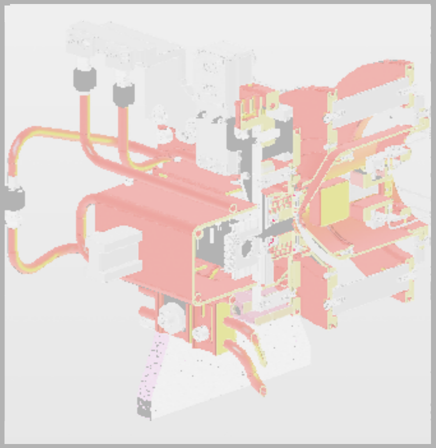
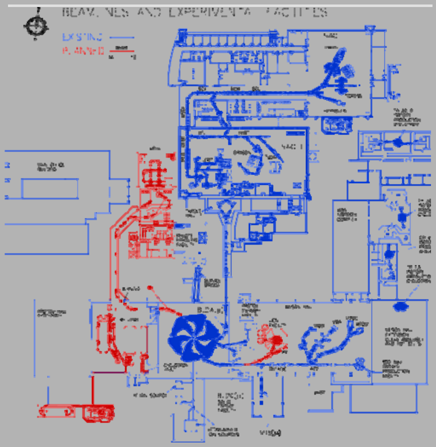
Progress towards new RIB and higher intensities at TRIUMF



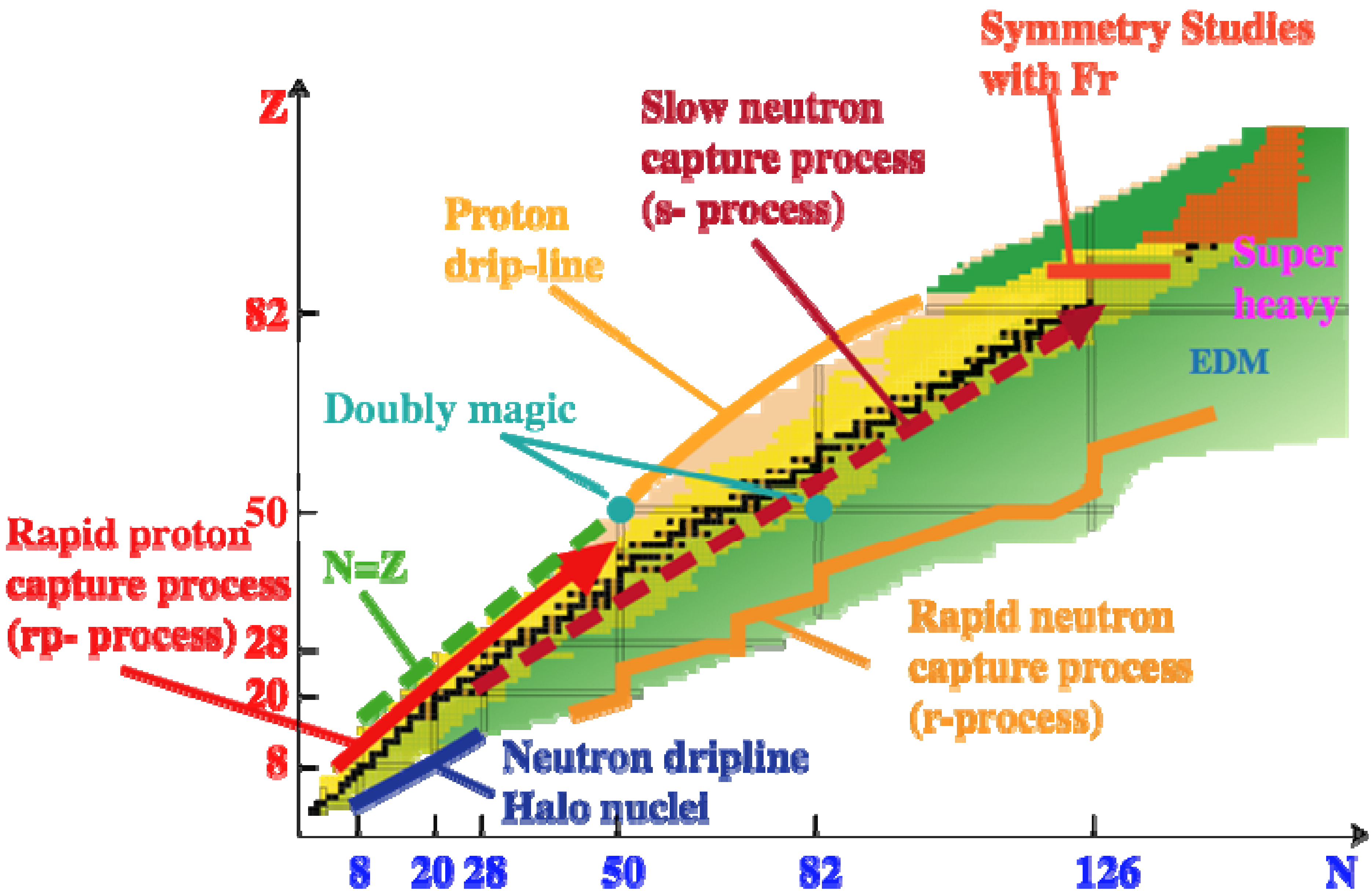


Pierre Bricault
Target/Ion source department,
TRIUMF

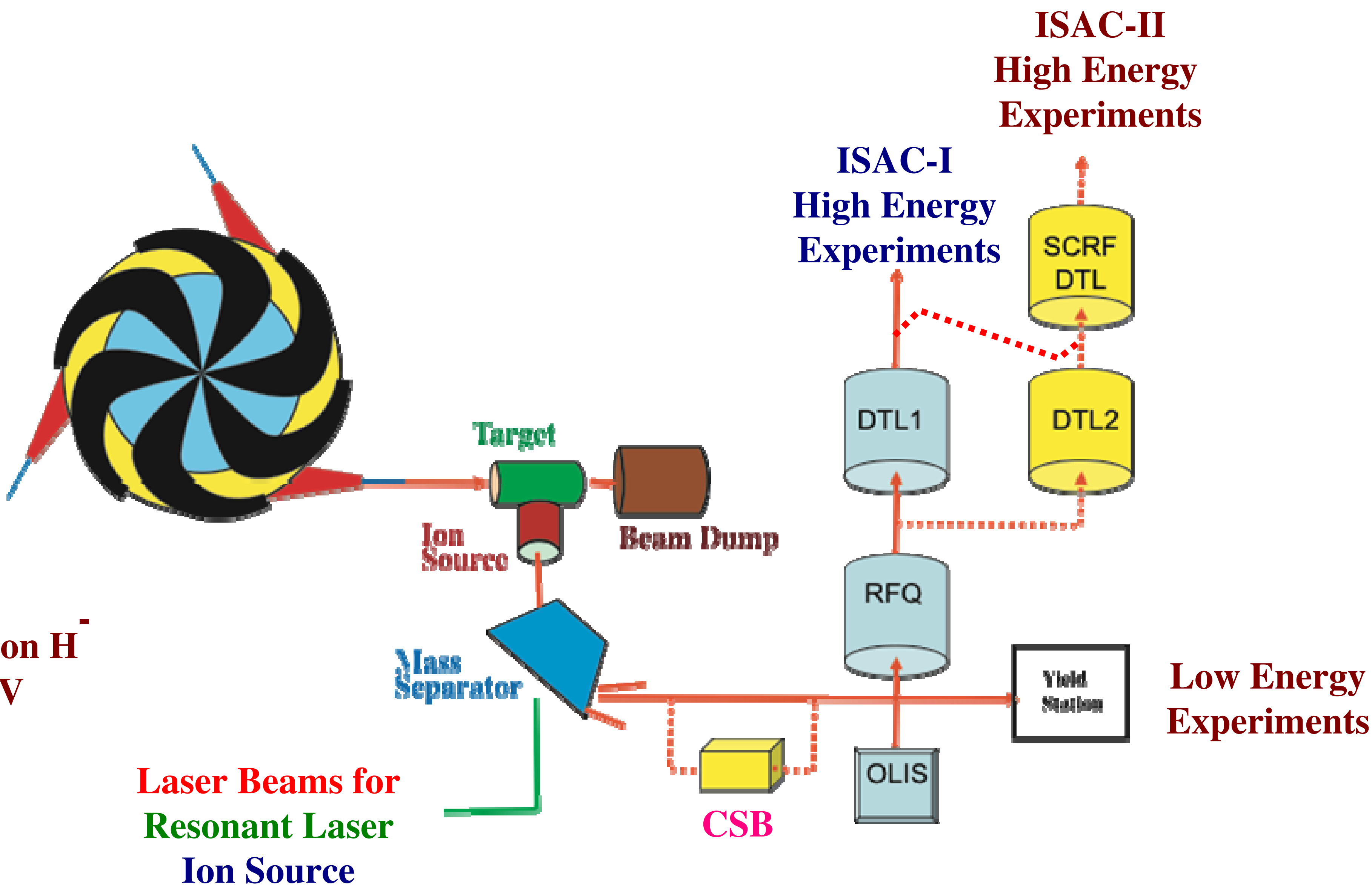
Topics

- Production of Rare Isotopes
  - ISOL method
- ISAC Target
  - High power target material, composite target
- ISAC ion sources for high power beam
- Uranium carbide target development
- ARIEL project
  - Photo-fission, converter study.
- Summary

Physics at ISAC



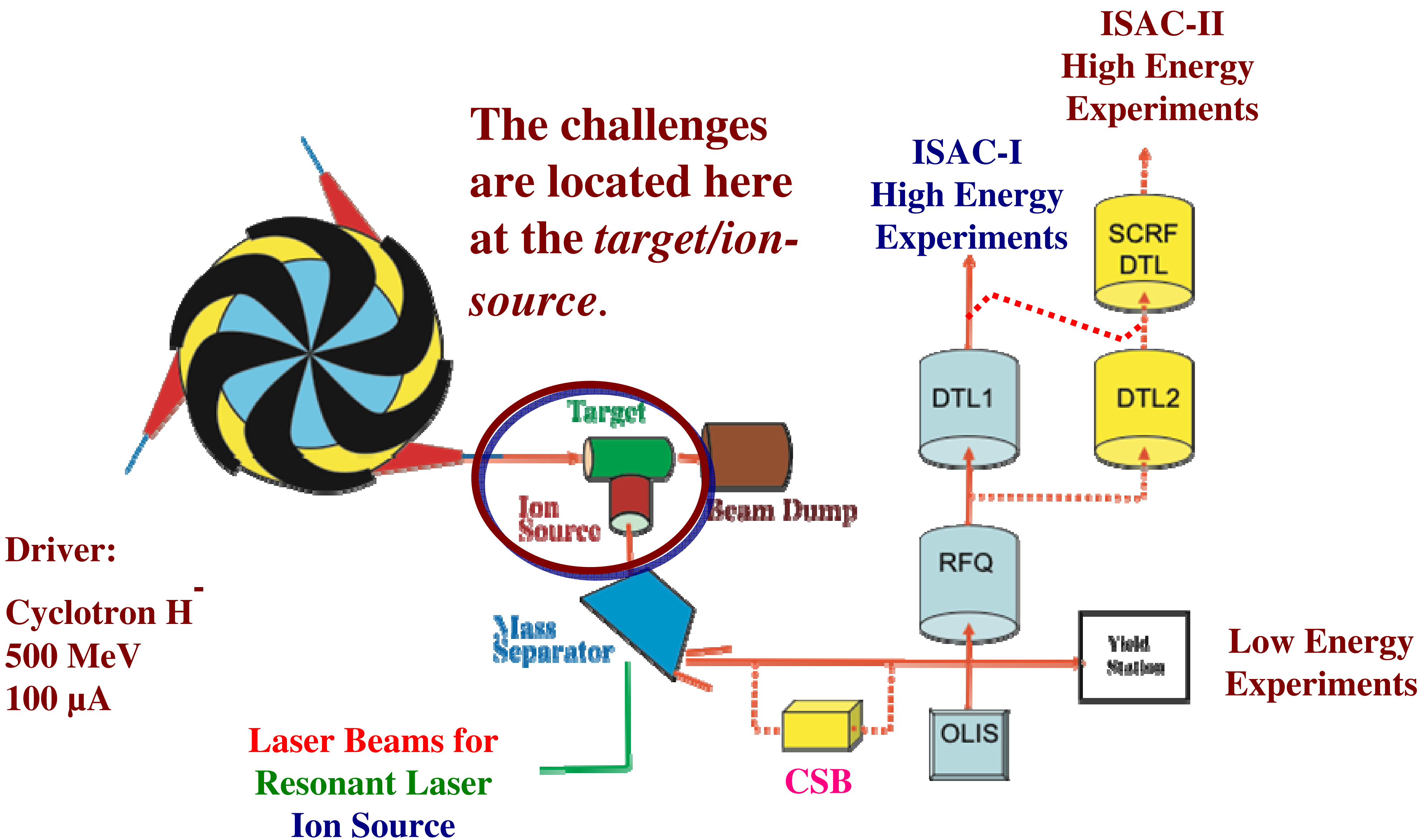
ISAC at TRIUMF



Driver:

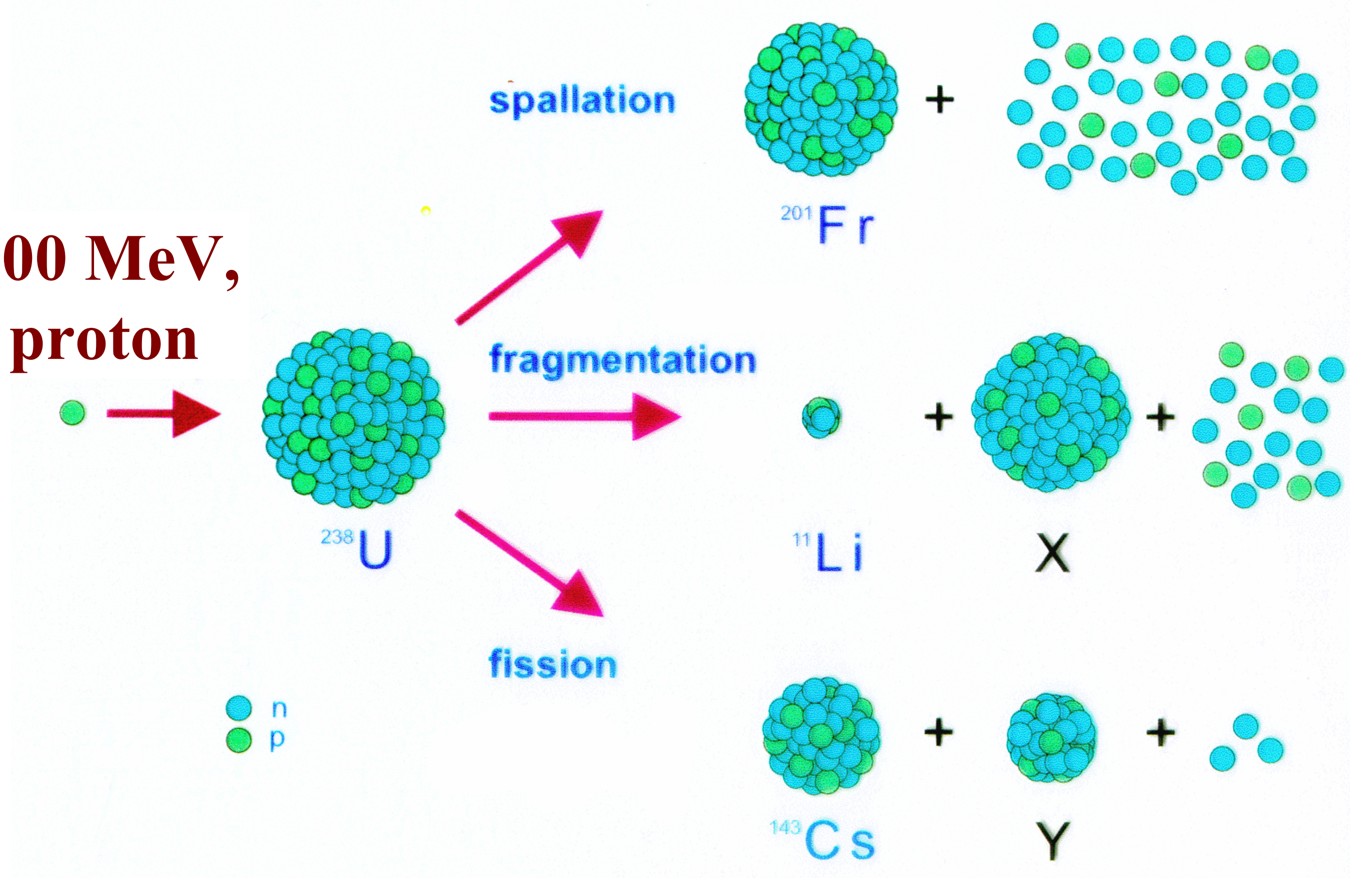
Cyclotron H^-
500 MeV
100 μA

ISAC at TRIUMF



RI Production Reaction Mechanisms

500 MeV, proton

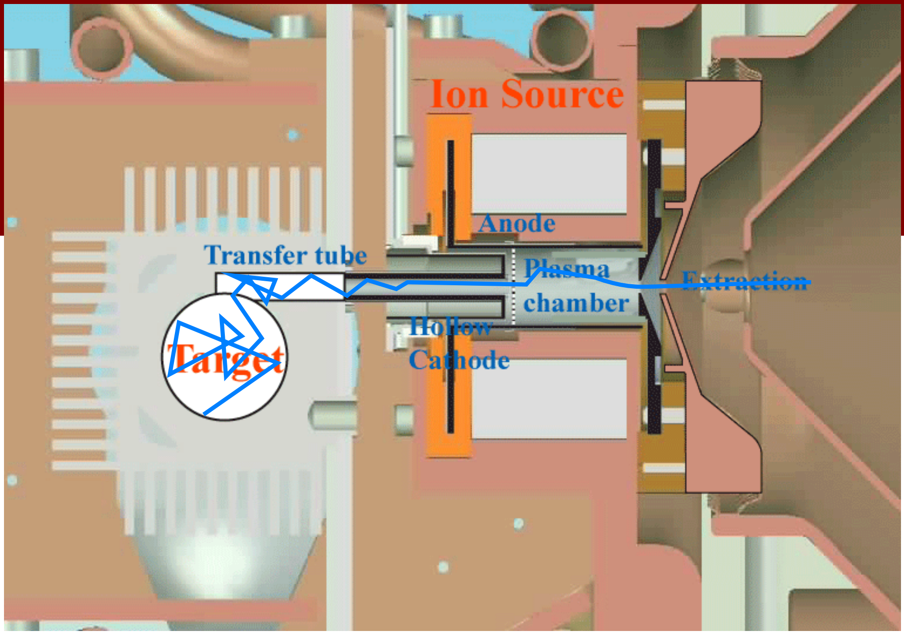


- **Spallation: products distribution peaks few mass units lighter than target.**
  - **Neutron deficient**
- **Fragmentation: product N/Z ratio reflects the target ratio.**
  - **Neutron rich.**
- **Induced fission into roughly equivalent mass products.**
  - **Medium range masse region**

ISOL Method

- **Rare Isotope Beam are a challenge to produce. Especially, the short-lived ones.**
- **The ISOL method can be described as the production of RI by bombarding a thick target nucleus by a fast projectile.**
- **The requirements for producing high intensity RI beams are:**
  - **High intensity and energy driver**
  - **A refractory target material inside a high power target container**
  - **A high resolution mass separator**

ISOL Method

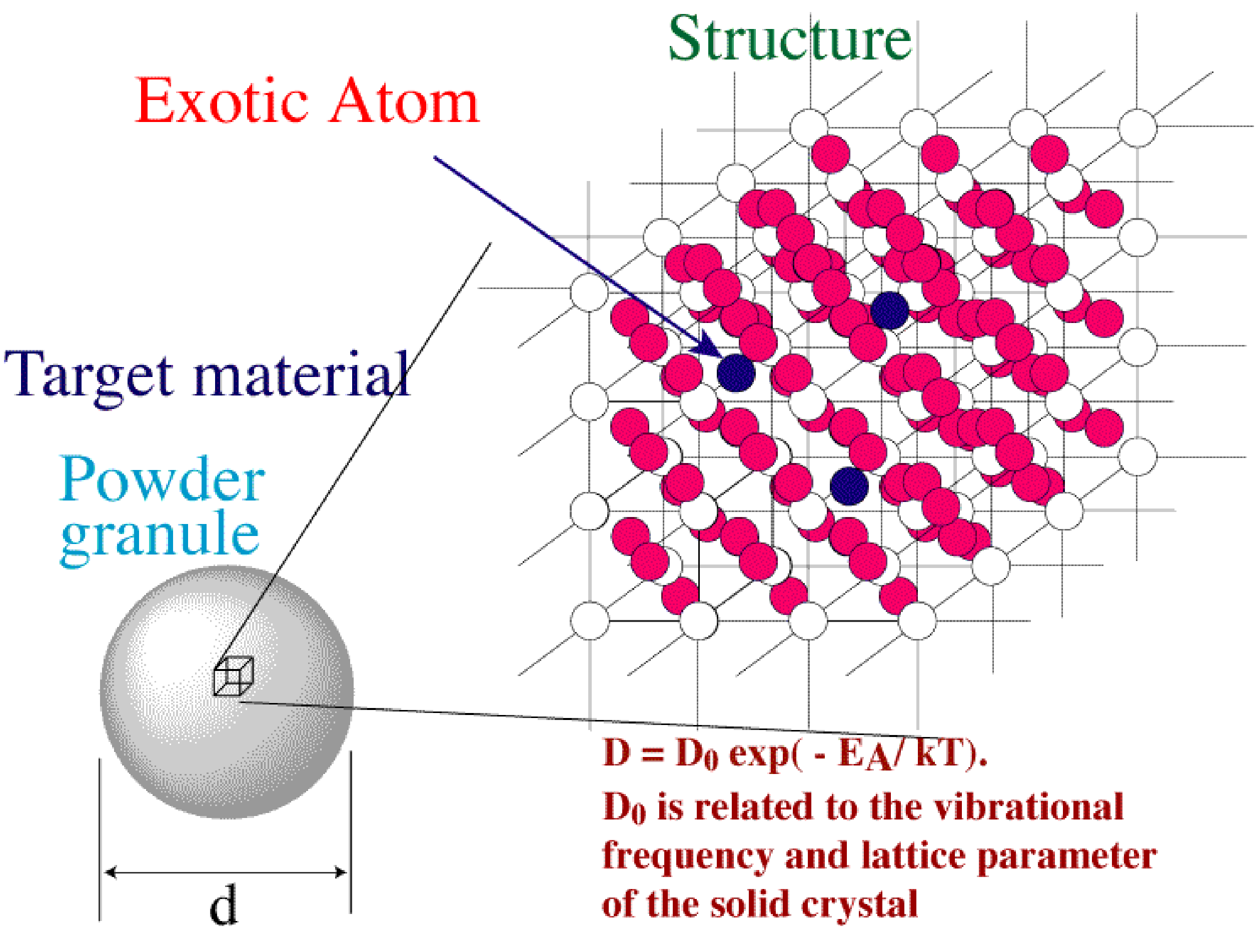


This method involves the interaction of light ion beam onto a thick high-Z target material,

The fragments are imbedded into the bulk of the target material.

- **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.**

Diffusion Process



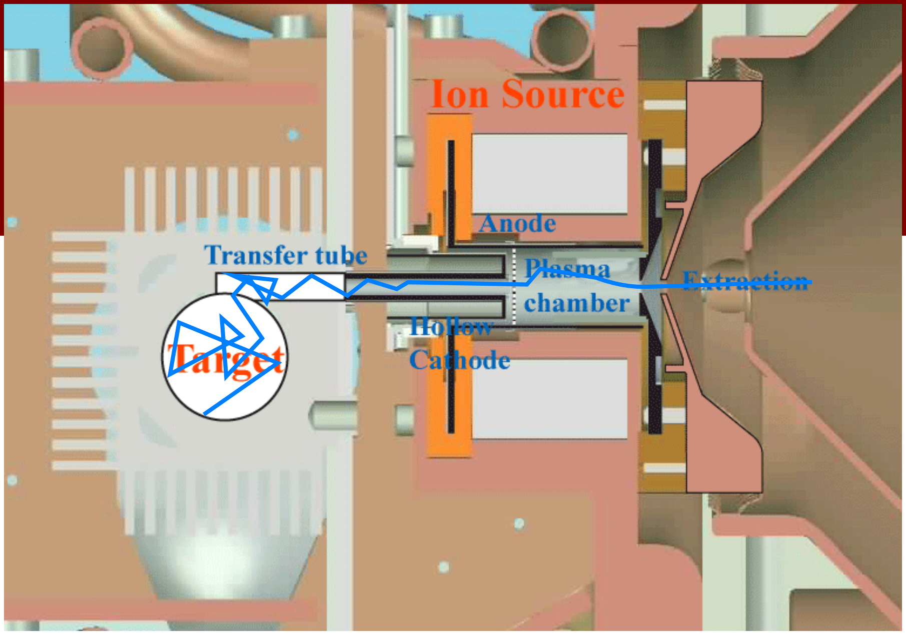
$D = D_0 \exp(-E_A/kT)$.

D_0 is related to the vibrational frequency and lattice parameter of the solid crystal

- The diffusion process is driven not only by the concentration gradient, but also by the activation energy E_A required to move the atoms from site to site through the solid.
- <u>High temperature operation speed up the diffusion process.</u>

ISOL Method

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.



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  - $Y = \Phi \ \sigma \ (N_A/A \ \tau) \ \varepsilon_D \ \varepsilon_E \ \varepsilon_I$
- High yield can be obtained by increasing the proton beam intensity.

Pure effusion

Once the exotic atom has diffused to the surface of the target material the subsequent effusion step is determined by:

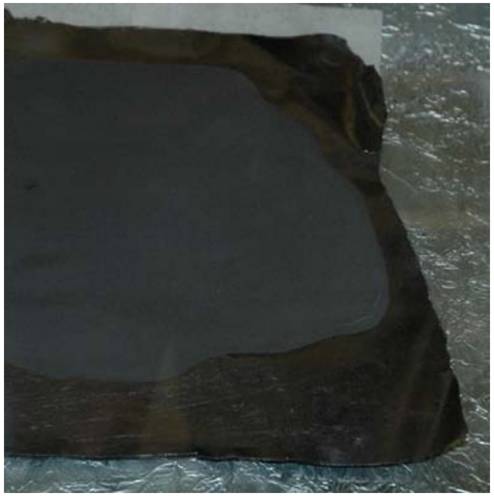
- **The mean number of collisions with the surface of the target material and the container before leaving enclosure.**
- **The mean free flight time τ_f between two wall collisions.**
- **The main sticking time τ per wall collision, which depends essentially on the <u>temperature</u> and <u>absorption enthalpy</u> ΔH_a of the surface of the enclosure.**

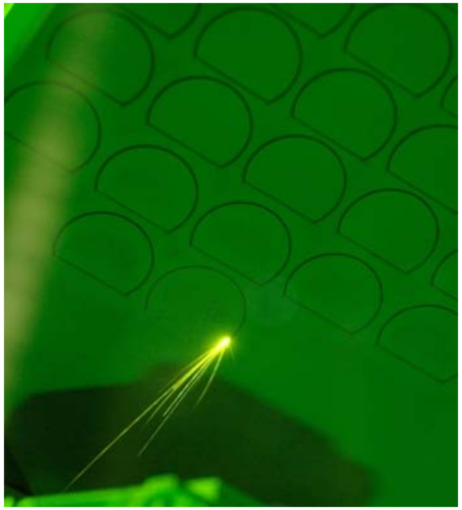
Target Material For High Power

- **Power dissipated into the target is very large demanding very high thermal conductivity target material and a target container capable of dissipating the power.**
- **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.**

High Power Target Material Fabrication

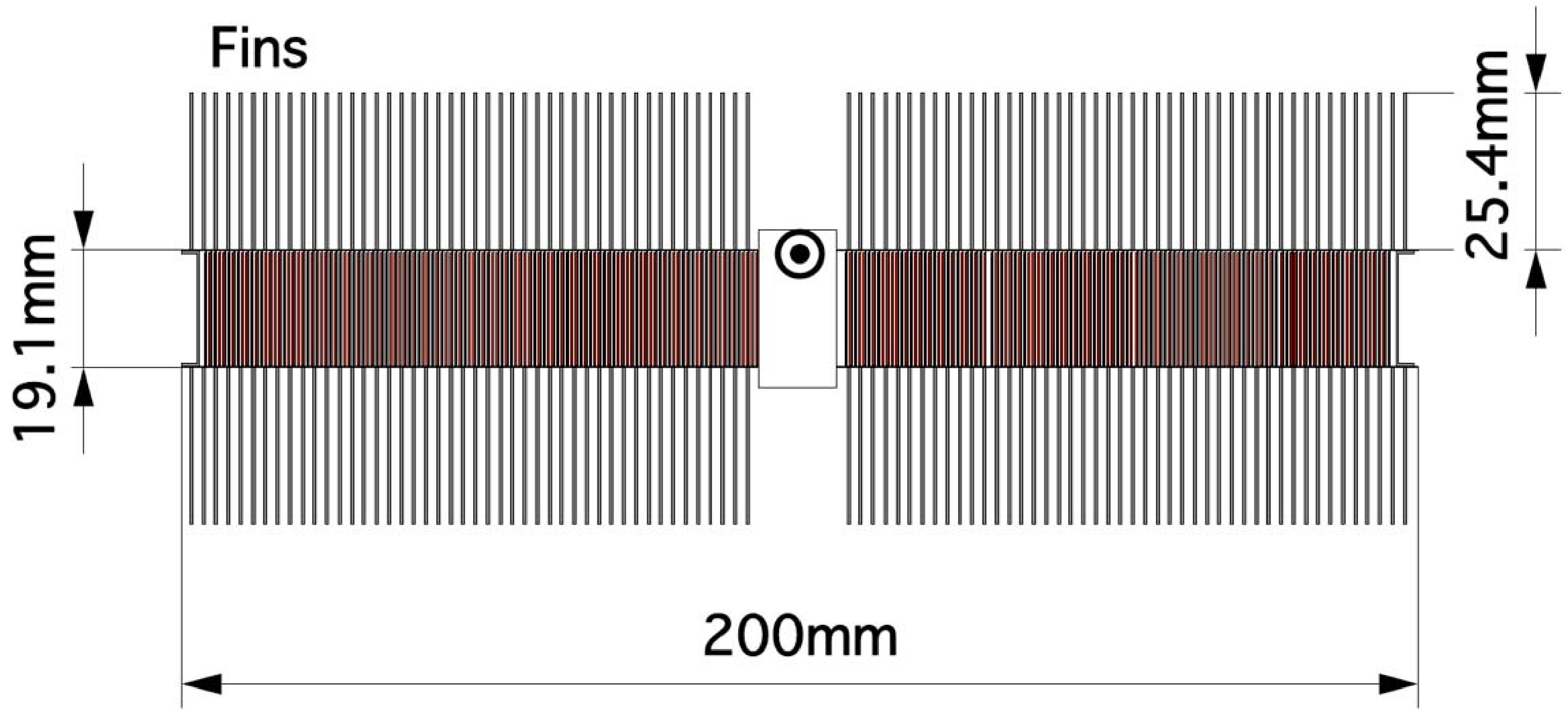
- The ceramic powder suspended in a solvent, which contains dissolved polymers that favor the powder dispersion.
- This mixture in suspension is poured into a mold or onto a backing foil and then allowed to dry.
- The dried slip cast is easily cut into the desired shape using LASER cutting.
- These carbide ceramics can be used up to 40 μA.
- For higher beam power it is necessary to increase the effective thermal conductivity of the carbide ceramics.
- We have developed a technique allowing us to pour the solution 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 0.1 mm thick.



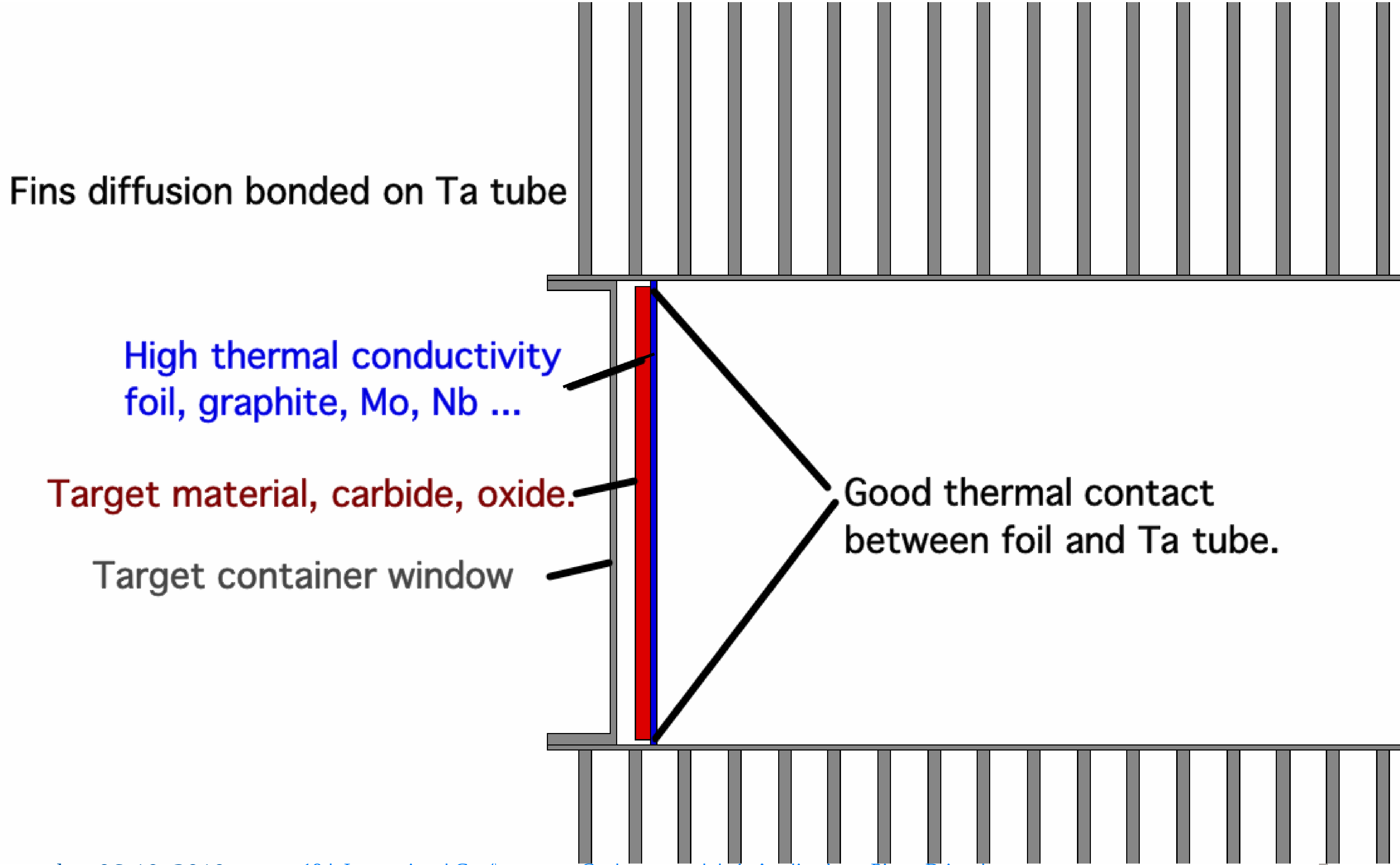


ISAC HIGH POWER TARGET

Section view of the High Power Target
Composite Target Material Concept



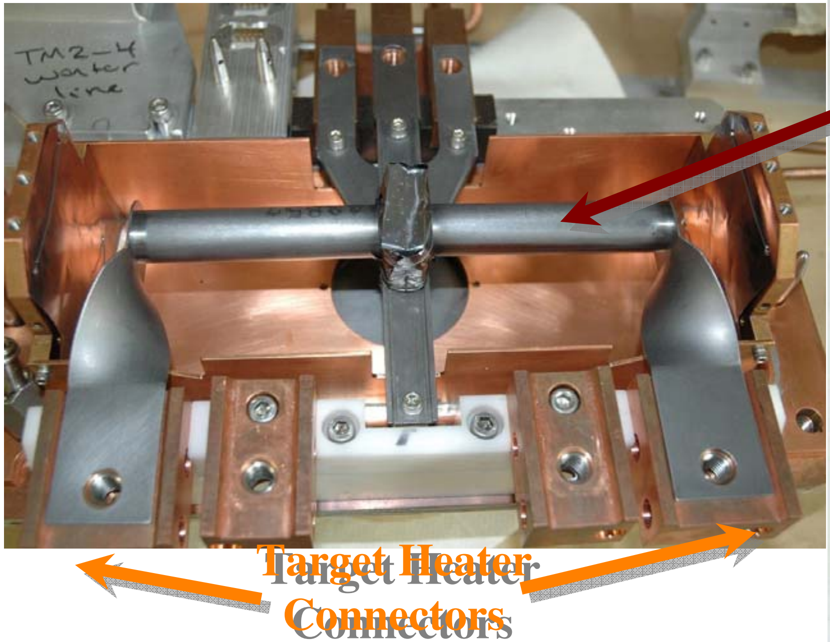
High Power Target Material, composite



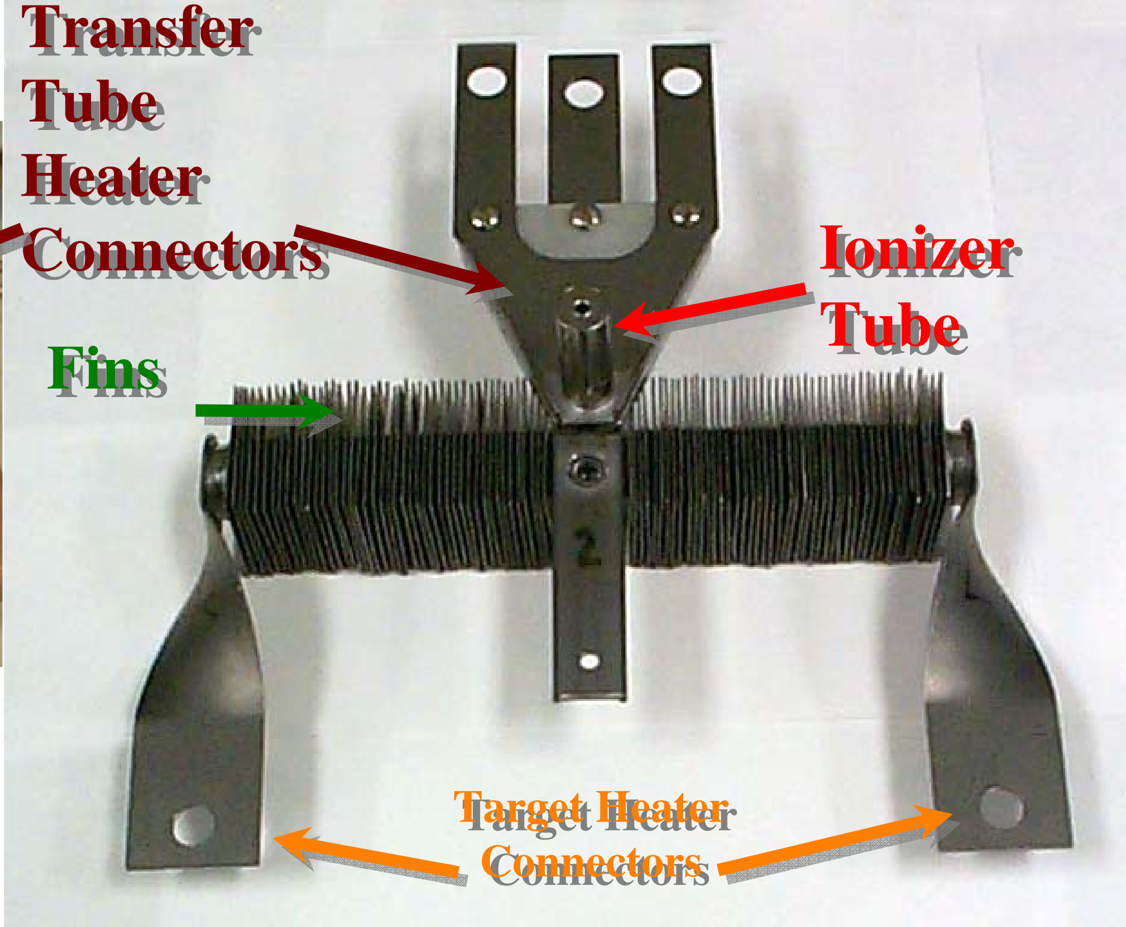
ISAC “Target Ovens”

Normal Target

High Power Target



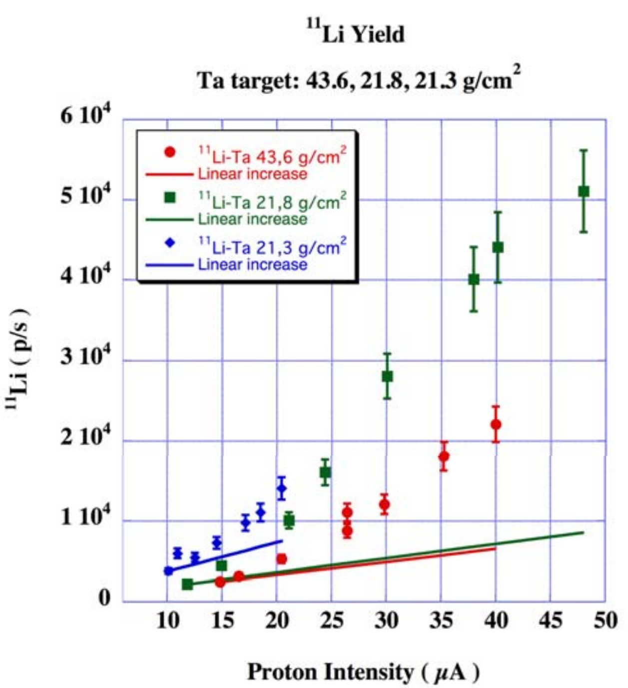
$I_{Proton} \leqslant 40\ \mu A$

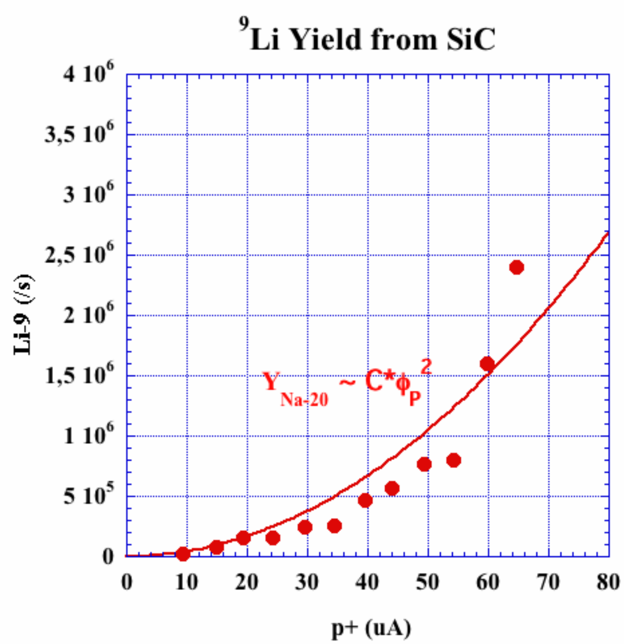


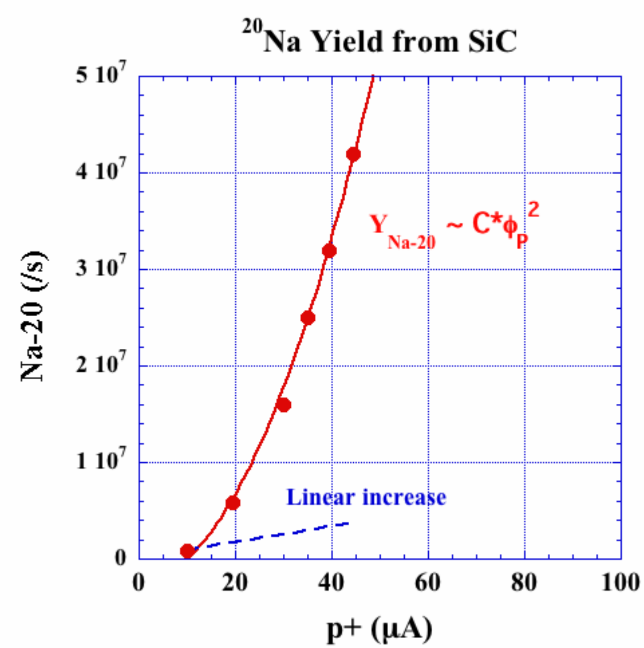
$55 \leqslant I_{Proton} \leqslant 100\ \mu A$

Radiation Enhanced Diffusion

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



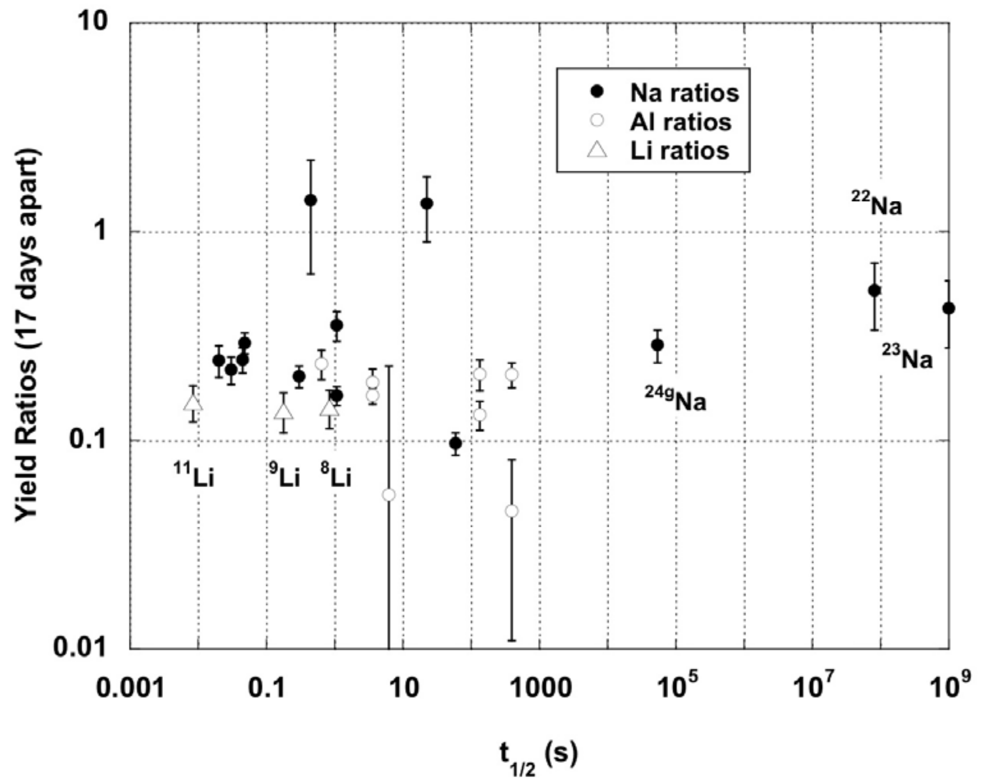




Yield ratios showing performance degradation

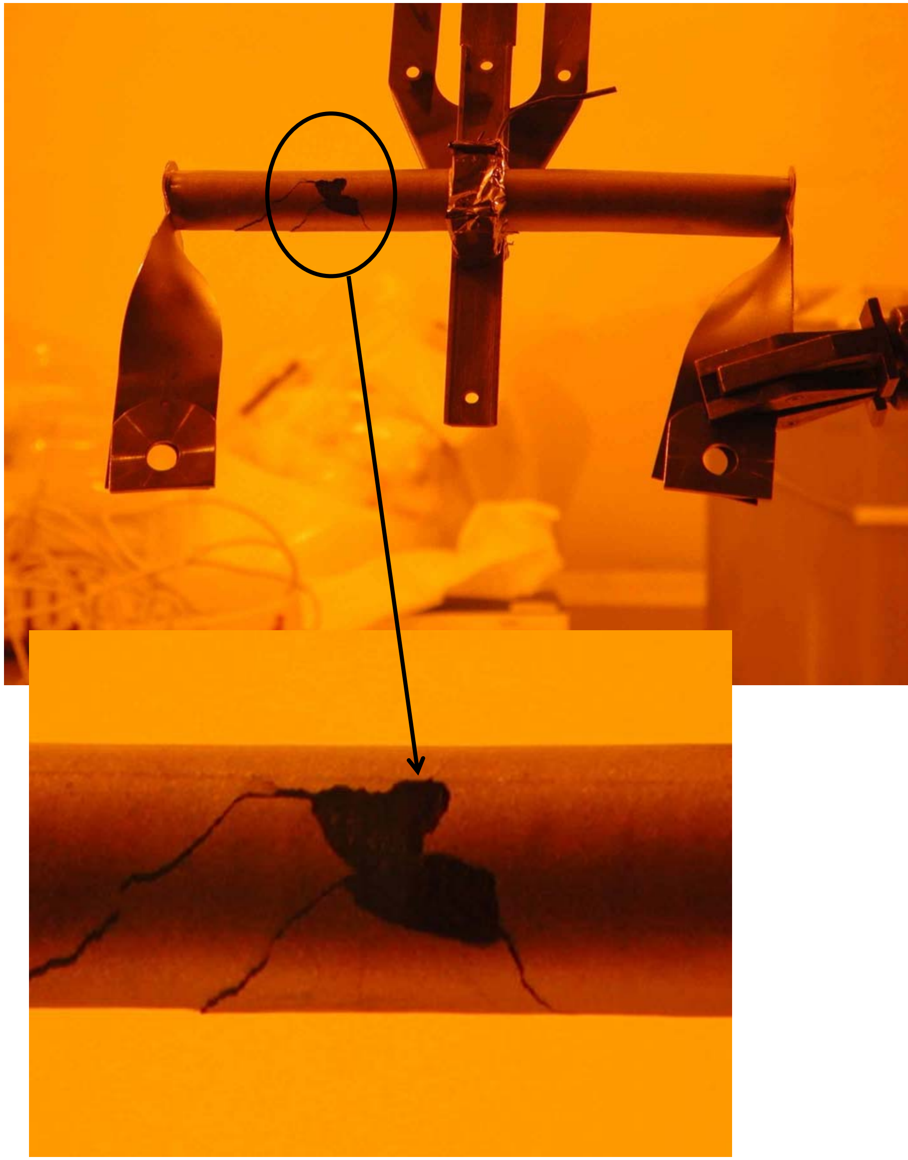
Possible reasons for degradation of performances

1. **Radiation damage of the target container and target,**
2. **Impurities created move to crystal interstice weakening the matrix.**
3. **Temperature cycling when proton beam goes off.**

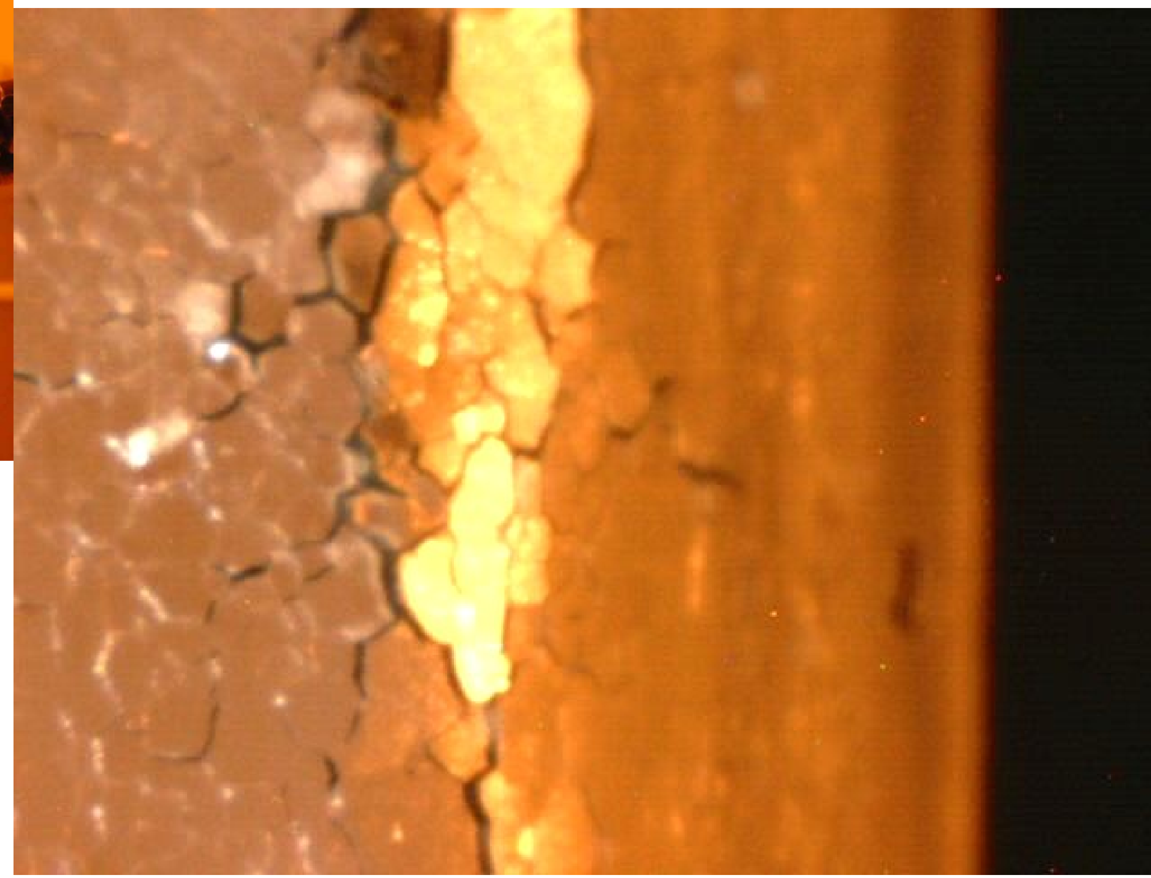


Yield ratios of $^{8\text{-}11}$Li, $^{20\text{-}27}$Na and $^{26,28\text{-}31}$Al measured 17 day apart. The average ~79% yields decrease is believed to result from loss of target container integrity.

Target container damages



$N_p \sim 1E19$ protons



Proton Beam Intensity On Target

Target Material	High Conductivity Support	Proton Beam Intensity (uA)
SiC	C (graphite foil, 0.1 mm thick)	70
TiC	C (graphite foil, 0.1 mm thick)	70
ZrC	C (graphite foil, 0.1 mm thick)	75
Ta		75-100
Nb		80-100
Nb5Si3	Nb (foil, 0.025 mm thick)	15
Al2O3	Nb (disk, 0.5 mm thick)	30

Ion Source Operation Domain

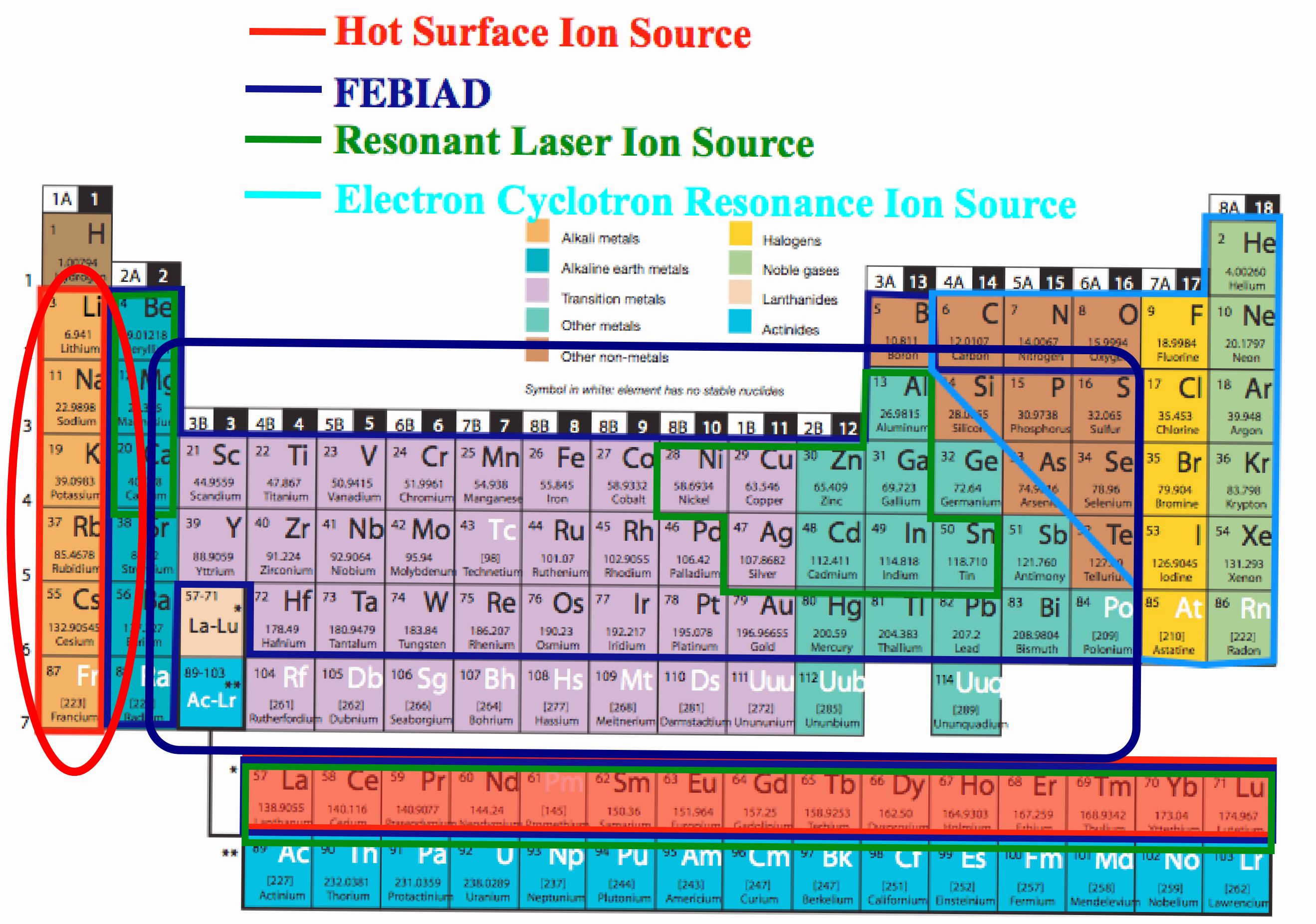
- There is *no universal* ion source for on-line application,
- We must develop ion source for each group of elements,

Hot Surface IS

LASER IS

Negative IS

ECR IS



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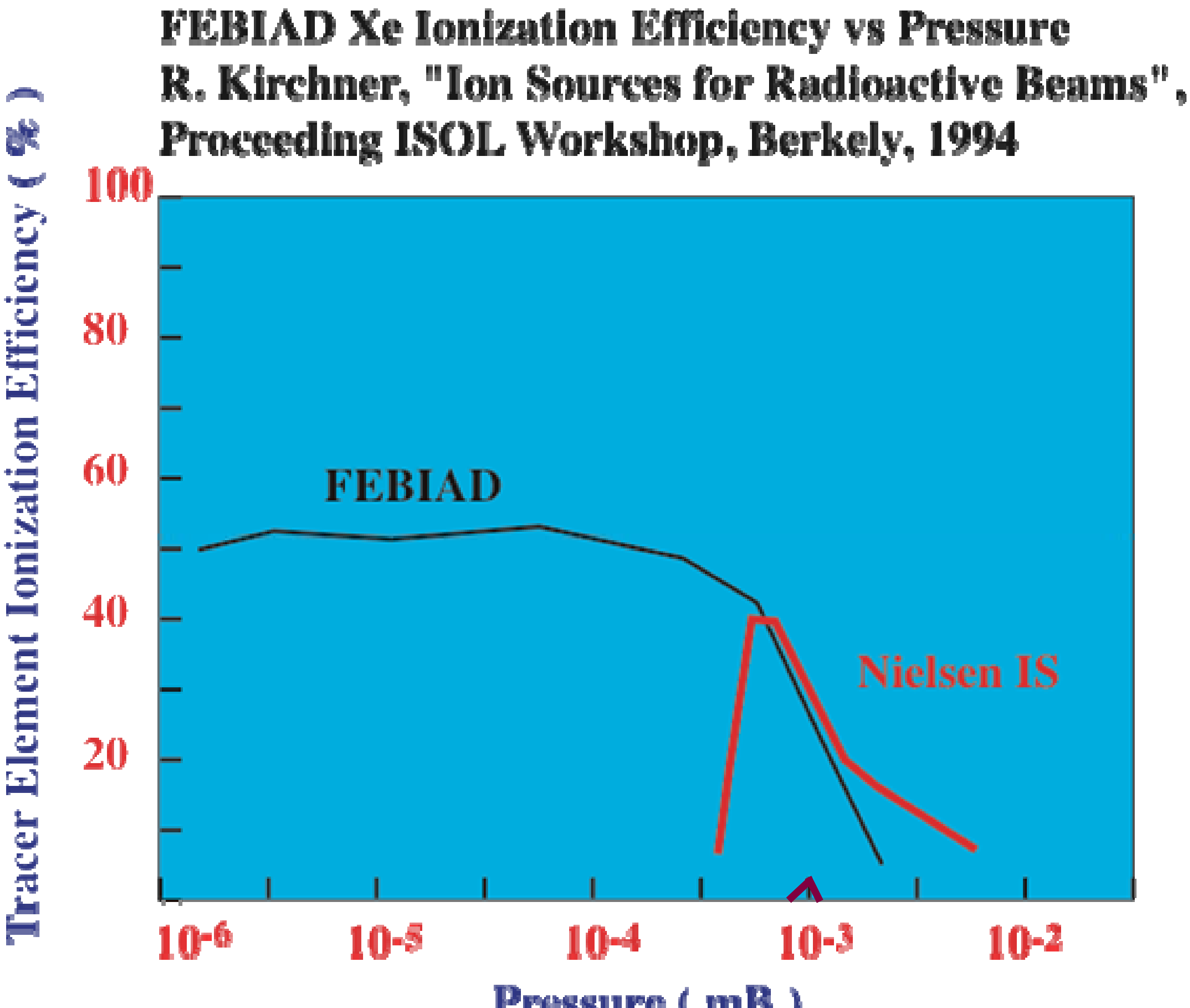
Ion Sources for High Power Operation

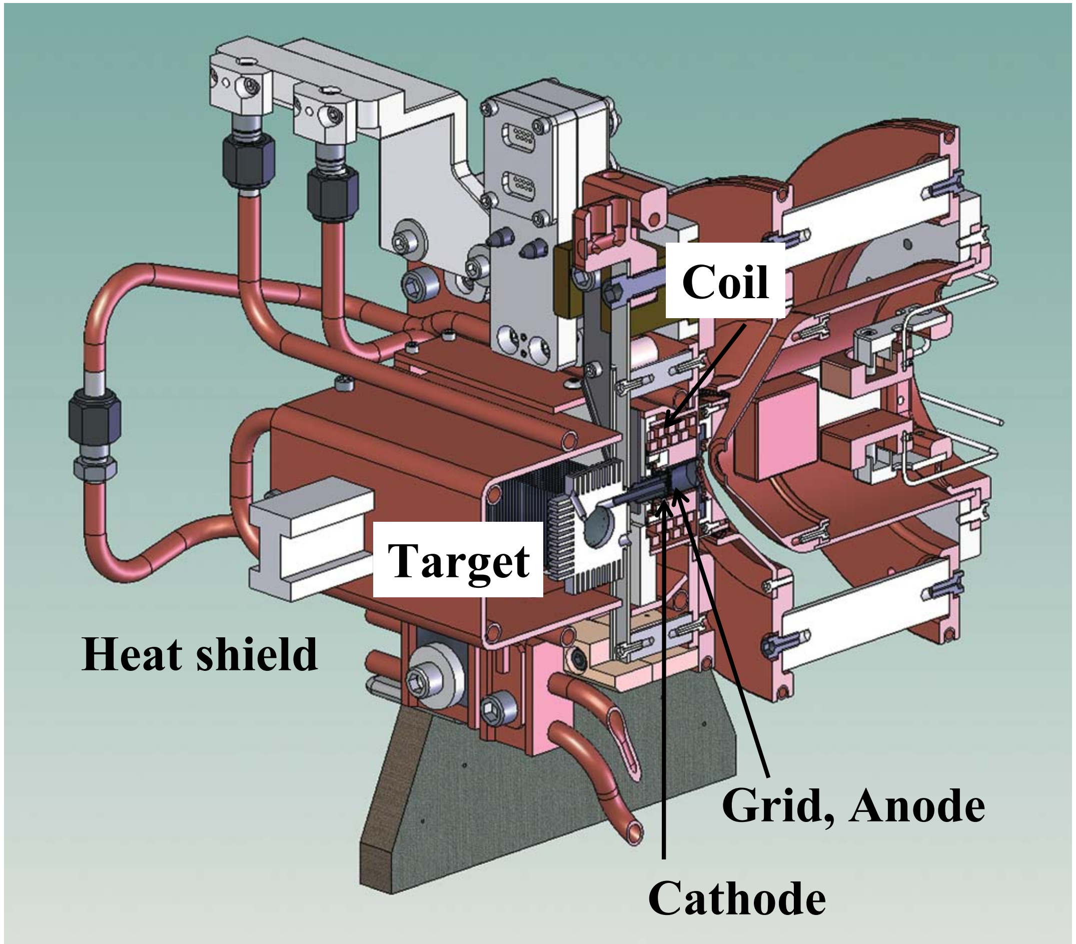
- **Ion sources that are not so much affected by the target outgas effect are:**
  - **The hot cavity surface ion source,**
  - **The Laser ion source.**
- **The plasma ion sources are much more affected by the target outgas,**
  - **ECR IS,**
  - **Nielsen and Bernas,**
  - **FEBIAD, is the one, which is less affected by the base pressure.**

FEBIAD Ion Source



Hot Plasma Ion Source, FEBIAD

- **It was used for TUDA $^{18}F(p, \alpha)^{15}O$ experiment,**
- **We operated the FEBIAD combined with a high power composite SiC/Cgr target at 70 µA,**
  - **Nov. 2007, I(^{18}F)= 9E+06 /s**
  - **May 2008, I(^{18}F)= 5E+07 /s**
- **ISOLDE, 1E+07/s,**
- **HRIBF, 2E+06 /s.**
- **One issue is sometime the outgasing of the carbide produces carbon fiber in the extraction electrode creating shorts.**

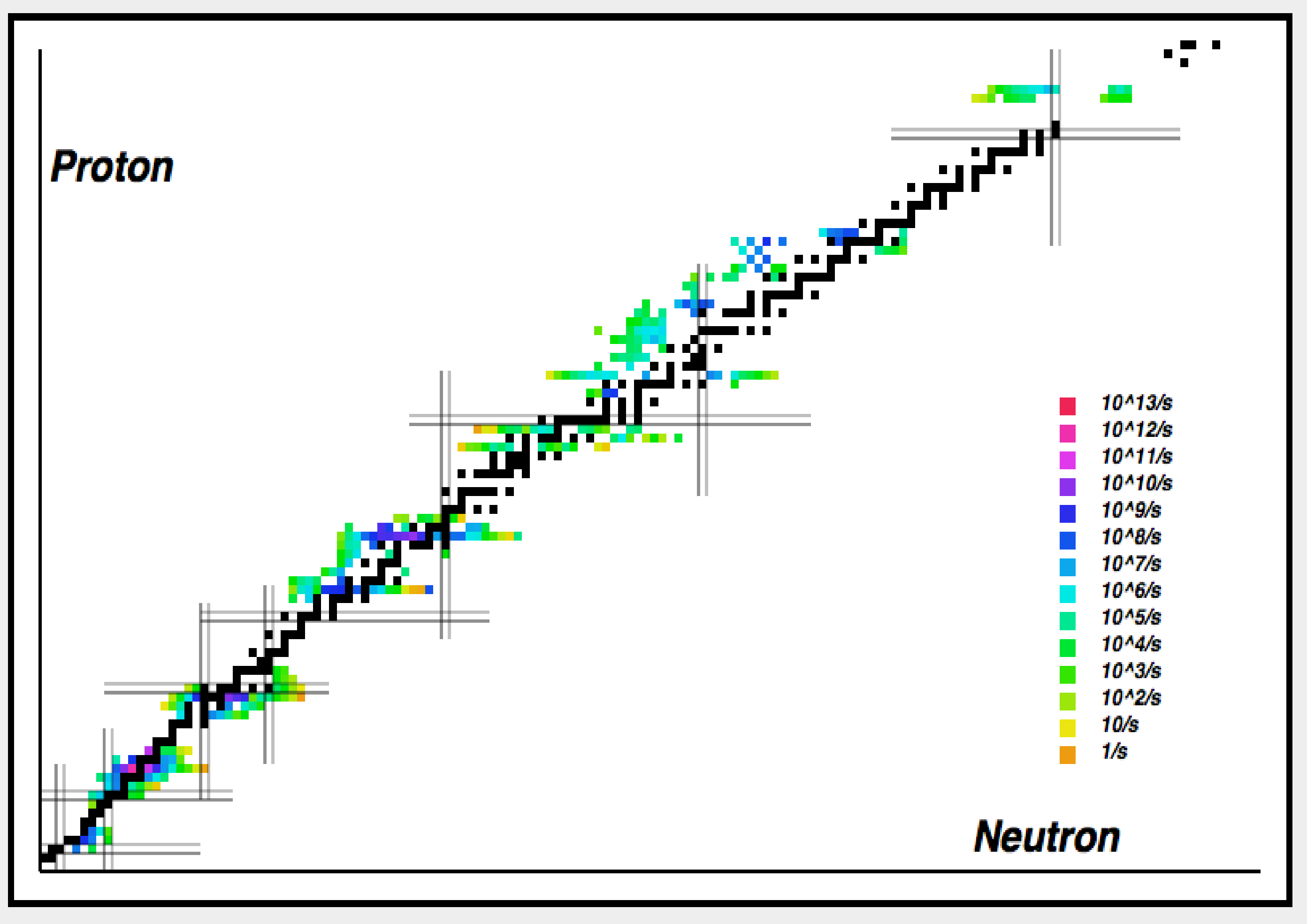


FEBIAD Ion Source, section view.

RI yield at ISAC

More RI with recent addition of ZrC and UO_2 targets since 2008.

To improve yield of Fr and Rn we need a UC_x target.



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

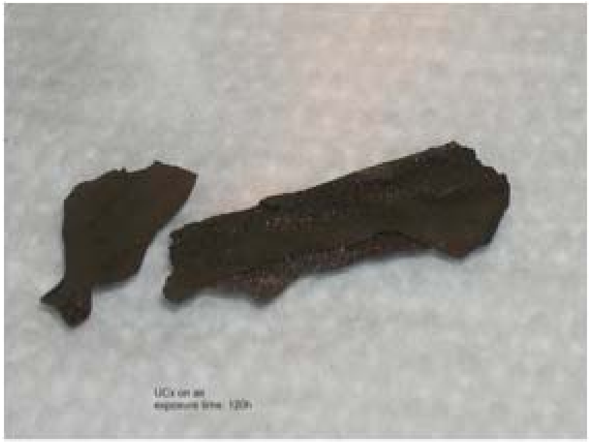
- UC_x was produced by from UO_2 + graphite,
- Using a ball mill machine they are ground to fine power in a plasticiser solution,
- Carbonization is done under vacuum,
- The resulting sheet is milled in a plasticiser solution again,
- The solution is then cast onto a graphite foil
- Target disks are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

"raw" UC_2

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.**

UCx exposure to air



22.5 H exposure

120 H exposure

- **Two samples were exposed in air at room temperature,**
  - **No visible effect after one day,**
  - **After 5 days we see some discoloration on the surface .**

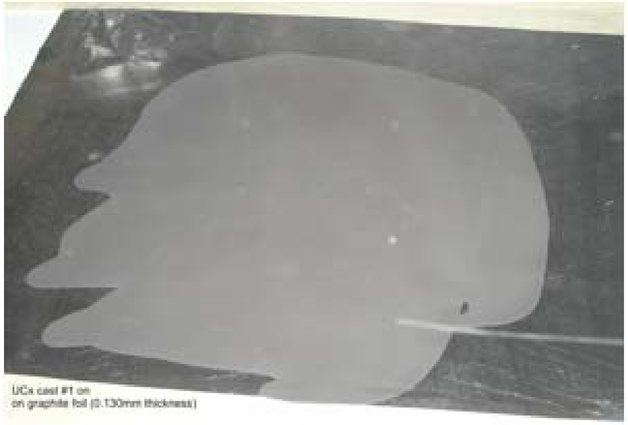
“raw” UCx at 400° C

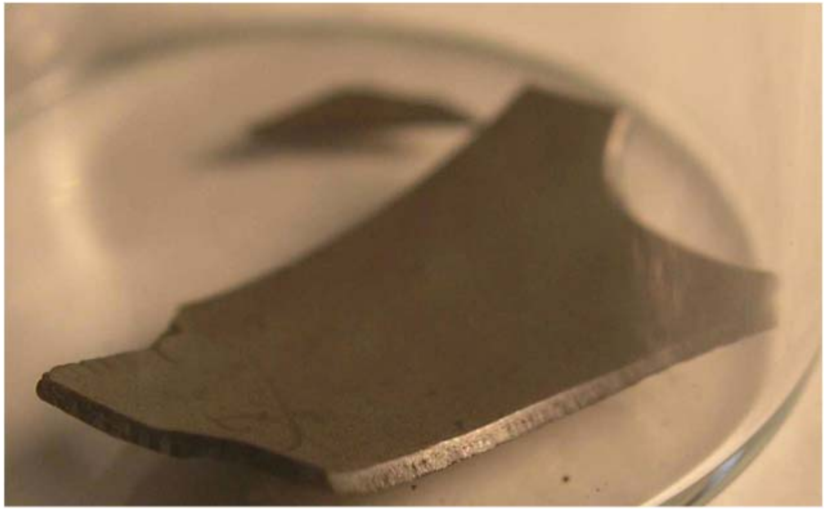
- Exposure to air at 400 ° C for one hour results in a slow decomposition of the carbide back into oxide.
  - No rapid oxidation.

Exposure to water

- Exposure to water at 20° C results in the decomposition of the product.
- This picture shows the "raw" UC_x after 22.5H in water.
  - No rapid oxidation observed.

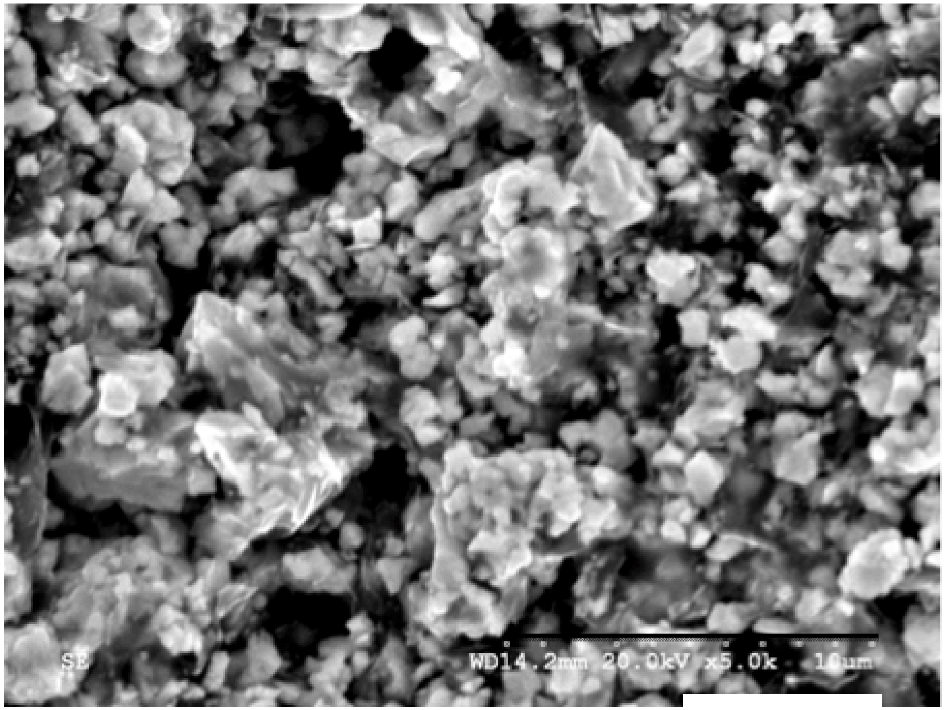
sintered UCx/C





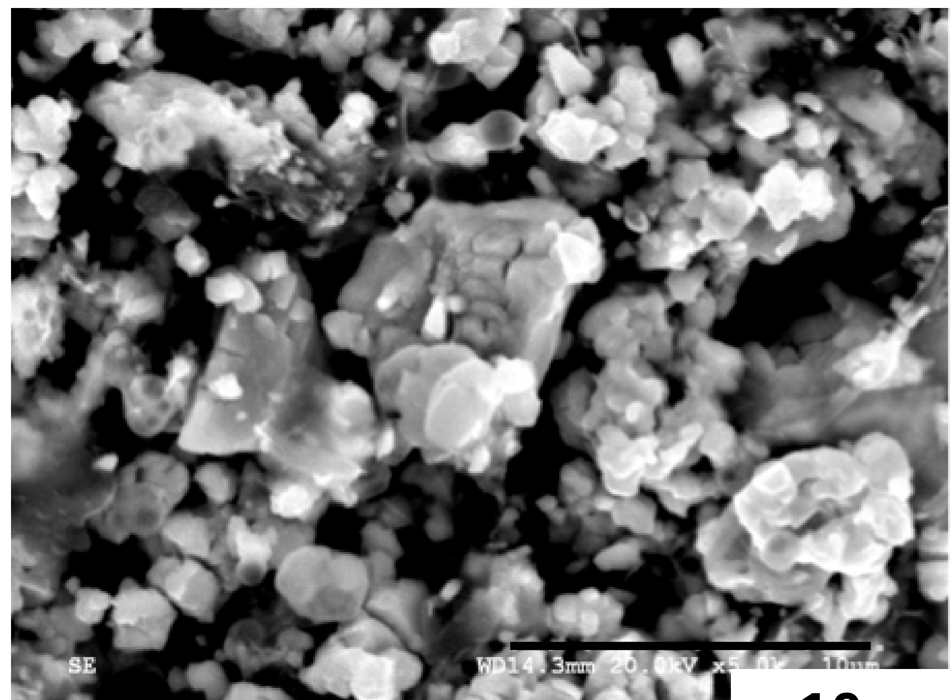
- **Same tests for the sintered material show that the chemical reactivity is even slower.**
  - **No rapid oxidation observed in all tests.**

SEM of “raw” and sintered UC_x



10 um

“raw” UC_x



Sintered UC_x

10 um

Status U Target and Future Plan

- First two runs with UO_2 at 1 and 2 uA.
  - Results of the assay for the noble gasses, Kr, Xe and Rn are in good agreement with the FLUKA prediction,
  - No contamination in the pump filters pass the first mass selecting slit.
  - No evidence of significant alpha or beta air activation in the target hall.
- We have received the authorization for the Canadian Nuclear Safety Commission to operate U target 1000 µA-H.
- First UC_x test is scheduled for December 2010.

Future Projects

- ISAC facility can deliver on one RI beam at the time, single user facility,
  - Backlog ~ 2-3 years
- In the last five-year plan proposal we proposed to build two new target stations,
  - Using electron for photo-fission
  - 500 MeV from existing beam port on the H- cyclotron,
- Combined with the actual ISAC we will be able to deliver 3 RI Beams simultaneously.

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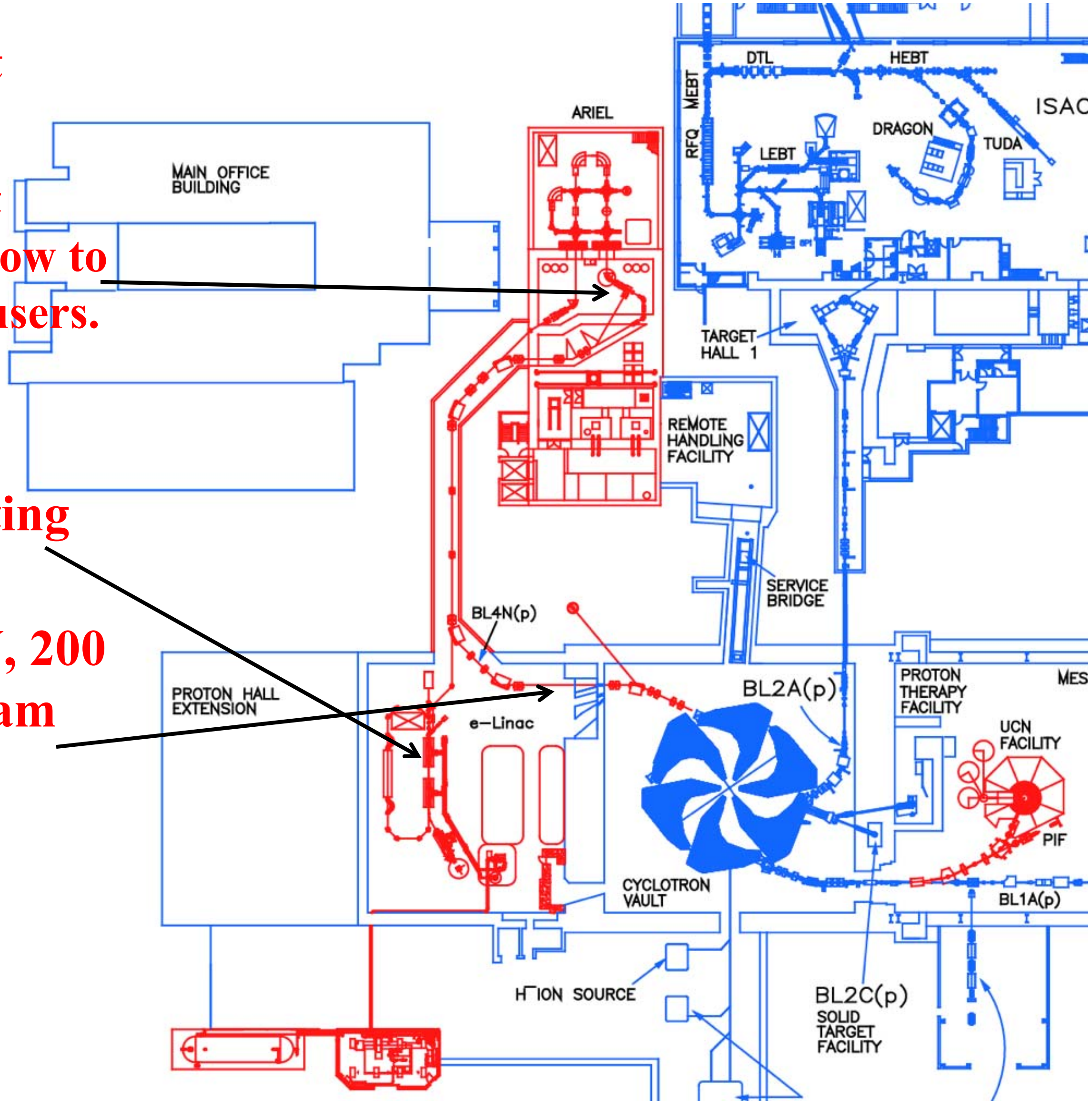
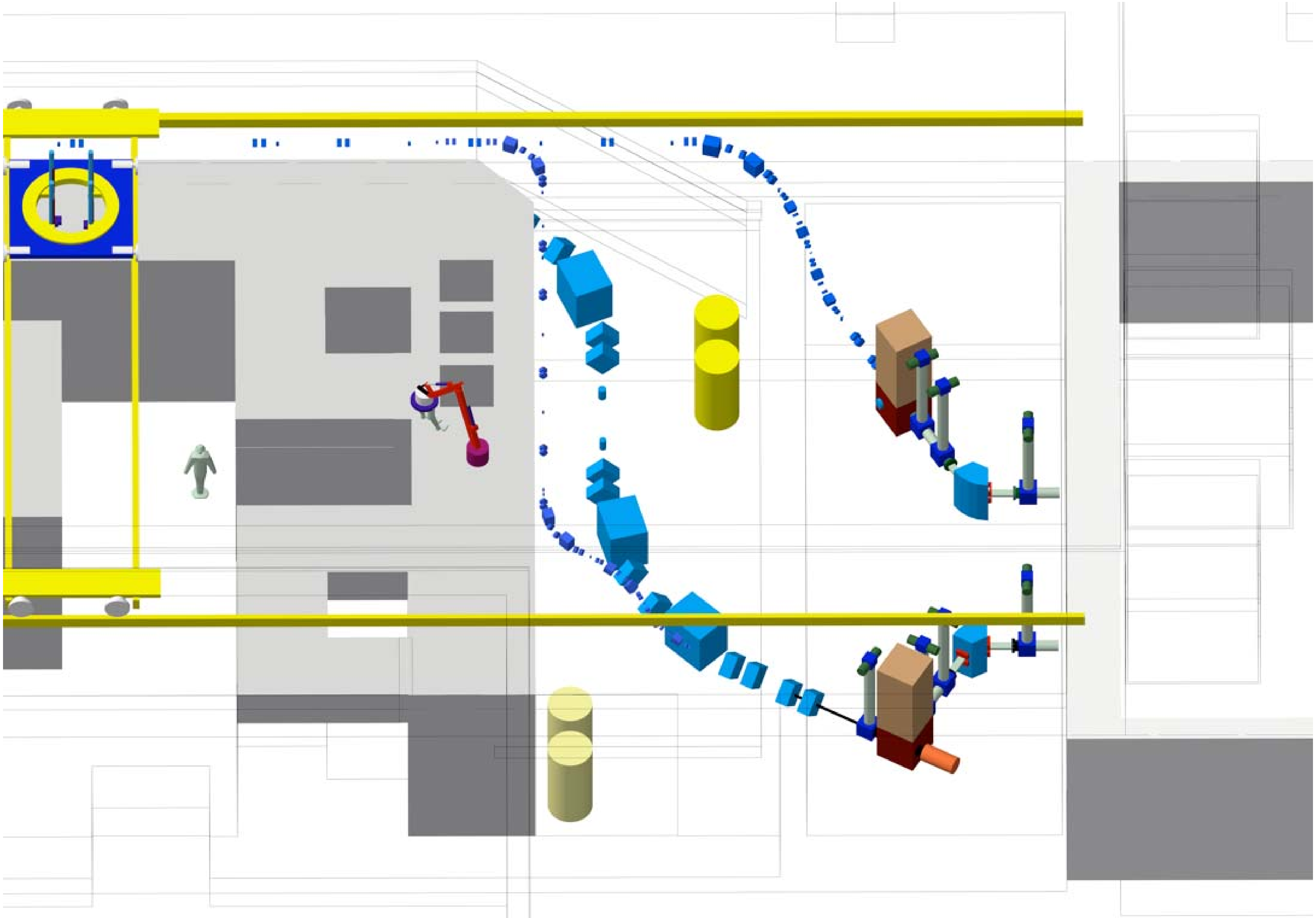
More RI Beams To Users

- **ARIEL project**
- **Add two target stations will allow to have multiple users.**
- **Electron Superconducting LINAC**
- **New 500 MeV, 200 µA proton beam line from H- Cyclotron**

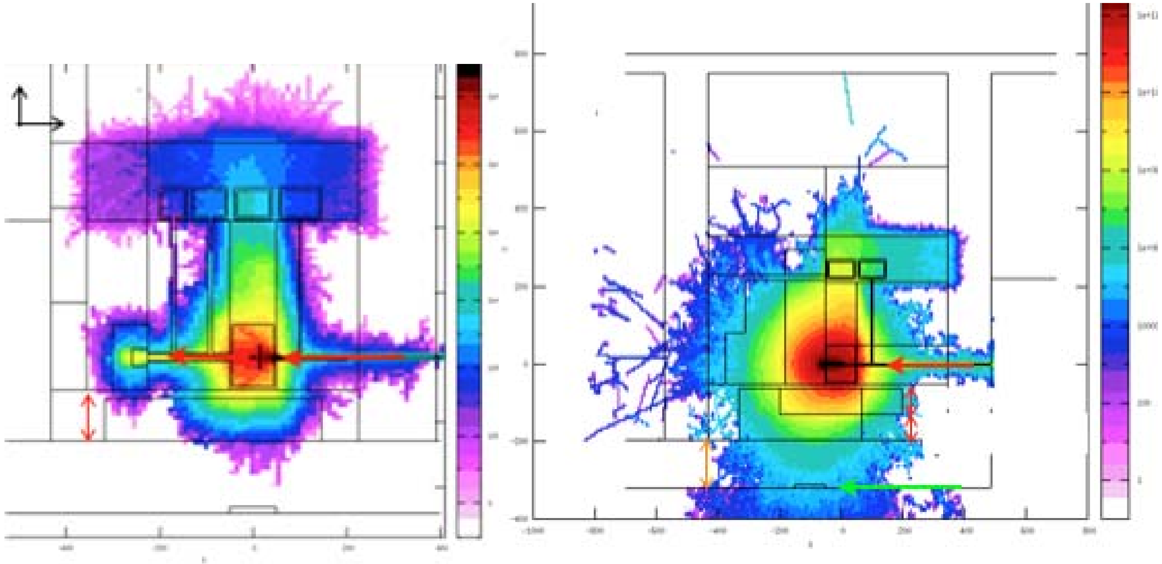


ISAC RI beam Facility is one user only. Back log is important

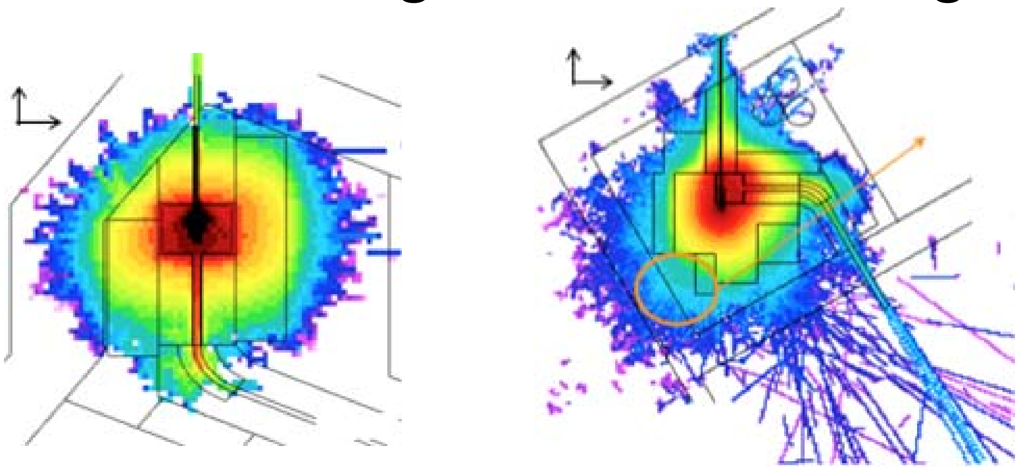
ARIEL project, Target stations concept



Shielding Simulation With FLUKA



Electron Target   Proton Target



- Simulations show that the separation and shielding between the target stations meet the operation requirement,
  - Operating one target station while the other is being maintained.

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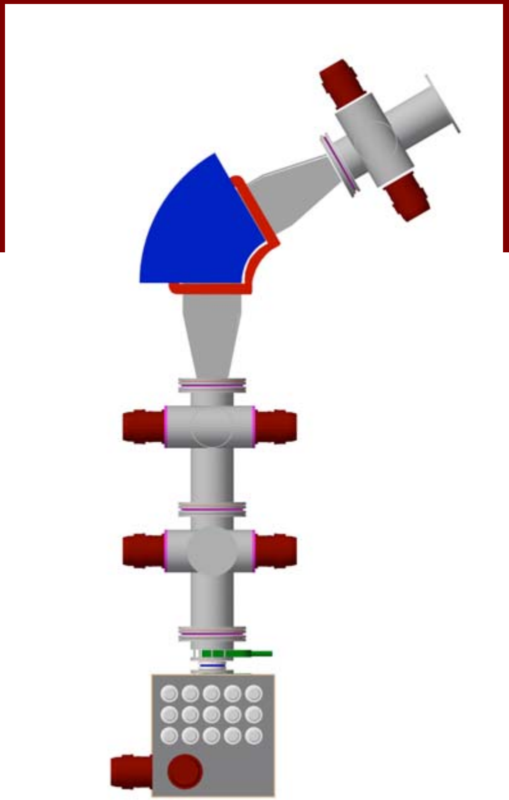
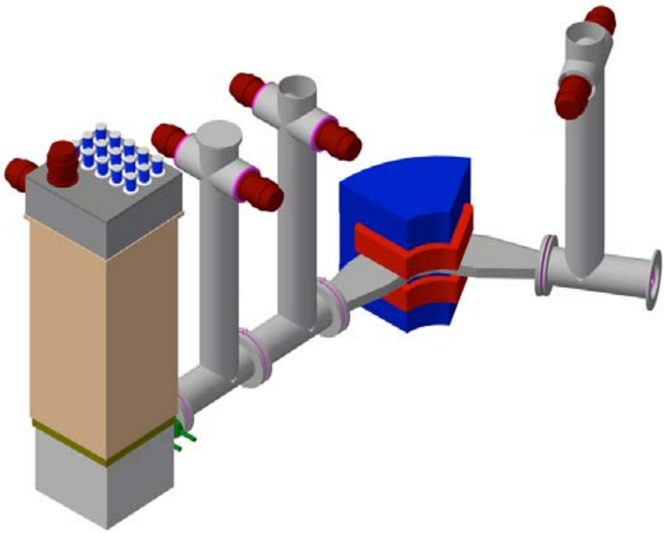
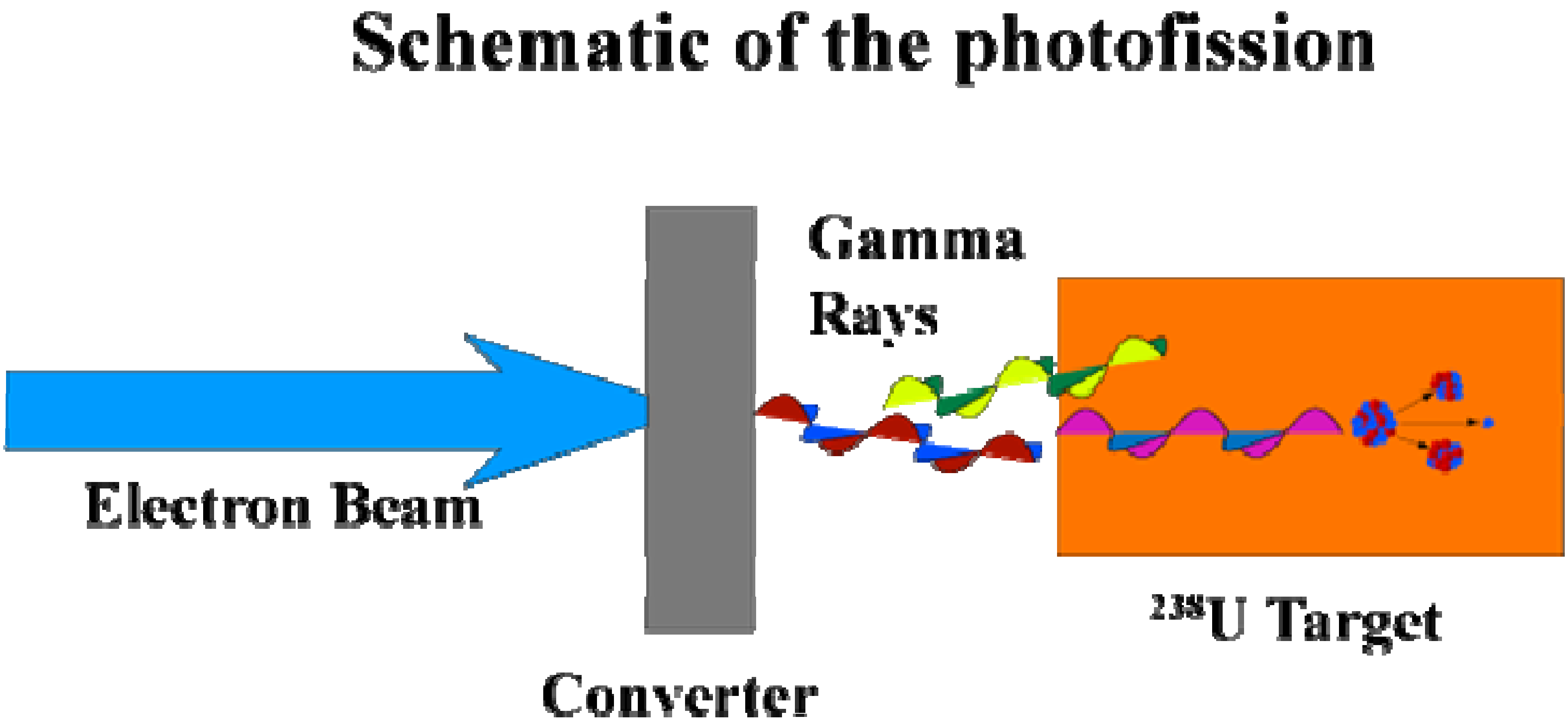
Target Station Concept



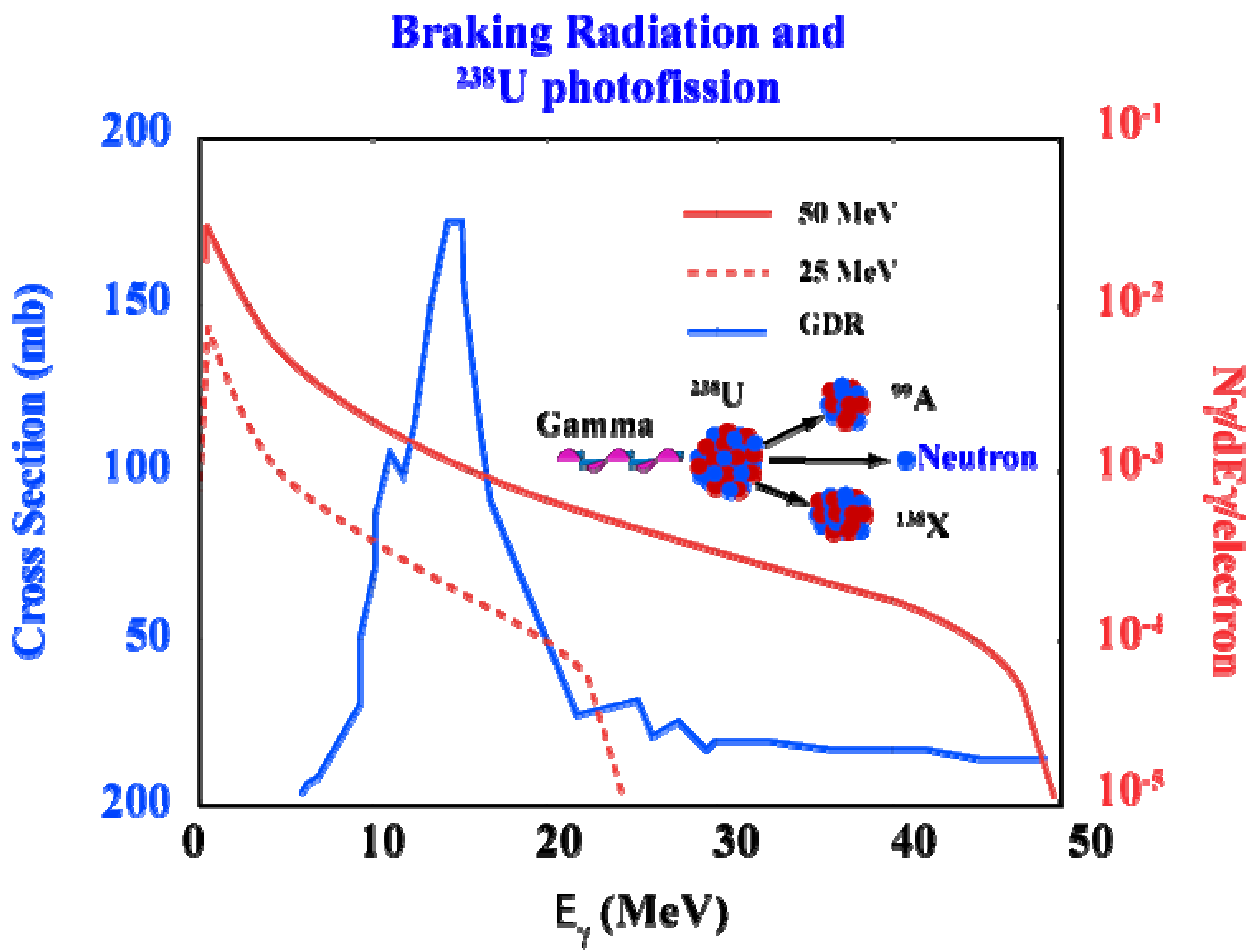
- Uses Target Module similar as for ISAC
  - Sealed containment box.
  - Simplified vacuum system.
  - Quick disconnect vacuum envelope using pillow seals technique developed for T2K.



Characteristics of the induced photo-fission



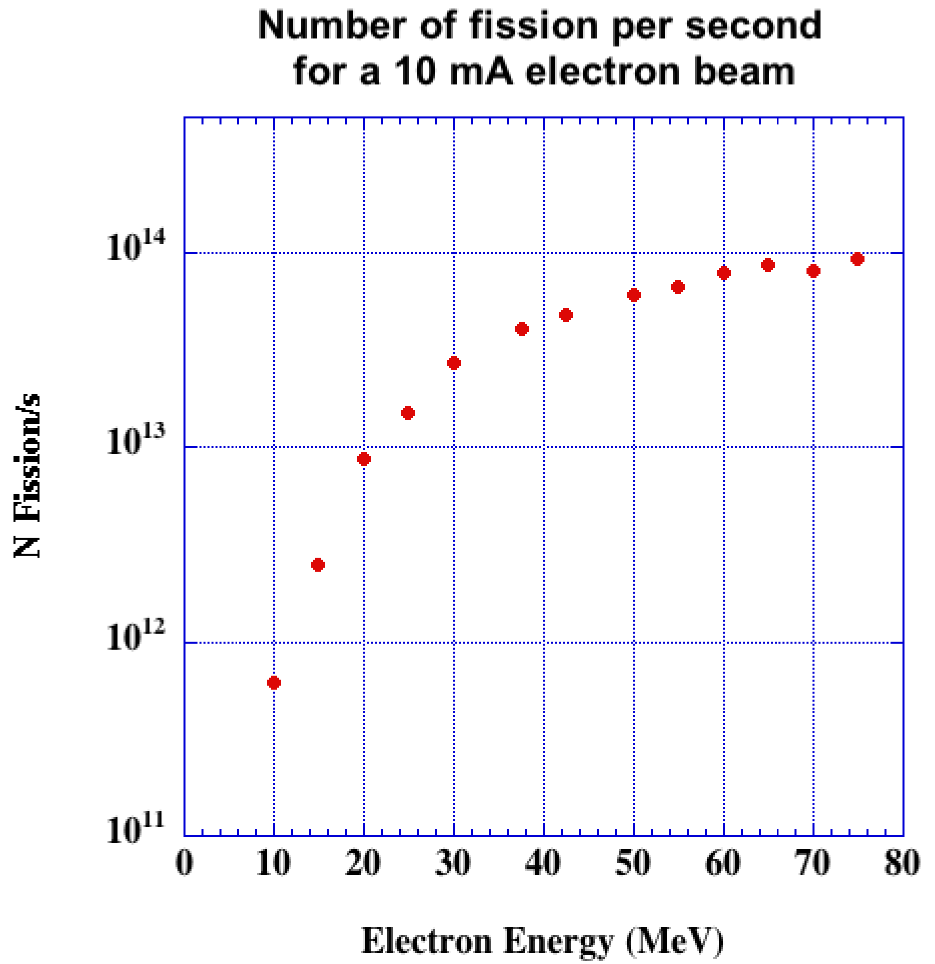
Bremsstrahlung spectrum and GDR



GEANT4 Simulation

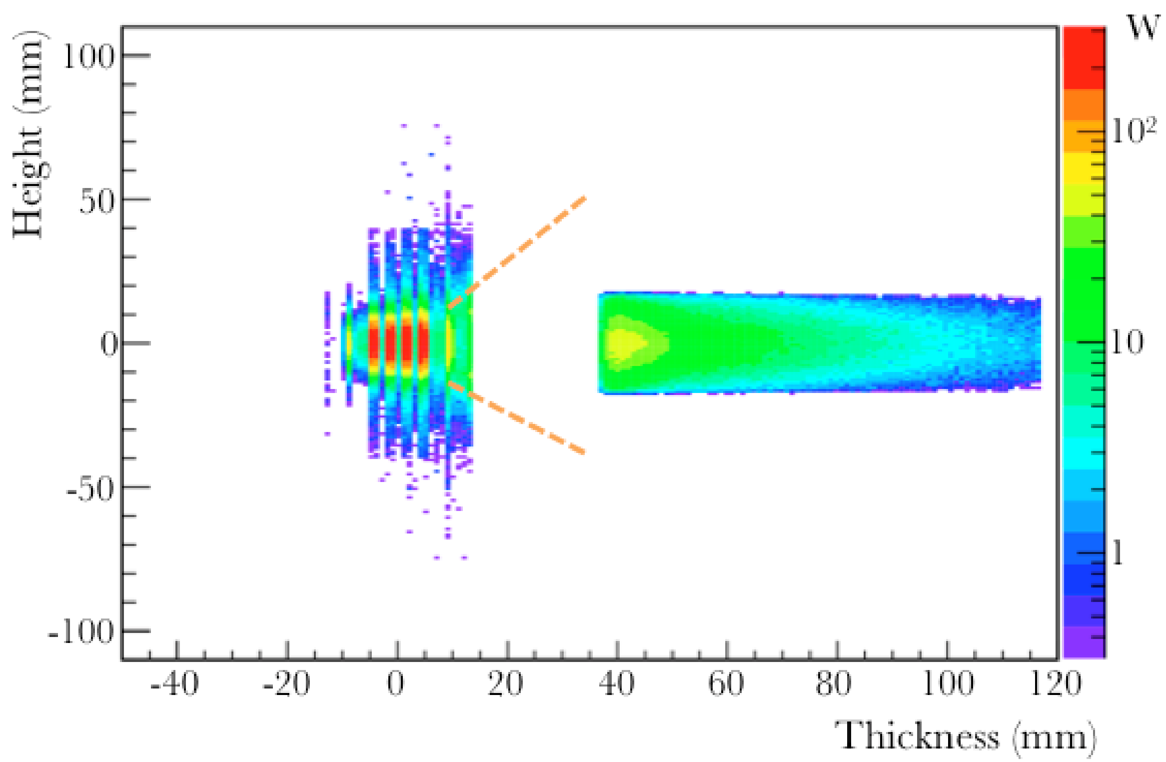
- **Number of fission as a function of the electron beam energy**

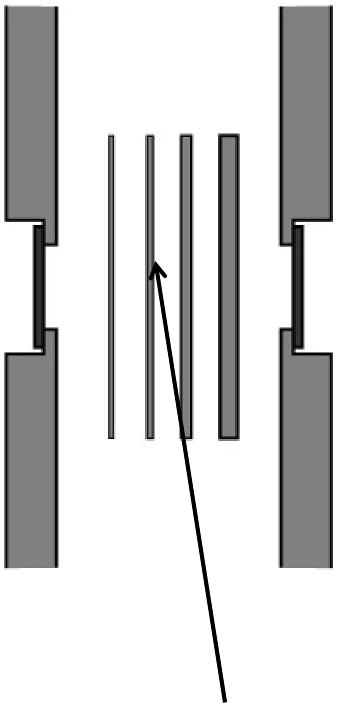
50 to 75 MeV seems to be optimum energy for photo-fission.



100 kW converter study

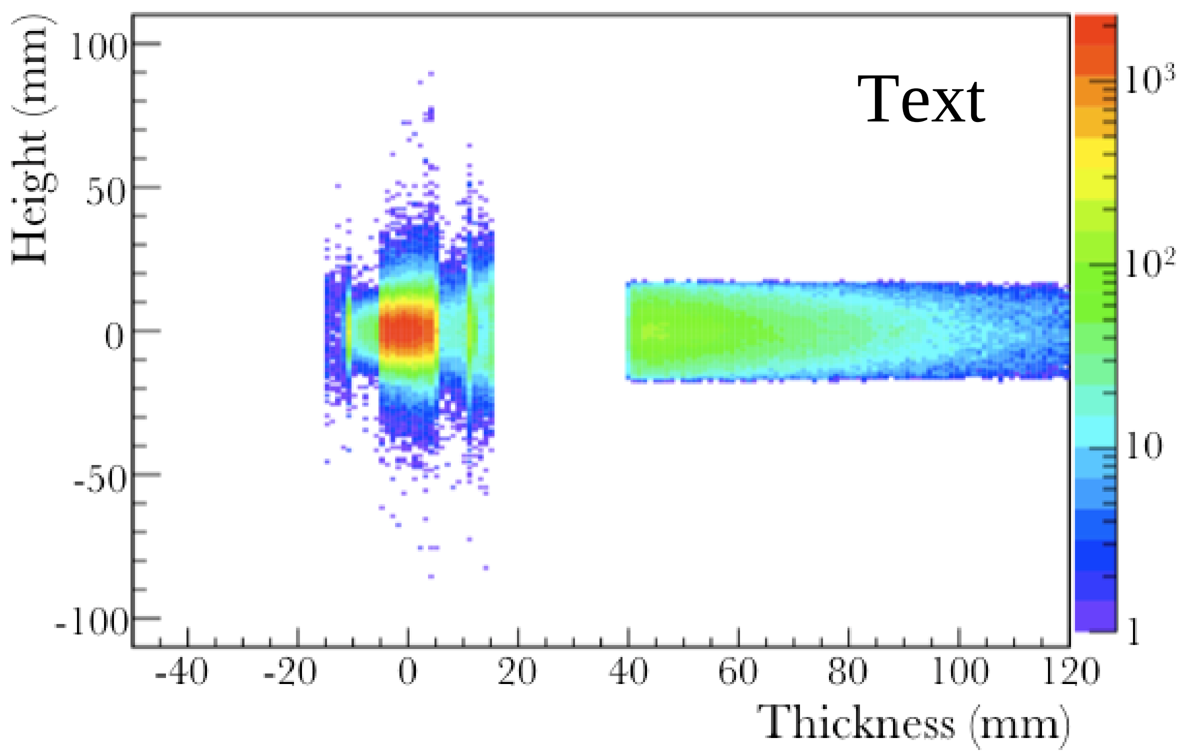
- **Power distribution for a 100 kW beam onto Ta converter and UC_2 target.**
  - **37 kW in converter**
  - **22 kW in target**

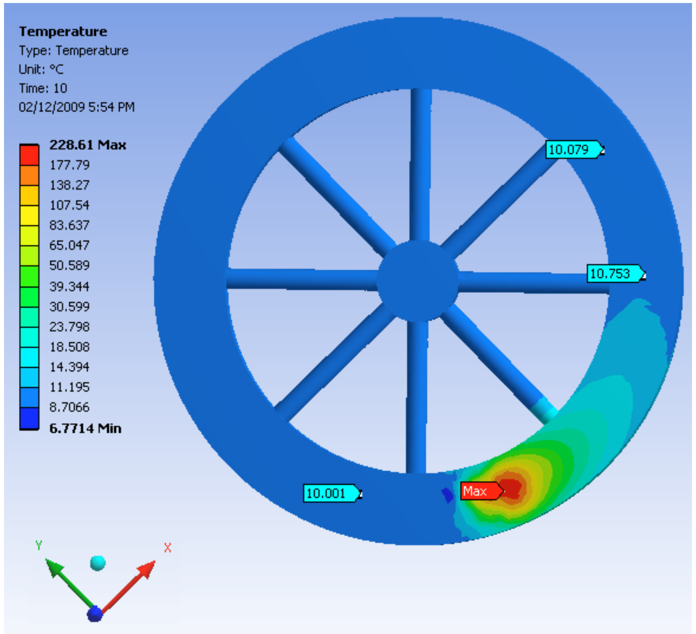




500 kW power distribution

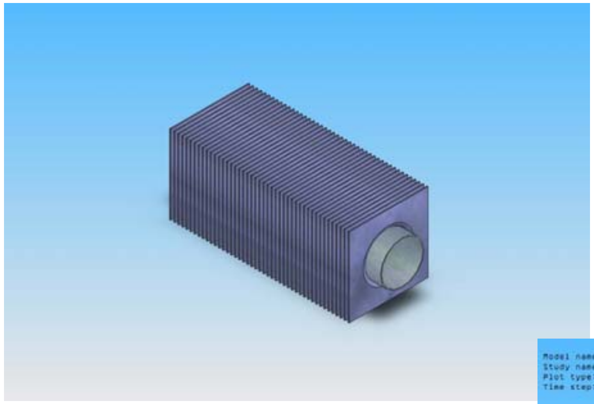
- **Rotating water-cooled wheel, Pb and Ta converter and UC_2/C target.**
  - **274 kW in the converter**
  - **66 kW in the target**

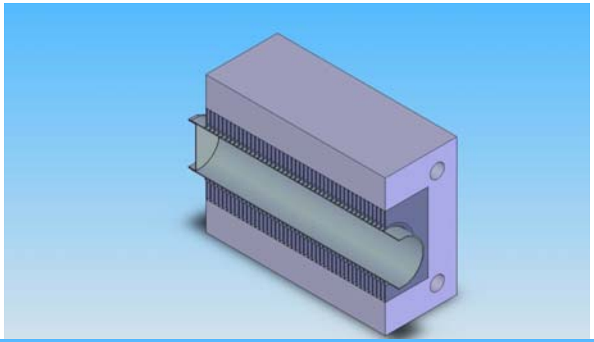


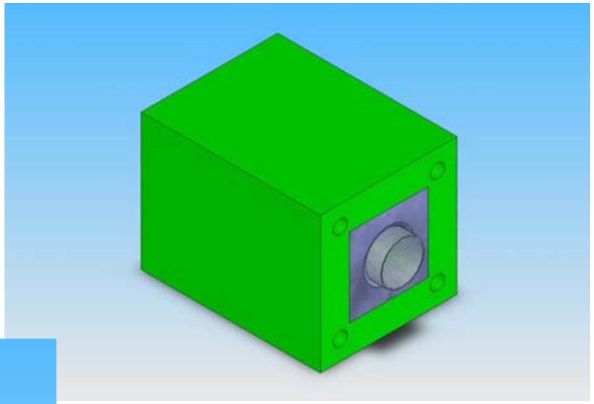


Cooling Concept, ARIEL High Power Target

Active cooling concept under study for power in the range of ~ 30 to 70 kW.







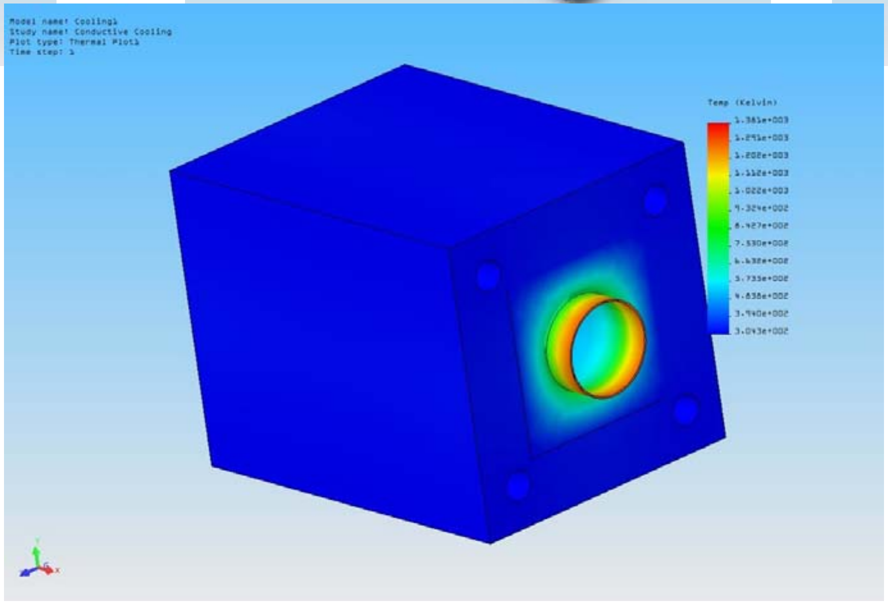
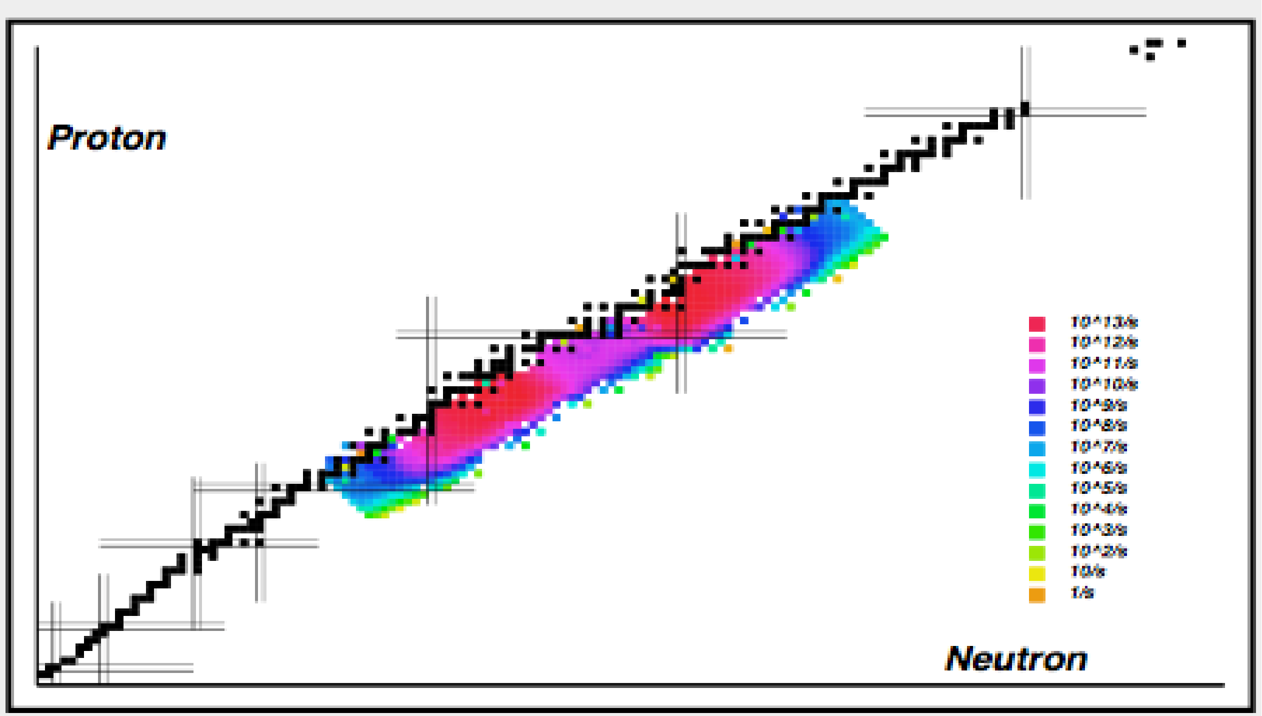


Photo-fission yield

Use GEANT4[1] and FLUKA[2] to simulate the photo-fission.

- **50 MeV,100 kW yields to ~ $2x10^{13}$ photo-fissions/s.**
- **50 MeV, 500 kW yields to ~ $6.5x10^{13}$ 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.

TRIUMF

Summary and Concluding Remarks

- We are developing new techniques for target material fabrication capable of operating at very high power,
  - Composite targets, carbide bonded on graphite successfully operate routinely up to 70 µA.
- The technique has been used to new target material,
  - High power oxide target, Al2O3 on Nb, EURISOL target test March 2009
  - Nb_3-Si_5 disks on Nb foil,
- Development of high power UC_2 target for ISAC and for future ARIEL project.
- Development of ion source capable of operating at such high power,
  - Surface ion, Laser and FEBIAD work under target outgas.
- Building on existing expertise and success in high power target will allow us to expand RI beam production using;
  - e-LINAC for 238U photo-fission,
  - New proton beam line, BL4N. => multi users facility

Thank You

List of collaborators

Marik Dombsky,

Friedhelm Ames,

Jens Lassen,

Vicky Hanemaayer,

Aurelia Laxdal,

Rick Maharaj,

Maico della Valle

ARIEL Project

- **ARIEL project phase 1,**
  - **TRIUMF received funding for electron superconducting LINAC through a the Canadian Foundation for Innovation,**
  - **and British Columbia government has allocated $30.7 M for the building.**
- **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.**

Faraday Cages and Laser ion source

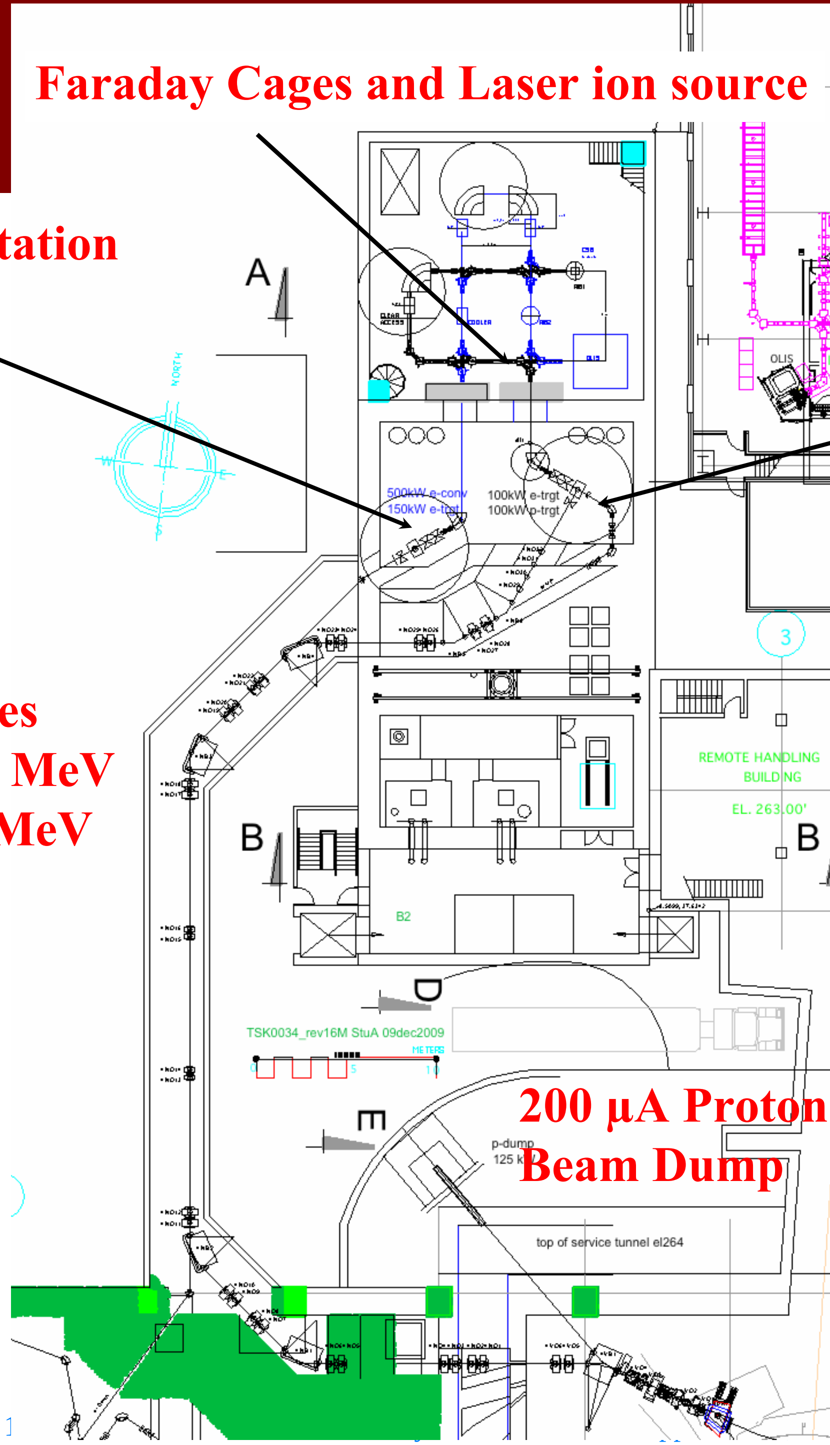
Second target station
2017
Electron only
P ~ 500 kW

First target station 2013

Electron and proton
P ~ 100 kW

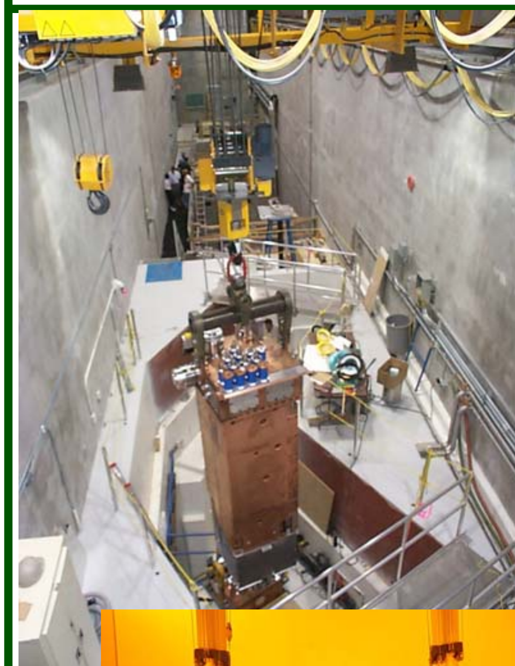
New tunnel for beam lines
200 µA proton; 450- 500 MeV
10 mA electron; 25 - 75 MeV

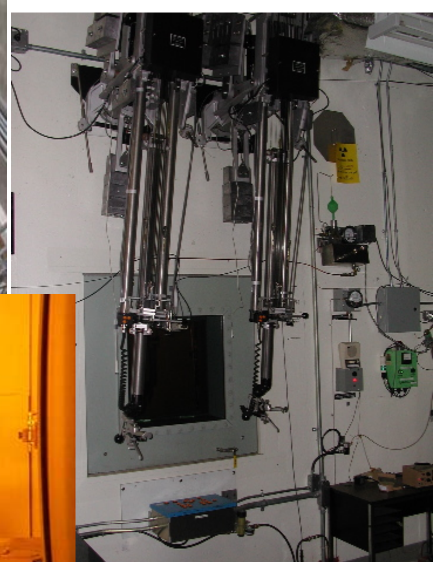
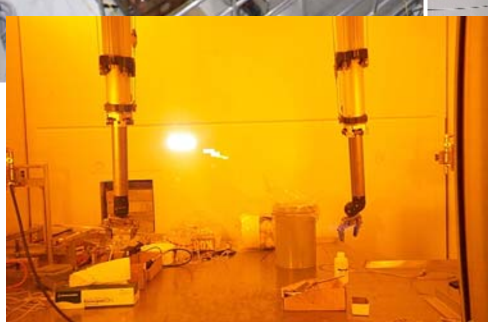
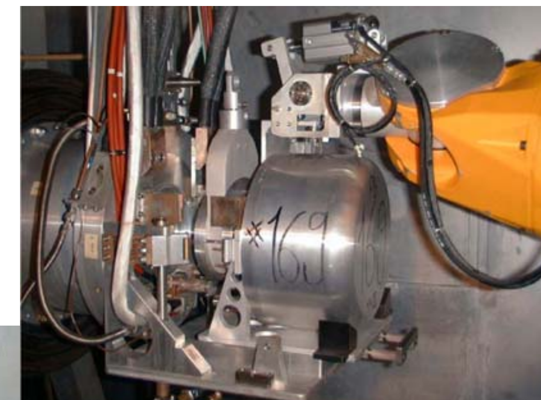
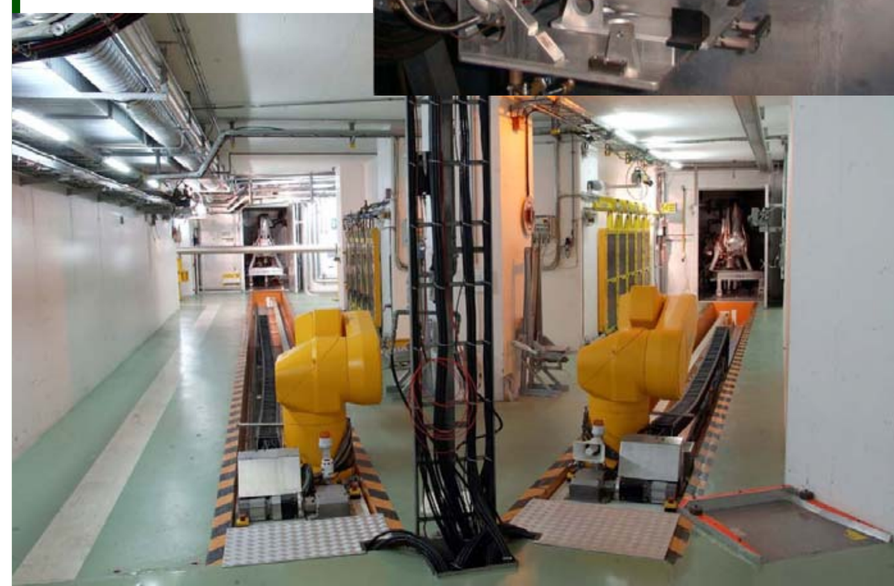
200 µA Proton
Beam Dump



ISAC Target Station Technology

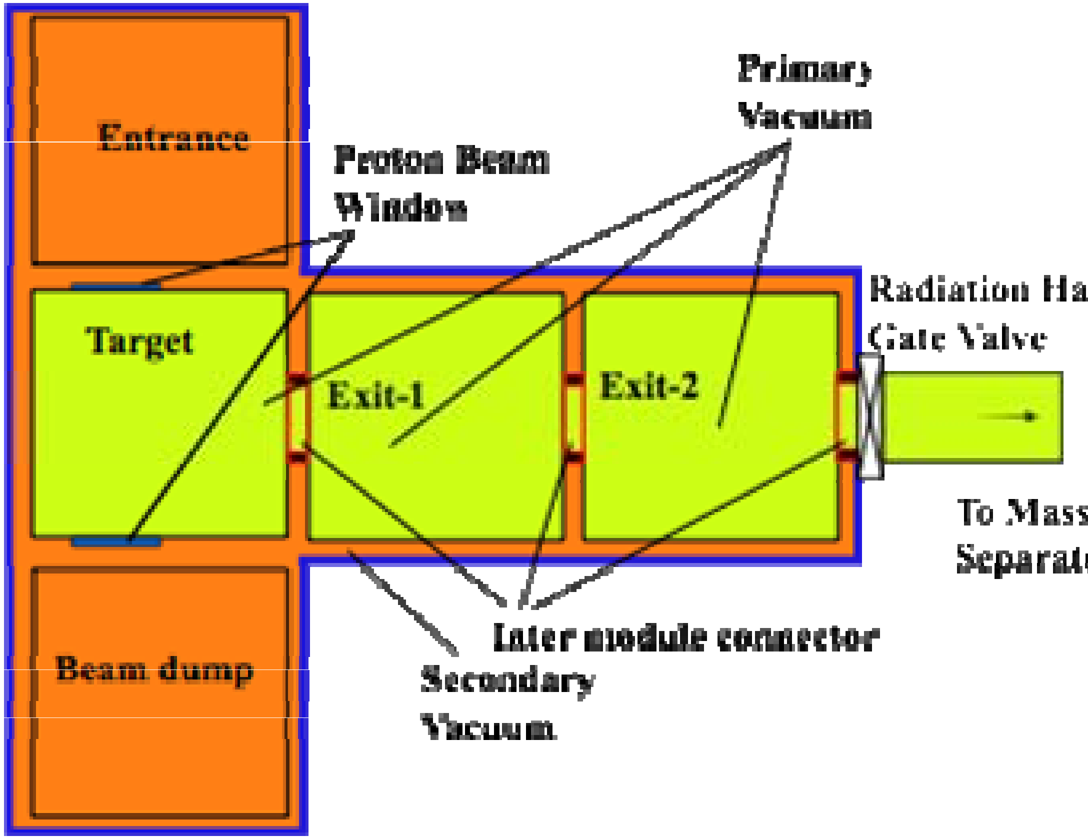
ISAC/TRIUMF	ISOLDE/CERN
Proton CW: 500 MeV Φ ~ 100 µA	**Proton Pulsed: 1.4 GeV** Φ ~ 2µA



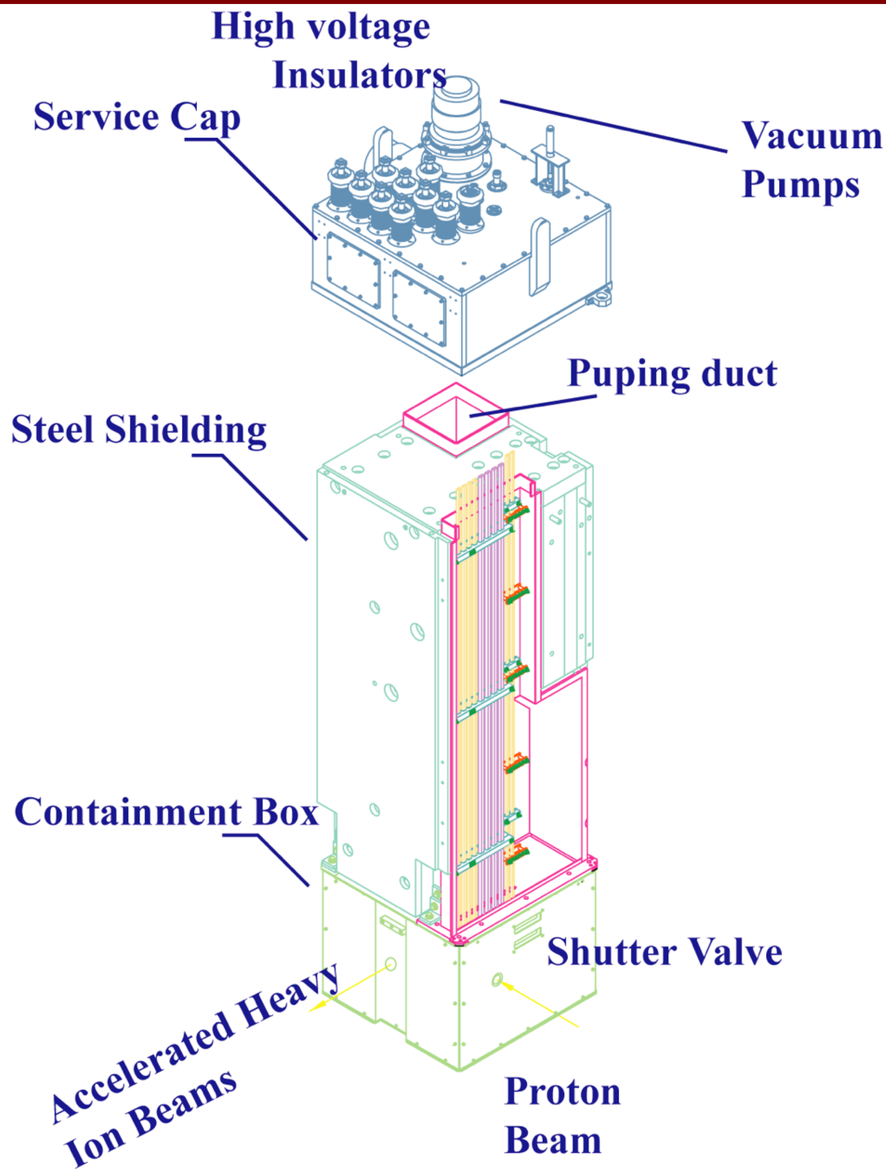





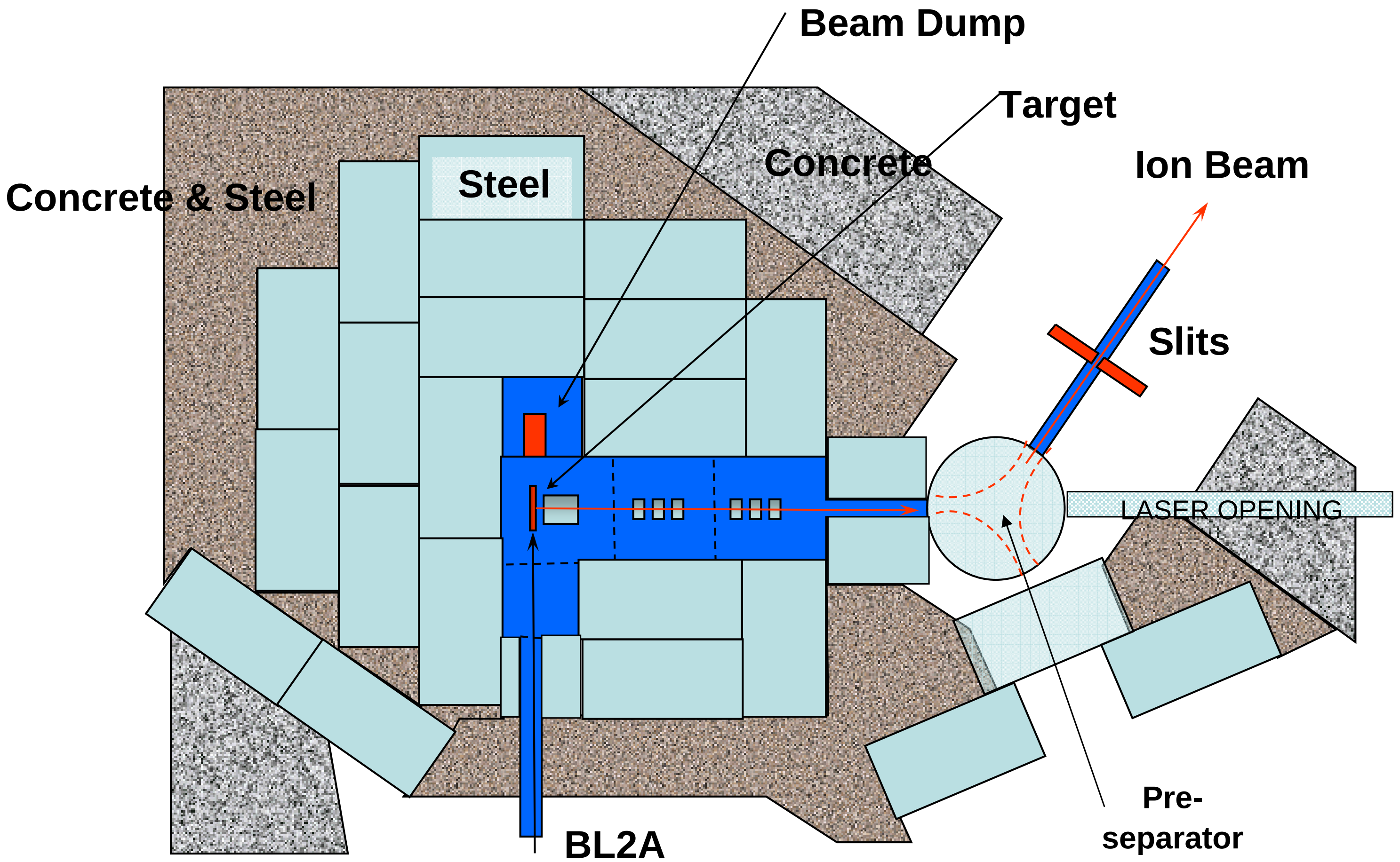
ISAC Facility Vacuum System

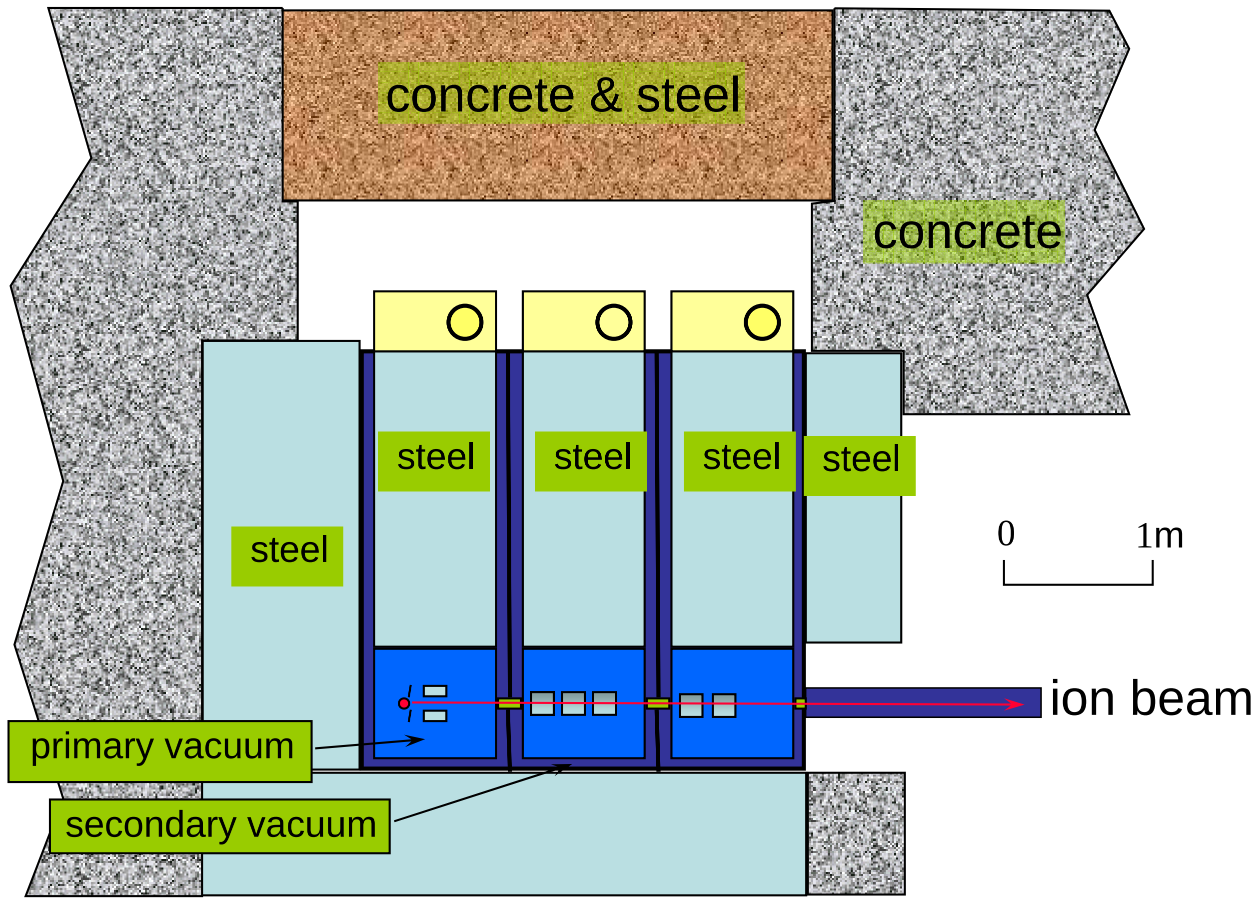
- Contrary to other ISOL facility we do have a complex vacuum system.
  - Containment box is not hermetically sealed.
    - The HI port on containment box closed during transport, but not sealed
- Primary and secondary vacuum are separated by differential pumping only.



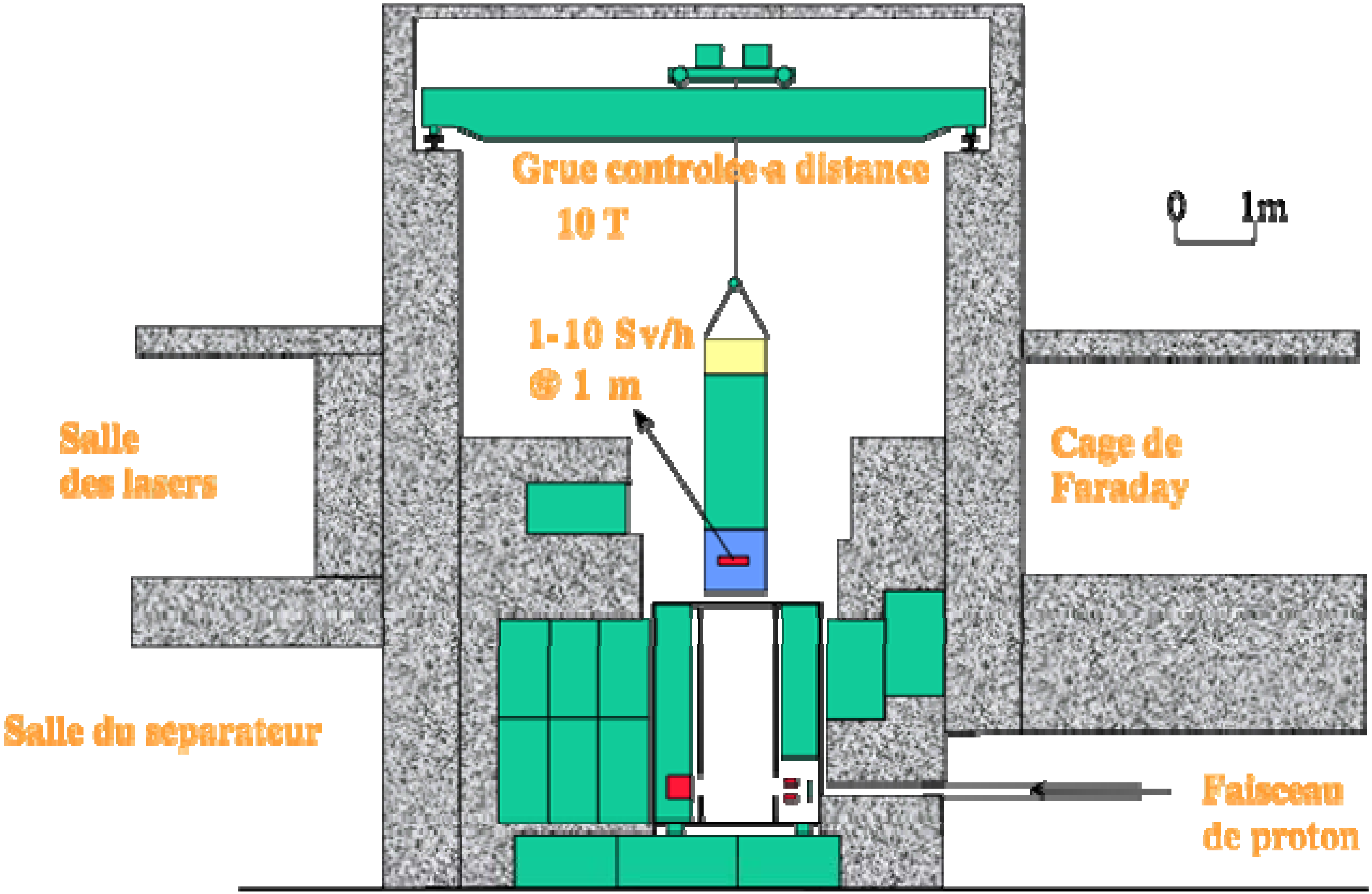
ISAC Facility Vacuum System

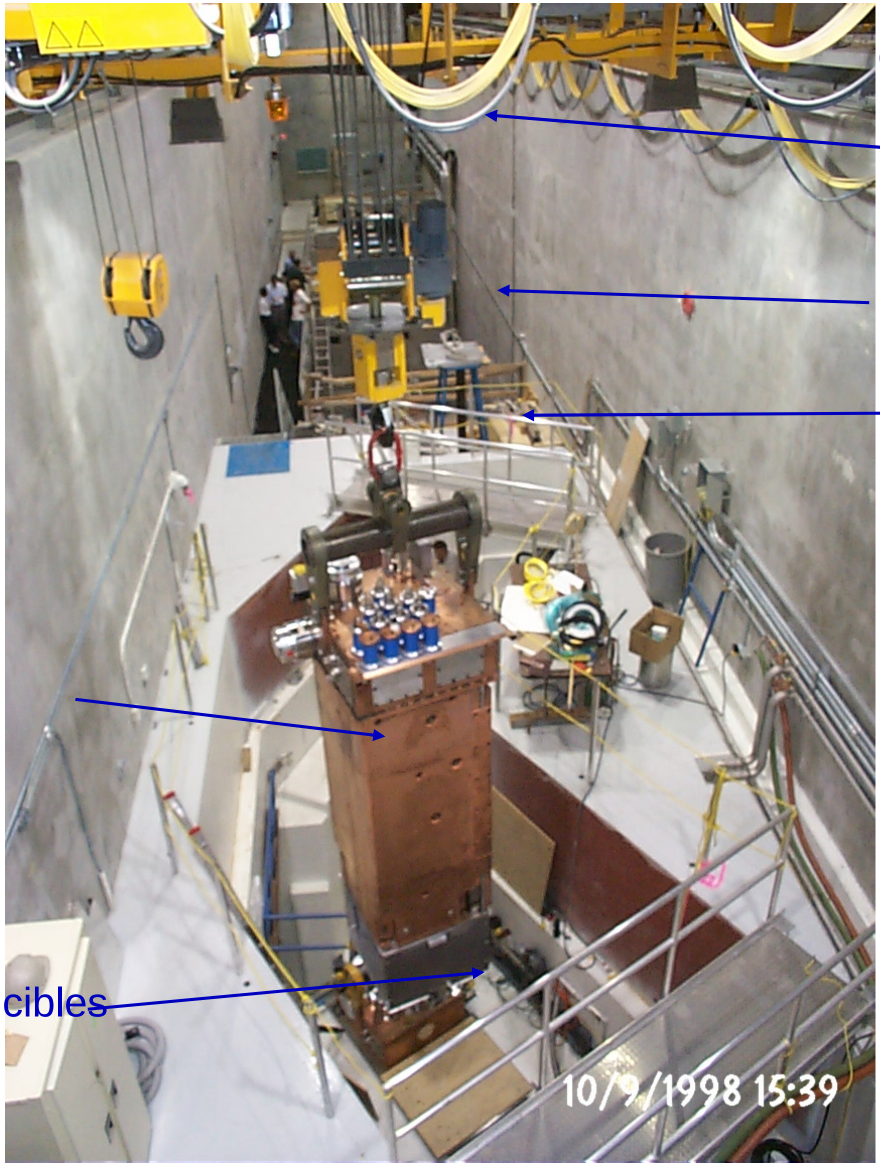



Beam Dump
Target
Concrete
Ion Beam
Concrete & Steel
Steel
Slits
LASER OPENING
Pre-
separator
BL2A


concrete & steel
concrete
steel
steel
steel
steel
steel
0
1m
ion beam
primary vacuum
secondary vacuum

TRIUMF


Grue controlée a distance
10 T
0 1m
1-10 Sv/h
@ 1 m
Salle
des lasers
Cage de
Faraday
Salle du separateur
Faisceau
de proton



Grue contrôlée
à distance

Cellules des
Manipulateurs

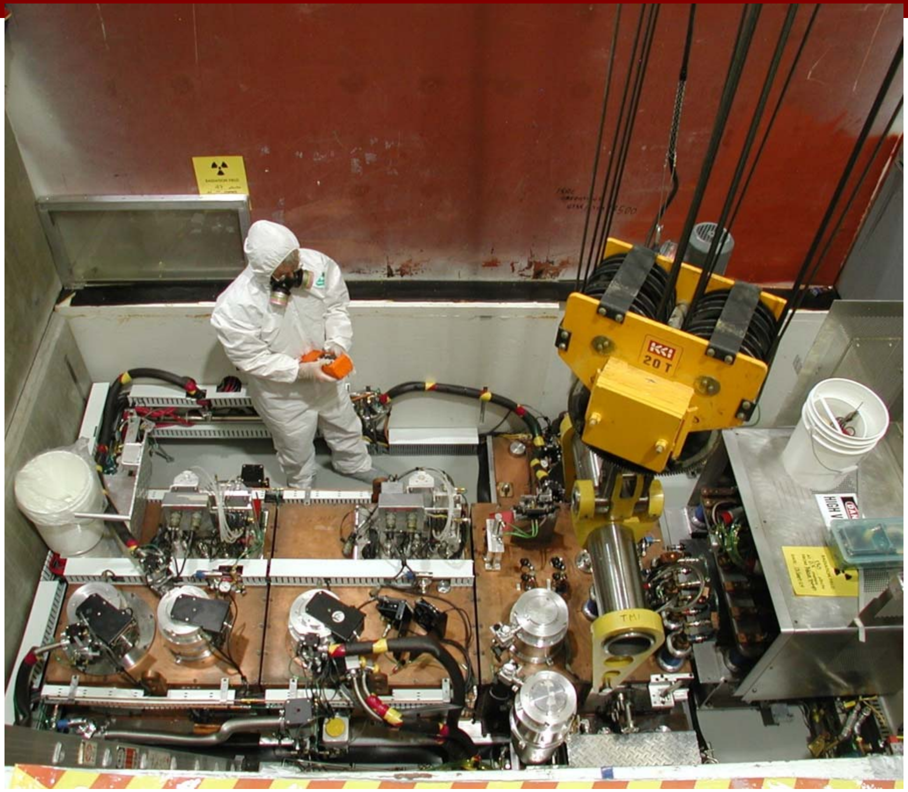
Stockage
de cibles

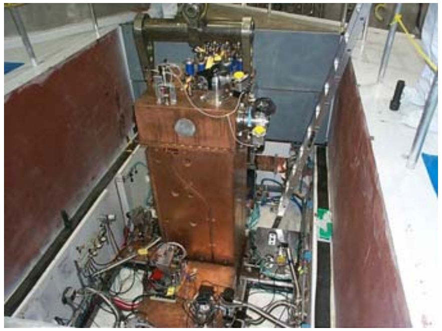
Module de la
Cible

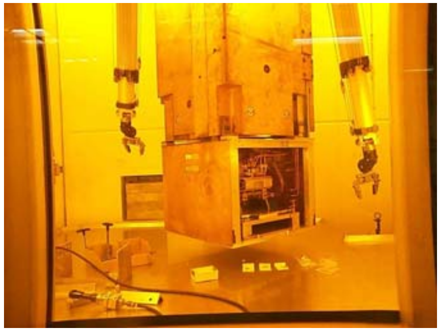
Puits des cibles

Target Exchange Process

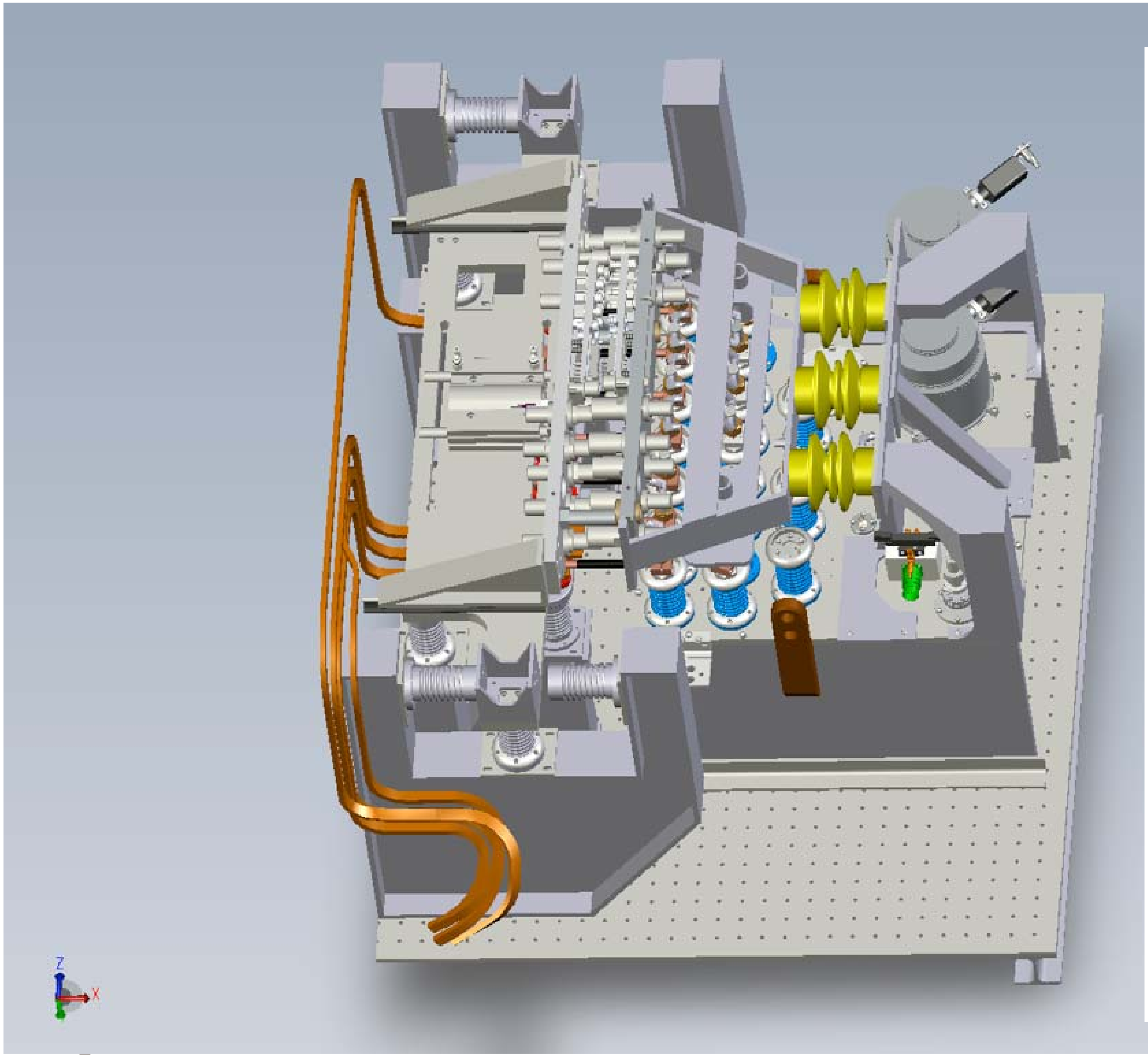
- **Hands On target module connection and disconnection**
  - **Need one week cool-down after beam off before starting services disconnection**
- **Target exchange takes from 3 to 4 weeks requiring proton beam off periods, ~ 200 H.**
- **The overall process limit RIB development due to large overhead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







Remote Services Connection/Disconnection



- More than 65 connections,
  - Electrical
  - Cooling
  - Signal
  - Vacuum
- Prototype under development
- Implementation spring 2012.

Pure effusion

$$p_\nu(t) = \nu e^{-\nu t}.$$

$$\tau_\nu^{del} = 1/\nu = \chi(\tau + \tau_f).$$

$$\tau = \tau_0 e^{-\Delta H_a / kT}$$

Profile distribution depends on the number of collisions on the target inner surface and on the activation energy to remove the wanted species from the target surface.

- χ is the number of collisions,
- ΔH_a is the activation energy,
- t_0 is the mean sticking time,

it depends on the lattice vibration (T dependent)

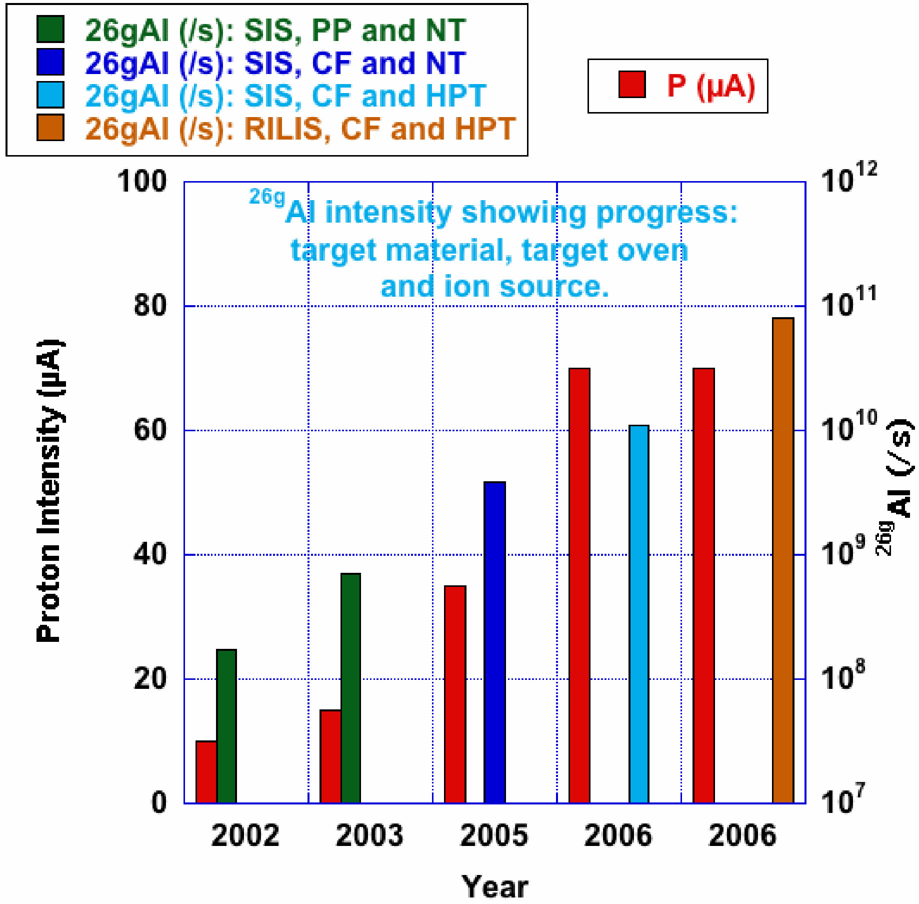
- t_f is the meantime between two collisions.

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.
- 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.

High Power Target Timeline

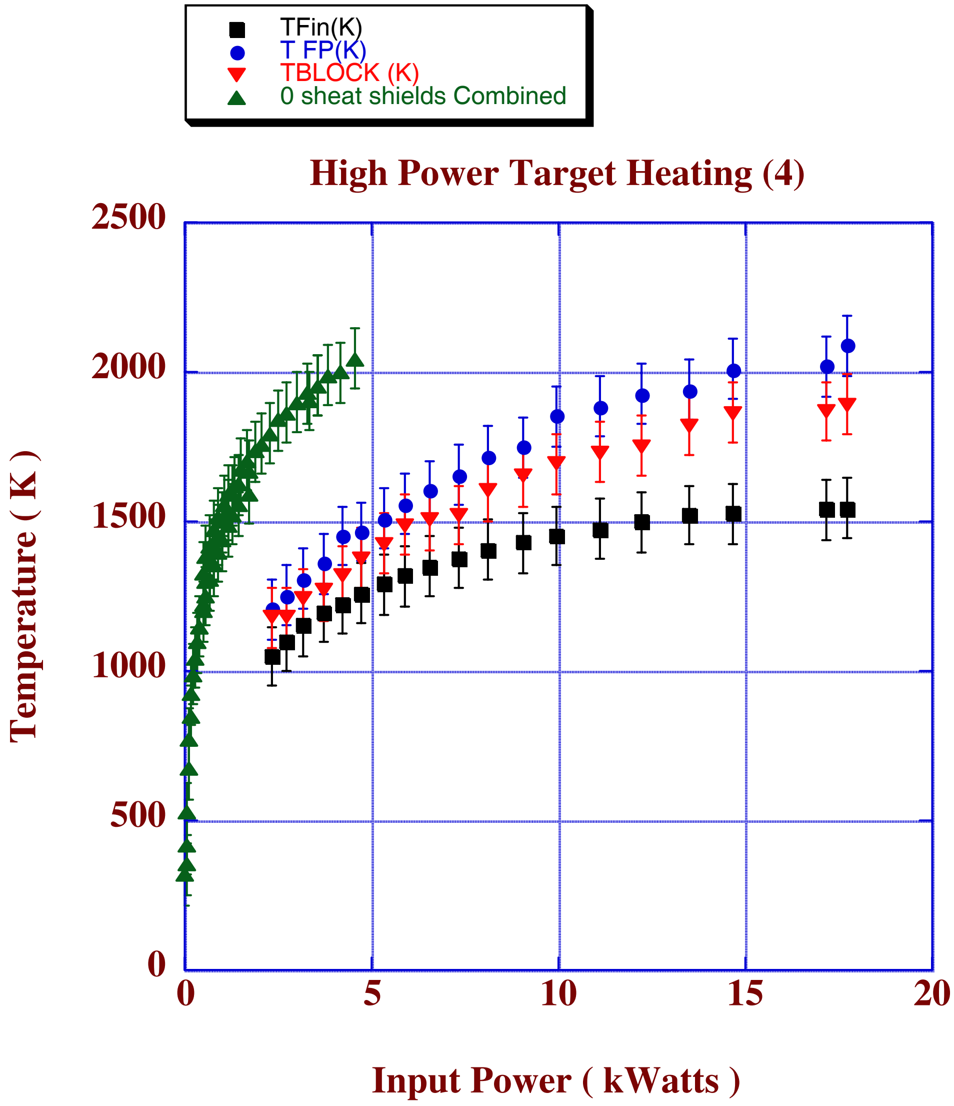
- This example shows the progress made over the year for ^{26g}Al.
- SiC composite target and high power “target oven” allows us to increase the ^{26g}Al yield by two order of magnitude.
- Addition of the RILIS improved the yield by another factor 7.



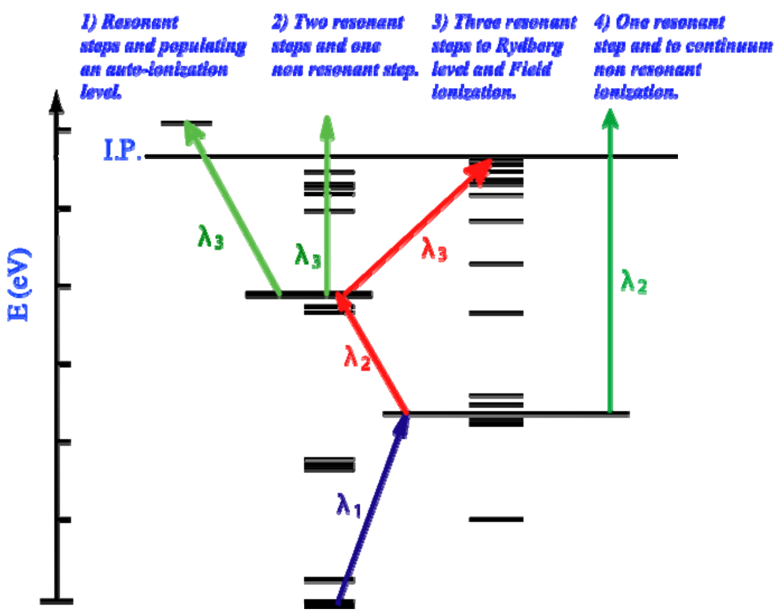
SIS, surface ion source
PP: pressed powder target material
NT: normal ISAC target
CF: composite foil, carbide target material bounded to graphite foil
HPT: high power target oven
RILIS: Resonant Ionization Laser Ion Source

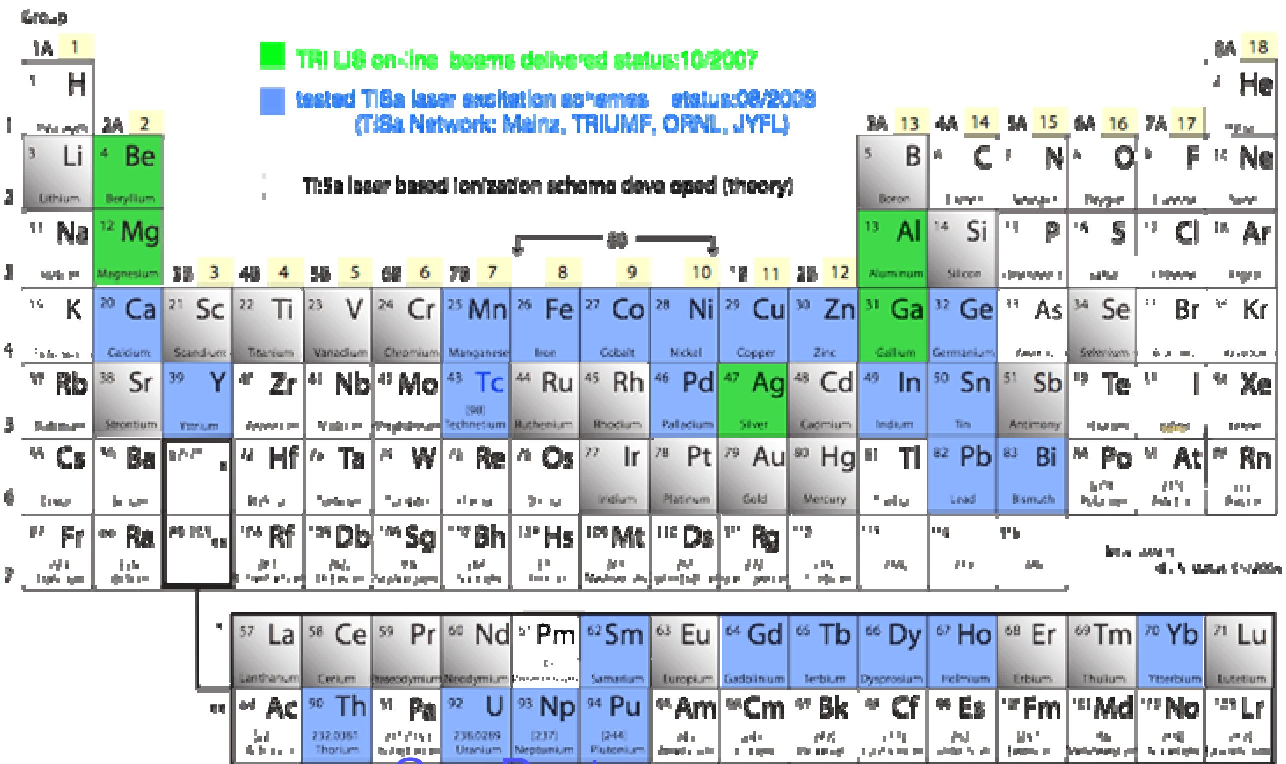
High Power Target

- Low power target oven can dissipate up to 4 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



Laser Ion Source progress





Resonant Ionization LIS

-> element selective

-> isobar free beams

See Posters

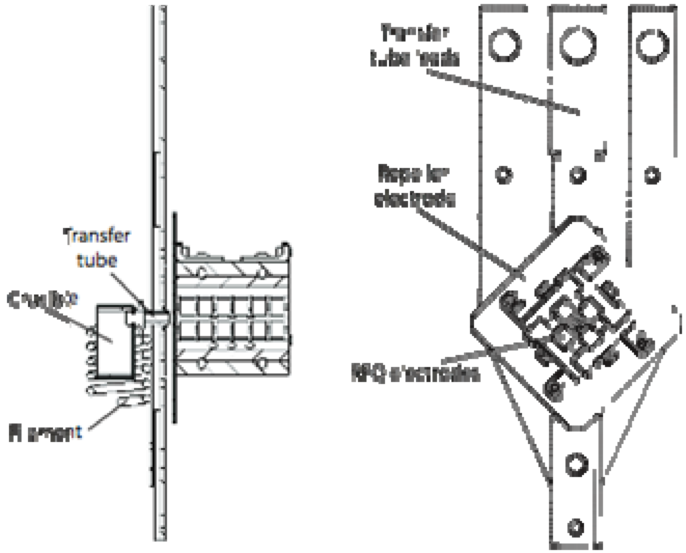
Andrea Teigelhofer, "*Grating Ti:Sa Laser*"

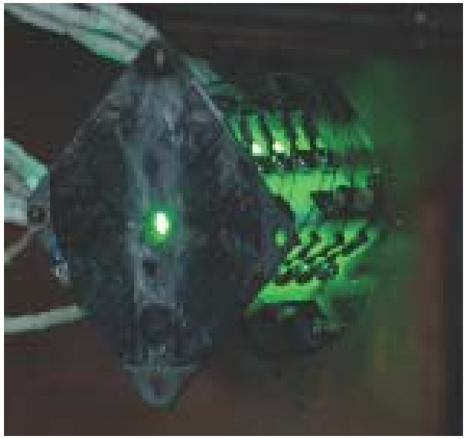
Jean Philippe Lavoie, *"Production of pure RIB using Laser Ion Source"*

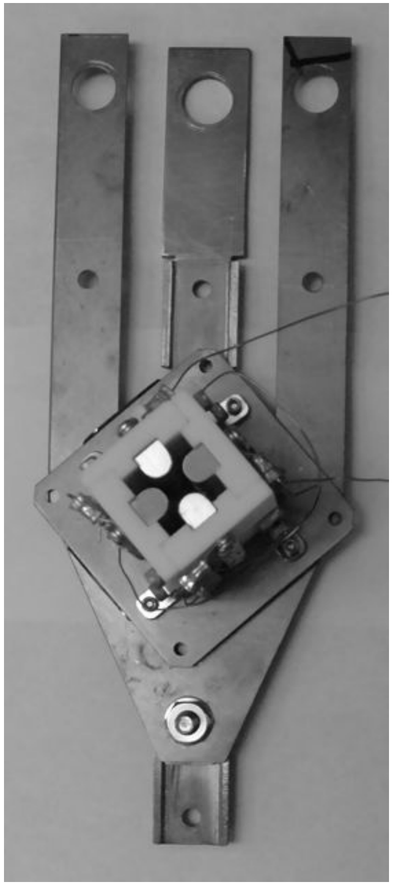
- The development of new resonant ionization laser schemes is done in collaboration with several institutions and laboratories: Mainz U, Oak Ridge-HRIBF, Jyväskulä-Finland, CERN-ISOLDE.

RFQ-RLIS

- **Ion sources development**
  - **RFQ-LIS**
    - **Suppress surface ion from target and transfer tube,**
    - **Final prototype operational,**
    - **Pure beam from Resonant Laser Ion Source,**
      - **Modules are ready for the RFQ-LIS,**
      - **Test on-line can take places**





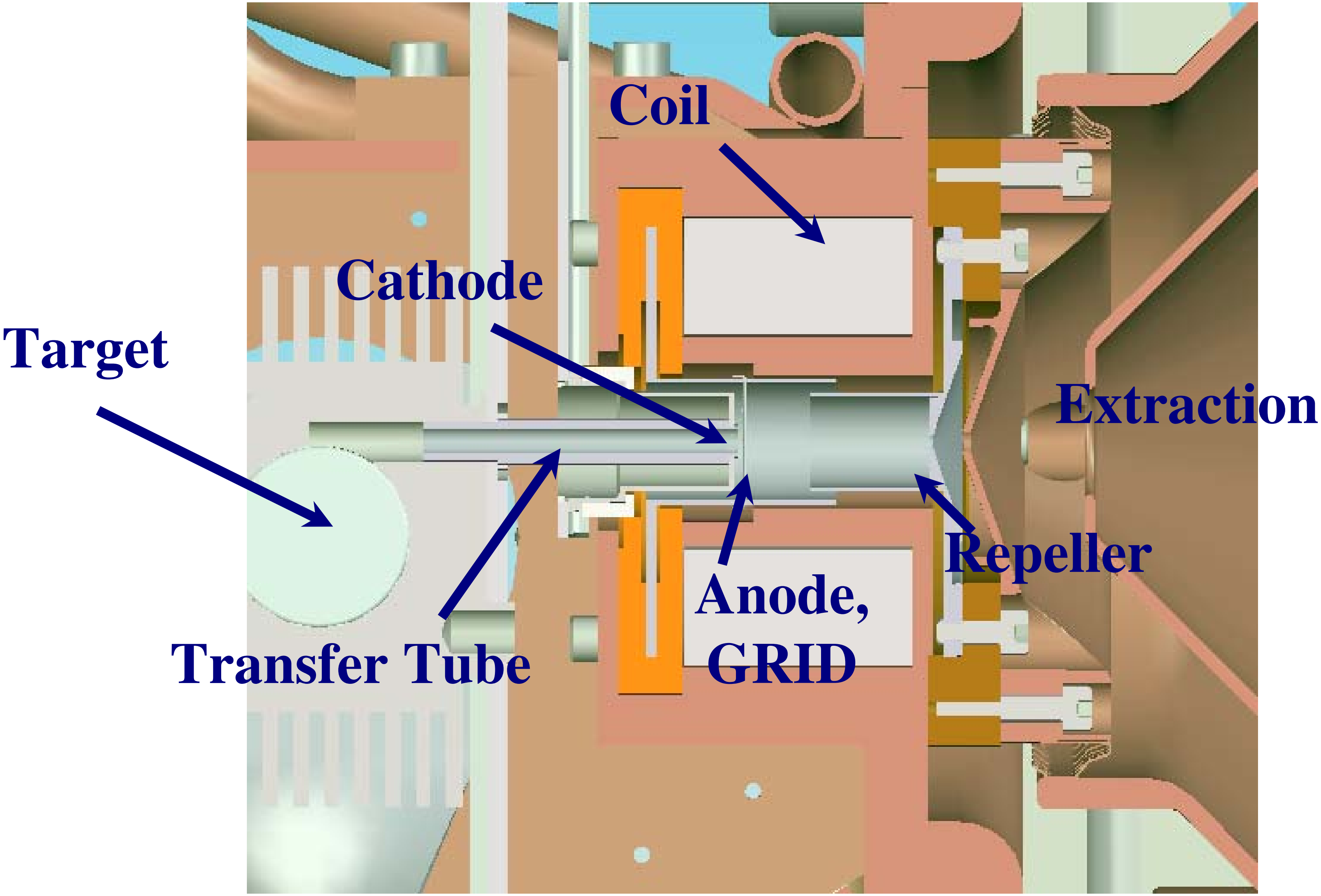


TRIUMF

500 kW-liquid metal

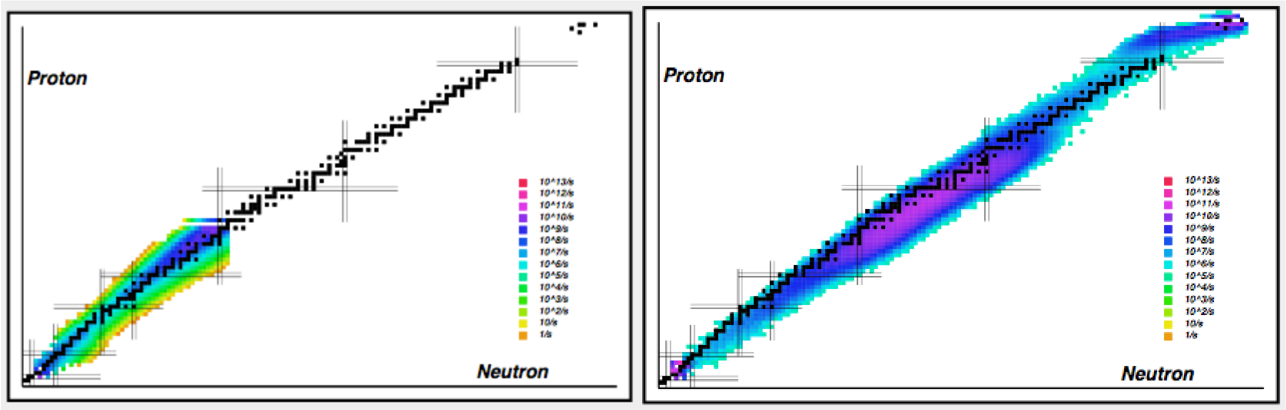
- The other option is using a liquid metal as a converter
  - Lead is a good option, preferable to Mercury from the point of view of personnel safety and environmental considerations
  - Liquid lead circulated by an electromagnetic pump
  - The power is then removed through two step heat exchanger: Pb- GaInSn- Water

FEBIAD-Mk-X


Coil
Cathode
Target
Extraction
Repeller
Anode,
GRID
Transfer Tube

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.**



500 kW converter study

- For beam power above 150 kW we cannot apply the static target solution for a converter.
- Options for a ½ MW converter under study,
  - Water-cooled rotating wheel,
  - Liquid metal converter.