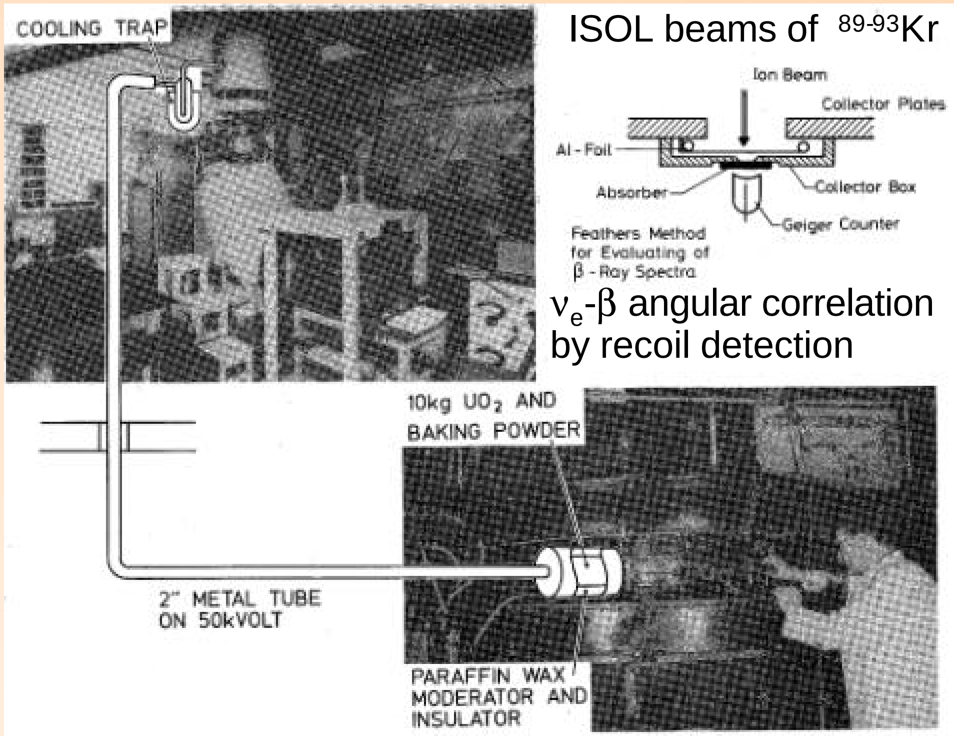
Ion sources for radioactive beams
- and the extra options

XXXVIIIth Rencontre de Moriond
Les Arcs
March 17-22nd
2003

Fredrik Wenander

LAYOUT OF THE TALK

- INTRODUCTION
- ION GUIDE ISOL
  - IGLIS
  - IGISOL
- THE SOURCE ZOO
  - SURFACE IONISERS
  - ELECTRON COLLISION SOURCES
  - LASER IONISERS
- SPECIAL 'TRICKS'
  - SELECTIVITY
  - BEAM BUNCHING
- EXTRA EQUIPMENT
  - DIRECT N$^+$ SOURCES
  - CHARGE BREEDERS
  - RFQ COOLERS
  - TRAPS
- CONCLUSIONS



ISOL beams of $^{89-93}$Kr

ν_e-β angular correlation by recoil detection

HISTORY AND MILESTONES

1944: DEMPSTER USED A HOT SPARK ION PRODUCTION, EFFICIENCY OF 1E-8

1951: FIRST ISOL BEAMS AT NIELS BOHR INSTITUTE (COPENHAGEN)

1966: TRISTAN AT THE REACTOR IN AMES, IOWA

1967: ISOLDE, CERN

NIELSEN AND NIER-BERNAS TYPE ION SOURCES WERE USED

1976: THE FEBIAD WAS INTRODUCED BY R. KIRCHNER

1987: THE FIRST HIGH EFFICIENCY ECR DESIGNED BY BECHTOLD

MID-1980S: THE LASER RESONANCE PHOTO IONISATION AVAILABLE

The task – ionisation

ISOL method

Techniques allow on-line production of ~80 out of 92 naturally occurring elements.

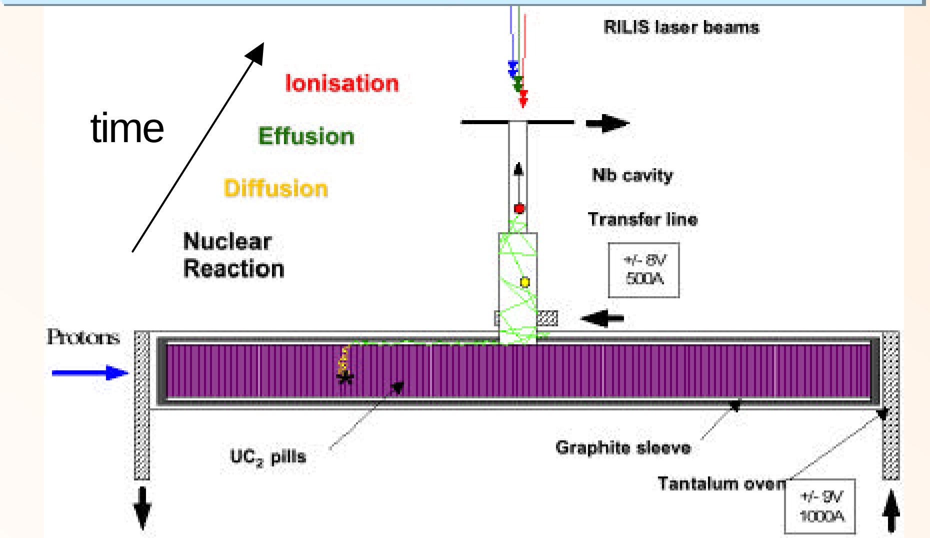
How to ionise them?

General design aspects

* Target, transfer tube, ionisation tube at elevated temperatures to enhance the diffusion and effusion rates

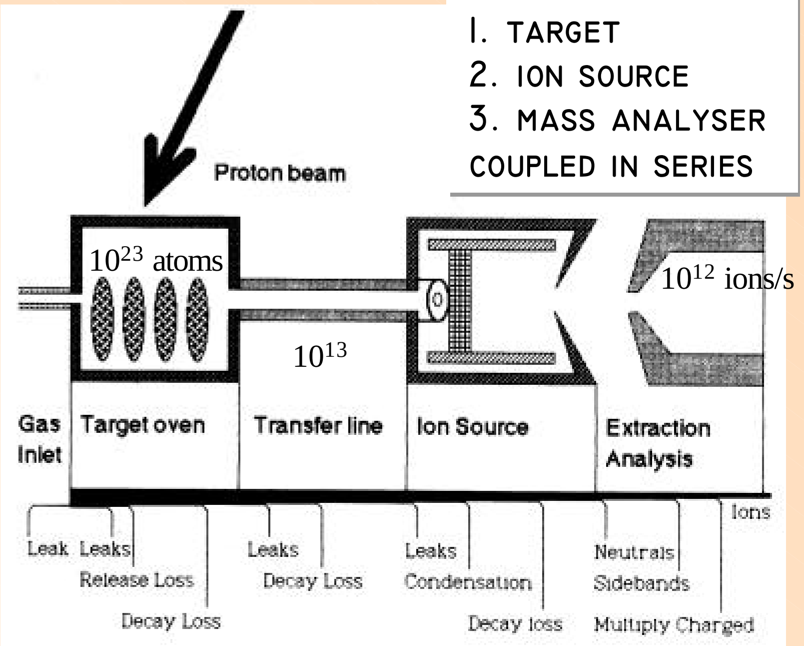
* The target–ion source distance should be small

* difficult to separate the ion source from target, vacuum system, radiation shielding



1. target
2. ion source
3. mass analyser

coupled in series



Standard requests

* Rapidity – half-life

* Efficient – limited amounts of radionuclides

* Selective – suppress isobaric contaminants

* Universal – advantage and drawback

New requests

* High intensity beams

~0.01 up to 1E14 atoms/s

* High brightness

for trap and charge breeder injection

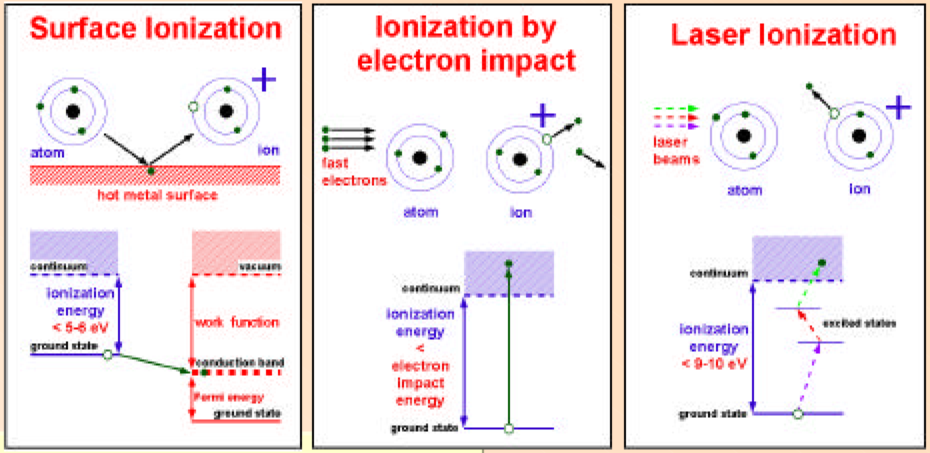
Also

* simple and reliable (consumables)

* radiation resistant

Ionisation methods

- * No universal ion source
- * specialised target/ion sources

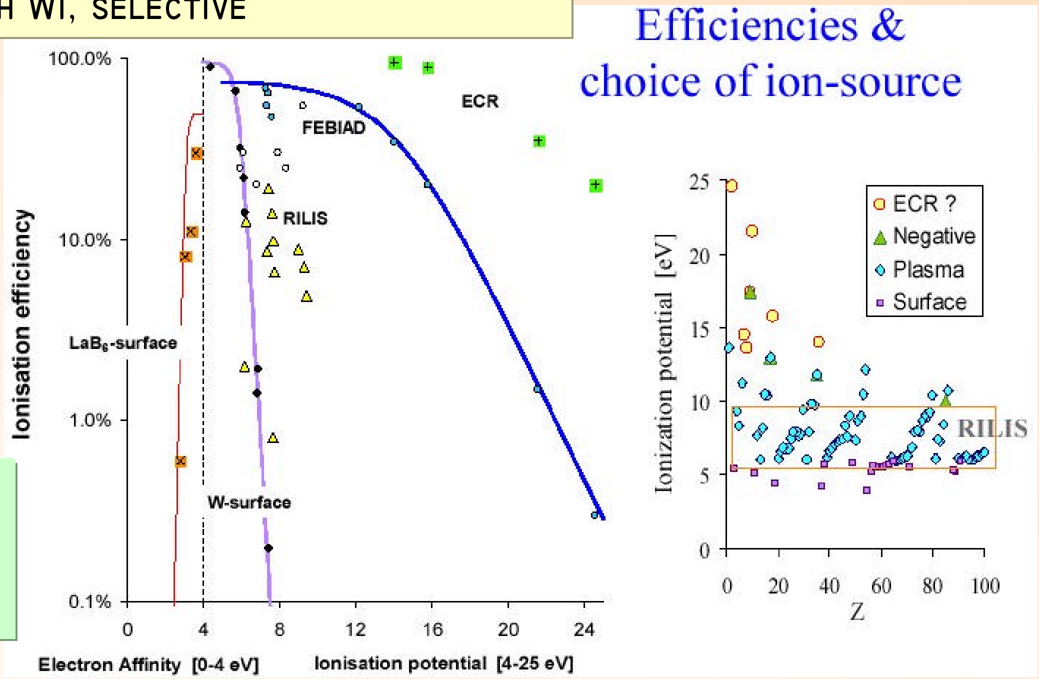


Ionising medium: heat, electrons or photons

Guidelines

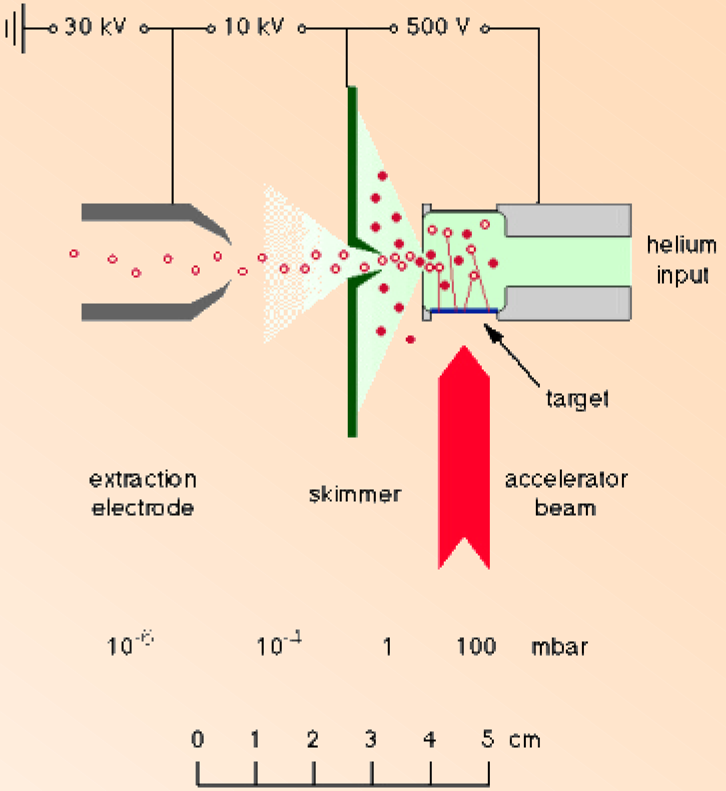
surface source	low Wi (alkali, alkaline earth, rare earth)
negative surface ionisation	high Electron affinity Ea (halogens)
low charge state ECRIS	high Wi, gaseous (noble gases)
high temp plasma sources	versatile
laser ion source	not too high Wi, selective

	Ha enthalpy of adsorption with respect to the walls	Wi ionisation potential
Surface ioniser	<7 eV	<6.5 eV
Discharge source	<6	-


Efficiencies & choice of ion-source

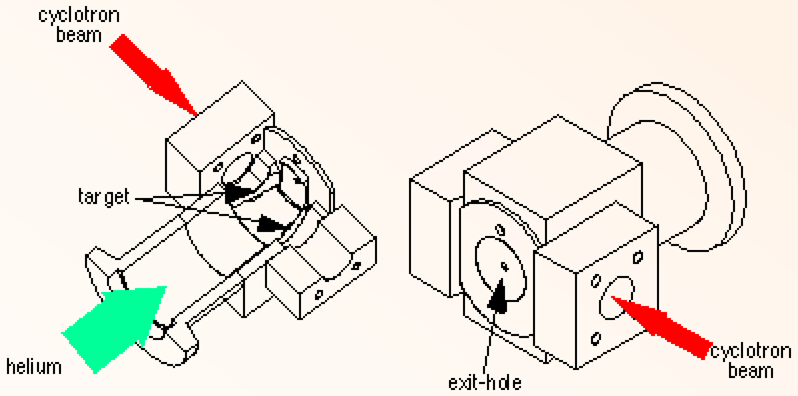
BUFFER GAS CELL I

* IGISOL – ION GUIDE ISOTOPE SEPARATOR ON LINE
* NO ION SOURCE IN THE CLASSICAL SENSE IS USED
* THE DRIVER BEAM IS NOT STOPPED IN A THICK TARGET



VIRTUES AND DISADVANTAGES

* ION GUIDE EFFICIENCY <0.1-10%
+ VERY FAST SOURCE OF IONS, SUITED FOR MS ISOTOPES
+ SUITED FOR REFRACTORY ELEMENTS
- LOW YIELDS <1E4 IONS/S DUE TO
  - THIN TARGET
  - PLASMA EFFECT (IONISATION OF BUFFER GAS)
- LARGE ENERGY SPREAD (>100 EV)
- WITHOUT ANY SELECTIVITY
- LOW EFFICIENCY FOR HIGH Z OF THE PROJECTILES



JYFL LIGHT-ION FUSION-EVAPORATION REACTIONS

BUFFER GAS CELLS
ARE FOUND
AND DEVELOPED AT:

JYFL, KU LEUVEN,
UNIVERSITY OF MAINZ,
GANIL, LMU MUNICH

Complementary!	Hot cavity	Gas cell
Thick target	+	-
Refractory elements	-	+
Delay time	+/-	+

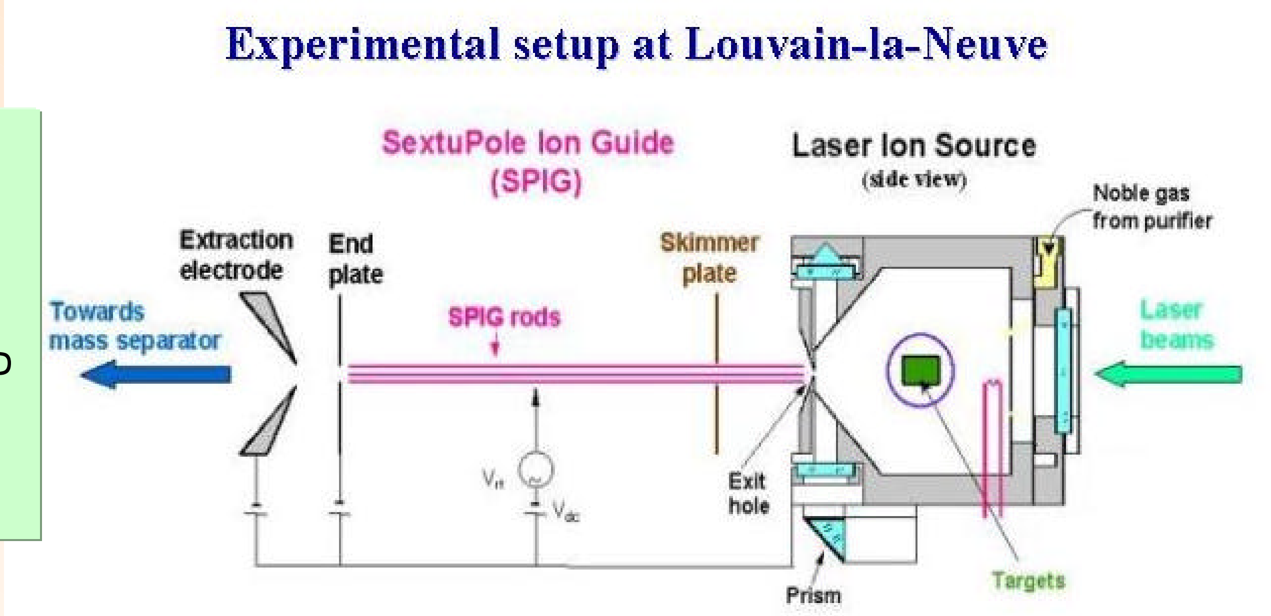
Buffer gas cell II

- * IGLIS – Ion Guide Laser Ion source
- * Neutralised recoil products are re-ionised
- * Noble gas flow transports neutrals to ionisation region

Virtues and Disadvantages

Similar to IGISOL but:

+ Selective post ionisation =>
  no problem of universality
+ SPIG => small energy spread
  (a few eV)
- Less fast than IGISOL
  (20-500 ms)



Experimental setup at Louvain-la-Neuve

Future

- * 40% efficiency claimed with electro-static guiding fields (DC and RF) at RIA

Ion catcher network

- * Glass cell with inner coating (IE4 V/m) and laminar gas flow
- * Superfluid helium as stopping medium and snowball creation
- * SHIPTRAP for FRS elements

Surface ioniser / Thermal ion source

Surface ionisation efficiency is described by the Saha-Langmuir equation

$$\varepsilon_{surface} = \frac{1}{1+\frac{g_0}{g_+}exp\left(\frac{W_i-\phi}{kT}\right)}$$

g_0 and g_+ are statistical weights of the atomic ground and ionic state respectively

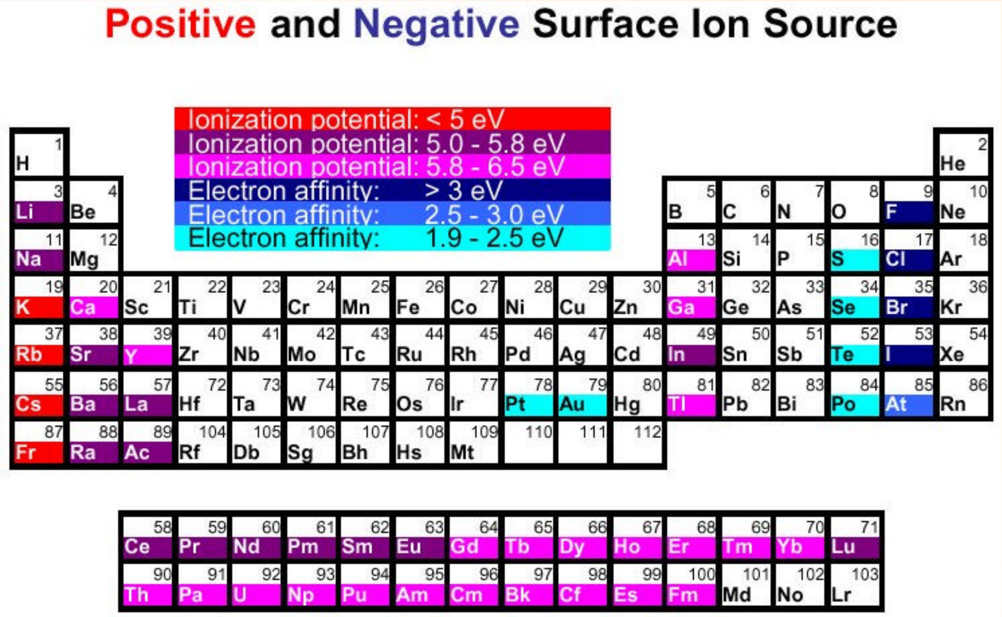
Surface ionisation inside a hot cavity

=> Amplification factor N, since

* multifold chance of being surface ionised

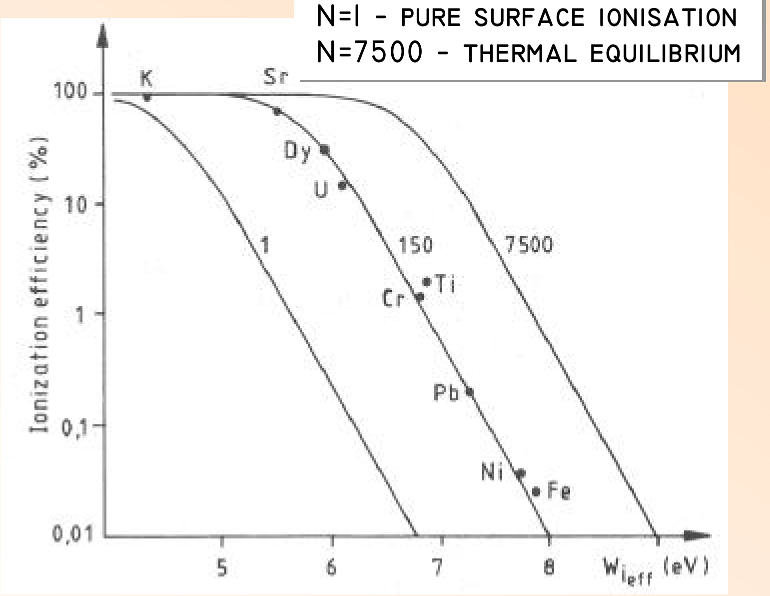
* trapping in plasma after thermalisation

=> Also increased ionisation efficiency for high Wi



Positive and Negative Surface Ion Source

- 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



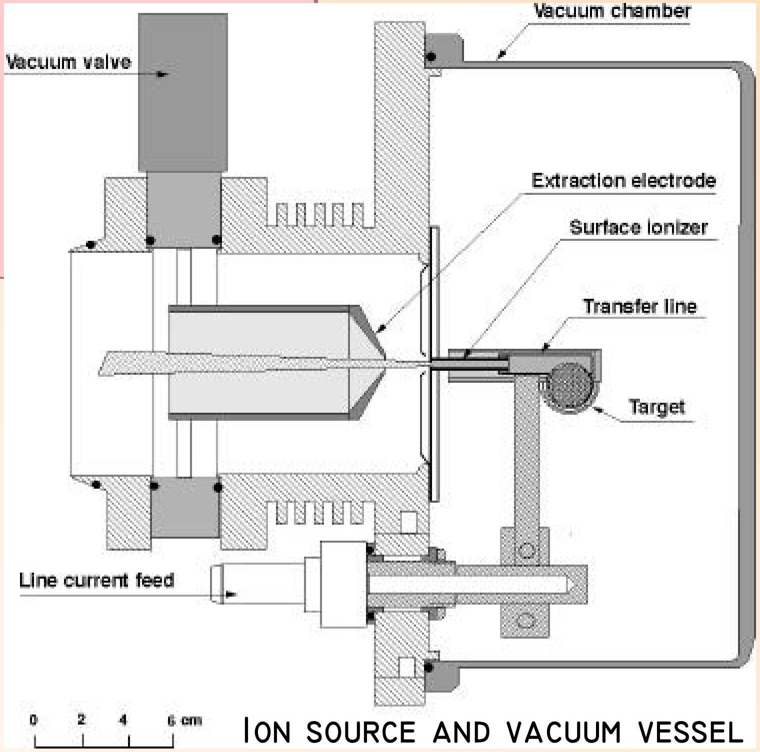
N=1 - pure surface ionisation

N=7500 - thermal equilibrium

Surface ioniser / Thermal ion source

Properties

- * Ionisation efficiency 100% for $W_i<5$ eV, few % for $W_i=6.5$ eV
- * Used for alkalines, alkaline earths, rare earths, Ga, In and Tl also molecules as BaF and SrF
- * Emittance ~ 10 π mm mrad (60 kV, 95%)
- * Energy spread <2 eV
- * max current 1 μA/mm^2
- * Short delay time (half-lives as short as 10 ms)
  - small ionisation volume
  - operates at elevated temperatures
  - closely coupled to targets



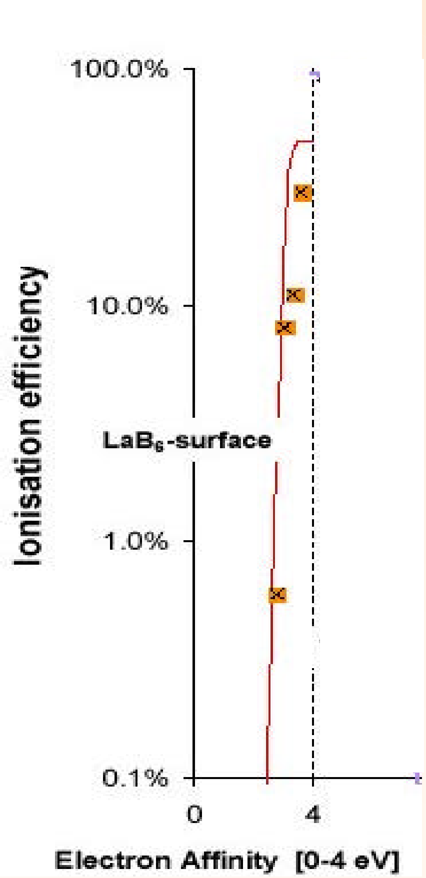
Ion source and vacuum vessel

Ionisation material

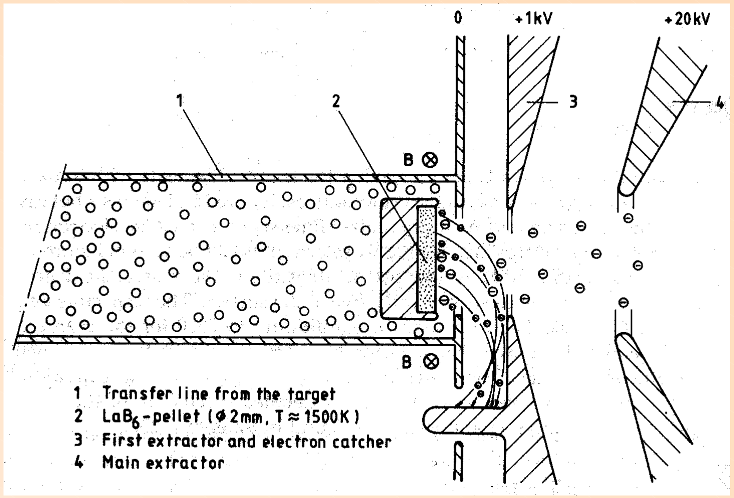
- * Ta, W, Re, Ir, Pt
- * temperatures up to 2800 K
- * e.g. tungsten with ϕ~4.5 eV at 2400 °C
- * Work function depends on crystal orientation, temperature and cleanliness

Negative surface ionisers

- * Injection into tandem
- * Stripper extraction in cyclotron



Effective for elements with high electron affinities A_E, such as halogens (>1.8 eV)



1 Transfer line from the target
2 LaB_6-pellet (ϕ 2mm, T ≈ 1500K)
3 First extractor and electron catcher
4 Main extractor

Working principle

- * LaB6, low ϕ=2.6 eV, act as ioniser (kept at 1200 °C)
- * Halogens pick up an electron from the surface
- * Permanent magnet ~1 kG, separate thermionic electrons, ~10 mA
- * Surface ionisation efficiencies >10% for Cl, Br and I

$$\varepsilon_{surface} = \frac{1}{1+\frac{g_0}{g_-}exp\left(\frac{\phi - A_E}{kT}\right)}$$

g_0 and g_- are statistical weights of the atomic ground and ionic state respectively

Alternatives

Cs-sputter technique

F^- efficiently

Laser plasma ionisation

high currents

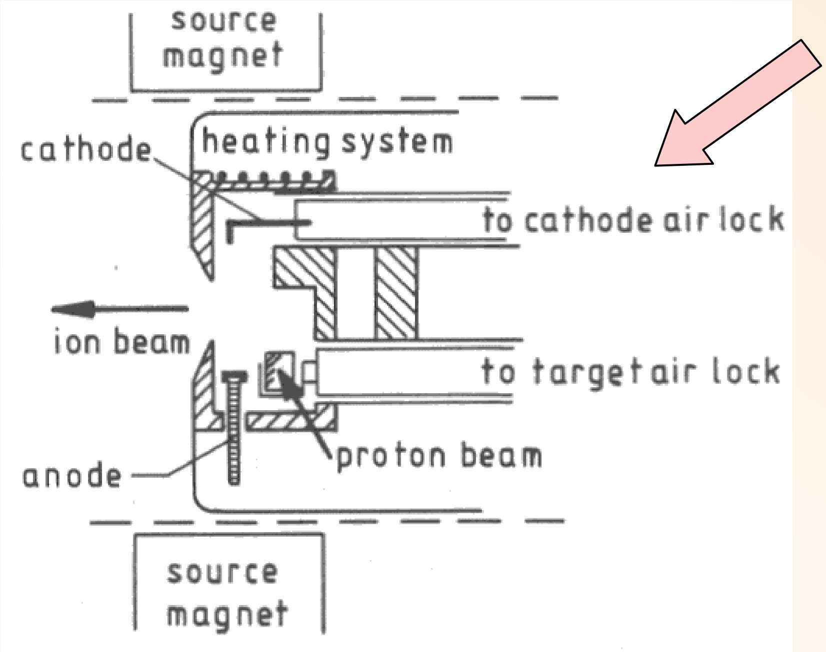
Electron collision sources - old sources

- * Low-pressure arc-discharge sources
- * Arc discharge sources has a high total current of <5 mA/mm^2
- * Quite high ionisation efficient (30% for Ar, Kr and Xe)

Why extinguished

- unstable
- cathode sputtering problems with filament lifetimes
- difficult to handle high current beams

? Future use thanks to their high current capability? ?



Bernas-Nier ion source

- * High current densities (>100 µA/cm^2)
- * Emittance and energy spread are low
  (0.01 π mm mrad, few eV)
- * Slit extraction geometry
  few wall collisions -> less adsorption problems
- * Efficient with short intrinsic delays
- * Foreseen as an option for PARRNe project

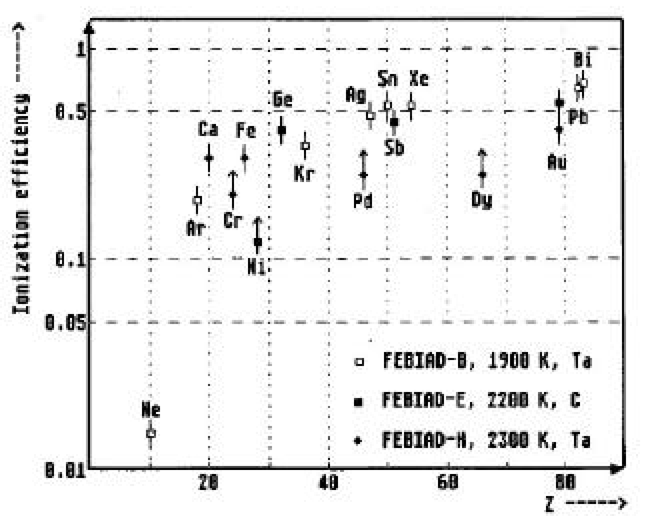
Hollow cathode ion source

- * ISOL-adapted since “very hot and very small”
- * notoriously short-lived
- * axial extraction on the cathode side
- * high efficiency at very high pressures
- * optimum pressure about 1E-2 mbar

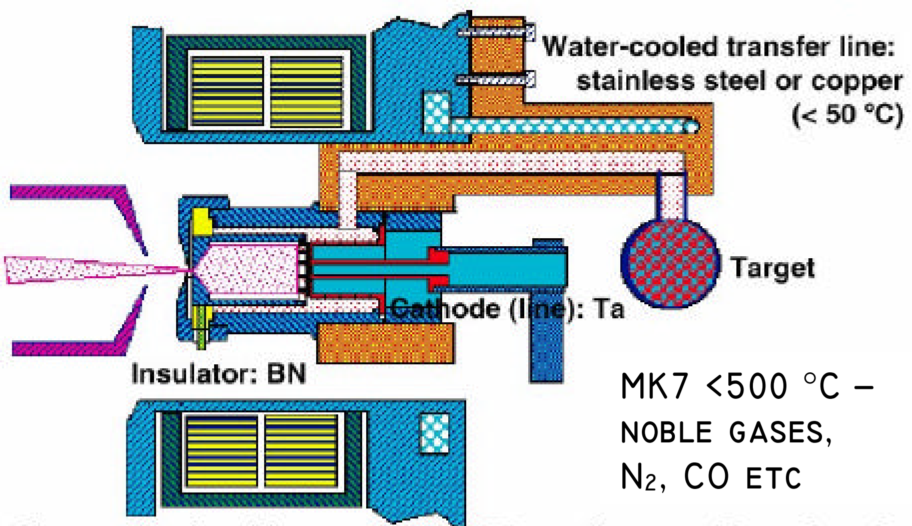
FEBIAD - Forced Electron Beam Arc Discharge

Properties

+ stable operation with little support gas (Pressures 5E-4 to 3E-5 mbar)
+ low ion current density (1-20 μA/mm^2)
+ moderate emittance (<20 π mm mrad at 15 kV, 95%)
+ low energy spread (<2 eV) (can be high for 2-anode, >20 eV)
+ volume as small as 1.3 cm^3 (6 ms intrinsic delay)
+ possible with high cavity enclosure temperatures



ISOLDE FEBIAD MK7 (water-cooled transfer line)



MK7 <500 °C – noble gases, N_2, CO etc

Plasma chamber: Mo or graphite, 12.5 mm diameter, 22 mm length
Source body: stainless steel

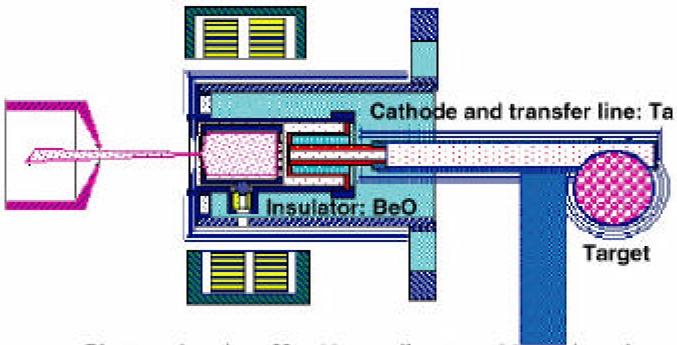
Efficiencies

* 20-70% for elements above neon
(>85% for bismuth, lead and tin)

* Efficient ionisation of gaseous and condensable elements
(relatively refractory elements: transition metals and lanthanides)

FEBIAD - Forced Electron Beam Arc Discharge

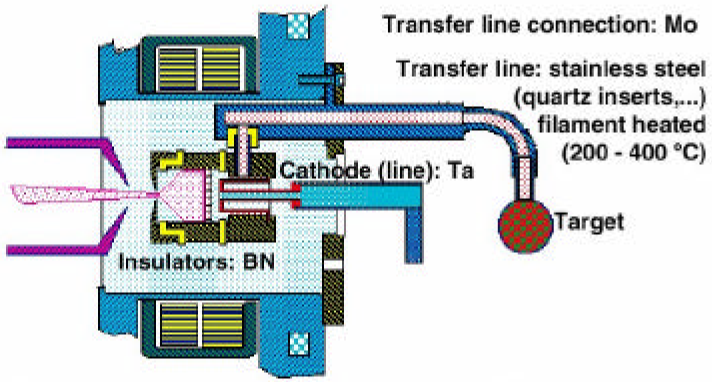
ISOLDE FEBIAD MK5 ("hot plasma")



Plasma chamber: Mo, 12 mm diameter, 21 mm length
Heat screens: Mo
Source body: graphite

MK5 1900 °C –
elements with low vapour pressure

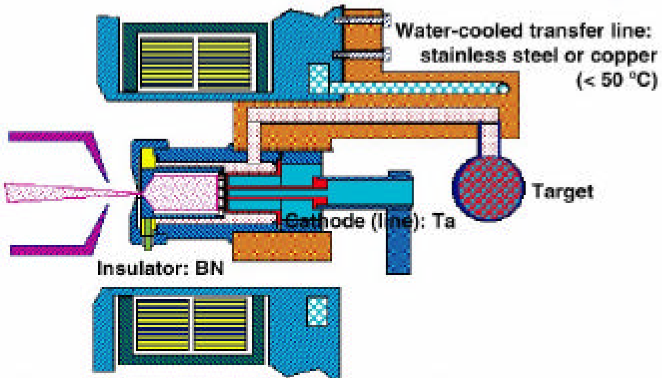
ISOLDE FEBIAD MK3 (cold transfer line)



Plasma chamber: graphite, 15 mm diameter, 25 mm length

MK6 1400 °C, intermediate to low vapour pressure
MK3 identical to MK6 but two anodes

ISOLDE FEBIAD MK7 (water-cooled transfer line)



Plasma chamber: Mo or graphite, 12.5 mm diameter, 22 mm length
Source body: stainless steel

MK7 <500 °C –
noble gases, N_2, CO etc

Selectivity

Plasma ion source universality =>
advantage and disadvantage

Use thermochromographic selection

THE FUTURE FOR ELECTRON COLLISION SOURCES

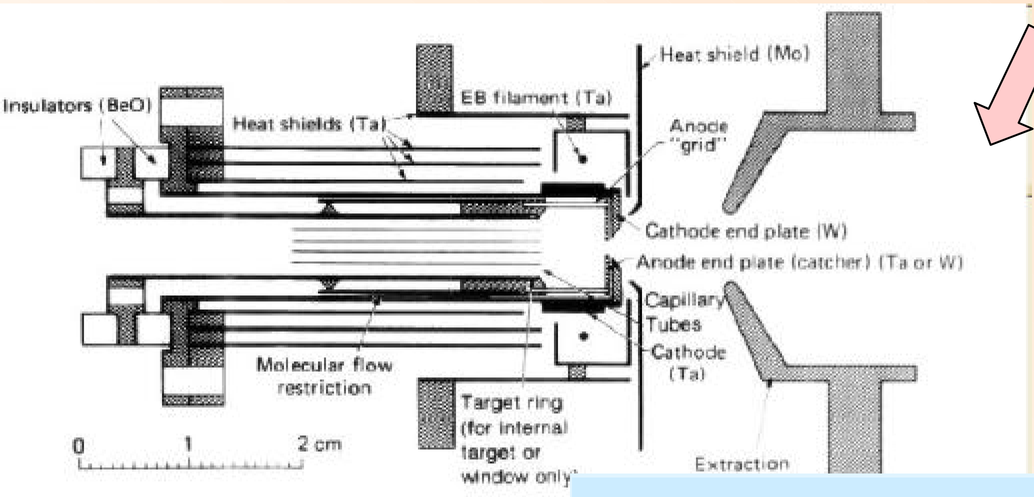
THE FEBIADS ARE ALMOST FULLY DEVELOPED

- * TANTALUM FREE SOURCE (NO GETTER EFFECT)
- * SOURCES OF GRAPHITE FOR C, O, AND N
- * STUDY THE RADIATION RESISTANCE (INSULATORS) (TO REACH EURISOL BEAM INTENSITIES)

ELECTRON-BEAM GENERATED
PLASMA ION-SOURCE

- \+ PERFORMANCE SIMILAR TO FEBIAD (35% IONISATION EFFICIENCY FOR KR)
- \+ SIMPLER DESIGN (NO MAGNETIC FIELD)
- \+ NO INSULATORS IN HIGH T REGION
- \+ COLD SPOT TEMPERATURE >2500 K
- \+ ONLY 0.4 CM^3 IONISATION REGION => SHORT INTRINSIC DELAY

- \- DELICATE AND CRITICAL DESIGN



FEBIAD AND BERNAS PROBLEM WITH LIGHT ELEMENTS

1. LOWER IONISATION CROSS SECTION
2. SHORTER TRANSIT TIMES THROUGH THE IONISING VOLUME

C, N, O PARTICULARLY TROUBLESOME SINCE ALSO THEIR VOLATILE MOLECULAR COMPOUNDS CO, CO_2, N_2, O_2 ARE VERY REACTIVE IN HOT ENCLOSURES

THE ANSWER TO THESE PROBLEMS IS COLD-ENCLOSURE ECR SOURCES

Multicusp ion source

Principle

* radial confinement by multicusp field
* alternately poled permanent magnets
* plasma heated by a filament or an RF antenna
* similar to an ECRIS

Data

\+ low energy spread and small emittance
(<0.01 π mm mrad)
\+ efficient ionisation over a wide pressure range
\+ potential for producing negative ions
\- currents of some mA
\- less high charge state production than in an ECRIS
\- permanent magnets => radiation sensitive

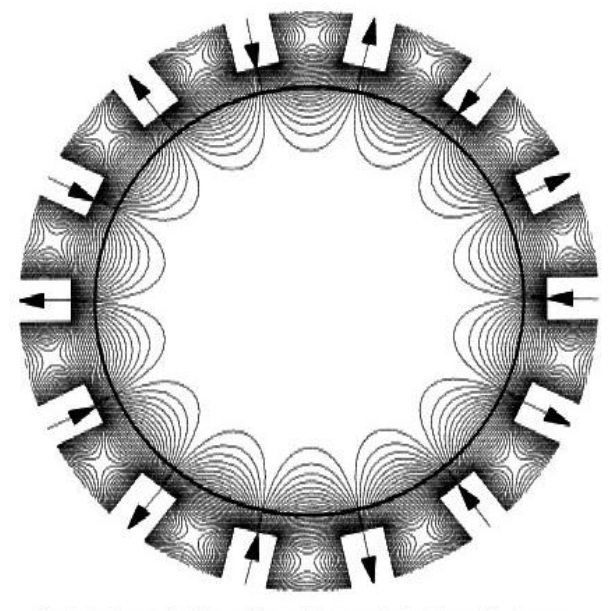


Fig. 2. Poisson calculation of the radial magnetic flux lines of the line cusp.

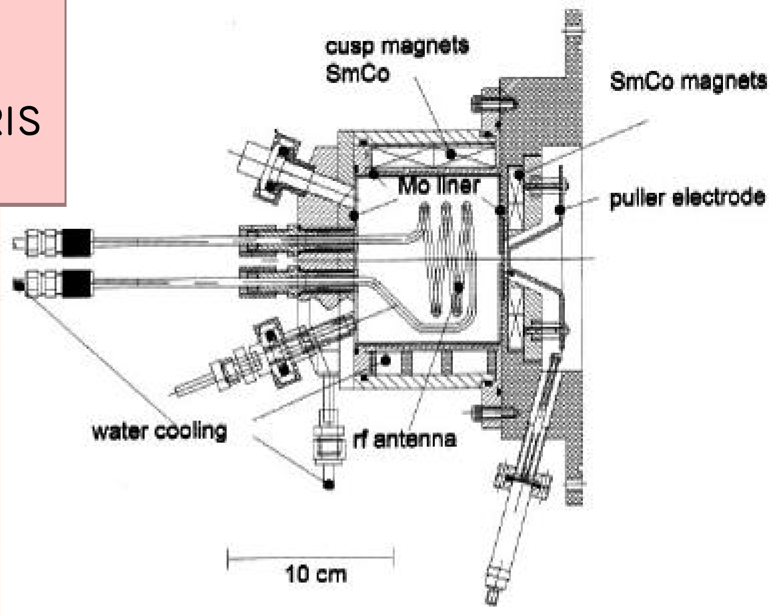


Fig. 1. Design drawing of the rf driven multicusp ion source.

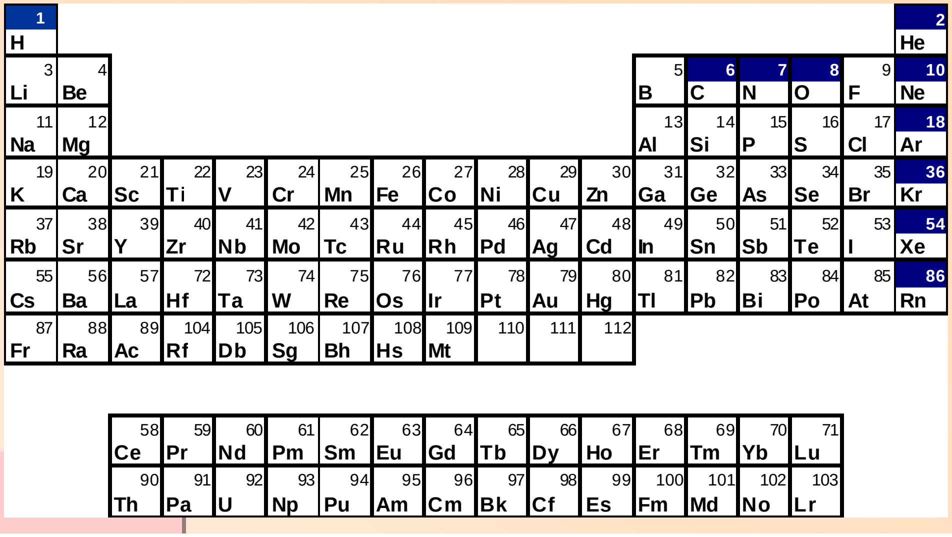
ECR ion sources

Principle

* Confining magnetic structure
* RF applied, few GHz
* ECR excitation of electrons
* Frequencies 2.45 GHz -28 GHz or higher
* Ionisation by electron-atom collisions

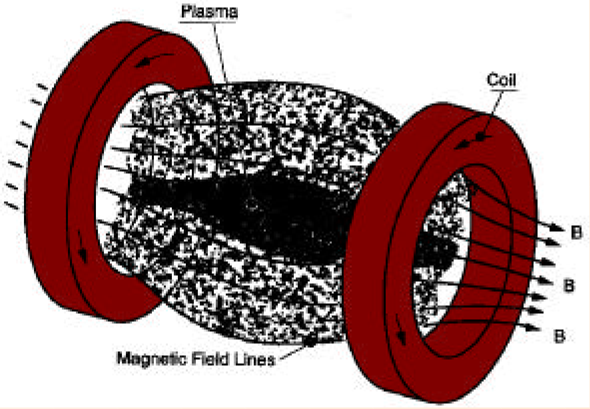
Data

+ no hot parts, no wearing parts (no filament)
+ suited for volatile elements (gases)
+ high ionisation efficiencies
+ possible to produce multiply charged ions
- high total currents (up to several mA)
- relatively long delay time (<100 ms)
- large emittance (0.1 π mm mrad)



1 **H**																	**2** **He**
3 Li	4 Be											5 B	**6** **C**	**7** **N**	**8** **O**	9 F	**10** **Ne**
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	**18** **Ar**
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**
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**
55 Cs	56 Ba	57 La	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**
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112						
		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		
		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		

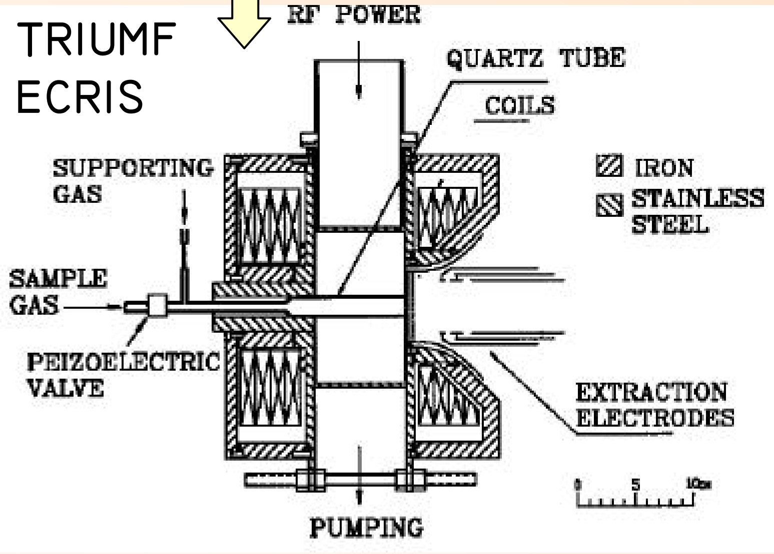
Elements compatible with a "cold-body" ECR ion source



monoECRIS - 1^+ ECR ion source

	Coil configuration		Permanent magnets
	good	radiation hardness	poor
	poor	confinement	good

TRIUMF ECRIS

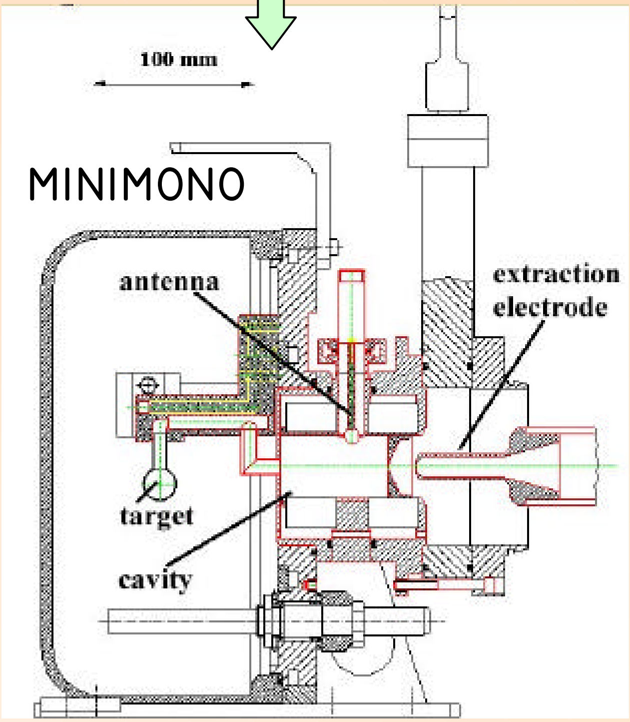


- Ionisation efficiency for N, O, Ne:
  20%, 20%, 12%
- Delay time <100 ms (?)
- energy spread <4 eV FWHM

Future

- Hot plasma enclosure - help or add problems?
  More background pressure? Reduced sticking time
- Higher frequencies (6.4 GHz and upwards)

MINIMONO

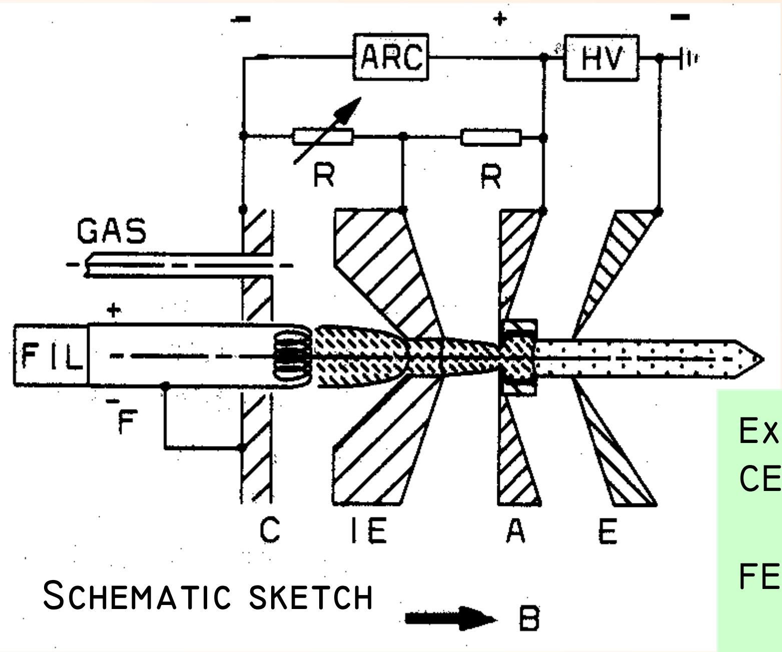


- Ionisation efficiency He, Ne
  He^+ >20%, Ne^+ >35%
- Total extracted current < 1 mA
  (>> 10 uA He^+ / Ne^+)
- Delay time (extraction 90%)
  He^+~50 ms, Ne^+~150 ms, Ar^+~250 ms

DUOPLASMATRON

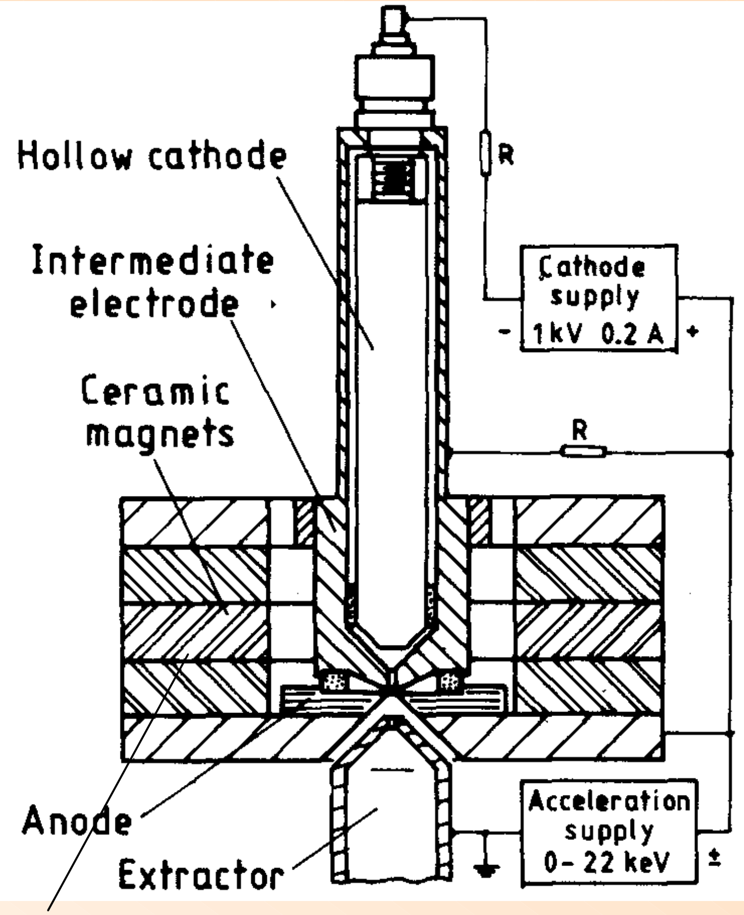
Properties

- * High current capability (mA)
- * Very high electron density 1E14 cm^{-3}
- * Suitable for gases (also He and Ne)
- * DC or pulsed operation (down to 20 µs)
- * Storage capacity 5E14 charges
- * High efficiency 90% (Ar)
- * Well-tested source - around since mid-50s



Schematic sketch

Hollow cathode type



Magnet can be of coil type

Examples:

CERN LINAC2: Pulsed operation 1 Hz, T_{EXT}=20-150 µs,
I_{PEAK}=250-300 mA, $Q_{SPACE\ CHARGE}$ >2·10^{14} charges

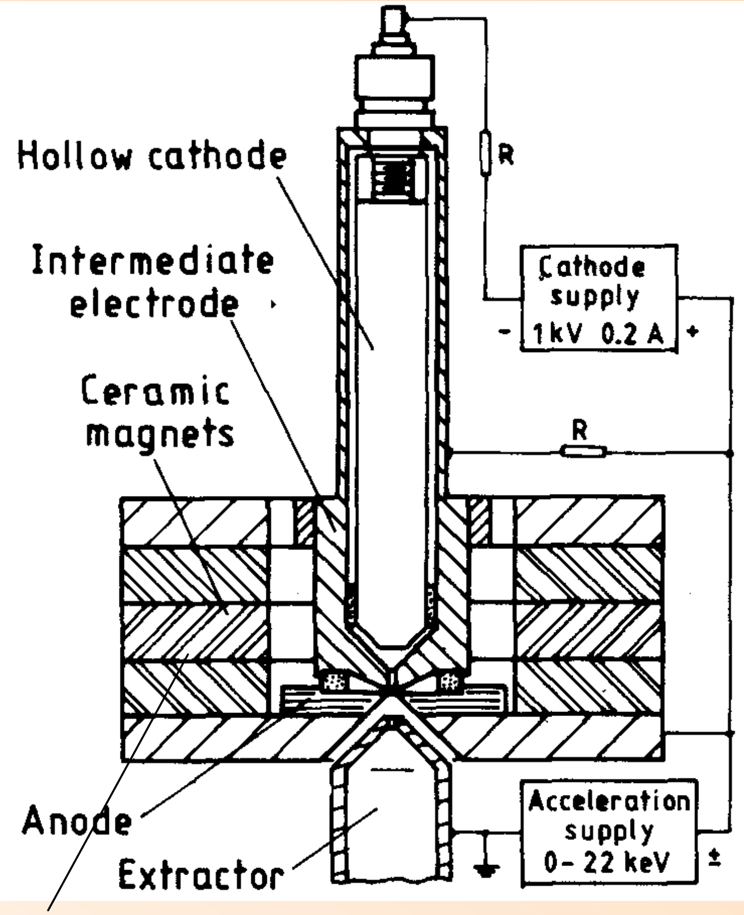
FERMILAB PET: Pulsed operation 360 Hz, T_{EXT}=80 µs,
I_{PEAK}=25 mA $^3He^+$, ionisation efficiency ~0.5%

Duoplasmatron

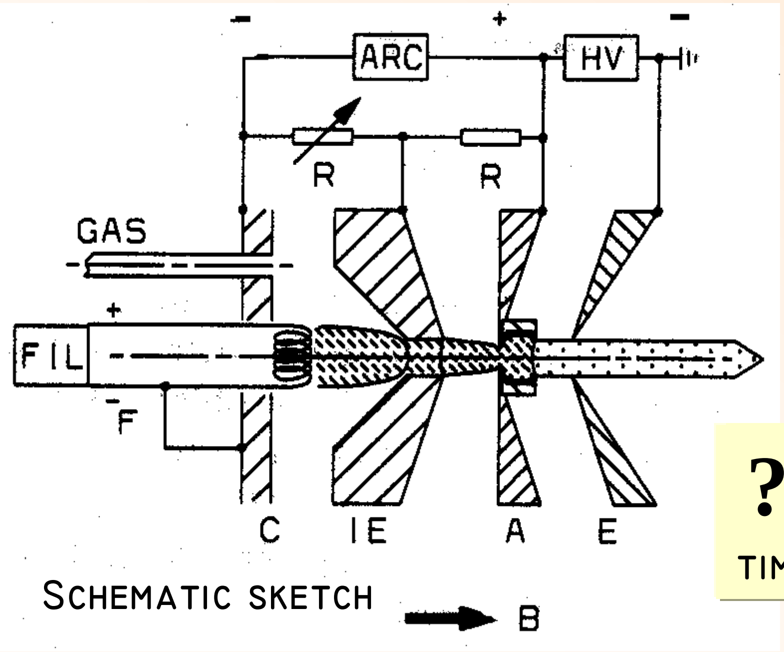
Limits and question marks

- * Delay time (target to source transport)?
- * Efficiency for pulsed operation?
- * Inappropriate for non-volatile materials
  (non-heated chamber walls)
- * Non-conventional RIB source - needs adaptation

Hollow cathode type



Magnet can be of coil type



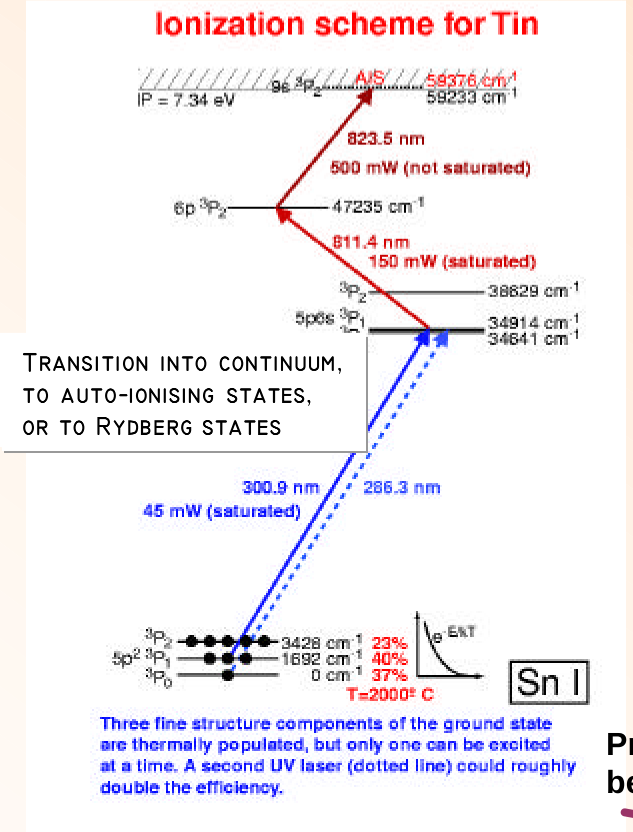
Schematic sketch

? Possibly to reach an efficiency of 5% for He and even higher for Ne, with an extraction time of 50-100 *m*s at an operation frequency of 200 Hz? ?

RESONANT IONISATION LASER ION SOURCE - PRINCIPLE

STEPWISE RESONANT LASER IONISATION VIA ONE OR MORE INTERMEDIATE LEVELS

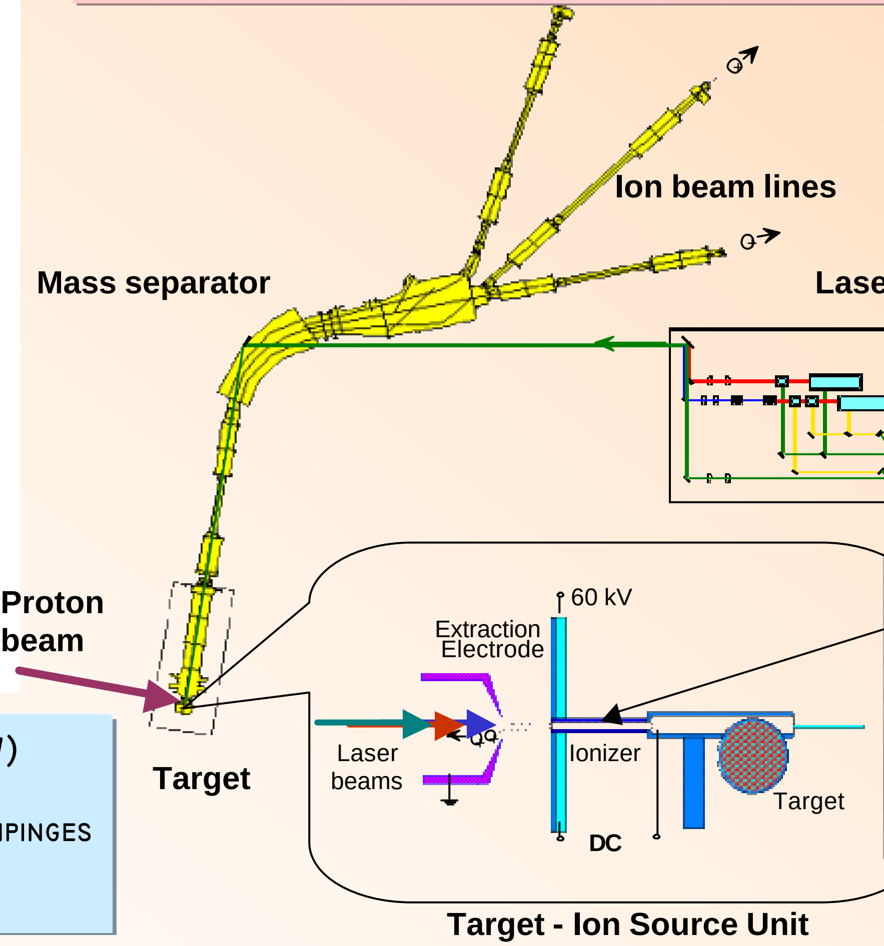
Ionization scheme for Tin



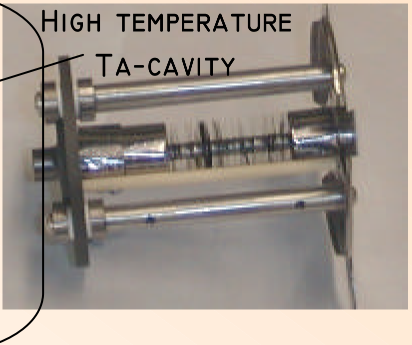
Three fine structure components of the ground state are thermally populated, but only one can be excited at a time. A second UV laser (dotted line) could roughly double the efficiency.

TRANSITION INTO CONTINUUM,
TO AUTO-IONISING STATES,
OR TO RYDBERG STATES

CHEMICALLY SELECTIVE, UNIQUE FINGERPRINT OF EACH ELEMENT
=> MINIMAL ISOBARIC CONTAMINATION



Target - Ion Source Unit



HIGH TEMPERATURE
TA-CAVITY

HEATED CAVITY (NB, TA OR W)

- \+ FAST RELEASE (SHORT STICKING TIMES)
- \+ CONFINES ATOMS UNTIL LASER PULSE IMPINGES
- \+ CONFINES IONS IN POTENTIAL TROUGH
- \- ACT AS THERMAL IONISER

Resonant Laser Ionisation – Results

Selectivity

- * Selectivity a function of cavity material 10-1E5

- * Sometimes

  isotope selective (strong isotope shift for light elements)

  isomer selective using the hyperfine splitting

- * Alkali suppression

  micro-gating

  Reduce cavity temperature

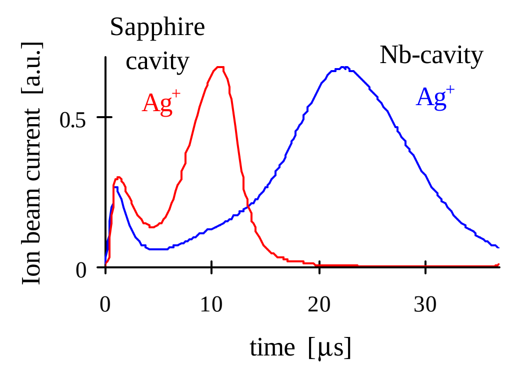
  choose low work-function cavity material

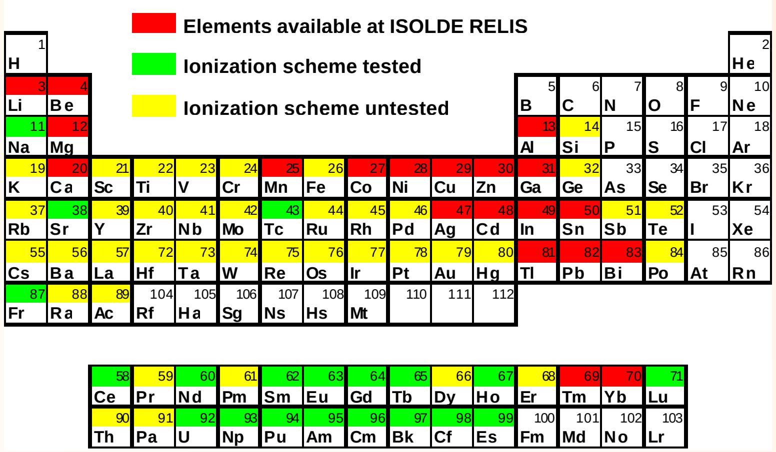
  transfer line with inverted polarity

Data

- * WI 4 to 9 eV

  (may be applied for most metals)
- * 1-30% ionisation efficiency
- * Energy spread <2 eV
- * 100 nA/mm^2 (?)





🟥 Elements available at ISOLDE RELIS

🟩 Ionization scheme tested

🟨 Ionization scheme untested

1 H																	2 He
🟥 3 Li	🟥 4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
🟩 11 Na	🟥 12 Mg											🟥 13 Al	🟨 14 Si	15 P	16 S	17 Cl	18 Ar
🟨 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
🟨 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
🟨 55 Cs	🟨 56 Ba	🟨 57 La	🟨 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
🟩 87 Fr	🟨 88 Ra	🟨 89 Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110	111	112						
		🟩 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		
		🟨 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		

Ionization Schemes Used with Dye Lasers Pumped by Copper Vapor Lasers

Pulsed beam structure

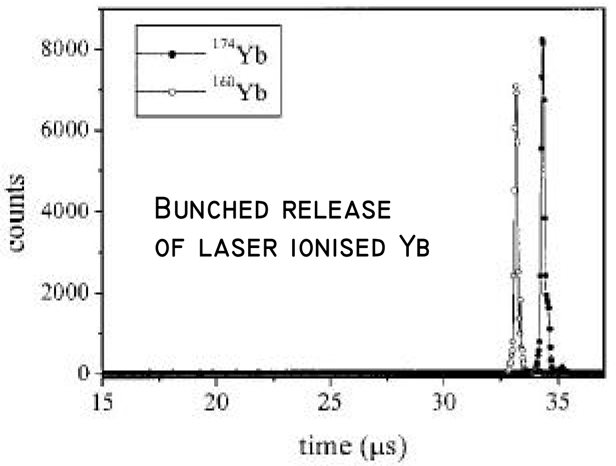
- * Pulse length ~20-40 µs FWHM for A=100
- * Also a direct peak of 0.4 µs
- * Higher field gradient -> shorter pulse

  (use high resistivity ceramic cavities)

Useful for gating out the surface ionised ions

better signal-to-noise ratio at the experiment

FUTURE LASER DEVELOPMENT



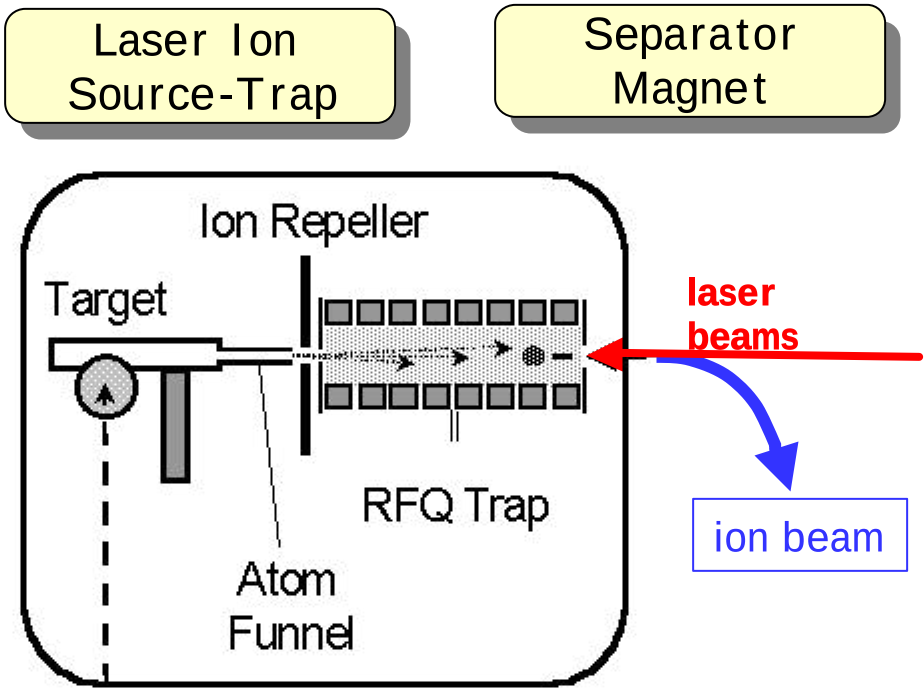
BUNCHED RELEASE

- * HIGH LONGITUDINAL ELECTRICAL FIELD
  - THIN NB FOIL CAVITY (60 µM WALL)
  - COATED INSULATORS
- * CLAIMED ION BUNCH HALFWIDTH=0.5 µS
- * BUNCHING EFFECT => SELECTIVITY ENHANCED BY A FACTOR OF 100

NEW CAVITY MATERIALS

- * LOW WORK FUNCTION
- * LONGTERM STABILITY
- * TAC, ZRC, IR_5CE, THO_2, CEO_2

PRINCIPLE SETUP OF LIST

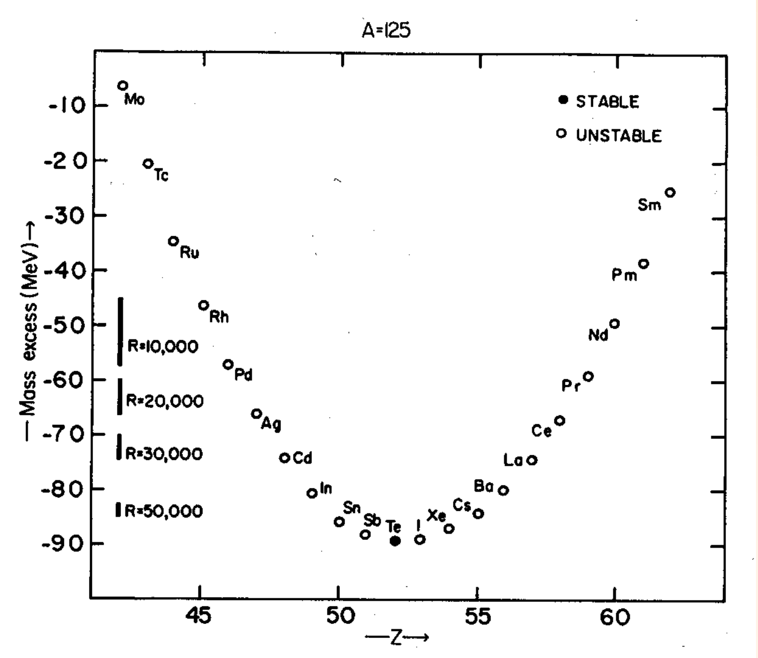


- * SUPPRESSION OF SURFACE-IONISED IONS
- * TRAPPING-ACCUMULATION IN LINEAR RFQ
  - BUNCHED OR DC ION BEAM RELEASE
- * BUFFER GAS COOLING
  - LOW-EMITTANCE ION BEAM
- * NUCLEAR POLARISATION BY OPTICAL PUMPING
- * TIME-FOCUSSING FOR MASS SELECTION

Mass separation

Once isobaric contaminants leave the source ionised,
only removed from the beam with high resolution mass separators

- expensive
- elaborate in use
- get strongly contaminated during long-term operation

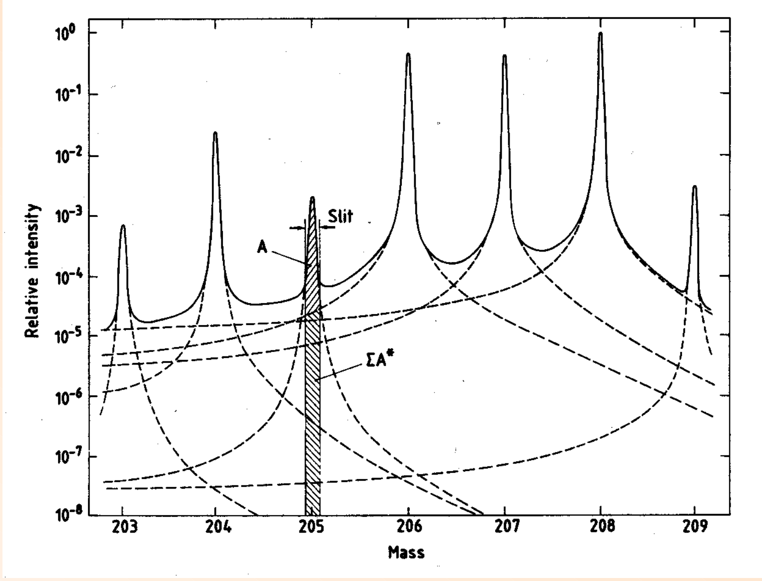


Near b-stability

Q_β<1 MeV, for A=100 => resolving power >1E5

Far from stability

Q_β is 3-10 MeV, resolution of 1000-30000 sufficient



Tails due to:

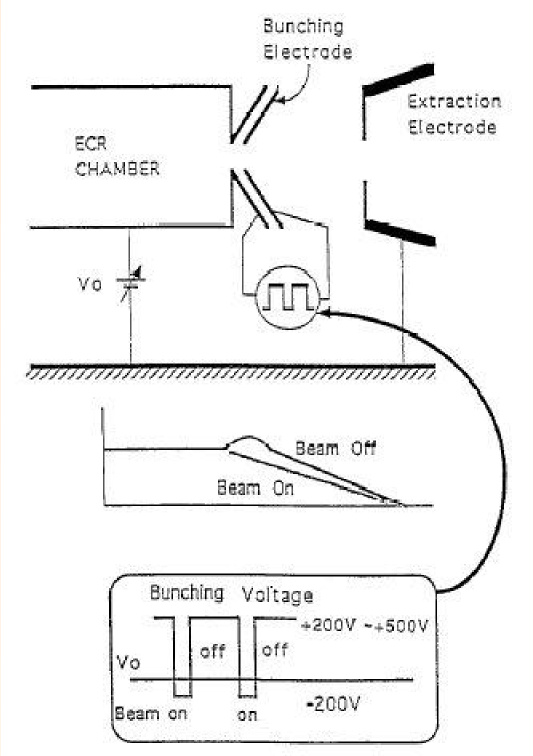
- collision with residual gas
- aberrations
- energy spread

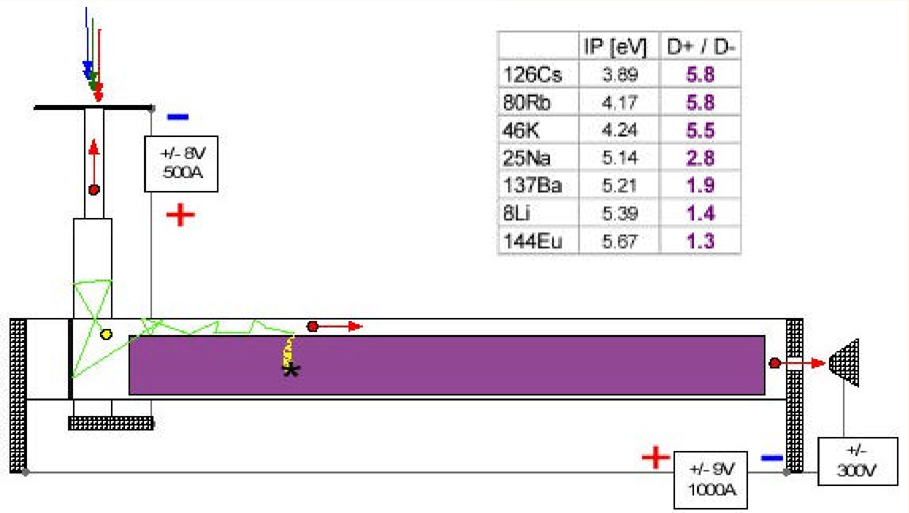
Reduce mass separator slit width

Element selectivity

Suppression of isobaric contaminants

1. Choice of the projectile and energy
   (e.g. neutron induced fission for actinide targets)
2. Choice of target material, geometry and thickness
3. Target-to-ion source transport
   Thermo chromatography
   Alkali suppression via internal drift fields
4. Selection in ion source
   (exemplified throughout the talk)
5. Molecular beams
   create volatile molecules (reduce wall-sticking time)
   create molecular side-bands, for instance SnS





	IP [eV]	D+ / D-
126Cs	3.89	5.8
80Rb	4.17	5.8
46K	4.24	5.5
25Na	5.14	2.8
137Ba	5.21	1.9
8Li	5.39	1.4
144Eu	5.67	1.3

Bunched extraction

improved selectivity and signal-to-noise ratio

* Pulsed driver beam
   ^{14}Be(4.35 ms) S/N ratio improved by 2 orders

* Laser ions sources
   RILIS micro gating at 10 kHz

* FEBIAD
   heatable cold trap

* ECRIS
   afterglow or electrostatic bunching

* EBIS, Traps and RFQ

‘Novel‘ ion sources

Important beam properties

* Beam brightness

emitted current density per solid angle $B=I/(\pi*\varepsilon)^2$

* Energy distribution

effective mass separation or beam focussing

* Transverse emittance

mass separation, transport efficiency and focal spot size

Future high intensity ion sources

? Radiation damage (insulators become electrically leading etc)

? Target out-gassing and vacuum pressure in ion source

? Gas scattering and resonance charge exchange due to high neutral gas flux

? Space charge expansion deteriorating the mass resolution

>100 µA space charge actions

- multi-electrode extraction system
- electron traps to compensate the beam
- magnetic lenses
- emittance meter close to the target-ion source

RIB post acceleration

Energy request

- Few eV for mass measurements
- keV for solid state and atomic physics
- MeV/nucleon to reach and pass Coulomb barrier
- GeV for beta beams

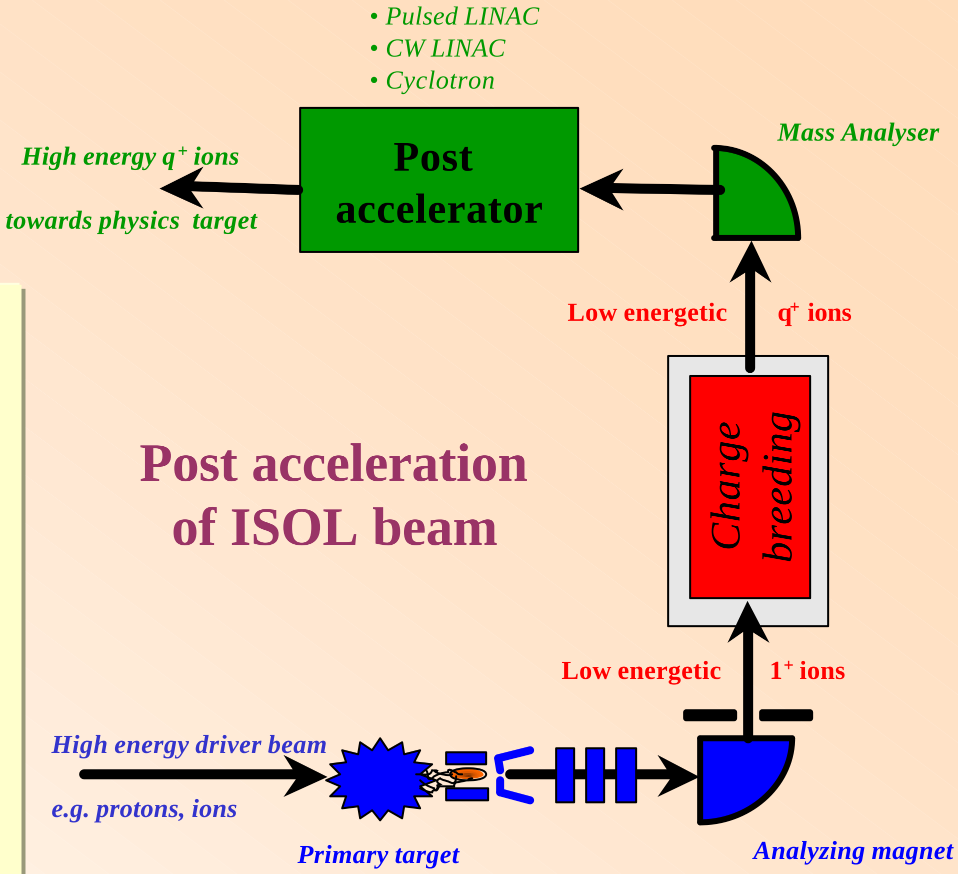
-> need for post acceleration of ISOL beams

And

Energy $\propto$ q in linac

q^2 in cyclotron

Mass-to-charge ratio $(A/Q) < 1/9$



Post acceleration of ISOL beam

The idea

Charge breed ($1+ \rightarrow n+$) low-energy ions

Simplicity(?)

Efficiency(?)

Compactness (shorter/simpler/cheaper LINAC)

Stripping technique

Classic concept – stripping technique

+ Simple method and Fast

- Not efficient at low energy (<150 keV/u)

⇨

Pre-acceleration before stripping necessary

example: ISAC at TRIUMF

Rare Isotope Accelerator (RIA)

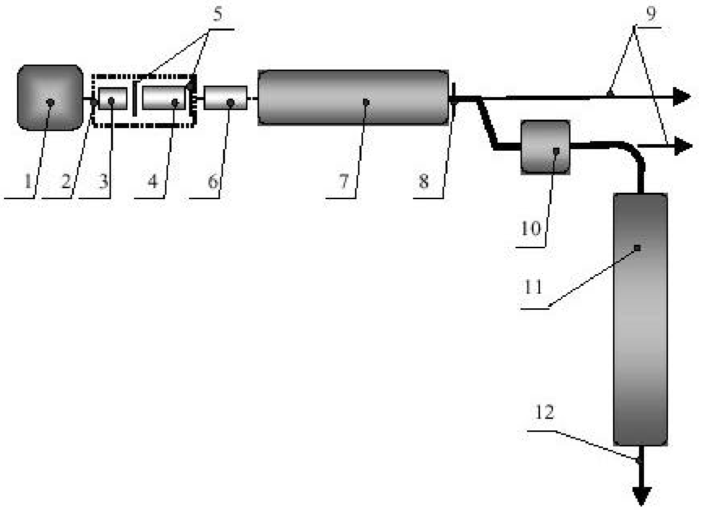
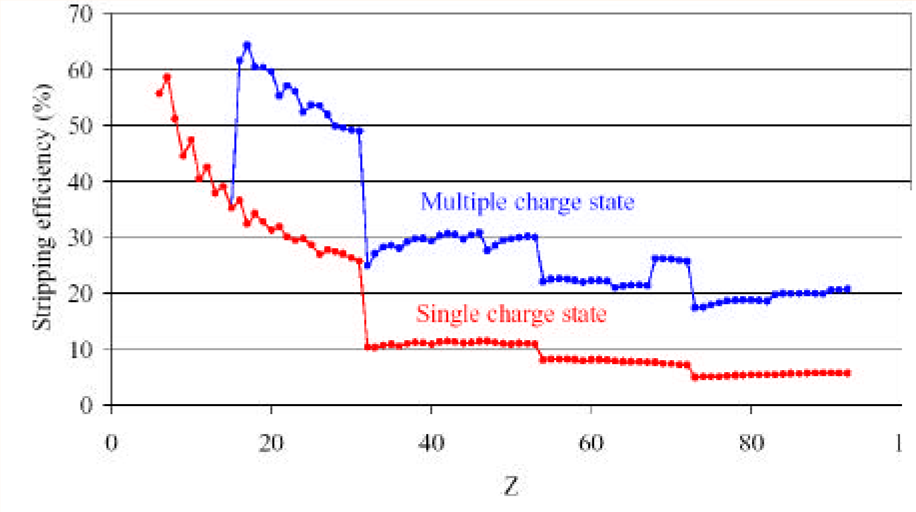
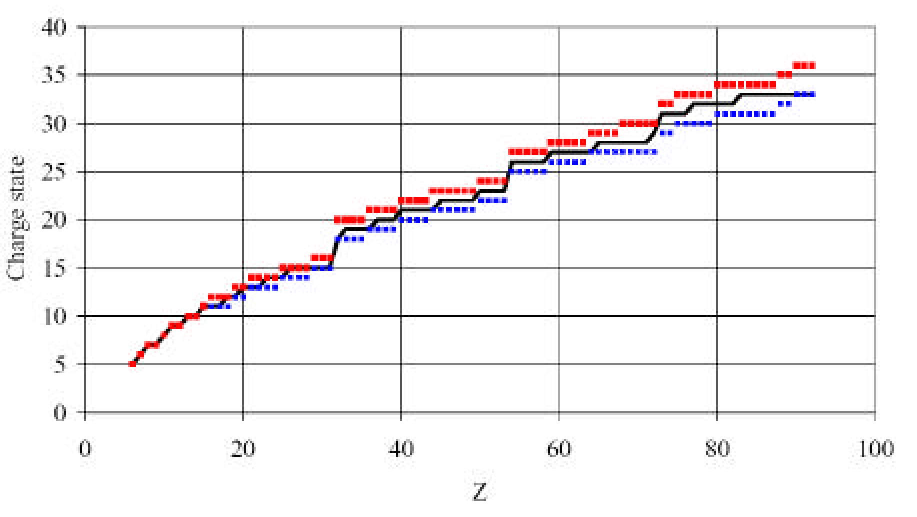
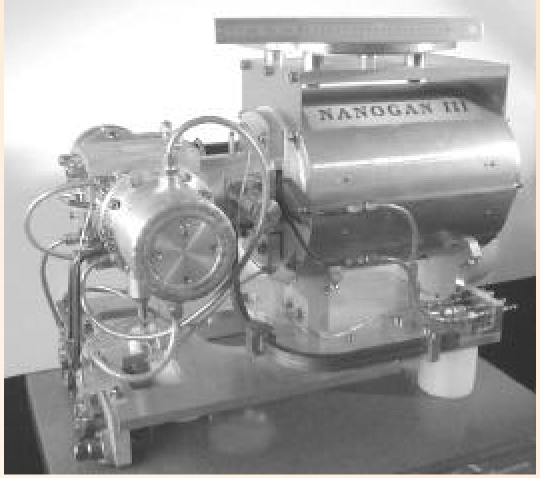


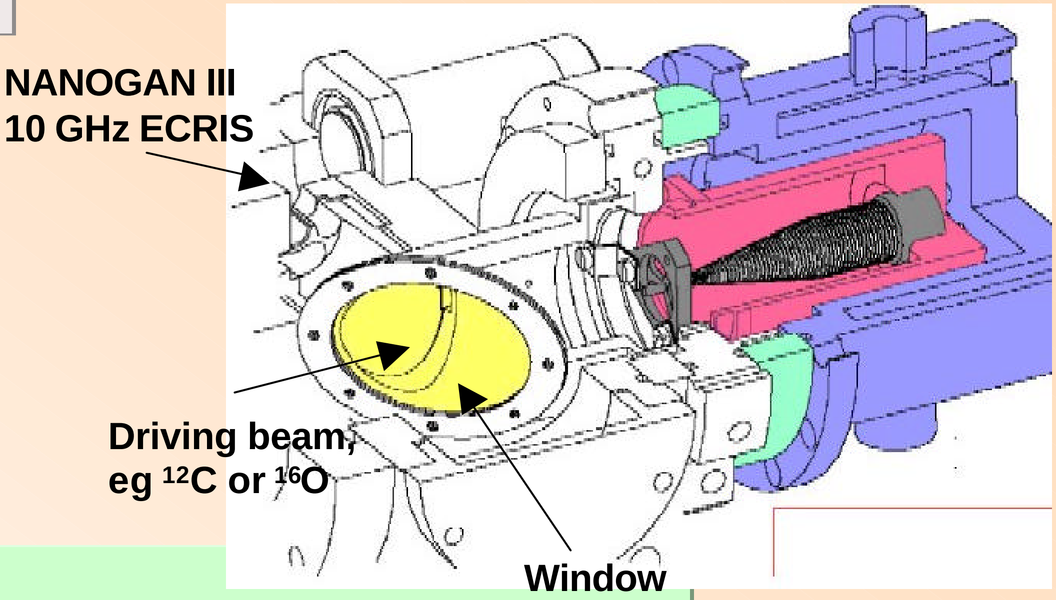
FIGURE 1. Block-diagram of the RIB Linac. 1 – Isobar separator, 2 – High voltage platform, 3 - 12 MHz RFQ, 4 – 12 MHz Hybrid RFQ, 5 – helium strippers, 6 - 24 MHz Hybrid RFQ, 7 – SC Linac between the strippers, 8 – carbon stripper, 9 – beams to astrophysics experiments, 10 – SC booster linac, 11 – ATLAS, 12 – high energy beams.





Multiply charged ions





Straight forward

N+ directly from ion source in the production cave

For instance NANOGAN III at SPIRAL, GANIL

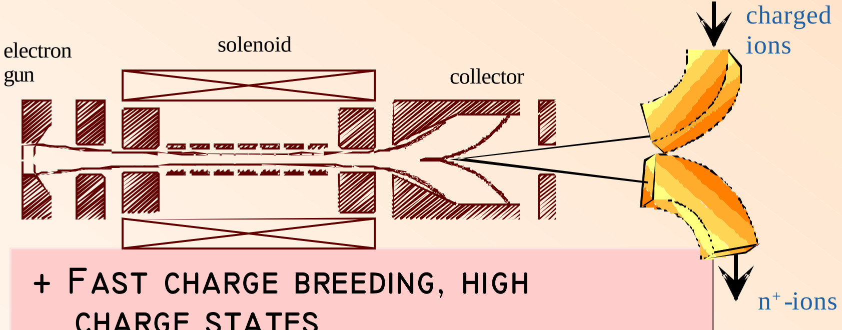
- * noble gases and volatile gases with short sticking time
  (N, O, F, He, Ne, Ar, Kr)
- * efficiency some percent (target diffusion * effusion * ionisation)
  14% for ^{18}Ne^{4+} ($T_{1/2}$=1.67 s)
  ~5% for ^{14}O^{+} and ^{13}N^{+}

Problems

Condensable elements -> SHyPHIE from GANIL
Activity deposited in the ECRIS

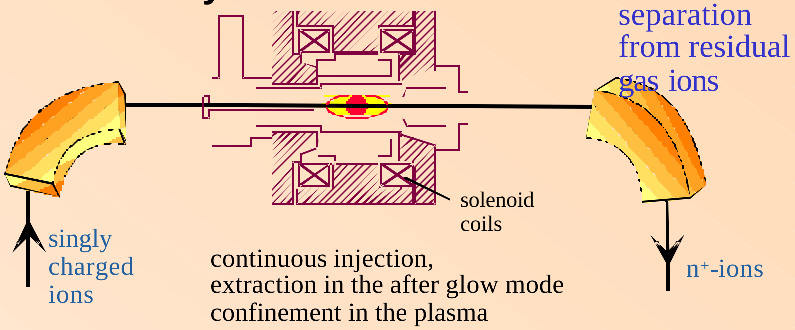
CHARGE BREEDING

Electron Beam Ion Source



- \+ FAST CHARGE BREEDING, HIGH CHARGE STATES
- \+ HANDLE VERY WEAK BEAMS <1 NA
- \- LIMITED CAPACITY
- \- COMPLEX, TRAP OR RFQ COOLER NEEDED
- +/- UHV

Electron Cyclotron Resonance Ion Source



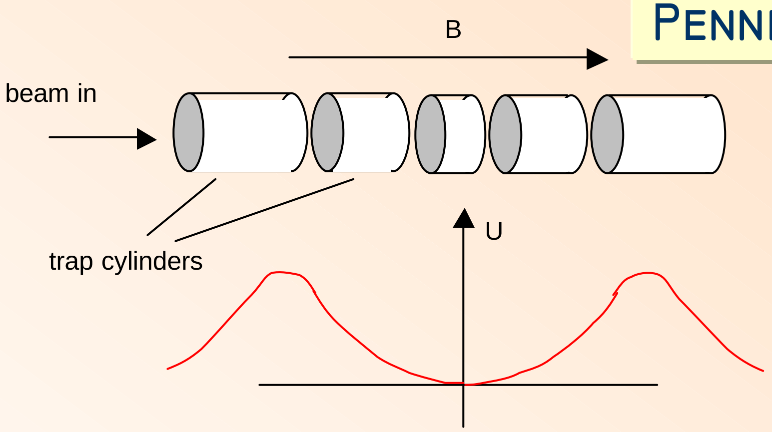
continuous injection,
extraction in the after glow mode
confinement in the plasma

- \+ LARGE CHARGE CAPACITY AND HIGH CURRENTS >10 NA
- \+ DC OR BUNCHED INJECTION
- \- HIGH BACKGROUND CURRENT
- \- LOWER CHARGE STATES

	TRAP/EBIS	ECRIS
* EFFICIENCY: (IN ONE CHARGE STATE)	5-10% (INCLUDING TRAP)	5-10% CW EXTRACTION 2-5% AFTERGLOW
* ENERGY SPREAD:	<50 EV*Q	FEW EV
* MAXIMUM THROUGHPUT:	1E9 IONS/S	1E12 IONS/S
* LOWER CURRENT LIMIT:	FA	10 NA
* BREEDING TIME:	A/Q < 4 IN 20 MS FOR A = 50 IN 160 MS FOR A = 150	A/Q < 6 IN 50 MS FOR A = 50
* STORAGE CAPACITY:	1E11 CHARGES/PULSE (PENNING TRAP LIMIT 1E7 CHARGES/PULSE)	>2E12 CHARGES/PULSE
* STORAGE TIME:	FEW SECONDS	< 100 MS?
* INJECTION:	PULSED - A FEW 10 µS	CW OR PULSED
* EXTRACTION:	PULSED - 10-50 µS	CW OR AFTERGLOW <MS

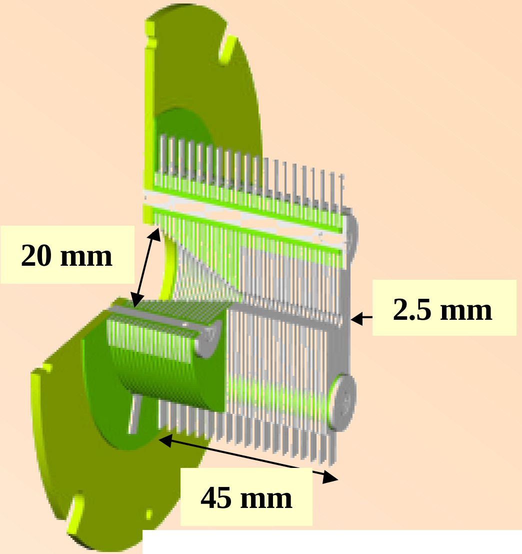
Beam cooling systems

Penning trap



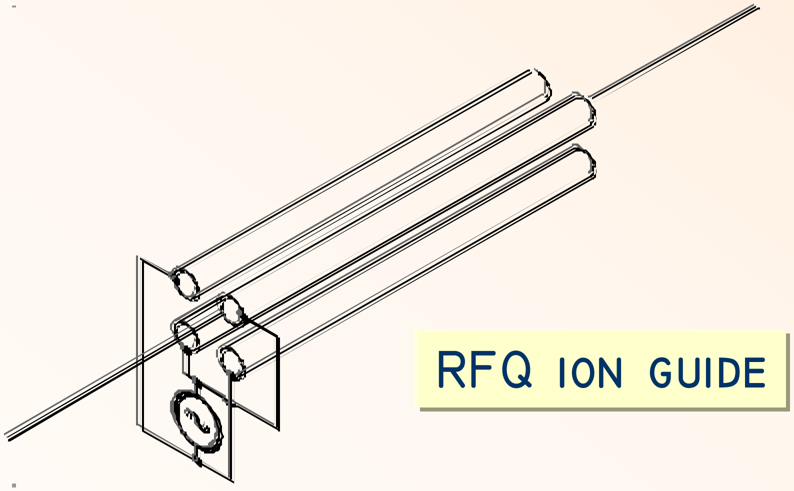
Reduce the transverse emittance, energy spread
provide mass selection and a bunched beam if necessary

RF-funnel



Worked on at LMU Munich
High current capability

RFQ ion guide



Places for traps and coolers

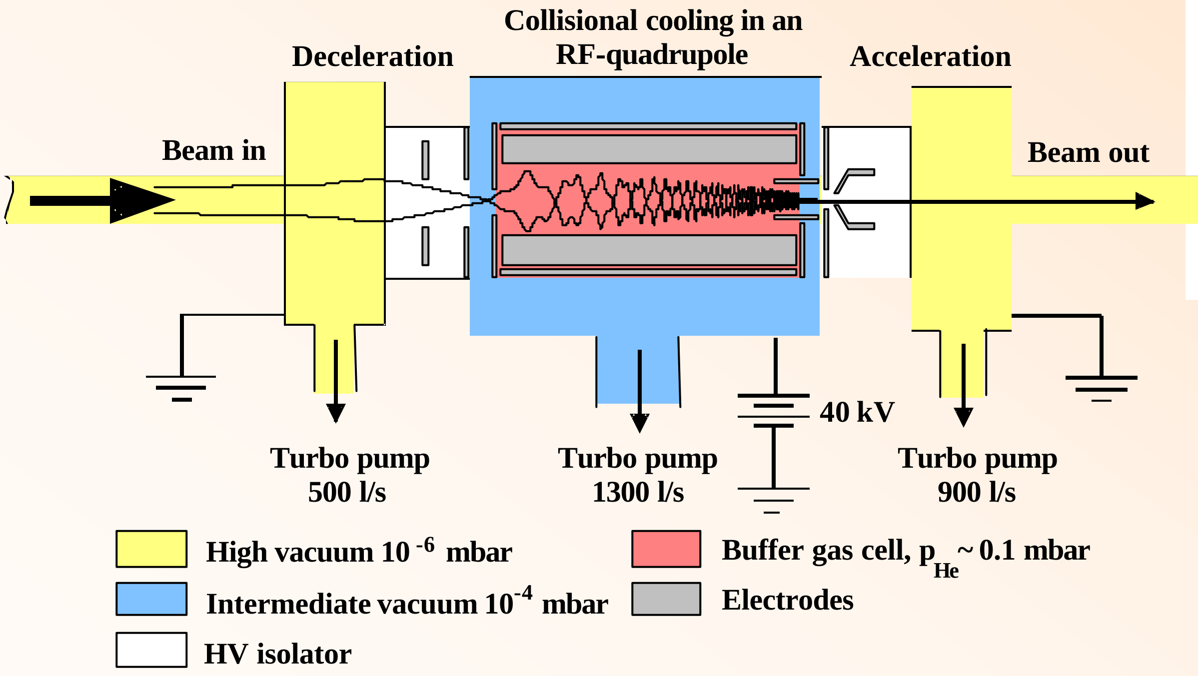
ISOLTRAP at ISOLDE	NSCL/MSU
JYFL	LPC/Caen
MISTRAL at ISOLDE	MAFF in Munich
SHIPTRAP at GSI	RIA at Argonne
CPT/Argonne	

and elsewhere...

RFQ COOLERS

BENEFITS

- * HIGHER BEAM TRANSPORT EFFICIENCY
- * HIGHER RESOLUTION IN MASS SEPARATOR
- * IMPROVED SENSITIVITY OF ANY PRECISION SPECTROSCOPY (E.G. LASER SPECTROSCOPY)
- * EFFECTIVE INJECTION IN TO CHARGE BREEDERS AND TRAPS
- * BEAM BUNCHING -> INCREASED NOISE-TO-SIGNAL RATIO



Collisional cooling in an RF-quadrupole

Deceleration

Acceleration

Beam in

Beam out

40 kV

Turbo pump 500 l/s

Turbo pump 1300 l/s

Turbo pump 900 l/s

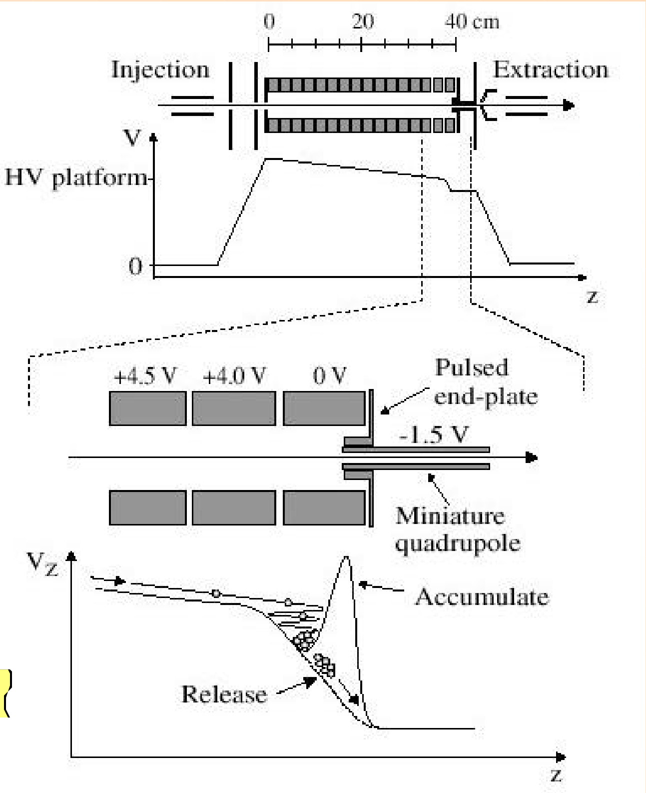
🟨 High vacuum 10^{-6} mbar

🟦 Intermediate vacuum 10^{-4} mbar

☐ HV isolator

🟥 Buffer gas cell, p_{He} ~ 0.1 mbar

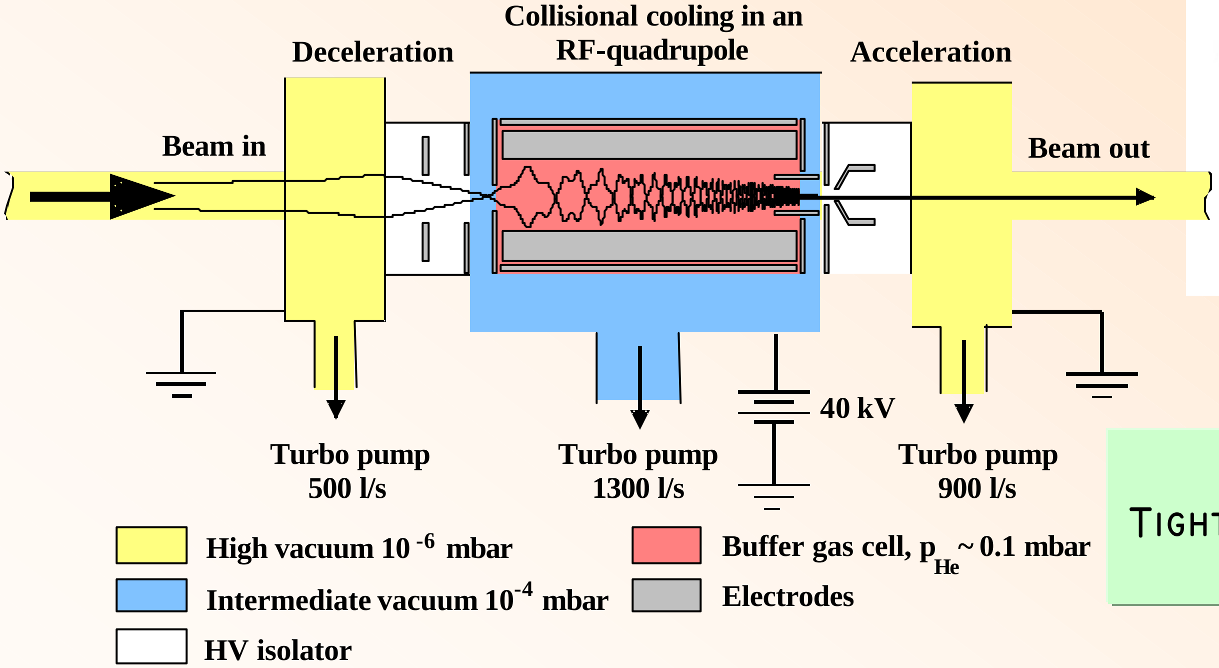
⬜ Electrodes

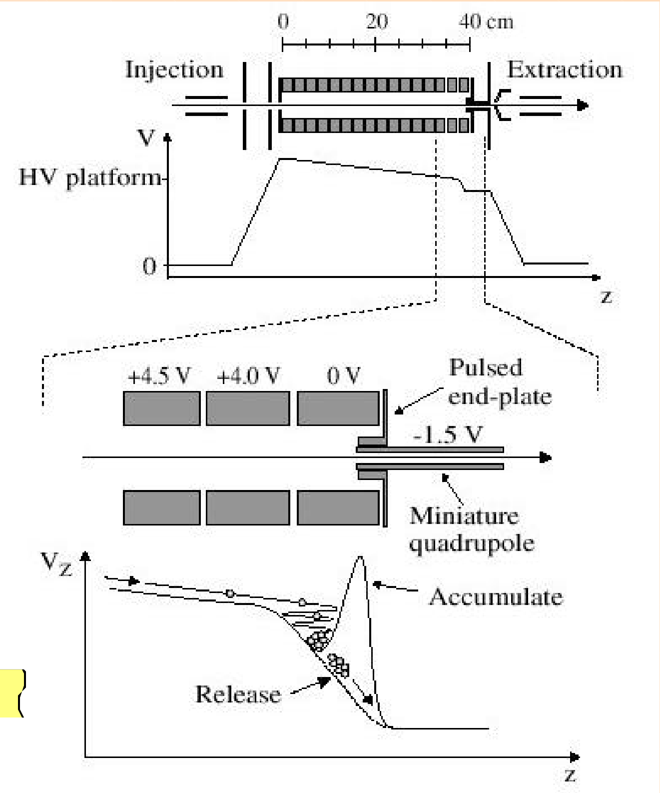


RFQ coolers

Data

- * Energy spread < 1 eV (from ~100 eV)
- * Transverse emittance - a few π mm mrad (40 keV)
- * Longitudinal emittance < 10 μs*eV
- * Capacity bunched mode - 1E3-1E5 ions
  DC - 10 nA
- * Transmission efficiency - ~50% (DC and bunched mode)
- * Delay time (with axial field) ~1 ms
- * Bunching Accumulation time 10 ms to 1 s
  Bunch width 5-20 μs (FWHM)

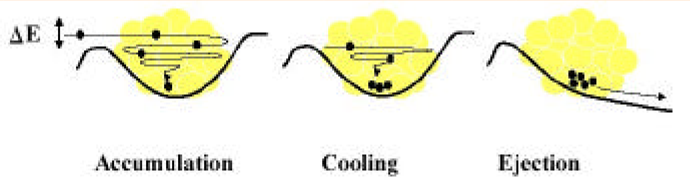




Limitations

Tighter space-charge restrictions than for a Penning trap

Penning traps



Data

- Continuous injection
- Cooling times 10-20 ms
- Pulsed extraction 10 µs
  (No DC ejection mode)
- Efficiency ≤ 40%
  (extracted cooled ions / injected ions)
- Storage capacity 1E7 ions per pulse
  - Space-charge effects over 1E6 ions/pulse
  - decrease in efficiency
  - upward shift in cyclotron frequency
- Mass resolution 300-500
  (1E5 in UHV traps)

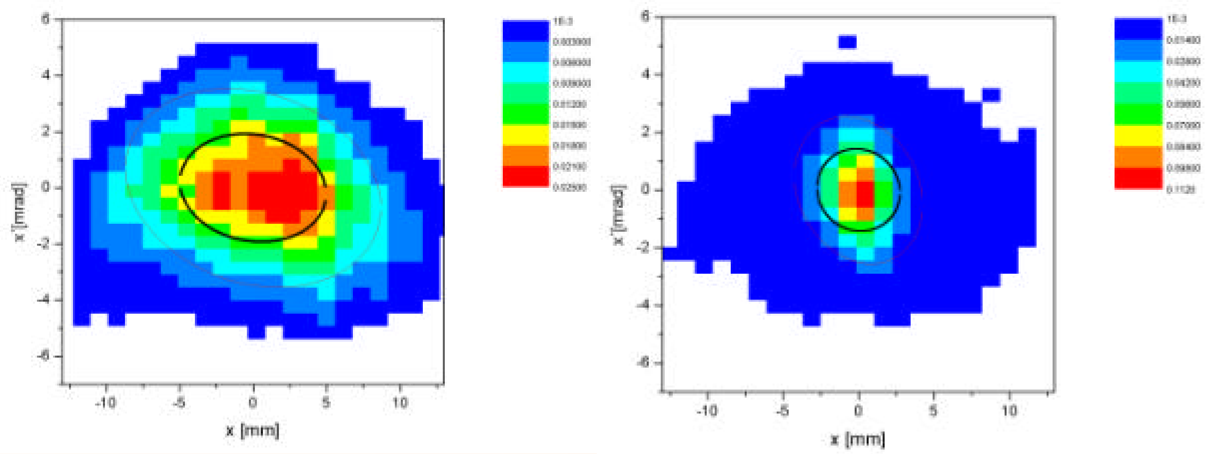
The large REXTRAP at ISOLDE

REXTRAP results

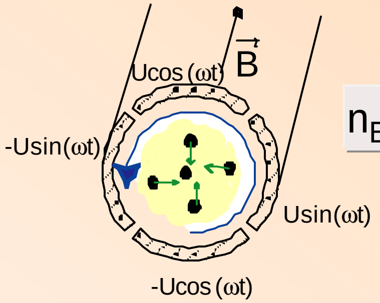
~3.5E4 stored K+, 30 keV ion energy, storage time 20 ms

Left: no cooling applied: 80% emittance 30 π mm mrad,

Right: side-band cooling: 80% emittance 10.6 π mm mrad



Penning traps - future



$n_B = (B^2\, \varepsilon_0) / (2\, m)$

Brillouin limit

The large REXTRAP at ISOLDE

Limitations

* Space charge limitation and cooling time

Future

* New cooling scheme:

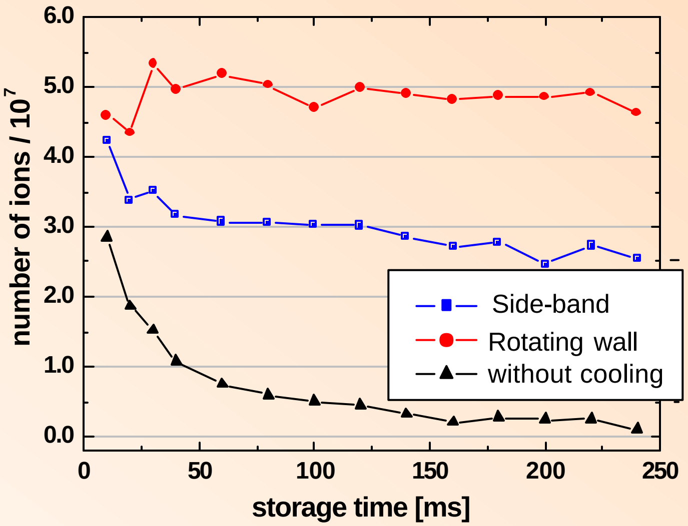
- rotating wall compression (Brillouin compression)
- Spin up the ion cloud
- dipole or quadrupole excitation

* Only dipole rotation tested so far

- 5E7 ions/bunch
- storage time now >100 ms

* Wild speculations

- theoretical limit, Brillouin limit, N_{MAX}=6E6 He$^+$ mm^{-3}
- 1E10(?) ions cooled per second or 1E9(?) ions per bunch



Comparison cooling schemes
side-band and rotating wall

CONCLUSIONS

* 80 OUT OF 92 ELEMENTS CAN BE PRODUCED AND IONISED SUFFICIENTLY(?) FOR PHYSICS EXPERIMENTS

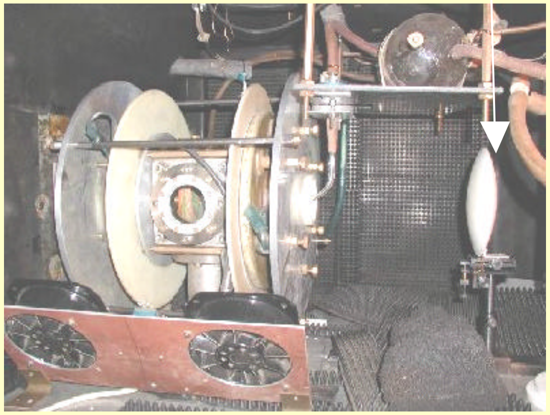
* STANDARD RIB ION SOURCES (FEBIAD, SURFACE) REACHED MATURITY
  IMPROVEMENT WITH MOLECULAR BEAMS FOR REACTIVE ELEMENTS

* RESONANT LASER ION SOURCE STILL POTENTIAL FOR DEVELOPMENT
  NEW IONISATION SCHEMES, HIGHER POWER

* UP-SAILING REQUESTS
  NOT ONLY EFFICIENCY - ALSO INTENSITY
  HIGH BRIGHTNESS BEAMS
  BEAM BUNCHING

* REVIVAL OF OLD HIGH CURRENT SOURCES?

* FREQUENT USE OF ECRIS



37 GHz ECIRs, optical RF coupling
More by Pascal Sortais

* BEAM TOOLS (BUILDING BLOCKS AS CHARGE BREEDERS, RFQ COOLERS ETC)