



Progress in development of ISOL RIB ion sources and targets for high power

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TRIUMF

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CANADA'S NATIONAL LABORATORY FOR
PARTICLE AND NUCLEAR PHYSICS
LABORATOIRE NATIONAL CANADIEN
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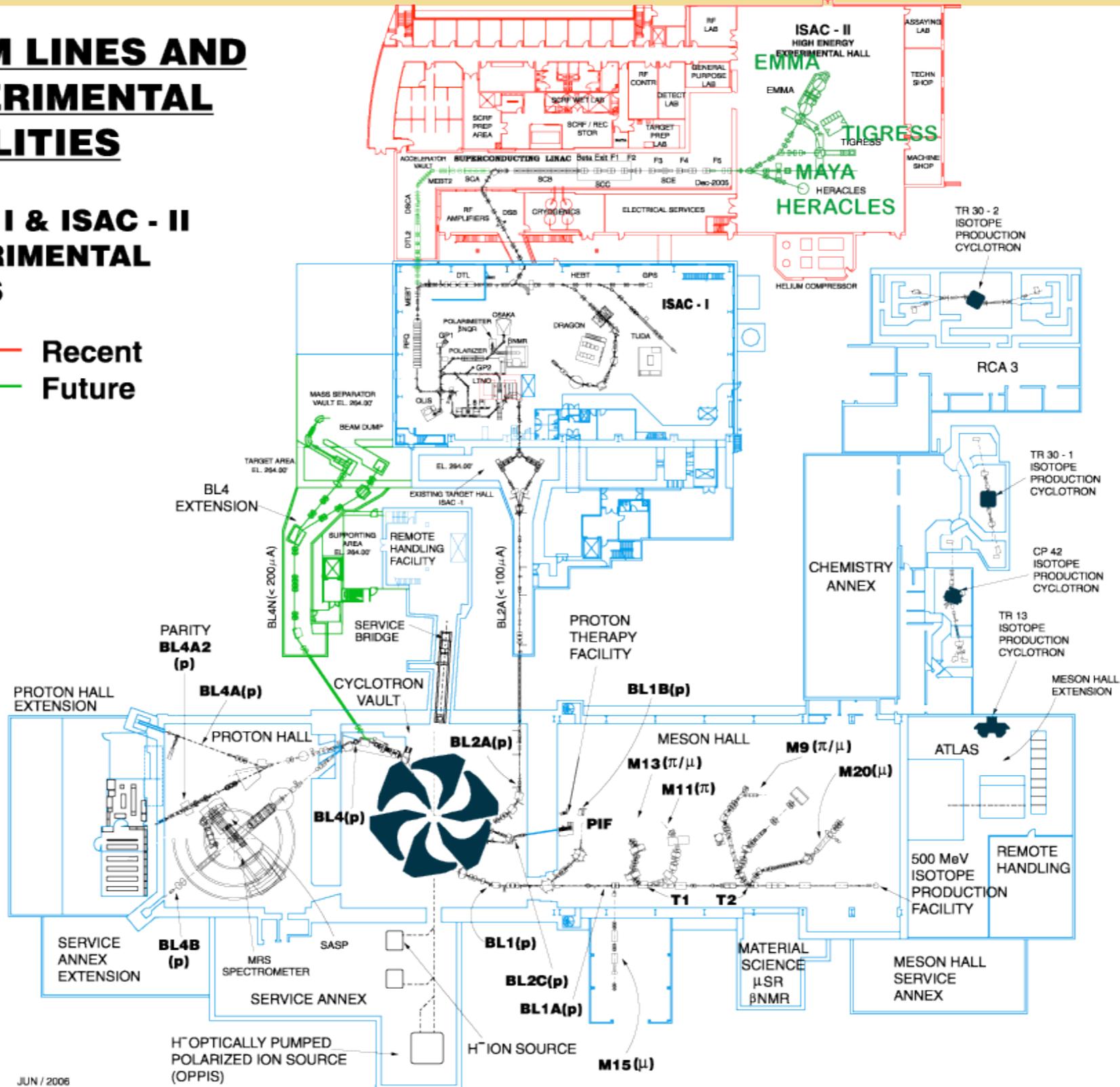


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BEAM LINES AND EXPERIMENTAL FACILITIES

ISAC - I & ISAC - II EXPERIMENTAL HALLS

— Recent
— Future



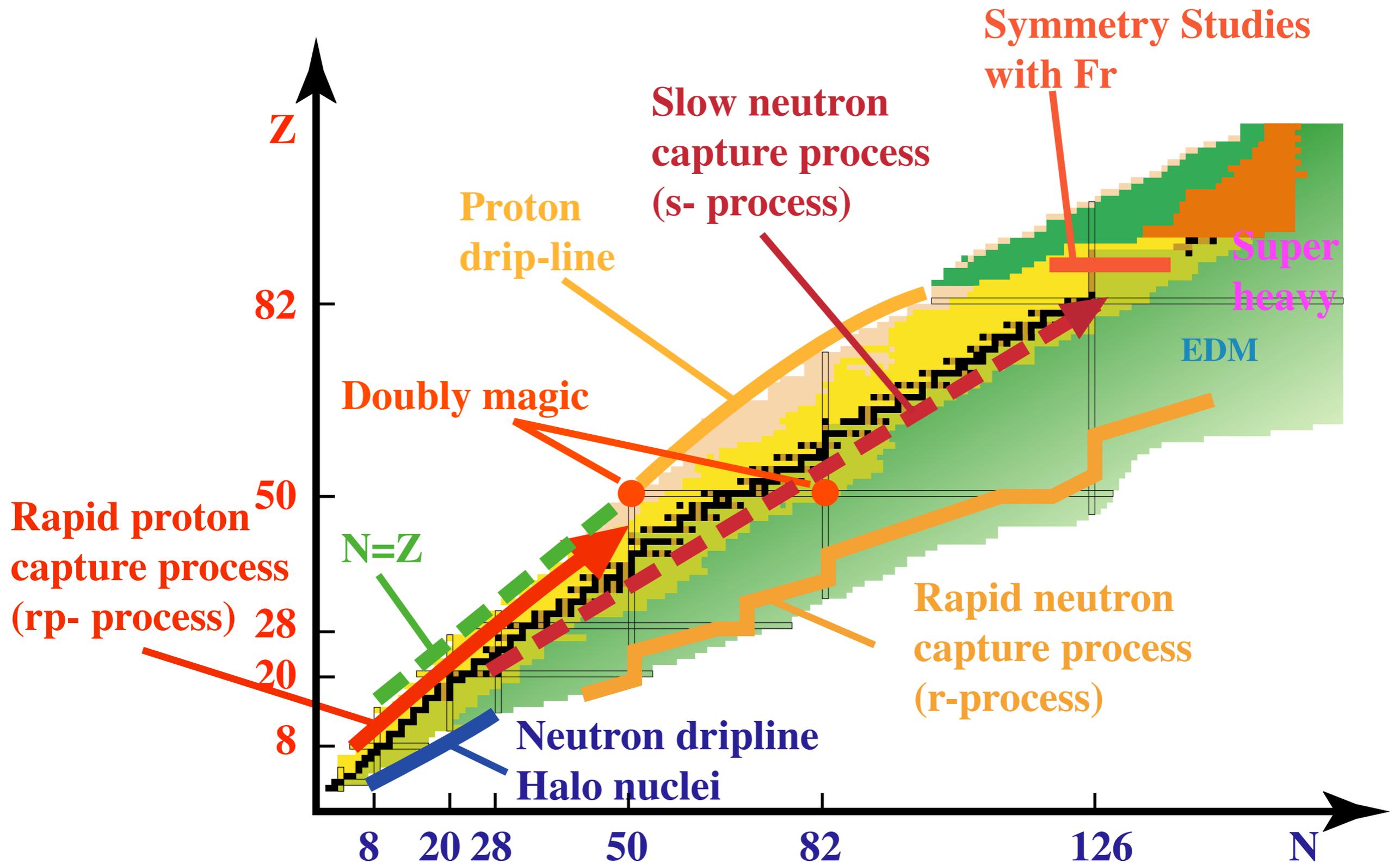
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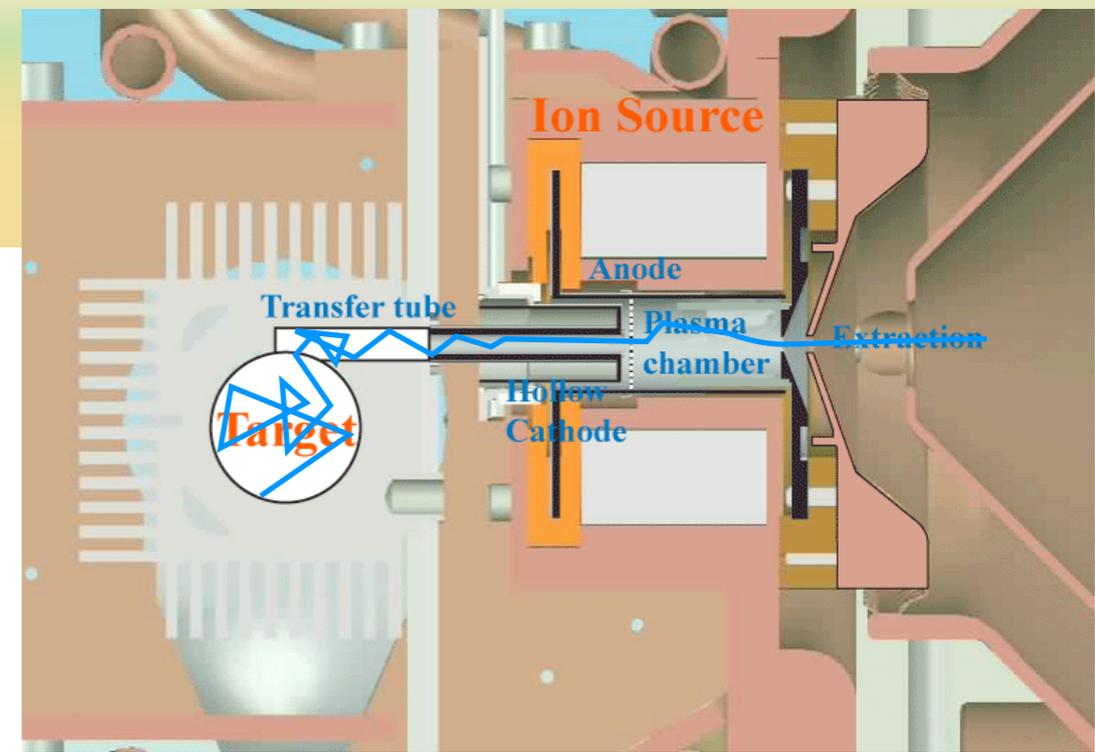
Outline

- **Introduction to RIB production using ISOL method**
- **Target Development**
 - **Composite targets**
 - **High Power Targets**
- **On-Line ion source development**
 - **Resonant Laser Ion Source**
 - **FEBIAD Ion Source**
 - **ECR Ion Source**
- **Future plans for TRIUMF RIB facility**
- **Summary**

Physics with RIB



ISOL Method



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

The fragments produced are stopped into the bulk of the target material

The radioactive atoms diffuse out of the target material matrix. => Diffusion process.

Then the radioactive atoms effuse out of the oven to the ion source . => Effusion process.

The radioactive atom is ionized => Ionization process.



ISOL method: Yield

The yield depends on the following parameters:

$$Y = \Phi \sigma \chi \varepsilon_R \varepsilon_E \varepsilon_i,$$

Φ = Incident beam intensity,

σ = Cross section,

χ = Target thickness,

ε_R = Diffusion efficiency, $f(D_0, E_A, T)$

ε_E = Effusion efficiency, $f(\chi, \Delta Ha, T)$

ε_i = Ionization efficiency.



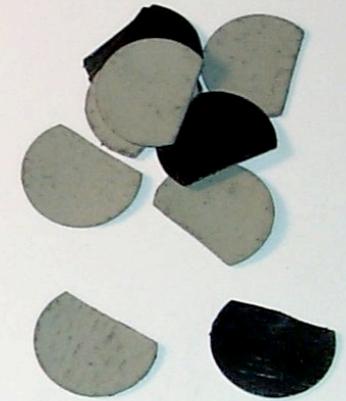
ISOL Target Development

- Target used at ISAC, refractory metals, Ta, Nb, ...
- Foils of thin layers of refractory carbides (SiC, TiC, ZrC, LaC₂ ~ 0.1 mm thick) deposited on flexible exfoliated graphite sheet
- Development of the composite foil technique has allowed carbide target operation with up to 70 μA proton beam.

Refractory Foils



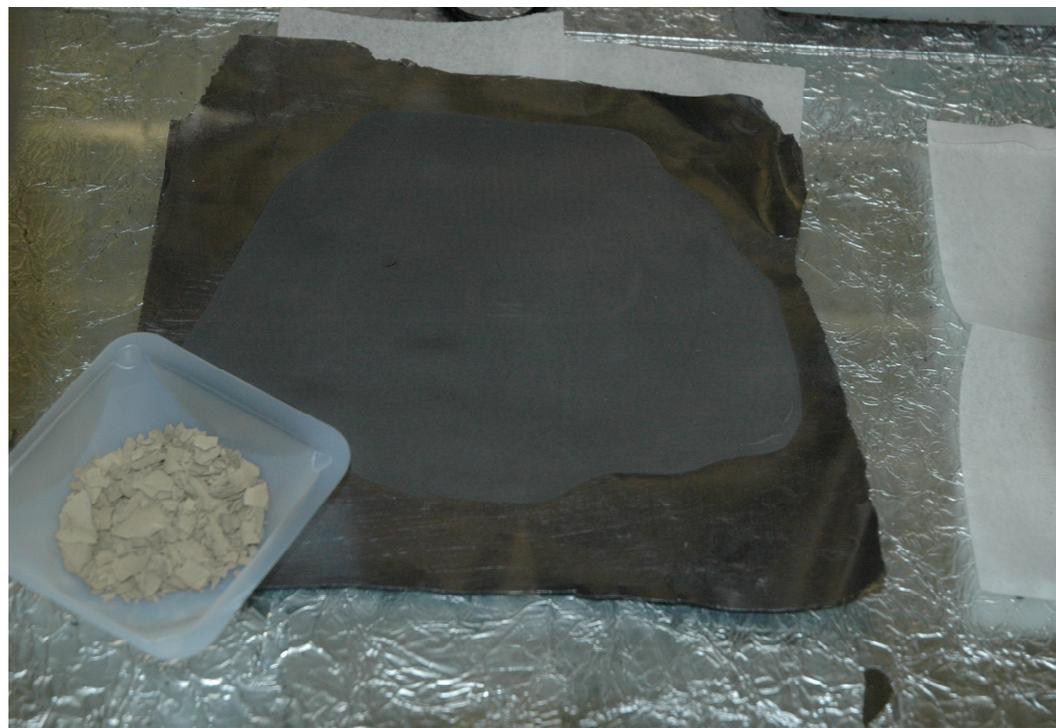
Composite Carbide Foils



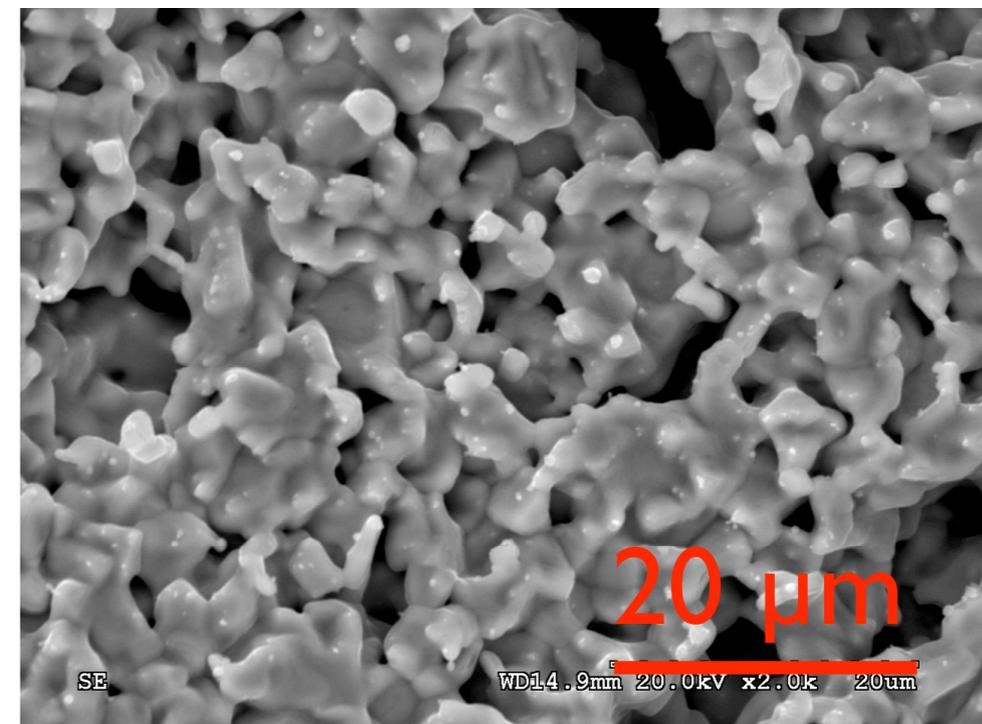
Tantalum Container
20 cm long
20 mm Diameter

Composite Targets

- To dissipate the power for the composite carbide target we developed a new technique. Using a slip cast method, the carbide target material is bounded onto an exfoliated graphite foil (0,13 mm thick).
- The target is then cut out of the cast and inserted into the Tantalum target container.



Slip cast onto exfoliated graphite foil (0.13 mm thick)



Electron Scan of the LaC₂ after slip cast and sintering at 1600 °C.



High Power Target

1986	Eaton & Ravn, CERN/ISOLDE: 100 μ A, 550 MeV, proton	Longitudinal fins on the Ta container
1991	Talbert et al., 100 μ A, 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
1991-1996	Nitchke, LBNL: 100 μ A, 800 MeV, proton Talbert et al., 100 μ A, 600 to 1200 MeV, proton Bennett, RAL: 100 μ A, 800 MeV, proton	Active conductive cooling using He gas flow. Active conductive cooling with thermal barrier Passive radiative cooling approach.
1998	Talbert et al., 100 μ A, 500 MeV, proton	Active conductive cooling using water channels. Test at TRIUMF at 100 μ A, 500 MeV, proton
1999	Bennett, RAL: 100 μ A, 800 MeV, proton Rutherford Ion Source Test, RIST project	Built a diffusion bounded Ta target, off-line test shows that emissivity $\sim 0,7-0,8$.

RIST target



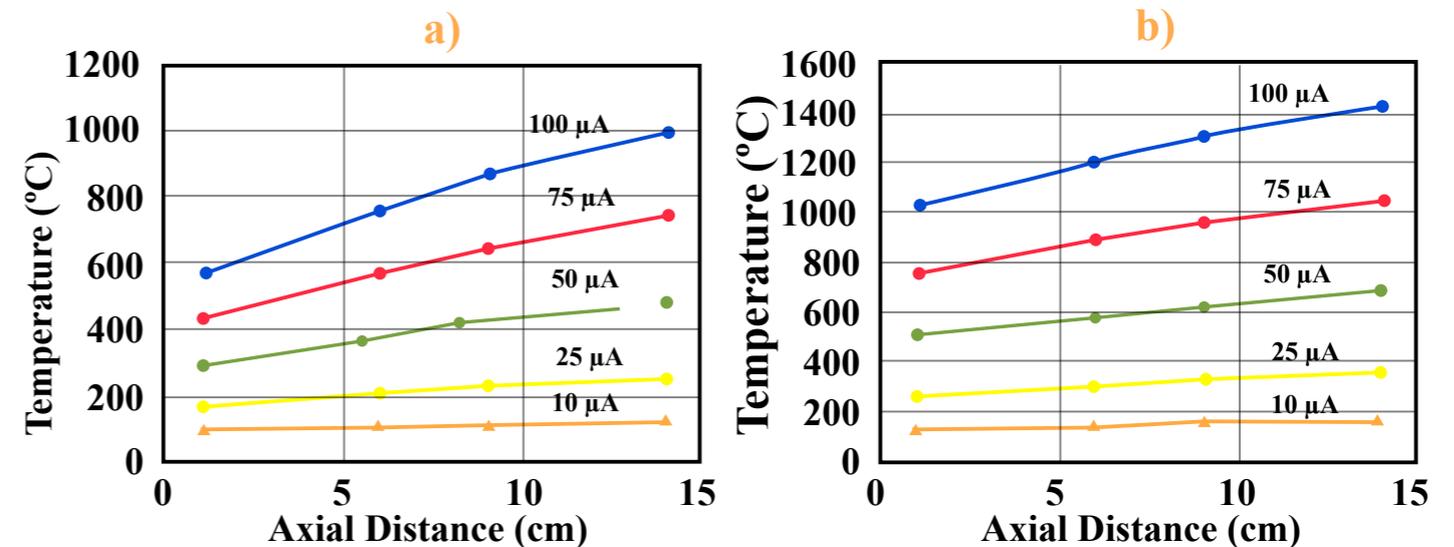
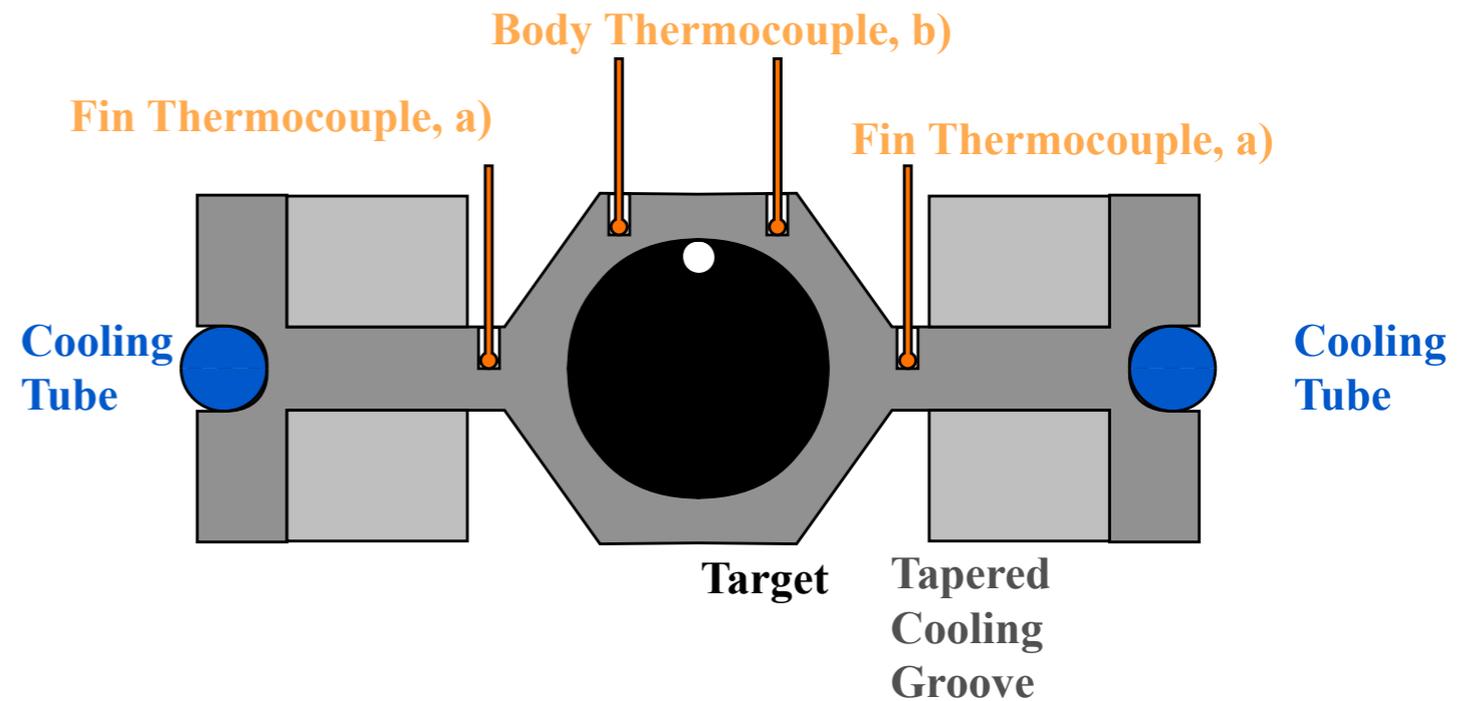
Target difficult to fabricate.

Very expensive target \approx £50 k!

Photo Courtesy of Roger Bennet, RAL.

- The RIST target was never put into practice, the test was never approved and further research on the subject abandoned.**
- This design allows only target made from refractory metals, Ta, Mo, ... Limiting the production of RIB species.**

Diffusion bounded Mo target



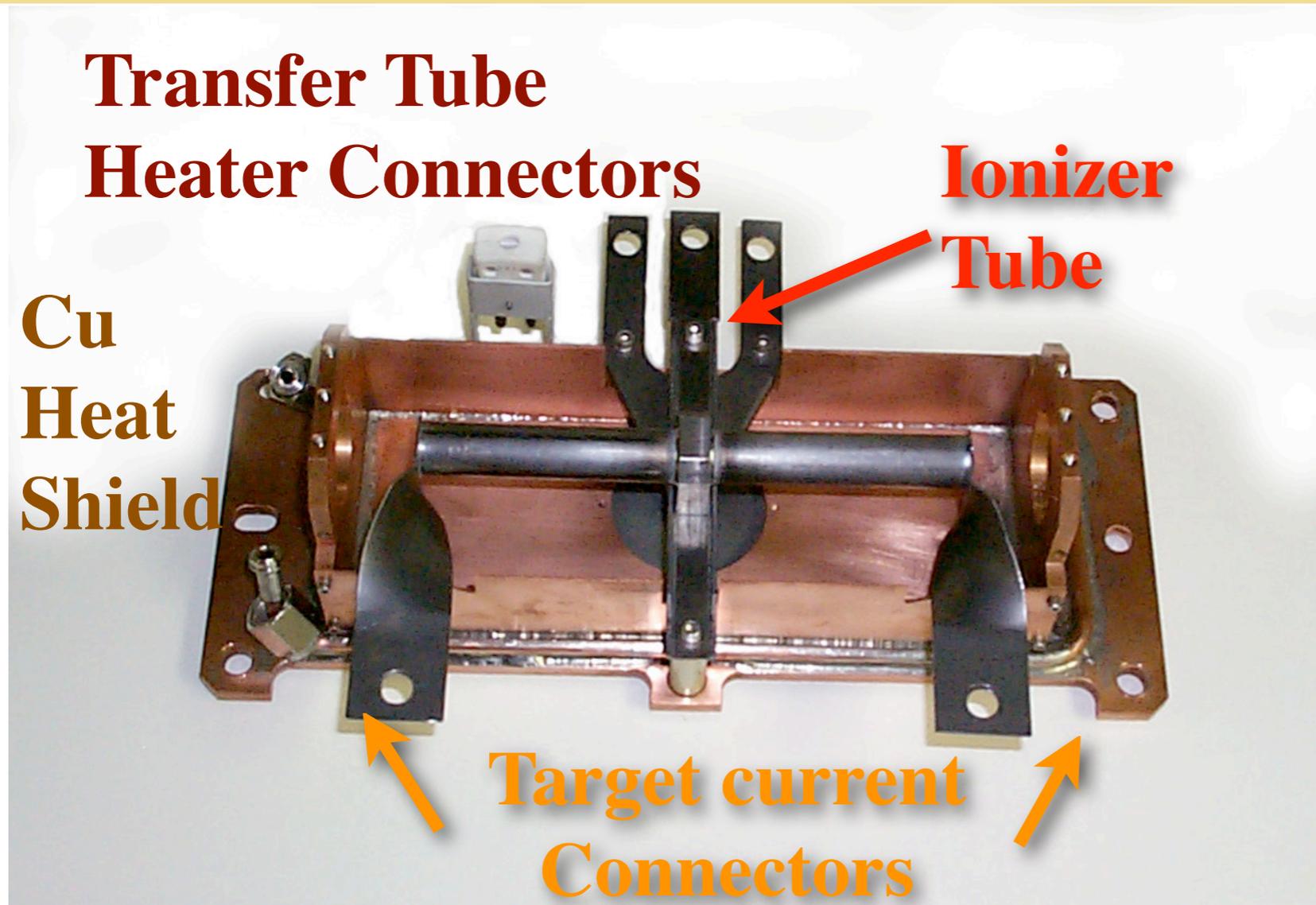
- The target temperature lower than the requested operating temperature, 2000 °C
- This design allows only target made from refractory metals, Ta, Mo, ...
- This is somehow limits the production of RIB species.



HPT development

- **Even though the ISAC facility has been designed for 100 μA , at the beginning (1998) it was not possible to operate the target with more than 1-3 μA .**
- **In 1999 a Nb foil target was operated with 10 μA .**
- **In 2000 both the Ta and Nb target were operated with 20 μA , and a SiC made from pressed powder into pellets was operated with 10 μA .**
- **In 2001 the proton beam intensity was raised to 40 μA on Ta and SiC/graphite composite target. This was obtained by removing all the thermal heat shield around the target and by reducing the target heating, while maintaining the target central temperature at the same value.**

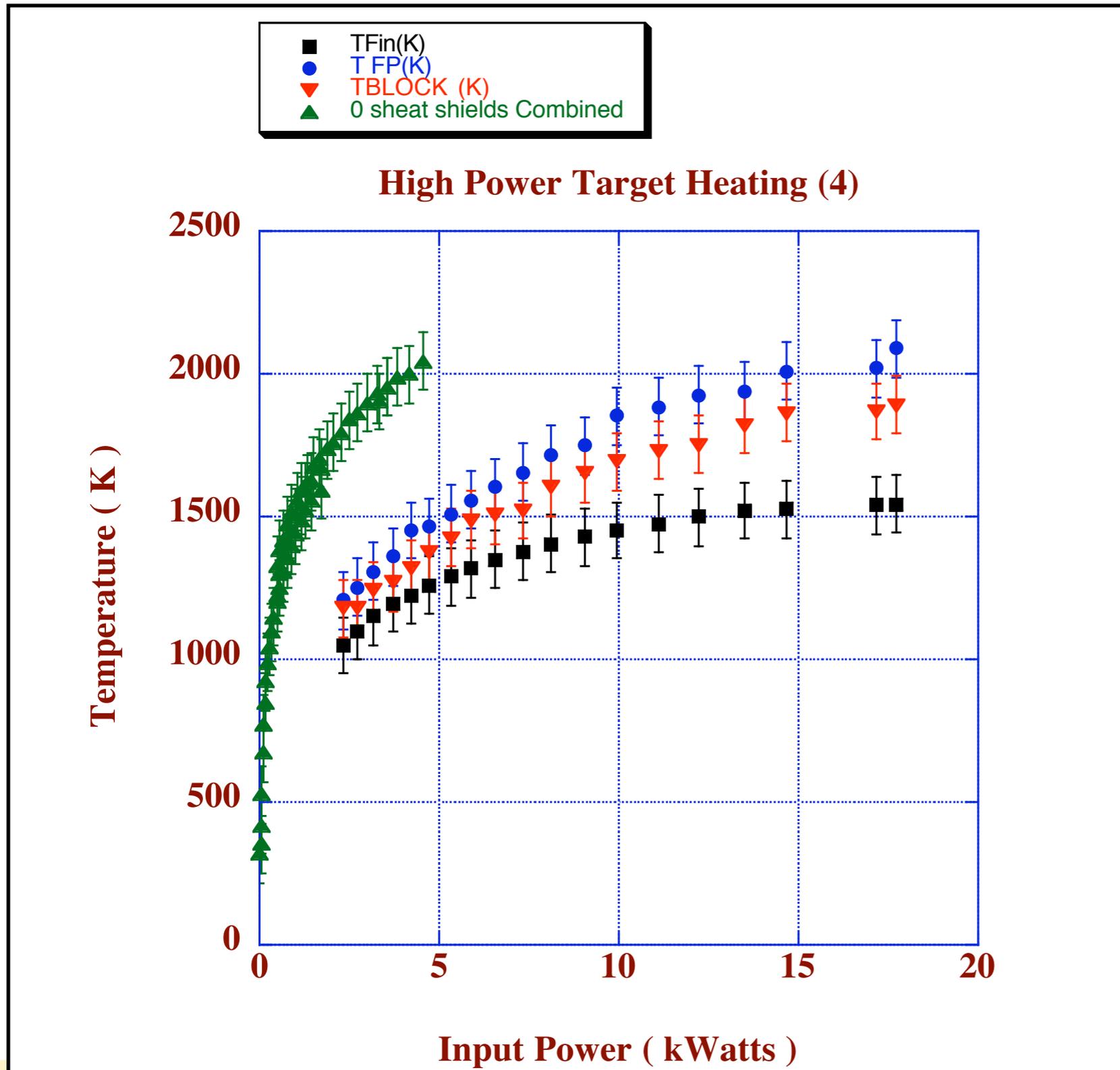
ISAC Target



**Initial Design
can only
dissipate
4-7 kW in the
target.**

- **With this target design we can go as high as $40 \mu\text{A}$.**
- **To go beyond this limit we have to add more effective cooling.**
- **We developed our own radiative cooling target by adding fins to the tantalum target container.**

High Power Target



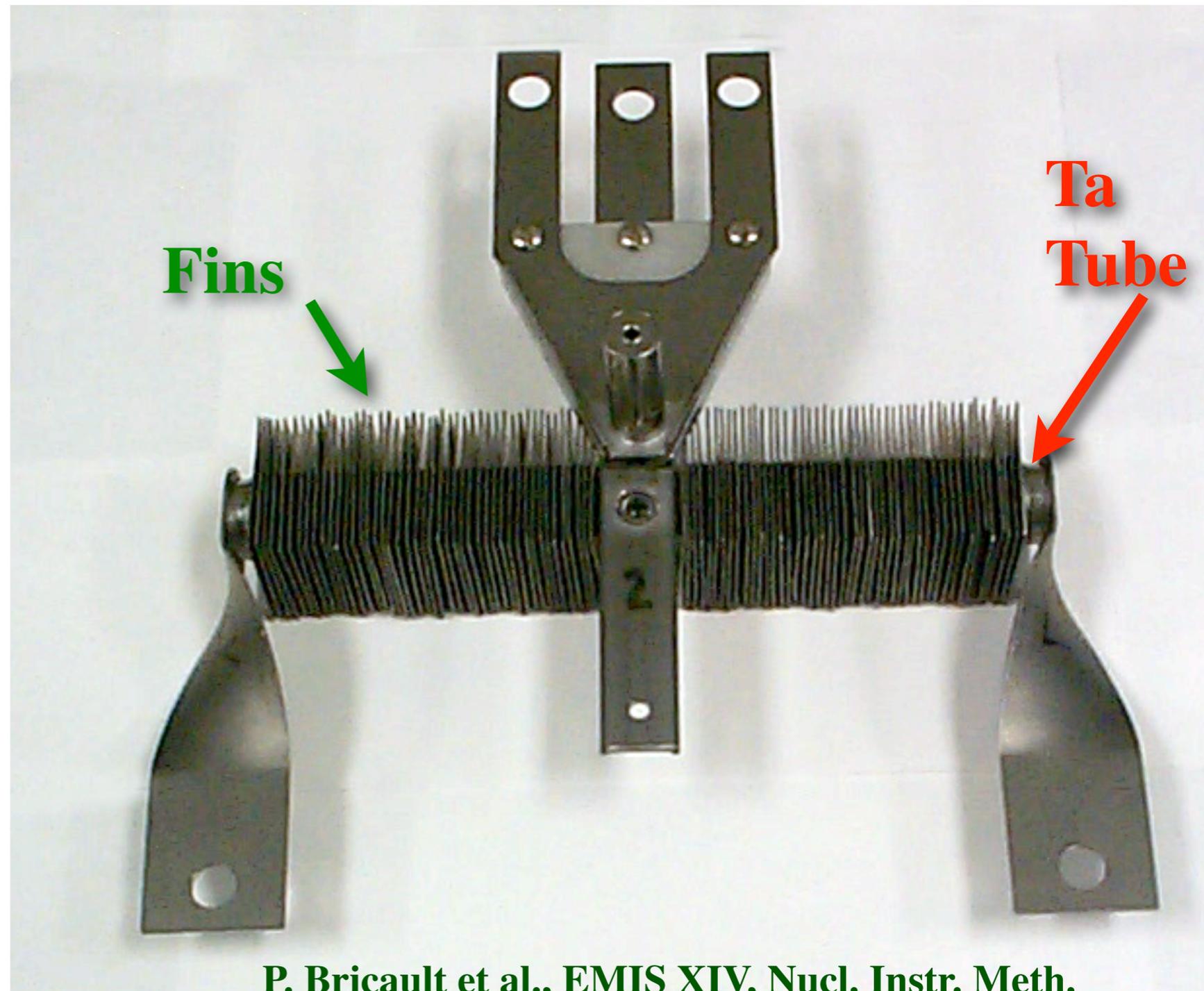
Improve the cooling by adding fins onto the target container. Emissivity: 0,92.

We demonstrated that a target equipped with fins can dissipate up to 17.5 kW.

High Power Target

Contrary to other designs we can use any target material, refractory metals or composite carbides or oxides, inside the Ta target container.

We demonstrated the operation of our HPT at $100\mu\text{A}$ level for a 500 MeV proton beam.



P. Bricault et al., EMIS XIV, Nucl. Instr. Meth.

Ion Sources

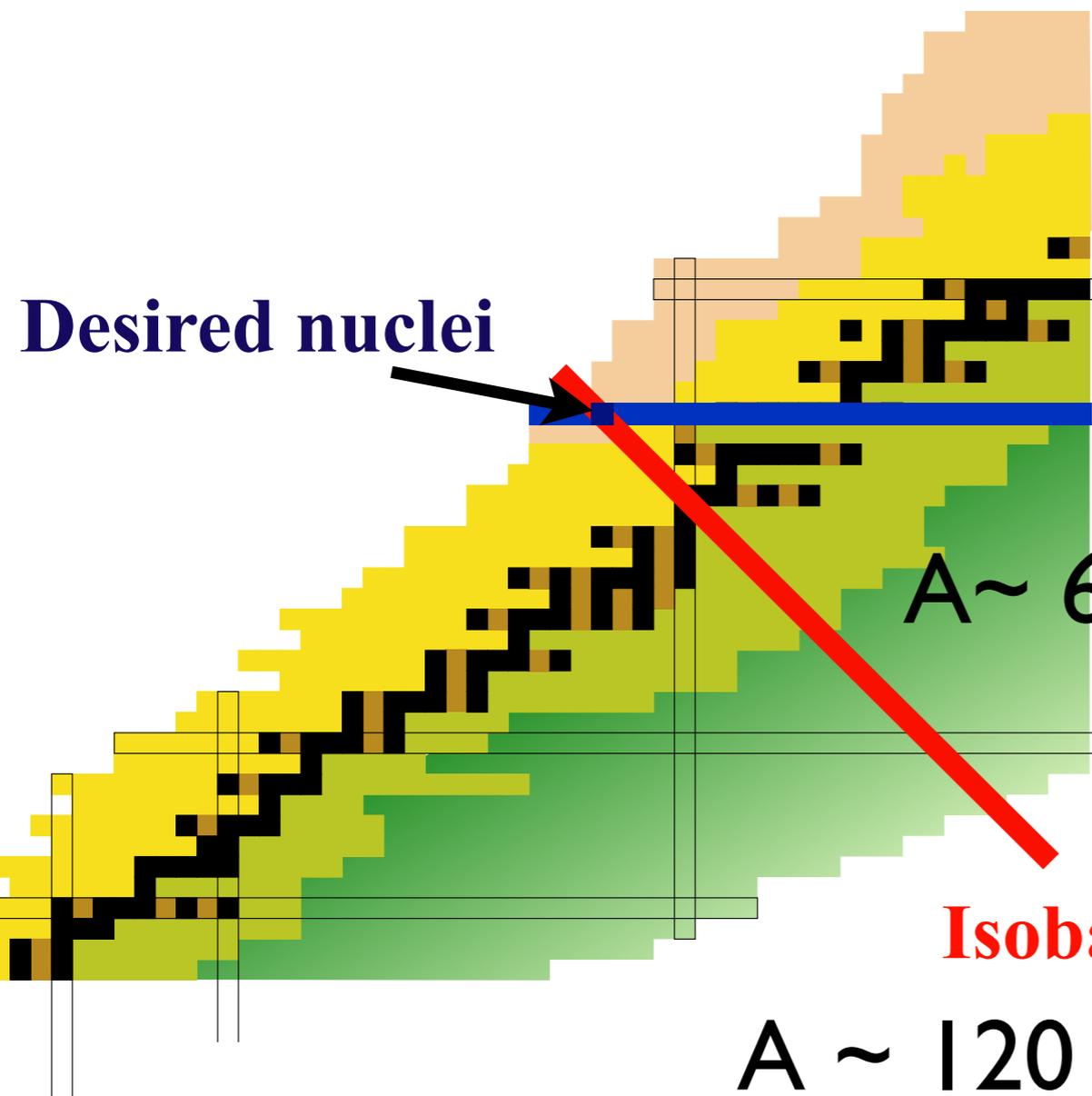
- **The requirement for an ISOL ion source diverge from to a certain degree from the ones for an off-line ion source;**
- **Because the production rate is somehow limited, We need highly efficient ion source,**
- **Ionization efficiency most be independent of the pressure fluctuation,**
- **Ion source free of instabilities in order to prevent reduction of the mass resolving power,**
- **Has to operate in high radiation field and at high temperature to avoid condensable element to stick on the walls,**
- **Maintenance free and long life-time,**
- **Small size to avoid large nuclear waste inventory.**



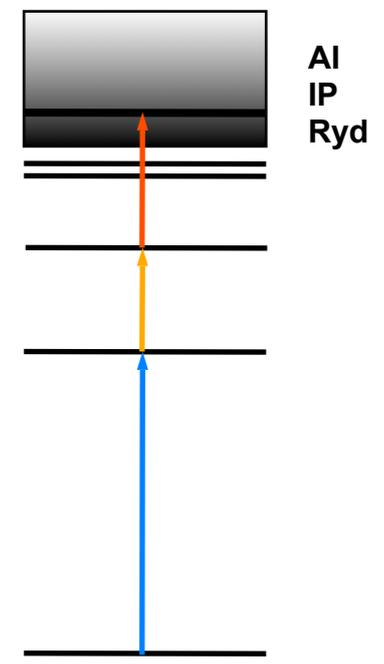
Laser Ion Source

Advantage in RIB production using Resonant Laser Ion Source (RLIS)

Resonant Ionization LIS
 -> element selective
 -> isobar free beams



$$R = \frac{m}{\delta m} = \frac{A}{1}$$

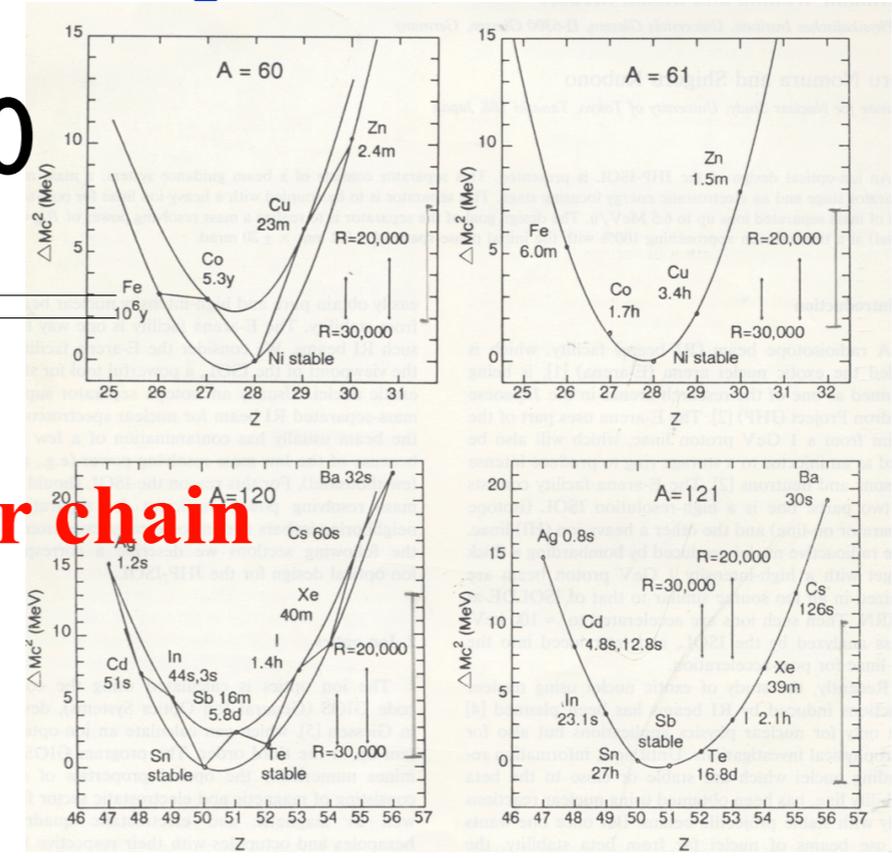


Isotopic chain

A ~ 60

Isobar chain

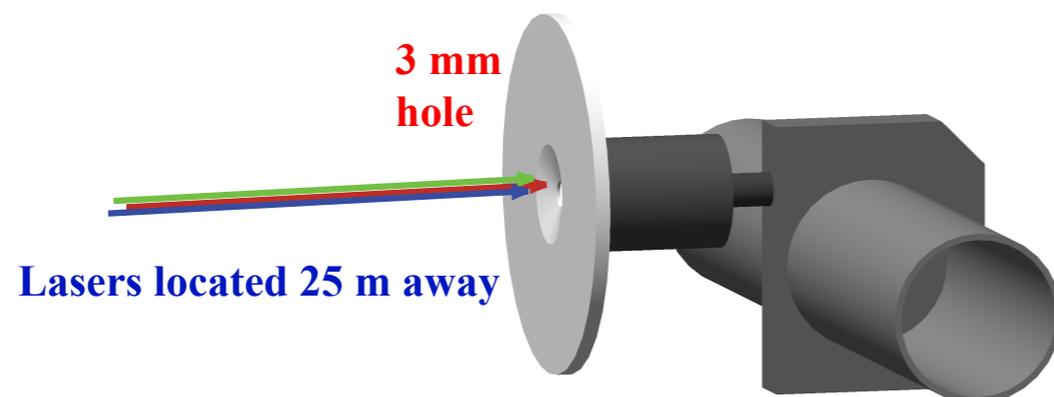
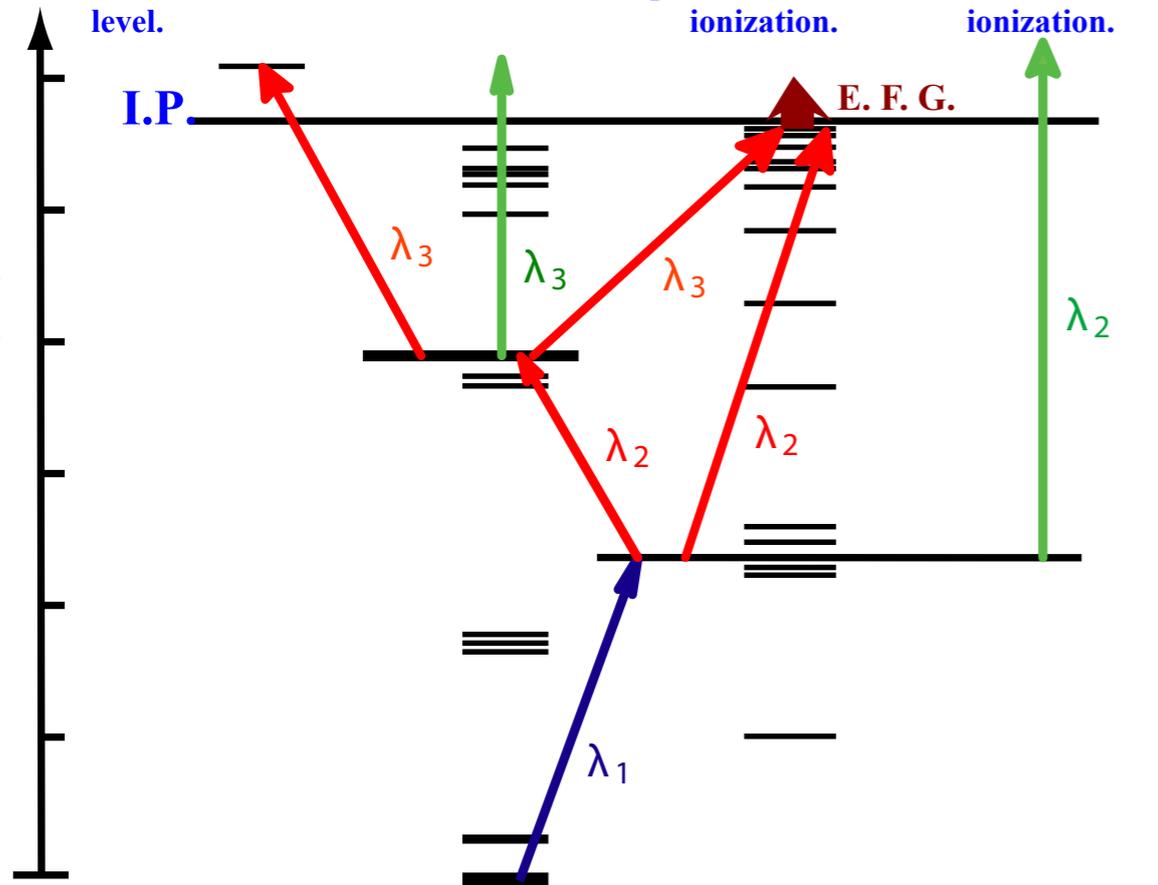
A ~ 120



Resonant Laser Ion Source

Principle of the Resonance Laser Ion Source (RLIS) ●

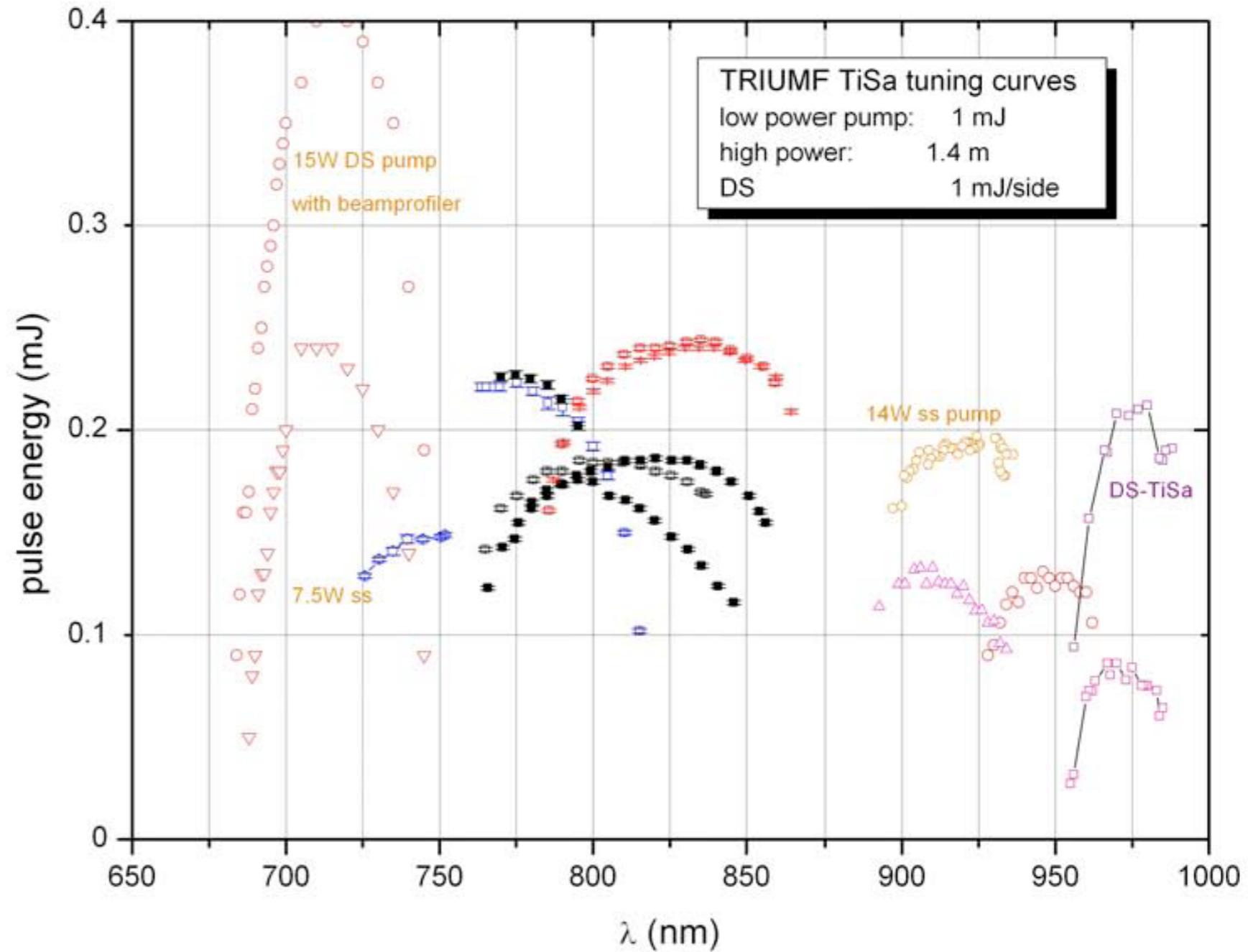
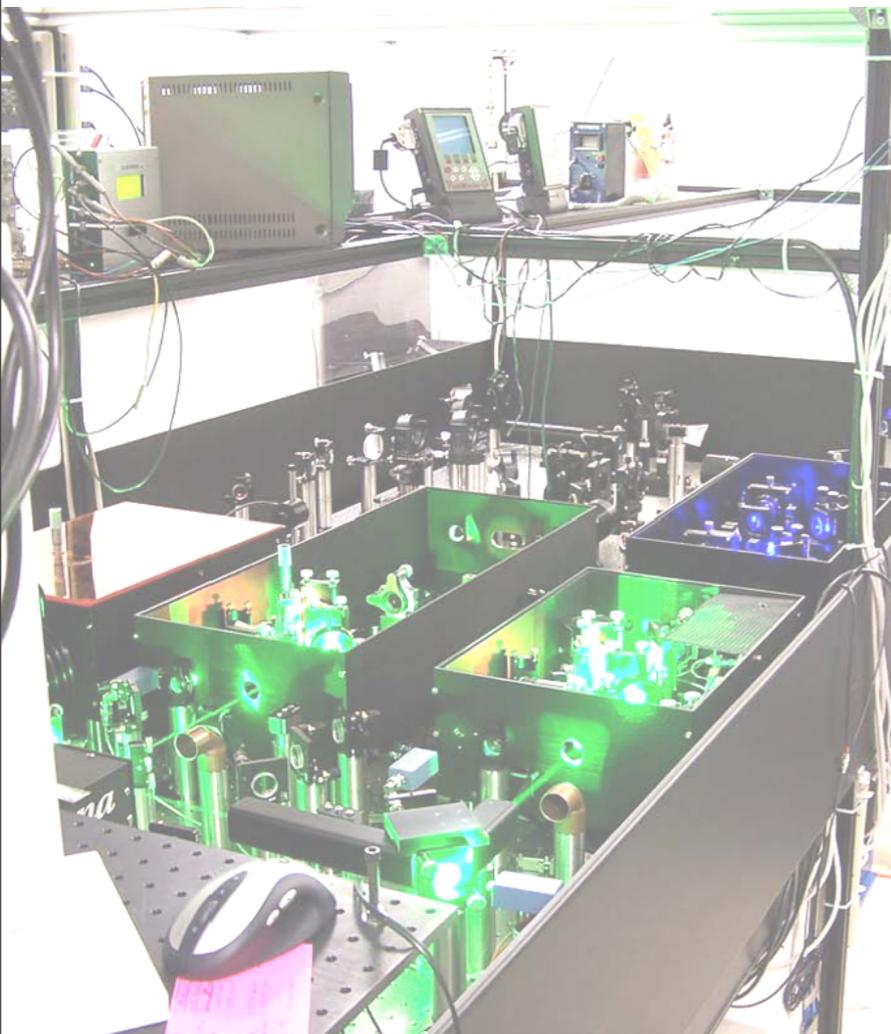
- 1) Resonant steps and populating an auto-ionization level.
- 2) Two resonant steps and one non resonant step.
- 3) Three resonant steps to Rydberg level and Field ionization.
- 4) One resonant step and to continuum non resonant ionization.



Laser requirements

- Laser must be applicable to a wide range of elements
- For selectivity at least two resonant steps are required and third one is even better.
- High repetition rate to ensure that the atom sees at least one laser pulse while traveling inside the transfer tube.
- Need to focus the laser beams into a 3 mm diameter hole, ~ 25 m away
 - Good laser beams quality is required.
 - Large optics elements.
- Need to synchronize the laser pulse such they arrive at the same time inside the transfer tube.

Ti:Sa tuning range





Laser Ion Source

Group

1A 1 2A 2 3A 13 4A 14 5A 15 6A 16 7A 17 8A 18

1 Hydrogen 2 Helium

2 Lithium Beryllium

3 Sodium Magnesium 3B 3 4B 4 5B 5 6B 6 7B 7 8 9 10 1B 11 2B 12 Aluminum Silicon Phosphorus Sulfur Chlorine Argon

4 Potassium Calcium Scandium Titanium Vanadium Chromium Manganese Iron Cobalt Nickel Copper Zinc Gallium Germanium Arsenic Selenium Bromine Krypton

5 Rubidium Strontium Yttrium Zirconium Niobium Molybdenum Technetium Ruthenium Rhodium Palladium Silver Cadmium Indium Tin Antimony Tellurium Iodine Xenon

6 Cesium Barium [57-71] Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn

7 Francium Radium [89-103] Rf Db Sg Bh Hs Mt Ds Rg 112 113 114 115

* 57 La 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb 71 Lu

** 89 Ac 90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No 103 Lr

Legend:

- Green: TRI LIS on-line beams delivered 12/06
- Red: tested TiSa laser excitation schemes (from TiSa Network: Mainz, TRIUMF, ORNL, JYFL)



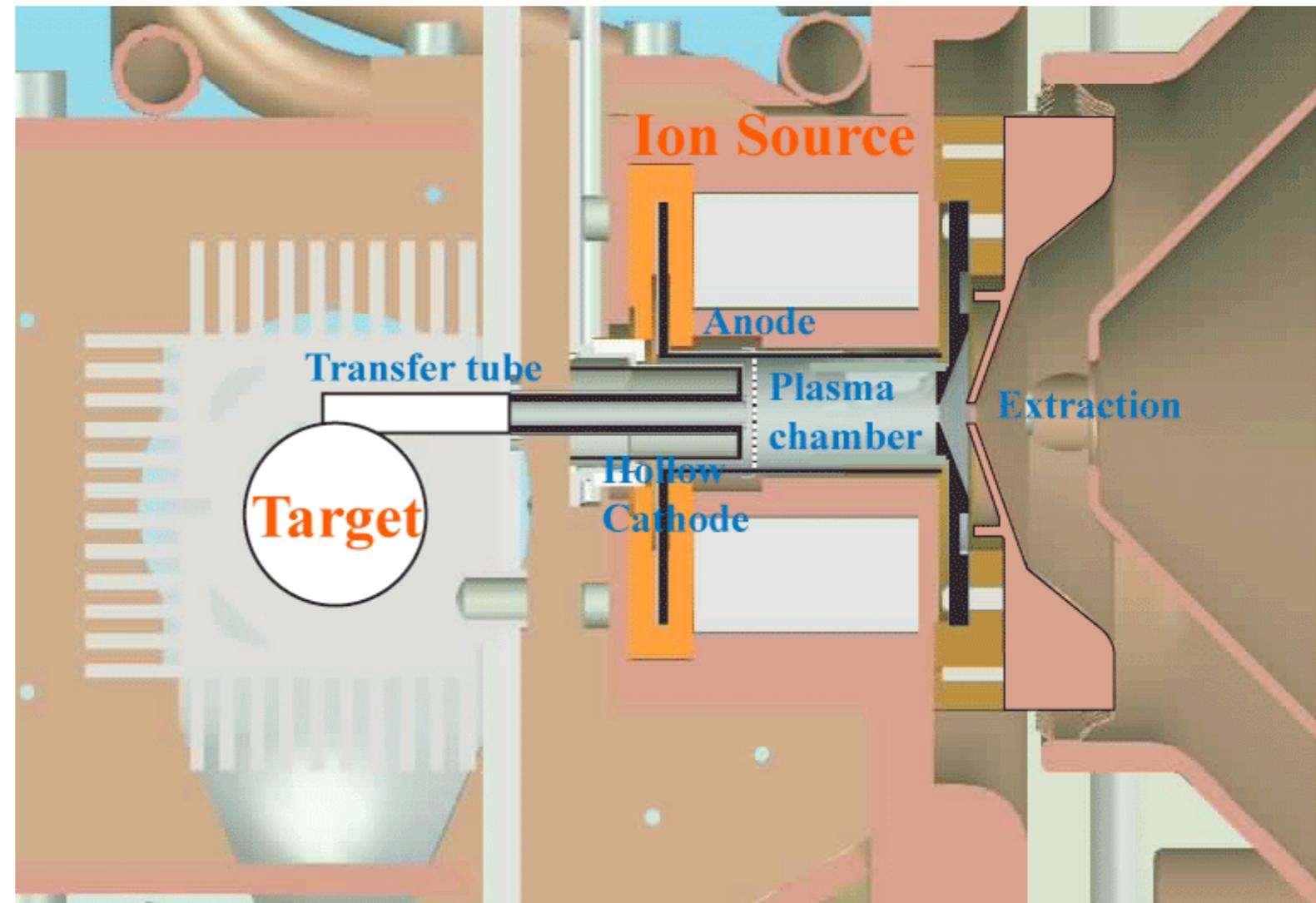
RIB Development

Plasma Ion Source Bernas-Nier



FEBIAD Ion Source

FEBIAD invented by
**R. Kirchner and E. Roeckl, Nucl.
 Instr. and Method 133 (1976) 187-204.**



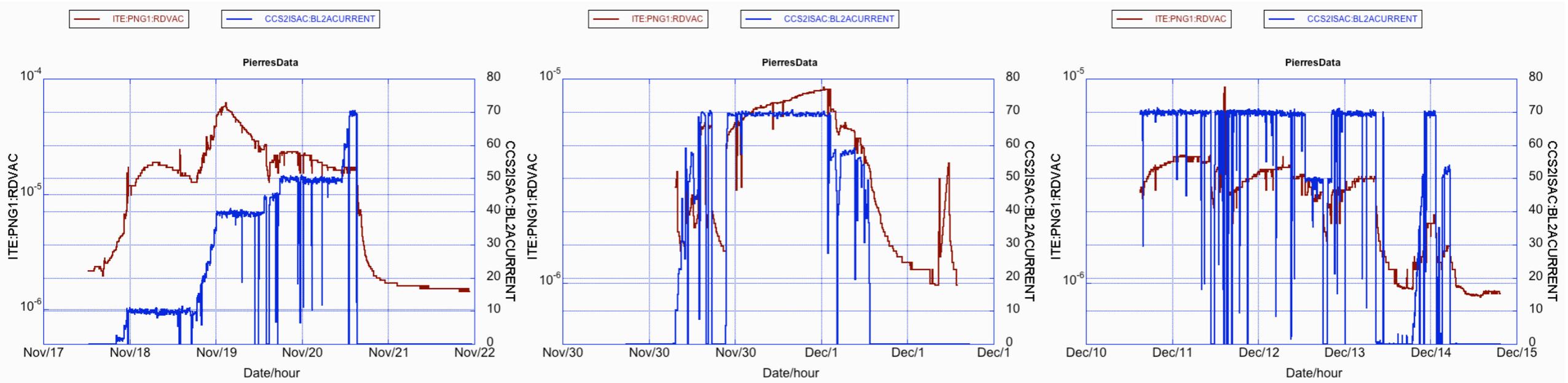
- **Our FEBIAD is similar to the ISOLDE hollow cathode design.**
- **On-line tests of the FEBIAD (Forced Electron Beam Induced Arc Discharge) Fall 2006 with a TiC/C_{gr} for $^{34}\text{Ar} > ^{34}\text{C} + \beta^+ + \nu$ experiment**
- **and June 2007 for ^{18}F experiment.**



FEBIAD first run

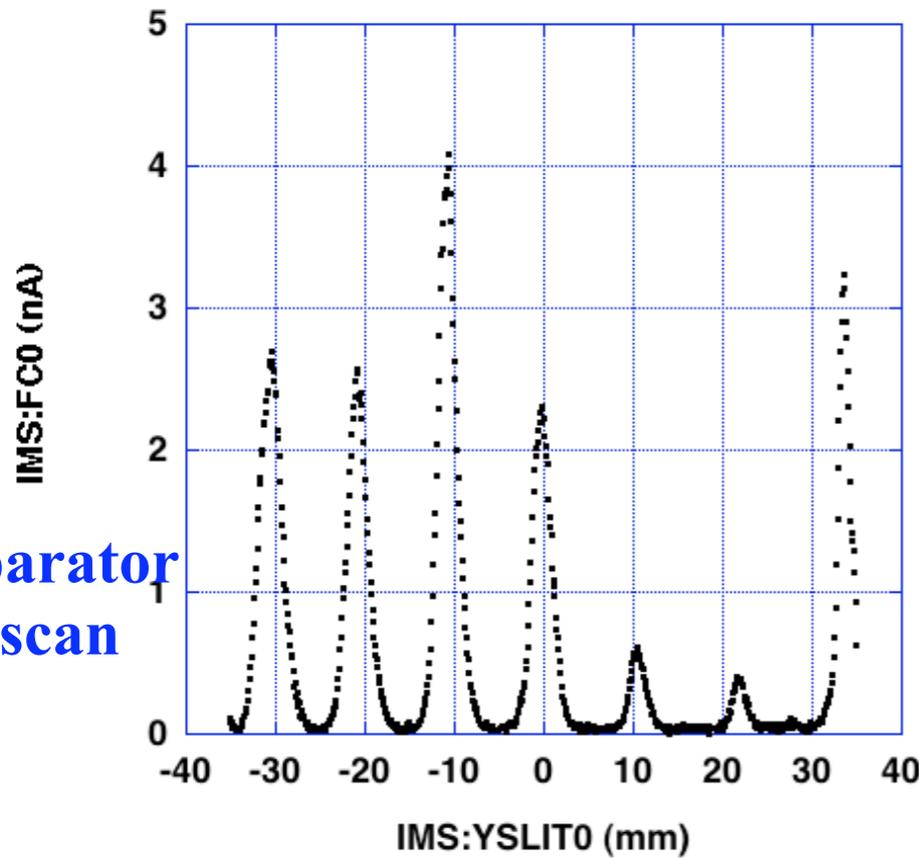


FEBIAD first run

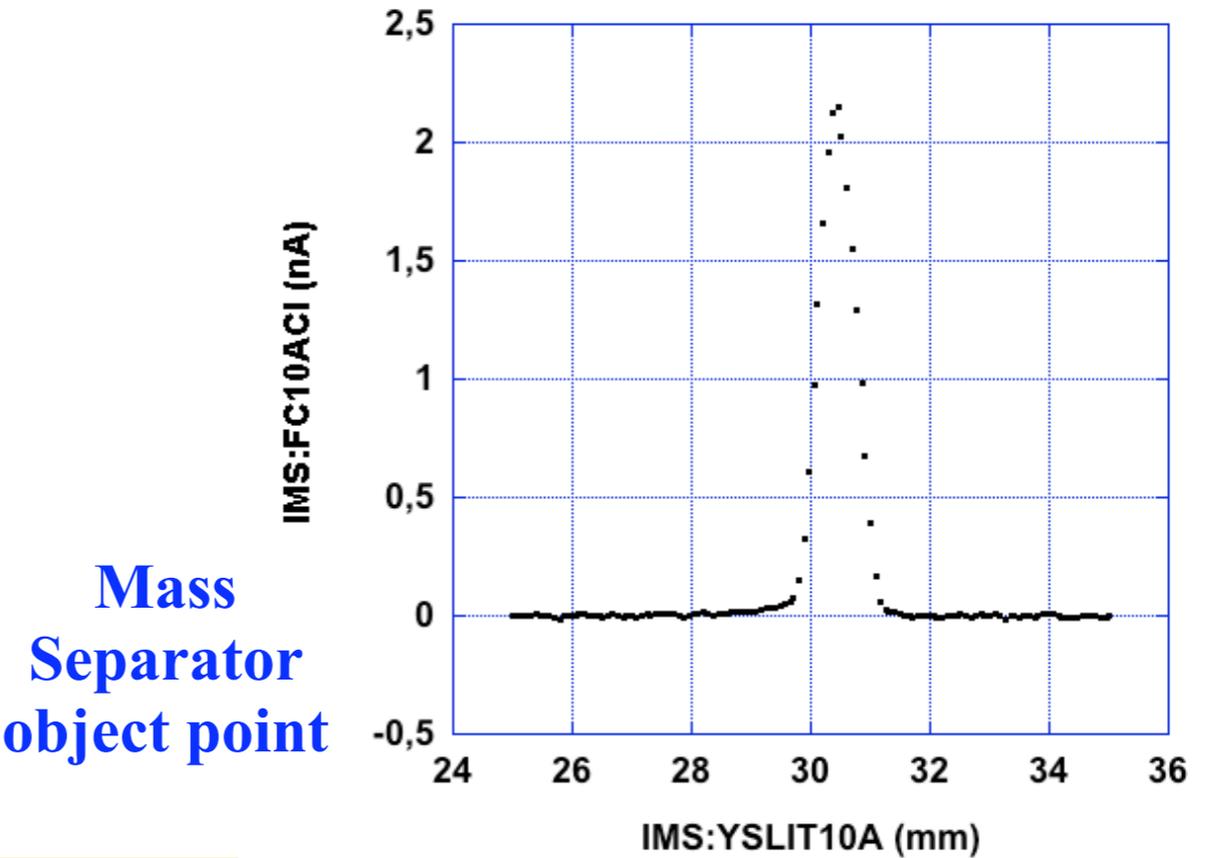


Mass Scan at the Pre-Separator Focal Plane

Beam profile at the at the Object point of Mass Separator



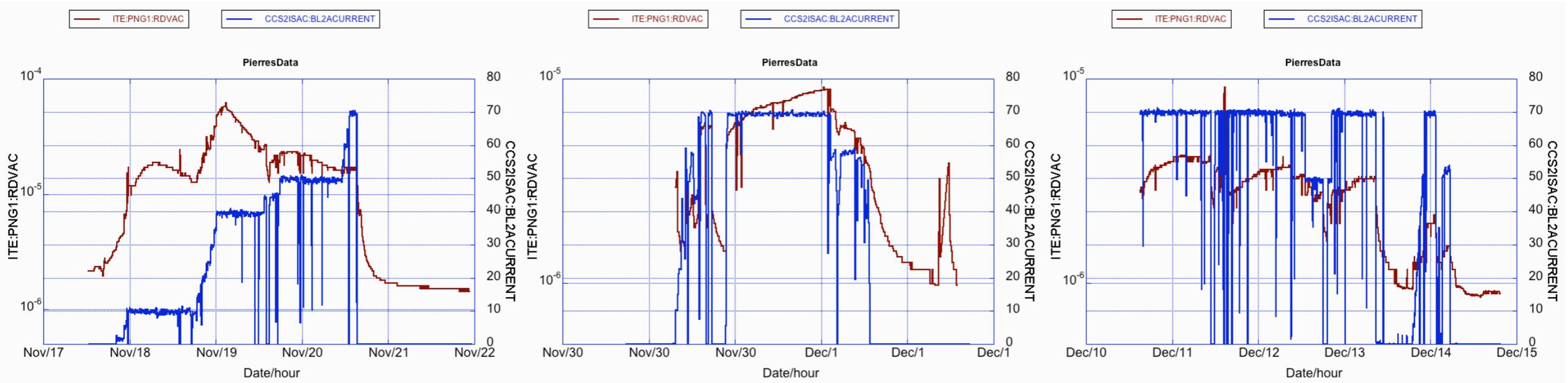
Pre-Separator mass scan



Mass Separator object point



FEBIAD first run

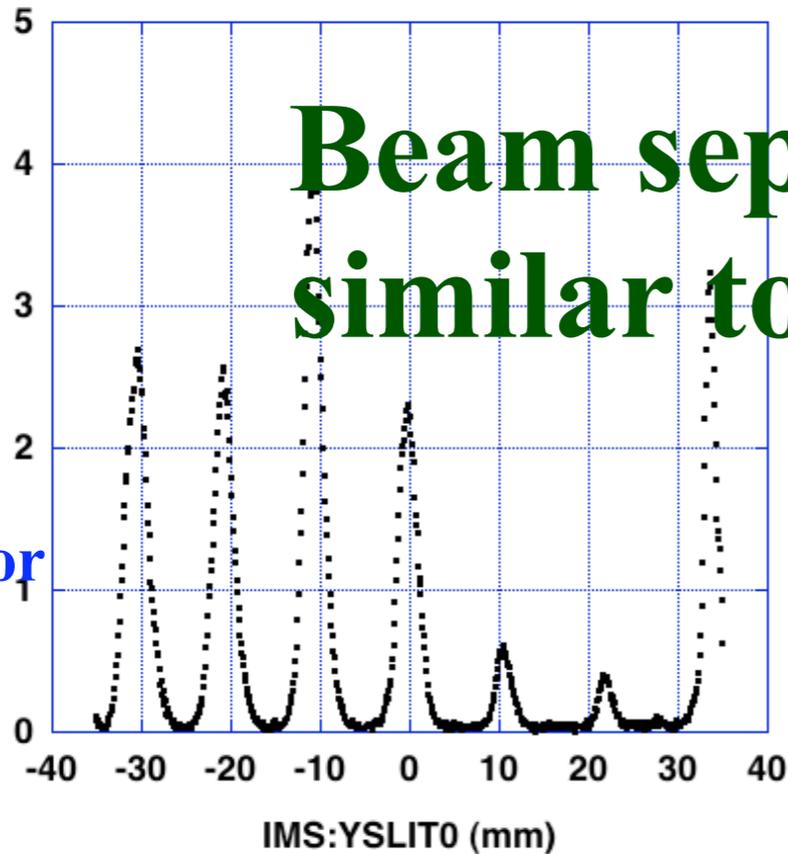


Mass Scan at the Pre-Separator Focal Plane

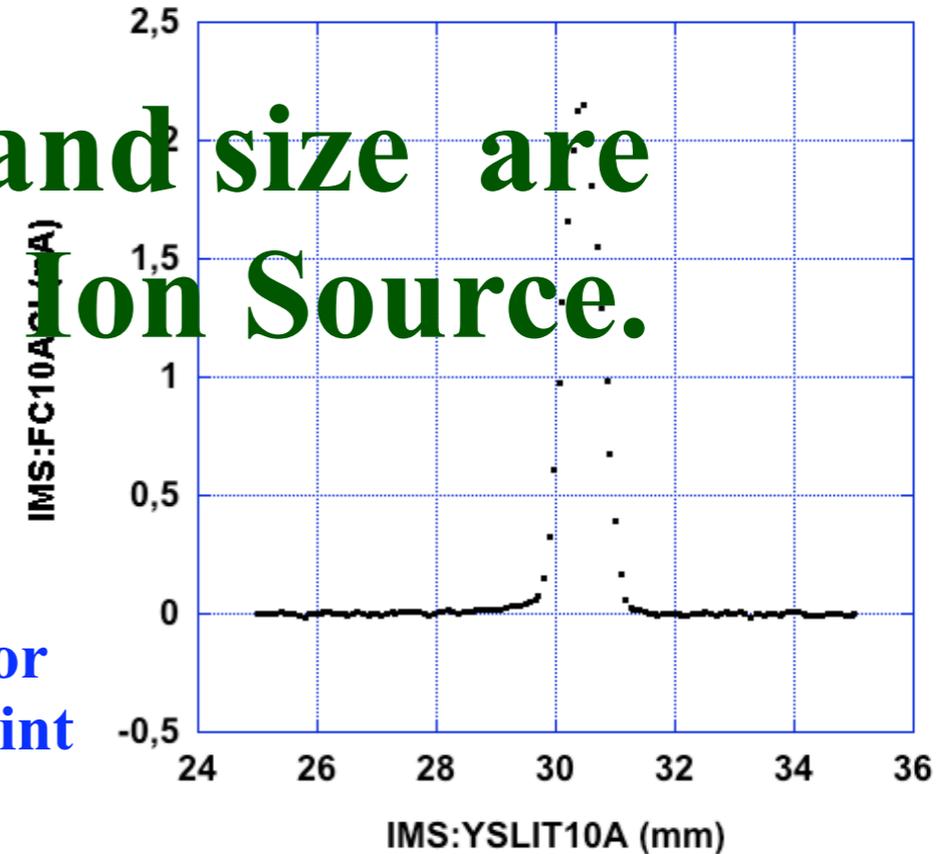
Beam profile at the at the Object point of Mass Separator

Beam separation and size are similar to Surface Ion Source.

Pre-Separator mass scan

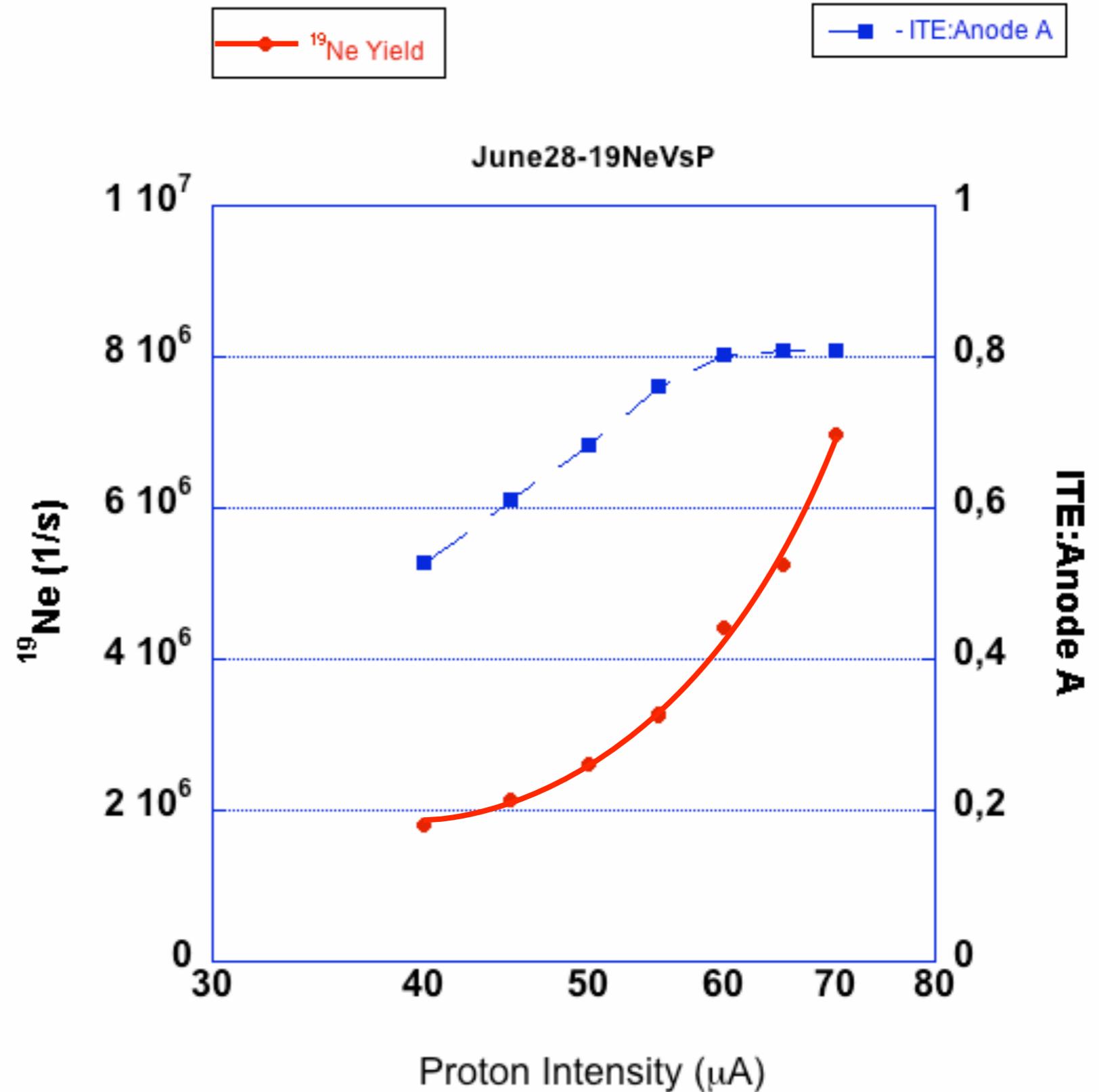


Mass Separator object point



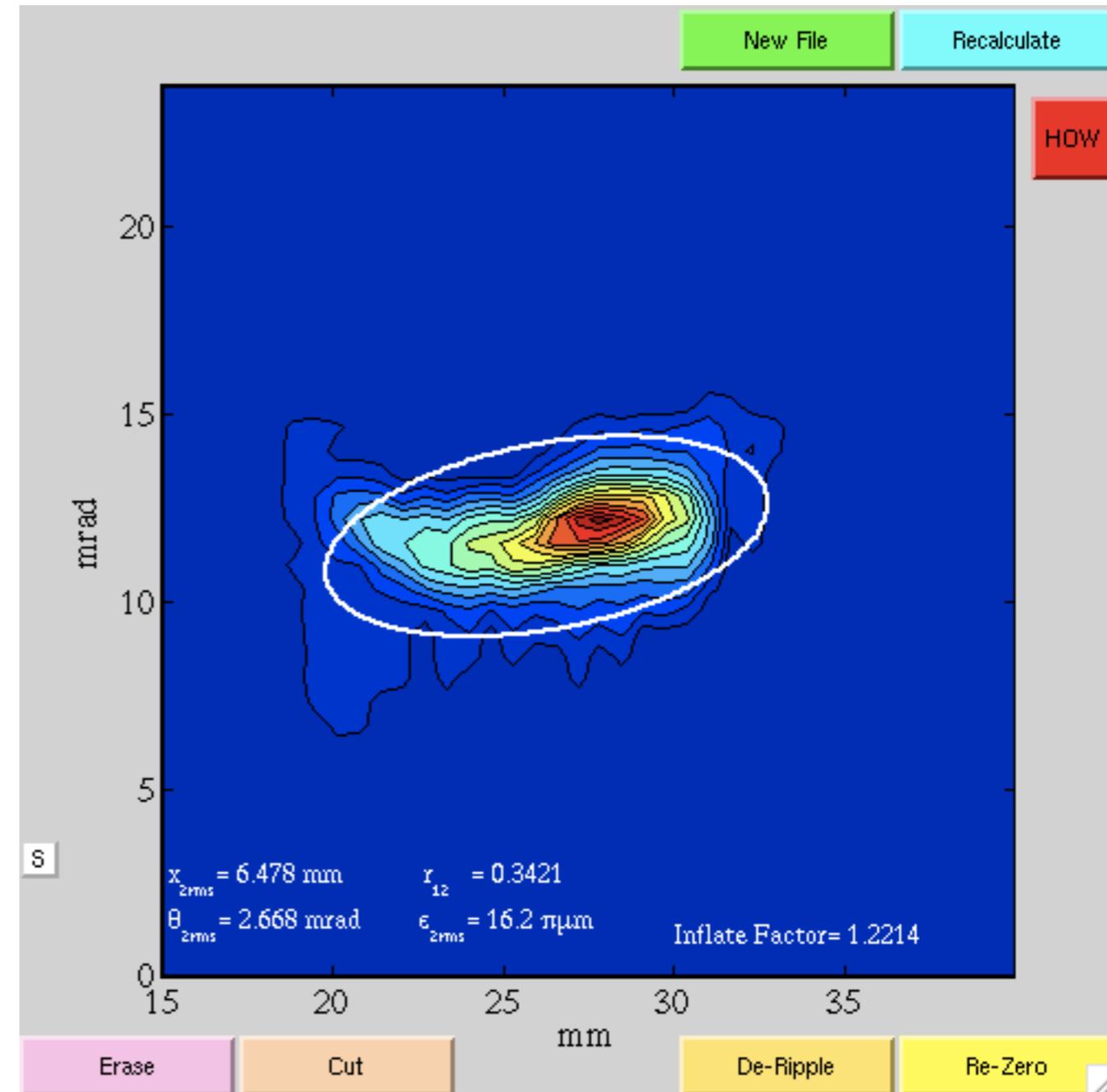
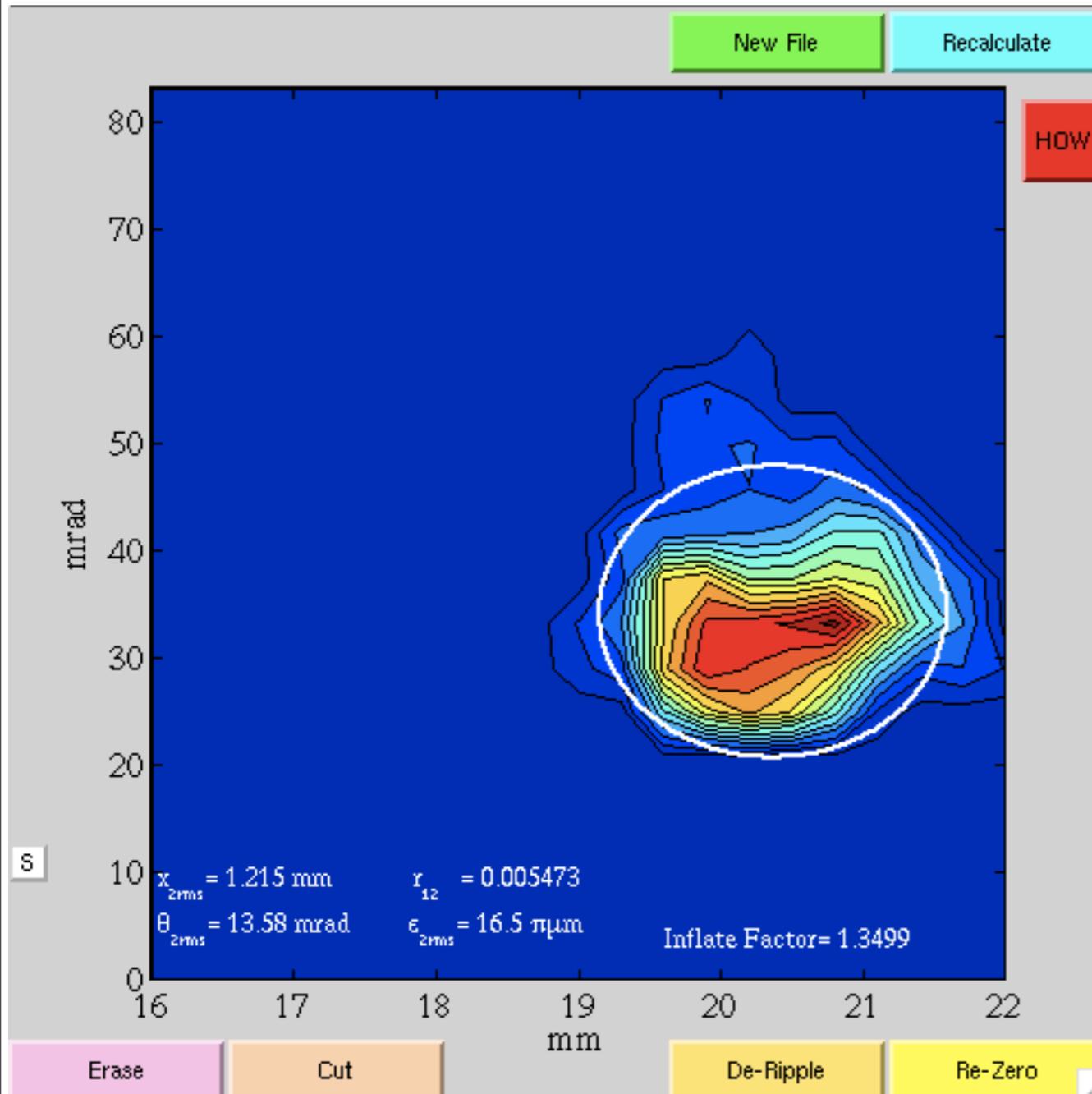
FEBIAD run#2

- ISOLDE SC ^{19}Ne
 $\sim 3 \times 10^7/\text{s}$ MgO
 target





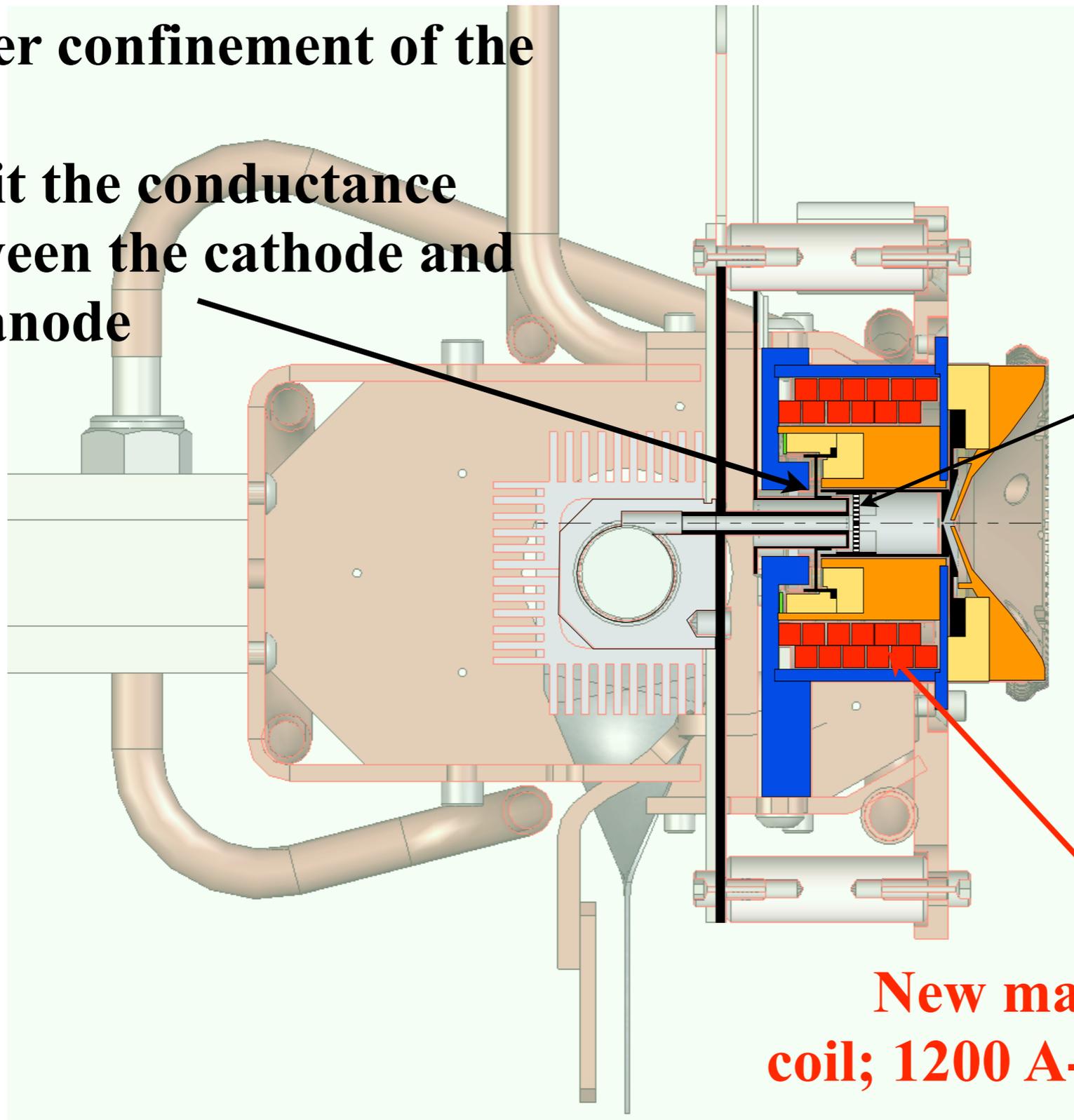
Measured H & V Emittances



$$\epsilon_{V,H} = 16 \text{ } \mu\text{m}$$

FEBIAD-Mk-XI

- Better confinement of the gas.
- Limit the conductance between the cathode and the anode



New grid



**12,7 mm diameter Ta,
1 mm thick**

**New magnetic
coil; 1200 A-t=> 500 G**

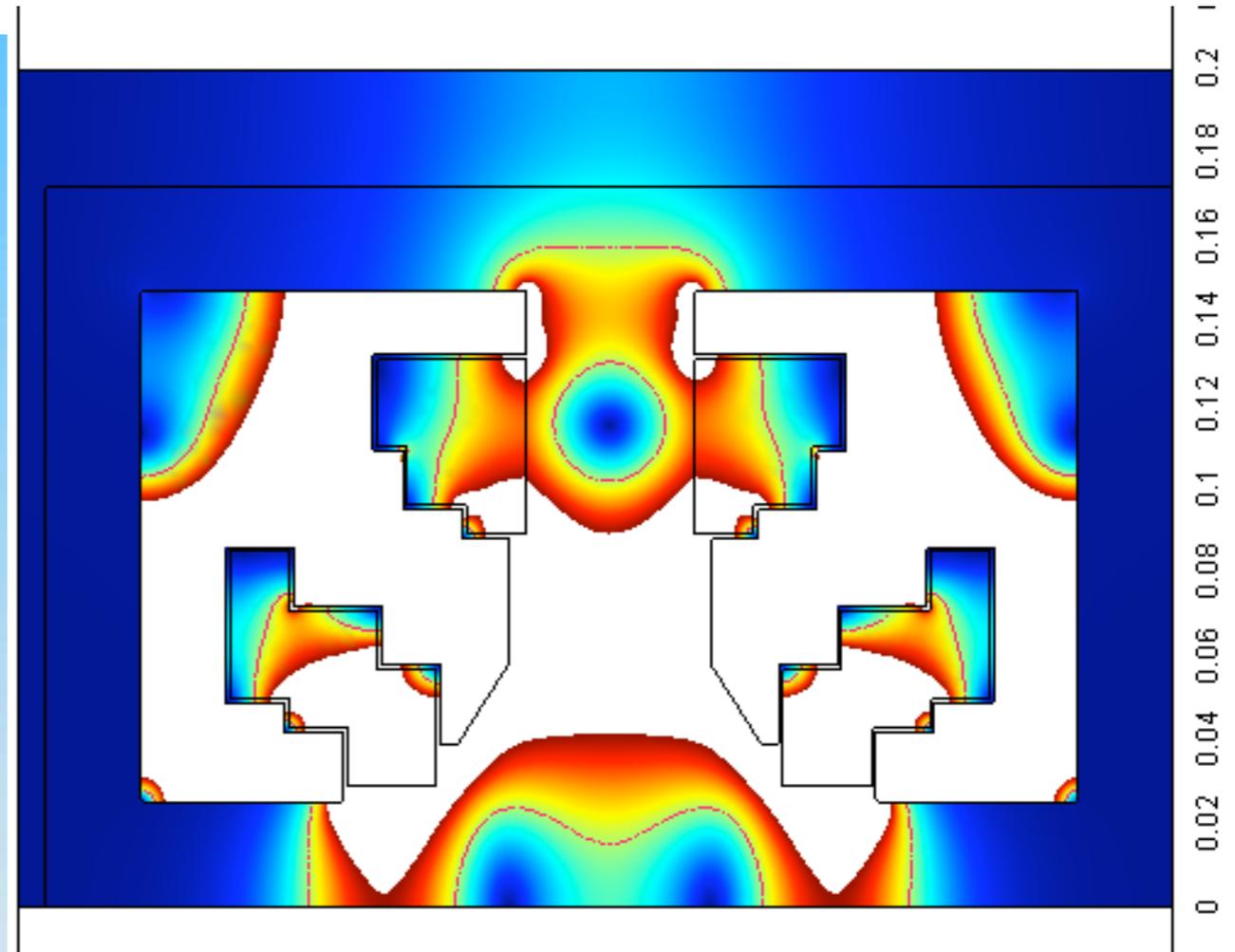
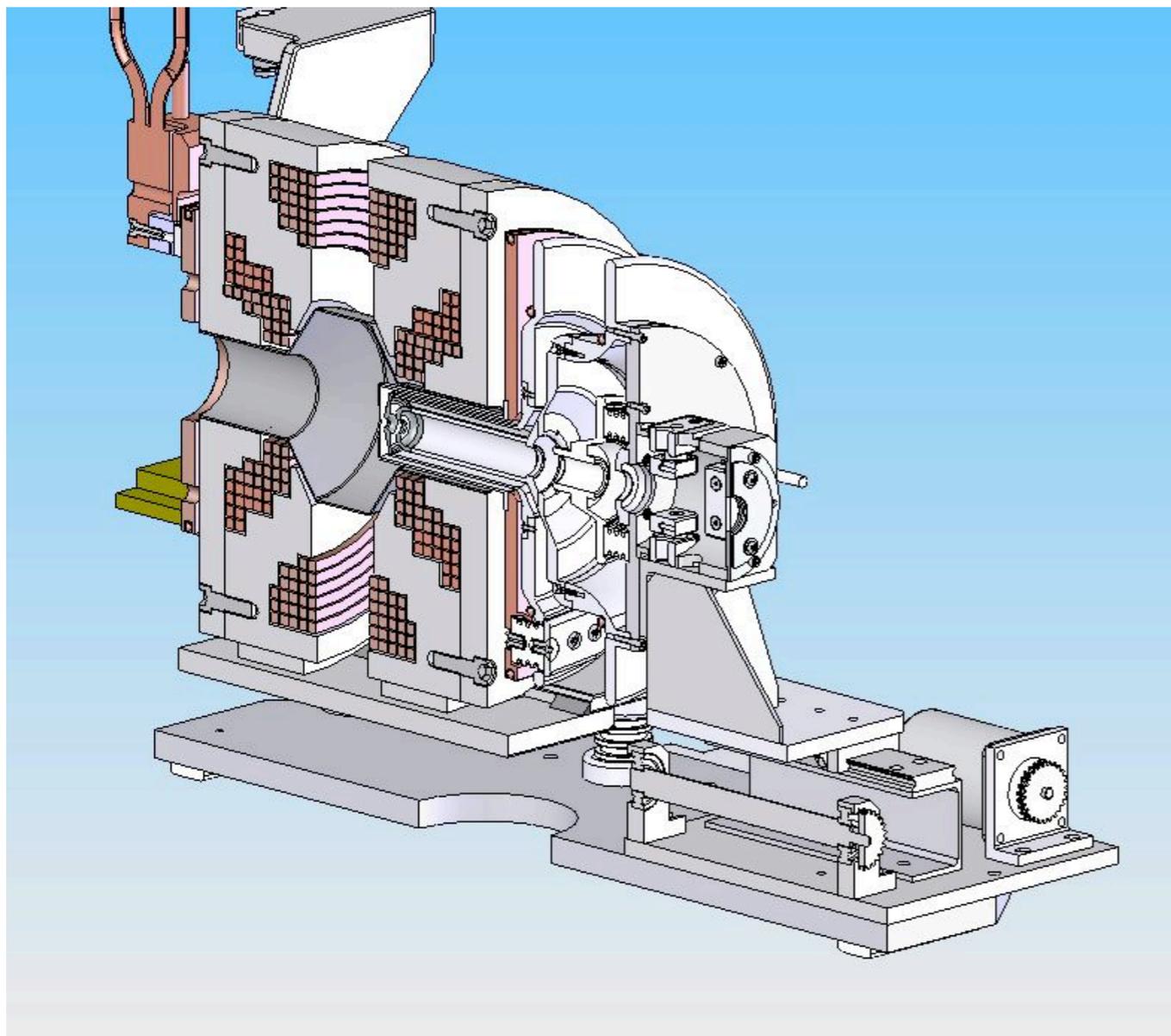


RIB Development

Electron Cyclotron Resonance Ion Source

1A	1																	8A	18															
1	H 1.00794 Hydrogen																	2	He 4.00260 Helium															
2	3 Li 6.941 Lithium	4 Be 9.01218 Beryllium																	10	Ne 20.1797 Neon														
3	11 Na 22.9898 Sodium	12 Mg 24.305 Magnesium	3B	3	4B	4	5B	5	6B	6	7B	7	8B	8	8B	9	8B	10	1B	11	2B	12	13	3A	14	4A	15	5A	16	6A	17	7A	17	18
4	19 K 39.0983 Potassium	20 Ca 40.078 Calcium	21 Sc 44.9559 Scandium	22 Ti 47.867 Titanium	23 V 50.9415 Vanadium	24 Cr 51.9961 Chromium	25 Mn 54.938 Manganese	26 Fe 55.845 Iron	27 Co 58.9332 Cobalt	28 Ni 58.6934 Nickel	29 Cu 63.546 Copper	30 Zn 65.409 Zinc	31 Ga 69.723 Gallium	32 Ge 72.64 Germanium	33 As 74.9216 Arsenic	34 Se 78.96 Selenium	35 Br 79.904 Bromine	36 Kr 83.798 Krypton																
5	37 Rb 85.4678 Rubidium	38 Sr 87.62 Strontium	39 Y 88.9059 Yttrium	40 Zr 91.224 Zirconium	41 Nb 92.9064 Niobium	42 Mo 95.94 Molybdenum	43 Tc [98] Technetium	44 Ru 101.07 Ruthenium	45 Rh 102.9055 Rhodium	46 Pd 106.42 Palladium	47 Ag 107.8682 Silver	48 Cd 112.411 Cadmium	49 In 114.818 Indium	50 Sn 118.710 Tin	51 Sb 121.760 Antimony	52 Te 127.60 Tellurium	53 I 126.9045 Iodine	54 Xe 131.293 Xenon																
6	55 Cs 132.90545 Cesium	56 Ba 137.327 Barium	57-71 La-Lu *	72 Hf 178.49 Hafnium	73 Ta 180.9479 Tantalum	74 W 183.84 Tungsten	75 Re 186.207 Rhenium	76 Os 190.23 Osmium	77 Ir 192.217 Iridium	78 Pt 195.078 Platinum	79 Au 196.96655 Gold	80 Hg 200.59 Mercury	81 Tl 204.383 Thallium	82 Pb 207.2 Lead	83 Bi 208.9804 Bismuth	84 Po [209] Polonium	85 At [210] Astatine	86 Rn [222] Radon																
7	87 Fr [223] Francium	88 Ra [226] Radium	89-103 Ac-Lr **	104 Rf [261] Rutherfordium	105 Db [262] Dubnium	106 Sg [266] Seaborgium	107 Bh [264] Bohrium	108 Hs [277] Hassium	109 Mt [268] Meitnerium	110 Ds [281] Darmstadtium	111 Uuu [272] Unununium	112 Uub [285] Ununbium	114 Uuq [289] Ununquadium																					
			*	57 La 138.9055 Lanthanum	58 Ce 140.116 Cerium	59 Pr 140.9077 Praseodymium	60 Nd 144.24 Neodymium	61 Pm [145] Promethium	62 Sm 150.36 Samarium	63 Eu 151.964 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.9253 Terbium	66 Dy 162.50 Dysprosium	67 Ho 164.9303 Holmium	68 Er 167.259 Erbium	69 Tm 168.9342 Thulium	70 Yb 173.04 Ytterbium	71 Lu 174.967 Lutetium																
			**	89 Ac [227] Actinium	90 Th 232.0381 Thorium	91 Pa 231.0359 Protactinium	92 U 238.0289 Uranium	93 Np [237] Neptunium	94 Pu [244] Plutonium	95 Am [243] Americium	96 Cm [247] Curium	97 Bk [247] Berkelium	98 Cf [251] Californium	99 Es [252] Einsteinium	100 Fm [257] Fermium	101 Md [258] Mendelevium	102 No [259] Nobelium	103 Lr [262] Lawrencium																

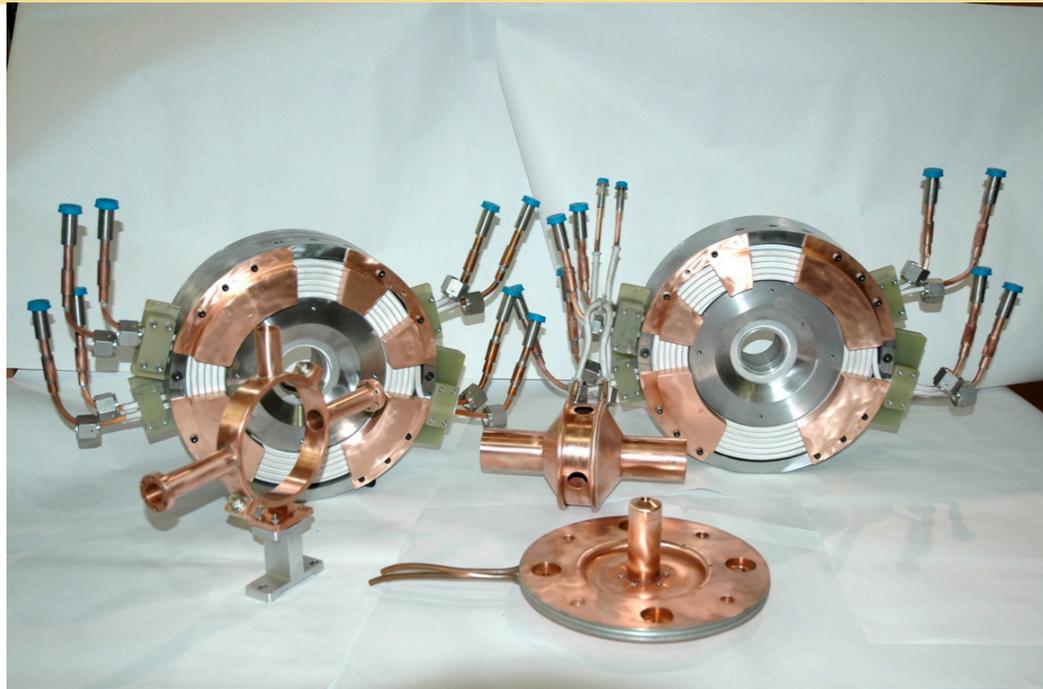
New ECR Ion Source



- MISTIC new ECR ion source, Collaboration between GANIL and TRIUMF,
- ECR with longitudinal and radial magnetic confinement.
- Operates at 3 - 6 GHz, N. Lecesne, P. Bricault-TRI-DN-05-23.

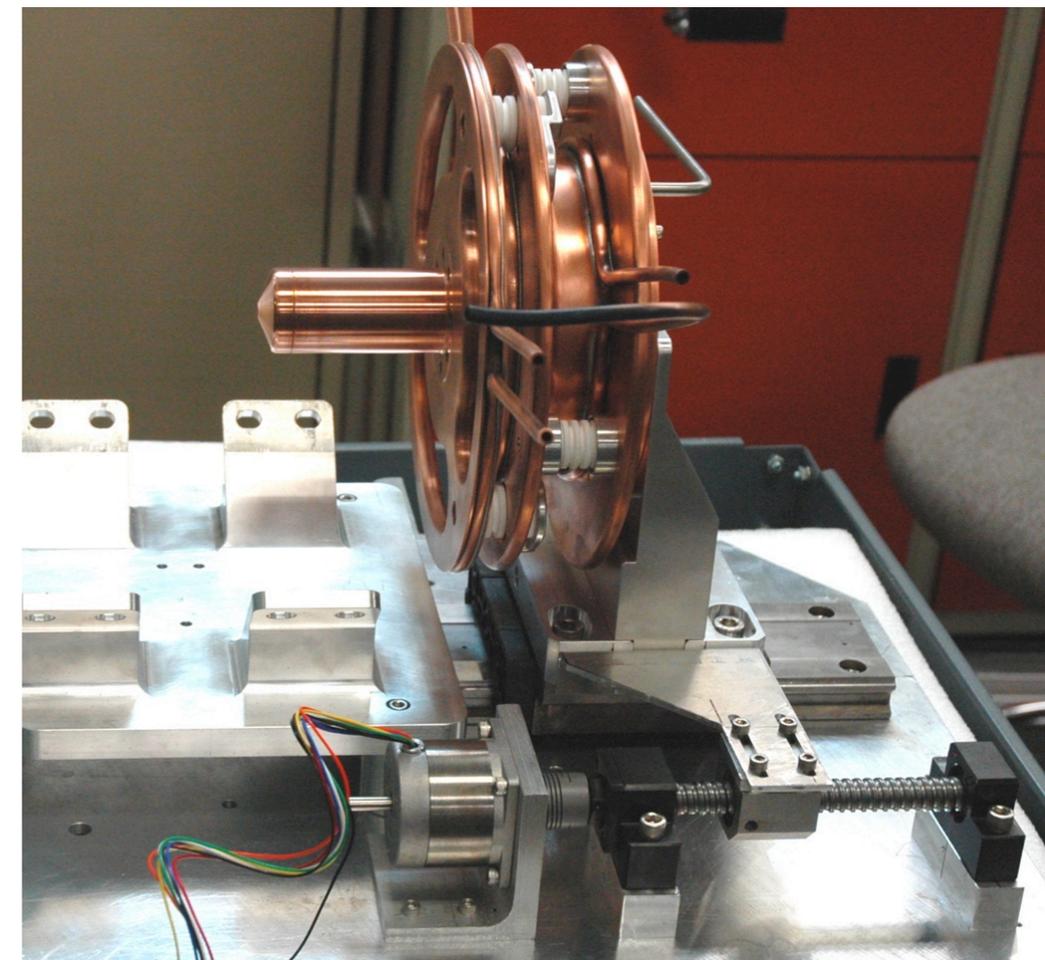
MISTIC

MISTIC fabrication is completed



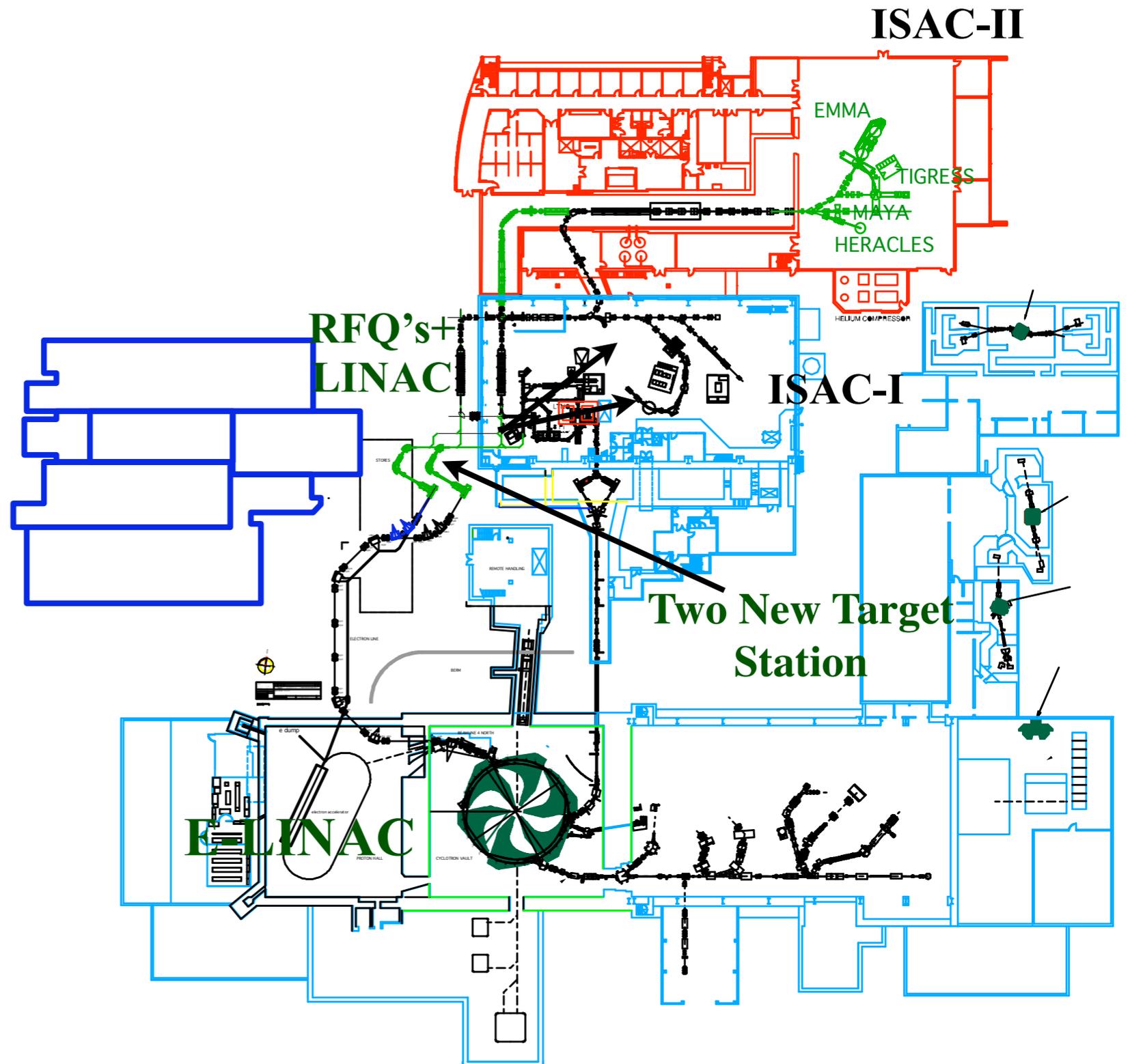
Quartz plasma chamber

Ion source equipped with a movable 2 gap extraction electrodes



Future plans

- Presently 1/4 of the ISAC beam time is devoted to T/IS Dev.
- Request for beam time for approved High priority experiments > 4 years
- Use of BL4 can provide up to 200 μA proton at 450 MeV,
- Two new target stations will allow;
 - RIB development,
 - Simultaneous RIB to two or three experiments simultaneously



Summary

- **ISAC High Power target operates at 100 μA level, => BL2A A/C steerer: October 2007.**
- **Composite carbide targets (SiC, TiC and ZrC) operate up to 70 μA routinely.**

Target	Target composition	Target Thickness	$I_{\text{Proton}} \mu\text{A}$	RIB
Ta #14 HP	Ta foils	21,8 g/cm ²	70	^{38m} K
Ta #15	Ta foils	21,8 g/cm ²	35	⁸ Li
Ta #16 HP	Ta foils	21,8 g/cm ²	100	^{9,11} Li, ⁵¹⁻⁵³ K
Ta #17	Ta foils	21,8 g/cm ²	35	⁸ Li, ¹⁵⁶ Ho, ¹⁶⁰ Lu
SiC #13 HP	SiC/C _{gr} foils	28 g/cm ²	65	^{8,9} Li, ^{20,21} Na
Ta #18	Ta foils	21,8 g/cm ²	35	⁸ Li, ¹¹ Li
TiC #2 HP	TiC/C _{gr}	24,1 g/cm ²	70	³⁴ Ar

Summary

- Since 1998, the vast majority of the Radioactive Ion Beams has been produces using a hot surface ion source.
- A large program to equip the TRIUMF-ISAC RIB facility with ion sources that can efficiently ionize nearly all elements is underway
- Resonant Laser Ion Source is quite advanced,
 - New generation of Ti:Sa solid state lasers.
 - FEBIAD ion source is being developed on-line. New design will incorporate a new radiation hard coil.
- ECR (MISTIC) prototype is ready for tests,
 - Goal is to finalize the tests for next spring and start specifications for a new target module. On-line tests end 2009.
- Future 5-year plan to equip ISAC facility with new target stations to allow 2 to 3 simultaneous RIB to experiments.



Thank you.

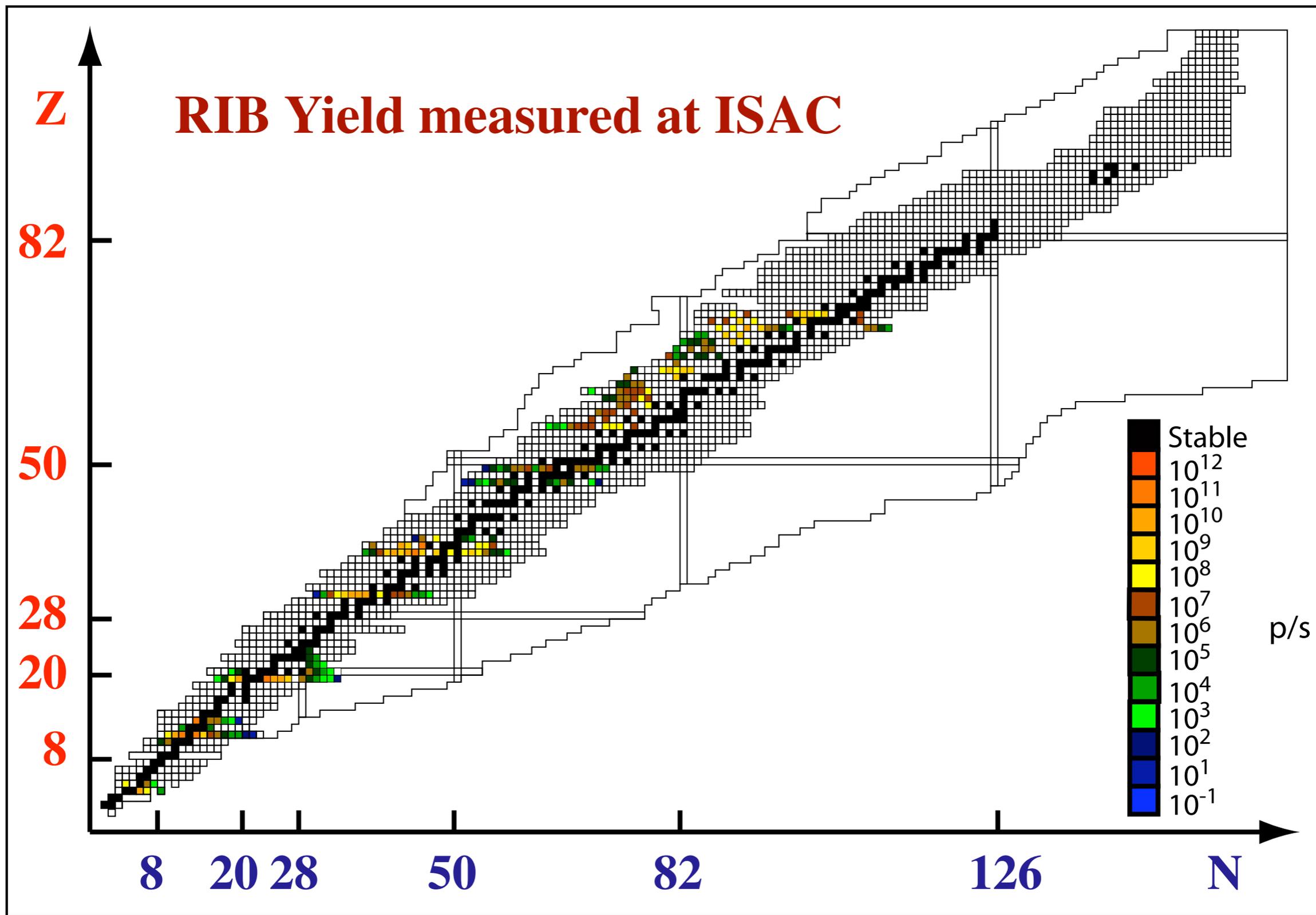


New RIB at ISAC

Target	Ion Source	Proton intensity (μA)	New RIB
Ta#15	TRILIS	35	$^9\text{-}^{12}\text{Be}$ and $^{104}\text{-}^{114},^{116}\text{-}^{119}\text{In}$
Ta#17HPT	TRILIS	65	$^{84},^{86},^{87},^{89},^{90}\text{Y}$ and $^{99}\text{-}^{113},^{116}\text{-}^{117}\text{Ag}$
TiC#2HPT, SiC#14HPT	FEBIAD	70	$^6,^8\text{He}$
TiC#2HPT	FEBIAD	70	$^{19},^{20}\text{O}$
TiC#2HPT, SiC#14HPT	FEBIAD	70	$^{17}\text{-}^{19},^{23}\text{-}^{25}\text{Ne}$
TiC#2HPT	FEBIAD	70	$^{27}\text{-}^{29}\text{Mg}$
TiC#2HPT	FEBIAD	70	$^{32},^{34},^{38}\text{-}^{45}\text{Cl}$
TiC#2HPT	FEBIAD	70	$^{33}\text{-}^{35},^{41}\text{-}^{45}\text{Ar}$
SiC#14HPT	FEBIAD	70	^{23}Mg
SiC#14HPT	FEBIAD	70	$^{17}\text{-}^{18}\text{F}$

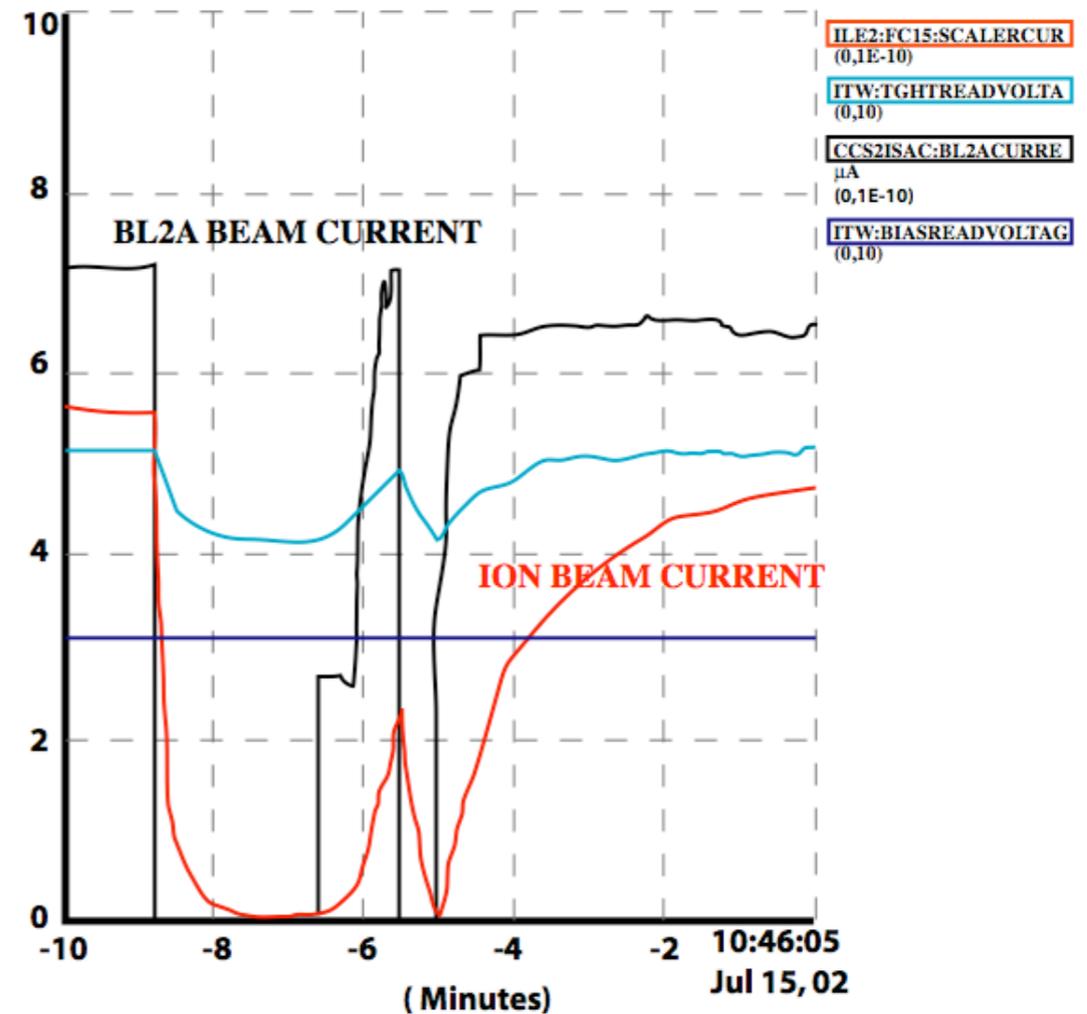
http://www.triumf.info/facility/research_fac/yield.php

ISAC RIB



Cyclotron Stability

- Above 20 μA we are relying on the proton beam to heat the target,
- When the proton beam goes off the target cooling occurs within seconds. It takes several minutes before the target reaches optimum temperature,
- We improved the proton beam stability to avoid disturbance in RIB delivery.



Now we can run for several hours without any beam interruption.