Radioactive Ion Sources

CERN Accelerator School

Thierry.stora@cern.ch
Target and Ion Source Development - ISOLDE
EN-STI-RBS

General layout of the lecture

This 1 hour lecture unfortunately can not be exhaustive

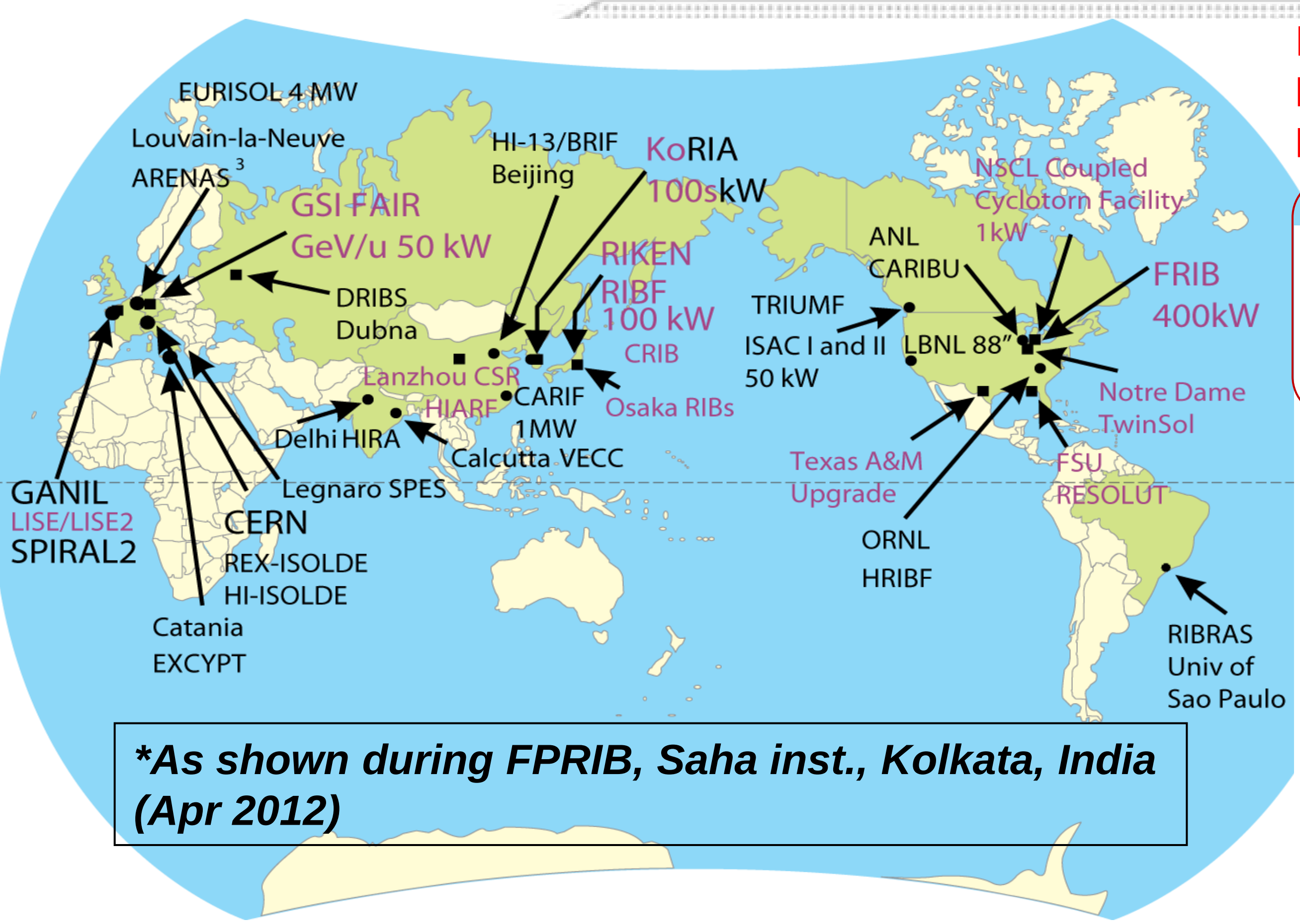
Structure of the lecture :

- Production of radioactive ion beams and specifities
- Some generic principles
- 3 case studies:
  - Surface ion sources
  - Forced Electron Beam Induced Arc Discharge ion sources
  - ECR ion sources

Production of radioactive ion beams and specifities

Some generic principles

World map of radioisotope ion beam facilities*



***As shown during FPRIB, Saha inst., Kolkata, India (Apr 2012)**

In-flight Fragmentation Facilities (in red)

Isotope Separation OnLine Facilities ISOL (in black)

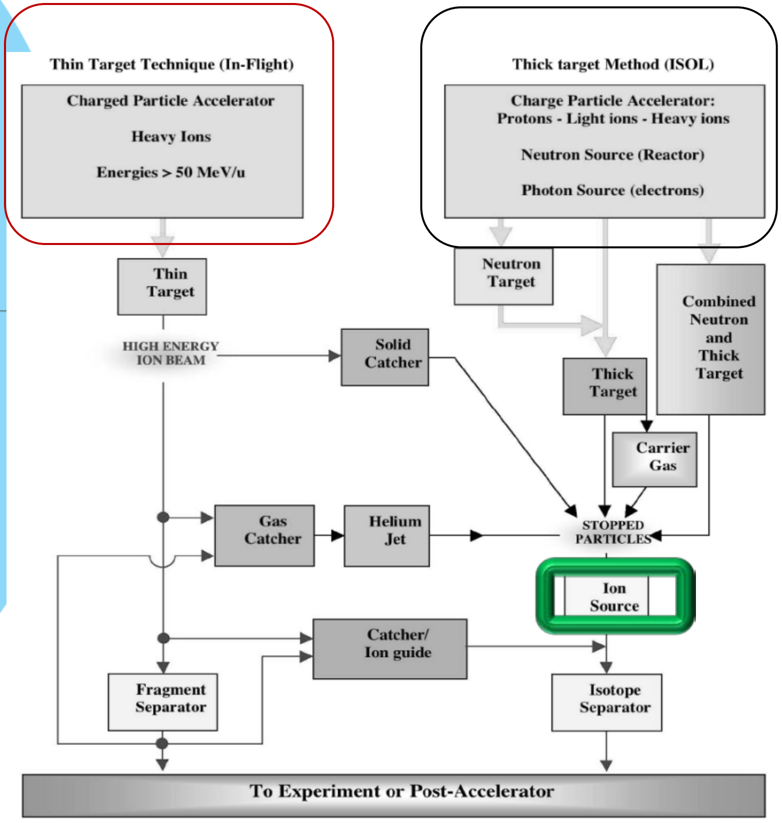
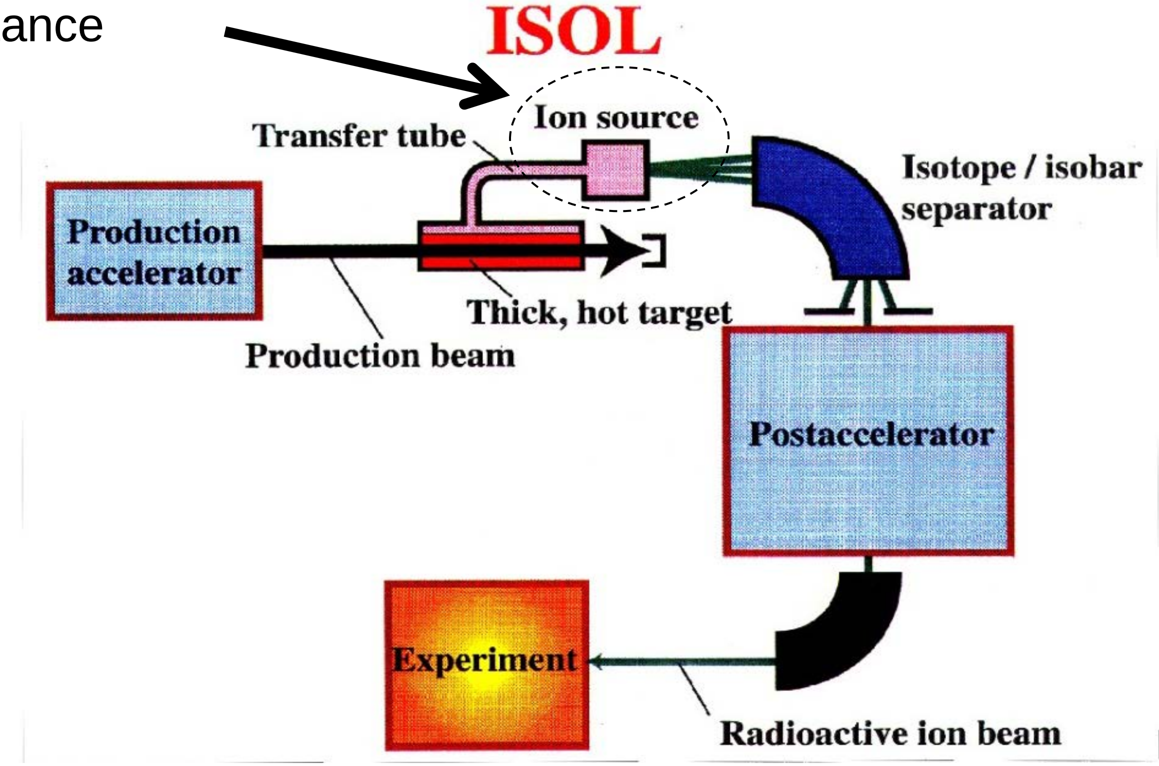
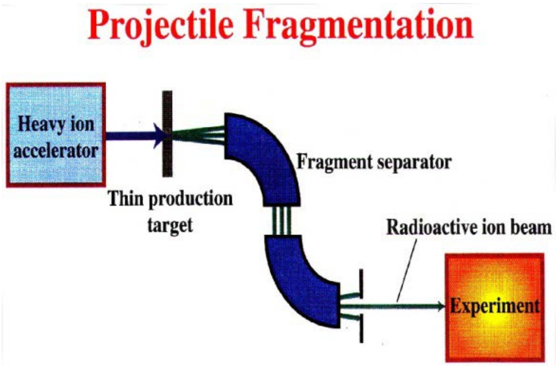


Figure of merit of a (ISOL) radioisotope ion beam facility

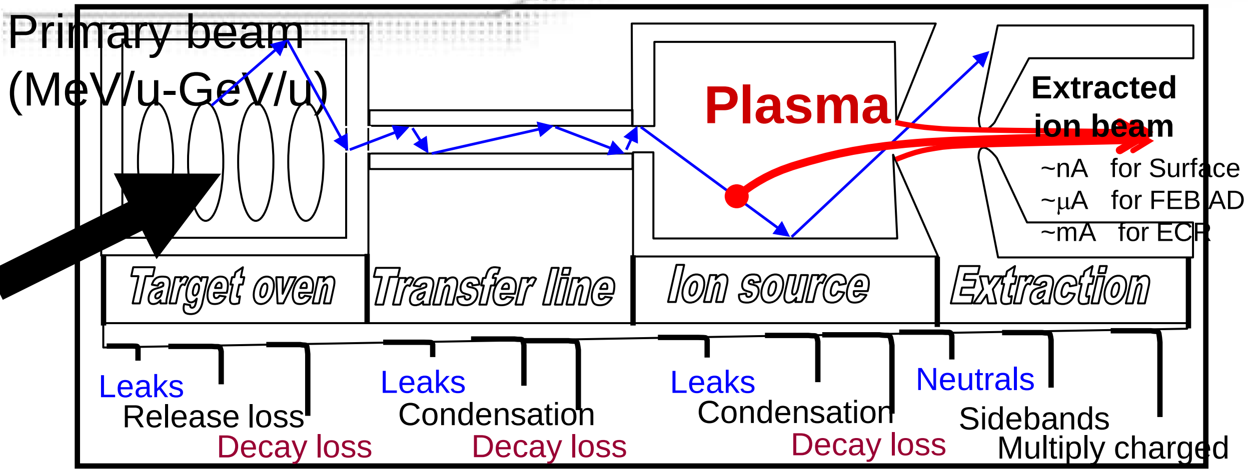
Not sorted by order of importance:

Number of different radioisotopes beam available
Beam intensity (secondary radioactive ion beam/primary beam μC)
Beam quality, for instance purity and emittance
Facility up-time
Stability of beam over time
(Post)Accelerated beam characteristics





Underlying principles of a radioactive ion source design



Primary beam (MeV/u-GeV/u)

Plasma

Extracted ion beam

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

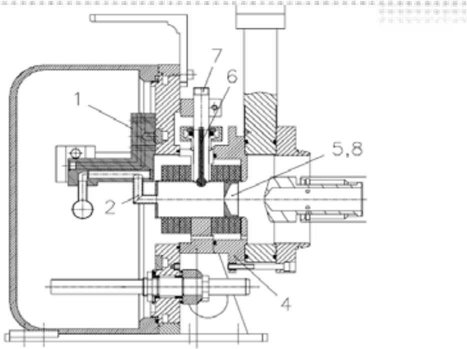
Target oven | Transfer line | Ion source | Extraction

Leaks
Release loss
Decay loss

Leaks
Condensation
Decay loss

Leaks
Condensation
Decay loss

Neutrals
Sidebands
Multiply charged



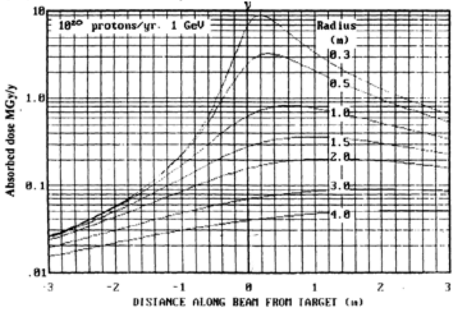
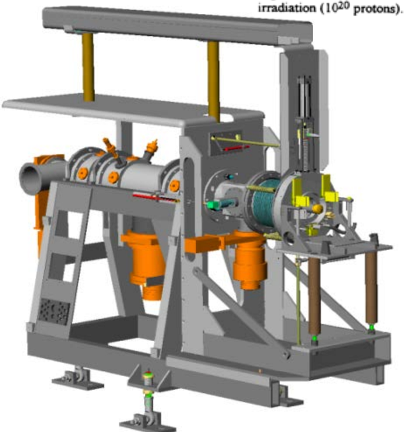
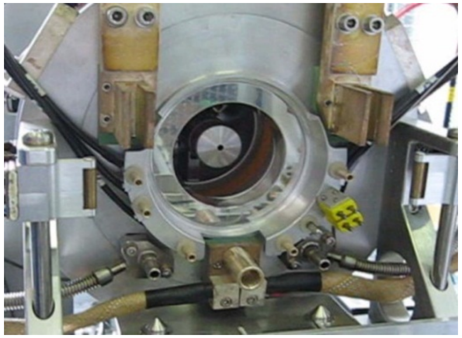


Figure 6. Contours of absorbed dose to an object near a one interaction length target after one years irradiation (10^{20} protons).

Ionize trace radioelements in larger&variable impurities loads

Must be compact
Must withstand 1 MGy
Compatible with standard connections/interfaces
(high current, 3kV, Thermocouples, …)
Example:
At CERN-ISOLDE, 1 production unit every 1-4 weeks
At ISAC-TRIUMF, 1 production unit every 4-6 weeks

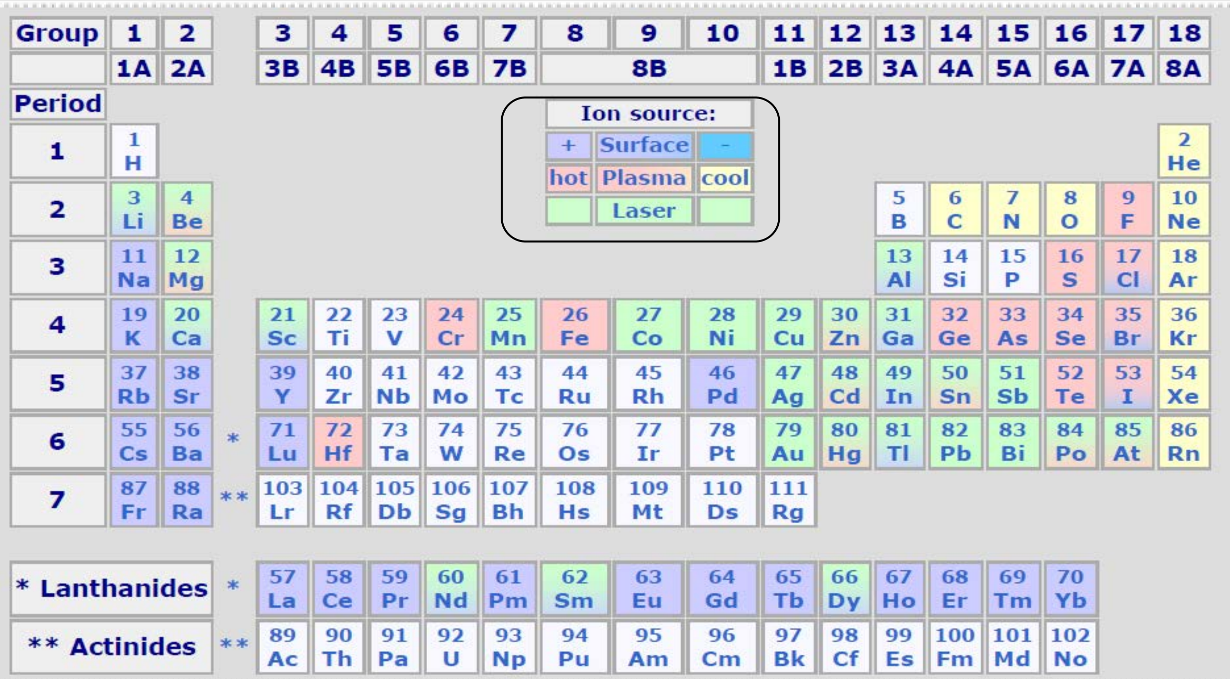




Beams and ion sources at CERN-ISOLDE

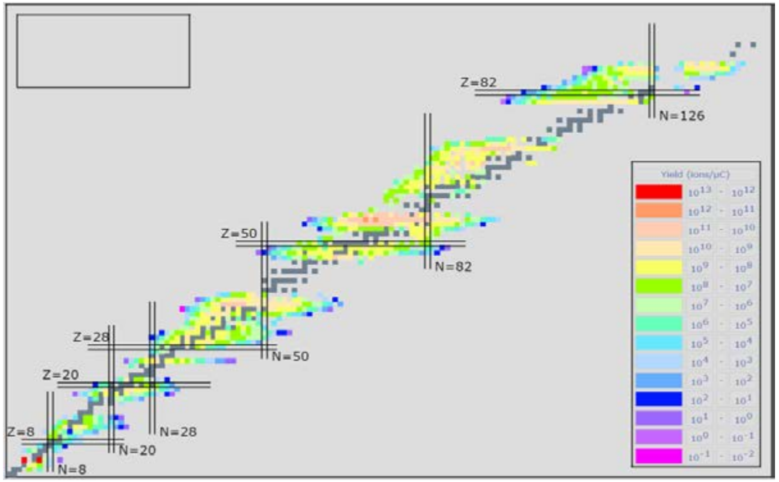
Figures of merit for a radioactive ion source:

Compatibility with Front End interfaces
Integration in production units
Robustness in radiations environment



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	

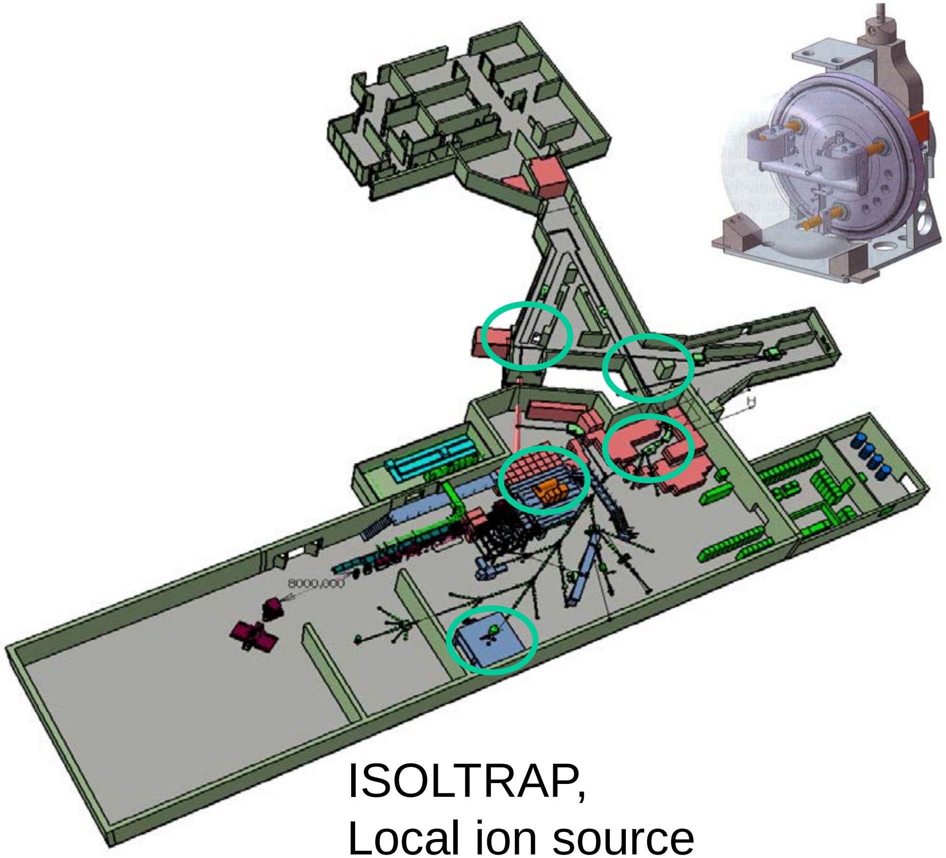


Operation in changing gas compositions and Contaminations
Maximal efficiencies for the desired beams
Low total extracted current intensities (0.1-100 μA)
Transverse emittance, energy spread
Eventually provides chemical selectivity

Where do we find ion sources

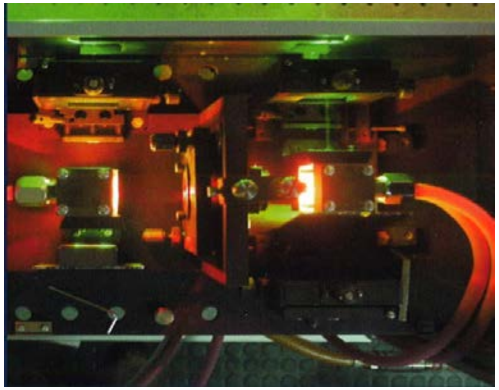
At ISOLDE, at CERN

F. Wenander
EBIS charge breeder
At REX-ISOLDE



T. Stora
Target and Ion Source
Units

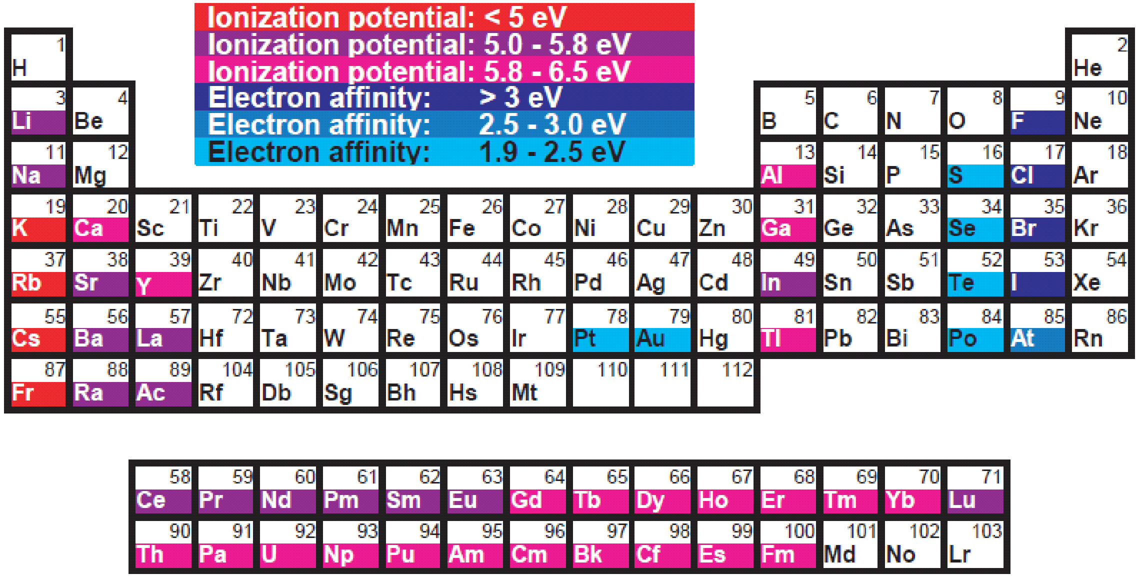
V. Fedosseev
Resonant Laser
Ion Source



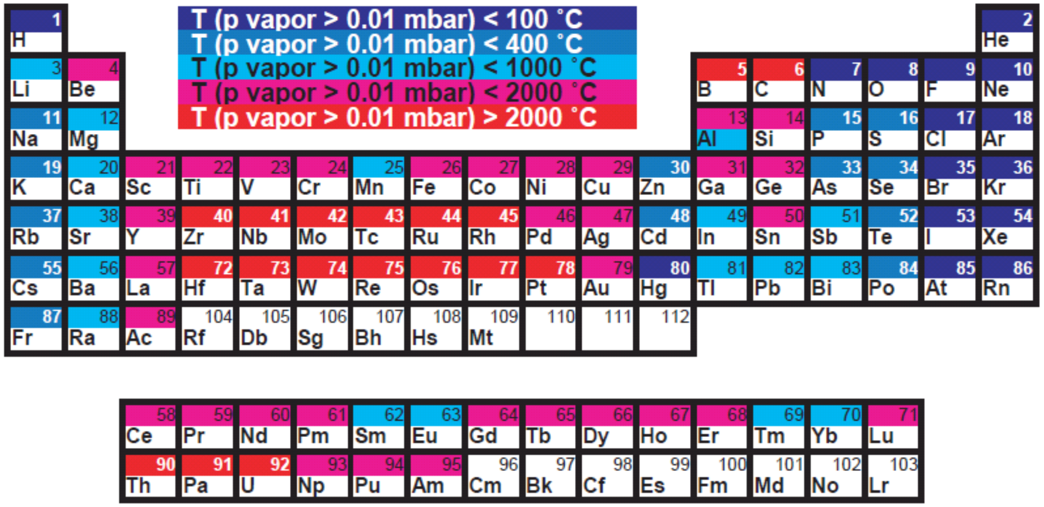
ISOLTRAP,
Local ion source
(heated alkali,
Laser sputtered C clusters)

Some key properties of chemical elements

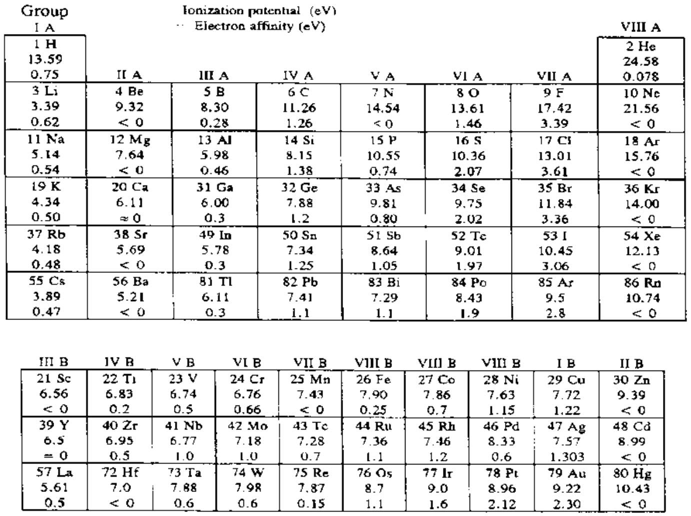
The related radio-isotopes have in addition
A finite half-life
(from a few ms to years at ISOL-Type facilities)



- Ionization potential: < 5 eV
- Ionization potential: 5.0 - 5.8 eV
- Ionization potential: 5.8 - 6.5 eV
- Electron affinity: > 3 eV
- Electron affinity: 2.5 - 3.0 eV
- Electron affinity: 1.9 - 2.5 eV



- T (p vapor > 0.01 mbar) < 100 ˚C
- T (p vapor > 0.01 mbar) < 400 ˚C
- T (p vapor > 0.01 mbar) < 1000 ˚C
- T (p vapor > 0.01 mbar) < 2000 ˚C
- T (p vapor > 0.01 mbar) > 2000 ˚C



Electron affinities and ionization energies of elements

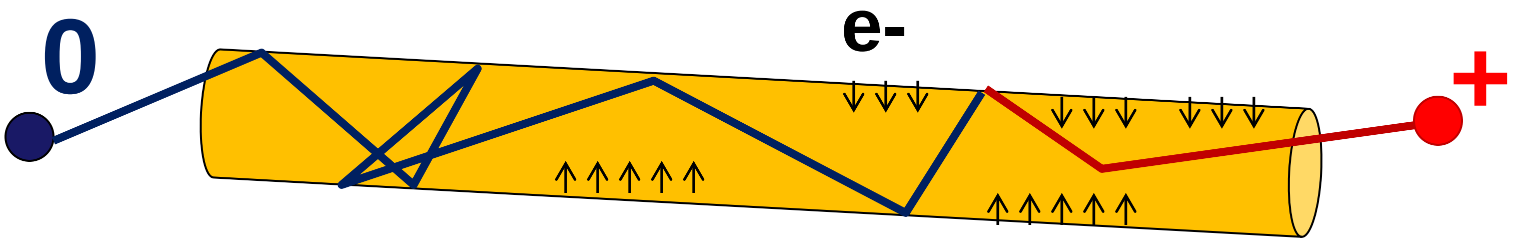
Ionization potential (eV)
·· Electron affinity (eV)

Group I A	II A	III A	IV A	V A	VI A	VII A	VIII A
1 H 13.59 0.75							2 He 24.58 0.078
3 Li 3.39 0.62	4 Be 9.32 < 0	5 B 8.30 0.28	6 C 11.26 1.26	7 N 14.54 < 0	8 O 13.61 1.46	9 F 17.42 3.39	10 Ne 21.56 < 0
11 Na 5.14 0.54	12 Mg 7.64 < 0	13 Al 5.98 0.46	14 Si 8.15 1.38	15 P 10.55 0.74	16 S 10.36 2.07	17 Cl 13.01 3.61	18 Ar 15.76 < 0
19 K 4.34 0.50	20 Ca 6.11 ≈ 0	31 Ga 6.00 0.3	32 Ge 7.88 1.2	33 As 9.81 0.80	34 Se 9.75 2.02	35 Br 11.84 3.36	36 Kr 14.00 < 0
37 Rb 4.18 0.48	38 Sr 5.69 < 0	49 In 5.78 0.3	50 Sn 7.34 1.25	51 Sb 8.64 1.05	52 Te 9.01 1.97	53 I 10.45 3.06	54 Xe 12.13 < 0
55 Cs 3.89 0.47	56 Ba 5.21 < 0	81 Tl 6.11 0.3	82 Pb 7.41 1.1	83 Bi 7.29 1.1	84 Po 8.43 1.9	85 Ar 9.5 2.8	86 Rn 10.74 < 0

III B	IV B	V B	VI B	VII B	VIII B	VIII B	VIII B	I B	II B
21 Sc 6.56 < 0	22 Ti 6.83 0.2	23 V 6.74 0.5	24 Cr 6.76 0.66	25 Mn 7.43 < 0	26 Fe 7.90 0.25	27 Co 7.86 0.7	28 Ni 7.63 1.15	29 Cu 7.72 1.22	30 Zn 9.39 < 0
39 Y 6.5 ≈ 0	40 Zr 6.95 0.5	41 Nb 6.77 1.0	42 Mo 7.18 1.0	43 Tc 7.28 0.7	44 Ru 7.36 1.1	45 Rh 7.46 1.2	46 Pd 8.33 0.6	47 Ag 7.57 1.303	48 Cd 8.99 < 0
57 La 5.61 0.5	72 Hf 7.0 < 0	73 Ta 7.88 0.6	74 W 7.98 0.6	75 Re 7.87 0.15	76 Os 8.7 1.1	77 Ir 9.0 1.6	78 Pt 8.96 2.12	79 Au 9.22 2.30	80 Hg 10.43 < 0

Surface ion sources

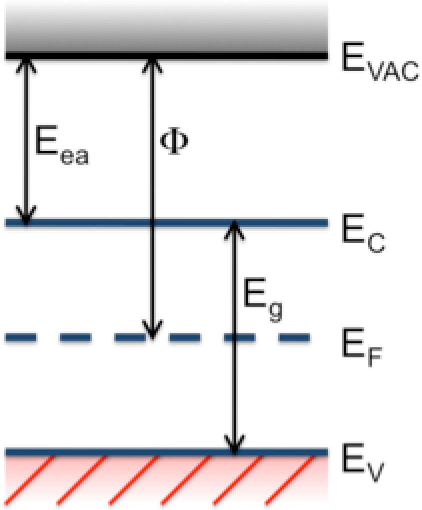
How to measure the Lr^+ 1st ionization potential W_i?

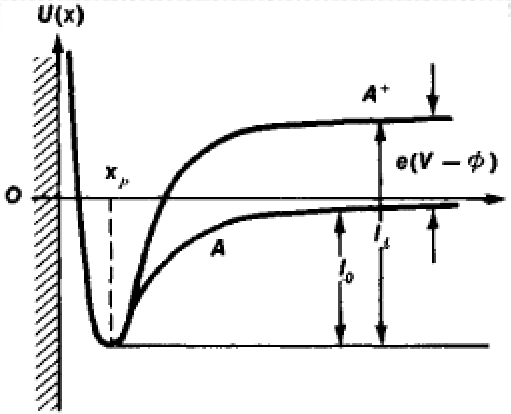


Hot tube

Saha-Langmuir Equation

Material work function Φ
Isotope 1st Ion. Pot. : Wi
Isotope e- affinity : Ea





$$\varepsilon_{\text{surface}} = \frac{1}{1+\frac{g_0}{g_-}\exp\left(\frac{\Phi - A_{\text{E}}}{kT}\right)}$$

For Iodine,
g_0=4 (2P3/2, degeneracy 4), g-=1

$$\varepsilon_{\text{surface}} = \frac{1}{1+\frac{g_0}{g_+}\exp\left(\frac{W_{\text{i}} - \Phi}{kT}\right)}$$

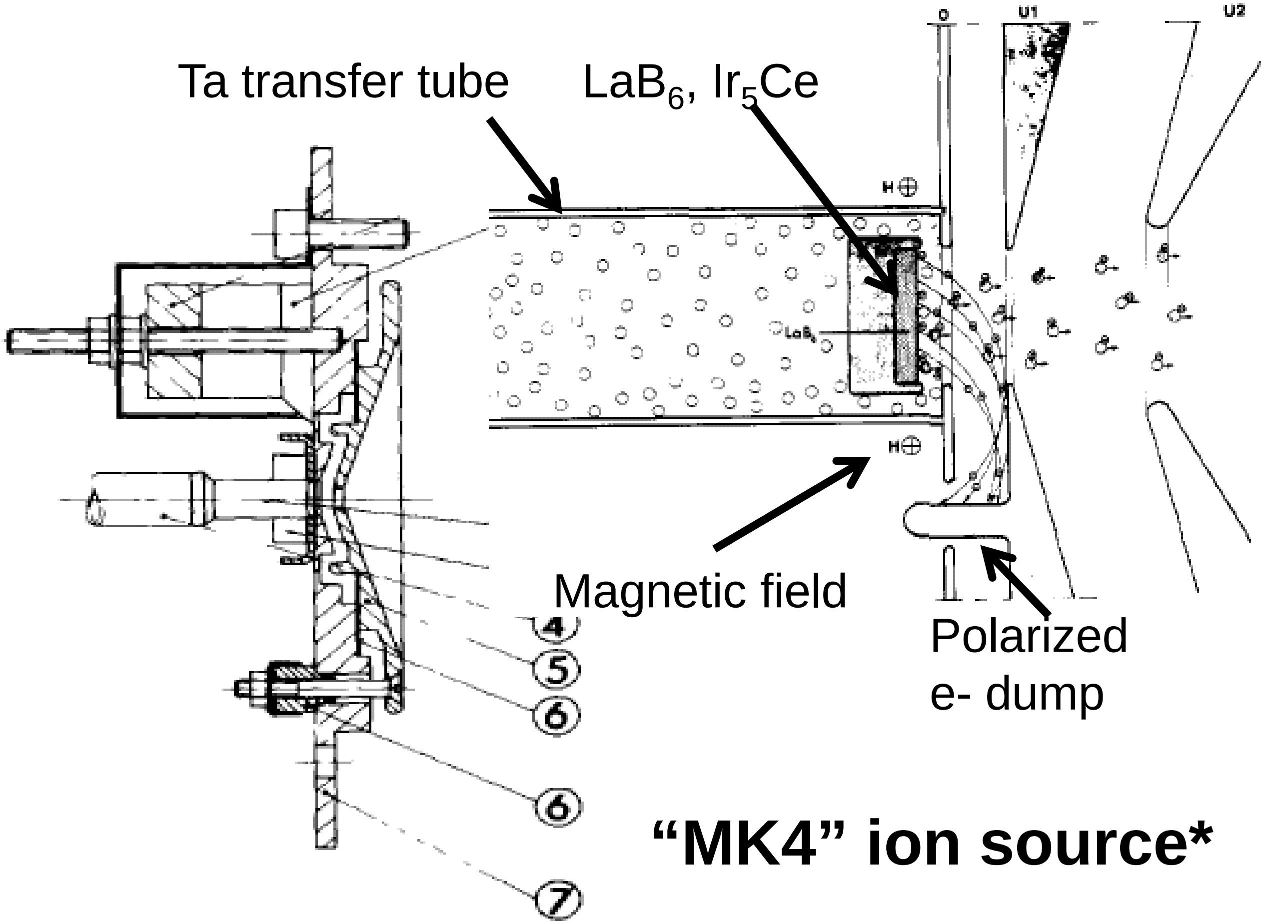
For Alkalis,
g_0=2 (2S1/2, degeneracy 2), g+=1

Some additional correction factors such as applied electrical potential or surface coverage

Meghnad Saha, 1920

CERN-ISOLDE negative ion source

material	Φ_0 [eV]	Operation temperature T [°C]	
Re	5.0	2200	For 1+ ions
W	4.5	2200	
Ta	4.3	2150	
Nb	4.0	2000	
LaB_6	2.4-3.3	1200	For 1- ions
GdB_6	1.5	1500	
Ir_5Ce	2.6	1600	
BaOSrO	1.0	1100	


Ta transfer tube

LaB_6, Ir_5Ce

Magnetic field

Polarized e- dump

“MK4” ion source*

** : What is the e- current to be deflected/dumped ?*

Cavity in (non)-thermal equilibrium

Effect of plasma properties in tubular surface ion source

$$\varepsilon_{tub} = \varepsilon_{surf}\, N_{TE} / (1 - \varepsilon_{surf}(1 - N_{TE}))$$

$$N_{TE} = \exp(-\Phi p.e/kT)$$

“Amplification factor” at thermal equilibrium

$$N_{nTE} = \omega\kappa$$

Amplification factor in non-thermal equilibrium, :

κ number of collision,

ω probability to leave cavity as 1+ ion

Plasma density	$\Sigma_\zeta n_{iv\zeta} \approx 10^9/\mathrm{cm}^3$,
Plasma potential	$\Phi_p = -2.2$ V,
Debye length	$\lambda_D = 0.12$ mm,
Amplification	$N_{TE} = \alpha_{vZ}/\alpha_{sZ} \approx 7500$ (independent of W_{iZ}^*).

Cavity length 1cm, Diameter 3mm For ωκ=150

Cavity material	ϕ b) [eV]	n_{es} [cm^{-3}]	N_{TE} c)	Ionization efficiency [%]					
				Sr (W_i^* = 5.52 eV)		U (W_i^* = 6.11 eV)		Pb (W_i^* = 7.25 eV)	
				Meas.	Calc.	Meas.	Calc.	Meas.	Calc.
Ta	4.25	2×10^{13}	2×10^4	58 ± 9	46	4.5 ± 0.7	7.1	0.1 ± 0.02	0.07
W	4.52	7×10^{12}	7500	70 ± 11	72	15 ± 3	19	0.2 ± 0.03	0.22
Re a)	5	1×10^{12}	1100	82 ± 13	95	39 ± 6	62	0.6 ± 0.1	1.5
According to eq. (2) with $\Sigma_\zeta n_{iv\zeta} = 10^9/\mathrm{cm}^3$				–	99	–	92		10

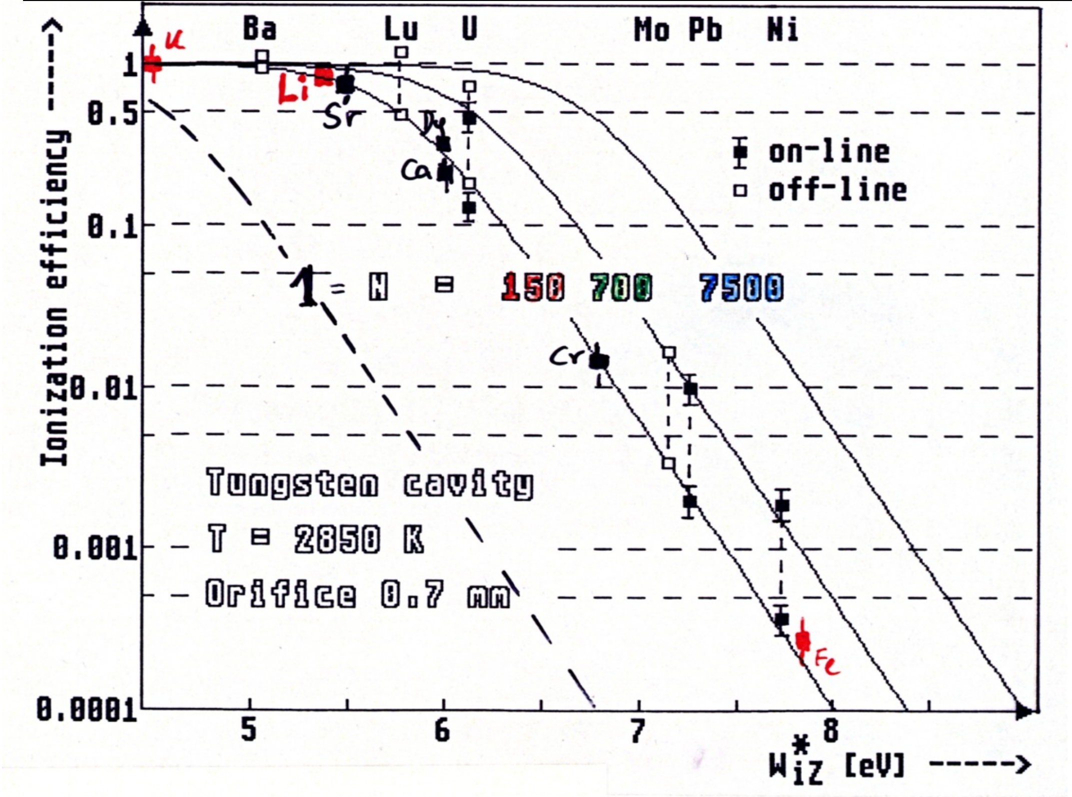
Ionization efficiencies for high-T. Cavity

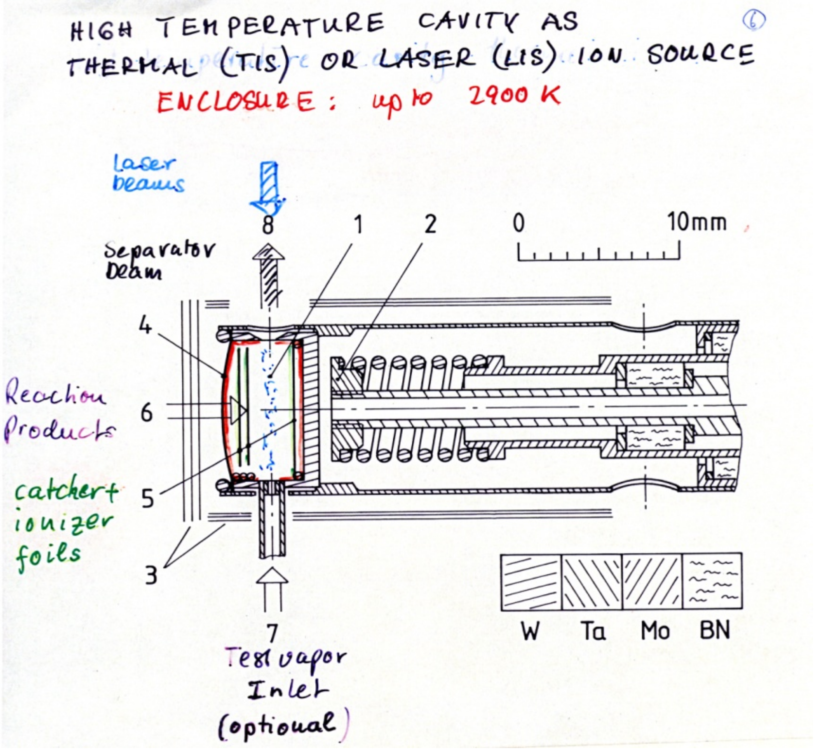
$N = 1$: prediction for single collision (Saha-Langmuir)

$N \approx 150$: measured (min. press.vp) $n_0 \approx 10^{11} / cm^3$

$N \approx 700 \approx k$:measured (high Xe pressure) $n_0 \approx 10^{15} / cm^3 \cong 0.1 mbar$

$N \approx 7500$: prediction for thermo-equilibrium: $\sum n_{iv}(Z) \approx 10^9 / cm^3$





Effect of 1+ ion density in the cavity

Ie, presence of unwanted impurities

Cavity length 1cm,.
Diameter 3mm
Orifice 0.7mm diameter

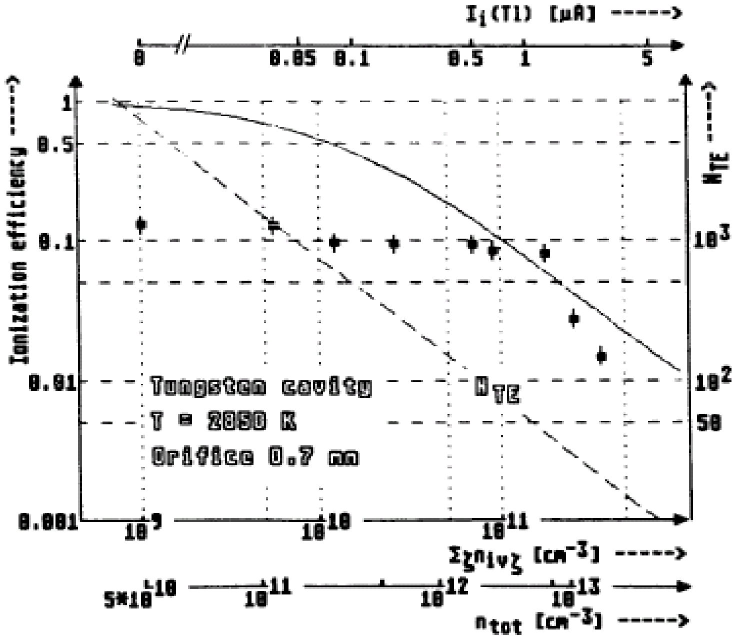


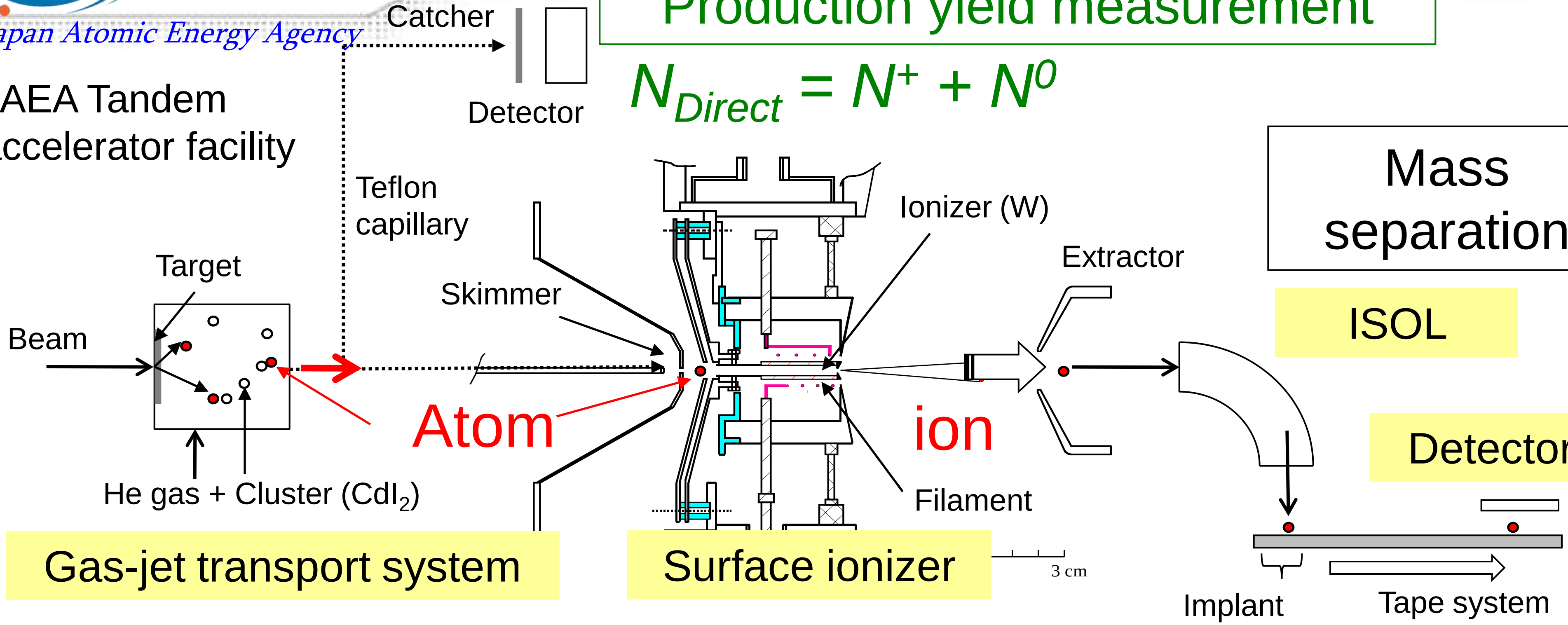
Fig. 3. Ionization efficiency of uranium (10^{10}/s implanted ^{238}U UNILAC beam particles) as a function of the plasma density $\Sigma_\xi n_{i\nu\xi}$, which is varied by feeding thallium vapour into the cavity. The plasma and total densities are determined from the ion current of thallium (upper scale) out of the source assuming thermal flow. Note that the ionization efficiency for thallium is about half that of uranium and should show (due to the similar ionization potential of $W_i^* = 6.28$ eV) about the same I_i(Tl) dependence. The solid curve gives η(U) assuming thermoequilibrium, the broken line shows the respective amplification factor N_{TE}, as calculated according to eqs. (2) and (4), respectively. Due to the impurities the minimum plasma density is around 10^9/cm^3.

ISOL set-up to measure Lr^+ Wi at JAEA-ARSC

Japan Atomic Energy Agency

Production yield measurement

$$N_{Direct} = N^+ + N^0$$



Catcher

Detector

JAEA Tandem accelerator facility

Teflon capillary

Target

Beam

Skimmer

Ionizer (W)

Extractor

Mass separation

ISOL

Atom

ion

Detector

Filament

He gas + Cluster (CdI_2)

Implant

Tape system

3 cm

Gas-jet transport system

Surface ionizer

Production and transport of isotopes

Ionization

S. Ichikawa *et al.*, Nucl. Inst. and Meth. in Phys. Res. B **187** (2002) 548.

Ionic yield measurement

$$N_{ISOL} = N^+$$

Overview on surface ion sources

T=1200-2300 °C (2700°C)

Tube: L= 1-5cm, diam=1-8mm, extr.: 0.5-3mm

Materials: Nb, Ta, Re, W, Ir5Ce

LaB6, GdB6, TaC, SrOBaO

Heating: Ohmic, e- bomb. 100-1000W

Plasma density : 10^8-10^{10}/cm^3

Total beam current @20-60kV : 10-1000nA

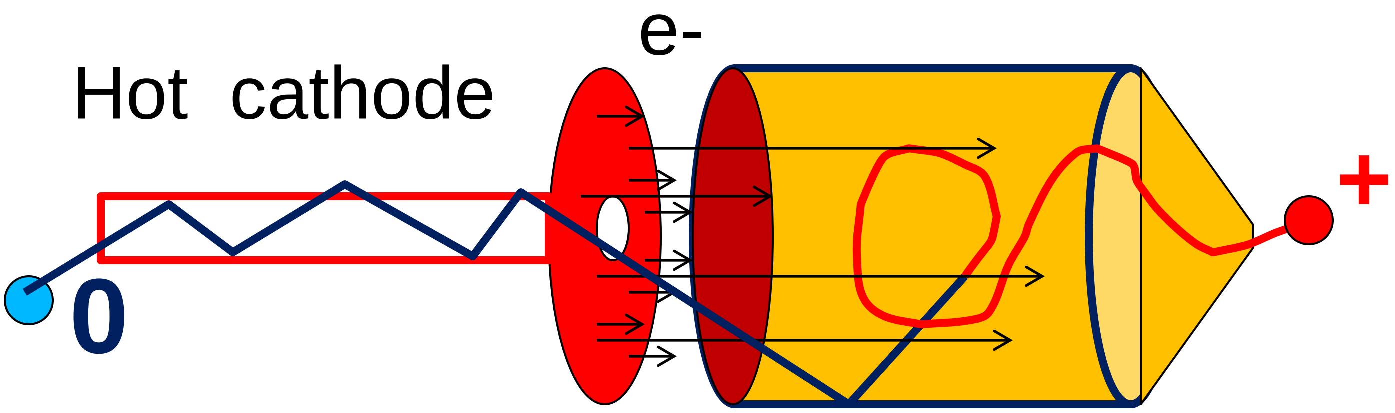
Plasma potential : -1 to -2V,

Eions = 0.2 eV

λ_{Debye} = 0.05 – 1mm

$\varepsilon_{95\%}$@30kV = 10-15 pi mm mrad

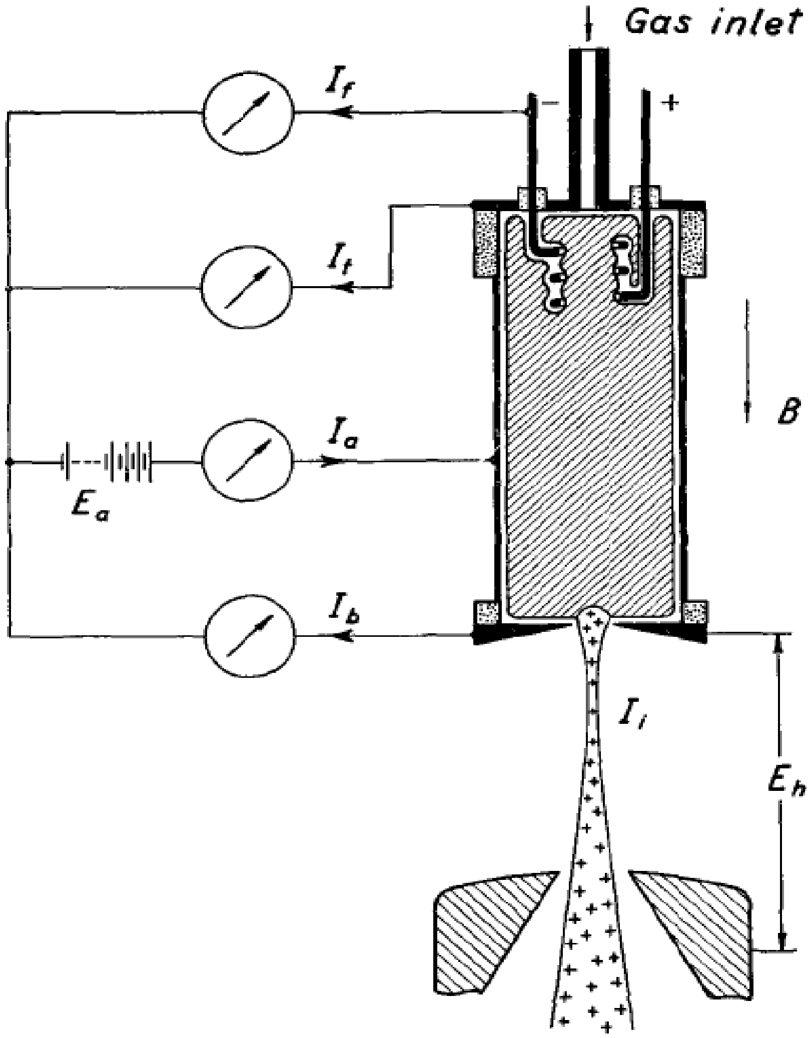
Forced Electron Beam Induced Arc Discharge (FEBIAD) ion sources



Hot cathode

Hot anode +100V

Nielsen source



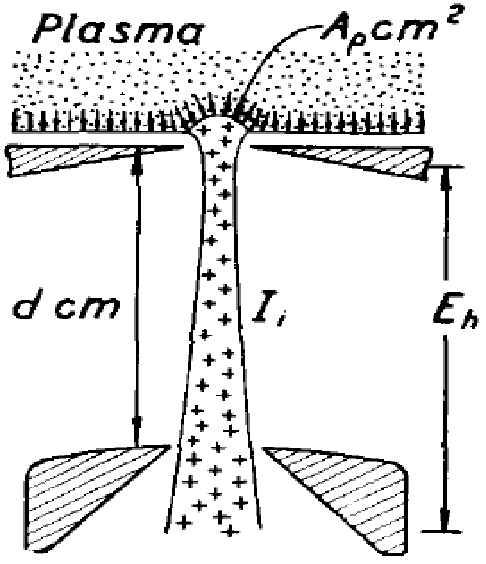
→ End extraction;

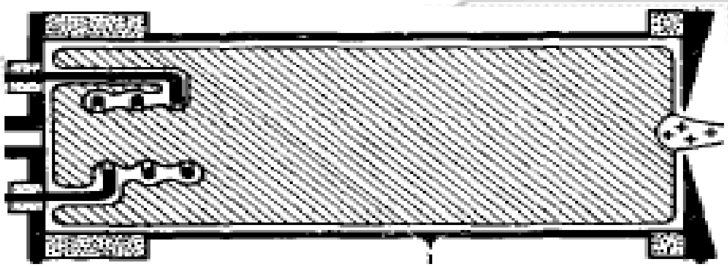
→ Long discharge chamber (for better efficiency);

→ Vapour tight (operation pressure: $10^{-4} \div 10^{-3}$ torr);

→ Discharge chamber heated by the filament (base version);

→ Gas inlet in the hottest part of the ion source (filament).





Currents to the cavity walls

$$i^+ \approx n^+ \sqrt{\frac{k \cdot T_e}{2\pi \cdot e \cdot m^+}}\, ions/cm^2 \cdot \sec$$

i^+ - current density through the plasma boundary
n^+ - density in the plasma
m^+ - mass of an ion (in grams)
T_e – electron temperature
$e \approx 2{,}718$
ε - electron charge
M – mass number

$$i^+ \approx 3{,}5 \cdot 10^{-10} \cdot n^+ \cdot \frac{T_e^{1/2}}{M^{1/2}}\, \mu A/cm^2$$

Remarks: i^+ independent of $(E_p - E_{t,b})$
Space charge limited current

The plasma potential depends
on the potentials of the surrounding walls

Et, Eb < Ea → **Ep < Ea**
Oscillating electrons

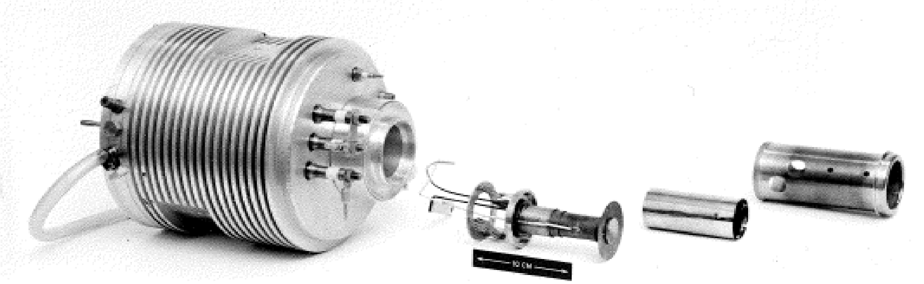
Et=Eb=Ea → **bigger *Ep***
I_a ~ 0,5 ÷1A (~ x10)
Shorter filament lifetime
Same I_i and RP
Hotter bottom plate

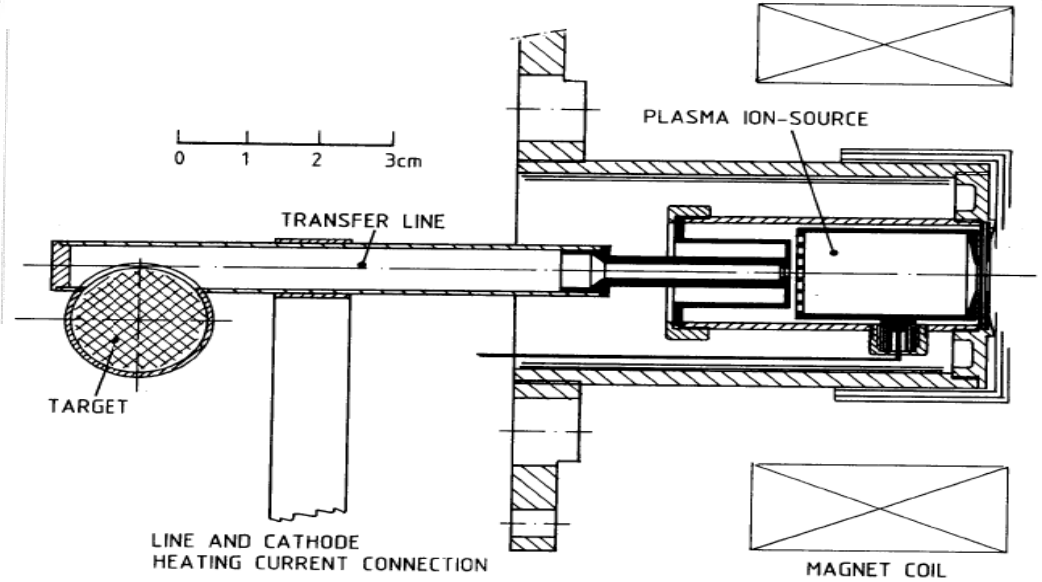
$(E_p – E_{a,t,b})$ determines **the thickness of the sheaths**

$$\boxed{x = 0{,}23 \cdot \frac{E_p^{3/4}}{M^{1/4} \cdot (i^+)^{1/2}} (cm)}$$

E_p=100V;
M=100; => x ≈ 0,7mm
$i^+ \approx$ 1mA /cm^2

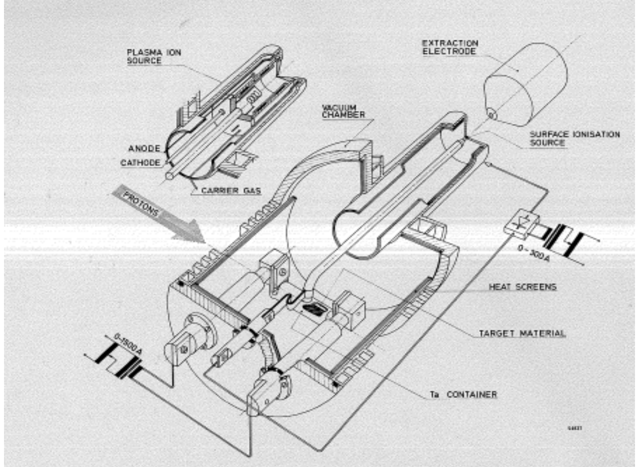
FEBIADs at ISOLDE





Sundell
NP

ISOLDE, MK IV, 1972



Targets

- ➢ Solid materials: metalic foils, powders, ceramics
- ➢ Molten metals Pb, Sn, Hg.

Ion sources

- ➢Surface ionizers
- ➢ “Plasma” source (FEBIAD)
- ➢ RILIS (laser ionization)
- ➢ Plasma sources (ECR, RF)

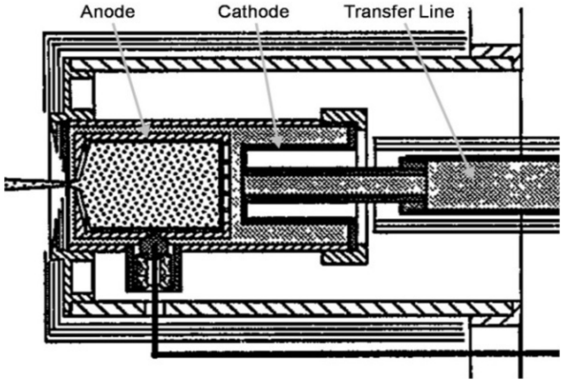
The 3 ISOLDE FEBIADs until 2009

FEBIAD: “Forced Electron Beam Induced Arc Discharge”

Materials used for the different models:

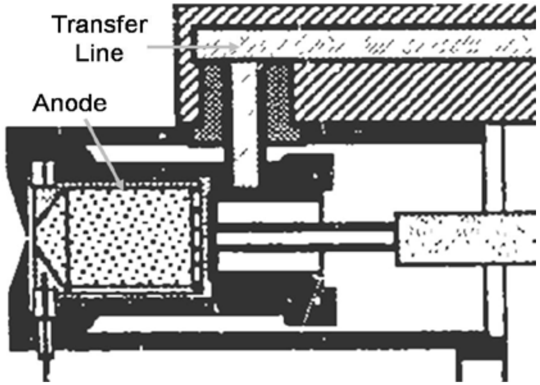
Cathode: Ta
Anode: Mo, C
Insulators: BN, BeO
Grid: (Ta) C
Heat screens: Mo
Transfer lines: Ta

MK5 3cm



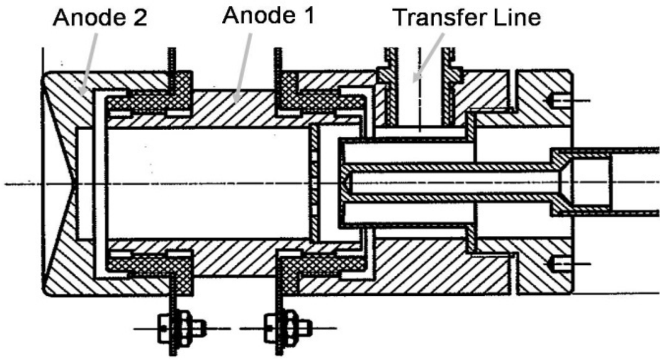
- Hot transfer line
- Employed for the ionization of the condensable elements

MK7



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

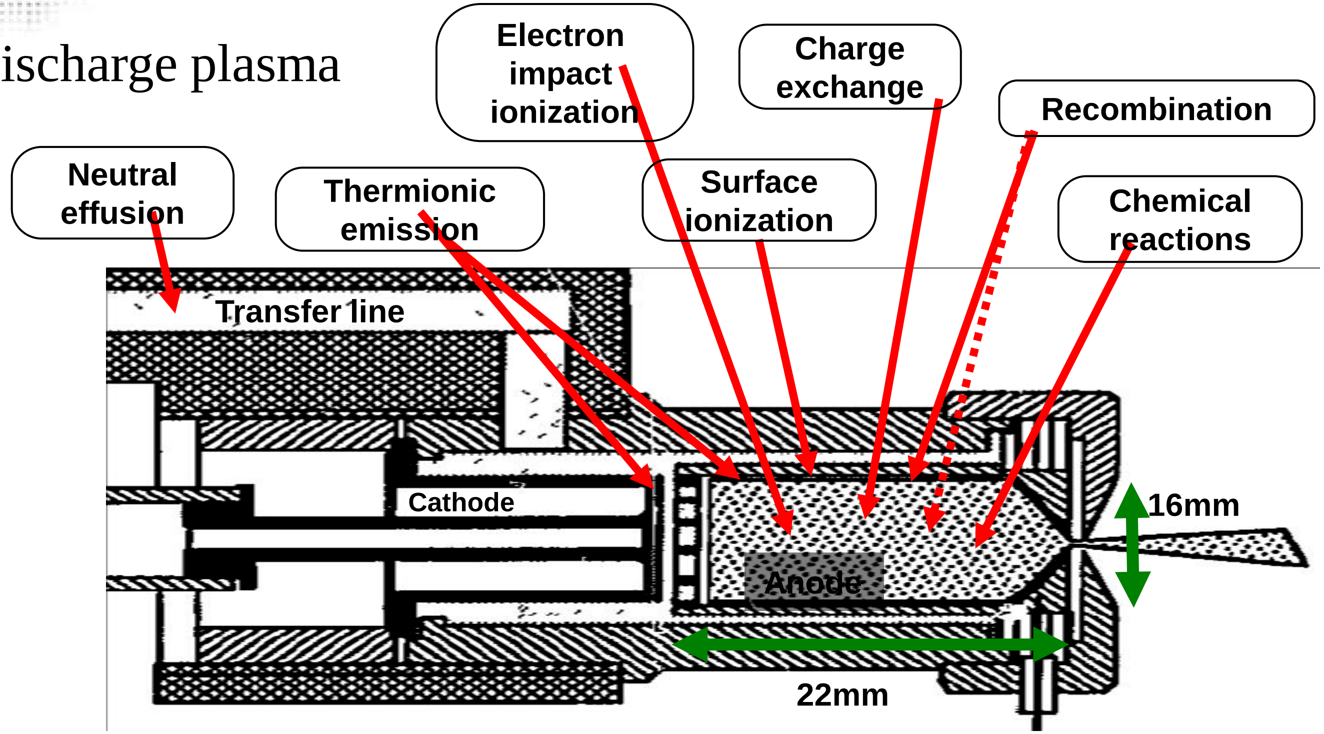
MK3



- Temperature controlled transfer line
- Coupled to the molten metal targets
- Full graphite, BN insulators

Modeling of “relevant phenomena”

Modeling of the arc discharge plasma



Electron impact ionization

Charge exchange

Recombination

Neutral effusion

Thermionic emission

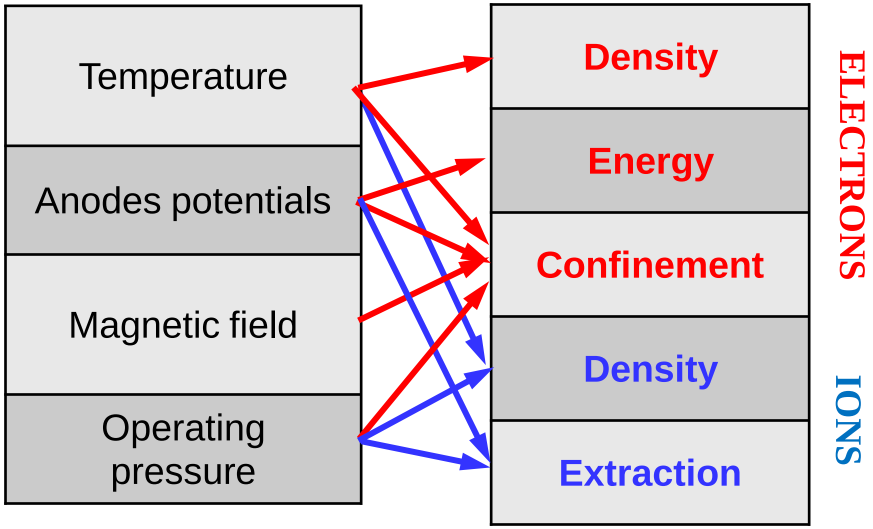
Surface ionization

Chemical reactions

- ➢ 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

Link between operational and physical parameters

Impact of operational parameters on physical parameters of a FEBIAD ion source



Temperature

Anodes potentials

Magnetic field

Operating pressure

Density

Energy

Confinement

Density

Extraction

ELECTRONS

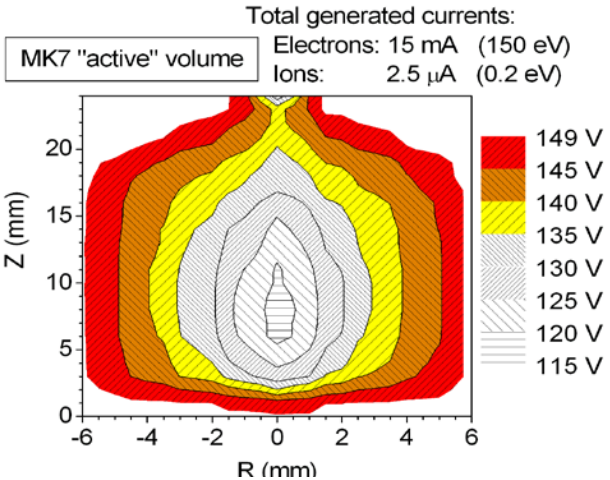
IONS

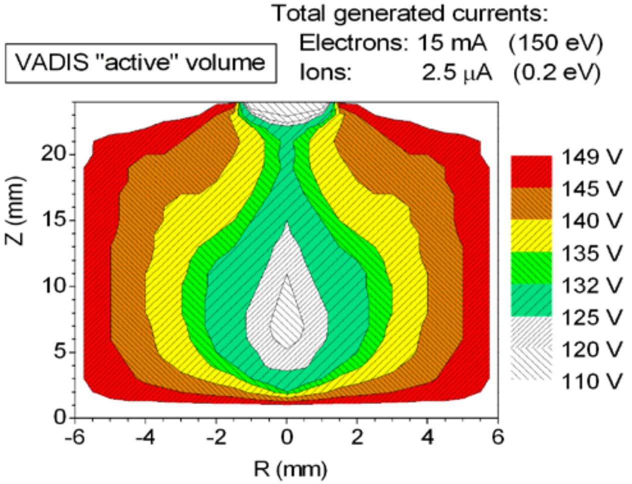
Parameters Accessible for Operation

Physical Parameters

Ionization efficiency modeling

CPO simulation of the internal electrical field distribution



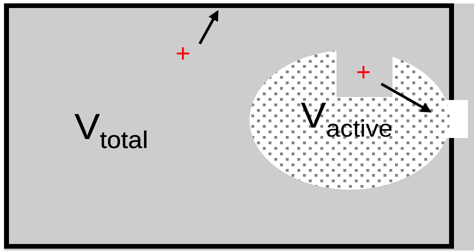


$$\varepsilon = f \times \frac{V_{source} R_{ioniz}}{n_{n\_in}} \quad \Rightarrow \quad \boxed{\varepsilon = f \times V_{source} \times \frac{n_e \times n_n \times \sigma_{ioniz} \times v_{rel}}{n_{n\_in}}}$$

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 here the generated ions are extracted from, due to avorable field distribution.

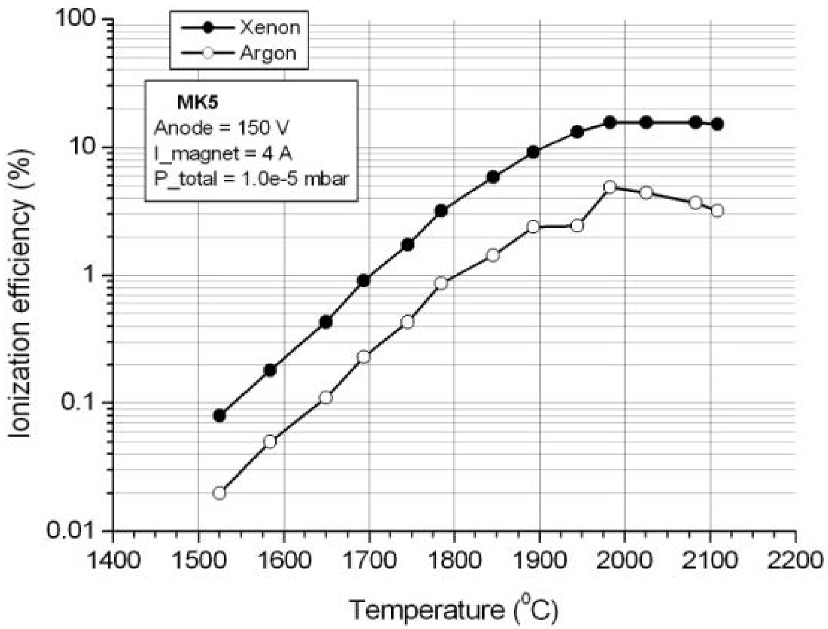


$$f \equiv \frac{V_{active}}{V_{total}}$$

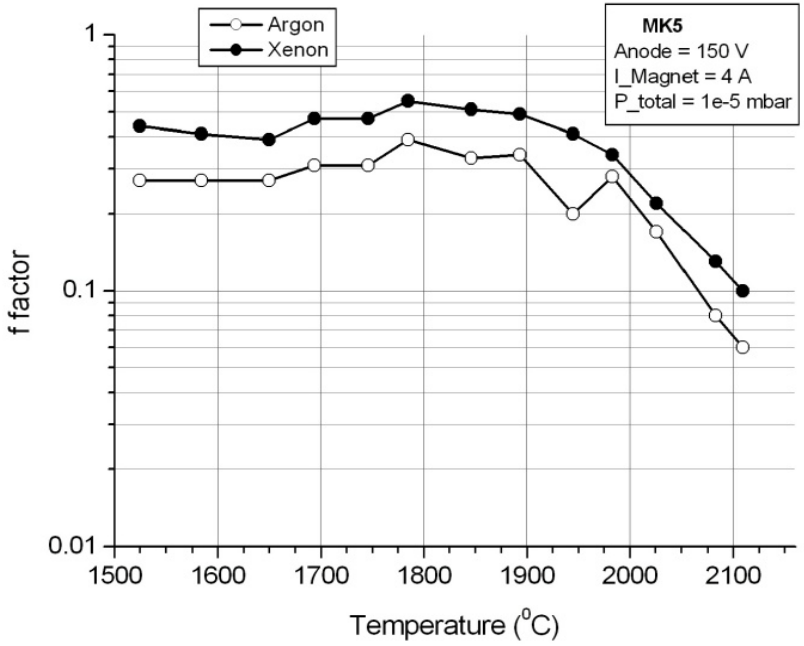
- ➢1 electron passage;
- ➢ no ion trapping;
- ➢ T_e = 150 eV (e·V_{anode}, initial energy);
- ➢ T_i = 0.17 eV (2300 K, thermal energy);
- ➢ n_e = temperature dependent (cathode emission given by Richardson Dushmann);
- ➢ n_n = dep. on pressure, n_{n_in}, C_{out}.

Validation of the theoretical model

Ionization efficiency (exp)



f factor (computed)



- ε measured directly
- f calculated for each set of operating parameters

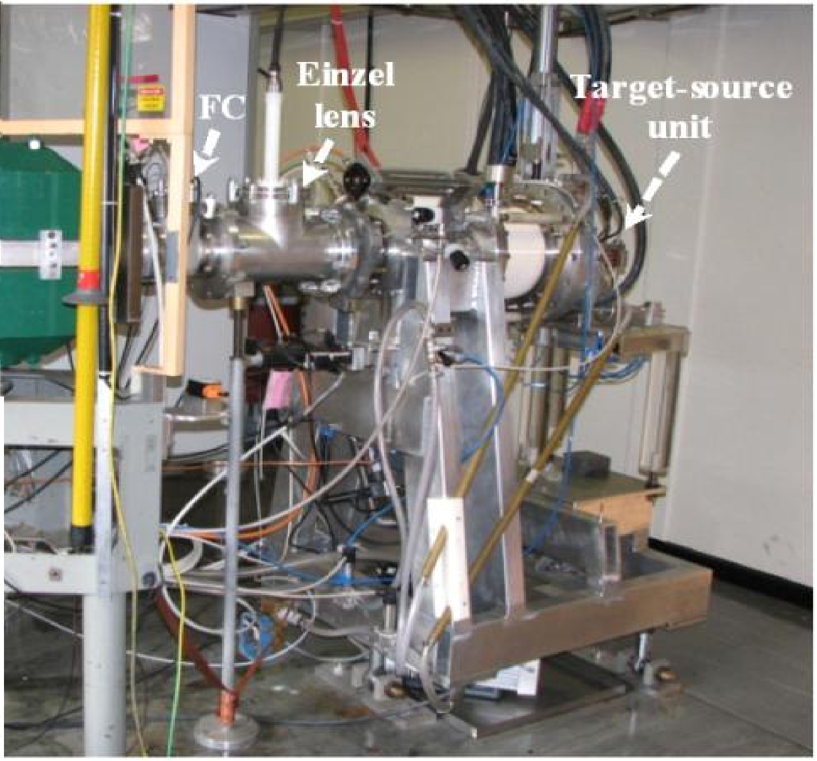
$$f = \varepsilon \times \frac{n_{n\_in}}{V_{source} \times n_e \times n_n \times \sigma_{ioniz} \times v_{rel}}$$

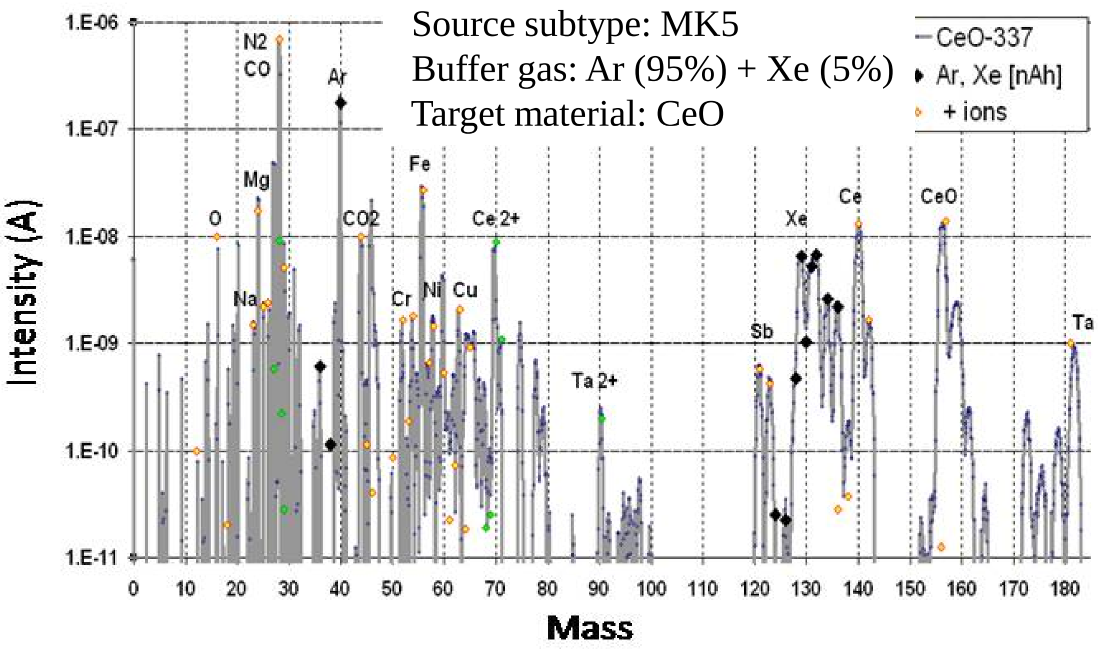
“ f ”

- **Quality Factor**
- **Plasma characterization**
- **Ionization limit! (f_{max}=1)**

Compute f for a MK5 ion source.

Offline mass-separator at ISOLDE



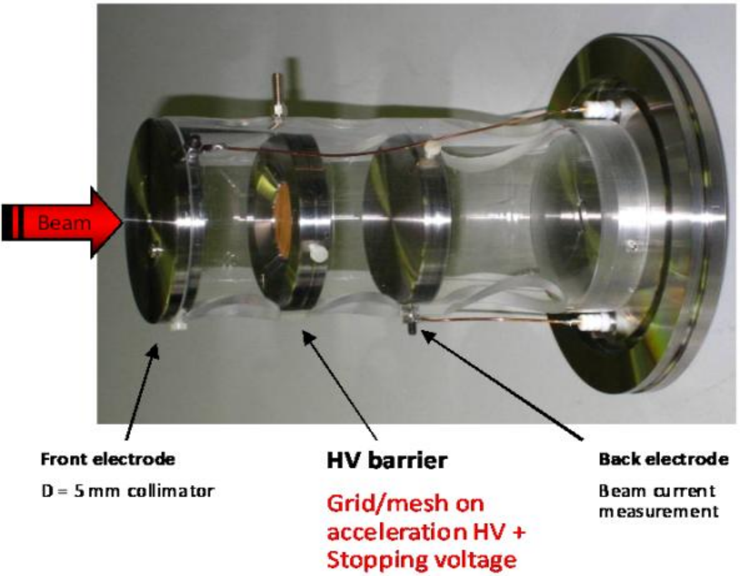


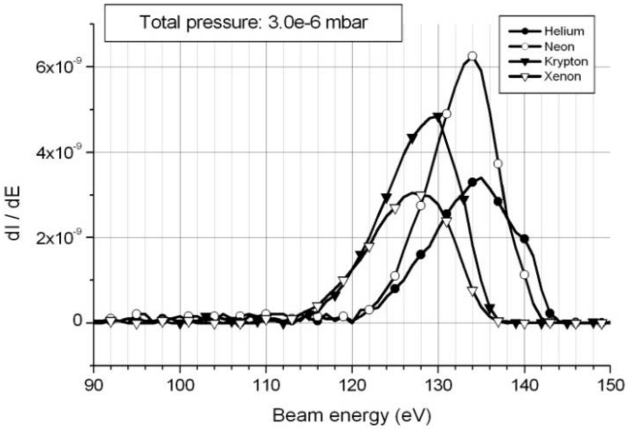
Source subtype: MK5
Buffer gas: Ar (95%) + Xe (5%)
Target material: CeO

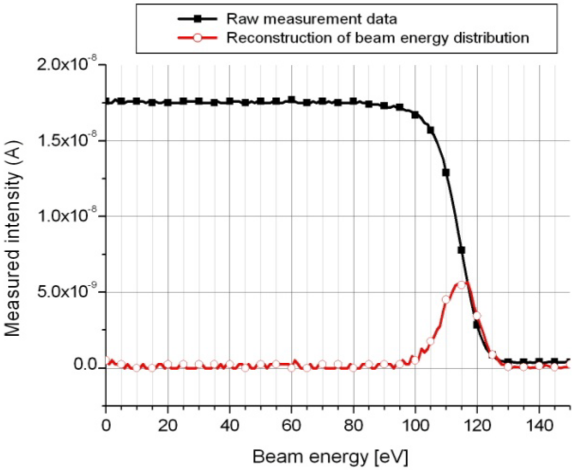
- Test of all the TIS units, before being mounted online
- Development studies
- Commissioning of new diagnostics
- Prototype testing & validation

Plasma potential and energy spread

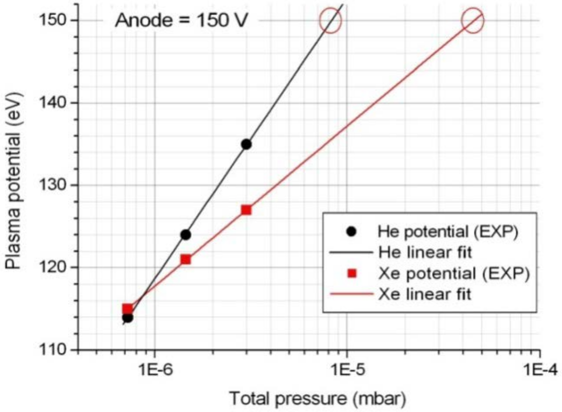
Beam energy measurement device







- Deceleration potential: $(V_{extraction} + \Delta V)$, with $\Delta V \in [0, 300V]$
- Recorded dependence: $I_{back\_electrode} = f(\Delta V)$
- Beam energy distribution reconstructed through the differentiation of the measured data
- Broad range of beam intensities (from nA to mA)



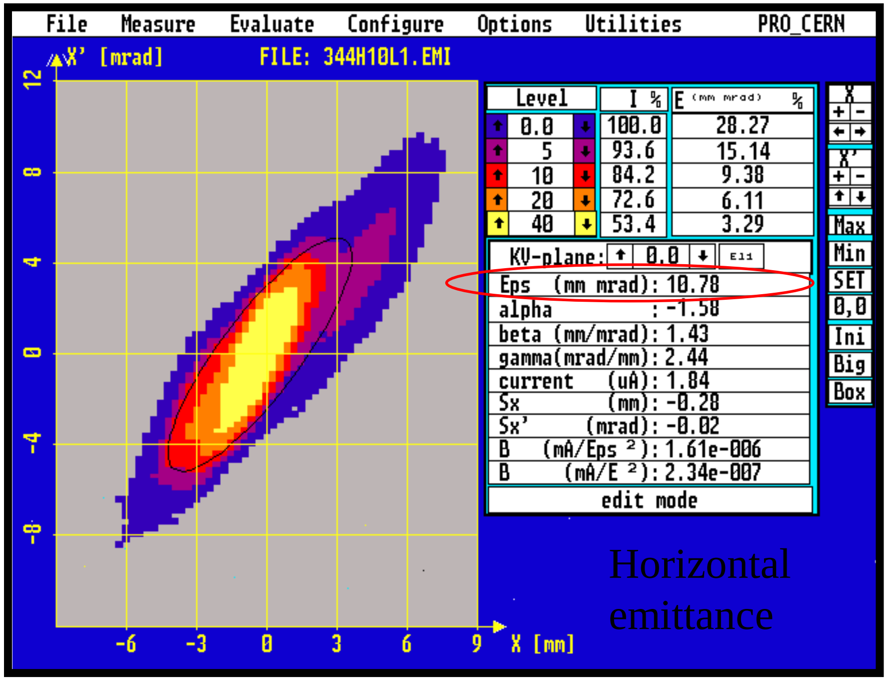
Emittance measurements

FEBIAD MK7

V_{extr}=30kV; I_{total} = 300nA
D_{extr}=70mm; Φ_{extr} = 1.6mm

Depending on:

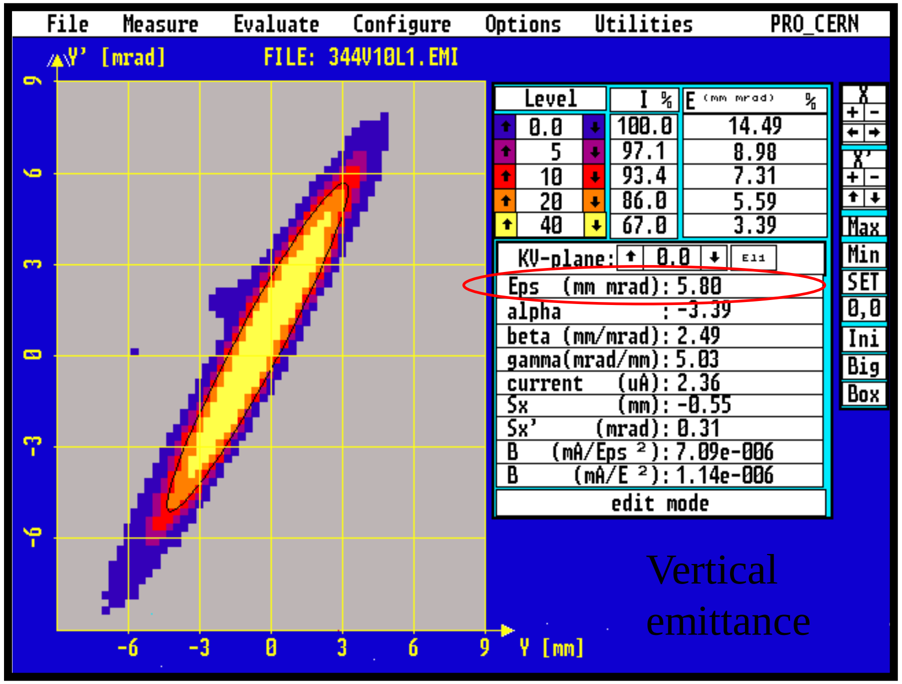
- Plasma density (by external field penetration)
- Outlet plate geometry (aperture, potential)
- Ion temperature
- Background pressure (by elastical collisions)



Level	I %	E (mm mrad) %
0.0	100.0	28.27
5	93.6	15.14
10	84.2	9.38
20	72.6	6.11
40	53.4	3.29

Eps (mm mrad): 10.78
alpha : -1.58
beta (mm/mrad): 1.43
gamma(mrad/mm): 2.44
current (uA): 1.84
Sx (mm): -0.28
Sx' (mrad): -0.02
B (mA/Eps ²): 1.61e-006
B (mA/E ²): 2.34e-007

Horizontal emittance

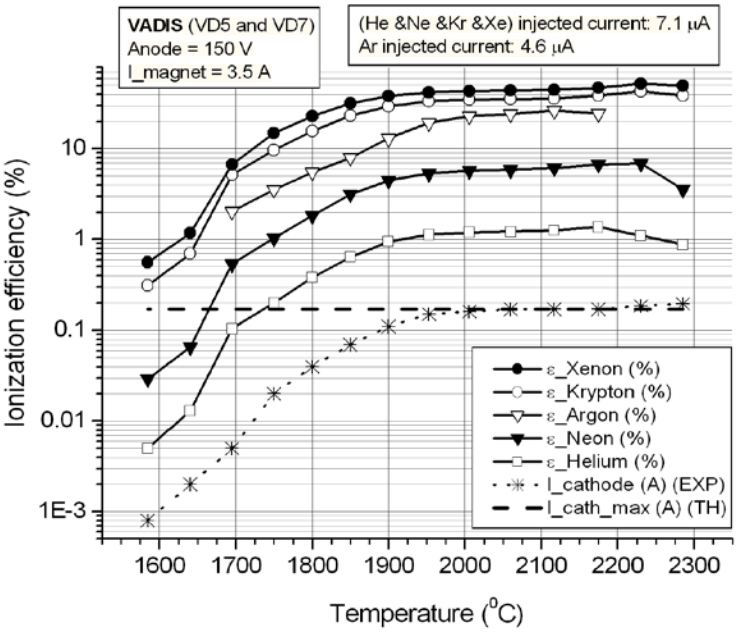


Level	I %	E (mm mrad) %
0.0	100.0	14.49
5	97.1	8.98
10	93.4	7.31
20	86.0	5.59
40	67.0	3.39

Eps (mm mrad): 5.80
alpha : -3.39
beta (mm/mrad): 2.49
gamma(mrad/mm): 5.03
current (uA): 2.36
Sx (mm): -0.55
Sx' (mrad): 0.31
B (mA/Eps ²): 7.09e-006
B (mA/E ²): 1.14e-006

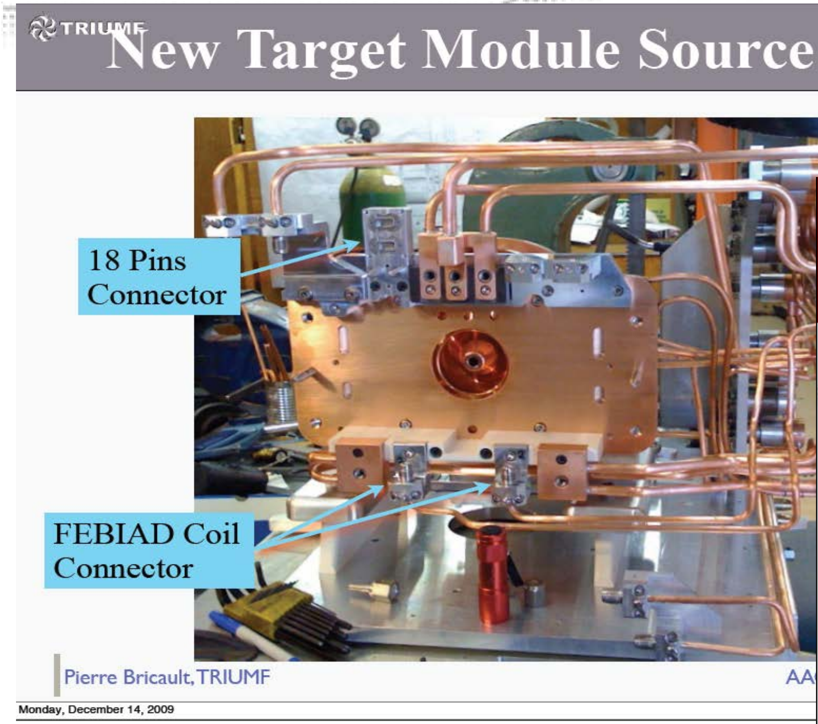
Vertical emittance

Present performance of the VADIS febiads at ISOLDE



YIELDS	**^{31}Ar (15 ms)**	**^{72}Kr (17 s)**	**^{73}Kr (26 s)**	**^{138}Xe (14.1 m)**	**^{229}Rn (~12 s)**
Measured (at/μC)	**5** *(CaO)*	**1.1e4** *(Nb)*	**1.2e6** *(Nb)*	**2.4e9** *(UC_x)*	**200** *(UCx)*
Database (at/μC)	**1.5** *(CaO)*	**2.0e3** *(Nb)*	**7.4e4** *(Nb)*	**5.7e8** *(UC_x)*	**-**
Multiplication factor	**>3.3**	**5.5**	**16**	**4.2**	**-**

FEBIAD at ISAC-TRIUMF

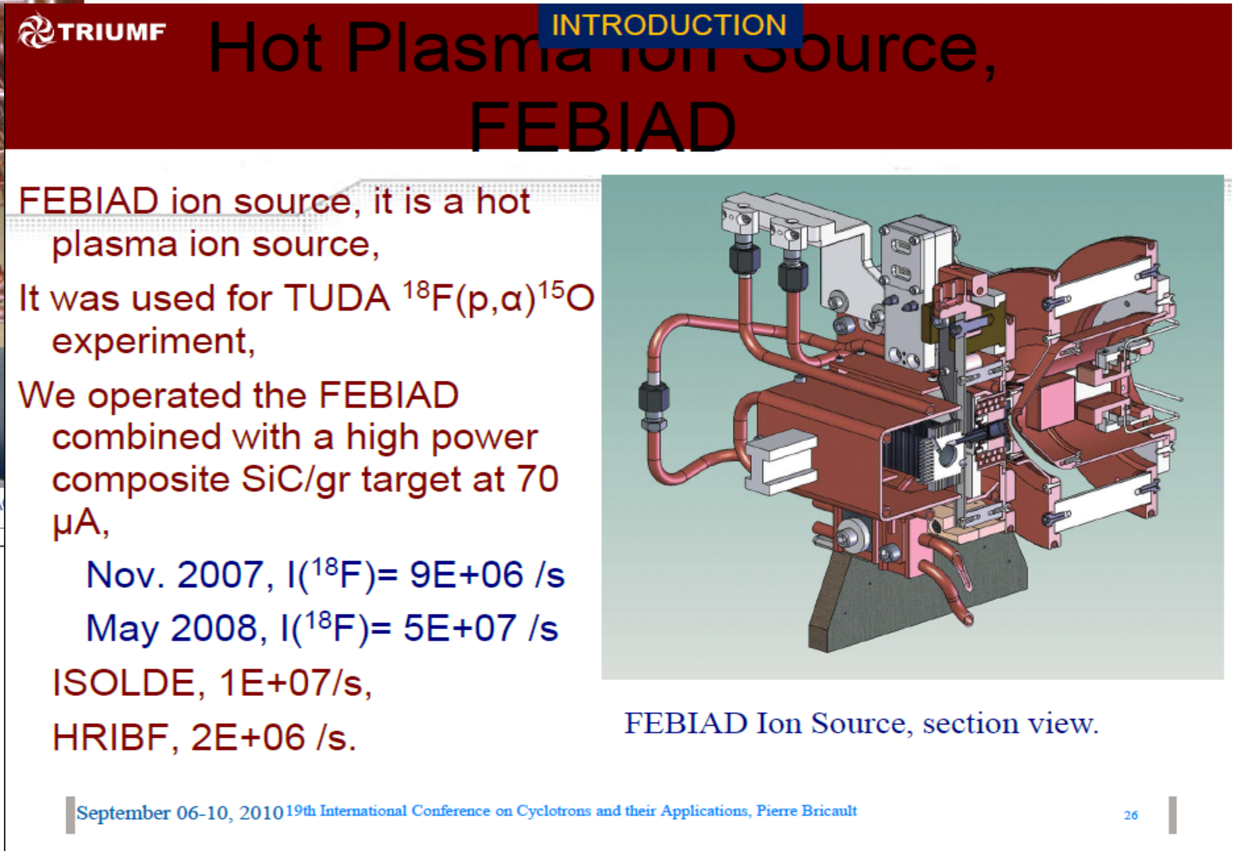


TRIUMF

New Target Module Source Tray

Pierre Bricault, TRIUMF AA

Monday, December 14, 2009



TRIUMF

INTRODUCTION

Hot Plasma Ion Source, FEBIAD

- FEBIAD ion source, it is a hot plasma ion source,
- It was used for TUDA $^{18}F(p,\alpha)^{15}O$ experiment,
- We operated the FEBIAD combined with a high power composite SiC/gr 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.

FEBIAD Ion Source, section view.

September 06-10, 2010 19th International Conference on Cyclotrons and their Applications, Pierre Bricault 26

Overview on FEBIAD ion sources

T = 1500-2300°C

Cavity: L= 2-3cm, diam=1-2cm, extr.: 0.5-3mm

Materials: C, Ta, Mo, W, BN, BeO

Cathode Heating: Ohmic, e- bomb. 100-1000W

Plasma density : 10^{7}-10^{10}/cm^{3}

Total beam current @20-60kV : 1-100μA

Plasma potential : 70% of Anode V (50-100V); ΔE_{ion}= 20eV

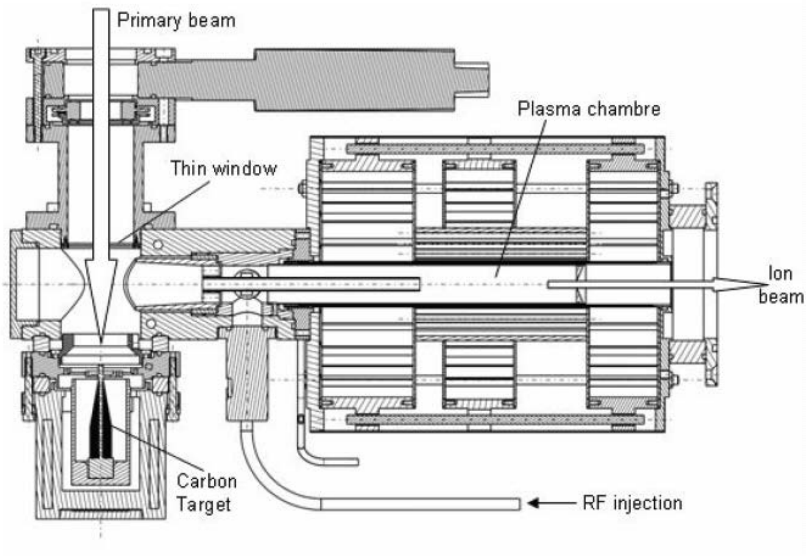
E_{e-} = 10-300 eV

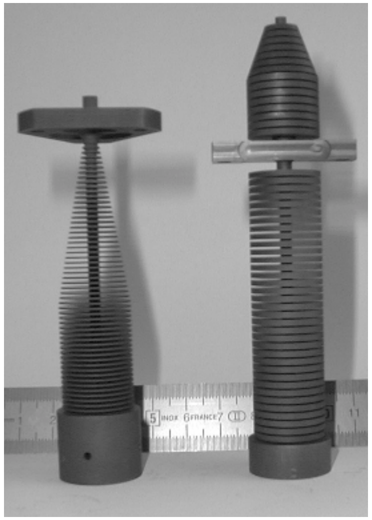
λ_{Debye} = 0.05 – 1mm

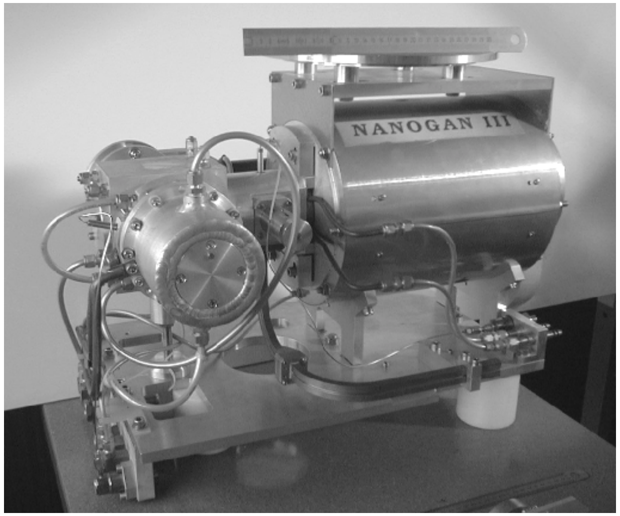
$\varepsilon_{95\%}$@30kV = 15-25 pi mm mrad

ECR and RF-driven ion sources for radioactive ion beams

ECR ion source in operation





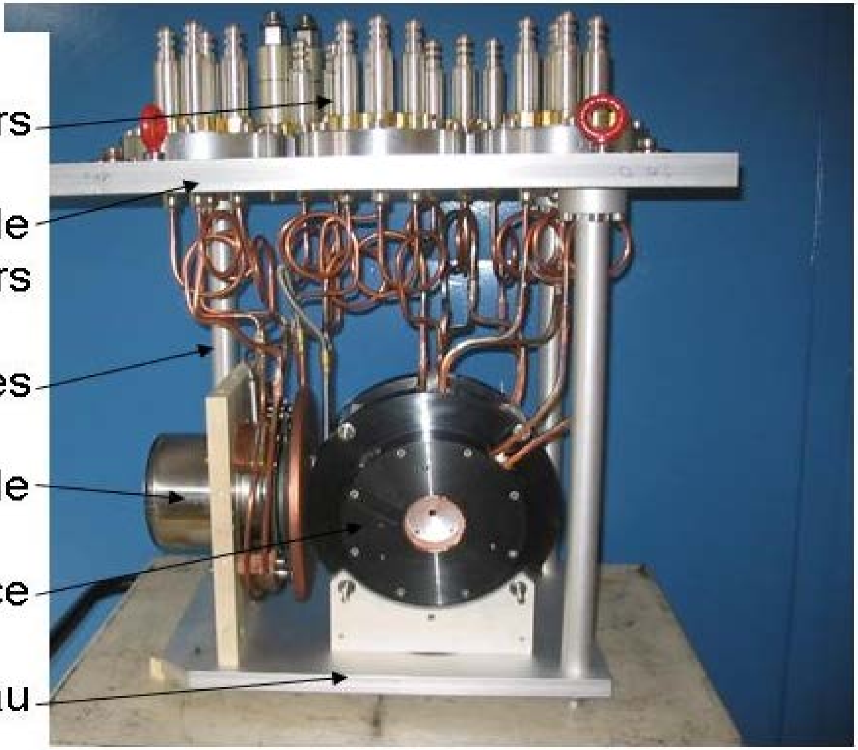


Target and Nanogan-III ECRIS at SPIRAL I-GANIL
Permanent magnets, 10GHz, 200W
Multicharged ECR.

For injection in post-accelerator, a 2-steps scheme 0 →1+, 1+ → N+ is now preferred.

2.45GHz 1^+ ECR ion source under commissioning

Monobob 2 for SPIRAL II



Connecteurs

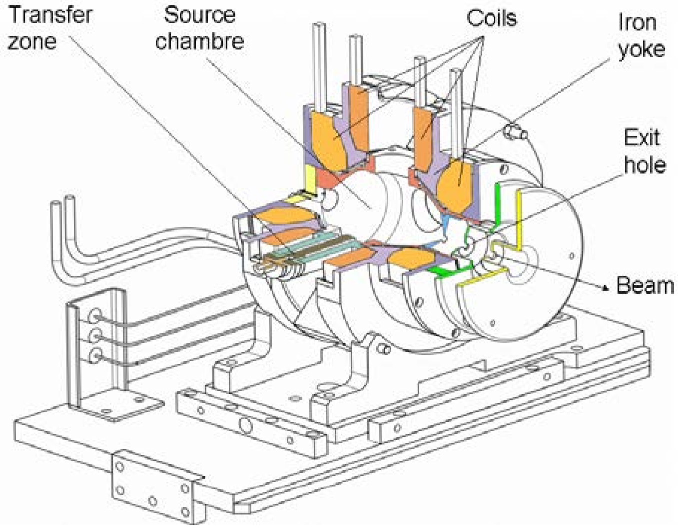
Platine de connecteurs

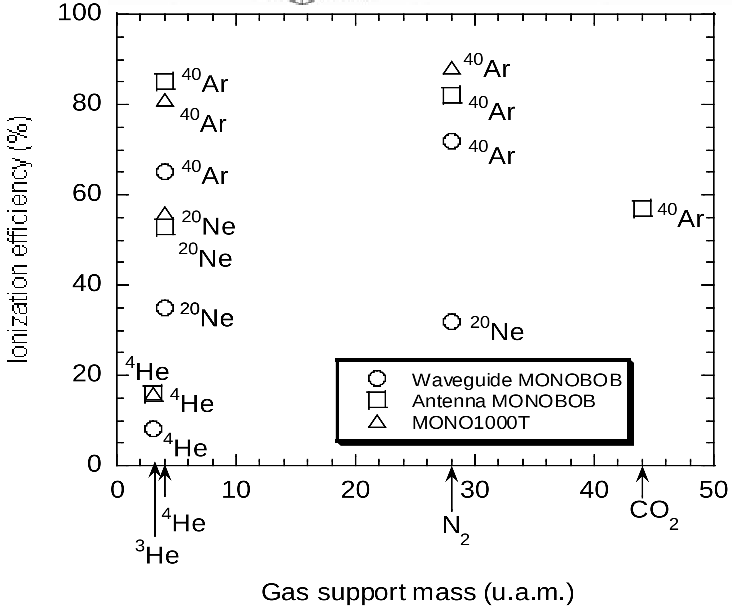
Colonnes

Cible

Source

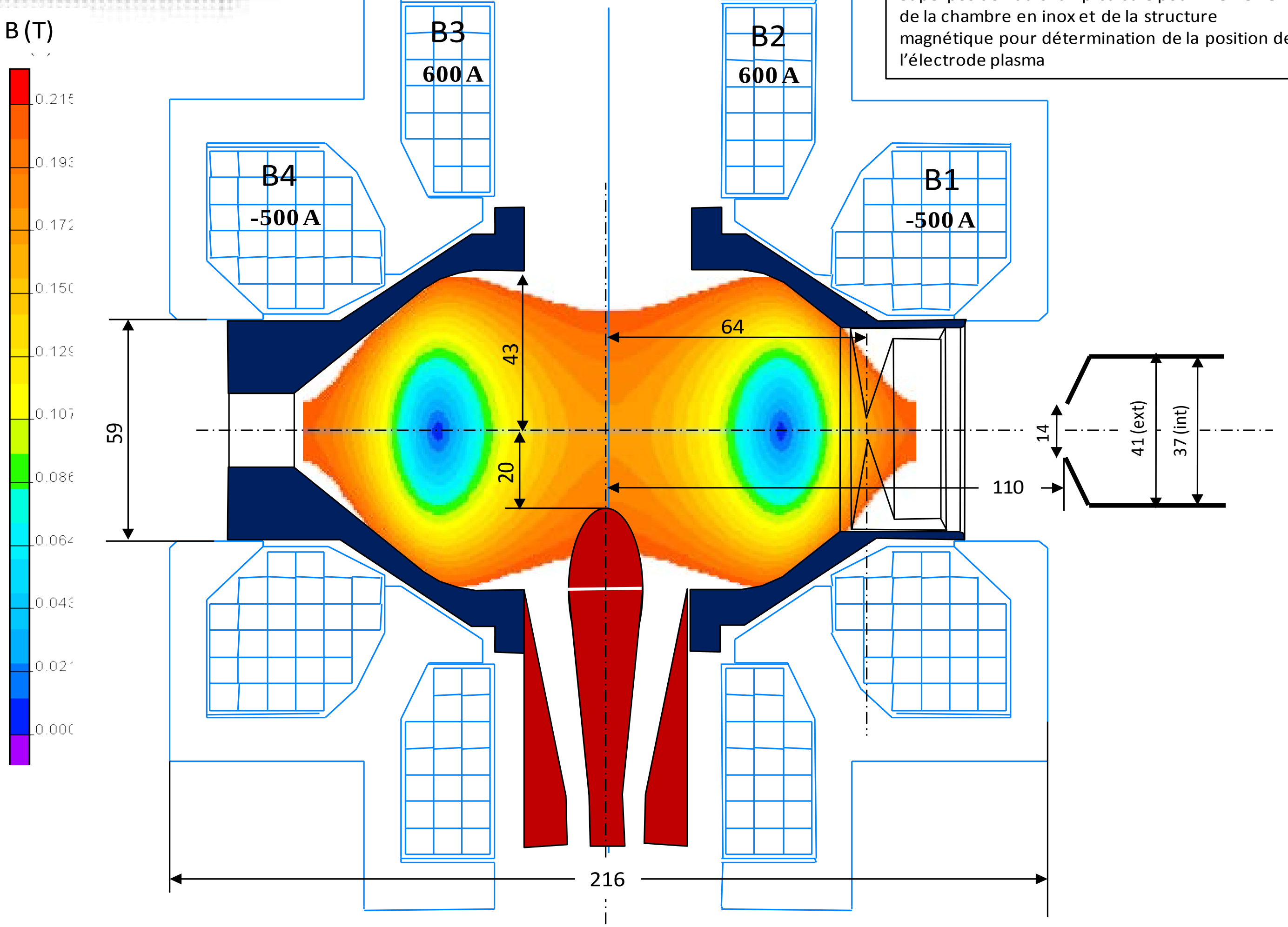
Plateau





Magnetic field Mapping

Le 15.4.2011.
Superposition du champ calculé pour MONOBOB, de la chambre en inox et de la structure magnétique pour détermination de la position de l'électrode plasma

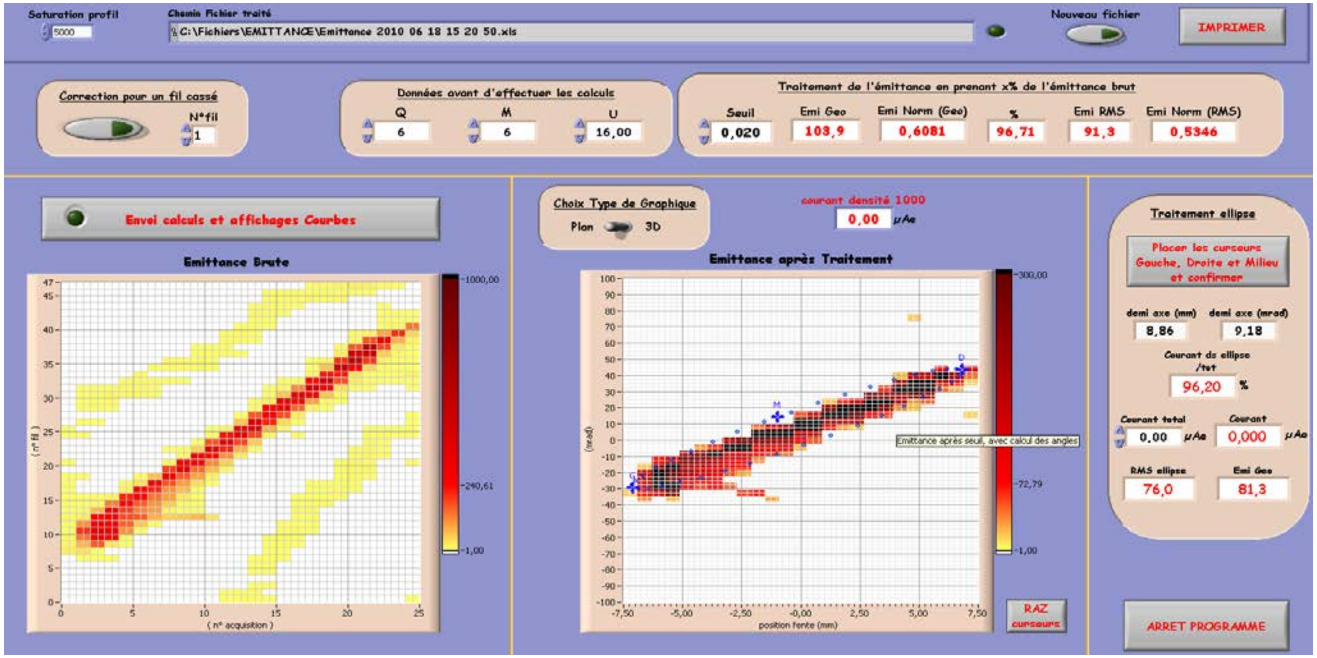


Ionization efficiencies

Gaz d’intérêt	Gaz support	Eff_{1+} x Eff_{transp}	Eff_{2+} x Eff_{transp}	Eff. transport	$I_{extrait}$
		%	%	%	µA
Ar	N_2	27	4	86	934
Ar	N_2+He	34	4	90	892
CO	Ar	30	/	88	816
Kr	N_2	39	8	53.1	843
Kr	Ar	40	7	49.4	764
Xe	Ar	47	7	39	798

Support gas flow is comprised between 1 and 7 10^{-4} mBar L/s

Emittance



Saturation profil: 5000

Chemin Fichier traité: C:\Fichiers\EMITTANCE\Emittance 2010 06 18 15 20 50.xls

Correction pour un fil cassé

N°fil: 1

Données avant d'effectuer les calculs

Q	M	U
6	6	16,00

Traitement de l'émittance en prenant x% de l'émittance brut

Seuil	Emi Geo	Emi Norm (Geo)	%	Emi RMS	Emi Norm (RMS)
0,020	103,9	0,6081	96,71	91,3	0,5346

courant densité 1000: 0,00 µAe

Emittance après seuil, avec calcul des angles

Traitement ellipse

demi axe (mm)	demi axe (mrad)
8,86	9,18

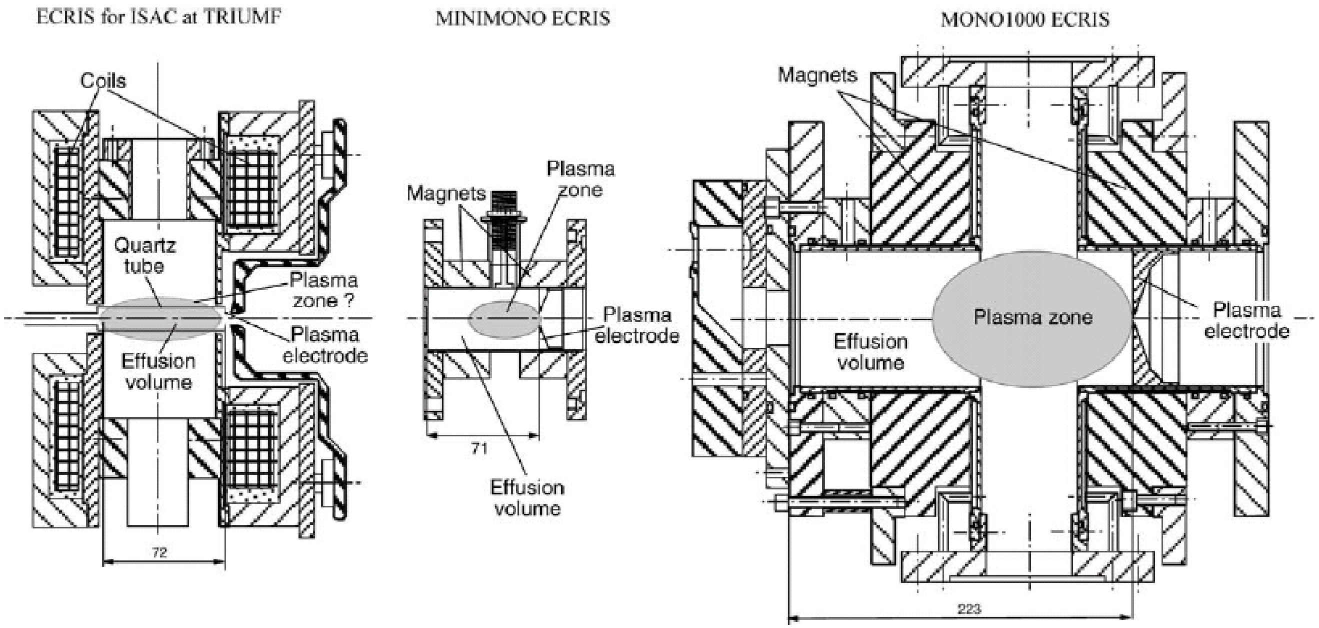
Courant ds ellipse /tot: 96,20 %

Courant total	Courant
0,00 µAe	0,000 µAe

RMS ellipse	Emi Geo
76,0	81,3

$^{40}Ar^{+}$Emittance : 76 π.mm.mrad (93% of the beam)

Comparison of different 1^+ ECR



Comparisons between expected and measured ionisation efficiencies with four 2.45-GHz ECR ion sources, for different isotopes of Ne

	ISAC TRIUMF	MINIMONO GANIL	MONO1000 GANIL	MONOBOB GANIL
Volume (cm^3)	18	**117**	**1500**	**687**
Exit diameter (mm)	**5**	**4**	7	**5**
Transient time (ms)	**<40**	34	15	81
Ion. efficiency (%)				
$^{20}Ne^+$ (stable)	11.5	**25**	**92**	**53**
$^{22}Ne^+$ (9.25 s)	**12**	25	92	53
$^{18}Ne^+$ (1.67 s)	11	25	91	51
$^{17}Ne^+$ (0.109 s)	10.5	19	81	30

Bold characters have been measured or directly deduced from measurements. The times written in normal characters have been estimated using the formula deduced from [14].

Overview on ECR ion sources

References

Special thanks to P. Bricault, P. Jardin, M. Schaedel, Y. Nagame for material used in the preparation of this course

Surface ion sources:
B. Vosicki et al., NIM186 (1981), 307.
R. Kirchner, NIM186 (1981), 275; NIMA292 (1990) 203.
S. Ichikawa et al., NIMB187 (2002) 548.

FEBIAD ion sources:
S. Sundell et al., NIMB70 (1992) 160.
R. Kirchner, NIMB204 (2003) 179.
L. Penescu et al., Rev Sci Instr 81 (2010) 02A906.

ECR ion sources for RIB:
C. Huet-Equilbec et al., NIMB240 (2005) 752.
F. Wenander et al., Nucl. Phys A746 (2004) 659.

Supplement

Nielsen model (for Nielsen ion sources)

$$\eta_{\max} = C \cdot l \cdot \nu \cdot \sigma_{ie} \qquad (4.1)$$

where l = the length of the plasma chamber;
ν = number of oscillations carried out by a primary electron;
σ_{ie} = effective ionization cross section (including all processes of ionization);
C = constant depending on the acceleration gap and potential.

Kirchner model (for FEBIADs)

$$\eta = \frac{j_i}{j_i + j_0}$$

$$j_0 = n_0 \sqrt{\frac{k \cdot T_{is}}{2\pi \cdot M_i}}$$

Bohm's formula

$$j_i = \gamma \cdot n_i \cdot \sqrt{\frac{k \cdot T_e}{M_i}}$$

$$\eta = \gamma \cdot \sqrt{2\pi} \cdot \sqrt{\frac{T_e}{T_{is}}} \cdot \frac{n_i}{n_0}$$

γ = Bohm's correction factor [61], $\gamma \in (1/3;2/3)$;
n_i = ion density ;
n_e = electron density ;
T_{is} = ion source temperature (assimilated with the ion temperature);
T_e = electron temperature ;
M_i = ion mass.

Alton model (for FEBIADs and EBGP)

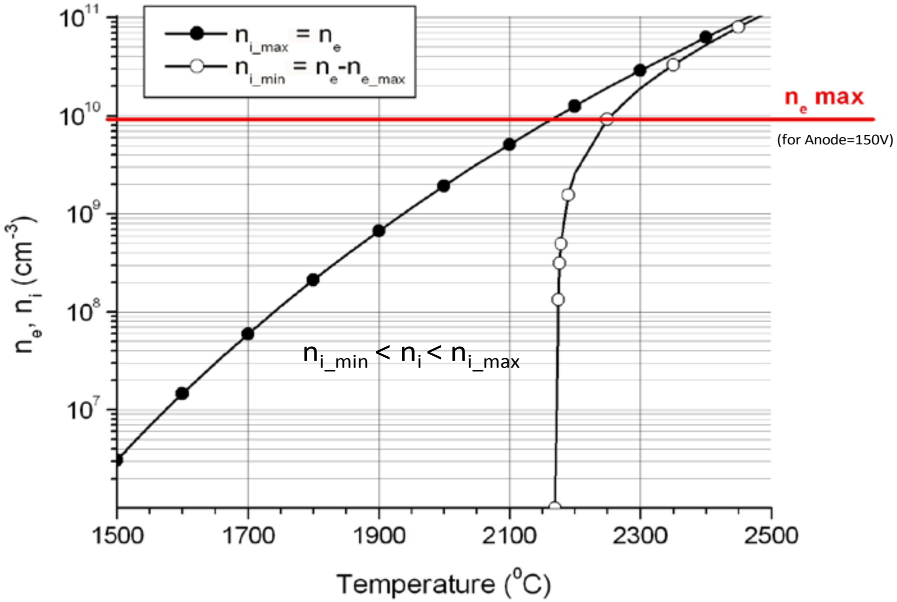
$$\eta_{calc} = \frac{4D_0 \cdot \dfrac{\langle l \rangle}{S_{out}} \cdot \sqrt{\dfrac{\pi \cdot M_i}{8kT_i}} \cdot l_e \exp\left[\dfrac{-I_p}{<kT_e>}\right]}{1 + 4D_0 \cdot \dfrac{\langle l \rangle}{S_{out}} \cdot \sqrt{\dfrac{\pi \cdot M_i}{8kT_i}} \cdot l_e \exp\left[\dfrac{-I_p}{<kT_e>}\right]}$$

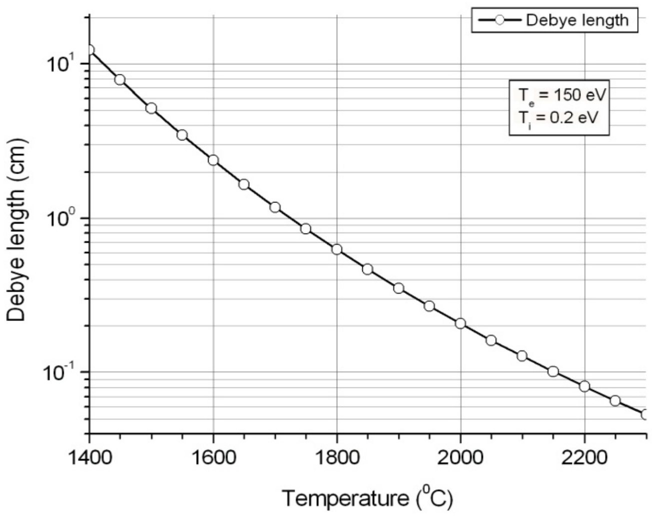
$$\eta_{calc} = \frac{\dfrac{C}{S_{out} \cdot j_{cath}}}{1 + \dfrac{C}{S_{out} \cdot j_{cath}}}$$

$\langle l \rangle$ = the average path length for a particle in the plasma;

S_{out} = the emission area of the source;
D_0 = constant (cm^2/s);
I_p = the ionization potential;
l_e = number of electrons in the valence shell of the atom with a given I_p;

FEBIAD plasma properties



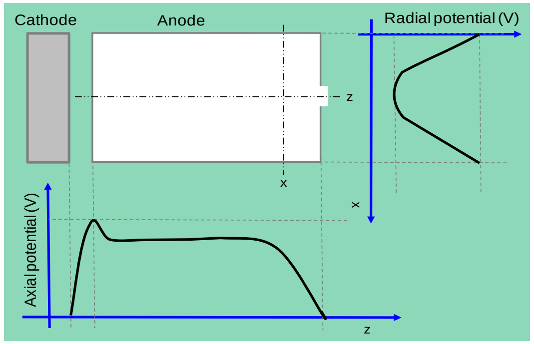


Electrons

- ➢ Their charge sustains the plasma;
- ➢ The generated potential well defines the source trap capacity;
- ➢ Generated by a hot cathode, $n_e = f(T)$;
- ➢ Their energy is defined by V_{anode};
- ➢ Primary beam can reach the space charge limit;
- ➢ There is a maximum excess n_e in the source.

Ions

- ➢ Generated mainly by electron impact;
- ➢ $n_i < n_e$;
- ➢ E_i = ~0.2 eV (thermal);
- ➢ For efficient operation at high temperatures, they are required for compensating the electron charges.



Improvement of the ionization efficiency at ISOLDE

Tests with noble gases (offline and online):

FEBIAD Ion source	**Ionization Efficiency (%)**					
	He	Ne	Ar	Kr	Xe	Rn*
Standard MK7	0.14	0.36	2.0	4.3	11	-
VADIS VD7	**1.4**	**6.7**	**26**	**38**	**47**	**62**
Multiplication factor	**10**	**18.6**	**13**	**8.8**	**4.3**	**-**