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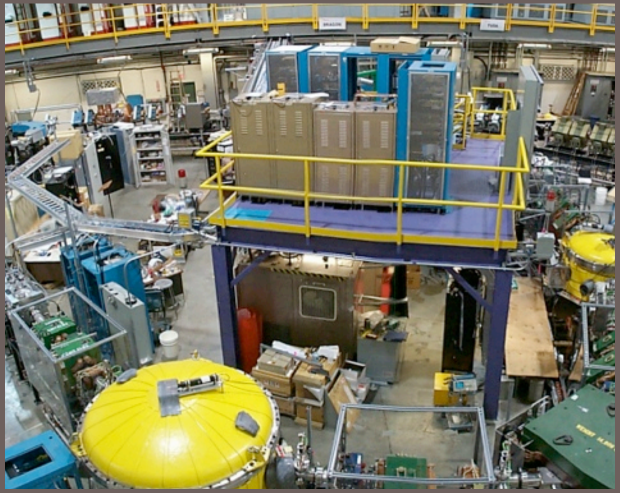
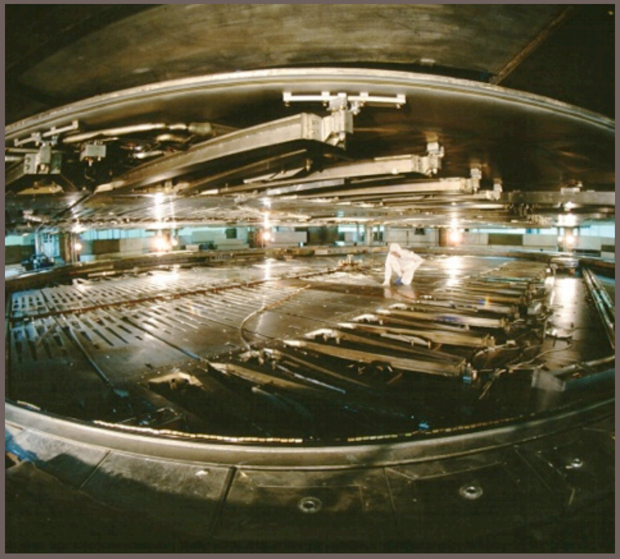
Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules





# High Power Targetry for ISOL Facilities


## Pierre Bricault

## SCK-CEN & TRIUMF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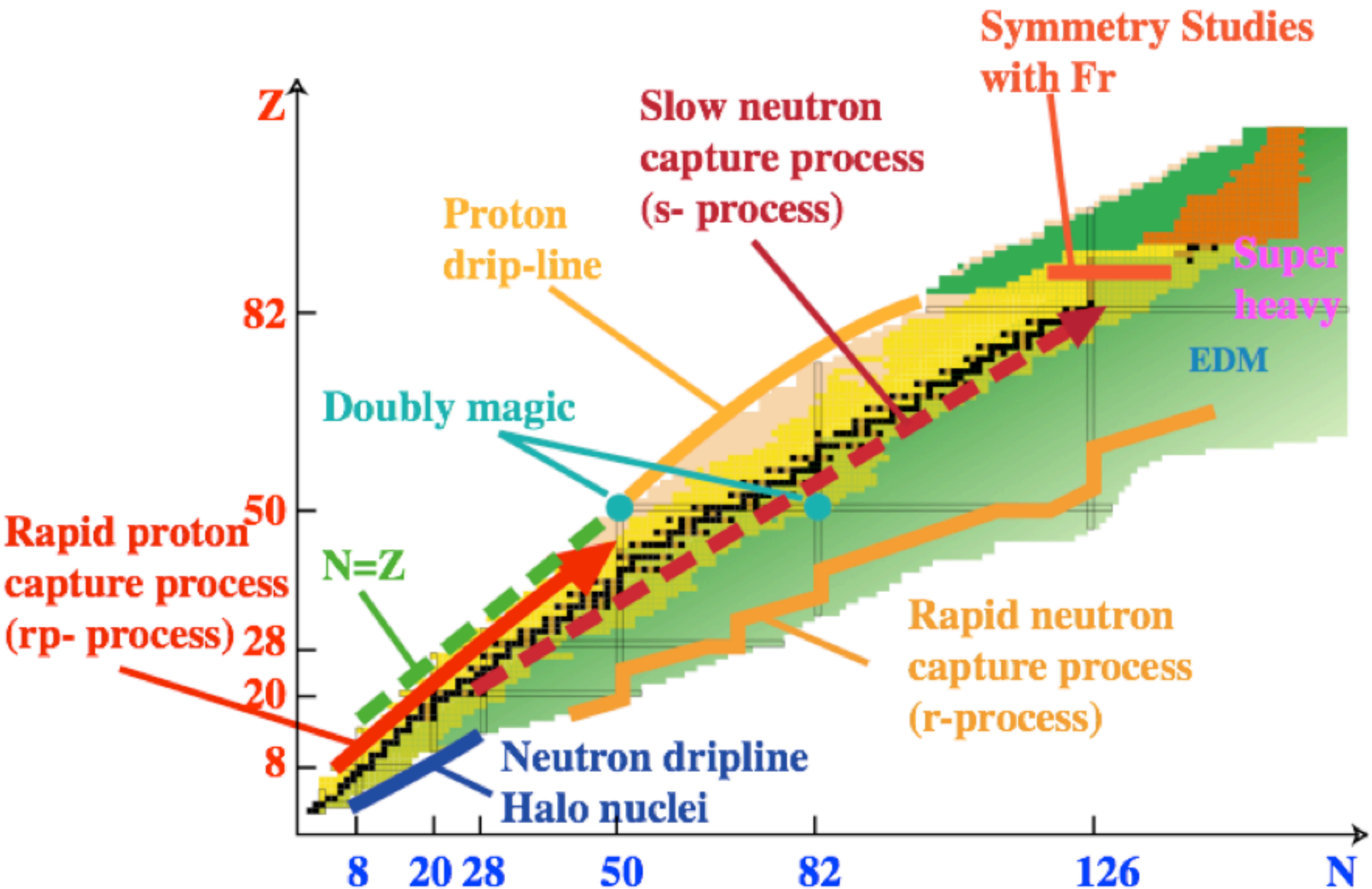
Conseil national de recherches Canada National Research Council Canada Canada

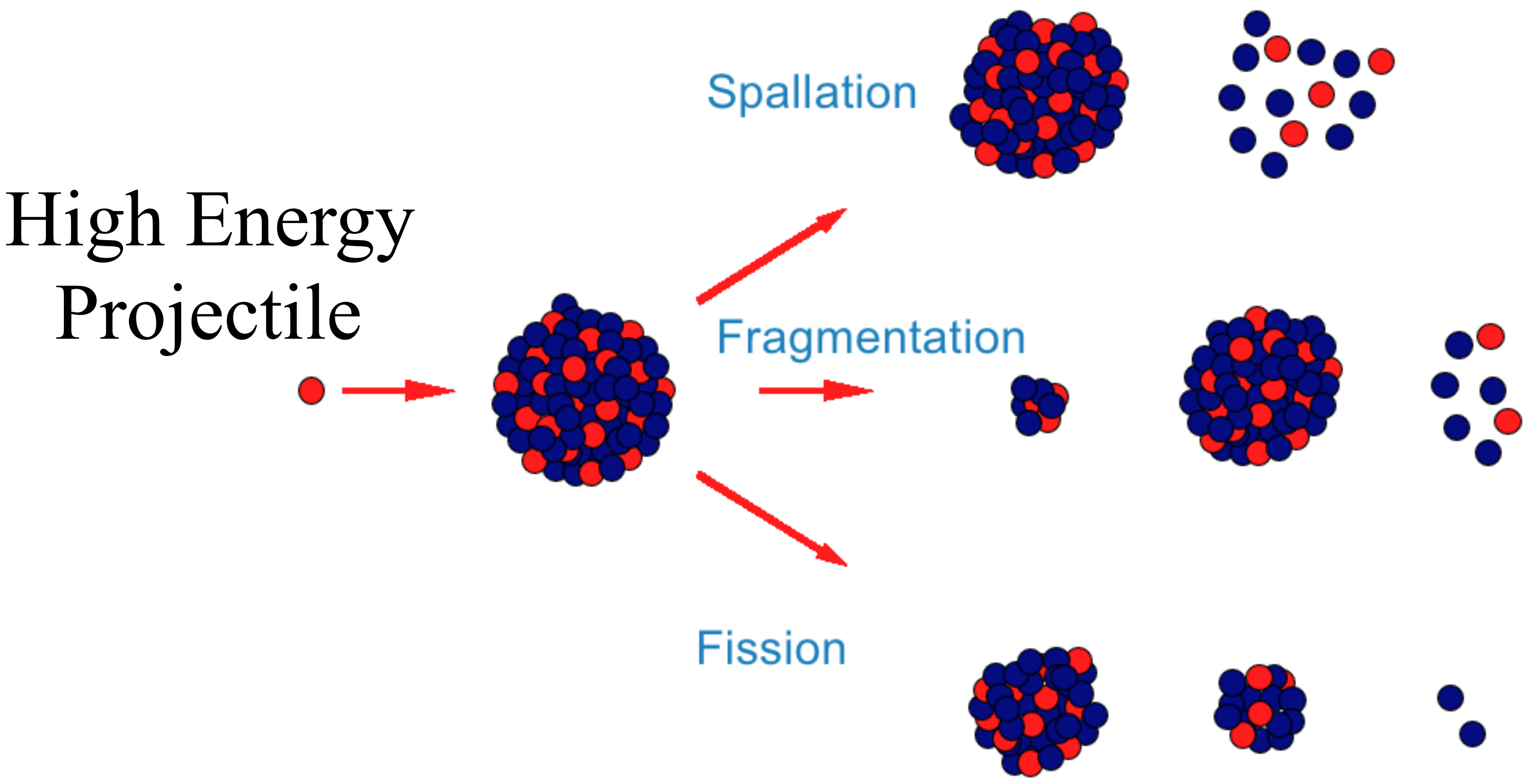
# Topic

- Production of Radioactive Ion Beams
  - Brief introduction the ISOL method
    - Progress toward high power target
      - High Power Target Container
      - High Power Target Material
- Future directions of the field
  - Increase RIB intensity by many order
  - Indirect and direct ISOL targets
- New ISOL Facilities

# Physics with Radioactive Ion Beam



# RIB production Nuclear Reactions




**Spallation: products distribution peaks few mass units lighter than target.**

**Neutron deficient**

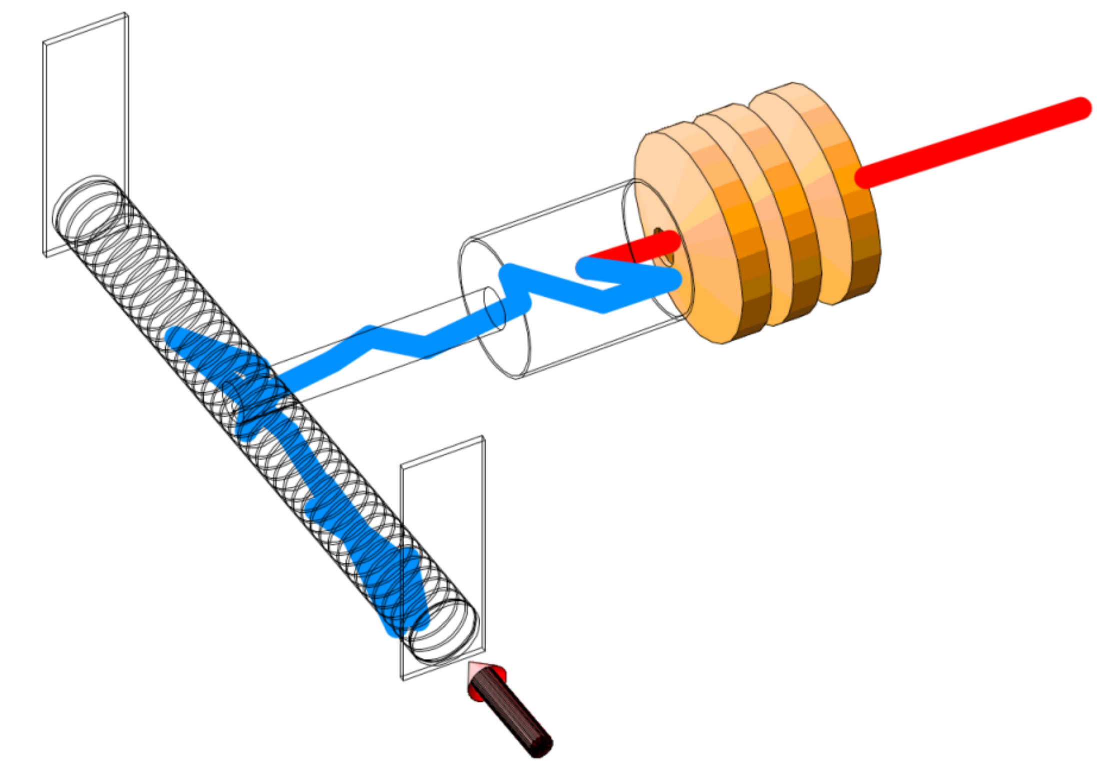
**Fragmentation: product N/Z ratio reflects the target ratio.**

**Neutron rich.**

**Induced fission into roughly equivalent mass products.**

**Medium range masse region**

# ISOL Method



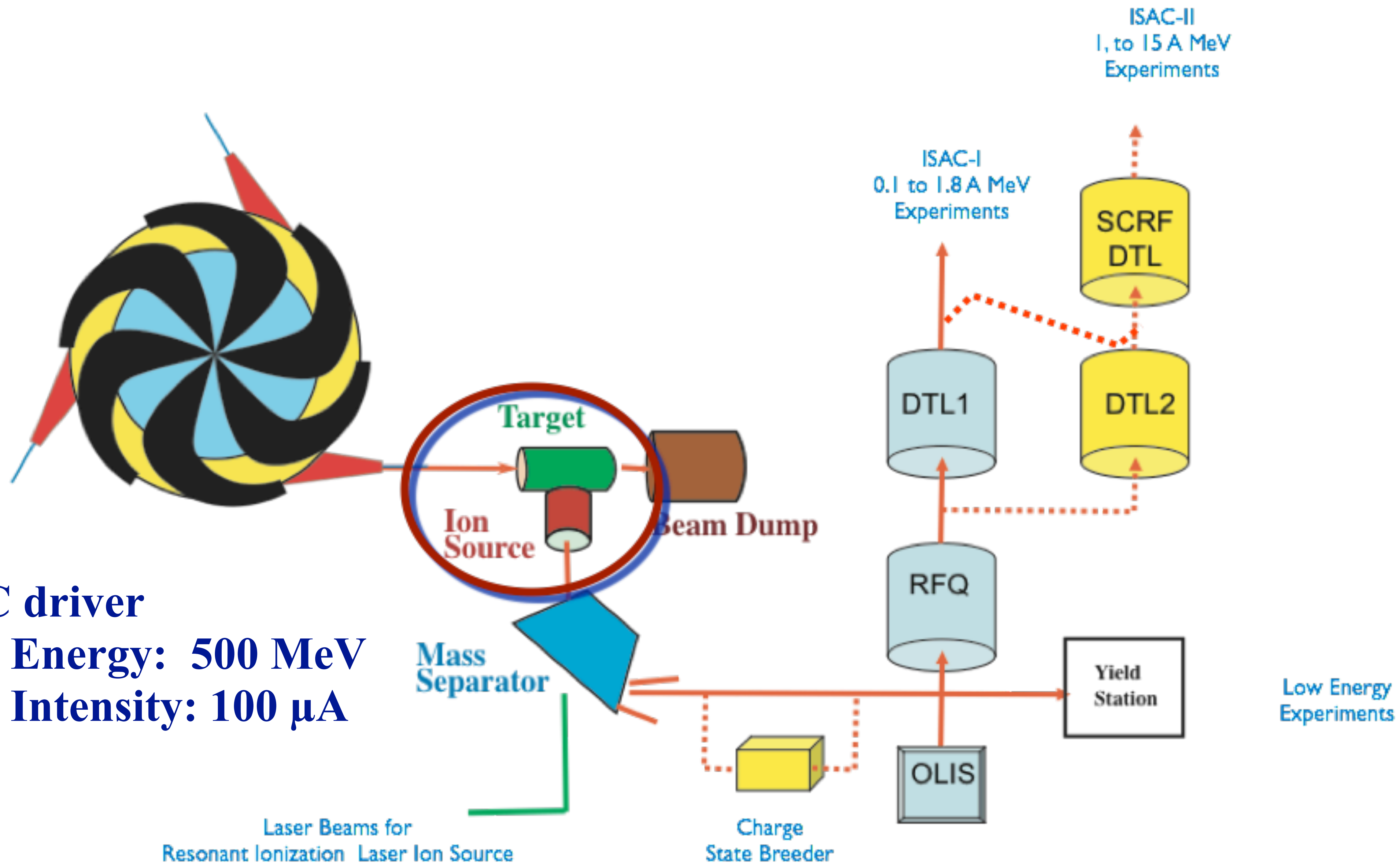
This method involves the interaction of light ion beam onto a thick high-Z target material,

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

- **The radioactive atoms diffuse to the surface of the grain material,**
  - **diffusion process with efficiency $\varepsilon_D$**
- **Then the atom undergo desorption and move from place to place randomly until it find the exit of the target container,**
  - **effusion process with efficiency $\varepsilon_E$**
- **The radioactive atom enter the ion source where it is ionized,**
  - **ionization process with efficiency $\varepsilon_I$**

$$Y = \Phi_p \, \sigma \, (NA/A \, \tau) \, \varepsilon_D \, \varepsilon_E \, \varepsilon_I$$

# ISOL Facility Concept Diagram




**ISAC driver**
**High Energy: 500 MeV**
**High Intensity: 100 µA**

# High Power ISOL Target 1)

- When increasing the driver beam power onto a direct ISOL target we have to solve two problems (target issues):
  - The target material has to survive the power deposition,
    - Issues are:
      - Target material evaporation => high pressure, not good for ion source and high voltage extraction (sparking problems),
      - Target material sintering => large grain formation, not good for fast diffusion release.
    - Best target material are:
      - Refractory metals,
      - Carbides,
      - Oxides, have lower operating temperature.
- Need to improve the target material overall thermal conductivity,
  - Composite target.

# High Power ISOL Target 2)

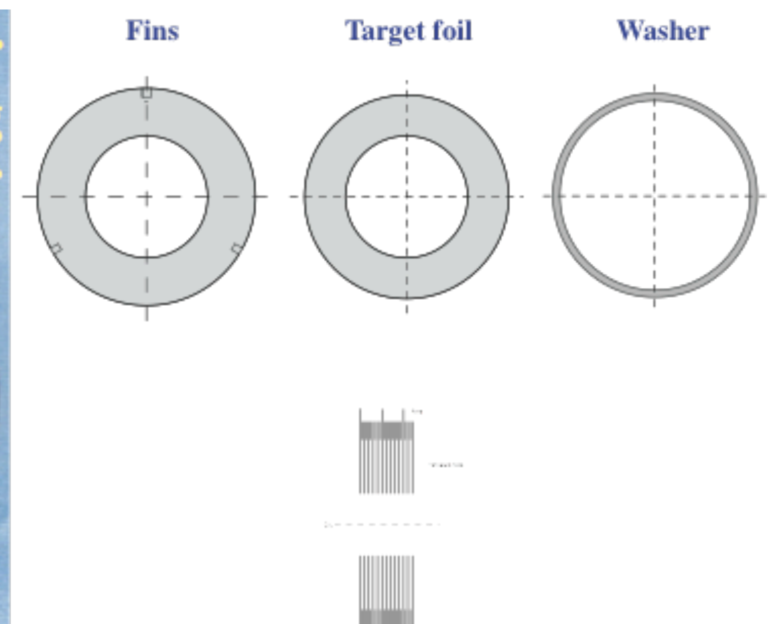
- The target container has to dissipate the power to an external power sink while keeping the target material uniformly at high temperature.
- The search for high power ISOL target  is not a new concept.

# Brief History of ISOL HPT

| | | |
|---|---|---|
| 1986 | Eaton & Ravn, CERN/ISOLDE:<br>100 µA, 550 MeV, proton | Longitudinal fins on the Ta container |
| 1991 | Talbert et al.,<br>100 µA, 600 to 1200 MeV, proton | Cooling design consisting of an annular solid thermal conductor encasing the target with an outer He-filled gap separating the conductor from a water-cooled outer jacket |
| 1991-<br>1996 | Nitchke, LBNL:<br>100 µA, 800 MeV, proton<br>Talbert et al.,<br>100 µA, 600 to 1200 MeV, proton<br>Bennett, RAL: development of a HPT for<br>100 µA, 800 MeV, proton | Active conductive cooling using He gas flow.<br><br>Active conductive cooling with thermal barrier<br><br>Passive radiative cooling approach. |
| 1998 | Talbert et al.,<br>100 µA, 500 MeV, proton | Active conductive cooling using water channels. Test at TRIUMF at 100 µA, 500 MeV, proton |
| 1999 | Bennett, RAL:<br>Rutherford Ion Source Test, RIST project<br>Tested at ISOLDE: 3 µA, 1000 MeV, proton | Built a diffusion bounded Ta target,<br>off-line test shows that emissivity ~ 0,7-0,8. |

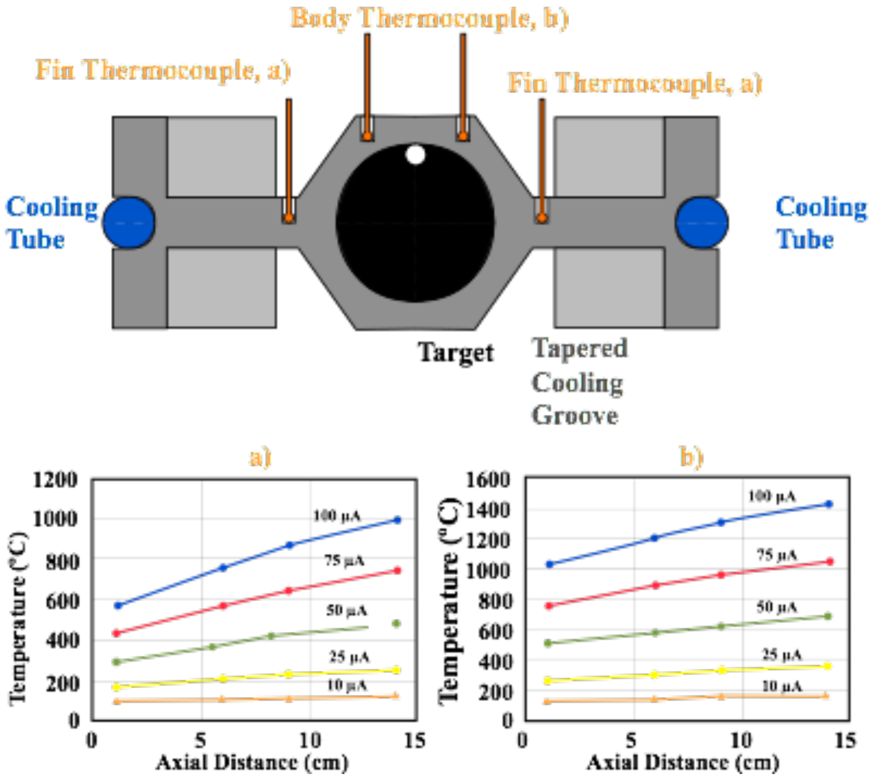
# Rutherford RIST Target

- The RIST is a high power target made using diffusion bounding of stacks of Ta discs and washers.
- Fin like surface enhances the emissivity coefficient,
  - normal tantalum has an emissivity of 0.3, the RIST has an emissivity of 0.72.
  - Technique limited to refractory metal only. Limitation on the type of material to be used as targets.

# Talbert at *al.* HPT

- **First ISOL target receiving high energy proton at 100 µA Made from diffusion bounded Mo foils.**
  - **Very robust but:**
    - **Cooling was too efficient!**
    - **Non uniform temperature!**



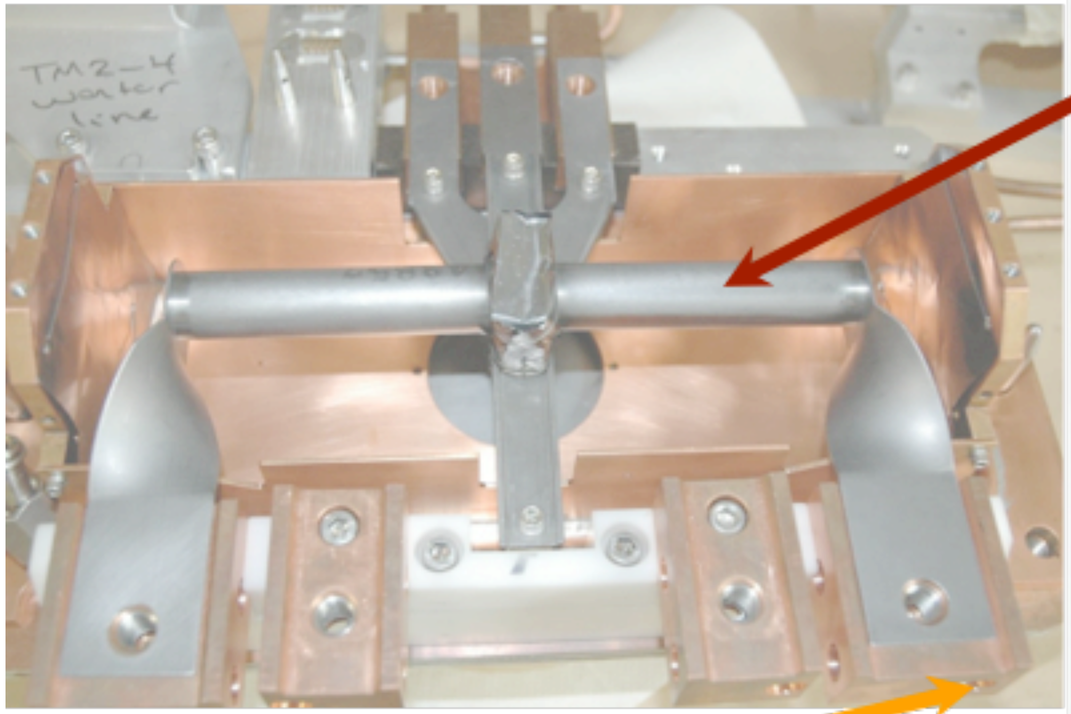
# ISAC High Power Target

- The Talbert's HPT shows limitations (refractory materials only: Nb, Mo & Ta) and difficulties managing a uniform temperature.
- The ISAC high power target was inspired by the RIST target where non-uniform fin like surface enhances the emissivity coefficient.
- Test using electron bombardment shows that enhanced emissivity can successfully cool the target container by radiative cooling.

# ISAC "Target Ovens"

## High Power Target

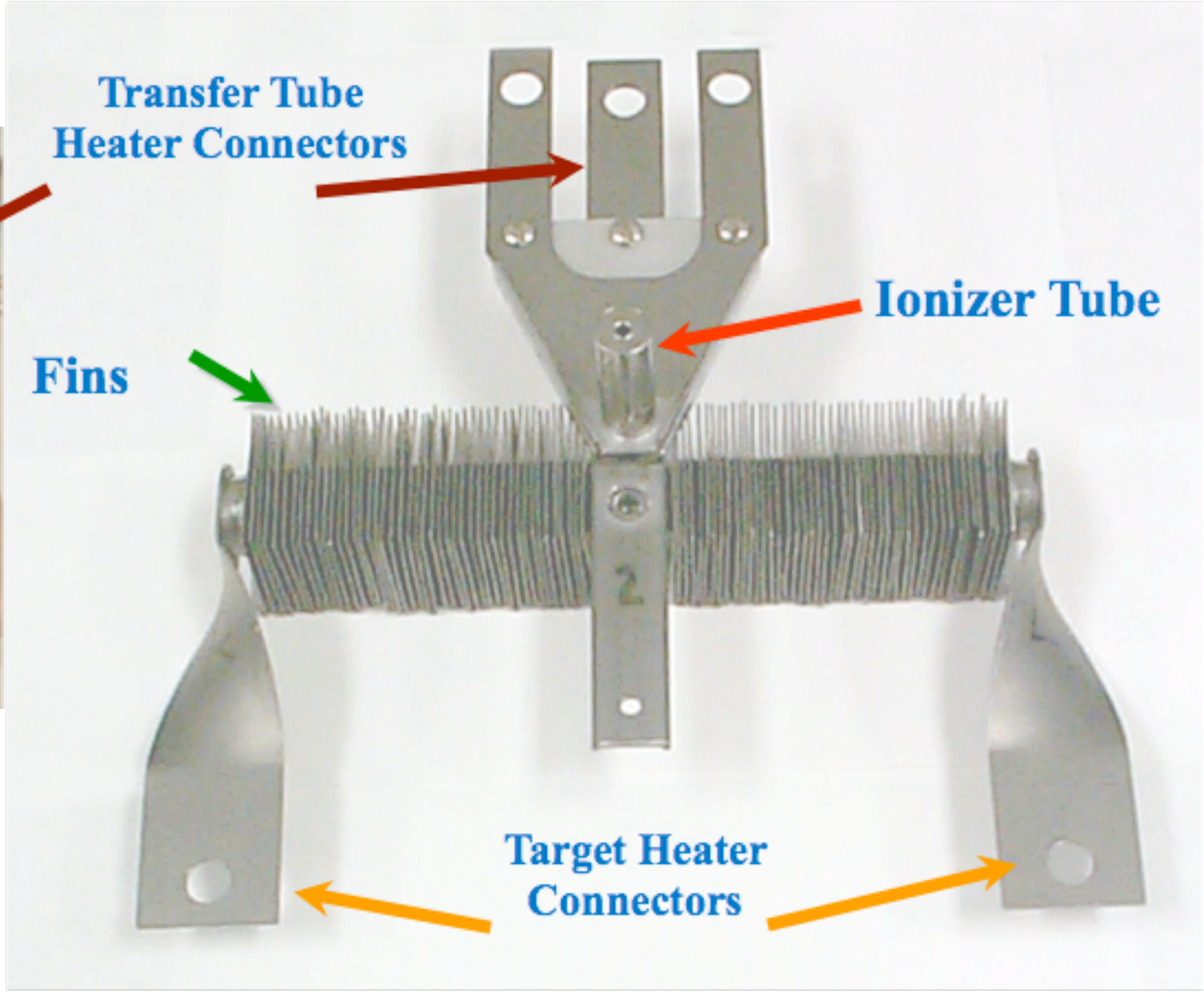
## Normal Target




Target Heater Connectors

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

$\varepsilon \approx 0.32$

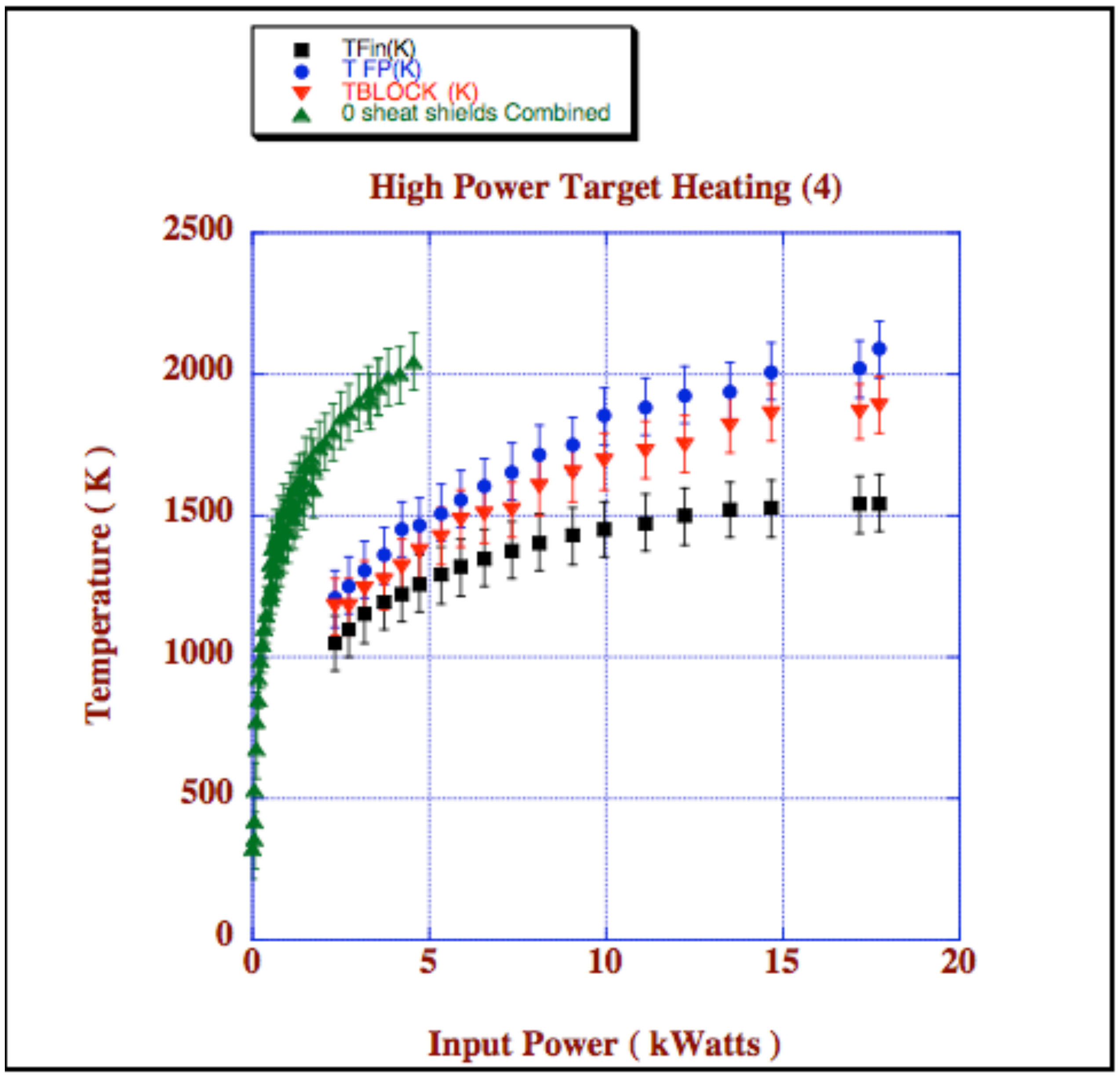


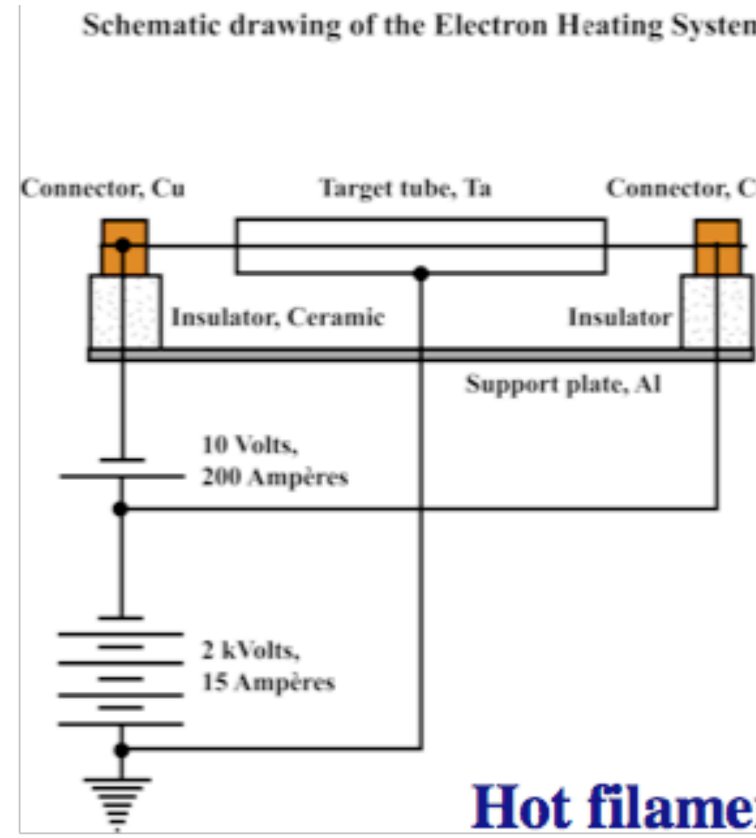

$55 \leq I_{Proton} \leq 100\ \mu A$

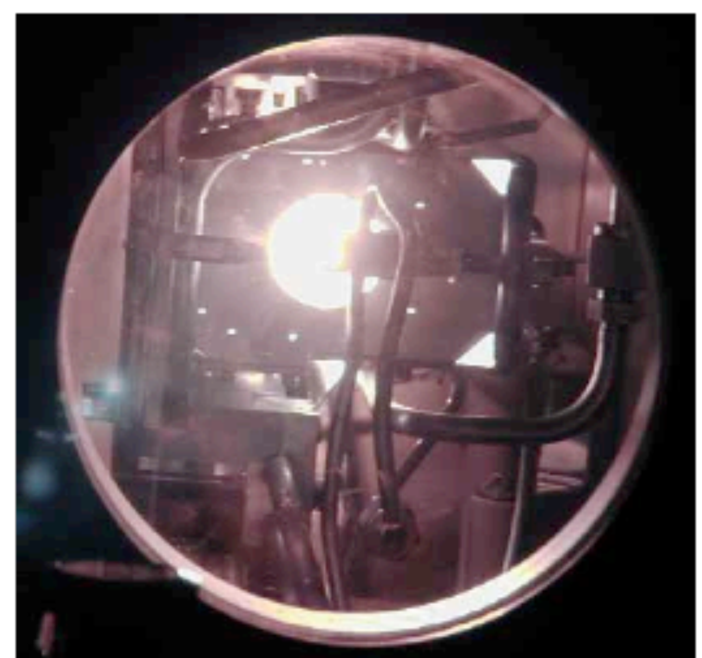
$\varepsilon \approx 0.92$

# ISAC High Power Target

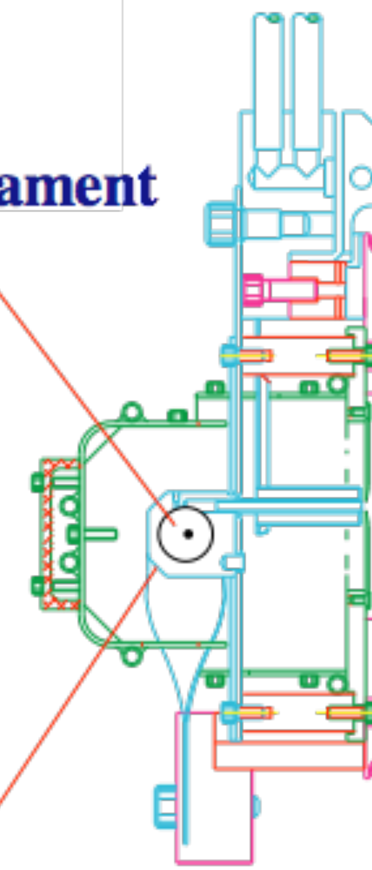
## Effective Emissivity ≈ 0.92!



Hot filament



Target container

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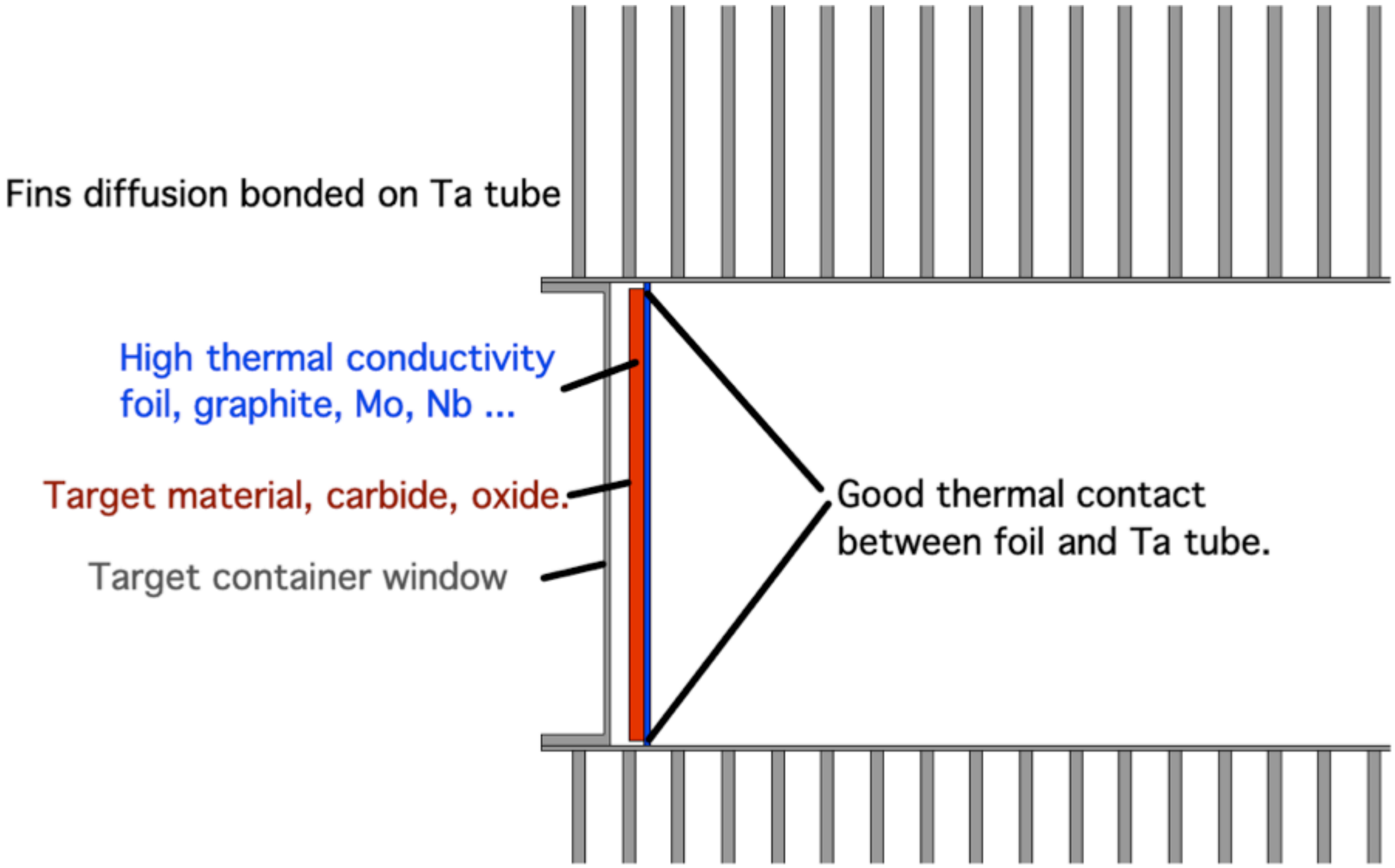
# Composite High Power Targets

- Very few target materials can sustain high power deposition,
  - Ta, Nb, Mo, W.
- RIB production demands for other type of target material.
  - Na, Mg and Al isotopes production for nuclear astrophysics experiments demand high proton intensity on carbide target material, SiC.
  - U target > 50% of the RI beam time.
- Development of high conductivity composite targets.

# High Power Target Material, composite



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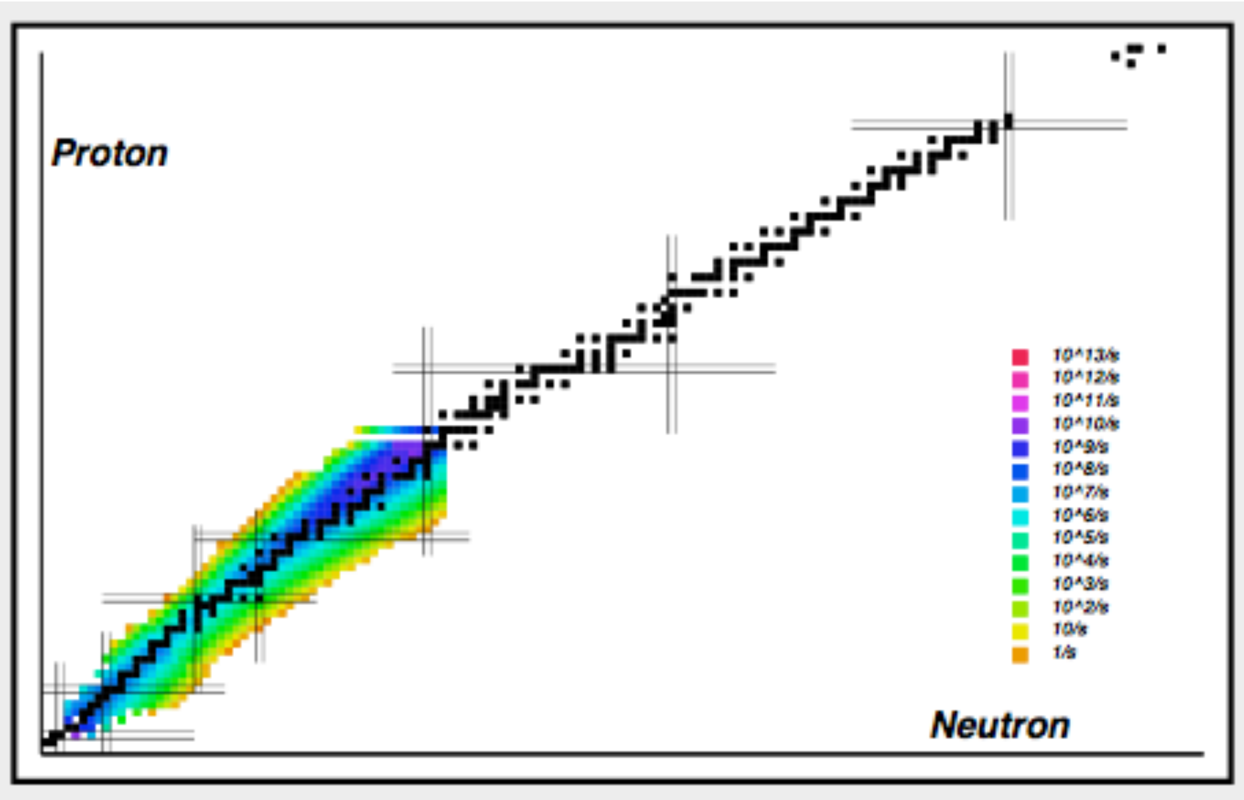
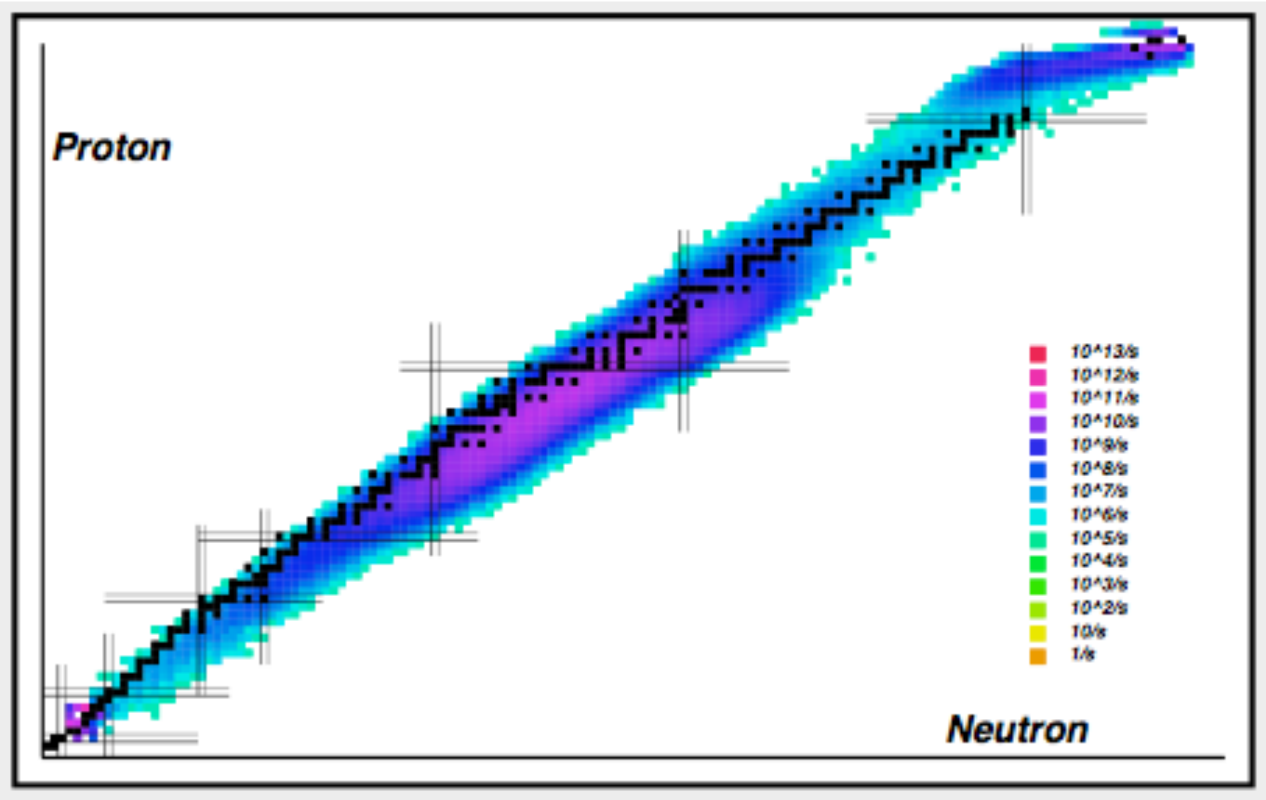
# Typical High Power Target at ISAC

| Target Material (RIB) | High Conductivity Support | Proton Beam Intensity (uA) |
|---|---|---|
| SiC (He, Li, Na, Mg, Al, F, Ne) | C (graphite foil, 0.1 mm thick) | 70 - 85 |
| TiC (K, Na, Ca, Ar, Cl ...) | C (graphite foil, 0.1 mm thick) | 70 - 85 |
| ZrC (Kr, Ga, Br, As ...) | C (graphite foil, 0.1 mm thick) | 75 - 100 |
| UC (At, Fr, Po, Ra, Rn, Pu, ...) | C (graphite foil, 0.1 mm thick) | Limited to 10<br>but capable of 65 - 100 |
| Ta (Li, Na, Ca, Cs, Sn, Ag, ...) | | 75-100 |
| Nb (Rb, Kr, ...) | | 80-100 |
| NiO (C) | Ni ( disk, 0.5 mm thick) | 30 |
| Nb5Si3 (Br, As) | Nb ( foil, 0.025 mm thick) | 15 |
| Al2O3 (Ne) (EURISOL HPT) | Nb ( disk, 0.5 mm thick) | 30 |

# RIB Production: Direct ISOL Target

- **Example of production using direct ISOL target:**
  - **P + Nb**
  - **P + U**



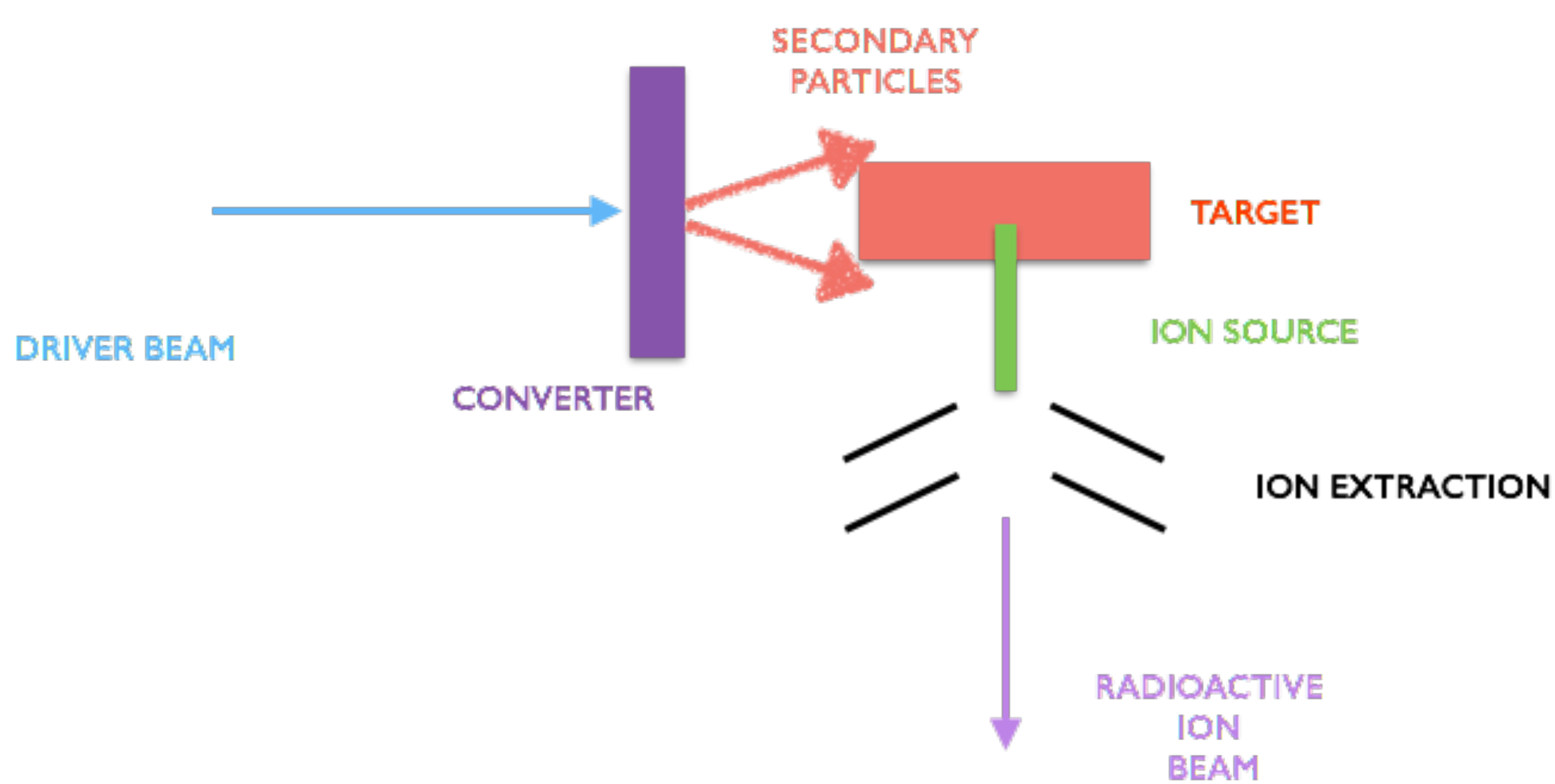
# Increasing RIB Intensity

- Demands for high RIB intensity,
  - Symmetry, Fr PNC
  - EMD
  - Nuclear astrophysics
  - …
- Indirect ISOL targets
- Future direct ISOL targets

# Indirect (Two-Step) ISOL Target

**Types of "Converter" target are envisaged:**

- Rotating wheel target,
- Stationary cooled plate target,
- Liquid metal target (Li, LBE, Hg …).



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# Indirect (Two-Step) ISOL Target

- Rotating wheel target,
  - Easier heat removal,
  - Smaller interaction of the primary and secondary beams with the coolant.
    - Lower production of radiologic $^{13}N$, $^{14,15}O$, $^{10,11}C$, $^{3}H$, …
  - But the price to pay is:
    - Larger "converter" target volume,
    - More complex mechanical system in highly radioactive environment,
      - Bearings, seals and driver mechanism,
      - Complex control and safety interlock system.

# Indirect (Two-Step) ISOL Target

- Stationary cooled plates target,
  - Limited lifetime due to radiation damage,
    - Swelling under radiation,
      - Expansion in part of the mechanical structure,
        - Issue with mechanical stability and leads to coolant leakage.
  - Primary beam very close to coolant, (water in most of the case)
    - Formation of large quantity of radiogenic isotopes,
  - Secondary beam (neutron, gamma) passes through coolant,
    - Need special treatment of the water, $^3H$
    - For electron machine, large production of hydrogen,
      - Risk of explosion!

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# Indirect (Two-Step) ISOL Target

- Liquid metal “converter” target (Li, Hg, Pb-Bi eutectic)
  - Operates at higher temperature,
    - Larger $\Delta T$ than with water cooling => more efficient cooling system.
  - Large production of radiogenic isotopes in the “converter” target,
    - requires special treatment and disposal, especially for Hg, which is liquid at room temperature.
  - Dynamic heat exchanger to compensate for variable beam intensity and interruption.
  - Material selection necessary to avoid corrosion and mechanical modification of the material properties,
    - Swelling and large cracks formation in steel alloys under radiation in presence of liquid heavy metal.

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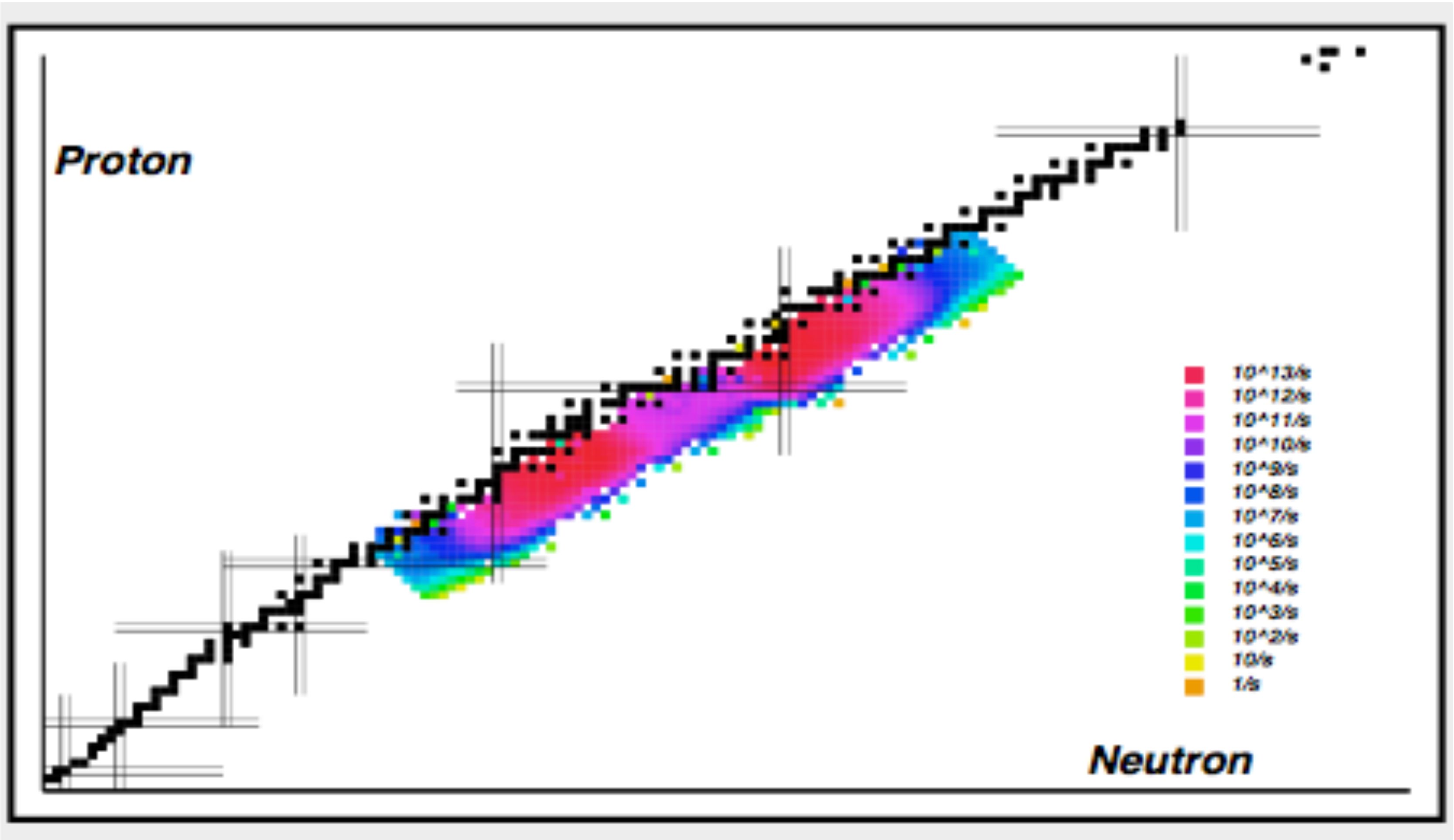
# Indirect ISOL Method + & -

- The main advantages of the indirect ISOL method are:
  - Less power deposition inside the ISOL target material,
    - when using neutrons as secondary particles.
    - not necessary true for photons, => $e^+$-$e^-$ production inside target material leads to high power density!
  - Disentangle the cooling issues of the converter and the ISOL target,
    - ISOL target can operate at its optimum temperature,
- The main disadvantages are:
  - Production limited to fission products mainly
  - Key experiments (fundamental symmetries, EDM, …) are requesting RIB species that are not produced using fission mechanism! *Need direct target production!*

# Indirect ISOL target

## RIB production with indirect ISOL target is limited mainly to fission products, (n,f) and (γ,f).



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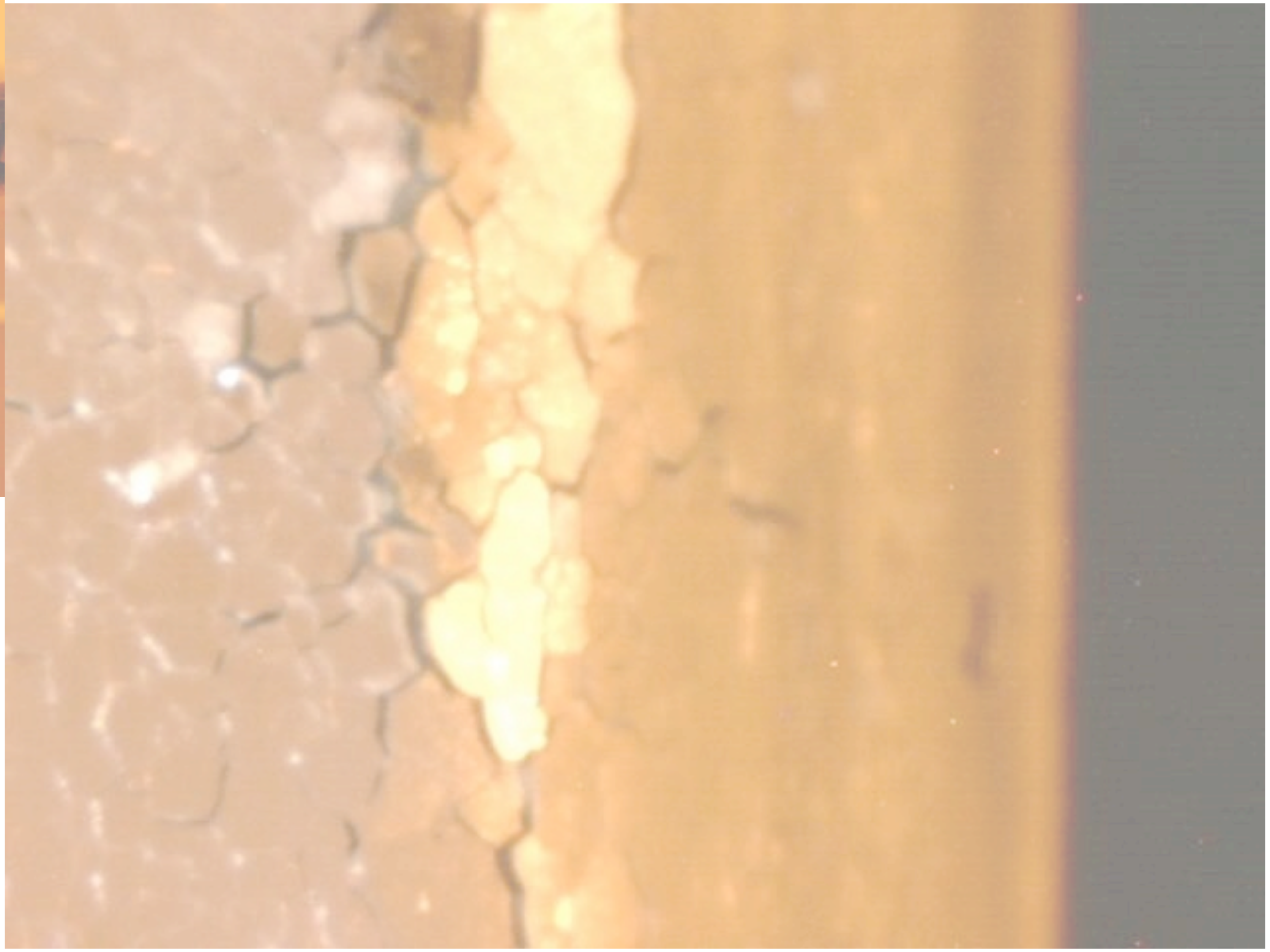
# High Power Direct ISOL Target

- Can direct target survive (months) of operation above 200 kW power?
- What are the best solution for cooling the target container, liquid or gas?
  - Cracks formation are important and leads to leaks in the target/ion source system,
    - Cannot use water, risk of sudden oxidation of target at high temperature!
      - UCx, LaC, ThC ...

# Target Oven Damage

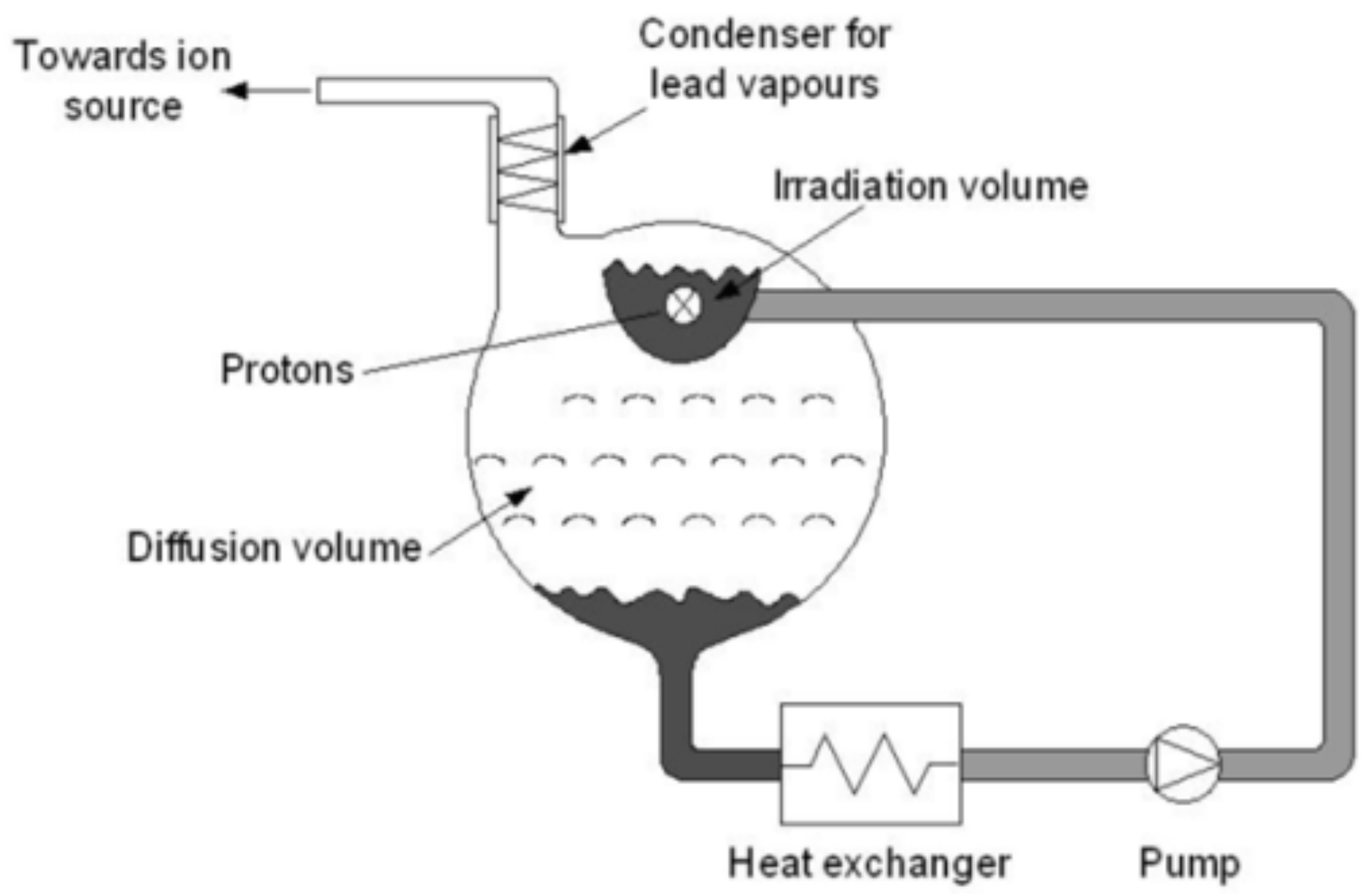


# Future High Power Direct ISOL Target

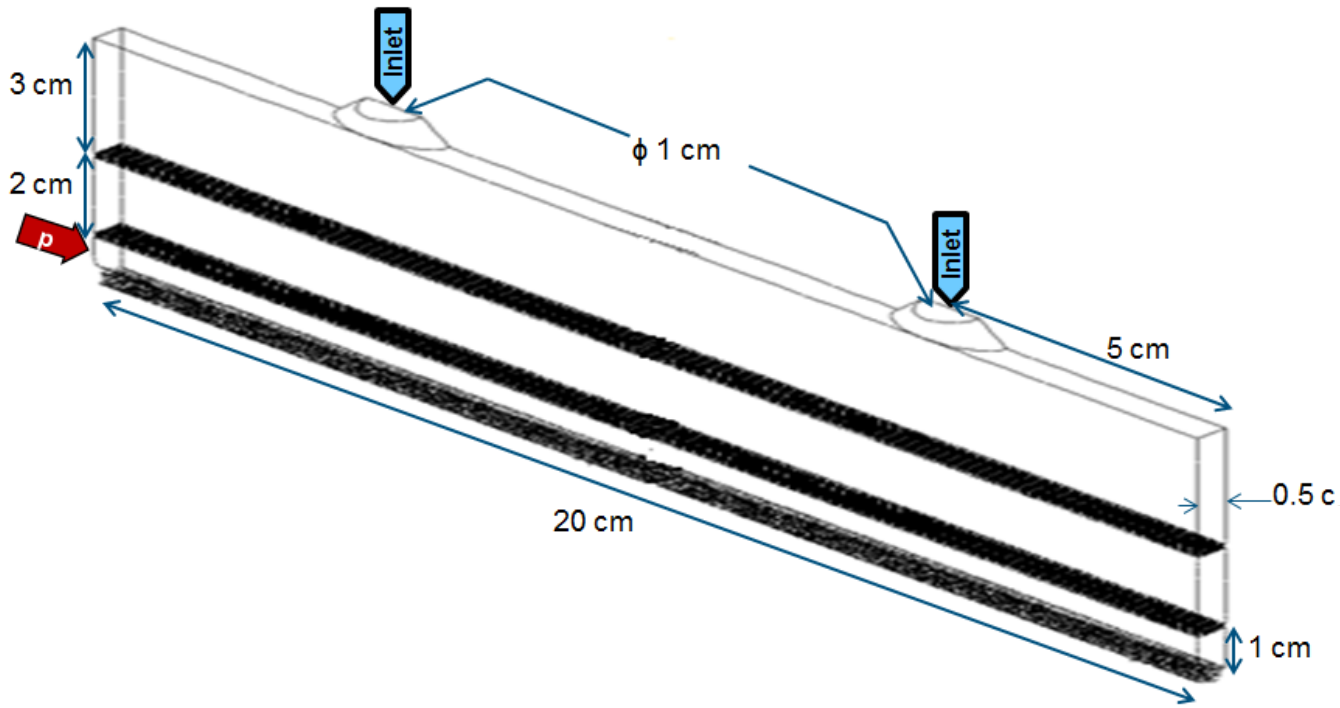
- Liquid target
  - LBE target with cooling loop
    - EURISOL proposal
    - LIEBE project at CERN, T. Stora.
- Flowing Powder Target
  - Proposed by L. Popescu at SCK-CEN.
  - Preliminary study shows that this target can sustain power of 200 kW

# High Power Target Loop

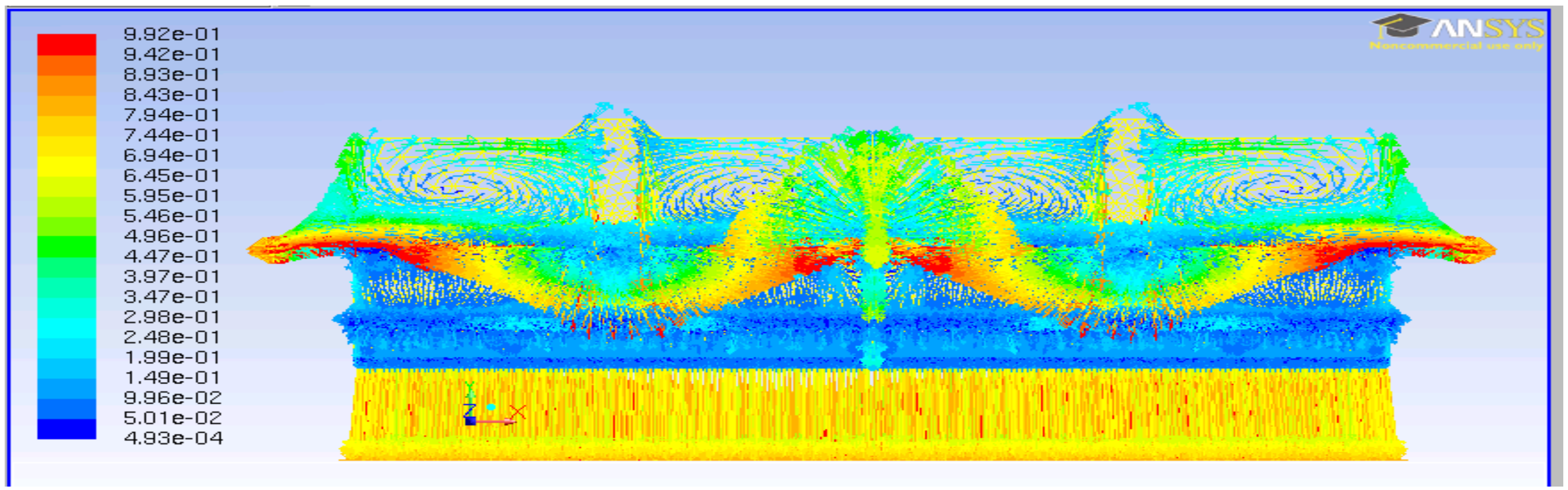
- Pb-Bi loop - production of short-lived volatile elements



# LIEBE-target design

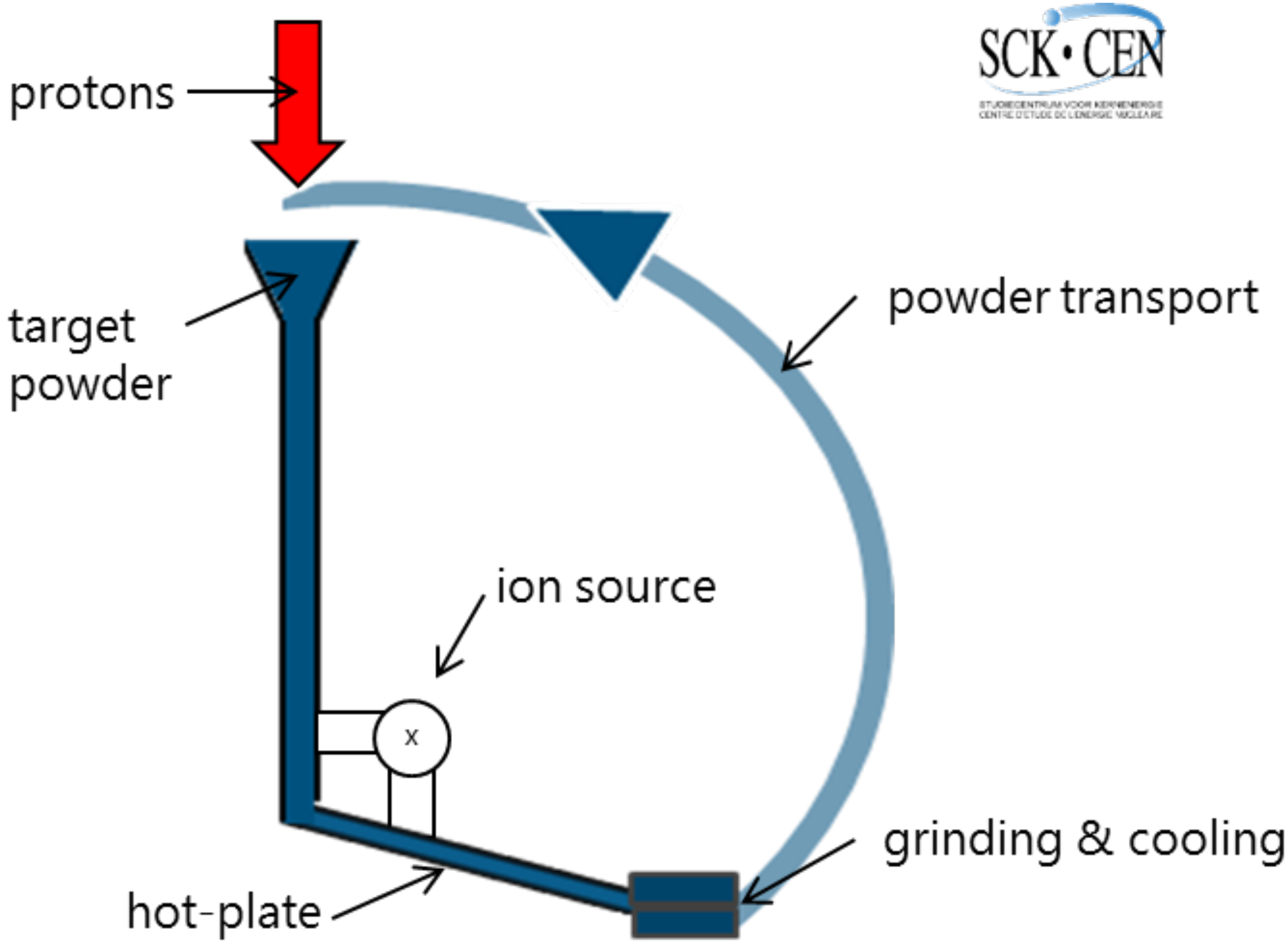



Double grid => distributed feeder volume.
Uniform irradiation




Full refreshment in 100 ms, with uniform evacuation velocity vectors

# High-Power Target Loop

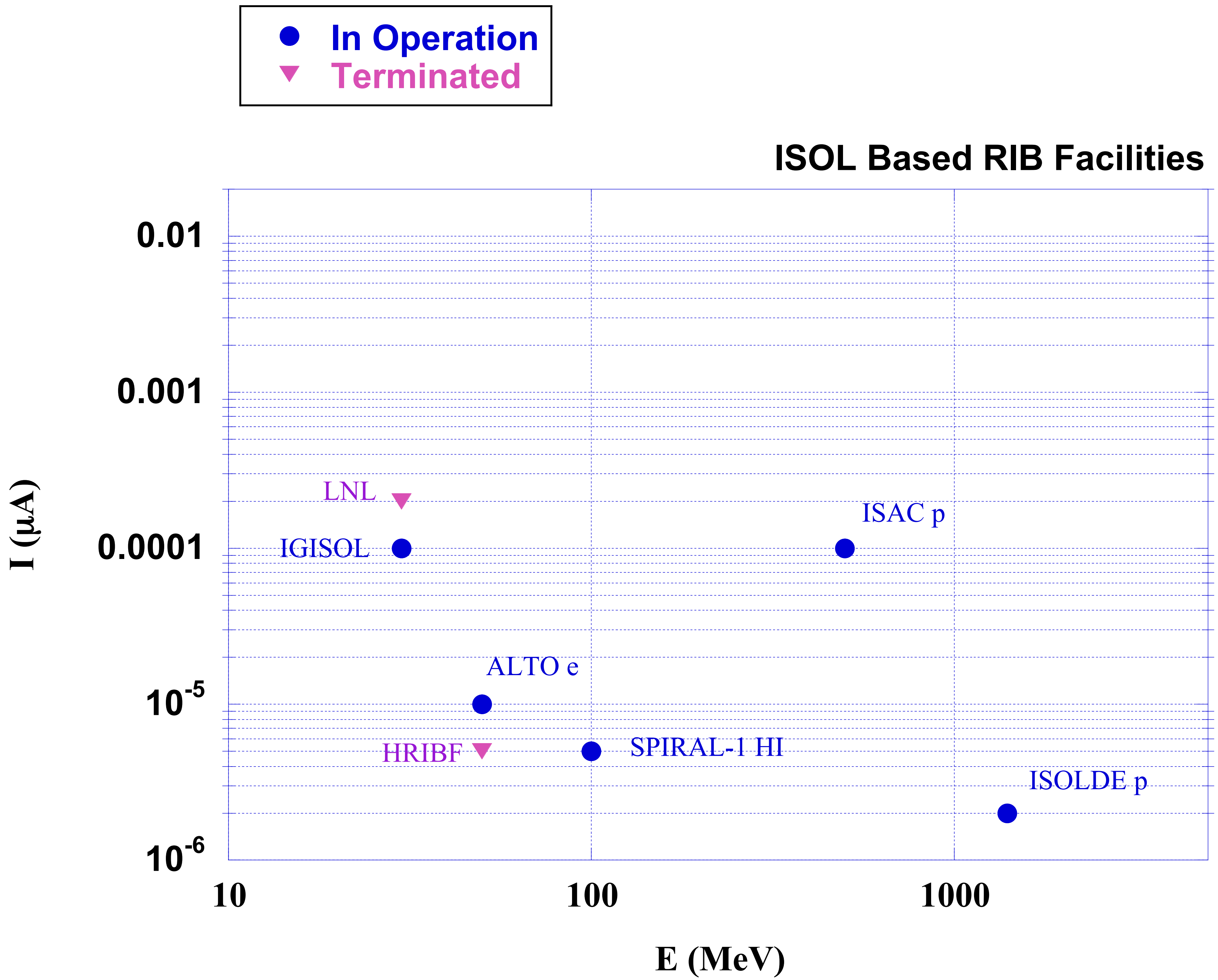



L. Popescu, "*High Power Target Loop*", Poster Session
Workshop on High Power ISOL Targets, Mol, Sept 2013,

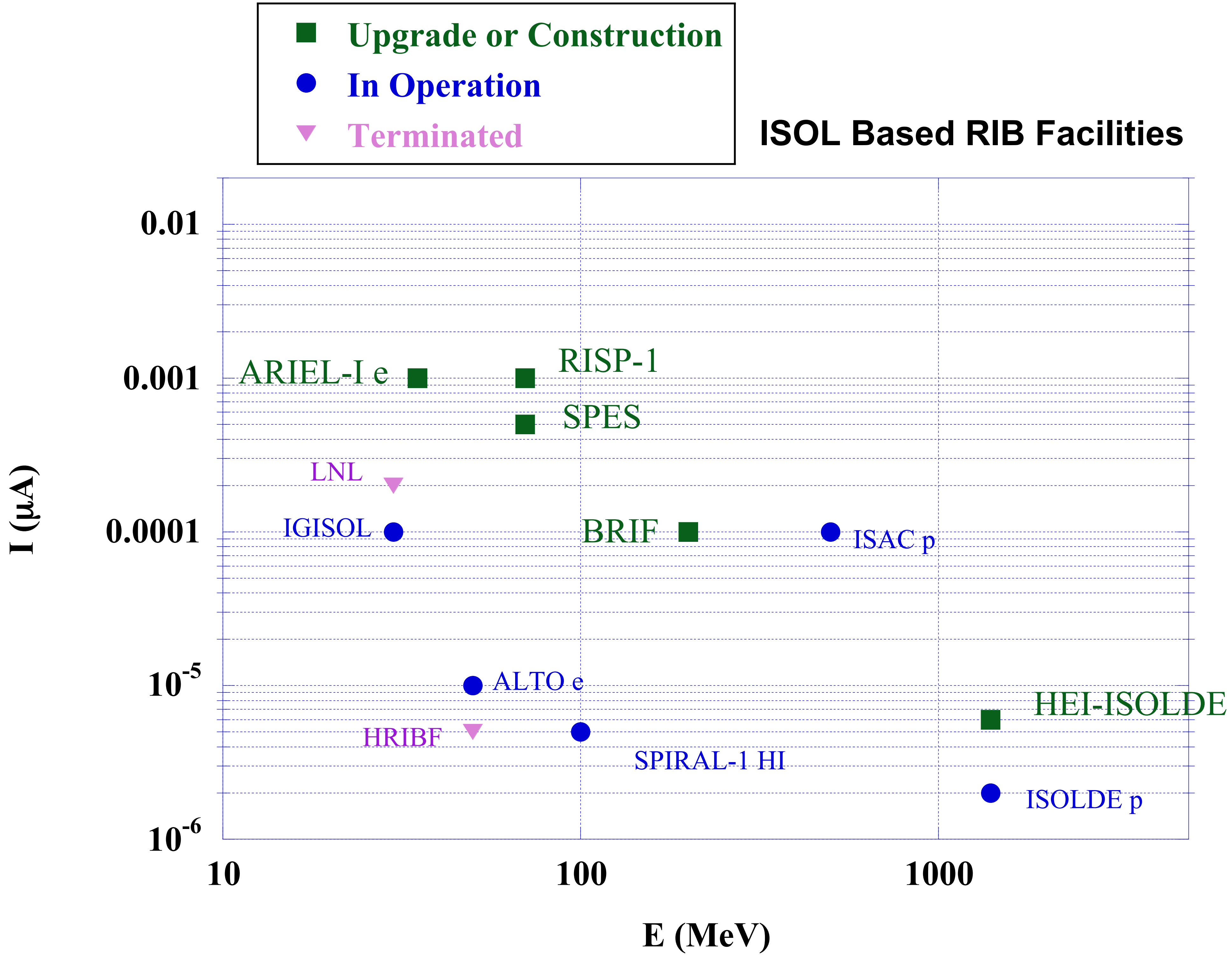
# ISOL Facilities in the World

| Facility | Energy (MeV) | Intensity ($\mu$A) | Power (kW) | Driver Beam | Method | Ind. Part. /Target |
|---|---|---|---|---|---|---|
| LNL | 30 | 200 | 6 | Proton | Direct ISOL | |
| HRIBF | 50 | 20 | 1 | Proton | Direct ISOL | |
| ISOLDE | 1400 | 2 | 2.8 | Proton | Direct ISOL | |
| ISAC | 500 | 100 | 50 | Proton | Direct ISOL | |
| SPIRAL-1 | 100 per Nucleon | 2.5 | 3 | Heavy Ions | Direct ISOL | IF+ catcher |
| ALTO | 50 | 10 | 0.5 | Electron | Direct ISOL | Uranium |
| IGISOL | 30 | 100 | 3 | Proton | ISOL & gas catcher | |
| HEI-ISOLDE | 1400 | 6 | 8.4 | Proton | Direct ISOL | |
| ARIEL-1 | 50 | 1000 | 50 | Electron | | Gamma/ Uranium |
| BRIF | 200 | 100 | 20 | Proton | Direct ISOL | |
| SPES | 70 | 500 | 35 | Proton | Direct ISOL | |
| RISP-1 | 70 | 1000 | 70 | Proton | Direct ISOL | |
| EURISOL (4) | 1000 | 100 | 100 | Proton | Direct ISOL | |
| EURISOL (4) | 1000 | 4000 | 4000 | Proton | | Neutron/Uranium |
| SPIRAL-2 | 40 | 5000 | 200 | Deuteron | | Neutron/Uranium |
| RISP-2 | 660 | 600 | 396 | Proton/HI | Direct ISOL | |
| ARIEL-2 | 50 | 10000 | 500 | Electron | | Gamma/Uranium |
| ANURIB | 50 | 1000 | 50 | Electron | | Gamma/Uranium |
| CARIF | < 10 | $10^{14}$ n/cm$^2$/s | 400 | Neutron | Direct ISOL | Uranium |
| ISOL@MYRRHA | 600 | 200 | 120 | Proton | Direct ISOL | |

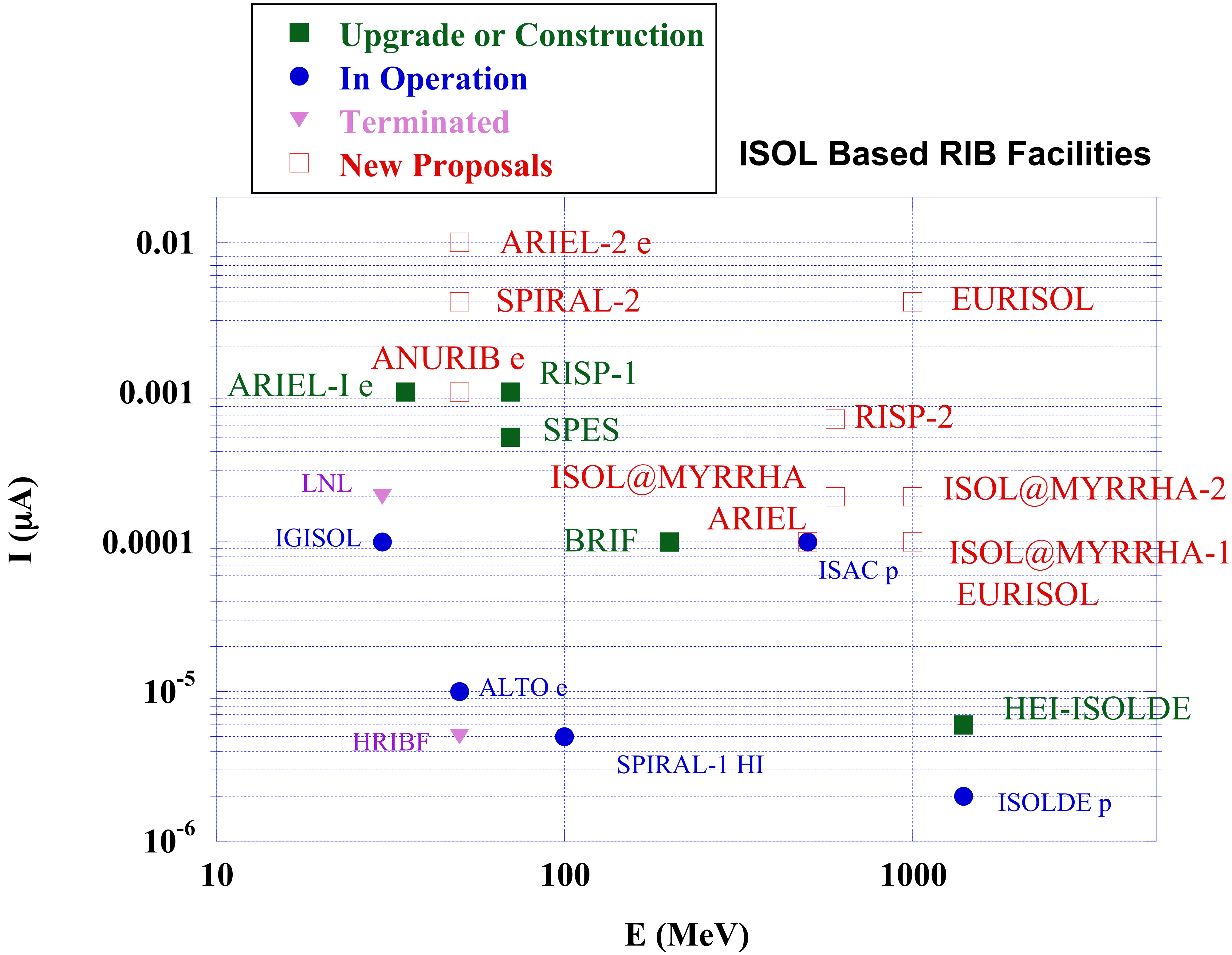
# ISOL Facilities



# ISOL Facilities



# ISOL Facilities



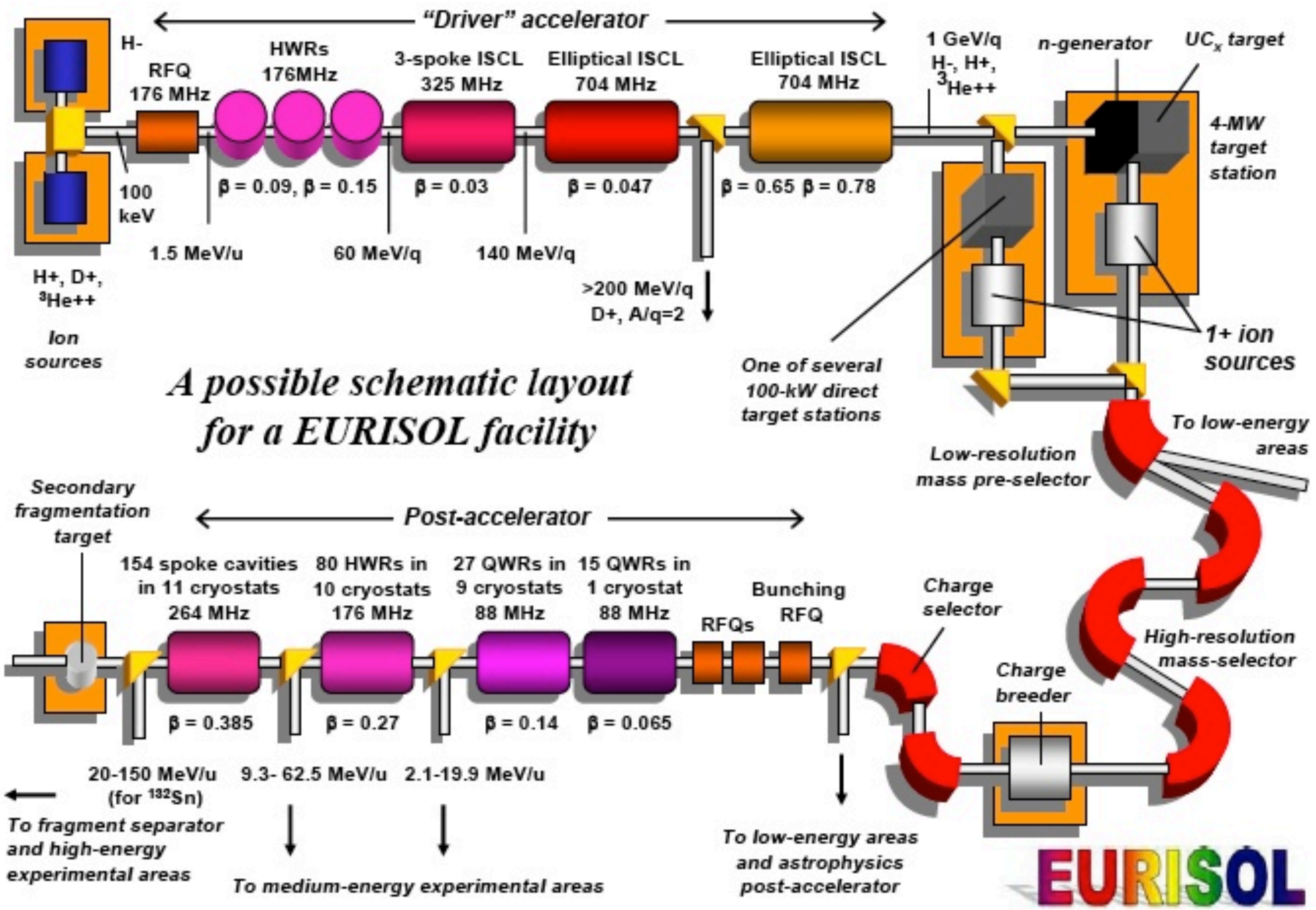
# EURISOL

- **EURISOL facility is foreseen as the ultimate ISOL facility combining several 100 kW targets and one multi MW target to serve multi-users.**
  - **Low energy physics,**
  - **Medium energy physics,**
  - **Post-accelerator for in flight fragmentation of neutron rich nuclei.**


- **Final Report of the EURISOL Design Study (2005-2009) A DESIGN STUDY FOR A EUROPEAN ISOTOPE-SEPARATION-ON-LINE RADIOACTIVE ION BEAM FACILITY November 2009,**
  Edited by John C. Cornell **Published by GANIL B.P. 55027, 14076 Caen cedex 5, France September, 2009**

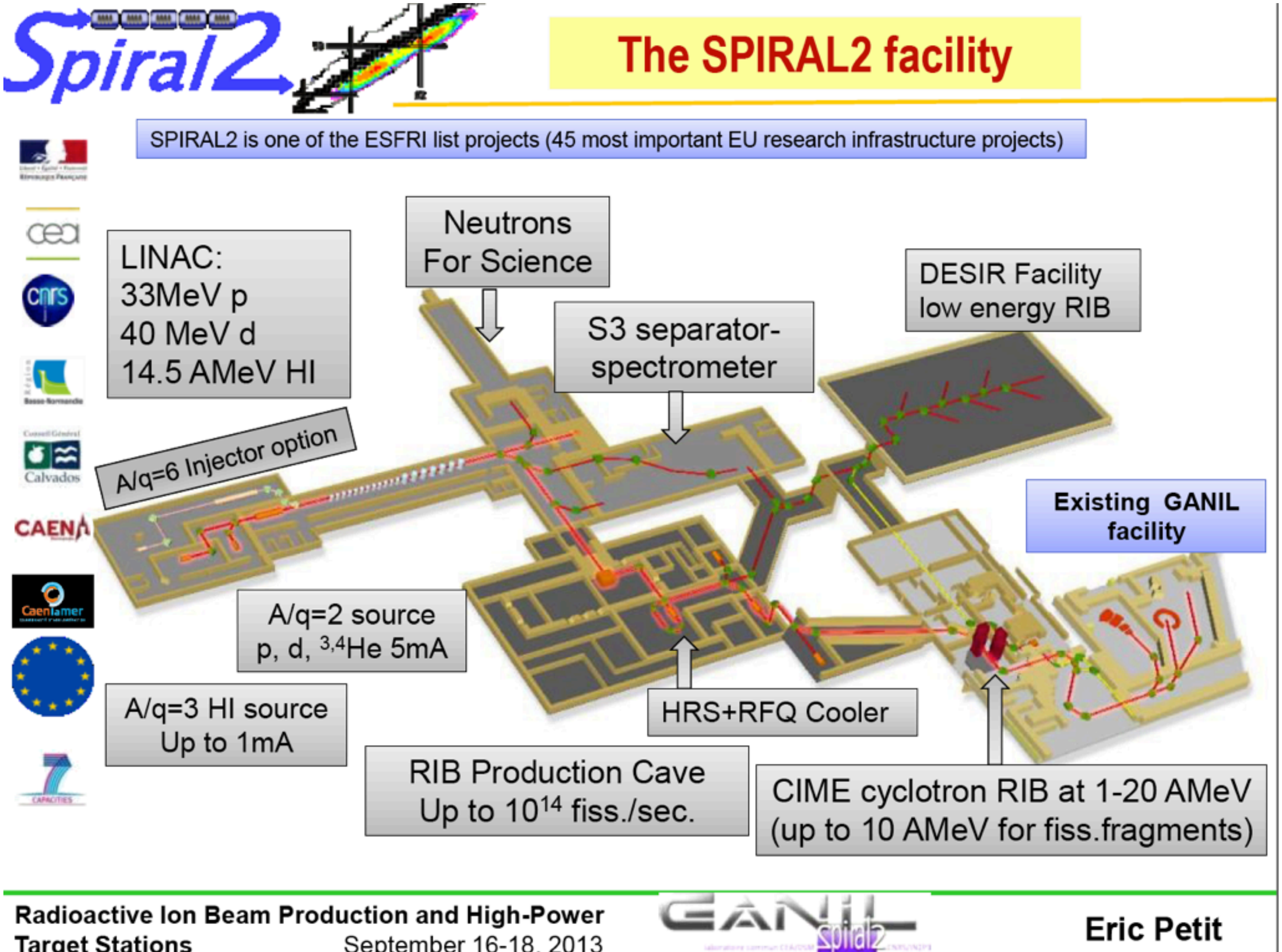
# EURISOL

The EURISOL Design Study Report

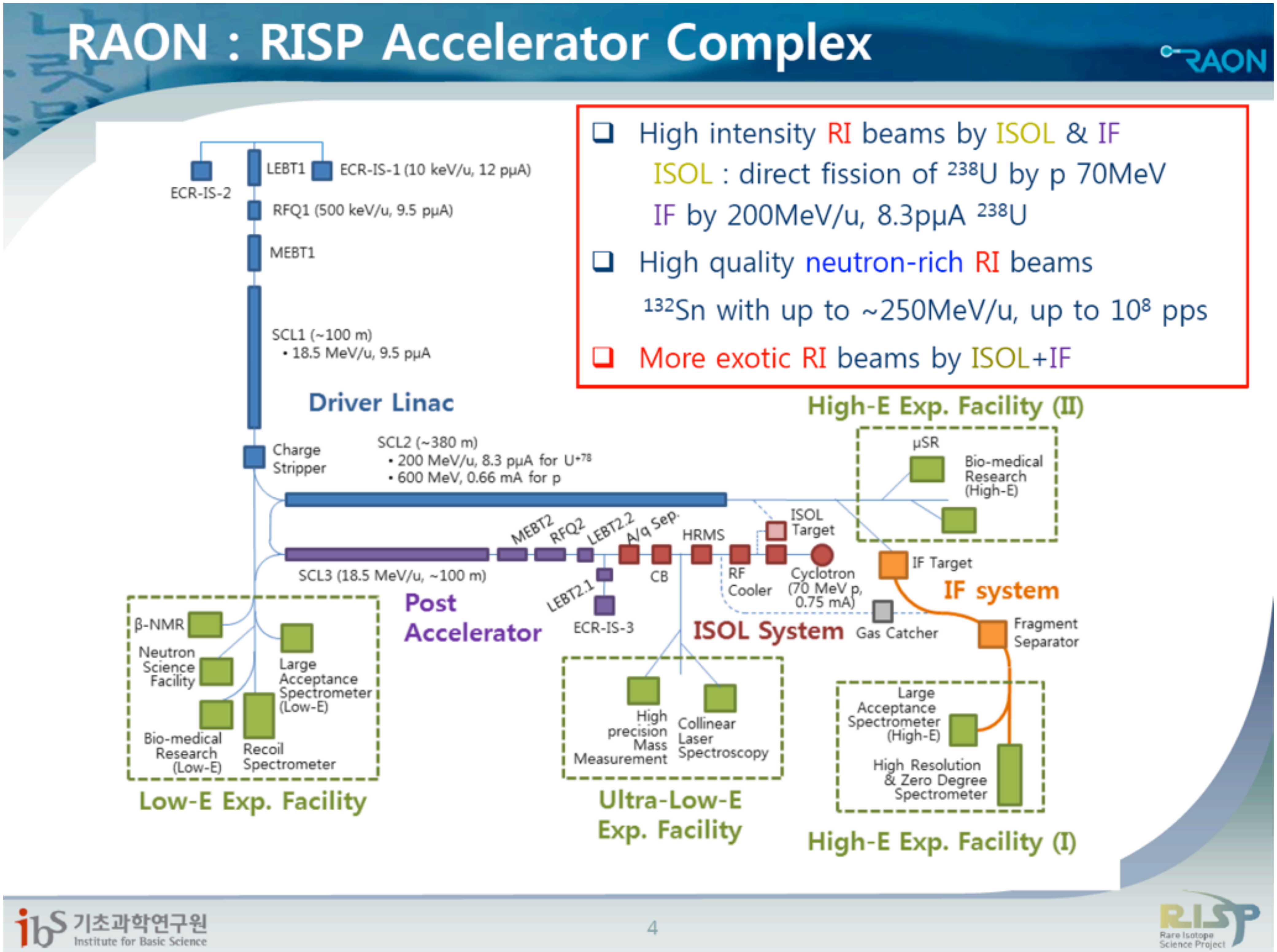



*A schematic diagram of the envisaged EURISOL facility.*

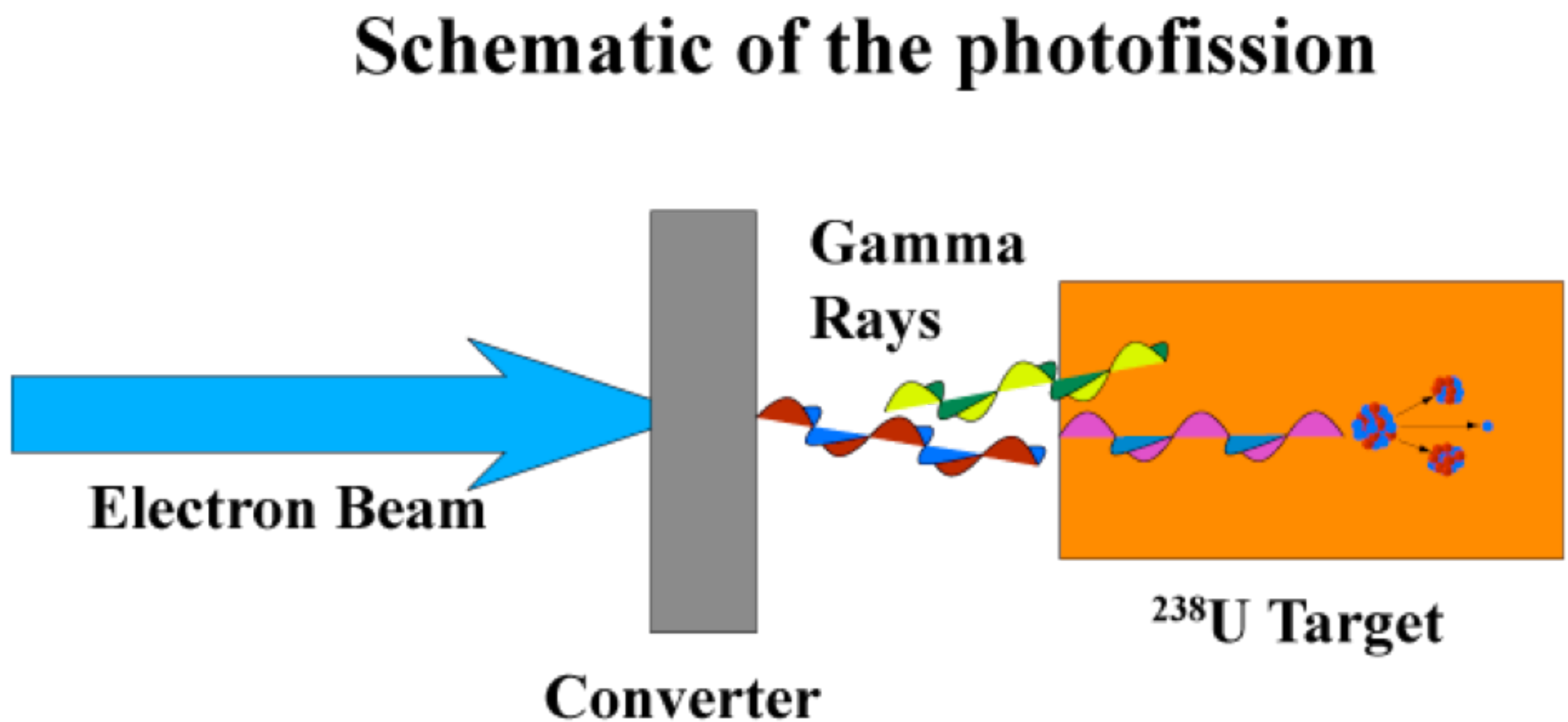
# SPIRAL-2


Spiral2
The SPIRAL2 facility
SPIRAL2 is one of the ESFRI list projects (45 most important EU research infrastructure projects)
LINAC:
33MeV p
40 MeV d
14.5 AMeV HI
Neutrons For Science
S3 separator-spectrometer
DESIR Facility low energy RIB
A/q=6 Injector option
Existing GANIL facility
A/q=2 source p, d, 3,4He 5mA
A/q=3 HI source Up to 1mA
HRS+RFQ Cooler
RIB Production Cave Up to 10^14 fiss./sec.
CIME cyclotron RIB at 1-20 AMeV (up to 10 AMeV for fiss.fragments)
CAENA
Calvados
Radioactive Ion Beam Production and High-Power Target Stations
September 16-18, 2013
GANIL
Eric Petit

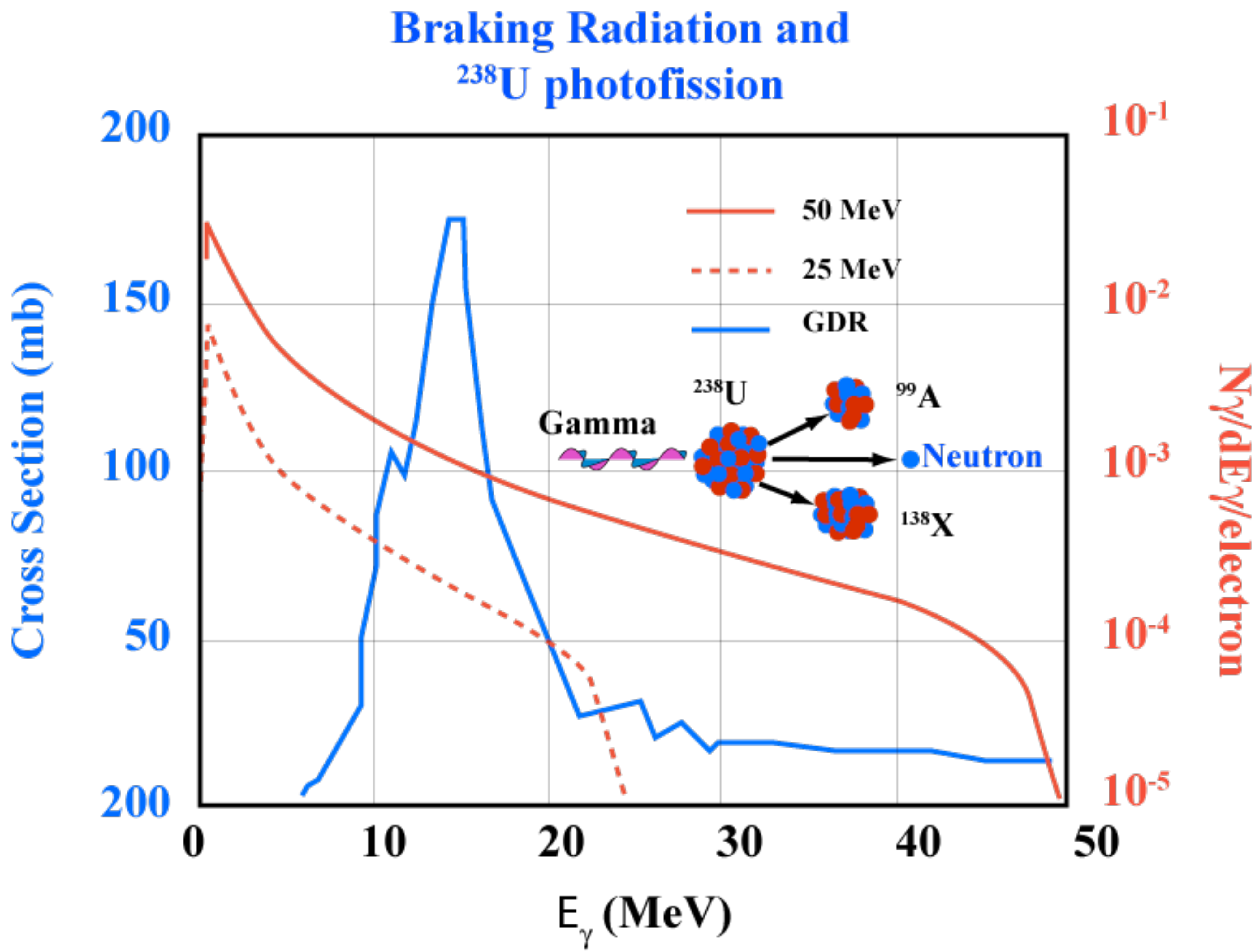
# RISP


RAON : RISP Accelerator Complex
RAON
High intensity RI beams by ISOL & IF
ISOL : direct fission of 238U by p 70MeV
IF by 200MeV/u, 8.3pμA 238U
High quality neutron-rich RI beams
132Sn with up to ~250MeV/u, up to 10⁸ pps
More exotic RI beams by ISOL+IF
ECR-IS-2
LEBT1
ECR-IS-1 (10 keV/u, 12 pμA)
RFQ1 (500 keV/u, 9.5 pμA)
MEBT1
SCL1 (~100 m)
• 18.5 MeV/u, 9.5 pμA
Driver Linac
Charge Stripper
SCL2 (~380 m)
• 200 MeV/u, 8.3 pμA for U+78
• 600 MeV, 0.66 mA for p
High-E Exp. Facility (II)
μSR
Bio-medical Research (High-E)
ISOL Target
MEBT2
RFQ2
LEBT2.2
A/q Sep.
HRMS
SCL3 (18.5 MeV/u, ~100 m)
CB
RF Cooler
Cyclotron (70 MeV p, 0.75 mA)
IF Target
IF system
LEBT2.1
ECR-IS-3
Post Accelerator
ISOL System
Gas Catcher
Fragment Separator
β-NMR
Neutron Science Facility
Large Acceptance Spectrometer (Low-E)
Bio-medical Research (Low-E)
Recoil Spectrometer
Low-E Exp. Facility
High precision Mass Measurement
Collinear Laser Spectroscopy
Ultra-Low-E Exp. Facility
Large Acceptance Spectrometer (High-E)
High Resolution & Zero Degree Spectrometer
High-E Exp. Facility (I)
ibS 기초과학연구원
Institute for Basic Science
4
RISP
Rare Isotope Science Project

# ARIEL using photo-fission



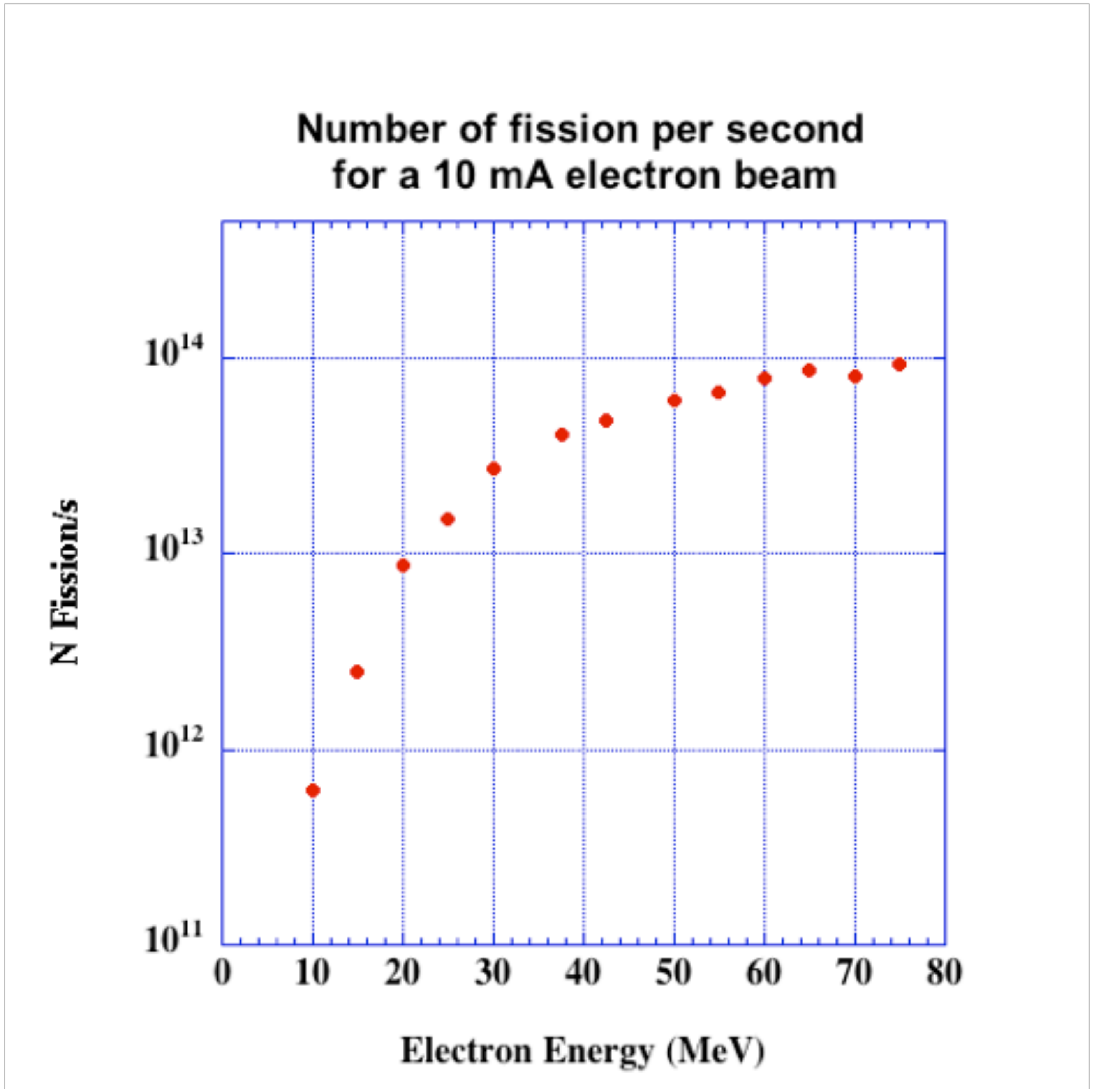
# Bremsstrahlung spectrum and GDR



# GEANT4 Simulation

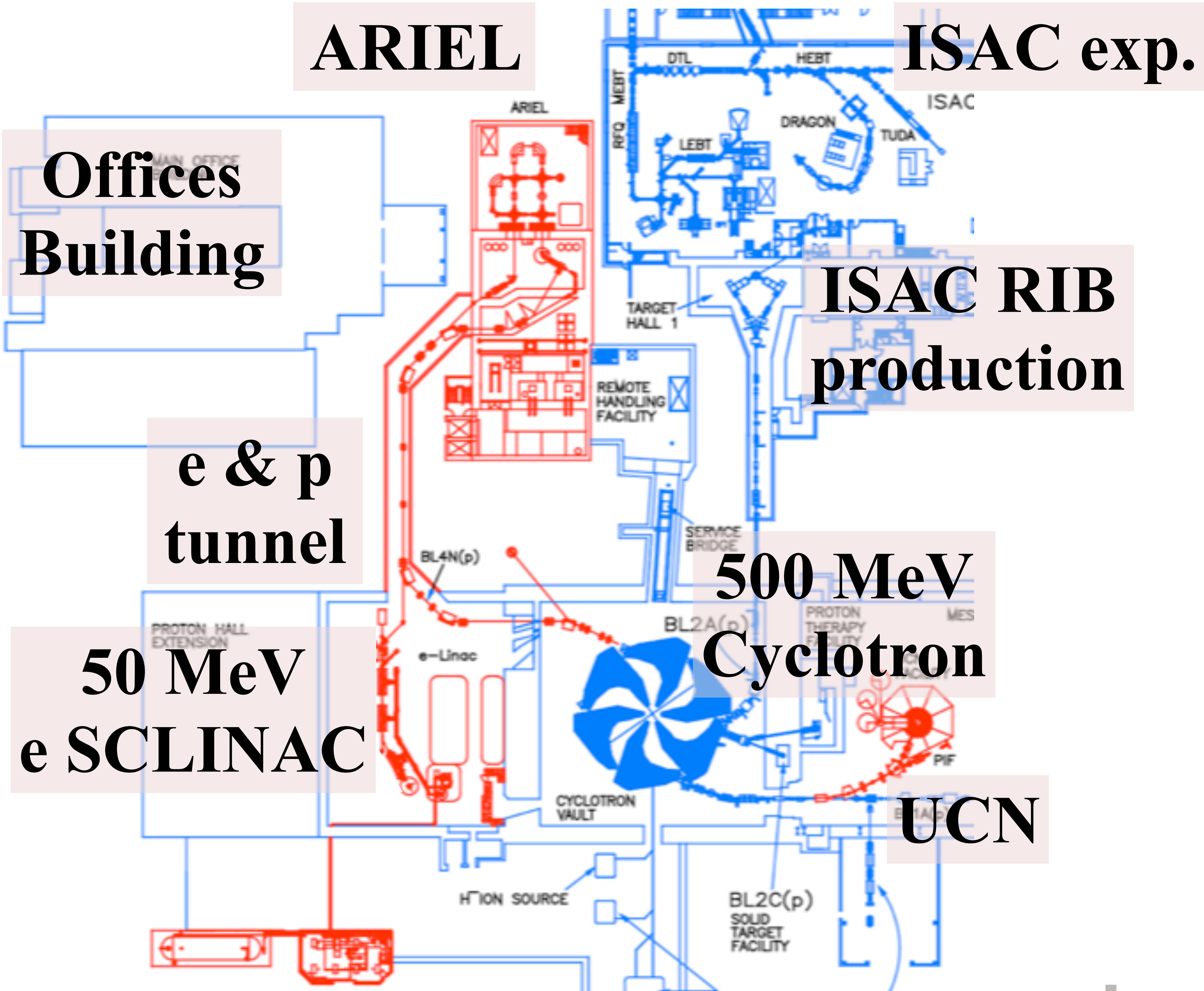
## Number of fission as a function of the electron beam energy

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



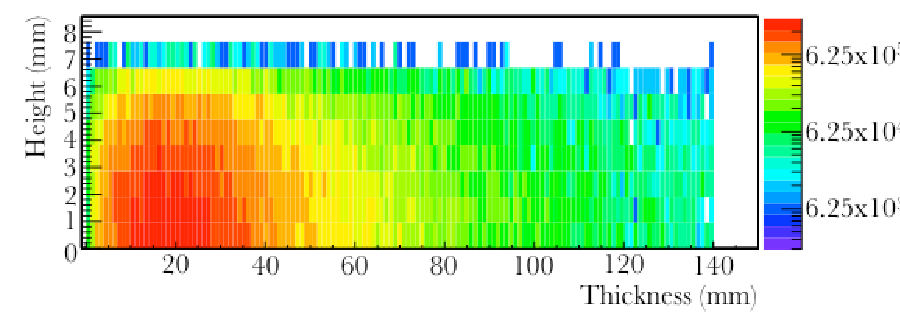
# TRIUMF: ARIEL projet

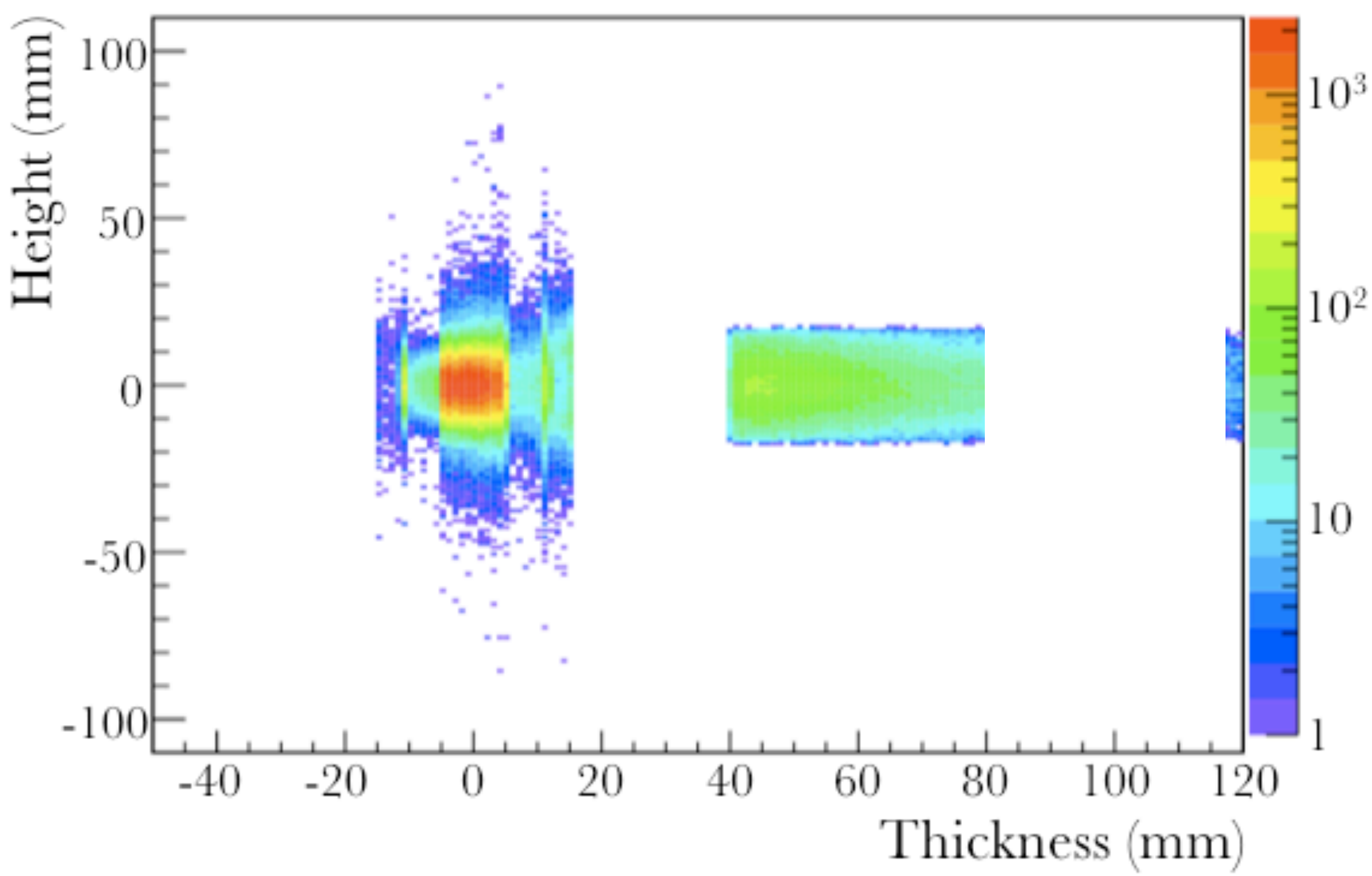
- Two components:
  - 50 MeV-10 mA SC electron LINAC
    - Photo-fission
  - 500 MeV-100µA proton beam
    - ISOL direct

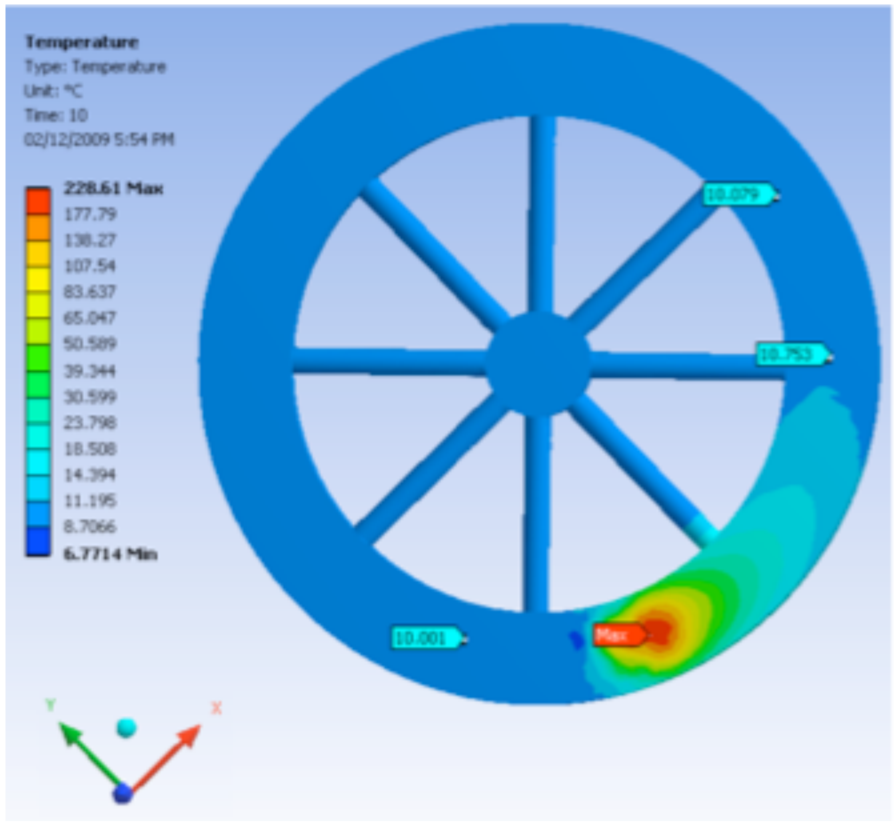


# ARIEL 500 kW

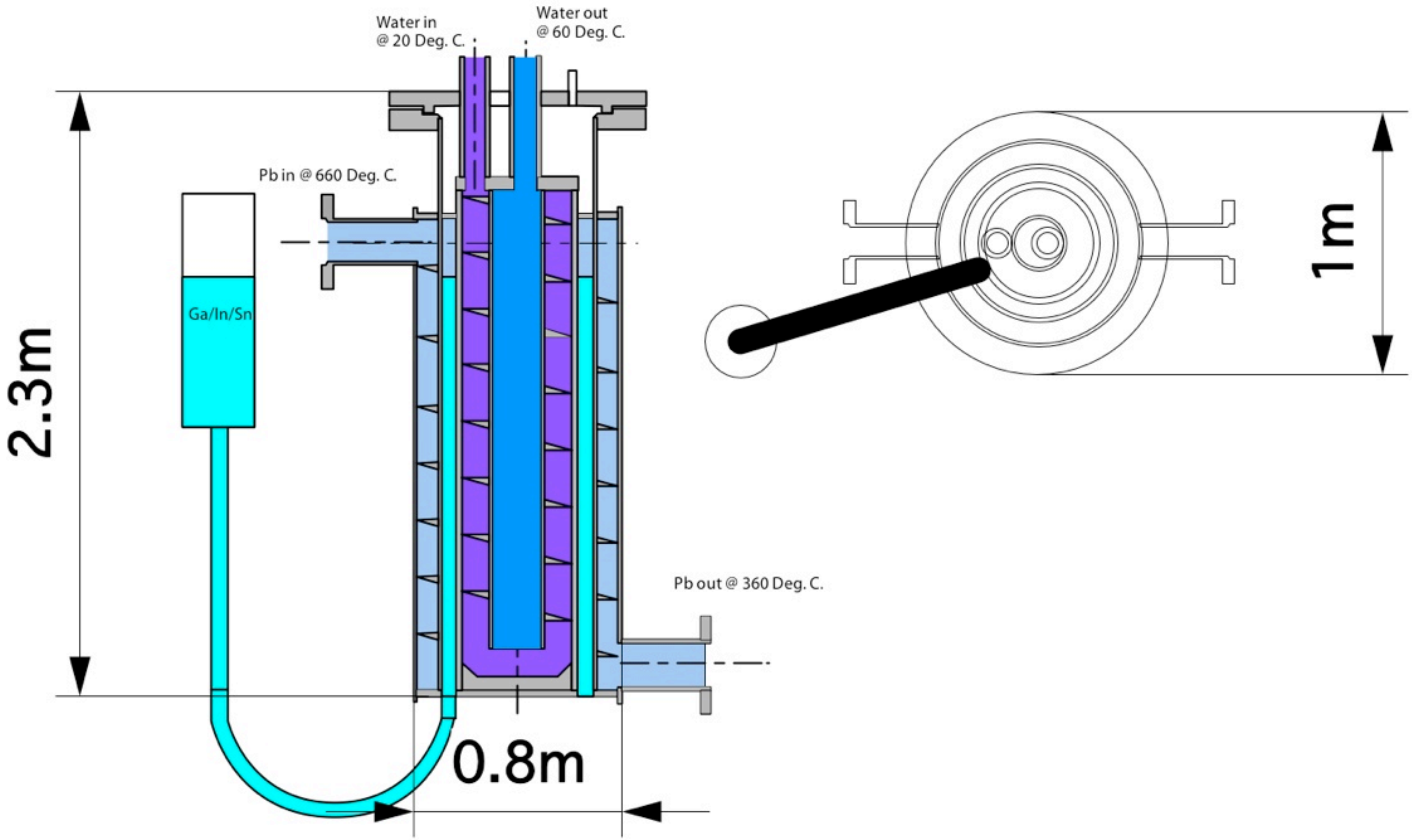
- Rotating water-cooled wheel, Pb and Ta converter and UC2/C target.
  - 274 kW in the converter, 120 kW in HS
  - 66 kW in the target.



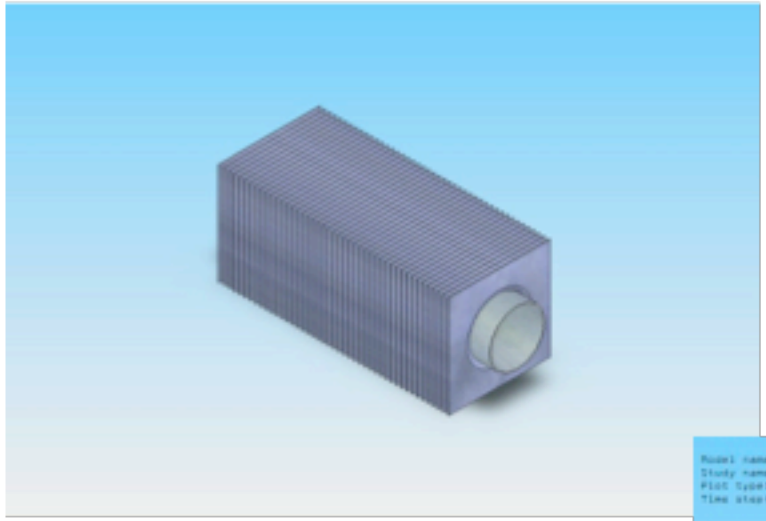
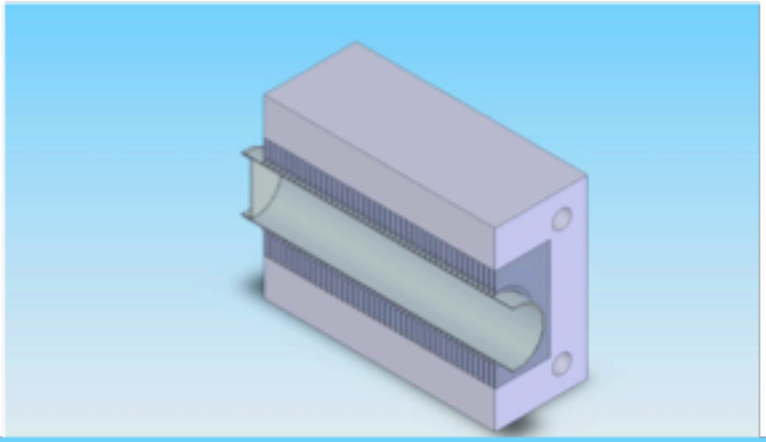
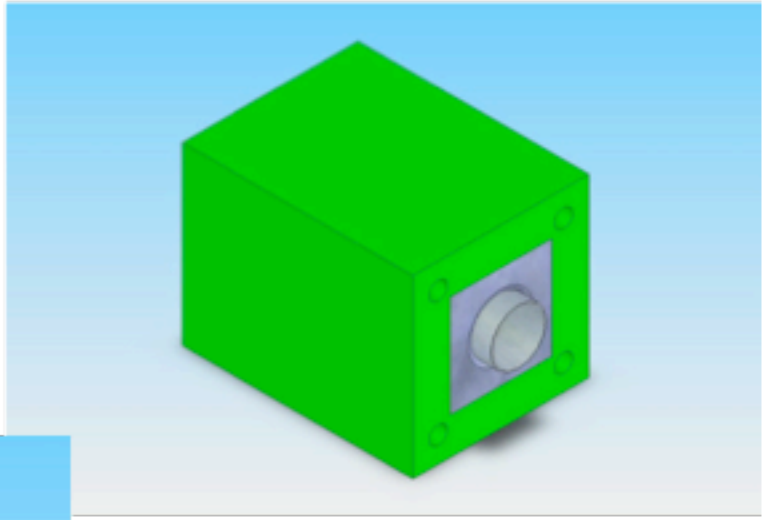
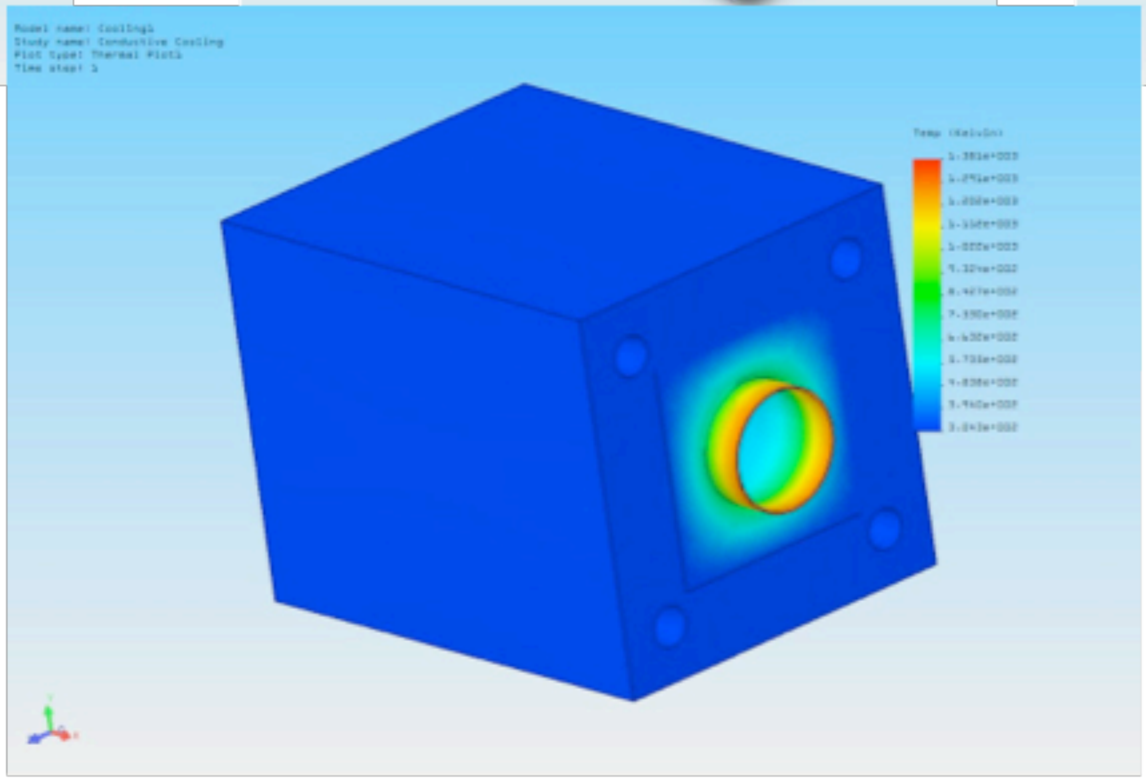



# Liquid Metal Heat Exchanger



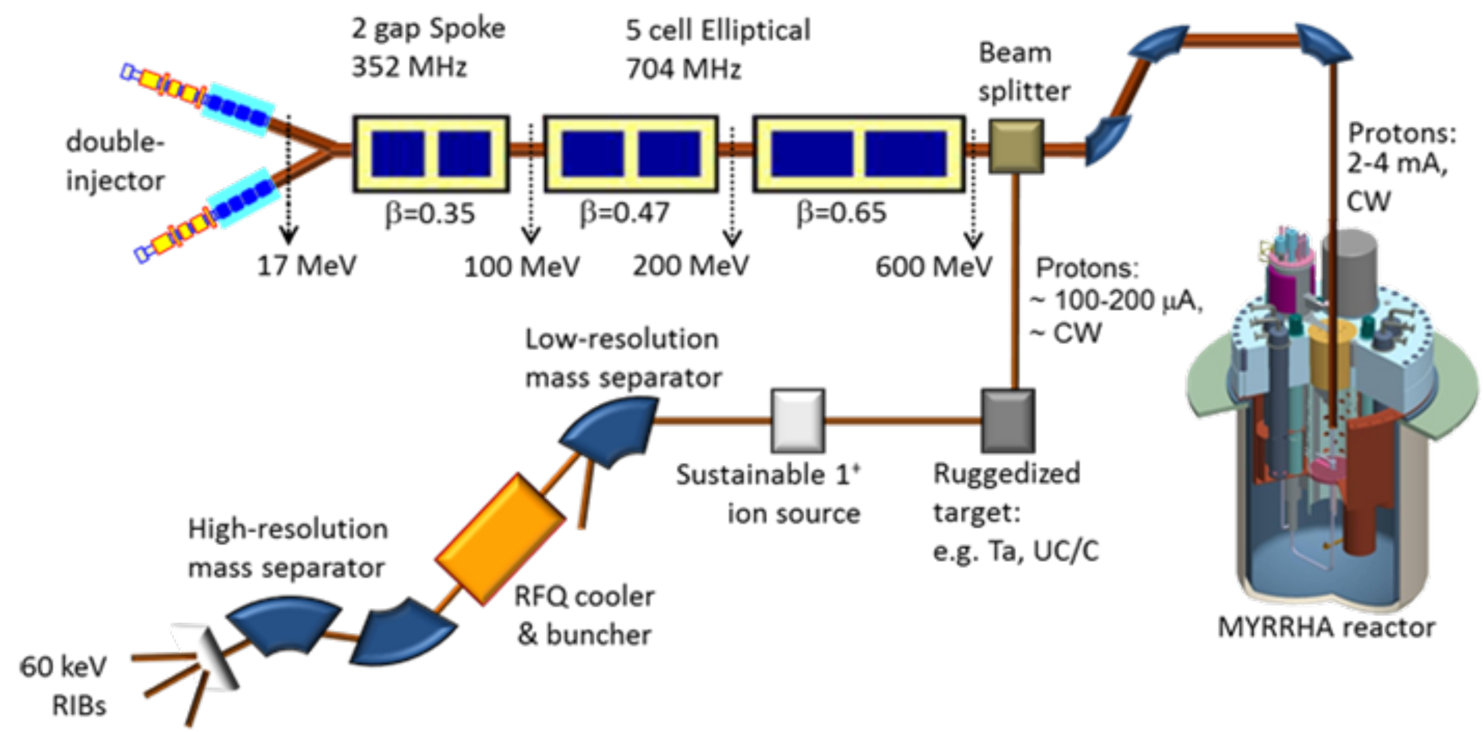
# Cooling Concept, ARIEL High Power Target

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

# ISOL@MYRRHA Concept

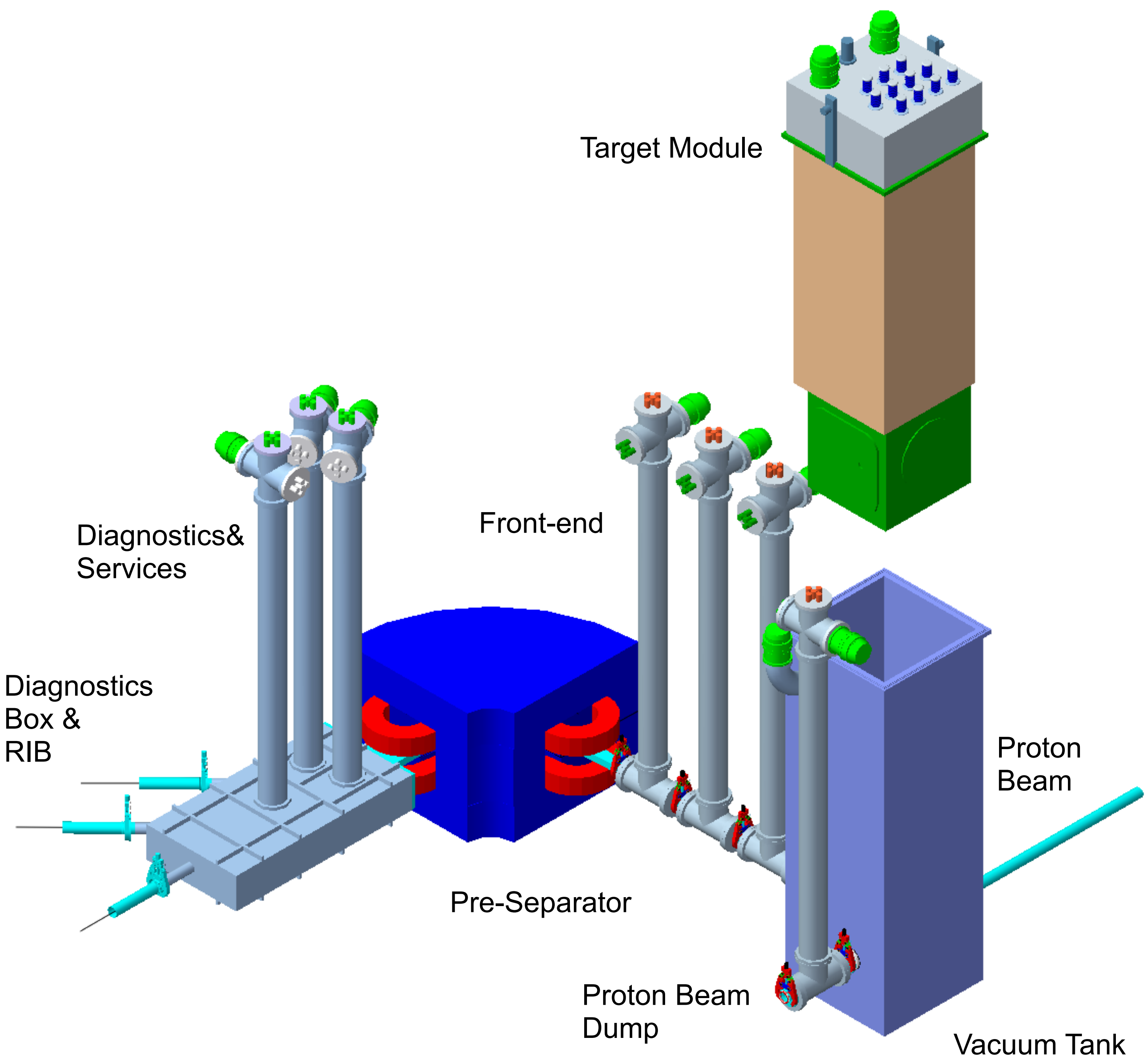
- **MYRRHA: Multi-purpose Hybrid Reactor is conceive as an accelerator driven system (ADS). Use fast neutron spectrum from spallation**




- Accelerator
  - Superconducting proton LINAC
  - High power LINAC: 600 MeV: 4 mA: CW
  - Ideal for isotopes production on-line,
- To verify the sub-criticality of the reactor, short proton beam interruption (200 μS).
  - ISOL@MYRRHA can utilize 100 to 200 μA proton beam in ~ CW
  - Possible extension of the ISOL@MYRRHA proton beam energy to 1.0 GeV
  - => next generation of ISOL facility.

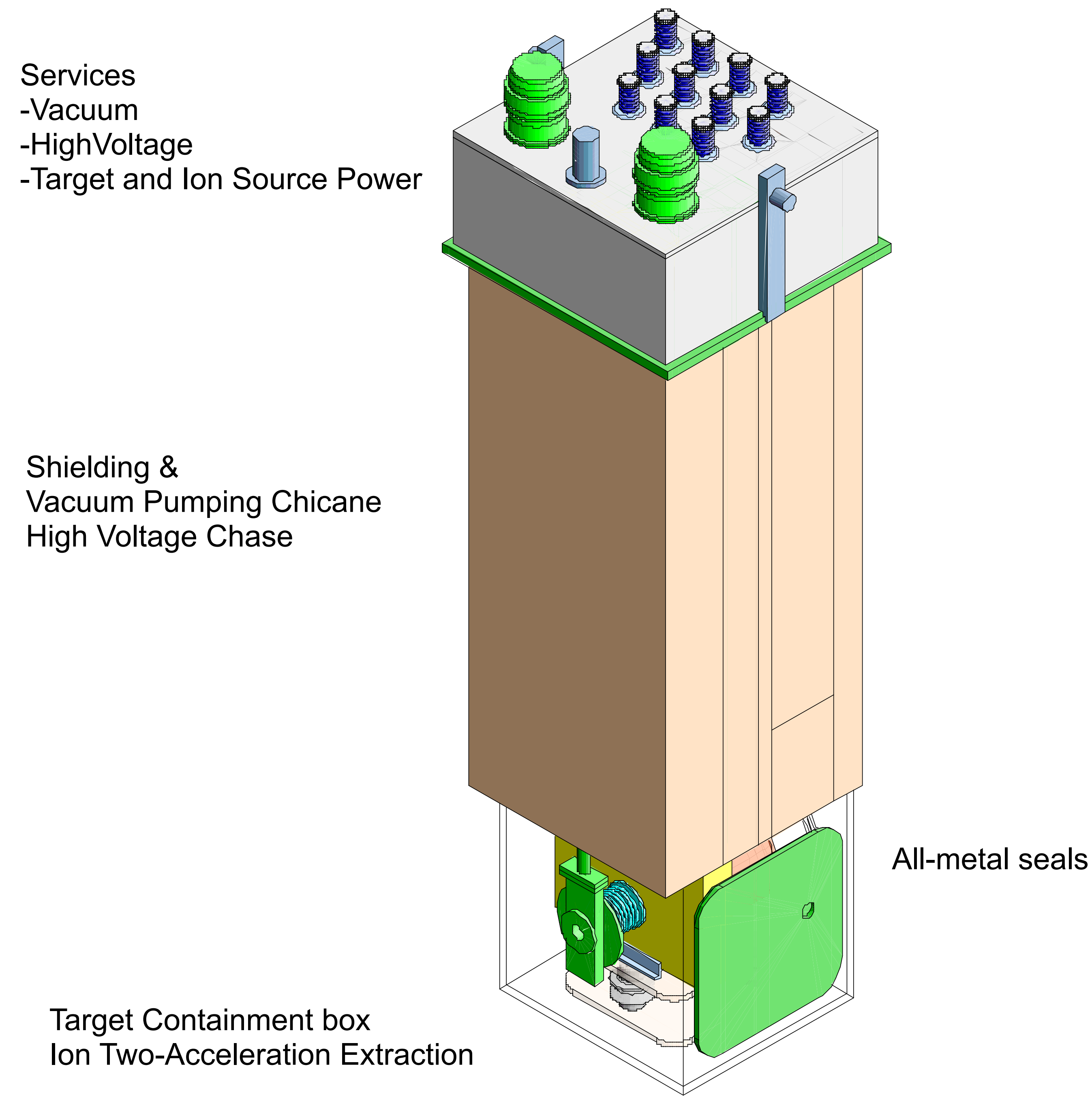
# ISOL@MYRRHA

- Target Station showing the target module insertion into the vacuum box.
- Two separate vacuum envelopes for better confinement.
- Front-end contains the optics and the vacuum pumps are located away from prompt radiation field.



# ISOL@MYRRHA TM

- Target Module, 2.5 m steel plug for shielding the components from prompt radiation.
- Vacuum pumps located behind shielding.
- Target containment box equipped with all-metal seals.
- Two-step acceleration for better RIB optics.



TRIUMF

# New Design Criterias

- **All metal seals,**
  - **Target/ion source operates in high radiation fields, and for longer period of time,**
    - **Elastomer joints (O-ring) cannot be used, they are destroy in less than one day.**
- **Vacuum tight target containment box,**
  - **Mitigate the risk of spreading contamination,**
  - **Allow usage of air sensitive target materials, ThC, UCx, LaC, ...**
- **Two-step acceleration system,**
  - **No movable parts in high radiation fields.**
- **Remove brazed and soldered joints in vacuum.**
  - **Improve reliability by using only electron-weld joints instead.**

# Summary

- Contrary to other high power target, the ISOL target have to operate at the optimum temperature to speed the release.
  - Temperature must be uniform over the whole target,
  - Target is couple to the ion source, must avoid pressure overload,
    - Cold transfer tube for volatile species only help.

- **Techniques were developed to reach high power beam on ISOL target,**
  - **Target material capable of operating at very high power deposition using composite target fabrication.**
  - **Target oven equipped with fins to enhance the emissivity allow power dissipation up to 20 kW.**

TRIUMF

# Summary

- Indirect ISOL target method allows to disentangle the cooling problem of the converter and the ISOL target.
  - Can reach higher power using secondary neutrons
    - But radioactive ion beams limited to fission products.
- New target concepts for high power direct ISOL are being proposed,
  - Liquid metal, LBE, salt
  - Powder flow

***Thank You***

***Merci***