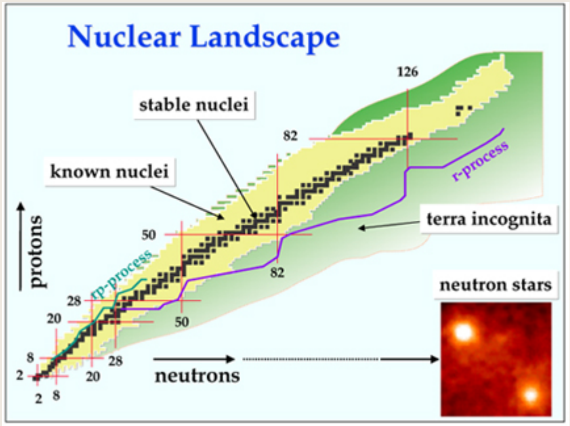
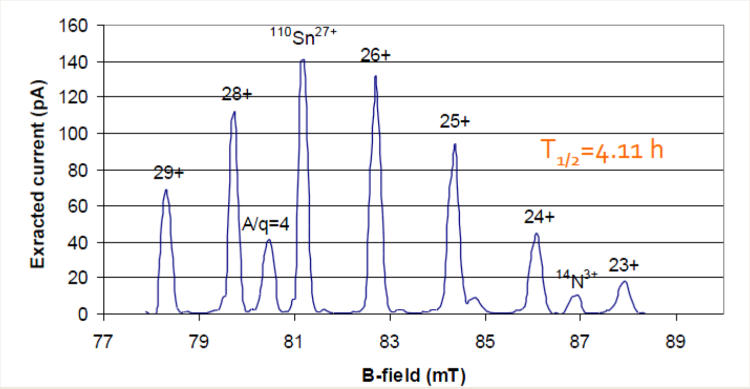


http://radchem.nevada.edu/

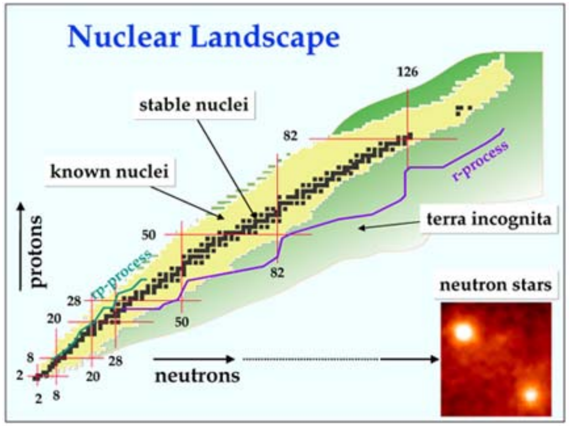


RADIOACTIVE ION SOURCES

An Introduction

Ion Source for Radioactive Ion Beams (RIB) facilities

- Motivation: study exotic nuclei far from stability
- Two exotic RIB production method:
  - Isotope Separation On-Line (ISOL)
  - Projectile separation



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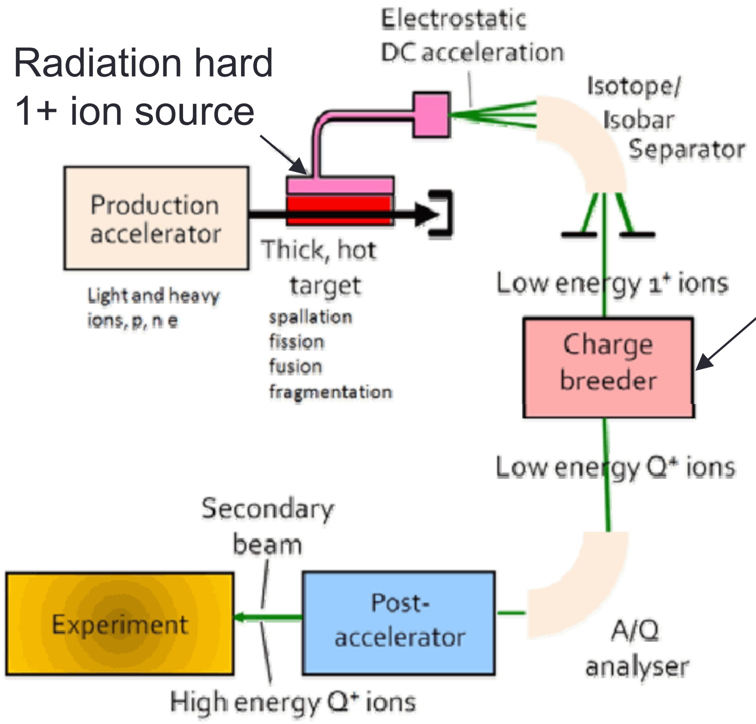
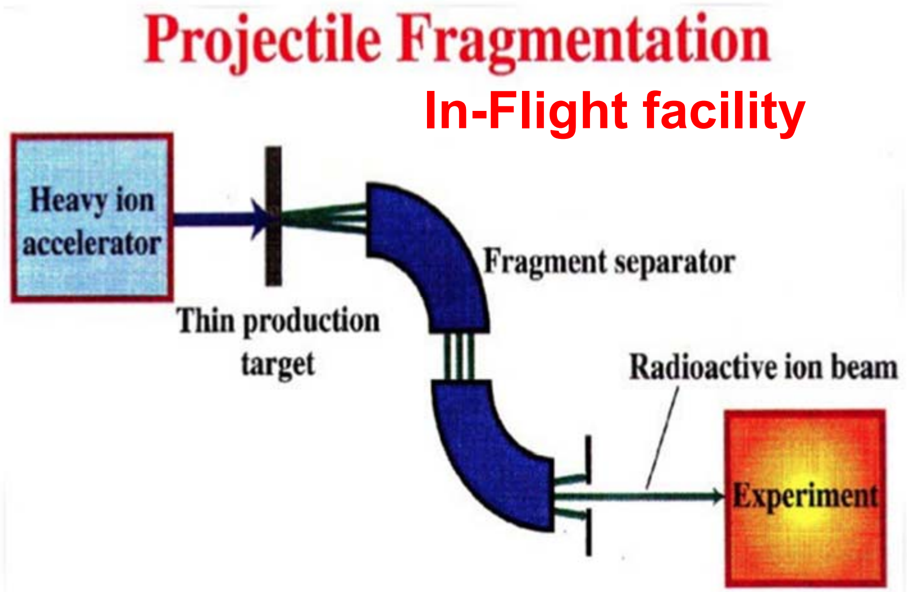


Radiation hard 1+ ion source

1+→N+ ion source

EURISOL, HIE-ISOLDE, SPIRAL2, SPES,…



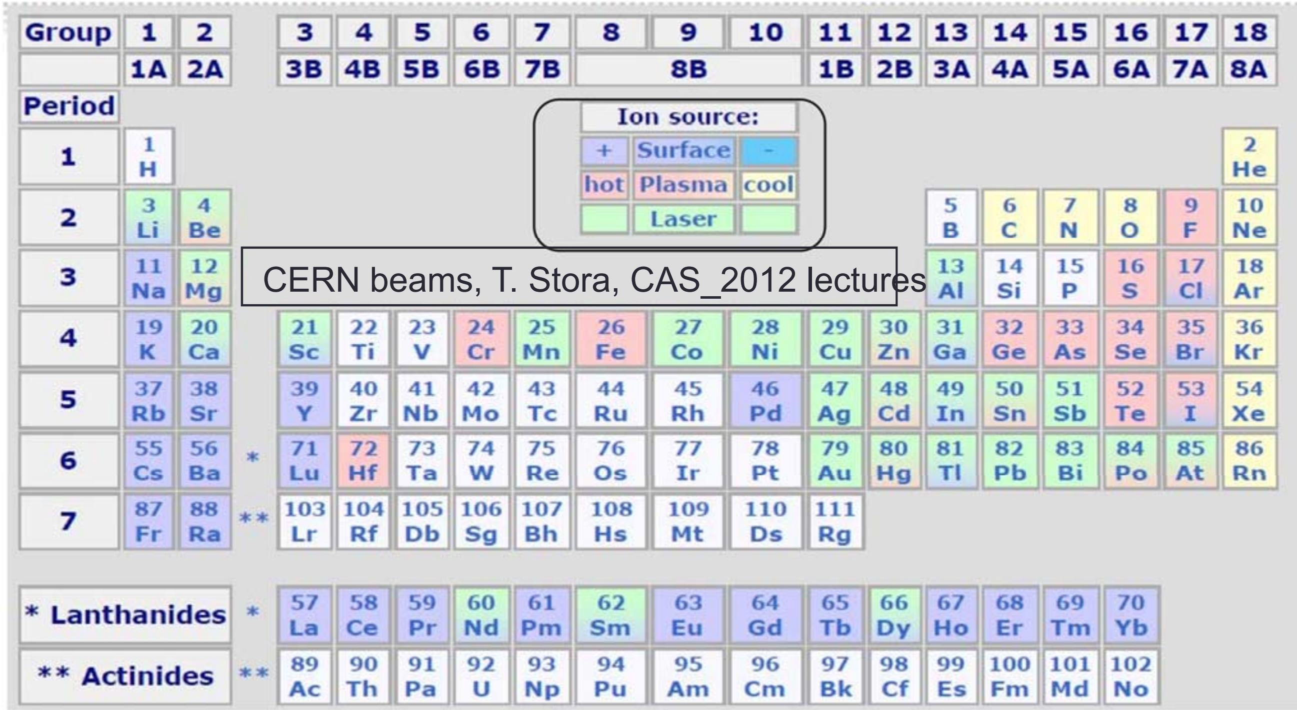
RIKEN RIBF, FAIR

(Slide H. Koivisto, JUAS2013)

1+ Radioactive source for ISOL

- Physics Requirement: Exotic nuclides may have a short half-life. The radioactive atoms have to be ionized and transferred to the beam line as fast as possible.

- Source Technical requirement:
  - Radiation hard (even 1 MGy)
  - Compact
  - Simple and reliable in use (no maintenance access due to the strong radiation level)



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		

CERN beams, T. Stora, CAS_2012 lectures

As an example: after the CERN production target, the following 1+ ion sources are mainly used:

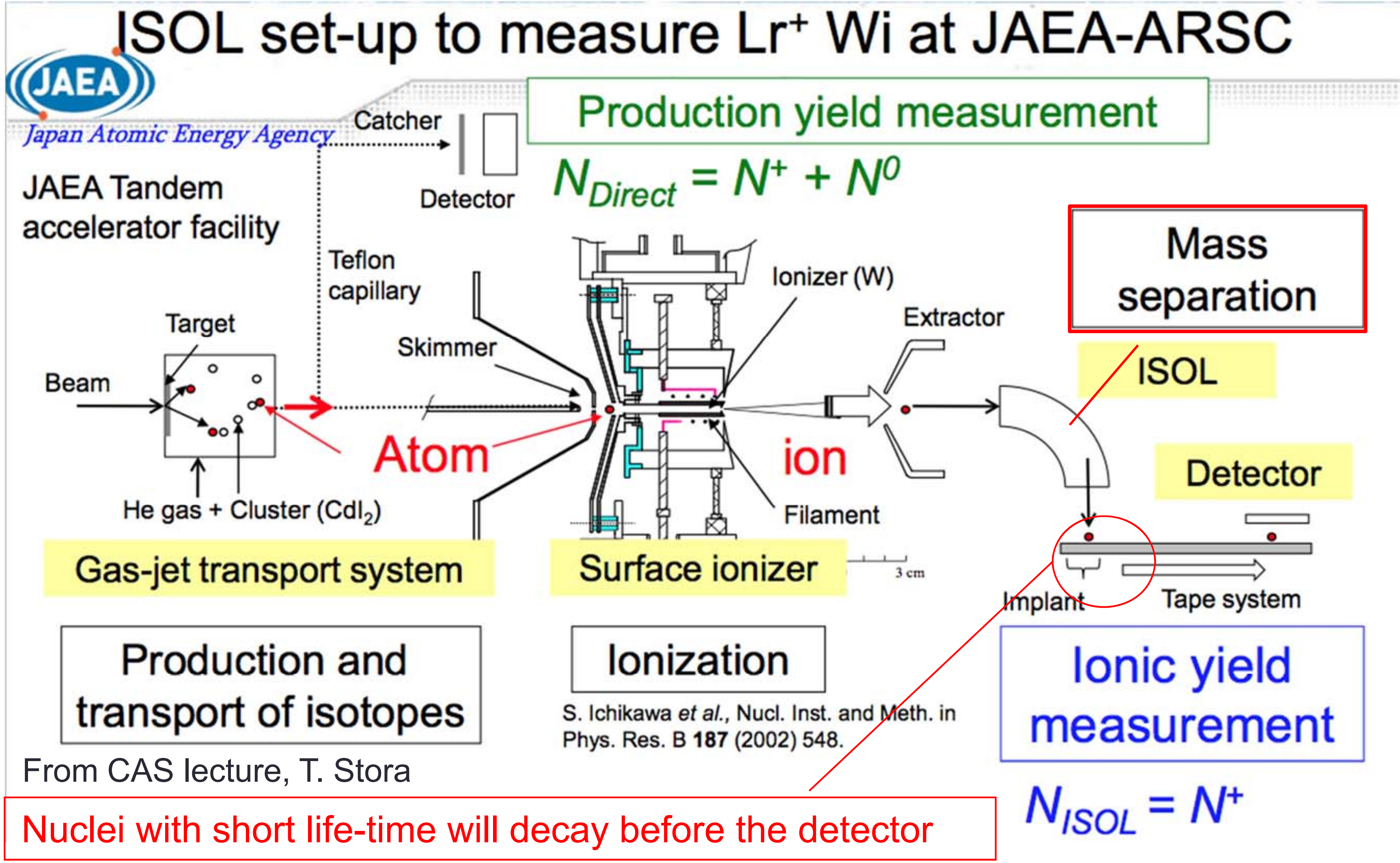
1. Surface Ion Source (SIS) (see ion source section)
2. Resonant Ionization Laser Ion Source (RILIS)
3. Forced Electron Beam Induced Arc Discharge (FEBIAD)

(Slide H. Koivisto, JUAS2013)

Surface Ion Source with ISOL-target

- Production target can produce large variety of different nuclei having the same mass
- Produced 1+ ions having same mass cannot be separated by a dipole magnet
- Some “selectivity” can be made by a tape system

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



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

$N_{ISOL} = N^+$

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

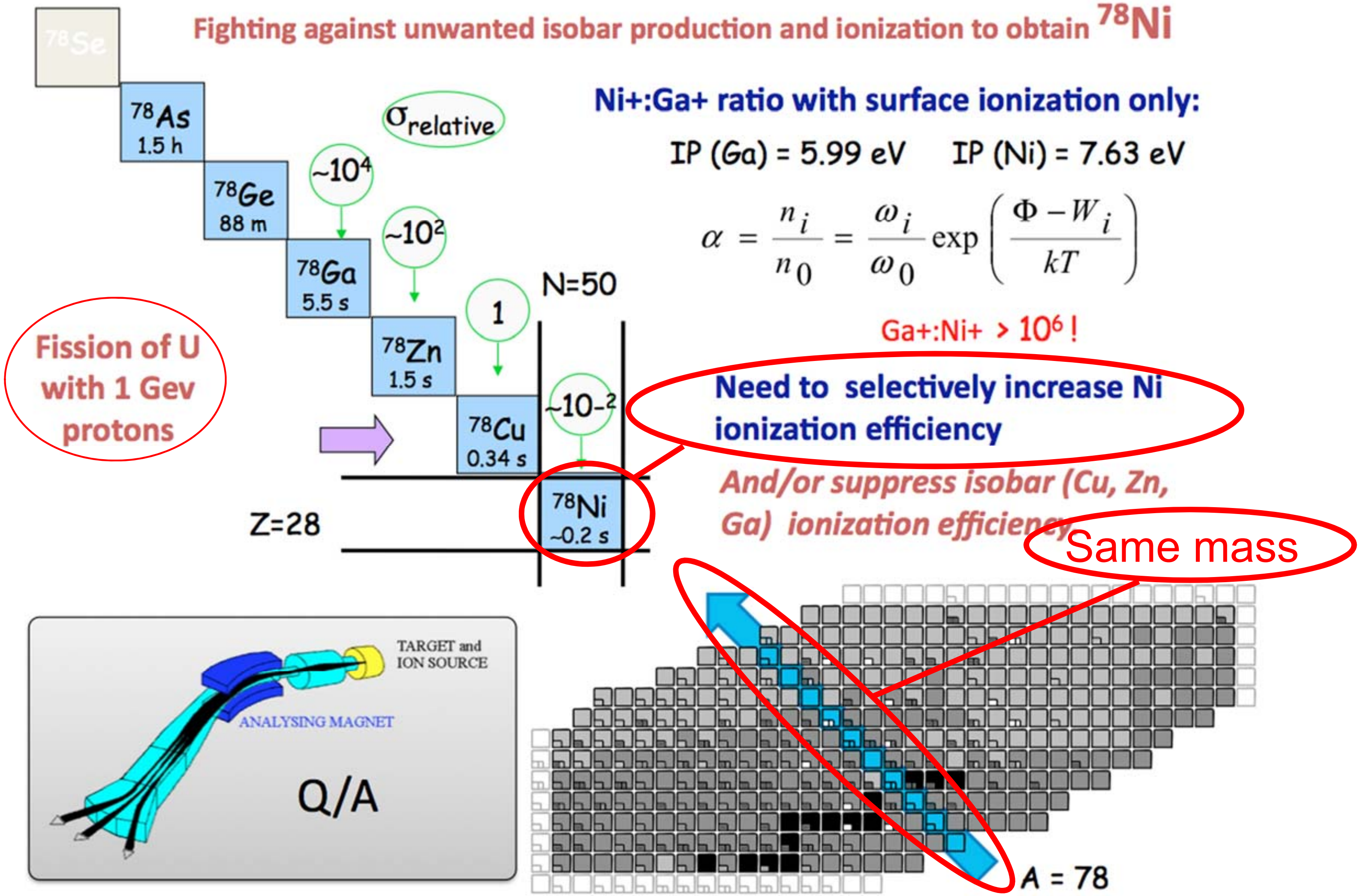
From CAS lecture, T. Stora

Nuclei with short life-time will decay before the detector

How to separate Iso-mass radioactive atoms?

- Sometimes only a very small amount of the element of interest is produced. This is a great problem if other elements having the same mass and higher abundance have been produced! For example:

Slide from CAS-Lecture: B. Marsh



Fighting against unwanted isobar production and ionization to obtain ^{78}Ni

Ni+:Ga+ ratio with surface ionization only:

IP (Ga) = 5.99 eV   IP (Ni) = 7.63 eV

$$\alpha = \frac{n_i}{n_0} = \frac{\omega_i}{\omega_0} \exp\left(\frac{\Phi - W_i}{kT}\right)$$

Ga+:Ni+ > 10^6 !

Need to selectively increase Ni ionization efficiency

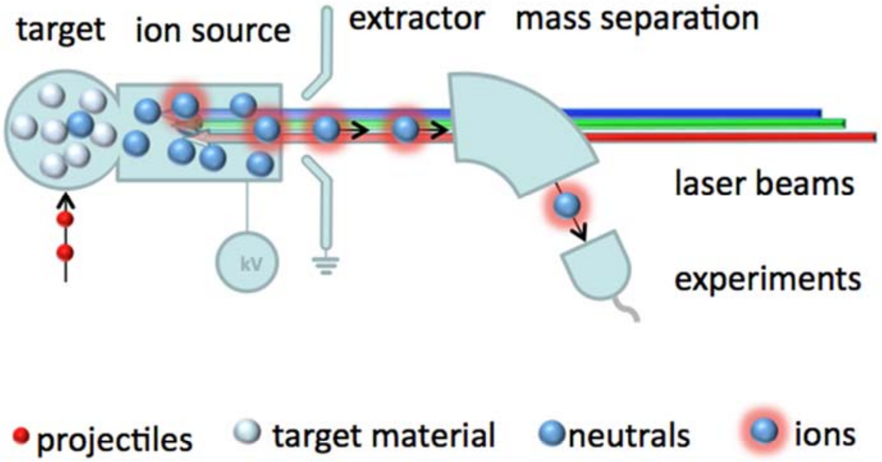
And/or suppress isobar (Cu, Zn, Ga) ionization efficiency

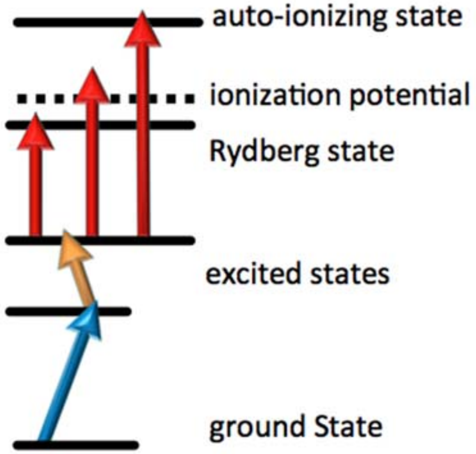
Same mass

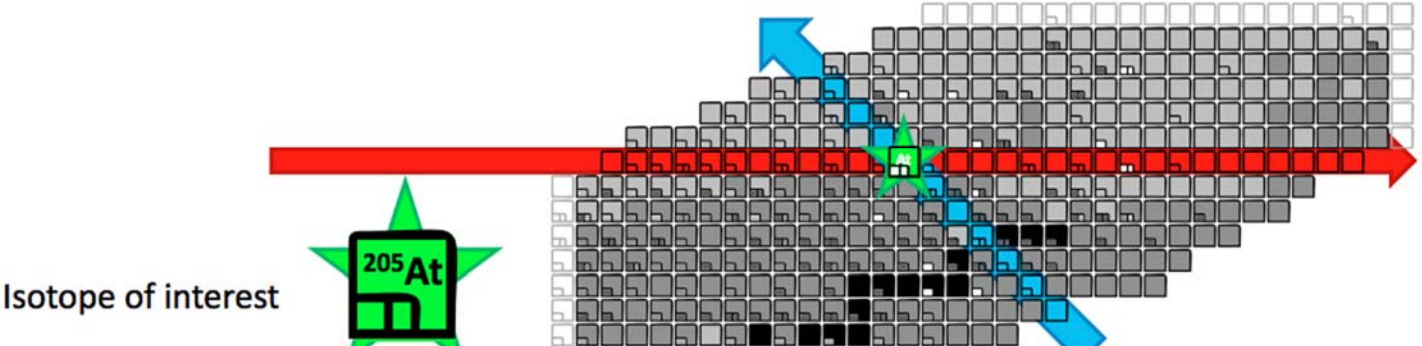
Fission of U with 1 Gev protons

Resonance Ionization Laser Ion Source (RILIS)

- The co-produced iso-mass radioactive atoms have specific electronic level states
- Lasers can help selecting the atom of interest using any specific resonant excitation state having a much higher cross section than others
- When using several appropriate lasers, **only the element of interest is ionized**!



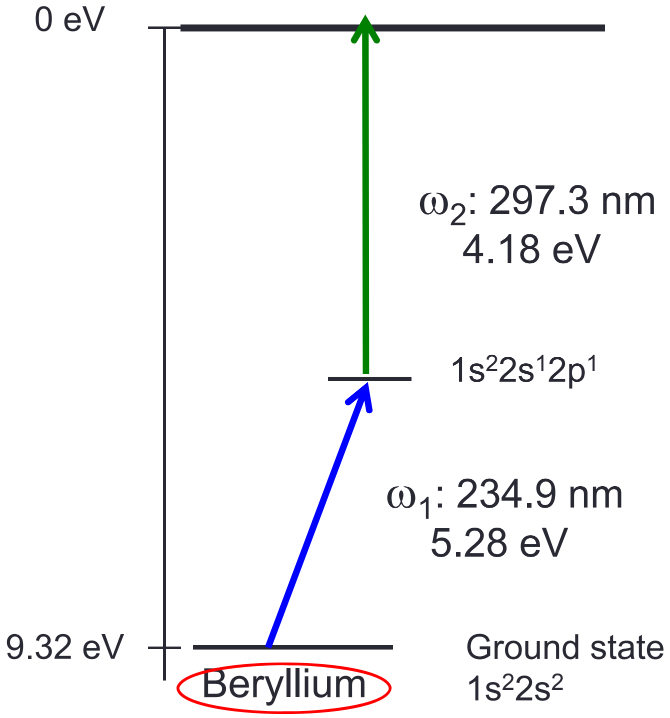


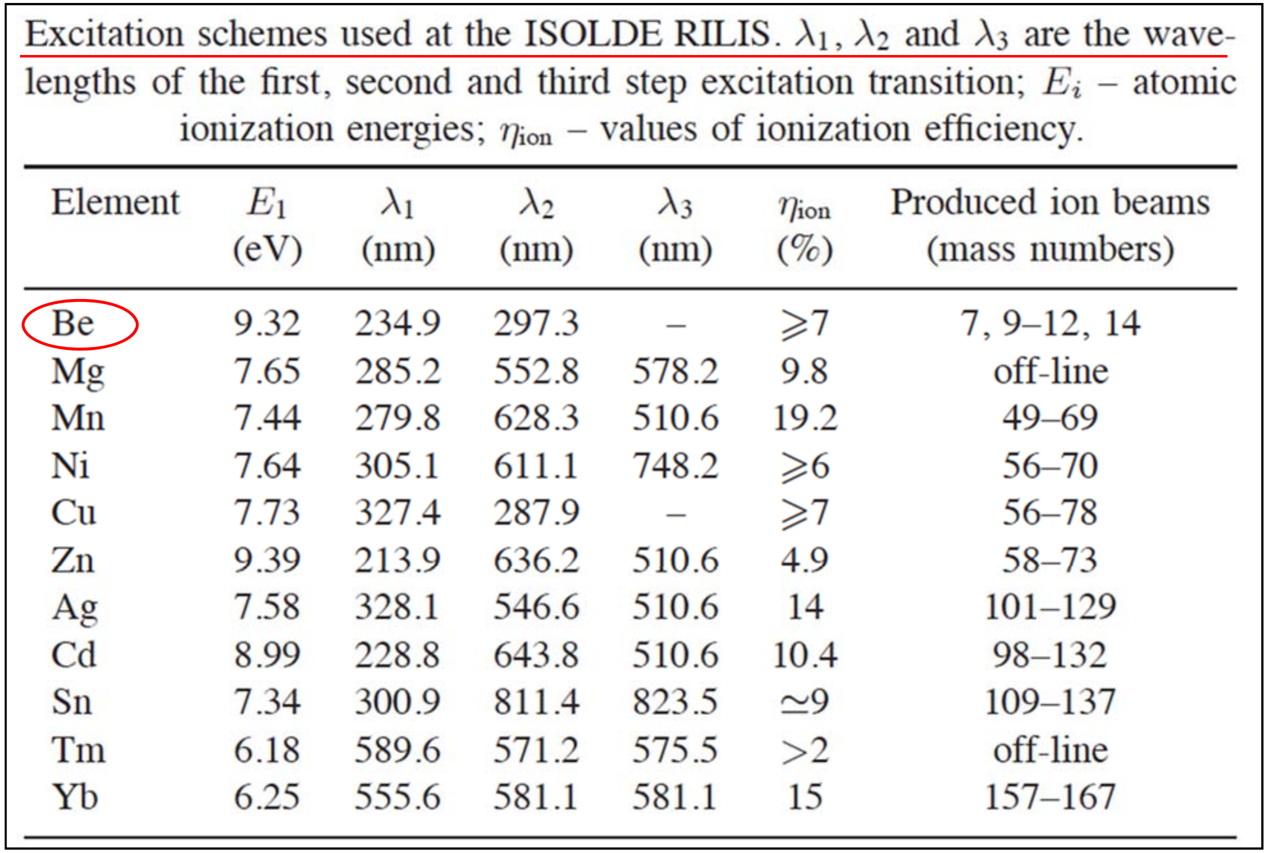


Slide from CAS-Lecture: B. Marsh

Resonance Ionization example

- Order of magnitudes photo-ionization cross sections:
  - non-resonant (direct ionization): $\sigma = 10^{-19} - 10^{-17}$ cm^2
  - resonant: $\sigma = 10^{-10}$ cm^2
  - auto-ionizing states (AIS): $\sigma = 10^{-14}$ cm^2
- Several laser wavelength are often required



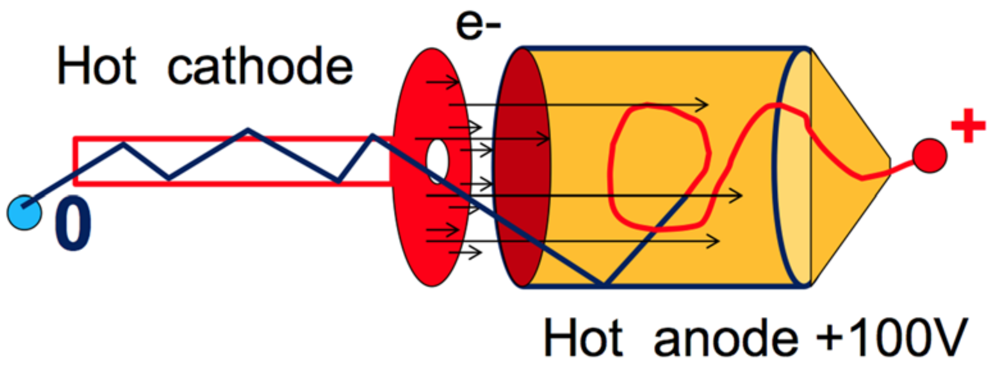


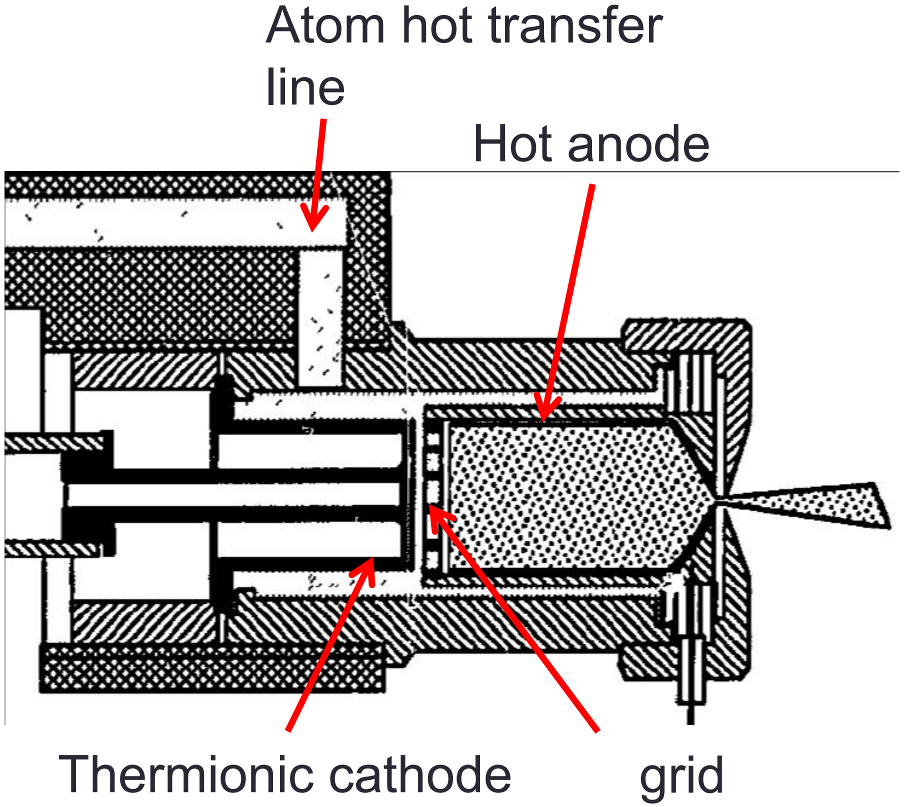
Excitation schemes used at the ISOLDE RILIS. λ_1, λ_2 and λ_3 are the wavelengths of the first, second and third step excitation transition; E_i – atomic ionization energies; η_{ion} – values of ionization efficiency.

Element	E_1 (eV)	λ_1 (nm)	λ_2 (nm)	λ_3 (nm)	η_{ion} (%)	Produced ion beams (mass numbers)
Be	9.32	234.9	297.3	–	$\geqslant 7$	7, 9–12, 14
Mg	7.65	285.2	552.8	578.2	9.8	off-line
Mn	7.44	279.8	628.3	510.6	19.2	49–69
Ni	7.64	305.1	611.1	748.2	$\geqslant 6$	56–70
Cu	7.73	327.4	287.9	–	$\geqslant 7$	56–78
Zn	9.39	213.9	636.2	510.6	4.9	58–73
Ag	7.58	328.1	546.6	510.6	14	101–129
Cd	8.99	228.8	643.8	510.6	10.4	98–132
Sn	7.34	300.9	811.4	823.5	$\simeq 9$	109–137
Tm	6.18	589.6	571.2	575.5	>2	off-line
Yb	6.25	555.6	581.1	581.1	15	157–167

Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source

- FEBIAD are used for example at CERN and TRIUMF to produce radioactive 1+ beams at ~µA intensity level.
  - the electrons are produced by a hot cathode
  - electrons are accelerated through a grid
  - Electron impact ionization of vapors emitted by the hot anode





Charge breeding ($1+\to Q+$)

- The charge breeding technique consists to increase the ion beam charge state online

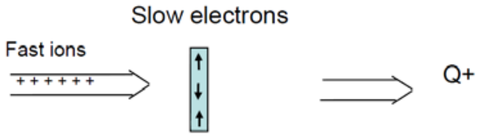
accelerator	Max. Energy reached (MeV/u)	parameters
Cyclotron	$K\left(\frac{Q}{A}\right)^2$	$K \sim (Br)^2$ $\boldsymbol{B}$: $cycl.magnetic\ field$ $\boldsymbol{r}$: $cycl.radius$
LINAC	$\frac{Q}{A}\langle E_{acc.}\rangle \mathrm{L}$	$\langle \boldsymbol{E}_{acc.}\rangle$: $average\ acceleration\ field$ $\boldsymbol{L}$: $LINAC\ length$

- Motivations to increase the radioactive ion charge state Q:
  - Higher energy reachable
  - Shorter accelerator dimension (COST REDUCTION)
  - Faster transport to the experiment
  - Furthermore, for LINAC, the RFQ radius decreases with the $\frac{Q}{A}$
  - LINAC cost $\sim length \times radius^n \quad 1 < n < 2$

Source : F. Wenander, CAS 2012

The 3 Charge breeding techniques

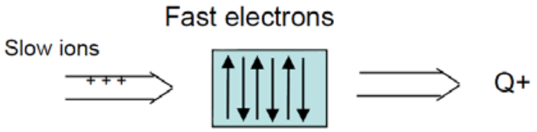
Carbon foil at CERN LINAC3



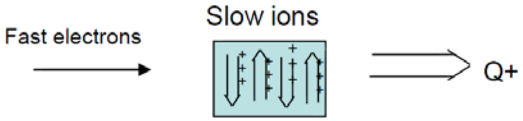
- Stripper foil
  - A foil is placed in the beam to multiionize the beam
    - Several charge states extracted
    - Mean charge state function of the beam velocity
    - Work with high currents, but Emittance increase
    - Not discussed here

Charge breeding Yield:

$$\eta = \frac{I(q+)}{q.I(1+)}$$



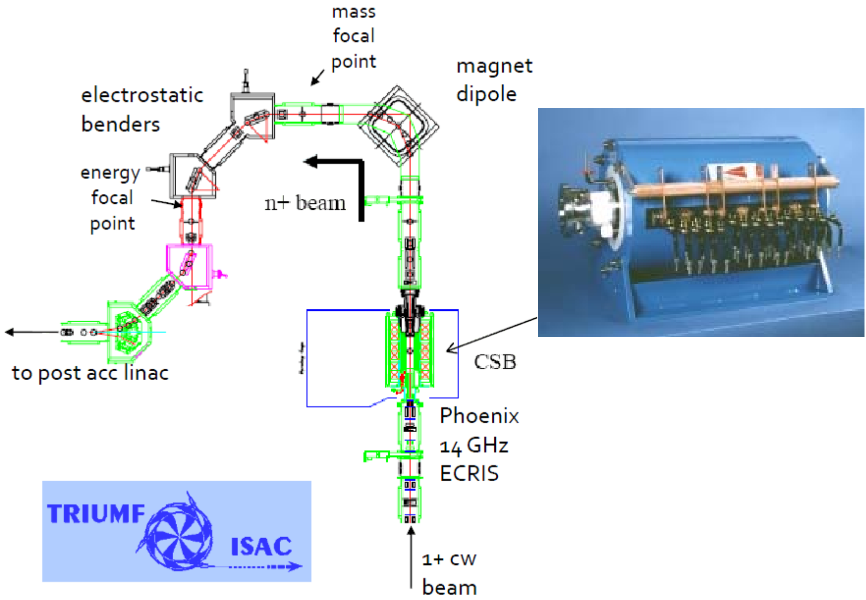
- ECR charge breeder
  - A decelerated 1+ ion beam passes through a plasma with hot electrons



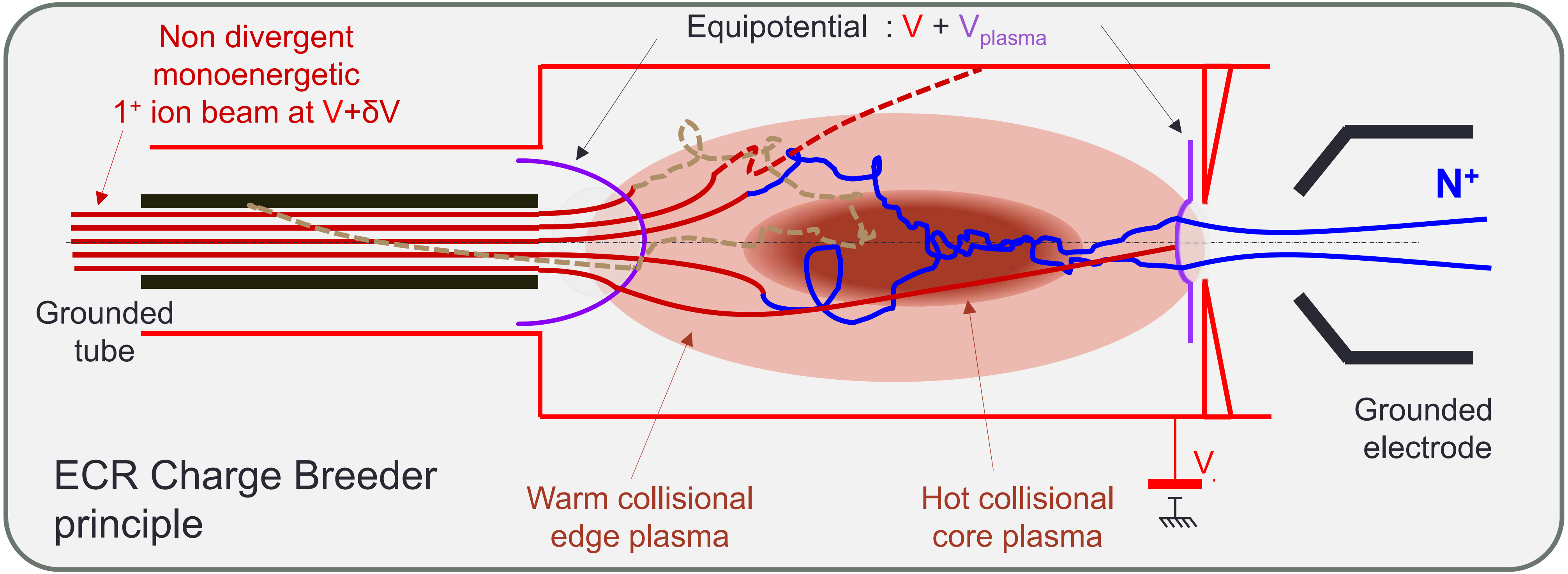
- EBIS charge breeder
  - A decelerated 1+ beam is trapped in an EBIS and crossed an intense electron beam

Partial source : F. Wenander CAS 2012

ECR charge breeder



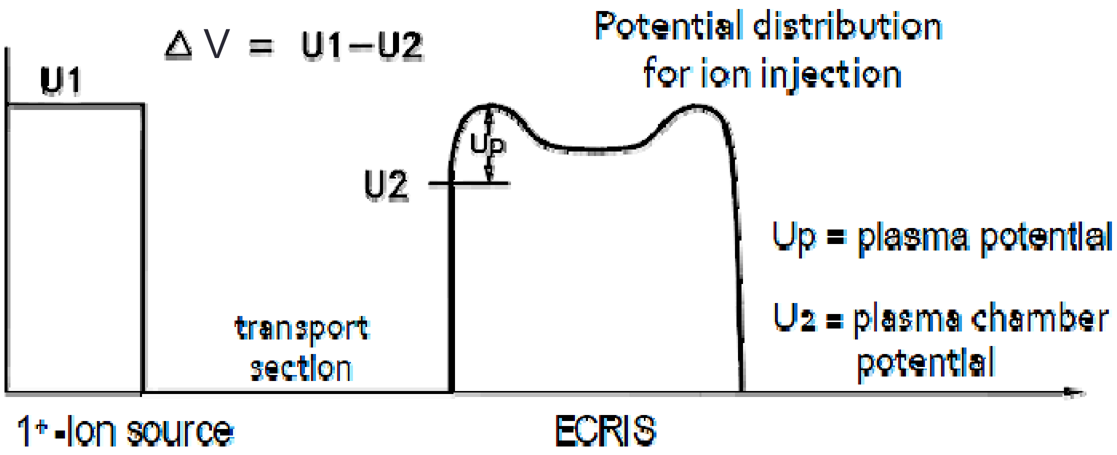
- Ions are decelerated down to a few eV and cross slowly a $10^{12}\ e^-/cm^3$ plasma with hot electrons
  - Ions are naturally decelerated to the ion plasma temperature
  - Ions collide with other ions (coulomb collision) and scatter => memory loss
  - Ions are ionized on flight
  - Ions are captured by the plasma, and finally extracted after having being multi-ionized

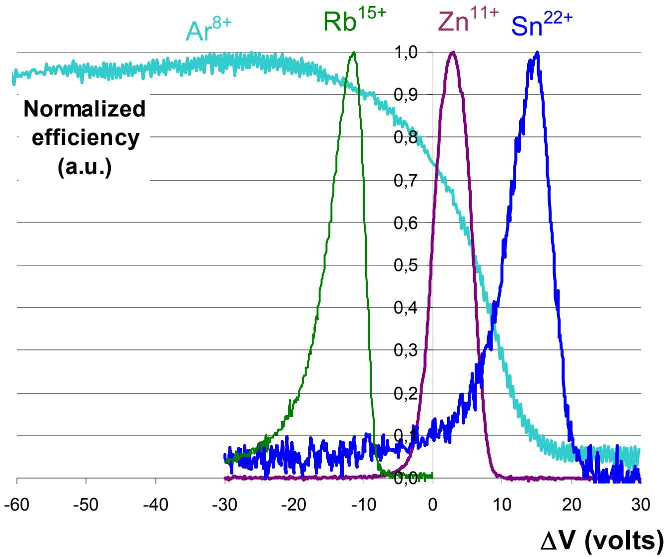


ECR Charge Breeder principle

ECR Charge breeder

- Optimization of ion beam capture: ΔV plot





  - The 1+ beam emittance and energy needs to be carefully tuned to grant plasma capture, specially for condensables which are lost if they touch the ion source wall

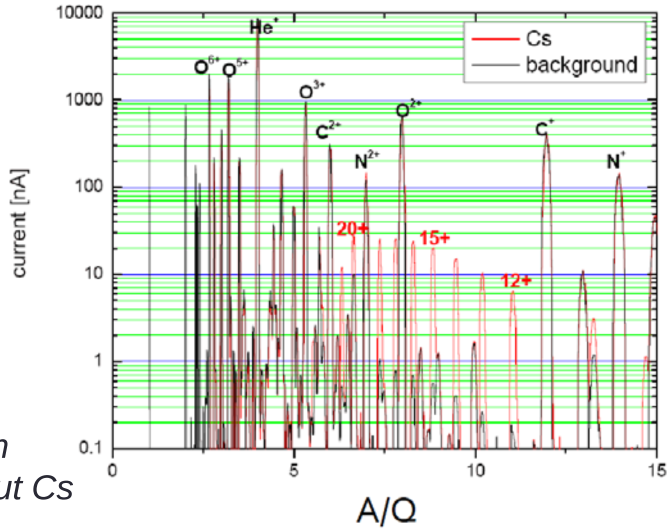
Source : F. Wenander CAS 2012

ECR Charge Breeder features

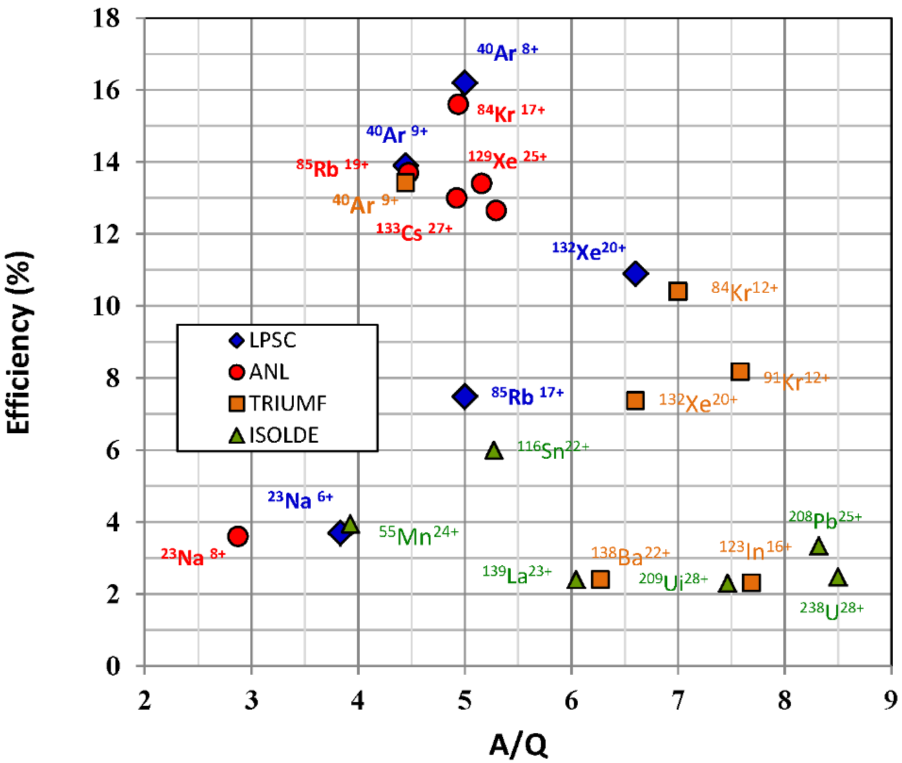
- 1+ beam intensity up to ~100 eµA
- Continuous Work operation
- Breeding time ~ 3-10 ms/charge
- Breeding efficiencies in the range : $\eta \sim 2 - 18\%$
- Extracted beam contaminated by any chemical species present in the source and vacuum (source operation a 10^{-7} mbar)
  - C,N,O,H,Fe,Cu,Al,Ar,Kr,Xe…
- Requires a very high resolution mass separator downstream to purify the beam

Charge breeding Yield:

$$\eta = \frac{I(q+)}{q.I(1+)}$$



Extracted beam
With and without Cs

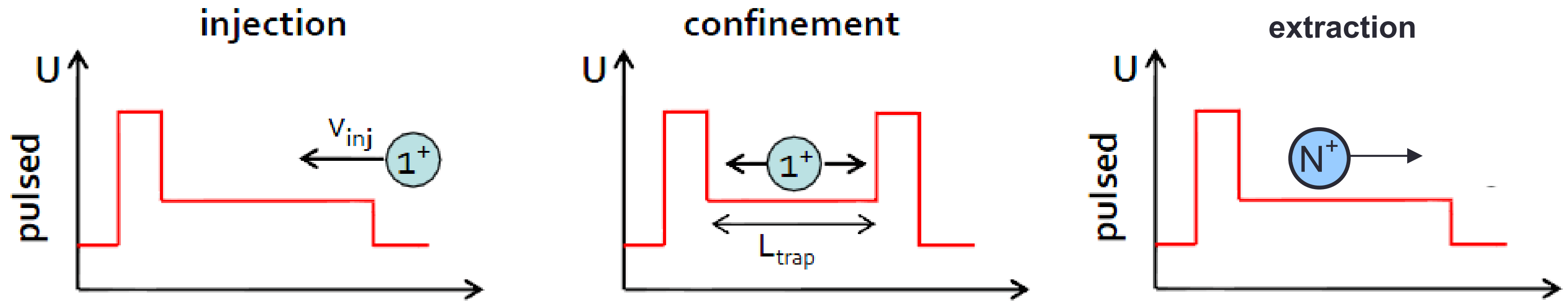


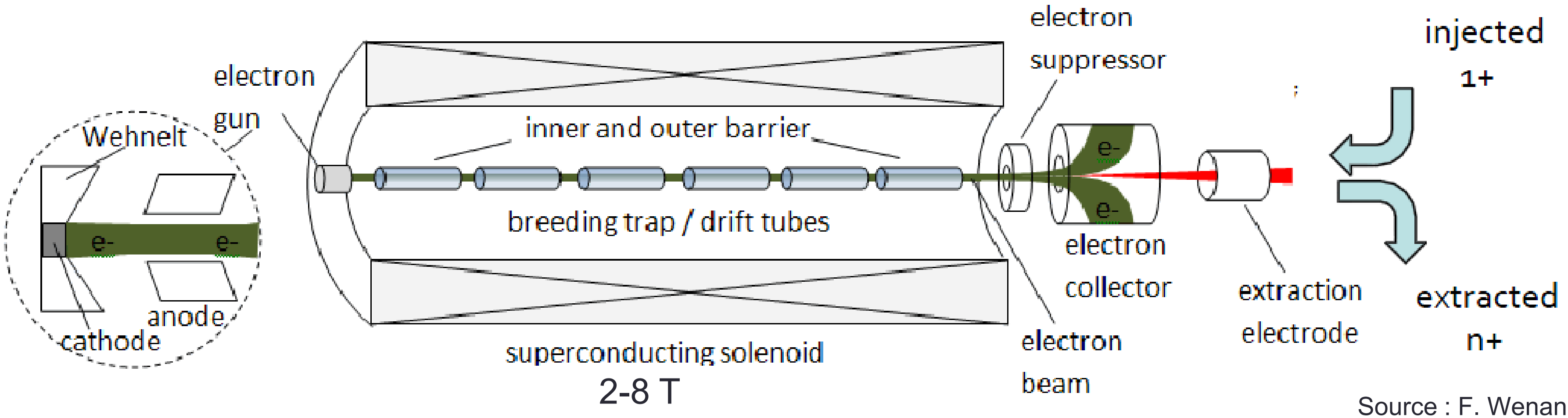
Typical Experimental ECR CB efficiencies

Source : F. Wenander CAS 2012

EBIS Charge Breeding

- Bunch of 1+ ions are introduced in an electron beam ion source
  - The ions are electrostatically confined and are ionized by an intense electron beam

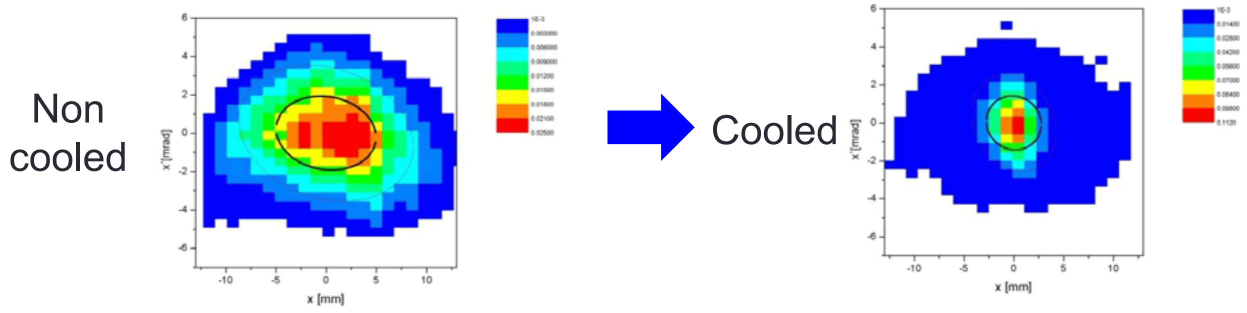




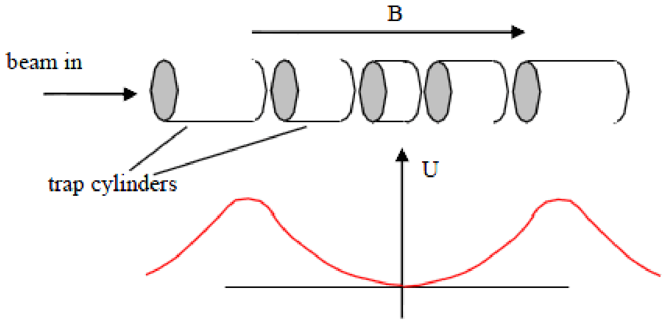
Source : F. Wenander CAS 2012

Ion cooling Prior to EBIS injection

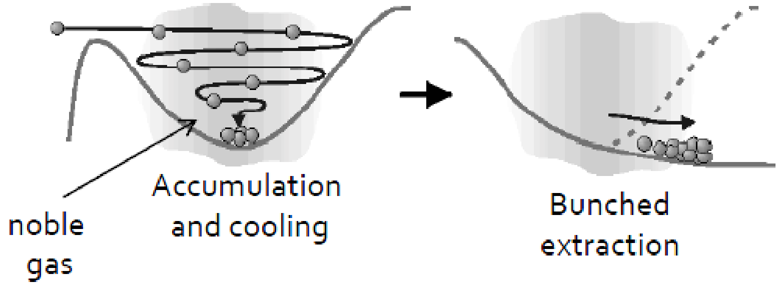
- Prior to EBIS injection, the 1+ RIBs needs to pass throught a Penning trap to:
  - Accumulate the beam
  - Bunch the beam
  - Cool down the ions to reduce the emittance



gas filled cylindrical Penning trap

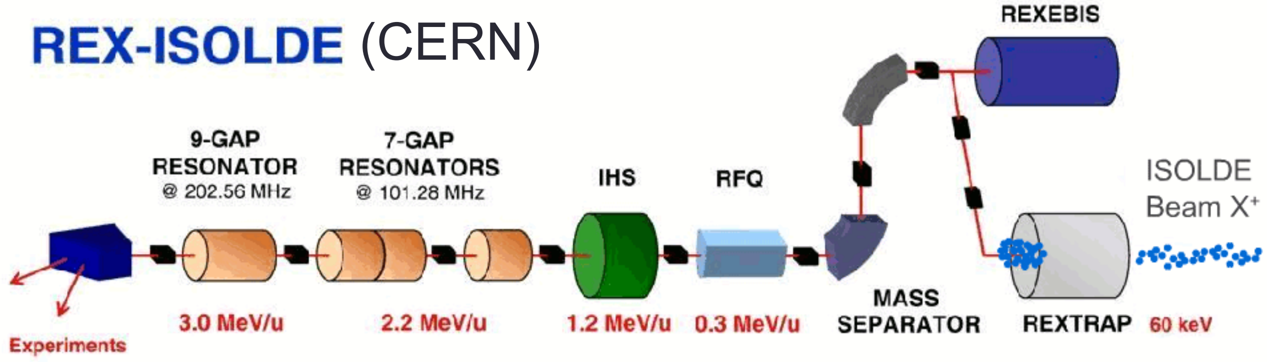


Axially - electrostatic field
Radially – magnetic field



Energy loss due to buffer gas collisions: F=-δmv

REX-ISOLDE (CERN)



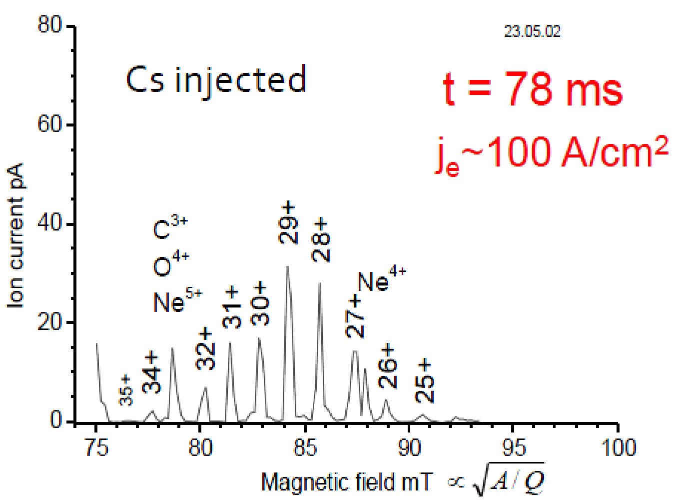
Source : F. Wenander CAS 2012

EBIS charge breeder features

Charge breeding Yield:

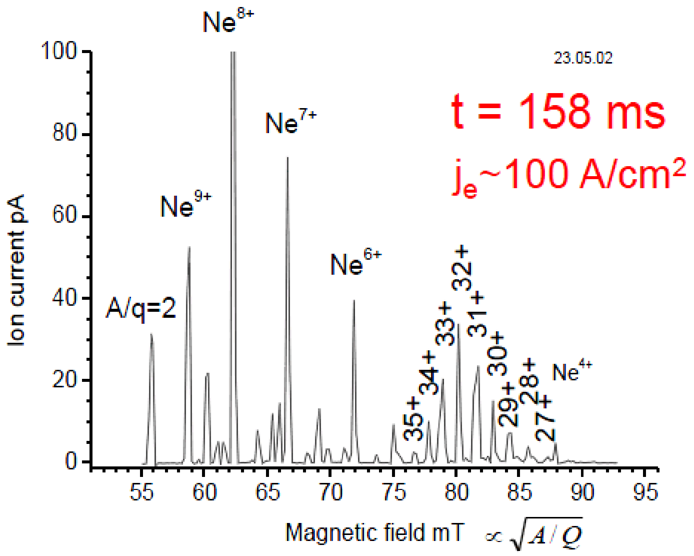
$$\eta = \frac{I(q+)}{q.I(1+)}$$

- Breeding time τ~1-5 ms/charge
- Breeding efficiency η~5-20%
- Limited extracted beam intensity : $10^9 - 10^{10}$ions/s (~1 enA)
- Very low contamination (P~10^{-10} mbar)
- Requires a beam cooling stage (Penning trap)



t = 78 ms

j_e~100 A/cm²



t = 158 ms

j_e~100 A/cm²

Source : F. Wenander CAS 2012

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