JOINT UNIVERSITY ACCELERATOR SCHOOL

PARTICLE SOURCES

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- TUTORIAL

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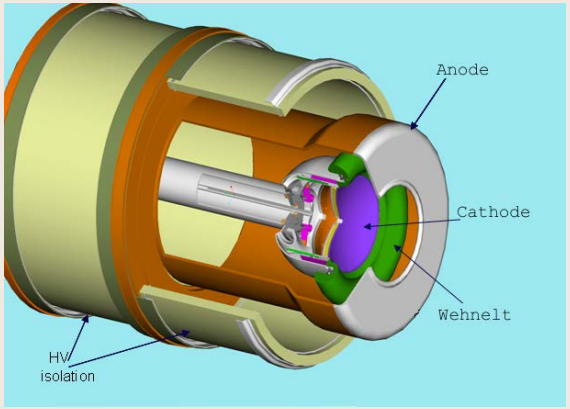
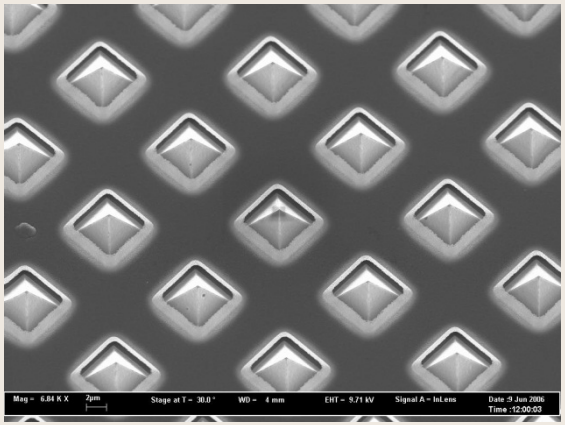
  - Low Enery Beam line Transfer

PARTICULE SOURCES

- Particle source activity requires both Physics and Engineering skills on many transversal topics
  - High voltage, magnetism, thermodynamics, chemistry, vacuum, condensed matter physics, plasma physics, atomic physics…
- Particule sources are legions!
  - There are as many particle sources as accelerators
  - Each of them would justify a one hour lecture…
- So…It is **IMPOSSIBLE** to give a detailed overview of the topic within a day lecture
  - Please consider this lecture as an introduction to the topic
- The philosophy of this lecture is to present shortly commonly used sources of particle and introduce the physics behind



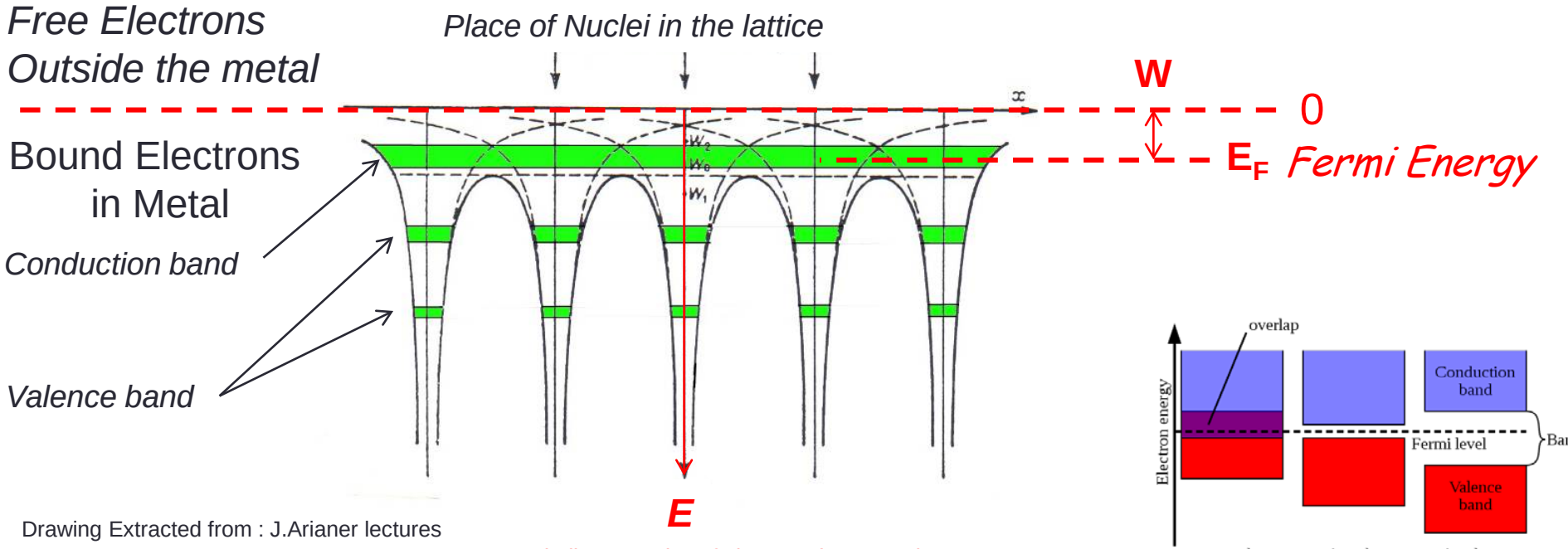


ELECTRON SOURCES

An introduction

Work Function of electrons in metals

- The **Work Function W** is the minimum energy needed to remove an electron from a solid to a point immediately outside of the solid surface
  - In a metal, some electrons are populating the Conduction Band
    - electrons shared by the lattice
  - The maximum binding energy of electrons in metal corresponds to the Fermi Energy: $W=E_F$ (whenT=0 Kelvin). So $W<E_F$ *when T>0.*



Drawing Extracted from : J.Arianer lectures

Binding energies of electrons in a metal

Work Function of electrons in metals (wikipedia)

- Units: eV electron Volts
  reference: CRC handbook on Chemistry and Physics version 2008, p. 12-114.
- Note: Work function can change for crystalline elements based upon the orientation.

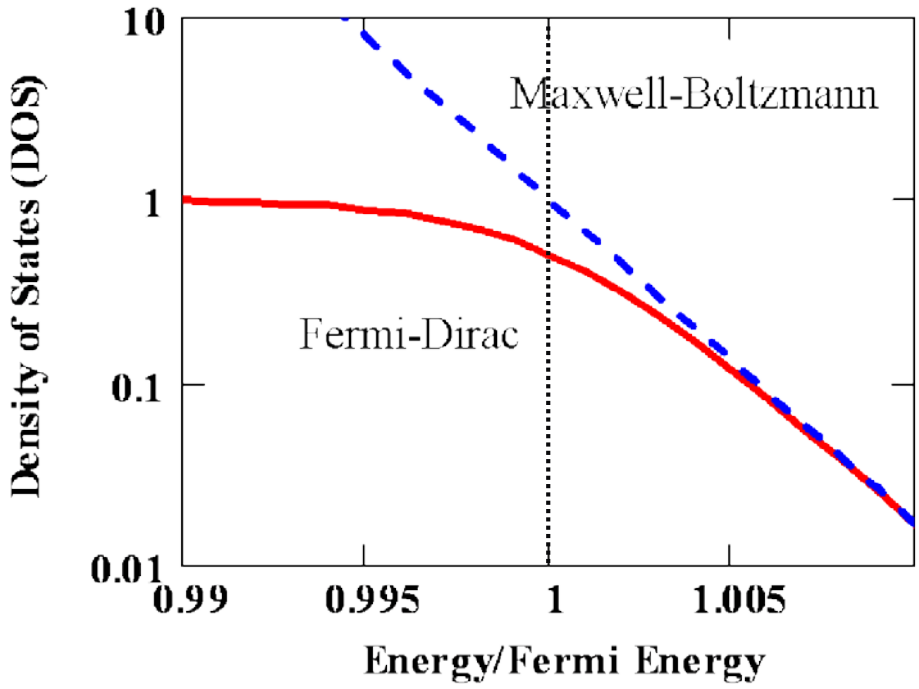
Element	eV	Element	eV	Element	eV	Element	eV	Element	eV
Ag:	4.52-4.74	Al:	4.06-4.26	As:	3.75	Au:	5.1-5.47	B:	~4.45
Ba:	2.52-2.7	Be:	4.98	Bi:	4.34	C:	~5	Ca:	2.87
Cd:	4.08	Ce:	2.9	Co:	5	Cr:	4.5	Cs:	2.14
Cu:	4.53-5.10	Eu:	2.5	Fe:	4.67-4.81	Ga:	4.32	Gd:	2.90
Hf:	3.9	Hg:	4.475	In:	4.09	Ir:	5.00-5.67	K:	2.29
La:	4	Li:	2.93	Lu:	~3.3	Mg:	3.66	Mn:	4.1
Mo:	4.36-4.95	Na:	2.36	Nb:	3.95-4.87	Nd:	3.2	Ni:	5.04-5.35
Os:	5.93	Pb:	4.25	Pd:	5.22-5.6	Pt:	5.12-5.93	Rb:	2.261
Re:	4.72	Rh:	4.98	Ru:	4.71	Sb:	4.55-4.7	Sc:	3.5
Se:	5.9	Si:	4.60-4.85	Sm:	2.7	Sn:	4.42	Sr:	~2.59
Ta:	4.00-4.80	Tb:	3.00	Te:	4.95	Th:	3.4	Ti:	4.33
Tl:	~3.84	U:	3.63-3.90	V:	4.3	W:	4.32-5.22	Y:	3.1
Yb:	2.60 [2]	Zn:	3.63-4.9	Zr:	4.05				

Max. (Os: 5.93)

Min. (Cs: 2.14)

Electron statistics and energy distribution function

- Electron, being fermions, follow the Fermi-Dirac statistics :
  - $f_{FM}(E) = \frac{1}{1+e^{\frac{E-E_F}{kT}}}$
    - E_F Fermi Energy
    - T electron temperature
- On the other hand, bosons obey the Maxwell-Boltzmann statistics:
  - $f_{MB}(E) = e^{-\frac{E}{kT}}$
- Practically, when $(E > 1.005\ E_F)$:
  - $f_{FM}(E) \cong e^{-\frac{E}{kT}}$
  - This approximation is of interest to derive electron current densities



See USPAS site : http://uspas.fnal.gov/materials/10MIT/Lecture2_EmissionStatisticsCathodeEmittance_text.pdf

Distorsion of the electric potential near to a metallic surface

- When an electron is emitted from a material, the **image charge effect** changes the electric potential profile near to the surface:

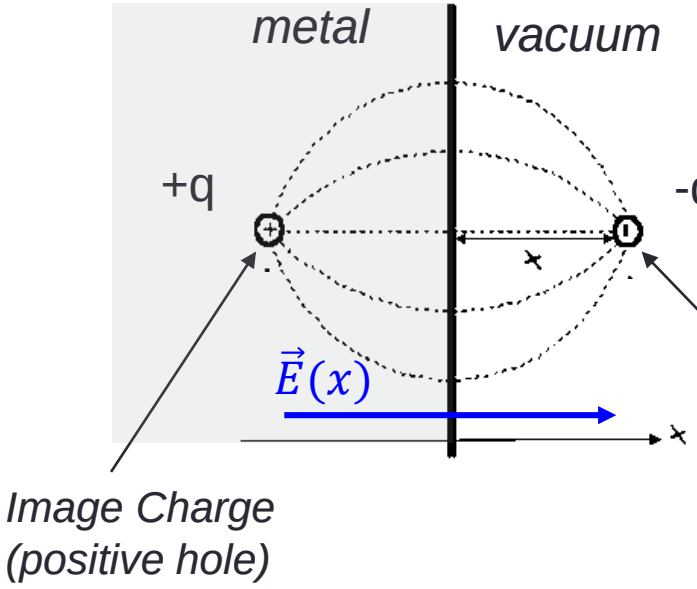


Image Charge (positive hole)

Electron extracted From the metal

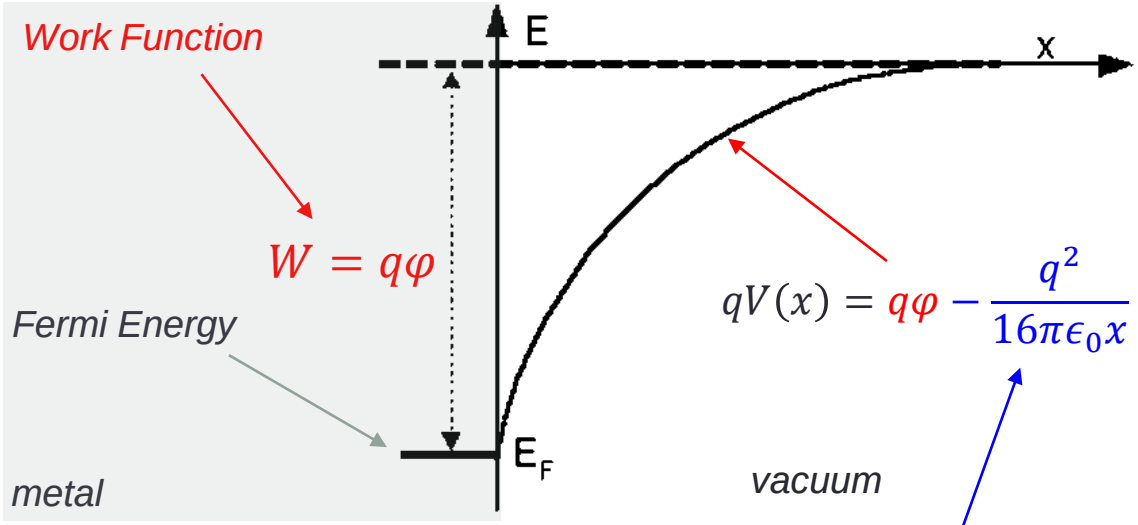


IMAGE CHARGE TERM

$$E(x) = \frac{q}{4\pi\epsilon_0(2x)^2}$$

$$V_{CI}(x) = -\frac{q}{16\pi\epsilon_0}\frac{1}{x}$$

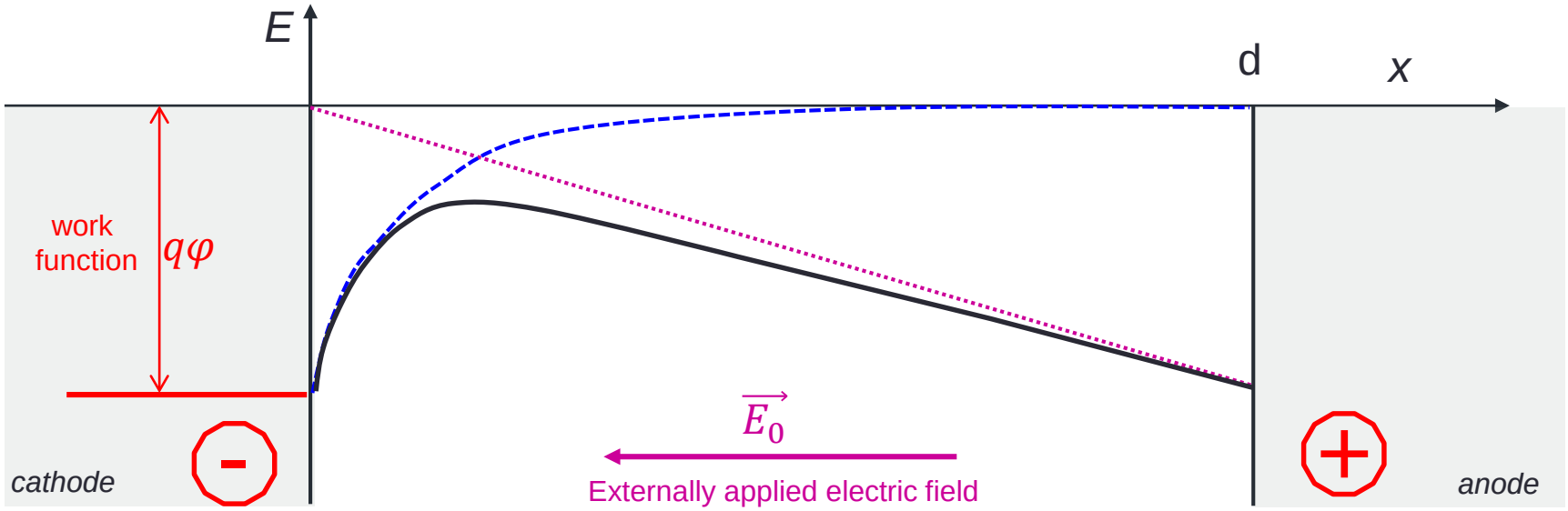
Electric potential energy as a function of distance near to a cathode with an externally applied electric field

$$qV(x) = q\varphi - \frac{e^2}{16\pi\epsilon_0 x} - E_0 x$$

Externally applied electric field

Image charge

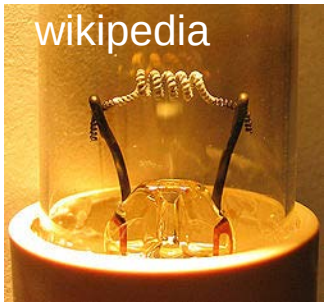
E=-V/d



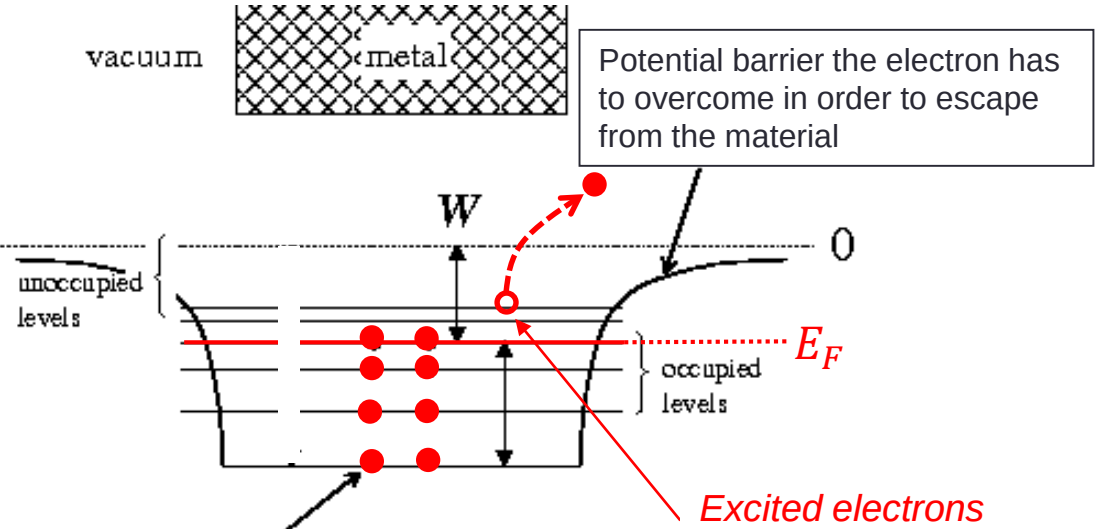
V(0)<0

V(d)=0

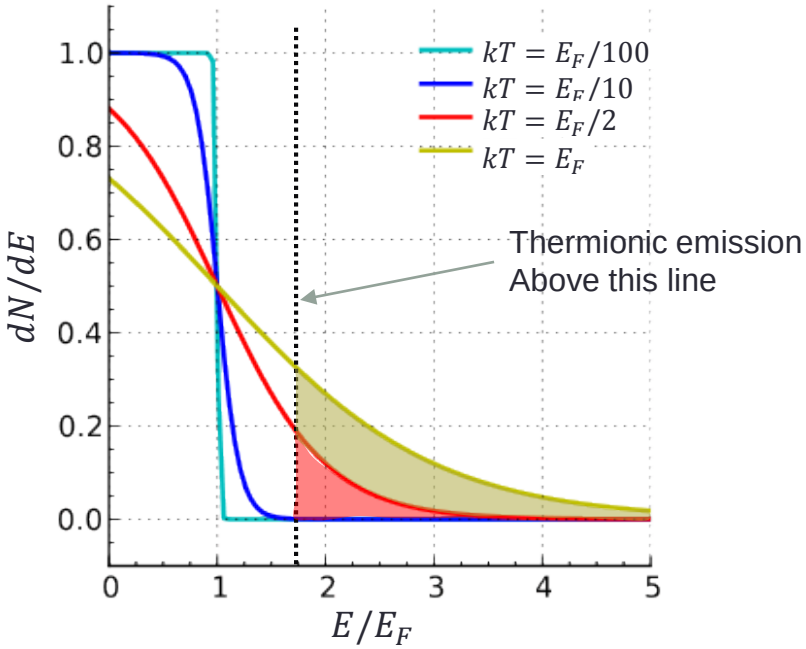
Thermionic emission of electrons



- A first way to extract electrons is to heat a material to a high temperature
  - When the material is heated, the thermal vibrations of the atoms are partially transferred to the electrons (E~kT_e) which can populate excited states above the Fermi level
  - Electrons are finally kicked out of the metal when their final energy **E** is higher than the Work Function **W** : **E > W**
- **The thermionic emission** is the resulting flow of electrons extracted from the heated material
- The application of a negative voltage (weak Electric field) helps to extract electrons from the metal surface (and accelerates them)

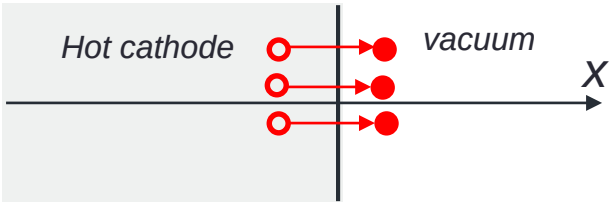


Potential (zero) inside the metal (*Wikipedia*)



Fermi-Dirac function

Thermionic emission of electrons : current density



- Electron kinetic energy:
  - $\frac{1}{2} m_e {v_x}^2 > e\varphi$

- Electron current density:
  - $j_{thermionic} = n_e e \langle v_x \rangle = \iiint_{v_x > \sqrt{2e\varphi/m_e}} v_x g(v) f_{FD}(v) dv_x dv_y dv_z$
  - $j_{thermionic} = n_e e \iiint_{v_x > \sqrt{2e\varphi/m_e}} v_x \frac{2m}{h^3} e^{-\frac{m}{2kT}(v_x^2+v_y^2+v_z^2)} dv_x dv_y dv_z$
  - Calculations → $j_{thermionic} = \frac{4\pi m_e k^2 e}{h^3} T^2 e^{-\frac{e\phi}{kT}}$

density of states function

Fermi-Dirac distribution function

Maxwell-Boltzmann approximation

- This is known as the Richardson-Dushman equation

Current density of Thermionic emission

- The experimental Thermionic emission flow is ruled by the Richardson-Dushman formula:
  - **J** current density (A/m^2)
  - **A** Richardson constant
  - **W** =q.φ work function
  - **T** temperature

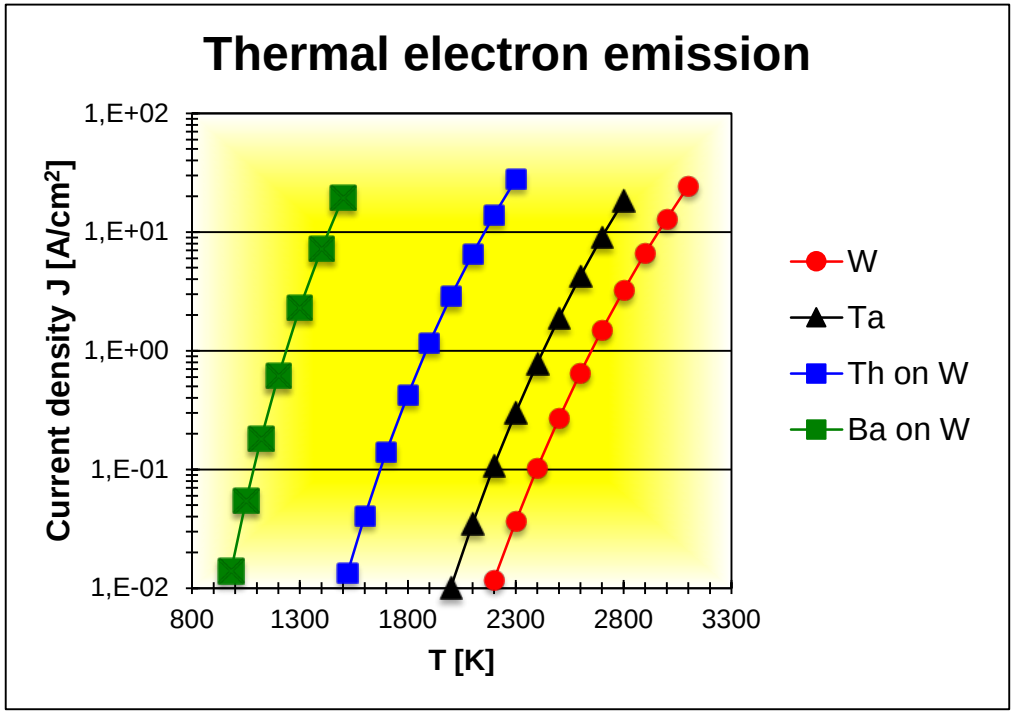
$$J = AT^2 e^{\frac{-W}{kT}} \qquad ,with\ A = A_0 \lambda_R$$

$$A_0 = \frac{4\pi m_e k^2 e}{h^3} = 1{,}20173 \times 10^6 A\, m^{-2} K^{-2}$$

- Order of magnitudes :
  - Wolfram : W_w~4.5 eV ; Tw~2900 K → J~10 A/cm^2
  - LaB_6 : W_{LaB6}~2.4 eV ; $TLaB_6$~2100 K → J~10^2 A/cm^2

Material	W	λ_R
Molybdenum	4.15	0.46
Nickel	4.61	0.25
Tantalum	4.12	0.50
Tungsten	4.54	0.50
Barium	2.11	0.50
Cesium	1.81	1.33
Iridium	5.4	1.42
Platinum	5.32	0.27
Rhenium	4.85	0.83
Thorium	3.38	0.58
Ba on W	1.56	0.01
Th on W	2.63	0.02
Thoria	2.54	0.02
Cs-oxide	0.75	0.00008
TaC	3.14	0.00
LaB6	2.4	0.24

Source: H. Koivisto, JUAS 2013
J. Arianer, IN2P3 Lecture

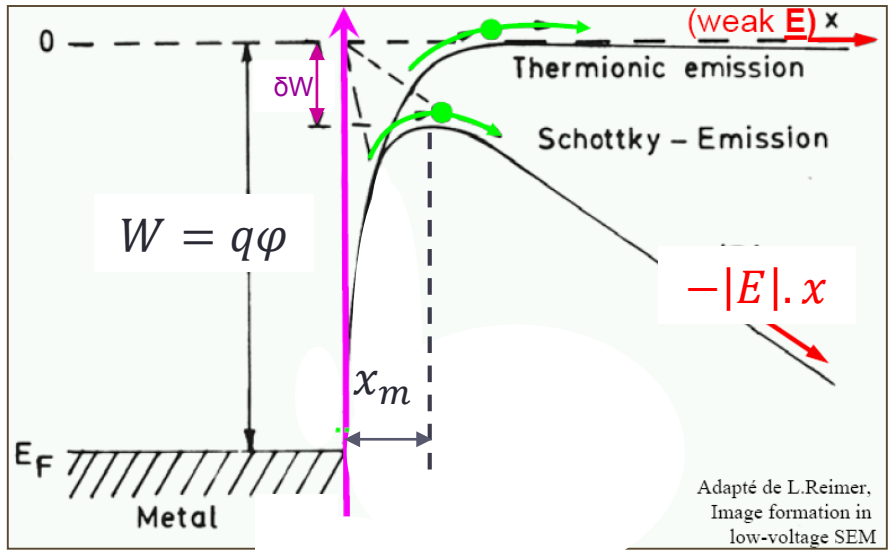


The Schottky effect

- The Schottky effect is the reduction of the electron work function when a strong external electric field E is applied to the hot cathode
  - This is the case for thermionic guns since cathodes are negatively biased
  - $qV_S(x) = q\varphi - \frac{q^2}{16\pi\epsilon_0 x} - qE.x$

Modified potential — *Work function* — *Image charge (slide 7)*

  - The work function is reduced by $\delta W = \sqrt{\frac{q^3 E}{4\pi\varepsilon_0}}$
  - The distance to the peak potential is $x_m = \sqrt{\frac{q}{16\pi\epsilon_0 E}}$

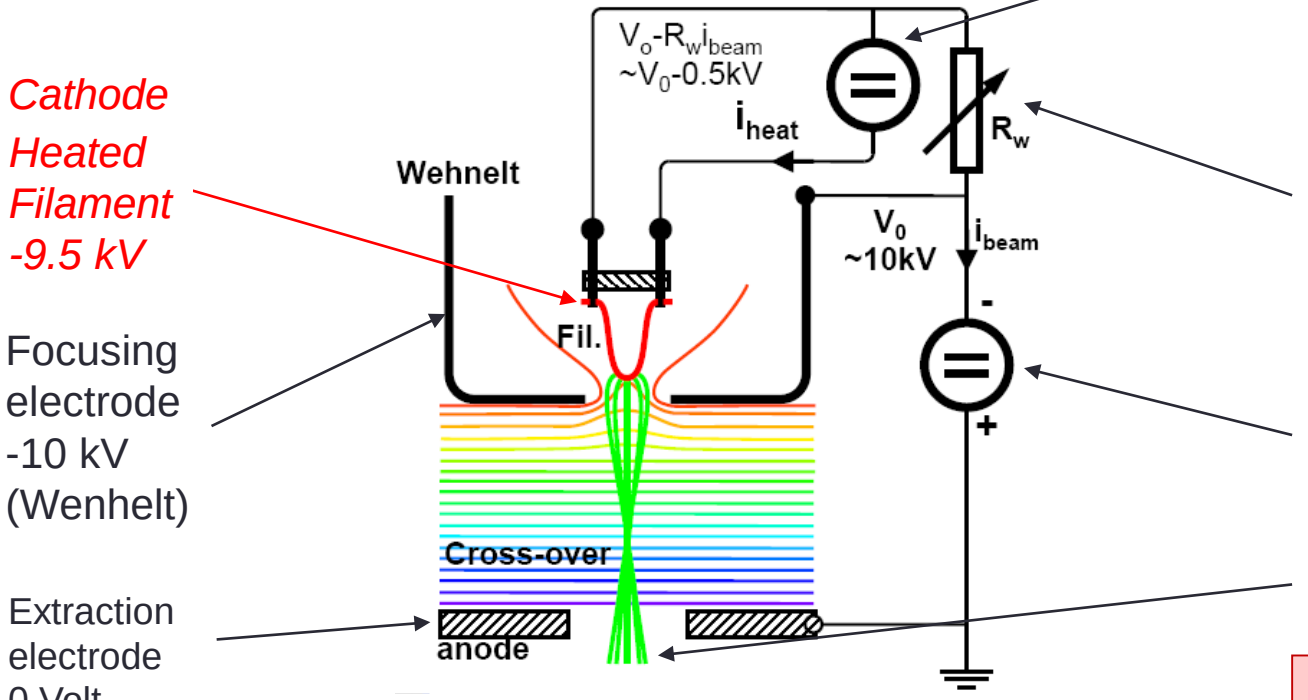


- Modified Richardson-Dushman formula:
  - $J = AT^2 e^{\frac{-(W-\delta W)}{kT}}$
- Shottky effect is usually of second order :
  - $E = 10\frac{kV}{cm} \rightarrow \delta W = 30\ meV$ and $x_m \sim 190\ \dot{A}$
  - $E = 100\frac{kV}{cm} \rightarrow \delta W = 100\ meV$ and $x_m \sim 60\ \dot{A}$
  - Schottky Effect valid up to $E \sim 1\frac{MV}{cm} \rightarrow \delta W = 0.3\ eV$ and $x_m \sim 19\ \dot{A}$

Can you show this?

The Thermionic Electron Source

- A very common electron source used in industry and research
  - klystron, TV tubes, electronic microscope, accelerators…
- Example of an electronic microscope source:

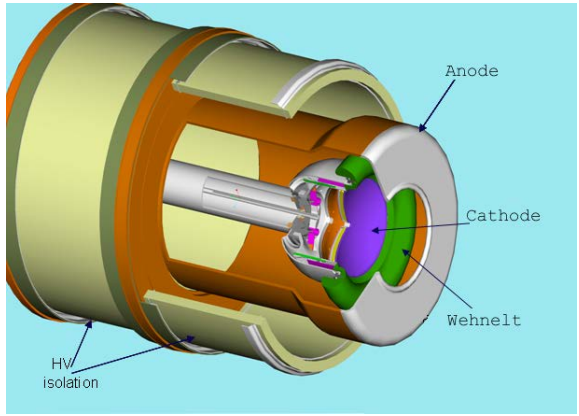


Filament
Lifetime ~ 10 to 1000 h

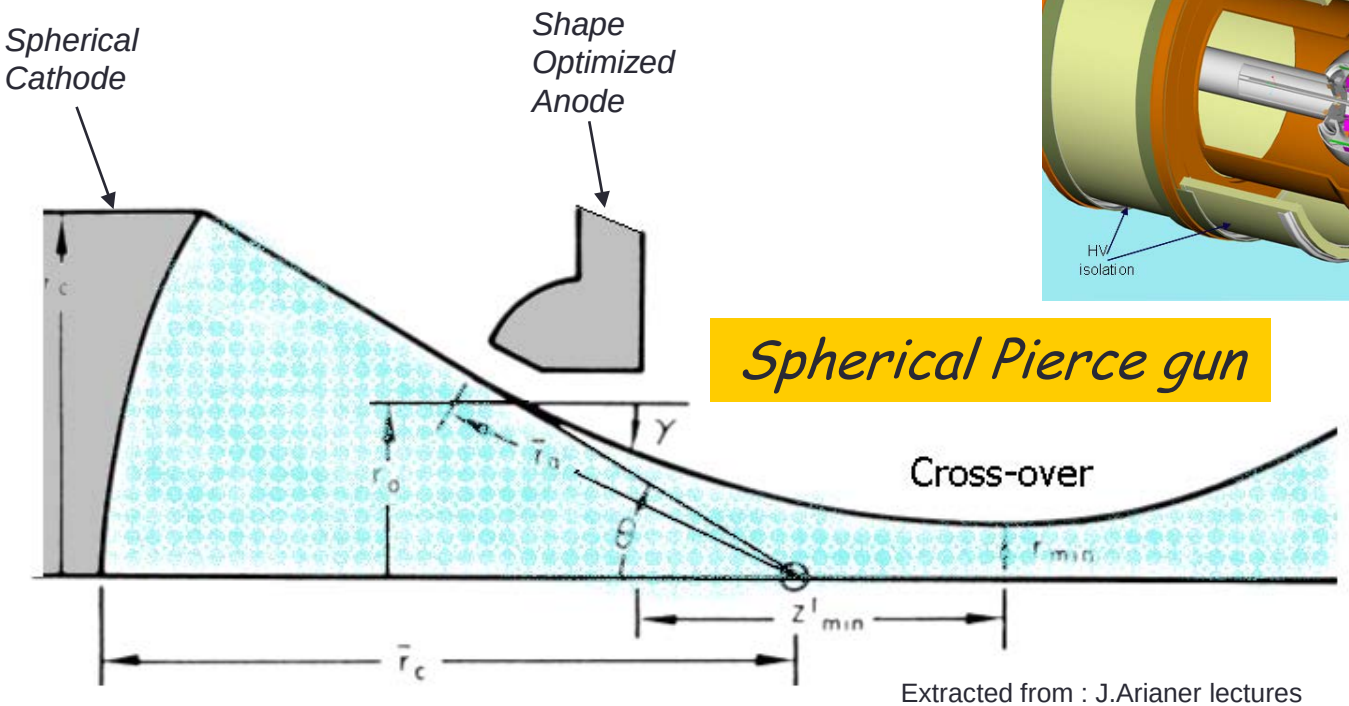
Extracted from : Microscopie Electronique 06/07, philippe.buffat@epfl.ch

High Intensity Thermionic Electron Gun

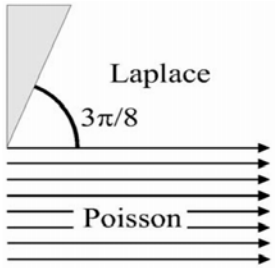
- The electronic current is increased by increasing the cathod surface
  - Depending on the design, the beam intensities span from ~µA to ~100 A
- « Pierce design » At high current, the electron beam space charge (which inflates the beam) is compensated by a careful design of the electrodes (which generate a focusing effect)



Example of cathodes



Spherical Pierce gun



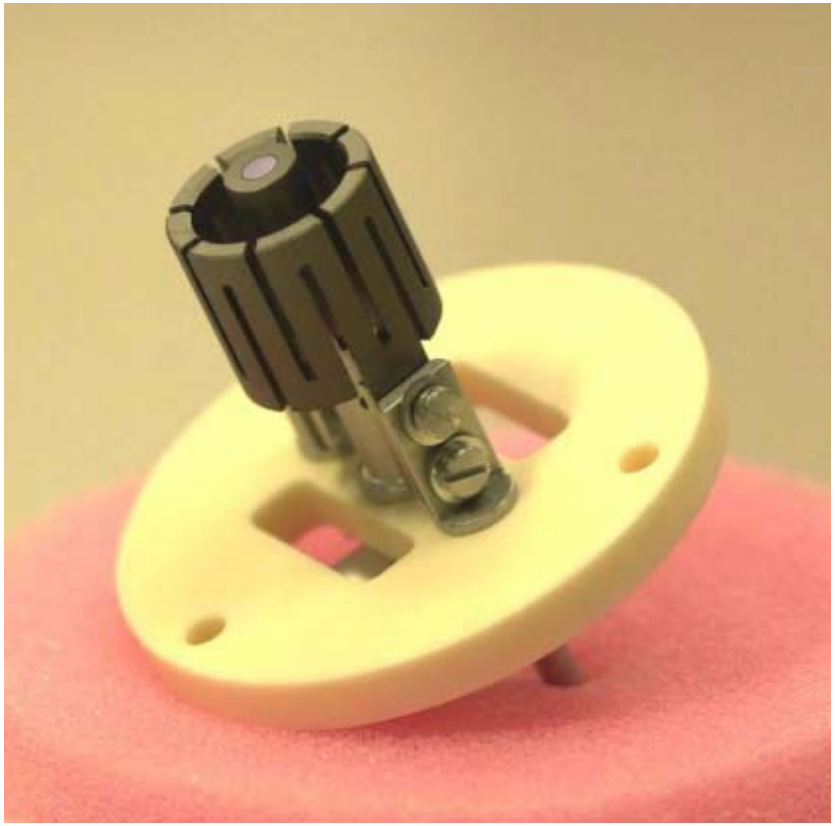
Pierce Angle
For a flat gun

Extracted from : J.Arianer lectures

Example of a modern accelerator thermionic gun

- Spring8 CeB6 Cathode for XFEL (SCSS)

Beam Energy	500 keV
Peak Current	1~3A
Pulse Width (FWHM)	2 μsec
Repetition Rate	60 Hz
Cathode Temperature	1400~1600 deg.C
Cathode Diameter	3mm
Theoretical Thermal Emittance (rms)	0.4 πmm.mrad
Measured Normalized Emittance (rms, 90% particles)	0.6 πmm.mrad [7]



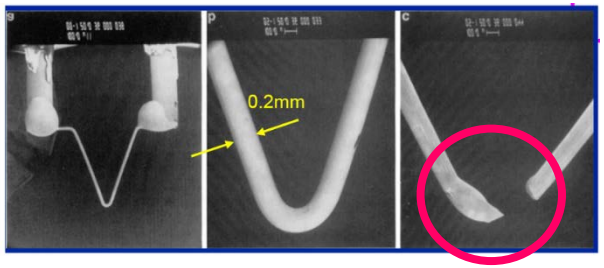
*K. Togawa et al., PAC03, 3332; NIMA **528** (2004) 312*
H. Tanaka et al., FEL06, 769

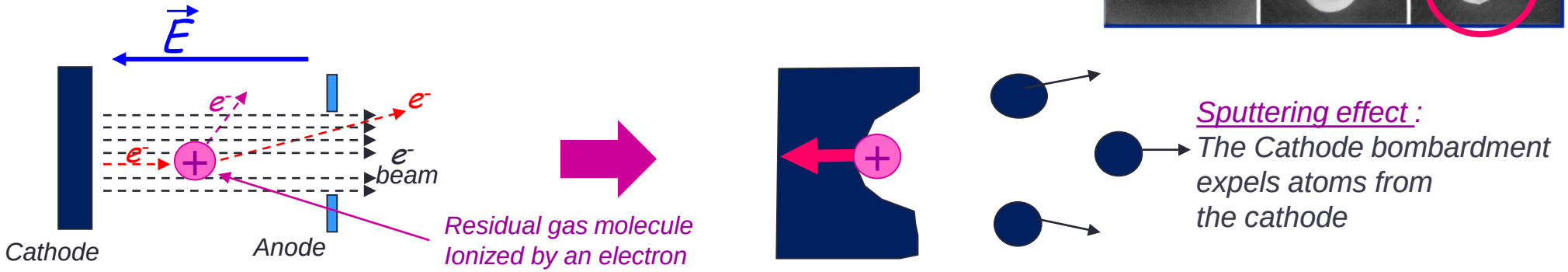
Slide extracted from Brookhaven lecture on cathode physics, M. Poelkerand and J. Smedley

Cathode and filament aging (by Sputtering)

- The lifetime of a cathode/filament strongly depends on the condition of operation
  - Cathode shape
    - a massive cathode will last much longer
  - Residual vacuum pressure
    - Electrons collide with the residual gas and generate ions which are accelerated toward the cathode => cathode sputtering
  - High Temperature:
    - Atom evaporation
    - chemical reaction induced by neighbor materials or gas
    - Thermal cycling generating cracks
    - Sudden burning, interruptions…
- Typical filament/cathode lifetime is 10^2~10^4 hours

cathodes damaged by sputtering



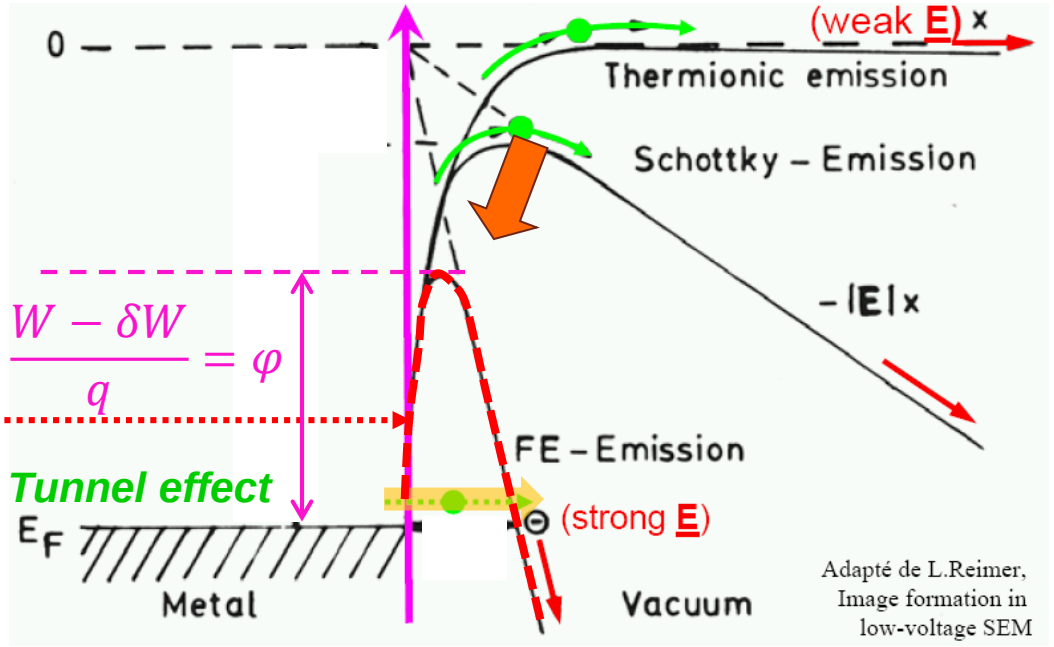


Electron Field Emission

- In the presence of a very strong electric field (E>10 MV/cm) , the working barrier is thin enough to allow electron emission through **Tunnel Effect**
- The associated emission is ruled by the Fowler-Nordheim theory (quantum physics)
- It is a **cold cathode emission** => no metal heating is required

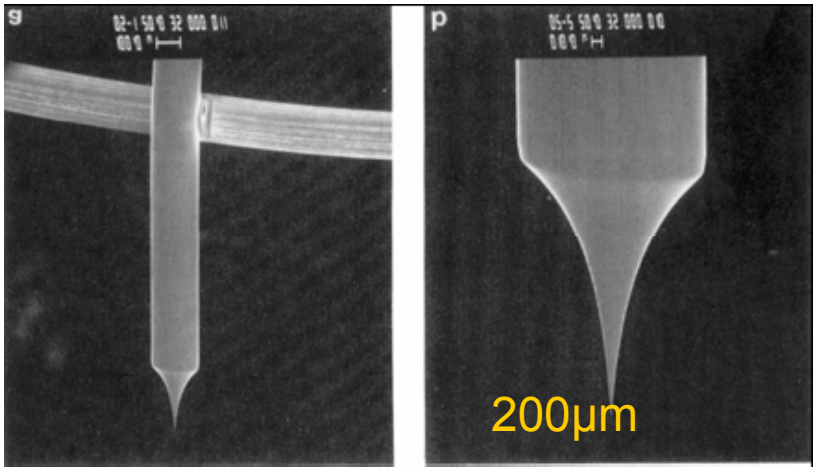
- $J \approx \frac{k_1 E^2}{\varphi} e^{-\left(\frac{k_2 \varphi^{3/2}}{E}\right)} A/m^2$
  - $k_1 = 1.4\ 10^{-6} (SI)$
  - $k_2 = 6.87\ 10^{7} (SI)$
- *J~1 MA/cm² !*

Field Emission (cold cathode)



Field Emission Electron Source (electronic microscopy)

Example of a tip which concentrates the Electric field



The lower the radius of the tip, the higher the electric field

(from J. Goldstein, Scanning electron microscopy)

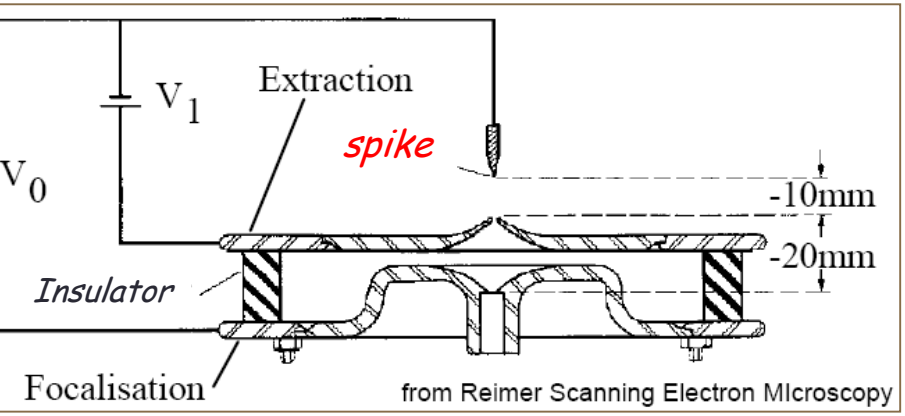
Electrostatic Point effect (Corona)

R Q — 2 Spheres with radius R>r — Same potential V — r q

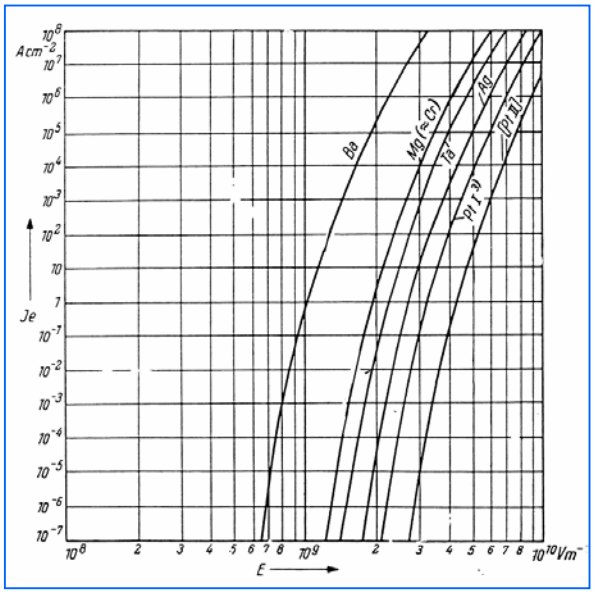
$$V = \frac{Q}{4\pi\epsilon_0}\frac{1}{R} = \frac{q}{4\pi\epsilon_0}\frac{1}{r}$$ at sphere surface

$$E_1(R) = \frac{Q}{4\pi\epsilon_0}\frac{1}{R^2} \qquad E_2(r) = \frac{q}{4\pi\epsilon_0}\frac{1}{r^2}$$

$$\Rightarrow E_2(r) = E_1(R).\frac{R}{r}$$

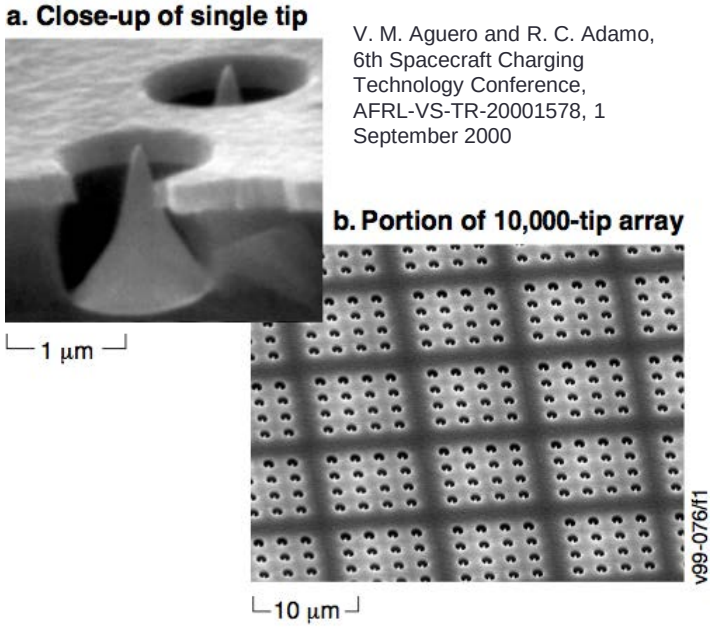


Extracted from : Microscopie Electronique 06/07, philippe.buffat@epfl.ch

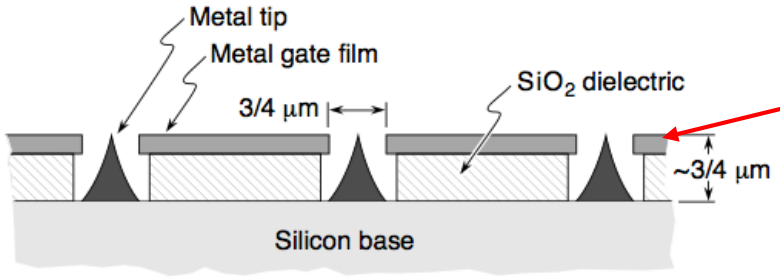


The Spindt Array

- Field Emitter Array (FEA) consists of a large amount of small field electron emitters.
- The original form of array (Spindt Array) has small, sharp Mo cones
- Each tip can emit current from nA to mA
- Provides mechanism for controlled high current (even above A) with low power.
- Limitations from parasitic heating and space charge effects



V. M. Aguero and R. C. Adamo, 6th Spacecraft Charging Technology Conference, AFRL-VS-TR-20001578, 1 September 2000



- The emission level is controlled by adjusting the gate voltage (< 100 V)
- Capacity of electron current up to 100 μA/tip has been demonstrated

Slide adapted from H . Koivisto

Field Emission Array Electron Source

Tests performed at PSI

- Several Companies developed Field Array emission gun (SRI Inc. , XDI Inc…) using the Spindt method
  - Array Built on Si base substrate, using semi-conductor technology
  - Generation of large Field emission array surface
    - 50000 Mo spikes (tips) on a Ø 1 mm disk for SRI Inc.
- The DC operation is subject to fluctuation and is limited to a few 100 µA, due to:
  - Thermal desorption of atoms inducing contamination, sputtering, parasitic discharges
  - Even destructive arcing if the pressure degrades too much
- **The pulsed operation is very promising**
  - Stable operation, no thermal issues, short pulses
  - High current density
  - Small intrinsic cathode emittance

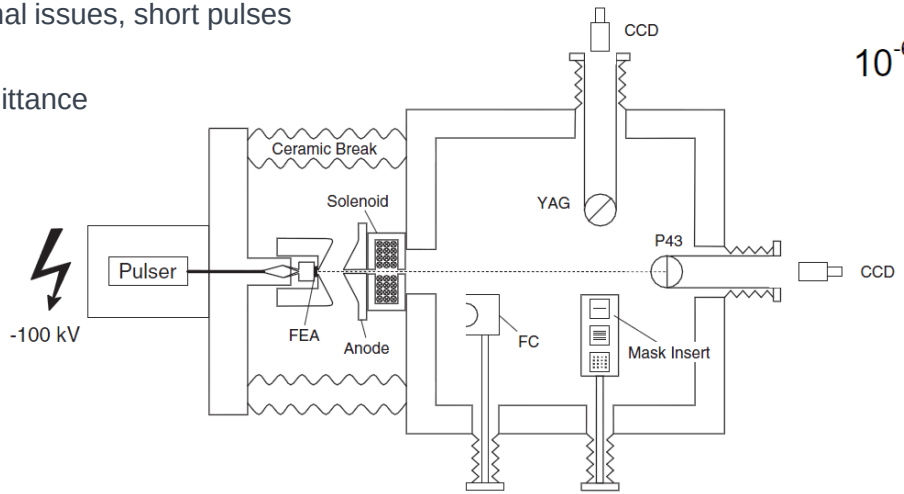


FIG. 1. Schematic overview of the 100 keV gun test stand (not to scale).

Ultra Low Emittance Electron Gun Project for FEL Application THP27, Proceedings of LINAC 2004, Lübeck, Germany, www.jacow.org

Figure 2: Current-voltage characteristic in DC and pulsed regime for a SRI Inc. FEA (1 µm diameter, 50,000 Mo tips) Insert: SEM picture of some conical Mo tips (SRI website [3]).

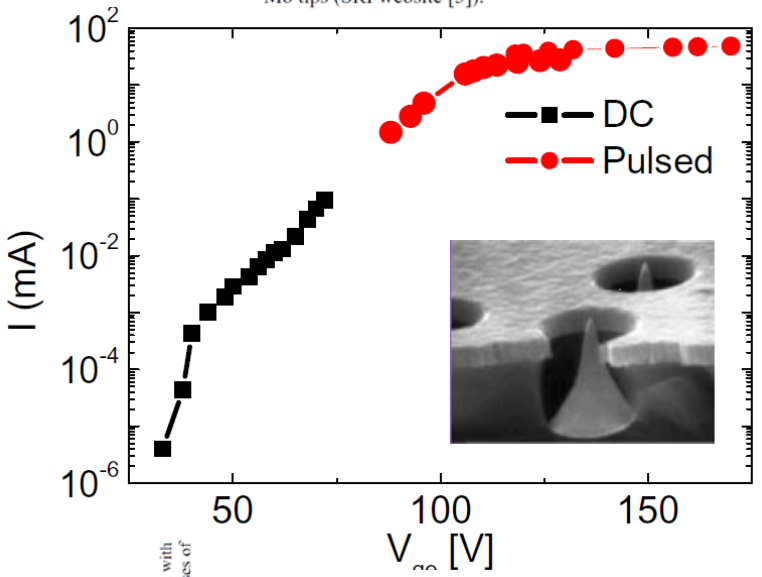
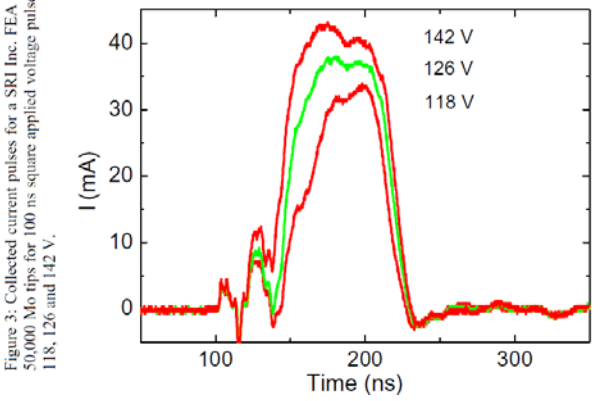
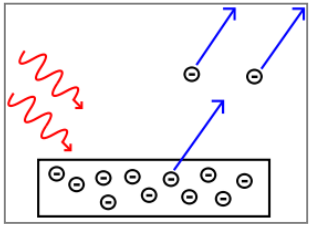


Figure 3: Collected current pulses for a SRI Inc. FEA with 50,000 Mo tips for 100 ns square applied voltage pulses of 118, 126 and 142 V.



Photoelectric Effect



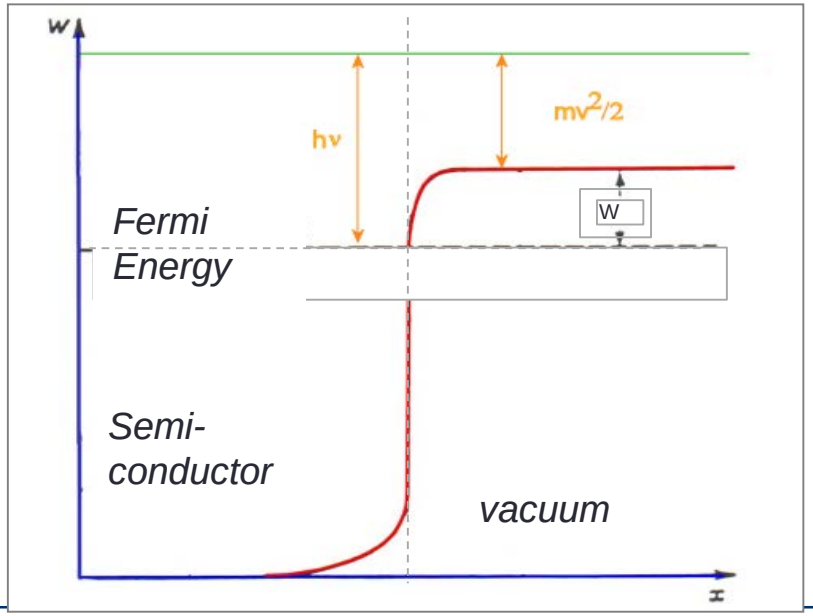
- The energy to emit an electron is given by a photon
  - A photocathode is a negatively charged electrode coated with a photosensitive compound. When it is struck by a photon, the absorbed energy causes electron emission due to the photoelectric effect.
  - A photocathode is usually composed of alkali metals with very low work functions (e.g. Cesium).

Photon energy

Electron kinetic energy

$$h\nu = W + \frac{1}{2}mv^2$$

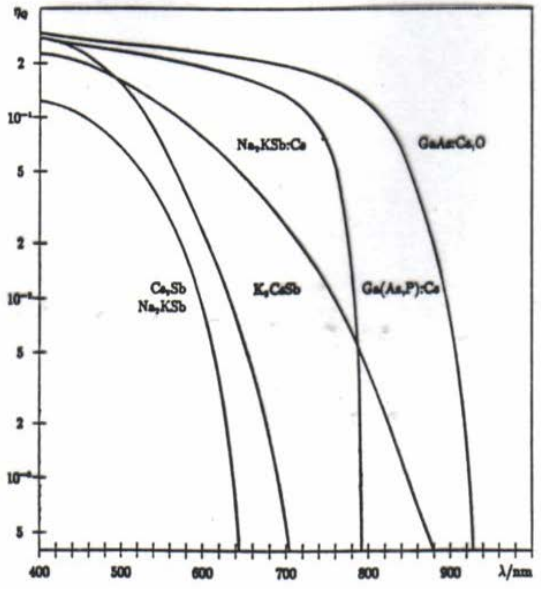
W = photocathode Work function



$$\lambda_{[nm]} = \frac{1234}{W_{[eV]}}$$

Material	ΔE [eV]	λ_0 [nm]
Cs_3Sb	1.95	640
K_2CsSb	1.8	700
Na_2KSb:Cs	1.4	890
GaAs:Cs,O	1.35	930

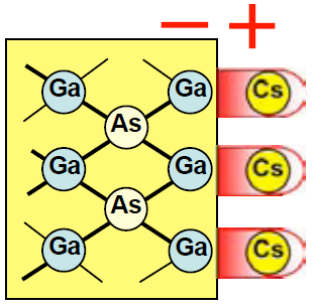
Photocathodes Quantum efficiencies (semi conductors)



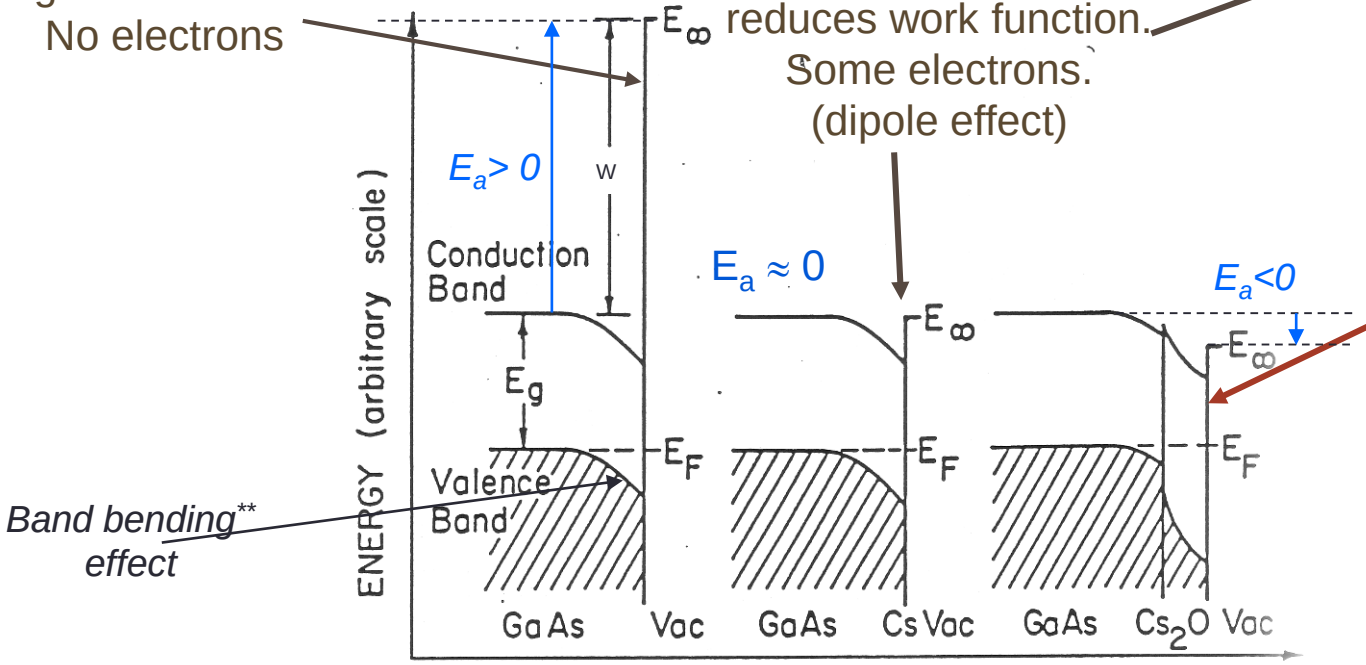
Negative Electron Affinity

Bare GaAs surface;
Large work function.
No electrons

Alkali (Cs) coating
reduces work function.
Some electrons.
(dipole effect)



Cesium + Oxidant (O or NF3)
"**N**egative **E**lectron **A**ffinity".
Many electrons



*Band bending*** *effect*

- NEA coating is deposited **directly on site** under ultra low vacuum (~10^{-12} mbar)
- NEA helps A LOT extracting electrons
- NEA coating is fragile, sensitive to contamination and sputtering
- Automatic coating on guns, see next slides

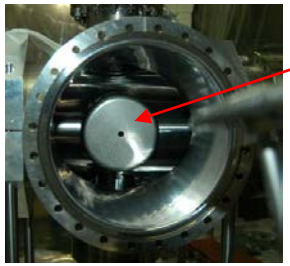
*Electron Affinity** : $E_a > 0$ $E_a \approx 0$ $E_a < 0$

Extracted slides from : J. Grames, JLab, USA
N. Nishimori, JAEA, Japan

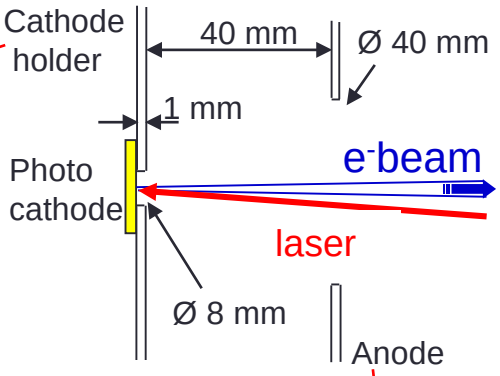
- *In solids, the Electron Affinity is the energy difference between the vacuum energy and the conduction band minimum.
- **Band bending refers to the local change in energy of electrons at a semiconductor junction due to space charge effects. The degree of band bending between two layers depends on the relative Fermi levels and carrier concentrations of the materials forming the junction.

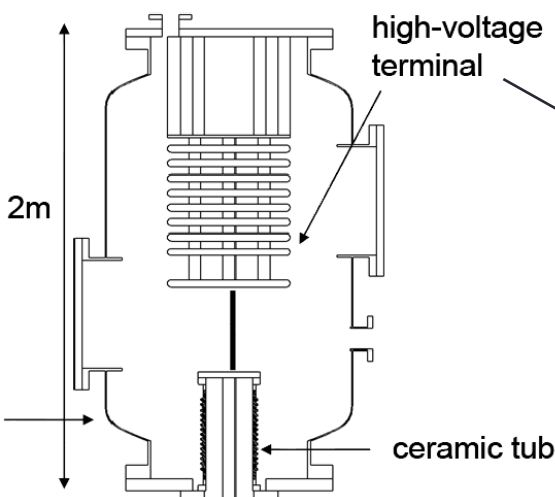
Example of a Photocathode DC SOURCE (JAEA-ERL)

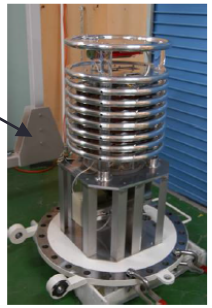
- A NEA-GaAs photocathode is hit by a laser beam
- Photoelectrons are accelerated by a 5 MV/m electric field
  - 250 kV High voltage / average 50 mA beam intensity
- Ultra low secondary vacuum (10^{-12} mbar) to increase photocathode lifetime
  - To prevent cathode contamination
  - To minimize sputtering from the residual gas ionized by the electron beam
- Load-Lock system to remove/install/coat photocathode on site



all the electrodes are made of Titanium



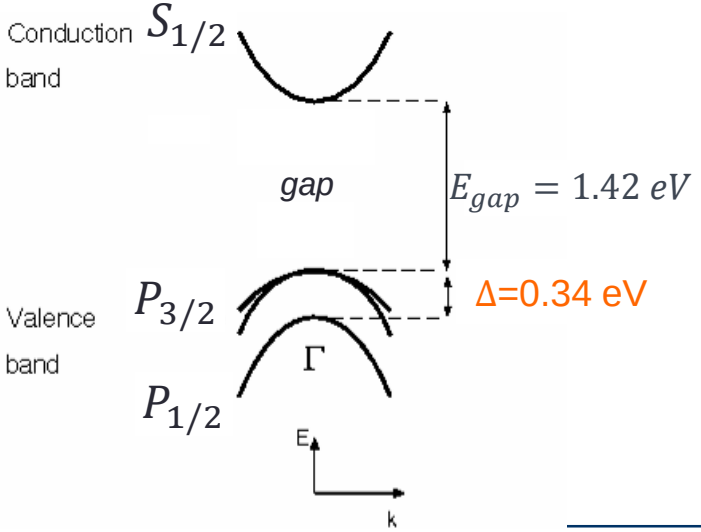




Slides extracted from www.jacow.org
TUPPH007,Proceedings of FEL 2006, BESSY, Berlin, Germany

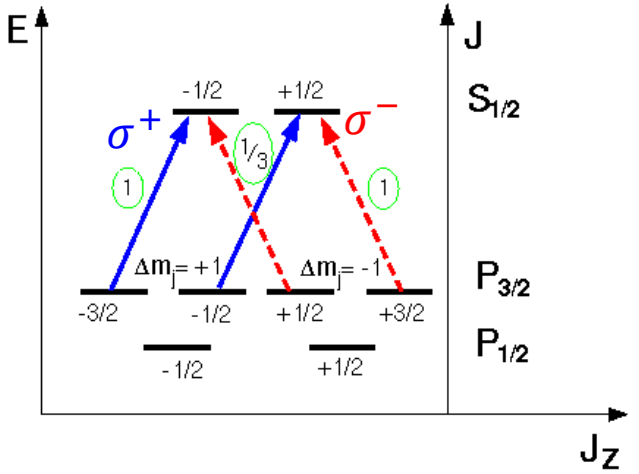
Polarized Photoemission electron source at Jlab (1/2)

- When the laser beam is circularly polarized, the electron beam is partially polarized
  - Optical pumping between $P_{3/2}$ and $S_{1/2}$ states
  - The photon energy E_γ is chosen such that $E_{gap} < E_\gamma < E_{gap} + \Delta$
  - Laser circularly polarized σ^+ or σ^-
  - The probability to populate $-\frac{1}{2}$ and $+\frac{1}{2}$ states on $S_{1/2}$ being different, a 50% excess of polarization is obtained



$$P_e = \frac{1 - \frac{1}{3}}{1 + \frac{1}{3}} = \pm 50\%$$

$$P_e = P\left(+\frac{1}{2}\right) - P\left(-\frac{1}{2}\right)$$



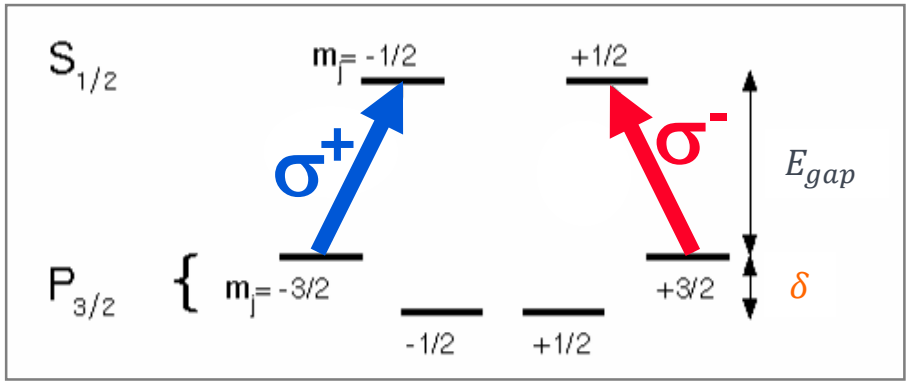
Slide adapted from : J. Grames, JLab, USA

Polarized Photoemission electron source at Jlab (1/2)

- A refinement of the polarization is obtained by adding extra layers on the photocathode :
  - Split degeneracy of $P_{3/2}$
  - Direct optical pumping between $P_{3/2}$ and $S_{1/2}$
  - When $E_{gap} < E_\gamma < E_{gap} + \delta$:

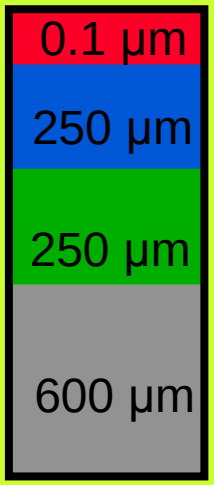
$$\boldsymbol{P_e = \pm 100\%}$$

  - Experimentally $\boldsymbol{P_e \sim \pm 85\%}$



Slide adapted from J. Grames, JLab, USA

Complicated semiconductor elaboration

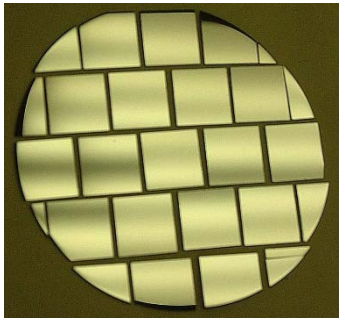


Strained GaAs

$GaAs_{1-x}P_x$ x=0.29

$GaAs_{1-x}P_x$ 0<x<0.29

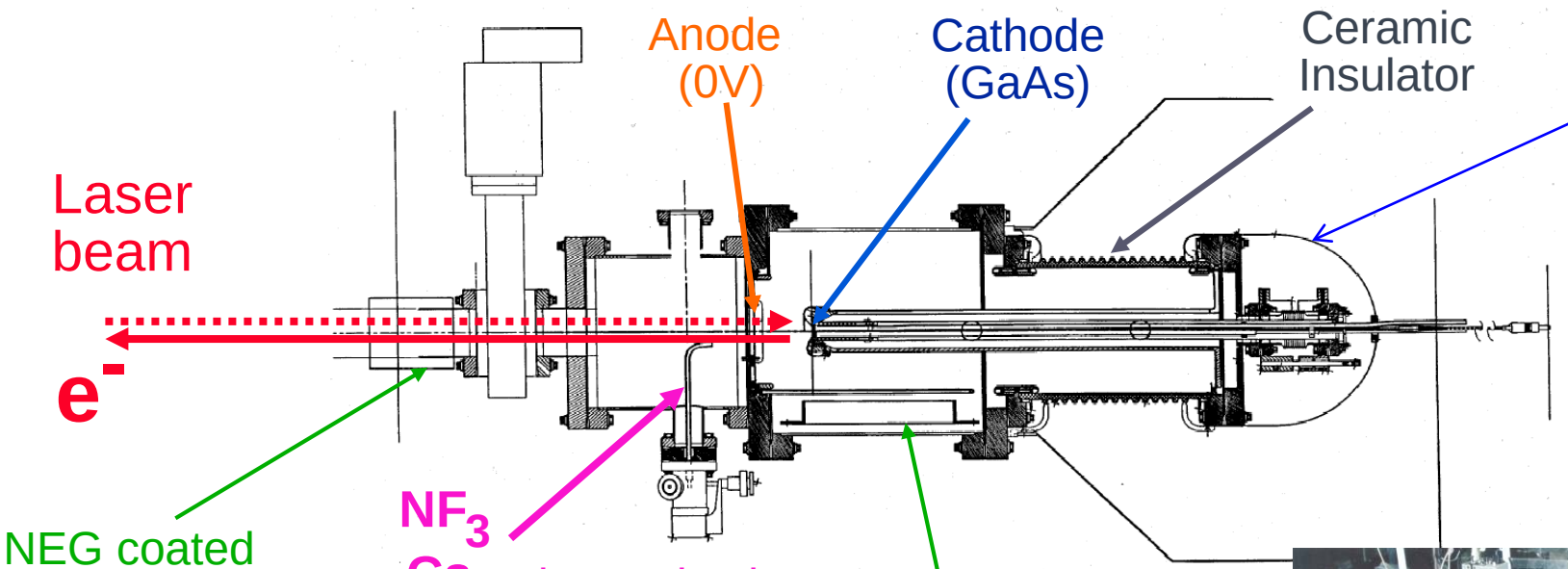
p-type GaAs substrate



3 ” wafer cut into square photocathodes

Stalk for supporting 1 Photocathode

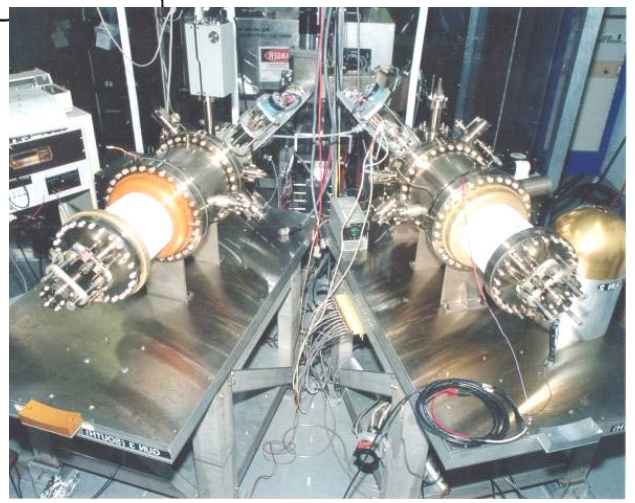
Jlab polarized Photoemission gun



Non evaporable getter pumps (NEG)
4,000 liter/s pump speed ⇒ ~410^{-12} mbar

↑

Mandatory to prevent Photocathode early aging

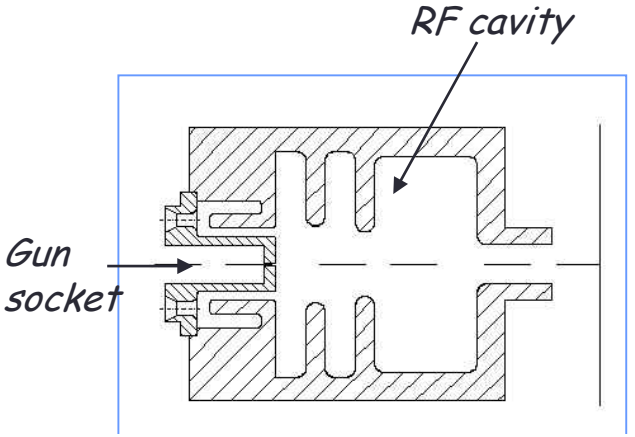


slide adapted from: J. Grames, JLab, USA

Radio Frequency Guns

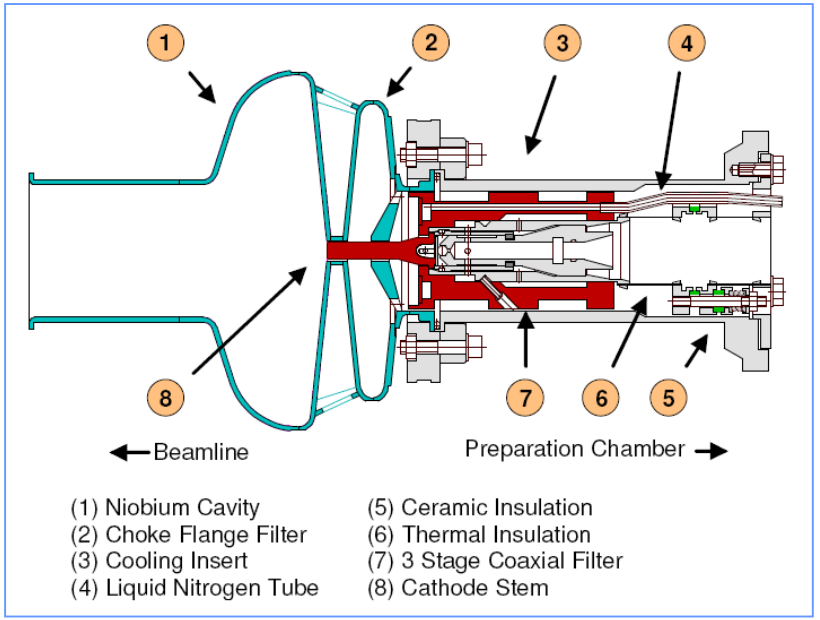
The RF gun is the name given when the electron ion source is directly coupled to a RF Cavity

- compact solution to accelerate directly above MeV Energies
- Work function reduced by the Shottky effect
- higher currents are reachable
  - space charge limitation at a much higher beam intensity
- Can be used with many kind of electron source



A 3 GHz thermionic RF gun has been designed. It will produce a 2.3 MeV electron beam with bunch charge up to 0.2 nC (600 mA) at 10 pmm mRad normalised emittance.

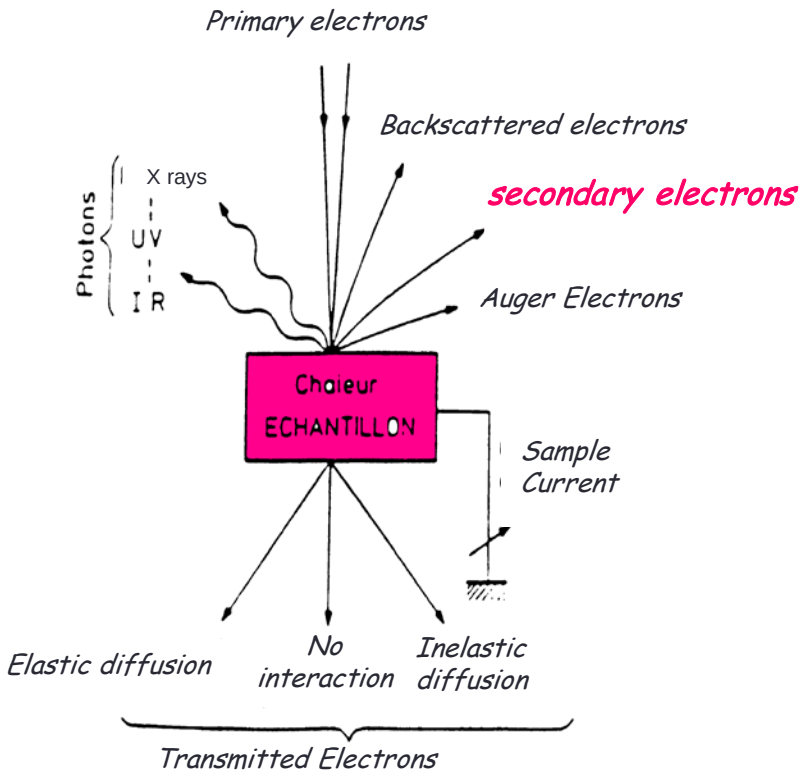
Rossendorf ½ cell Supercon. RF gun prototype



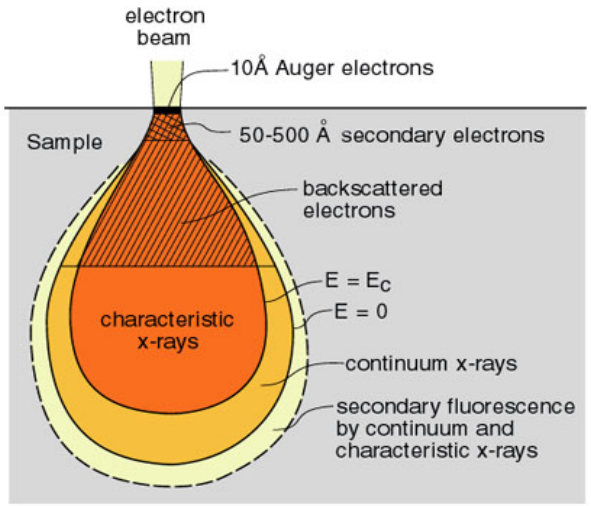
D.Janssen et al., NIM A507(2003)314.

Secondary electron emission

- Any particle (ion, electron, photon) impinging on a material with an energy higher than the electron work function *W* of this material can eject **secondary electrons** (among many other things…)
  - Electron penetration depth: $x(\mu m) = \frac{0.1E^{1,5}}{\rho}$, ρ material density in *g/cm³* , E *kinetic energy in KeV*



Interaction volume of different effects



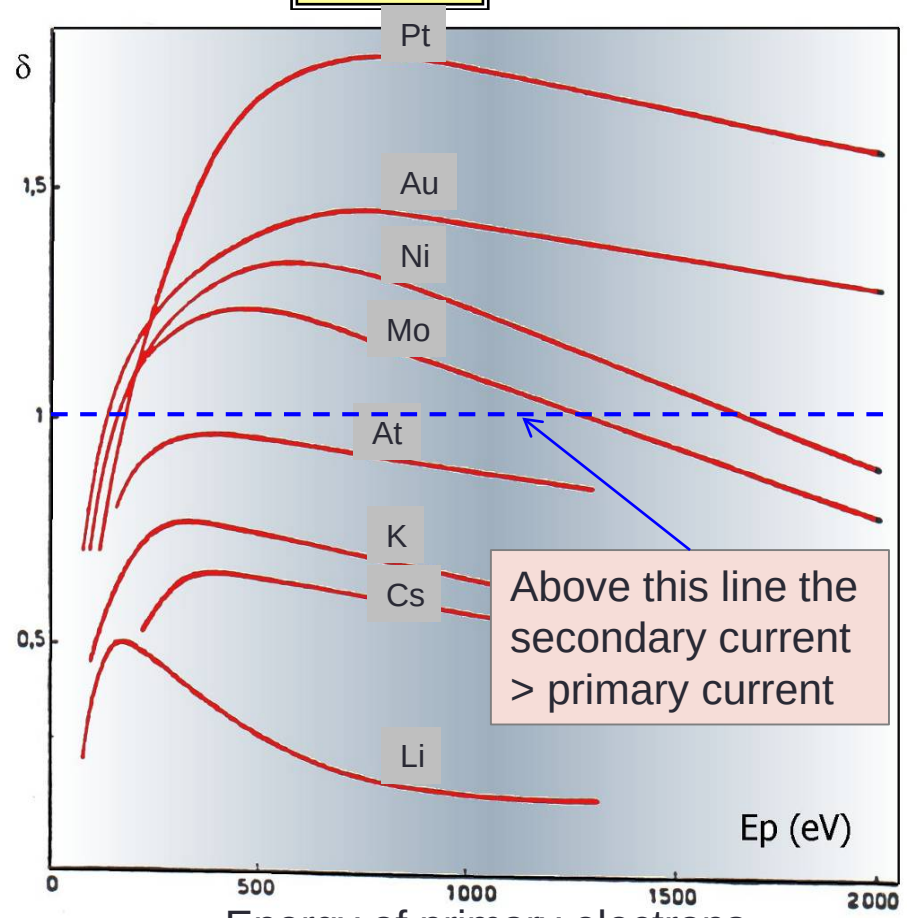
http://www4.nau.edu/microanalysis/microprobe-sem/signals.html

Slide adapted from J. arianer, H. Koivisto

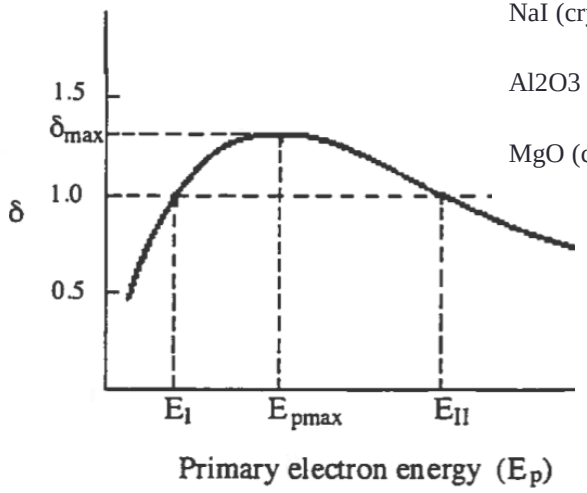
Secondary electron Yield

SE Yield: $\delta = \frac{N_{e_s}}{N_{e_p}}$ *Secondary electrons* / *Primary electrons*

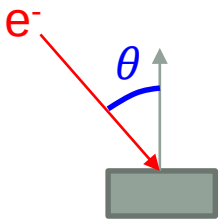
Element	δ_{max}	E_p (eV)	E_I (eV)	E_{II} (eV)
Cu	1.3	600	200	1500
Fe	1.3	600	200	1500
Pt	1.8	700	350	3000
Ta	1.3	600	250	>2000
Compounds	δ_{max}	E_p (eV)		
NaI (crystal)	19	1300		
Al2O3 (layer)	2 to 9			
MgO (crystal)	20 to 25	1500		



Energy of primary electrons

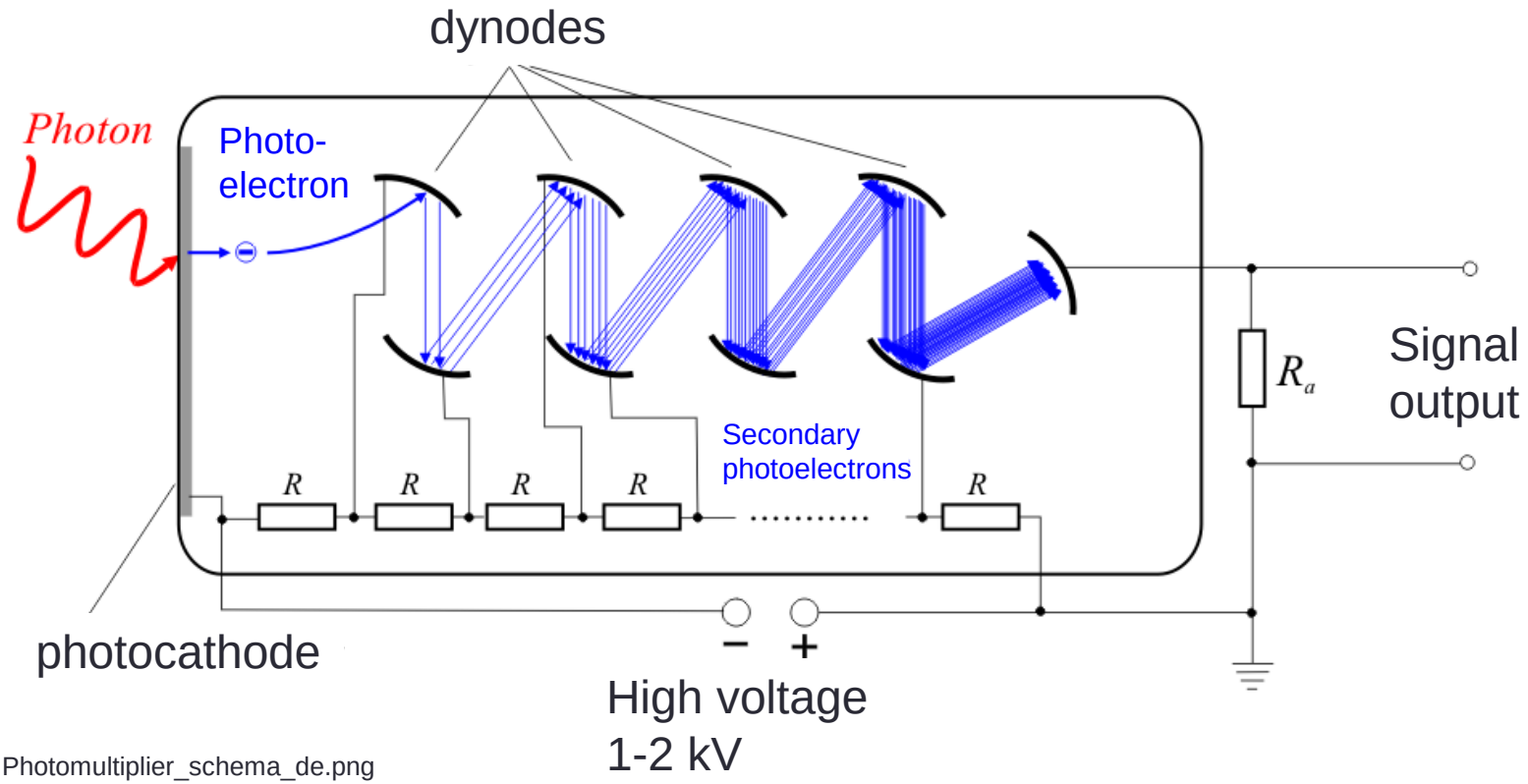


- SE Yield depends on:
  - Material
  - Contamination
  - Energy
  - Incident angle : $\delta(\theta) \sim \frac{\delta_0}{\cos\theta}$
  - SE emission can be used to amplify an electron signal!



The photomultiplier

- It's not exactly an electron source, but a concept of interest in this lecture….
  - Can detect a single photon
  - 1 photon →1 photo-electron→ n secondary elecotron/dynode/electron
  - The electron signal is amplified (and accelerated) through a set of dynodes



http://commons.wikimedia.org/wiki/File:Photomultiplier_schema_de.png

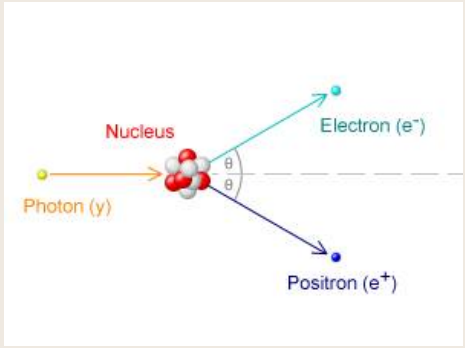
Electron source beam emittance

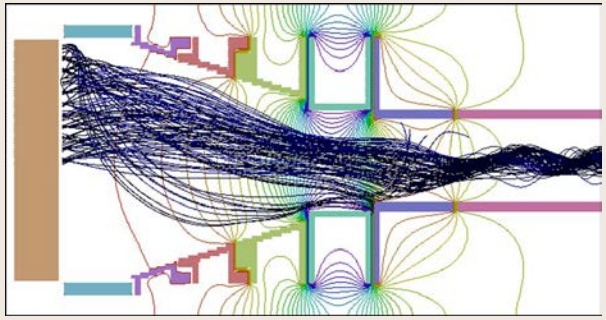
- General formula for a 1 σ RMS normalized transverse emittance: $\epsilon_N = \gamma\beta\sigma_x\sigma_{x'}$
  - $\sigma_x = \sqrt{\langle x^2 \rangle}$ RMS beam size, calculated on the cathode surface
  - $\sigma_{x'} = \frac{\sqrt{\langle p_x{}^2 \rangle}}{p}$
- Thermionic gun
  - $\epsilon_N = \sigma_x \sqrt{\frac{kT}{m_e c^2}}$
    - $\sigma_{x'} = \frac{\sqrt{\langle p_x{}^2 \rangle}}{\gamma\beta m_e c} = \frac{\sqrt{\langle v_x{}^2 \rangle}}{\gamma\beta c} = \frac{1}{\gamma\beta c}\sqrt{\frac{kT}{m_e}}$, assuming a Maxwell Boltzmann distribution
- Field emission
  - $\epsilon_N = \sigma_x \sqrt{\frac{E_F}{m_e c^2}} \left[\frac{4E_F}{\hbar F}\sqrt{2m_e w}.\, t(y) - 1\right]^{-1/2}$
    - $F = e \times [Electric\ field\ intensity]$
    - w *work function of cathode*
    - E_F *Fermi energy*
    - $t(y) \cong 1 + \frac{1}{9}y^2(1 - \ln(y))$, with $y = \sqrt{\alpha\hbar cF}/w$, $\alpha = e^2/\hbar c 4\pi\epsilon_0$
- Photo emission (pulsed beam)
  - $\epsilon_N = \sigma_x \sqrt{\frac{\hbar\omega - w - \sqrt{\alpha\hbar cF}}{3m_e c^2}}$

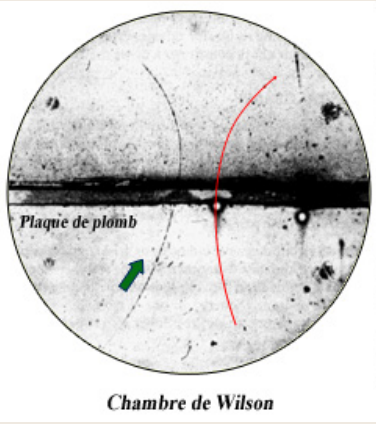
Electron source type	ϵ_N/σ_x [micron/mm]
Thermionic	~0.3
Field Emission	~0.5-1
Photo Emission	~0.5-2

N.B. : micron is a commonly used unit in the electron beam community:
- $1\ \pi.mm.mrad$ emittance corresponds to
- $3.14 \times 10^{-6}\ m.rad \Leftrightarrow 3.14\ \mu m$

See K.L. Jensen et al., Jour. Appl. Phys. 107, 014903 (2010)







Chambre de Wilson

Carl Anderson

C.D. Anderson, Physical Review 43, 491 (1933)

POSITRON SOURCE

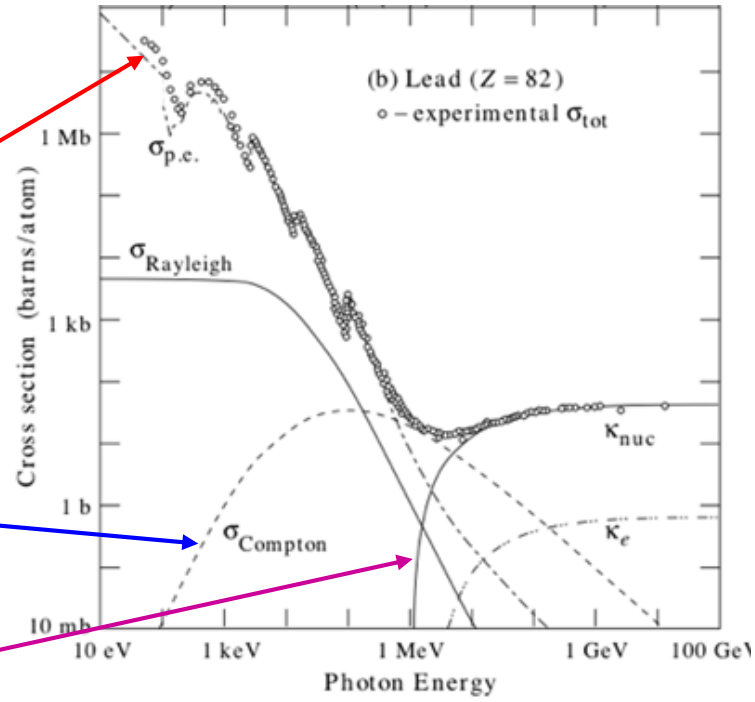
An introduction

Positron Source

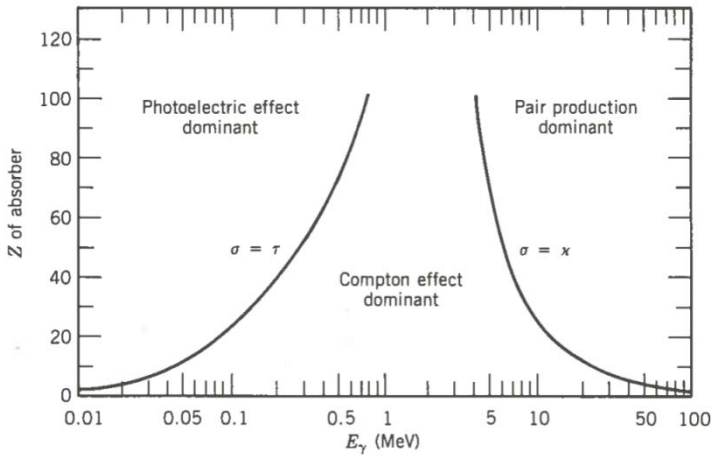
- The positron is the antiparticle of the electron, it has a positive charge
- Mechanism to make a positron:
  - β^-decay :
    - ${}^A_Z N \rightarrow {}^A_Z N' + e^+ + \nu_e$
    - Many nuclear reactions occur through the β^-decay channel
  - Pair production:
    - $\gamma + X \rightarrow X + e^+ + e^-$, where X is either a nucleus or an electron
    - The gamma photon must have an energy $E > 2m_e c^2 \sim 1\ MeV$
    - The pair production process is dominant at high energy
- Interaction of positron with matter
  - The positron interact with an electron to form a quasi-stable positronium which eventually anihilates into two photons: $e^+ + e^- \rightarrow \gamma + \gamma$
- Interest of the positron:
  - Condensed matter study: positrons can penetrate deeply into matter and can help making non-destructive 3D analysis of materials
  - Accelerator : positron is foreseen to be used in a leptonic collider able to accelerate both $e^+$and e^- in the same vacuum pipe → **CLIC**

Photon Interaction with matter

- The main photon interaction with ordinary matter depends on its energy:
  - Low energy: the photoelectric effect is dominant (*E<1 keV*). Interaction of the photon with the bound electrons.
  - Medium energy: the Compton effect is dominant (*1 keV<E<1 MeV*). Diffusion of the photon on a knocked-out electron
  - High Energy: the **pair production** is the dominant effect (*E>1 MeV*)
    - $\gamma + X \rightarrow X + e^+ + e^-$
    - X is either a nucleus or an electron
    - Threshold energy $E > 2m_e c^2 \sim 1\ MeV$
- The cross section of these processes increases with the atomic number Z

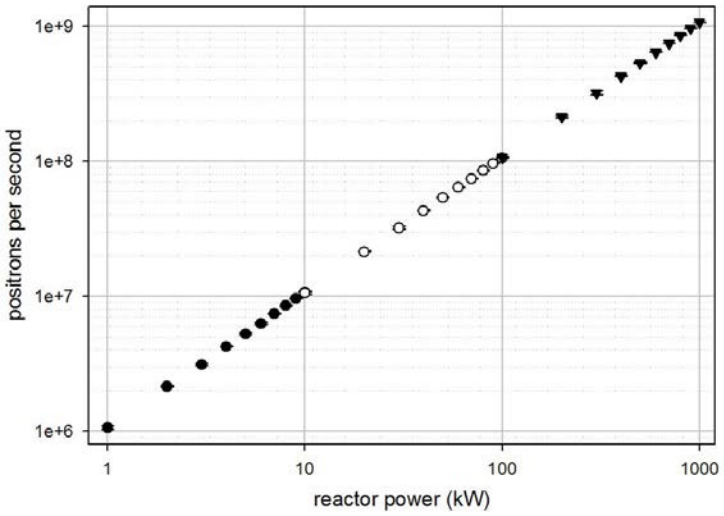


K.S. Krane, Introductory Nuclear Physics

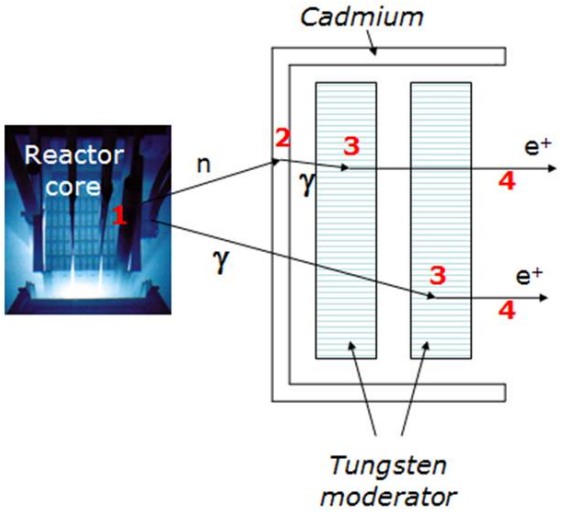


Positron beam at NC State University (1/2)

- A 1 MW nuclear reactor (PULSTAR) generates neutrons and gammas
  - Neutrons are converted into γ in a cadmium shroud
  - γ are converted in $e^+ + e^-$ pair in Tungsten metal strips
  - The tungsten strips also play the role of moderator to slow down e^+ to a few eV



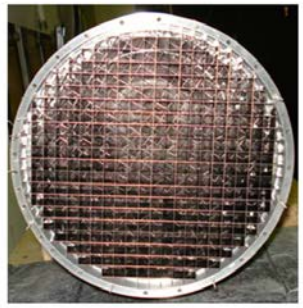
Positron beam intensity available for experiments



1. Neutrons (n) and gammas (γ) are emitted from fission reactions in the reactor core.
2. Neutrons react in the cadmium shroud producing additional gamma rays.
3. Gamma rays interact by pair production in the tungsten moderator to form positrons.
4. Positrons thermalize and are emitted from the tungsten surface with energies of a few electron volts (eV).

Tungsten Moderator Assembly

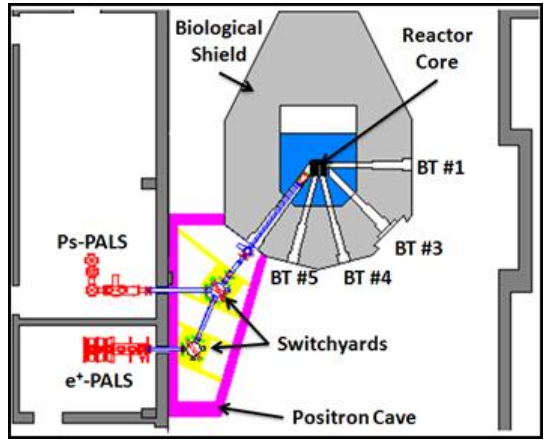
- 2 Moderator Banks
- Made from Tungsten metal strips
- Each bank 8" OD, 1 in thick
- Cleaned and annealed at 2200K for 4 hours
- Evacuated to 5E-8 millibar



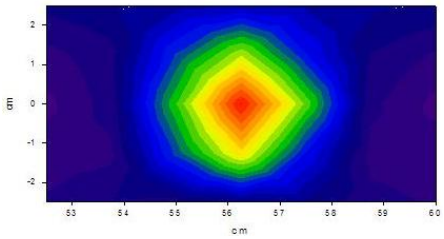
Content extracted from http://www.ne.ncsu.edu/nrp/ips.html

Positron beam at NC State University (2/2)

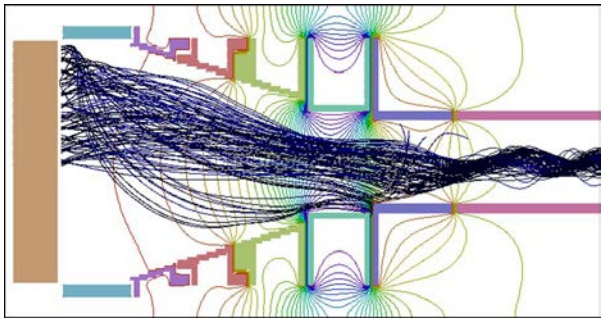
- e^+ are focused by Electrostatic lenses at the exit of the converter
- e^+ beam is transported in a magnetic LEBT toward experimental caves
- Application of positron beam: non destructive technique to detect defects and free volume in a wide variety of material
  - Pore sizes ranging from several angstroms to ~30 nm can be determined
  - Positron often form meta-stable positronium ($e^+ - e^-$bound state)
  - Positron and positronium naturally seek out the defects and void due to coulomb and dielectric interaction



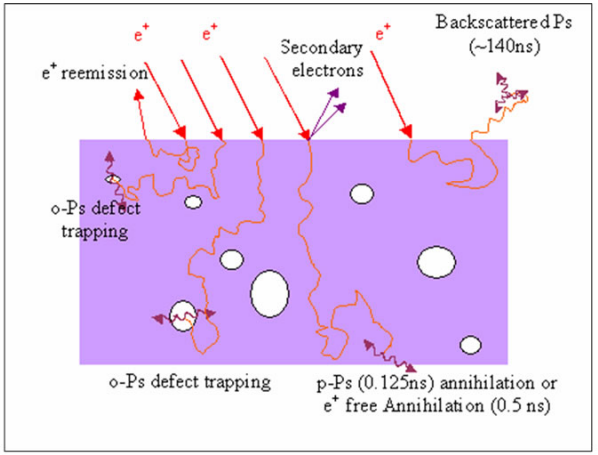
Beam line overview with the reactor



Beam profile



Electrostatic Focusing Lens

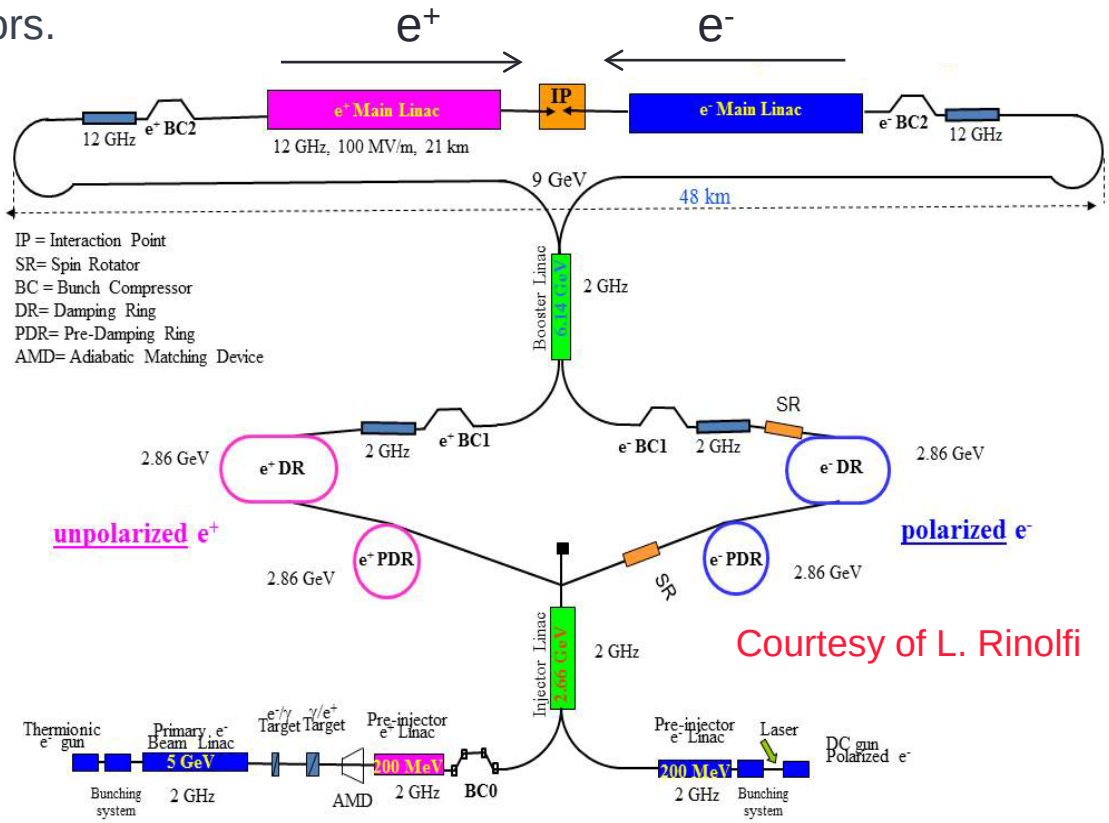


Positron and Positronium Interactions with Condensed Matter

Figure courtesy of NanoPos group, Dept. of Physics, Univ. of Michigan

Positron beam for the CLIC facility

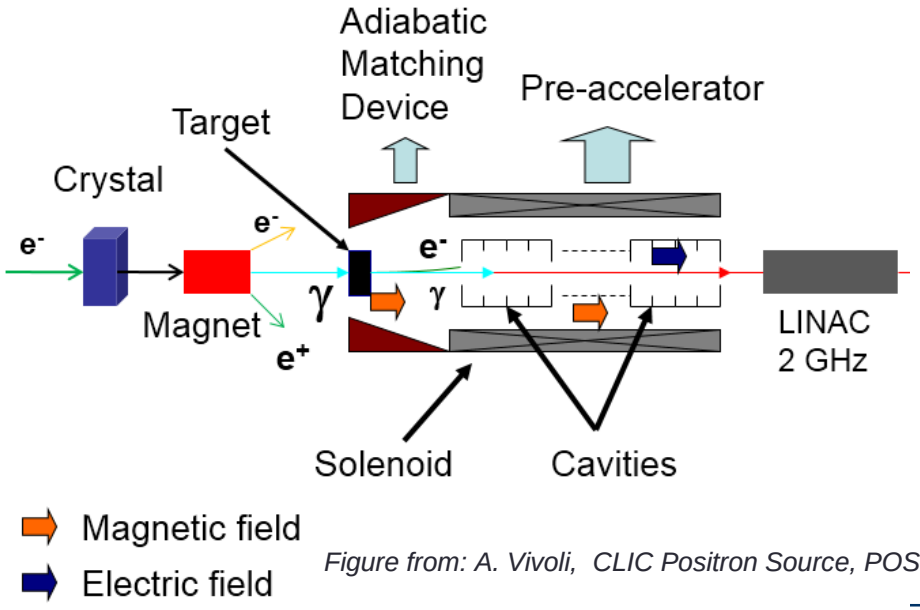
- CLIC (Compact LInear Collider) is a proposed future e^+e^- collider, designed to perform electron-positron collisions
  - e^+e^- colliders can be used to determine parameters with a much higher precision than proton colliders (LHC).
  - Allows physicists to explore a new energy region in the multi TeV range beyond the capabilities of today's particle accelerators.
  - Number of positrons/pulse (at IP) $\approx 11.5 \times 10^{11}$
  - Flux: $1.1 \times 10^{14} e^+/s$ (challenging!)



CLIC baseline scenario

A possible scheme to produce positrons for CLIC

- Scheme A, (up to date) Conventional way:
  - a 5 GeV primary e^- pulsed beam is first converted into γ in a tungsten crystal oriented on its <111> axis.
    - γ escape the target helped with the **channeling effect**
    - e^+e^-, also created in this section, are next swept away by a magnetic dipole
  - The γ are next converted into e^+e^- pairs in a thick amorphous tungsten target
  - An Adiabatic Matching Device (tapered axial magnetic field) focuses the e^+ beam
  - A pre-injector LINAC capture the e^+ bunches and accelerate them up to 200 MeV



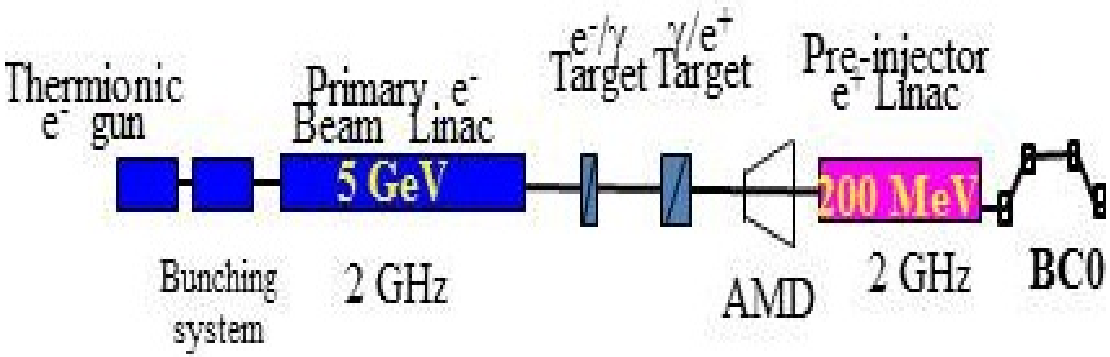
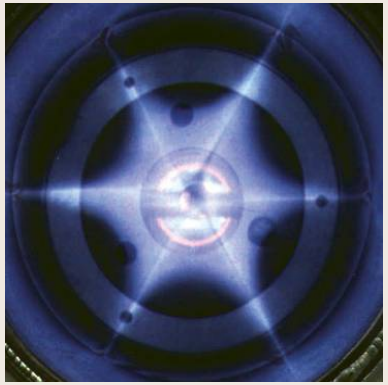


Figure from: A. Vivoli, CLIC Positron Source, POSIPOL 2009, LYON

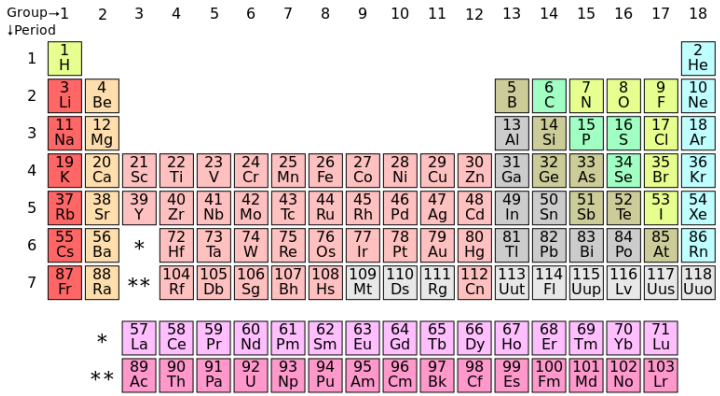


ION SOURCES

An introduction to ion sources

Introduction to ion sources (1/2)

- The need for ion beam covers the whole Periodic table
- The process to ionize a specific atom depends on the group (column) to which it belongs
  - The atom chemical properties are of great importance to decide how to ionize it



- There are several ways to ionize atoms in ion sources:
  - **With a low density plasma** under vacuum (very common)
    - Works great for any gas and also condensable like metals, provided the metal can evaporate at high temperature
  - **On a surface** (specific technique)
    - Works great with the first group: Alcaline
  - **Directly from solid** (specific technique)
    - Via sputtering (uncommon technique used for negative ion production, discussed later)

Introduction to ion sources (2/2)

- Another complication specific to ion beams comes from the fact that ions are very heavy with respect to electrons and that the acceleration process is proportional to Q/M ratio.
- To save money, you want to shorten your linear accelerator and accelerate the highest Q/M ratio to reduce the total length
- Multicharged ion sources have been developped for this purpose
  - They are much more complicated and expensive
  - But finally, they can save several M€ on an accelerator budget by shortening the acceleration section
- The lecture will review a large number of ion sources…
  It's impossible to go into detail !
- Prior to presenting an ion source, the lecture will start with some background physics

Electronic configuration of atoms

- Each atom has a specific electronic cloud configuration
- Each electron has a spin number $\boldsymbol{s}$ up (↑) or down (↓)
- The electrons are splitted into shells defined by quantum numbers:
- principle quantum number $\boldsymbol{n}$:
  - *K* ($n = 1$), *L* ($n = 2$), *M* ($n = 3$),…
  - Each shell can host $2n^2$ electrons, i.e. *K* shell 2 electrons, *L* shell 8 electrons, *M* shell 18 electrons, etc….
- Quantum orbital number $\boldsymbol{l}$:
  - $\boldsymbol{0 < l < n}$
  - Each shell is divided into orbital subshells l: *s*, *p*, *d*, *f* (l=0, 1, 2, 3)
  - Maximum number of electrons in the subshell: $2(2l + 1)$, i.e. *s*: 2, *p*: 6, *d*: 10, *f*: 14
- Third quantum number $\boldsymbol{m_l}$:
  - m_l is the projection of the orbital number l along the z-axis.
  - In each orbital subshell, $-l < m_l < l$
- So on each shell, individual electron is specified by its unique quantum numbers: $\boldsymbol{n, l, m, s}$

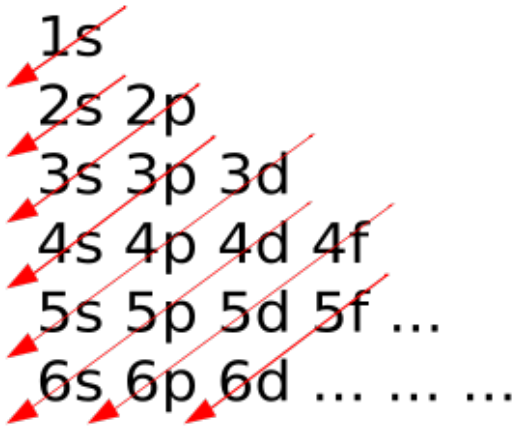
Kshell: $n = 1 \rightarrow l = 0 \rightarrow m = 0 \rightarrow s = \begin{cases} \uparrow \\ \downarrow \end{cases}$

Lshell: $n = 2 \rightarrow l = \begin{cases} 1 \rightarrow m = \begin{cases} -1 \rightarrow s = \begin{cases} \uparrow \\ \downarrow \end{cases} \\ 0 \rightarrow \ \ s = \begin{cases} \uparrow \\ \downarrow \end{cases} \\ 1 \rightarrow s = \begin{cases} \uparrow \\ \downarrow \end{cases} \end{cases} \\ 0 \rightarrow m = 0 \rightarrow s = \begin{cases} \uparrow \\ \downarrow \end{cases} \end{cases}$

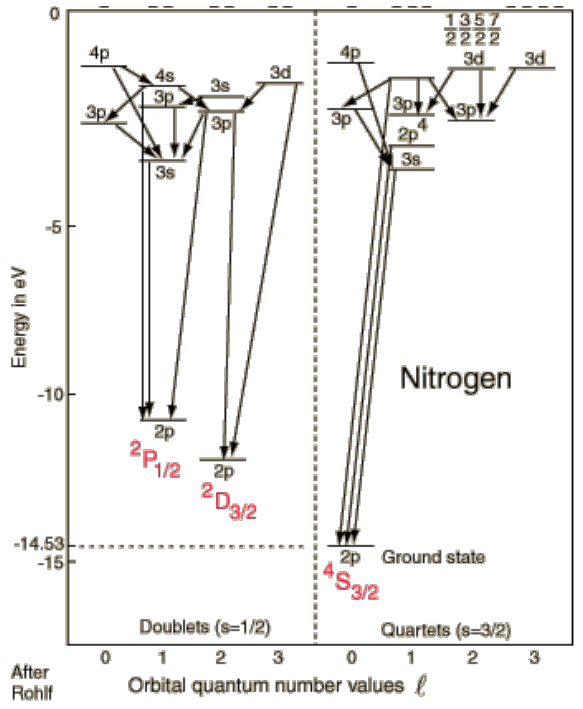
Material compiled from H. koivisto, JUAS12 lecture

Electronic configuration of atoms

- The shells/subshells are filled up following the Klechkovski (Madelung) rule:
  - With $n + l$ increasing
  - In case of equality, the first shell filled is the one with the lowest n
    - Nitrogen (Z=7): $1s^2 2s^2 2p^3$
    - Neon (Z=10): $1s^2 2s^2 2p^6$
    - Argon (Z=18): $1s^2 2s^2 2p^6 3s^2 3p^6$
  - Electrons are bound to the deepest layers with the maximum bound energy
- The rule is not absolute: exceptions exist
  - Ex.: Cr, Cu, Mo, Pd, Ag, La, Ce, Gd…



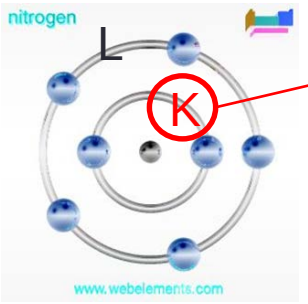
Klechkovski (Madelung) rule

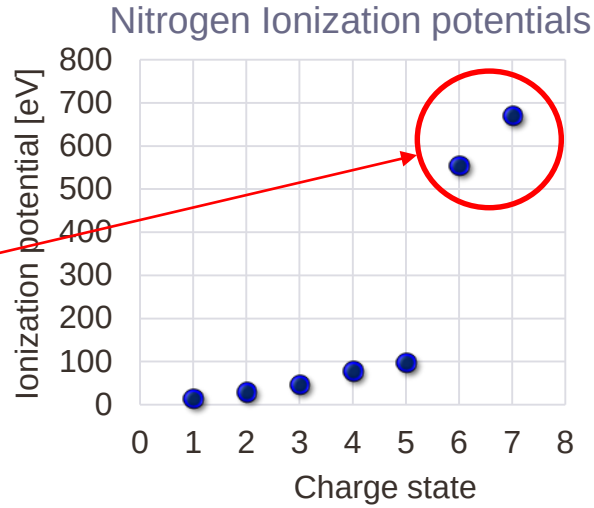


Material compiled from H. koivisto, JUAS12 lecture

Electrons binding energy in atoms

- Electrons are bound to the atom nucleus with and energy depending on the atom number Z, and the quantum numbers n, l, m
  - The deeper the electron shell (lower n), the higher the binding energy
  - For a given subshell, The higher the Z, the higher the binding energy
- The first ionization energy (or « ionization potential ») is the minimum energy that must be brought to the atom to expell a first electron
- The second ionization energy is the minimum energy required to remove a second electron from the highest occupied subshell
- Etc…





Ion charge state

	1+	2+	3+	4+	5+	6+	7+	8+	9+
H	13,6	-	-	-	-	-	-	-	-
He	24,6	54,4	-	-	-	-	-	-	-
N	14,5	29,8	47,7	77,9	98,4	554	670		
Ne	21,6	41,0	63,5	97,1	126	157	207	239	1195
Ar	15,8	27,6	40,7	59,8	75,0	91,0	124	144	422
Kr	14,0	24,4	36,9	52,5	64,7	78,5	111	126	231
Xe	12,1	21,2	32,1	44,6	57,0	68,4	96,4	109	205

Electron binding energy (eV) of some gas vs ion charge state

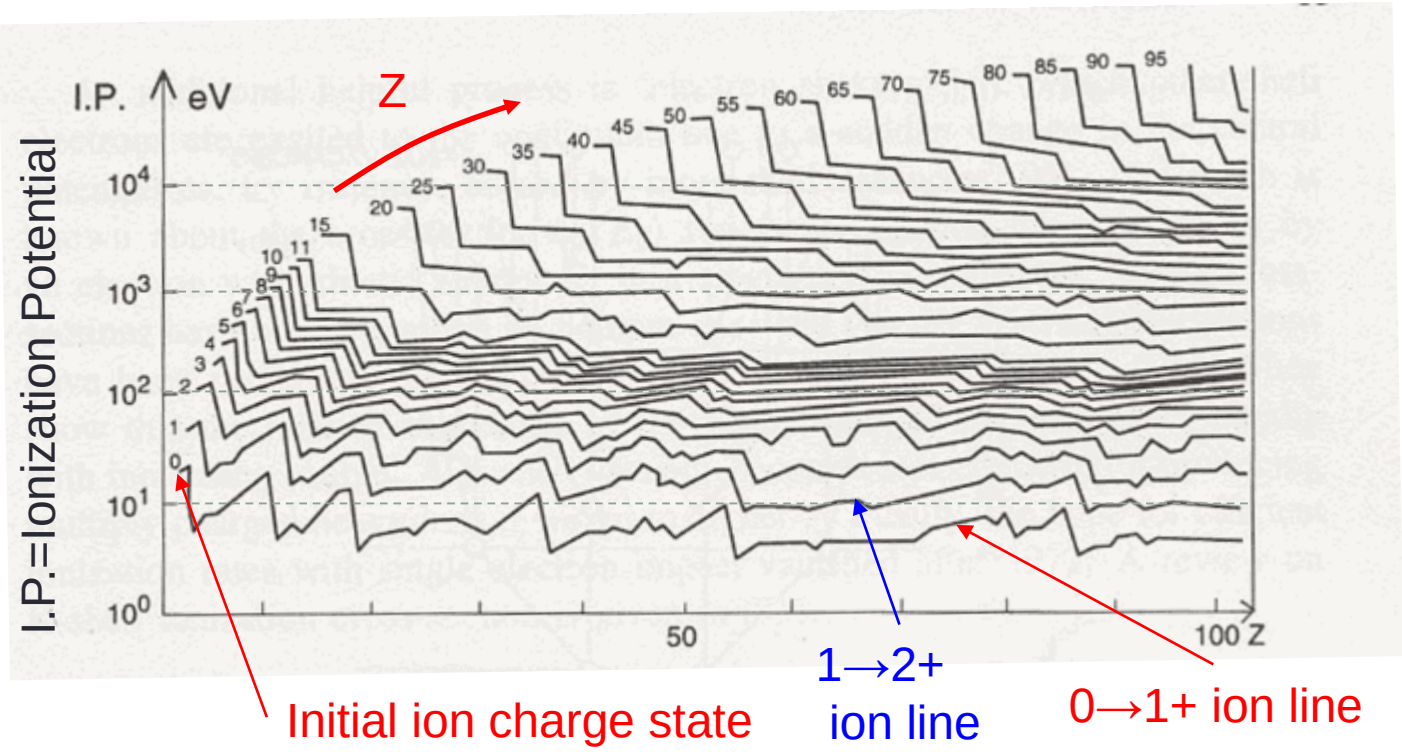
See T. Carlson, CALCULATED IONIZATION POTENTIALS FOR MULTIPLY CHARGED IONS , ATOMIC DATA, 2, 63-99 (1970)

Material compiled from H. koivisto, JUAS13 lecture

Electrons binding energy in atoms

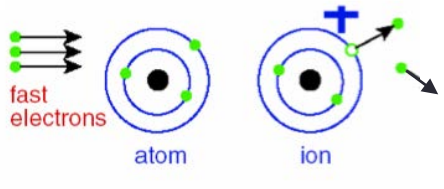
- This plot represents the $(n+1)^{th}$ ionization potential lines of ion with initial charge state n as a function of the atom number Z
- The deepest shell electron binding energy increases drastically with Z :

- $Z = 2 \rightarrow \sim 10^2\ eV$
- $Z = 8 \rightarrow \sim 10^3\ eV$
- $Z = 25 \rightarrow \sim 10^4\ eV$

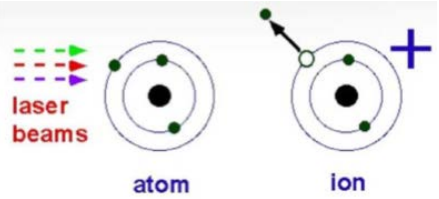


How to Ionize an atom

- **Electron Impact**: an energetic electron collide with an atom (ion) and expells one shell electron
  - $e^- + A^{n+} \overset{I_n}{\rightarrow} A^{(n+1)+} + 2e^-$
  - Threshold energy: the n[th] Ionization potential I_n
  - The electron impact is the most convenient method used in ion sources. It is developped later

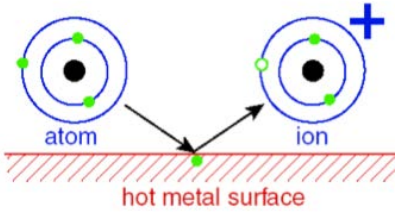


- **Photon ionization**: a photon with an energy close to the n[th] Ionization potential I_n gives its energy to the atom and frees one electron
  - $h\nu + A^{n+} \overset{I_n}{\rightarrow} A^{(n+1)+} + e^-$
  - The photon disappears
  - The photon ionization process is of interest for specific applications like ionizing atoms in a Radioactive Ion Beam facility.
    - In this case, a set of lasers are used to guide an electron from shell to shell until it is freed.



Figures from JUAS lectures: M. Kowalska

- **Surface Ionization:** an atom is directly ionized by a hot surface
  - $A + X \rightarrow A^+ + e^- + X$
  - Tunnel effect (quantum mechanics), discussed later in the lecture
  - Very efficient method to ionize Alcaline atoms



How to recombine an ion

- Very easily!
- Ions are surrounded by an electric field which attracts back electrons

- The main channels for an ion to lose a charge state are:

  - **Charge exchange**: an ion and an atom cross one each other, the ion electric field sucks up an electron from the atom

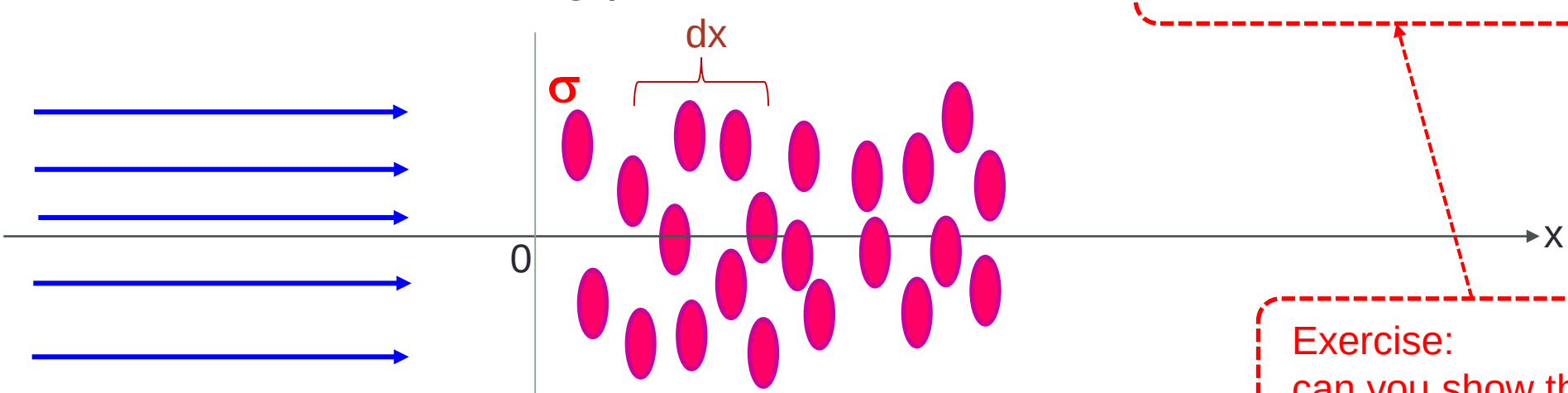
    

    - $A^{n+} + B^0 \rightarrow A^{(n-1)+} + B^{1+} + radiative\ processes$
      - Dominant process
    - $A^{n+} + B^{m+} \rightarrow A^{(n-1)+} + B^{(m+1)+} + radiative\ processes$
    - Any ion grazing a surface will suck up electron from it
    - Worst case: any ion **touching a surface** is immediately **neutralized**

  - **Radiative recombination:** a slow electron is re-captured by an ion
    - $e^- + A^{n+} \rightarrow A^{(n-1)+} + h\nu$
    - This term is usually neglected in ion source field, because electrons are too fast to recombine

Microscopic processes : particle collision (1/3)

- Cross-section: **σ** *(cm^2 or barn)*
  - The cross section **σ** is the effective area which governs the probability of a specific physical interaction between two particles.
  - 1 *barn* =10^{-24} cm^2
- Number of surviving particles to a collision: $N(x) = N(0)e^{-n\sigma x}$



N incoming particles A
Propagating along x
Uniformily distributed

Fixed Targets B with $x \in [0, +\infty[$:
- n uniform density (cm^{-3})
- **σ** Interaction Cross section A→B

Exercise:
can you show this?

Microscopic processes : particle collision (2/3)

- Mean Free Path: $\lambda = \frac{1}{\sigma n}$ *(cm or m)*
  - The MFP is the mean distance λ covered by a particle between two interactions with a target of the same type.
  - the MFP can also be considered as the mean distance to damp a population of particle by a factor e^{-1}through a collision process

$$N(x) = N(0)e^{-\frac{x}{\lambda}}$$

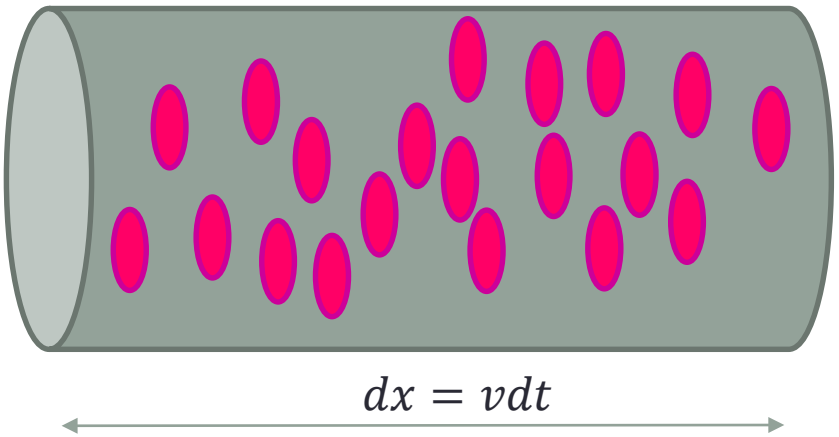
Exercise:
can you show this?

- Probability of collision after travelling a distance x:

$$\mathrm{x} \in [0, +\infty[: \quad P(x) = \frac{1}{\lambda}(1 - e^{-\frac{x}{\lambda}})$$

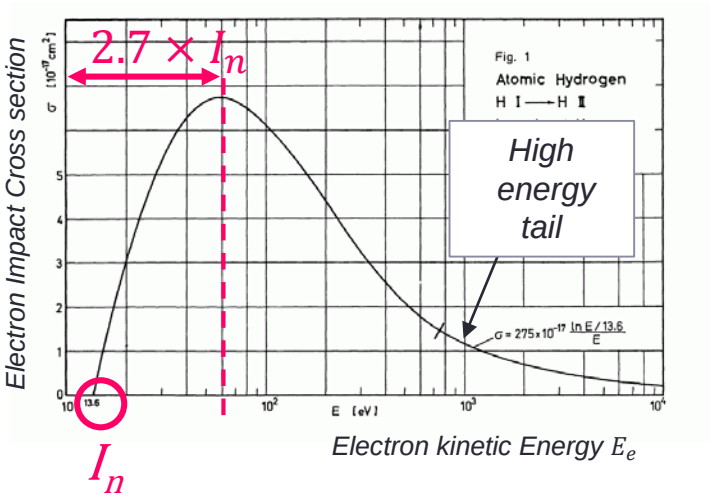
Microscopic processes : particle collision (3/3)

- Collision rate: $n\sigma v$ *(Hz or* s^{-1}*)*
  - The number of collision $N_{col.}$ between a single particle with a velocity v and a set of fixed targets with a density n during a time lapse dt is given by:
- $N_{col.}(t, t+dt) = n\sigma v dt = \frac{\boldsymbol{vdt}}{\boldsymbol{\lambda}}$
  - σ is the cross section associated to this particular collision
  - $\sigma v dt$ is the volume swept by the particle during a time *dt*
  - The collision rate is $\frac{N_{collision}}{dt} = n\sigma v = \frac{\boldsymbol{v}}{\boldsymbol{\lambda}}$ in Hertz (s^{-1})

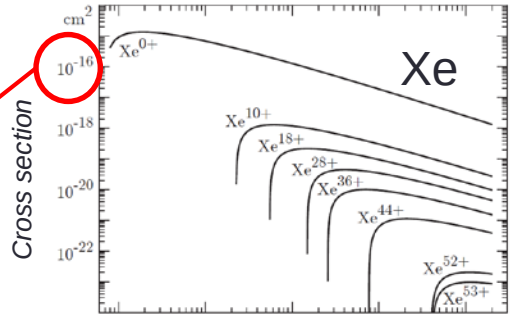


Electron Impact Ionization

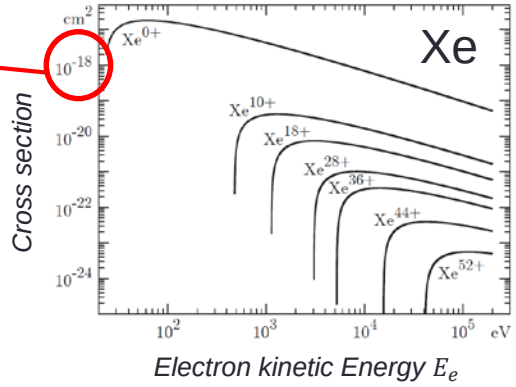
- Ions are produced through a direct collision between an atom and a free energetic electron
  - $e^- + A^{n+} \rightarrow A^{(n+1)+} + e^- + e^-$
    - single impact, most probable
  - $e^- + A^{n+} \rightarrow A^{(n+2)+} + 2e^- + e^-$
    - double impact, much less probable
  - etc…
  - Kinetic energy threshold E_e of the impinging electron is the binding energy I_n of the shell electron: $E_e > I_n$
  - Optimum of cross-section for $E_e \sim 2.7 \times I_n$
  - Higher energy electrons can contribute significantly



Electron impact *Single* ionization $\sigma \sim 10^{-16}\ cm^2$



Electron impact *Double* ionization $\sigma \sim 10^{-18}\ cm^2$



Xe plots from F. Wenanders, CAS2012

Electron Impact Ionization

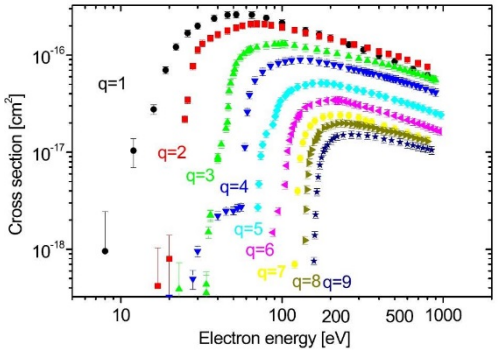
- Electron impact ionization cross section can be estimated by the semi-empirical Lotz Formula (valid for $E >> P_i$):

  - $\sigma_{q\to q+1} \sim 4.5 \times 10^{-14} \sum_{i=1}^{N} q_i \frac{\ln(\frac{E}{P_i})}{EP_i} \ (cm^2)$

Exercise: show that σ is max for $E = 2.7P_i$

  - E *incident electron kinetic energy*
  - Sum on the N atom/ion electrons subshells : (n,l fixed = 1 subshell #i)
  - q_i degeneracy: number of ways to put electrons included on the subshell i
  - P_i binding energy of electrons on the subshell i: $P_i = E_{n,l}$
  - Each electron on an ion contributes individually to the global cross section of ionization $\sigma_{q\to q+1}$
  - High charge state production requires hot electrons as P_i increases dramatically for deep subshells
  - The higher the charge state, the lower the cross section intensity

Shell name	Subshell name	Subshell max electrons	Shell max electrons
K	1s	2	**2**
L	2s	2	**2 + 6 = 8**
	2p	6	
M	3s	2	**2 + 6 + 10 = 18**
	3p	6	
	3d	10	
N	4s	2	**2 + 6 + + 10 + 14 = 32**
	4p	6	
	4d	10	
	4f	14	



Example for Bismuth

Z	I_n (eV)	$\sigma_{max}\ (cm^2)$
1+	7.2	~2.4×10^{-16}
22+	159	~4.9×10^{-19}
54+	939	~1.4×10^{-20}
72+	3999	~7.8×10^{-22}
82+	90526	~1.5×10^{-24}

Charge Exchange

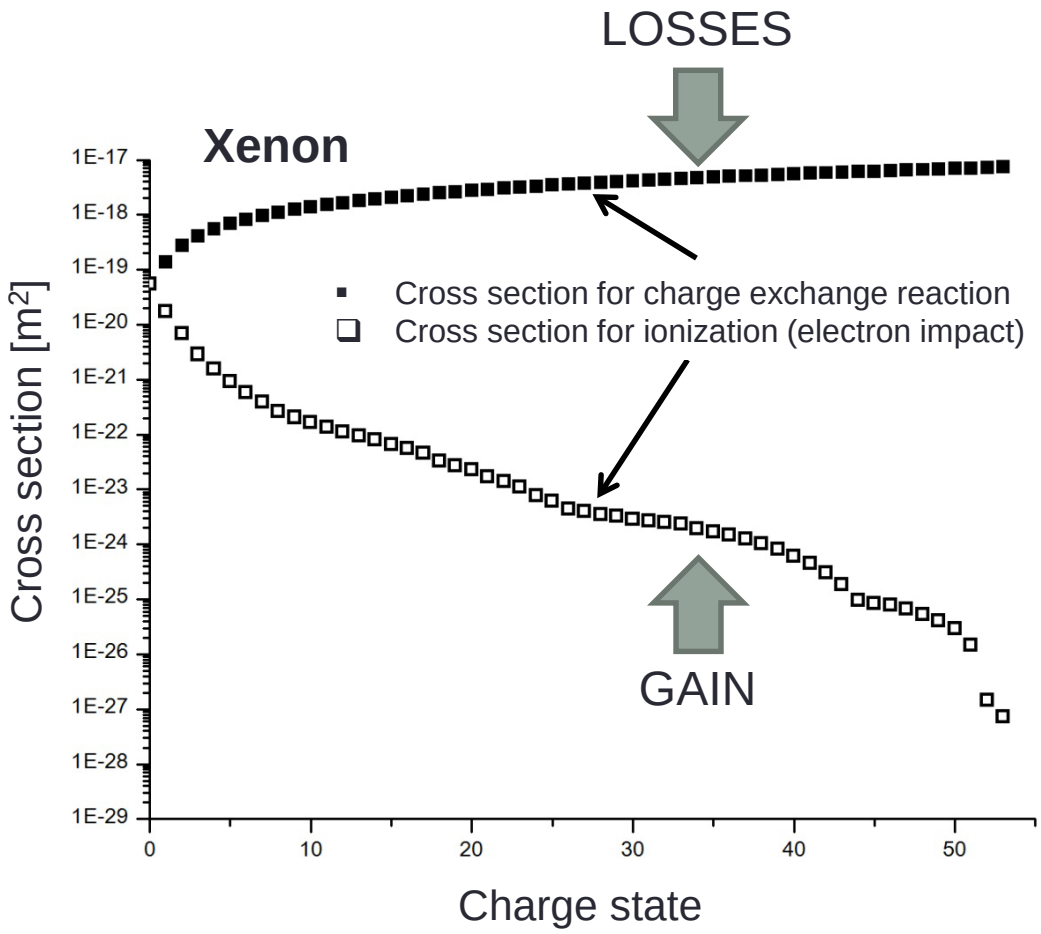
- The main process to reduce an ion charge state is through atom-ion collision
  - $A^{n+} + B^0 \rightarrow A^{(n-1)+} + B^{1+}$ (+radiative transitions)
    - Long distance interaction: the electric field of the ion sucks up an electron from the atom electron cloud
    - Any ion surface grazing signs the death warrant of a high charge Ion
  - semi-empirical formula :
    - $\sigma_{CE}(n \rightarrow n-1) \sim 1.43 \times 10^{-12} q^{1.17} {I_0}^{-2.76}\ (cm^2)$ (A. Müller, 1977)
    - I_0 1st ionization potential in eV, q ion charge state

Example :
Bismuth with O_2

Z	1+	22+	54+	72+	82+
σ_{CE} (cm2)	1.5×10^{-15}	5.6×10^{-14}	1.6×10^{-13}	2.2×10^{-13}	2.6×10^{-13}

Electron Impact vs Charge Exchange

- The charge exchange cross section is always above the electron impact one…
  - Loss > creation!
- How to reduce the net ion loss through charge exchange?
  - By reducing the pressure in the source to minimize the neutral atom population
  - By having a large population of fast electrons to produce more ionization!



A simple Charge state balance model

- The ion charge state distribution in an ECRIS can be reproduced with a 0 Dimension model including a set of balance equations:

creation

destruction

$$\frac{\partial n_i}{\partial t} = \sum_{j=j_{\min}}^{i-1} n_e n_j \left\langle \sigma^{EI}_{j\to i} v_e \right\rangle + n_0 n_{i+1} \left\langle \sigma^{CE}_{i+1\to i} v_{i+1} \right\rangle - n_0 n_i \left\langle \sigma^{CE}_{i\to i-1} v_i \right\rangle - \sum_{j=i+1}^{j_{\max}} n_e n_j \left\langle \sigma^{EI}_{i\to j} v_e \right\rangle - \frac{n_i}{\tau_i}$$

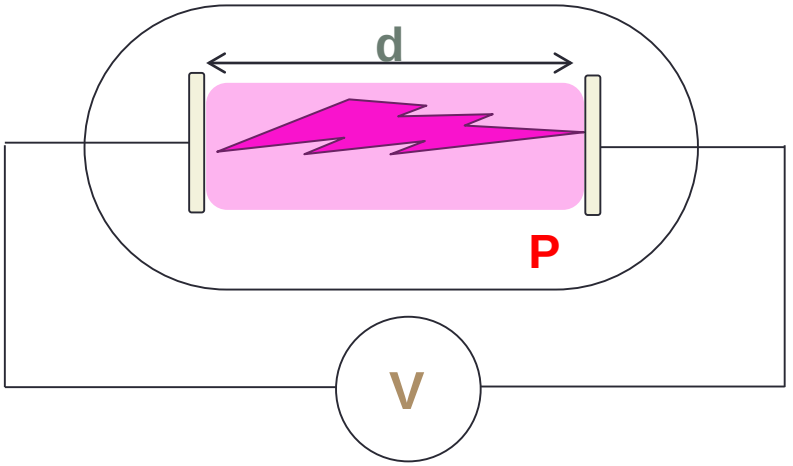
Losses (ion extraction, wall…)

- n_i : ion density with charge state i
- n_e, v_e : electron density, velocity
- σ , cross section of microscopic process
  - Electron impact or charge exchange here only
- $\langle \sigma v_e \rangle = \frac{\int \sigma v_e f(v_e) dv_e}{\int f(v_e) dv_e}$
- τ_i is the confinement time of ion in the source
- $-\frac{n_i}{\tau_i}$ represents the ion losses for species i (to the wall, or extracted current intensity)
- Free Parameters: $n_e, f(v_e), \tau_i$

- Model can be used to investigate ion source physics
- Model can be refined using second order effect: radiative recombination, dielectric recombination

The Paschen Law

- The Paschen Law describes the condition to initiate a (violent) breakdown in a gas tube (equipped with an anode and a cathode at each end) as a function of:
  - The pressure ***P*** (*P*=*nkT*, *n* gas density)
  - The voltage ***V*** between 2 electrodes
  - The distance ***d*** between 2 electrodes
  - α, β constants for one gas

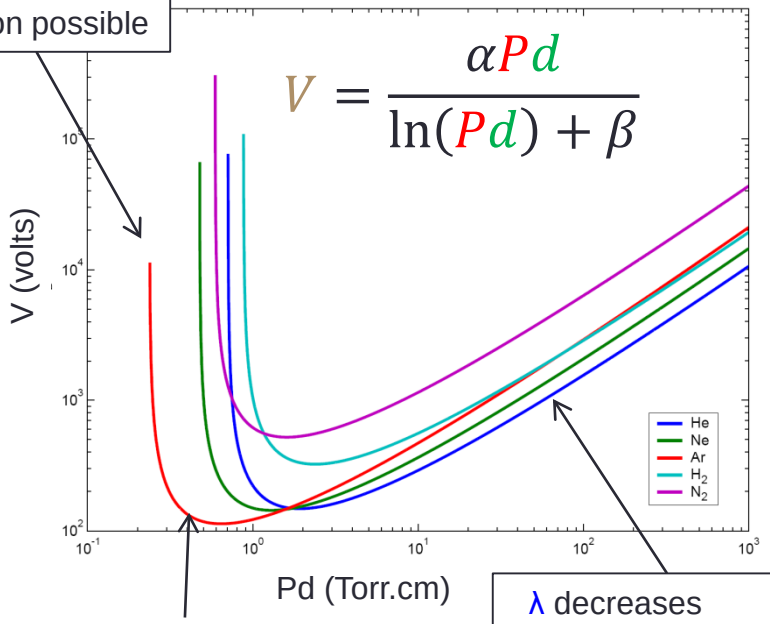


- Why is there a disruption?
  - A single free electron is accelerated by the electric field E=V/d
  - The distance between 2 collisions with gas molecule is the mean free path λ.
  - If the energy gained between 2 collisions is greater than the 1st ionization potential of the gas, a second electron is created via **electron impact** => avalanche=> breakdown of a plasma

- Asymptotic behaviour
  - The higher the pressure (density), the lower λ and the higher the necessary voltage V to make a disruption (more atoms to ionize on a shorter distance). The curve increases.
  - At low pressure, λ ~d and no more chain reaction is possible, the avalanche breakdown is no more possible.

λ ~d
⇒ No chain reaction possible

$$V = \frac{\alpha P d}{\ln(Pd) + \beta}$$



Paschen Minimum

λ decreases
⇒ V must increase
To keep disruption

Basics of plasma physics - generalities

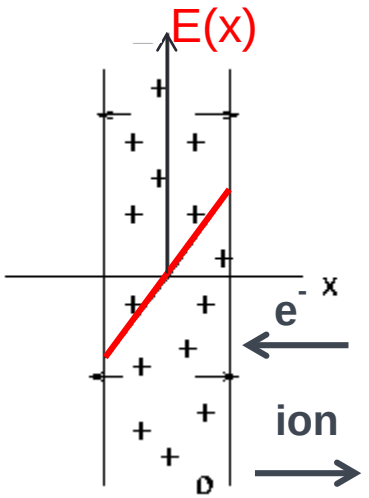
- Plasma is considered as the 4th state of matter
- It can be considered as a ionized gas, composed of ions and electrons and possibly of neutral atoms.
  - The degree of ionization of a plasma is $\alpha = \frac{n_i}{n_i+n}$, n is the density of neutral, and n_i is the ion density
- A plasma is always neutral taken as a whole
  - $n_i \times e + n_e \times (-e) = 0$ (n_i= ion density of single charge state, n_e= electron density)
- Plasma exists on a wide range of density, pressure and temperatures
  - a Hot (Thermal) Plasma is such that it approaches a state of local thermodynamic equilibrium where Ti=Te (Ti ion temperature, Te electron temperature).
  - a Cold Plasma is such that the move of ions can be neglected with respect to electrons, so Te>>Ti. A cold plasma is out of local thermodynamic equilibrium.
- Usual laboratory plasmas are created under vacuum and sustained by injecting electromagnetic power.

- Plasma applied to particle source are mainly **cold plasmas**, since their goal is to create low emittance beam, and the lower the ion temperature, the smaller the beam emittance

Basics of plasma physics – Quasi neutrality – Debye Length

- Any local difference between n_i and n_e gives rise to a huge electromagnetic force that tends to reduce it, to tend back to neutrality. One talks about collective behaviour of a plasma.
  - If $n_i \neq n_e$, then a local space charge appears: $\rho = e(n_i - n_e)$
  - A local electric field appears: $div(\vec{E}) = \frac{\rho}{\varepsilon_0}$
  - Let's consider a one dimension slab of plasma with a n_i excess
  - $\frac{dE}{dx} = \frac{\rho}{\varepsilon_0}$ => $\mathrm{E(x)} = \frac{\rho}{\varepsilon_0}\mathrm{x}$
  - The resulting force $\boldsymbol{F_x(x) = (\pm e)\frac{\rho}{\varepsilon_0}x}$ expells ions and attracts nearby electrons, tending eventually to reduce the space charge

$$\rho = e(n_i - n_e) \rightarrow 0$$



- So plasma are also **locally neutral**
- The smallest dimension scale at which the plasma is quasi−neutral is called the Debye Length
  - $\lambda_D \sim \sqrt{\frac{\epsilon_0 k T_e}{n e^2}}$, k is the Boltzmann constant, n plasma density (cold plasma)

Basics of plasma physics – electron and ion mobility

- The mean velocity of a particle in a plasma at temperature T is expressed as:

$$\frac{1}{2}\mathrm{m}v^2 = \frac{3}{2}kT$$

- For a plasma with $T_i=T_e=T$, the electrons are moving faster than ions:

$$\frac{v_i}{v_e} = \sqrt{\frac{m_e}{m_i}} \ll 1$$

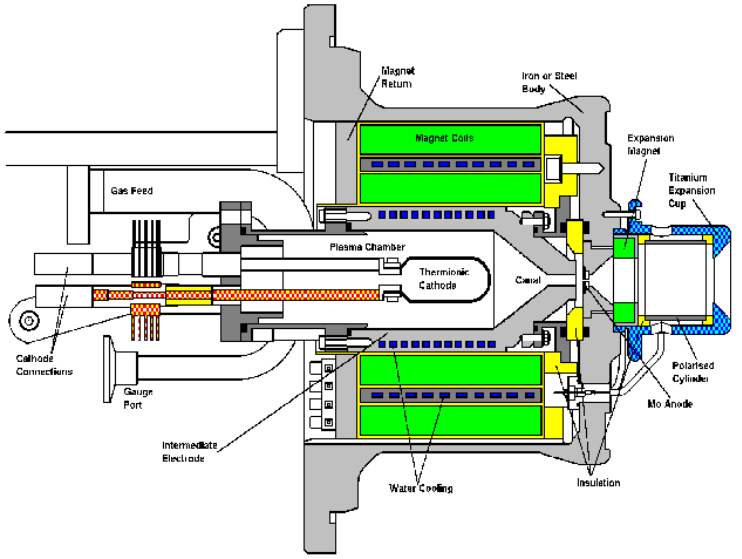
- Electrons are also more sensitive than ions to any electric field E:

$$F_x = m\frac{dv}{dx} = qE \Rightarrow \left|\frac{dv_i}{dv_e}\right| = \frac{m_e}{m_i} \ll 1$$

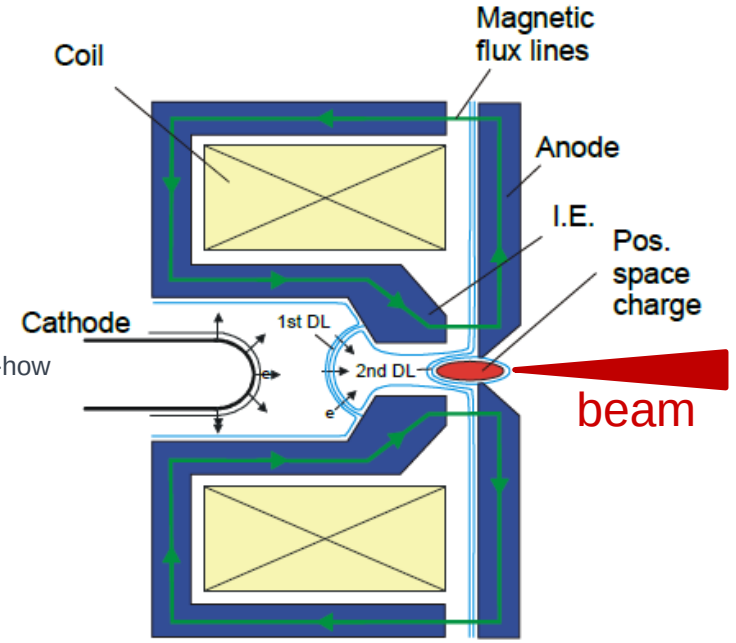
- In a cold plasma with $T_e>>T_i$, it is often assumed that the motion of ions is negligible with respect to the one of electrons.
  - Simplification of theory and calculations
  - Case of Many Ion Sources

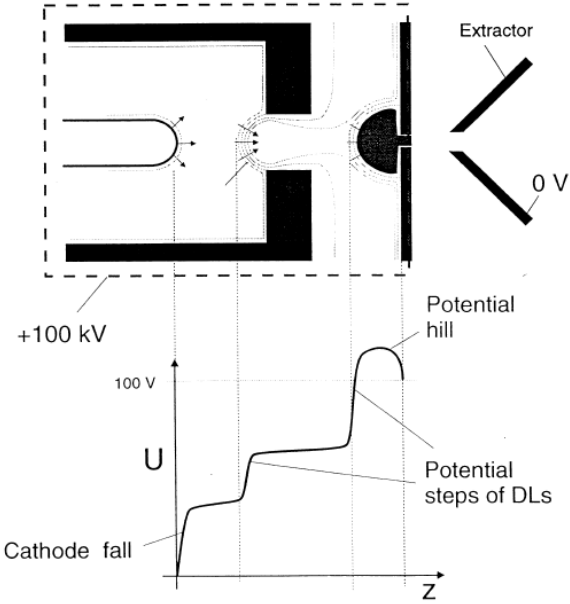
The Duo-plasmatron Ion source

- The duo-plasmatron is a 1+ ion source able to produce beam from any gas
- A gas is injected at ~0.1-1 mbar in the plasma chamber
- A hot cathode is emitting thermionic electrons which are accelerated two times toward the anode located right at the extraction of the source
- The second place of electron acceleration coincides with a **magnetic compression** induced by the solenoid iron yoke
- In this area, the pressure is optimum to breakdown a 1+ ion plasma which drifts naturally toward the extraction hole



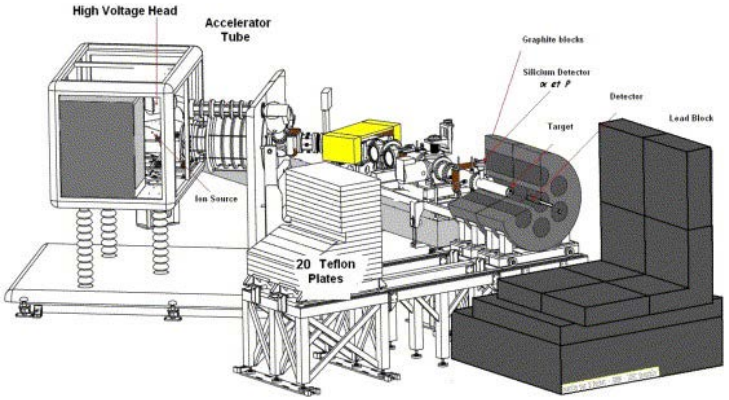
- The Duoplasmatron produces up to 300 mA of H+ beam in pulsed mode (1 Hz - 20-100 µs) at CERN
- Gas Ionization Efficiency <1%
- PRO:
  - Very High current, short pulses
  - Small source
- CONS:
  - Fast Cathode aging by ion sputtering in CW
  - Delicate Cathode formation, requires a specific know-how



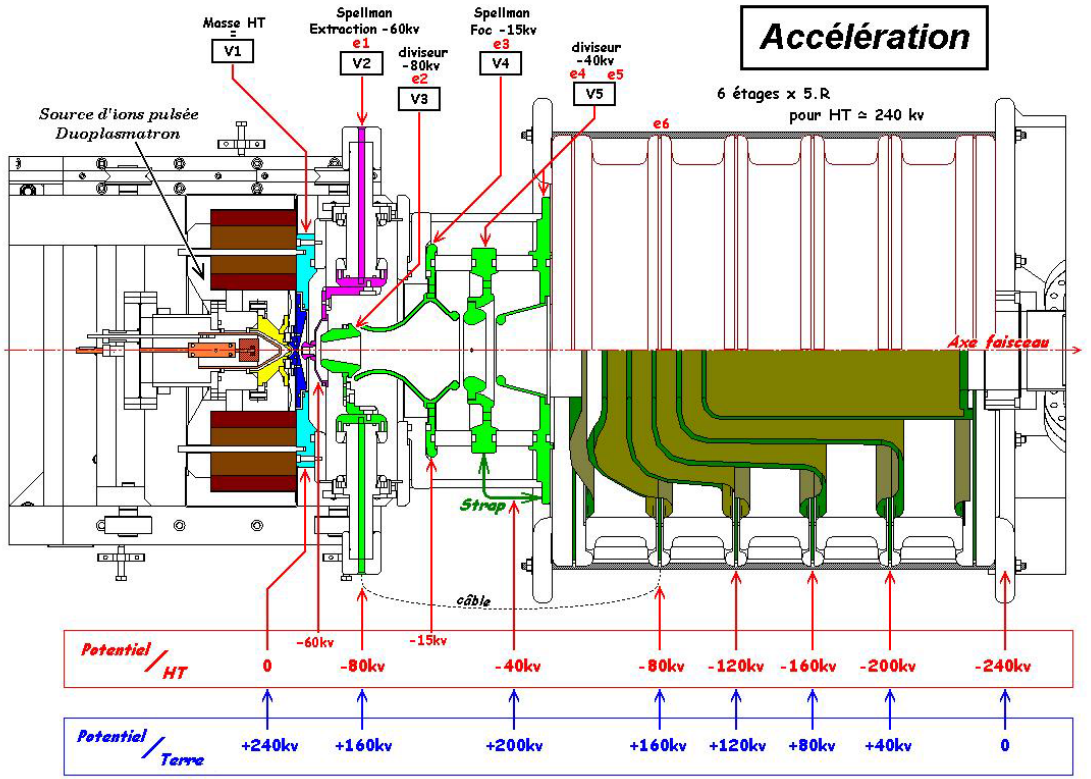


Extracted from, P. Sortais, JUAS 2006

GENEPI Duoplasmatron (LPSC)

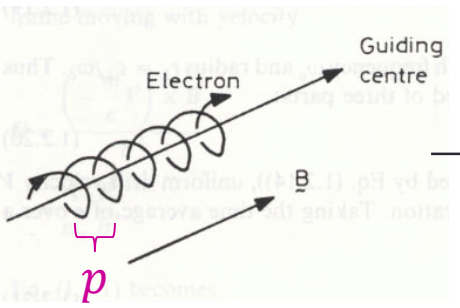


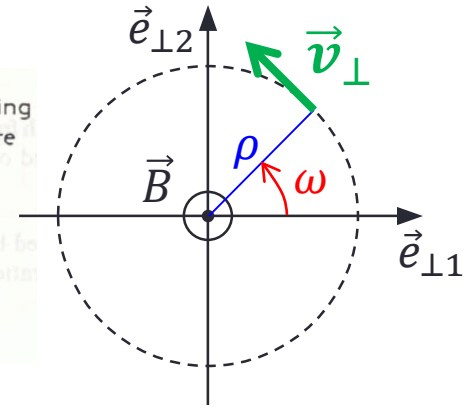
- High intensity pulsed ion beams are produced with a very low space charge compensation in the accelerator
- A short pre-acceleration is mandatory to prevent the beam to blow up before reaching the area of experiment or the next accelerator stage
- Example of the GENEPI accelerator where the source is set on high voltage platform at 180 kV, I~30 mA
- The ion source is set at +60 kV with respect to the platform
- Electrostatic lenses focused and accelerate the beam toward the acceleration tube



Motion of a charged particle in a constant magnetic field

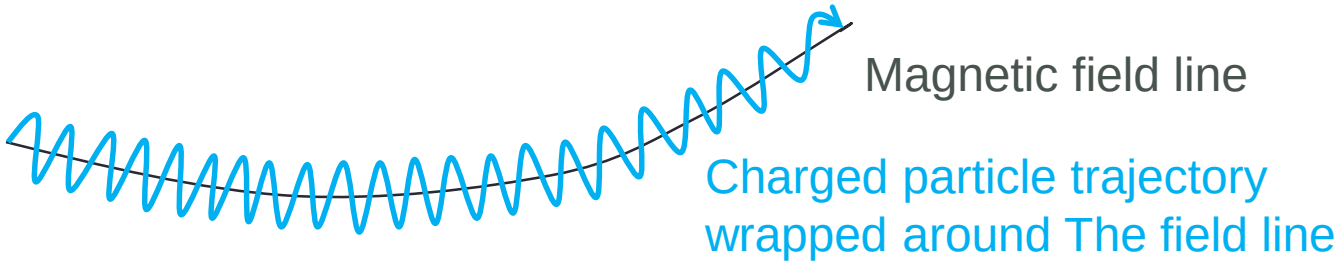
- The Individual motion of a charged particle in a magnetic field is ruled by:
- $m\frac{d\vec{v}}{dt} = q\vec{v} \times \vec{B}$
- Velocity is decomposed as $\vec{v} = \vec{v}_{\parallel} + \vec{v}_{\perp}$ with $\vec{v}_{\perp} . \vec{B} = 0$ and $\vec{v}_{\parallel} \parallel \vec{B}$
  - We define the space vectors $\vec{e}_{\parallel} = \frac{\vec{B}}{B}$, $\vec{e}_{\perp 1} = \frac{\vec{v}_{\perp}}{v_{\perp}}$ and $\vec{e}_{\perp 2} = \vec{e}_{\parallel} \times \vec{e}_{\perp 1}$
- General solution for the velocity is:
- $$\begin{cases} v_{\parallel} = const \\ \vec{v}_{\perp} = \rho\omega(\sin \omega t . \vec{e}_{\perp 1} + \cos \omega t . \vec{e}_{\perp 2}) \end{cases}$$
- $\omega = \frac{qB}{m}$ is the cyclotronic frequency
- ρ is the Larmor radius (constant)
- The particle trajectory is an helix with radius ρ and pitch $p = \frac{2\pi v_{\parallel}}{\omega}$



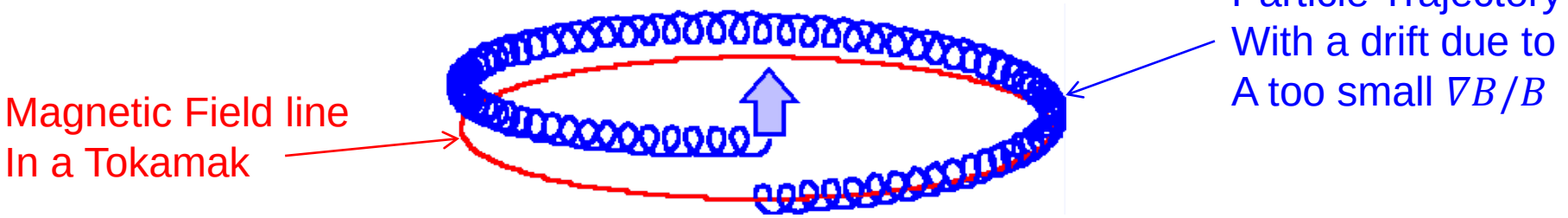


Motion of a particle in a non-uniform magnetic field

- If the spacial variation of B is much larger than the larmor radius ($\frac{1}{\left|\frac{\vec{\nabla}\vec{B}}{\vec{B}}\right|} \gg \rho$), then the particle follows the curved field line:



- If $\frac{1}{\left|\frac{\vec{\nabla}\vec{B}}{\vec{B}}\right|} \sim \rho$, then a slow drift of the particle with respect to the actual field line occurs

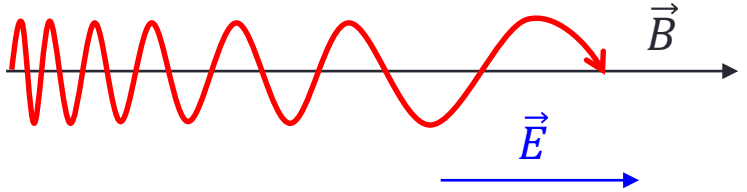


http://www-fusion-magnetique.cea.fr

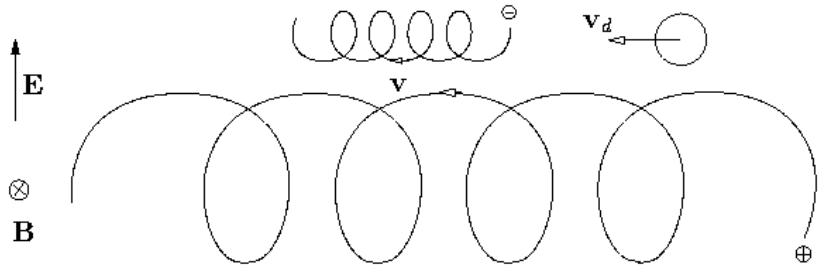
Motion of particles in a $\vec{E} + \vec{B}$ Field

$$m\frac{d\vec{v}}{dt} = q\vec{E} + q\vec{v} \times \vec{B}$$

- Motion of a charged particle with $\vec{E}||\vec{B}$
  - $v_{||}$ increases linearly with time
  - Helical trajectory with an increasing thread pitch

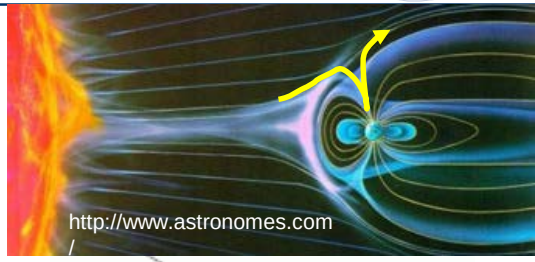


- Motion of a charged particle with $\vec{E} \perp \vec{B}$
  - Cycloidal trajectory
  - No Mean acceleration due to E !
  - Drift velocity : $\overrightarrow{v_D} = \frac{\vec{E}\times\vec{B}}{B^2}$



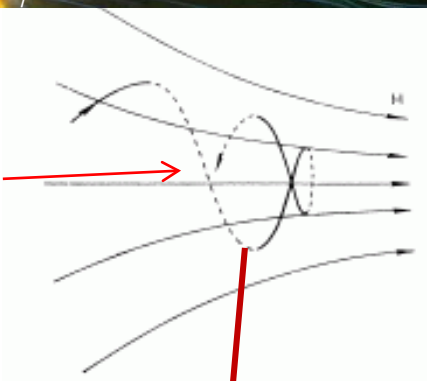
The Magnetic Mirror Effect

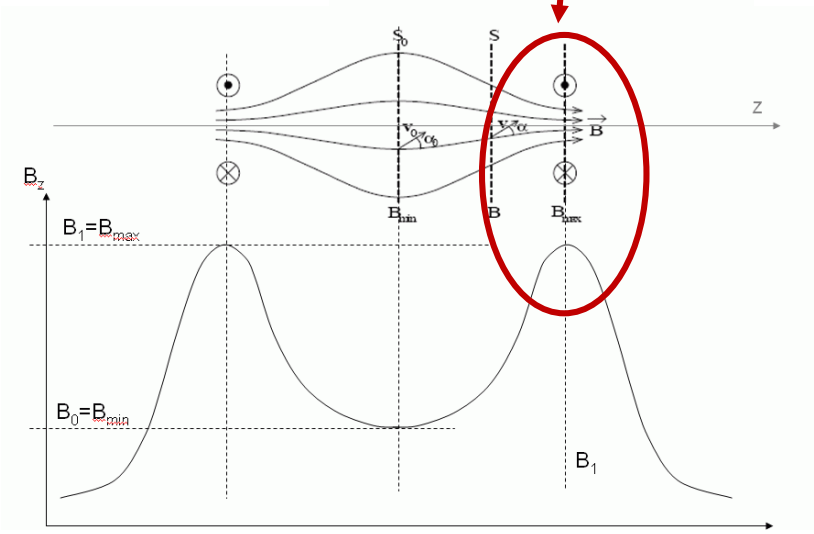
Solar wind reflection by the Earth magnetosphere



- When a charged particle propagates toward a higher magnetic field region, it may be reflected back
  - $T_{kin} = W_{\parallel} + W_{\perp} = \frac{1}{2}m{v_{\parallel}}^2 + \frac{1}{2}m{v_{\perp}}^2 = const$
  - $\mu = \frac{m{v_{\perp}}^2}{2B} = \frac{W_{\perp}}{B} \sim const$ (magnetic moment)
- $T_{kin}(z) = \frac{1}{2}m{v_{\parallel}}^2(z) + \mu B(z) = const$
  - When B increases, then the velocity is adiabatically transferred from $v_{\parallel}$ to $v_{\perp}$
- The particle is stopped at $z = z_1$ where $(v_{\parallel} = 0)$ and $B(z_1) = \frac{T_{kin}}{\mu}$
  - $T_{kin}(z_1) = \frac{1}{2}m{v_{\perp}}^2$
  - The particule is forced to go backward

A particle can be reflected By a high magnetic field intensity





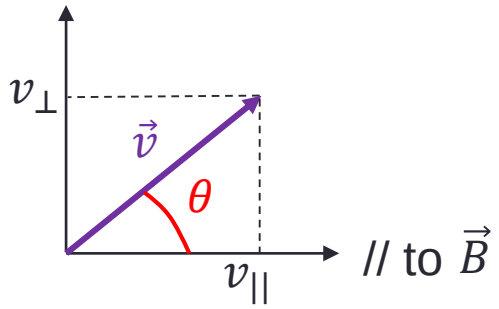
Axial magnetic mirror done with a set of 2 coils

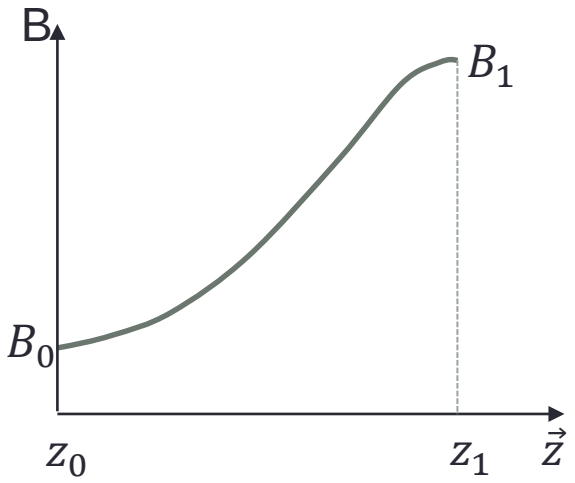
The velocity pitch angle θ

- $\vec{v} = \vec{v}_{\perp} + \vec{v}_{||}$, with $\vec{v}_{||}$ // to $\vec{B}$
  - $v_{\perp} = v \sin\theta$
  - $v_{||} = v \cos\theta$
- Can you show that a particle at z_0 with a pitch angle θ is reflected at z_1 provided

- $\sin\theta \geq \sqrt{\frac{B_0}{B_1}}$?

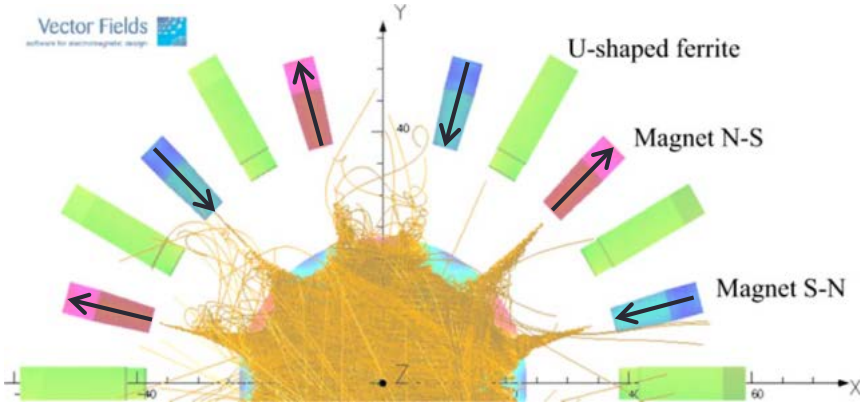
- The mirror ratio is usually defined as:
- $R = \frac{B_1}{B_0}$



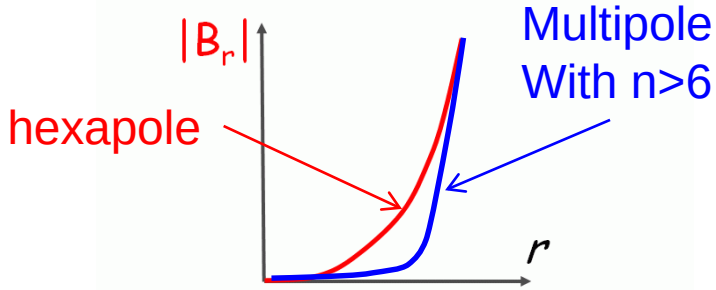


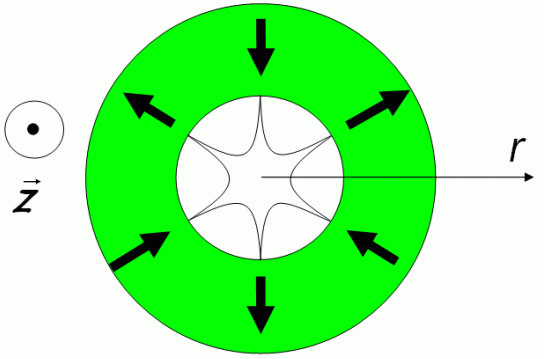
Radial magnetic mirror

- An axial magnetic mirror is done with a set of solenoids
  - See former slide
- A radial confinement can be achieved with a so-called « multipole structure »
  - A set of radial magnets are placed along a circular path with an alternated direction of magnetization
  - The magnetic intensity in the center is zero
  - The magnetic intensity increases with the radius and is maximum near to the magnets
  - The lower the multipole order, the higher the magnetic field at an intermediate radius



Trajectories of e^- in a CUSP magnetic structure (CERN), Rev. Sci. Instrum. 81, 02A723 (2010))





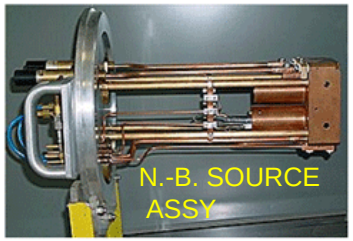
Radial Mirror

(Permanent magnet hexapole)

The Indirectly Heated Cathode (IHC) Ion Source

- An upgraded Niel-Bernas filament Ion Source
- Used in industrial implanters to produce intense 1+ ion beams up to ~**40 mA**
- The ion source contains two cathodes:
  - A first classical thermionic cathode
  - A second massive **indirectly heated thermionic cathode** which protects the first one from the intense ion sputtering from the plasma
  - Filament lifetime 200-800h, depending on condition of operation
  - The anode is the source body itself
  - A uniform magnetic field $\vec{B}$ forces the electrons to spiral along the ion source length
  - An electron repeller located at the other end is added to produce an electrostatic electron confinement
    - Secondary electrons created by an electron impact in the plasma are created at a potential lower than the repeller one
      => electrons reflected back to the plasma
  - Extraction through a slit (1mm x20~40 mm)
  - Pressure in the source ~10^{-3}-10^{-5} mbar
  - Ionization efficiency ~1%

Niels-Bernas (not IHC!)

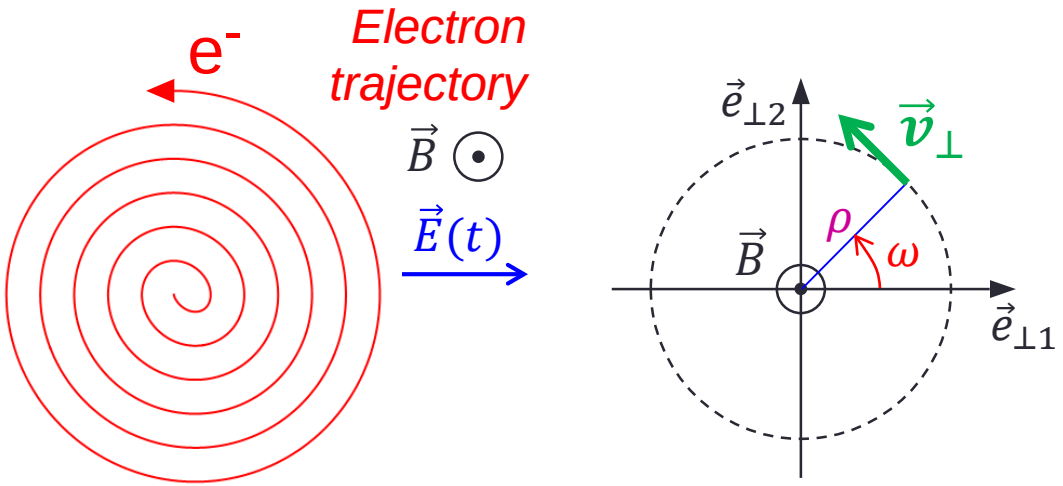


(introduction to) the Electron Cyclotron Resonance (ECR)

- When a particle is located in a magnetic field $\vec{B}$ and a transverse time varying electric field $\vec{E}(t)$, a resonant transfer of energy from the electric field to the particle can occur, provided the particule cyclotronic frequency equals the electric field frequency

  - $\vec{B} = B\vec{z}$
  - $\omega = \frac{qB}{m}$ cyclotronic frequency
  - $\vec{E}(t) = E\cos(\omega_{HF}t)\,\vec{x}$
  - ECR resonance condition:

$$\omega_{HF} = \omega = \frac{eB}{m}$$

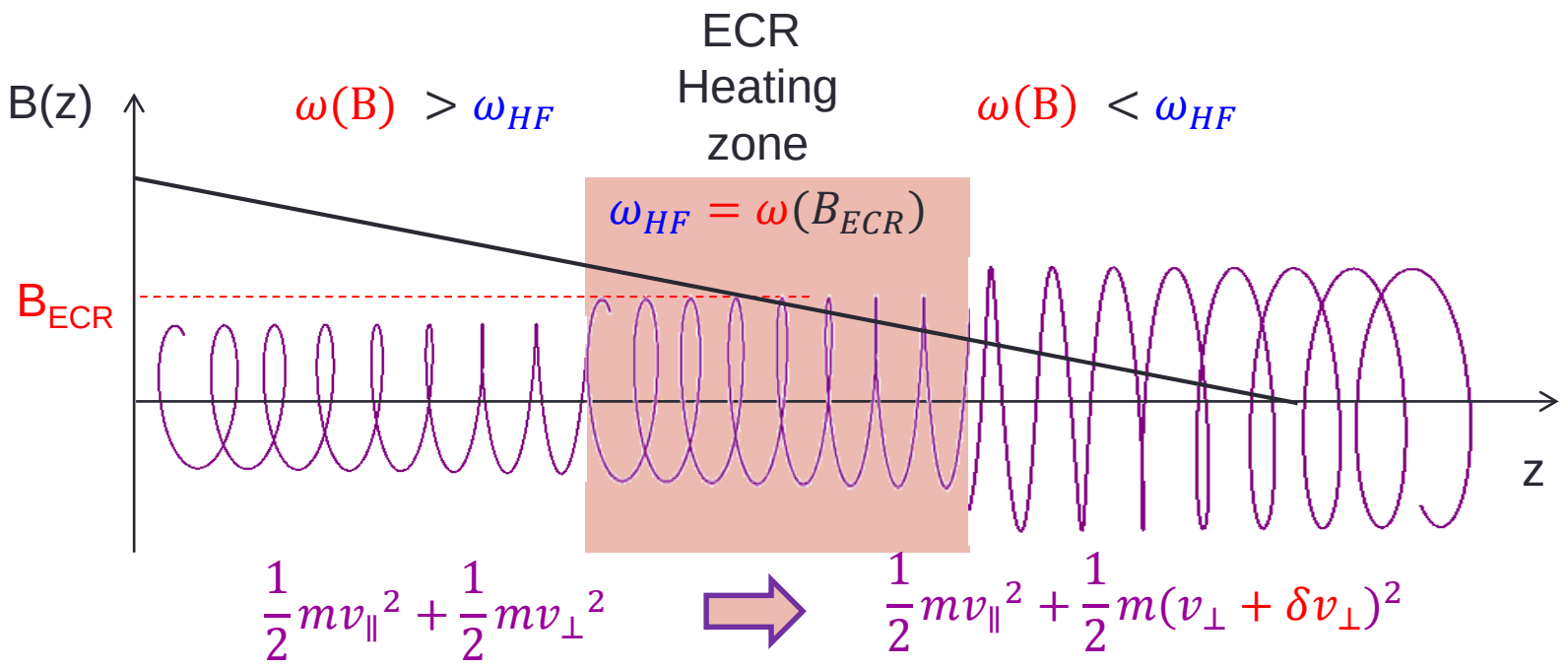


- Since the electric field turns at the same velocity as the particle (an electron here), the particule sees a constant electric field in its own framework => **constant acceleration**
- The particle describes a spiral and gains transverse energy:
  - $\vec{v} = \vec{v}_{\parallel} + \vec{v}_{\perp}$
  - $\vec{v}_{\parallel} = const$ and $\vec{v}_{\perp} = \rho(t)\omega$ with $\rho(t) \uparrow$
- That's a very convenient way to accelerate electrons!

PS: the ECR heating mechanism is More complicated than Presented.

ECR Heating in a Magnetic Gradient

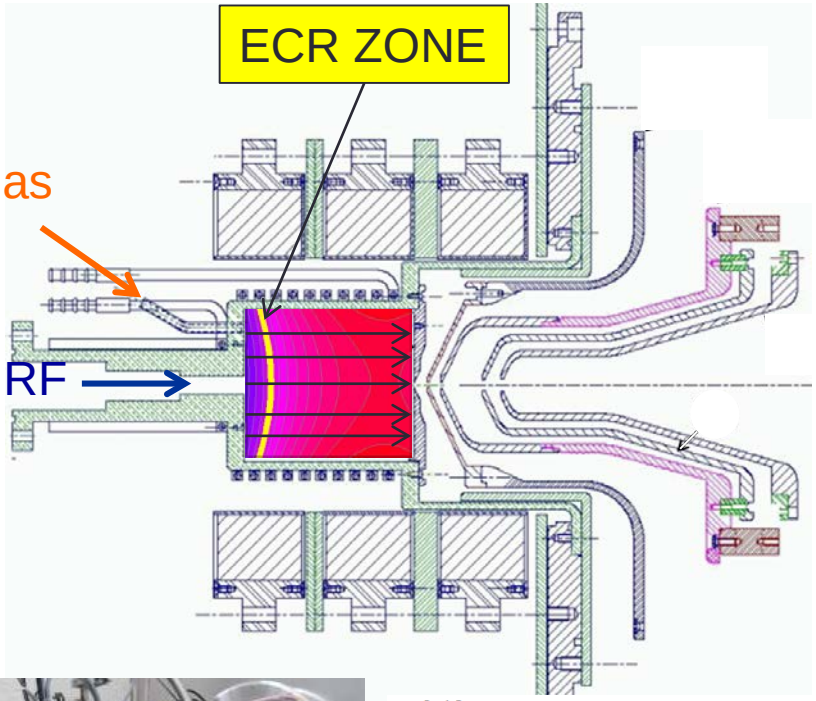
- In ECR Ion Sources, the ECR zone is usually reduced to a surface, inside a volume, where B is such that $\omega_{HF} = \omega = \frac{eB}{m}$
  - When electrons pass through the ECR surface they are slightly accelerated (in mean) and may gain a few eV of kinetic energy
  - The parallel velocity $v_{\parallel}$ is unchanged, while $v_{\perp}$ increases
  - The ECR zone thickness is correlated to the local magnetic field slope

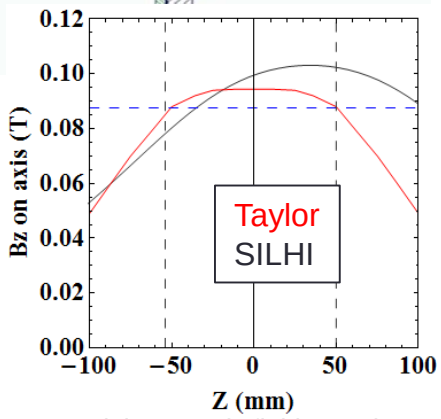


1+ Electron Cyclotron Resonance Ion Source

Known as « microwave source »

- SILHI source with permanent magnets (CEA/IRFU)
  - Suitable for any gas
  - RF frequency: 2.45 GHz ($\lambda \sim 12\ cm$)
- The plasma chamber is filled with a flat axial magnetic field generated by permanent magnets
- A single ECR surface is located in the chamber
    - ECR located at the maximum of RF electric field, near to the RF input.
    - A second resonance is located out of the chamber in the extraction system (when the magnetic field decreases)
  - The plasma electrons are heated when passing through the ECR zone to ~10-20 eV which allows creating 1+ ions
  - Secondary electron emission from the chamber wall helps keeping the ion production balance to equilibrium
  - The source can produce ~100 mA of H+
    - 80% of proton fraction H^+, 20% of H_2^+ and H_3^+
  - High voltage extraction : 40-100 kV
- Main advantage of ECR Ion source: NO FILAMENT!
  - The source can stay for long term operation without any maintenance



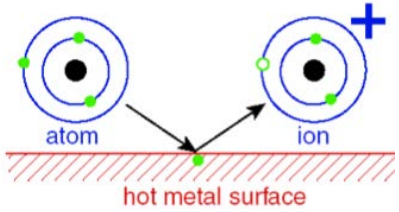


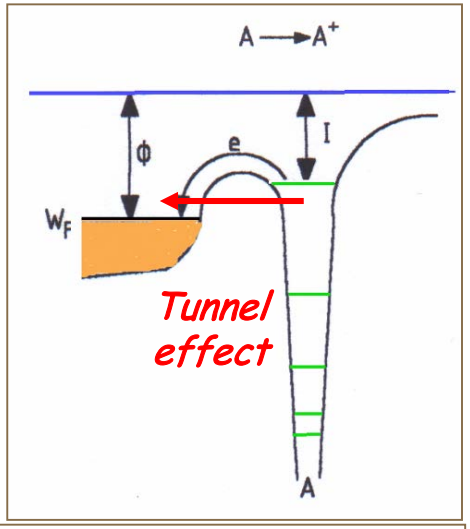
Axial magnetic field on axis

Ionization of atoms on surfaces

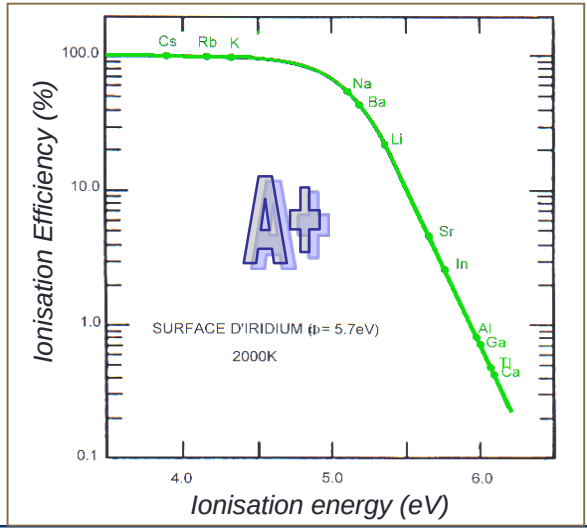
- A metal with a High Work Function can steal an electron to an adsorbed atom through Tunnel Effect
  - The ion production efficiency is given

    by the **SAHA relation**: $\frac{N^+}{N_0} = C^+ e^{-\frac{\varphi - I}{kT}}$, provided $\varphi > I$
    - I First Ionisation Potential of adsorbed atom
    - φ metal work function
    - T metal temperature



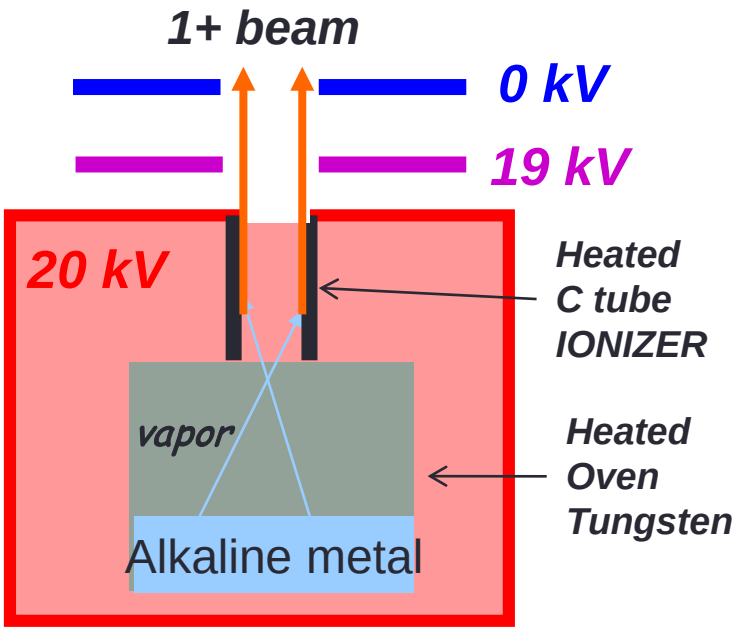


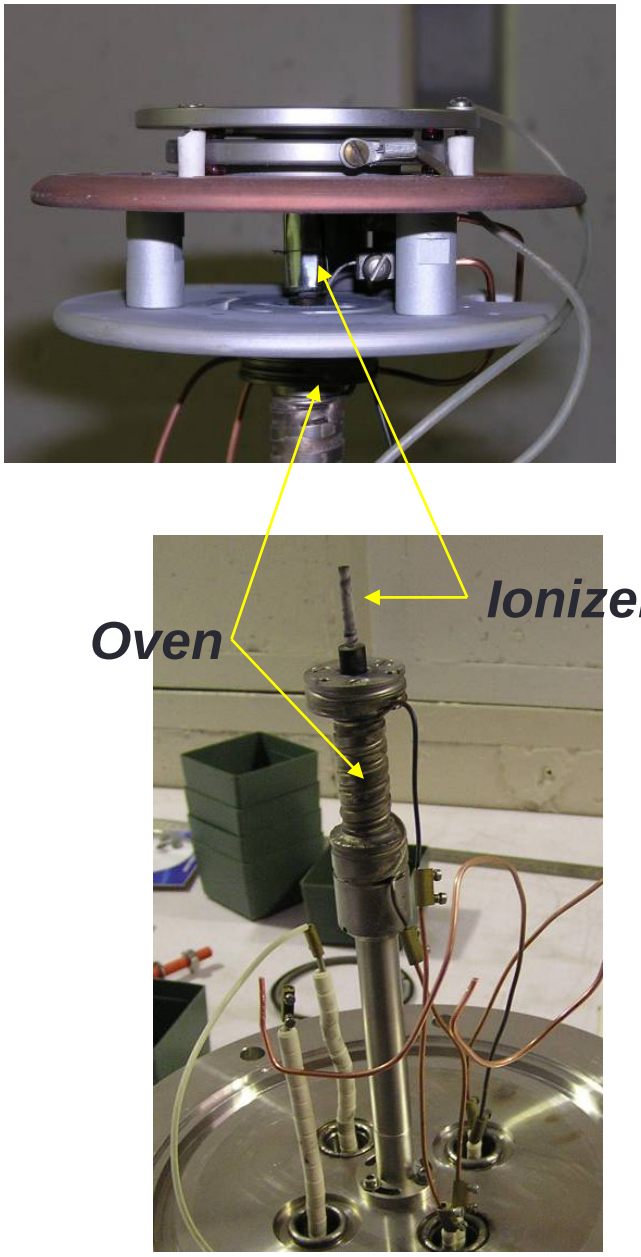
Works with High φ metals and low *I* atoms
  - Metals used : W-Ox, Ir, Pt, C, Re , W
  - Atoms ionized : Alkalines, Alkaline earths
- High Temperature helps to desorb atoms
- Very efficient method, very selective technique



1+ Surface Ionization Source

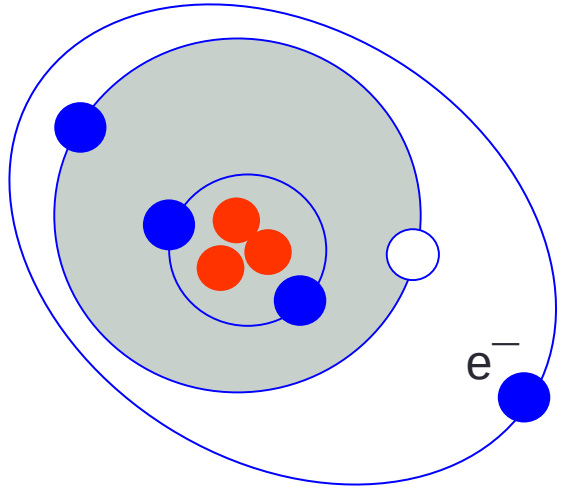
- An alkaline metal (or alkaline earth) is heated in an oven
- Atoms evaporate toward a heated ionizer tube made up with a high work function metal
- Atoms are adsorbed on the wall
- Atom desorbs at high Temperature with one e^- stolen by the metal => ionization



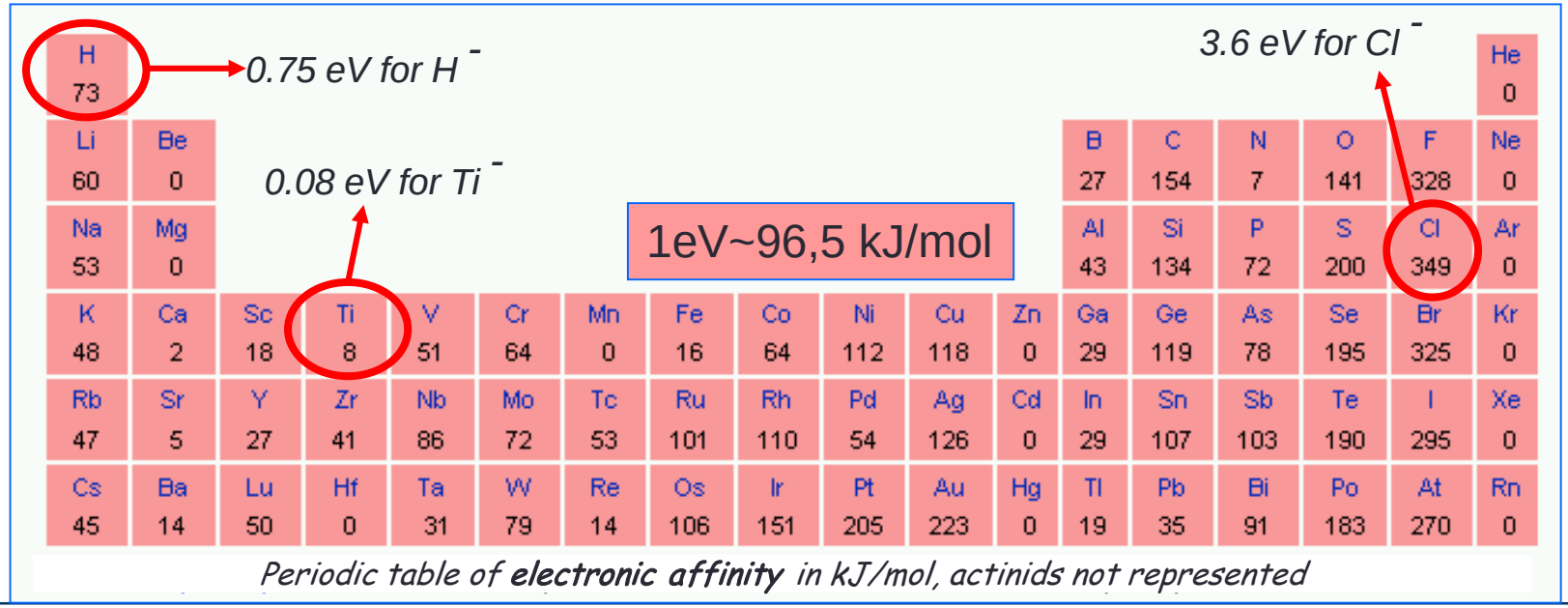


Negative Ions- Electron Affinity

Negative ION Materials from M. Stockli, ORNL, J. Arianer, IPNO,H. Koivisto, JYFL

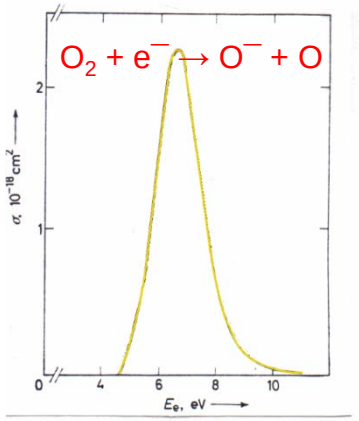


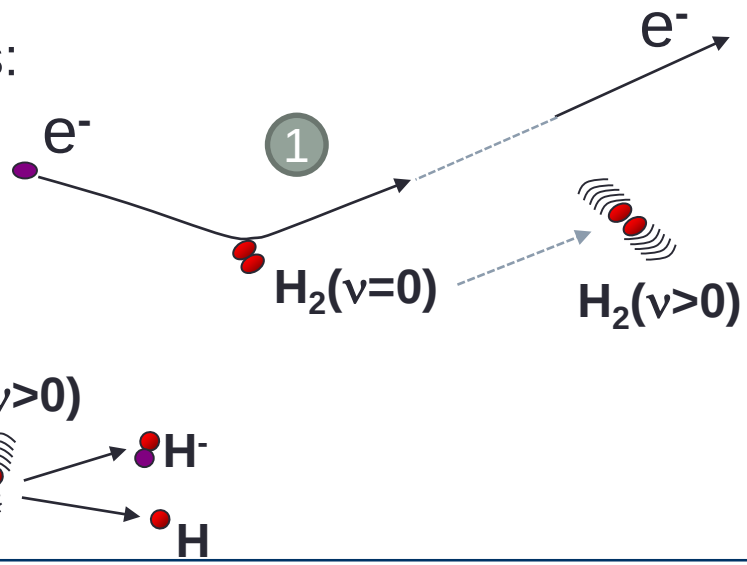
- What is a Negative Ion?
  - Atoms with unclosed shells can accept an extra electron and form a stable ion with a net charge of -e
  - The stability is quantified by the Electron Affinity, the minimum energy required to remove the extra electron.
  - The electron affinities are substantially smaller than the ionization energies, covering the range between 0.08 eV for Ti^- and 3.6 eV for Cl^-.
- Negative ions are very fragile!
  - (M)any Collision can break the binding (see next slides).



How to create a negative ion? (1/2)

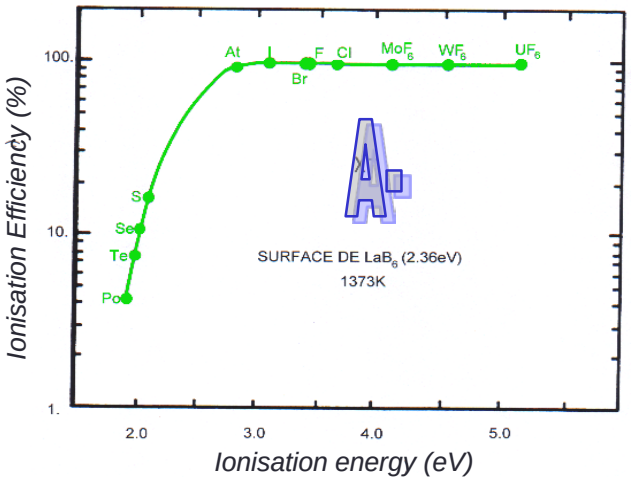
- The creation of negative ions is exothermic. Excess energy should be dumped to a third particle. Negative ions can be produced on surfaces and in a plasma (« volume ionization »).
- Volume ionization:
  - Dissociative attachement:
    - the excess of energy is transferred to a third particle when dissociating a molecule
    - $AB + e^- \rightarrow A^- + B$ (rare event)
  - 3 body collision:
    - $A + B + e^- \rightarrow A^- + B$ (rare event)
- Example of H^- production which requires 2 steps:
  - Step 1: H_2 excitation by electron impact
  - $e^-(fast) + H_2 \rightarrow H_2^v + e^-$, ($v$=molecule **high vibrational state**)
  - Step 2: Dissociative attachement
  - $H_2^v + e^- \rightarrow H^- + H$

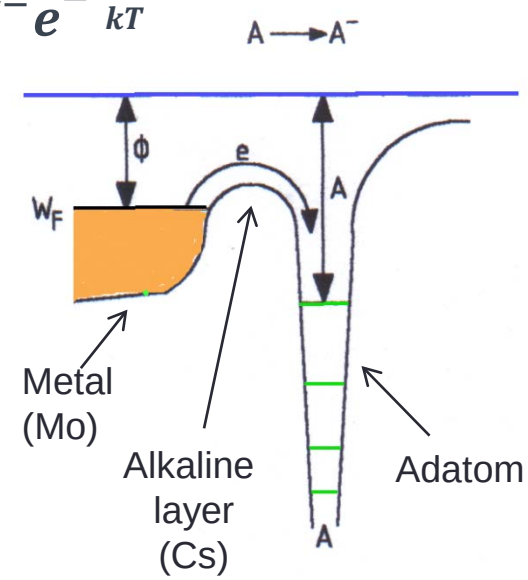


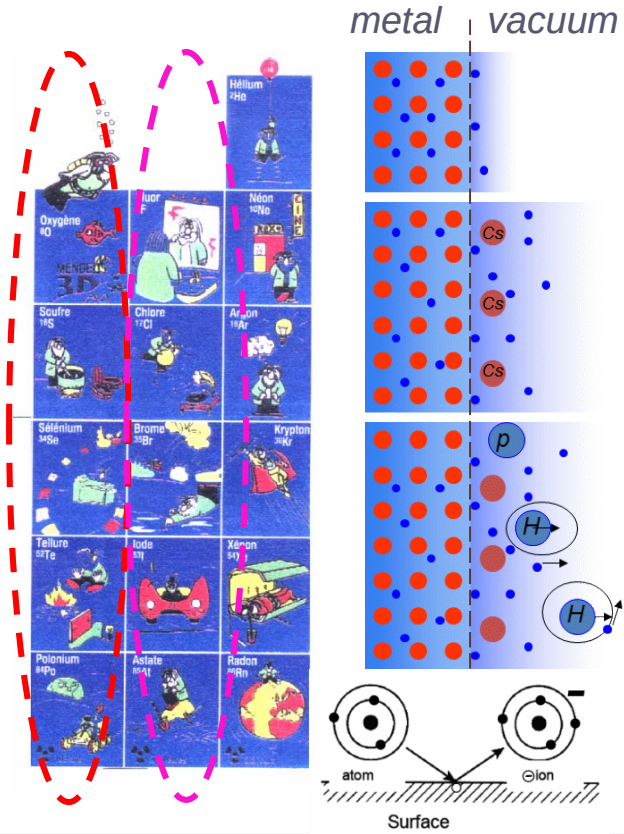


How to create a negative ion? (2/2)

- **Surface production:**
  - As seen in the Electron source part, Metals host an abundance of loosely bound electrons (conduction electrons) but it takes about 4.5 to 6 eV to remove an electron from the surface.
  - Alkaline metals have lower work functions (2-3 eV). When adsorbed on a metal surface as a partial monolayer, **alkaline atoms** can **lower the surface work function** *(Φ)* to values even below their bulk work function, e.g. ~1.6 eV for **Cs on Mo**.
  - Electrons from metal can be captured by atoms stuck on surface (adatoms) through **tunnel effect,** provided $\mathbf{A} > \boldsymbol{\varphi}$
  - Surface ionization works efficiently with Halogens and Chalcogens
  - Langmuir-Saha Formula: $\frac{N^-}{N_0} = C^- e^{-\frac{A-\varphi}{kT}}$
  - High kT helps to desorb A^-

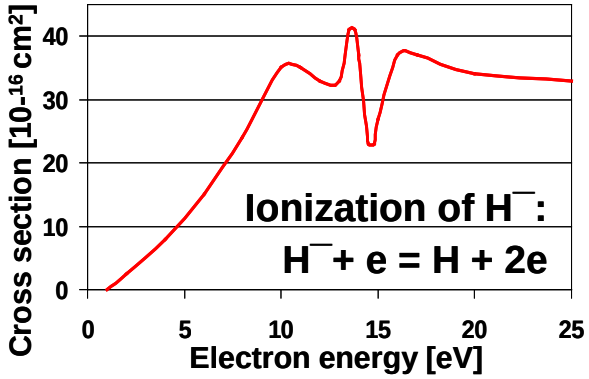


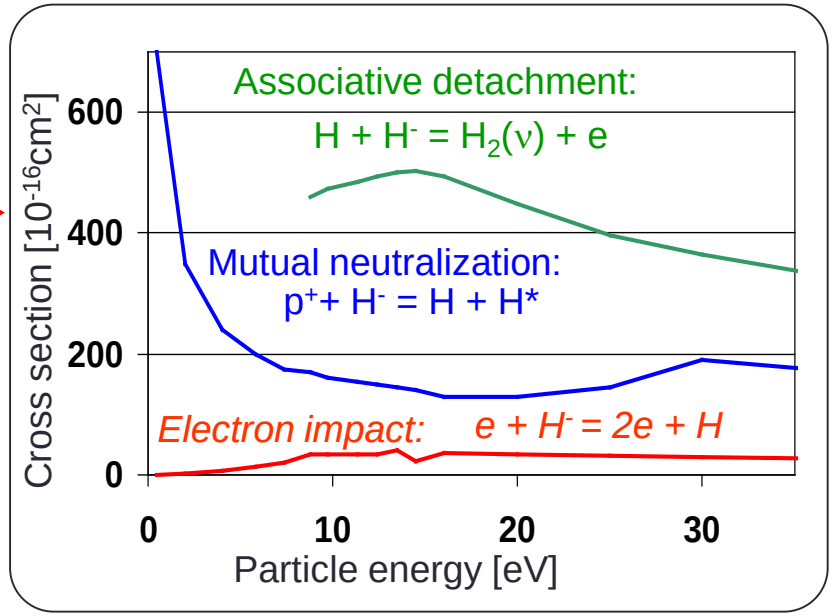




How to lose a negative ion?

- Very very easily!
  - Electron impact ionization:
    $A^- + e^- \rightarrow A + 2\,e^-$
  - Mutual neutralisation (Recombination)
    $A^- + H^+ \rightarrow A + H$
  - Collisional Detachment:
    $A^- + B \rightarrow A + B^+ + e^-$
  - Associative Detachment:
    $A^- + B \rightarrow AB + e^-$
  - Negative ions are totally destroyed **a few cm** away from their place of birth in a $n \sim 10^{13}$ cm^{-3} plasma
  - **Negative ions must be extracted close to their place of birth**

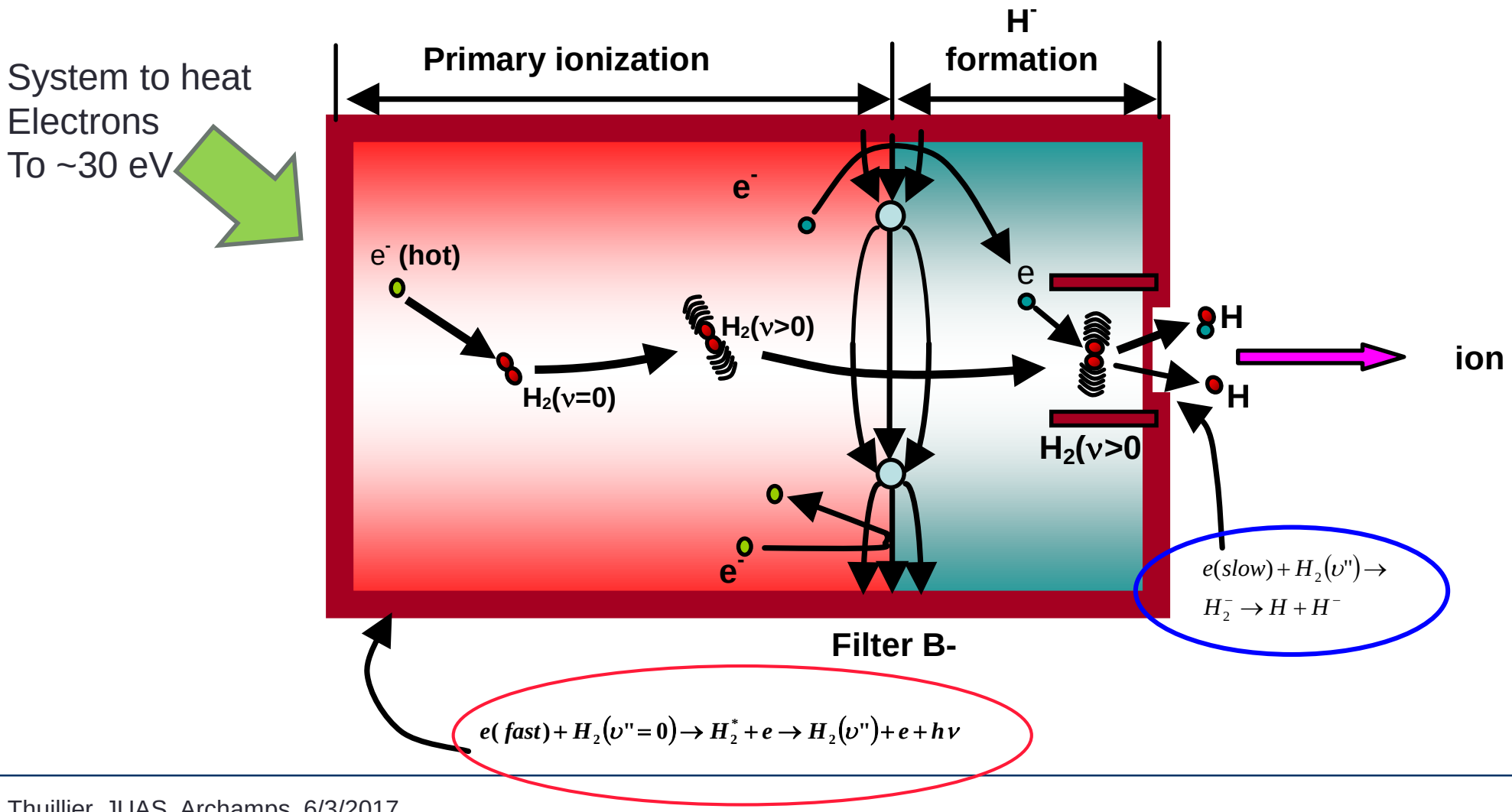




Example of H$^-$ destruction process

Volume production of H^-

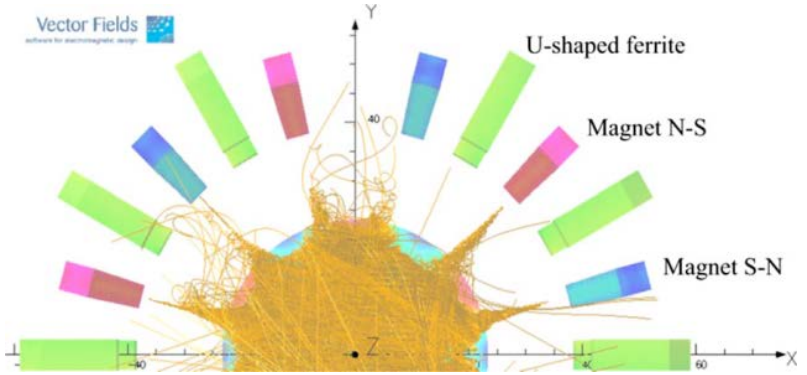
- "Hot" electrons are reflected back by a filter B-field.
- Cold electrons are highly collisional and are not magnetically confined

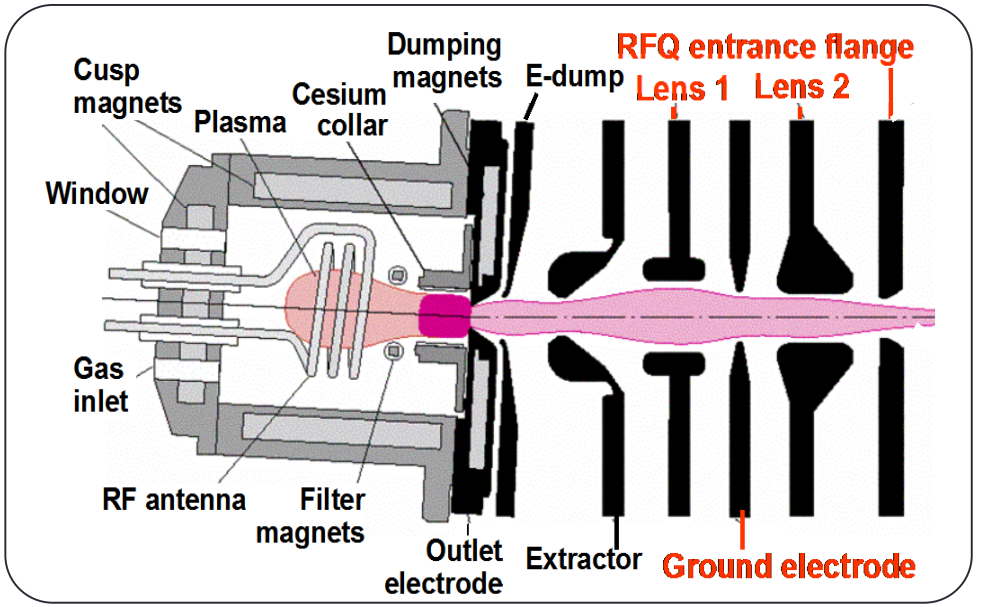


Radio-Frequency Negative Ion Source

- Example of the ORNL H^- Ion Source
  - A multicusp magnetic structure provides a radial plasma confinement
  - H_2 gas is injected on the rear part
  - A pulsed RF antenna under vacuum generates the plasma (see next slide) and ionizes hydrogen to produce H^+, H_2^v ,e^-
  - Two filter magnets (SmCo 200 Gauss) repel hot electrons generated by the RF. (e.g. a 35 eV electron turns around on a 1 mm radius).
  - A Cs collar is present near to the source extraction to boost H^- production (by ~200%)
  - Source is pulsed with 6% Duty Cycle to produce 50 mA of H^-
  - Advantage: no filament! But the use of Cs collar is tricky and maintenance is required every 6 weeks

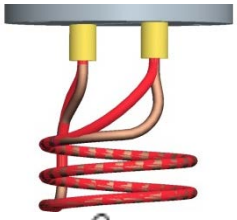
Trajectories of e^- in a CUSP magnetic structure (CERN), Rev. Sci. Instrum. 81, 02A723 (2010))

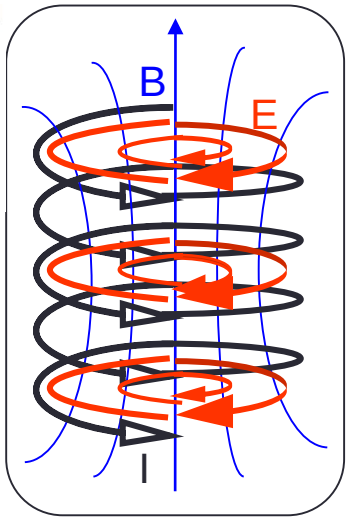




Radio-Frequency Negative Ion Source – Plasma Generation

- The plasma is inductively driven by a RF antenna making 3 turns around the plasma
  - The axial time varying magnetic field B(t) generated by the antenna induces a circular electric field in the plasma. This electric field accelerate electrons up to ~30 eV.
- A multicusp magnetic field confines the plasma towards the center
- A CW low power plasma is maintained by a 13 MHz amplifier (~300 W)
- The “Main” plasma is pulsed by a 2 MHz amplifier (50-60 kW), with a pulse length
  1 ms @ 60 Hz



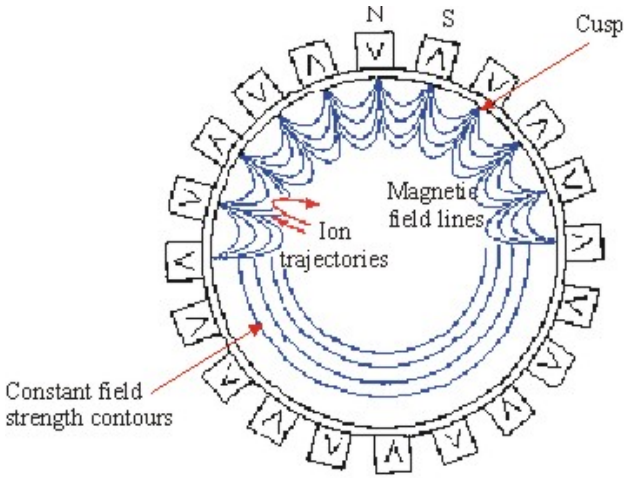


$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

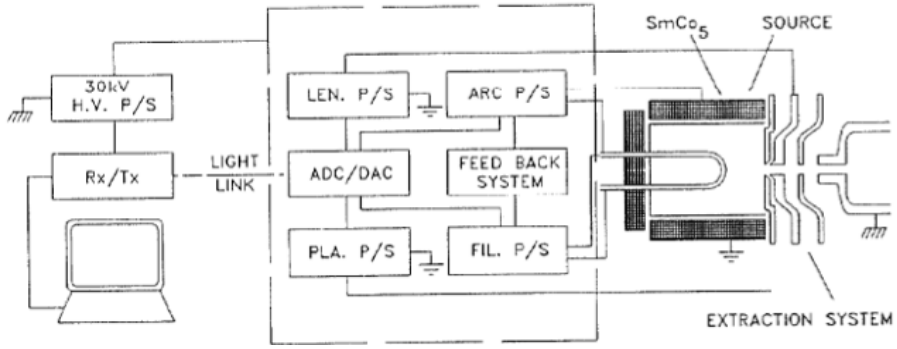
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

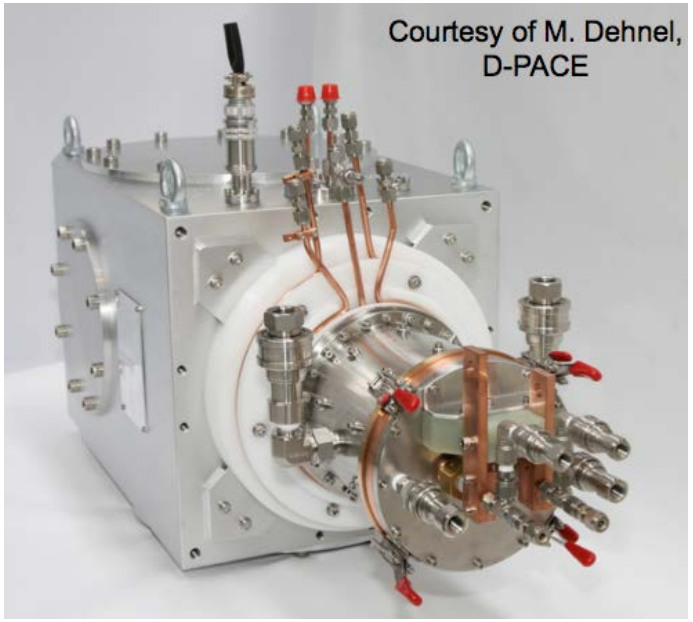


Filament driven Triumf H- ion source: Volume production

- The TRIUMF H- source was developed ~1990 to inject H- into the TRIUMF Cyclotron
- A filament driven plasma is confined by a multicusp field
- Filter field generated by two inverted cusp magnets near the outlet.
- Licensed to and sold by D- PACE at www.d-pace.com
  - Beam current: 15 mA continuous
  - Ion energy: 20-30 kV
  - Efficiency: 3 mA/kW
  - Filament lifetime: 2 weeks at peak current
  - Cesium free

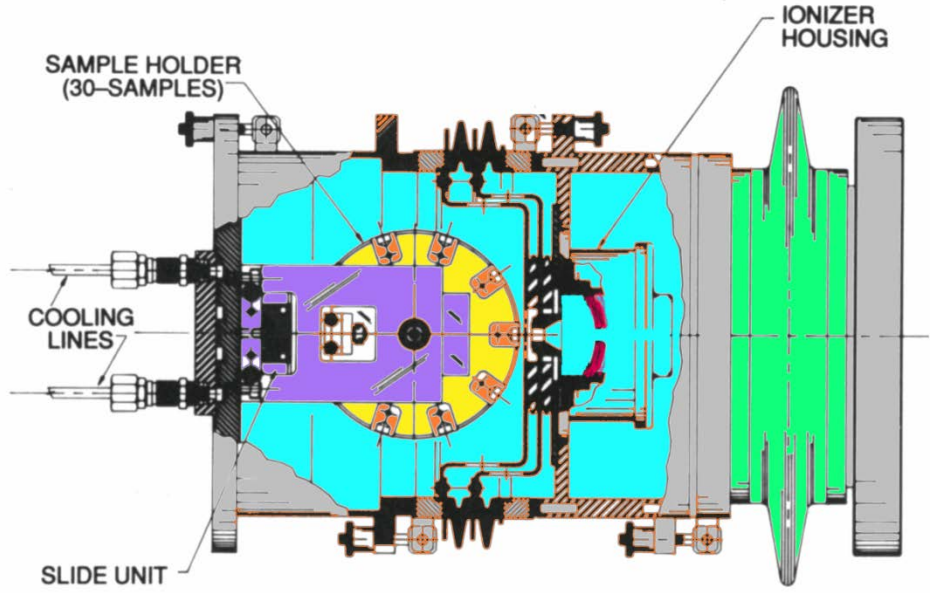
K. Jayamanna, M. McDonald, D.H. Yuan, P.W. Schmor, EPAC (1990) 647

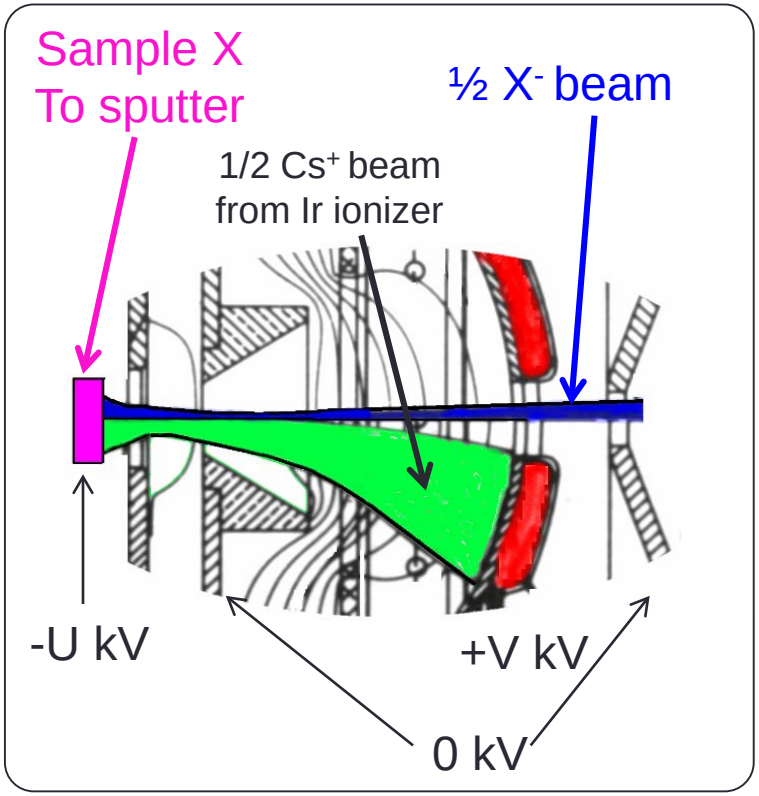




Negative Metallic Ion Source

- Inversed Middleton Source
  - A Surface Ionization Source produces Cs^+ beam around the extraction aperture of the source
  - Cs^+ Ions are accelerated toward a metallic sample holder set to a negative voltage
  - The Cs induces sputtering AND reduces the work function of the metal target
  - Negative Metal Ions are produced (helped with high kT)
  - Rotation of Sample to sputter to increase beam time

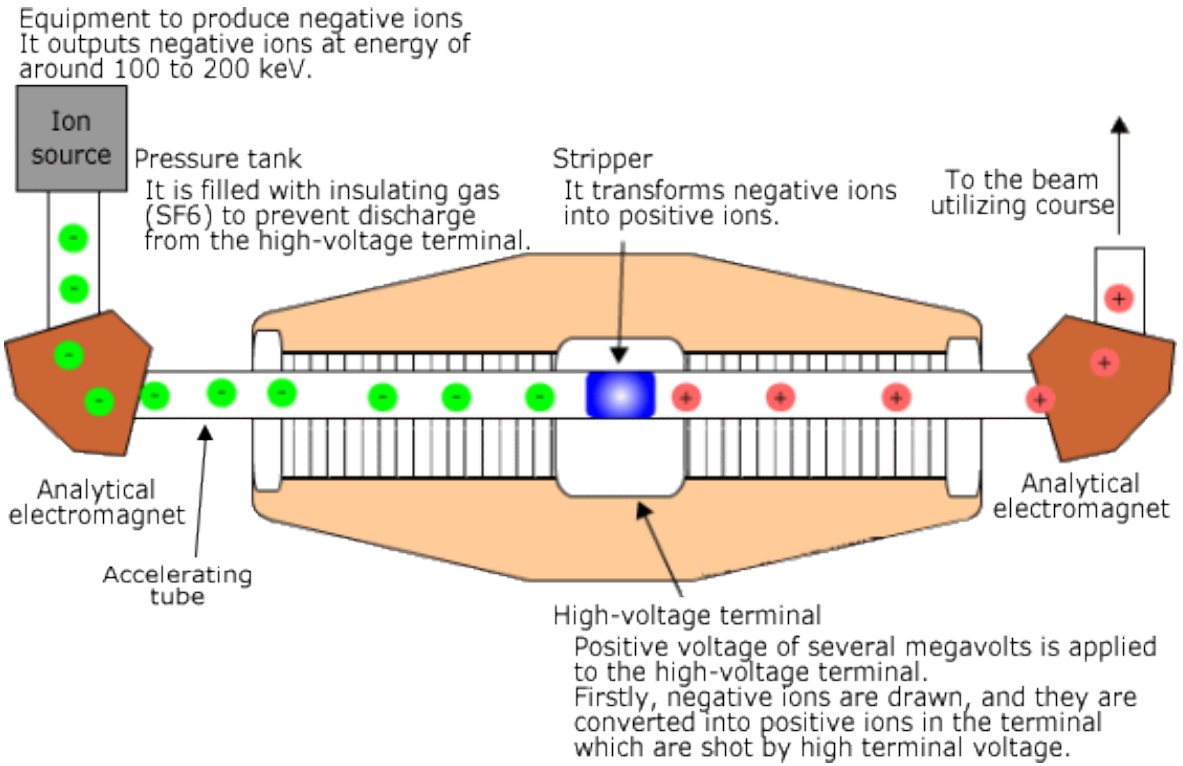




- Negative Metal Ions are produced (helped with high kT)
- Automatic Rotation of Sample to sputter to increase the beam time

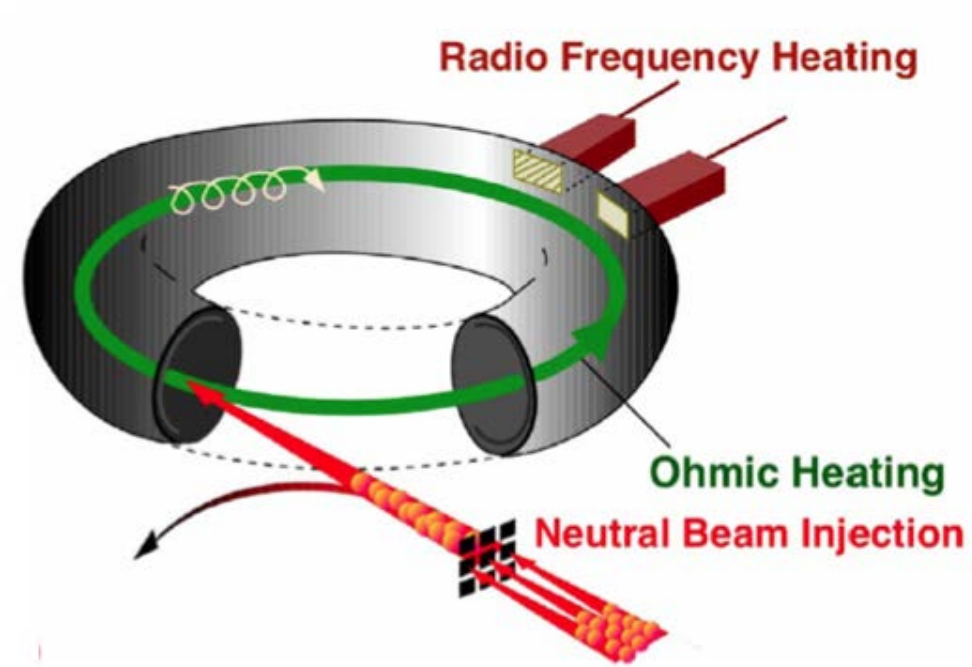
Negative Ion Source Applications for TANDEM

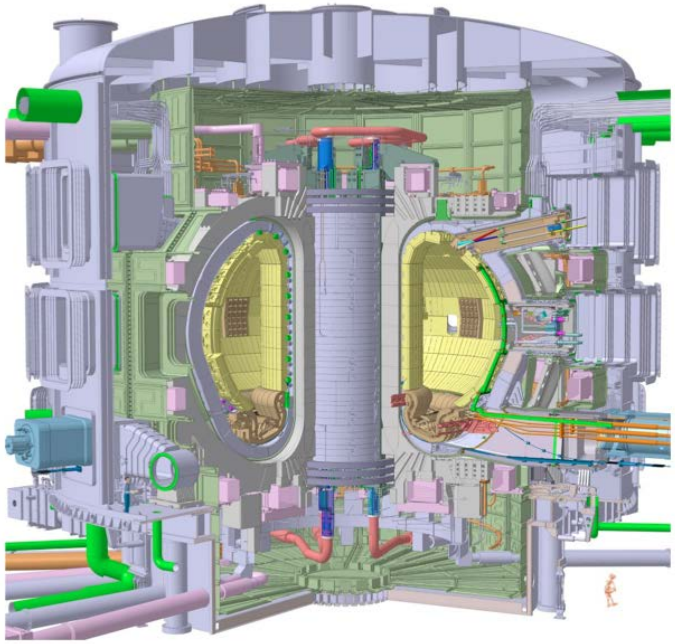
- TANDEM Accelerator http://www.werc.or.jp/english/reseadeve/activities/accelerator/accelerator/tandem/index.htm
  - The negative ion beam is accelerated up to the tandem center set at at high positive voltage
  - The negative ions are then stripped in a target transforming them into positive ions
  - The ions undergo a new acceleration toward the tandem exit.



Negative Ion Application for TOKAMAK

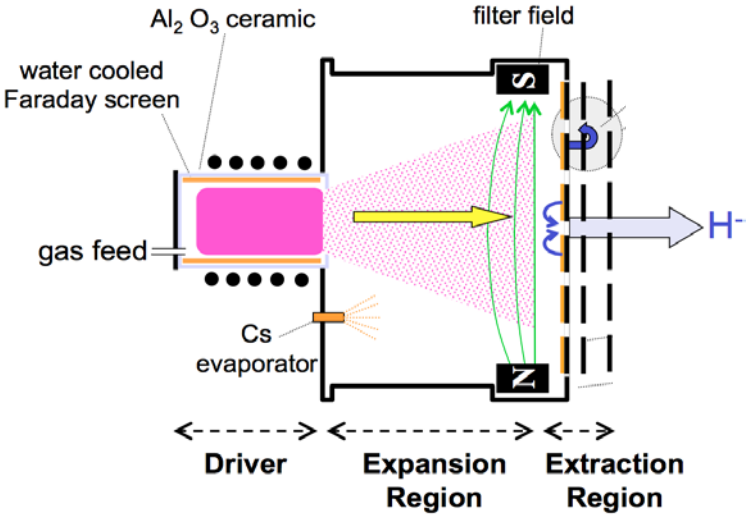
- ITER: Neutral beam injection:
  - Heating power requirement > 50 MW
  - Neutral Beam Injection ≈ 33 MW
  - Ion Cyclotron Heating ≈ 20 MW, ECR Heating ≈ 20 MW
  - A D^- beam is produced and accelerated; it is then neutralized before being injected into the plasma

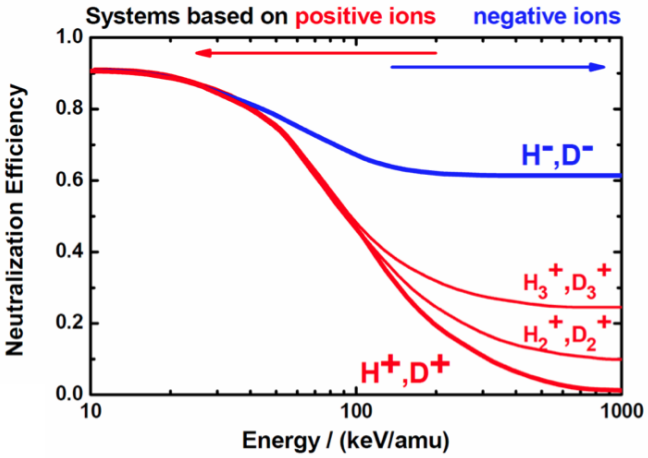




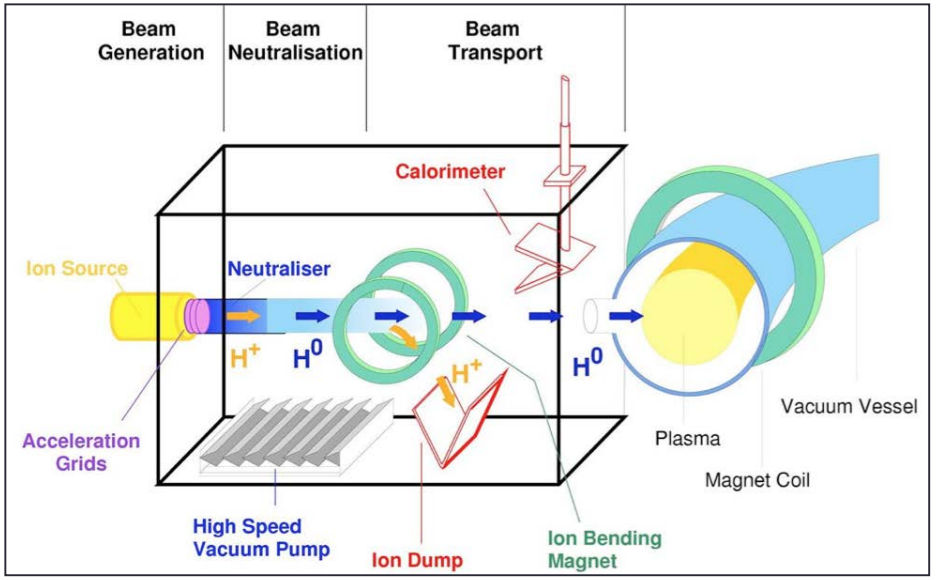
D^- Ion source for ITER

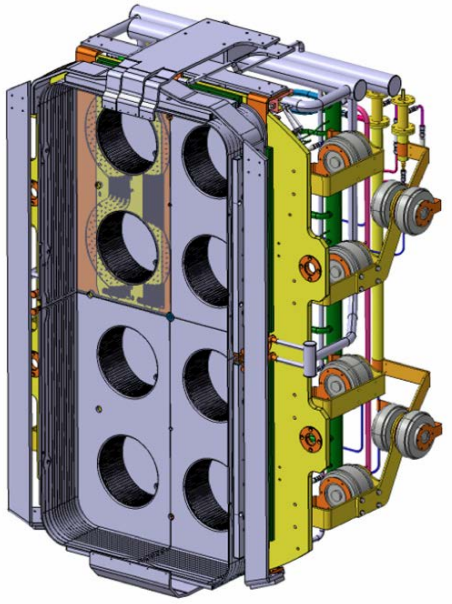
- Beam Requirement: 40 A (D^-) @1 MeV
  - D^- is used because of its much higher neutralisation efficiency at 1 MeV
- The D^- beam is neutralized before its injection in the Tokamak





ITER source 1.9 x 0.9 m²

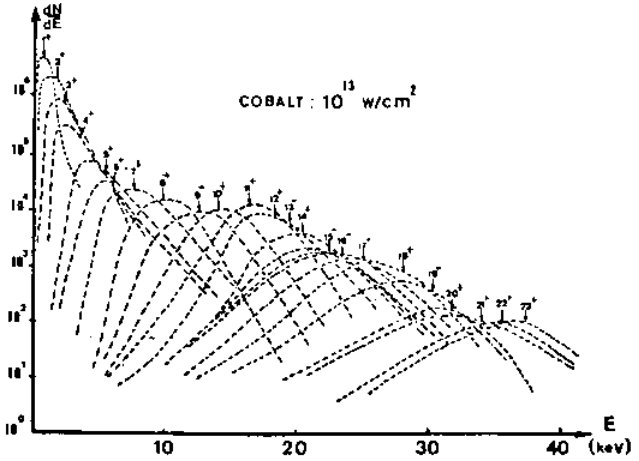


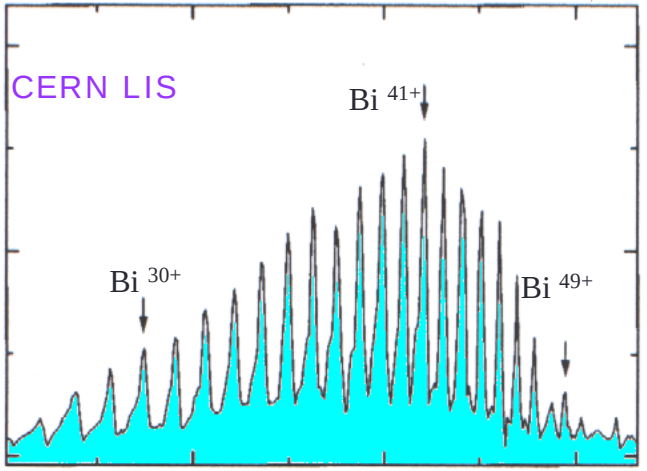


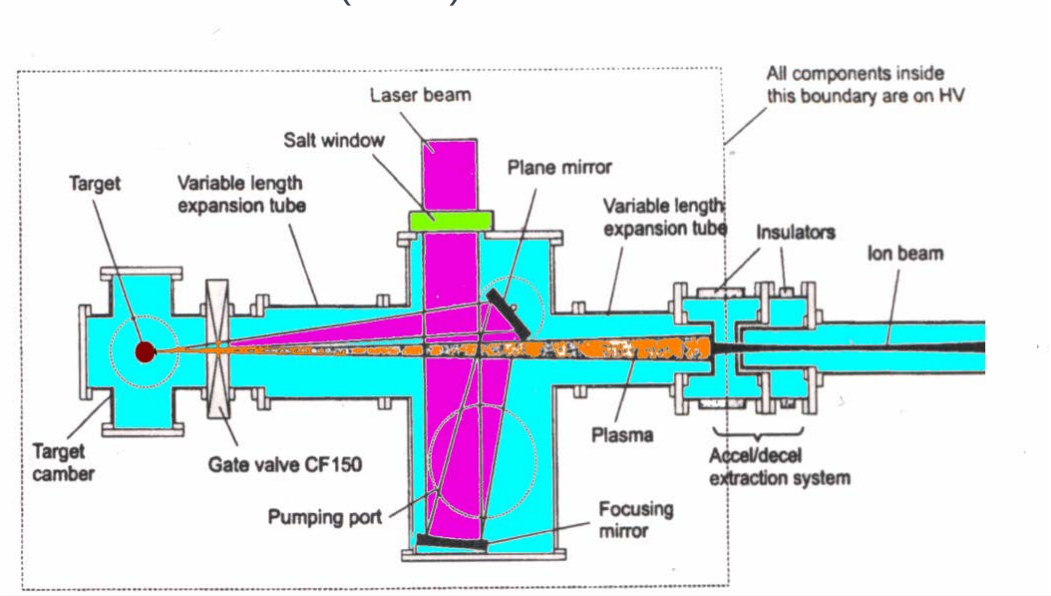
Material from CAS2012: W. Kraus

Laser Ion Source

- A very strong power laser pulse evaporates solid matter and generates a medium to high charge state hot plasma
  - Very High density plasma
  - Complicated plasma physics behind
  - High charge state ions created
  - High currents
  - But Very Hot ions (KeV to MeV)
    - Complicated extraction and acceleration process
  - Complicated laser
  - Pulsed beams (~1 Hz)







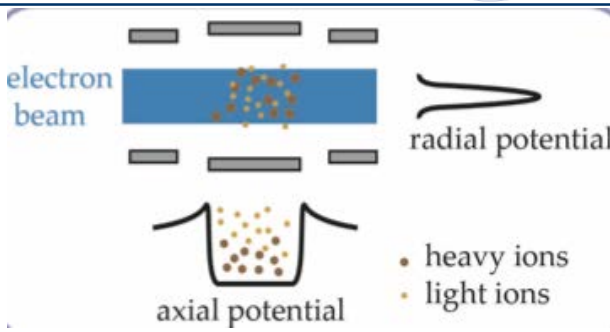
Specifications :

CO_2-N_2-He laser 100J-10^{13}W.cm^{-2}

pulses of 50ns at 1Hz

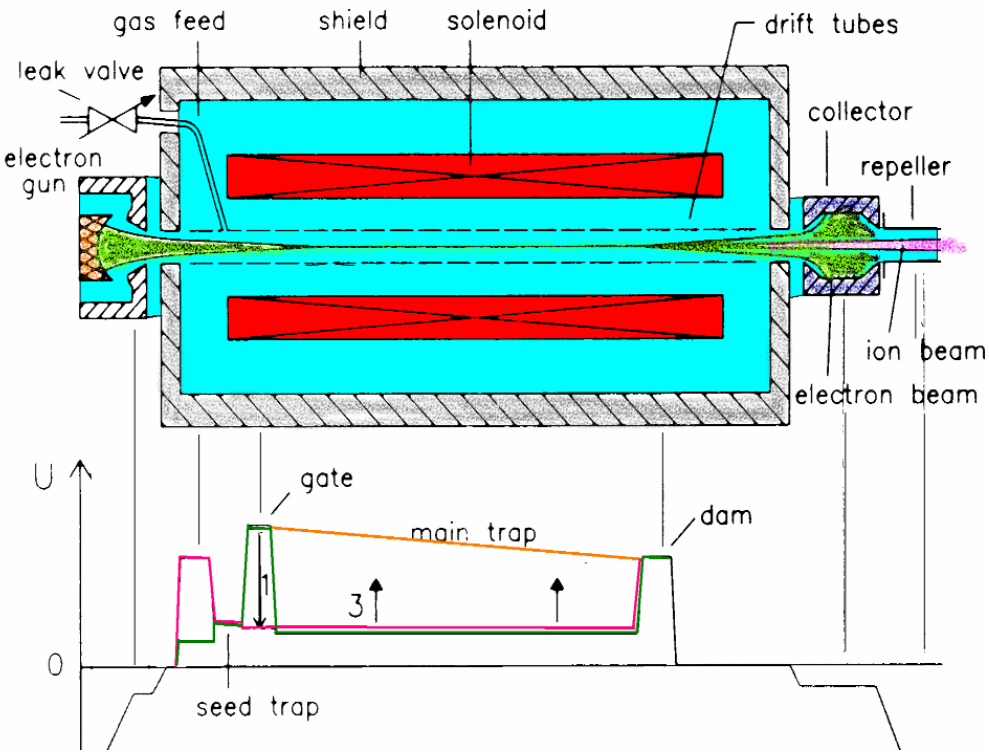
1.4 10^{10} Pb^{25+} per pulse

Electron Beam Ion Source (EBIS)



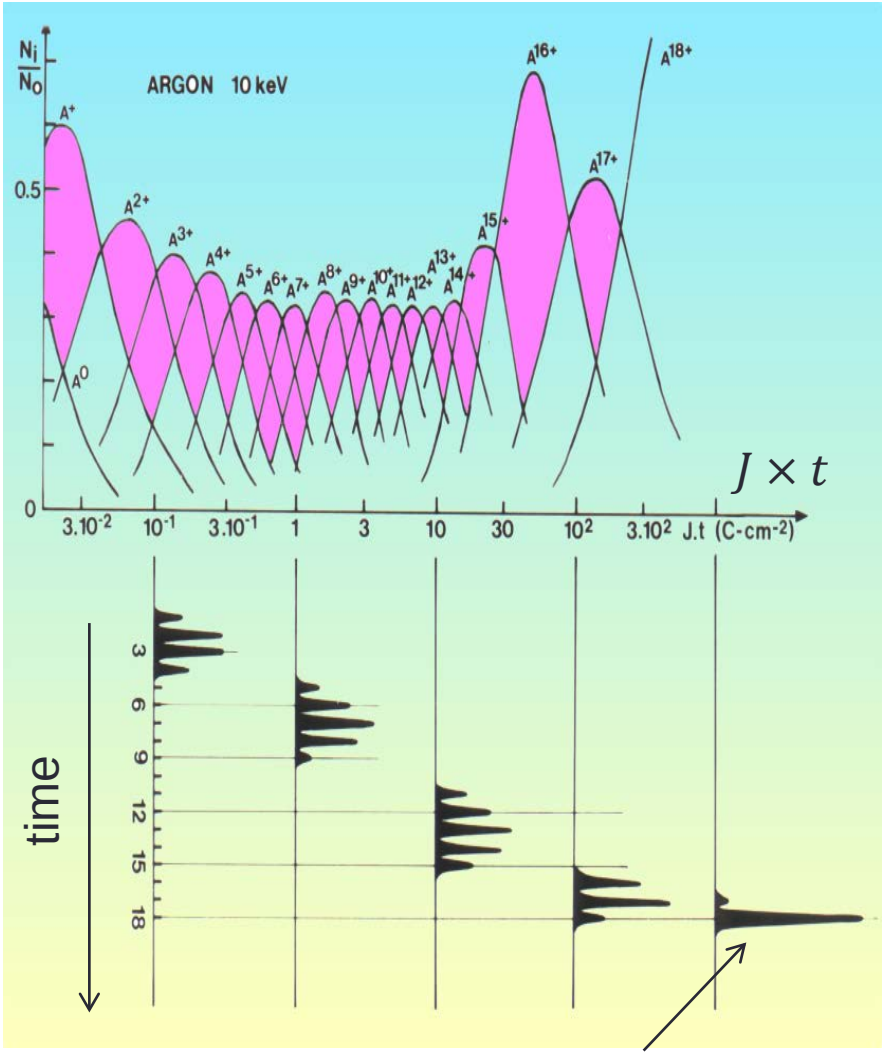
Zschornack, CAS2012 lectures

- Electron beam issued from a thermionic gun (V up to 200 kV, 1 A)
  - injected as a Brillouin flow on the axis of a long solenoid, to get very high current densities. Close to the collector, it is generally slowed down to save power.
- Stepwise ionization by e- impact.
  - The charge exchange is avoided owing to a pulsed neutral injection.
- Ion confinement
  - due to the combination of the radial space charge e^- potential well and a longitudinal voltage distribution applied on a series of tubes.
- The source is cyclic (pulsed operation)
  - 3 phases : neutral injection, containment and expulsion
  - obtained by programming the tube potentials. The source output is then limited. The variation of the containment time allows to adjust the CSD.
- Low Pressure requirement: P< 10^{-9} mbar



EBIS Performance

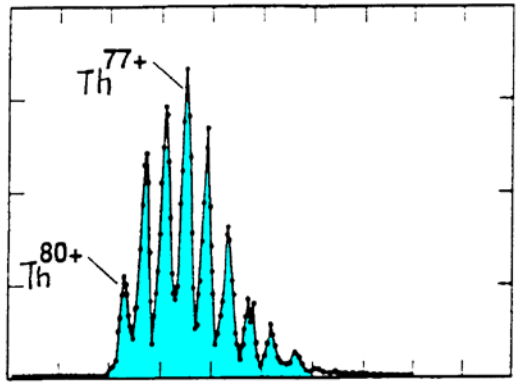
- Production of Very High Charge state
  - The Ions charge state distribution increase with the “cooking time”
  - Charge state distribution is narrow
  - Ultra high charge state achievable
- Limited pulse repetition rate
  - Long Cooking time (10-100 ms)
  - Suitable for LINAC & synchrotrons
- Limited beam intensity
  - Max. space charge in the trap:
  - $Q \leq 3.36 \times 10^{11} \frac{IL}{\sqrt{E}}$
    - I, E electron beam intensity, energy
    - L trap length
    - Q max ion charge trapped



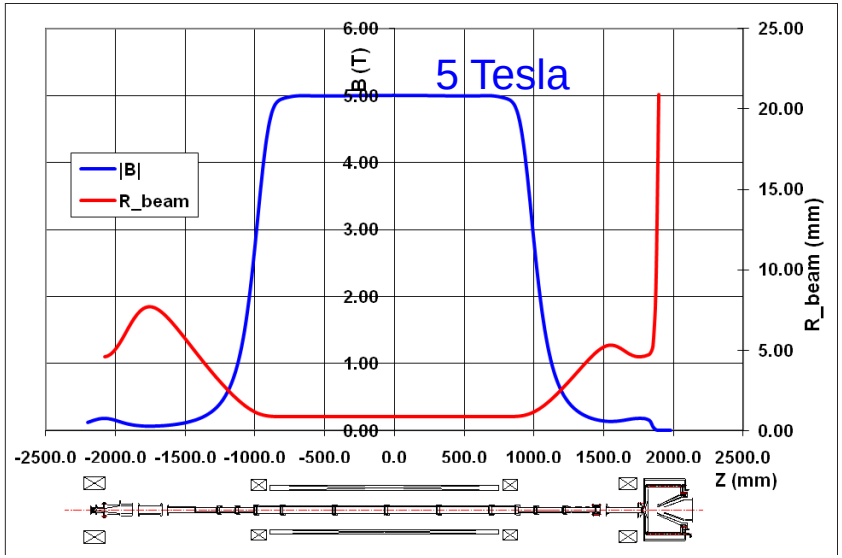
Fully stripped Argon!

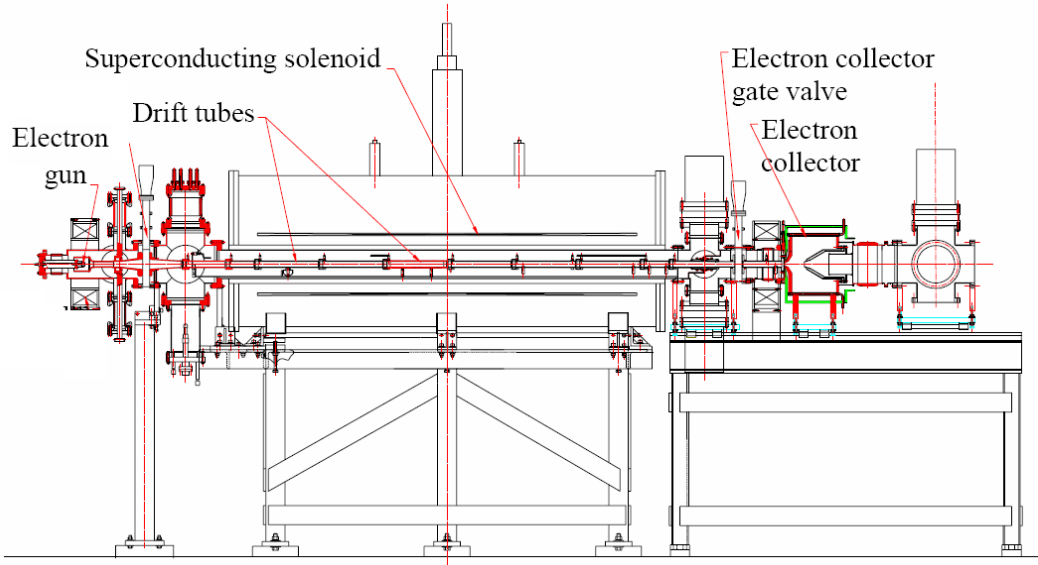
High Intensity EBIS at RHIC

- 1.7 mA – 10 µs – 5 Hz



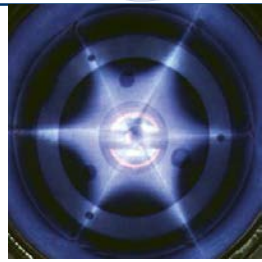
Narrow charge state distribution for Th beam



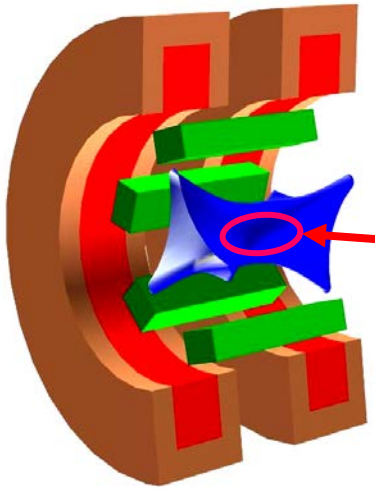


Magnetic field profile along the trap – Electron beam envelope

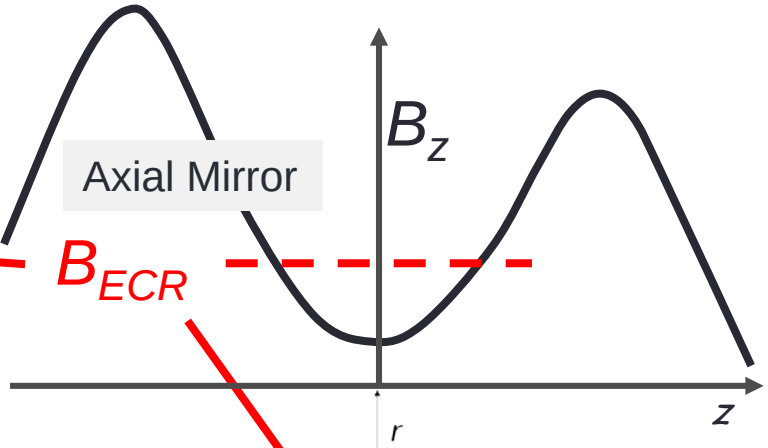
Electron Cyclotron Resonance Ion Source

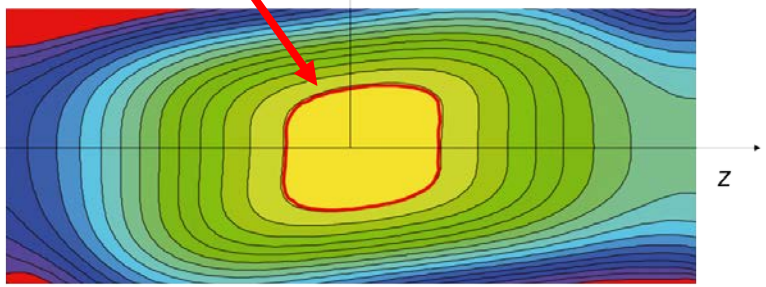


- ECR ion sources feature a sophisticated magnetic field structure to optimize charged particle trapping
  - Superimposition of axial coils and hexapole coils
  - The ECR surface (place where |B|=B_{ECR})is closed
  - ECR surface =place where the electrons are heated by a microwave



Source LBNL

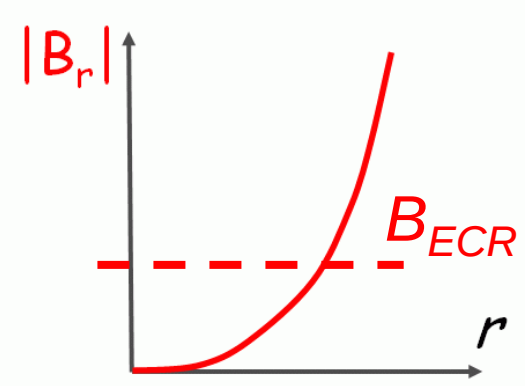




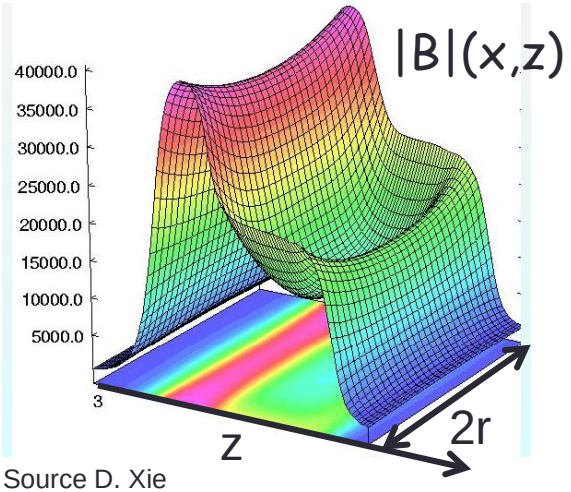
Source RIKEN, Nakagawa

Iso B lines

$$\omega = \omega_{ce} = \frac{qB_{ECR}}{m}$$

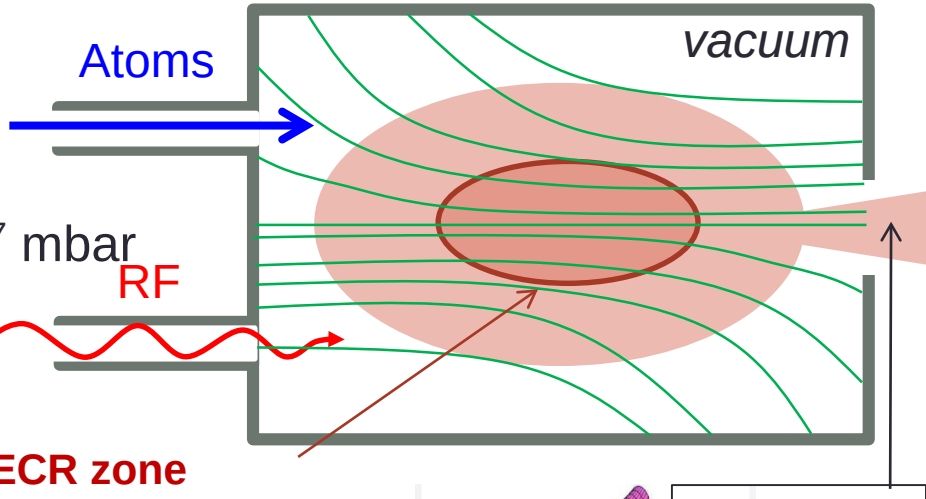


Hexapolar Field

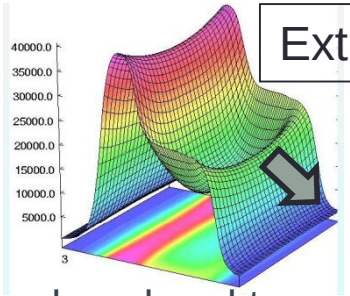


Source D. Xie

ECR Plasma build up

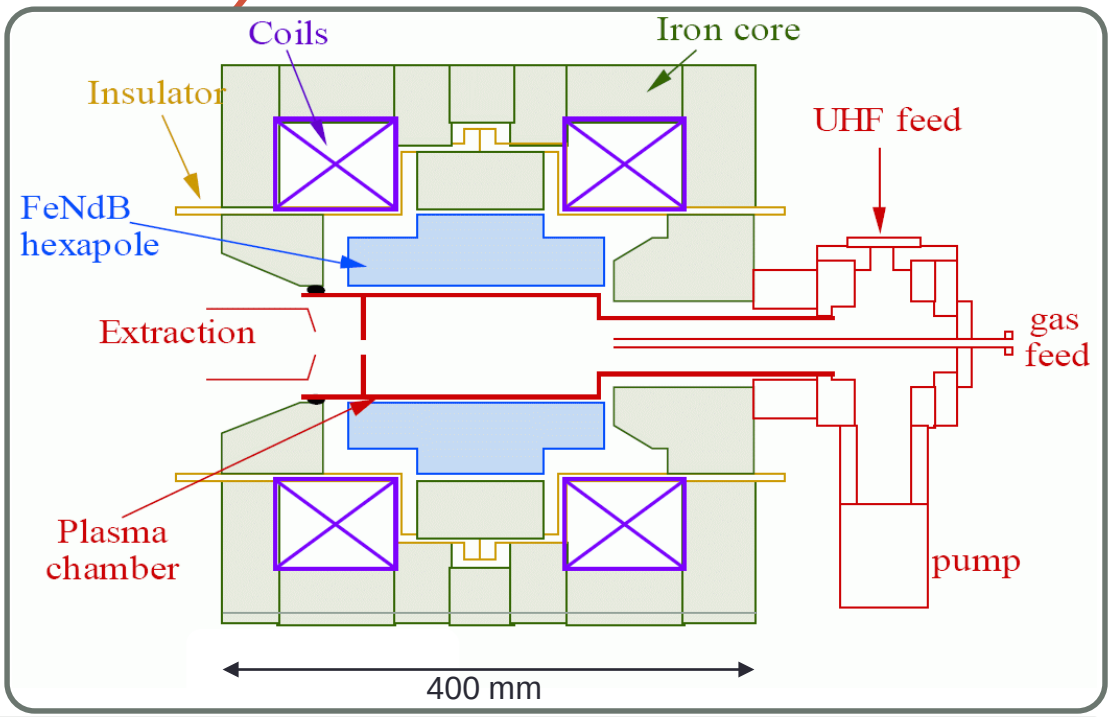


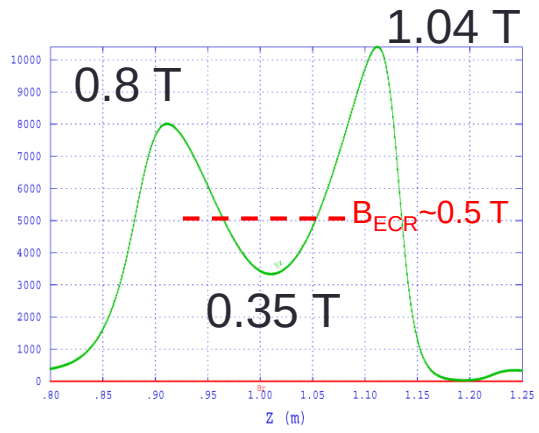
- Pumping & Gas Injection to reach P~10^{-6} to 10^{-7} mbar in the source
- Microwave injection from a waveguide
- Plasma breakdown
  - 1 single electron is heated by a passage through the **ECR zone**
  - The electron bounces thousands of time in the trap and kT_e increases
  - When kTe>I_1^+, a first ion is created and a new electron is available
  - Fast Amplification of electron and ion population (~100 µs)
  - =>plasma breakdown
- Multicharged ion build up
  - When Te is established (kT_e~1-5 keV), multicharged ions are continuously produced and trapped in the magnetic bottle
  - Ions remain cold in an ECR: kT_i~1/40 eV, (m_e<<m_i)
- Population of the loss cone through particle diffusion (coulombian interaction)=> constant change in the particle trajectory=> random redistribution of $\vec{v} = \vec{v}_{\parallel} + \vec{v}_{\perp}$
- => ion extraction through the magnetic **loss cone** on the side of the source presenting the minimum magnetic field intensity

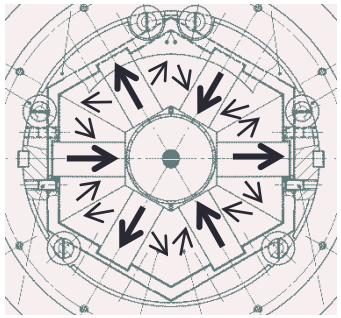


Example of ECR4 (GANIL)

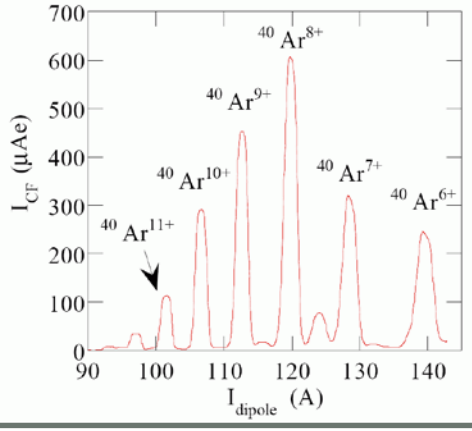
- Microwave: f=14.5 GHz-1.5 kW (B_{ECR}=0.64 T)
- Coaxial RF coupling from a cube located outside the source, equipped with a movable rod (not shown) able to adapt RF impedance to the ECR cavity.
- Axial Mirror: 1.04 T – 0.35 T – 0.8 T
- Hexapole: 1 T FeNdB magnets
- Typical Ion Beam: ~650 µA Ar^{8+} CW
- Chamber volume (Ø64 mm×L200 mm) V~0.5 liter
- Can produce any gas and many condensable beams

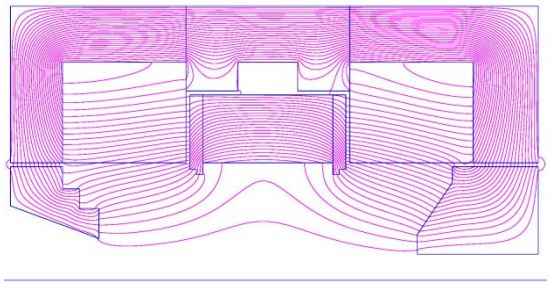






FeNdB hexapole

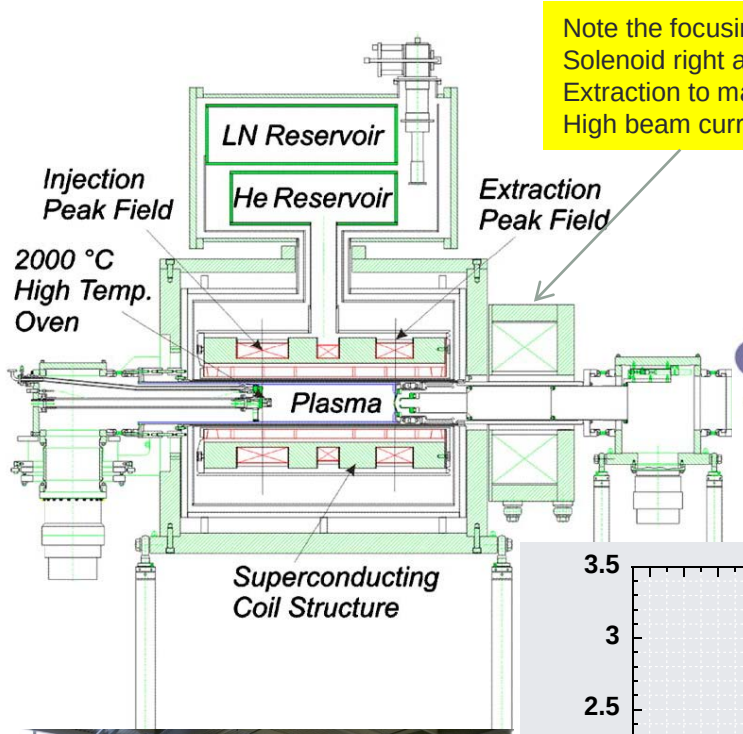


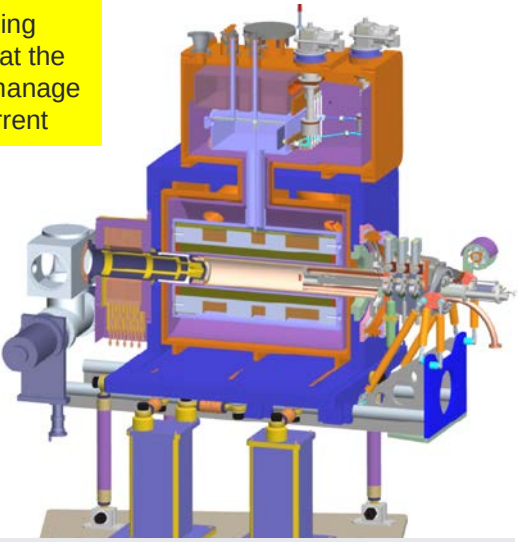


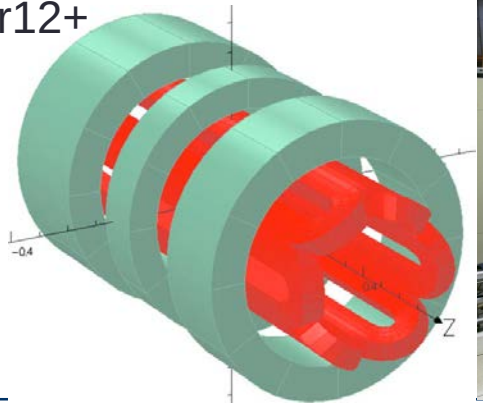
Axial Magnetic field lines (ECR4M)

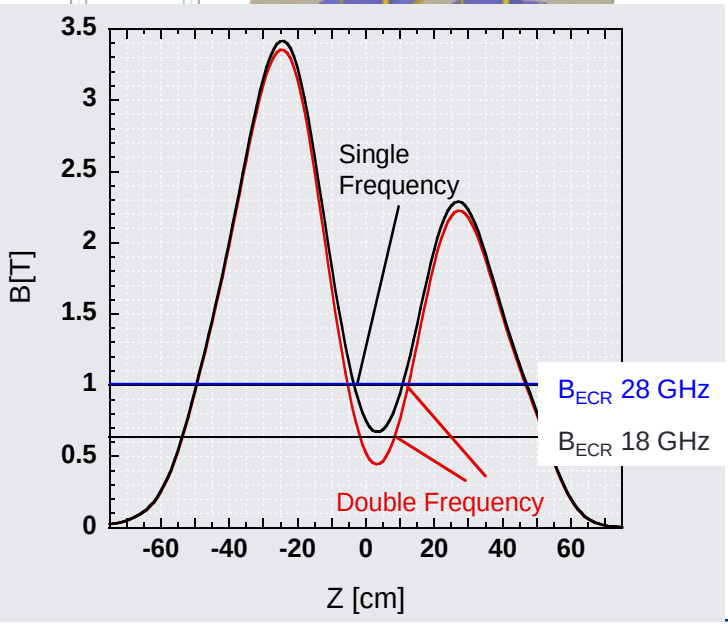
VENUS ECR Ion Source (LBNL)

- f=18+28 GHz - (2+6) kW
- B_{ECR}=1 T
- Fully superconducting ECRIS
  - NbTi:Cu wire technology
  - 4K LHe + thermal 40 K shield
  - 4×1.4 W cryocooling
- Axial profile 3.5-0.35-2.2 T
- Radial hexapole at wall Br=2.2 T
- Dedicated to very high intensity, very high charge state applied to cyclotron acceleration
- Plasma Chamber volume V~8.5 liter
  - Ø~15 cm , L~50 cm
- V~25 kV
- Typical beams: 3 mA O^{6+}, 0.86 mA Ar12+

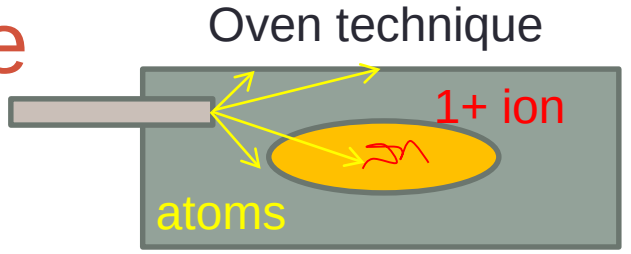


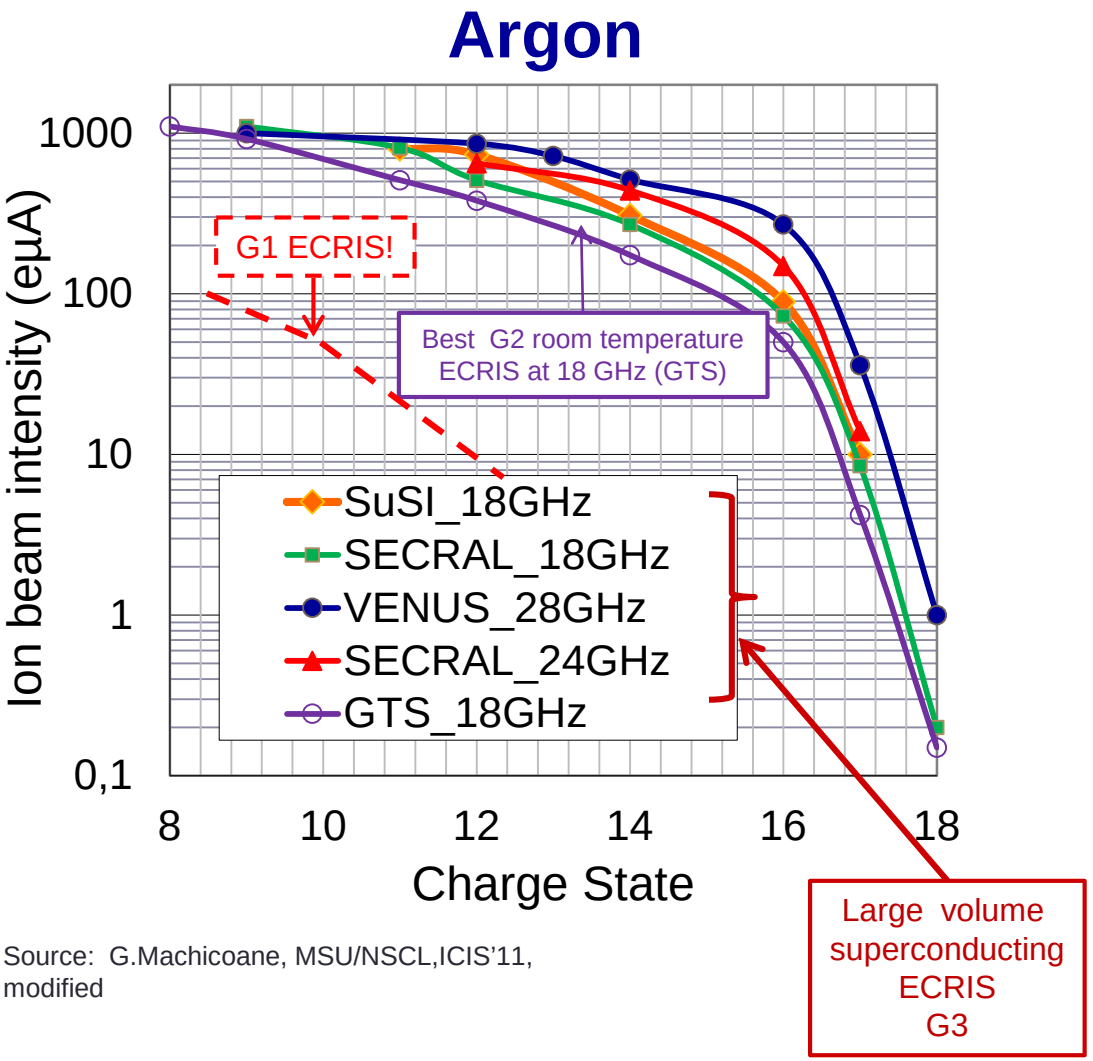




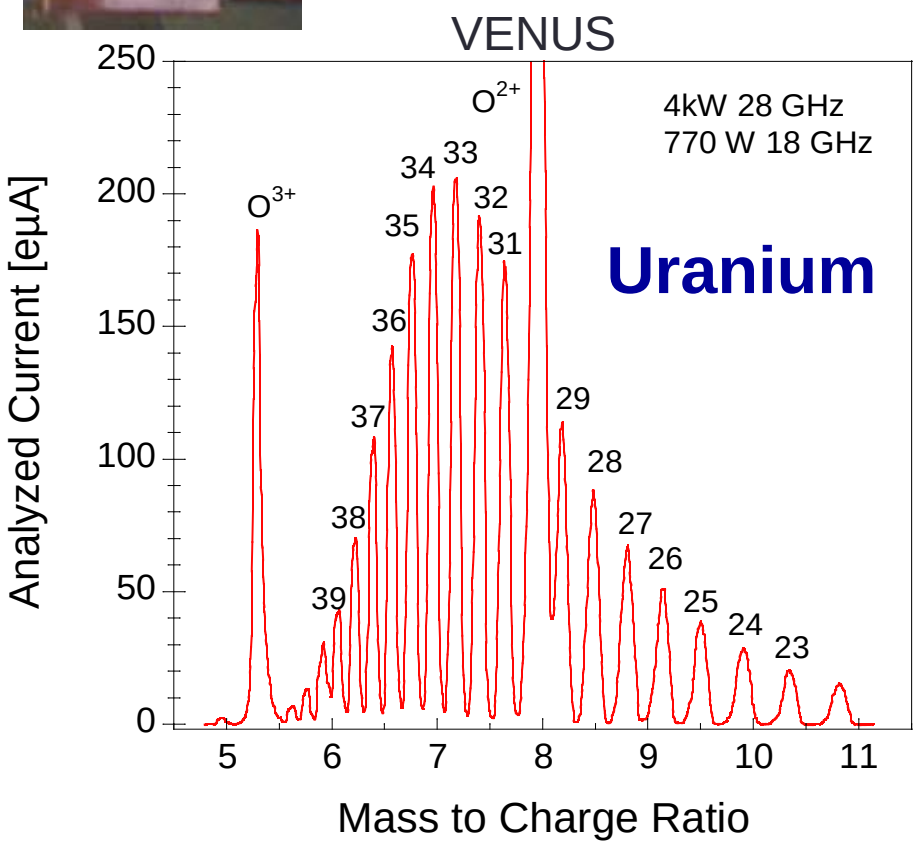


Example of Today ECR performance





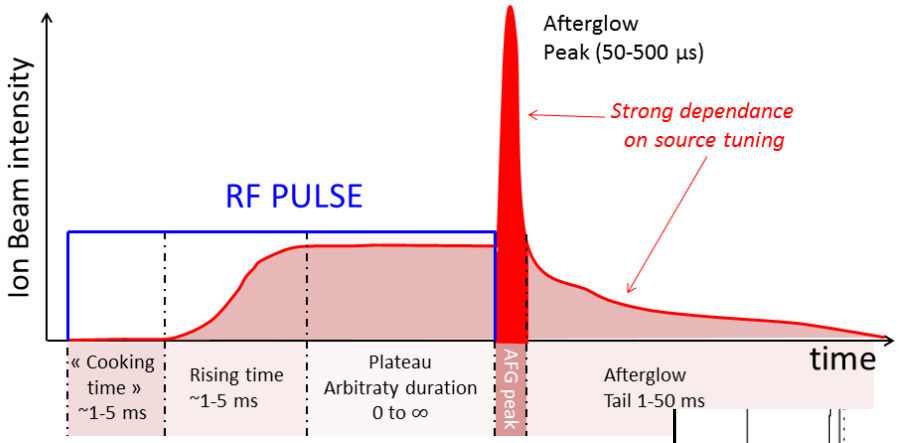
Source: G.Machicoane, MSU/NSCL,ICIS'11, modified

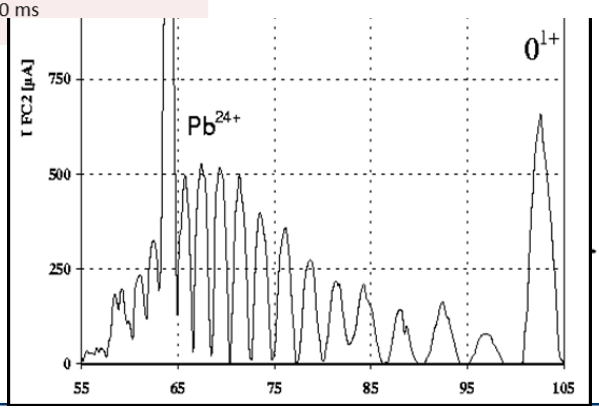


Metallic vapors (from an oven)
Injected in an oxygen plasma

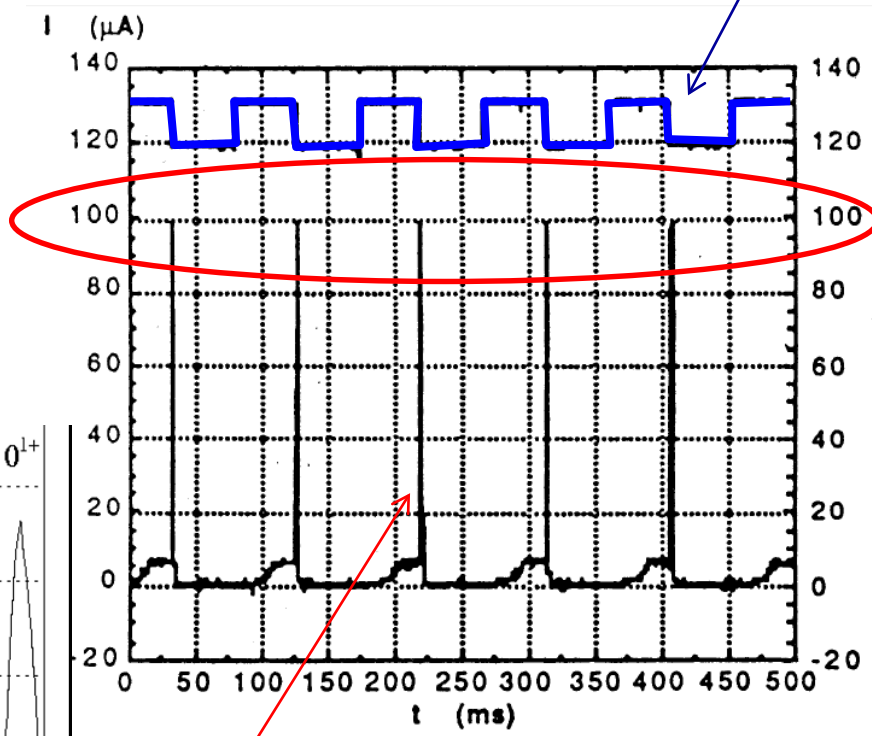
ECR Pulse Mode operation for Synchrotrons

- When the RF is pulsed, ECRIS can be tuned to produce a high intensity peak with a duration $\delta t \sim 50 - 400\ \mu s$, suitable for multi-turn Synchrotron injection
- LHC Lead beams are produced in Afterglow mode (GTS ECR)





500 µA Pb^{24+} with the PHOENIX source

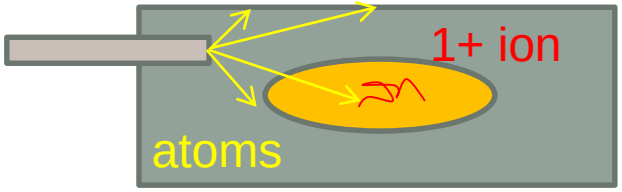


Pb^{28+} pulses (ECR4 GANIL)

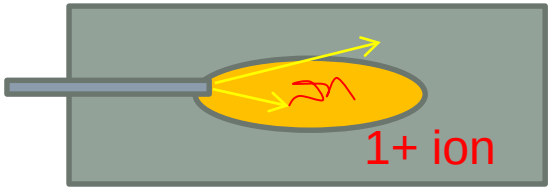
Condensable Ion Beam production in ECR Ion Sources

- The high plasma density of ECR ion Sources features a short mean free path for 1st ionization of atoms: $\lambda_{0\to 1+} \sim 1 - 10\ cm$
- On flight ionization of condensable or refractory atom can be performed by severa techniques in ECRIS
  - **Oven technique**: An miniature oven is inserted in front of the ECR plasma and heated up to the temperature at which a condensable atom evaporates under vacuum
  - **Sputtering technique**: when the evaporation temperature is unreachable, a sample of condensable is introduced inside the plasma which sputters the material. The sample can be biased to negative voltage to increase sputtering yield.
  - **MIVOC technique** (Metal Ions from VOlatile Compounds): condensable atoms are chemically inserted in an organic molecule that is gaseous under vacuum. The gas diffuses to the plasma.
  - **Wall heating**: It is complementary of oven or sputtering technique. A refractory cylindrical metallic liner (Mo, Ta, W) is placed around the plasma chamber with a weak thermal interaction with the water cooled wall. The liner temperature increases due to RF and plasma heating. The sticking time of condensable is reduced, which allows wall recycling and improve the global ionization efficiency.

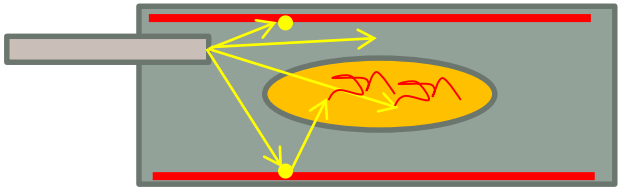
Oven technique



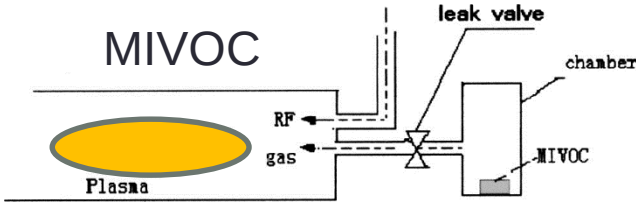
Sputtering technique



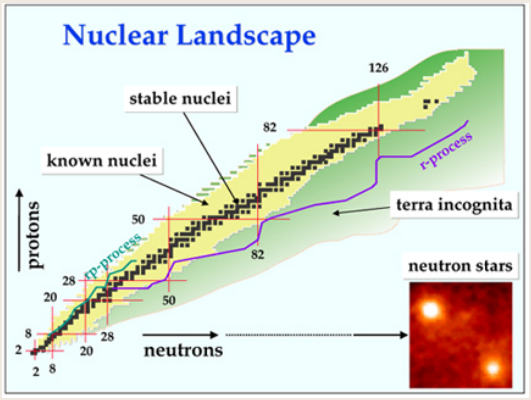
Hot Wall liner



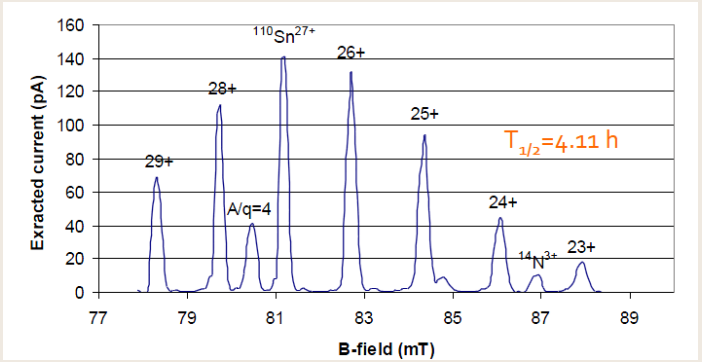
MIVOC



Lanzhou, IMP, china



http://radchem.nevada.edu/

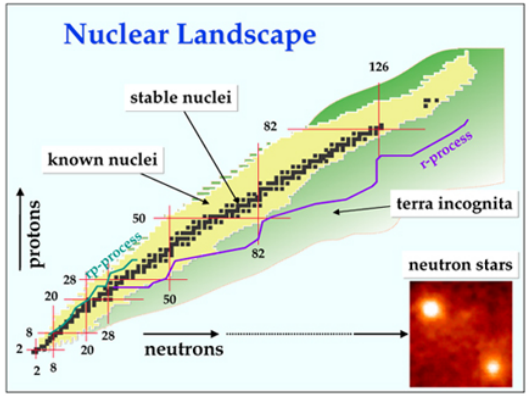


RADIOACTIVE ION SOURCES

An Introduction

Ion Source for Radioactive Ion Beams (RIB) facilities

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



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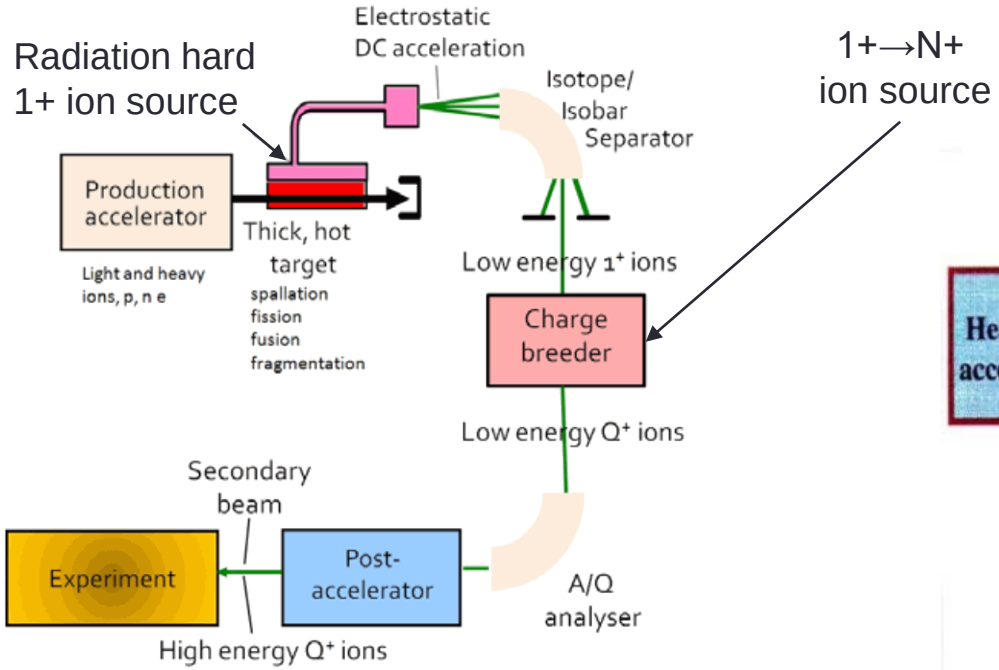
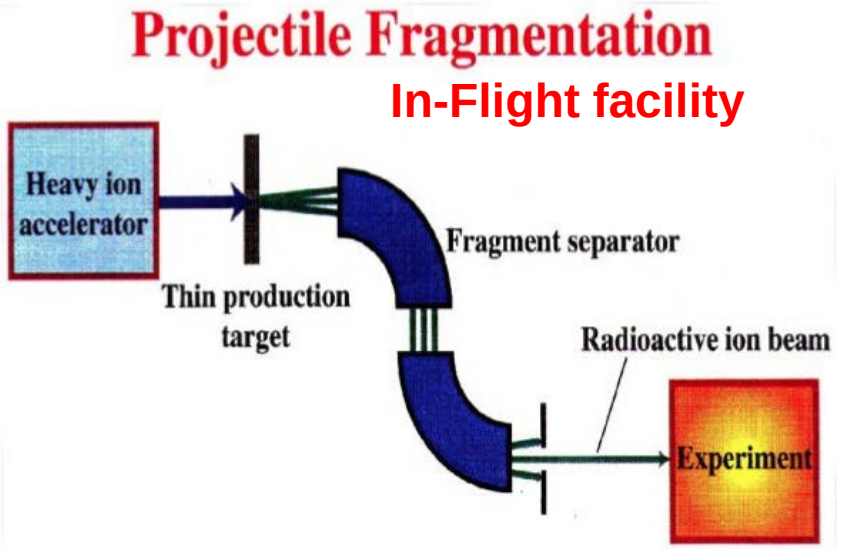


EURISOL, HIE-ISOLDE, SPIRAL2, SPES,…



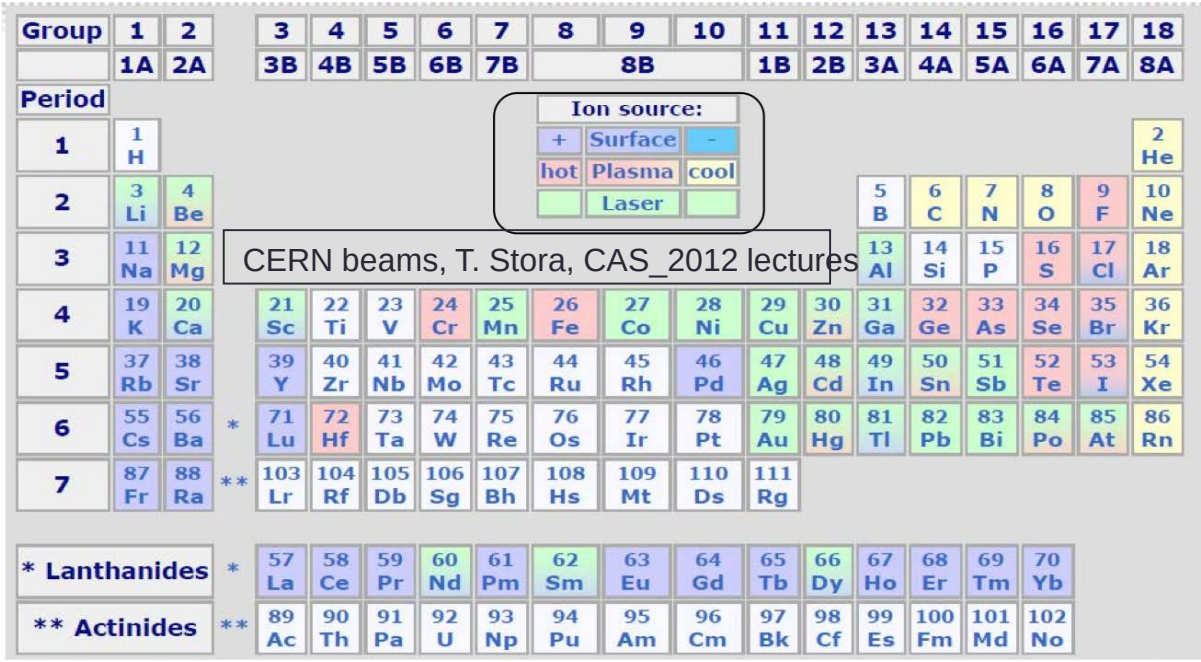
RIKEN RIBF, FAIR

(Slide H. Koivisto, JUAS2013)

1+ Radioactive source for ISOL

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

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



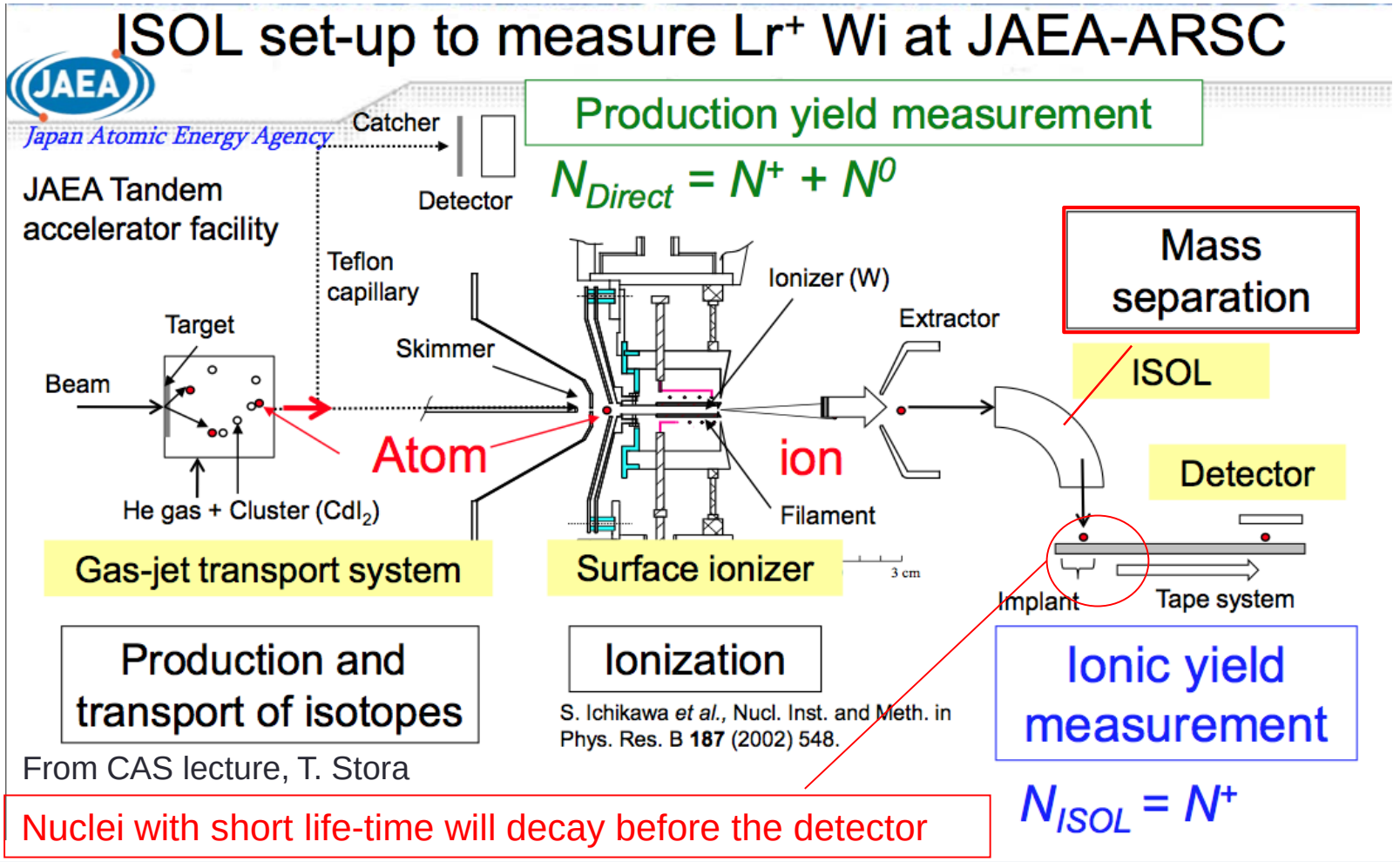
As an example: after the CERN production target, the following 1+ ion sources are mainly used:

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

(Slide H. Koivisto, JUAS2013)

Surface Ion Source with ISOL-target

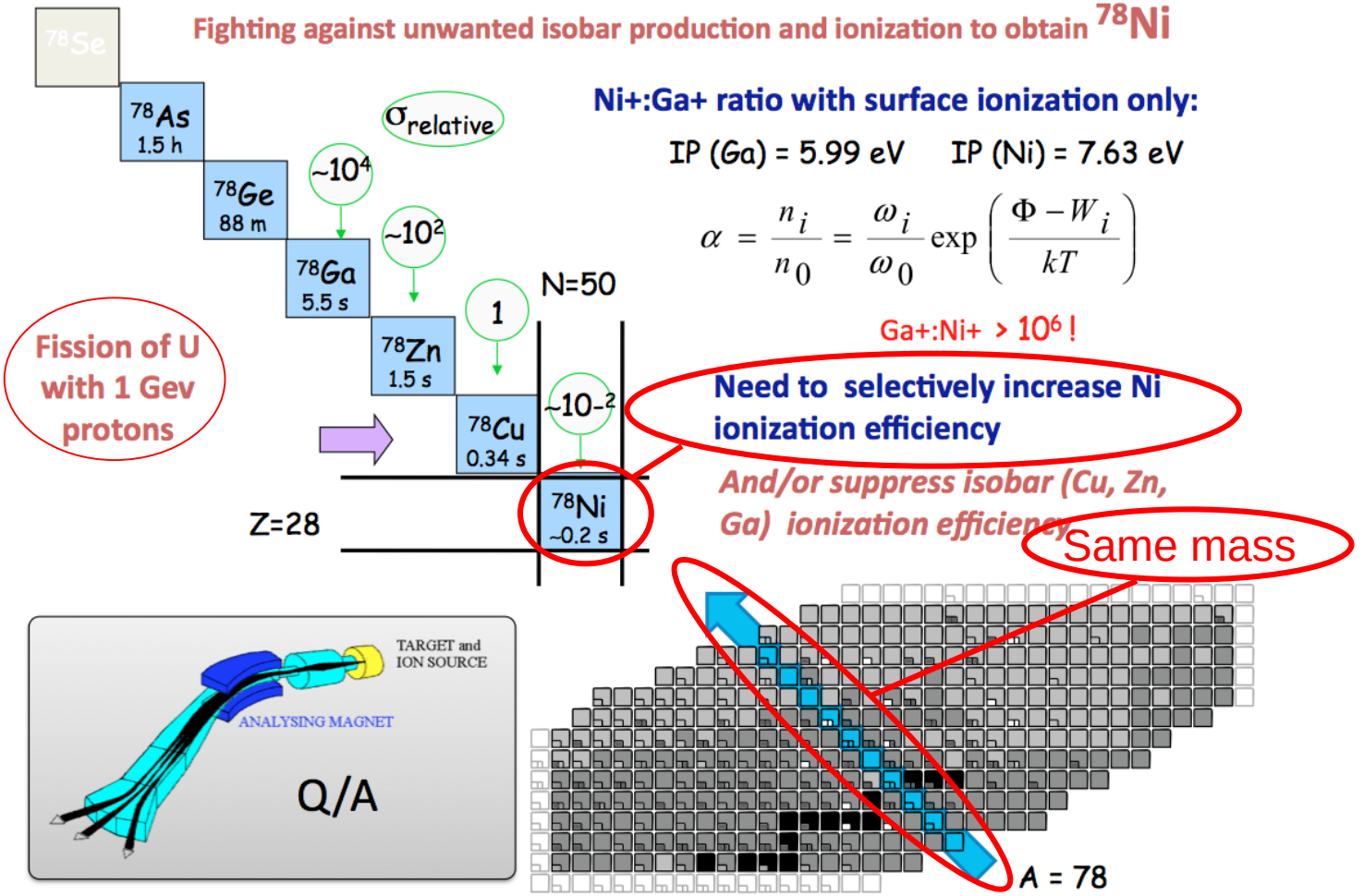
- Production target can produce large variety of different nuclei having the same mass
- Produced 1+ ions having same mass cannot be separated by a dipole magnet
- Some “selectivity” can be made by a tape system



How to separate Iso-mass radioactive atoms?

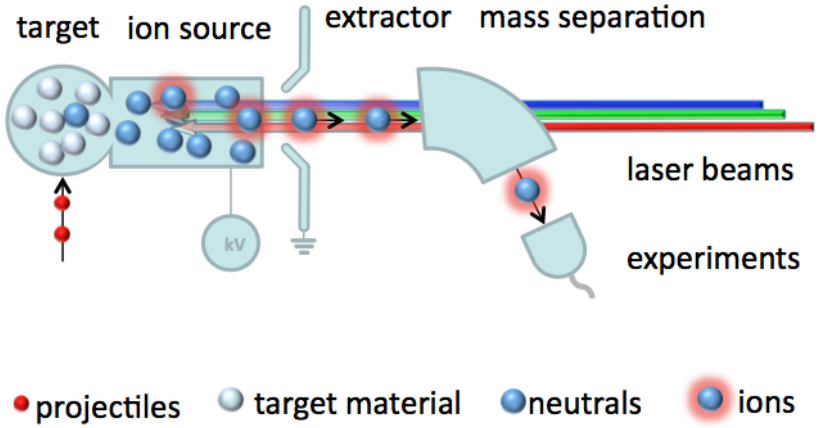
- Sometimes only a very small amount of the element of interest is produced. This is a great problem if other elements having the same mass and higher abundance have been produced! For example:

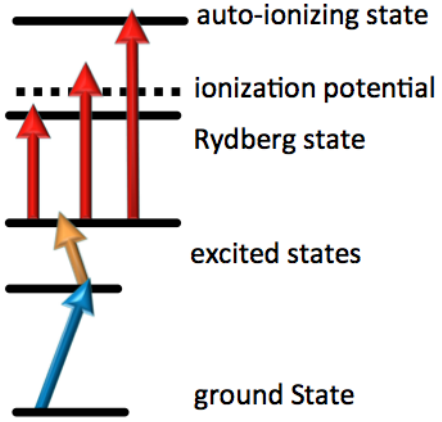
Slide from CAS-Lecture: B. Marsh

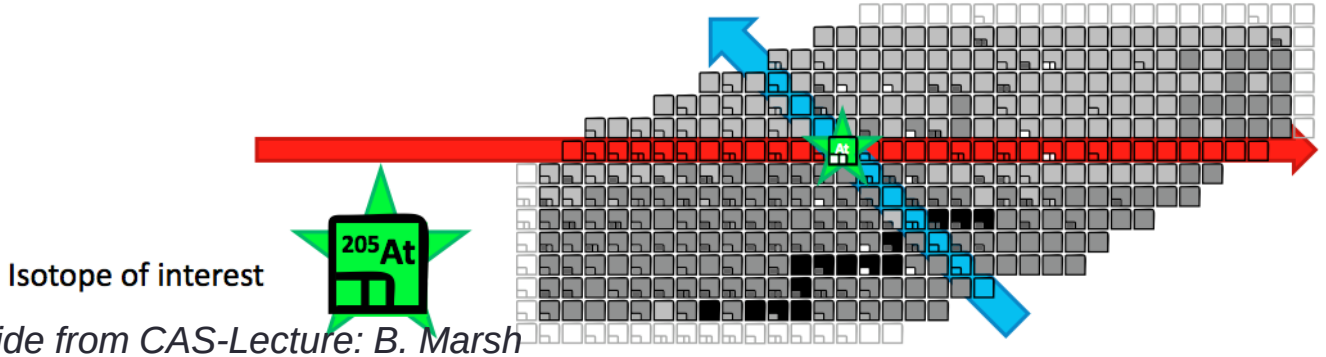


Resonance Ionization Laser Ion Source (RILIS)

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



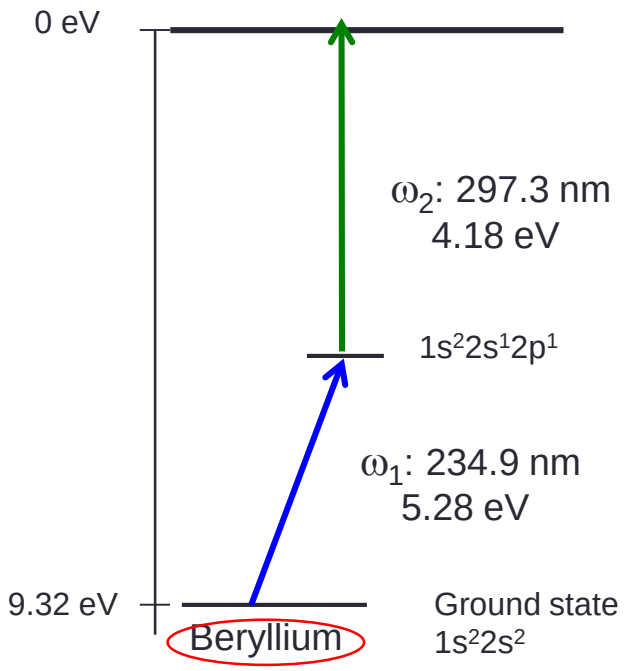




Slide from CAS-Lecture: B. Marsh

Resonance Ionization example

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

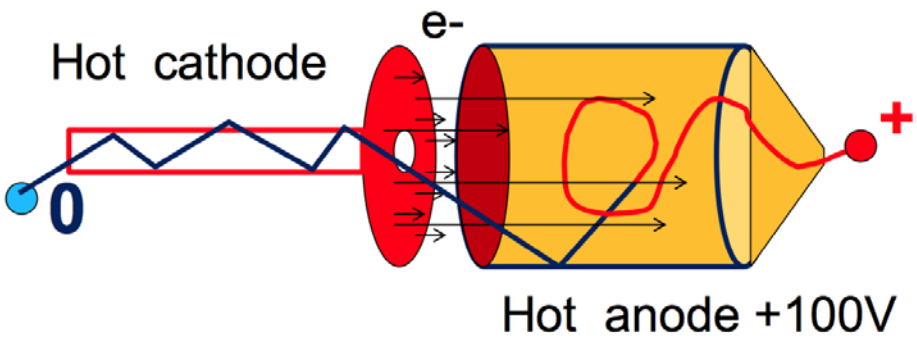


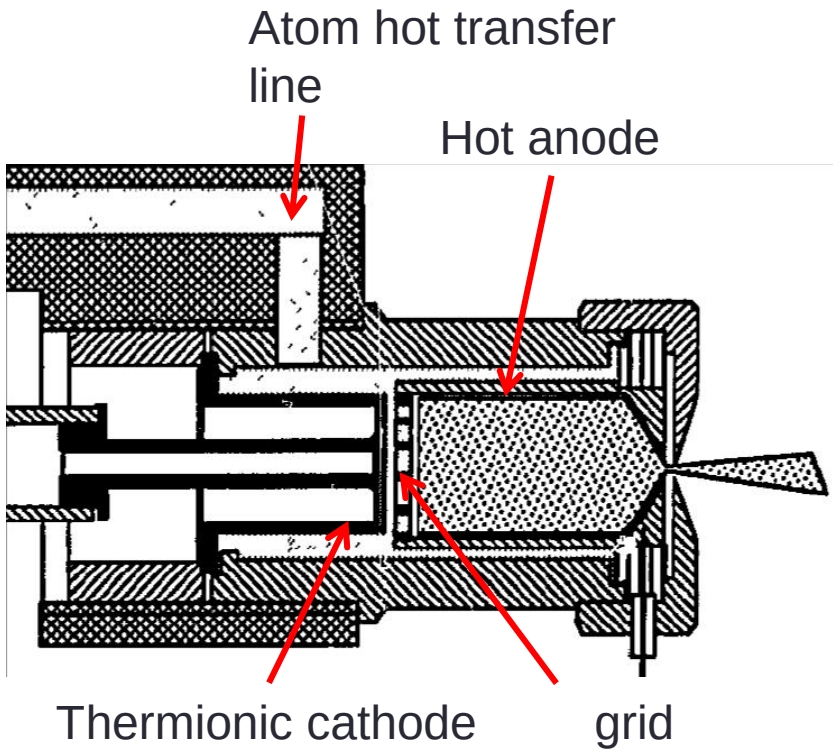
Excitation schemes used at the ISOLDE RILIS. λ_1, λ_2 and λ_3 are the wavelengths of the first, second and third step excitation transition; E_i – atomic ionization energies; η_{ion} – values of ionization efficiency.

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

Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source

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





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

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

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

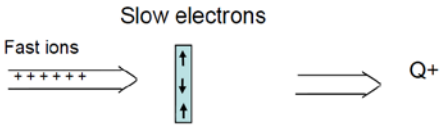
- Motivations to increase the radioactive ion charge state Q:
  - Higher energy reachable
  - Shorter accelerator dimension (COST REDUCTION)
  - Faster transport to the experiment
  - Furthermore, for LINAC, the RFQ radius decreases with the $\frac{Q}{A}$
  - LINAC cost $\sim length \times radius^n \quad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

Source : F. Wenander, CAS 2012

The 3 Charge breeding techniques

Carbon foil at CERN LINAC3

- Stripper foil

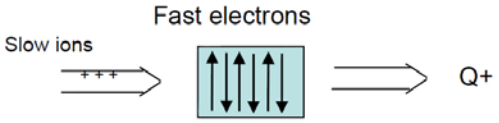


  - A foil is placed in the beam to multiionize the beam
    - Several charge states extracted
    - Mean charge state function of the beam velocity
    - Work with high currents, but Emittance increase
    - Not discussed here

Charge breeding Yield:

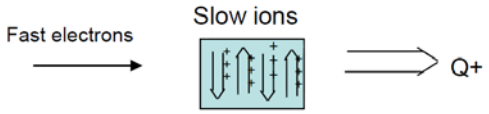
$$\eta = \frac{I(q+)}{q.I(1+)}$$

- ECR charge breeder



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

- EBIS charge breeder

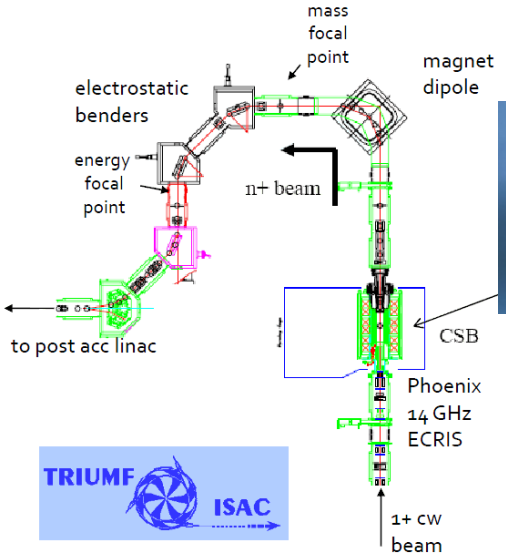


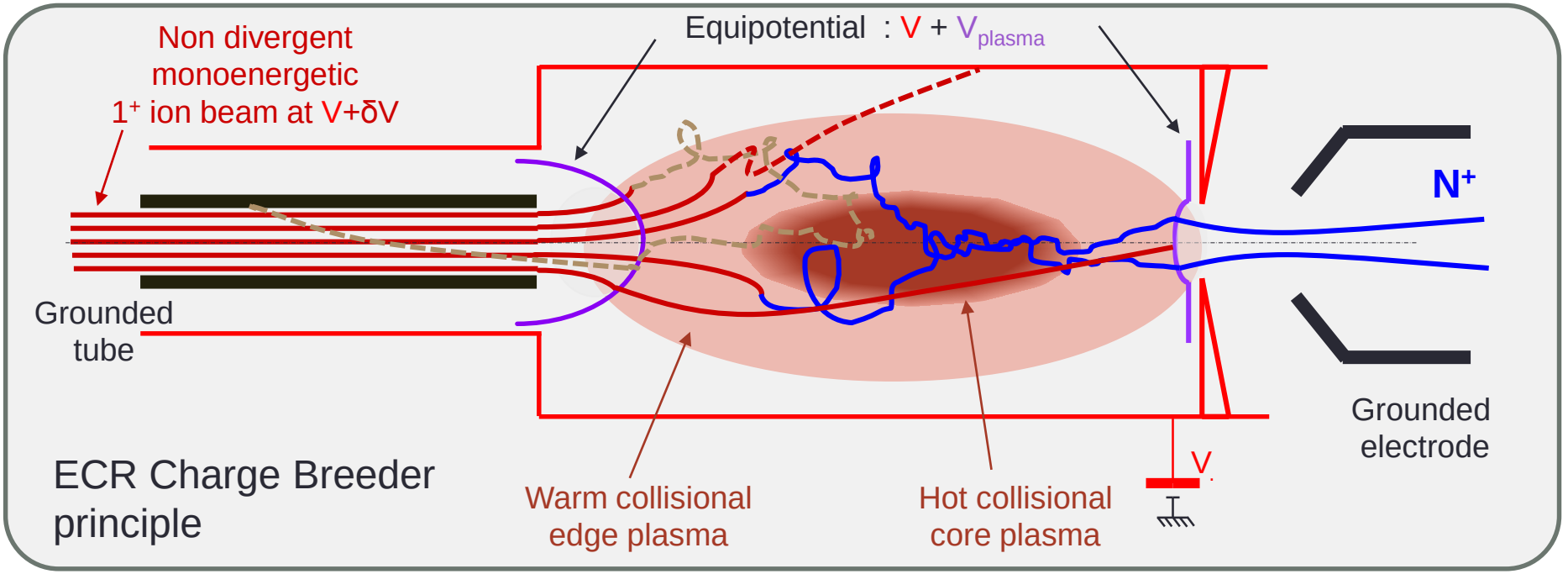
  - A decelerated 1+ beam is trapped in an EBIS and crossed an intense electron beam

Partial source : F. Wenander CAS 2012

ECR charge breeder

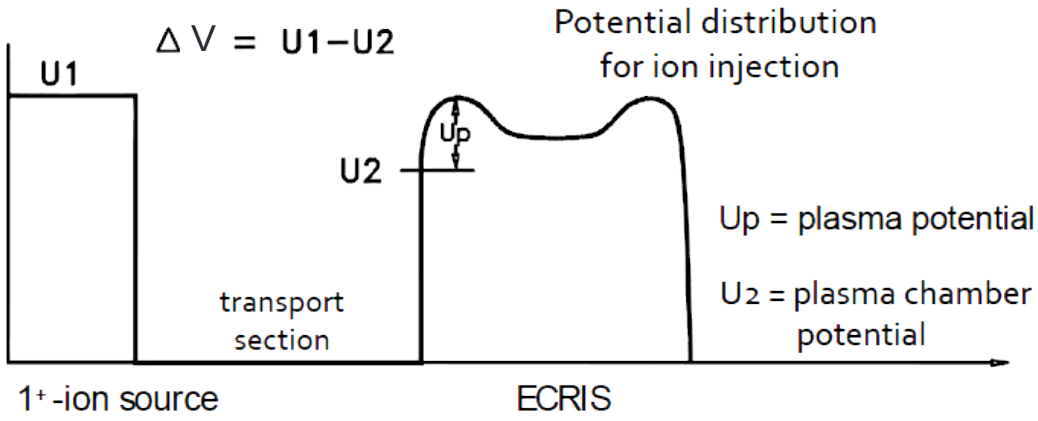
- Ions are decelerated down to a few eV and cross slowly a $10^{12}\ e^{-}/cm^{3}$ plasma with hot electrons
  - Ions are naturally decelerated to the ion plasma temperature
  - Ions collide with other ions (coulomb collision) and scatter => memory loss
  - Ions are ionized on flight
  - Ions are captured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

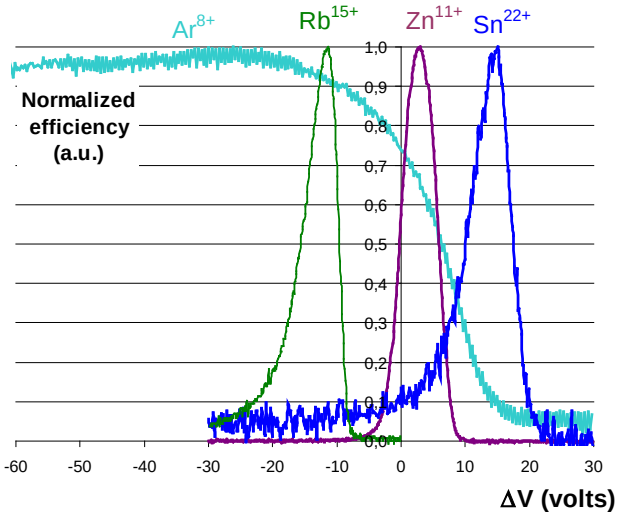




ECR Charge breeder

- Optimization of ion beam capture: ΔV plot





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

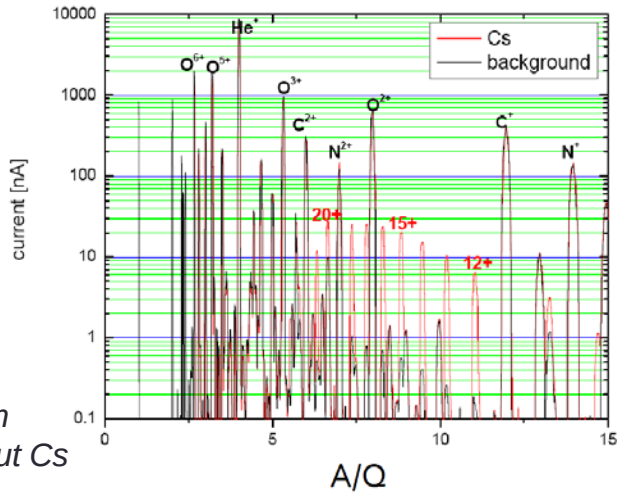
Source : F. Wenander CAS 2012

ECR Charge Breeder features

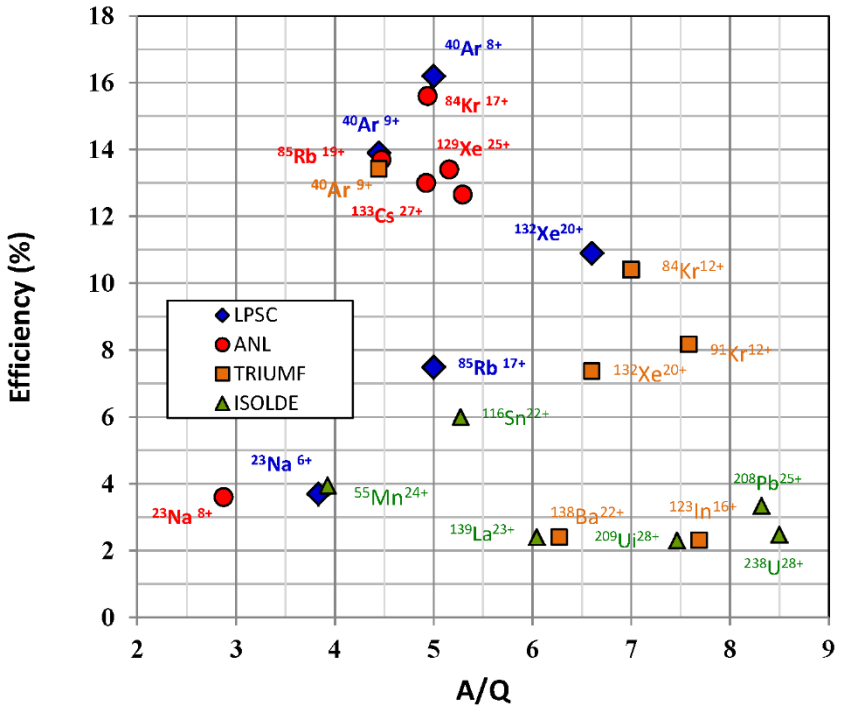
- 1+ beam intensity up to ~100 eμA
- Continuous Work operation
- Breeding time ~ 3-10 ms/charge
- Breeding efficiencies in the range : $\eta \sim 2 - 18\%$
- Extracted beam contaminated by any chemical species present in the source and vacuum (source operation at 10^{-7} mbar)
  - C,N,O,H,Fe,Cu,Al,Ar,Kr,Xe…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

Charge breeding Yield:

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



Extracted beam
With and without Cs

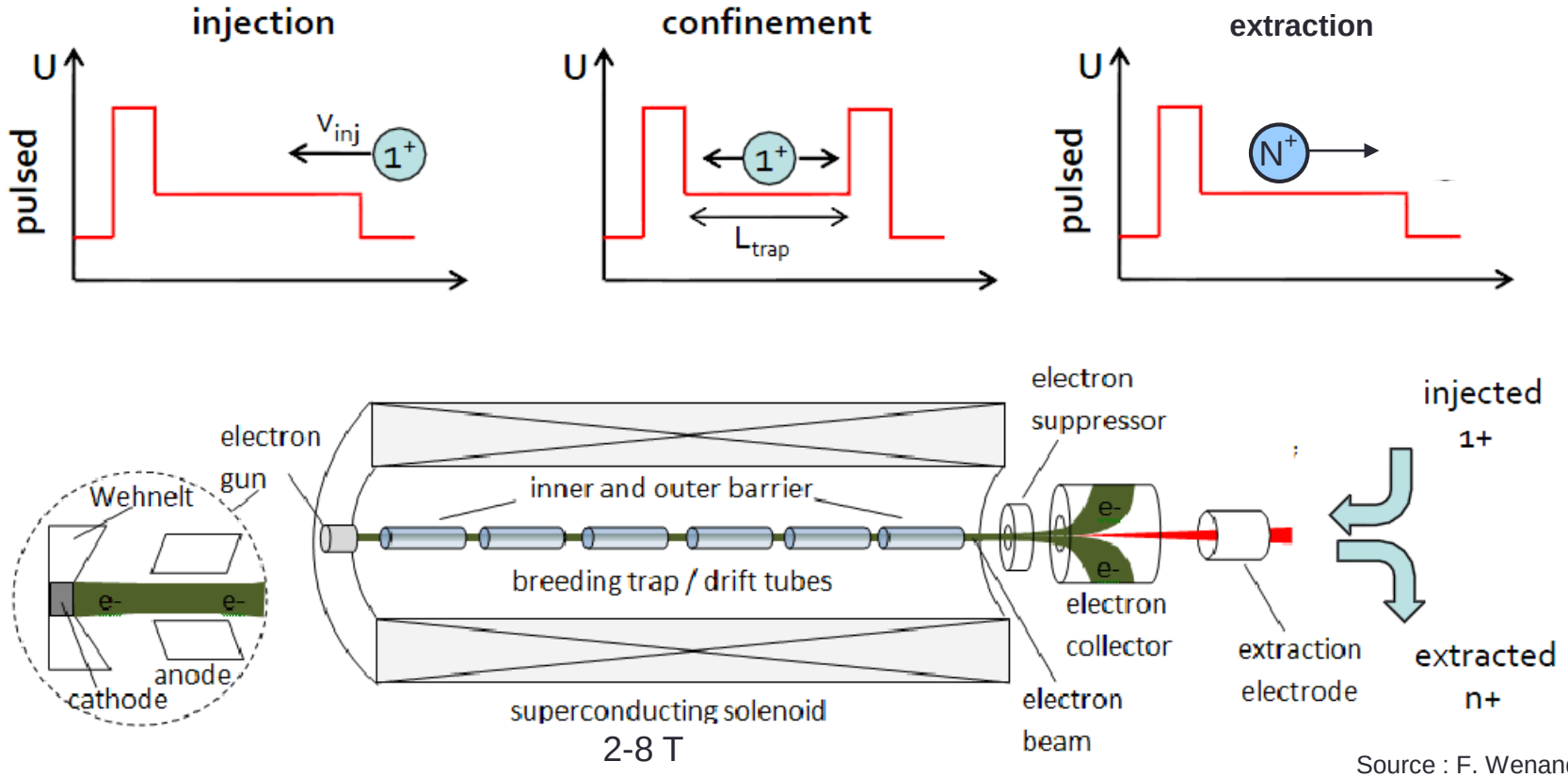


Typical Experimental ECR CB efficiencies

Source : F. Wenander CAS 2012

EBIS Charge Breeding

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

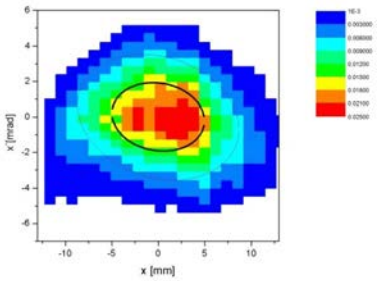


Source : F. Wenander CAS 2012

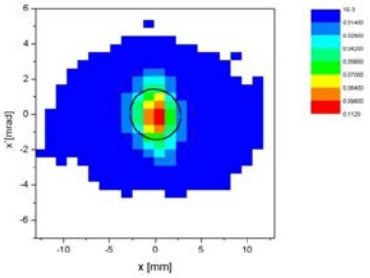
Ion cooling Prior to EBIS injection

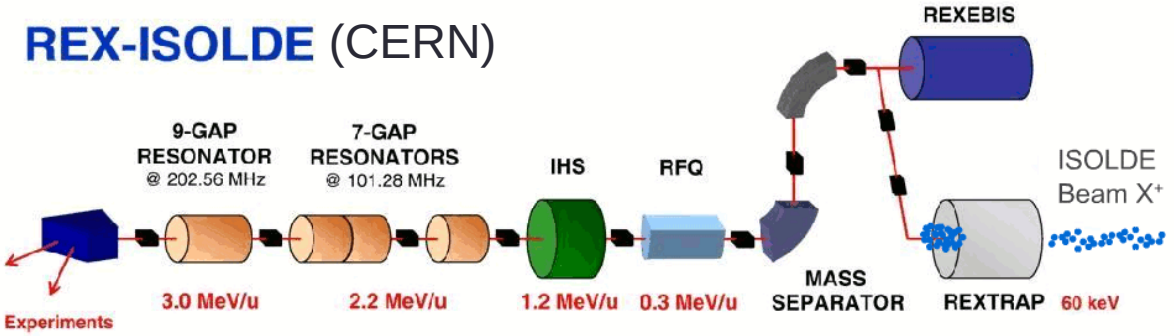
- Prior to EBIS injection, the 1+ RIBs needs to pass throught a Penning trap to:
  - Accumulate the beam
  - Bunch the beam
  - Cool down the ions to reduce the emittance

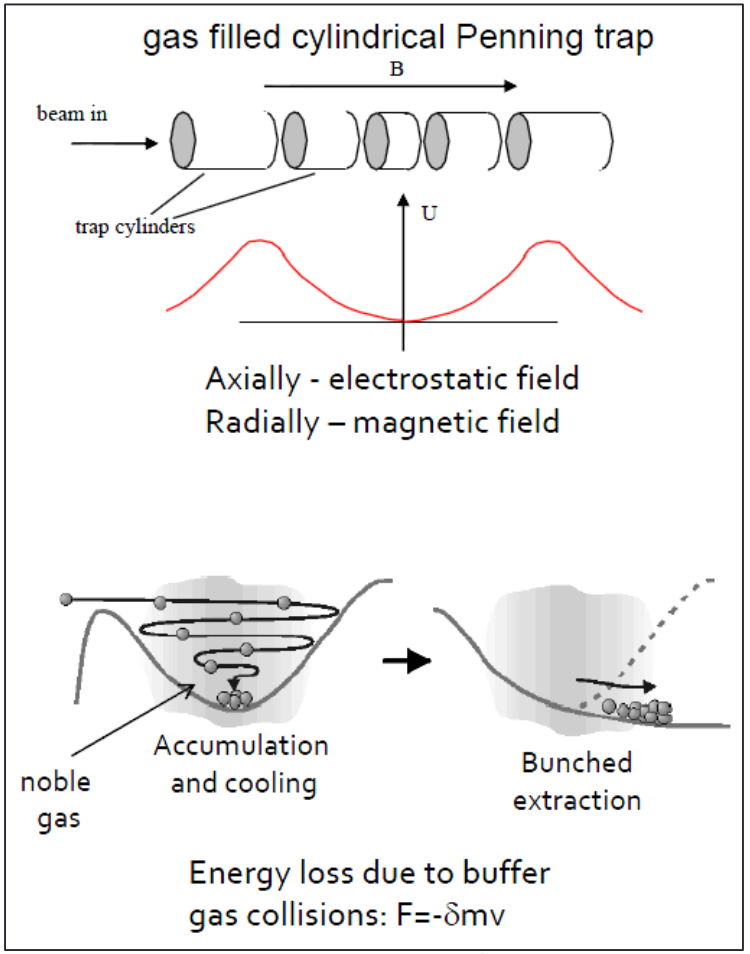
Non cooled



Cooled







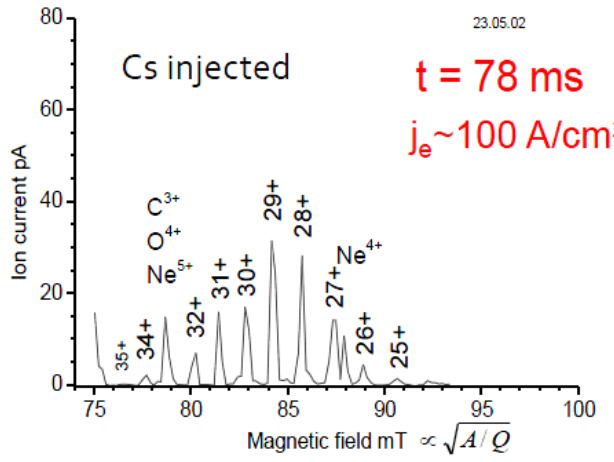
Source : F. Wenander CAS 2012

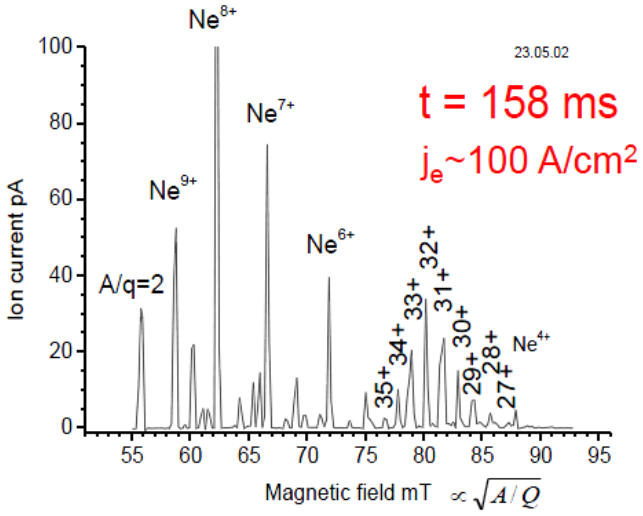
EBIS charge breeder features

Charge breeding Yield:

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

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





Source : F. Wenander CAS 2012

Element of Bibliography

- J.R. Pierce, Theory and Design of Electron Beams, Van Nostrand Company, 1954
- S. Schiller, U. Heisig, S. Panzer, Electron beam technology, John Wiley & Sons Australia, Limited, 1982
- Low Emittance Thermionic Electron Guns, SLAC-PUB-4843, January 1989
- V. M. Aguero and R. C. Adamo, 6th Spacecraft Charging Technology Conference, AFRL-VS-TR-20001578, 1 September 2000
- Ultra Low Emittance Electron Gun Project for FEL Application THP27, Proceedings of LINAC 2004, Lübeck, Germany, www.jacow.org
- Beam characterization for the field-emitter-array cathode-based low-emittance gun, S. C. Leemann,A. Streun, and A. F. Wrulich, Phys. Rev. Special Topics - Accelerators and Beams 10, 071302 (2007)
- K.L. Jensen et al., Jour. Appl. Phys. 107, 014903 (2010) (electron source emittance
- D.H. Dowell, USPAS 2008, January, High Brightness Electron Injectors for Light Sources
- A. Hawari, D. Gidley, J. Xu, J. Moxom, A. Hathaway, B. Brown, R. Vallery; "The Intense Slow Positron Beam Facility at the NC State University PULSTAR Reactor"; Application of Accelerators in Research and Industry; 20th International Conference; 2009
- L. Rinolfi, R. Chehab, O. Dadoun , T. Kamitani, V. Strakhovenko, A. Variola, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **309** (2013) 50-55
- Ian G. Brown - The Physics and Technology of Ion Sources, Wiley & Sons,ISBN 3-527-40410-4
- R. Geller, Electron Cyclotron Resonance Ion Sources,ISBN 0-7503-0107-4
- F. Wenander, CAS 2012, Senec, Charge Breeding of Radioactive Ions