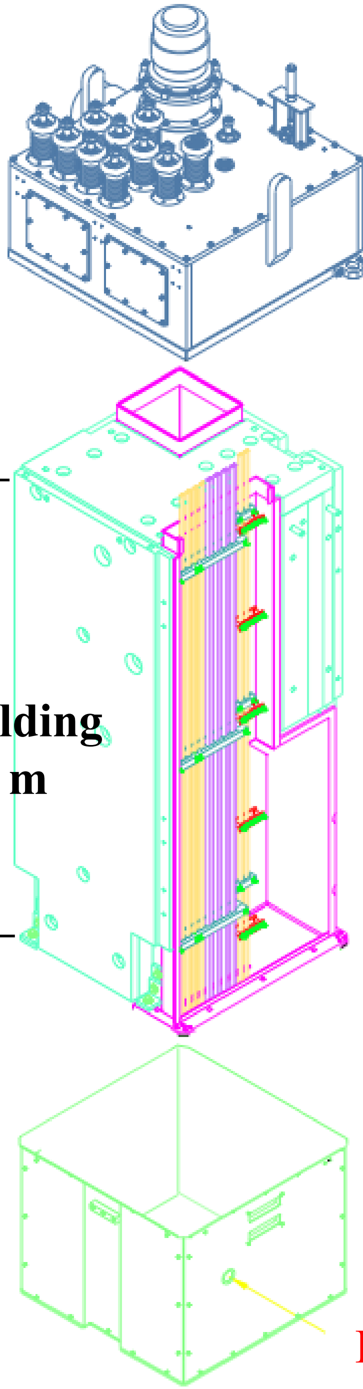
Target station top view



Proton beam

**Shielding**

**High voltage Faraday cage**



2.5 m

Service Cap

Steel shielding ~ 1.75 m

Service Duct

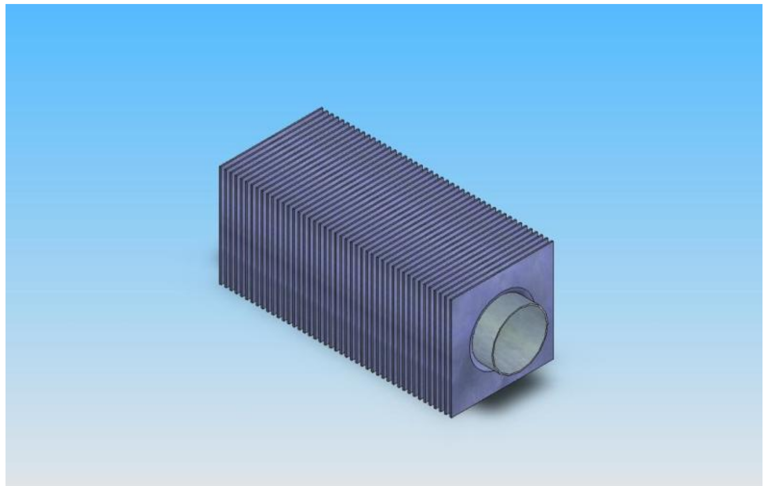
1 m³

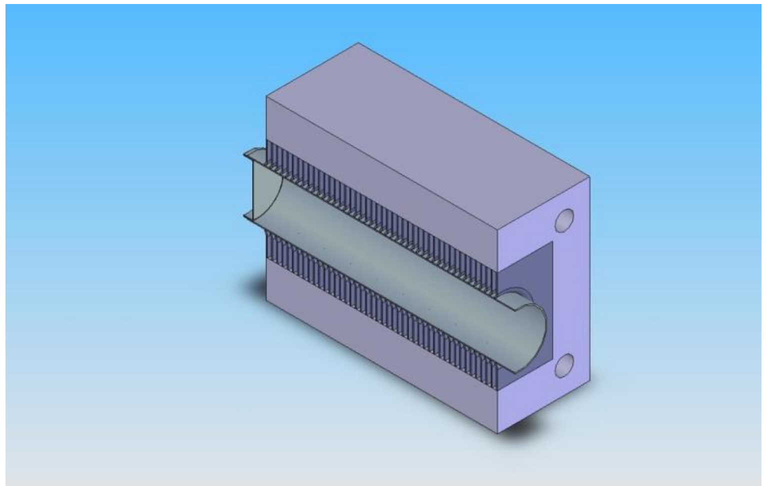
Target/ion-source box

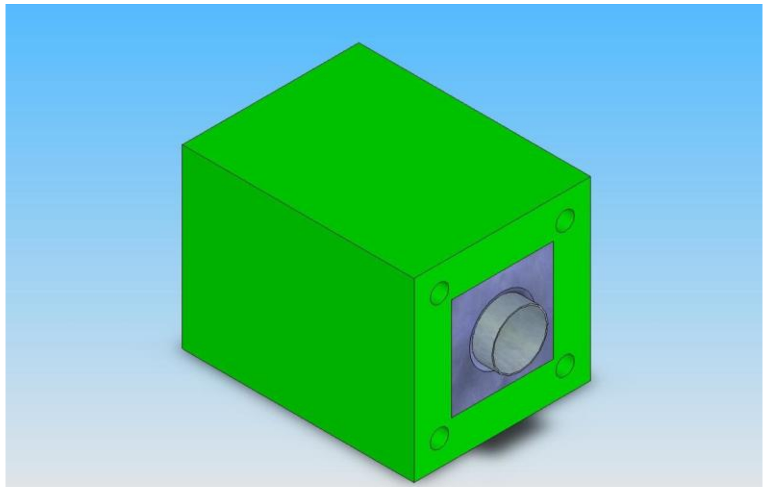
Proton beam

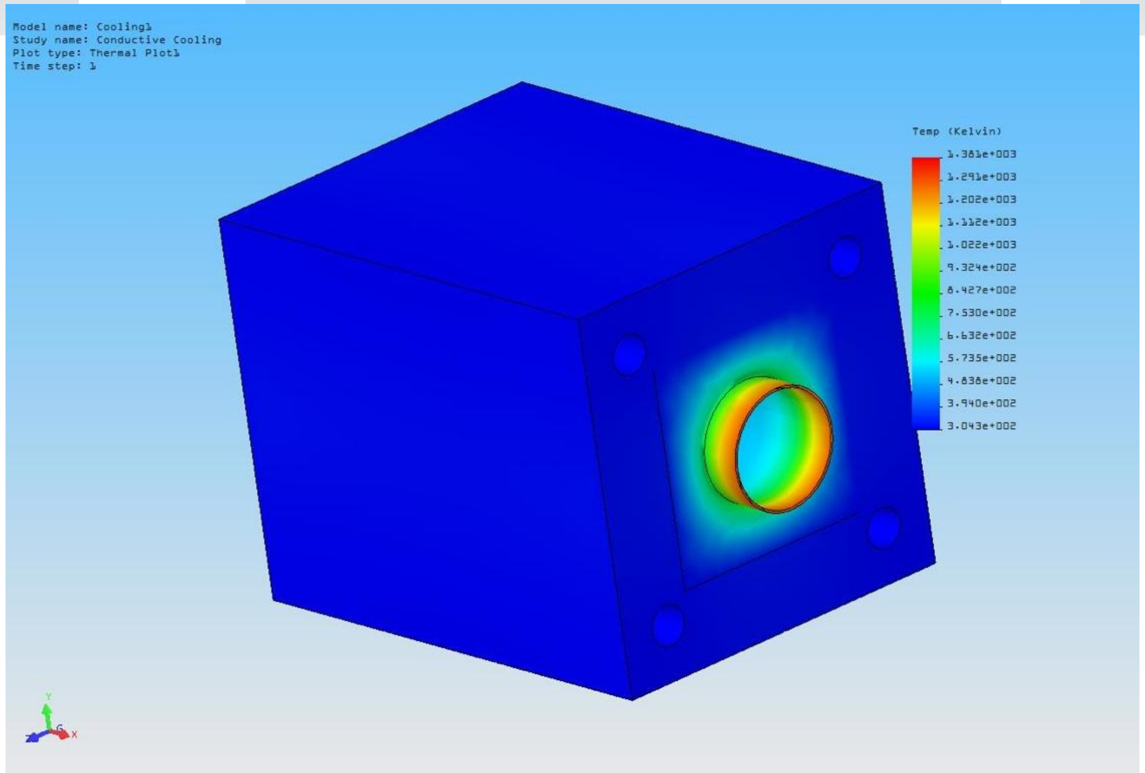
# Cooling High Power Target

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





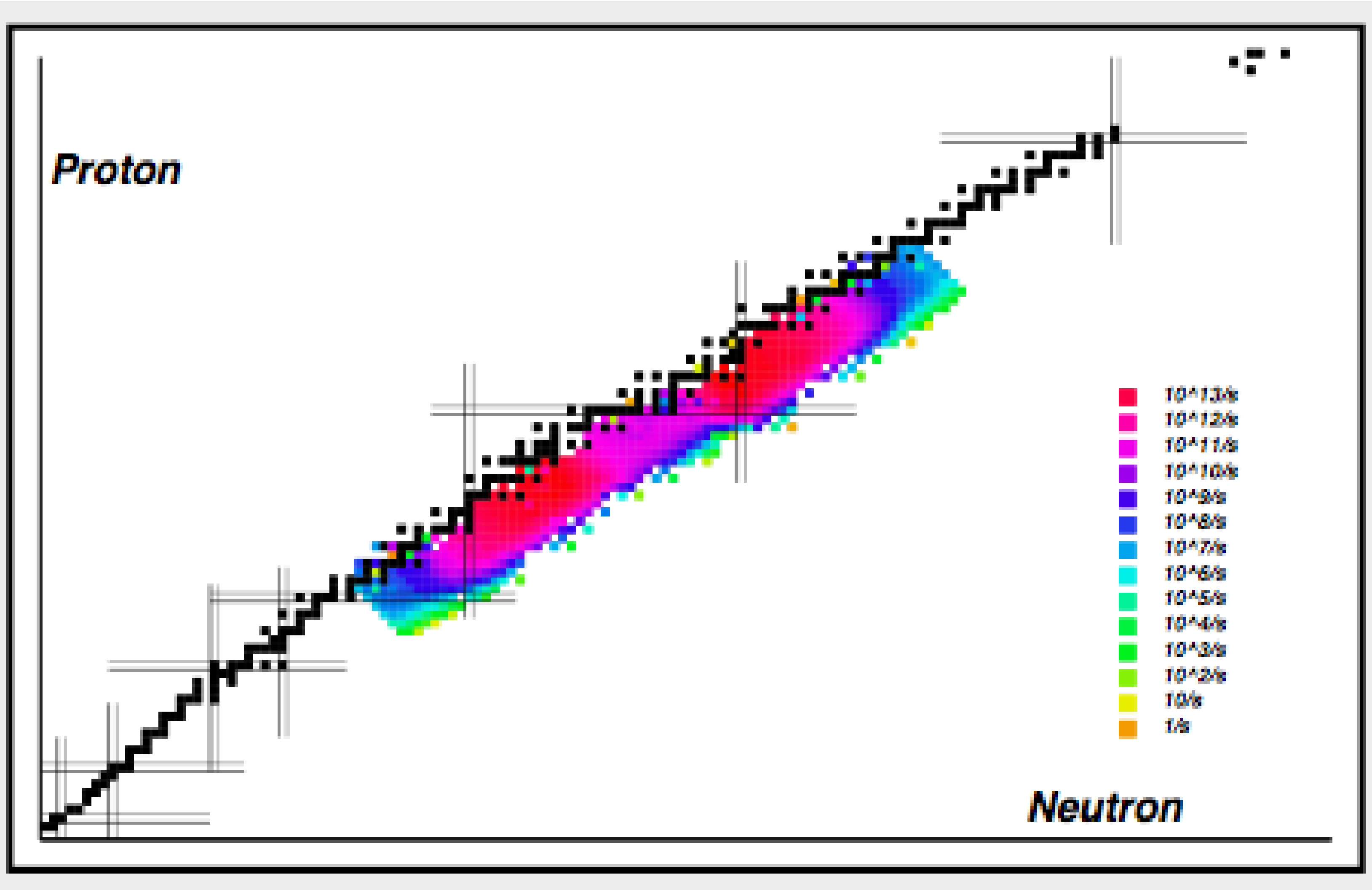




Model name: Cooling1
Study name: Conductive Cooling
Plot type: Thermal Plot1
Time step: 1

# Photo-fission yield

- Use GEANT4[1] and FLUKA[2] to simulate the photo-fission.
  - 50 MeV,100 kW yield to ~ $1\text{x}10^{13}$ 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.**