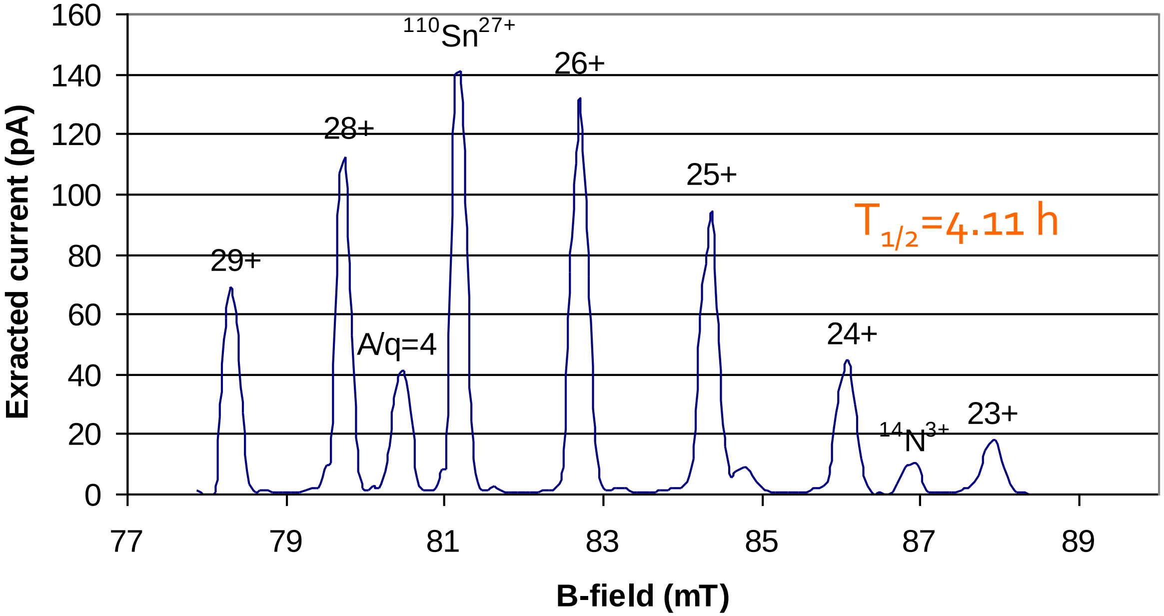
Charge breeding

aka

Charge state boosting

aka

1+ -> n+ transformation



Fredrik Wenander

BE/CERN

on Ion Sources, Senec Slovakia, 2012

The CERN Accelerator School

Lecture layout

1. Introduction and motivation

2. ISOL beam parameters and breeder criteria

3. Atomic physics processes for multiply charged ions

4. The different concepts
    - Stripping
    - ECRIS
    - EBIS

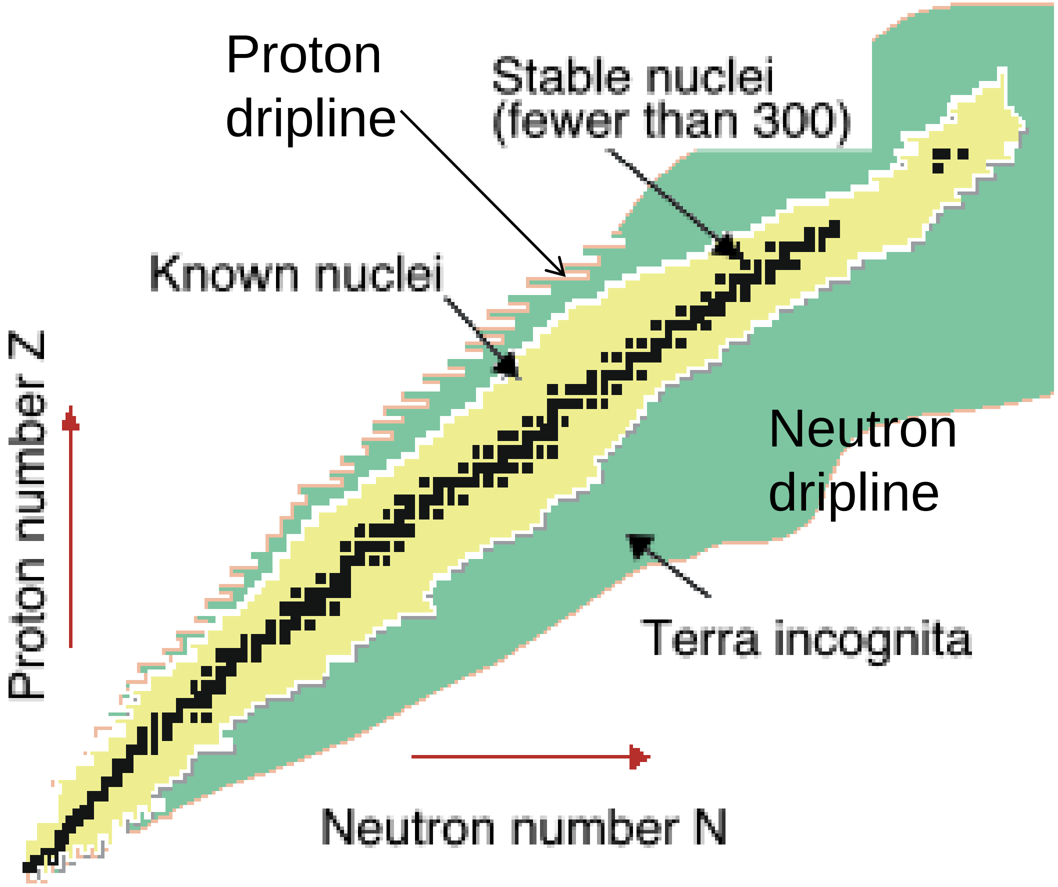
5. Preparatory devices and tricks

6. Facilities and the future

Introduction and motivation

Setting the stage

Potential beams

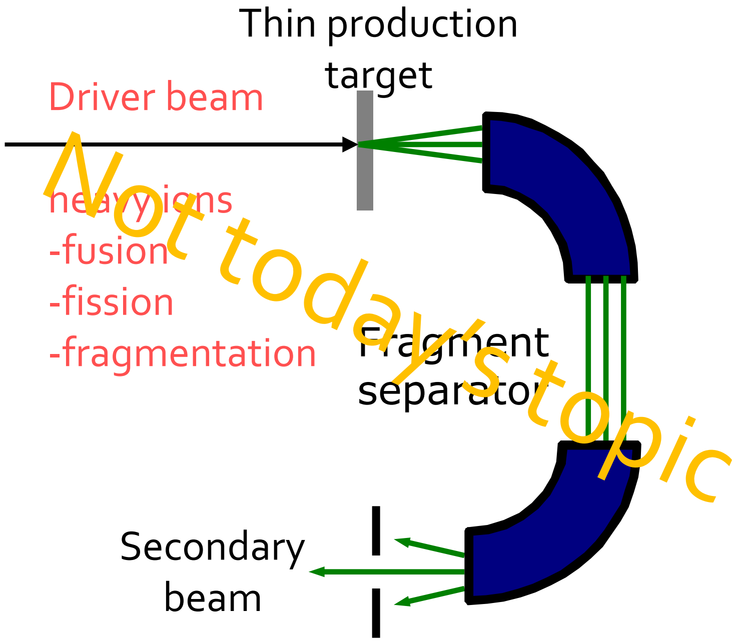


To this date:
~6000 nuclei believed to ‘exist’
~3000 different nuclides experimentally observed
Less than 10% stable

Radioactive nuclei: main interest for nuclear physics

RIB production techniques

IF (In-Flight fragment separator)

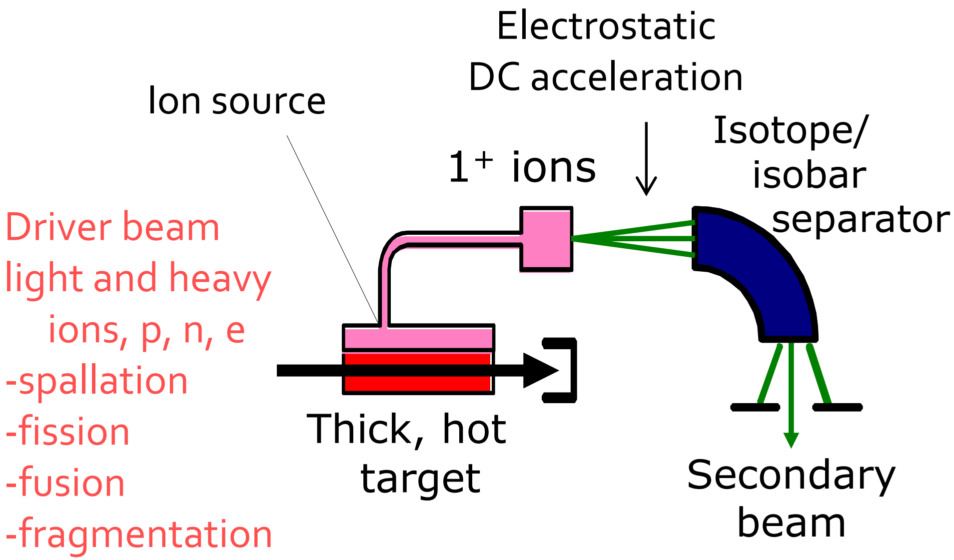


Driver beam
heavy ions
-fusion
-fission
-fragmentation

Not today's topic

Down to us lifetimes
Large transverse emittance
Large energy spread
GeV beam energy

Isotope Separation Online (ISOL)



Driver beam
light and heavy ions, p, n, e
-spallation
-fission
-fusion
-fragmentation

Pencil-like beams
Chemistry involved
Higher beam intensities than IF
Lifetimes >10 ms
$W_{total} < 100$ keV

Closing the energy gap

Interesting physics at 0.1 – 10 MeV/u

- Coulomb excitation
- Few-particle transfer
  (d,p), (^{9}Be,2α) , (^{10}Be,2 α), (p,γ), $(p,p)_{res}$…
- Fusion reactions at the Coulomb barrier

NB! W_{kin}(total)=MeV/u*A

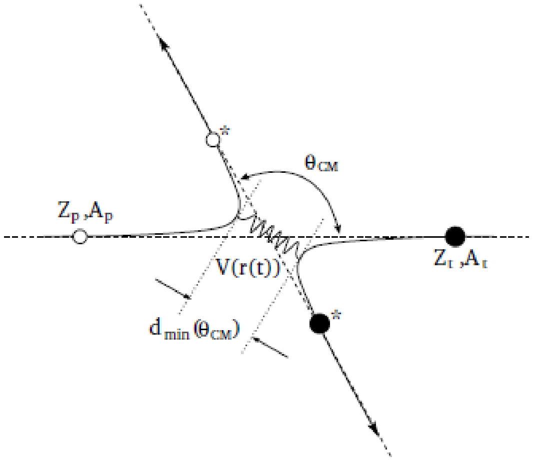
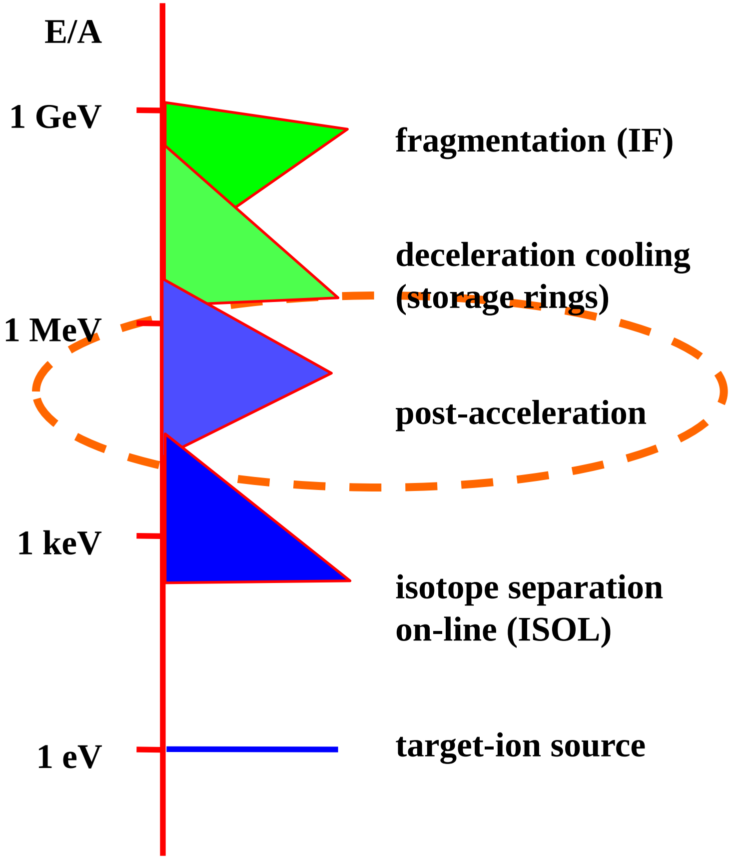
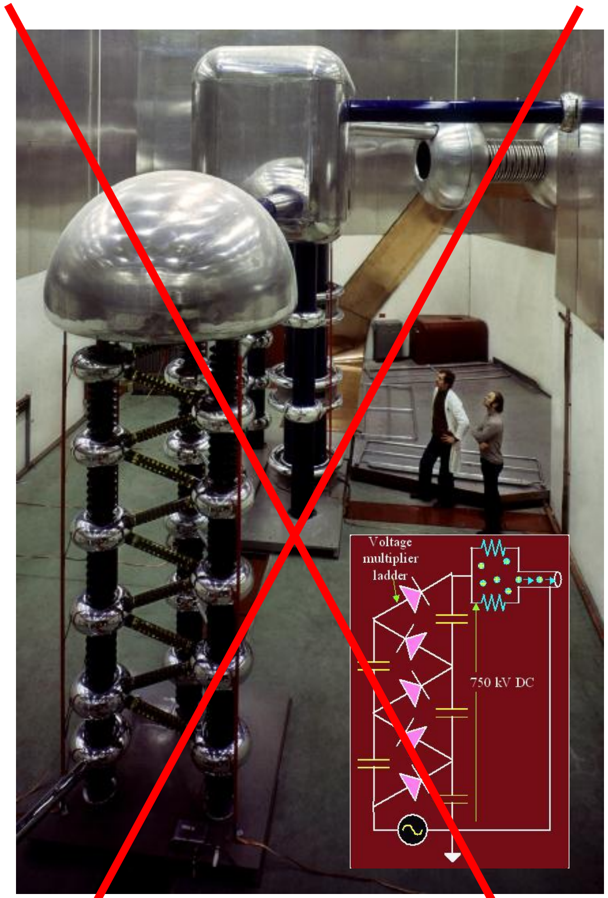


Figure 3.22: Schematic diagram of the Coulomb excitation process of a projectile nucleus (Z_p,A_p), scattering inelastically on a target nucleus (Z_t,A_t), in the center-of-mass system.



! Fill with *post-accelerated* ISOL-beams

Motivation for Q^+



Old 750 kV Cockroft-Walton proton source at CERN

=> 0.015 MeV/u for A=50

1st motive for high Q

	W_{final} (MeV/u)	Time structure
Cyclotron	$K*(Q/A)^2$	cw (micro structure)

$K \sim (Br)^2$, [B]=T, [r]=m (cyclotron B-field and radius)

Linac	$Q/A*E(ave)*L$	SC - cw NC - usually pulsed

E(ave)=average acceleration field ~3 MV/m for NC*
[L]=m (linac length)

=> Linac length ~ A/Q

Extra

Kilpatrick limit (valid for NC)
$f(MHz) = 1.64E(peak)^2 e^{(-8.5/E(peak))}$
[E(peak)]=MV/m

Motivation for Q^+

2nd motive for high Q

If A/Q high => require low f_{RF} to achieve adequate :

a. transverse focusing (focal strength ~ $1/\sqrt{f_{RF}}$)

b. period length (L_{period}) of the first RF structure as the source extraction velocity is limited

Extra

Example: A=220, Q=1, U_{extr}=100 kV, L_{period}=2 cm

$$v_{extr} = \sqrt{\frac{2U_{extr}Q}{A}\frac{e}{u}} = 3E5 \text{ m/s}$$

$f_{RF} \sim v_{extr}/L_{gap}$ = 15 MHz

open RFQ

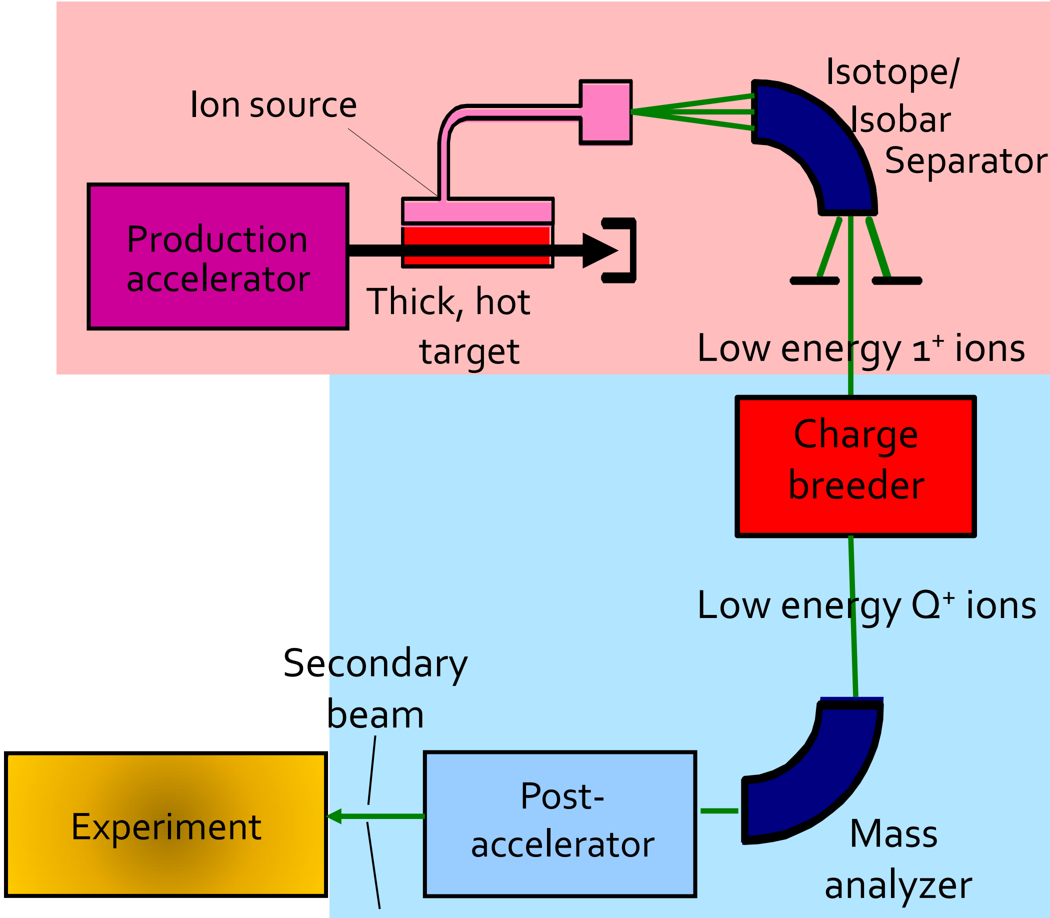
ISAC 35 MHz RFQ for A/Q<30

Transverse tank dimensions scale with $1/f_{RF}$

Bottom line: low A/Q =>
+ short linac
+ small transverse dimension

*Linac cost ~ length*radius^p 1<p<2*

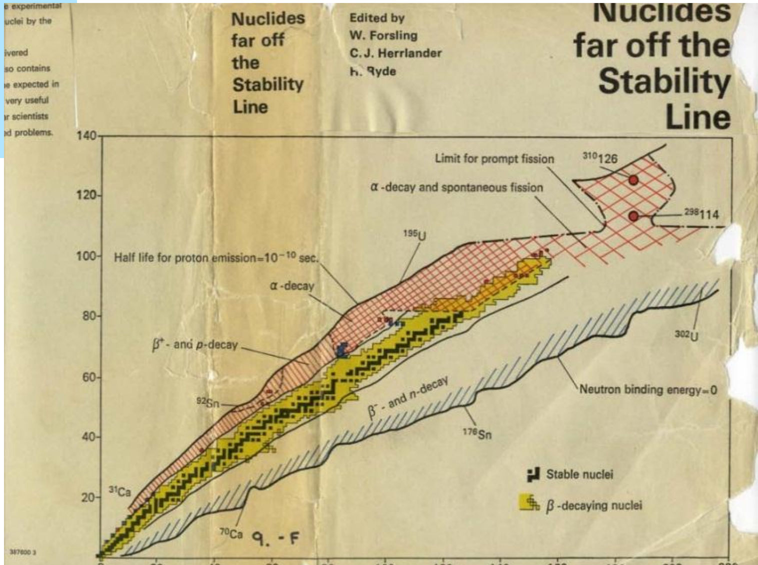
Post accelerator layout



Isotope Separation Online

Post accelerator

First ideas/suggestions for post-acceleration of radioactive ion beams: “Nuclides far off the Stability Line” (1966) Sweden


Nuclides far off the Stability Line

Edited by
W. Forsling
C. J. Herrlander
H. Ryde

Nuclides far off the Stability Line

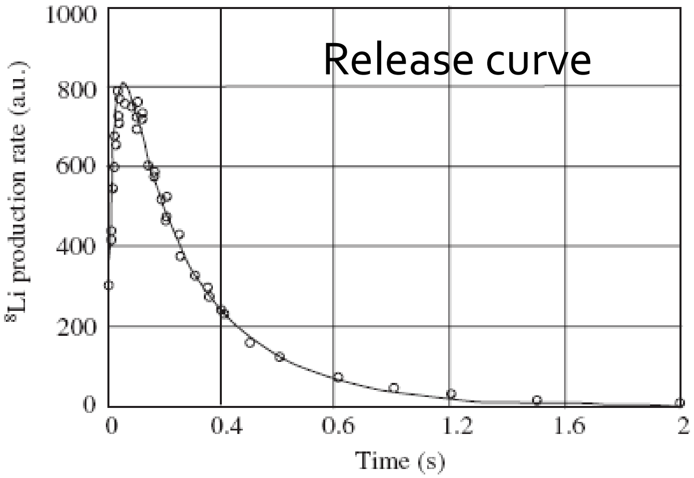
ISOL beam parameters and breeder criteria

What comes in and goes out

For ion source details
see T. Stora's lecture

ISOL beam parameters

Ion mass	4 to >250	He to >U
Intensity	few to >1E11 ions/s	Large dynamic range
Charge	1+	Some (undesired) 2^+, 3^+,…
Energy	several tens keV	
Energy spread	few eV	
Temporal structure	cw or quasi-cw	Driver beam – cw or pulsed



^{8}Li ($T_{1/2}$ = 840 ms) produced by target fragmentation of tantalum foils

at CERN period time = n*1.2 s

Extra

$$P(t,\lambda_r,\lambda_f,\lambda_s,\alpha)=\frac{(1-e^{-\lambda_r t})}{Norm}\left[\alpha e^{-\lambda_f t}+(1-\alpha)e^{-\lambda_s t}\right]$$

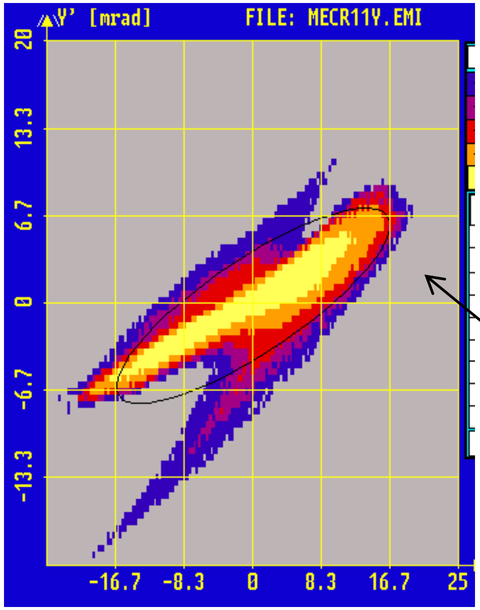
Semi-continuous

depending on release properties and ionization time

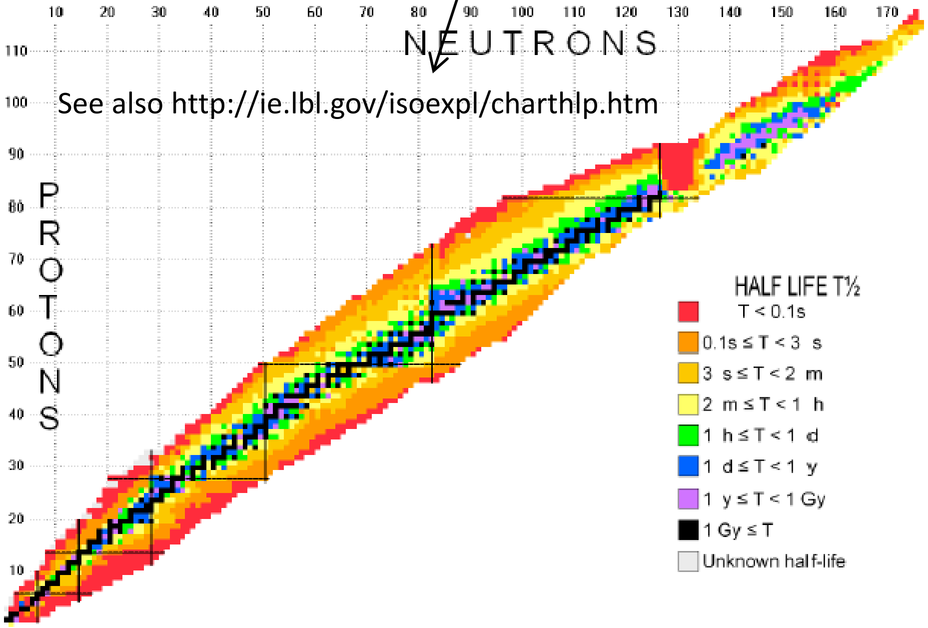
typical tens ms to minutes

(r=rise, f=fast, s=slow)

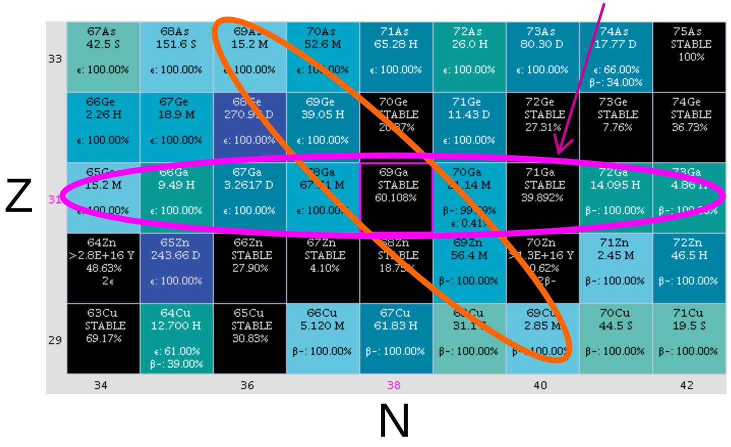
ISOL beam parameters



Transverse emittance	10-50 mm mrad	90% at 60 keV
Half-life	>10 ms	Limited by ISOL-system
Selection	Not necessarily isobarically clean	Use e.g. resonant ionizing laser ion source



See also http://ie.lbl.gov/isoexpl/charthlp.htm



ISOL magnet selects A/Q (Q=1)

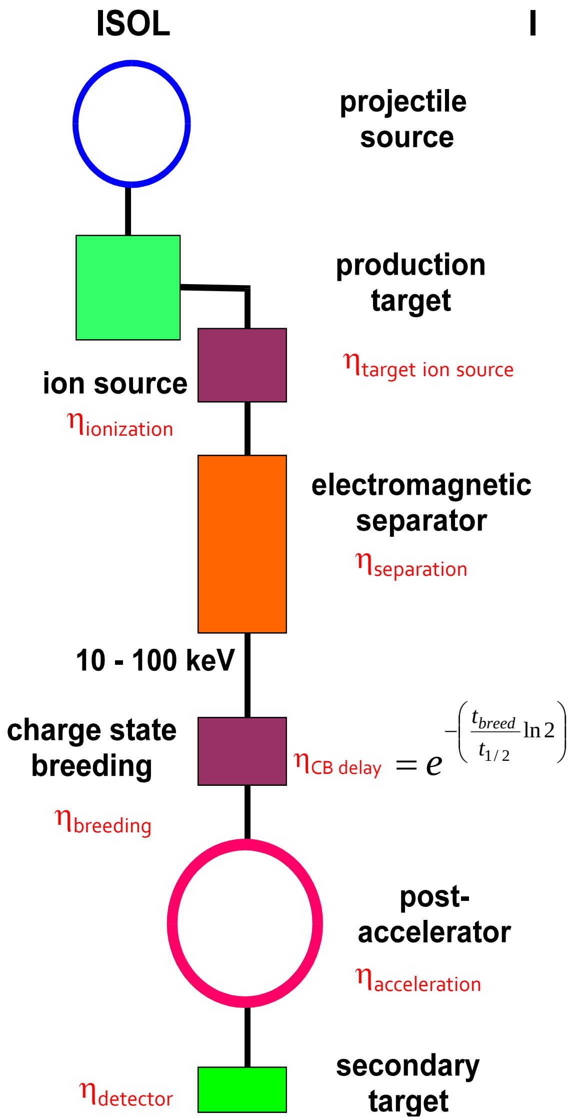
resonant laser separation

Z \ N	34		36		38		40		42
33	67As 42.5 S ϵ: 100.00%	68As 151.6 S ϵ: 100.00%	69As 15.2 M ϵ: 100.00%	70As 52.6 M ϵ: 100.00%	71As 65.28 H ϵ: 100.00%	72As 26.0 H ϵ: 100.00%	73As 80.30 D ϵ: 100.00%	74As 17.77 D ϵ: 66.00% β-: 34.00%	75As STABLE 100%
	66Ge 2.26 H ϵ: 100.00%	67Ge 18.9 M ϵ: 100.00%	68Ge 270.95 D ϵ: 100.00%	69Ge 39.05 H ϵ: 100.00%	70Ge STABLE 20.37%	71Ge 11.43 D ϵ: 100.00%	72Ge STABLE 27.31%	73Ge STABLE 7.76%	74Ge STABLE 36.73%
31	65Ga 15.2 M ϵ: 100.00%	66Ga 9.49 H ϵ: 100.00%	67Ga 3.2617 D ϵ: 100.00%	68Ga 67.71 M ϵ: 100.00%	69Ga STABLE 60.108%	70Ga 21.14 M β-: 99.59% ϵ: 0.41%	71Ga STABLE 39.892%	72Ga 14.095 H β-: 100.00%	73Ga 4.86 H β-: 100.00%
	64Zn >2.8E+16 Y 48.63% 2ϵ	65Zn 243.66 D ϵ: 100.00%	66Zn STABLE 27.90%	67Zn STABLE 4.10%	68Zn STABLE 18.75%	69Zn 56.4 M β-: 100.00%	70Zn >1.3E+16 Y 0.62% 2β-	71Zn 2.45 M β-: 100.00%	72Zn 46.5 H β-: 100.00%
29	63Cu STABLE 69.17%	64Cu 12.700 H ϵ: 61.00% β-: 39.00%	65Cu STABLE 30.83%	66Cu 5.120 M β-: 100.00%	67Cu 61.83 H β-: 100.00%	68Cu 31.1 S β-: 100.00%	69Cu 2.85 M β-: 100.00%	70Cu 44.5 S β-: 100.00%	71Cu 19.5 S β-: 100.00%

Breeder criteria

Checklist for breeder design

0	Achievable A/Q (3<A/Q<9)
1	High breeding efficiency rare radionuclides limit machine contamination chain of machines $\eta_{breed} = \frac{I(Q)}{Q \cdot I(1^+)}$
2	Short breeding / confinement time handle short-lived ions
3	Clean extracted beams
4	High ion throughput capacity
5	Good beam-quality (large α, small ε_{trans}, small ΔE_{extr}) good trapping effieincy high linac/separator transmission η good mass separation
6	Pulsed or cw machine / beam extraction time structure dependent on accelerator
7	Easy handling and reliable to be used in an accelerator chain on a production basis



Atomic physics processes for multiply charged ions

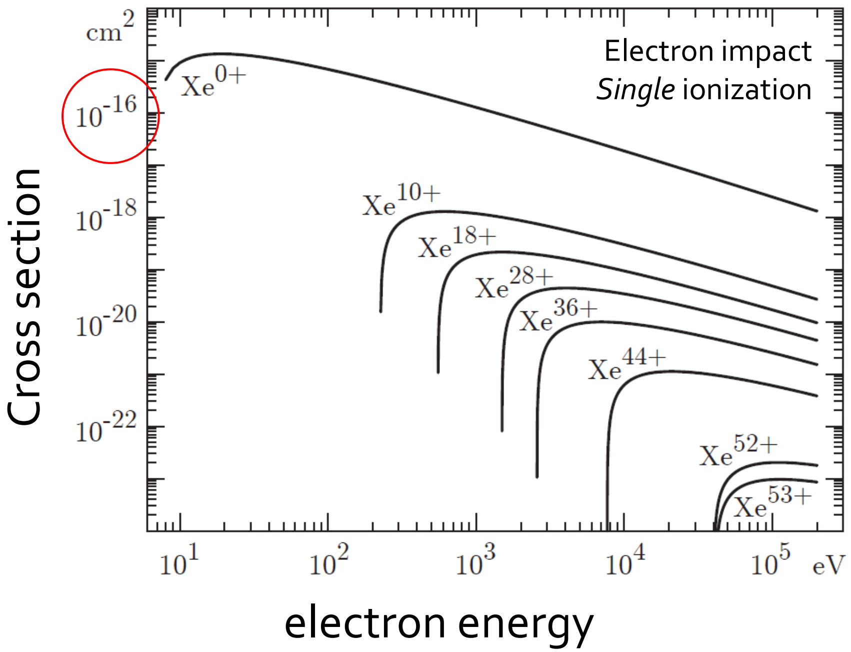
Short revision

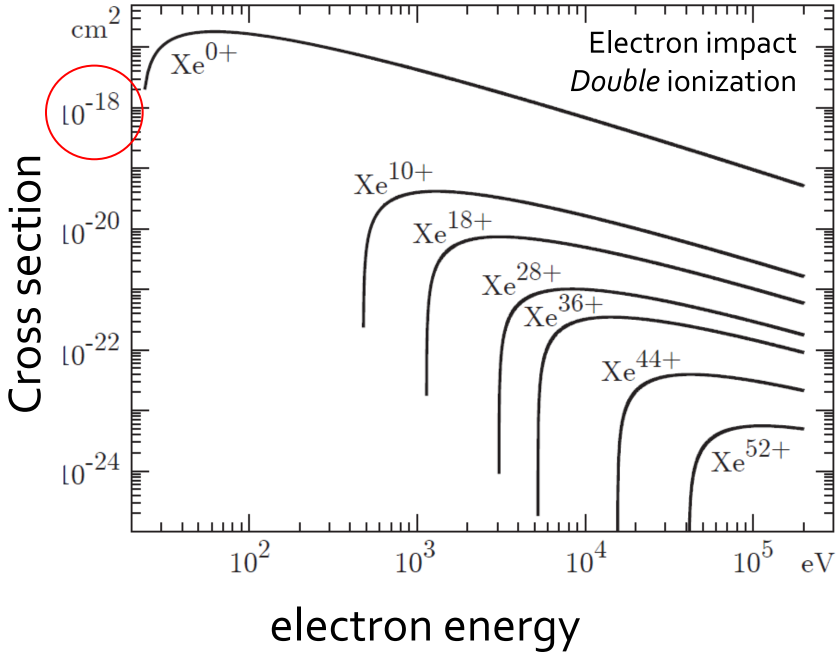
See also lectures by
M. Kowalska and G. Zschornack

Ionization process

Electron impact ionization

more efficient than proton and photon impact $\hbar\nu$





Multistep (successive) ionization $e + A^{i+} \rightarrow A^{(i+1)+} + 2e$

the process takes time

Ionization time has to be shorter than lingering time in the source

Ionization time

Average time to reach the charge state q with multistep ionization for electrons with *defined kinetic* energy:

$$\bar{\tau}_q = \sum_{i=1}^{q-1} \bar{\tau}_{i\to i+1} = \frac{e}{j_e}\sum_{i=1}^{q-1}\frac{1}{\sigma_{i\to i+1}}$$

Lotz's semi-empirical electron impact ionization cross-section formula for the case of high ionization energies $E_{kin} > P_i$ is:

$$\sigma_{q\to q+1} = 4.5\cdot 10^{-14}\cdot\sum_{nl}\frac{\ln\left(E_{kin}/P_i\right)}{E_{kin}\cdot P_i}\qquad\left[\mathrm{cm}^2\right]$$

Energies in eV and nl sum over n shell and subshell l

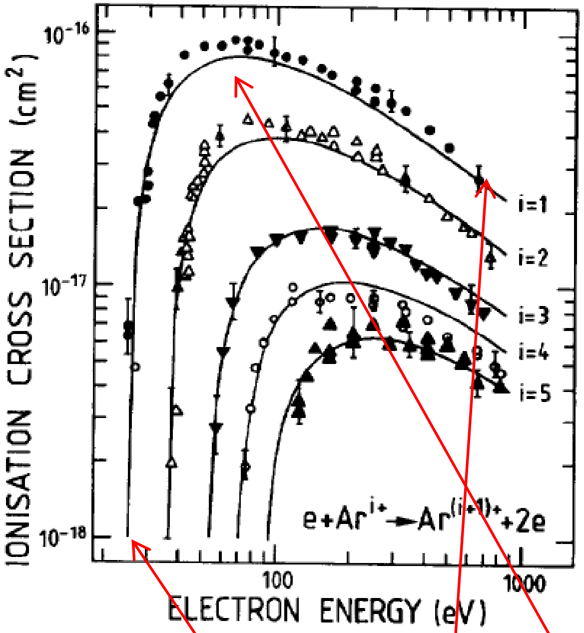
E_{kin} - energy of the incident electron

$P_i=E_{nl}$ - *binding energy*

σ – single ionization cross-section cm^2

j_e – electron current density $\mathrm{A/cm}^2$

valid for electrons with fixed energy



Cross-section

* Energy threshold = ionization energy

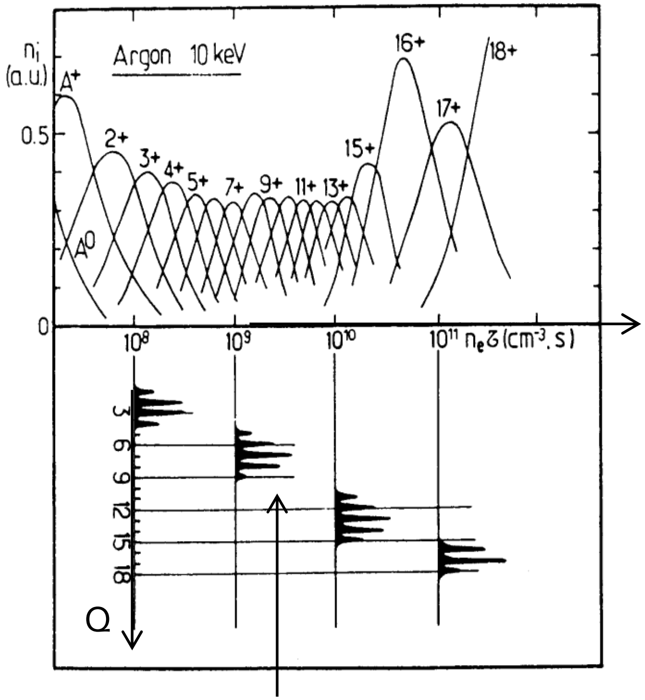
* Max at ~2.7 times the ionization potential

* Decreases with charge state for very high electron energies

Charge state distribution

Ionization a statistical process
⇒ charge state distribution

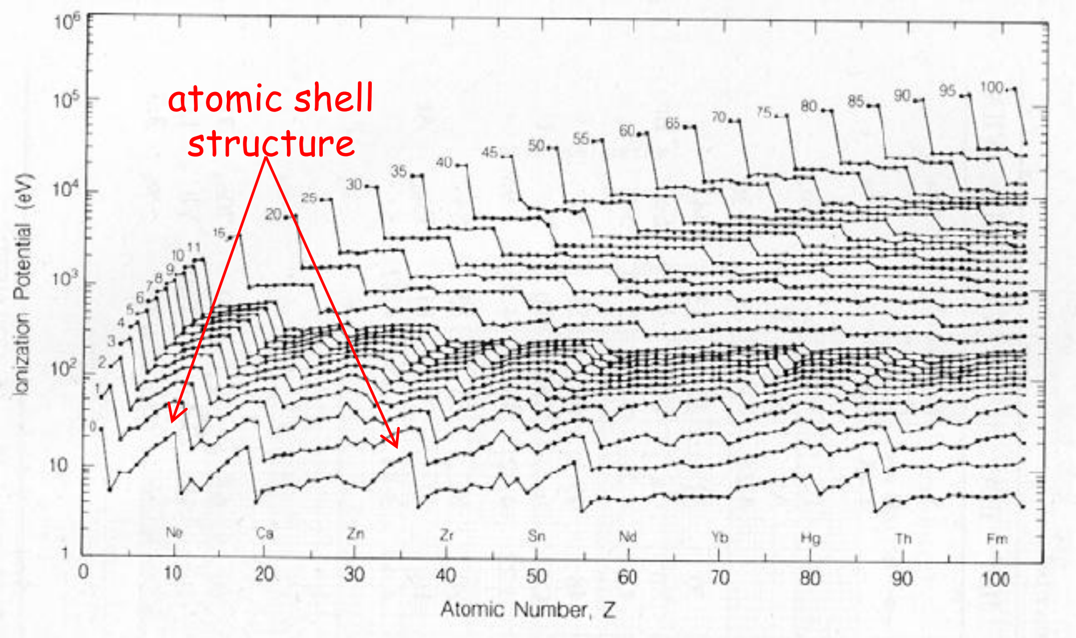
Typically 15-25% in most abundant state

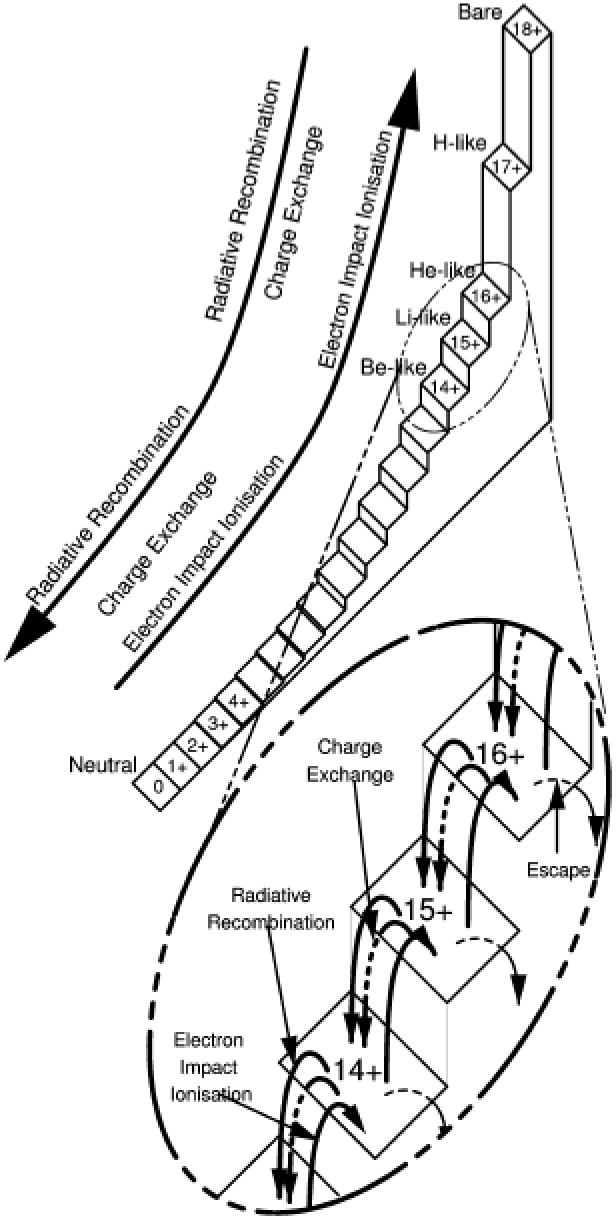


Charge state distribution as function of n_e*$T_{confinement}$

Electron energy

10 to 40 eV for singly charge ions
several 100 eV for multi-charged states
keV to tens of keV for highly charged ions


atomic shell structure



Competing processes

$$\frac{dN_i}{dt} = n_e \upsilon_e [\sigma^{EI}_{i-1\to i} N_{i-1} - (\sigma^{EI}_{i\to i+1} + \sigma^{RR}_{i\to i-1} + \sigma^{DR}_{i\to i-1}) N_i$$

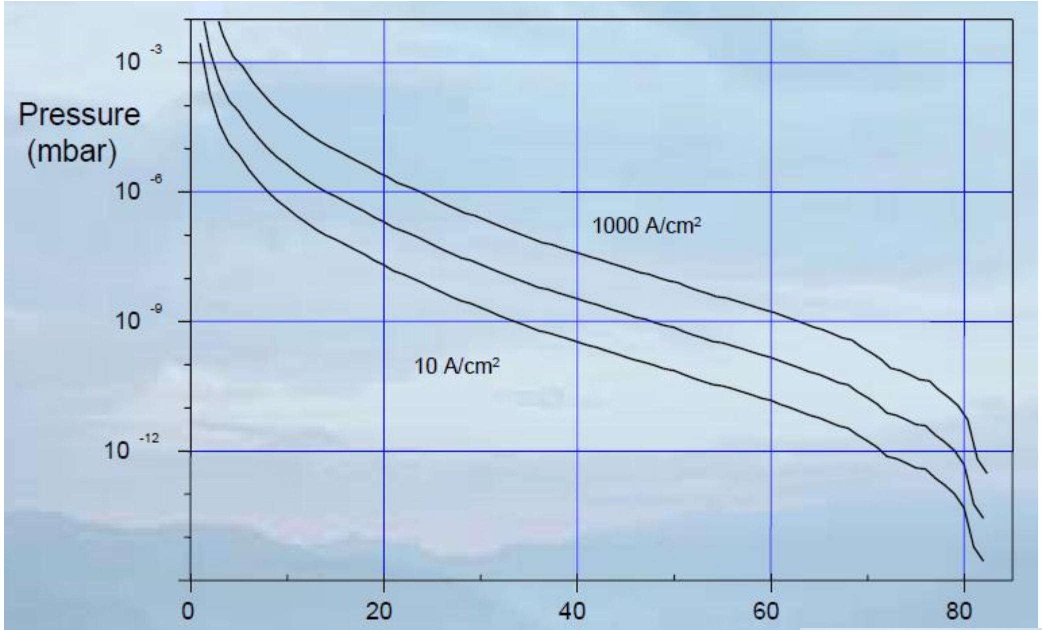
$$+ (\sigma^{RR}_{i+1\to 1} + \sigma^{DR}_{i+1\to i}) N_{i+1}]$$

$$- n_0 \upsilon_{ion} [\sigma^{CX}_{i\to i-1} N_i - \sigma^{CX}_{i+1\to i} N_{i+1}] - N_i R_i^{ESC}$$

N_i – number of ions with charge i
n_e, υ_e – electron density and velocity
n_o – neutral particle density
$\upsilon_{ion} = \sqrt{2kT_{ion} / M_{ion}}$ – averaged ion velocity

EI – electronic ionization
RR – radiative recombination
DR – dielectronic recombination
CX – charge exchange
R_i^{ESC} – escape rate

← See also AIP Conf. Proc. 572, 119 (2001)



Charge exchange vs ionization

Vacuum pressure at which gain by ionization equals loss by charge exchange for lead ions

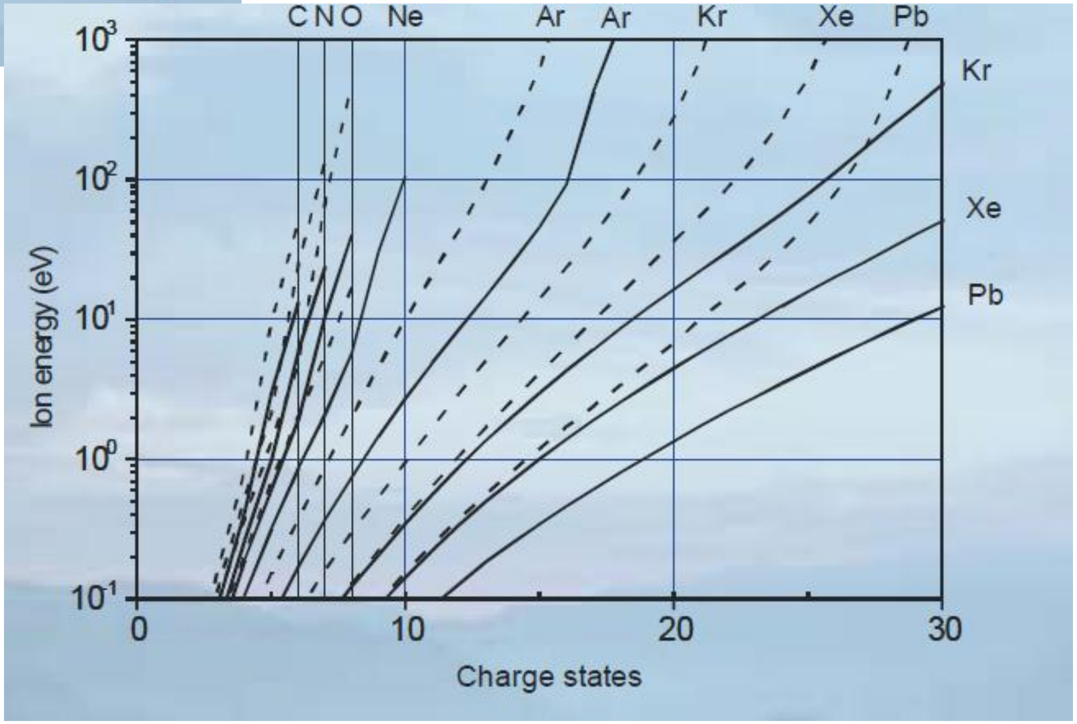
From R. Becker

Electron ion heating

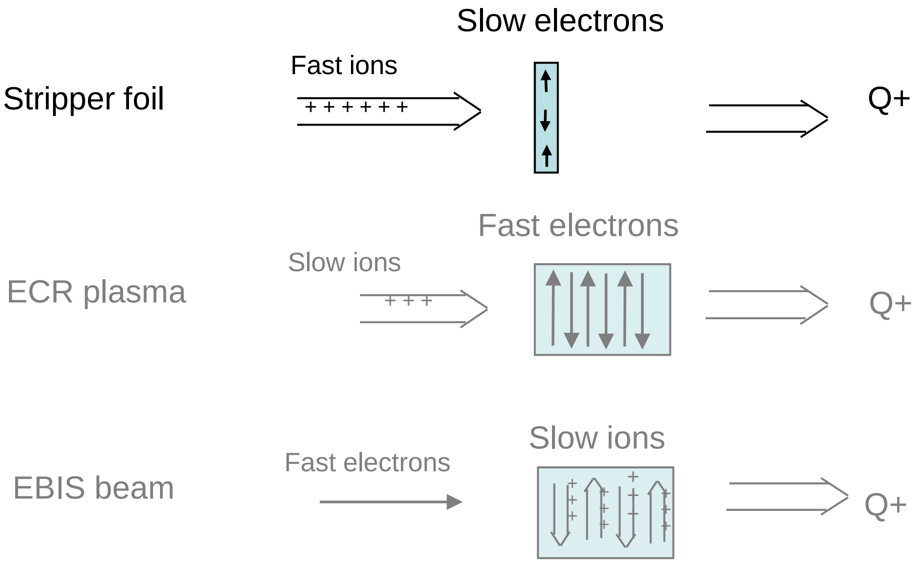
Radial well voltages $eU_{trap}=kT_{ion}$ to trap multiply charged ions heated by electrons of 1 keV (dashed line) and 10 keV (full lines)

$$\Delta U_{radial}[V] = \frac{6.2}{Z \cdot A} e \sum_{i=1}^{Q} \frac{i^2}{\sigma_{i->i+1}^{ionization}}$$

See R. Becker, Proc 3rd EBIS Workshop 1985, Ithaca, eds. V. Kostroun and B.W. Schmieder, p.185



The First Alternative



Stripper foil

Fast ions

Slow electrons

Q+

ECR plasma

Slow ions

Fast electrons

Q+

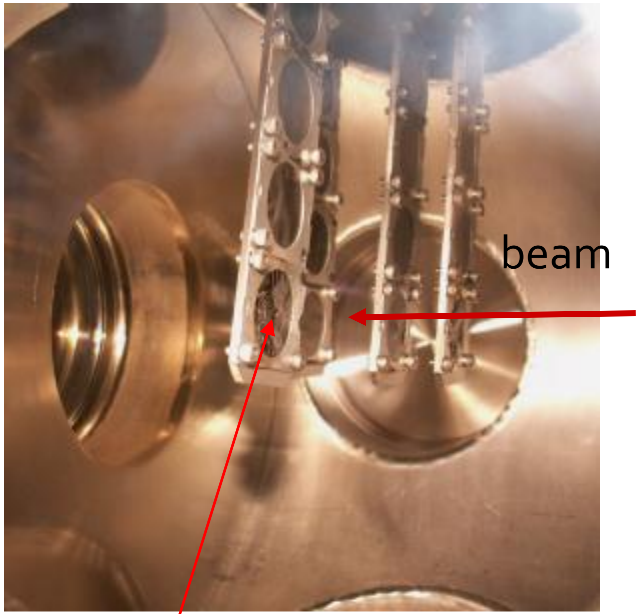
EBIS beam

Fast electrons

Slow ions

Q+

Classic concept – stripping



carbon foils at CERN Linac3

* Doesn't really classify as charge breeder

- \+ Simple method, passive elements.
- \+ Sub-us half-life isotopes easily reachable
- \+ Very high beam capacity >100 eμA
- \+ No additional beam contamination

* Foil materials: Be, C, Al, Al_2O_3, mylar

* Bohr criterion: electrons whose orbital velocity is larger than projectile velocity are retained

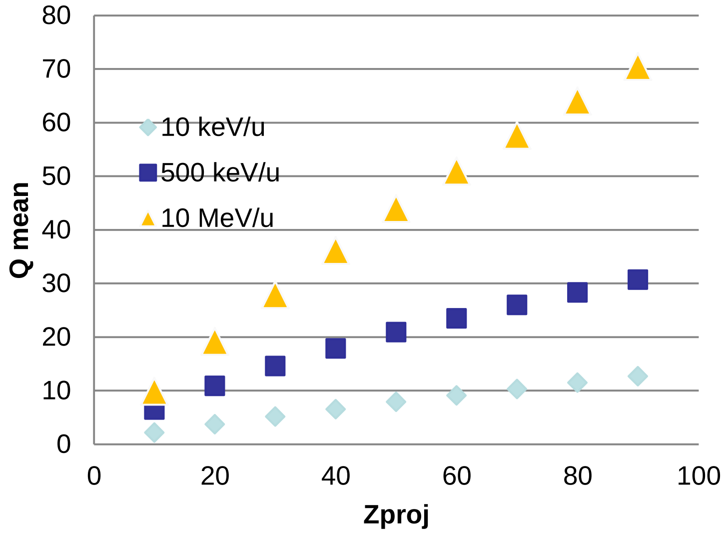
Extra

Baron's formula for equilibrium charge state distribution (CSD)

$$\overline{Q} = Z_{proj}\cdot C_1\left(1-C_2 e^{-83.28\beta/Z_{proj}^{0.447}}\right)$$

$C_1=1$ for $Z_{proj}<54$
$C_1=1-\exp(-12.905+0.2124Z_{proj}-0.00122Z_{proj}^2)$ for $Z_{proj}\geq 54$
$C_2=1$ for energies $W>1.3$ MeV/u
$C_2=0.9+0.0769W$ for $W<1.3$ MeV/u

NB! ~only dependent on velocity $v_{proj}=\beta c$ and Z_{proj}



Stripper foil CSD

Extra

Gaussian CSD distribution
* assuming no significant atomic shell effects
* $\overline{Q}$ is not too close to Z

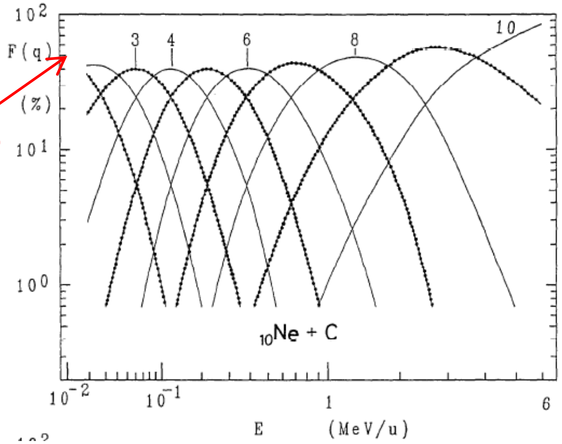
$$\sigma = 0.5\sqrt{\overline{Q}\cdot\left(1-\left(\frac{\overline{Q}}{Z_{proj}}\right)^{1.67}\right)}$$

for $Z_{proj}<54$

$$\sigma = \sqrt{\overline{Q}\cdot\left(0.07535+0.19(\overline{Q}/Z_{proj})-0.2657\left(\overline{Q}/Z_{proj}\right)^{2}\right)}$$

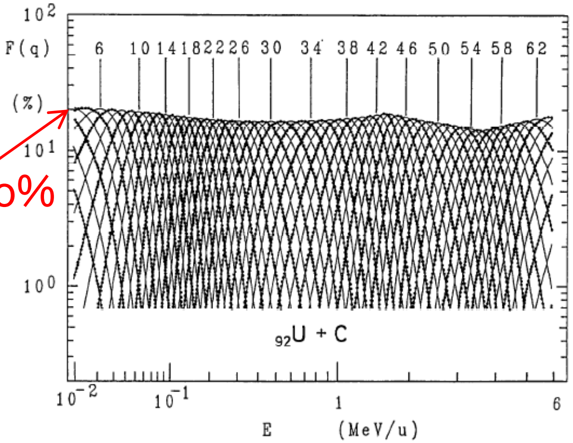
for $Z_{proj}\geq 54$

Light elements (low Z_{proj})
=> narrow distribution
=> high fraction in a single charge state



35%

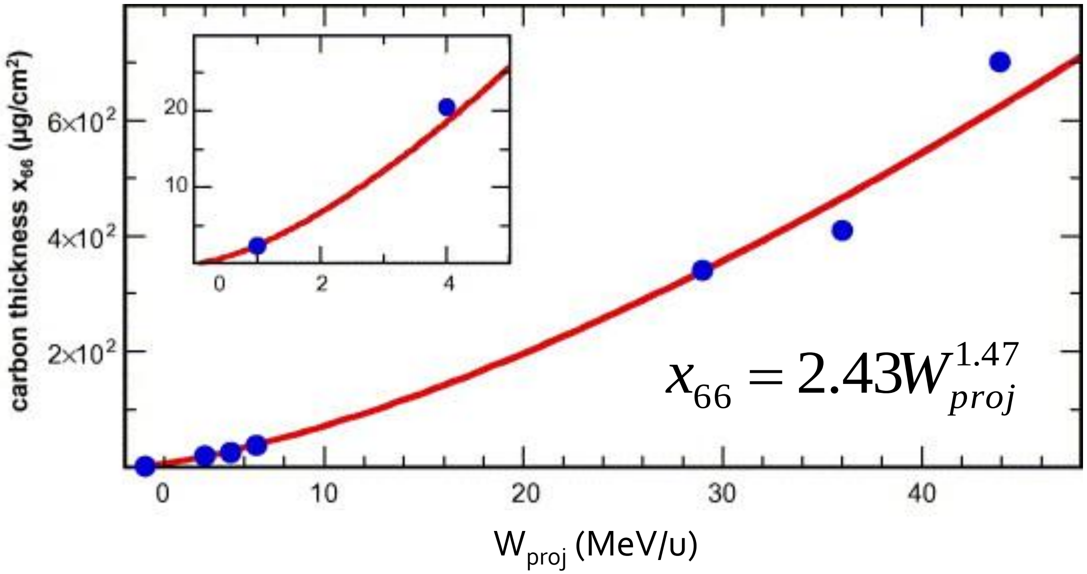
Heavy elements (high Z_{proj})
=> wide distribution
=> less fraction in a single charge state



15-20%

See also: G. Schiwietz, P.L. Grande, Improved charge-state formulas NIMB 175-177 (2001) 125-131
Refined formulae for foil and gas stripping

Foil equilibrium thickness



M. Toulemonde, 'Irradiation by swift…', Nucl Instrum Meth B250 (2006) 263-268

Equilibrium thickness => CSD do not change when the target thickness is further increased

Equilibrium thickness $\approx 2 * x_{66}$

* Typical carbon foil thicknesses: 5-1000 ug/cm^2 -> 25 nm to 5 um

* Pre-acceleration to >500 keV/u

* Foil thicknesses < 5 ug/cm^2 (< 25 nm) practically difficult to mount
  => use gas strippers for low velocity beams

Extra

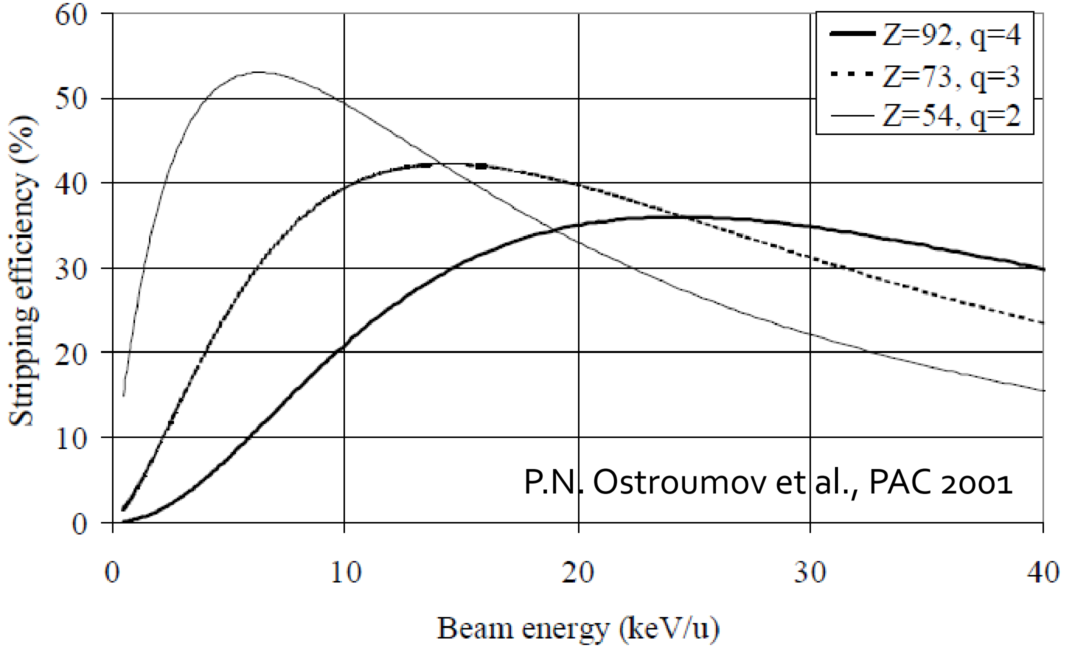
Gas stripping

* Used for very low velocity: 5-25 keV/u

* Very thin integrated thickness: fraction of ug/cm²

* Usually noble gases

* Small charge increase from 1+ to 2+, 3+ or 4+



P.N. Ostroumov et al., PAC 2001

Helium stripping efficiency of heavy ions as a function of beam energy.

Extra

In solid stripper the collision frequency is larger the frequency of Auger and radiative decays => higher Q than in same integrated thickness for gas stripper

Facility based on stripping technique

Ideally strip as soon the increased velocity enables a higher charge state

+ make maximum use of the accelerating voltage

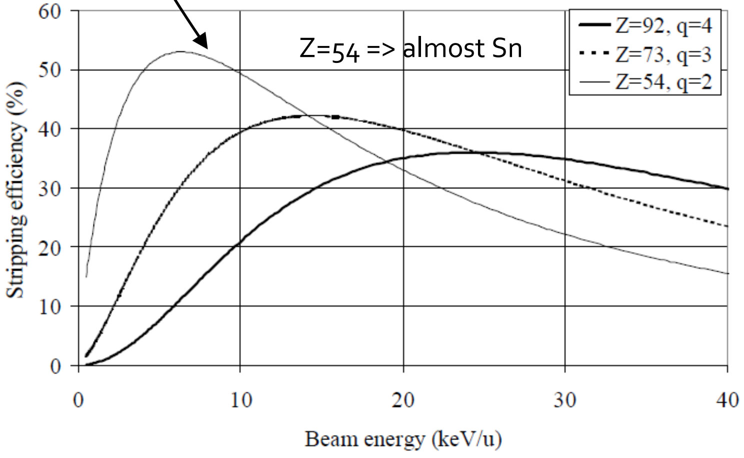
- but at each stripping stage the transmission is reduced due to the CSD

Example

Bunching efficiency	65%
Gas stripping to 2+ at 8 keV/u	~55%
Stripping foil to 23+ at 500 keV/u	20%
In total (single charge acc of ^{132}Sn)	7%

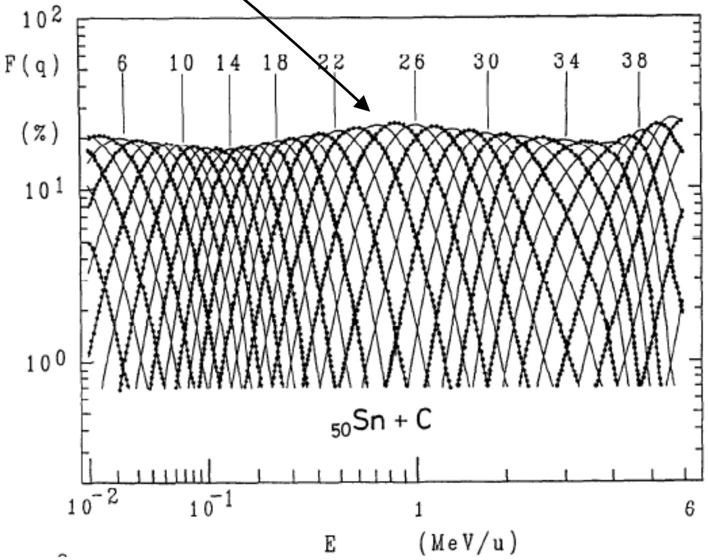
A bunch rotating rf cavity is mandatory in order to generate a time focus at the stripper to minimise the longitudinal emittance growth due to energy straggling.

Extra



Z=54 => almost Sn

Figure 1: Helium stripping efficiency of heavy ions as a function of beam energy.



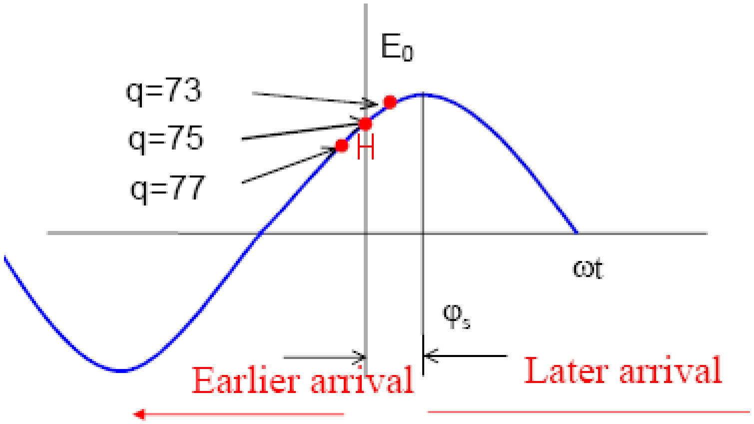
Extra

Multi-charge state acceleration

* Accelerate multiple q after the stripper

* Δq/q of ~20% can be accepted

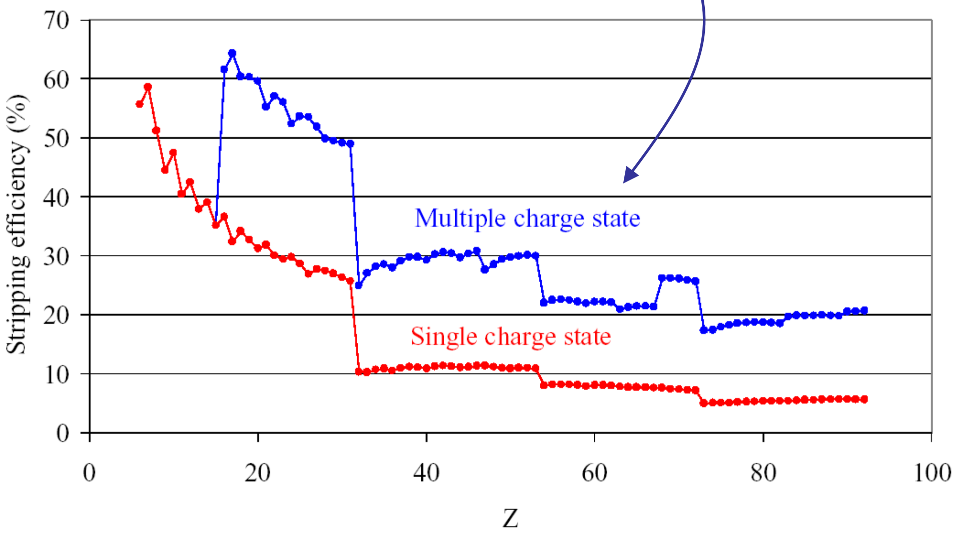
☺ Higher intensities



* Synchronous phase of multi-q beam

* The same final energy for all charge states

☹ ε (trans. and long.) ~3 larger compared with single charge state acceleration

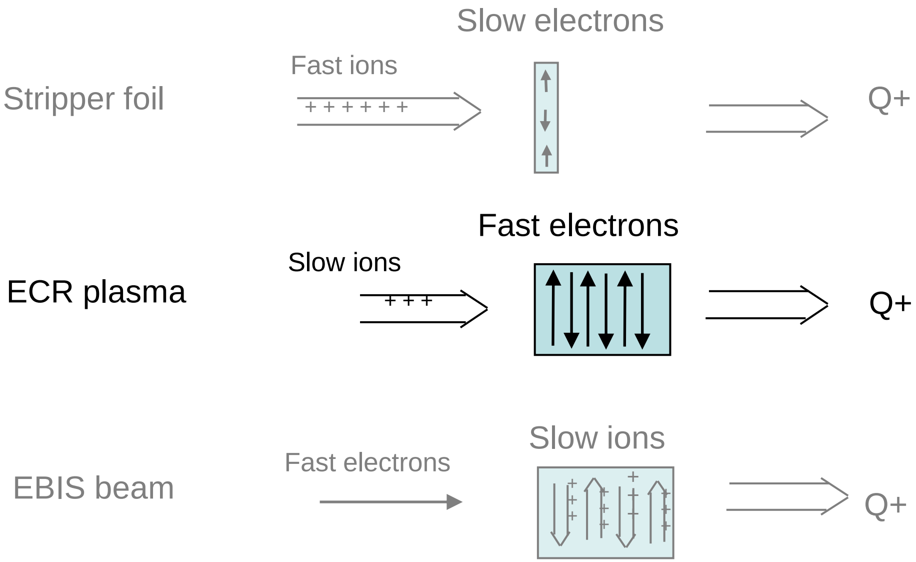


MCA and overall stripping efficiency (RIA proposal)

Stripping technique drawbacks

☹ Needs pre-acceleration	in gas stripping 8 to 20 keV/u **in foil stripping ~500 keV/u**
☹ Emittance increase	Energy straggling Angular straggling $\theta^2_{T1/2} = \theta^2_{I1/2} + \theta^2_{S1/2}$ $\varepsilon_T = \pi \cdot x_{T1/2} \cdot \theta_{T1/2}$ $x_{T1/2} = x_{I1/2}$=incident beam spot size $\theta_{T1/2}$=divergence exiting beam I =Incident, T=traverse, S=Scattering
😐 No macro-bunching capability	=> CW accelerator needed
? Foil lifetime	1. Radiation damage 2. Sublimation at high power levels (>150 W/cm2) => Not limiting for radioactive beam intensities
☹ Limited efficiency for high-Z elements	

The Second Alternative



Slow electrons

Stripper foil

Fast ions

+ + + + + +

Q+

Fast electrons

ECR plasma

Slow ions

+ + +

Q+

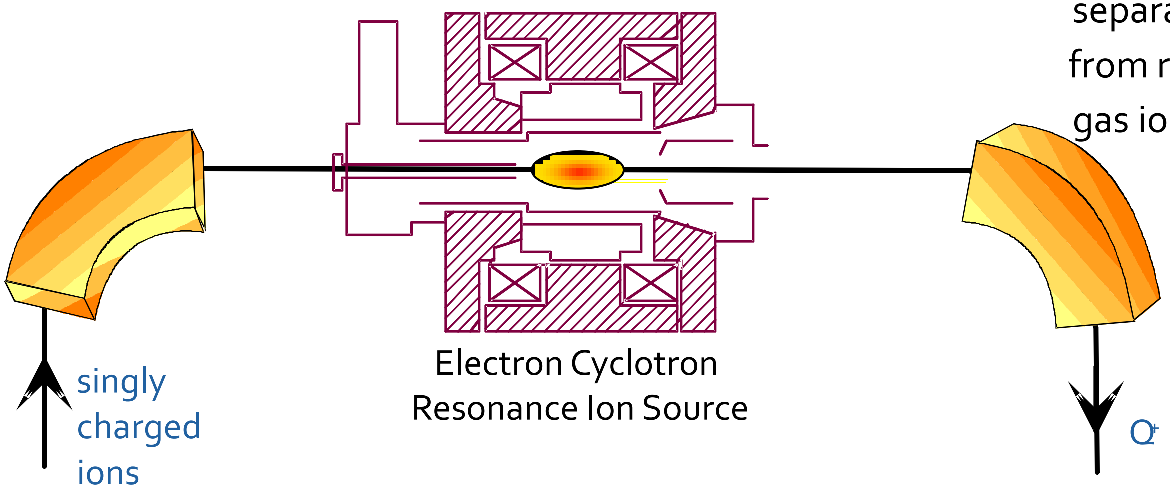
Slow ions

EBIS beam

Fast electrons

Q+

ECRIS
as charge breeder

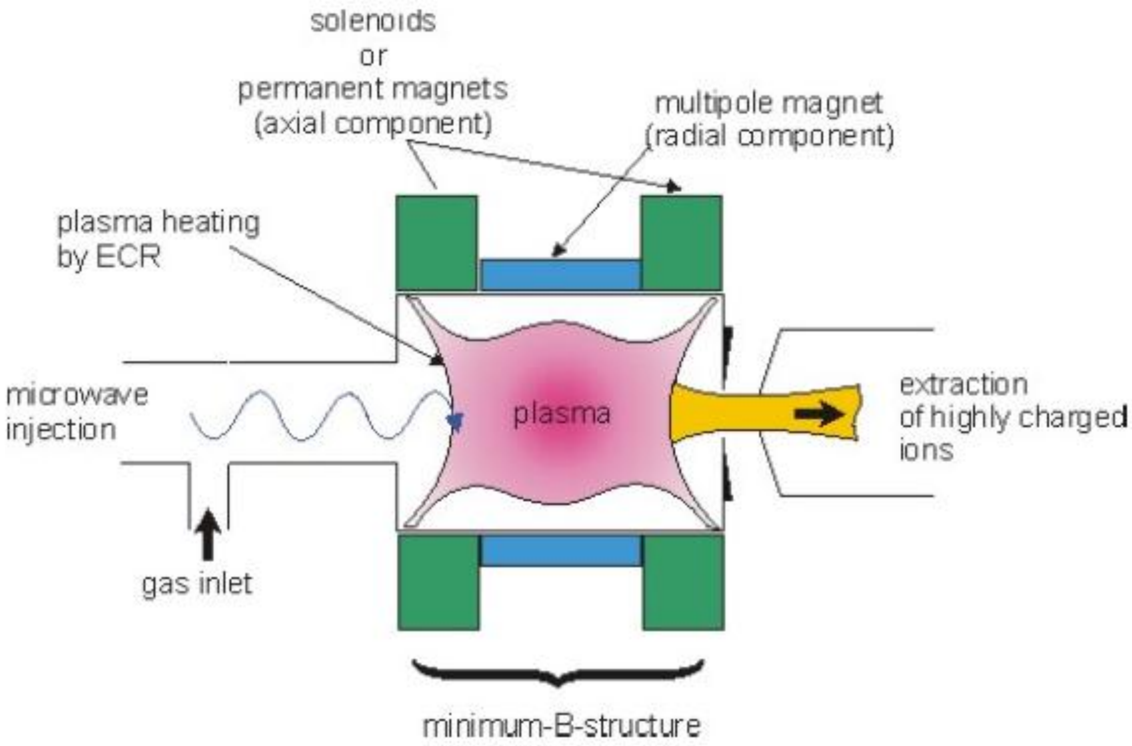


singly charged ions

Electron Cyclotron Resonance Ion Source

separation from residual gas ions

Q^+ ions



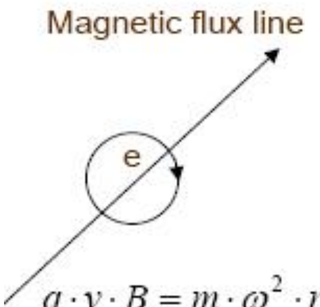
General principle

- inject very slow ions through a plasma of hot e^-

ECRIS physics

$$\omega_e = \frac{e \cdot B}{m} = \omega_{rf}$$

Plasma is resonantly heated with microwaves



$$q \cdot v \cdot B = m \cdot \omega^2 \cdot r$$

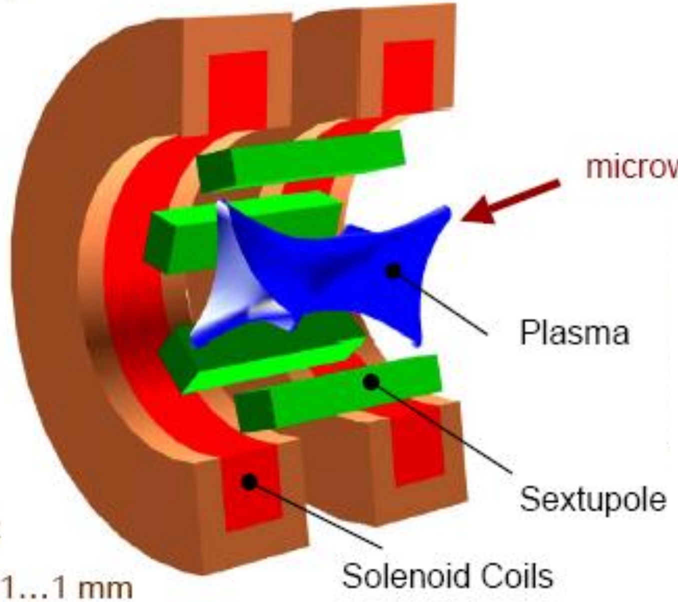
$$\omega = \frac{v}{r}$$

$$r = \frac{m \cdot v}{q \cdot B}$$

B= 1T

f=28 GHz

r_{Lamor}=0.01…1 mm



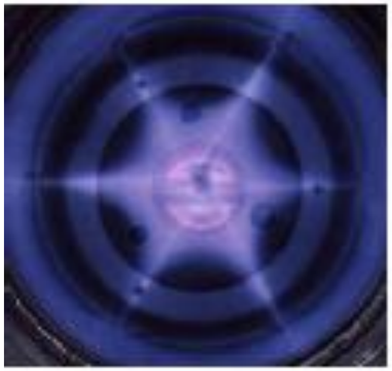


Photo of plasma

‘Magnetic bottle‘ confinement of plasma

* Longitudinally by Helmholtz coils
* Radially by powerful permanent multipole
=> min-B field – increases in all directions

e^- temperature distributions

Cold <200 eV: lowest confinement time
Warm < 100 keV: ionization process
(main source of bremstrahlung)
Hot > 100 keV: highly confined

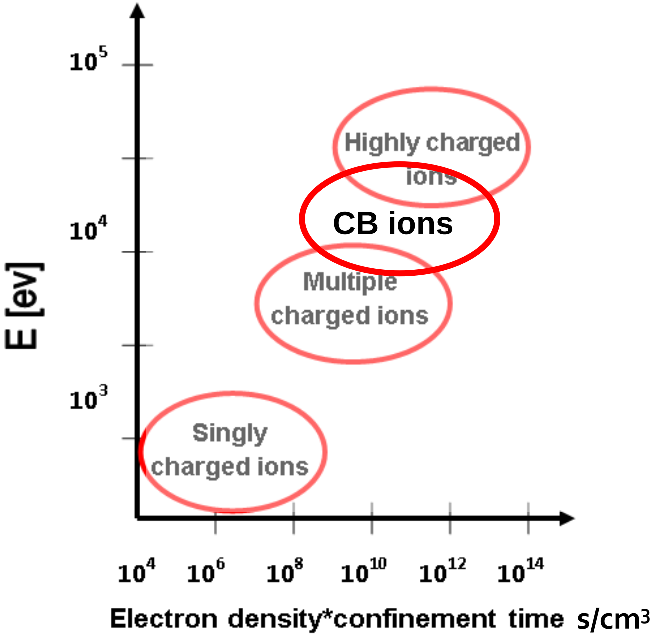
Extra

Electron confinement time: $\tau_e = \frac{T_e^{3/2}}{n_e} \cdot const$

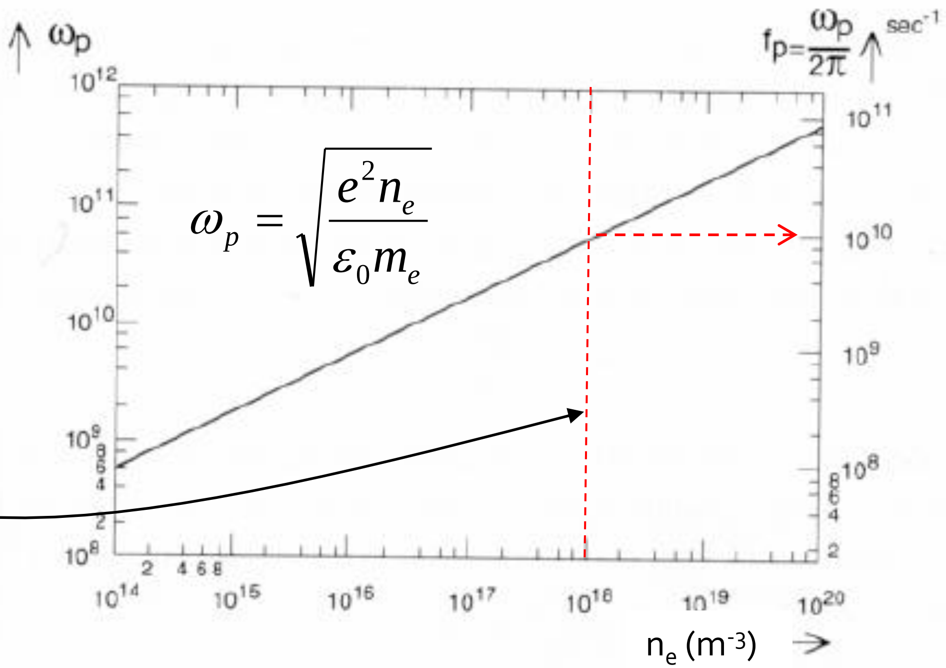
What RF is needed?

f_{RF} needs to be higher than the plasma frequency f_p (cut-off frequency)

$n_e < 1.2E10\ f_{RF}^2\ cm^{-3}$
f_{RF}= in gigahertz



Typical confinement time 0.1 s
=> need n_e ~1E12 cm^{-3}



$$\omega_p = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}}$$

Plasma frequency versus plasma density

Extra

Compare with stripper foils
n_e~1E24 cm^{-3} inside the foil
v_{ion}=1E9 cm/s, d_{carbon_foil}=0.5 um =>
$n_e * \tau$=5E10 s/cm³

ECRIS capacity

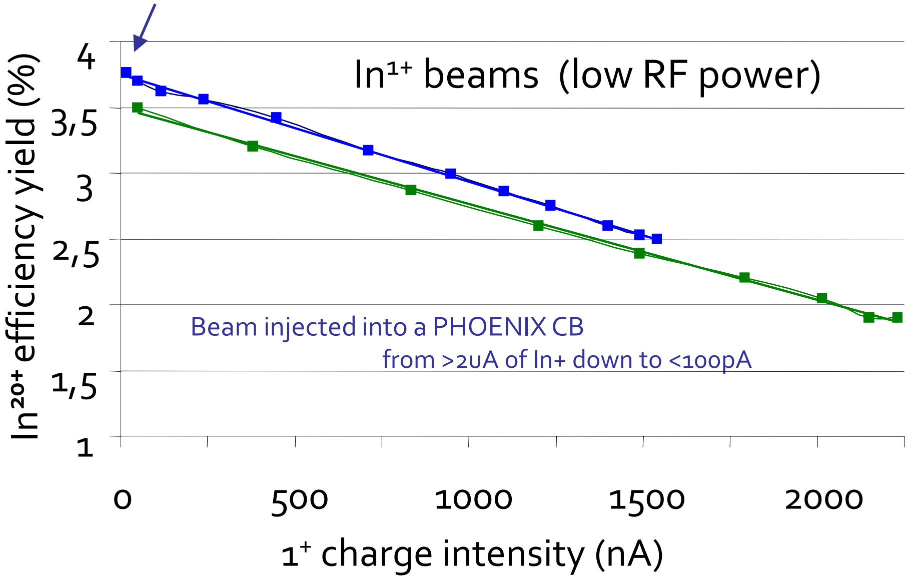
We know n_e ~ 1E12 cm^{-3} for charge breeding ECRIS

Assume:

- plasma volume r=2 cm, l=10 cm
- confinement time 0.1 s
- 10% radioactive ions
- 20% in the desired charge state 10+

=> 2.5E12 radioactive ions/s extracted (0.4 puA)

10 nA reached



In^{1+} beams (low RF power)

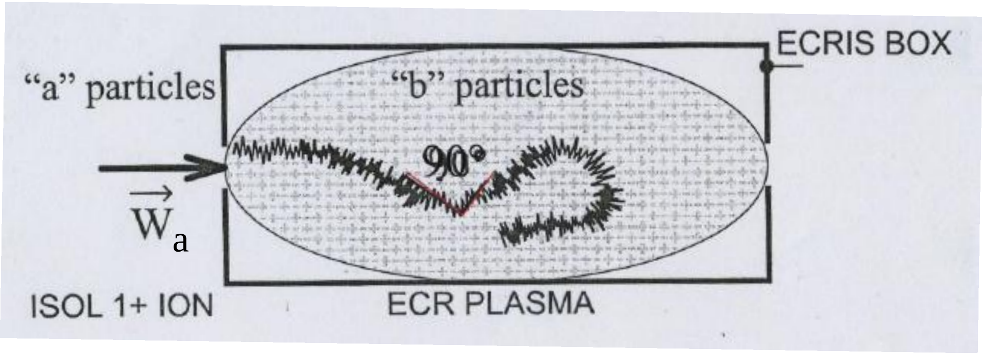
Beam injected into a PHOENIX CB from >2uA of In+ down to <100pA

The large capacity – a major strength of the ECRIS CB concept!

Stopping ions in ECRIS plasma

** Stopping of ions tricky and critical*
** No wall-collision tolerated*

1st electrostatic slow-down
2nd subsequent long-range
ion-ion Coulomb collisions
lead to 90° deflection*
3rd ionized
=> Ions trapped



* Cumulative deflection due to small-angle scattering is larger than those due to single large-angle scattering (Spitzer/Chandrasekhar theory)

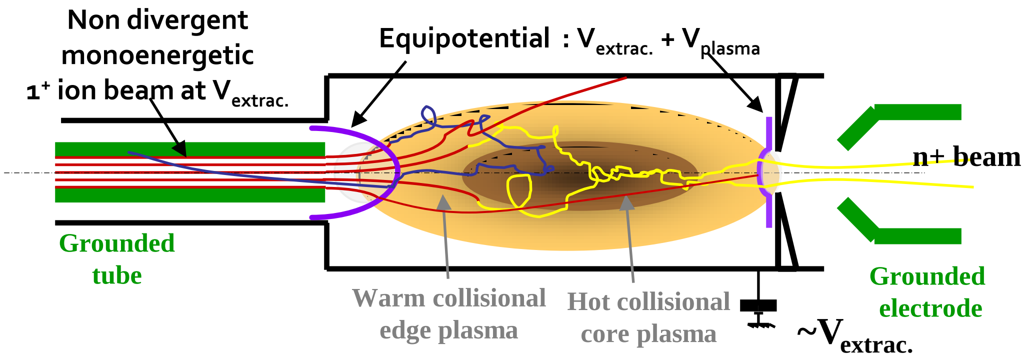
Mean free path for 90° deviation smaller than plasma size?

$$\lambda_{90^\circ} \approx \frac{W_a}{4\pi n_e z_a z_b e^2 \ln\Lambda}$$

Coulomb logarithm

$W_a=10$ eV $z_a=1$, $z_b=10$, $\ln\Lambda=10$

=> $\lambda_{90^\circ}\sim 5$ cm



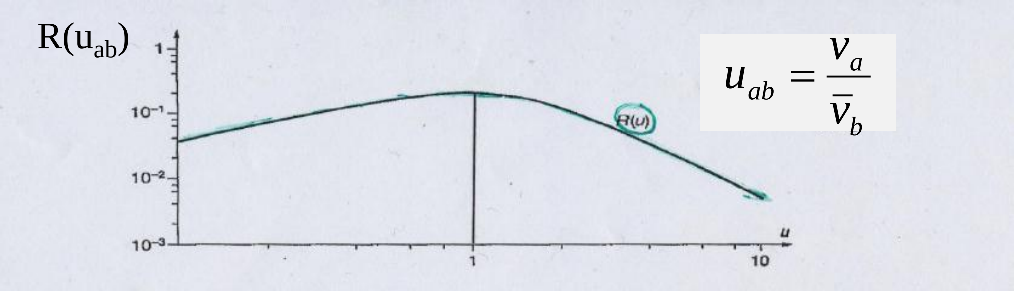
Injection velocity into ECR plasma

Extra

What is the optimal velocity for stopping inside a plasma?

Assumption
1. low intensity of injected particles
2. only interaction via long distance cumulative plasma collisions
3. plasma particles Maxwellian velocity distribution
4. distance between 90° deviations < plasma size

$$\frac{\Delta v_a}{\Delta t} \sim \frac{n_b}{2\pi\varepsilon_0}\left[\frac{Z_a Z_b e^2}{m_a \bar{v}_b}\right]^2 R(u_{ab})\ln\Lambda$$



$$u_{ab} = \frac{v_a}{\bar{v}_b}$$

Optimal slowing down when:

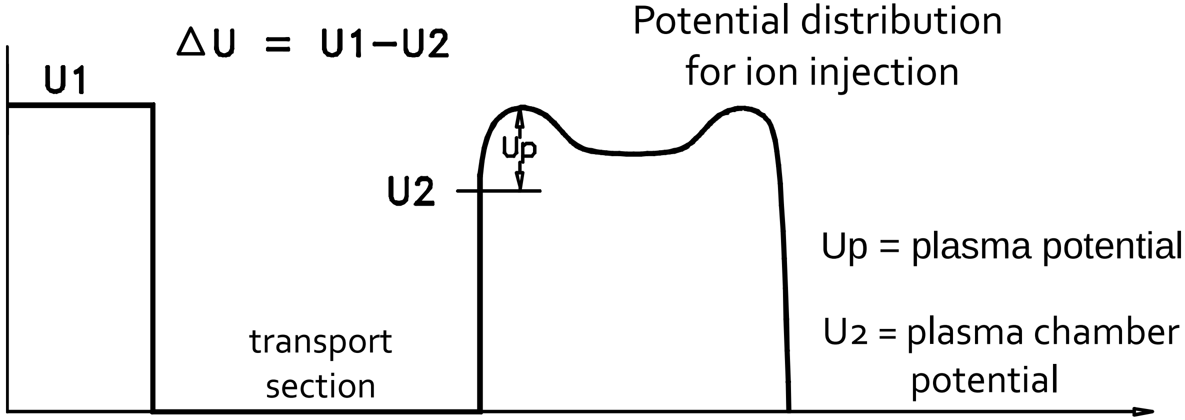
$v_{\text{injected particle}} = \langle v \rangle_{\text{plasma particles}}$

Example
* ECR oxygen plasma T^+=2 eV
* Rb^{1+} ISOL ions
$\Rightarrow E_{inj}(Rb^{1+}) \sim 2eV*m_{Rb}/m_O \sim 10$ eV

If we'd like to inject $^{11}Li^+$, optimum energy would be <2 eV => difficult

Compatible with previous slide!

Longitudinal acceptance



Potential distribution for ion injection

Up = plasma potential

U2 = plasma chamber potential

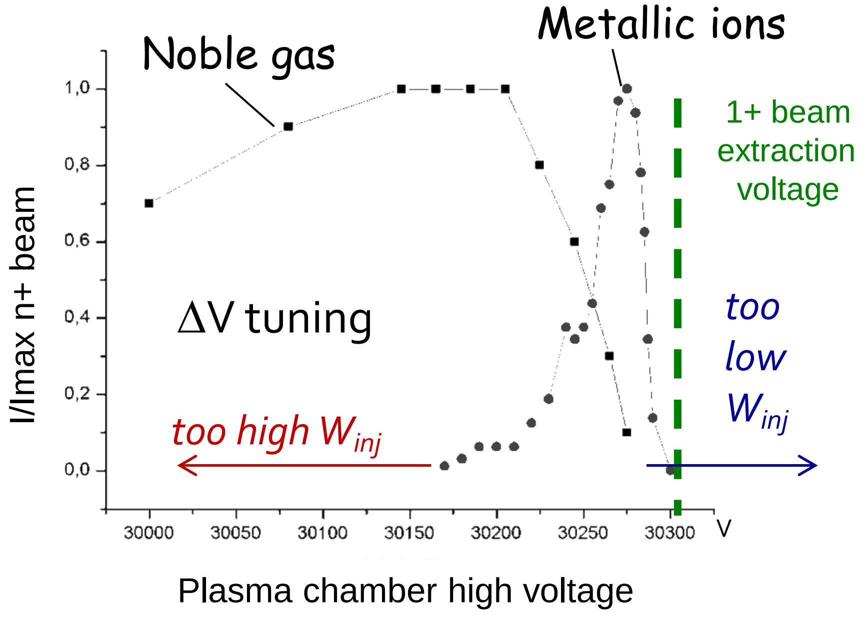
transport section

1+ -ion source

ECRIS

Noble gases
  - wall recycling

Condensable/metallic elements
  - only one trapping chance



Ionization efficiency vs injection voltage

Extra

Mean sojourn time given by Frenckel's law

$$\tau_d = \tau_0 e^{E_d / k_B T}$$

τ_0~1E-13 s, E_d – binding energy

Wide range: Ar 1E-11 s, Ni 100 years

How to change the charge state?

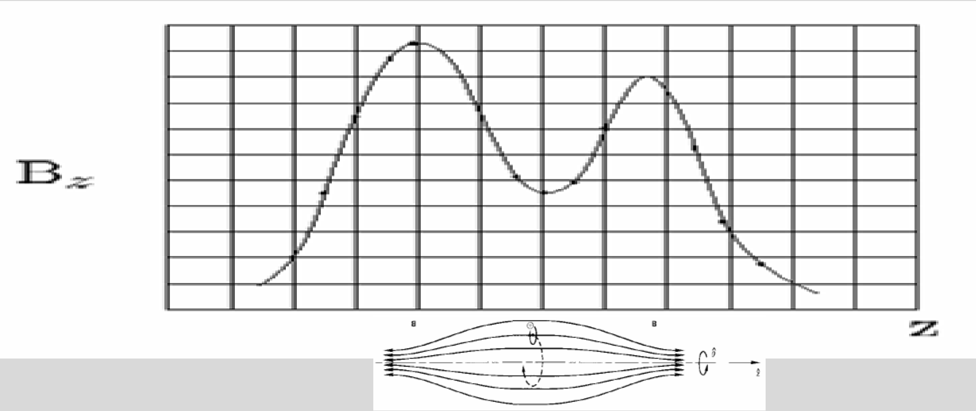
The attainable charge state is mainly depending on the:

electron density n_e
confinement time τ_{ion}
electron energy distribution EEDF

In reality adjust:

1. RF power $Q_{opt} = P_{RF}^{1/3}$
2. buffer gas pressure or mixture ->
   ion-ion cooling
   charge exchange probability
3. B_{ext} since $Q_{opt} \propto \ln B_{ext}$ →

Axial B-field



$$F_z = -\frac{1}{2}\frac{mv_r^2}{B}\frac{\partial B_z}{\partial z} = -\mu\frac{\partial B_z}{\partial z}$$

Conserved
total energy
magnetic moment μ

=> Magnetic bottle

longer τ_e -> longer τ_{ion}

Extra

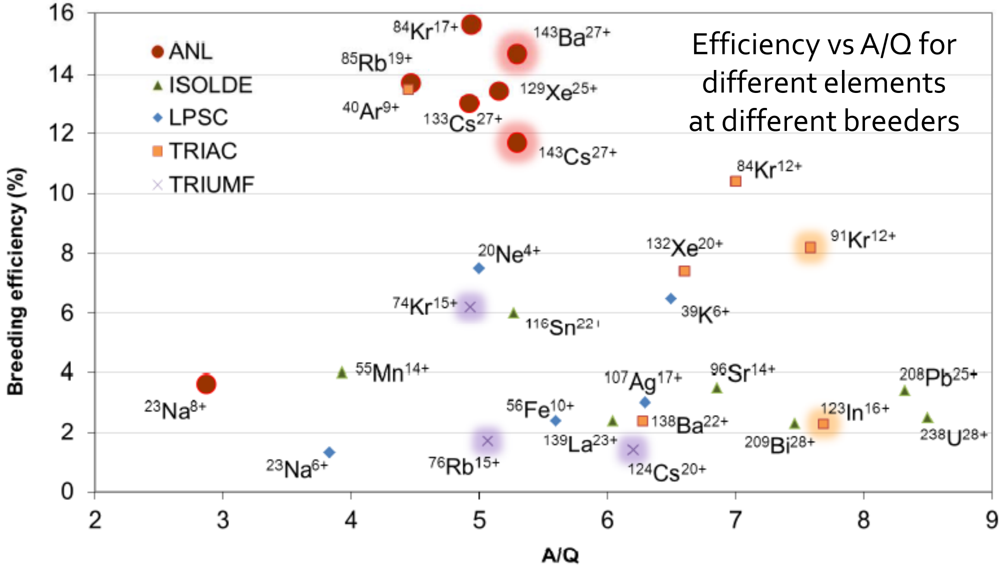
Extracted beam properties

* Extracted energy spread few eV

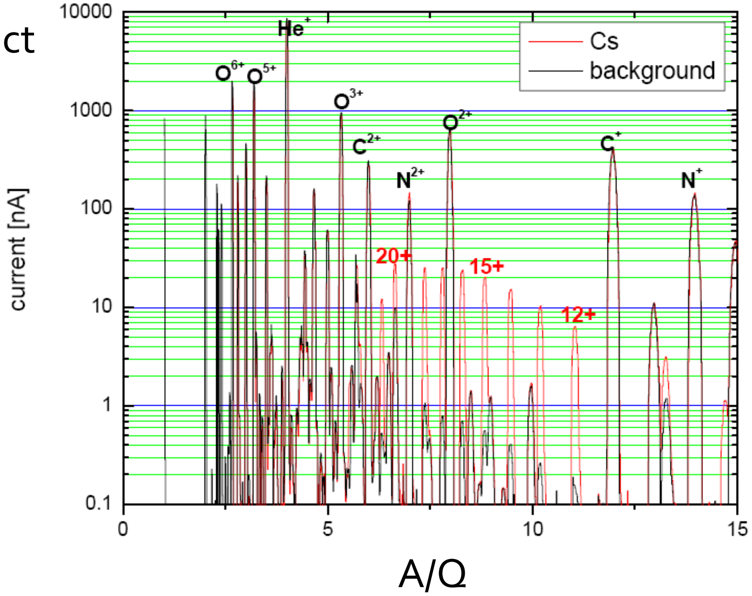
* Total $I_{extracted}$ ~100 uA:
+ radioactive ions

- buffer gas ions (He, Ne or O)

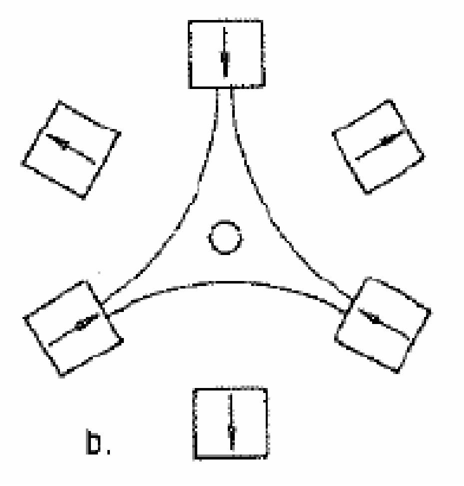
- ions from the plasma chamber
  sputtering of chamber material
  desorption of implanted ions – memory effect



Efficiency vs A/Q for different elements at different breeders



Extracted beam with and without Cs+



Loss lines for a hexapole structure

ECRIT mode

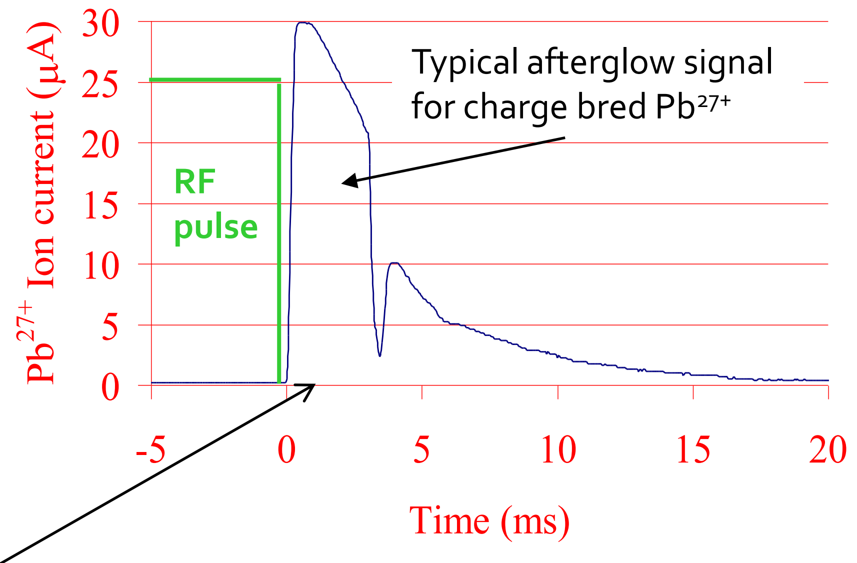
Normal operation mode:

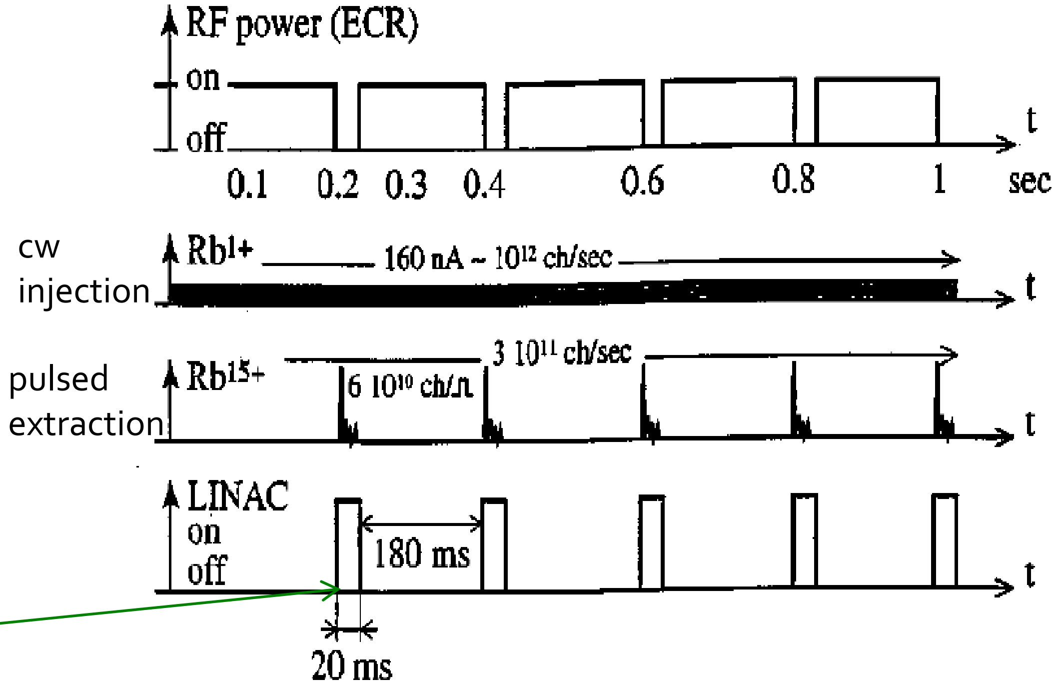
cw injection

cw extraction

Make use of afterglow:

1. Switch off RF
2. Heating of electrons stops
3. Electron confinement stops
4. Plasma instability / Coulomb expulsion of trapped ions





Result:

a. ion trapping (some 100 ms)

b. pulsed beam extraction (some ms)

Pulsed linac operation possible

Extra

Practical design aspects

* Similar magnetic-field relations for charge breeding ECRIS CB as for high-Q ECRIS:

$B_{inj}/B_{ecr} \sim 4$, $B_{ext}/B_{ecr} \sim 2$, $B_{min}/B_{ecr} \sim 0.8$, $B_{rad}/B_{ecr} > 2$, $B_{ext}/B_{rad} < 0.9$

B_{inj} (B_{ext}) is the B-field max at injection side (extraction side)
B_{rad} the radial B-field of the sextupole at the plasma chamber wall
B_{min} the minimum B-field between the magnetic mirrors

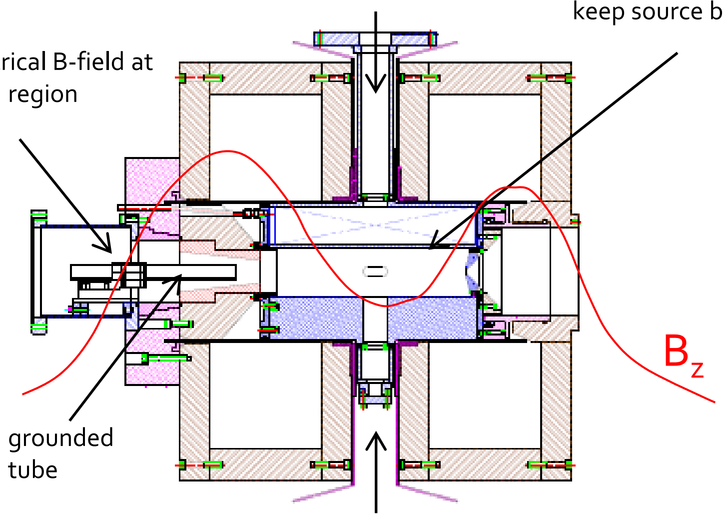
* Grounded injection tube just inside B_{inj}

* Radial RF injection preferred to axial

Better pumping of the chamber

Only put plasma chamber on HT, keep source body at ground

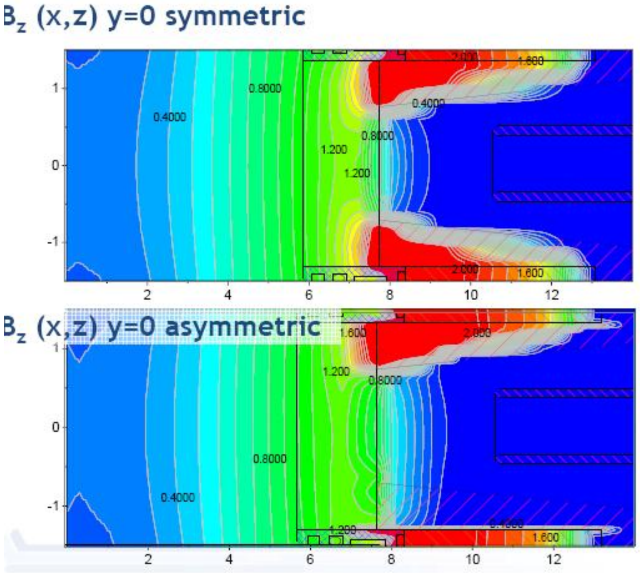
Symmetrical B-field at injection region



Movable grounded injection tube

RF injected radially

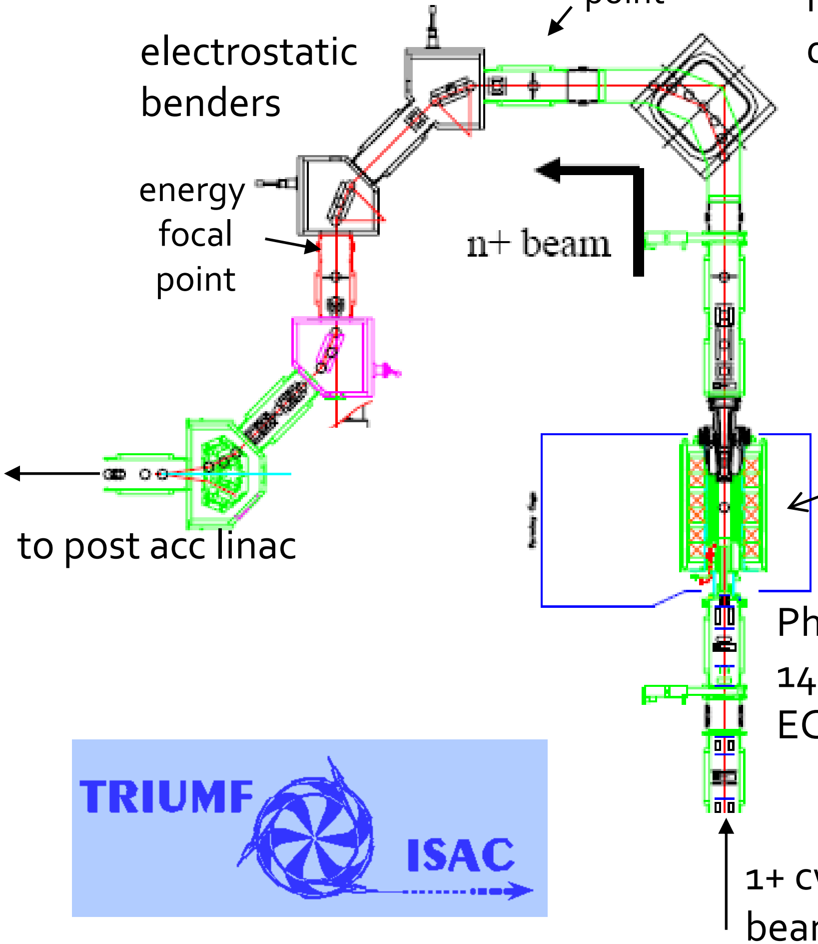
Radial RF wave-guide



Axial RF wave-guide

Asymmetric B-field deflects injected particles

ECRIS CB facility



mass
focal
point

magnet
dipole

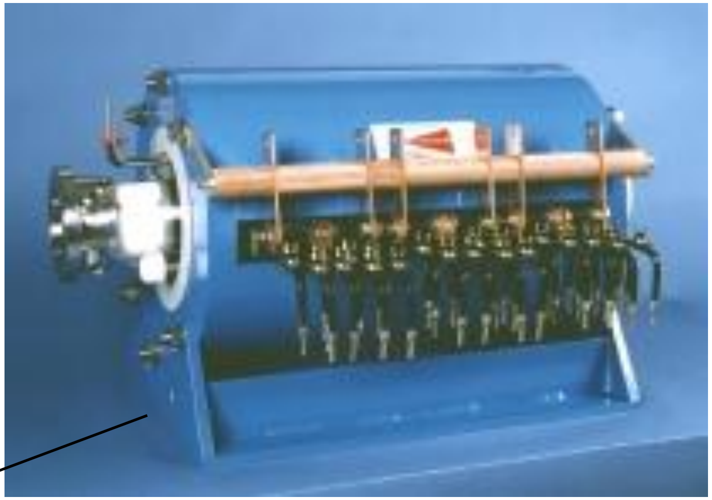
electrostatic
benders

energy
focal
point

to post acc linac

Phoenix
14 GHz
ECRIS

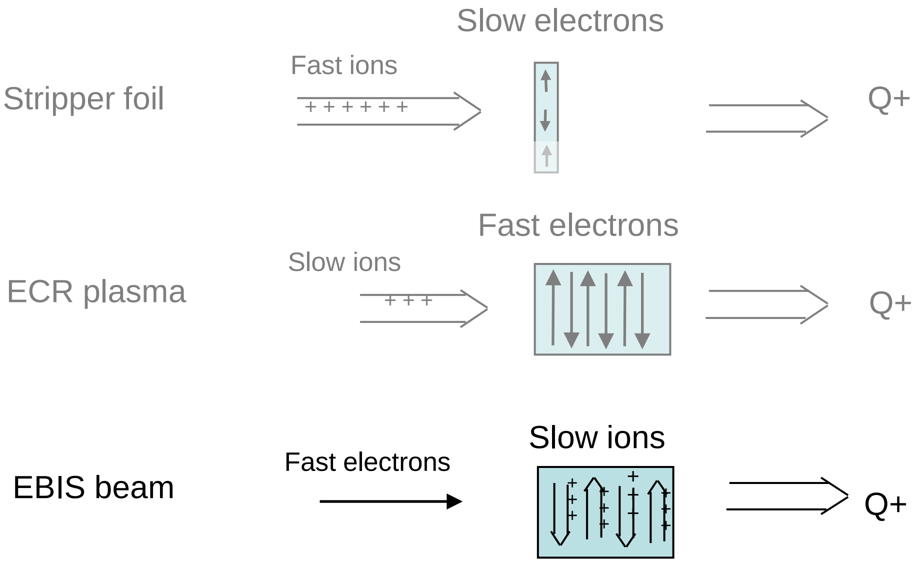
1+ cw
beam



TRIUMF ISAC

- * ECRIS charge breeder specifications:
  A/Q<7 for A<150
- * cw injection and extraction
- * Superconducting linac
- * Combined electrostatic and magnetic selection

The Third Alternative



Stripper foil

Fast ions

Slow electrons

Q+

ECR plasma

Slow ions

Fast electrons

Q+

EBIS beam

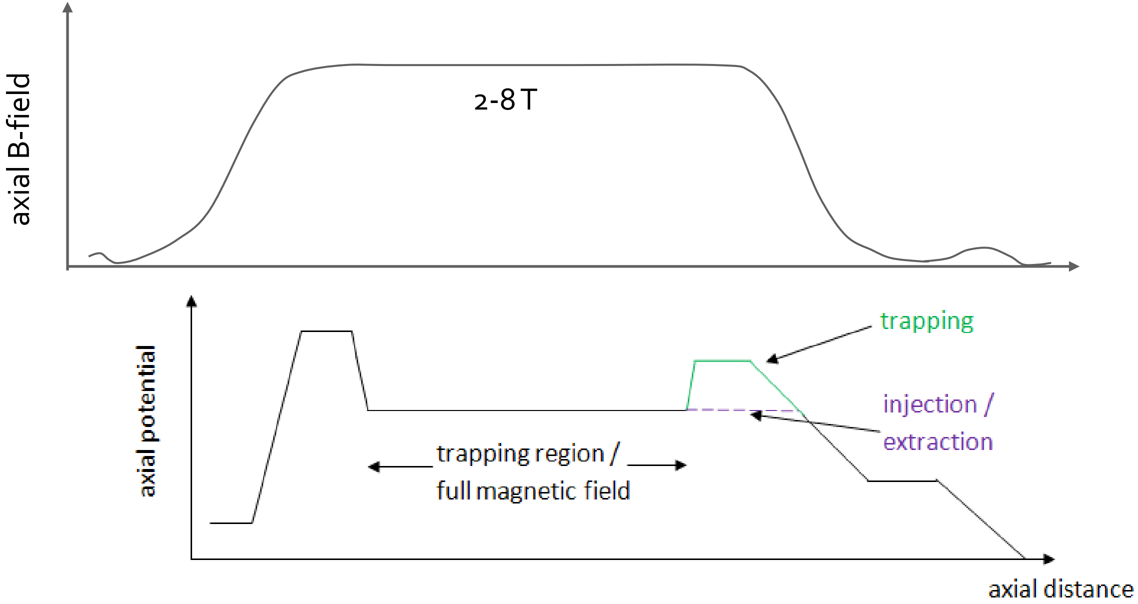
Fast electrons

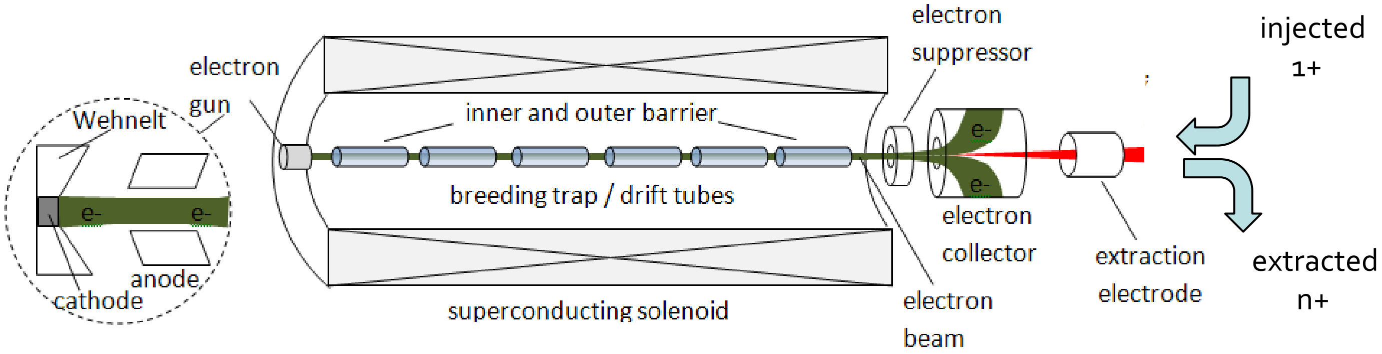
Slow ions

Q+

Electron Beam Ion Source /Trap

- Produces highly charged ions
- e^- beam compressed by solenoid B-field
- Ions are trapped in a magneto-electrostatic trap
- Ionisation by e^- bombardment from a fast, dense mono-energetic e^- beam





EBIT - in principle an EBIS but:

1. higher electron current density
2. shorter (few cm)
3. smaller r_{ebeam}

Some consequences for CB!

Breeding time

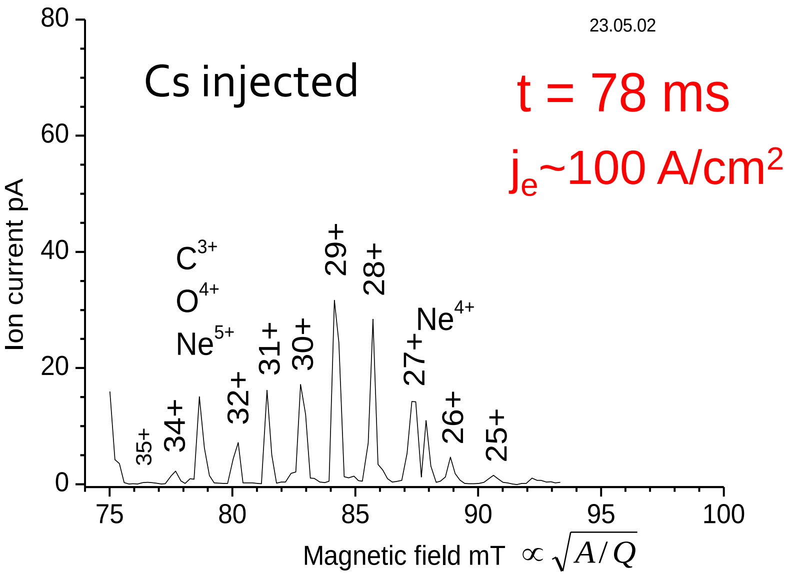
The average time necessary to reach the charge state *q*:

$$\bar{\tau}_q = \sum_{i=1}^{q-1} \bar{\tau}_{i\to i+1} = \frac{1}{j_e}\sum_{i=1}^{q-1}\frac{e}{\sigma_{i\to i+1}}$$

σ – single ionization cross-section cm²
j_e – electron current density A/cm²
valid for mono-energetic electrons

j_e usually machine fix
j_e between 50 and 5000 A/cm²

⇒ Chose A/Q by adjusting the breeding time

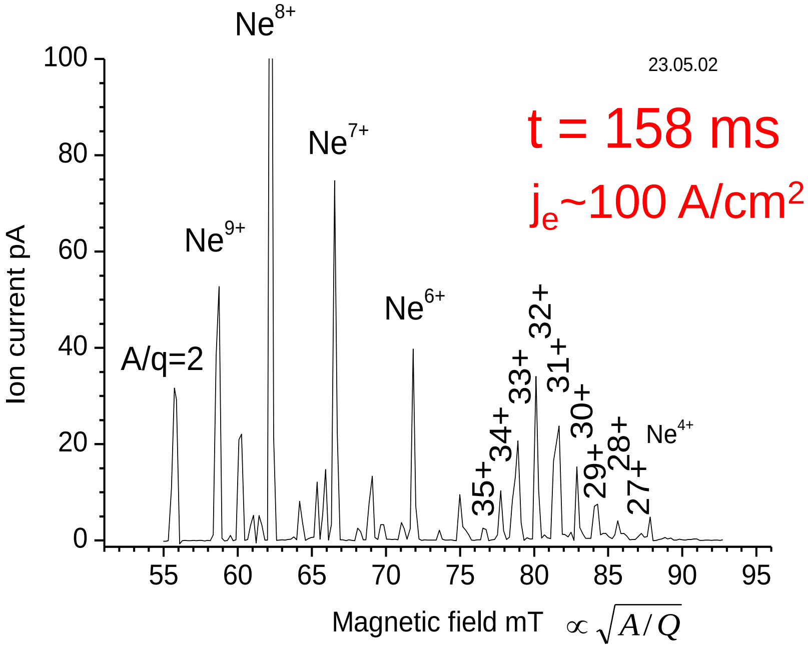


23.05.02

Cs injected

t = 78 ms

j_e~100 A/cm²



23.05.02

t = 158 ms

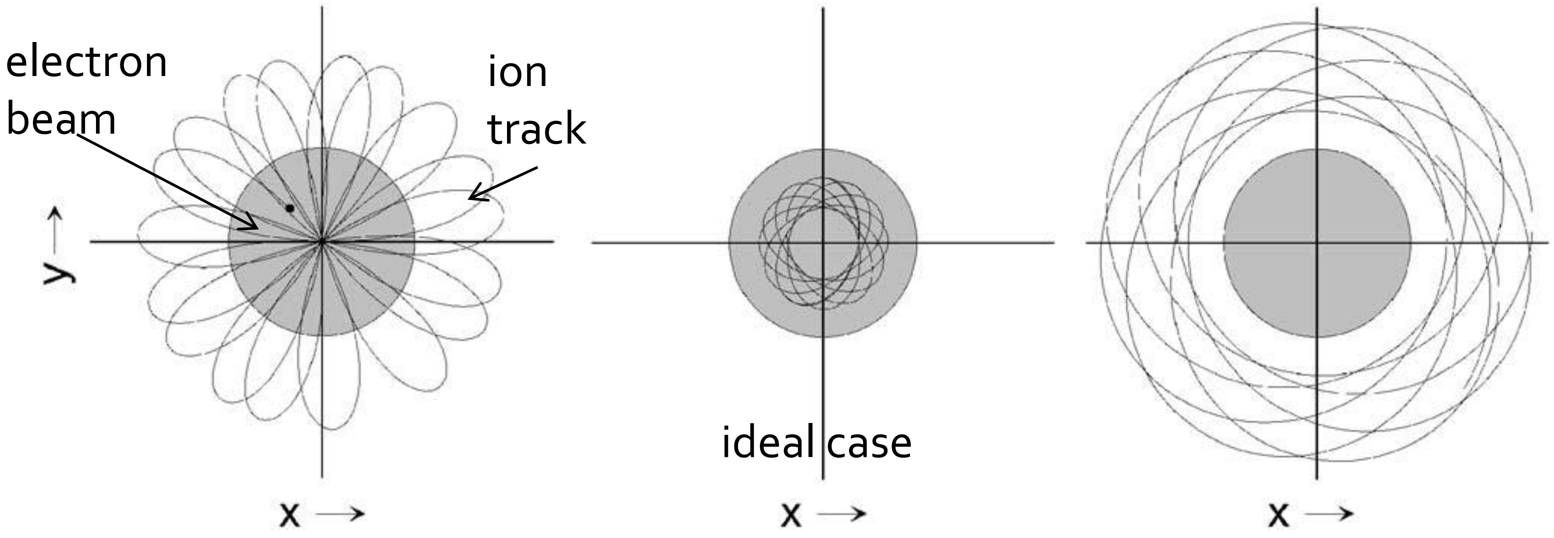
j_e~100 A/cm²

NB! $I_e=j_e*r_{ebeam}^2*\pi$ *1st reason for high I_e*

Ion injection EBIS

Desired: overlap between injected ion beam and electron beam

If injection outside electron beam => effective j_e low => increased T_{breed}



Geometrical transverse acceptance

magnetic confinement

$$\alpha_{\max} = \pi \frac{r_{ebeam}}{\sqrt{2U_{ext}}} \cdot \left(Br_{ebeam}\sqrt{\frac{q}{m}} + \sqrt{\frac{qB^2 r_{ebeam}^2}{4m} + \frac{\overset{\text{ebeam space charge per meter}}{\rho_l}}{2\pi\varepsilon_0}} \right)$$

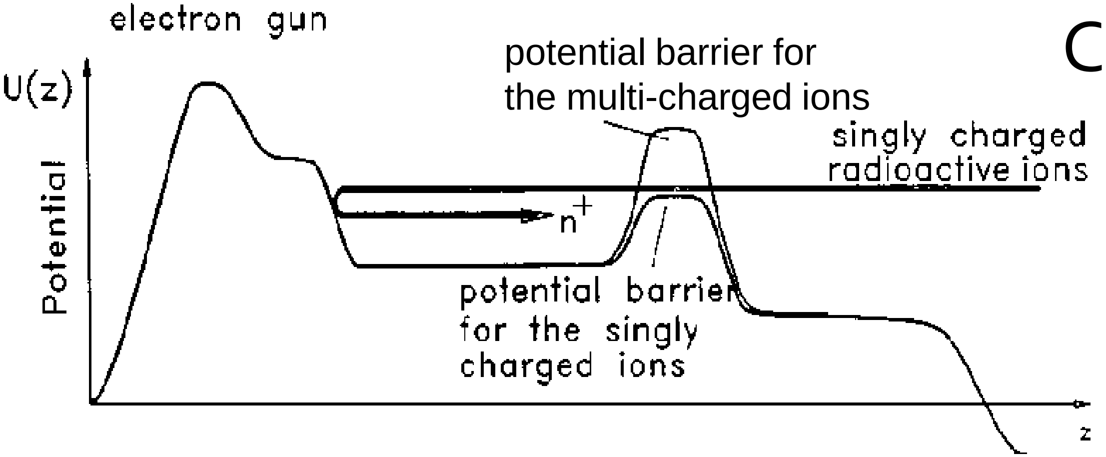
2^{nd} reason for large I_e

NB1. ion neutralization reduces the acceptance

NB2.+ EBIS/T small ε ->
- EBIS/T small α

* REXEBIS value **~10 π mm mrad** for 90% @ 60 keV

CW ion injection EBIS



Condition for trapping

1. Transverse acceptance
2. Ionization

No dissipative forces but
$U_{barrier}$ doubles when 1+ -> 2+
=> axially confined

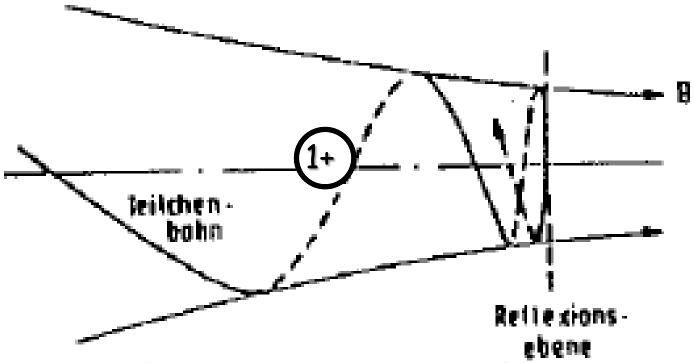
$t_{1\text{->}2}$ -> $e/(\sigma_{1\text{->}2} \cdot j_e)$
Prob(1^+ -> 2^+)=1-exp($-t_{inside\_ebeam}/t_{1\text{->}2}$)

Example ^{14}N
$\sigma_{1\text{->}2}$=1E-17cm^2
j_e=200 A/cm^2
Prob=0.5

$t_{1\text{->}2}$ = 55 us

Thus:
Inject with low energy for long round-trip time

But too low energy =>
magnetic reflection



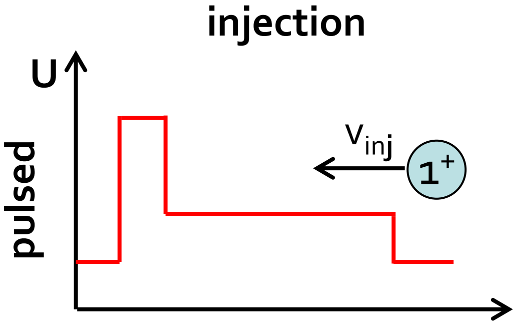
Ion reflection in magnetic field

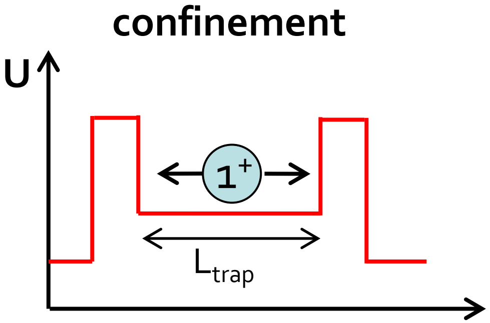
High acceptance for a CW injected beam is obtained, if a L_{trap} long and r_{ebeam} large and j_e large

(last two in contradiction as $I_e=j_e*r_{ebeam}^2*\pi$)

Extra

Pulsed ion injection EBIS



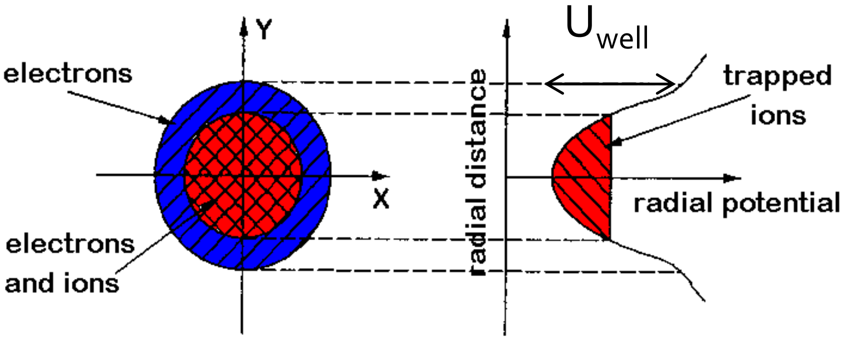


Longitudinal acceptance:

$W_{inj} < e \cdot U_{well}$ (some 100 eV)

$\Delta T < 2 \cdot L_{trap}/v_{inj} \sim 50$ us

(L_{trap}=1 m, W_{inj}=100 eV, A=14)



Radial potential

$$U_{well} = \frac{I_e}{4\pi\varepsilon_0}\sqrt{\frac{m_e}{2eU_e}}$$

I_e – electron beam (A)
U_e – electron beam voltage (V)

Extra

Reality even more complicated…

1. Entangled parameters
2. Benefits from reduced emittance

–> preparatory RFQ buffer gas cooler
or Penning trap

Extra

Electron beam energy

How to choose electron beam energy U_e for charge breeders?

1. Related to the available current through the perveance:
   $I_e=PU^{3/2}$ (practical limit P~5 uPerv) Example I_e=1 A => U_e > 3500 eV
2. U_e has to be larger than the ionization potential I_p for required charge state Q.
   Worst case - reach elements close to neutron dripline, since excess of neutrons.

Z	**A (neutron rich)**	**Q (A/Q~4)**	**$I_{ionization}$ (eV)**
20	60	15	900
40	110	27	1500
60	161	40	2800
80	210	52	3100

Cross section max at $2.7*I_{ionization}$

$\Rightarrow$ No need for U_e > 9000 eV

EBIS capacity

Space charge capacity – determined mainly by the electron beam

$$N^- = k\frac{L_{trap} r_{ebeam}^2 \pi}{e}\rho_e \qquad \rho_e = \frac{j_e}{v_e} = \frac{I_e}{\pi \cdot r_{ebeam}^2}\sqrt{\frac{m_e}{2eU_e}} \quad \Rightarrow \quad \boxed{N^- = 1.05\cdot 10^{13}\frac{kL_{trap}I_e}{\sqrt{U_e}}}$$

N^- = number of elementary charges

I_e and U_e = electron beam current and energy

k = attainable space charge compensation degree

L_{trap} = trap length

3rd reason for high current

Example $^{132}Sn^{34+}$ using REXEBIS parameters:

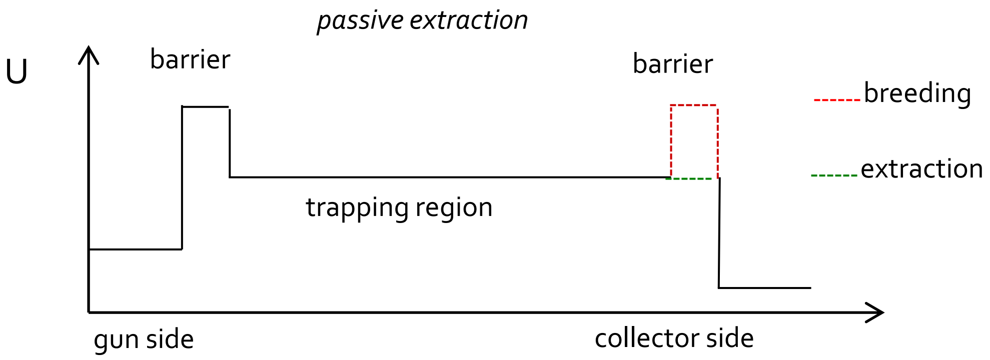
I_e = 0.5 A, U_e = 5 keV, L = 0.8 m, k = 50%=> ~$3\cdot 10^{10}$ charges

=> 3E10/34*0.2 = 2E8 ions/pulse

~20% in desired charge state

NB! Ion throughput (ions/s) = (ions/pulse) / T_{breed}

Beam extraction scenarios



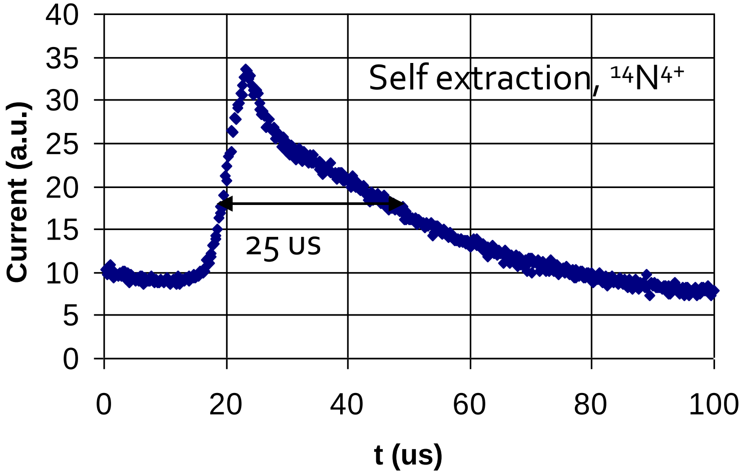
For REXEBIS duty factor
T_{extr}/T_{breed} ~ 100 us /100 ms

=> Good signal-to-noise-ratio

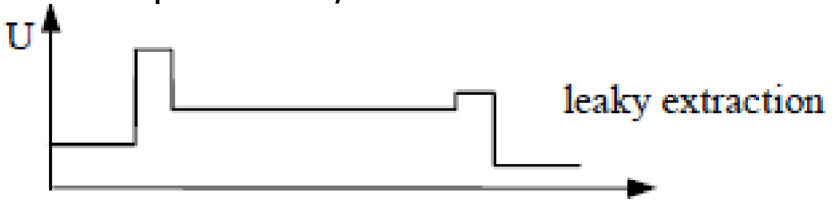
if heating by e- and ion-ion cooling neglected

$v_{ion\_extr} \sim v_{ion\_inj}$ (W_{inj} ~ 100 eV)

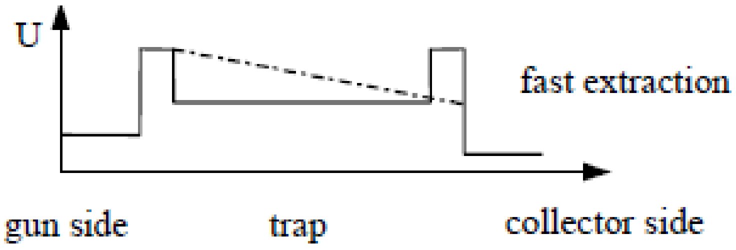
$\Delta T_{extr} \sim L_{trap} / v_{ion\_extr}$ ~ 25 us for ^{14}N



Reduce instantaneous rate
to experiment, 1 ms

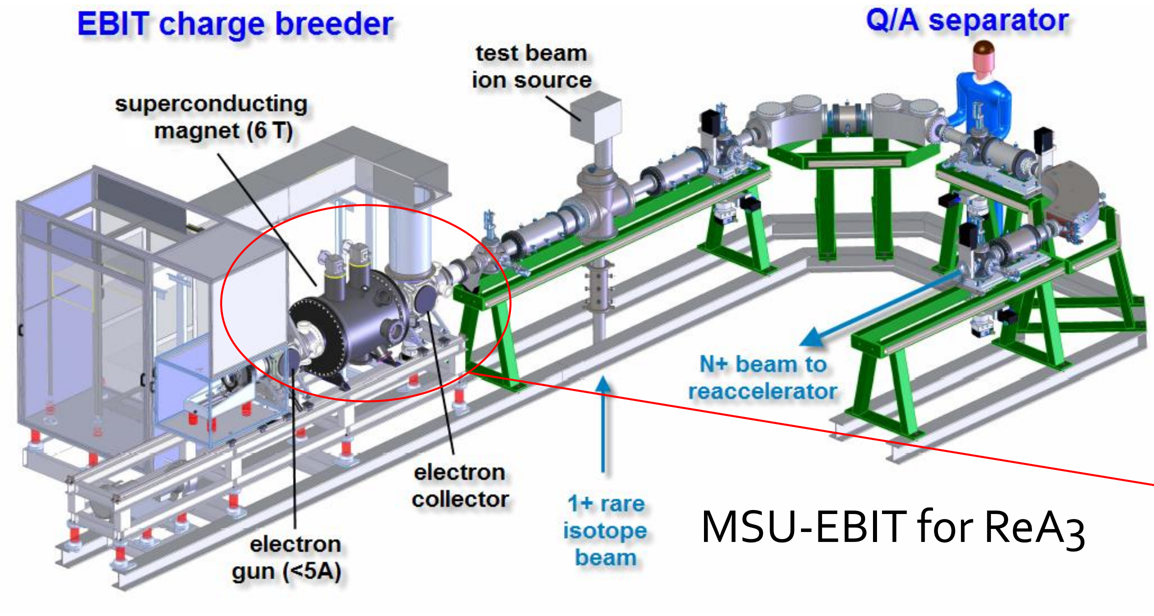


Speed up extraction for multi-turn
injection into synchrotron <10 us



EBIT CB facility

3 MeV/u re-accelerator of thermalized projectile fragmentation and fission beams



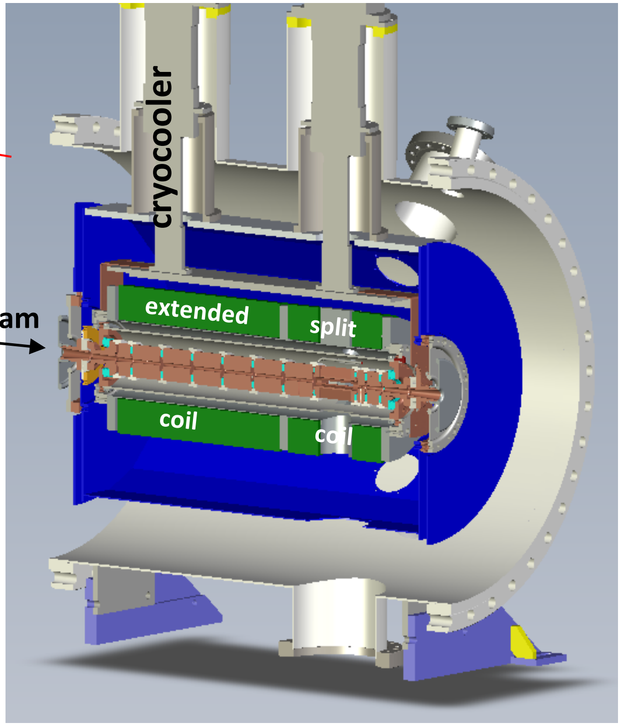
MSU-EBIT for ReA3

With 1E4 A/cm2 ->

1. charge breed ions with Z<35 into Ne-like or higher within 10 ms
2. ionize from 1+ to 2+ within <1 us

Design goals

- Continuous injection and accumulation of ions
- Variable extraction duty cycle
  (ms pulse to quasi-continuous)
- Electron current density >1E4 /cm2
- Beam rates >1E9 ions/s
- Highest efficiency
  (> 50% in a single charge state)



Cryogenic trapping region

Preparatory devices and tricks

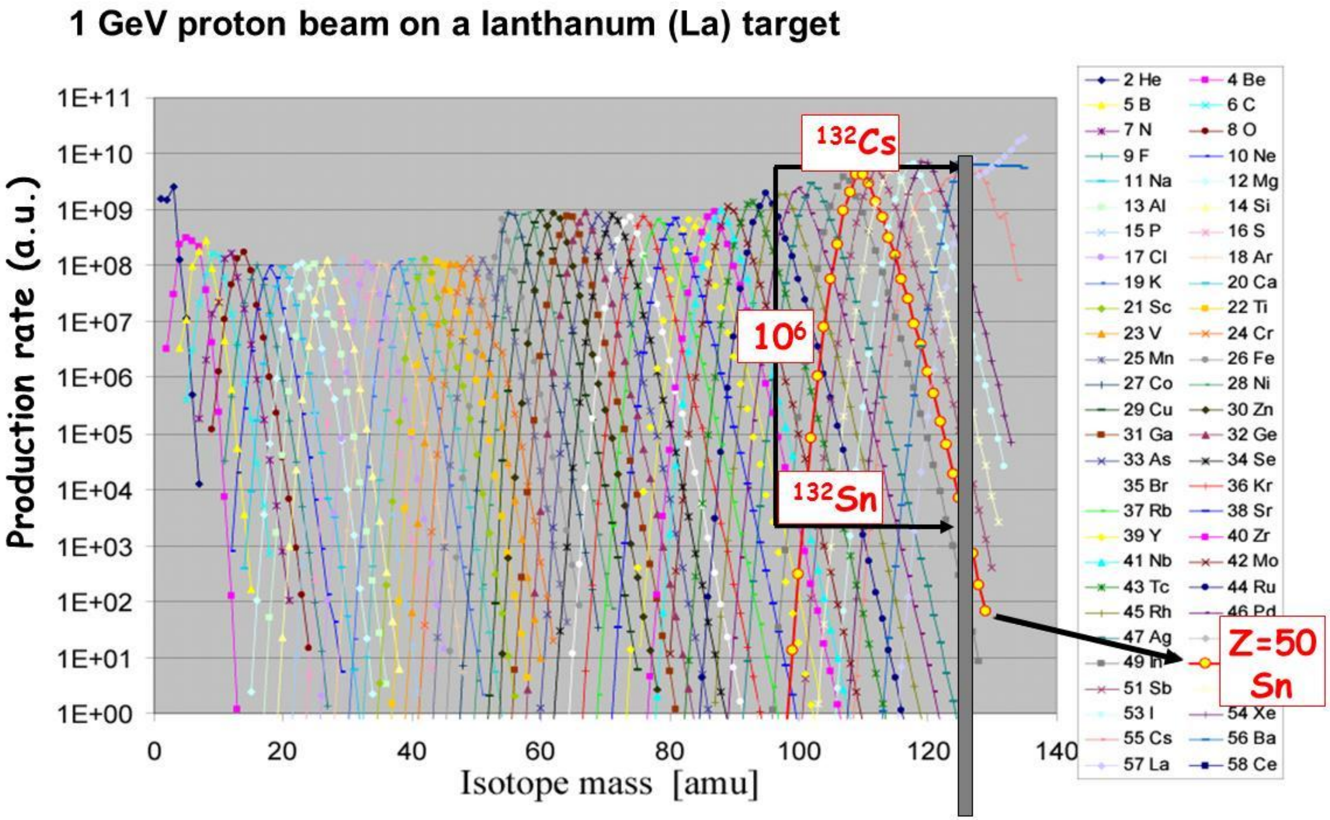
Beam contamination

Can't see the trees for the forest

Remember: often deal with <1E4 pps => 1.7 fA

Beam impurities:

a. isobaric contamination
   from ISOL-target

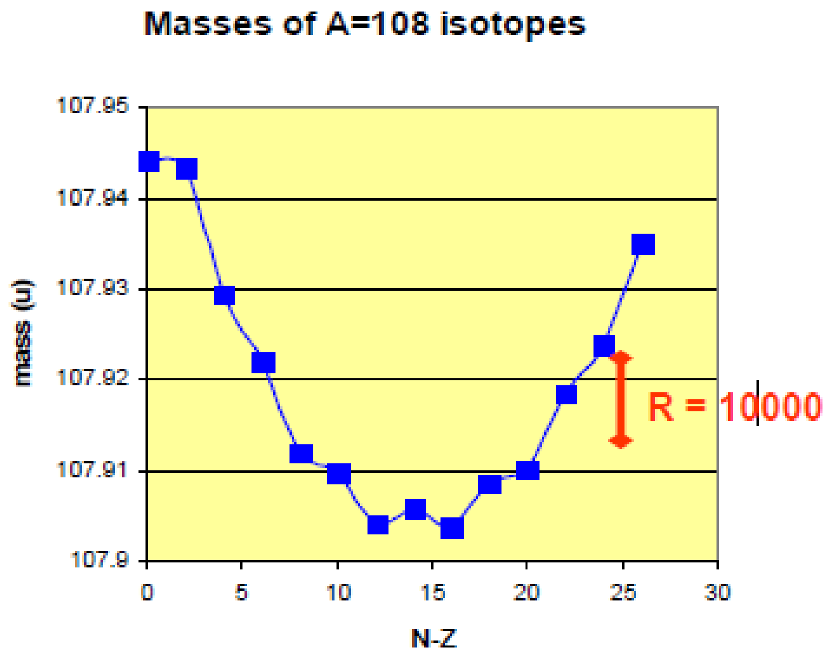


1 GeV proton beam on a lanthanum (La) target

J. Lettry, V. Fedoseev (CERN)

Extra

ISOL beam separation



Problem: isobaric separation difficult

* Requires RFQ cooler for pre-cooling of transverse ε

* Tails of high intensity masses may go through selection system

Resolution required to separate:

Neighbouring mass:	R=250
Molecular ions (e.g. CO from N_2):	R=500-1000
Isobars (e.g. ^{96}Sr from ^{96}Rb):	R=5000-50000
Isomers:	R=1E5 - 1E6

Solution

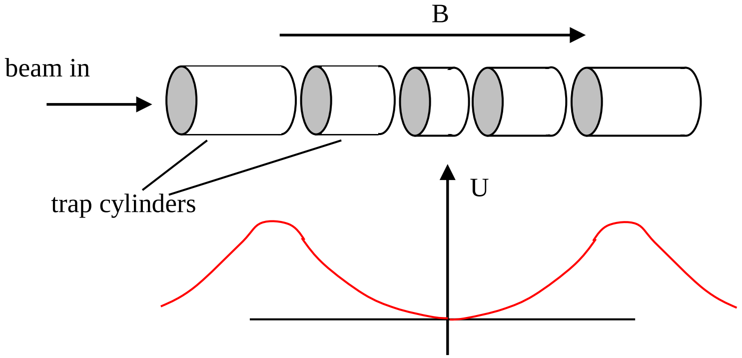
1. Isobaric mass resolution inside Penning trap
2. Molecular beams

Preparatory beam cooling

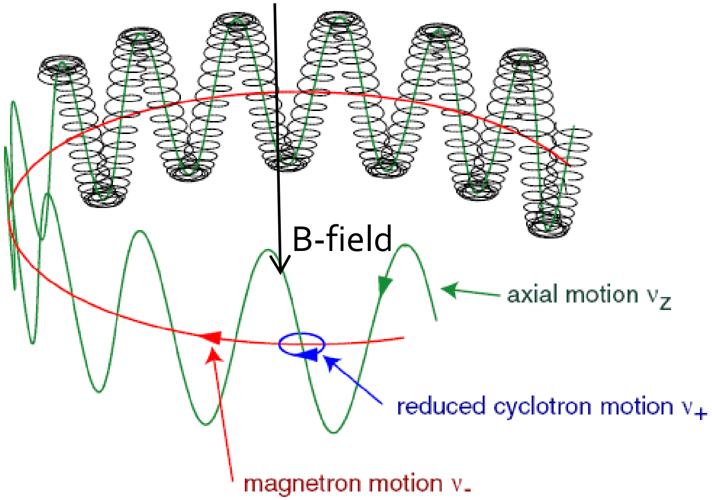
Introduce a *Penning trap* in ISOL-line to:

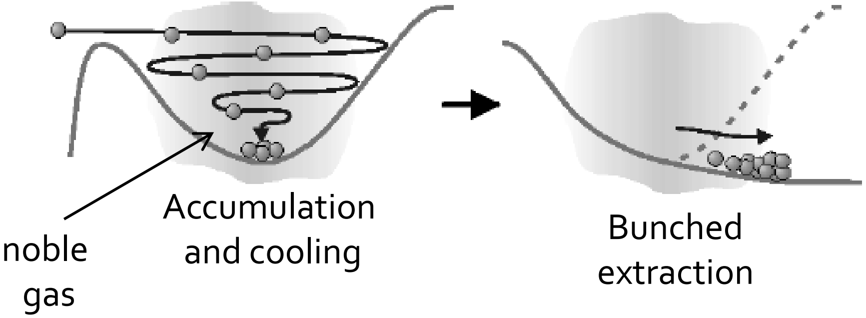
accumulate
phase space cool
bunch the beam

gas filled cylindrical Penning trap



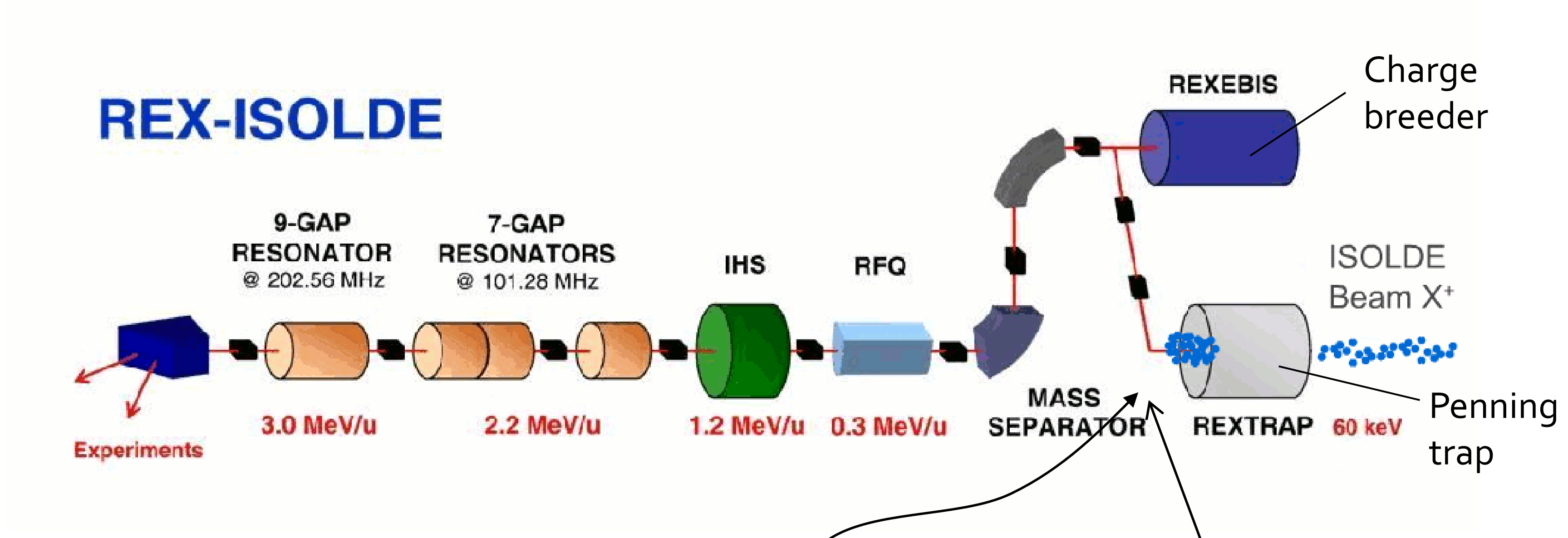
Axially - electrostatic field
Radially – magnetic field



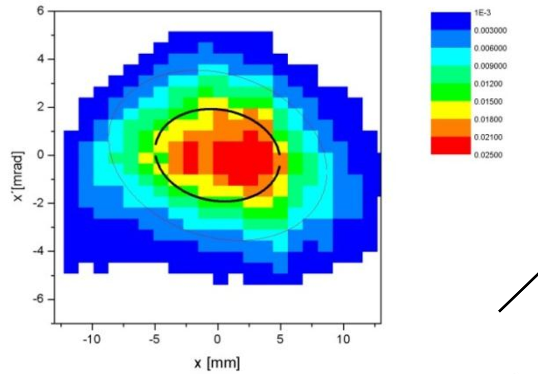


Energy loss due to buffer gas collisions: $F=-\delta m v$

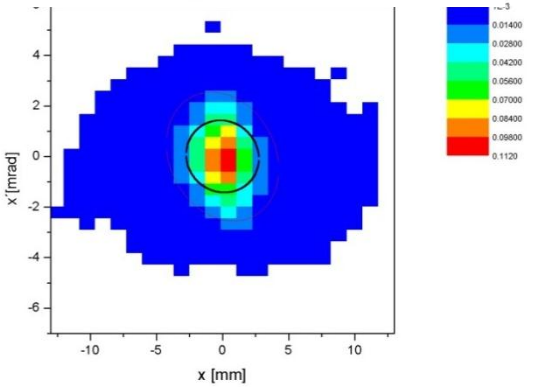
With buffer gas and RF coupling between ν_+ and ν_- all three motions cooled => amplitudes reduced

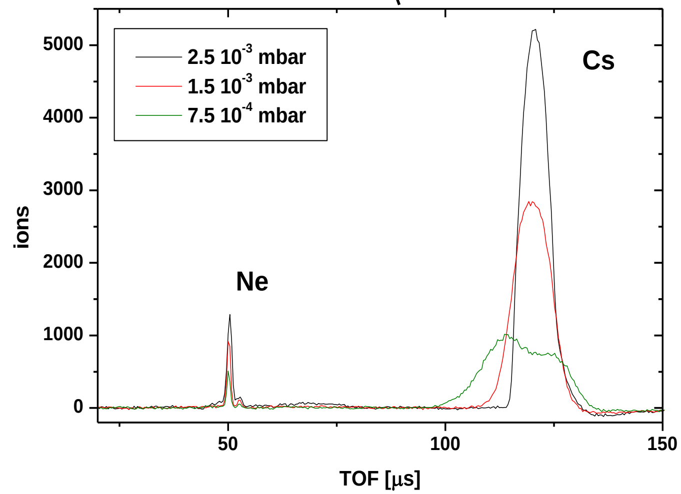


Non-cooled



Cooled





- * Bunching: few us
- * Transverse emittance: 25 -> ~10 π mm.mrad at 30 keV
- * ΔE·Δt~10 eVus

EBIS injection ok!

Resolving isobars in Penning trap

* Low m/Δm~300 in REXTRAP in normal mode
* Can be setup with m/Δm>10000

cyclotron axial

$$\omega_\pm = \frac{\omega_c}{2}\left(1 \pm \sqrt{1 - \frac{2\omega_z^2}{\omega_c^2}}\right)$$

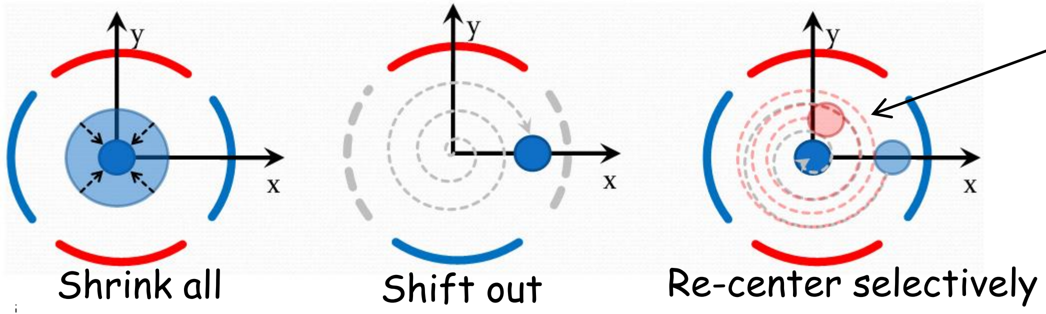
$$\omega_+ + \omega_- = \omega_c = \frac{e}{m}B$$

magnetron reduced cyclotron

Procedure

- cool down the ion cloud (normal operation)
- shift out the ion cloud (desired and contaminants) with a mass independent dipolar excitation $\nu_{RF} = \nu_-$ to r>5 mm
- selectively re-centre the desired species with $\nu_{RF} = \nu_c$
- at extraction only the centered ions survive

NB! Re-centering is mass dependent



See also G. Bollen, Europ. Phys. J. A15, 237-343 (2002)

Extra

Molecular beams

The idea

1. Use chemical properties to separate isobars e.g. ^{96}Rb from ^{96}Sr

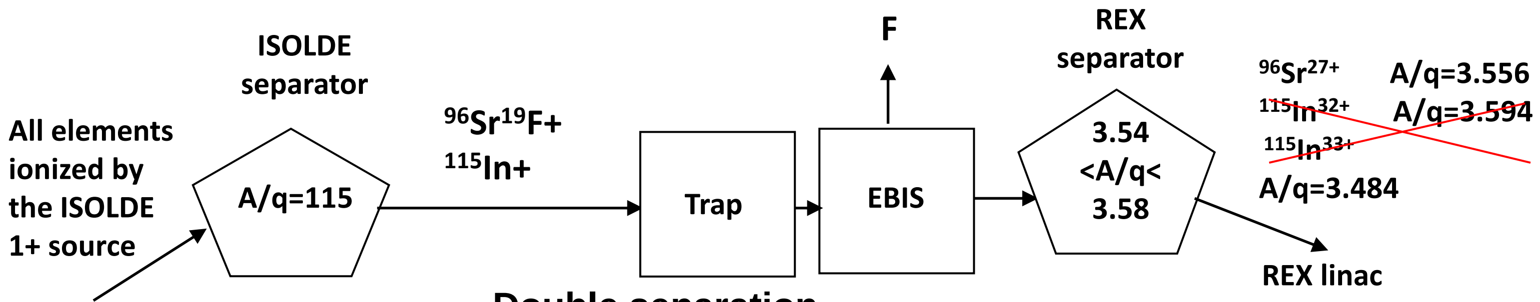
2. Create a molecular sideband (^{96}Sr^{19}F^{+}) with gas leak at ISOL-target

3. Molecular ions are extracted and selected in the separator
(A=115 selection)

4. Keep molecules inside trap, break them in EBIS

5. Charge breed as usual and obtain clean ^{96}Sr

Works also with ECRIS!



All elements ionized by the ISOLDE 1+ source

ISOLDE separator

A/q=115

^{96}Sr^{19}F+

^{115}In+

Trap

F

EBIS

REX separator

3.54 <A/q< 3.58

^{96}Sr^{27+} **A/q=3.556**

~~^{115}In^{32+}~~ ~~A/q=3.594~~

~~^{115}In^{33+}~~

A/q=3.484

REX linac

Double separation

Beam contamination

Can't see the trees for the forest

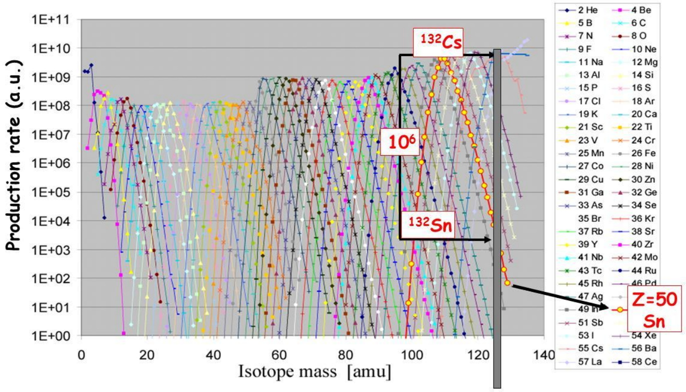
Remember: often deal with <1E4 pps => 1.7 fA

Beam impurities:

a. isobaric contamination
 from ISOL-target

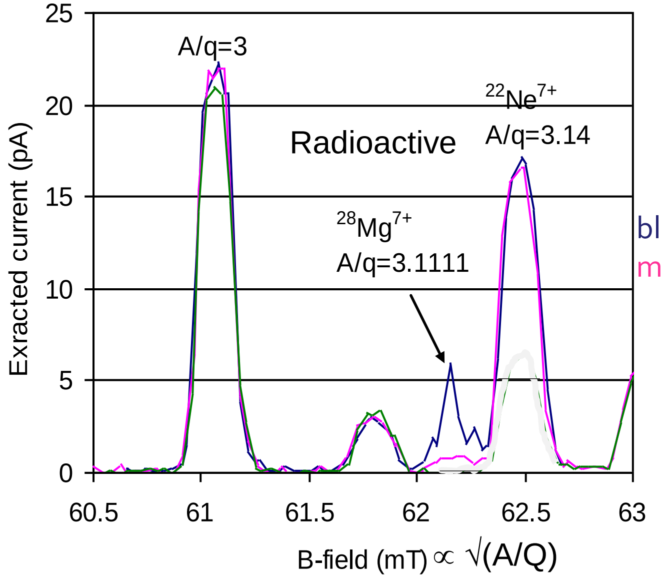
b. residual gases in CB

$I_{residual} \propto \sigma_{0->1+} \, P_{res\ gas}$



1 GeV proton beam on a lanthanum (La) target

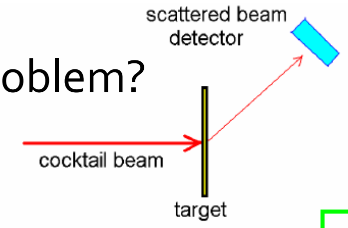
J. Lettry, V. Fedoseev (CERN)



blue – with ^{28}Mg
magenta - background

EBIS extracted spectrum

What's problem?



$$\text{Yield} = C \; . \; \sigma \; . \; \varepsilon \; . \; \boxed{\Sigma i_{beam}}$$

10% impurity
small correction

75% impurity
determine Z
e-by-e

99% impurity
difficult

Extra

Separator after breeder

1. **Separator magnet** selects A/Q

$$B\rho = Av/Q$$

ambiguous A/Q if Δv large $\frac{\Delta x}{x} \approx \frac{\Delta A}{A} + \frac{\Delta v}{v}$

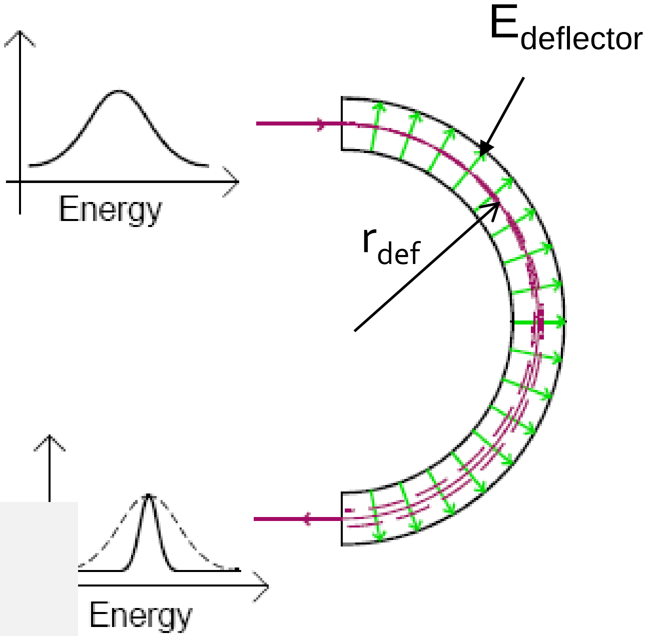
2. **Electrostatic deflector** performs a potential selection

$$E_{def}r_{def} = 2U_{ext}$$

Combine 1 & 2 => $\underbrace{E_{def}r_{def}}_{\text{fix}} = \underbrace{(B\rho)^2}_{\text{fix}} (A/Q)$

*** Only a single A/Q transmitted**

*** Can suppress ions with wrong energy**



Even so, some A/Q contaminants difficult to resolve

$^{7}Be^{3+}$ from $^{14}N^{6+}$	R=450
$^{18}F^{9+}$ from $^{12}C^{6+}$	R=19200

$\frac{\Delta(A/Q)}{(A/Q)}$ typically a few hundred for a breeder separator

Facilities and the future

CB for low-energy experiments

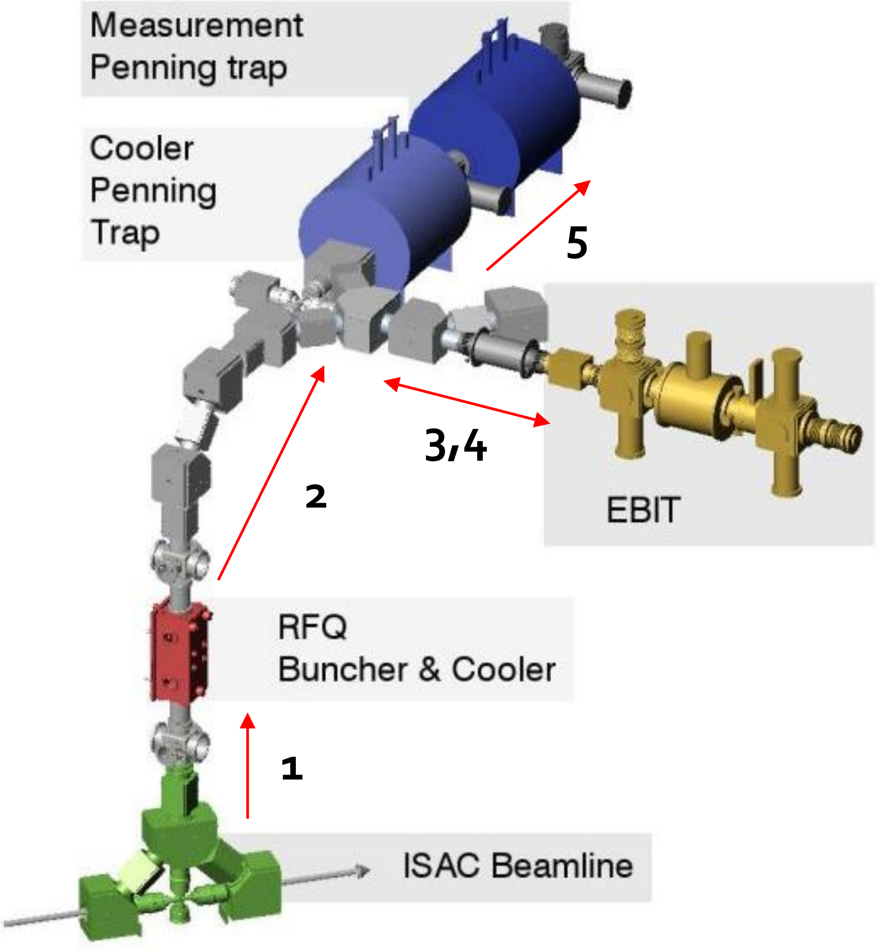
TITAN
ISAC-TRIUMF

* Not only for post-acceleration!

High precision mass measurements

$$\frac{\Delta m}{m} \sim \frac{m}{qT_{rf}B\sqrt{N}}$$

m – ion mass
q – ion charge
T_{rf} – rf excitation time
B – magnetic field
N – number of measurements



Ideally only one ion per measurement cycle

Charge breeders for RIBs worldwide

ISAC, TRIUMF
* ECRIS
* Operation

REX-ISOLDE, CERN
* EBIS/ECRIS
* Operation/Stopped

KoRIA
* ECRIS and EBIS
* Design

TITAN, TRIUMF
* EBIT
* Operational

ARIEL, TRIUMF
* EBIS?
* Planning

EURISOL, Europe
* EBIS/ECRIS
* Design

ReA, MSU
* EBIT
* Commissioning

TRIAC, JAERI
* ECRIS
* Stopped

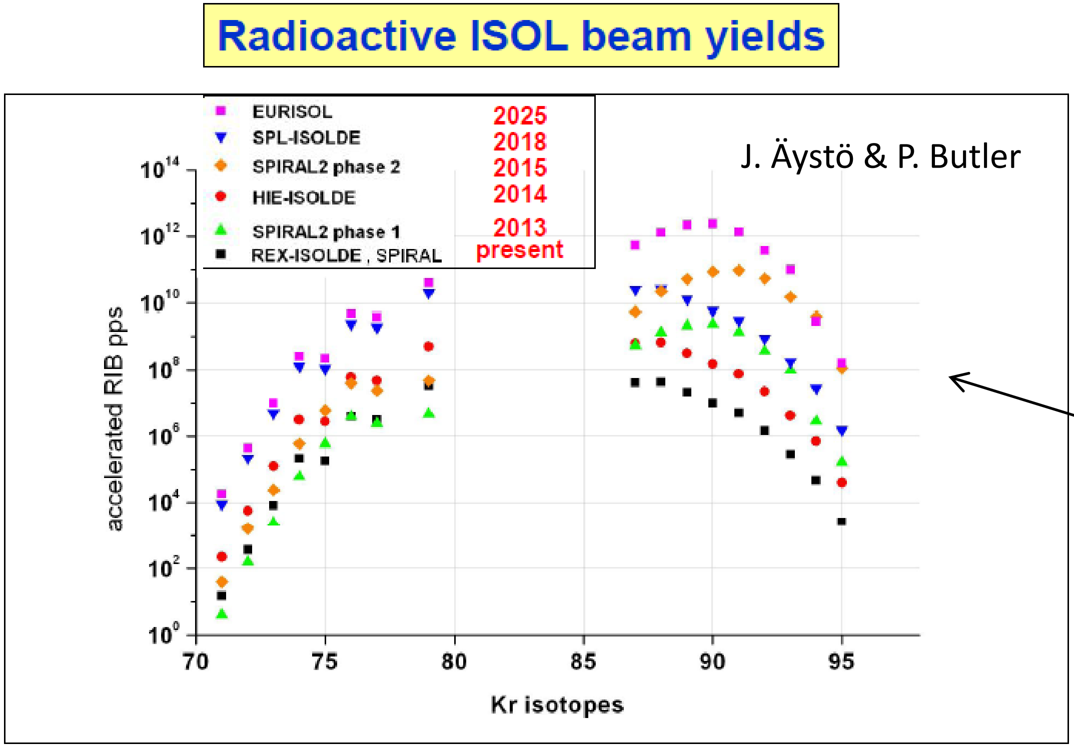
CARIBU, ANL
* ECRIS/EBIS
* Operation/Commissioning

SPIRAL/SPIRAL2
* ECRIS
* Design

SPES, LNL
* ECRIS
* Design

VECC
* ECRIS
* Commissioning

What to expect?



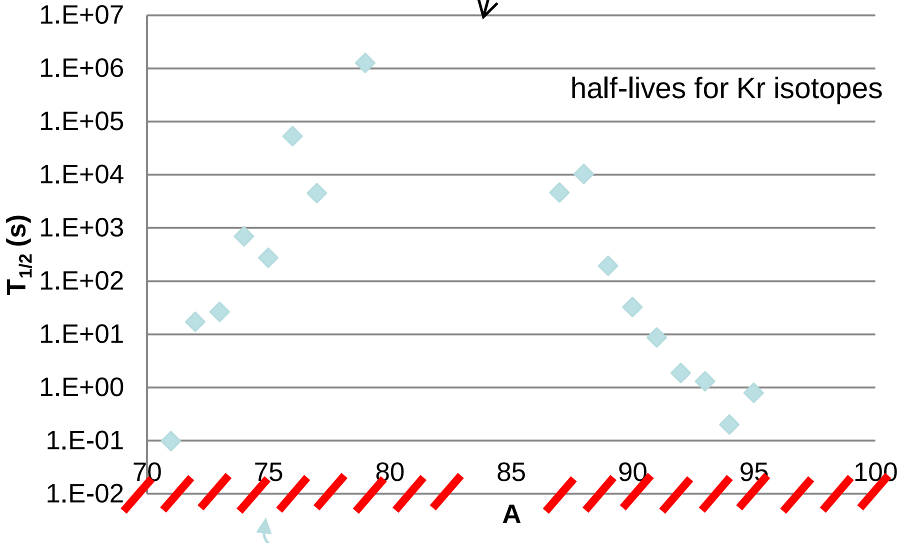
Radioactive ISOL beam yields

J. Äystö & P. Butler

Next generation facilities

* Increased intensities

* Shorter half-life along drip lines

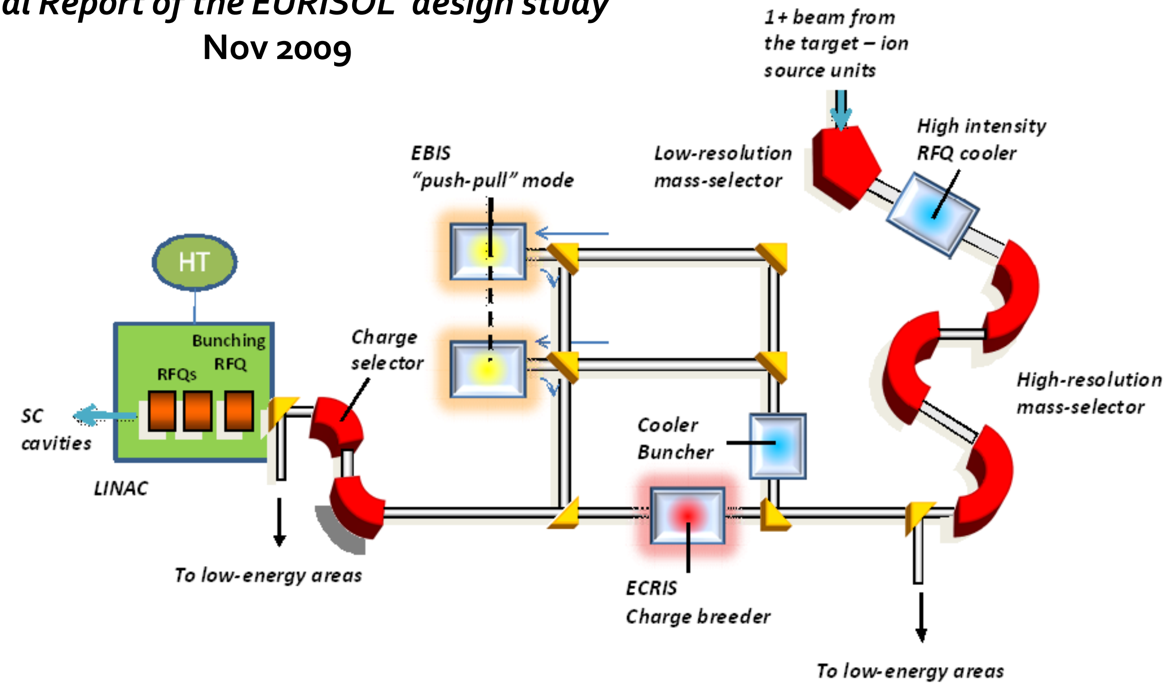


half-lives for Kr isotopes

diffusion/effusion limit for ISOL facilities

What to expect?

Further information
'Final Report of the EURISOL design study'
Nov 2009



Detail of the EURISOL Layout

Modified from P. Butler's presentation, NuPECC meeting June 2007

Two main paths

1. Very exotic low-intensity (<1E7 ions/s) beams for 'standard' experiments

2. High intensity beams (>1E9 ions/s) to generate even more neutron rich beams – beam purity not of utmost importance

Extra

The *real* challenges:

1. Inject ions into storage rings
$\Rightarrow$ fully stripped charge for Z>60

2. Breeding of beta beams
(e.g. ^{6}He and ^{18}Ne)
=> 1 s trapping of high intensity

	Stripper	EBIS	ECRIS
Simplicity	3, passive element	1, complicated (SC, UHV, e-gun)	2, medium (RF, beam tuning)
Beam properties in	3, no special requirements	1, bunched, small acceptance	2, CW, medium acceptance
Beam properties out	1, emittance blow-up	3, us or ms bunch, small emittance	2, CW or ms bunch
Low intensities	3, no contamination	2, some <0.1 pA	1, high rest-gas level
Rapidity	3, instant, us isotopes	2, 10 to few 100 ms	1, some 10 ms to a few 100 ms
CSD	3, narrow, varying charge state	3, narrow, high charge state	2, broad CSD, moderate charge
CSD tuning	1, not tunable	3, change T_{breed}	2, many parameters
Machine contamination	2, foil exchange	1, multiple parts	2, change plasma liner
Storage time	1, non existing	3, up to several s	2, ~100 ms
Beam capacity	3, very high, 100 uA	1, limited to nA	2, several uA
Energy spread	1, ΔW/W~1‰	2, a few 10 eV*q	3, some eV*q
Efficiency	2, 5-15%	2, 5-20%	2, 5-20%
Mass range	1, heavy masses difficult	3, full mass range	1, light masses difficult
Life-time	2, foil breakage, 50 mC/cm^2	1, electron cathode	3, klystron lifetime
Price	1 high, (incl. pre-acc)	2, ~1 Meuro	3, ~0.5 Meuro

Bibliography

General books

- Handbook of Ion Source, B. Wolf, Boca Raton, FL: CRC Press, 1995
- Ion Sources, Zhang Hua Shun, Berlin: Springer, 1999.
- The Physics and Technology of Ion Source, I. G. Brown, New York, NY: Wiley, 1989
- Introduction to Plasma Physics and Controlled Fusion, Vol 1: Plasma Physics, F. F. Chen, Plenum Press 1974
- Electron Cyclotron Resonance ion Source and ECR Plasmas, R Geller, IOP 1996

General charge breeding papers

- Charge breeding results and future prospects with electron cyclotron resonance ion source and electron beam ion source, R. Vondrasek, Rev. Sci. Instrum. 83, 02A913 (2012)
- Charge breeding of radioactive ions with EBIS and EBIT, F. Wenander, J. Instrum. 5, C10004 (2010)
- Evaluation of charge-breeding options for EURISOL, P. Delahaye O. Kester, C. Barton, T. Lamy, M. Marie-Jeanne and F. Wenander, Eur. Phys. J. A 46, 421 (2010).
- Charge breeding application of EBIS/T devices, O. Kester, AIP Conf. Proc. Vol. 1099 (2009) 7-12.
- European research activities on charge state breeding related to radioactive ion beam facilities, T. Lamy, J. Angot, and T. Thuillier, Rev. Sci. Instrum. 79, 0A2909 (2008)
- Charge State Breeders: on-line results , F. Wenander, Nucl. Instrum. Methods Phys. Res. B 266, 4346 (2008).
- Status of charge breeding with electron cyclotron resonance ion sources, T. Lamy et al. Rev Sci Instrum. 77 (2006) 03B101
- Charge Breeding Techniques, F. Wenander Nucl Phys A746 (2004) 40c
  (extended version as CERN note, CERN-AB-2004-035)

Miscellaneous relevant conference proceedings

- International Workshop on ECR ion sources
- International Symposium on EBIS/T
- Radioactive Nuclear Beams (discontinued)
- International Conference on Electromagnetic Isotope Separators and Techniques Related to their Applications (EMIS2012)

http://www.eurisol.org/ Task 9

Executive summary

Stripper

Fast but expensive

(pre-acc. LINAC)

ECRIS

Large capacity but dirty

EBIS

Clean but low capacity