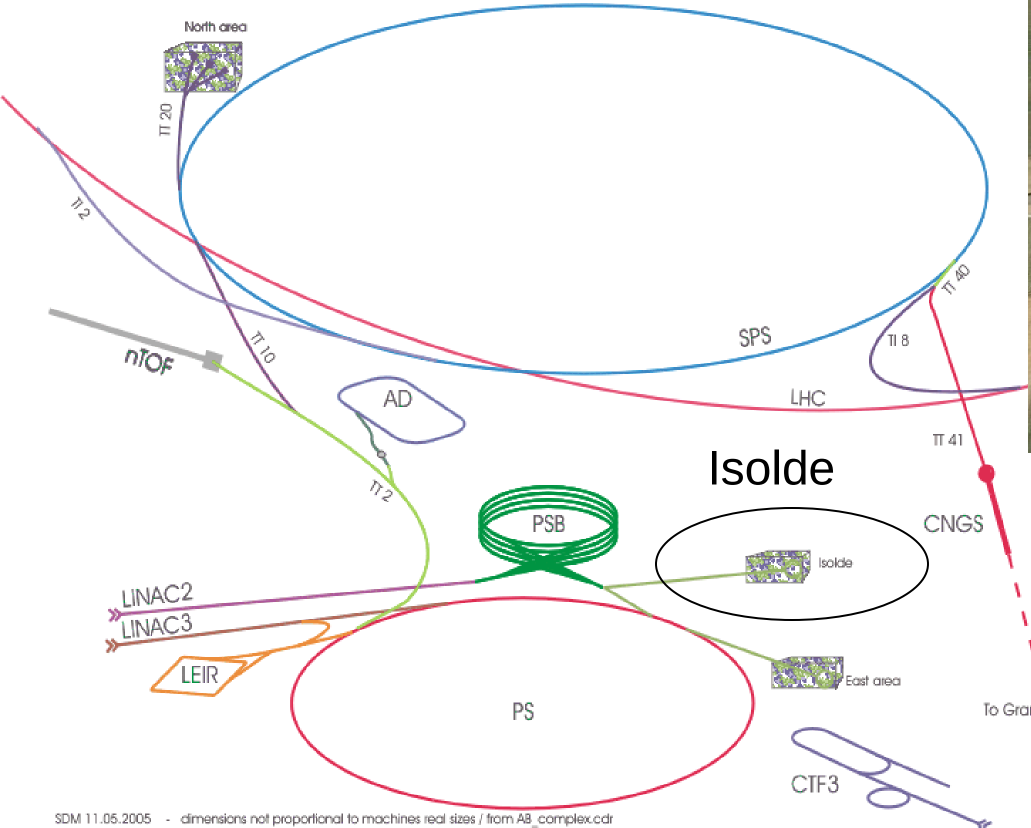
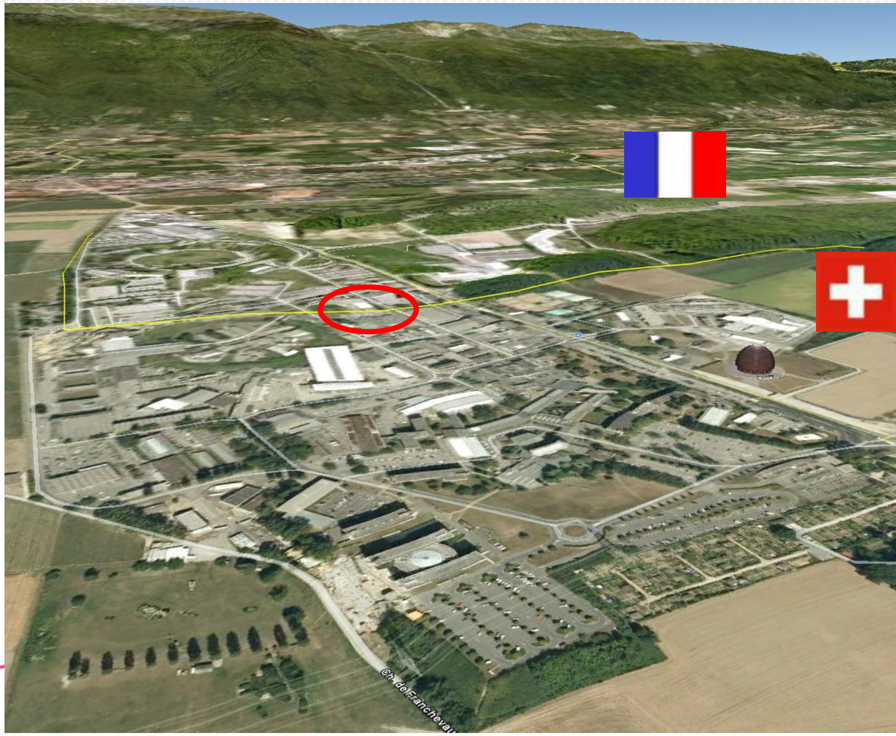
Beams available at (HIE)-ISOLDE

Thierry.stora@cern.ch

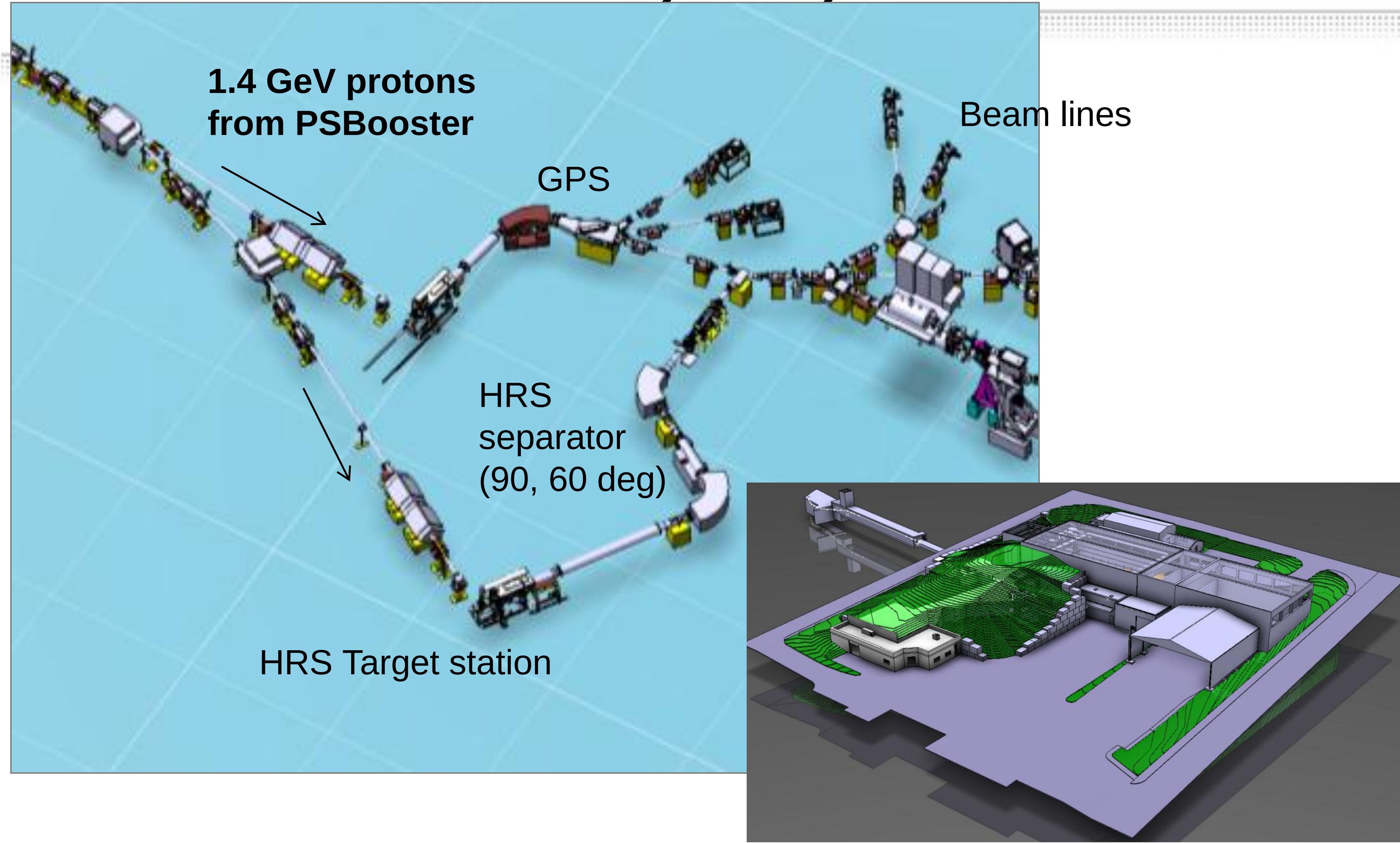
Target and Ion Source Development
Team Leader
CERN-ISOLDE

The CERN Accelerator Complex





Facility Layout



1.4 GeV protons from PSBooster

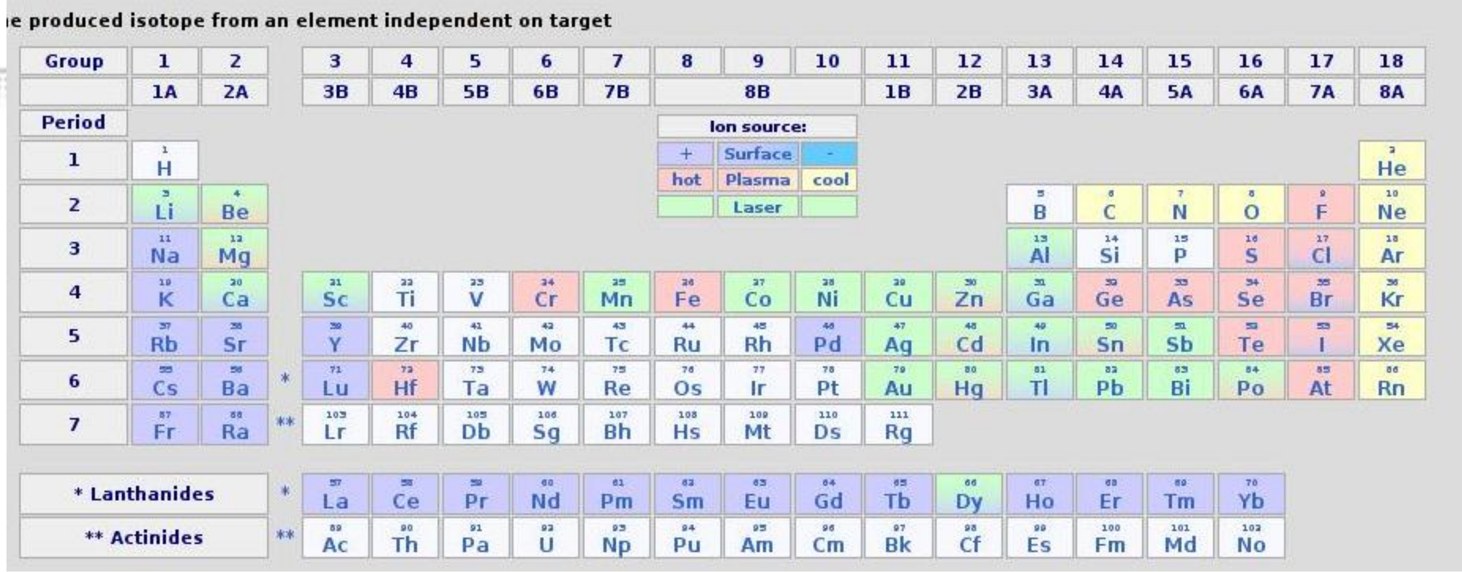
GPS

Beam lines

HRS separator (90, 60 deg)

HRS Target station

Beams at ISOLDE and requested for HIE-ISOLDE

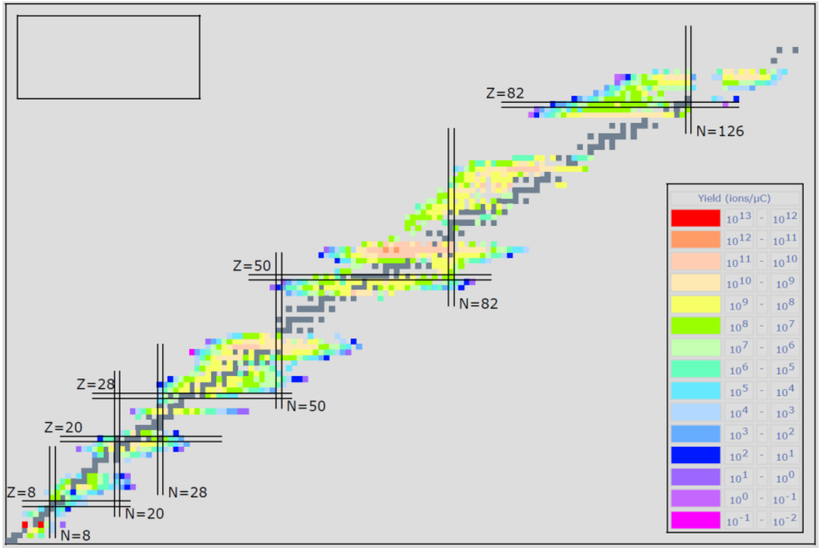


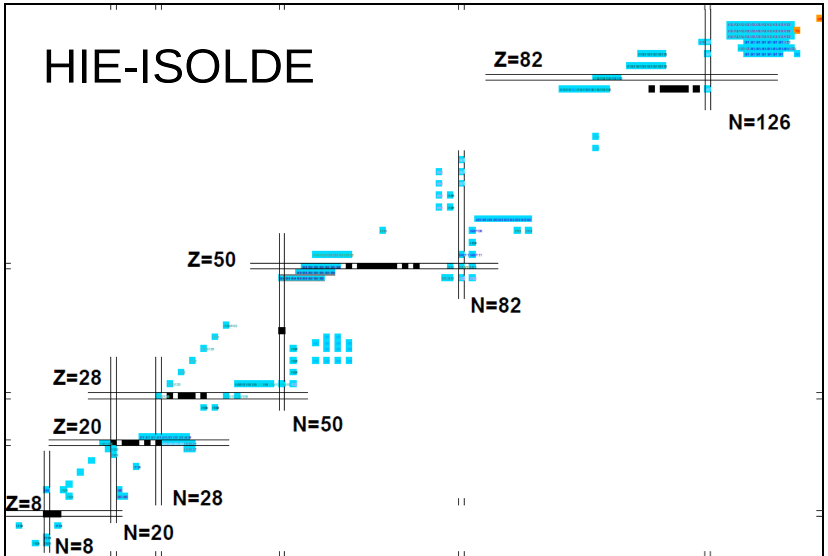
e produced isotope from an element independent on target

Group	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	1A	2A		3B	4B	5B	6B	7B	8B			1B	2B	3A	4A	5A	6A	7A	8A
Period																			
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg							
* Lanthanides			*	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		
** Actinides			**	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		

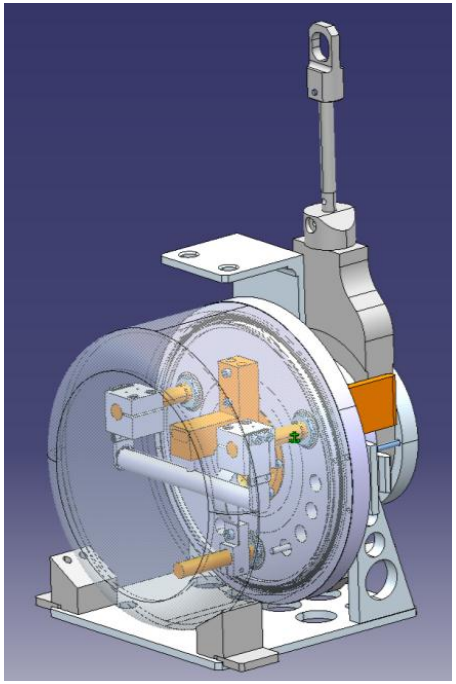
Ion source:

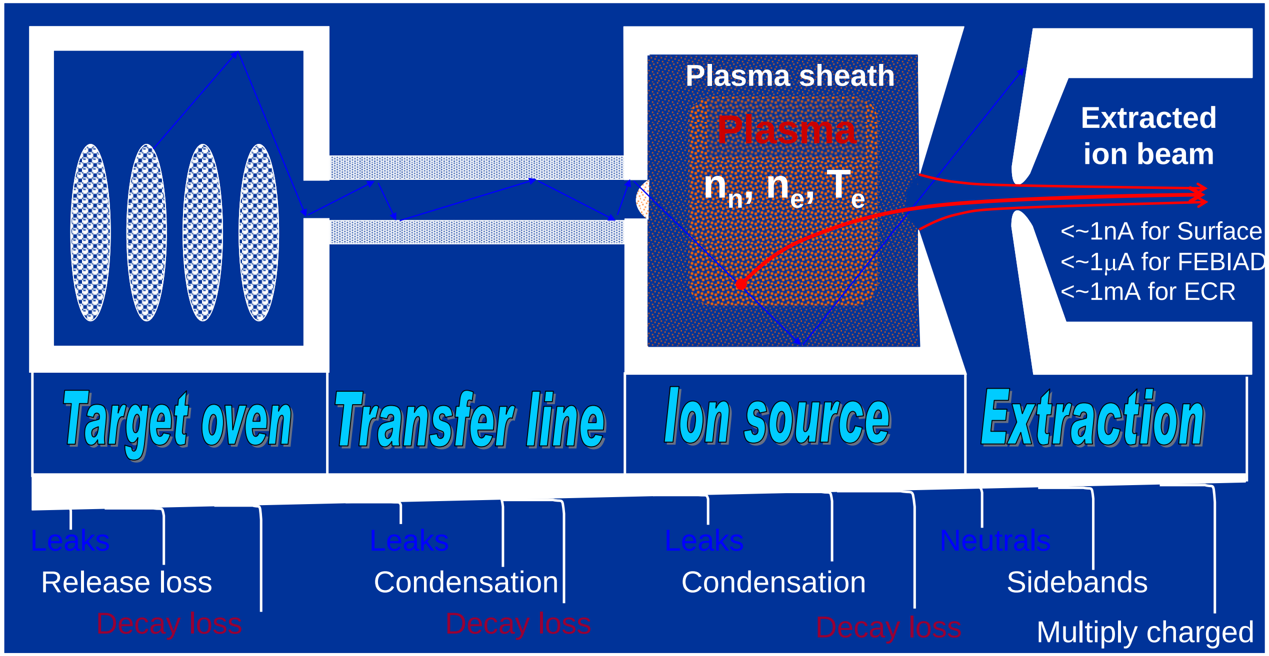
+	Surface	-
hot	Plasma	cool
	Laser	





How to produce a radioactive ion beam with the “ISOL” technique





Plasma sheath

Plasma

n_n, n_e, T_e

Extracted ion beam

<~1nA for Surface
<~1µA for FEBIAD
<~1mA for ECR

Target oven	Transfer line	Ion source	Extraction
Leaks Release loss Decay loss	Leaks Condensation Decay loss	Leaks Condensation Decay loss	Neutrals Sidebands Multiply charged

2238U&232Th targets for ISOL radioisotope beams

RIB intensity $[s^{-1}\ \mu A^{-1}]$

Proton beam Intensity $[s^{-1}\ \mu\ A^{-1}]$

Avogadro Numb.

Diffusion+ Effusion Efficiency

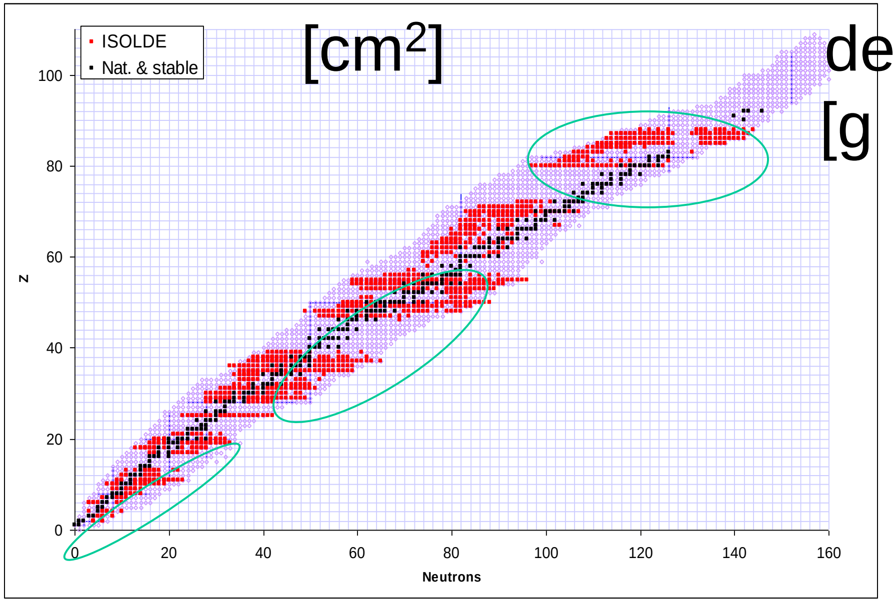
$$I = \int \sigma(E)\ \Phi(E, x)\ \rho(x)\ N/A\ dx\ \varepsilon_{diff+eff}\ \varepsilon_{ion}$$

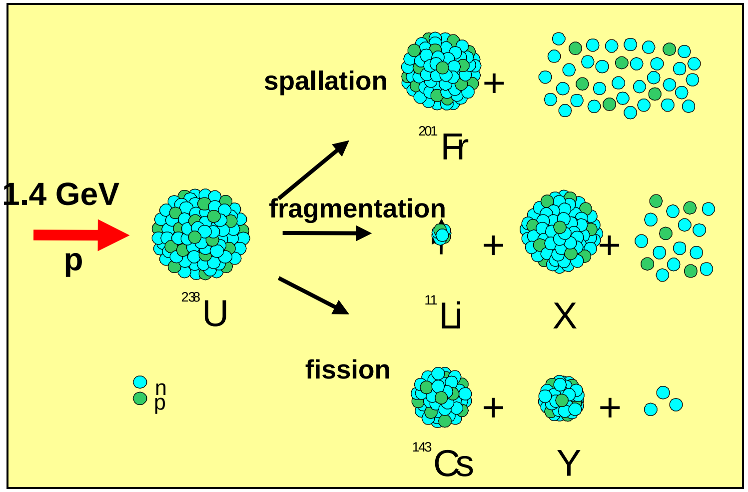
Cross section $[cm^2]$

Target density $[g\ cm^{-3}]$

Target Atomic Mass [g]

Ionization Efficiency





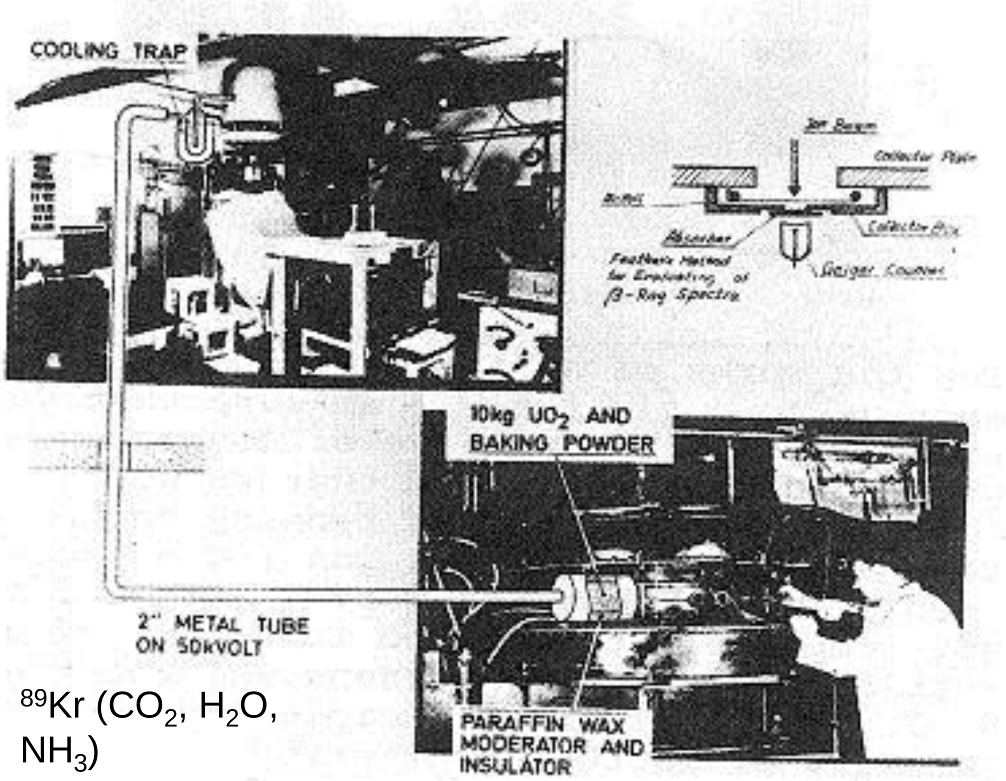
THE BIRTH OF ON-LINE ISOTOPE SEPARATION

ISOLDE “0”

O.Kofoed-Hansen

K.O. Nielsen

Dan. Mat.Fys.Medd. 26, no. 7 (1951)

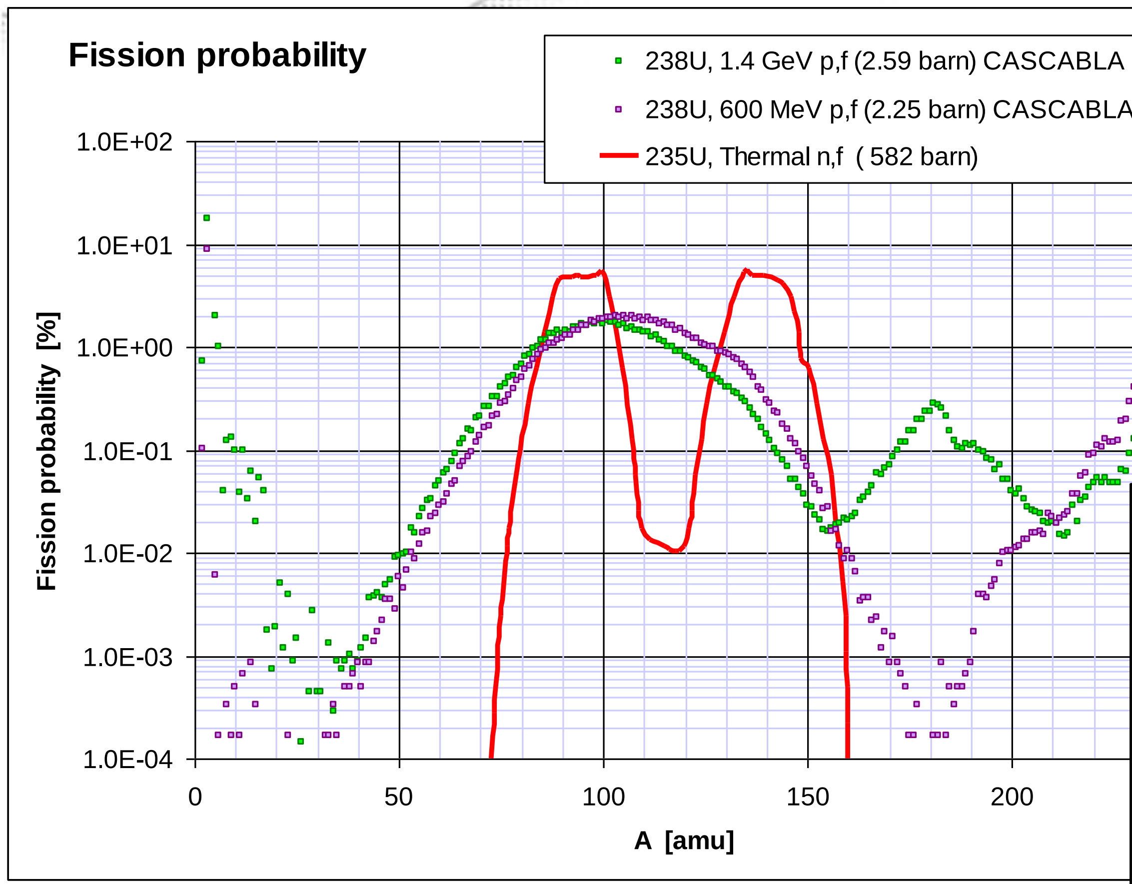


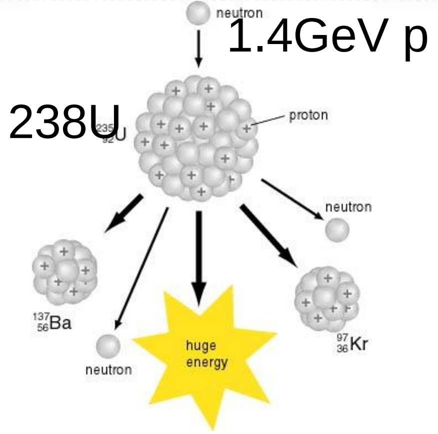
^{89}Kr (CO_2, H_2O, NH_3)

From CERN 76-13, 3rd conf. nuclei far from stability

10 MeV deuterons
d-to-n converter (Be)
n moderator (wax)
UO_2 (10 kg)
Baking powder

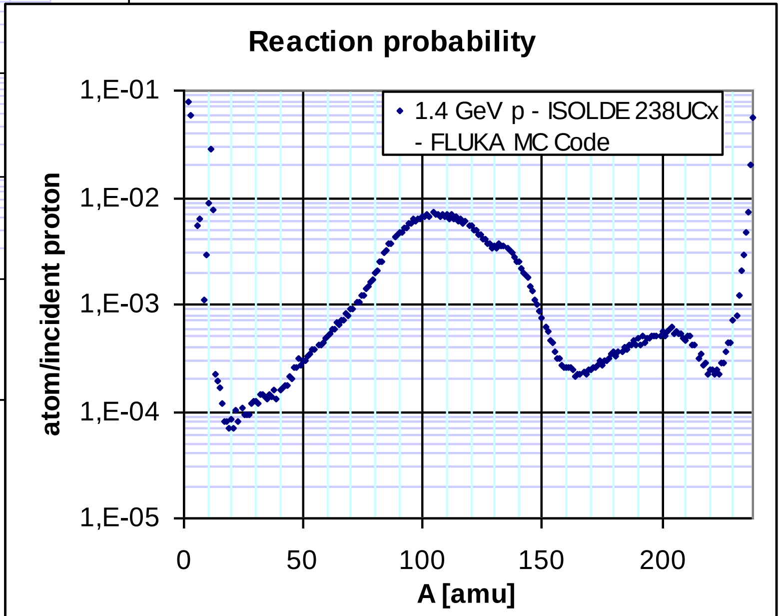
Uranium targets for ISOL beams





Fast n,
1.4GeV p

238U



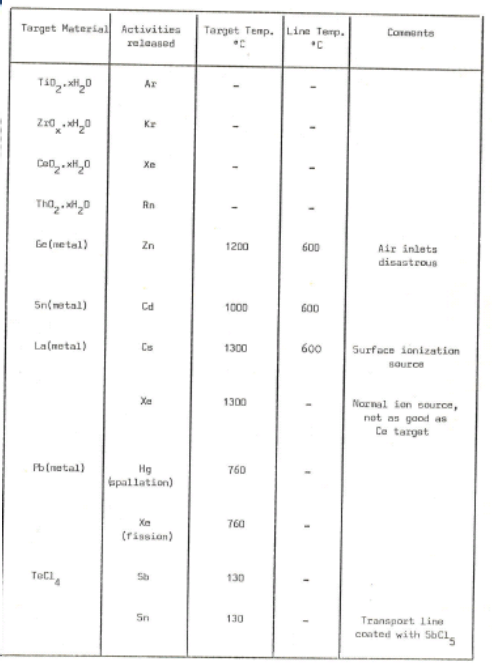
Bundesministerium für Bildung und Wissenschaft

Forschungsbericht K 70-28

Kernforschung

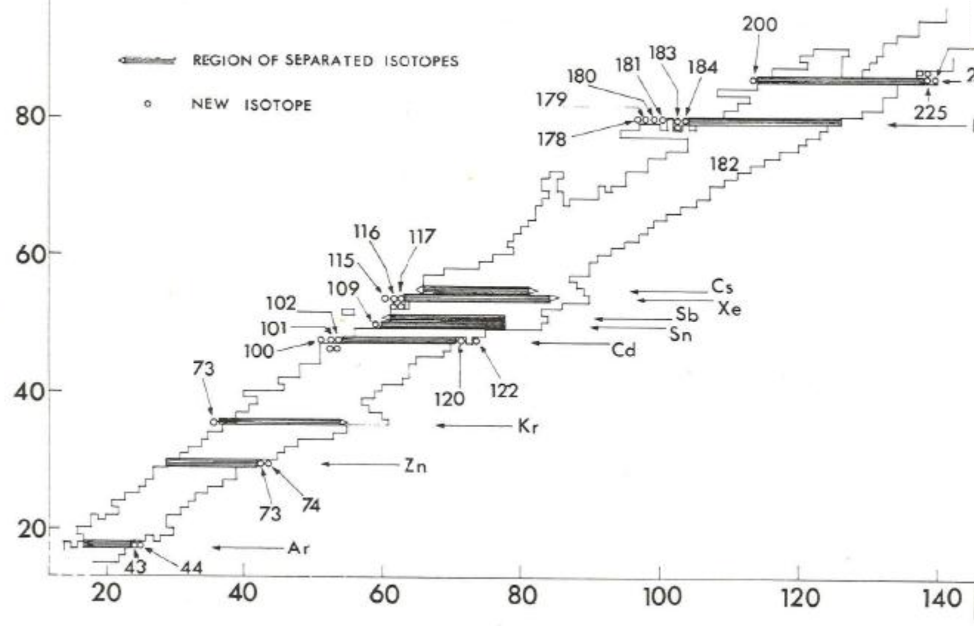
PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON ELECTROMAGNETIC ISOTOPE SEPARATORS AND THE TECHNIQUES OF THEIR APPLICATIONS

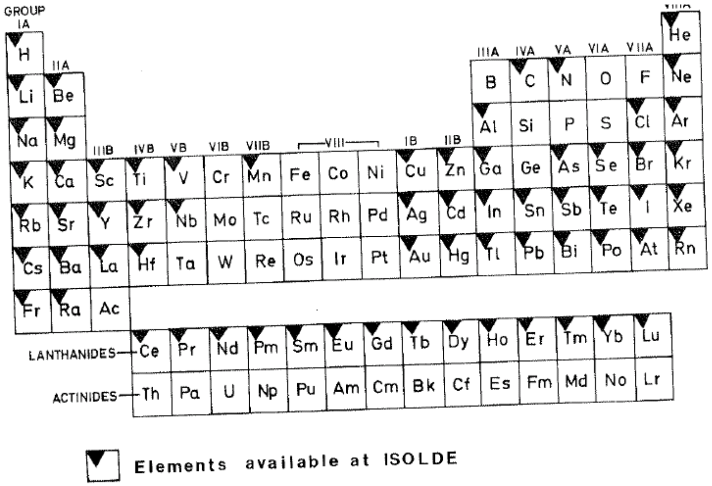
Marburg, Sept. 7 to Sept. 10, 1970



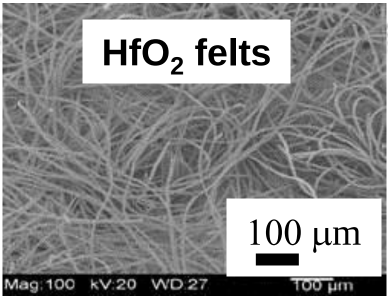
Target Material	Activities released	Target Temp. °C	Line Temp. °C	Comments
$TiO_2.xH_2O$	Ar	–	–	
$ZrO_x.xH_2O$	Kr	–	–	
$CeO_2.xH_2O$	Xe	–	–	
$ThO_2.xH_2O$	Rn	–	–	
Ge(metal)	Zn	1200	600	Air inlets disastrous
Sn(metal)	Cd	1000	600	
La(metal)	Cs	1300	600	Surface ionization source
	Xe	1300	–	Normal ion source, not as good as Cs target
Pb(metal)	Hg (spallation)	760	–	
	Xe (fission)	760	–	
$TeCl_4$	Sb	130	–	
	Sn	130	–	Transport line coated with $SbCl_5$

CERN 86–05
Experimental Physics Division
18 July 1986





ISOL targets and ion sources

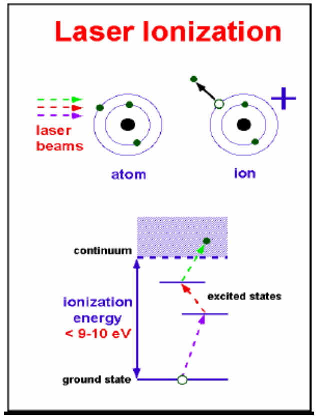

HfO_2 felts

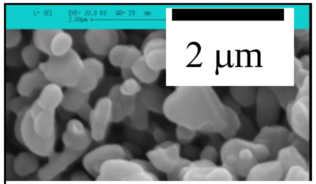
Target materials (30):

- Refractory oxides and carbides (Al_2O_3, SiC)
- Solid metals (Ta, Nb, Mo)
- Molten metals (Pb, La, Sn).

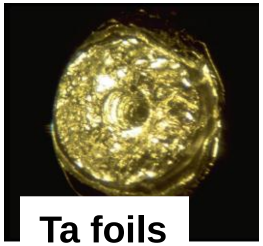
Ion sources (>5):

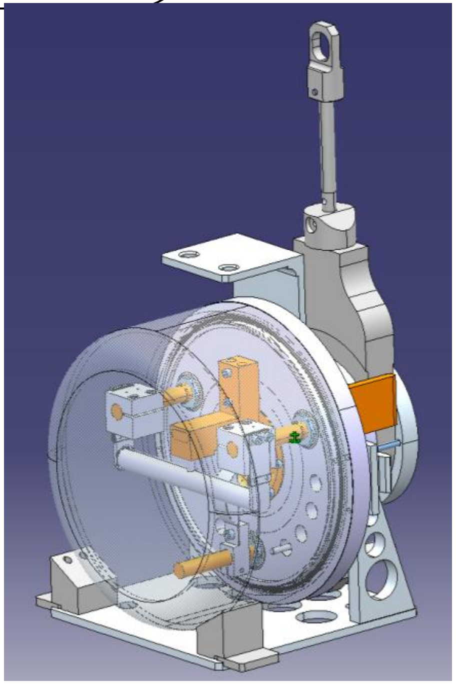
- Surface
- FEBIAD, Plasma
- RILIS

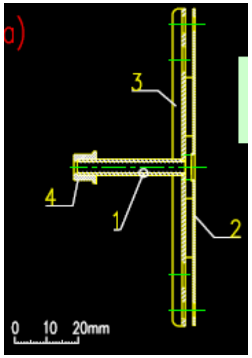


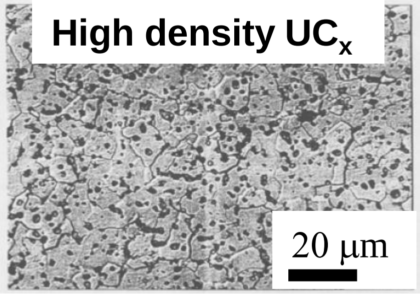


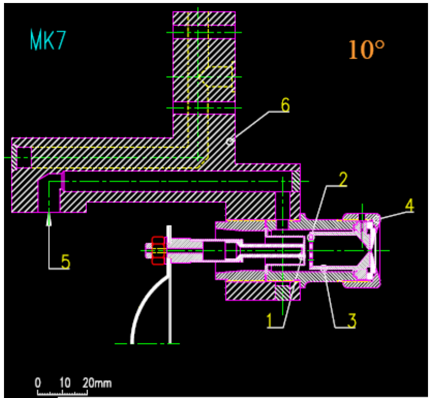
nm/sub-µm SiC


Ta foils



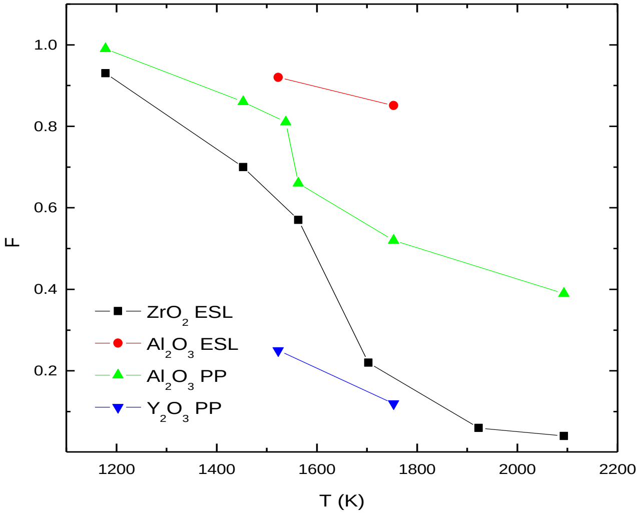


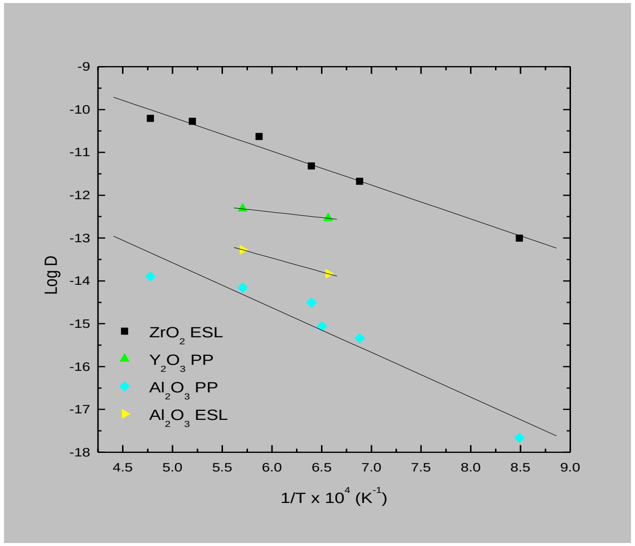

High density UC_x

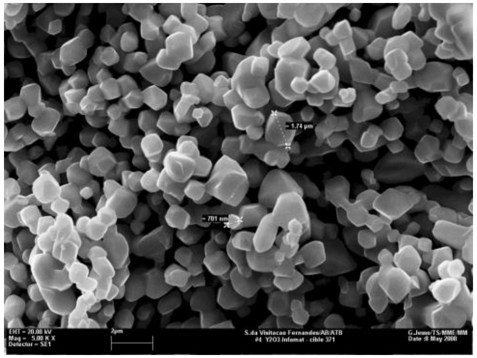



ISOLDE UC_xpressed pellets

Release properties of Kr isotopes





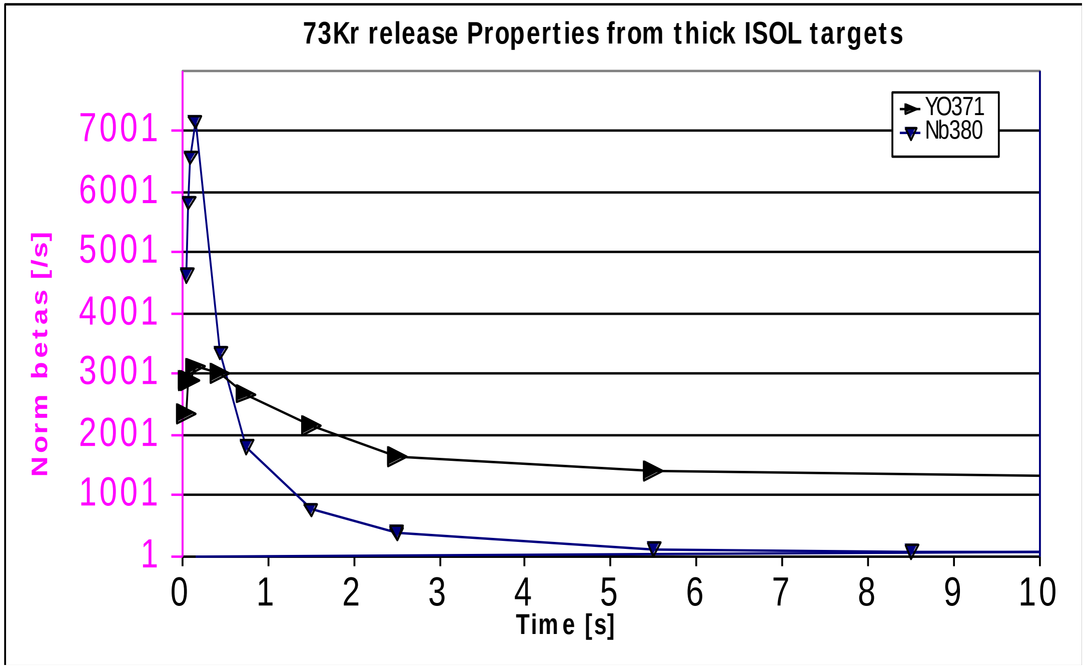


$$(\varepsilon_{target})_{off} = \frac{3}{\pi}\sqrt{\left(\frac{\mu_s}{\lambda}\right)}$$

Nuclide	$t_{1/2}$ (s)	λ (s^{-1})	μ_s (s^{-1})	$\varepsilon(\text{target})_{off}$
^{72}Kr	17.2	0.0405	1.766E-3	0.199
^{73}Kr	27.0	0.0265		0.246

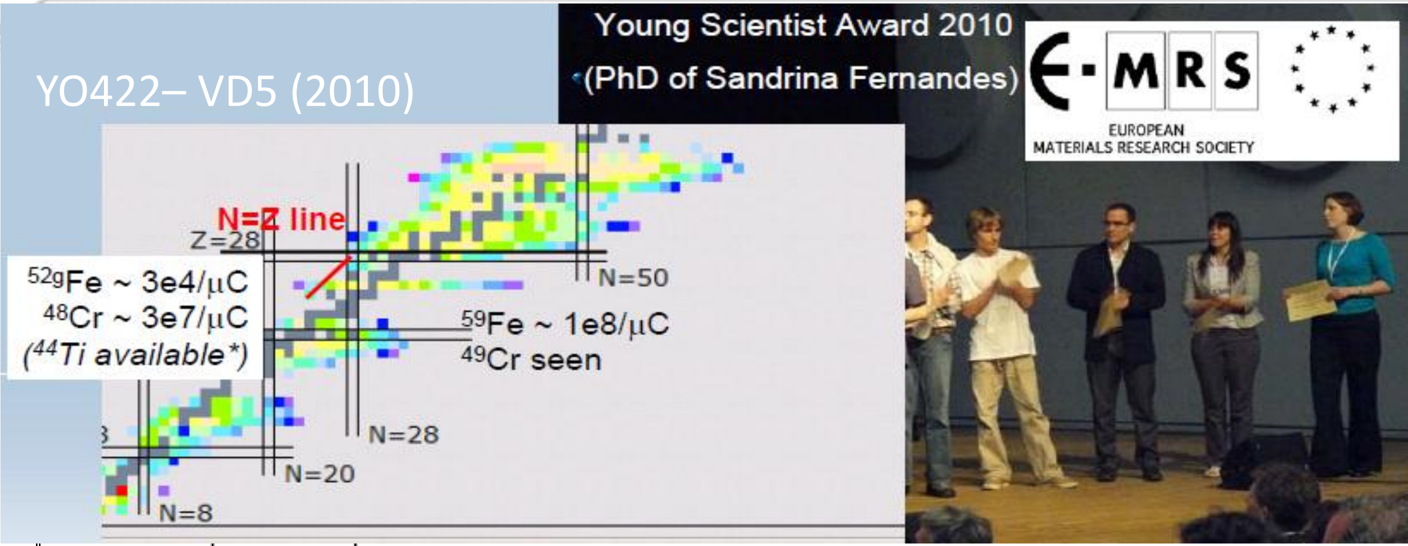
Online yield of Kr

Release curve Y2O3 sub-micron target vs Nb foils (30μm)



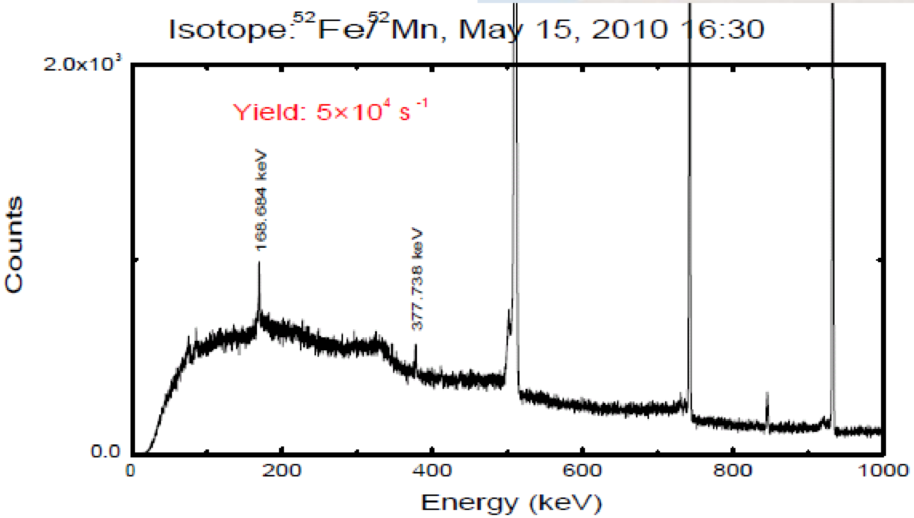
Yields of ^{72}Kr have been improved by x10 from 2 10^3/ μ C to 2 10^4/ μ C (combining prod cross section, target thickness, release efficiency and ion source efficiency)

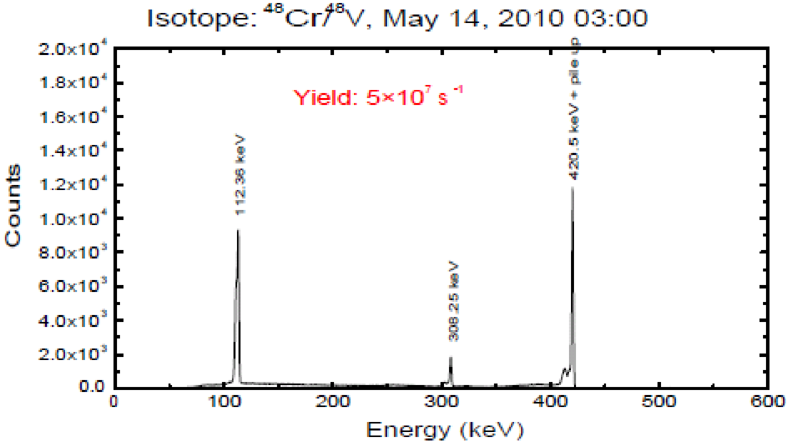
Direct Fe beams at ISOLDE


YO422– VD5 (2010)

Young Scientist Award 2010
(PhD of Sandrina Fernandes)

Courtesy of
K. Johnston,
M. Deicher
et al.



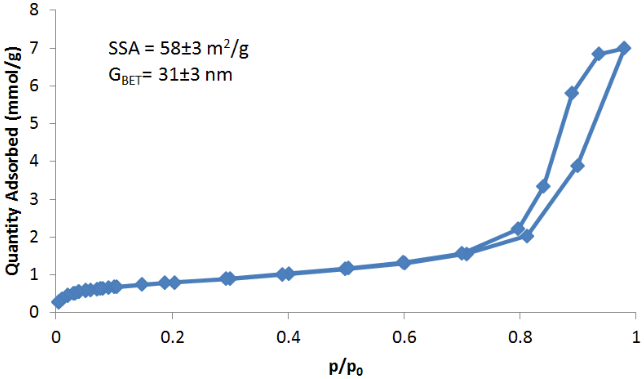


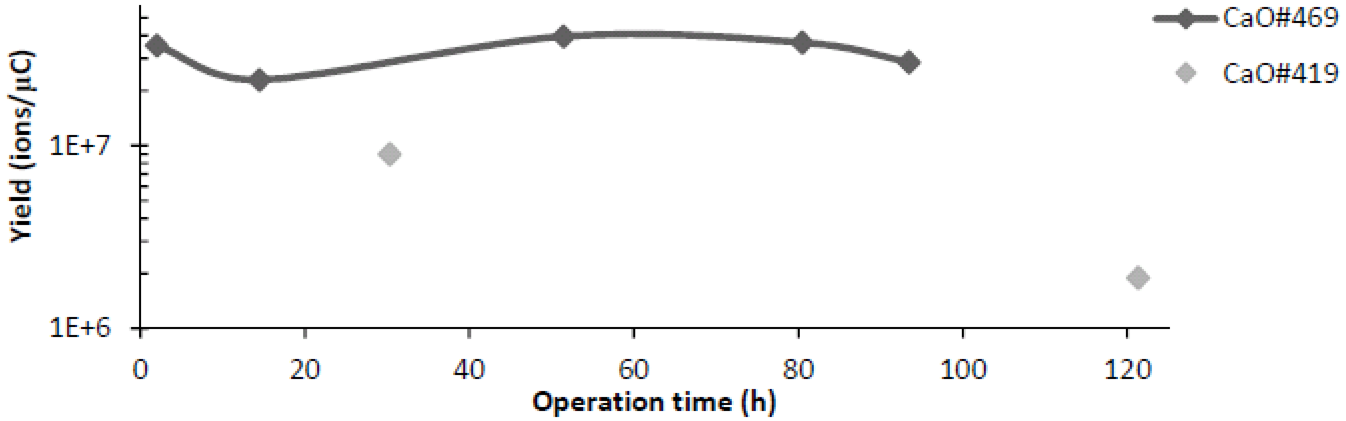
T. Stora, Invited chapter “Nanomaterial-based innovations for particle accelerators” in book on Emerging Topics in Nanotechnology, Wiley ed, in preparation

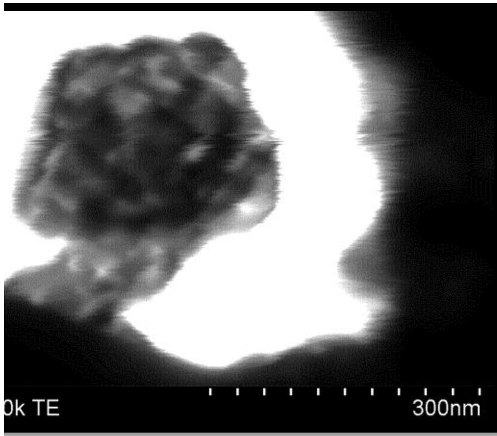
CaO nanomaterials

JP Ramos et al.

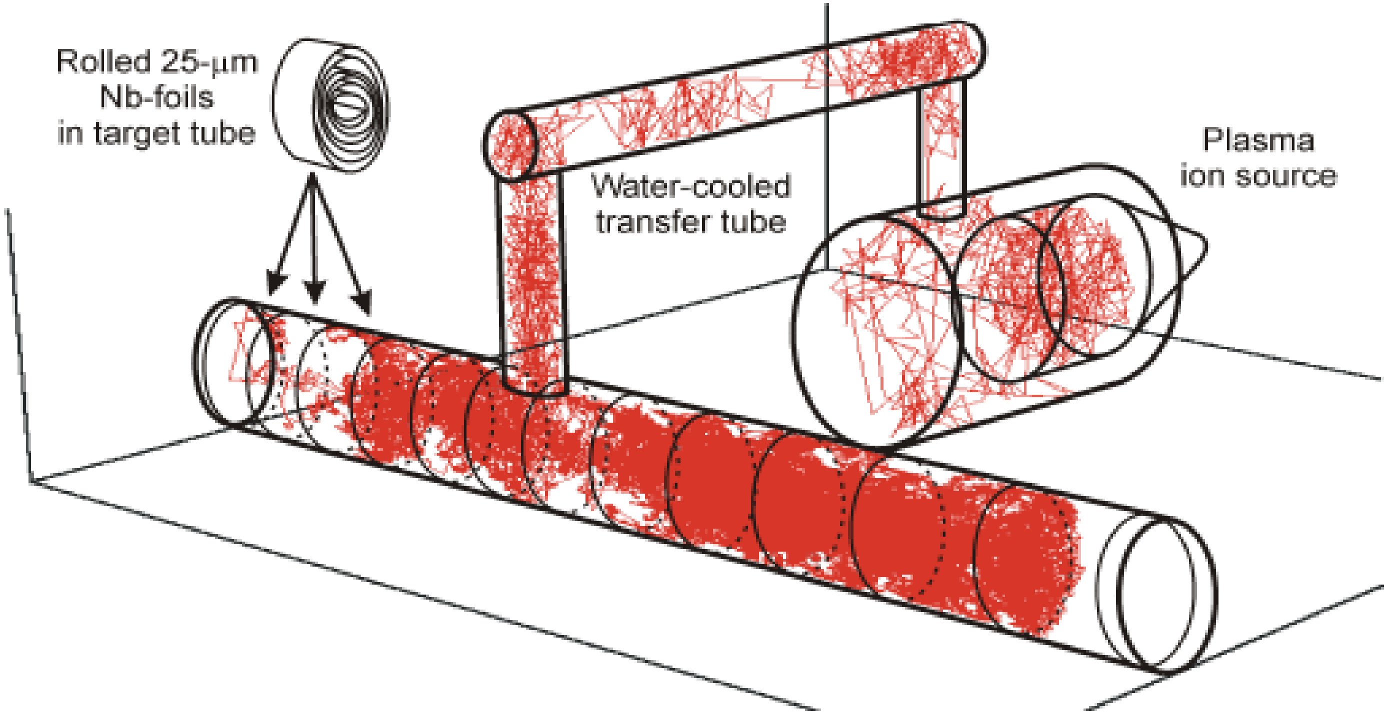
Target	Isotope	Temperature (°C)	ε_{is} (%)	Y_{prod} (ions/μC)	Y_{obs} (ions/μC)	ε_{rel}(%)
CaO#469	^{31}Ar	650		3.2x10^4	4.2x10^1	0.9
	^{32}Ar			1.1x10^6	2.4x10^3	1.6
	^{33}Ar		14.0	2.0x10^7	1.2x10^5	4.3
	^{35}Ar	520	7.2	3.4x10^9	8.9x10^6	3.6
		650	8.0		3.5x10^7	12.9
		730	6.1		3.9x10^7	19.2
		840	19.4		2.0x10^8	29.8
CaO#123	^{31}Ar	1050	9	1.8x10^4	1.5x10^0	0.1
	^{32}Ar			6.2x10^5	3.3x10^3	5.9
	^{33}Ar			1.1x10^7	3.8x10^4	3.8
	^{35}Ar			1.9x10^9	4.3x10^7	25.1
CaO#408	^{31}Ar	>1050	21	2.0x10^4	5.0x10^0	0.1
CaO#419	^{35}Ar	950 (run begin)	8	1.8x10^9	9.0x10^6	6.2
		950 (run end)			1.9x10^6	1.3







Monte Carlo code to compute trajectories

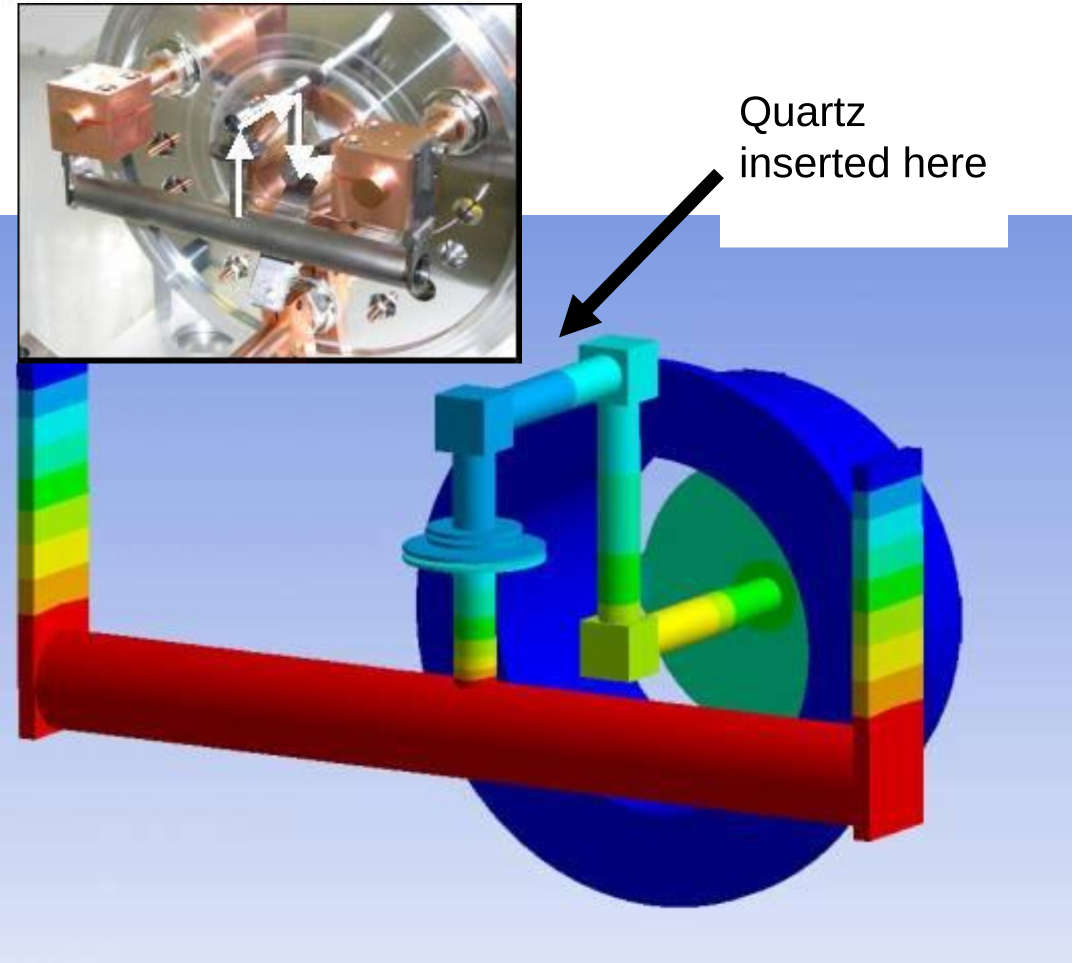


Monte Carlo numerical simulation of isotope trajectory (RIBO code)

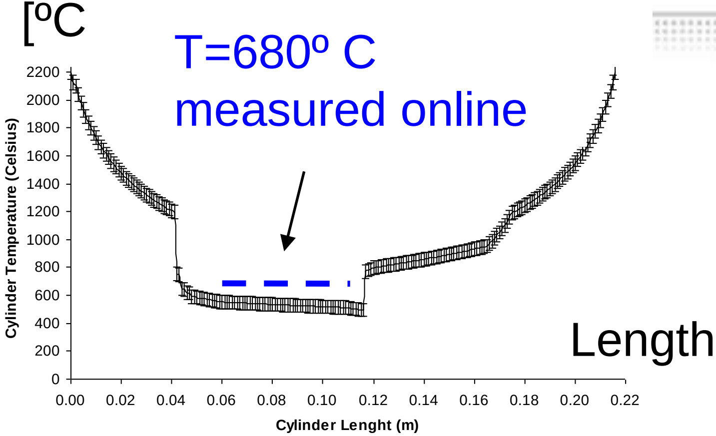
UCx – 314 (Quartz Insert)

ppress Alkalis (Cs, Rb)

for pure beams of G



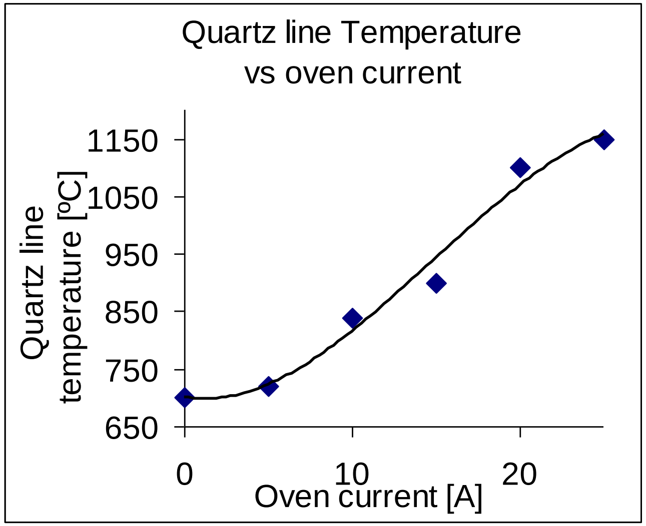
Quartz
inserted here



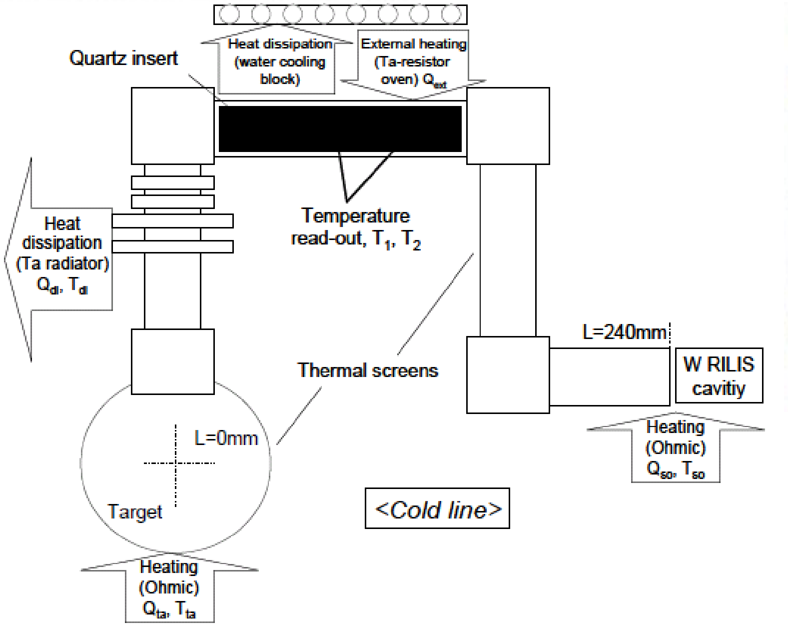
[ºC]

T=680º C
measured online

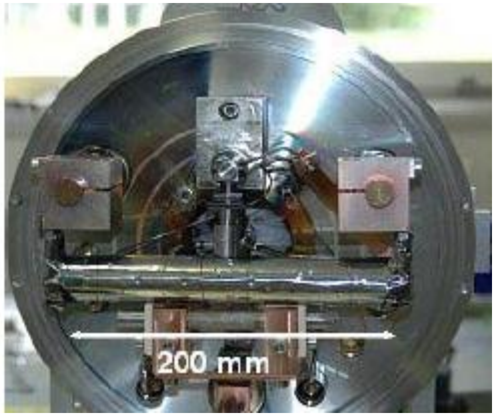
Length

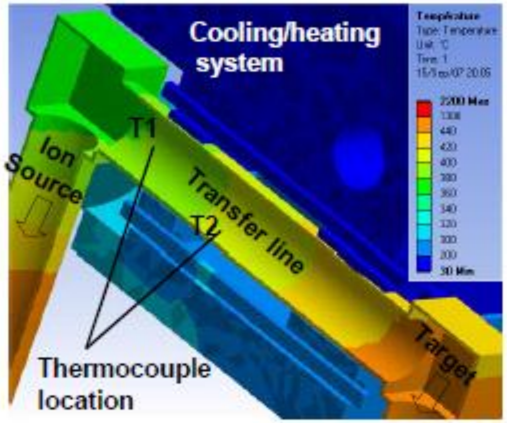


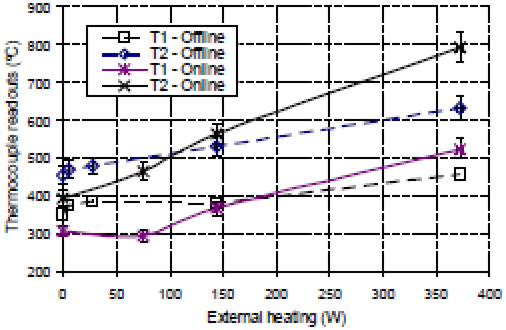
Heating, temperature profiles…

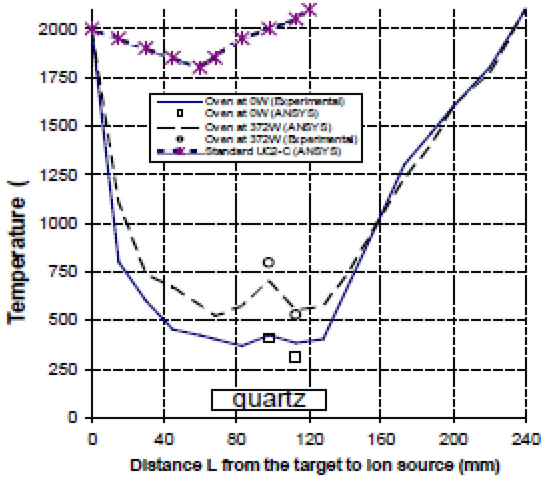


<Cold line>

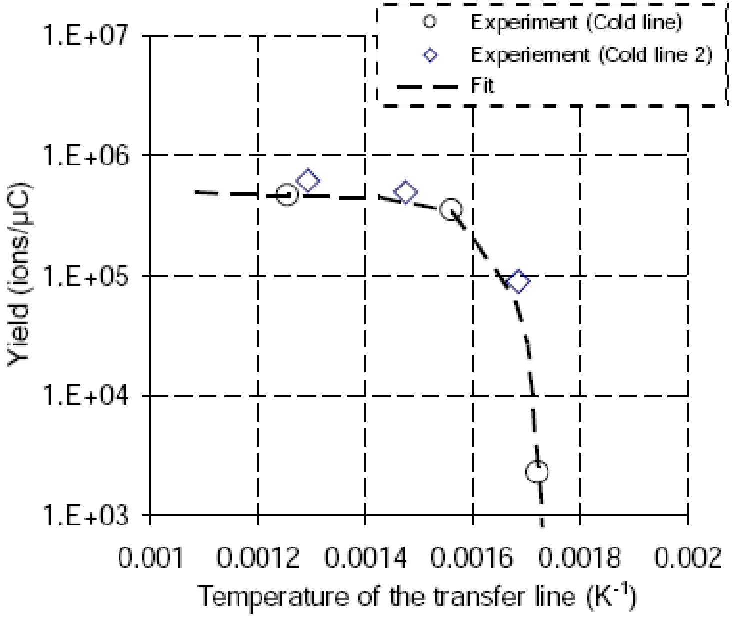


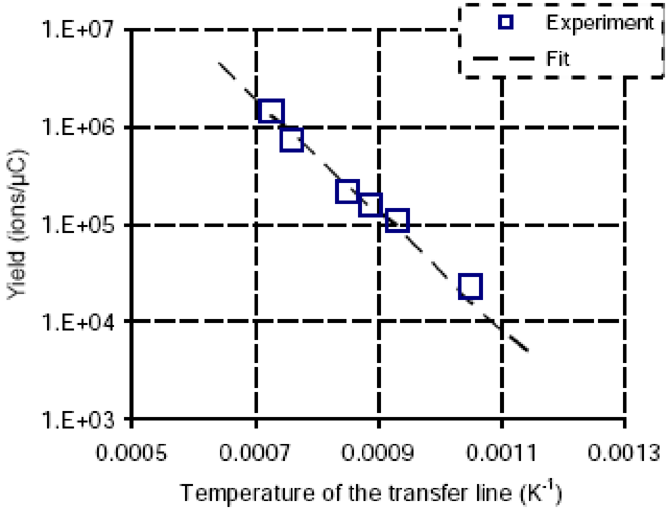






Purification of 80Zn&130Cd beams





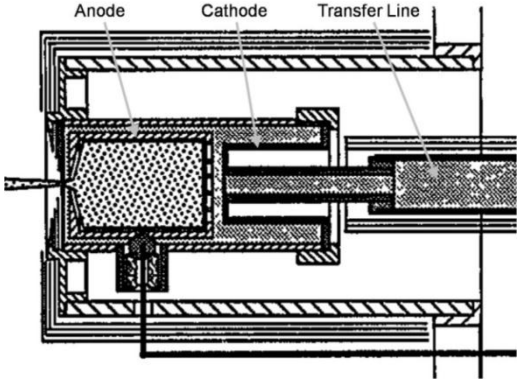
126Cs yield function of quartz temp
Fit with ΔHads = - 145 +- 20 kJ/mol
as only free parameter
Isothermal vacuum chromatography
is ca -180 kJ/mol

80Rb yield function of quartz temp
Fit with ΔHads = - 242 +- 20 kJ/mol
as only free parameter
Isothermal vacuum chromatography
is ca -270kJ/mol

E. Bouquerel et al., Nucl Instr. Meth B266, 4298 (2008)

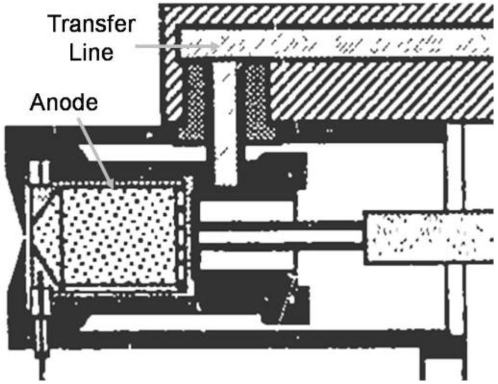
The 3 most "recent" ISOLDE FEBIADs up to 2009

MK5



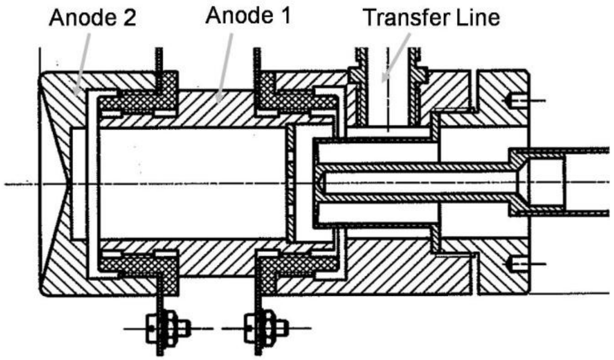
- Hot transfer line
- Employed for the ionization of the condensable elements

MK7



- Water-cooled transfer line
- Employed for the ionization of the noble gases and molecular compounds

MK3

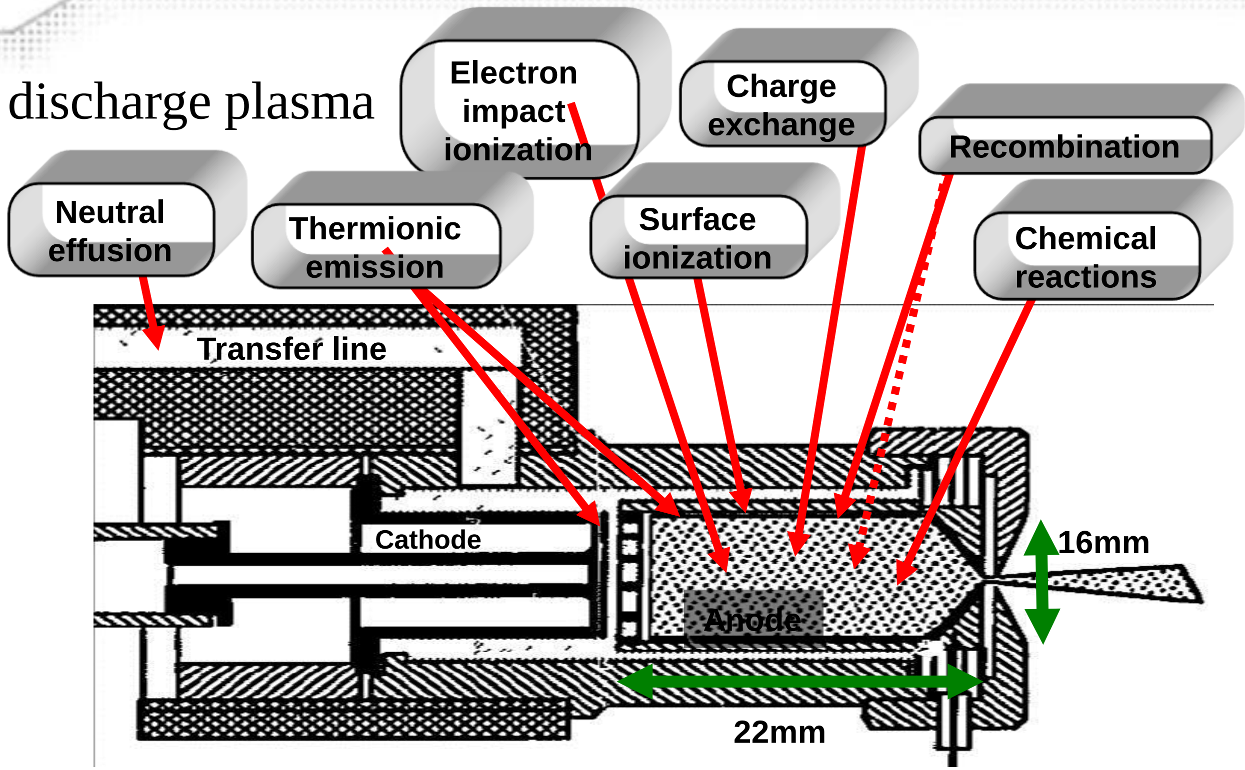


- Temperature controlled transfer line
- Coupled to the molten metal targets

FEBIAD: "Forced Electron Beam Induced Arc Discharge"

Investigation tools: Analytical

Modeling of the arc discharge plasma



- Full cocktail of possible phenomena.
- Not all appearing all over the variation range of the operation parameters.
- Some of them can be neglected at the nominal parameters.
- Application range has been investigated (experiment vs. theory).
- Performance limitations could be pointed out, justified and removed

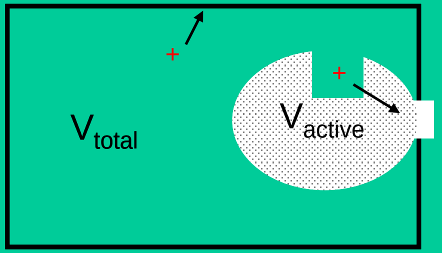
Ionization efficiency modeling

$$\varepsilon = f \times \frac{R_{ioniz}}{n_{n\_in}} \quad \Rightarrow \quad \varepsilon = f \times V_{source} \times \frac{n_e \times n_n \times \sigma_{ioniz} \times v_{rel}}{n_{n\_in}}$$

The extraction factor, f

f = the fraction of the produced ions that are extracted before losing their charge on the ion source walls or being pumped.

f (geometrical) = the fraction of the source volume where the generated ions are extracted from, due to favorable field distribution.

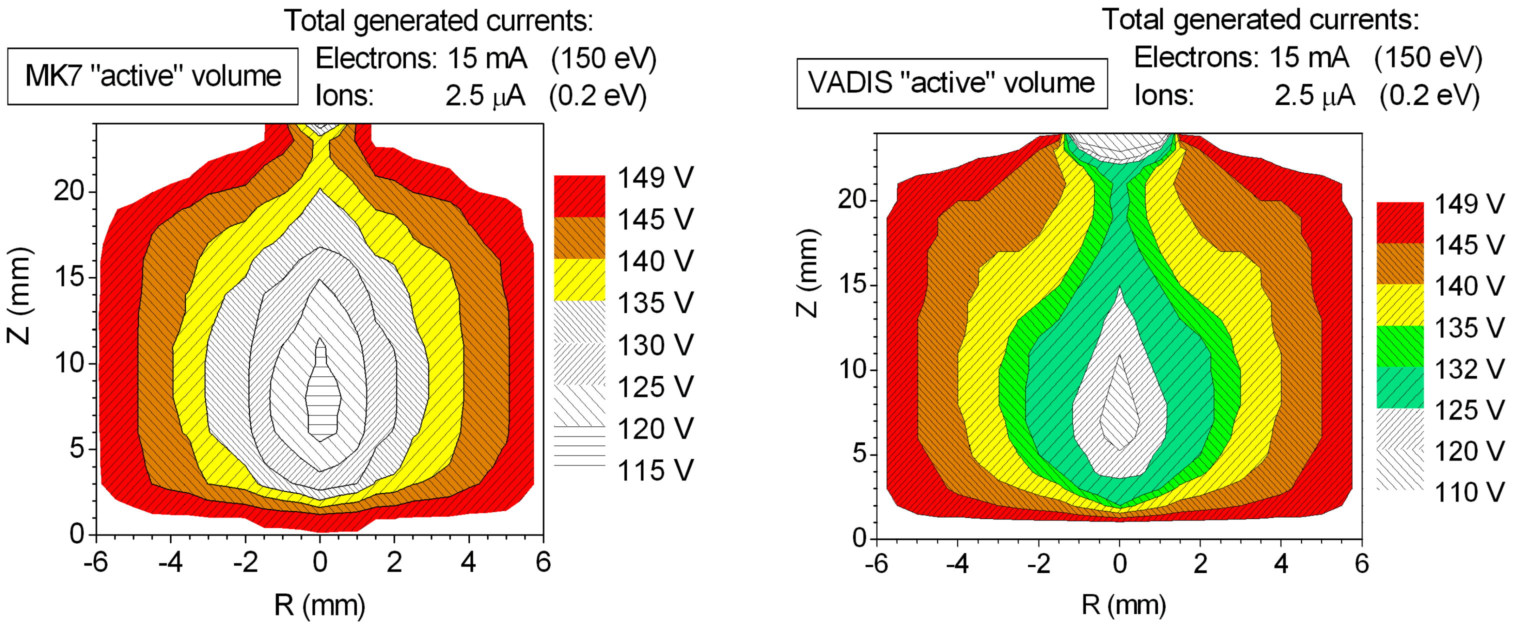


$$f \equiv \frac{V_{active}}{V_{total}}$$

- 1 electron passage;
- no ion trapping;
- T_e = 150 eV ($e \cdot V_{anode}$, initial energy);
- T_i = 0.17 eV (2300 K, thermal energy);
- n_e = temperature dependent (cathode emission given by Richardson Dushmann);
- n_n = dep. on pressure, n_{n_in}, C_{out}.

1st prototype: simulation (2/2)

CPO simulation of the internal electrical field distribution


MK7 "active" volume

Total generated currents:
Electrons: 15 mA (150 eV)
Ions: 2.5 μA (0.2 eV)

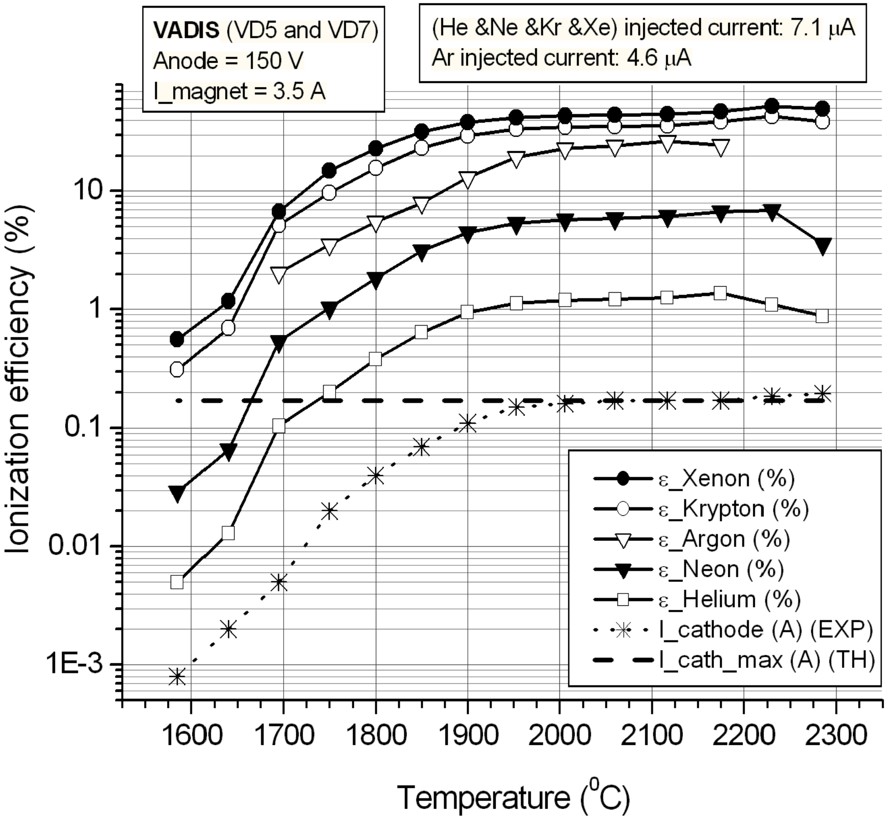
VADIS "active" volume

Total generated currents:
Electrons: 15 mA (150 eV)
Ions: 2.5 μA (0.2 eV)

- ➢ With electrical charges (1 passage through the volume)
- ➢ Active volumes (in color): (132V; 149.8V) for MK7;
  (130V; 149.8V) for MK5

=> The difference in active volumes can justify the efficiency difference.

2nd prototype: results



=> Better efficiencies, with understood limitations.

L. Penescu et al., Rev. Sci. Instr. 81(2), 02A906 (2010)

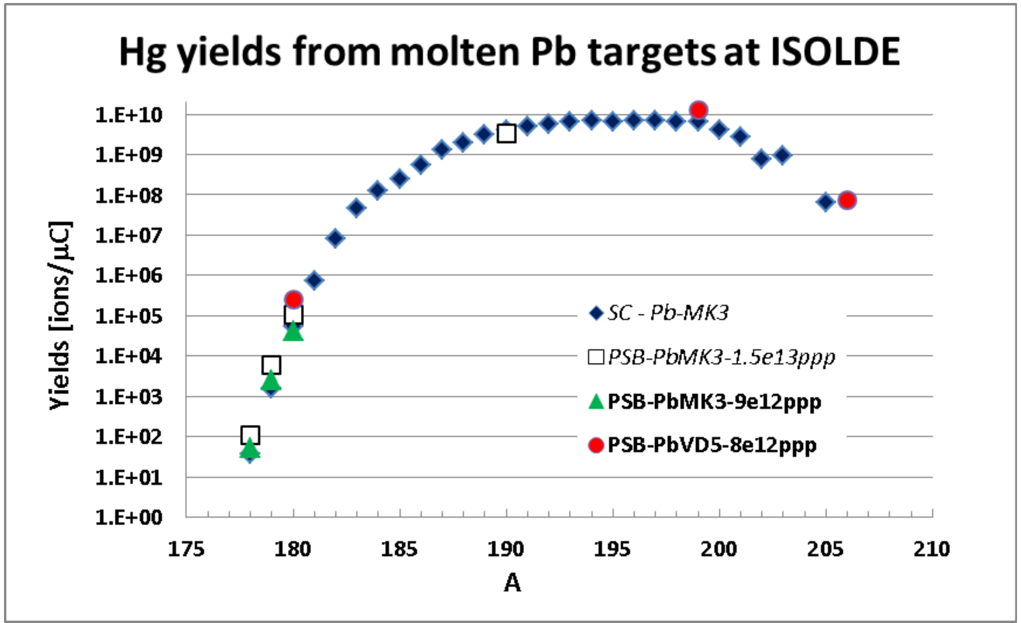
Outcome & perspectives

Novel VADIS ion sources

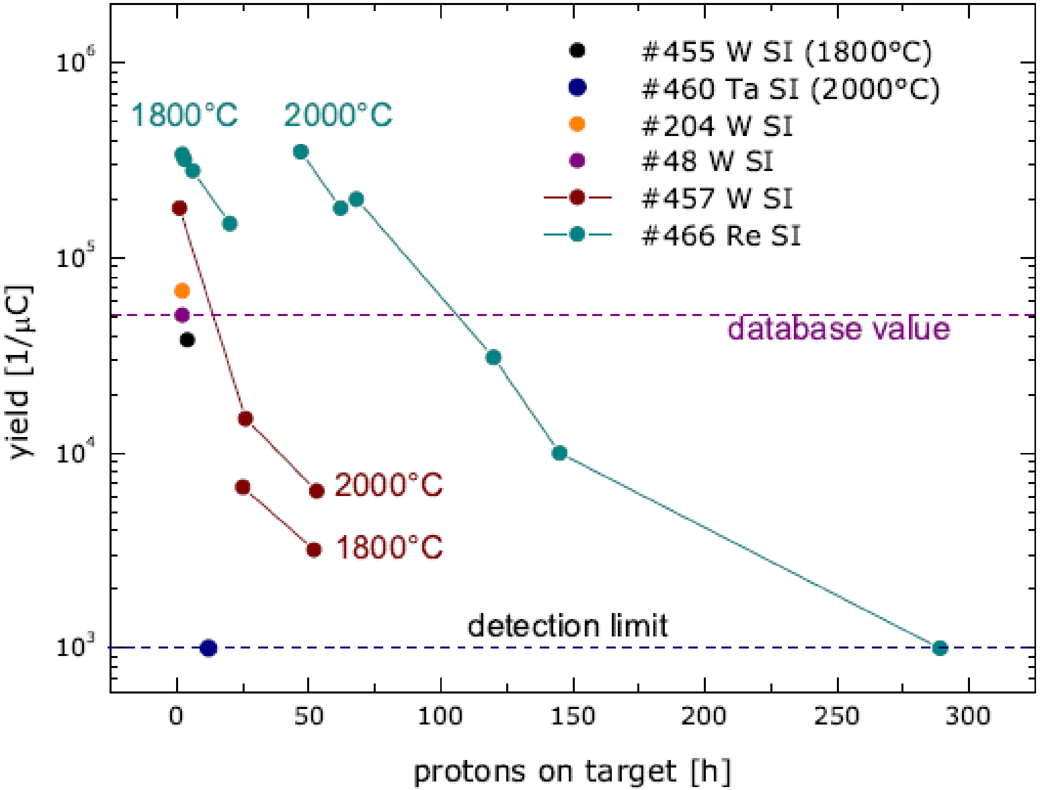
yields on noble gases: x5-10 vs previous figures
^{229}Rn, D. Neidherr et al., Phys Rev Lett 102, 112501 (2009)

Other elements : improvements, eg Hg beams : x5

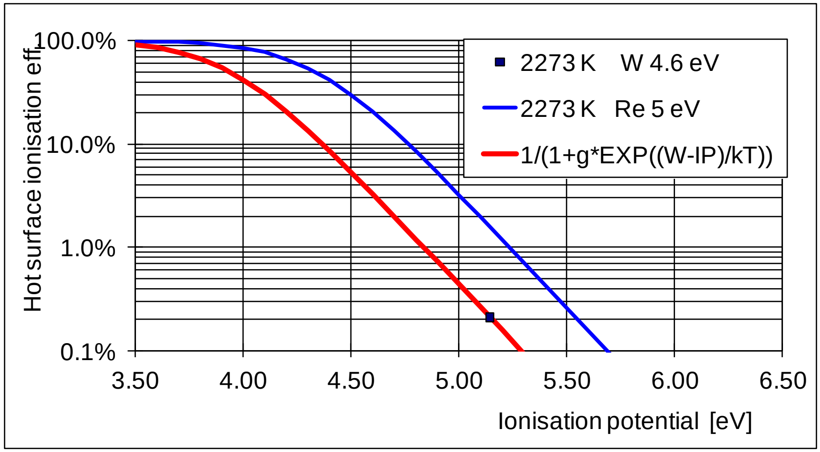
Ongoing tests of laser ion source in VADIS cavity for refractory elements



Recover of historical ^{30}Na yields



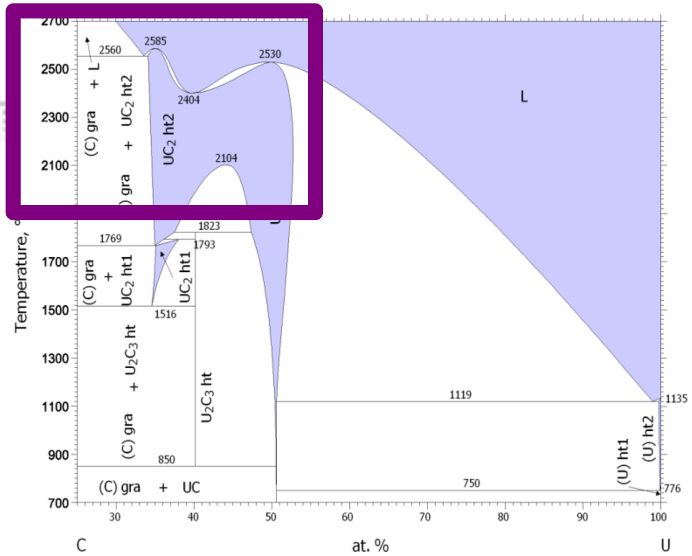
Manufacturing of
a bulk Rhenium Cavity
as hot surface ionizer



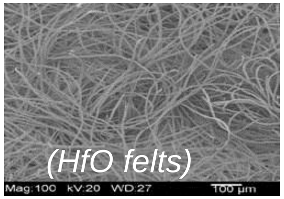
Evolution of yields of ^{30}Na from UCx targets over time under irradiation at ISOLDE

Actinide Target production at ISOLDE

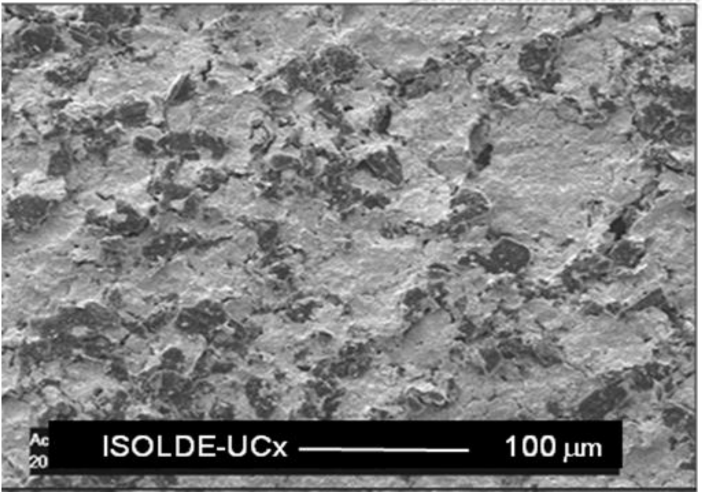
- Uranium Carbide Pills
  - $UO_2 + 6C \rightarrow UC_2 + 2C + 2CO$
    - Target of ~$50 gcm^{-2}$

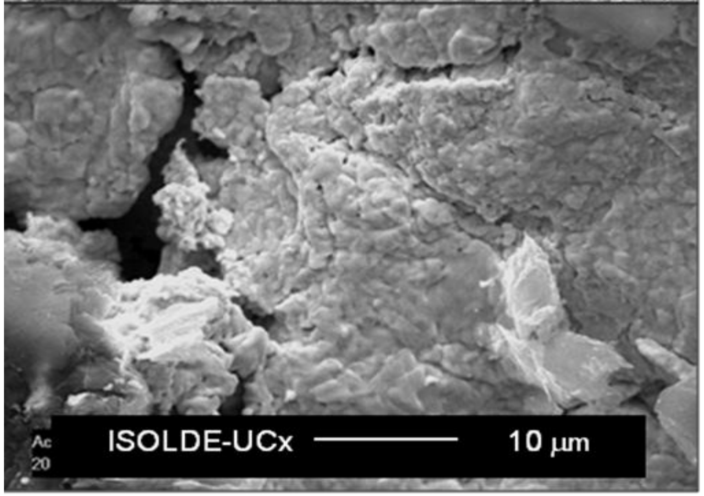


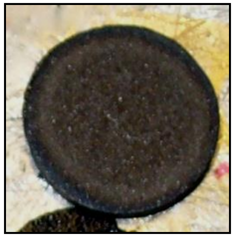
- Uranyl Nitrate $UO_2(NO_3)_2$
  - $U_3O_8 + 20C \rightarrow 3UC_2 + 6C + 8CO$
- Thorium Carbide
  - $ThO_2 + 6C \rightarrow ThC_2 + 2C + 2CO$
- Thoria felt



Characterization UCx ISOLDE

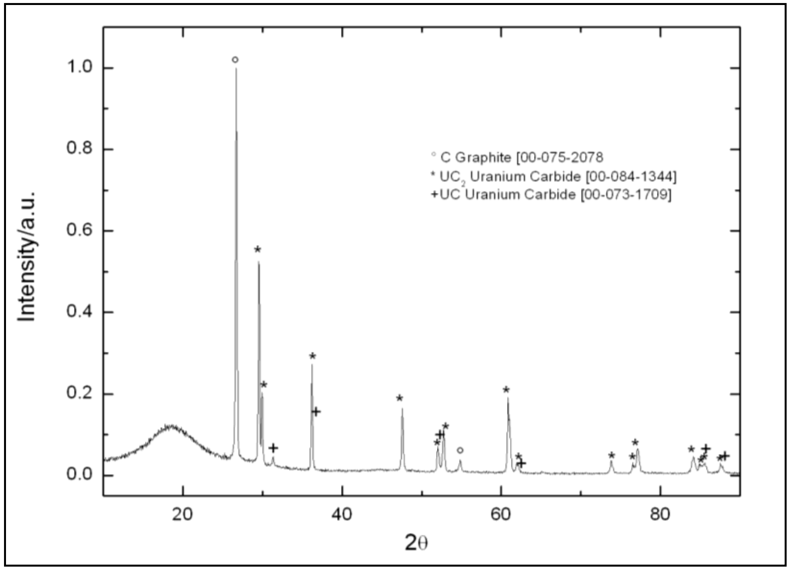






ρ_{bulk}**= 3.5 g/cm^3**

L. Biasetto et al.



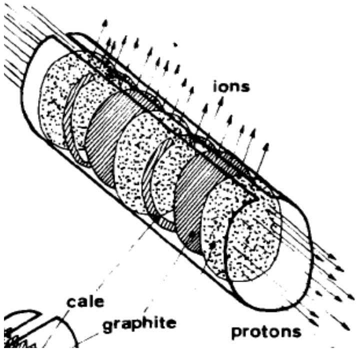
How to do release modeling from this material ?

A Gottberg et al.
FP7 ENSAR ActILAb

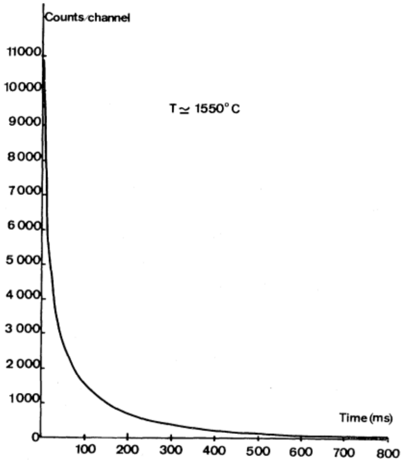
1st Targets used at CERN-PS for alkali metals (p 10-24 GeV)

Target preparation:
5cm long, 6mm diameter.
36x 70μm C, 1-10μm (1-8mg/cm^2) U compound, 100μm gap: tot 0.3g/cm^2 U
Operated at ca 1500°C

$UO_2(NO_3)_2.6(H_2O)$ layer, converted to UO_3 at 200°C
Heated further to obtain U_3O_8 / UC /UC_2 / oxycarbide



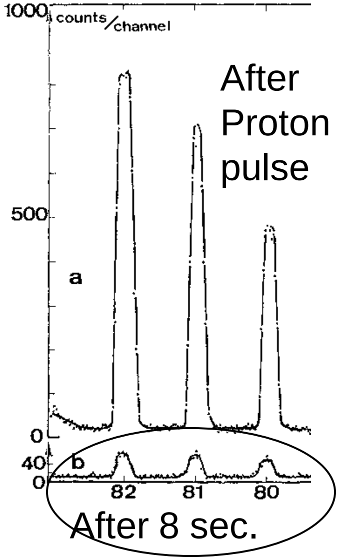
R. Klapish et al.
(UCx at CERN-PS&IPNO/CSNSM, 1967)



Na from Ir/C target

Fission
(***10.5GeV p on ThCx***)
Rb release

Phys Rev Lett, 1968

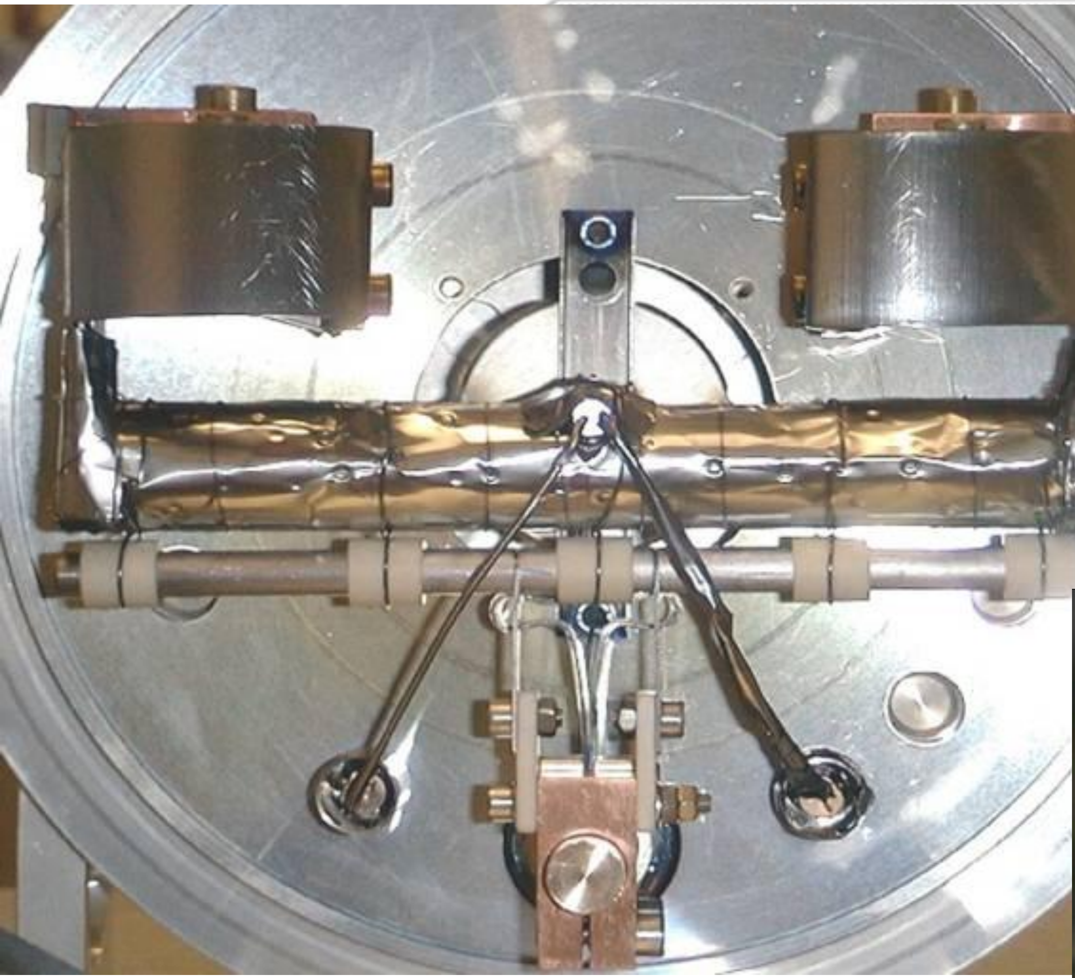


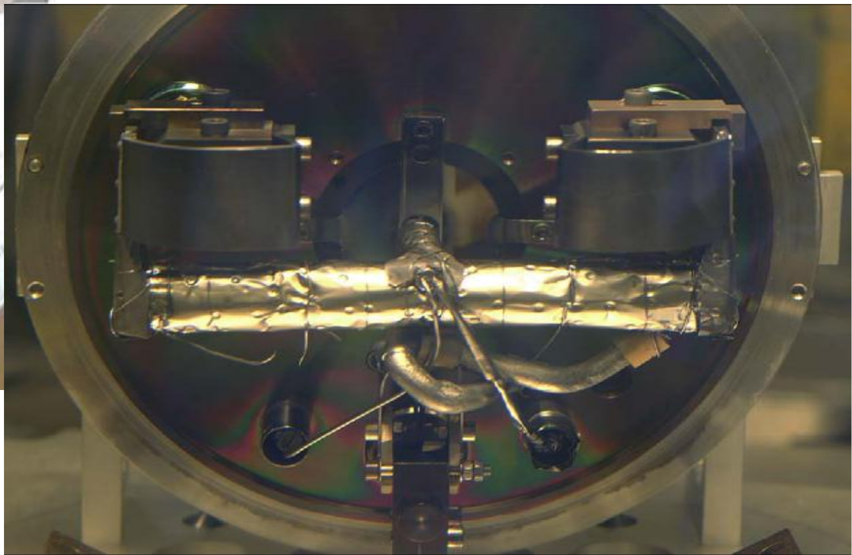
After Proton pulse

After 8 sec.

Target-converter unit at ISOLDE

ISOLDE n-spallation source: Ta(W)-rod mounted below the UC target (before and after irradiation)

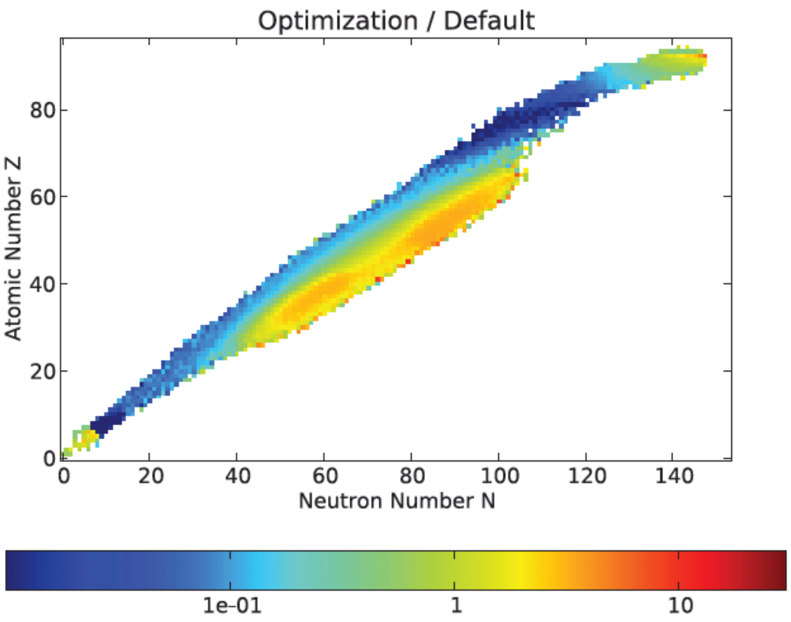


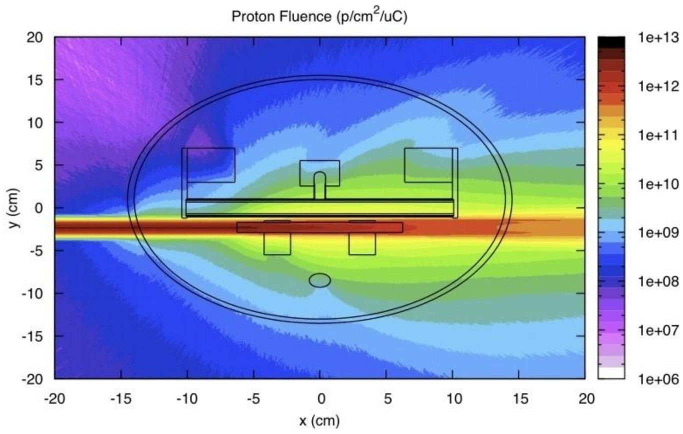


Developments of ISOLDE n-converter

Improvement of fission yields (for ex. ^{80}Zn, ^{130}Cd)

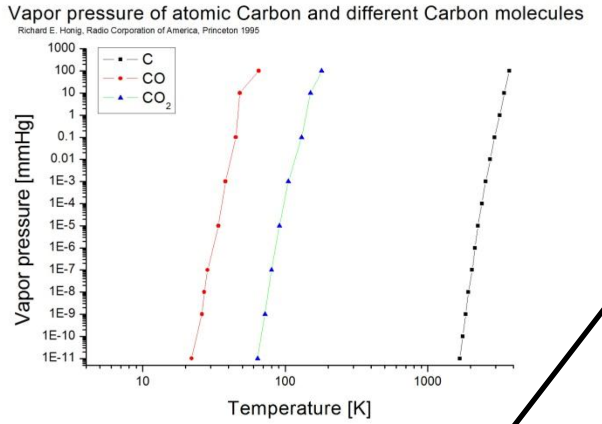
and further reduction of isobaric contaminants (^{80}Rb, ^{130}Cs)



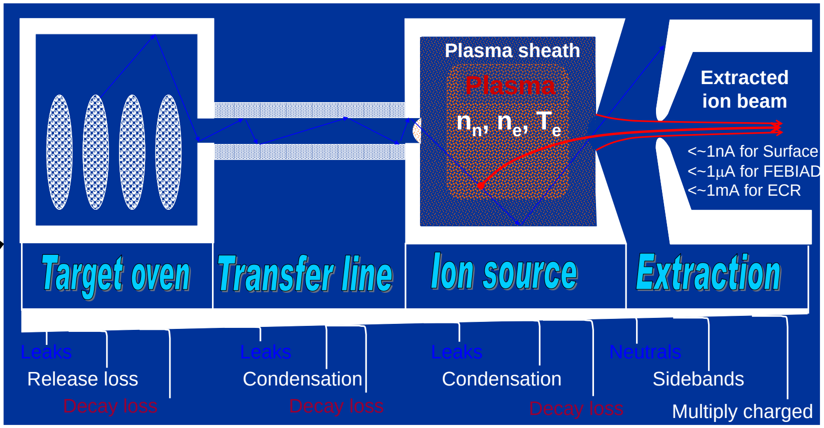


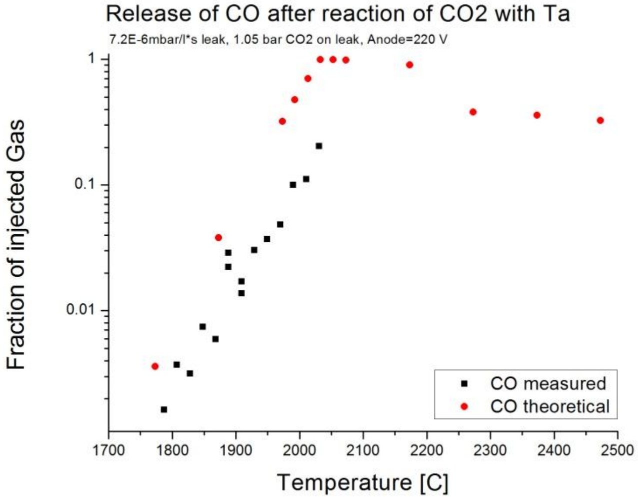
R. Luis et al.
Eur. Phys J. A
Subm.

C beams as CO^+, CO_2^+

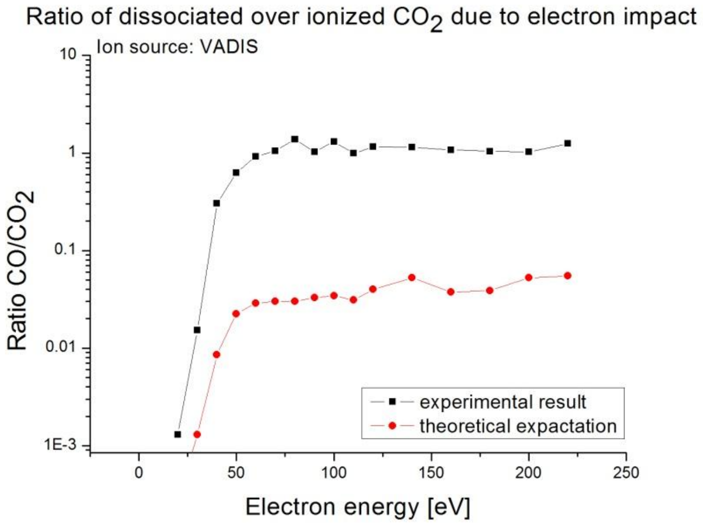

Vapor pressure of atomic Carbon and different Carbon molecules

Richard E. Honig, Radio Corporation of America, Princeton 1995




Release of CO after reaction of CO2 with Ta

7.2E-6mbar/l*s leak, 1.05 bar CO2 on leak, Anode=220 V

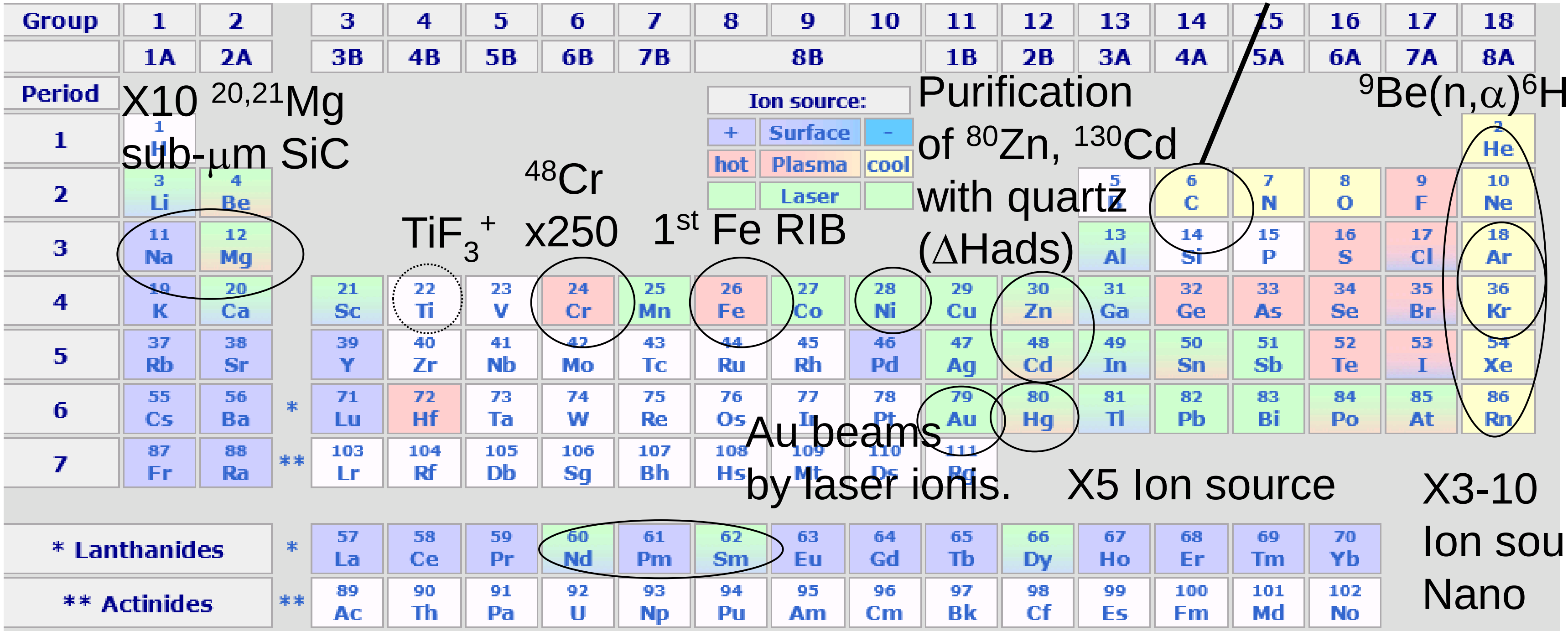

Ratio of dissociated over ionized CO_2 due to electron impact

C. Seiffert et al.

92 elements will be produced @ ISOLDE ?

Beam evolution in the past 5 years

17C as CO+
Helicon
Ion source



Group	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	1A	2A		3B	4B	5B	6B	7B	8B			1B	2B	3A	4A	5A	6A	7A	8A
Period																			
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg							
* Lanthanides			*	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		
** Actinides			**	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		

Ion source:		
+	Surface	-
hot	Plasma	cool
	Laser	

X10 ^{20,21}Mg
sub-µm SiC

^{48}Cr
x250

TiF$_3^+$

1st Fe RIB

Purification
of ^{80}Zn, ^{130}Cd
with quartz
(ΔHads)

^{9}Be(n,α)^{6}He

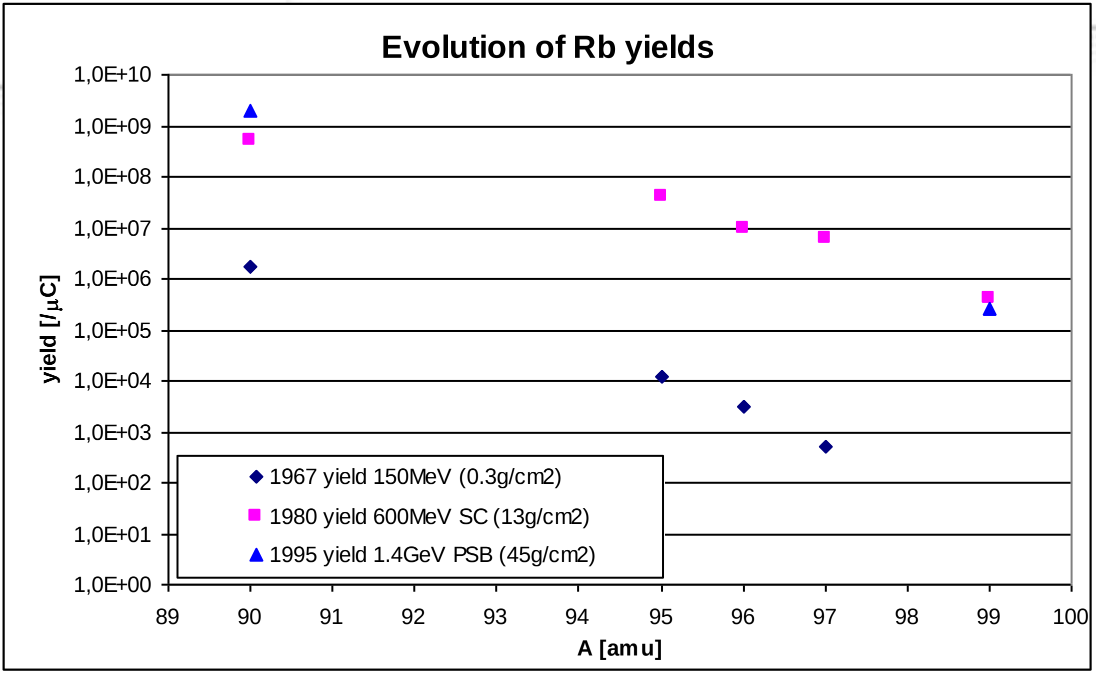
Au beams
by laser ionis.

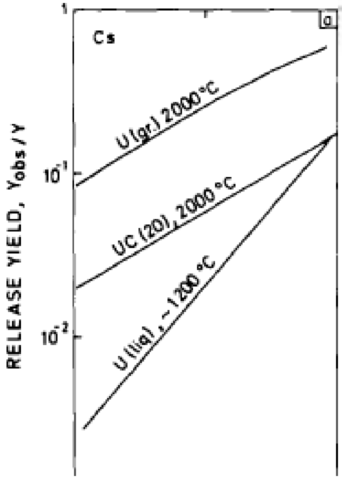
X5 Ion source

X3-10
Ion source
Nano
CaO Y$_2$O$_3$

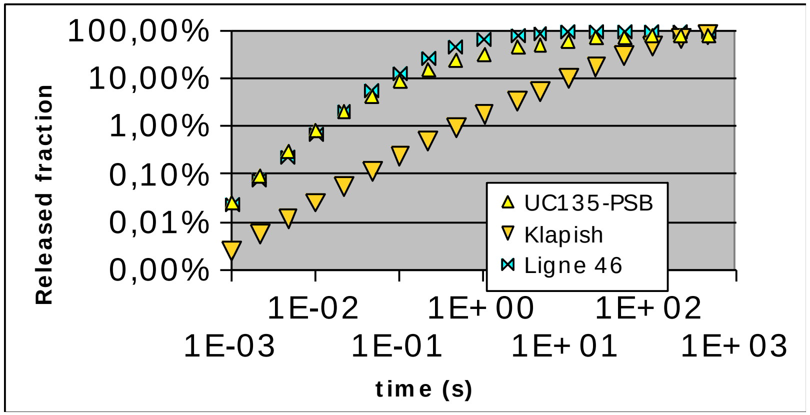
Purification of lanthanide beams :
GdB$_6$ ion source cavity + RILIS

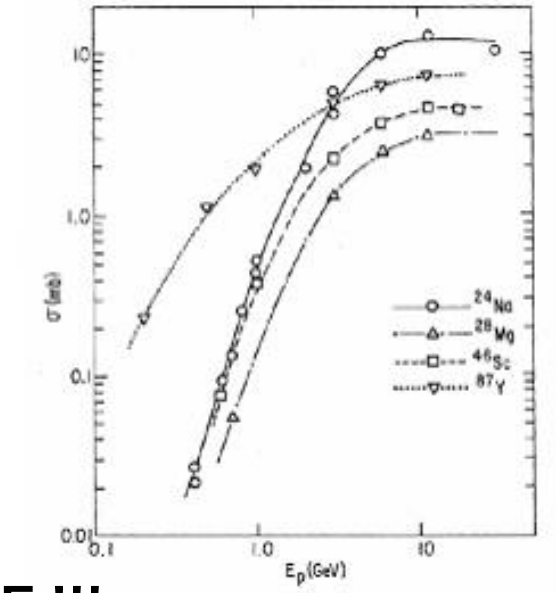
Evolution of yields over years





T1/2 (s)

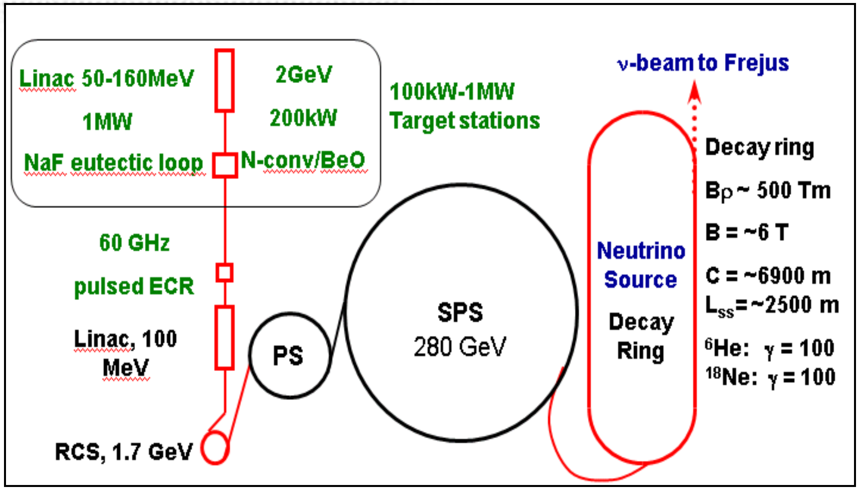




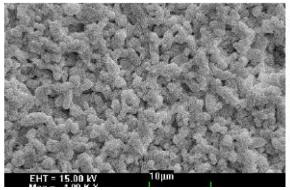
2 GeV, 10kW ideal for HIE-ISOLDE !!!

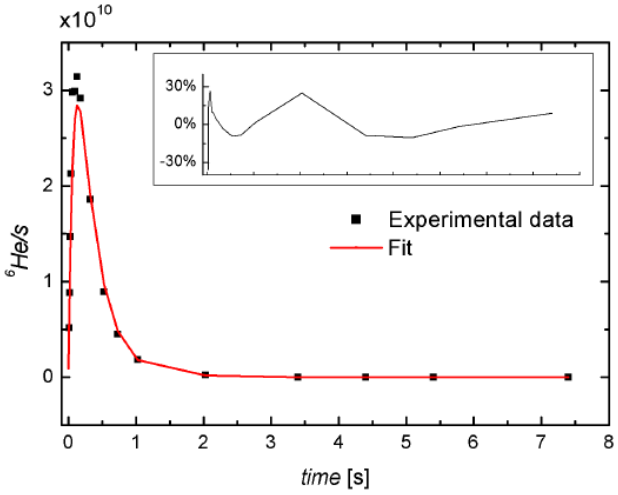
Ions for β beams

T. Mendonca



^{9}Be (n,α) ^{6}He





$$p(t) \propto p_{eff}(t) \star p_{diff}(t)$$

Temperature [°C]	t_{eff1} [ms]	t_{eff2} [ms]	t_{diff} [ms]	Release efficiency [%]	^{6}He production (N_0)
700	5.5	32	320	59	2.7 10^{10}
800	5.6	28	150	71	2.6 10^{10}
1000	4.7	28	1600	51	4.1 10^{10}
1130	3.3	27	190	79	3.1 10^{10}
1400	1.8	24	270	82	2.9 10^{10}

T. Stora et al., Europhysics Letters, in the press

Team & Collaborations

- Dr. M. Kronberger : ion sources
- C. Seiffert : molecule evaporation

- R. Luis : neutronics (ITN, Lisboa)

- Dr. A. Gottberg : target materials, incl. Uranium (ENSAR-FP7, ActILab).
- J. P. Ramos : Target nanomaterials (Univ. Aveiro)
- M. Czapski : material analysis support (CATHI ITN Marie-Curie program)

- Dr. T. Mendonca : High power targetry for neutrino physics
- S. Cimino : High power targetry

GANIL, IPNO, INFN, PSI (Uranium, ENSAR “ActiLab”) + ORNL,TRIUMF
ITN, PSI (neutronics)
EPFL, Aveiro, ITN (materials)
ESS, CEA, SCKCEN-Myrrha, SINP (high power targetry)

Selective adsorption to trap impurities : isothermal chromatography
PhD of E. Bouquerel and related publications

Improved isotope release from porous high T nano(sub-μm) ceramics
PhD of S. Fernandes and related publications (+ CERN patent)

New plasma ion source VADIS
PhD L. Penescu, discovery of 229Rn, related publications

High power targettry
EURISOL and beta beams