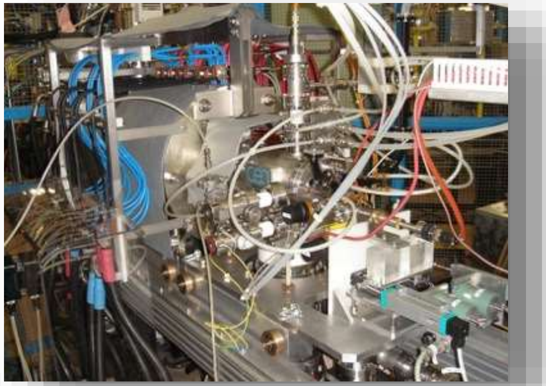
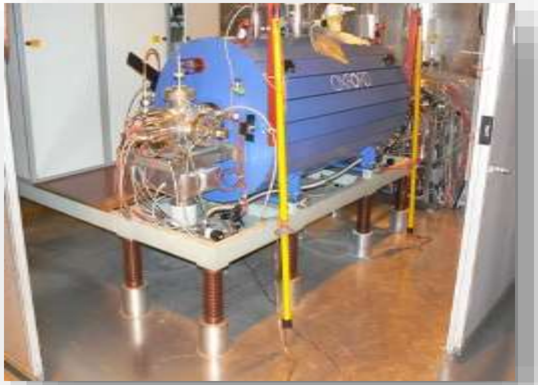
Ion sources for radioactive beams and cancer therapy

Promed-MEDICIS summer school, CNAO 2017

F. Wenander


Radioactive ion sources


Sources for H and C


Charge breeding


Some basic ion source theory

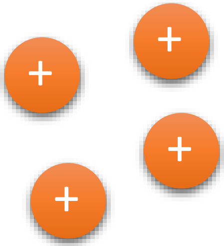
Ion source – what's the point?

Electric field E – accelerate, steer, focus and defocus particle beams
Magnetic field B – steer, focus and defocus particle beams

$$\vec{F} = (q\vec{v} \times \vec{B} + q\vec{E})$$

An ion source is a device to create a charged particle beam

- ionizes the particles
- shapes a beam



Determines:

* charge state
* beam intensity
* beam shape and emittance
* time structure (continuous or pulsed)

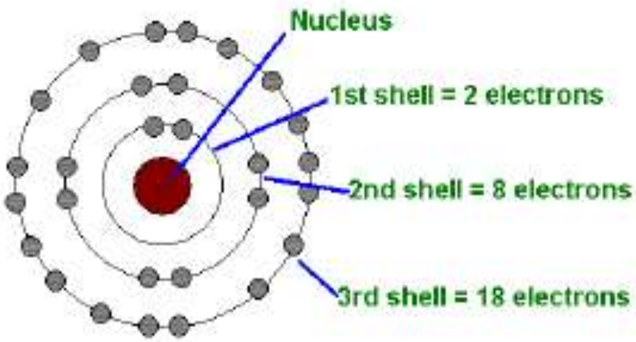
– all influences the layout of consecutive accelerator

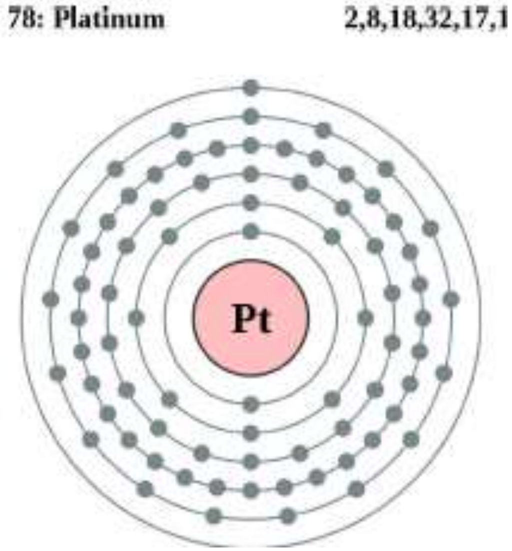
Electrons in an atom

Electrons orbit the atomic nucleus in orbits of fixed energy

The energy of each electron shell/orbit is determined mostly by attraction of the nucleus and to a smaller degree by the repulsion of other electrons

Quantum mechanics is behind the existence of shells and the number of electrons in each shell

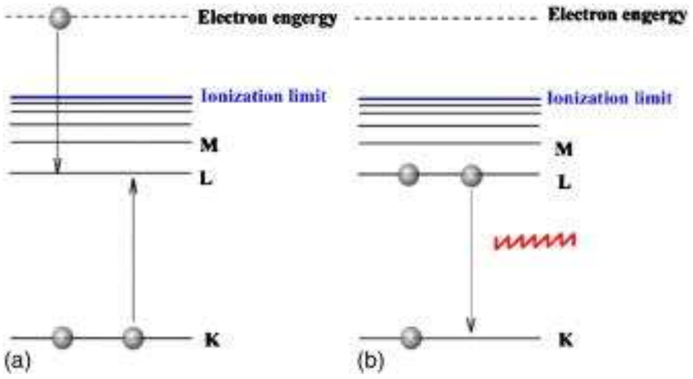




Minimal atomic physics

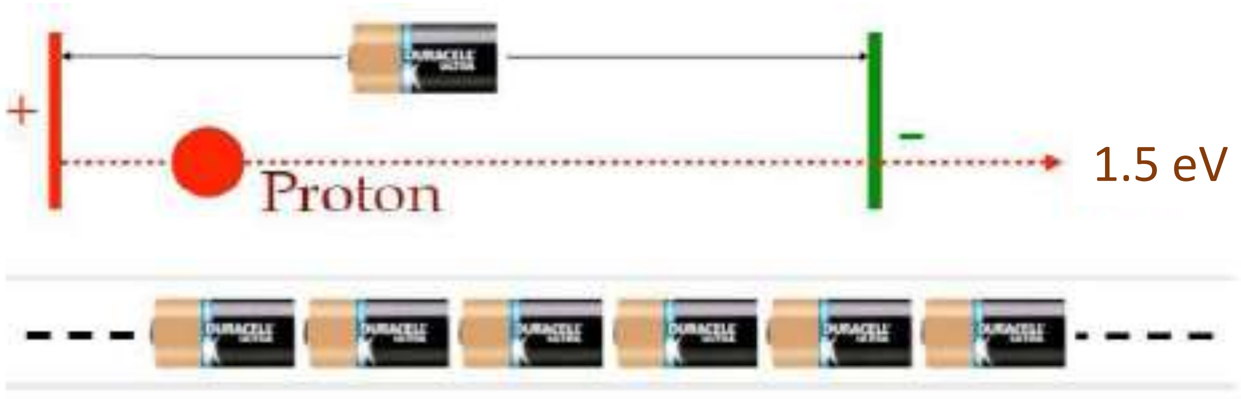
Ignore

- Charge exchange
- Radiative recombination
- Di-electronic recombination
- Electron heating
- Elastic collisions e-e, e-i, i-e + residual gas



Physical quantities and units

- Kinetic energy of charged particles is measured in *electron volts* (eV)

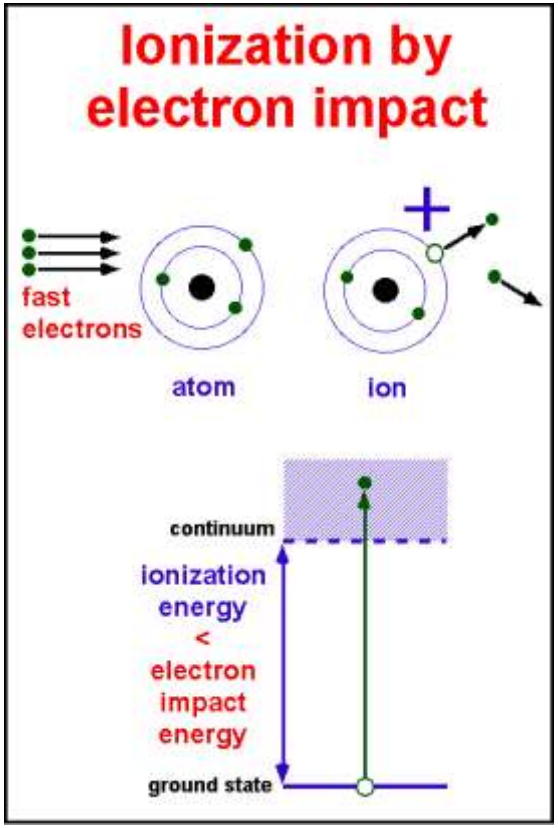


- Elementary charge of a particle is $e = 1.6022 \cdot 10^{-19}$ C (or A·s)
- 1 eV = e * 1 Volt = $1.6022 \cdot 10^{-19}$ J
- 1 eV = thermal energy kT at 11600 K
- Mass of electron: $m_e = 9.109 \cdot 10^{-31}$ kg
- Mass of proton: $m_p = 1.672 \cdot 10^{-27}$ kg
- Atomic mass unit = 1/12 ^{12}C mass: 1 u = $1.6606 \cdot 10^{-27}$ kg
- Boltzmann's constant $k = 1.38 \cdot 10^{-23}$ J/K

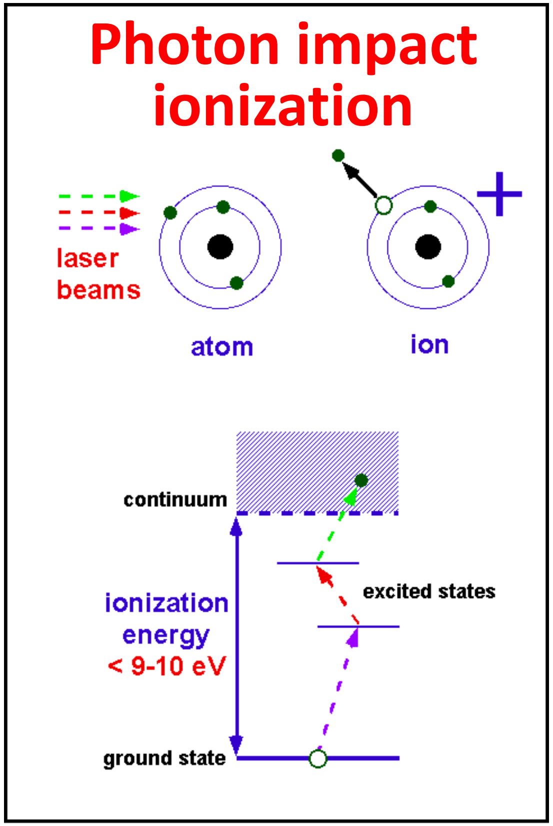
20 °C = ?? eV

The only slide worth paying attention to

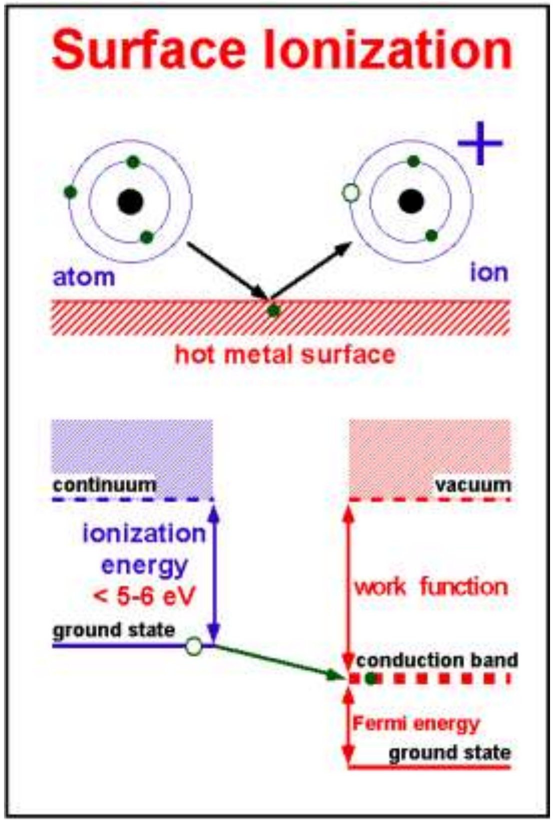
Three different paths (not the only ones) to atom ionization



Ionization by electron impact



Photon impact ionization

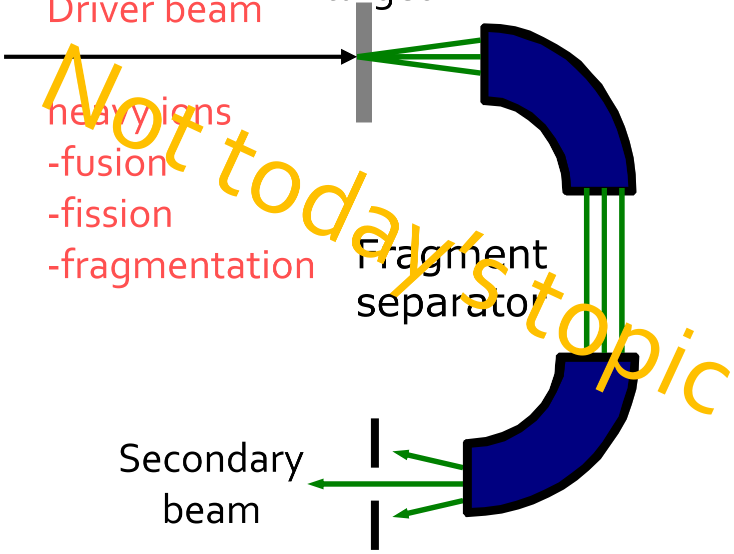


Surface Ionization

The $\underbrace{\text{Isotope On-Line}}_{\text{ISOL}}$ production process

RIB production techniques

IF (In-Flight fragment separator)



Thin production target

Driver beam

heavy ions

-fusion

-fission

-fragmentation

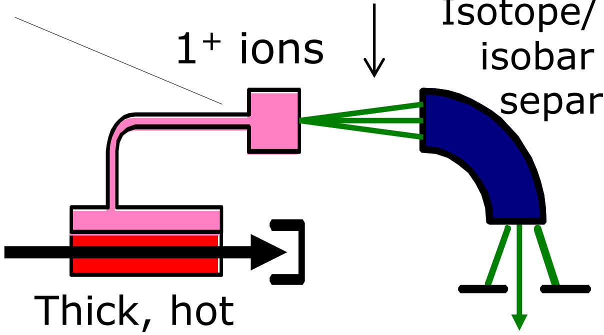
Fragment separator

Secondary beam

Not today's topic

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

Isotope Separation Online (ISOL)



Electrostatic DC acceleration

Ion source

1^+ ions

Isotope/ isobar separator

Driver beam

light and heavy ions, p, n, e

-spallation

-fission

-fusion

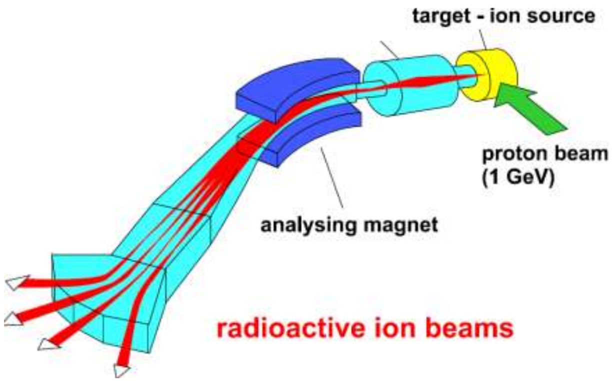
-fragmentation

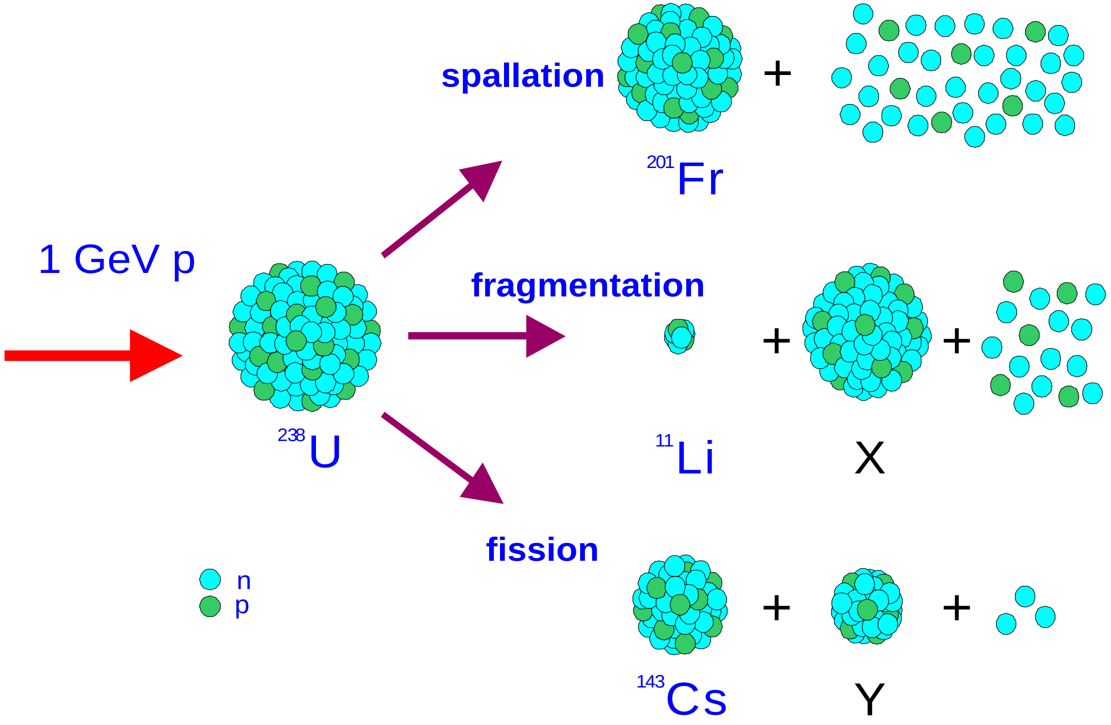
Thick, hot target

Secondary beam

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

The nuclear reactions



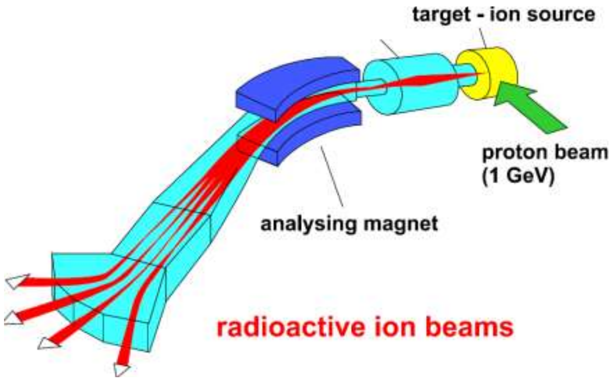


Projectiles
p, deuterons, He,…

Energies
tens of MeV to GeV

Targets
CaO, Hg, Ta, UC_x…

Diffusion - effusion



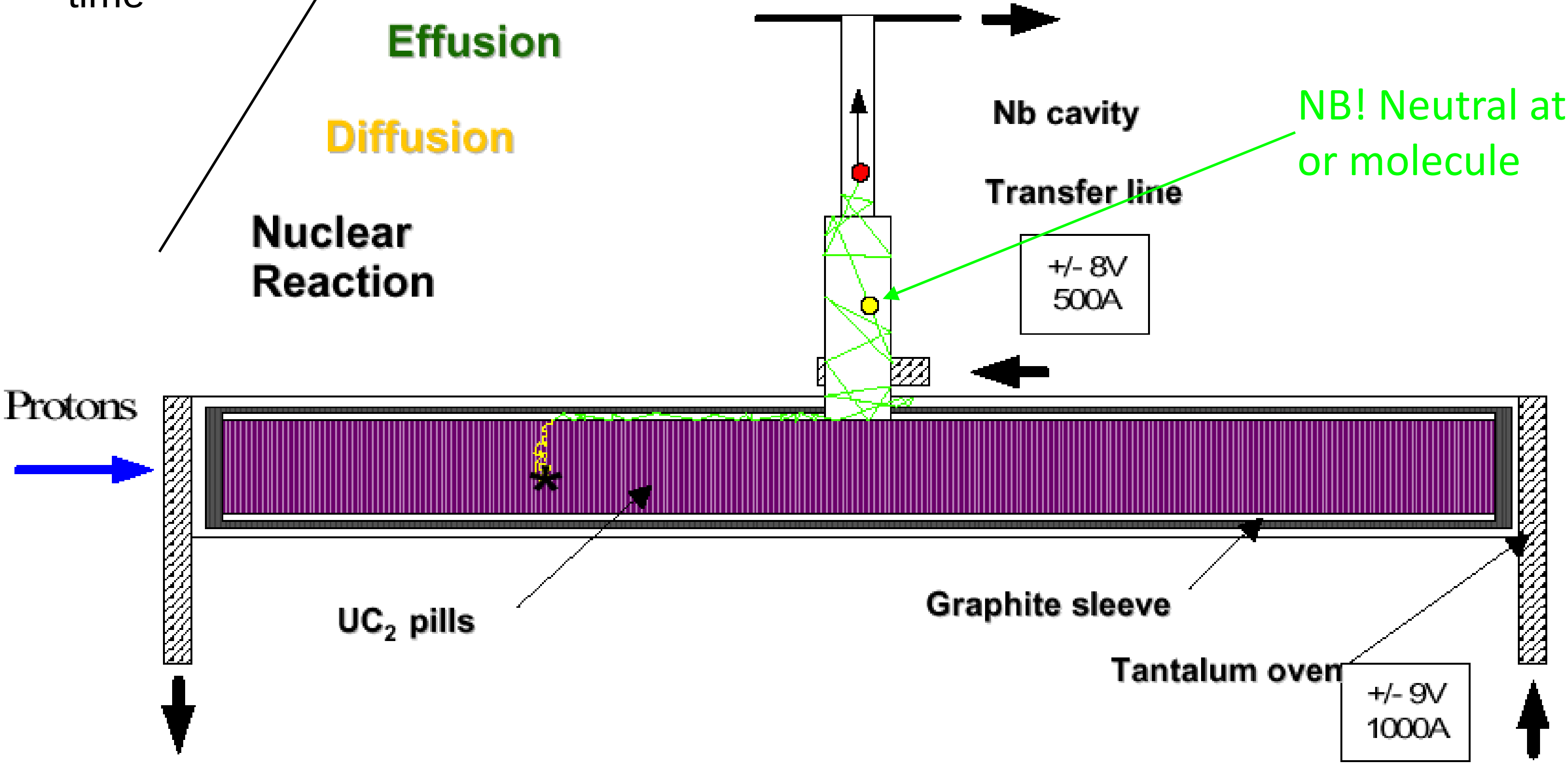
time

Ionisation

Effusion

Diffusion

Nuclear Reaction



Nb cavity

Transfer line

+/- 8V
500A

NB! Neutral atom or molecule

Protons

UC_2 pills

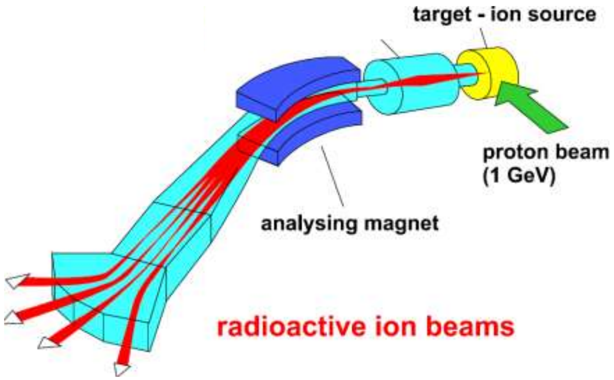
Graphite sleeve

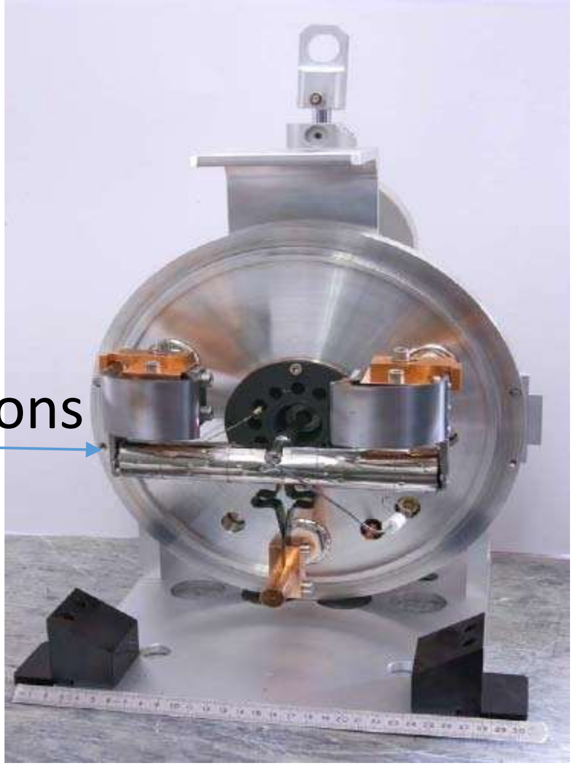
Tantalum oven

+/- 9V
1000A

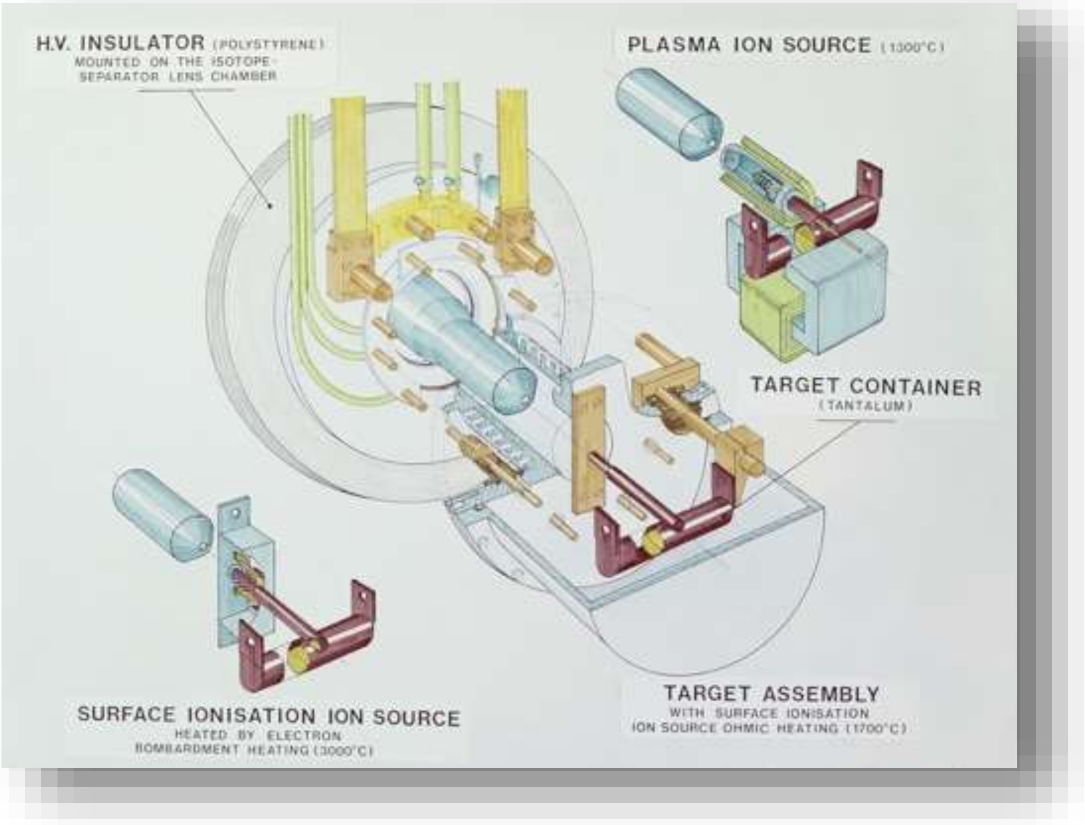
Target and ion source assembly

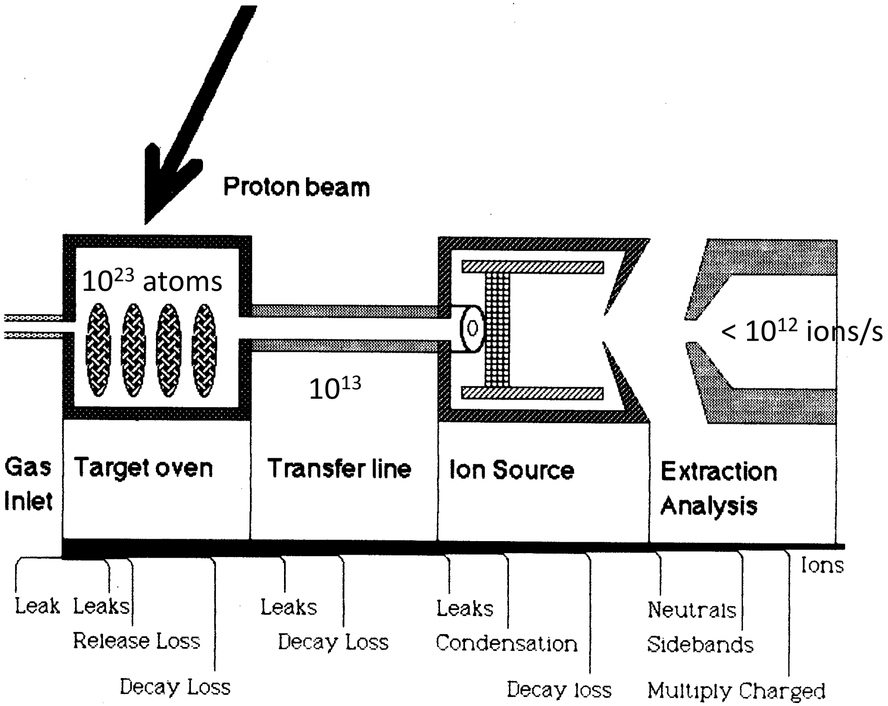
The ion source is often combined with the target





protons





Target and ion source

Target and ion source are combined in order to optimise:

1. $T_{release}$ of the ions from the target

NB! Not an issue for all/most cancer treatment ions

2. Efficiency

3. Chemistry of the ion in the target and the ion source

Universality - advantage and drawback

Selectivity - suppress isobaric contaminants

What beams to expect?

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

No universal target / ion source!

Need to have different options and choose the optimal one depending on the requested case and priorities for the beam characteristics.

Zoo of sources

Bayard-Alpert type ion source
Electron bombardment ion source
Hollow Cathode ion source
Reflex Discharge Multicusp source
Cold-& Hot-Cathode PIG
Electron Cyclotron Resonance ion source (ECRIS)
Electron Beam Ion Source (EBIS)
Surface contact ion source
Cryogenic anode ion source
Metal Vapor Vacuum Arc ion source (MEVVA)
Sputtering-type negative ion source
Plasma surface conversion negative ion source
Electron heated vaporization ion source
Hollow cathode von Ardenneion source
Forrester PorusPlate ion source
Multipole confinement ion source
EHD-driven Liquid ion source
Surface Ionization ion source
Charge exchange ion source
Inverse magnetron ion source
Microwave ion source
XUV-driven ion source
Arc plasma ion source
Capillary arc ion source
Von Ardenneion source
Capillaritronion source
Canal ray ion source
Pulsed spark ion source
Field emission ion source
Atomic beam ion source
Field ionization ion source
Arc discharge ion source
Multifilament ion source

Duopigatron
Penning ion source
Laser ion source
Monocuspion source
Bucket ion source
Metal ion source
Multicusp ion source
Kaufman ion source
Flashover ion source
Calutronion source
CHORDIS

RF plasma ion source
Freeman ion source
Liquid metal ion source
Beam plasma ion source
Resonant ionization laser ion source
Magnetron ion source
Nierion source
Bernas ion source
Nielsen ion source
Wilson ion source
Recoil ion source
Zinnion source
Duoplasmatron

We will discuss:

Surface ionization ion source

Resonant ionization laser ion source

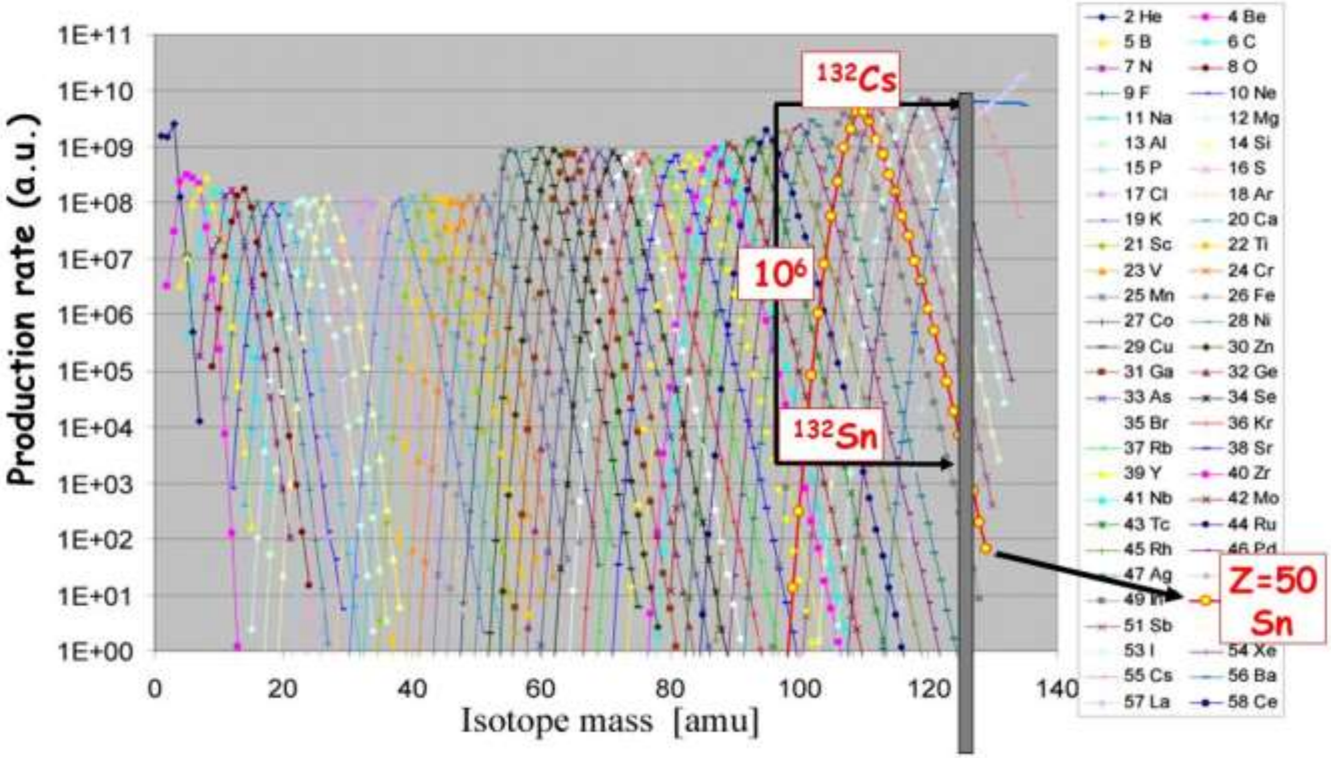
Electron bombardment ion source

Electron Cyclotron Resonance ion source

Beam contamination

Can’t see the trees for the forest

A whole range of elements and isotopes are produced in a single target



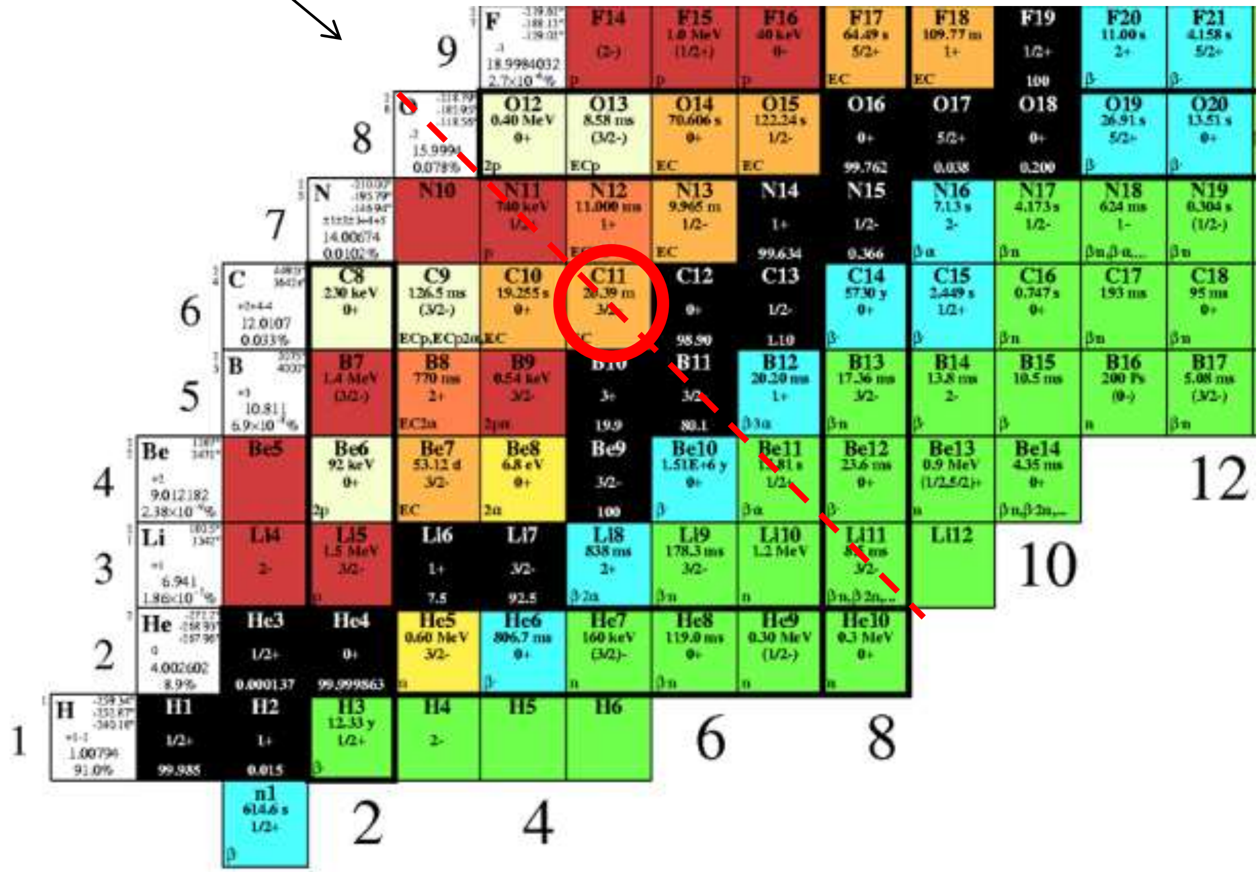
1 GeV proton beam on a lanthanum (La) target

J. Lettry, V. Fedoseev (CERN)

Beam contamination

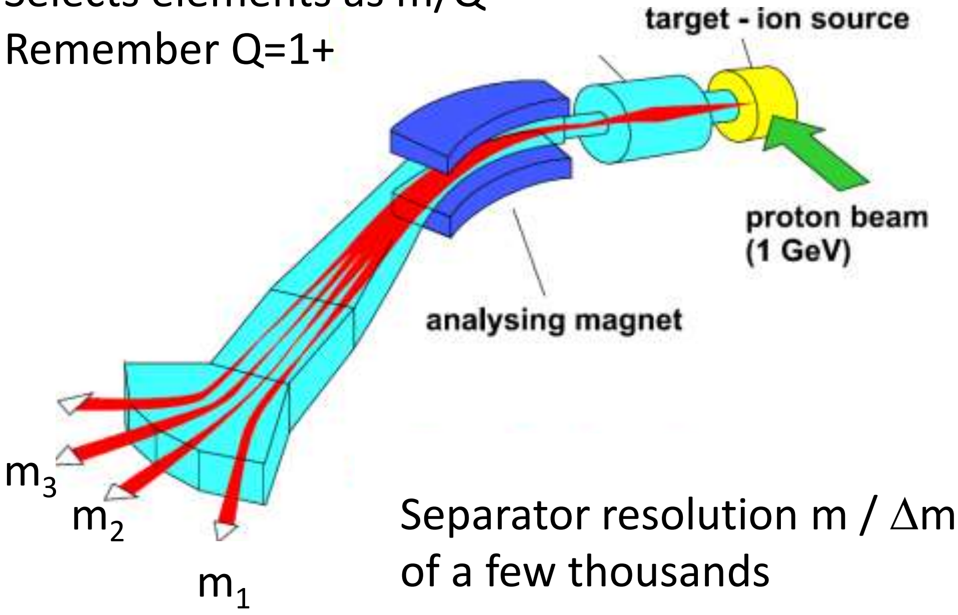
Can’t see the trees for the forest

Also isobaric contaminations along A=11



Beam contamination

Selects elements as m/Q
Remember Q=1+



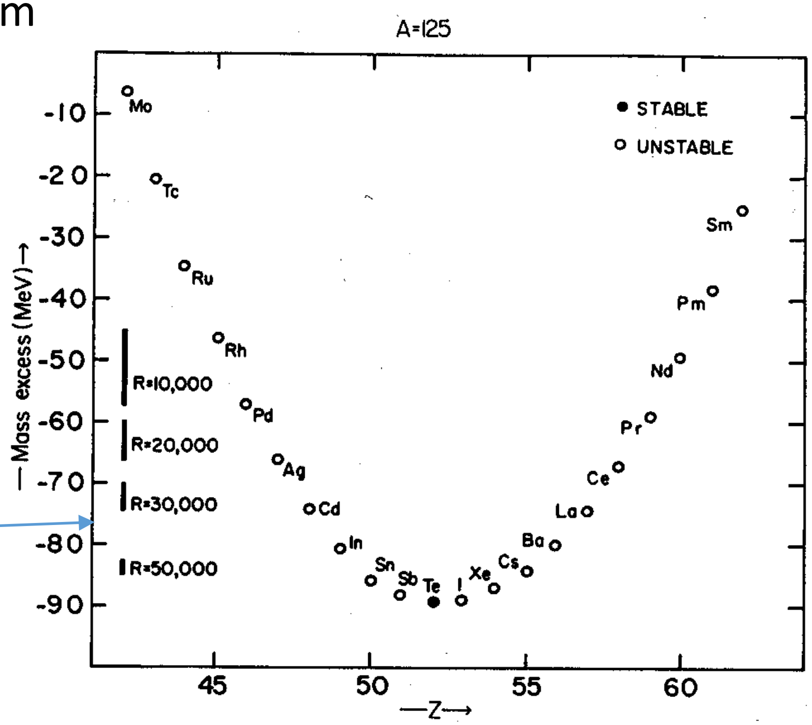
Separator resolution m / Δm
of a few thousands

Isobaric contaminants leaving the source ionised can only be removed from the beam with high resolution mass separators

- * expensive
- * elaborate in use
- * get strongly contaminated

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



Suppression of isobaric contaminants

Talk later this week

1. Choice of the projec energy

   (e.g. ne uced fission for actinide targets)

2. Choice rget material, geometry and thickness

3. Target-to-ion source transport

   thermo-chromatography

   chemical suppression

4. Selection of ion source

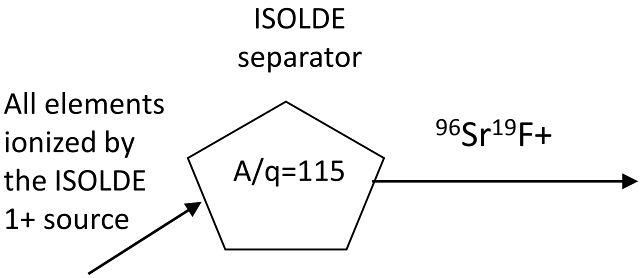
   e.g. work function ϕ

Rb doesn't bind to F, while Sr does

5. Molecular beams

ease extraction, e.g. for C as CO$^+$

separate isobars, e.g. ^{96}Sr from ^{96}Rb



ISOLDE separator

All elements ionized by the ISOLDE 1+ source

A/q=115

^{96}Sr^{19}F+

Wake-up

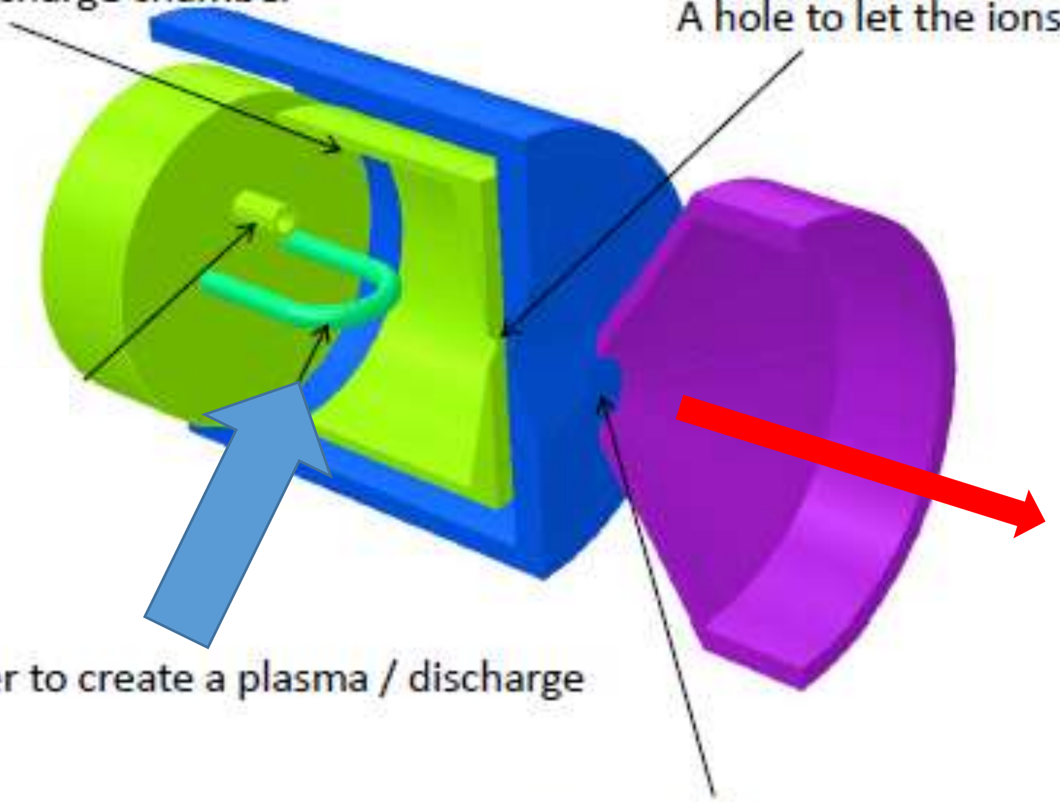
What’s the rarest element in the Earth’s crust (that isn't a transuranic element)?

How much of it can be found?

Astatine … [is] miserable to make and hell to work with.
P Durbin, Human Radiation Studies: Remembering the Early Years, 1995

Ion source & beam characteristics

Source layout



A plasma or discharge chamber

A hole to let the ions out!

Power to create a plasma / discharge

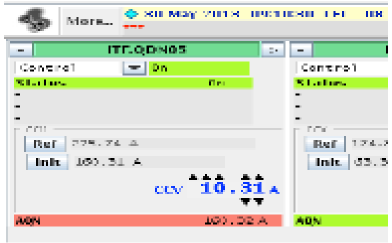
An extraction system

Beam out

What else is needed?

Power Source
Power Supplies / RF / Laser

Vacuum Pumping



Control system

Cooling

Beam diagnostics

Interlocking +
Safety Systems

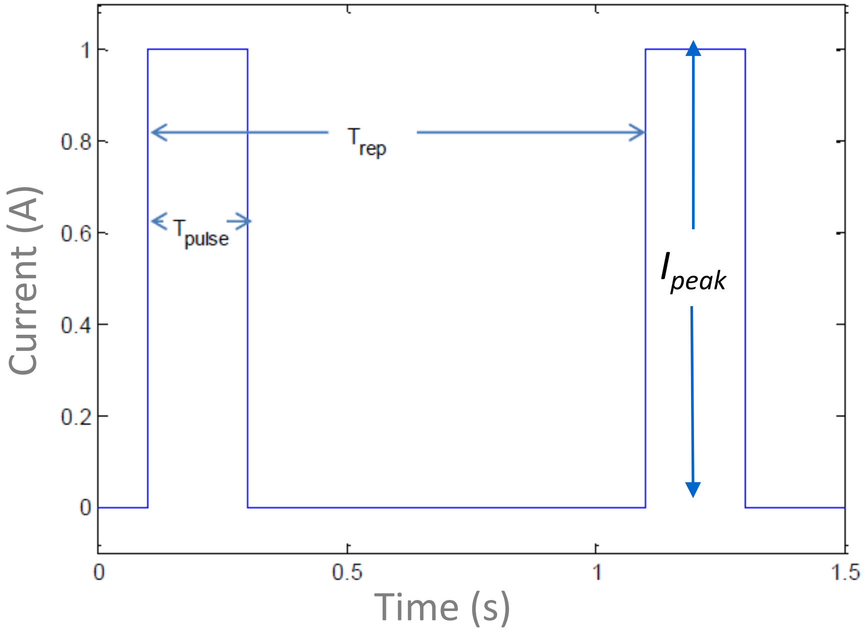
Plasma diagnostics

User interface

Don’t underestimate the development effort – use existing devices/designs!

Beam current

$$\text{Duty factor} = \frac{T_{pulse}}{T_{rep}}$$



Differ between *electrical* current:

$$I_{electric\_current} = \frac{QeN_{ions}}{T}$$

and *particle* current:

$$I_{particle\_current} = \frac{I_{electrical\_current}}{Q}$$

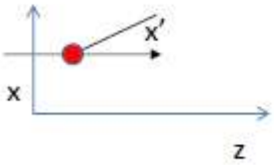
What is T? T_{pulse} or T_{rep} => I_{peak} or $I_{average}$

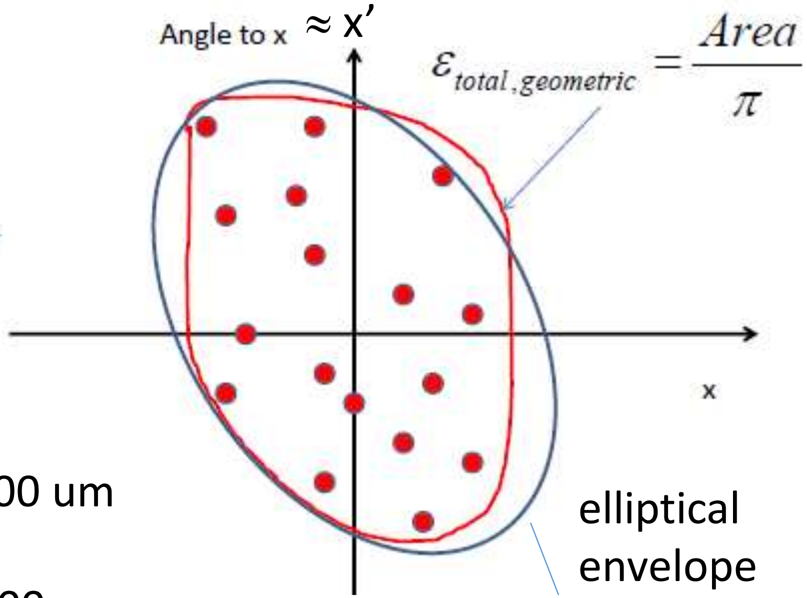
NB! When injecting into a synchrotron, the beam is only useful for a fraction of the synchrotron cycle (< 100 us)

Emittance

The emittance is defined as the 6-dimensional volume limited by a contour, of particle density in the (x, p_x, y, p_y, z, p_z) phase space.

In one plane





$$\varepsilon_{total,geometric} = \frac{Area}{\pi}$$

elliptical envelope encircling the particle bunch

Kill the π!

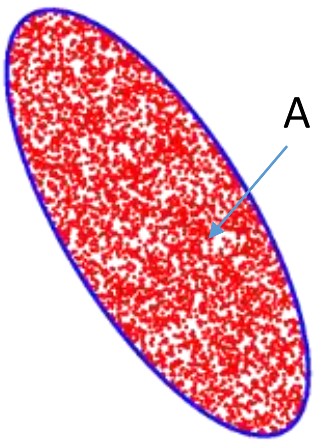
100 π mm.mrad = 100 mm.mrad = 100 um

Area is 100 π, and the emittance is 100

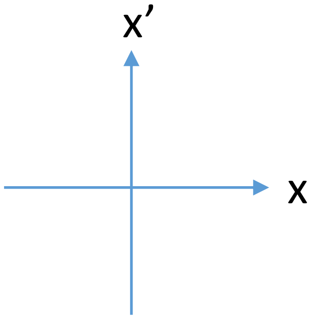
Why bother about emittance?

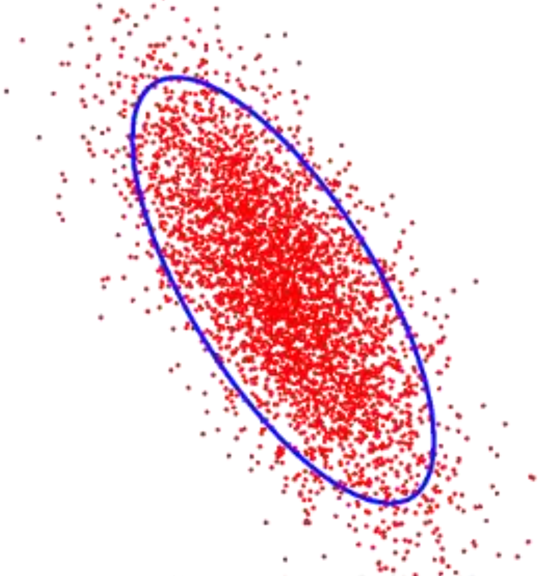
- ε determines the distance and diameter beam transport elements need to have
- ε has to be small for injection into charge breeders
- ε determines *the size of the final focus at a certain focal length* from the focusing device

Emittance



Uniform density





Gaussian fall-off

Geometrical emittance

$$\varepsilon_{x,geometric,100\%} = A/\pi$$

RMS emittance

$$\varepsilon_{x,rms,100\%} = \frac{1}{N}\left(\sum x^2 \sum x'^2 - \left(\sum xx'\right)^2\right)^{1/2}; \quad \bar{x} = \bar{x'} = 0$$

N: Total number of particles

$$\varepsilon_{normalised} = \beta\gamma\varepsilon_{geometric}$$

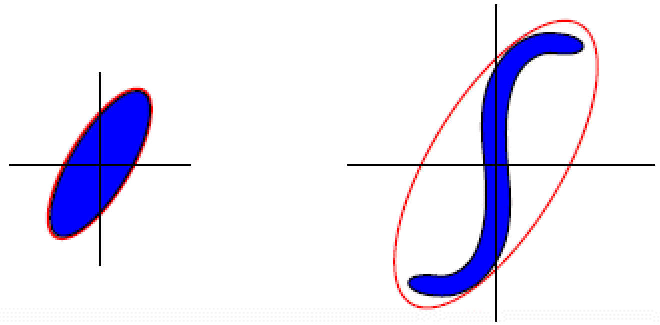
normalized emittance
conserved with acceleration

What is β?

Extra

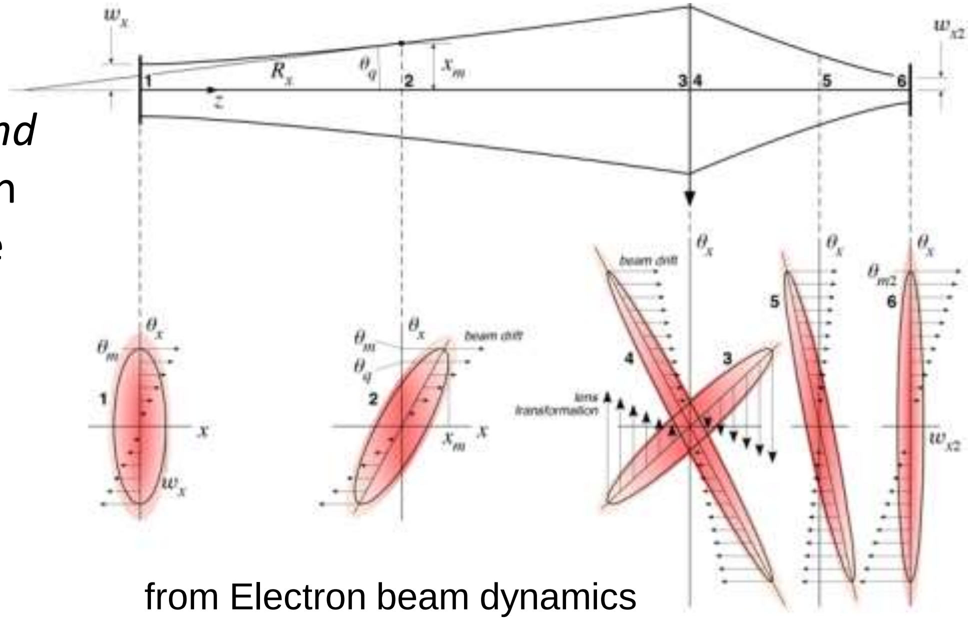
Emittance

The *phase space volume (blue)* obeys the Liouville theorem and is constant in *conservative fields.*



The area of the *elliptical envelope, and RMS emittance,* are only conserved in case of linear forces (e.g. quadrupole elements)

But it changes the shape!



quadrupole lens

from Electron beam dynamics
Eric B Szarmes

Emittance estimation

Extra

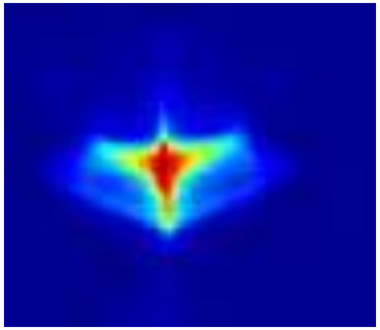
The minimum emittance of a plasma source is limited by the aperture (r), and the ion temperature in the plasma (T_i).

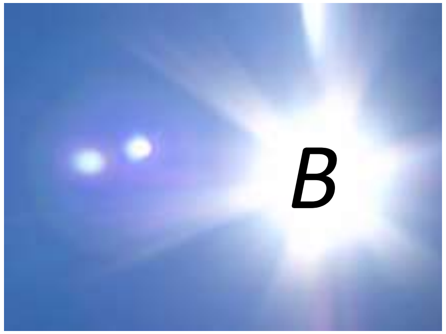
$$\epsilon_{x,\text{ rms, n}} = 0.0164 r \sqrt{\frac{kT_i}{M_i}}$$

ε – temperature dependent normalized rms emittance
r – radius of the extraction aperture (in mm), kT_i – ion temperature (in eV)
M_i – ion mass (in amu)

Small apertures and low ion temperature plasmas are good

Reality not so easy!





Beam brightness

Brightness is usually defined as current density per unit solid angle

$$B = \frac{J}{d\Omega} = \frac{dI}{dS\,d\Omega}$$

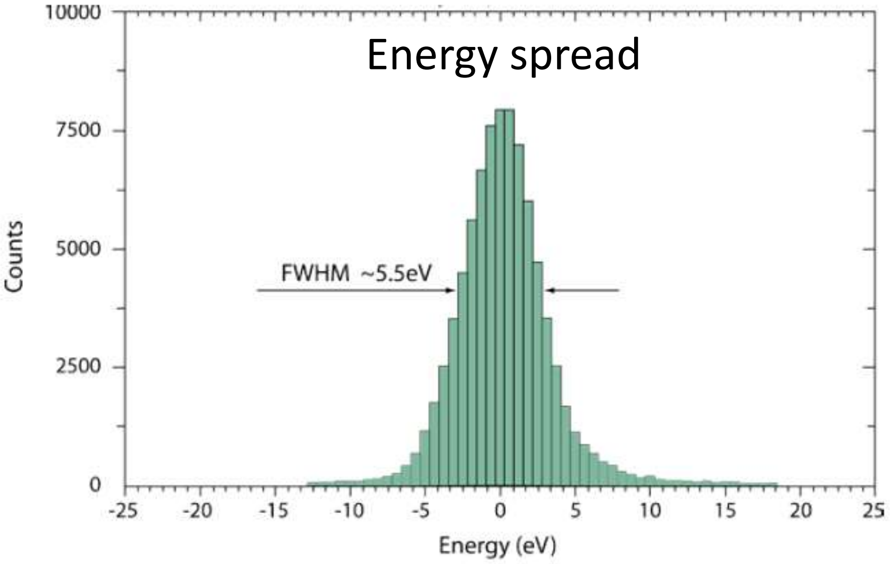
Or in terms of the transversal projections

$$B = \frac{2I}{\pi^2 \epsilon_x \epsilon_y} \qquad \left[\frac{A}{m^2\text{-}rad^2}\right]$$

$$B_n = \frac{B}{\beta^2\gamma^2} \qquad B_{90\%} = \frac{2 \cdot 0.9 \cdot I}{\pi^2 \epsilon_{x\text{-}90\%}\, \epsilon_{y\text{-}90\%}}$$

Watch out for inconsistency in pre-factors!

Beam energy



Energy spread

e.g. $^{11}C^{6+}$, 50 kV

Total ion energy after extraction

$W_{kin} = QeV_{extraction}$ 300 keV

Energy per nucleon

$W_{kin}/nucleon = QeV_{extraction}/A$ 27.44 keV/u

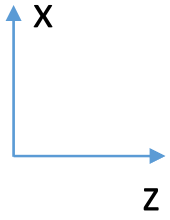
+ high beam energy

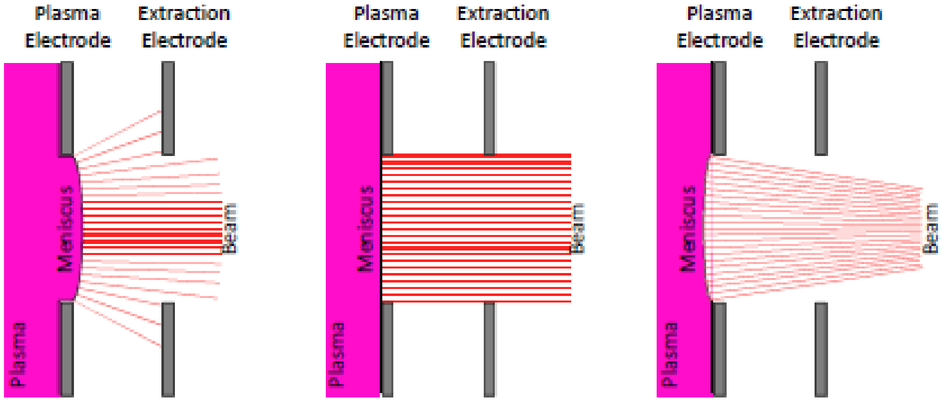
- Space charge reduced –> higher beam currents possible
- Reduces the geometrical emittance => smaller apertures
- Higher velocity makes it easier to inject into an RF accelerator (e.g. DTL).

\- high beam energy

- Technically difficult, higher fields for beam devices, higher risk of sparking
- Longer RFQ (input cells become longer)
- Higher Energy = Higher Beam Power => consequences for beam intercepting devices.

Which goes to which?

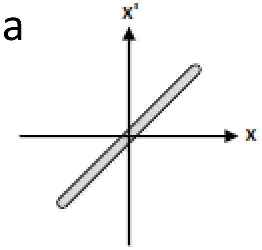




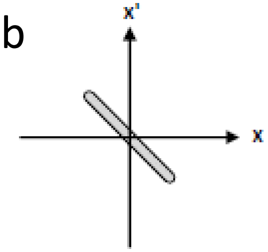
Convex Flat Concave

Not including space charge effects

a



b



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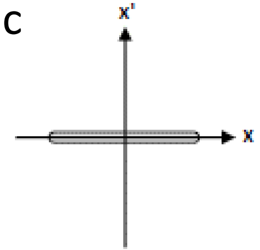
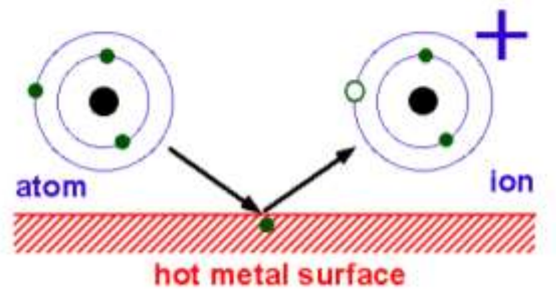
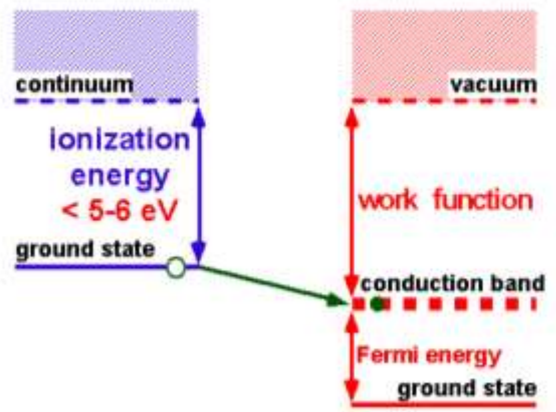


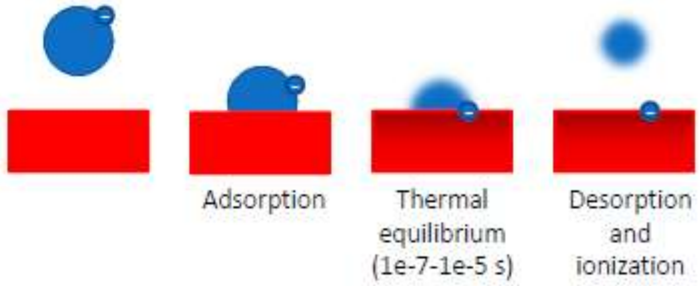
Surface ionization

Surface ionization

Ionization by contact with a (metal) surface





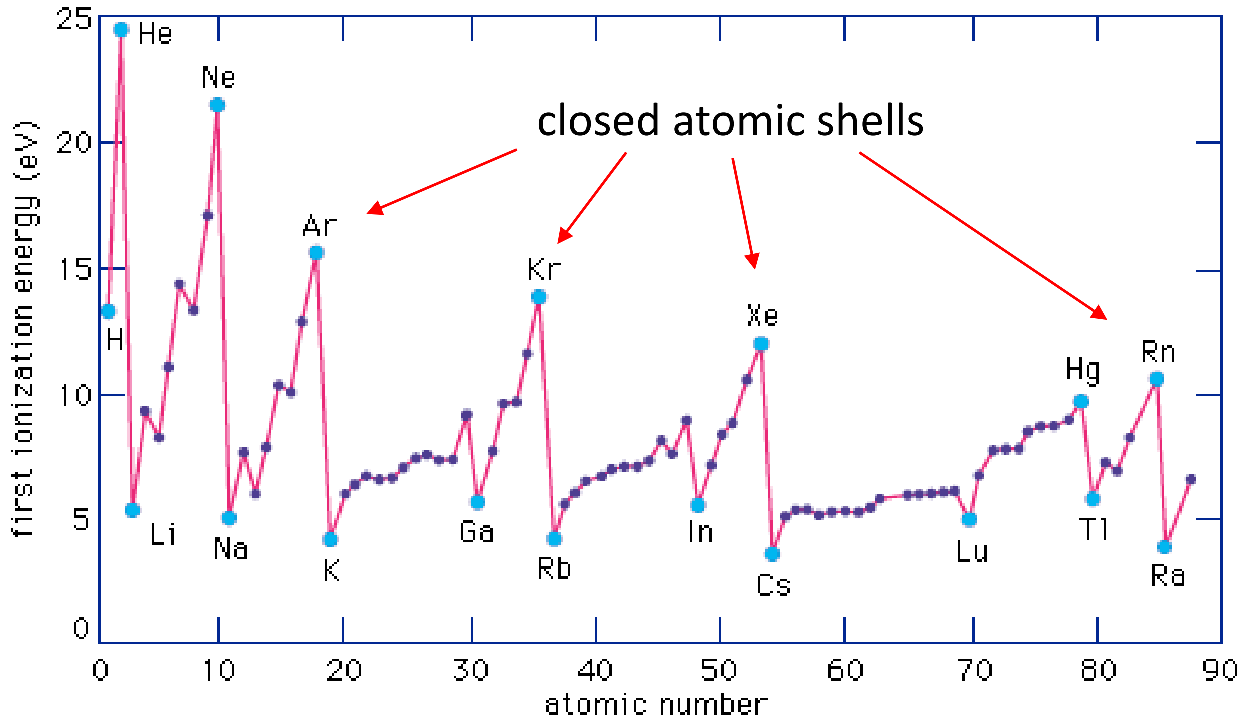


Requirements:

1. Atom sticks (is adsorbed) to the surface long enough to reach thermodynamic equilibrium => atom valence electron is “broadened” and can move between atom and surface

2. Surface is hot enough to desorb particles

Ionisation energy and work function



closed atomic shells

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I_e = energy required to remove the most loosely bound electron in a *free atom*

Material work function ϕ = minimal energy required for an electron to escape the material surface

ϕ is highly dependent on other properties of the material such as crystal structure and surface characteristics

Extra

ϕ for elements follows a trend similar to ionization energy

Surface ionization

Degree of positive surface ionization given by *Saha-Langmuir* equation

Constant describing atom properties

Atom ionization energy

Material work function

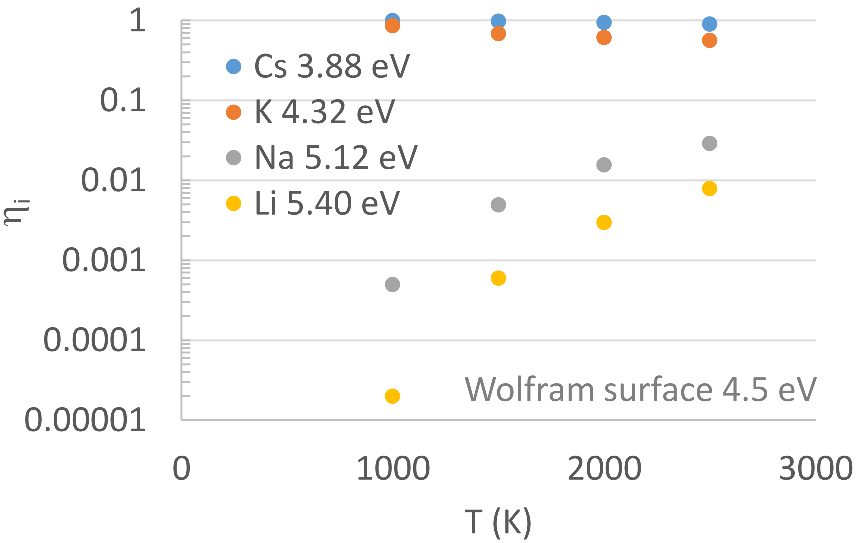
$$\eta_i = \frac{ions}{atoms + ions} = \frac{1}{1 + G\,\exp\left(\frac{I_e - \phi}{kT}\right)}$$

Boltzmann’s constant

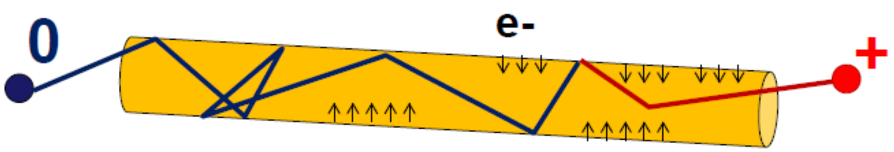
Material temperature

$O(G)=1$

Positive ionization of atoms with low ionization potential on heated metal surfaces with a high work function



Hot cavity effects



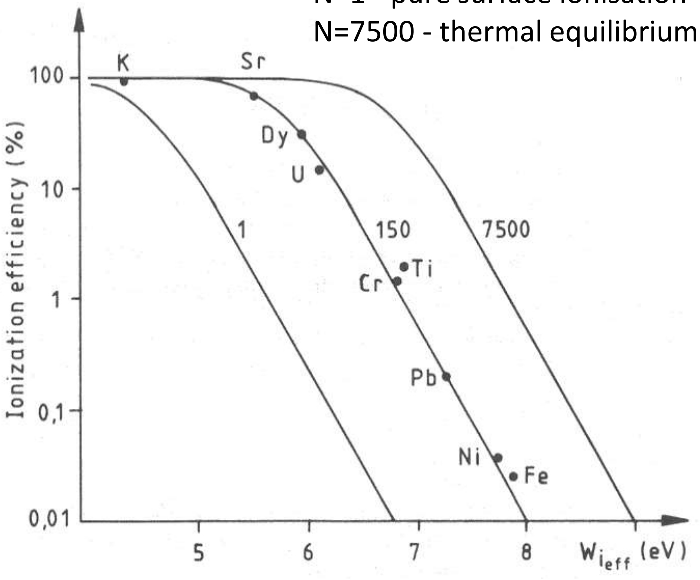
Hot cavity

Amplification factor N inside a hot cavity, since:

A. multi-fold chance of being surface ionised
B. trapping in plasma after thermalization

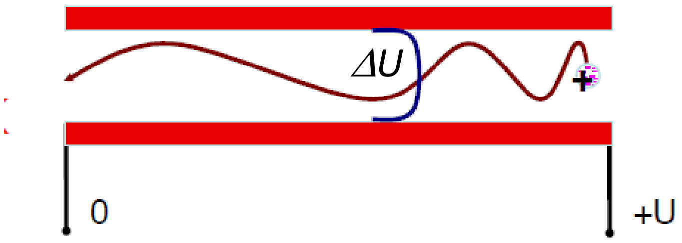
A.

N=1 - pure surface ionisation
N=7500 - thermal equilibrium



B. Plasma sheath caused by thermionic electron emission

$$\Delta U = \frac{kT}{e} \ln\left(\frac{A_0 T^2}{e n^+}\left(\frac{kT}{2\pi m_e}\right)^{1/2}\right) - \frac{\phi}{e} \quad \sim 2\text{ eV}$$



Mechanical design

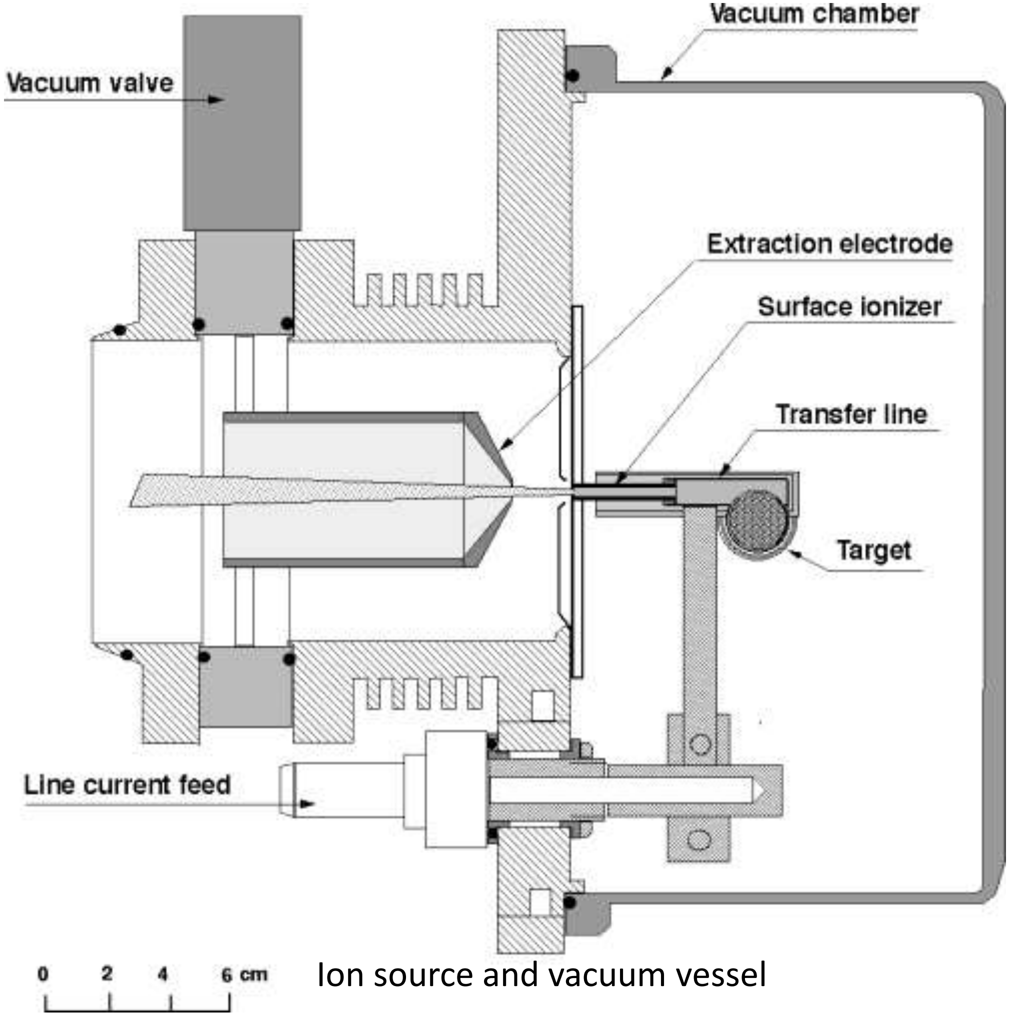
material	Φ_0 [eV]	operation temperature T [°C]
Re	5.0	2200
W	4.5	2200
Ta	4.3	2150
Nb	4.0	2000

For 1+ ions

T=1200-2500 °C

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

Heating: usually ohmic



Ion source and vacuum vessel

Surface ioniser properties

* Ionisation efficiency 100% for I_e<5 eV, few % for I_e=6.5 eV

* Used for alkalines, alkaline earths, rare earths, Ga, In and Tl
also molecules as BaF and SrF

* 10-1000 nA, max current 1 μA/mm^2

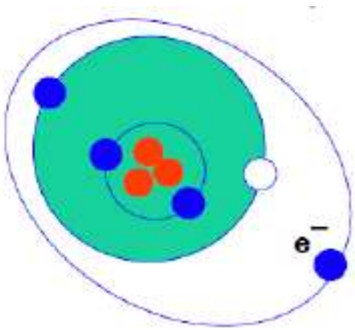
* Emittance ~ 10 mm mrad (60 kV, 95%)

* Energy spread <2 eV

* Short delay time (half-lives as short as 10 ms)
small ionisation volume

Negative ion sources

Ripping electrons off is easy!
It is much harder to add them on….



…but some atoms with an open shell configuration can attract an extra electron and form a stable ion with a net charge of –e

* Volume – throu[illegible]s, e-capture and molec[illegible]ation, negative ions can be [illegible]

Not covered here

$AB + e \rightarrow A^- + B$

$AB^* + e \rightarrow A^- + B$

$A + B \rightarrow A^- + B^+$

$A^+ + B \rightarrow A^- + B^{2+}$

* Surface – an atom on a surface can be desorbed with an extra electron (whose wave-function overlapped the atom)

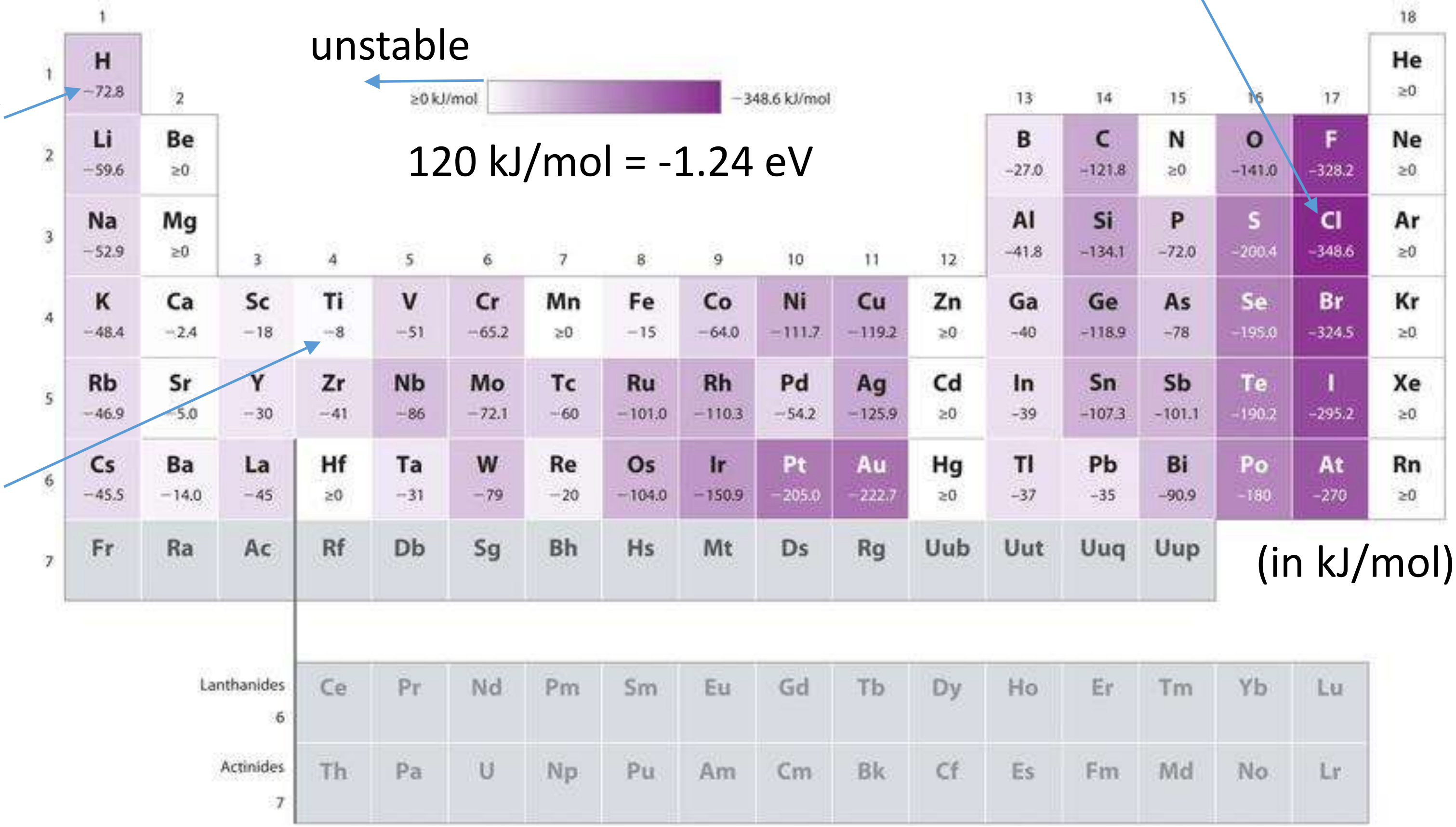
Electron affinity

The bonding energy for an electron onto an atom is the electron affinity A_e (eV)

Ions that have a positive A_e are stable

Noble gases not stable, i.e. $A_e < 0$

Large A_e for halogens (Cl 3.6 eV)



0.75 eV

0.08 eV

unstable

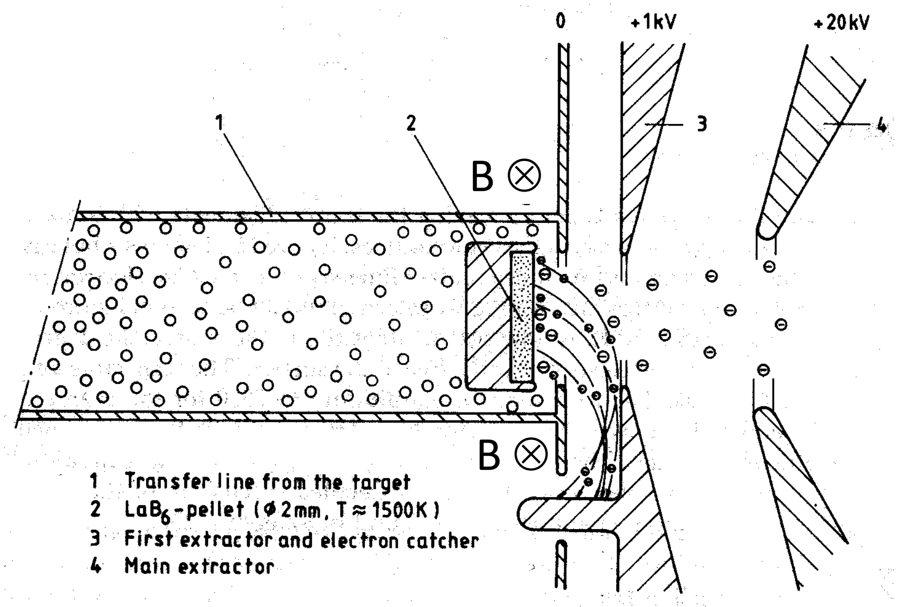
120 kJ/mol = -1.24 eV

(in kJ/mol)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	**H** −72.8																	**He** ≥0
2	**Li** −59.6	**Be** ≥0											**B** −27.0	**C** −121.8	**N** ≥0	**O** −141.0	**F** −328.2	**Ne** ≥0
3	**Na** −52.9	**Mg** ≥0											**Al** −41.8	**Si** −134.1	**P** −72.0	**S** −200.4	**Cl** −348.6	**Ar** ≥0
4	**K** −48.4	**Ca** −2.4	**Sc** −18	**Ti** −8	**V** −51	**Cr** −65.2	**Mn** ≥0	**Fe** −15	**Co** −64.0	**Ni** −111.7	**Cu** −119.2	**Zn** ≥0	**Ga** −40	**Ge** −118.9	**As** −78	**Se** −195.0	**Br** −324.5	**Kr** ≥0
5	**Rb** −46.9	**Sr** −5.0	**Y** −30	**Zr** −41	**Nb** −86	**Mo** −72.1	**Tc** −60	**Ru** −101.0	**Rh** −110.3	**Pd** −54.2	**Ag** −125.9	**Cd** ≥0	**In** −39	**Sn** −107.3	**Sb** −101.1	**Te** −190.2	**I** −295.2	**Xe** ≥0
6	**Cs** −45.5	**Ba** −14.0	**La** −45	**Hf** ≥0	**Ta** −31	**W** −79	**Re** −20	**Os** −104.0	**Ir** −150.9	**Pt** −205.0	**Au** −222.7	**Hg** ≥0	**Tl** −37	**Pb** −35	**Bi** −90.9	**Po** −180	**At** −270	**Rn** ≥0
7	**Fr**	**Ra**	**Ac**	**Rf**	**Db**	**Sg**	**Bh**	**Hs**	**Mt**	**Ds**	**Rg**	**Uub**	**Uut**	**Uuq**	**Uup**			

Lanthanides 6	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Actinides 7	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Negative surface ion source



$$\eta_i = \frac{1}{1+G\exp\left(\frac{\phi - A_E}{kT}\right)} \qquad O(G)=1$$

operation temperature

material	Φ_0 [eV]	T [°C]
LaB_6	2.4-3.3	1200
GdB_6	1.5	1500
Ir_5Ce	2.6	1600
BaOSrO	1.0	1100

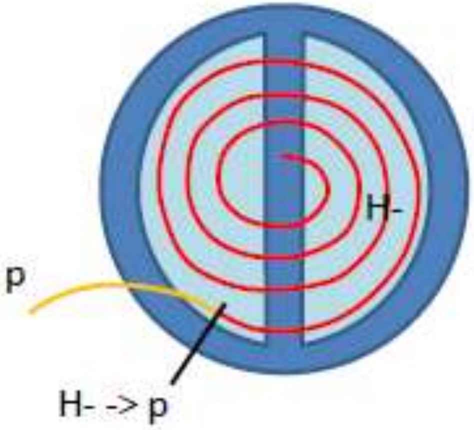
For 1- ions

Looking for low work function material

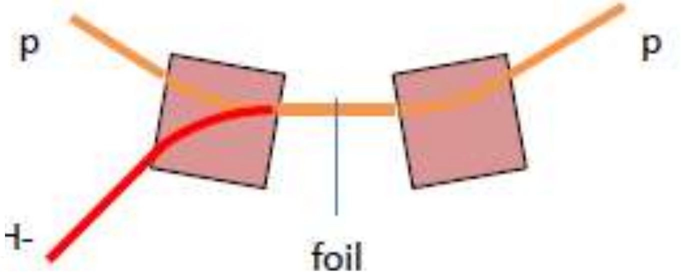
Surface ionisation efficiencies >10% for Cl, Br and I

Why negative ions?

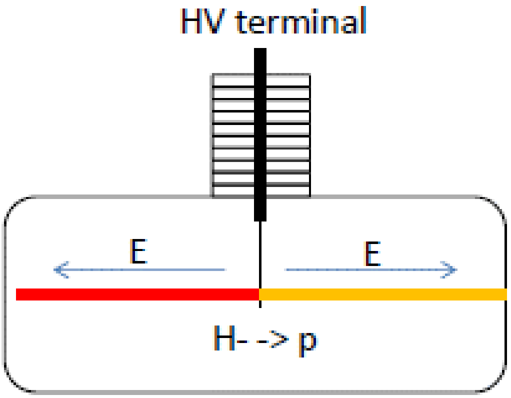
Extraction (from cyclotrons)
* Change the charge in a foil, and the positive ion leaves



Charge exchange injection (to synchrotrons)
* Overlap the negative and (circulating) positive ions, then strip to positive –> overcome Louiville!



Tandem
* Negative accelerated to foil, positive ion back to ground



Resonant photon impact ionization

Resonant ionization by photons

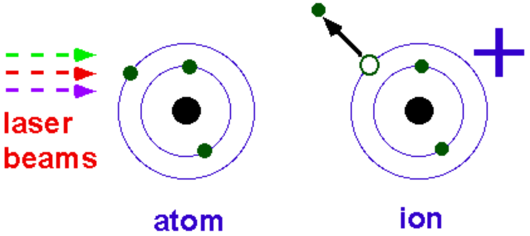
* The atomic line spectra is an element’s fingerprint

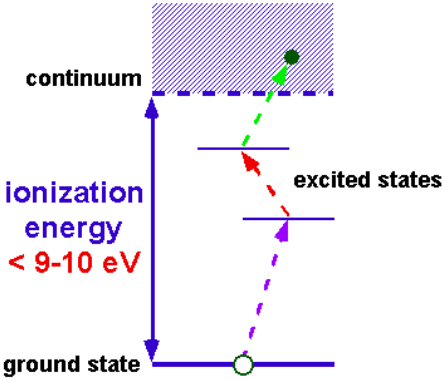
* Stepwise resonant laser ionisation via one or more intermediate levels

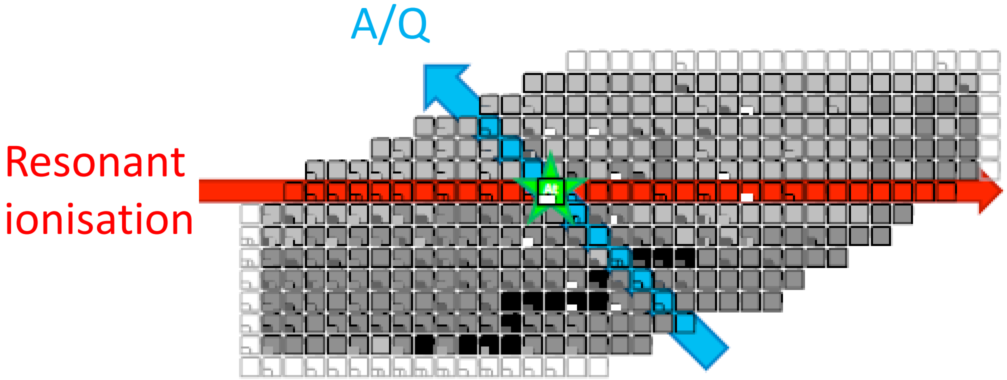
-> chemically (element) selective

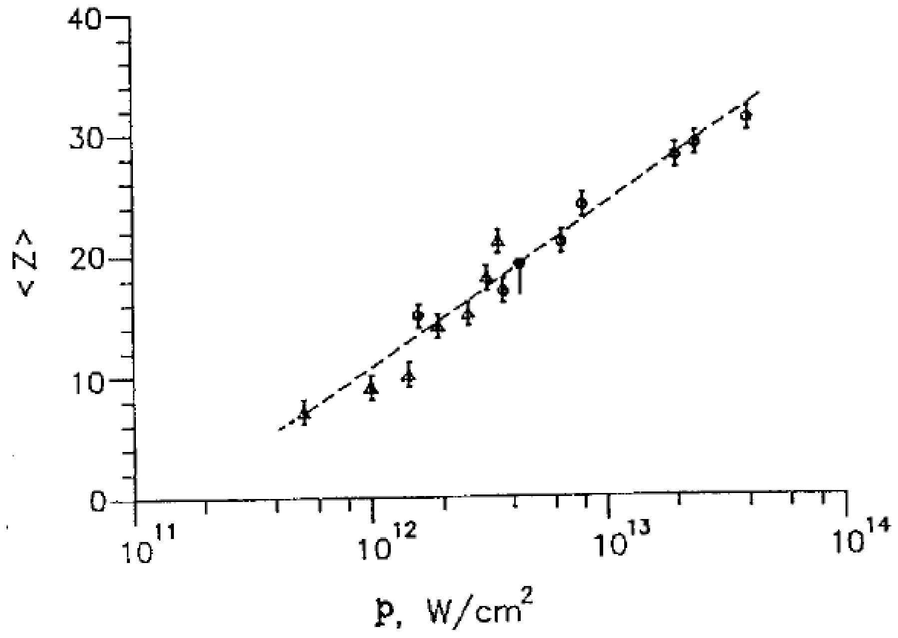
-> isobar free beams

* 2-3 ionization steps to ensure selectivity







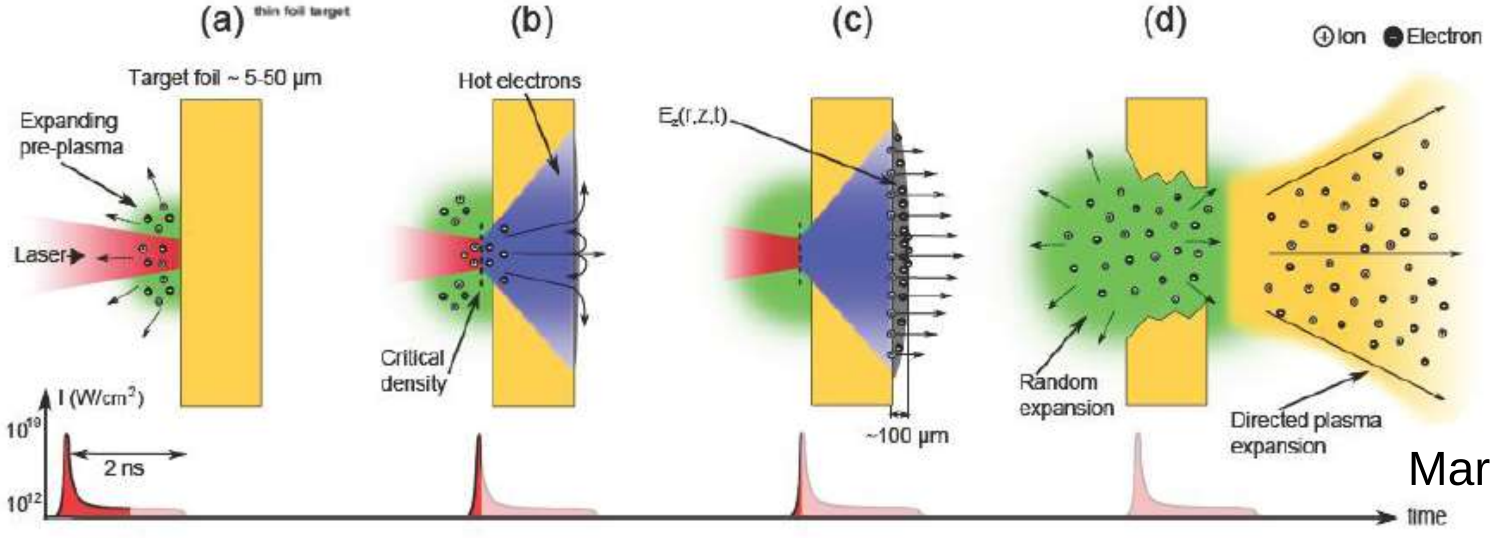


Not talking about…

…high-power non-resonant ionisation for production of highly charged ions

A high power laser (10^{20} to $10^{22}/\text{cm}_2$) is focused on a thin foil target or gas jet

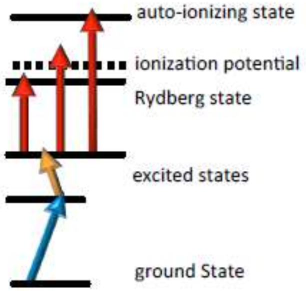
Ions are formed in the expanding plasma and accelerated to 10s to 100s of MeV energies directly

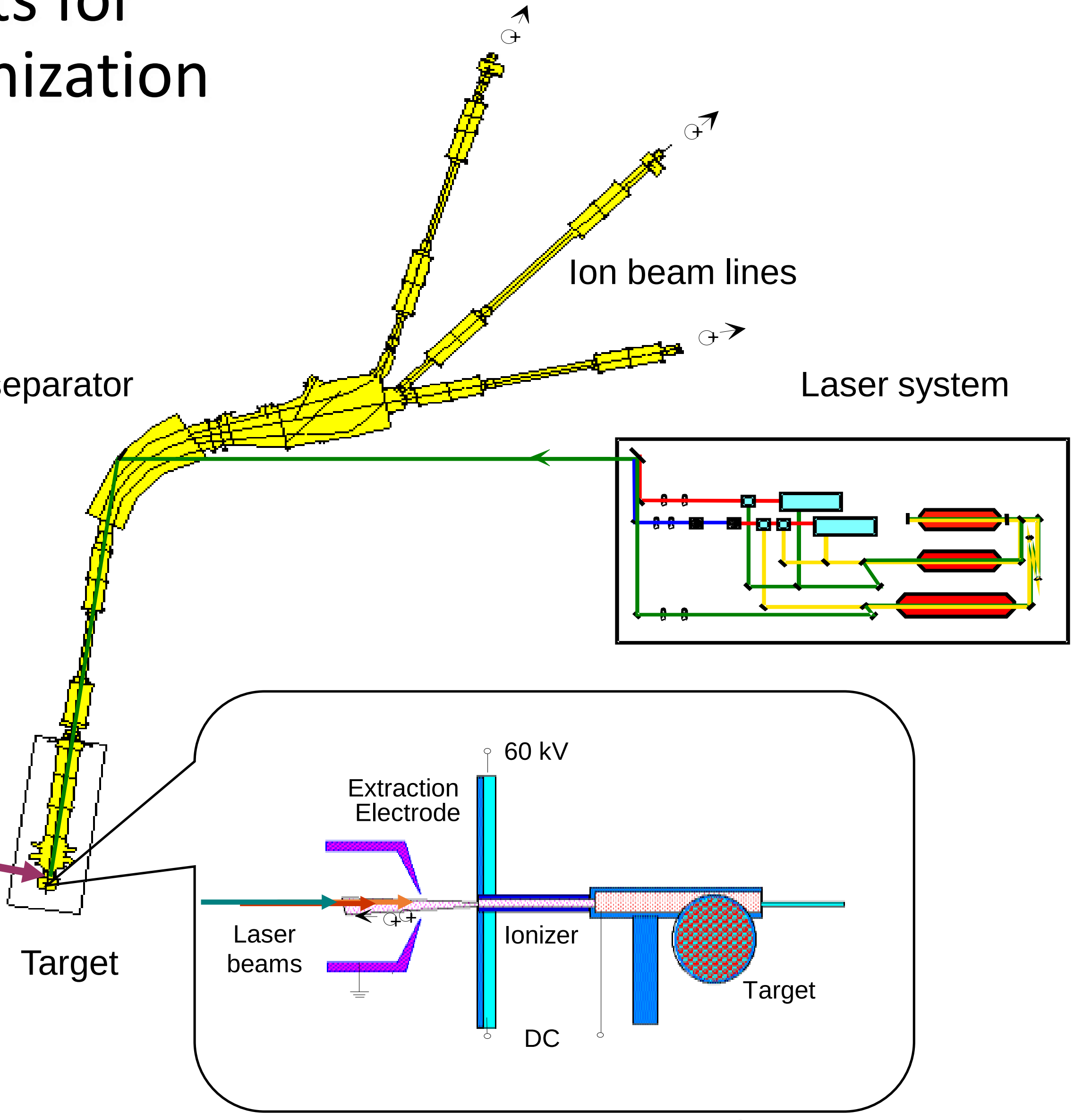


Marcus Roth

Essential elements for resonant laser ionization

Correct excitation scheme




Ion beam lines

Mass separator

Laser system

Proton beam

Target

60 kV

Extraction Electrode

Laser beams

Ionizer

Target

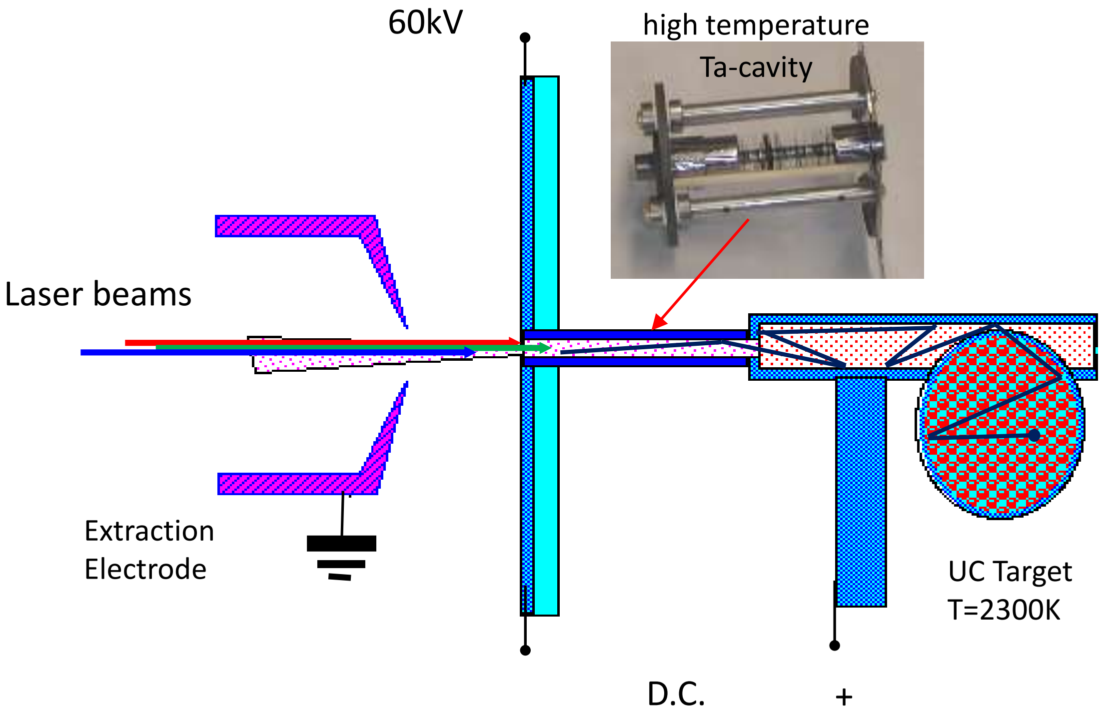
DC

Target - Ion Source Unit

The hot cavity

One wants:

* cavity that confines the atoms until laser impingement
* electron emission for potential well
* hot surface to avoid long sticking times
* low work-function to reduce surface ionization



$$\text{Selectivity} = \frac{\text{Laser Ionization Efficiency}}{\text{Surface Ionization Efficiency}}$$

$\Rightarrow$ depends on a. the ionization potentials of isobar atoms
b. cavity material

Efficiency:

$$\eta = \frac{P_{\text{Ionisation}}}{P_{\text{Ionisation}} + P_{\text{Effusion}}}$$

$$\eta = \frac{\nu_{rep}\ \varepsilon_{ion}}{\nu_{rep}\ \varepsilon_{ion} + \frac{2dv}{3L^2}}$$

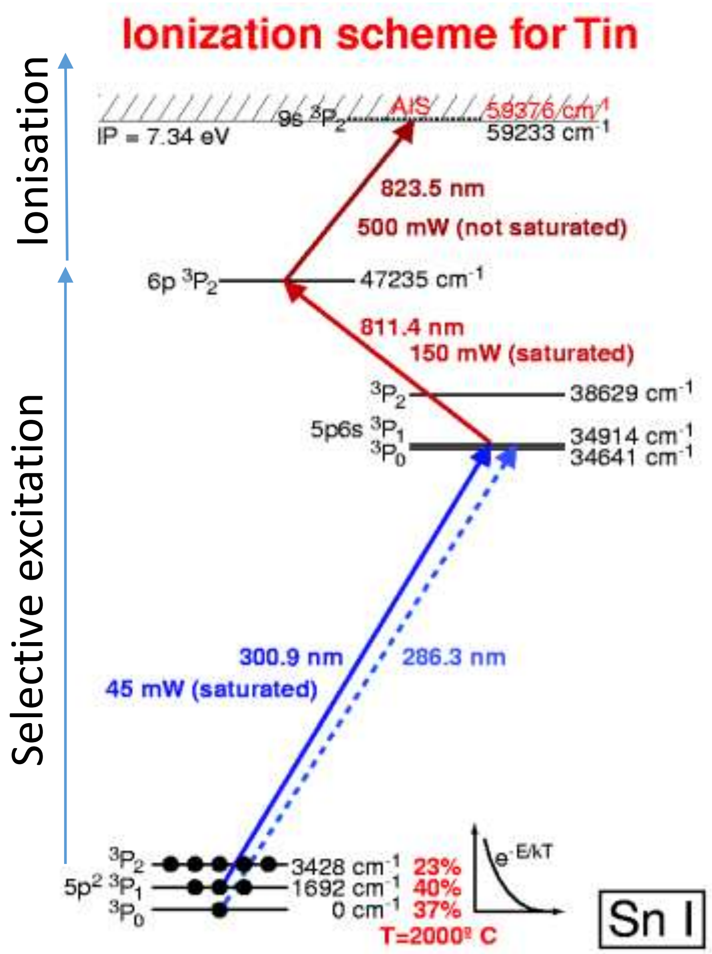
=> high laser pulse repetition rate ν_{rep}=11.000 Hz

=> long cavity L

η_{laser} = 2% - 30%

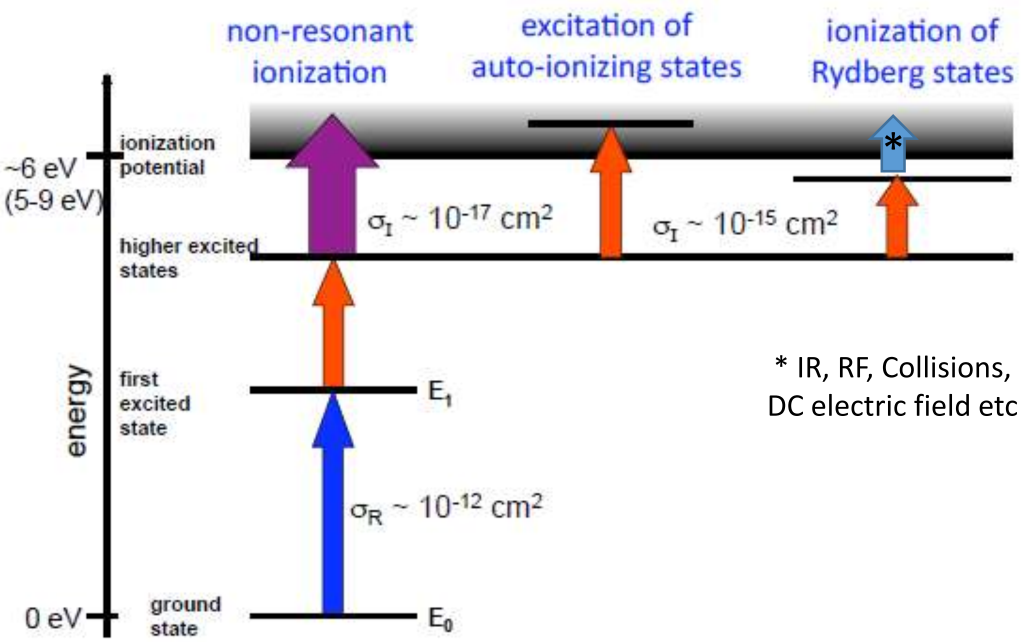
$$\eta_{surface} \begin{cases} > 5\% & \text{- alkalies} \\ = 0.1\% - 2\% & \text{- In, Ga, Ba, lanthanides} \\ < 0.1\% & \text{- others} \end{cases}$$

The stepwise ionization


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,
to Rydberg states



* IR, RF, Collisions, DC electric field etc

$$N_{event}=N_{incident}\cdot\underbrace{n_{target}\cdot d_{target}}_{\text{atoms/cm2}}\cdot\sigma$$

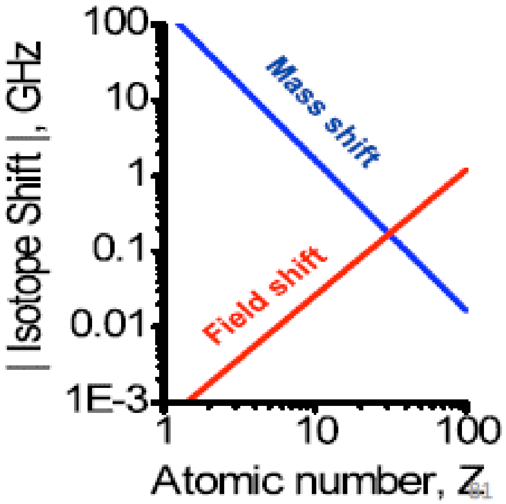
Extra

Isotope shift & auto-ionizing states

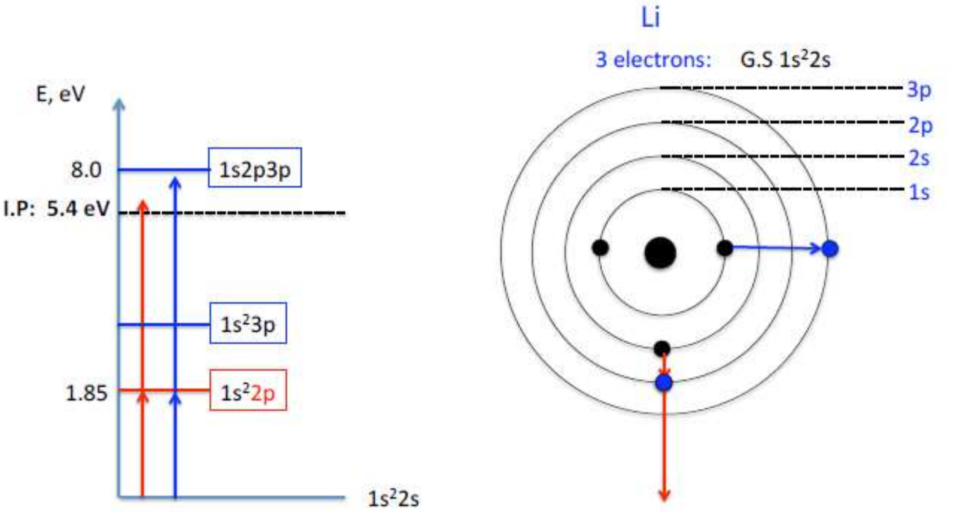
The frequency difference in the electron transition between 2 isotopes of an element

CAUSED BY these properties:

Finite nuclear mass	**MASS SHIFT**
Nuclear Volume (not point-like)	**FIELD SHIFT**



"Atoms and ions may be excited in various processes to states which in turn spontaneously decay by electron emission. Such a radiationless transition mechanism is called autoionization. An autoionizing state lies energetically above the lowest ionization treshold, embedded in the electron-continuum."

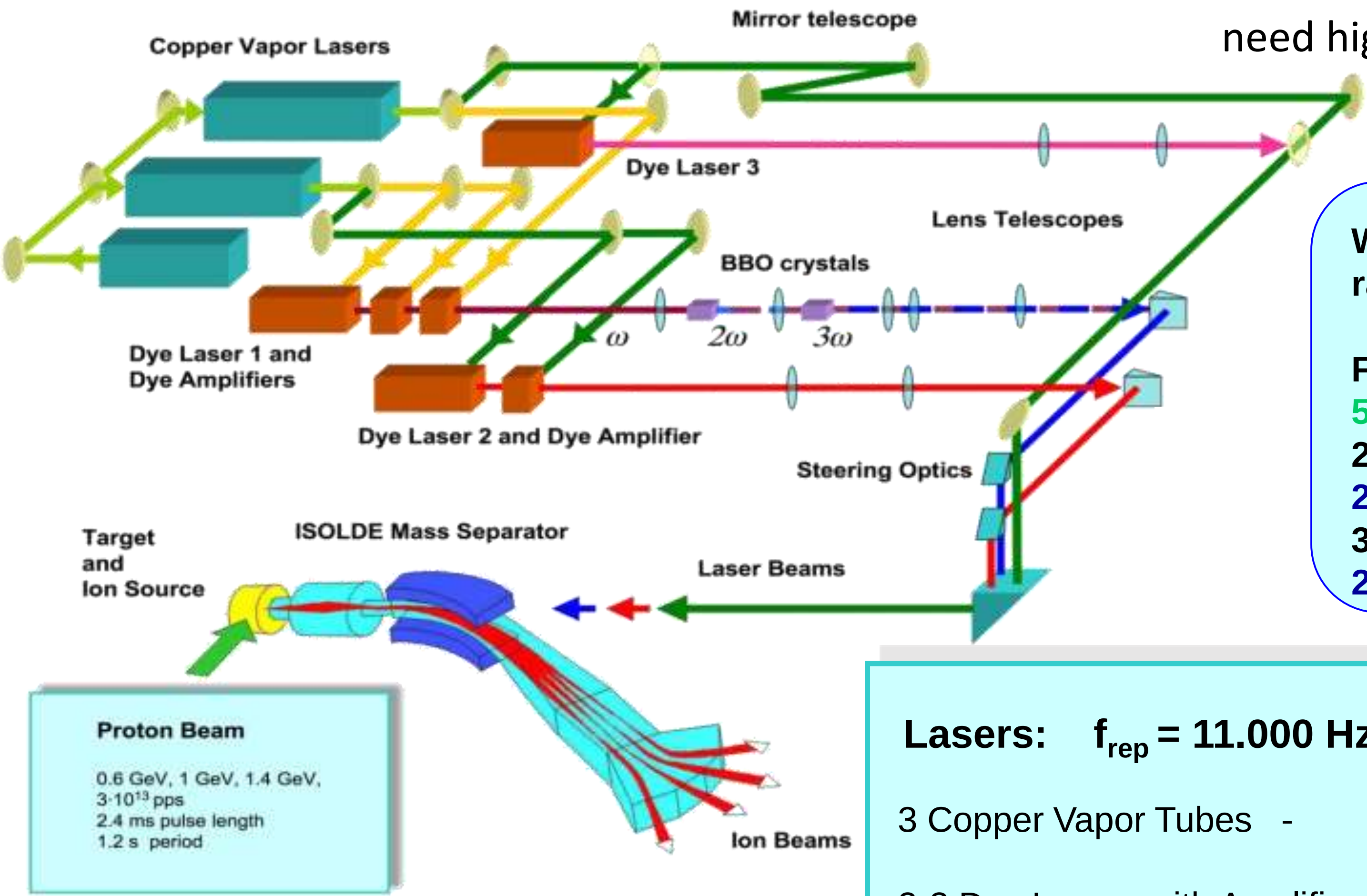


Decay from the AIS is either by photon emission or by electron-electron energy transfer via the coulomb interaction: more likely if the 2 electrons share similar shaped orbits (temporal overlap) and if the energy transfer does not have to be to a discrete state - *continuum*

Extra loss channel → reduced lifetime of state → broader resonance

(Old) laser set-up for 3-step resonance ionization

NB! Lasers are pulsed - > need high repetition rate



Wavelength tuning range:

Fundamental (ω)
530 - 850 nm
2nd harmonic (2ω)
265 - 425 nm
3rd harmonic (3ω)
213 - 265 nm

Lasers: $f_{rep} = 11.000$ Hz, $t_{pulse} = 15$ ns

3 Copper Vapor Tubes - $P_{Cu}^{total} \le 80\,W$

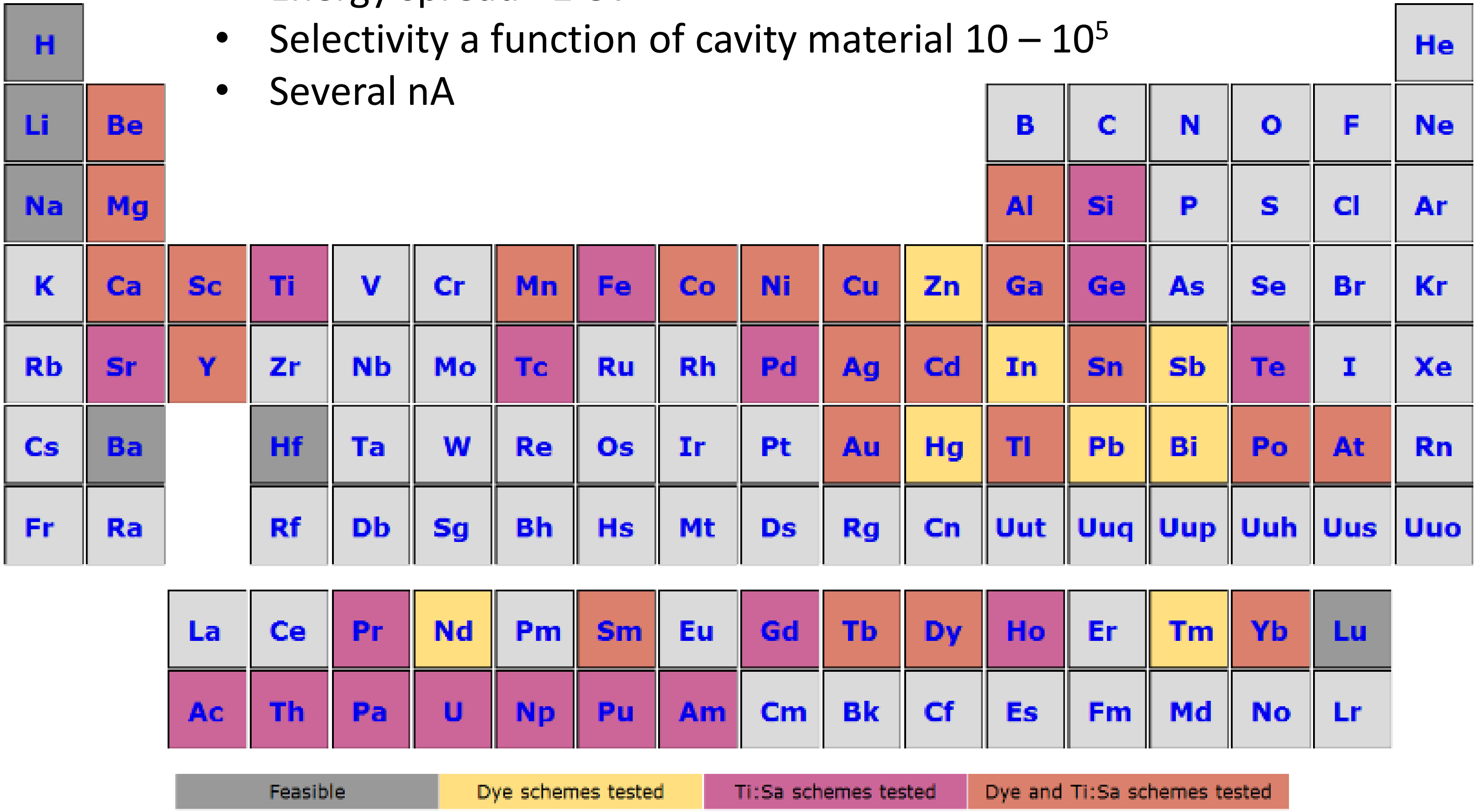
2-3 Dye Lasers with Amplifiers - $P_{dye} \le 8\,W$

Nonlinear Crystals BBO - $P_{2\omega} \le 2\,W$

$P_{3\omega} \le 0.2\,W$

Elements and general data

- I_e 4 to 9 eV
- 2-30% ionisation efficiency
- Energy spread <2 eV
- Selectivity a function of cavity material 10 – 10^5
- Several nA

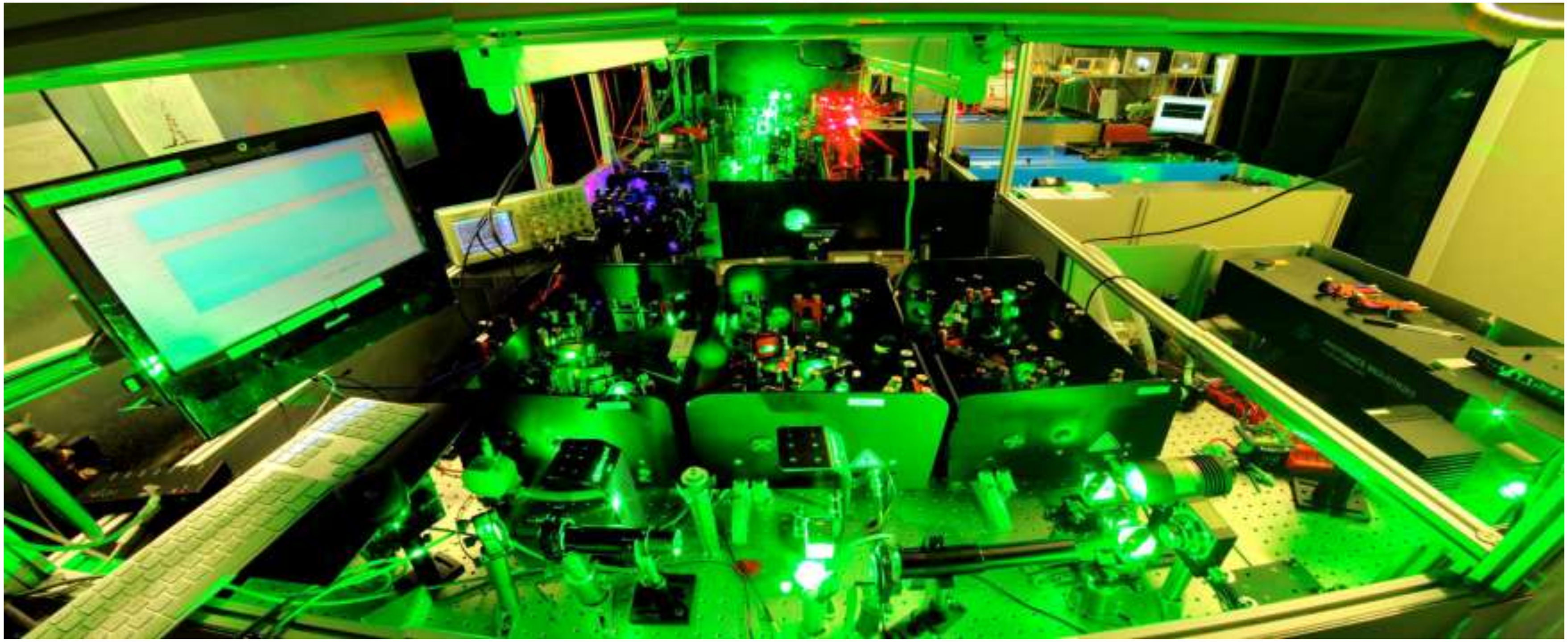


http://rilis.web.cern.ch/elements

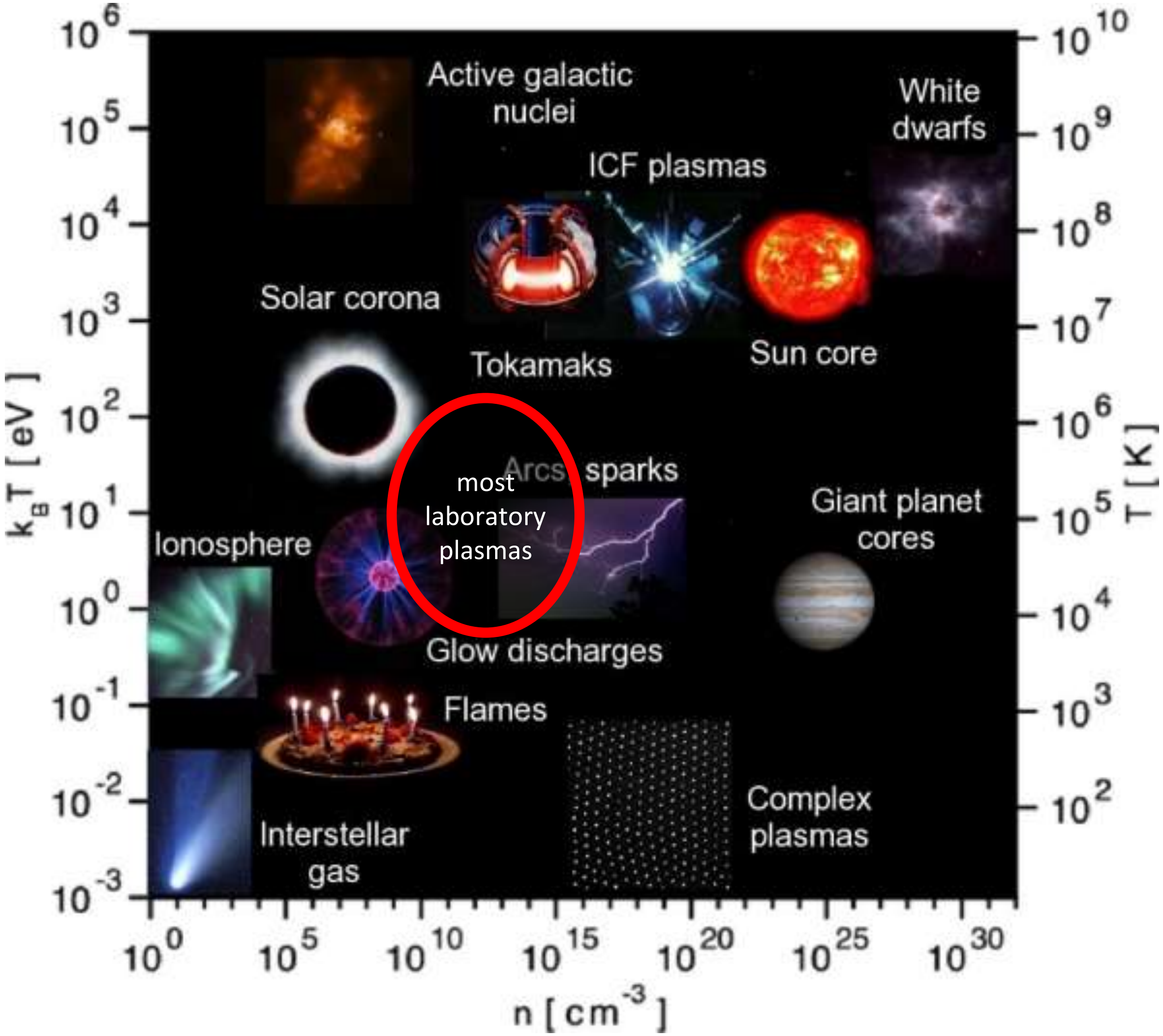
ISOLDE resonant laser ion source

What did DG Fabiola Gianotti say?

a. Red is my favourite colour.
b. ISOLDE is a cornerstone in the diversed physics programme of CERN.
c. Italy, Italy, Italy. Everyone just talks about Italy.



Plasma map



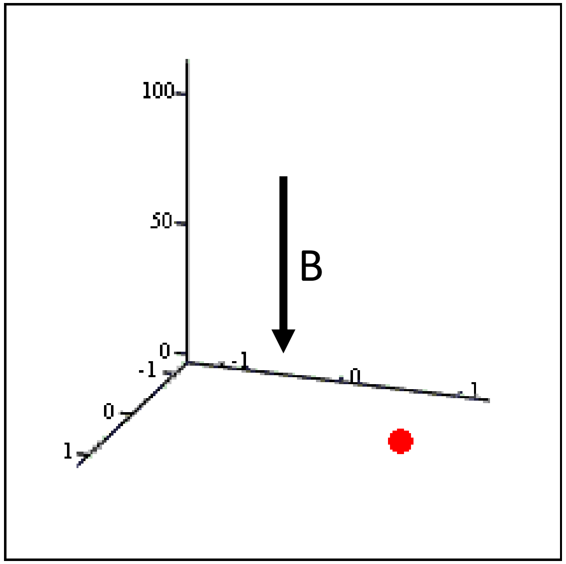
Plasmas exist in a wide range of densities and temperatures

Particle motions

$$\vec{F} = qe\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

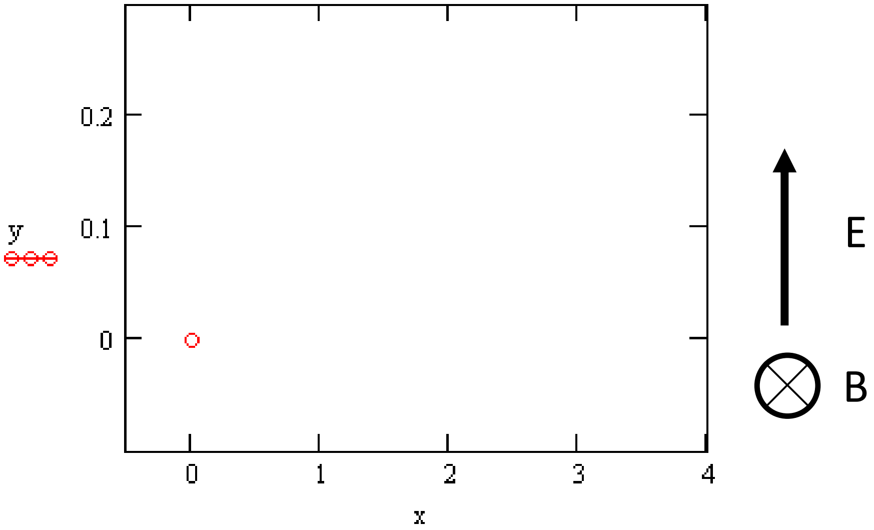
Charged particles in a magnetic field

$$\rho_{ce}[cm] = 0.00033 \frac{\sqrt{T_e[eV]}}{B[T]} \qquad \rho_{ci}[cm] = 0.0014 \frac{\sqrt{AT_i[eV]}}{qB[T]}$$



$$\rho_c = \frac{\sqrt{2mW_{kin,\perp}}}{qeB}, \omega_c = \frac{qeB}{m}$$

E cross B drift

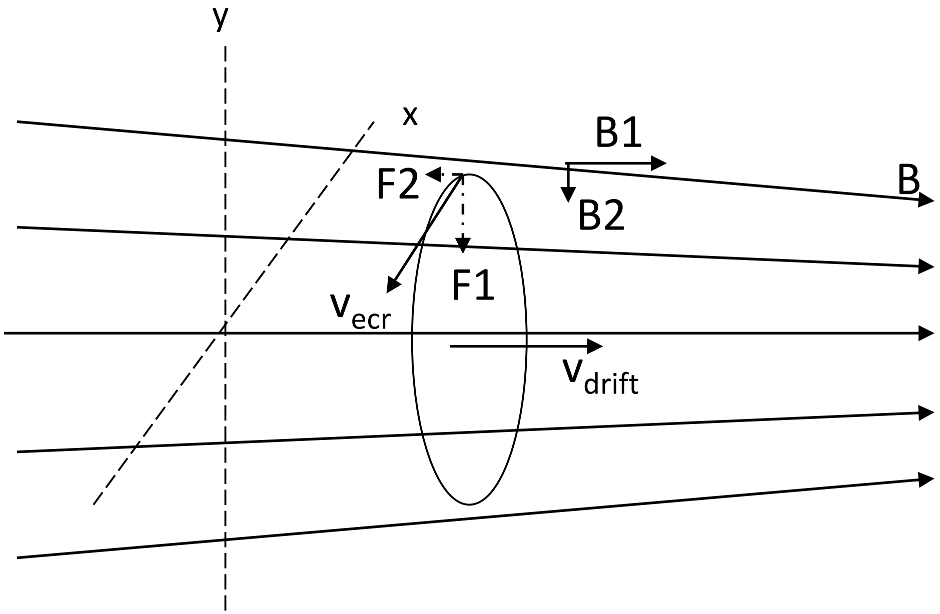


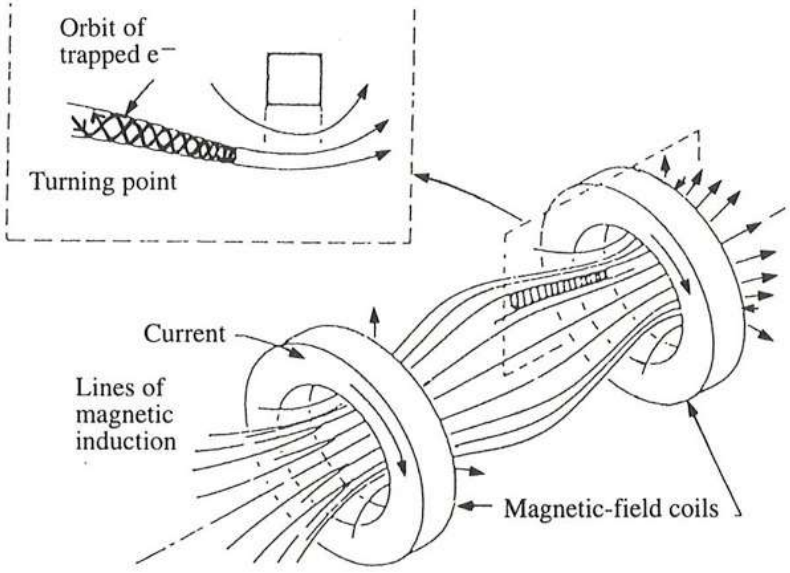
$$v_{drift} = \frac{\vec{E} \times \vec{B}}{B^2}$$

Magnetic mirror

Increasing B-field =>

A force acts in the opposite direction to the increasing B-field
Energy is transferred from v_{drift} to v_{ecr}





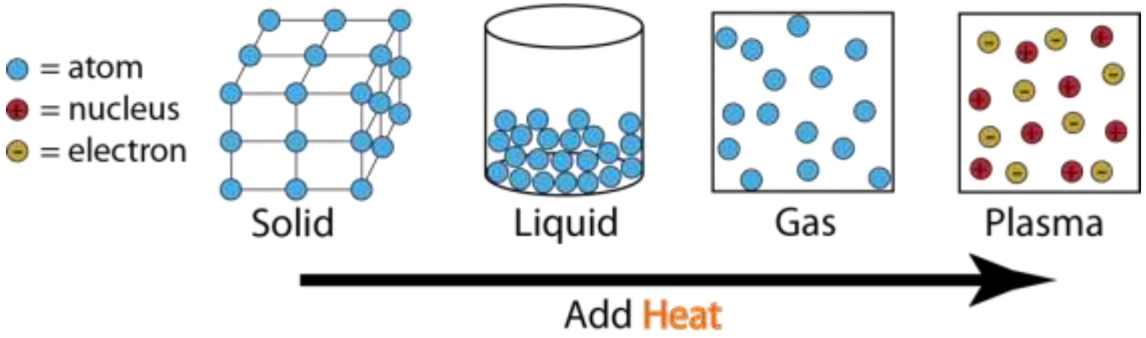
$$v_{drift} = \left\{ \frac{2}{m} \left(W_{kin} - \mu B \right) \right\}^{1/2}$$

$$\mu = \frac{m v_{\perp}^{2}}{2B}$$

μ = magnetic moment conserved
W_{kin} = total kinetic energy

What is a plasma?

A plasma is a quasi neutral gas of charged and neutral particles



Overall charge neutrality is preserved

$$\sum_{i} q_i n_i = n_e$$

Otherwise large electrical fields

In a fully ionized plasma the collisions are Coulomb collisions

There are elastic (energy transfer) and inelastic collisions (atomic processes)

Collisions are described by collision frequency (typical time scale) and mean free path (typical length scale)

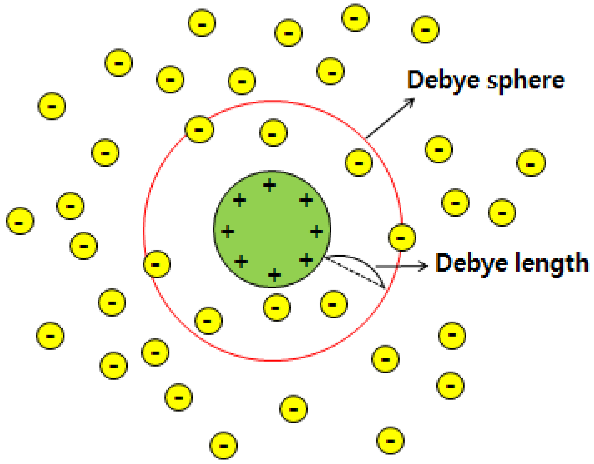
Debye length

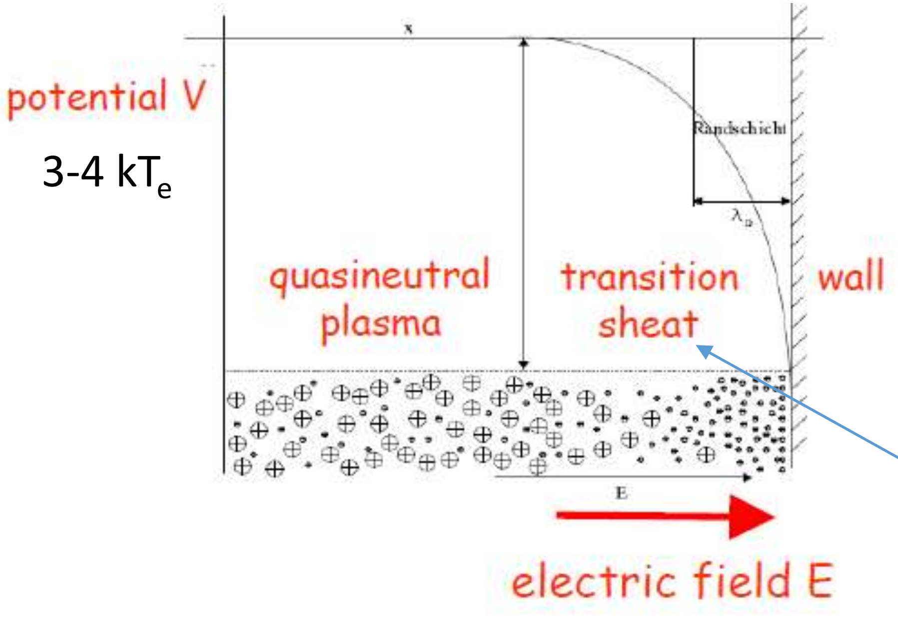
The Debye length defines the sphere in which the electric fields have an influence. Outside this sphere the electric charges are shielded.

$$l_D = \left(\frac{e_0 k T_e}{n_e e^2} \right)^{1/2}$$

mm to 0.01 mm

$$l_D[\mathrm{cm}] = 743\left(T_e[\mathrm{eV}] / n_e\left[\mathrm{cm}^{-3}\right]\right)^{1/2}$$





3-4 kT_e

electrons move faster ->

higher loss rate than ions ->

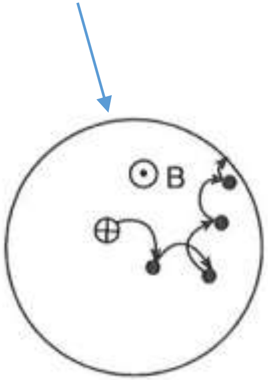
plasma charges up to maintain neutrality

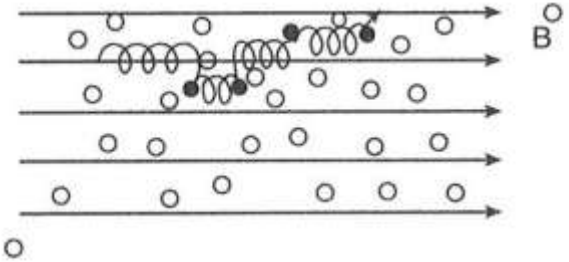
plasma sheath

Plasma confinement

- Electrons are mainly lost along B-field lines //
- Ions mainly lost transversally to B-field lines due to collisions ⊥

Collisional Drift





A plasma needs heating and confinement

e.g. magnetic bottle (minimum-B mirror)

or gravity in a star

Extra

Plasma frequency

Macroscopically the plasma is charge neutral, microscopically the imbalance leads to micro instabilities, fluctuations and oscillations

$$E = \frac{e}{\epsilon_0} n x$$

$$F = eE = \frac{e^2}{\epsilon_0} n x = m_e \frac{d^2 x}{dt^2}$$

- Electric field by a local charge separation along a distance x
- The charge unbalance leads to a restoring force
- Equation of an harmonic oscillator with eigen-frequency ω

$$\omega_e = \sqrt{\frac{e^2 n_e}{\epsilon_0 m_e}}$$

Plasma frequency in GHz range

$$\omega_i = \sqrt{\frac{e^2 n_e}{\epsilon_0 m_i}}$$

Plasma frequency in MHz range

Ion extraction

Ion extraction

Two cases:

1. space charge limited
(space-charge cloud in front of the extraction system)

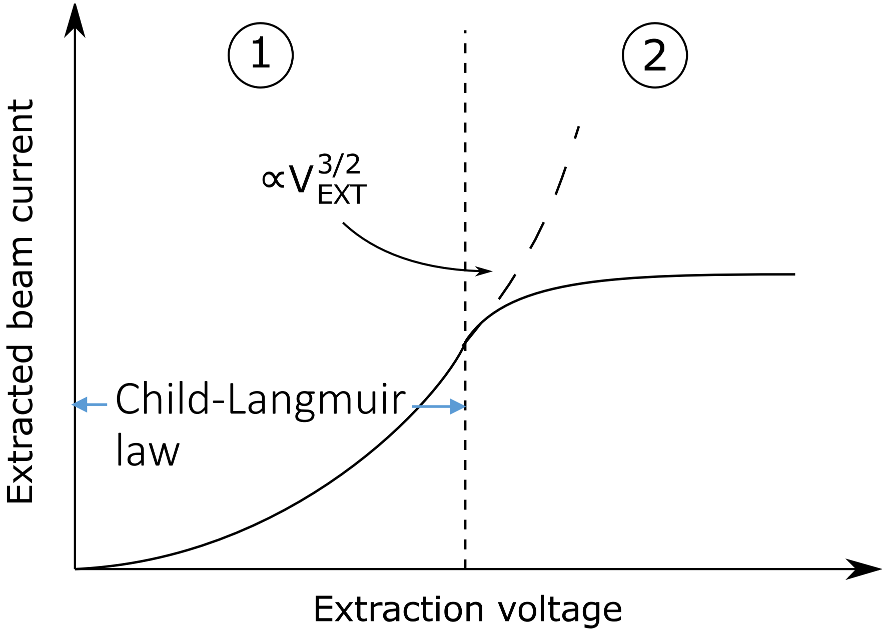
   e.g. stable beams for cancer treatment

2. emission limited
(plasma / source can not deliver ‘enough’ particles)

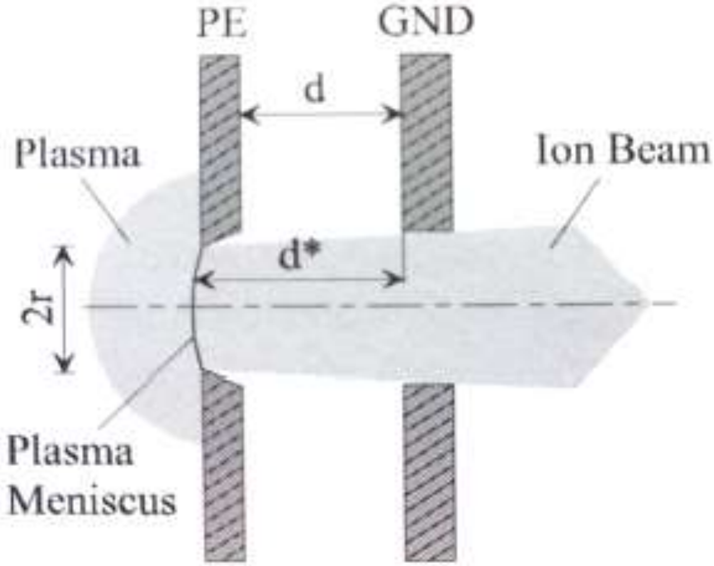
   e.g. most radioactive beams

higher extraction voltage

helps doesn’t help



Ion extraction



Child-Langmuir defines the maximal extractable emission current density

$$j = \frac{4e_0}{9}\sqrt{\frac{2q}{m}}\frac{U^{3/2}}{d^2}$$

q – ion charge state
m – ion mass
U – extraction voltage
d – extraction gap
j – A/m^2

conditions

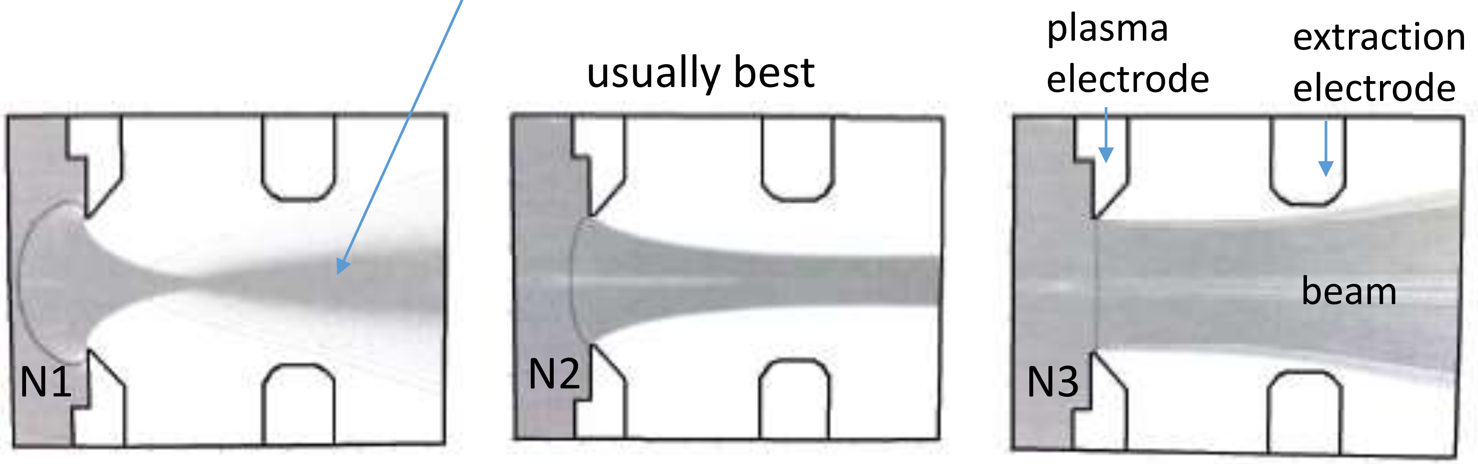
- planar and indefinite emission area
- particles have zero initial longitudinal energy

d* is self-adjusting so the electrical field at the meniscus becomes zero

Ion extraction

Poisson equation + current continuity + energy conservation

$$\underbrace{\nabla^2\phi = \frac{d^2\phi}{dz^2} = -\frac{\rho}{\varepsilon_0} \qquad j_z = \rho\dot{z}=\text{const} \qquad \frac{m}{2}\dot{z}^2 = -q\phi(z)}$$



Same extraction voltage for different plasma densities N1 < N2 < N3

The emissive surface of the plasma is often referred to as plasma meniscus*

The dynamic equilibrium between the plasma and the extracted particles creates the meniscus

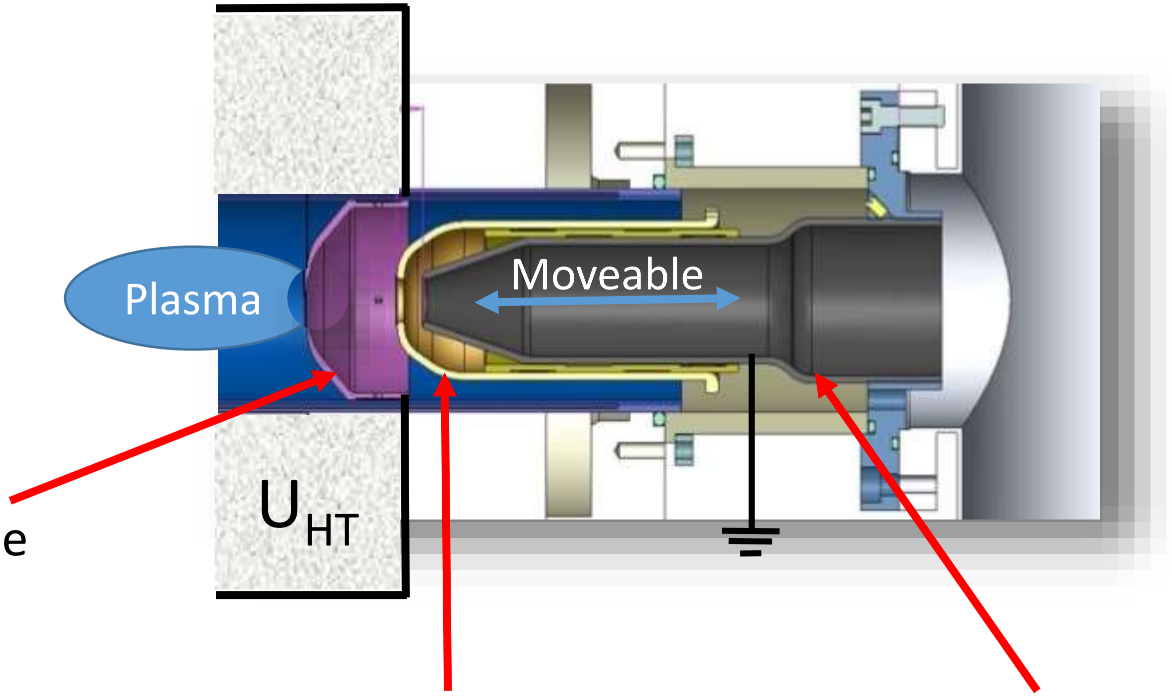
Shaping the extraction system electrodes can give a focusing force to compensate for the transverse space-charge forces

plasma meniscus is not actually a surface because of the Debye length it has a thickness

Extraction system

The extraction system consists of two or more electrodes

- in general the source body is on high voltage and the beam line on ground potential
- additional electrodes can serve for electron suppression or beam shaping



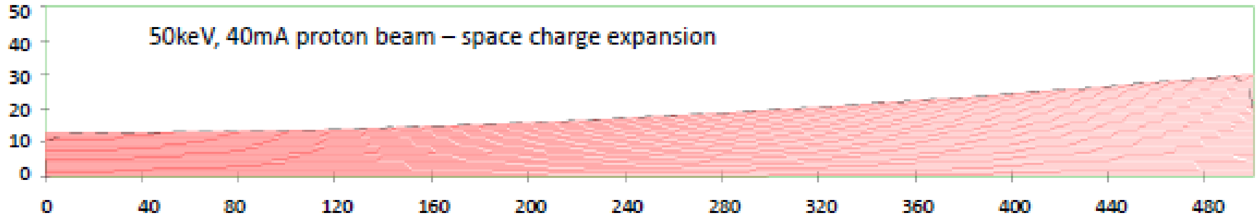
Plasma electrode

Intermediate electrode (-1 to -5 kV)

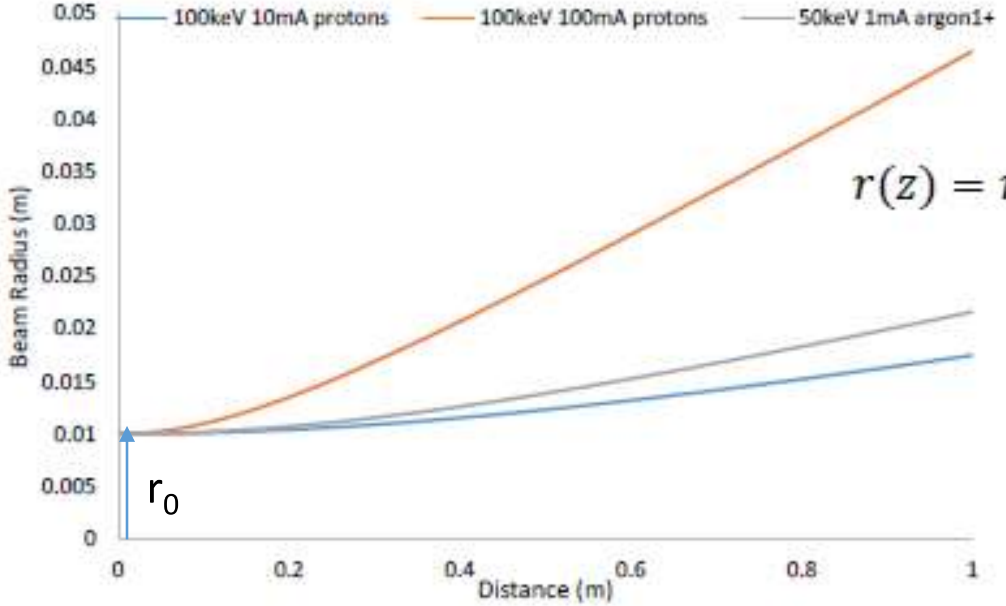
Puller / extraction electrode

Space charge

The beam is repulsed by its own space charge



Direct space charge becomes very strong at low energy (non-relativistic beams)



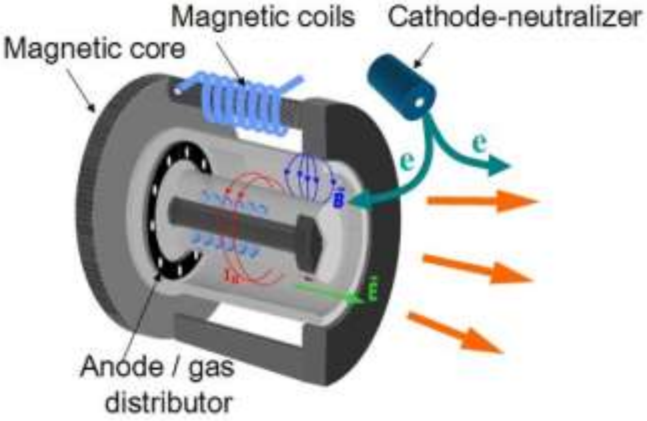
$$r(z) = r_0\sqrt{1 + \frac{qI_0z^2}{2\pi\epsilon_0r_0^2mv^3}}$$

No worry for radioactive beams as current so low

Estimation (uniform density cylindrical beam, non-relativistic)

Space charge compensation

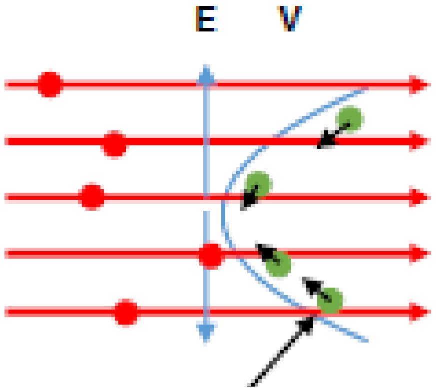
?



Electrons!

Extra

Space charge compensation



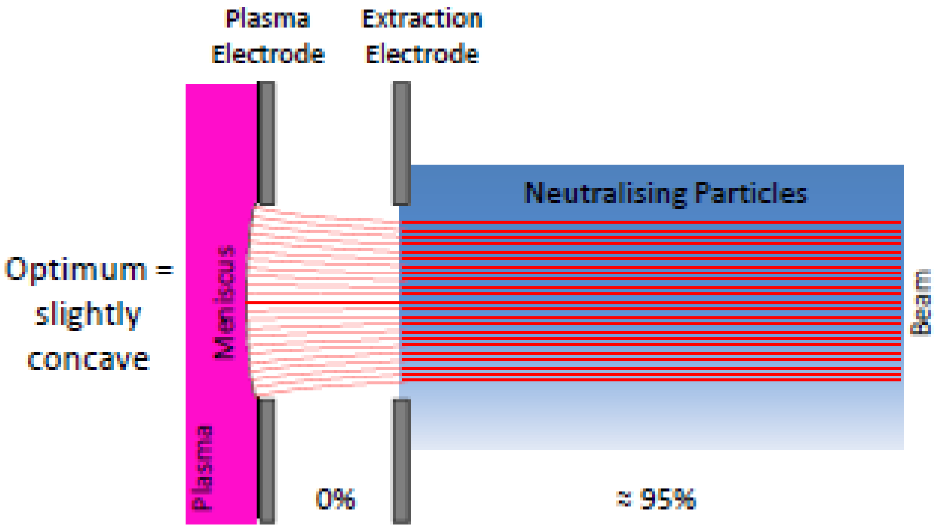
e⁻ from ionized gas atoms

Nature is for once kind:

* The particle beams can ionize the residual gas left in the beam line

* The resulting electrons are contained by the potential of the beam

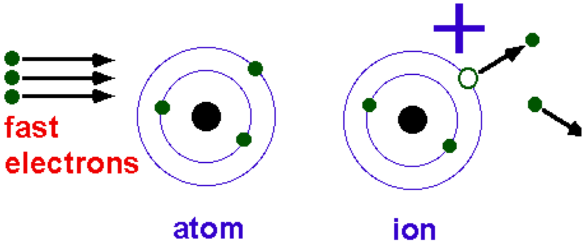
* The trapped particles suppress the beams own self-induced electric field, allowing it to be more easily transported

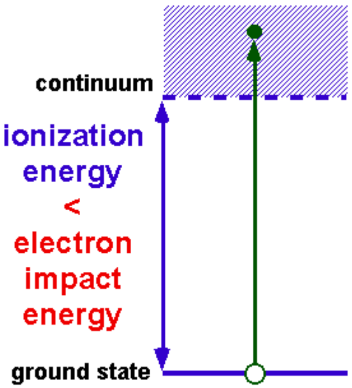


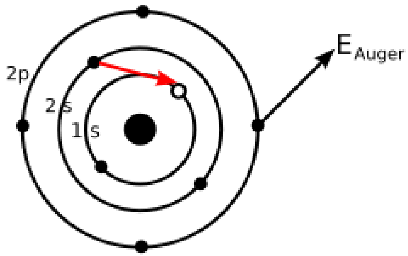
Percentage compensation

Electron bombardment ion source

Ionization by electron impact





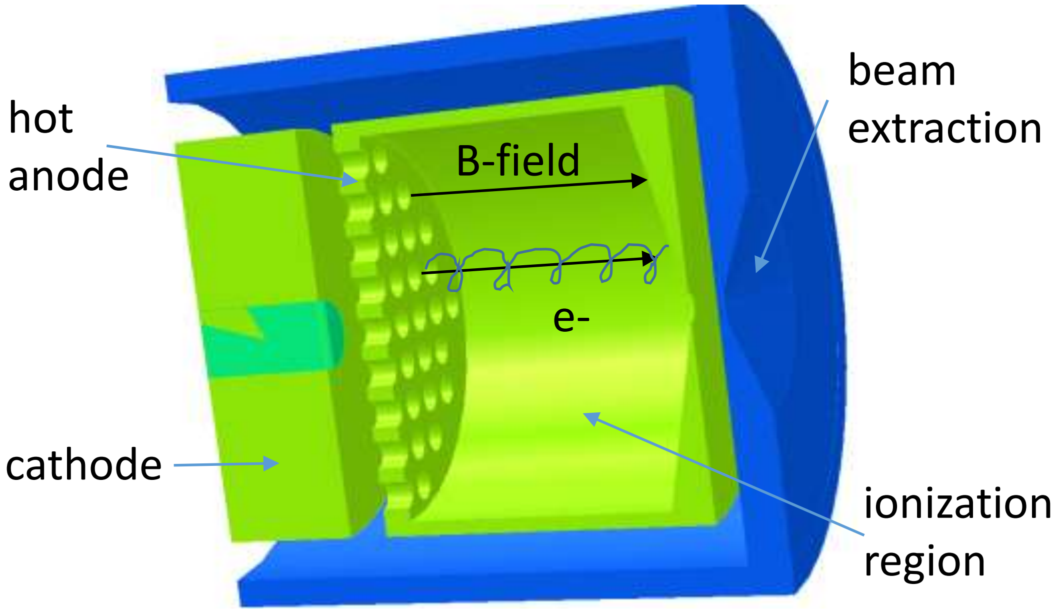


Auger electron emission

Electron bombardment ion source

Processes involved

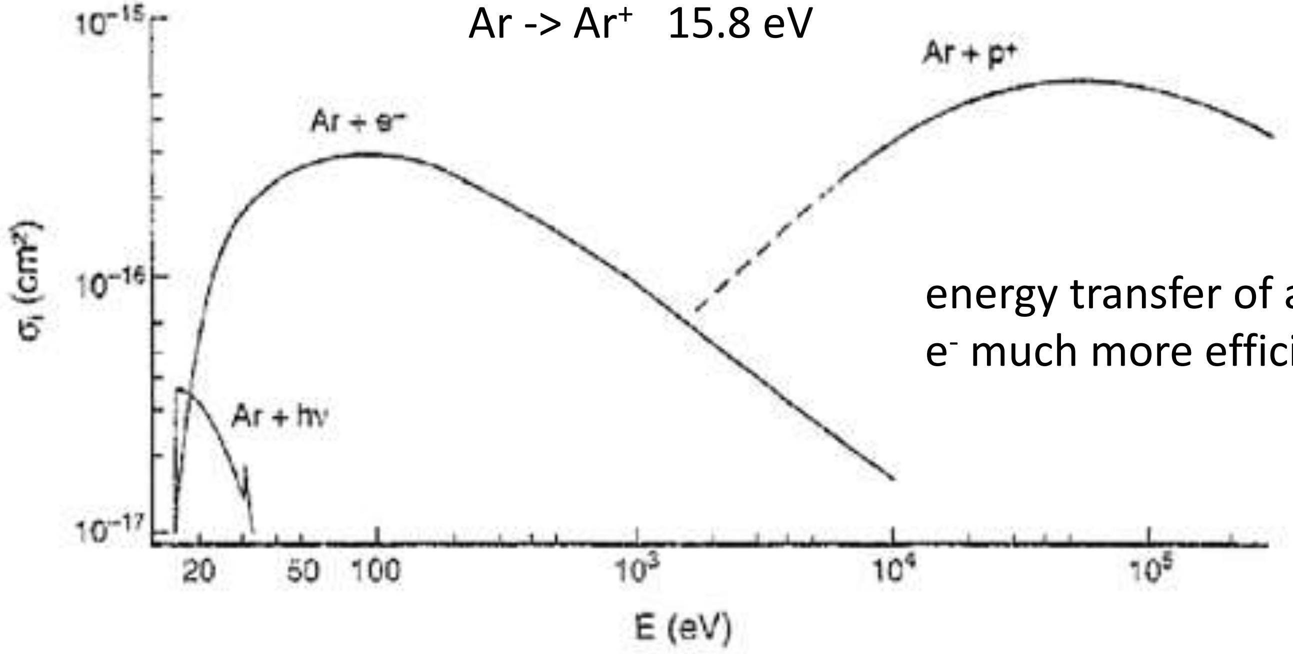
- Direct knockout ionization
- Indirect processes (based on inner-shell excitation and subsequent auto-ionization); more important for heavier atoms



Ionization by particle impact

Ionization cross sections for Ar vs energy of ionizing collisions with:

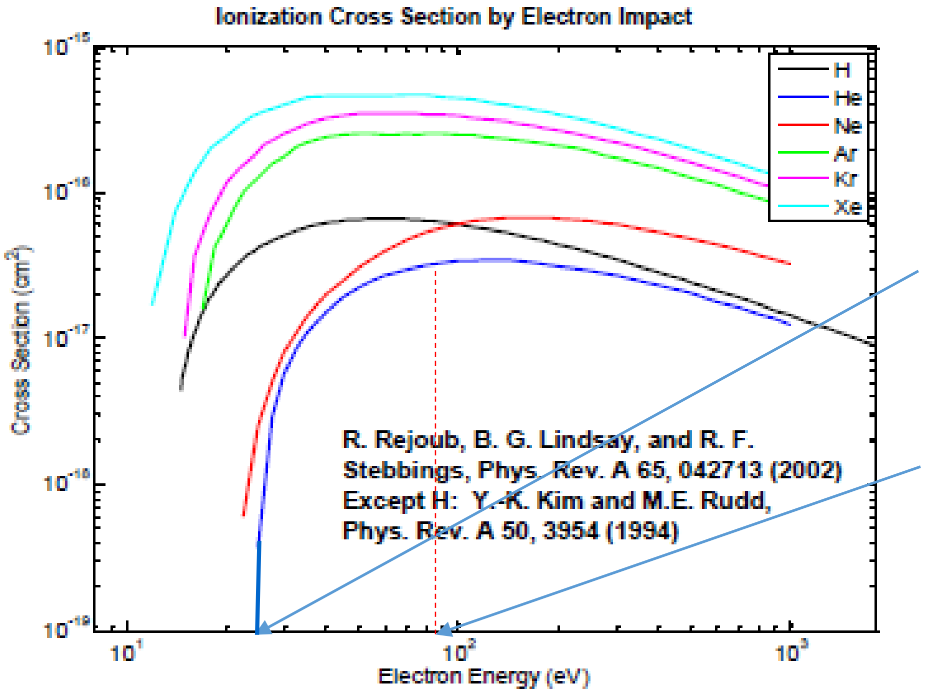
- * Photons
- * Electrons
- * Protons



Ar -> Ar^+ 15.8 eV

energy transfer of a heavy particle is lower
e^- much more efficient than protons

Atomic processes

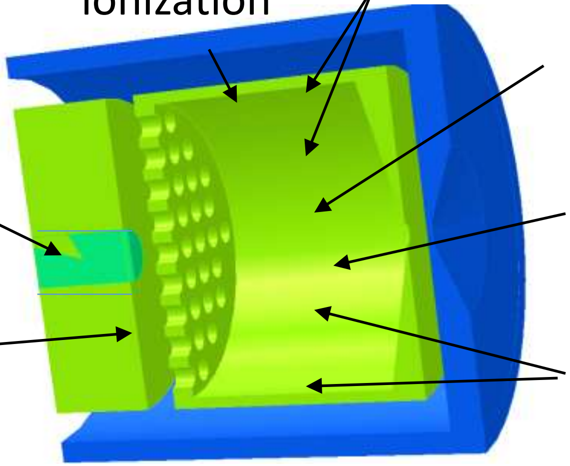


R. Rejoub, B. G. Lindsay, and R. F. Stebbings, Phys. Rev. A 65, 042713 (2002)
Except H: Y.-K. Kim and M.E. Rudd, Phys. Rev. A 50, 3954 (1994)

* Ionization starts at the ionization threshold E_I.

* Optimal energy for ionization is nearly 3 times the ionization energy of the weakest bound electron, i. e. the ionization energy.

Some cross section data available in:
hcp://physics.nist.gov/PhysRefData/Ionization/Xsection.html



surface ionization

chemical reactions

electron impact ionization

neutral effusion

charge exchange

thermionic emission

recombination

* The source can run with and without (noble) support gases

* Plasma or not plasma?

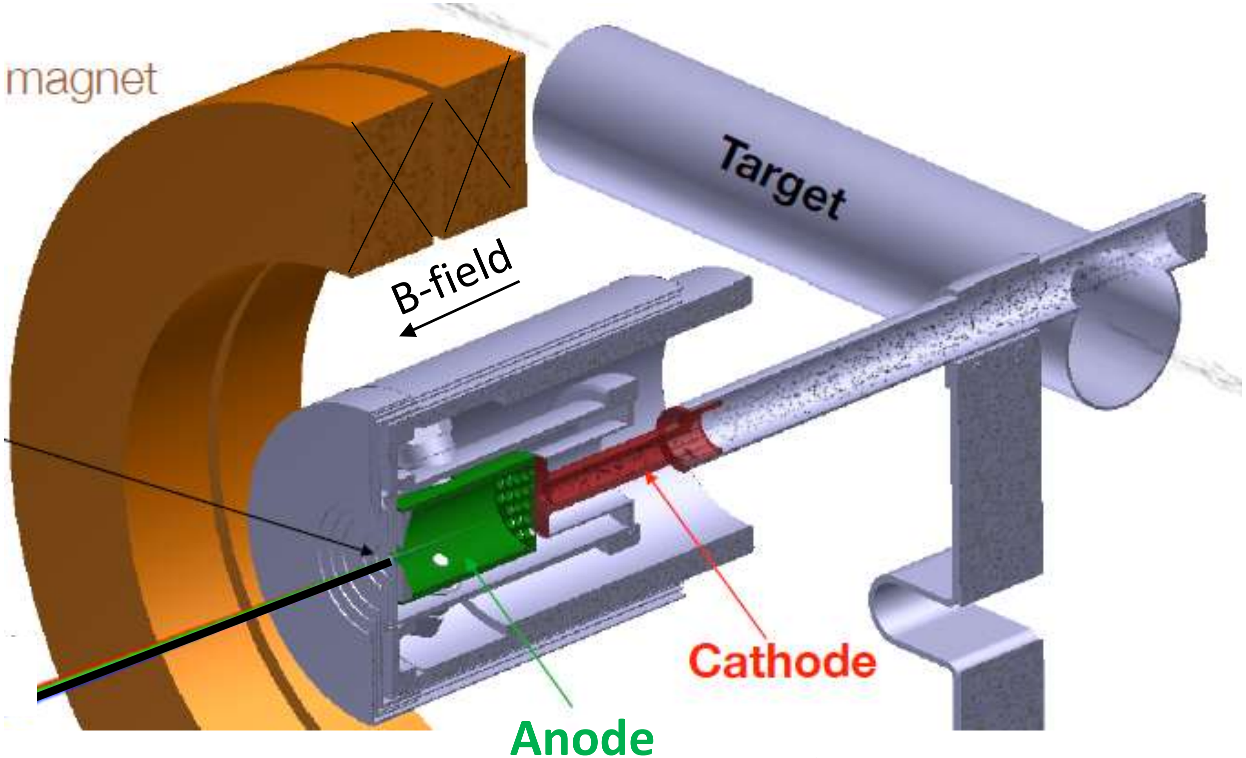
See L. Penescu's PhD work, CERN

Forced Electron Bombardment Induced Arc Discharge
FEBIAD

Mechanical design

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

V_{anode}=10-300 V
I_{anode} < 200 mA



Cavity
extr. hole: 0.5-3 mm
length= 2-3 cm
diam=1-2 cm

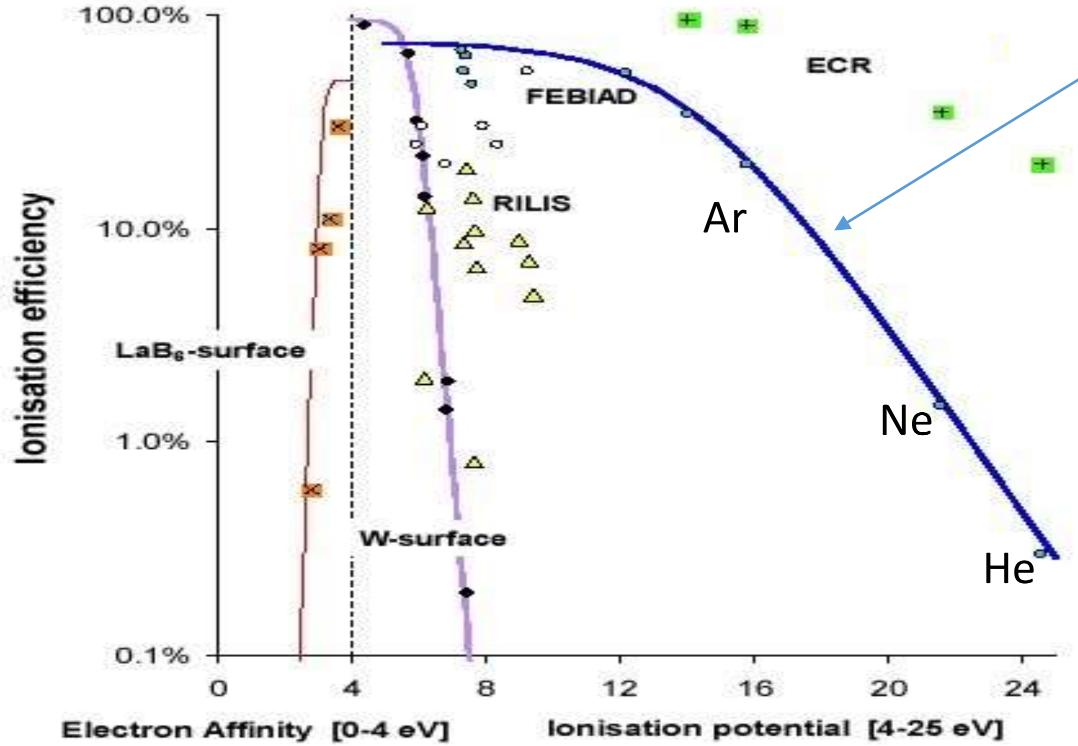
T = 1500-2300°C

Pressures $5\cdot10^{-4}$ to $3\cdot10^{-5}$ mbar

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

FEBIAD properties

+ stable operation with little support gas
+ low ion current density 1-20 μA/mm^2, up to 100 uA total
+ emittance 15-20 mm mrad (30 kV, 95%)
+ volume as small as 1.3 cm^3 (only 6 ms intrinsic delay)



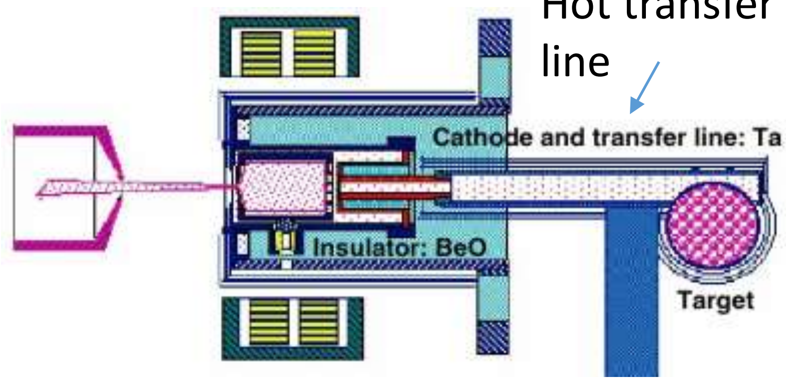
Very efficient, even for elements with high ionisation potentials

Why is there a mass trend?

Effusion velocity $\sim \frac{1}{\sqrt{A}}$

Selectivity in a FEBIAD

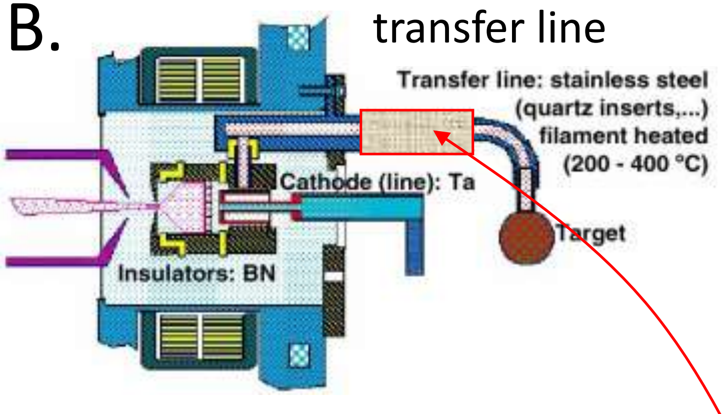
Hot transfer line



MK5 1900 °C
elements with low vapour pressure

Medium temperature transfer line

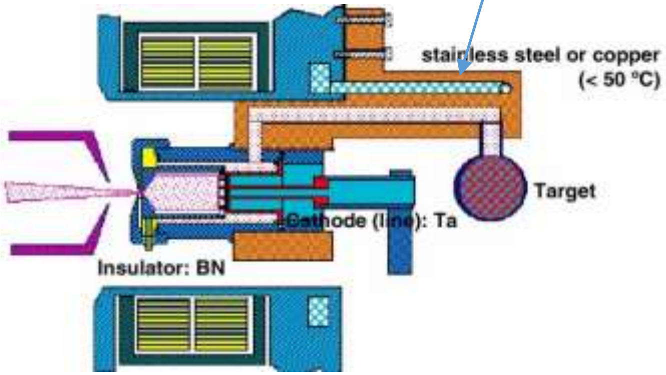
B.



MK6 1400 °C, intermediate to low vapour pressure elements

Water-cooled transfer line

A.



MK7 < 500 °C
noble gases, N_2, etc

Selectivity

A. Use thermo-chromographic selection

B. Use chemical selection e.g. quartz transfer tube. Adsorbs e.g. Ga and lets Zn pass.

Electron Cyclotron Resonance Ion Source

Microwave Ion Sources

Off resonance

= Microwave discharge ion sources

Not discussed here

On resonance

= Electron Cyclotron Resonance (ECR) sources

Pantechnik source
permanent magnets

To be used for:

* Traditional cancer therapy centres

stable $\left\{\begin{array}{l}H^+, H_2^+, H_3^+ \text{ production}\\ C^{4+} \text{ production}\end{array}\right.$

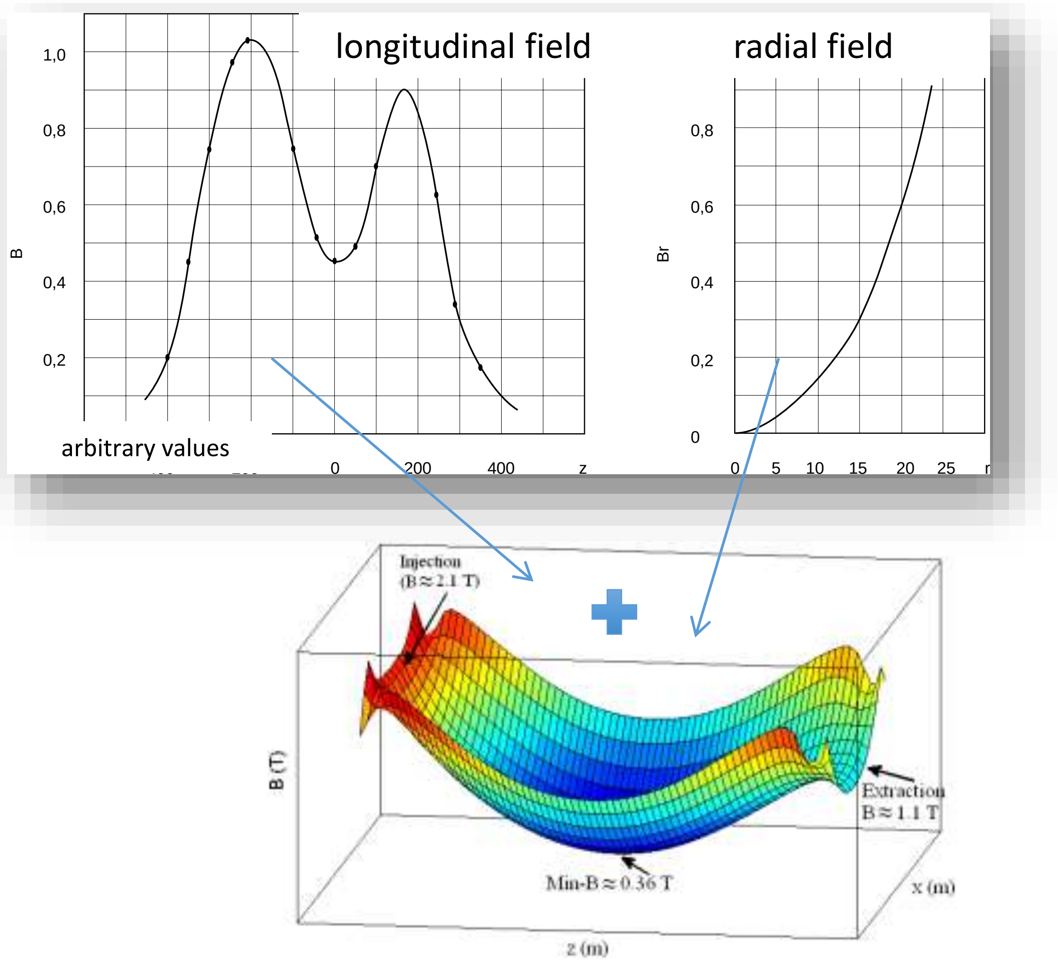
* 1^+ radioactive ion beams

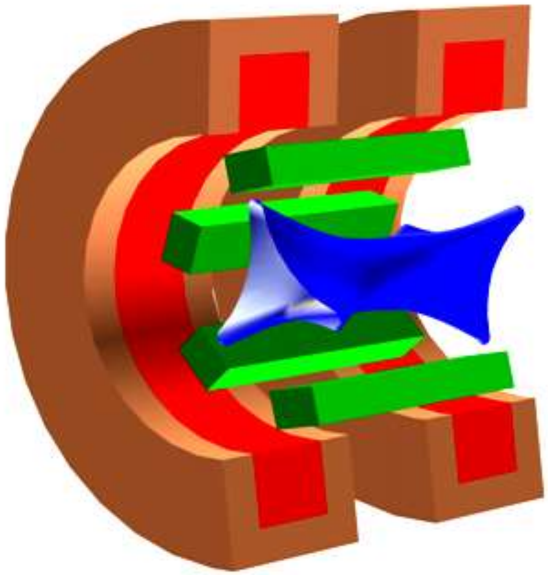
* Not to be used for charge breeders ☺

‘Magnetic bottle‘ confinement of plasma

ECRIS

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

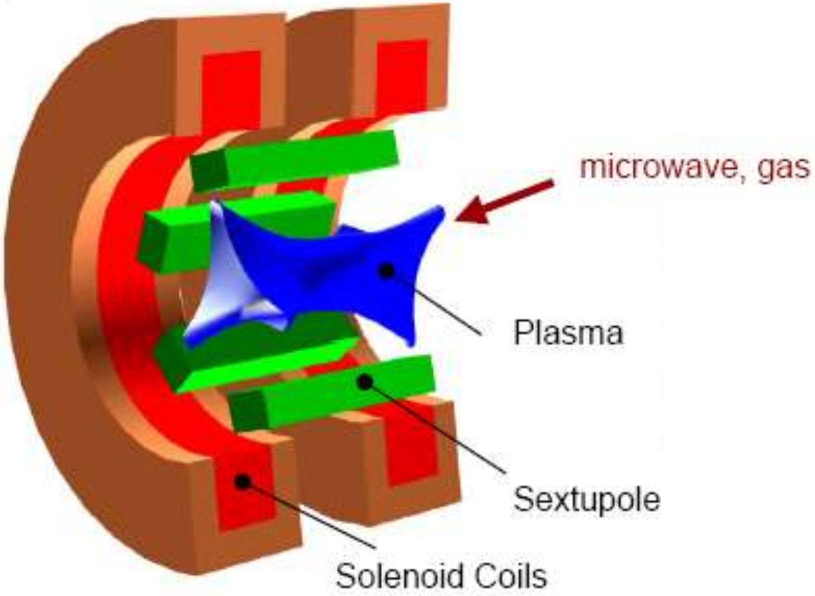


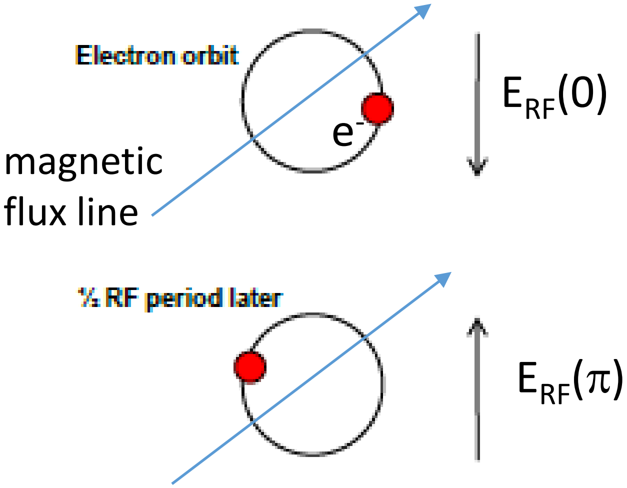


ECRIS physics

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

Plasma is resonantly heated with microwaves





On a surface within the source, there is a magnetic field at which the revolution frequency of the non-relativistic electrons agrees with applied RF

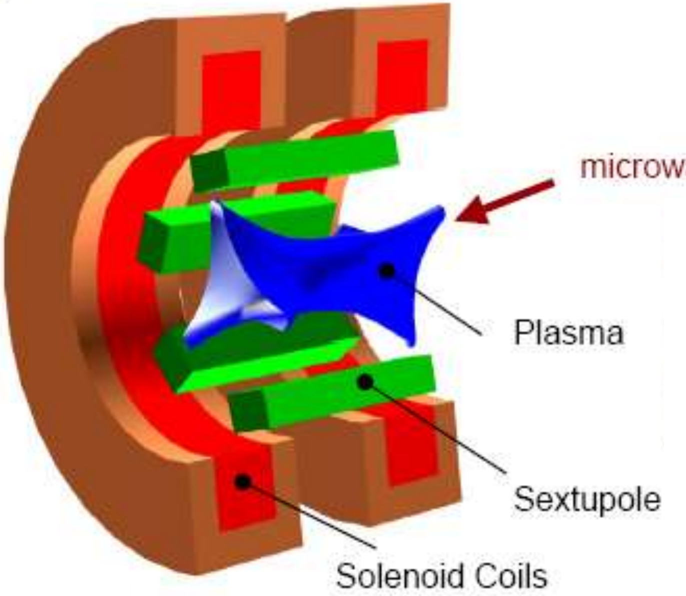
The plasma electrons will absorb energy at this frequency

Stochastical process

ECRIS physics

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

Plasma is resonantly heated with microwaves



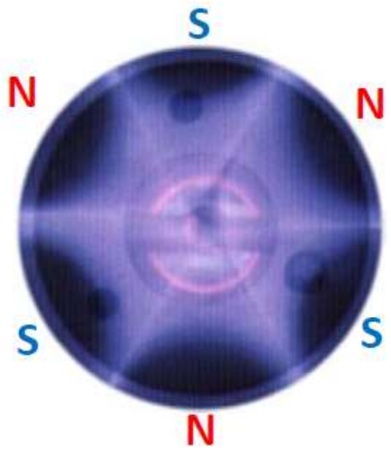


Photo of plasma
(Multipole=hexapole)

$$f_{ce}\,[\text{GHz}] = 2.8 \times B[\text{kG}]$$

e^- temperature distributions

Cold <200 eV: lowest confinement time
Warm < 100 keV: ionization process
Hot > 100 keV: highly confined

=> ionisation by electron-atom collisions

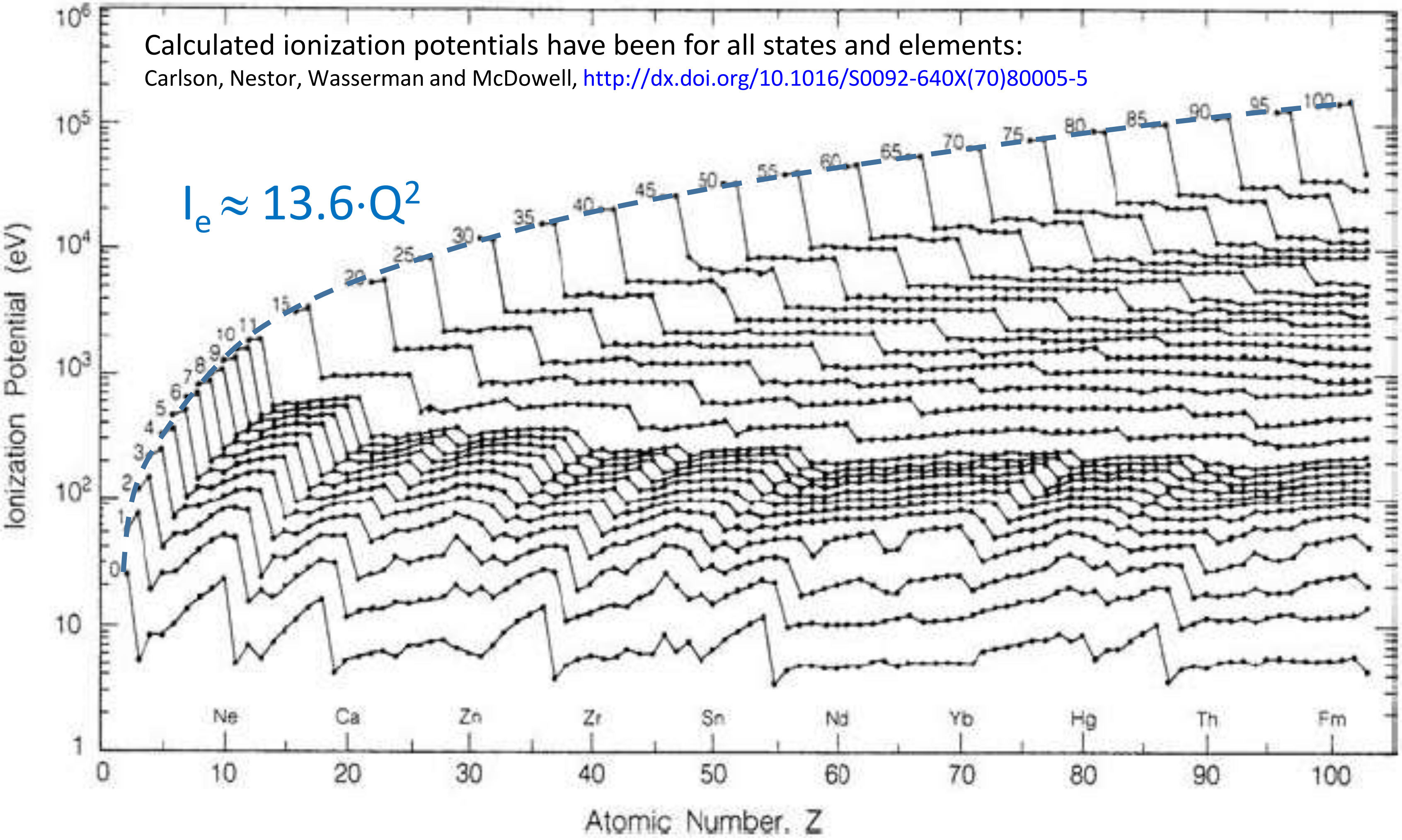
What's the ionization potential of $_{100}Fm^{99+}$?

(I_e for H is 13.6 eV)

Higher charge states

To produce highly charged ions one needs:

1. high energy electrons



Calculated ionization potentials have been for all states and elements:

Carlson, Nestor, Wasserman and McDowell, http://dx.doi.org/10.1016/S0092-640X(70)80005-5

$I_e \approx 13.6 \cdot Q^2$

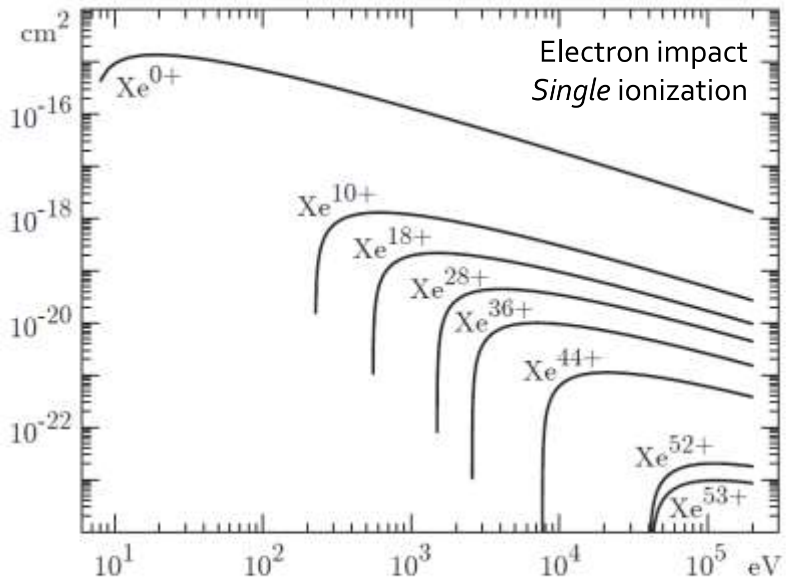
Higher charge states

To produce highly charge ions one needs:

1. high energy electrons
2. the ions to be confined for sufficient time

Stepwise ionization!

$0 \to 1^+ \to 2^+ \to 3^+ \ldots$



Electron impact
Single ionization

cross section σ

electron energy

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

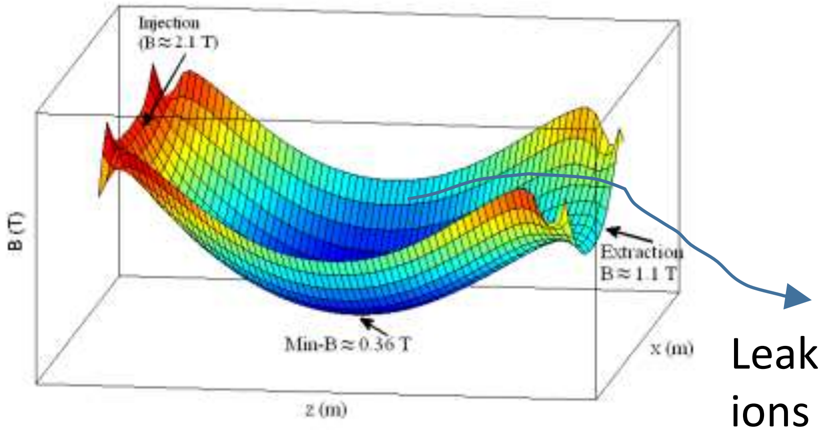
$$\bar{\tau}_q = \sum_{i=1}^{q-1} \bar{\tau}_{i\to i+1} = \frac{e}{j_e} \sum_{i=1}^{q-1} \frac{1}{\sigma_{i\to i+1}}$$

Higher charge states

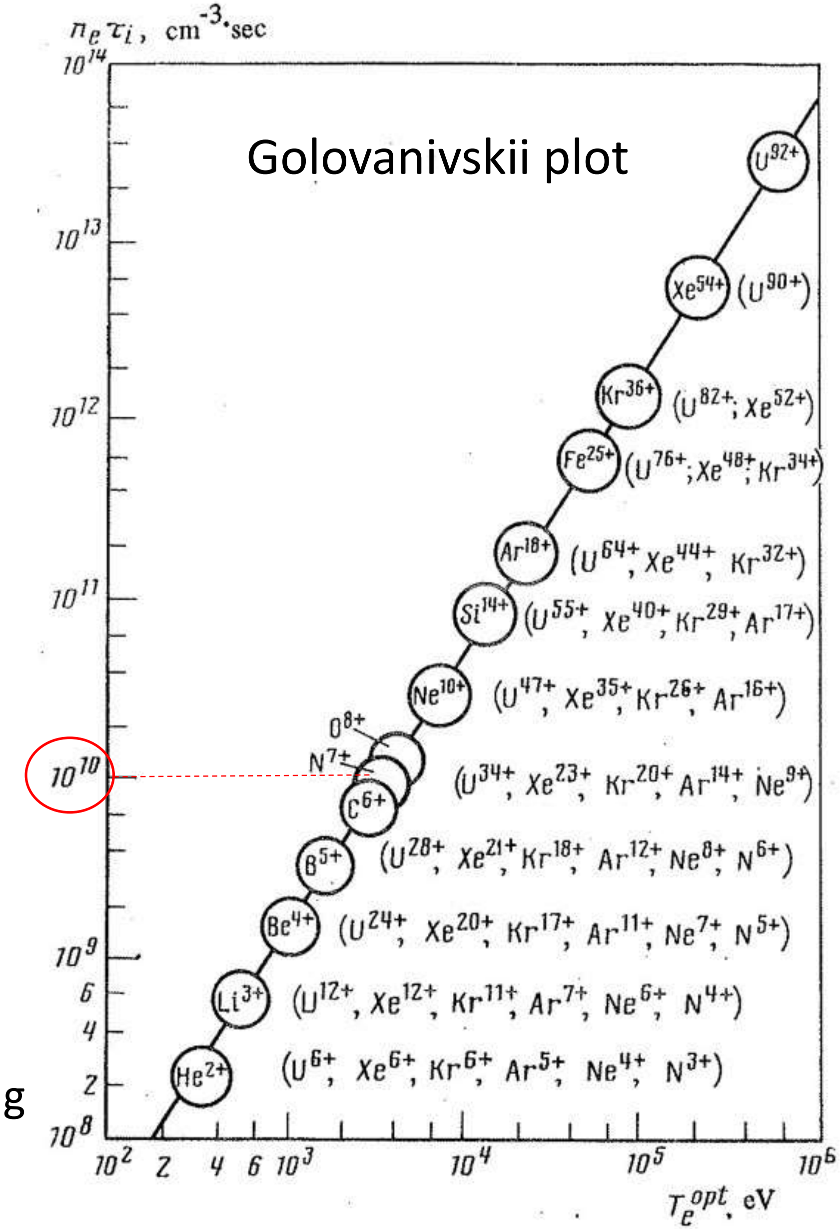
To produce highly charge ions one needs:

1. high energy electrons
2. the ions to be confined for sufficient time

The ion confinement time τ_c and the electron density n_e are influencing the maximum charge state that could be reached.



Leaking ions



Golovanivskii plot

Extra

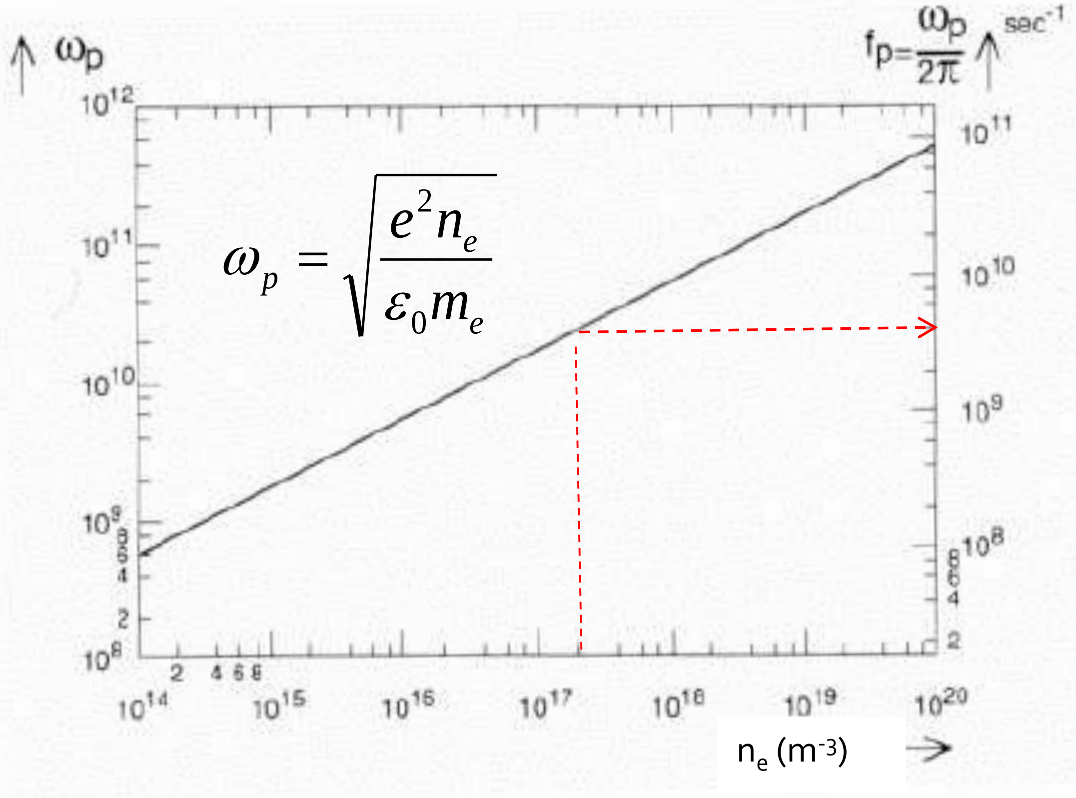
What RF is needed?

1. Assume the ions stay around 50 ms inside the plasma => need 10^{10} / 0.05 = $2 \cdot 10^{11}$ e / cm^{-3} = $2 \cdot 10^{17}$ e / m^{-3}

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

> 4 GHz

rule $n_e < 1.2 \cdot 10^{10} f_{RF}^2$ cm^{-3}
$[f_{RF}]$ = GHz



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

Plasma frequency versus plasma density

Mechanical design

* RF 2.45 GHz

* Ionisation efficiency He, Ne

He^+ >20%, Ne^+ >35%

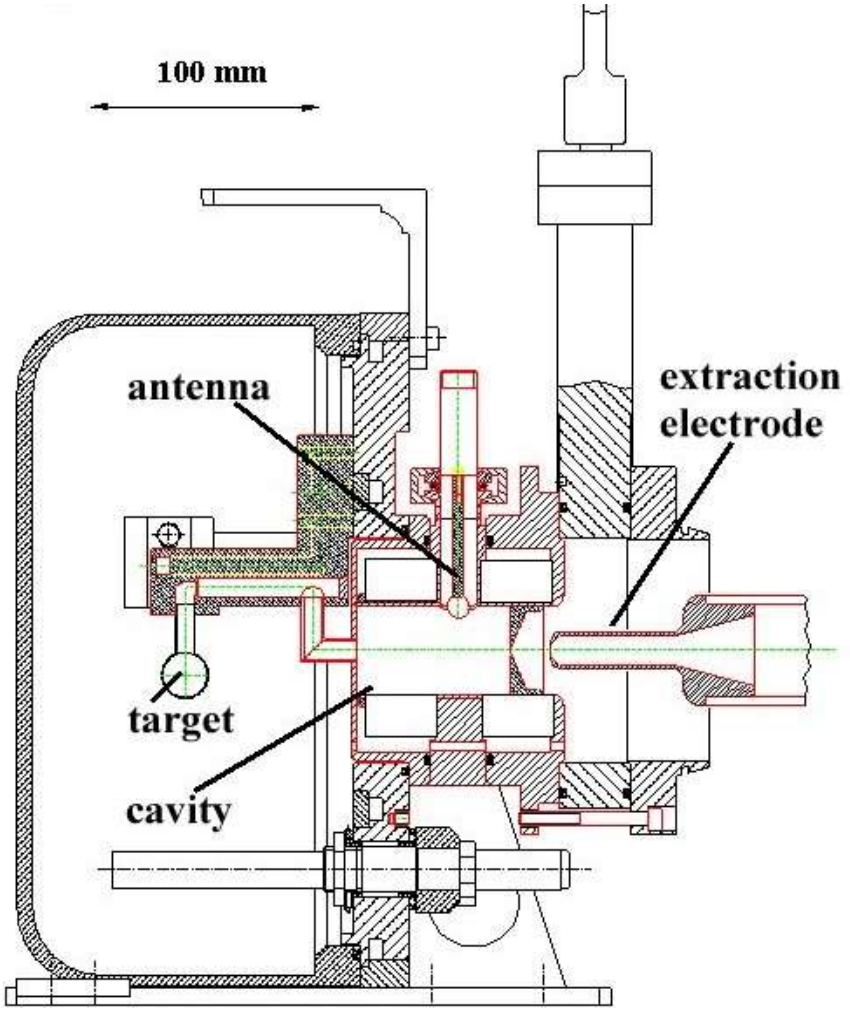
* Total extracted current < 1 mA

(>> 10 uA He^+ / Ne^+)

Cold surfaces -> no reaction with CO

$\eta_{ionisation}$ = 14.4% for $^{13}C^{16}O^+$

PhD thesis H. Franberg 2008



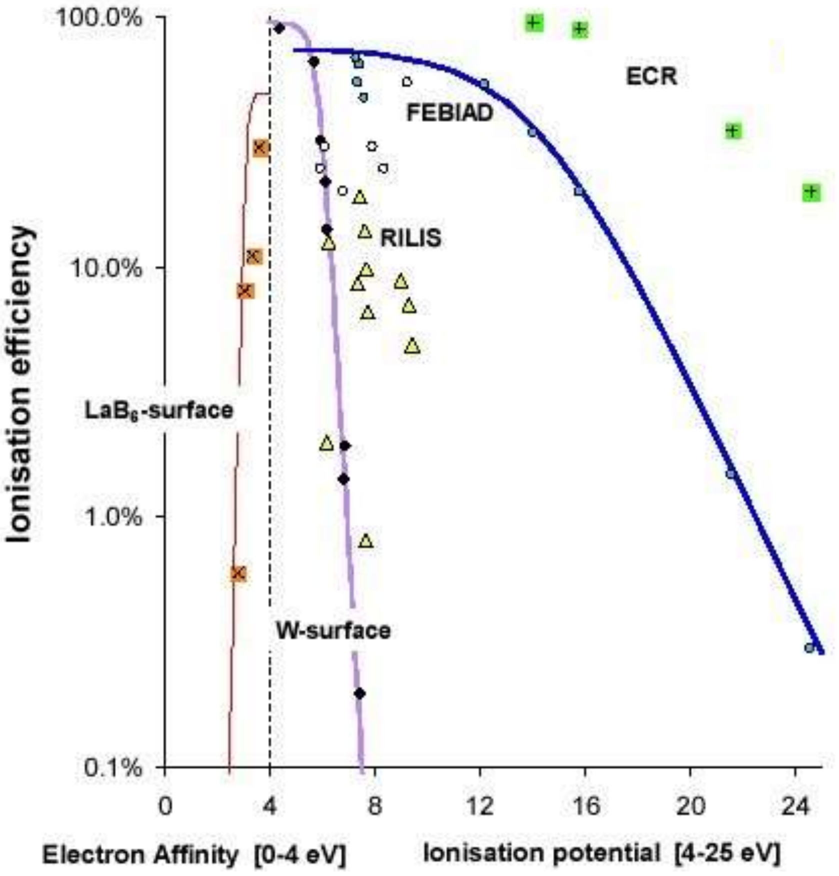
MINIMONO

1^+ ECR ion source

ECRIS summary

Singly, multiply and highly charged ions can be produced by these sources - although the source construction will influence this

RF 2.45 GHz -28 GHz



Not easy to summarize ECR ion sources – too broad spectrum

+ Suited for volatile elements (gases)
+ High ionization efficiency
+ Long-term stability and reliability
+ High intensities (μA to mA are available)
+ Low $\Delta E=10^{-4}$

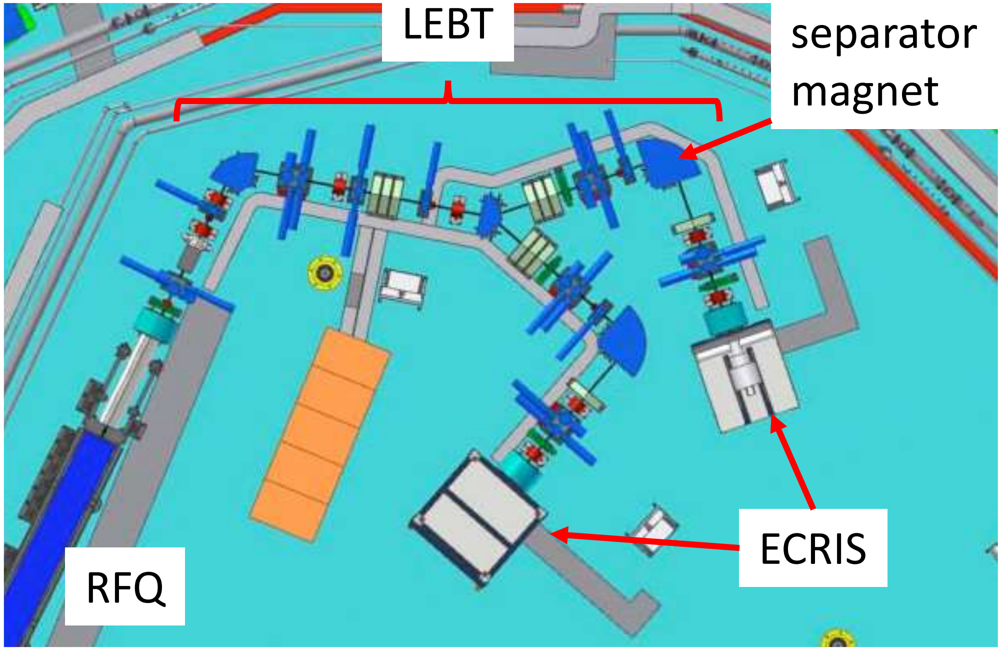
- Large emittance 30 to >150 mm mrad (30 kV, 95%)
- Shortest pulse extraction > 1 ms
- No possibility of ion storage
- Difficult to produce fully stripped ions

Ion sources for cancer therapy

SUPERNANOGAN

* 14.5GHz ECR ion source

* both the axial and radial magnetic fields generated by permanent magnets
=> less power required



Layout of CNAO injection section with two identical ECR ion sources – for sake of redundancy

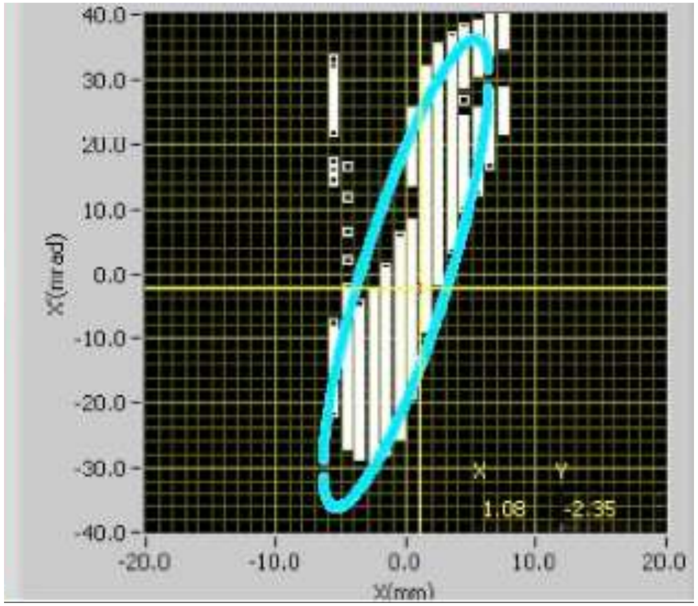
Beam specification and acceptance tests

CNAO

Specification

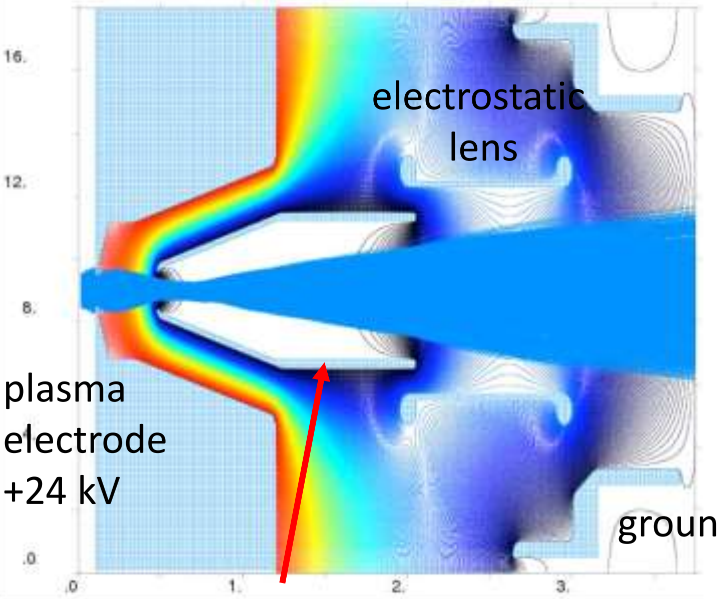
$^{12}C^{4+} > 160$ µA
$H_3^+ > 700$ µA
same charge-to-mass ratio 1/3 in the beam line

Alternatively H_2^+, reached 1 mA



Measured emittance for 250 eµA beam of C^{4+}: the rms-normalized, 100% emittance value is 0.52 mm mrad

Improved extraction system



electrostatic lens

plasma electrode +24 kV

ground

screening electrode
(to avoid backstreaming of e- to the ECR ion source)

Simulation program Kobra 3D

Info from G. Ciavola et al, Proceedings of EPAC08, Genoa, Italy

Beam specification and commissioning

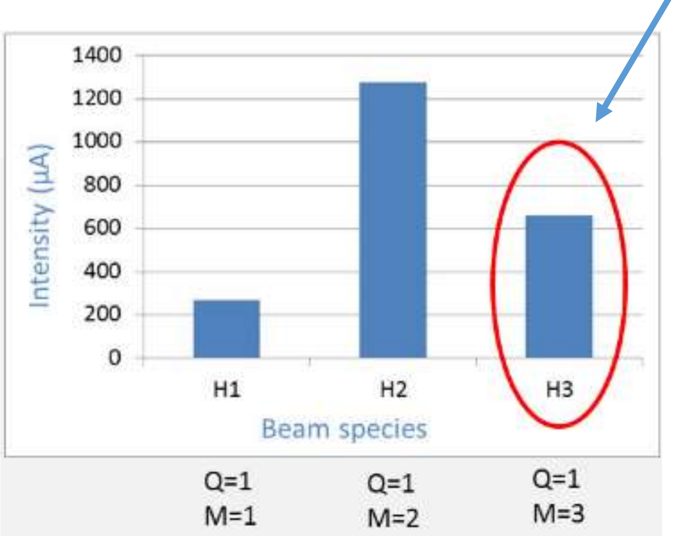
MEDAUSTRON

Some specifications

Repetition rate 0.5 to 1 Hz
Injection time < 100 us
Emittance (30 kV, 95%) < 180 mm mrad
Intensity and emittance stabilty < 4%
(peak-to-peak)

When injecting H_2 gas

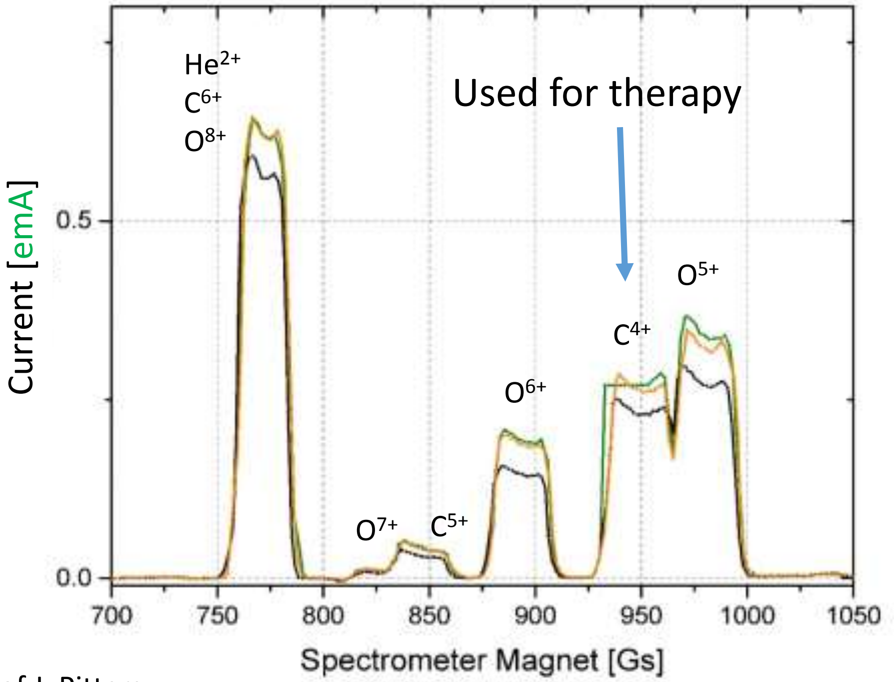
Used for therapy



Charge state distribution

When injecting CO_2 + support gas He (2:3)

Used for therapy



Courtesy of J. Pitters

General design considerations

Design criteria

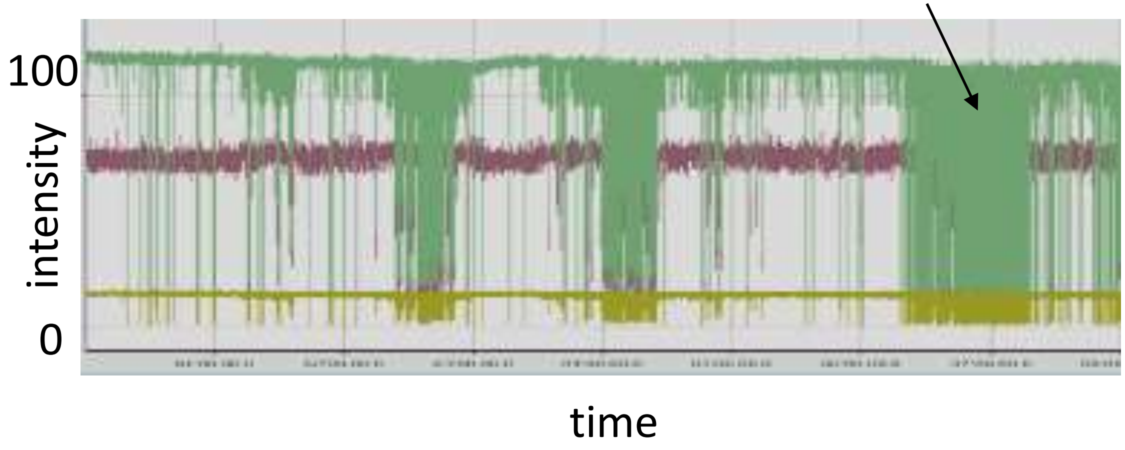
Apart from already discussed efficiency, current, emittance, energy spread, contaminations…

Reliability

- Operational sources should deliver >98% availability
- Service interval compatible with operating schedule

Stability

- What is should *not* look like



Design criteria

Material Choices

1. Sources usually employ a wide *range of materials* in their construction.

2. A whole range of *material properties* are used for ion source engineering:

- Electrical insulators and conductors
- Thermal conductivity
- Magnetic properties
- Melting and boiling points
- Thermal expansion
- Mechanical strength, embrittlement, creep
- Secondary electron yield
- Work function (affects electron emission)
- Thermal emissivity
- Sputtering rate
- Outgassing rate
- Ease of construction – welding – brazing – surface finish

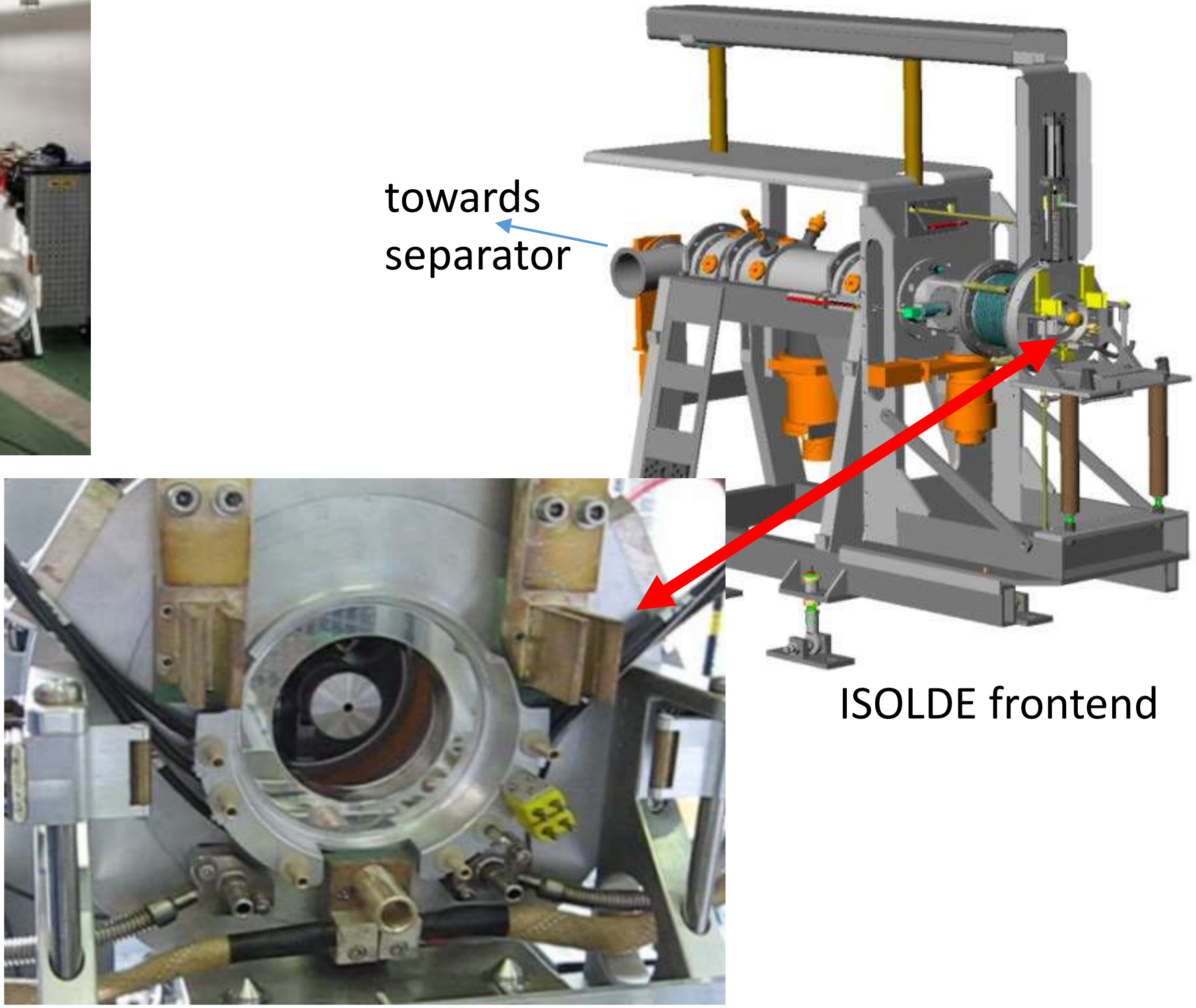
Check list!

Design criteria

radioactive ion beam sources

Weight limitation

Space limitations



ISOLDE frontend

Handled by robots

Target coupling /
interface

Design criteria

Radioactive ion beam sources

Should withstand 1 MGy

Radiation hardness for radioactive ion sources

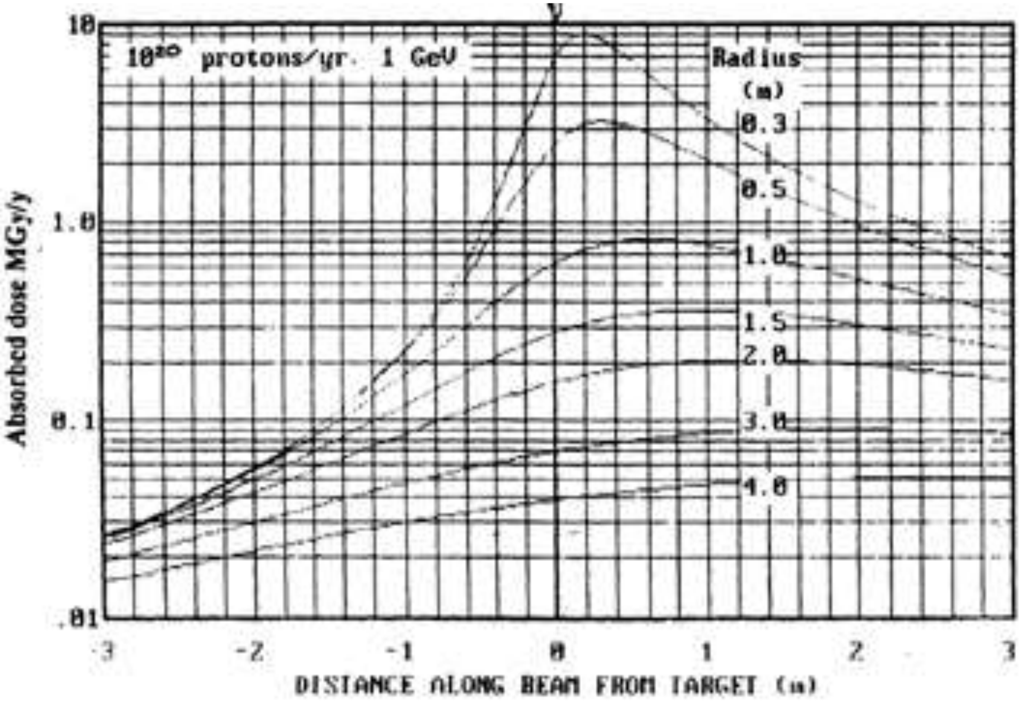


Figure 6. Contours of absorbed dose to an object near a one interaction length target after one years irradiation (10^{20} protons).

Design criteria

Radioactive ion beam sources

Typical curative therapy dose for a solid epithelial tumor?

Ranges from 60 to 80 Gy

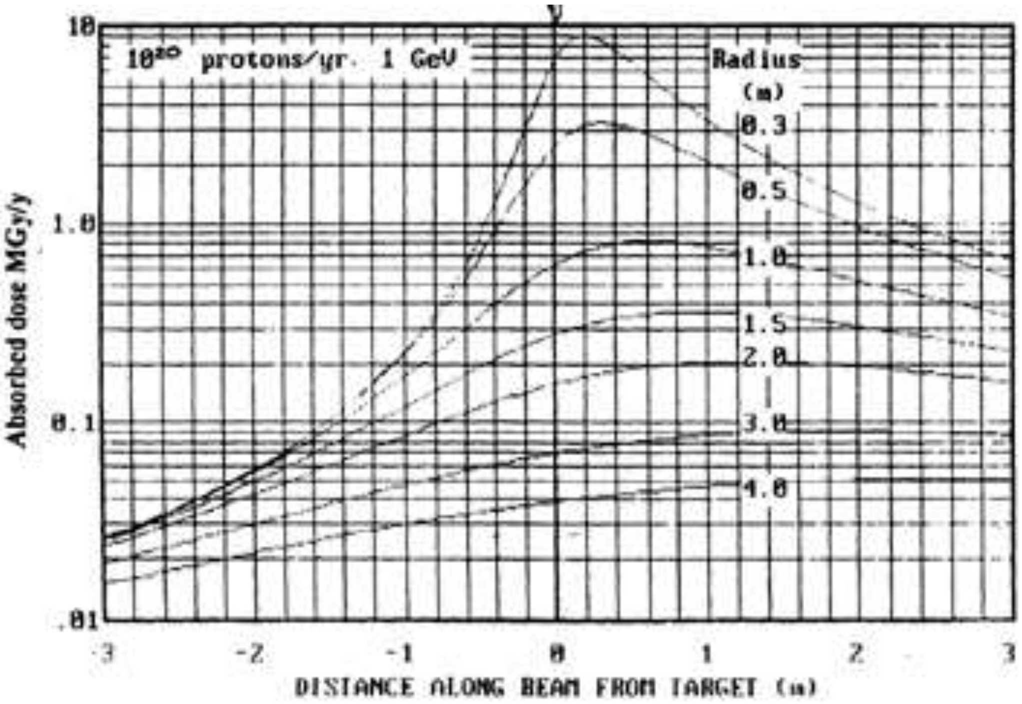
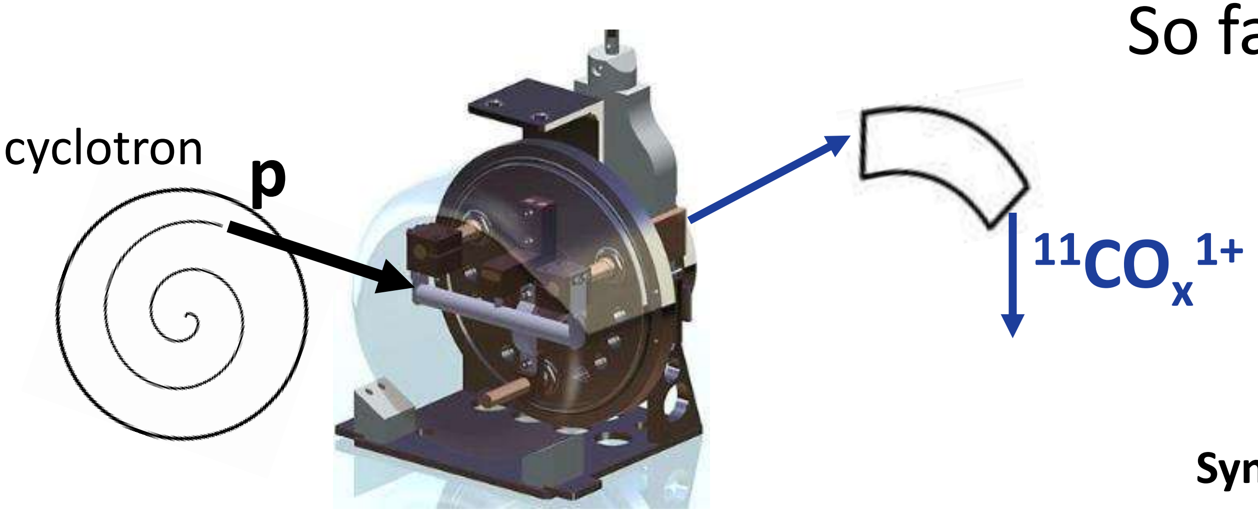
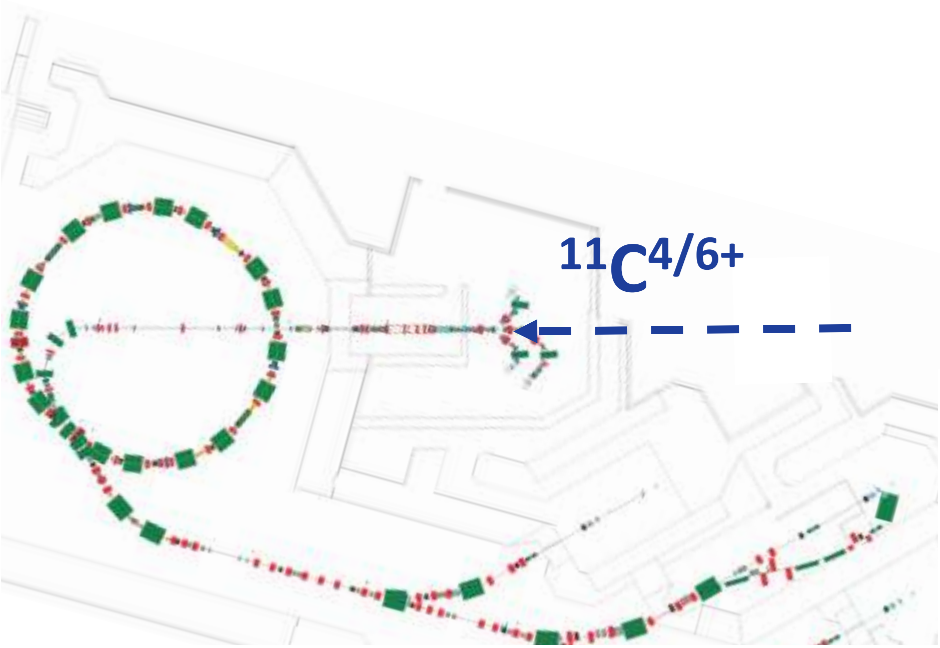


Figure 6. Contours of absorbed dose to an object near a one interaction length target after one years irradiation (10^{20} protons).

Charge breeding

So far so good



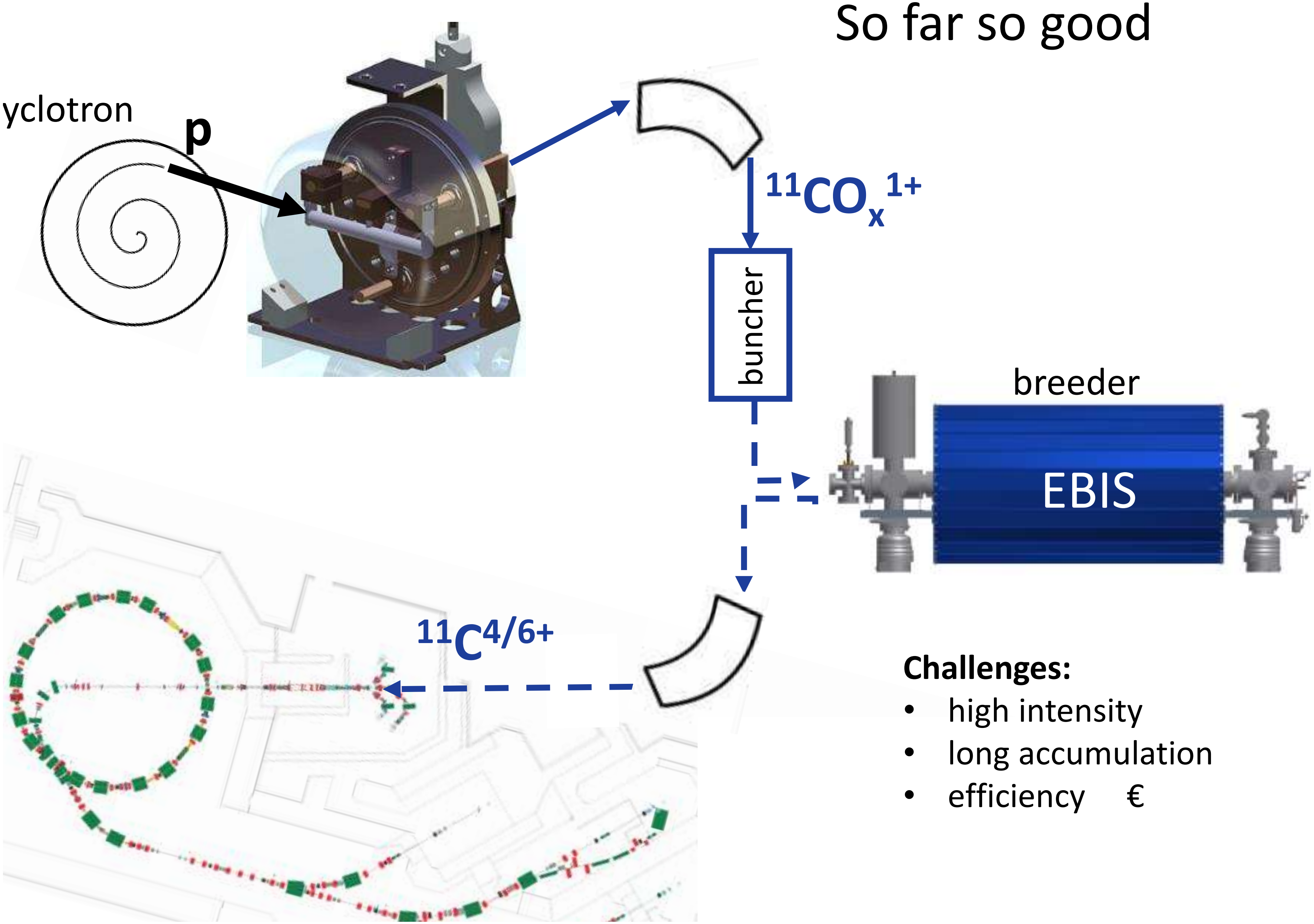


?

Synchrotron

* Low repetition rate < 1 Hz
* $T_{injection}$ ~ tens of us
* 10^9 ions/bunch
* Pre-acceleration in linac
* 6^+ ions

So far so good



yclotron

p

$^{11}CO_x^{1+}$

buncher

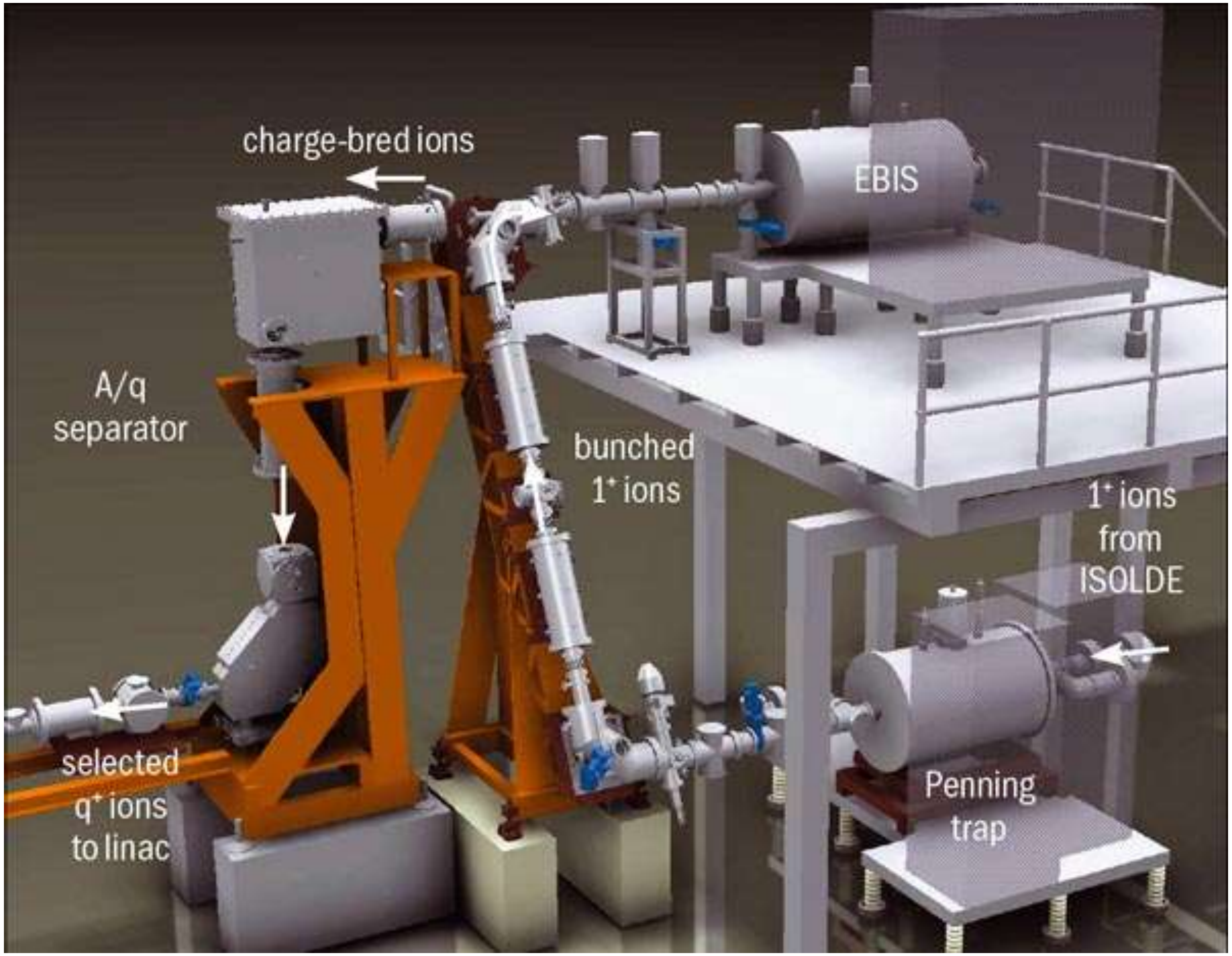
breeder

EBIS

$^{11}C^{4/6+}$

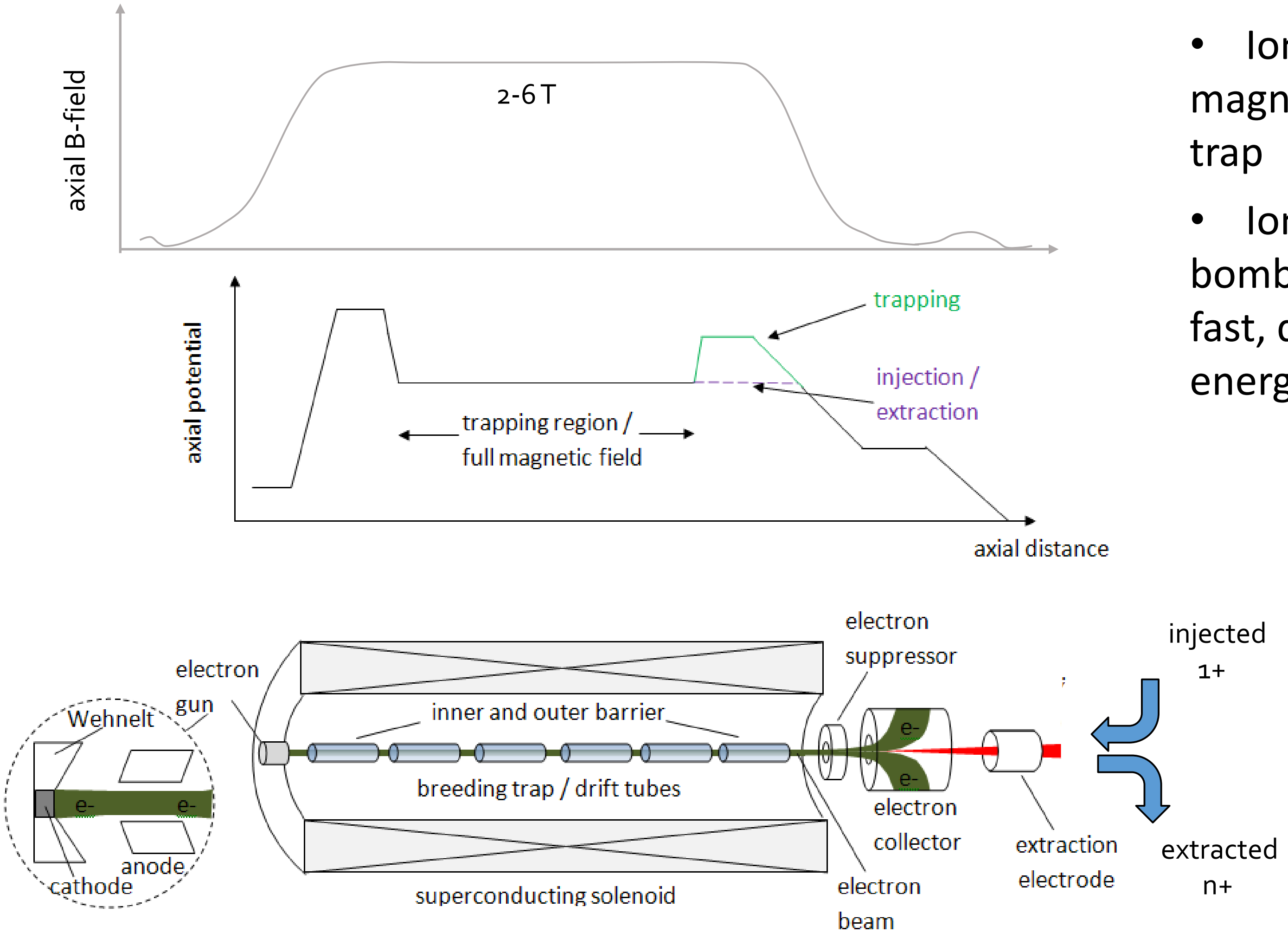
Challenges:
- high intensity
- long accumulation
- efficiency €

The cumbersome pioneer



REX-ISOLDE charge breeding system

Electron Beam Ion Source

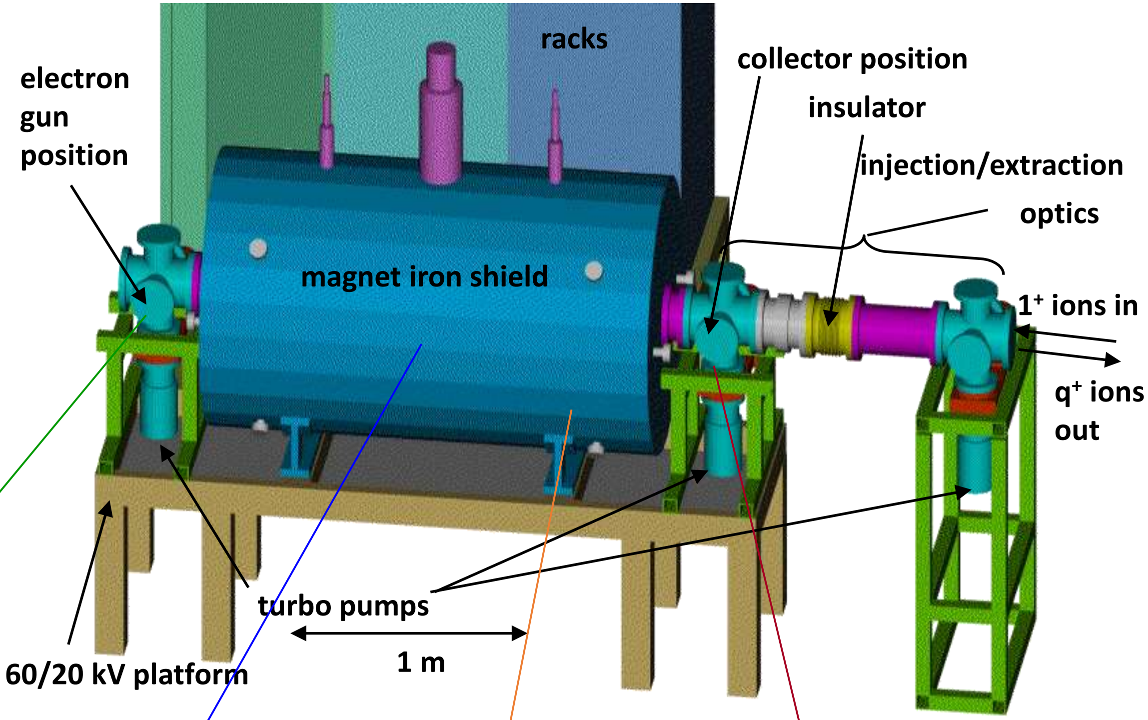


- e^- beam compressed by solenoid B-field
- Ions are trapped in a magneto-electrostatic trap
- Ionisation by e^- bombardment from a fast, dense mono-energetic e^- beam

REXEBIS at ISOLDE

Who built this EBIS?

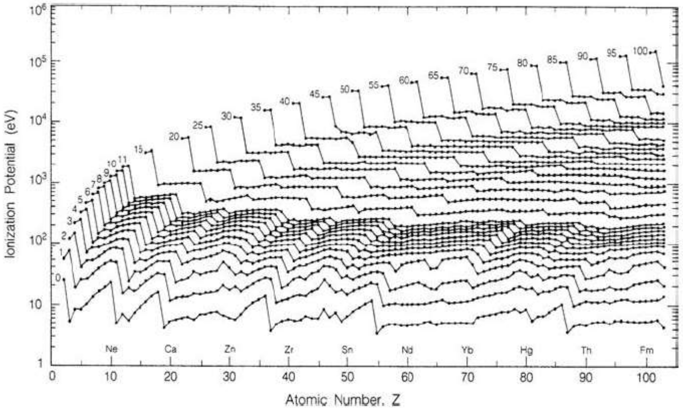
- Super conducting solenoid, 2 T
- Trap length < 0.8 m
- Electron beam < 0.3 A and 3-6 keV
- Electron current density
  < 150 A/cm^2
- Breeding time 3 to > 300 ms
- Trapping vacuum few 10^{-11} mbar
- Total capacity < $3 \cdot 10^{10}$ charges



EBIS characteristics

A

Remember ionisation potentials



B

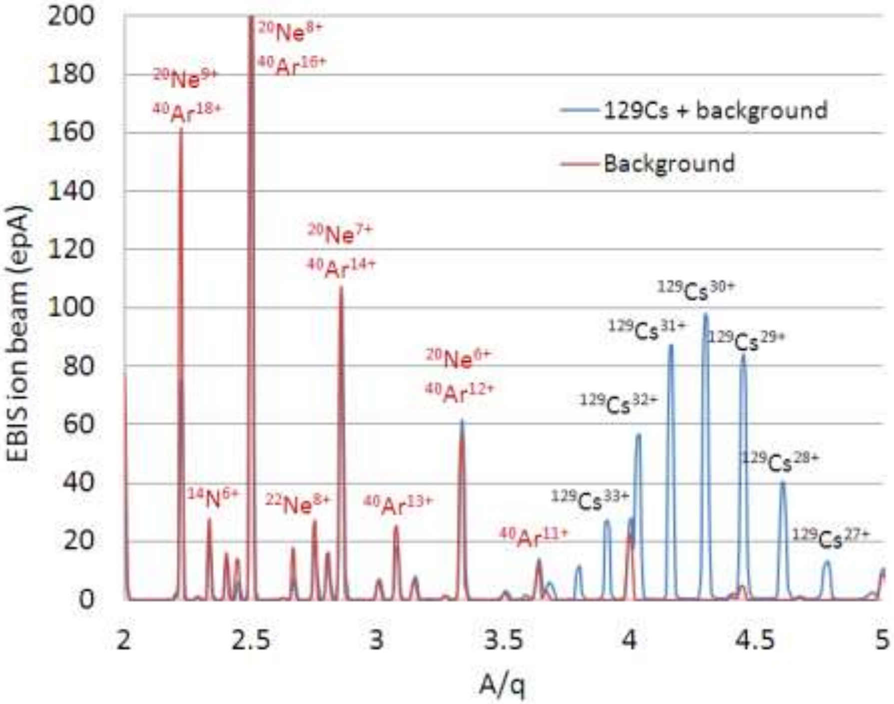
Remember stepwise ionization!

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

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

C

Excellent vacuum



Ion capacity…

…and extraction

$$N^{-} = 1.05 \cdot 10^{13} \frac{k L_{trap} I_{e}}{\sqrt{U_{e}}}$$

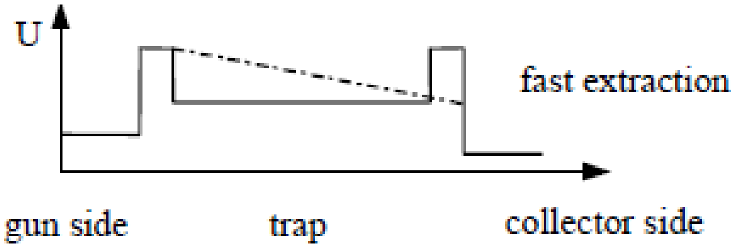
N^- = number of elementary charges

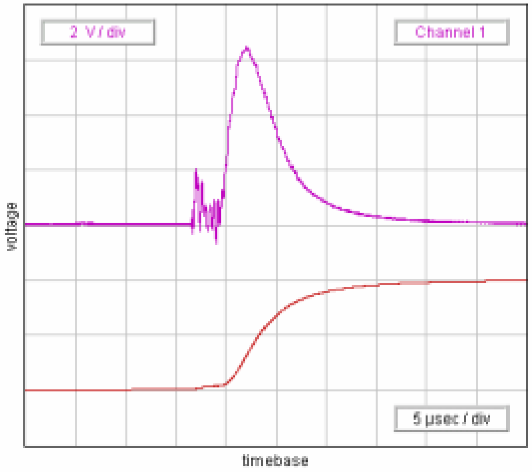
I_e and U_e = electron beam current and energy

k = attainable space charge compensation degree

L_{trap} = trap length

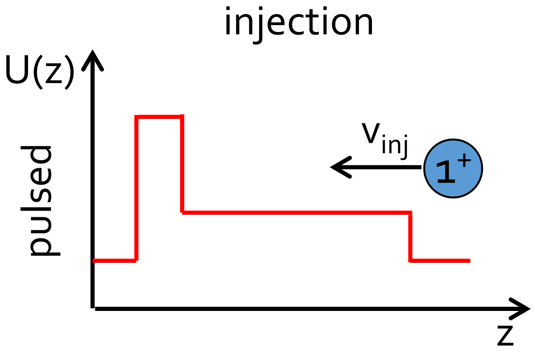
Speed up extraction for multi-turn injection into synchrotron <10 us

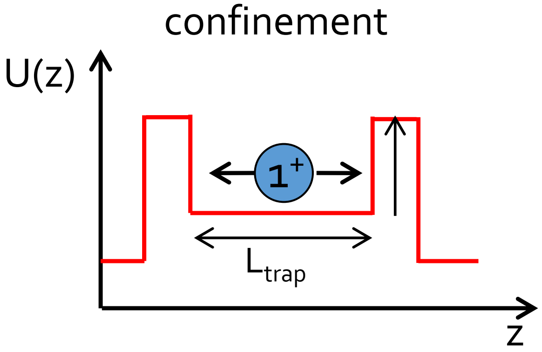




TestEBIS BNL
Ne
$2.4 \cdot 10^{11}$ charges/pulse

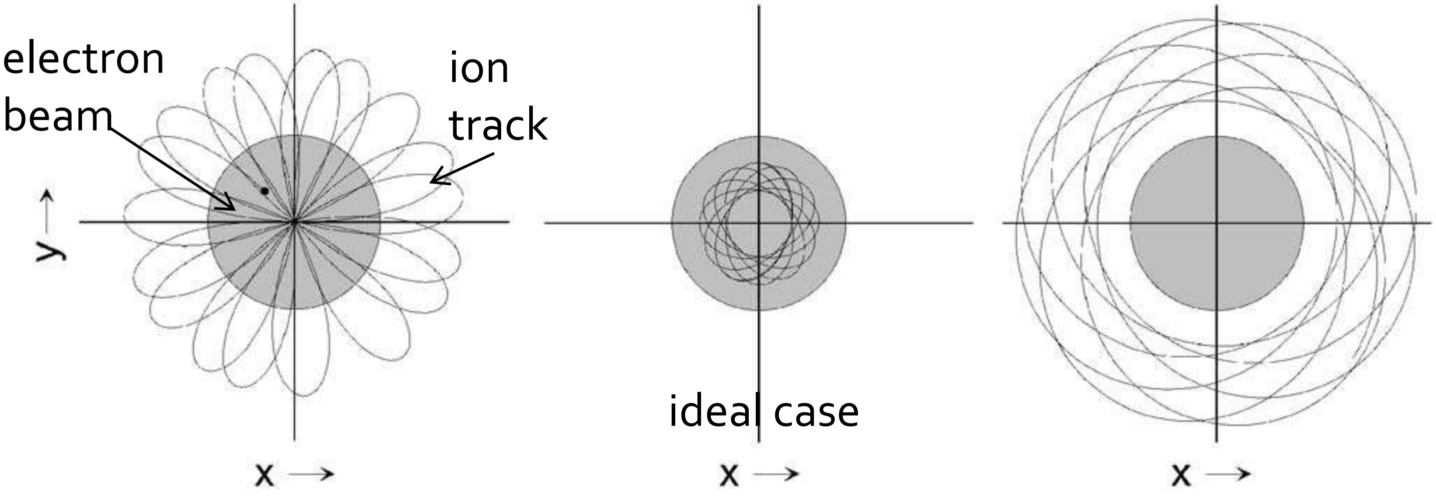
Ion injection into EBIS





Desired: overlap between injected ion beam and electron beam

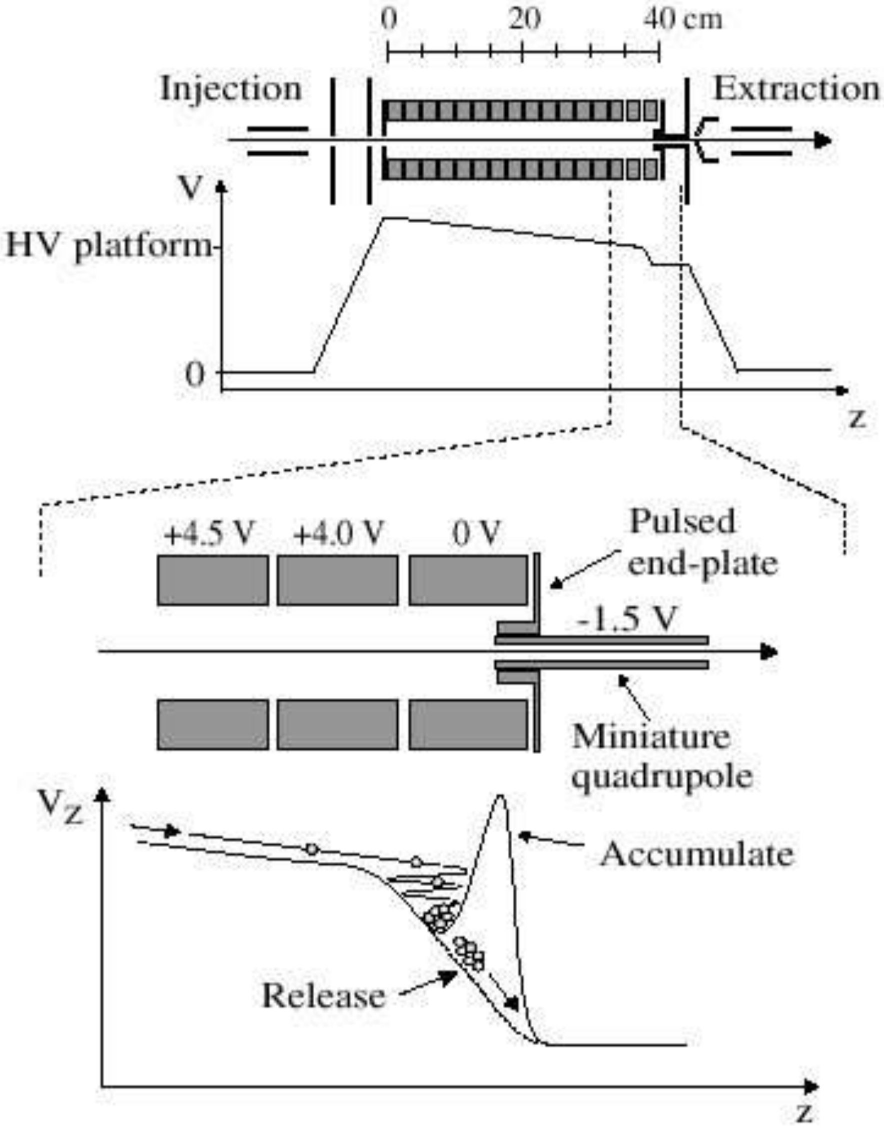
If injection outside electron beam => effective j_e low => increased T_{breed}



Small → $$\alpha_{\max} = \pi \frac{r_{ebeam}}{\sqrt{2U_{ext}}} \cdot \left(Br_{ebeam}\sqrt{\frac{q}{m}} + \sqrt{\frac{qB^2 r_{ebeam}^2}{4m} + \frac{\rho_l}{2\pi\varepsilon_0}} \right)$$

see *CERN-OPEN-2000-320*

RFQ cooler



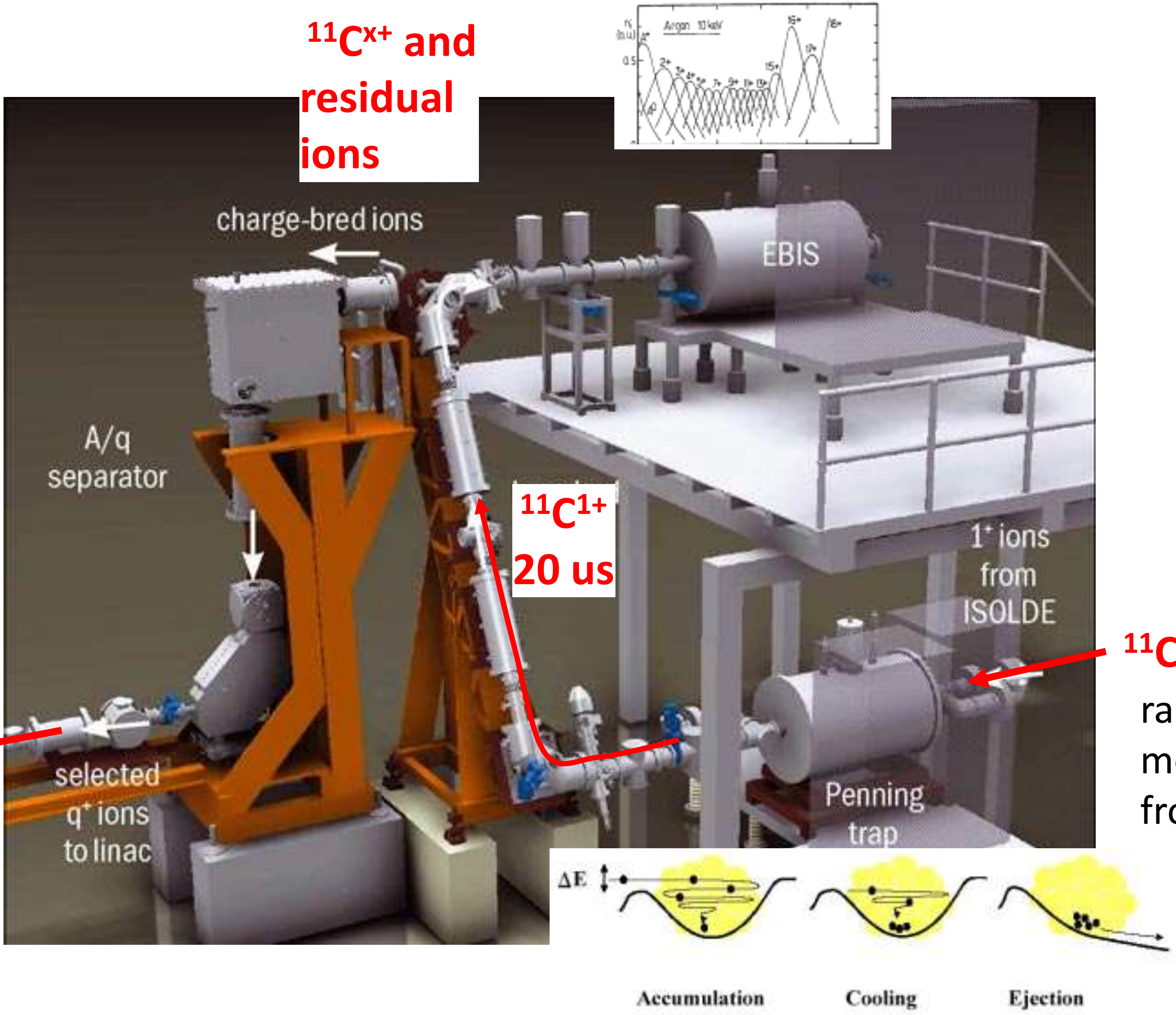
Gas filled trap with quadrupolar RF field superimposed with low axial field

* Accepts large emittance beams

* Accumulation time ~ 1 s
* Capacity
bunched mode some 10^8 ions
DC > 10 nA

* Energy spread < few eV
* ε < 10 mm mrad (30 keV, 95%)
* Bunch width 5-20 μs (FWHM)

The cumbersome pioneer



$^{11}C^{x+}$ and residual ions

$^{11}C^{1+}$
20 us

$^{11}C^{6+}$

$^{11}C^{16}O^{+}$
radioactive molecular beam from ISOL

Ion sources for future cancer therapy

MEDeGUN

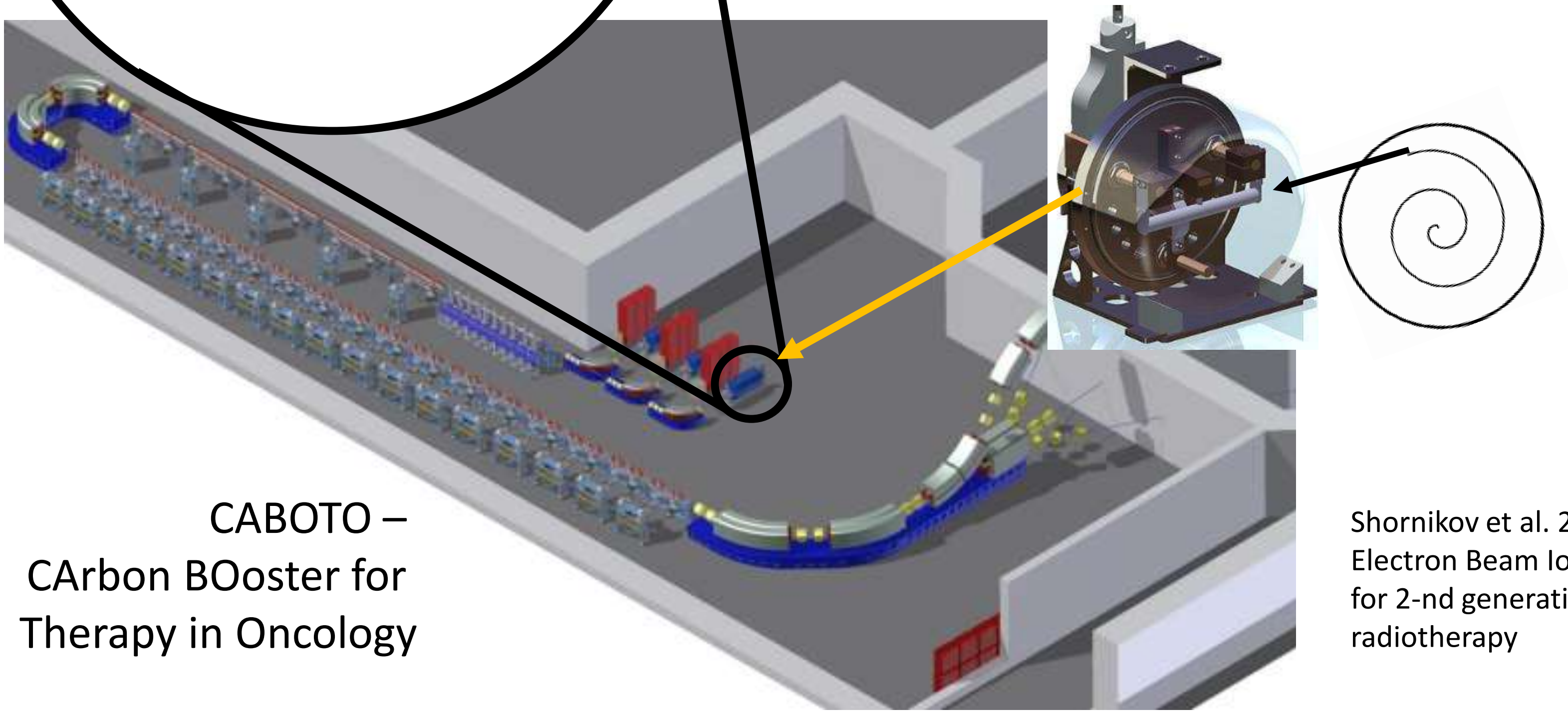
Speak to Johanna Pitters

Concept also valid for other light ions e.g. He, Li, Be, B, N, O, Ne, …

HF-linac requirements:

- **300 – 400 Hz**
- **<5 µs** pulses
- **$10^8\ {}^{12}C^{6+}$** ions per pulse

-> EBIS could do this



CABOTO –
CArbon BOoster for
Therapy in Oncology

Shornikov et al. 2016 – Advanced Electron Beam Ion Sources (EBIS) for 2-nd generation carbon radiotherapy

Confession

The people I stole from…

Magda Kowalska
Detlef Küchler
Richard Scrivens
Valentin Fedosseev
Bruce Marsh
Daniela Leitner
Thierry Stora

…who probably stole from someone else

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