

JOINT UNIVERSITY ACCELERATOR SCHOOL

PARTICLE SOURCES

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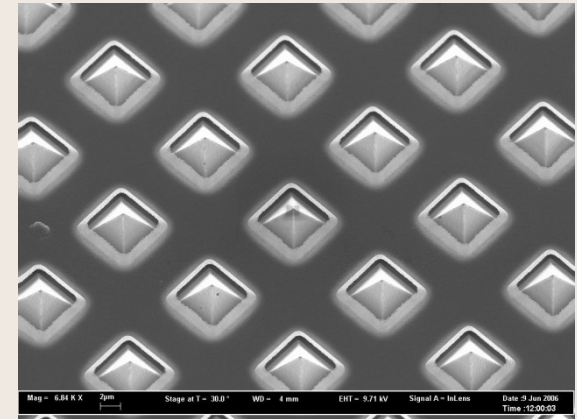
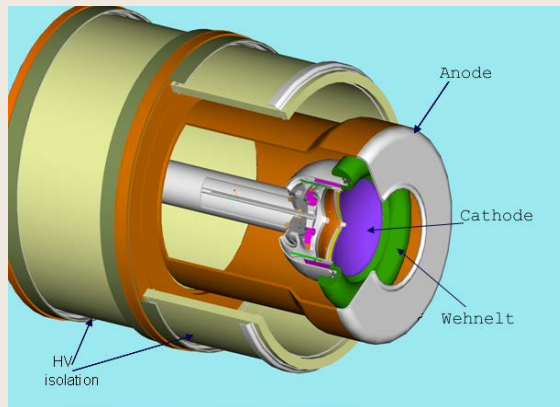


OUTLINE

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- TUTORIAL

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 one hour lecture...
- So...It is **IMPOSSIBLE** to give a detailed overview of the topic within a 3H 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 explain on which physic concept they are relying

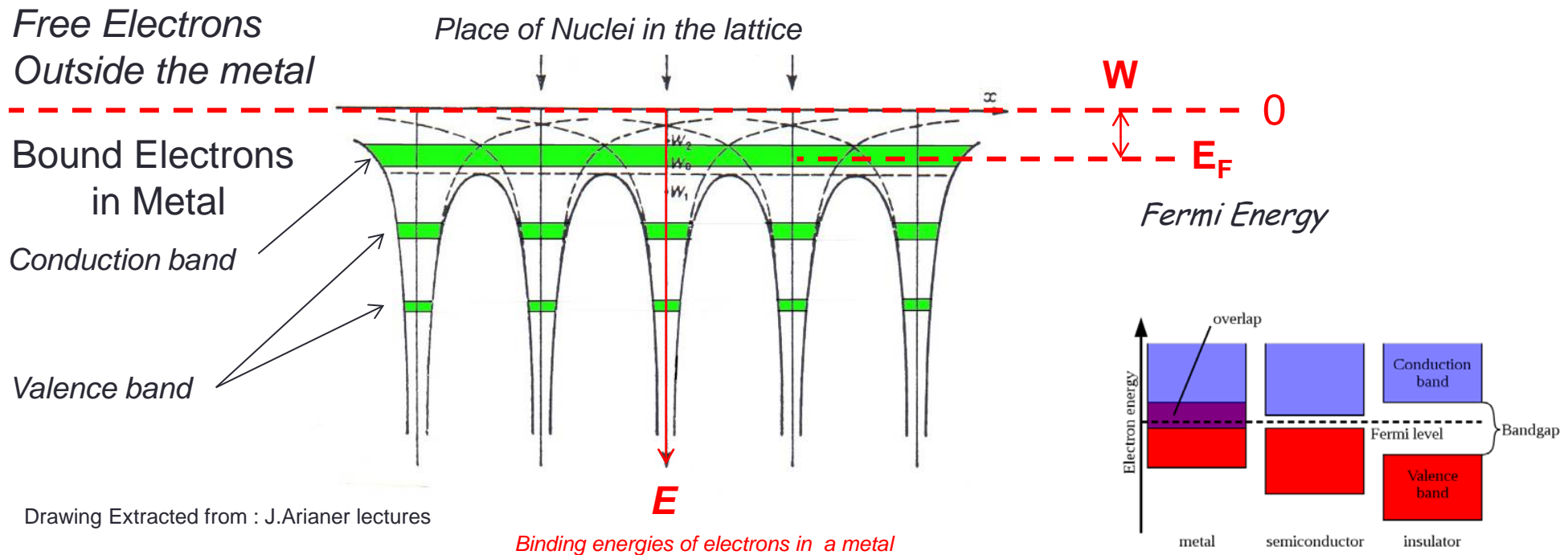


ELECTRON SOURCES

Introduction to Electron and positron sources

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 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: $W = E_F$ (when $T = 0$ Kelvin). So $W < E_F$ when $T > 0$.



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.

Max.

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				

Min.

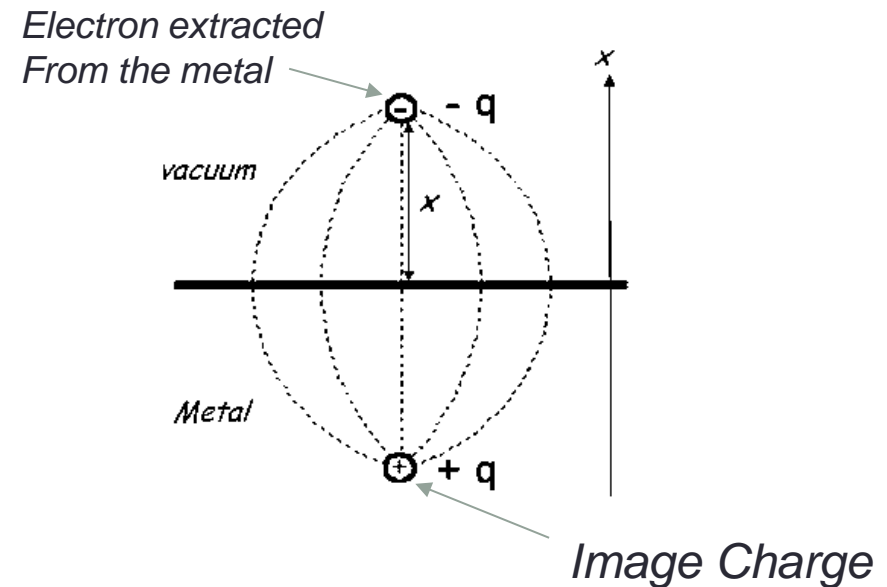
Distorsion of the electrical potential near to a metallic surface (1/2)

- The Image charge
- When an electron ($-q$ charge) is extracted from a metal, a $+q$ image charge (hole) is created in the metal that screens exactly the electric field generated by the electron at the metal surface (at $x=0$)
 - The Electric Field $E(x)$ generated by the charge image (hole) acting on the electron is:

$$E(x) = \frac{+q}{4\pi\epsilon_0} \frac{1}{(2x)^2}$$

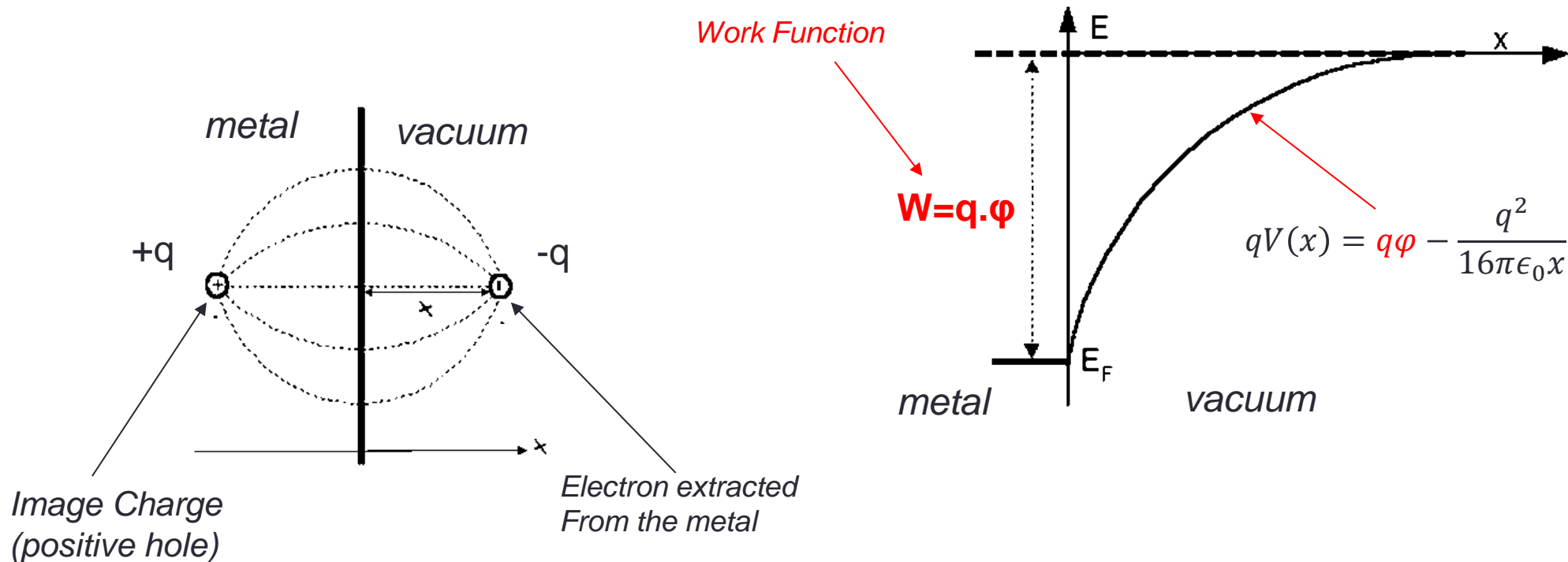
- This electric field tends to attract back the electron toward the metal
- The Associated potential energy $V_{CI}(x)$ is:

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



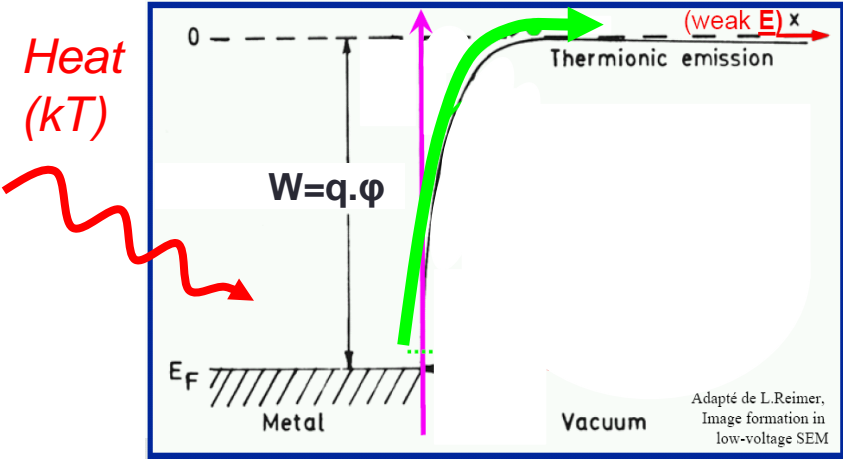
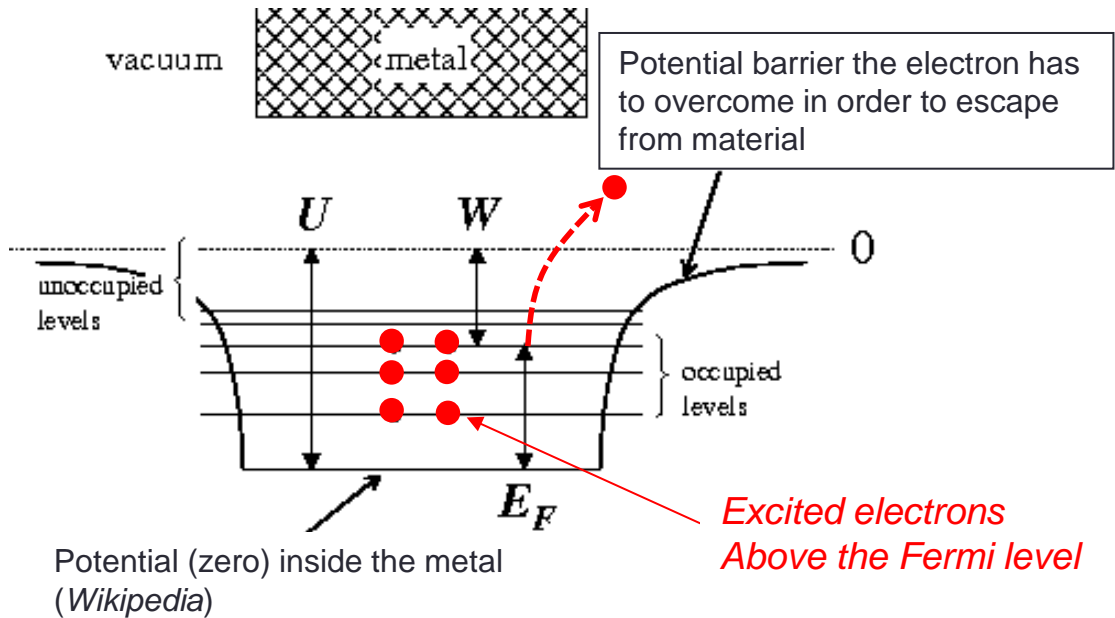
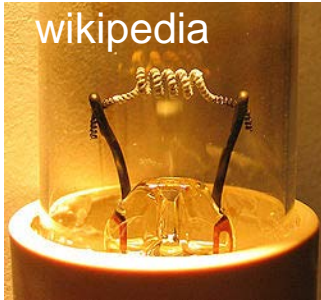
Distorsion of the electrical potential near to a metallic surface (2/2)

- The image charge changes the electrical potential profile near to the metallic surface



Thermionic emission of electrons

- A first way to extract electrons is to heat the metal to a high temperature T
 - When the metal is heated, the thermal vibrations of the atoms are randomly transferred to some electrons ($E \sim kT$) which can populate excited states
 - Electrons are finally kicked out of the metal when their final energy is higher than the Work Function : $E > W$
- **The thermionic emission** is the resulting flow of electrons extracted from the heated metal
- The application of a negative voltage (weak E field) helps electron extraction from the metal surface



Current density of Thermionic emission

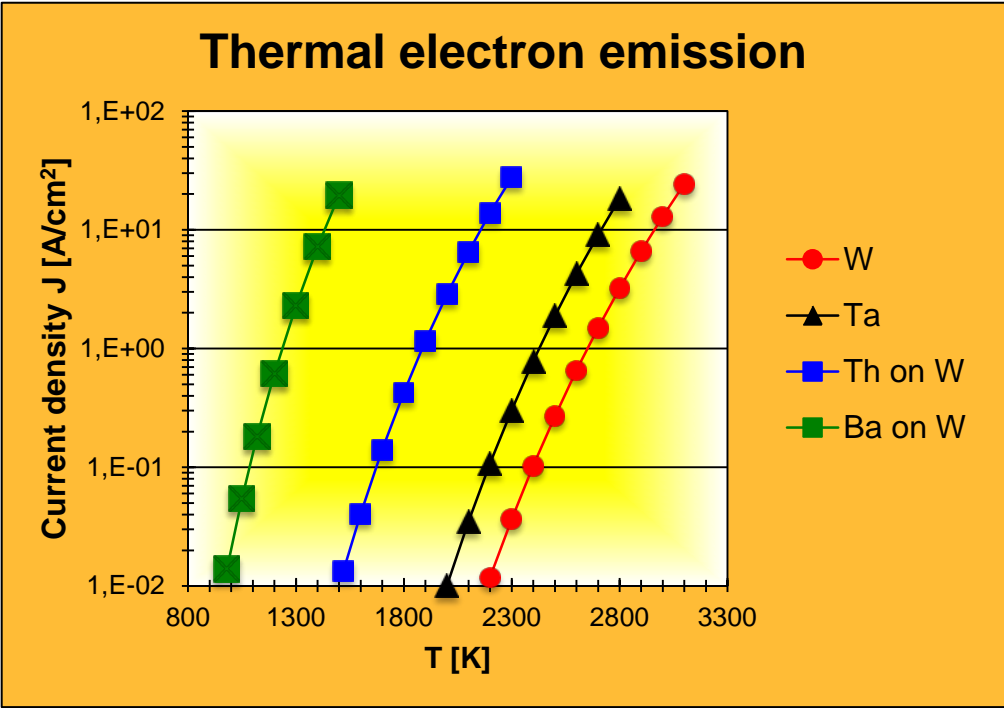
- The Thermionic emission flow is ruled by the Richardson-Dushman formula
 - **J** current density (A/cm²)
 - **A** Richardson constant
 - **W** = q.φ work function
 - **T** temperature
- Order of magnitudes :
 - Wolfram : W_w~4.5 eV ; Tw~2900 K → J~10 A/cm²
 - LaB₆ : W_{LaB6}~2.4 eV ; TLaB₆~2100 K → J~102 A/cm²

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

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

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	2.7	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 an external electric field E is applied to the hot cathode

• This is the case for thermionic guns since cathodes are negatively biased

$qV_S(x) = q\phi - \frac{q^2}{16\pi\epsilon_0 x} - qE \cdot x$

Modified potential Work function Image charge (slide 7)

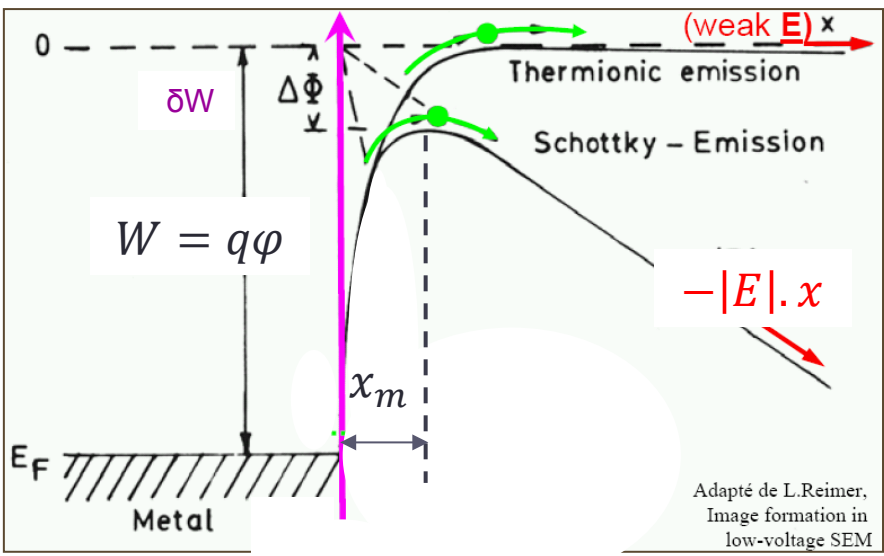
- The work function is reduced by $\delta W = \sqrt{\frac{q^3 E}{4\pi\epsilon_0}}$
- The distance to the peak potential is $x_m = \sqrt{\frac{q}{16\pi\epsilon_0 E}}$

• Modified Richardson-Dushman formula:

$J = AT^2 e^{\frac{-(W-\delta W)}{kT}}$

• Shottky effect is usually a second order effect:

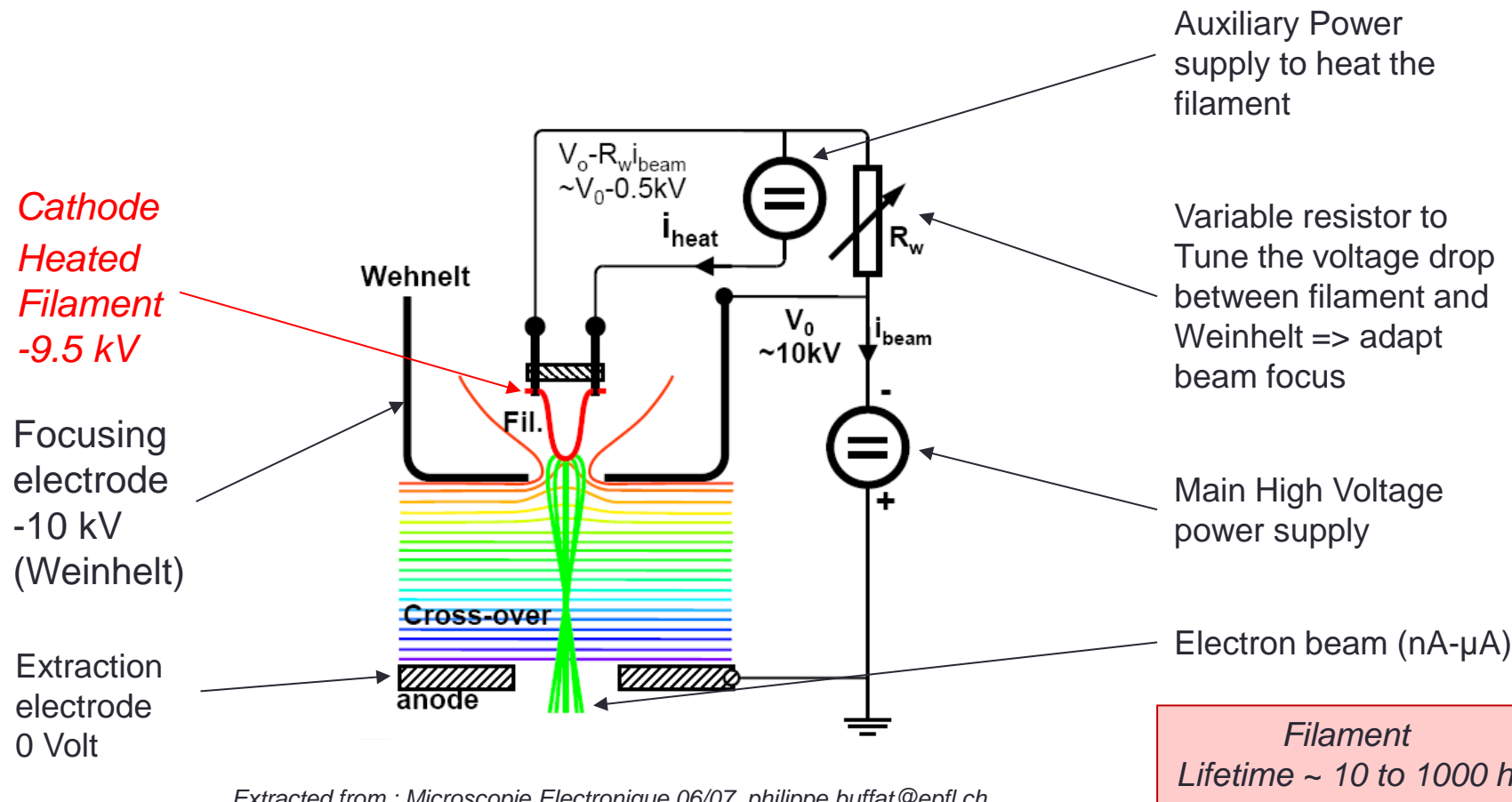
- $E = 10 \frac{kV}{cm} \rightarrow \delta W = 30 meV$ and $x_m \sim 190 \text{ \AA}$
- $E = 100 \frac{kV}{cm} \rightarrow \delta W = 100 meV$ and $x_m \sim 60 \text{ \AA}$
- Schottky Effect valid up to $E \sim 1 \frac{MV}{cm} \rightarrow \delta W = 0,3 eV$ and $x_m \sim 19 \text{ \AA}$



Adapté de L.Reimer, Image formation in low-voltage SEM

The Thermionic Electron Source

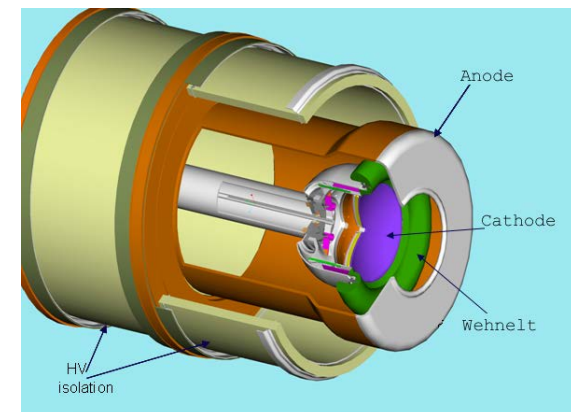
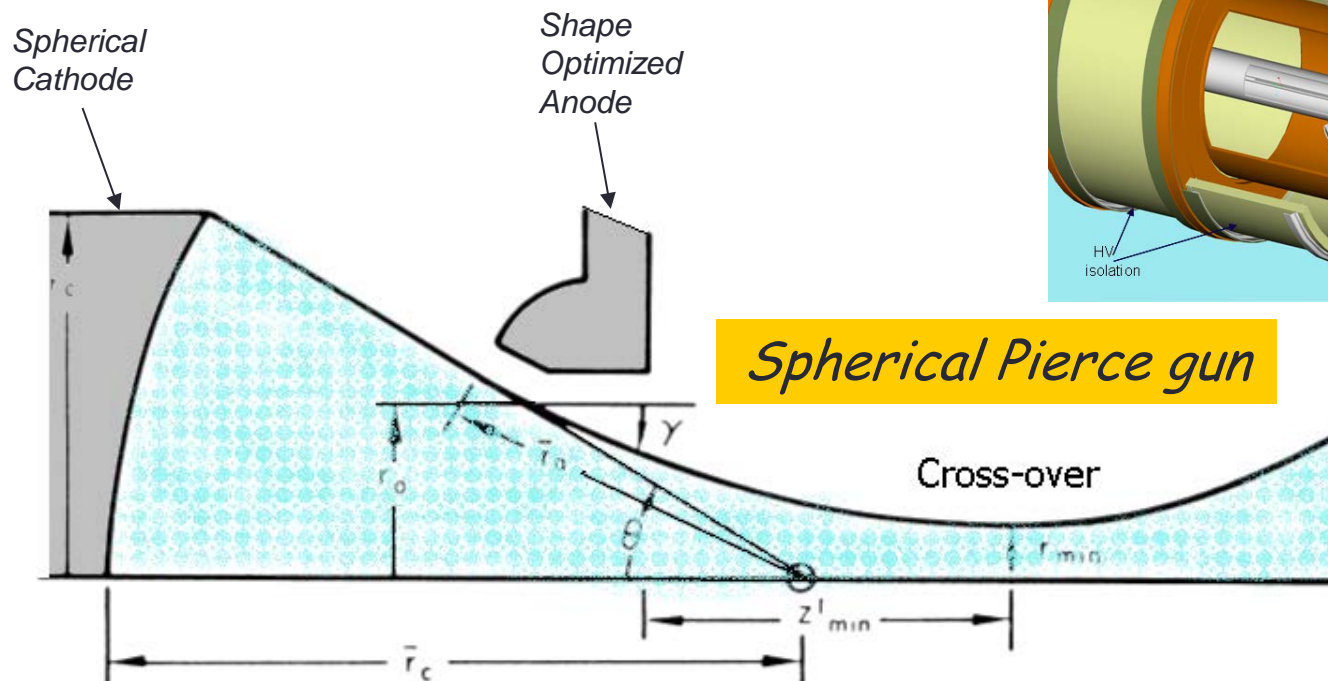
- A very common electron source used in industry and research
 - klystron, TV tubes, electronic microscope, accelerator...
- Example of an electronic microscope source:



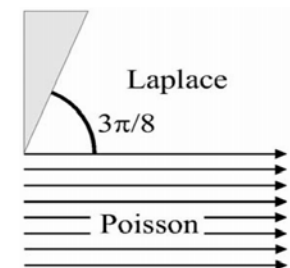
Extracted from : Microscopie Electronique 06/07, philippe.buffat@epfl.ch

High Intensity Thermionic Electron Gun

- The electronic current is increased by increasing the cathod surface
 - Depending on the design, the beam intensities span from $\sim \mu\text{A}$ to $\sim 100\text{ A}$
- « 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



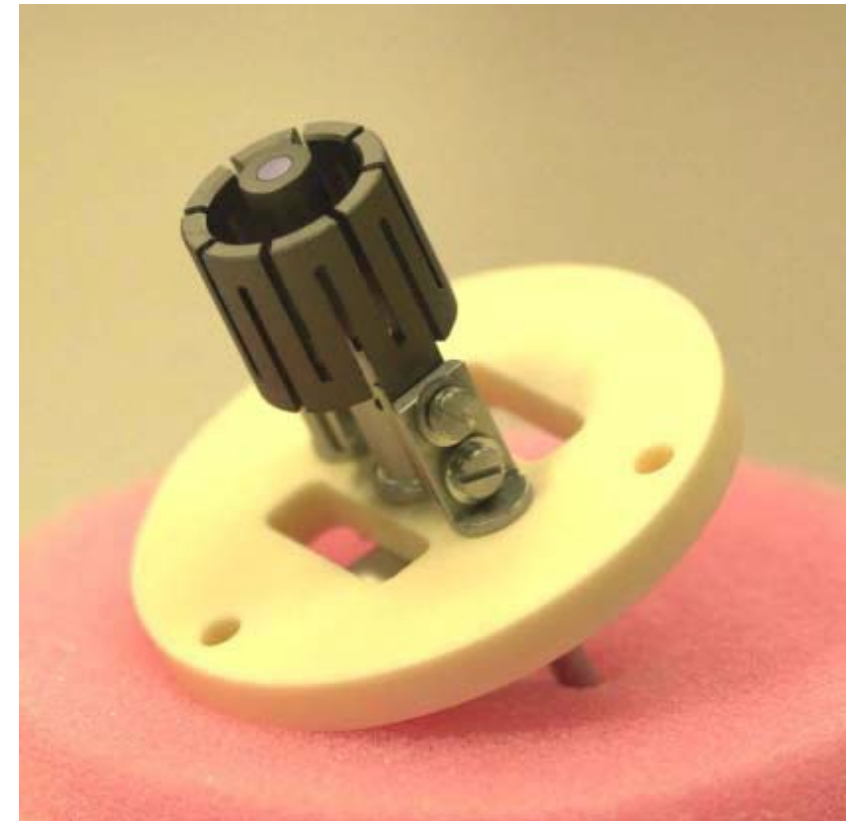
Pierce Angle
For a flat gun

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 μ sec
Repetition Rate	60 Hz
Cathode Temperature	1400~1600 deg.C
Cathode Diameter	3mm
Theoretical Thermal Emittance (rms)	0.4 π mm.mrad
Measured Normalized Emittance (rms, 90% particles)	0.6 π mm.mrad [7]



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

H. Tanaka et al., FEL06, 769

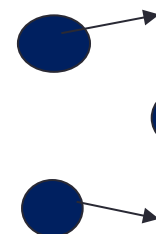
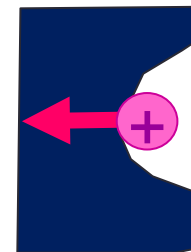
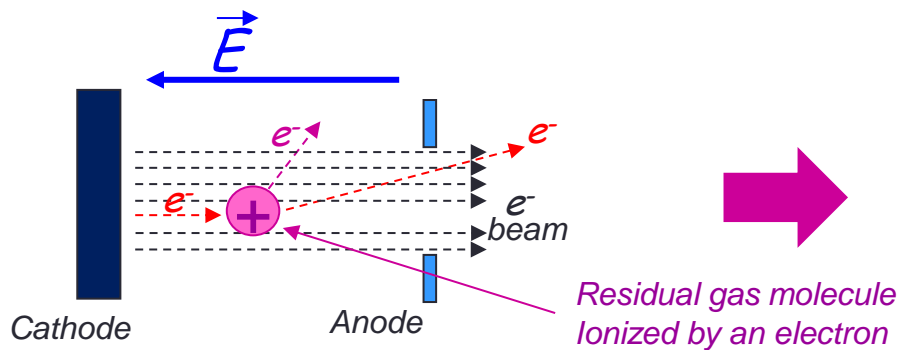
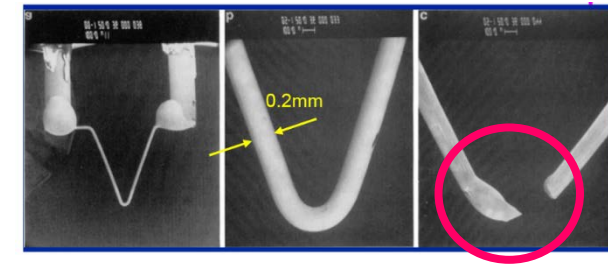
Slide extracted from Brookhaven lecture on cathode physics, M. Poelkerand and J. Smedley

Cathode and filaments aging

- 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 $10^2 \sim 10^4$ hours



cathodes damaged by sputtering



Sputtering effect :
The Cathode bombardment
expels atoms from
the cathode

Electron Field Emission

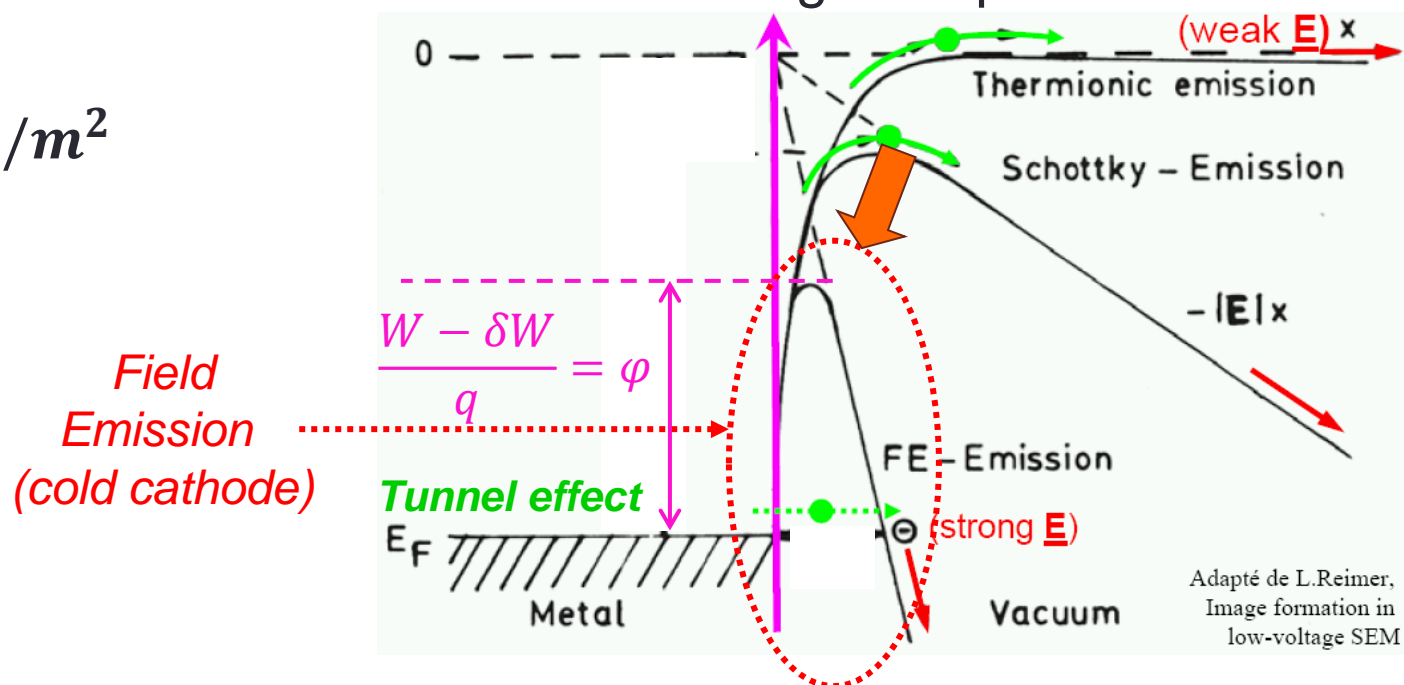
- In the presence of a very **strong electric field** ($E > 10 \text{ MV/cm}$), the working barrier is thin enough to allow electron emission through Tunnel Effect
- The associated emission is ruled by the Fowler-Nordheim theory (quantum physics)
- It is a **cold cathode emission** => no metal heating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

$$J \approx \frac{k_1 E^2}{\phi} e^{-\left(\frac{k_2 \phi^{3/2}}{E}\right)} \text{ A/m}^2$$

- $k_1 = 1.4 \cdot 10^{-6} \text{ (SI)}$

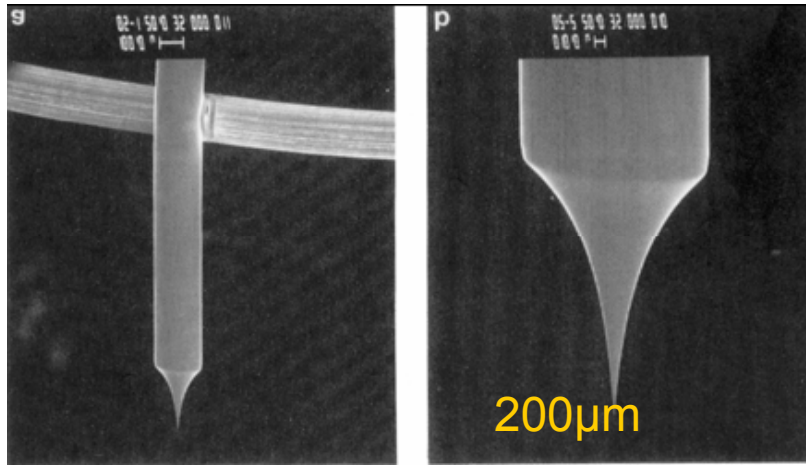
- $k_2 = 6.87 \cdot 10^7 \text{ (SI)}$

- $J \sim 1 \text{ MV/cm}^2$!

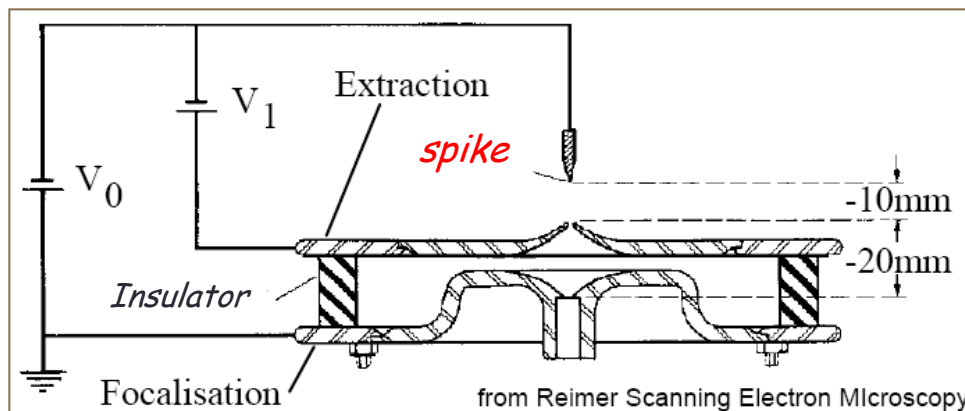


Field Emission Electron Source (electronic microscopy)

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)



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

Electrostatic Point effect (Corona)

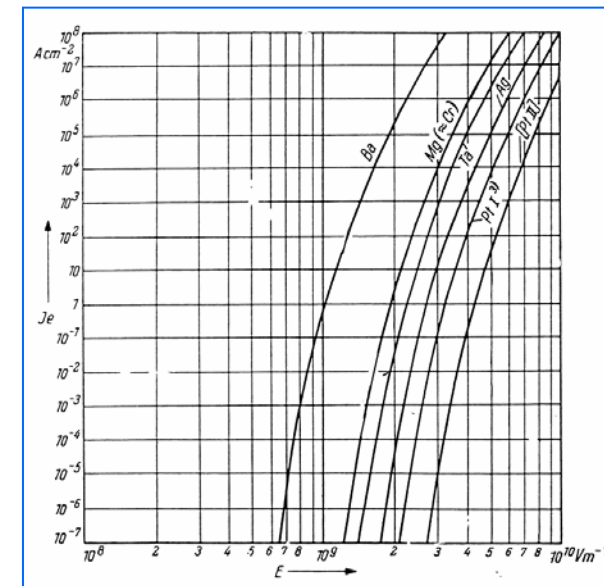
2 Spheres with radius $R > r$
Same potential V

R Q r q

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

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

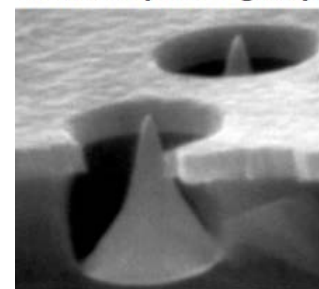
$$\Rightarrow E_2(r) = E_1(R) \cdot \frac{R}{r}$$



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 heating and space charge effects (check with packing density of up to $5 \cdot 10^7$ tips/cm², 1 - 100 μ A/tip)

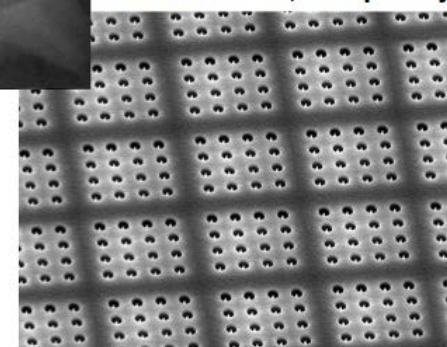
a. Close-up of single tip



1 μ m

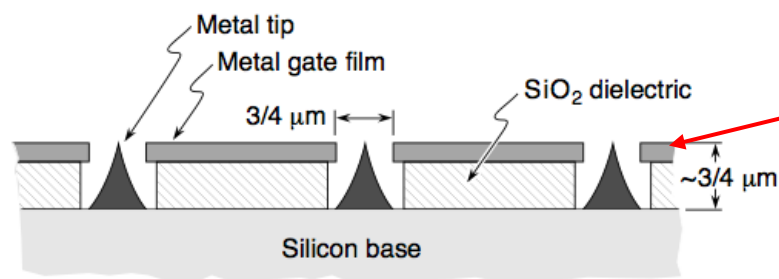
V. M. Aguero and R. C. Adamo,
6th Spacecraft Charging
Technology Conference,
AFRL-VS-TR-20001578, 1
September 2000

b. Portion of 10,000-tip array



10 μ m

v99-076/f1



The emission level is controlled by adjusting the gate voltage (< 100 V)

- Capacity of up to 100 μ A/tip has been demonstrated!

Slide adapted from H. Koivisto



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 μ A, due to:
 - Thermal desorption of atoms inducing contamination, sputtering
 - Even destructive arcing if the pressure degrades too much
- **The pulsed operation is very promising**
 - Stable operation, no thermal issues
 - High current density
 - Small intrinsic cathode emittance

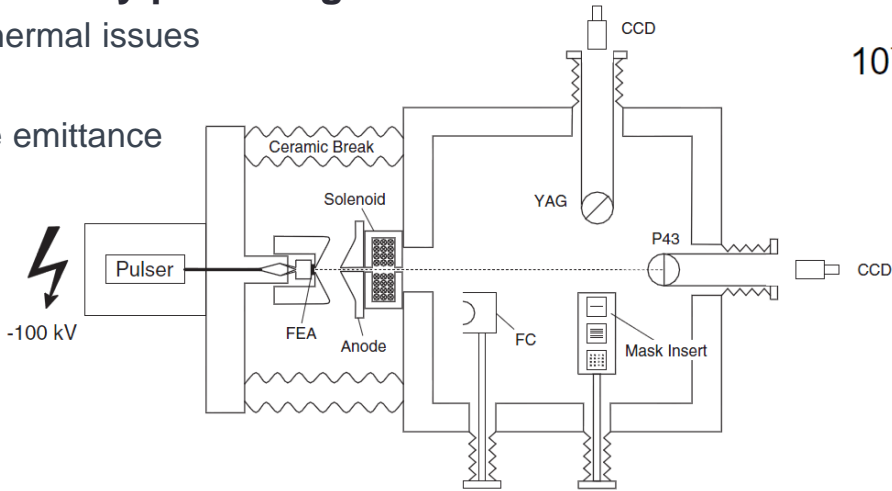


FIG. 1. Schematic overview of the 100 keV gun test stand (not to scale).

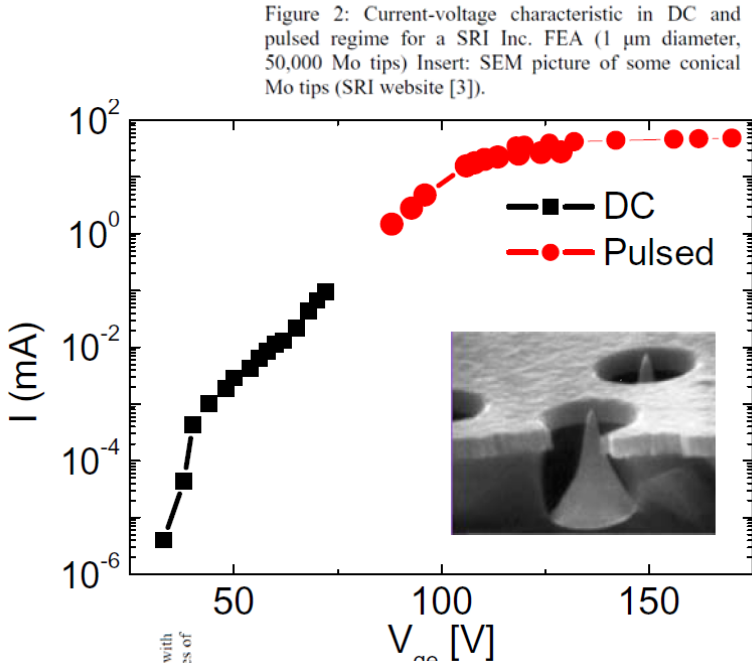
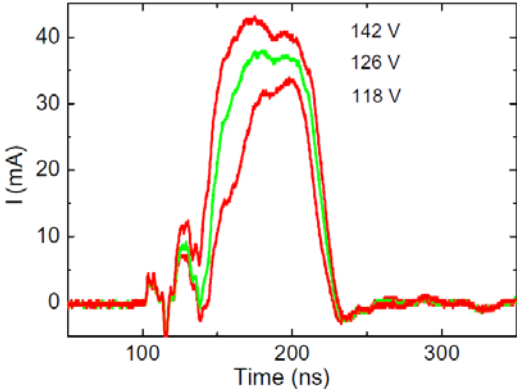


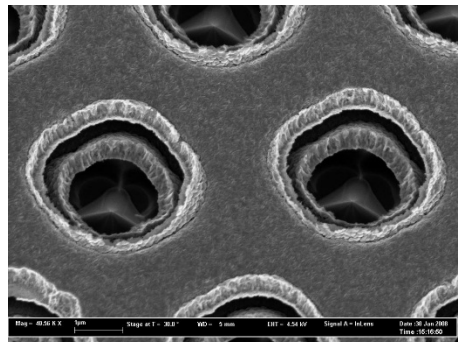
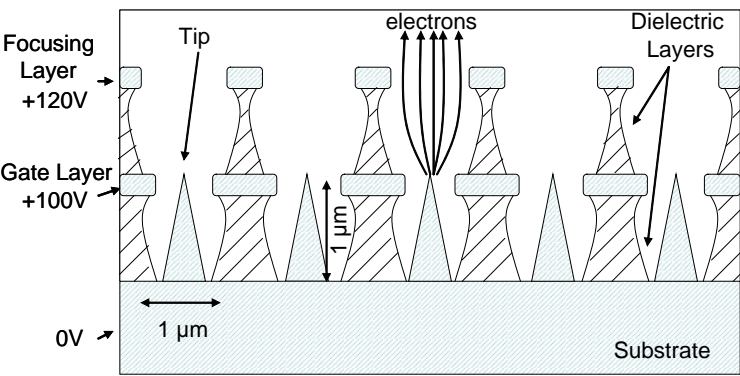
Figure 2: Current-voltage characteristic in DC and pulsed regime for a SRI Inc. FEA (1 μ m diameter, 50,000 Mo tips) Insert: SEM picture of some conical Mo tips (SRI website [3]).

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.



Double Gated Field Array Source – PSI R&D

- The goal is the design of a high intensity, low emittance electron source for a free electron Laser facility

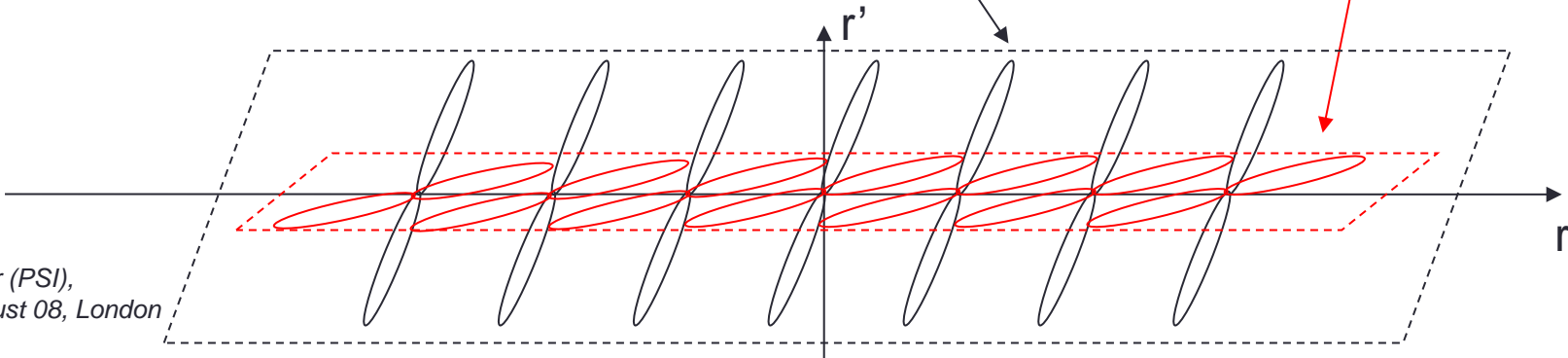


$$\epsilon_{n,rms}(1^{st} Gate) \sim \beta\gamma.n.\delta x.\vartheta$$
$$\beta\gamma.\vartheta = 5mrad \quad n=100; \delta x=2\mu m$$
$$\epsilon_{n,rms}(1^{st} Gate) \sim 2 \text{ mm.mrad}$$

$\epsilon_{n,int r.}(2^{nd} Gate) < 0.1 \text{ mm.mrad}$

Initially
 $\epsilon_n \sim 2 \text{ mm.mrad}$

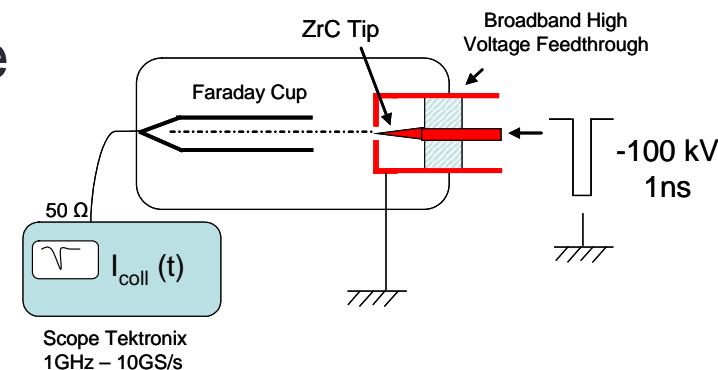
After Focusing
 $\epsilon_n < 0.1 \text{ mm.mrad}$



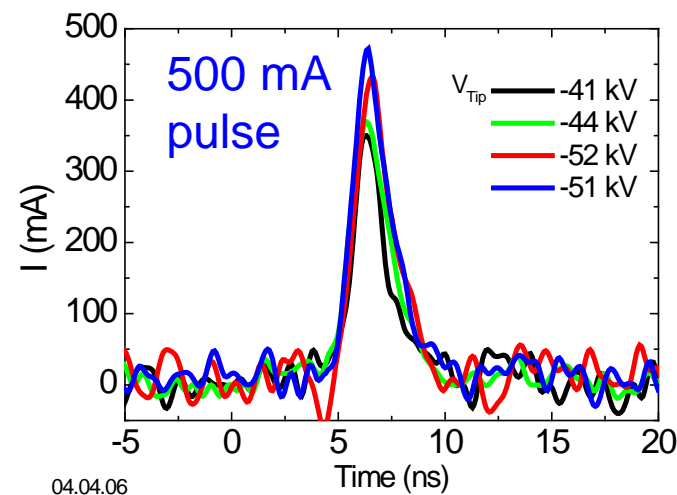
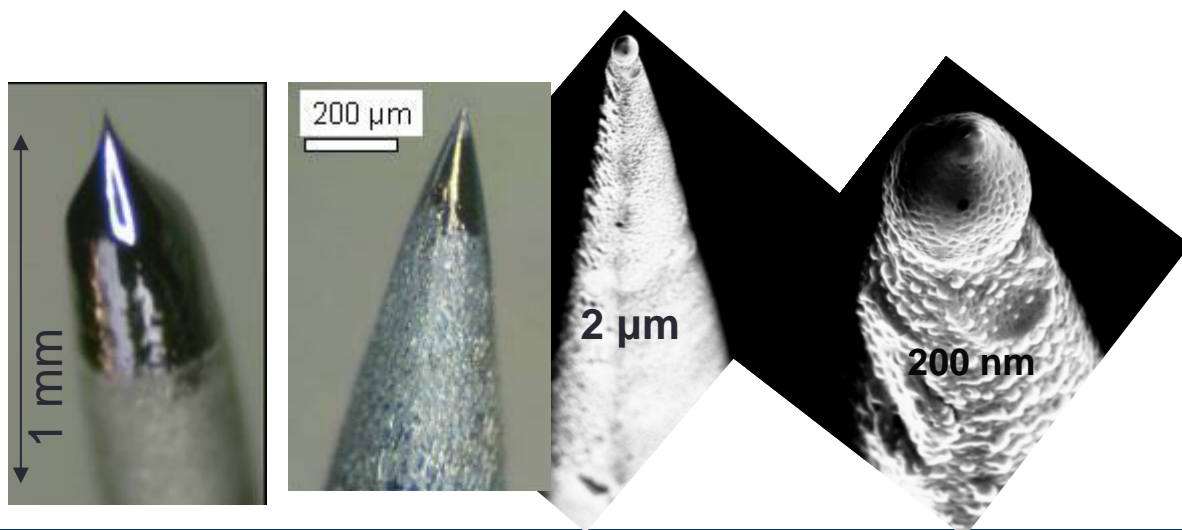
Slide: R. Ganter (PSI),
IVESC08, August 08, London

Needle Cathode Electron Source (PSI R&D)

- The cathode consists of a single ZrC needle
 - $W_{\text{ZrC}} = 3.5 \text{ eV}$
- Pulsed operation:
 - A 1 ns High Voltage pulse is applied to the needle
 - Peak intensity measured up to 500 mA

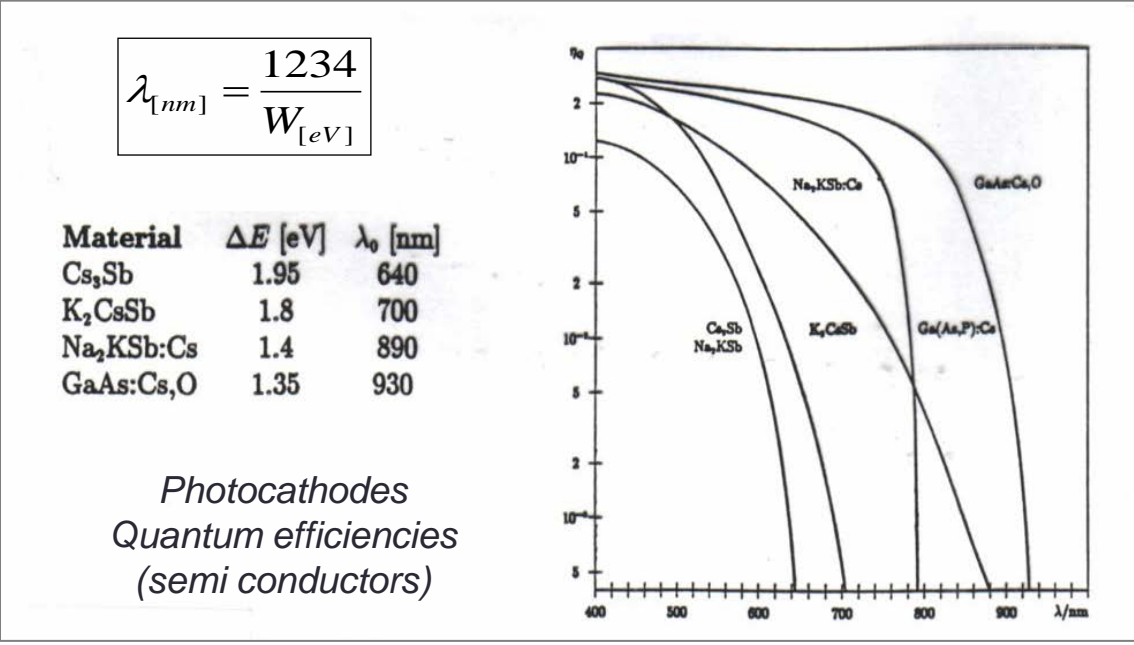
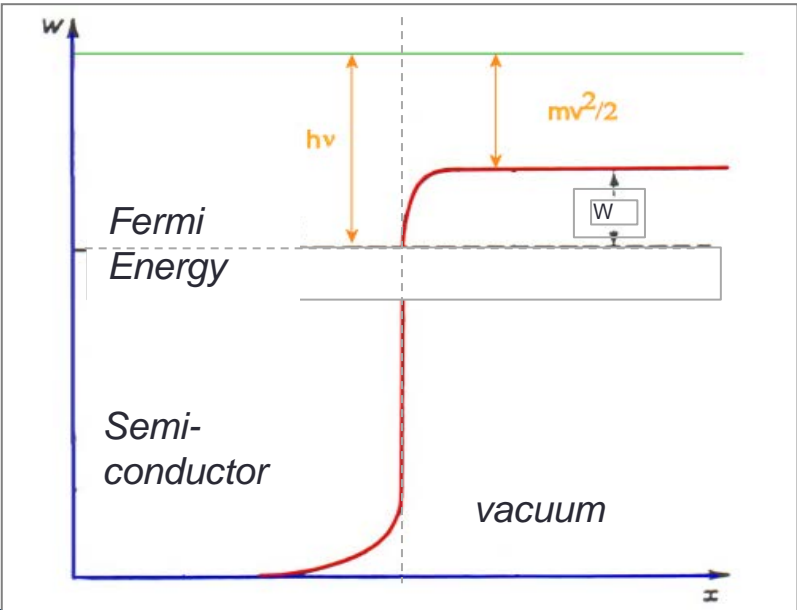
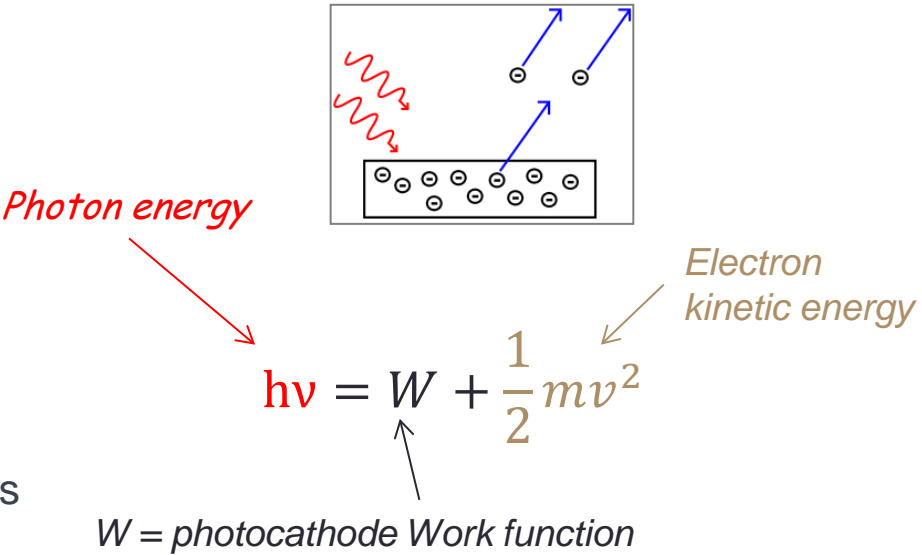


Commercial Devices from A. P. Tech Inc.



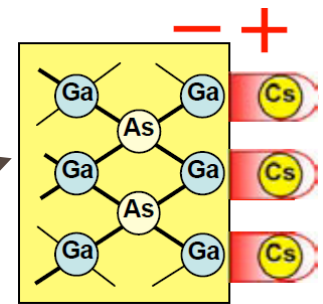
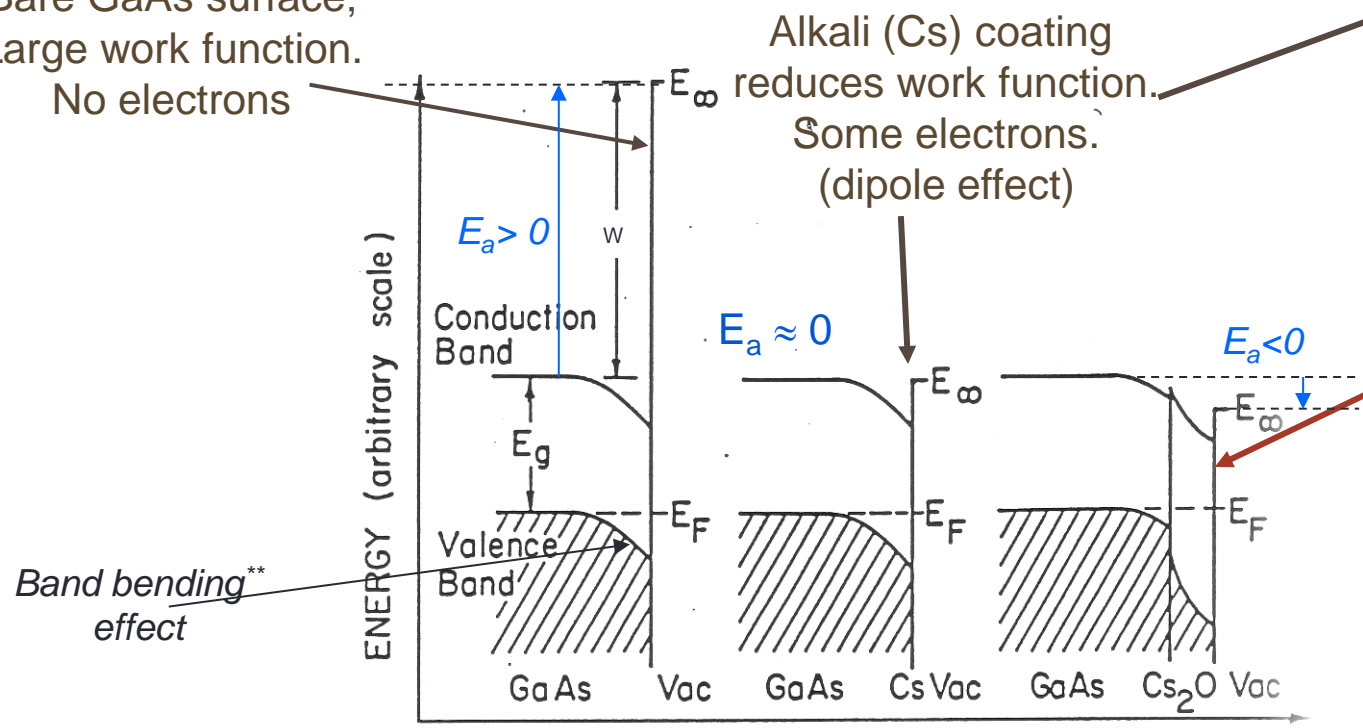
Photoelectric Effect

- 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).



Negative Electron Affinity

Bare GaAs surface;
Large work function.
No electrons



Cesium + Oxidant (O or NF3)
“Negative Electron Affinity”.
Many electrons

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

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

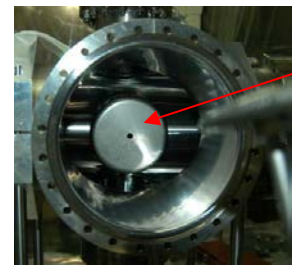
Extracted slides from : J. Grames, JLab, USA
N. Nishimori, JAEA, Japan

• *In solids, the **Electron Affinity** is the energy difference between the vacuum energy and the conduction band minimum.

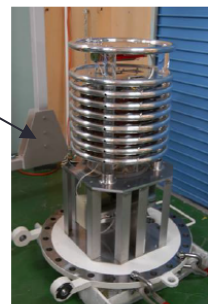
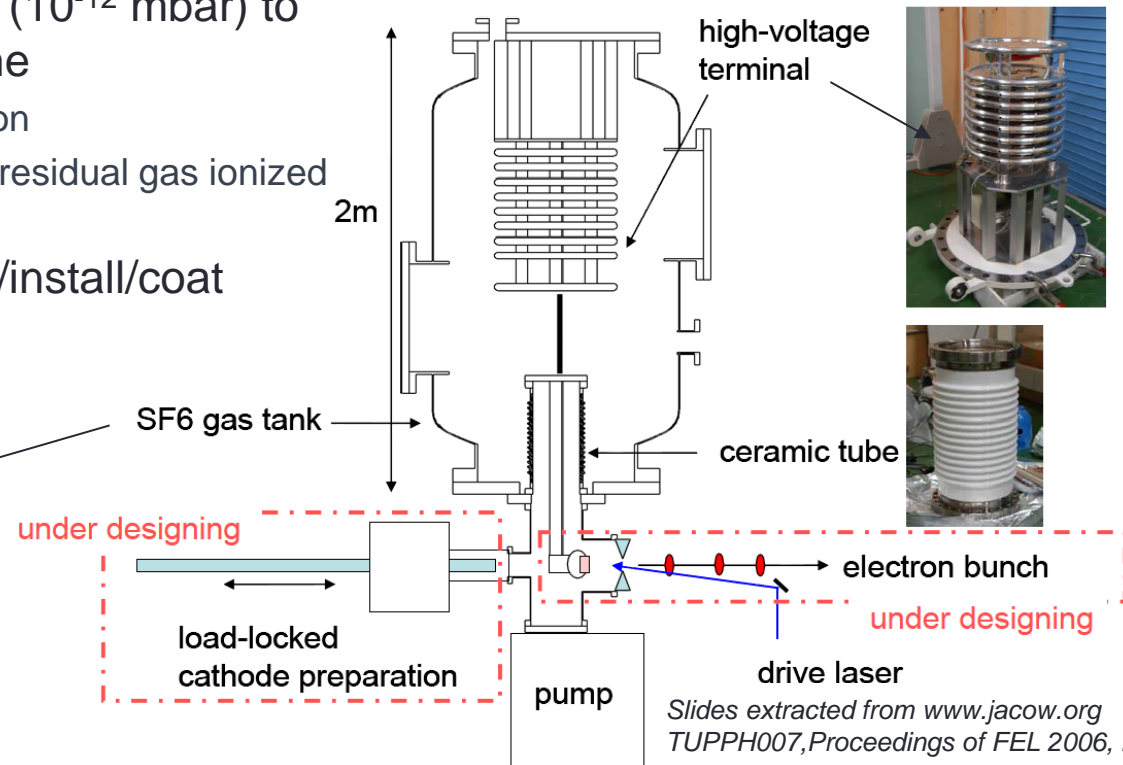
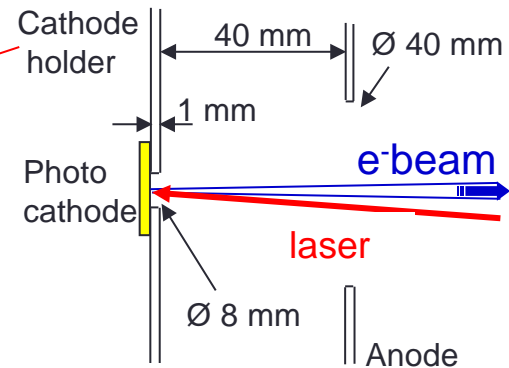
• **Band bending refers to the local change in energy of electrons at a semiconductor junction due to space charge effects. The degree of band bending between two layers depends on the relative Fermi levels and carrier concentrations of the materials forming the junction.

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



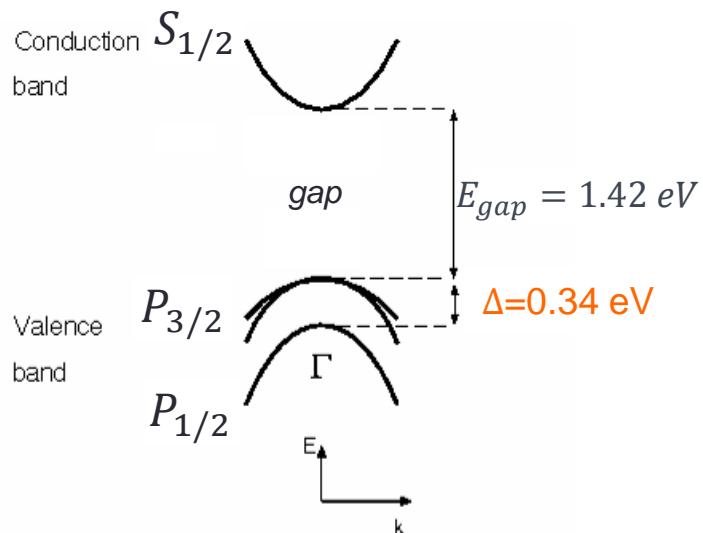
all the electrodes are made of Titanium



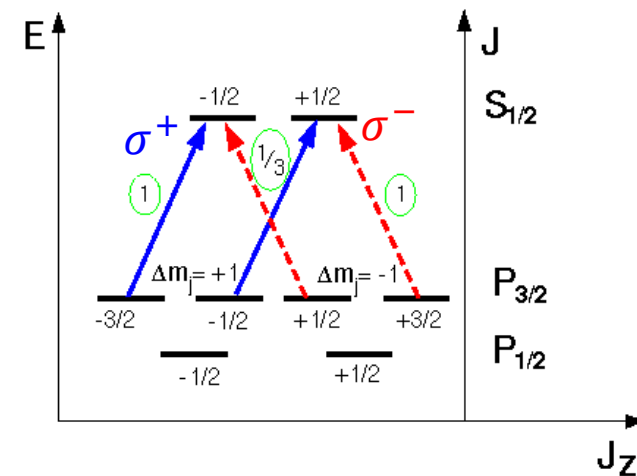
Slides extracted from www.jacow.org
TUPPH007, Proceedings of FEL 2006, BESSY, Berlin, Germany

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



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



Slide adapted from : J. Grames, JLab, USA

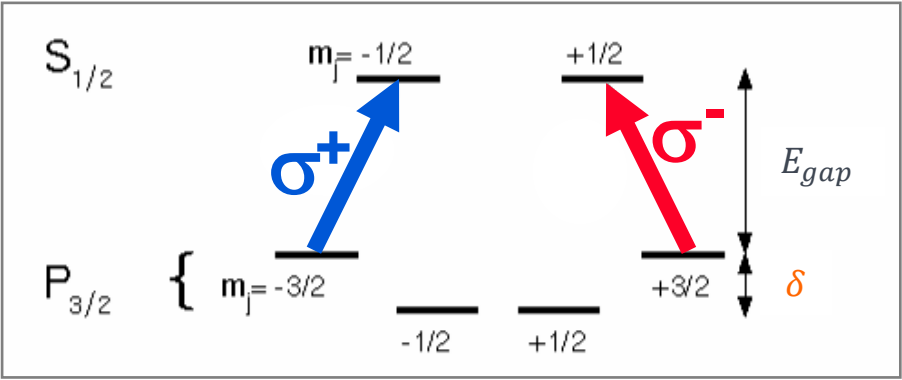
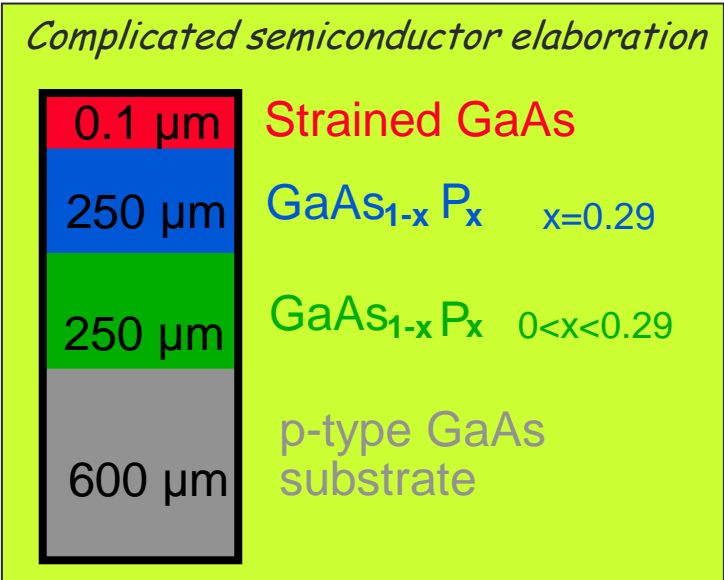
Polarized Photoemission electron source at Jlab (1/2)

• A refinement of the polarization is obtained by adding extra layers on the photocathode :

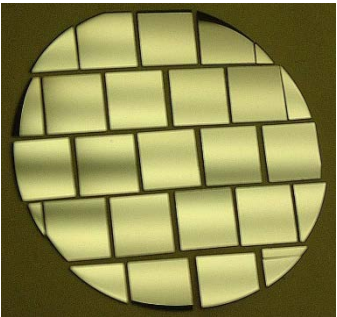
- Split degeneracy of $P_{3/2}$
- Direct optical pumping between $P_{3/2}$ and $S_{1/2}$
- When $E_{gap} < E_{\gamma} < E_{gap} + \delta$:

$$P_e = \pm 100\%$$

- Experimentally $P_e \sim \pm 85\%$



Slide adapted from
J. Grames, JLab, USA

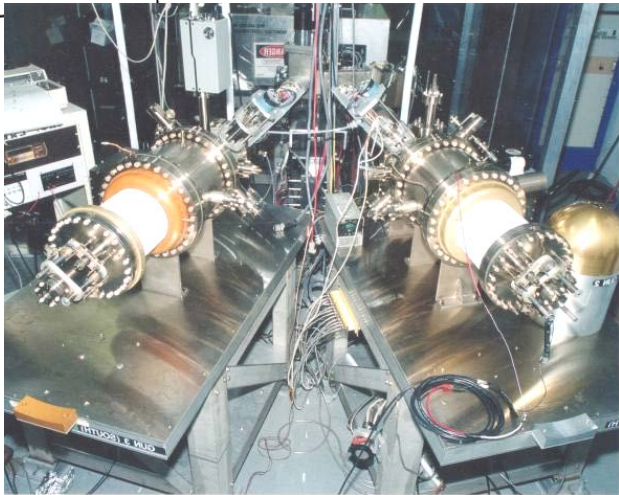
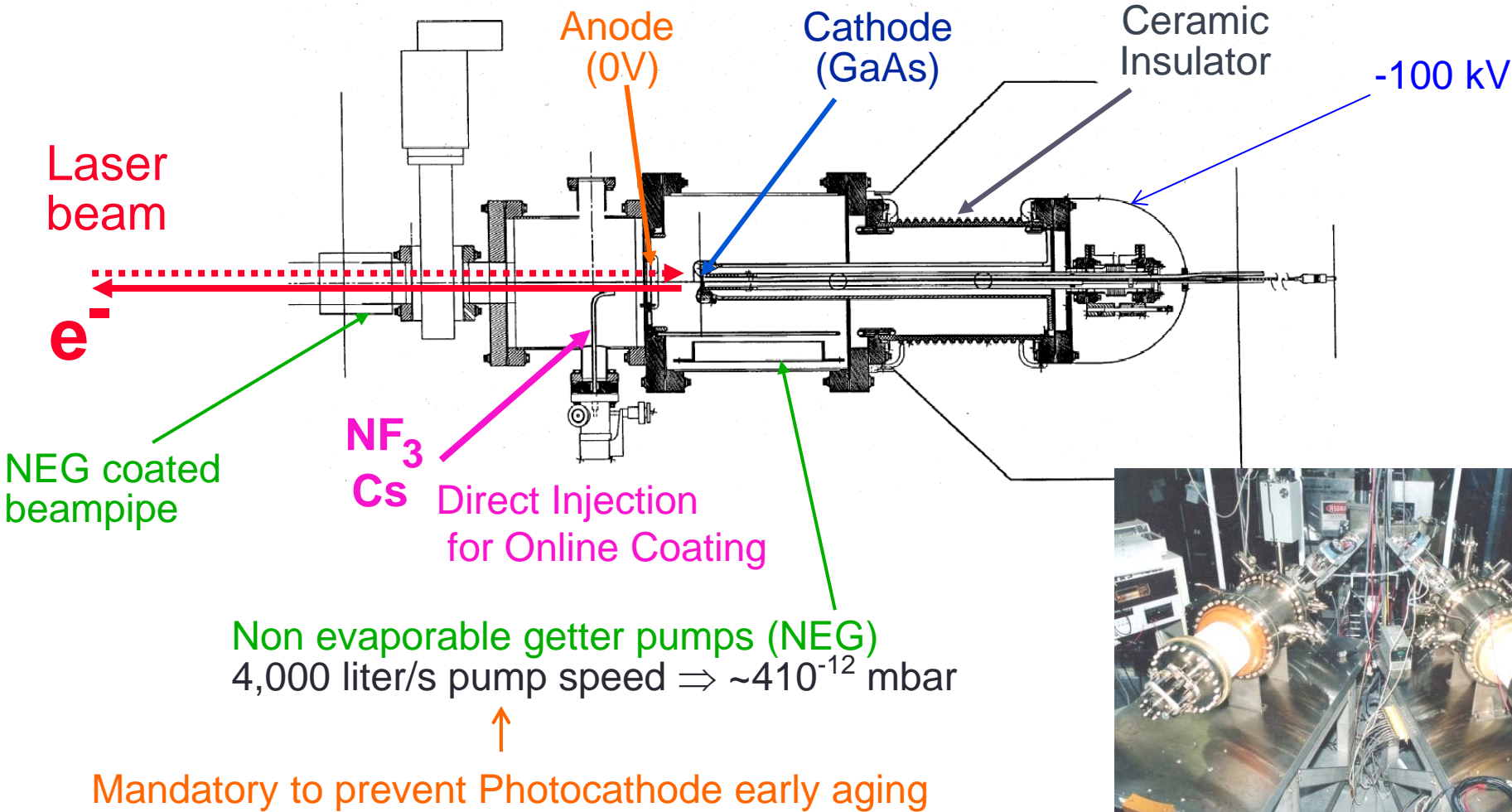


3 " wafer cut into
square photocathodes



Stalk for supporting
1 Photocathode

Jlab polarized Photoemission gun



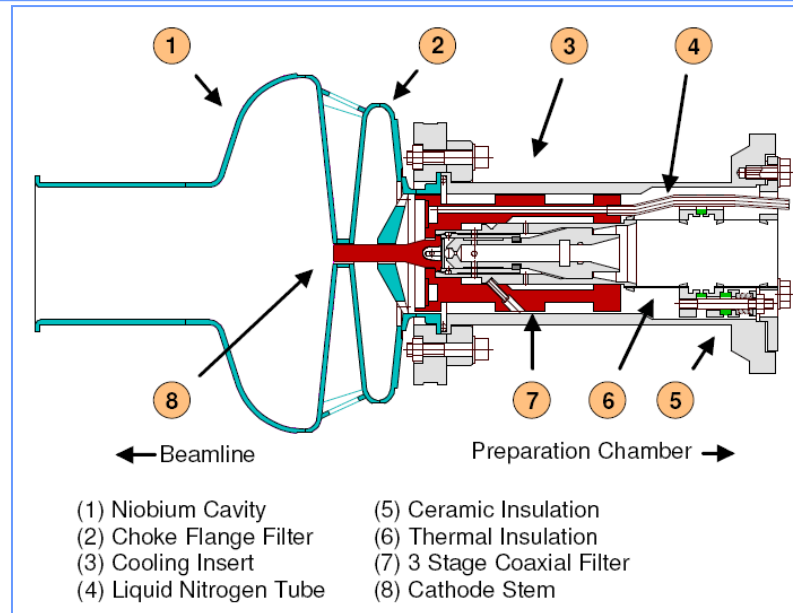
slide adapted from: J. Grames, JLab, USA

Radio Frequency Guns

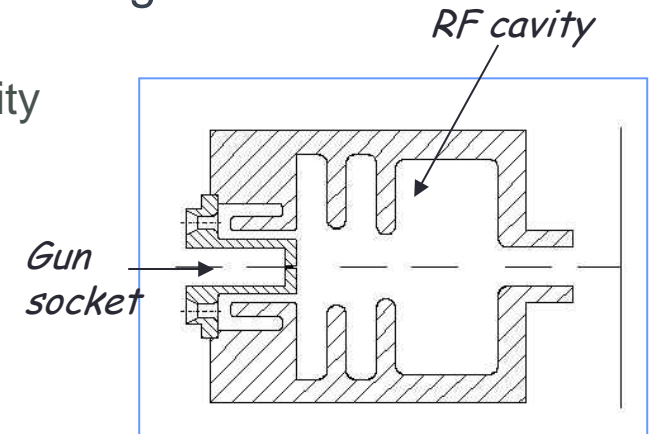
The RF gun is the name given when the electron ion source is directly coupled to a RF Cavity

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

Rossendorf ½ cell Supercon. RF gun prototype



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



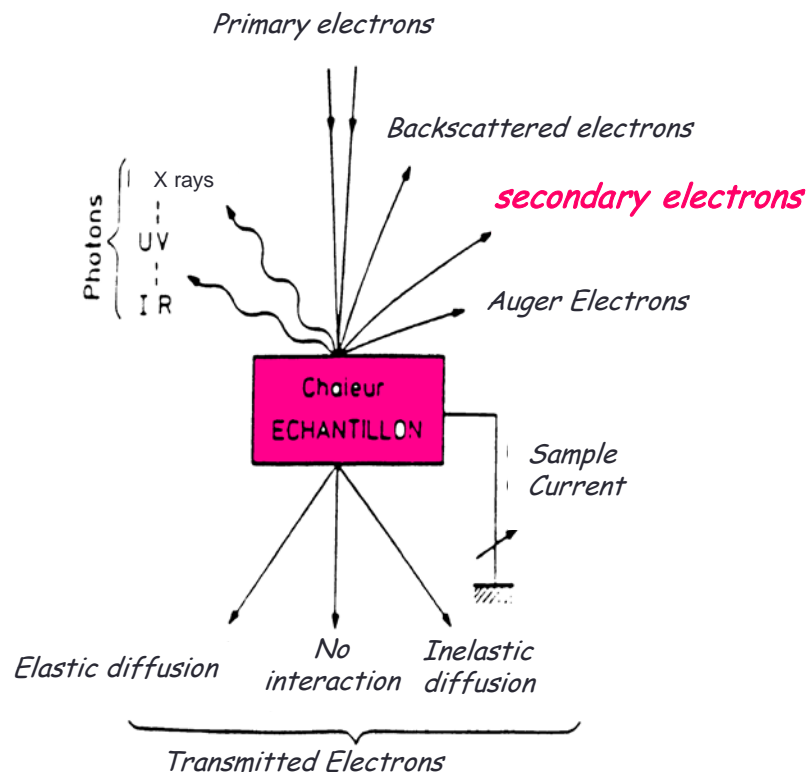
A 3 GHz thermionic RF gun has been designed. It will produce a 2.3 MeV electron beam with bunch charge up to 0.2 nC (600 mA) at 10 pmm mRad normalised emittance.



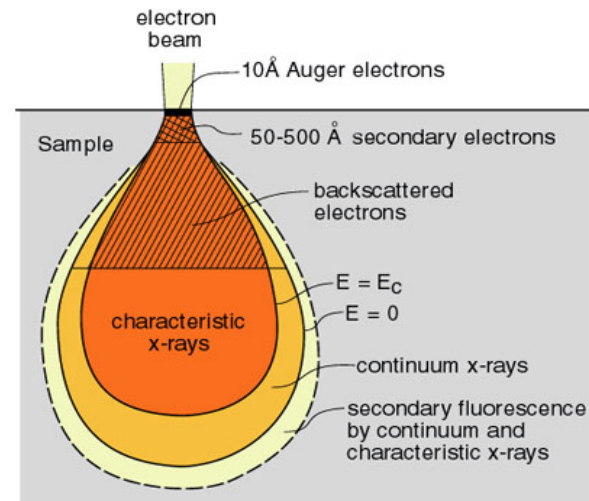
Secondary electron emission

- 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/cm^3 , E kinetic energy in KeV



Interaction volume of different effects

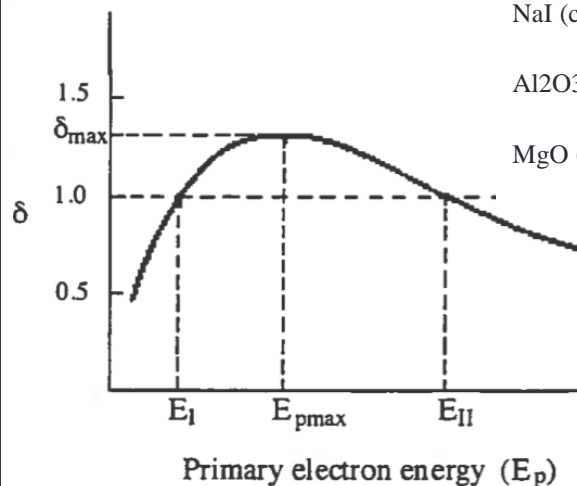
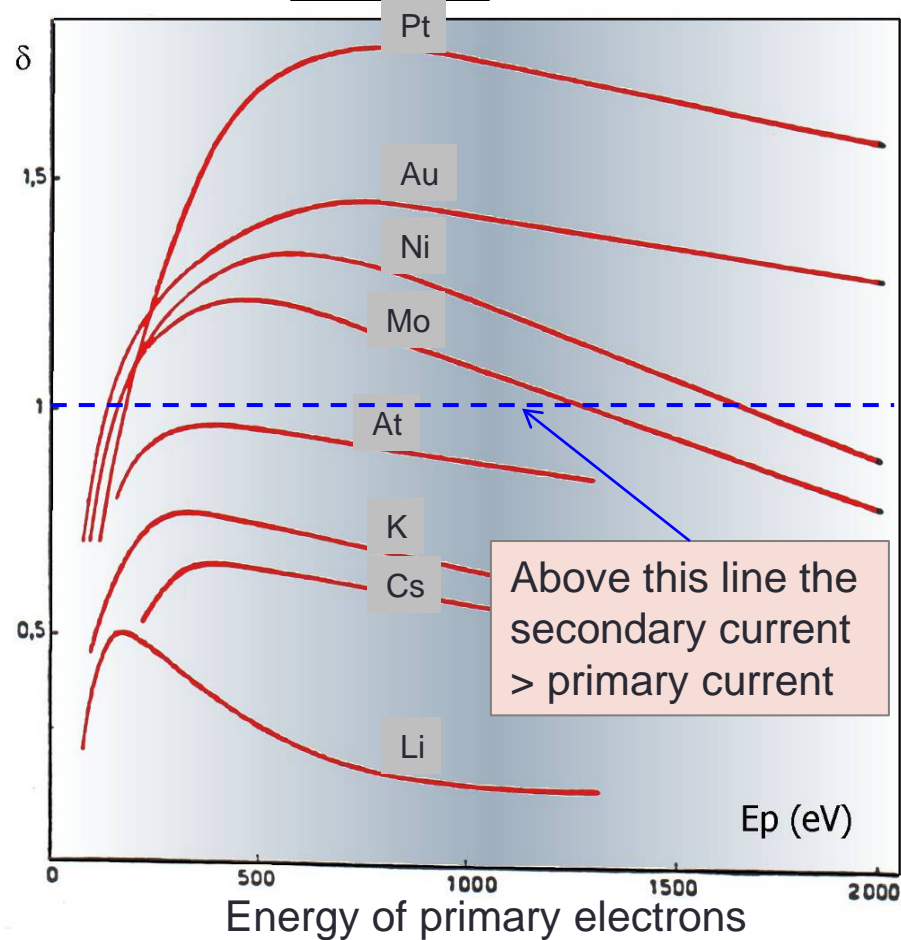


<http://www4.nau.edu/microanalysis/microprobe-sem/signals.html>

Slide adapted from J. arianer, H. Koivisto

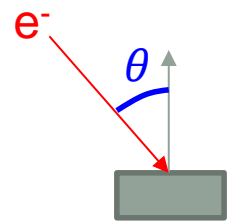
Secondary electron Yield

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



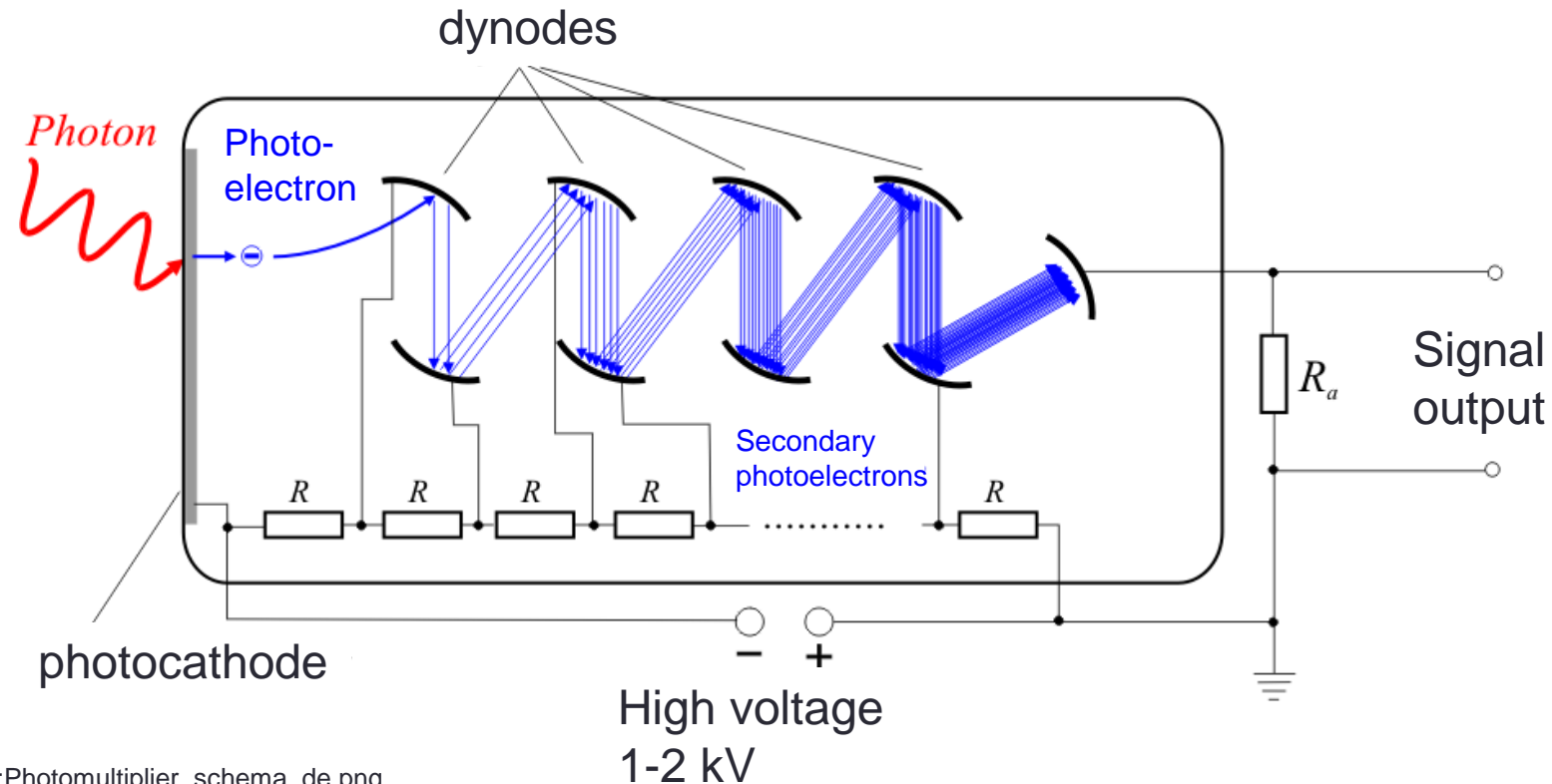
Element	δ_{max}	E_p (eV)	E_I (eV)	E_{II} (eV)
Cu	1.3	600	200	1500
Fe	1.3	600	200	1500
Pt	1.8	700	350	3000
Ta	1.3	600	250	>2000
Compounds	δ_{max}	E_p (eV)		
NaI (crystal)	19	1300		
Al ₂ O ₃ (layer)	2 to 9			
MgO (crystal)	20 to 25	1500		

- 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 electron/dynode/electron
 - The electron signal is amplified (and accelerated) through a set of dynodes



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

Positron Source

- The positron is the antiparticle of the electron it has a positive charge
- Mechanism to make a positron:
 - β^- decay :
 - ${}^A_ZN \rightarrow {}^A_ZN' + e^+ + \nu_e$
 - 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 $E > 2m_e c^2 \sim 1 \text{ MeV}$
 - The pair production process is dominant at high energy
- Interaction of positron with matter
 - The positron interact with electron to form a quasi-stable positronium which eventually annihilate into two photons: $e^+ + e^- \rightarrow \gamma + \gamma$
- Interest of 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

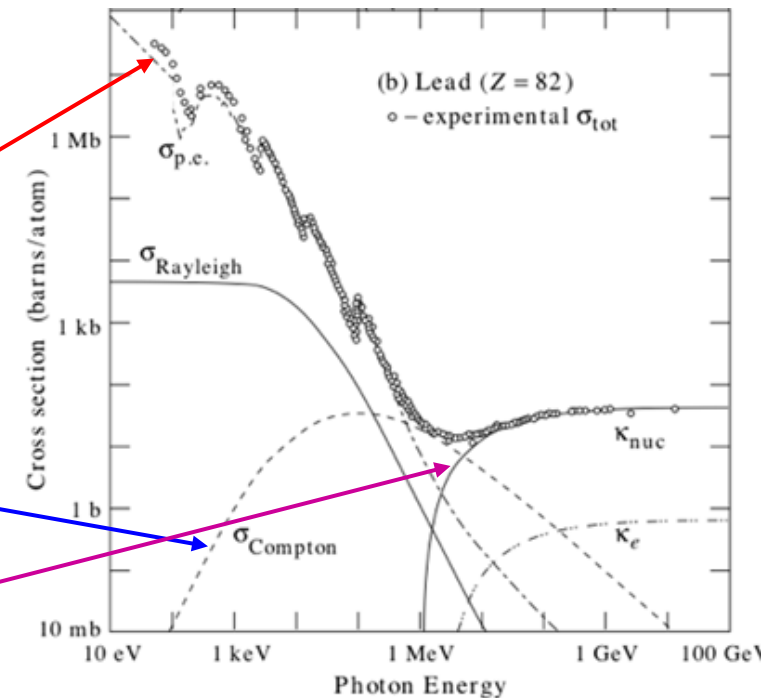
Photon Interaction with matter

- The main photon interaction with ordinary matter depends on its energy:

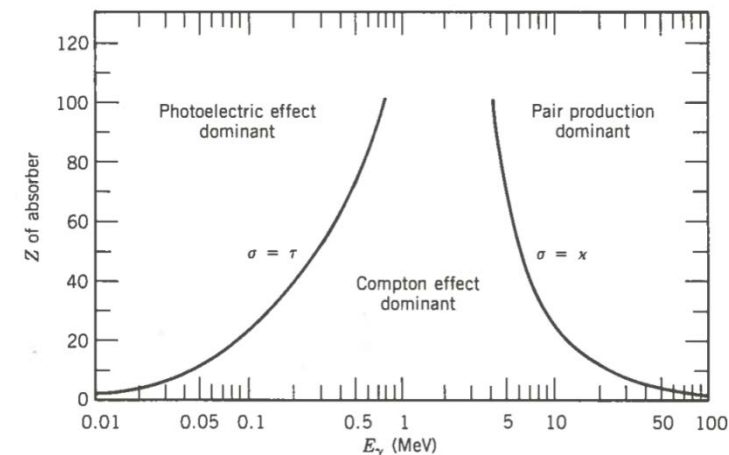
- Low energy: the **photoelectric effect** is dominant ($E < 1 \text{ keV}$). Interaction of the photon with the bound electrons.
- Medium energy: the **Compton effect** is dominant ($1 \text{ keV} < E < 1 \text{ MeV}$). Diffusion of the photon on a knocked-out electron
- High Energy: the **pair production** is the dominant effect ($E > 1 \text{ MeV}$)

- $\gamma + X \rightarrow X + e^+ + e^-$
- X is either a nucleus or an electron
- Threshold energy $E > 2m_e c^2 \sim 1 \text{ MeV}$

- The cross section of these processes increases with the atomic number Z

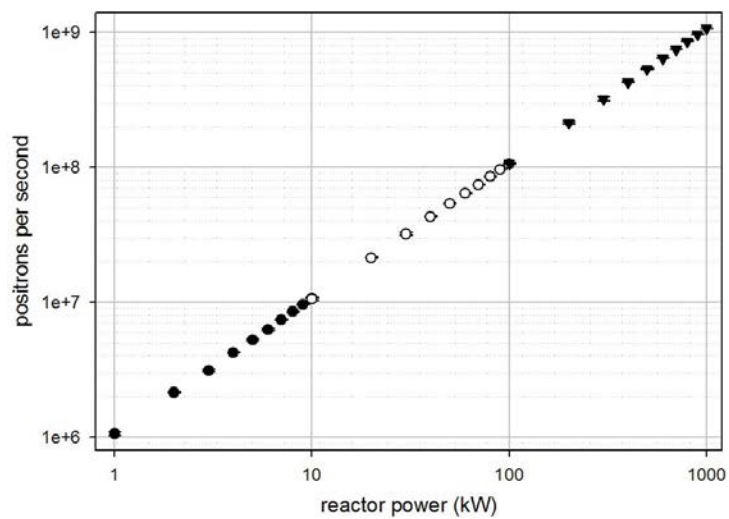


K.S. Krane, *Introductory Nuclear Physics*

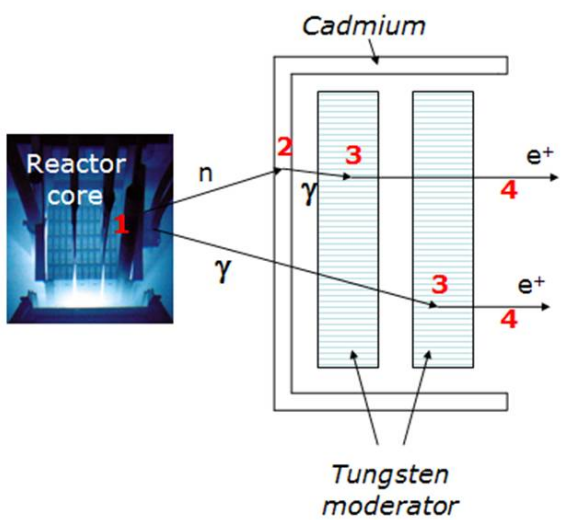


Positron beam at NC State University (1/2)

- 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

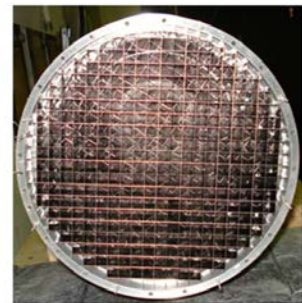


Positron beam intensity available for experiments



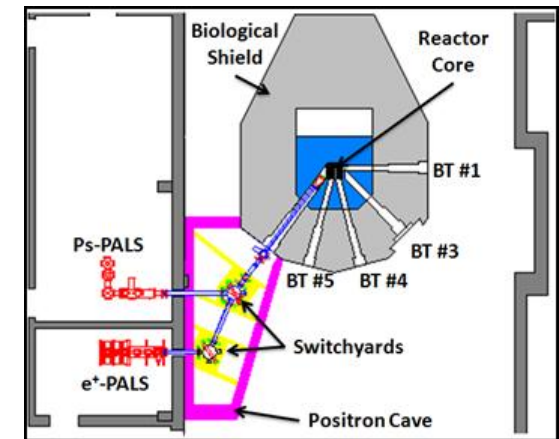
1. Neutrons (n) and gammas (γ) are emitted from fission reactions in the reactor core.
2. Neutrons react in the cadmium shroud producing additional gamma rays.
3. Gamma rays interact by pair production in the tungsten moderator to form positrons.
4. Positrons thermalize and are emitted from the tungsten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

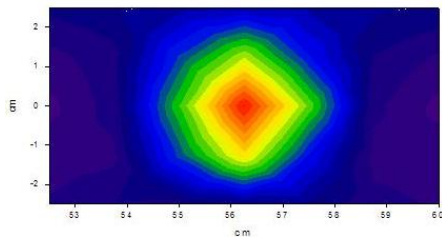


Positron beam at NC State University (2/2)

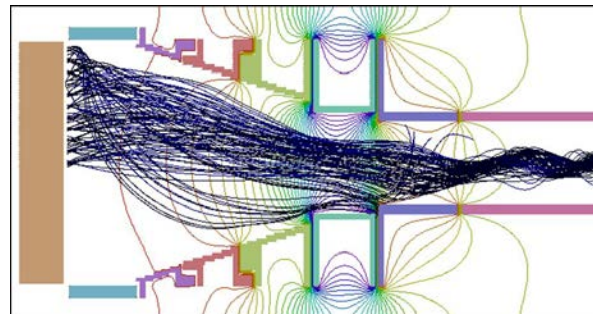
- e^+ are focused by Electrostatic lenses at the exit of the converter
- e^+ beam is transported in a magnetic LEBT toward experimental caves
- Application of positron beam: non destructive technique to detect defects and free volume in a wide variety of material
 - Pore sizes ranging from several angstroms to $\sim 30\text{nm}$ 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



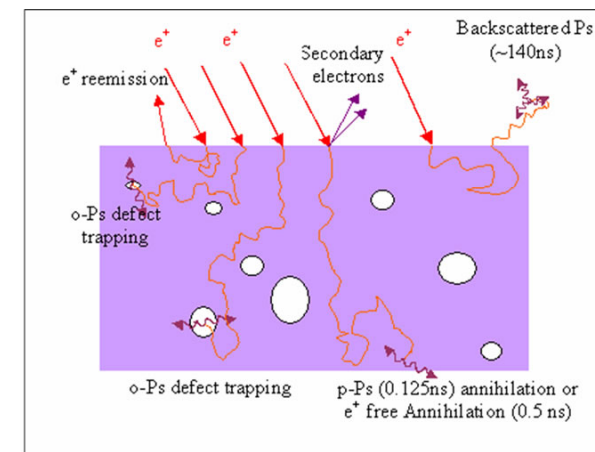
Beam line overview with the reactor



Beam profile



Electrostatic Focusing Lens



Positron and Positronium Interactions with Condensed Matter

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



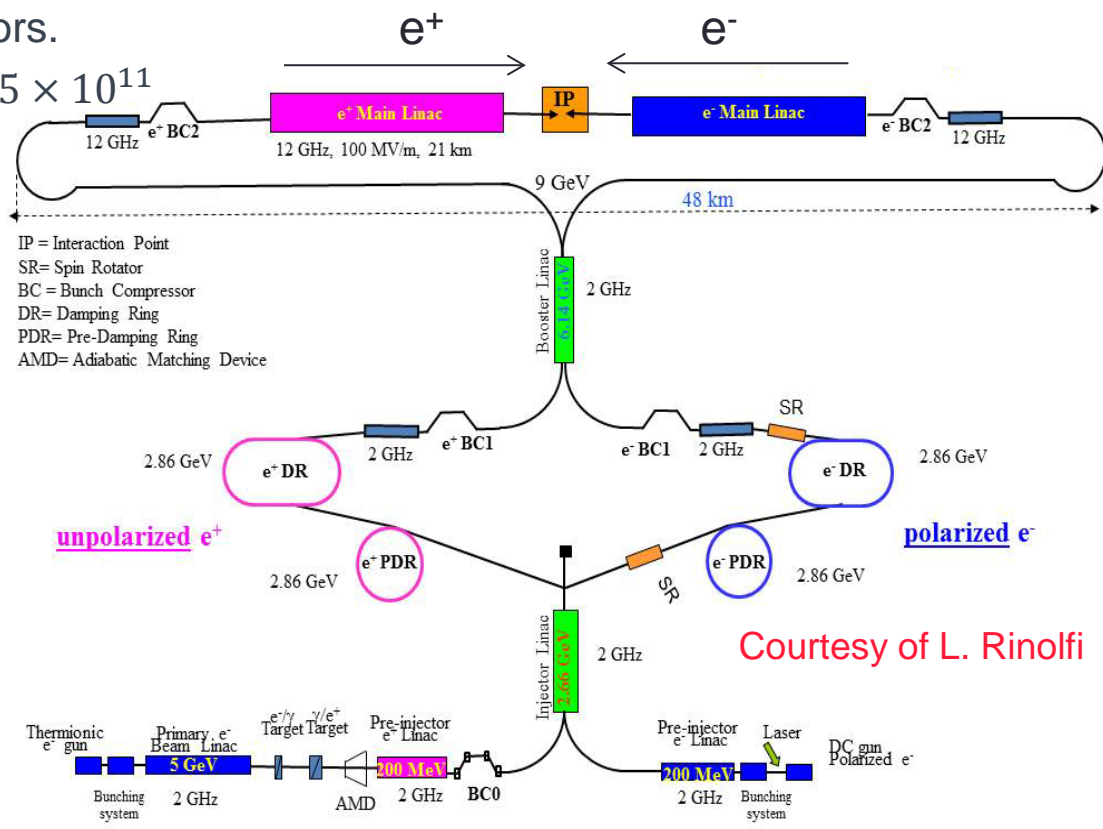
Positron beam for the CLIC facility

- 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!)

How to produce such a Flux?



3 schemes.../...



Courtesy of L. Rinolfi

CLIC baseline scenario

Possible schemes to produce positrons for CLIC (1/3)

• 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 $\langle 111 \rangle$ 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

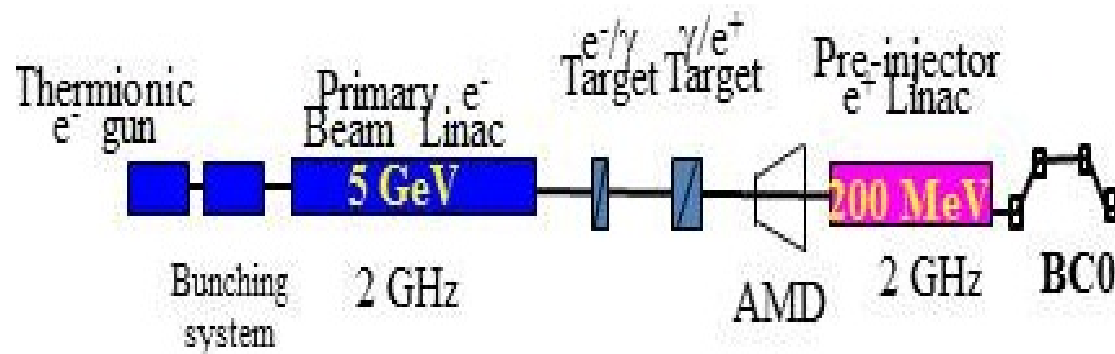
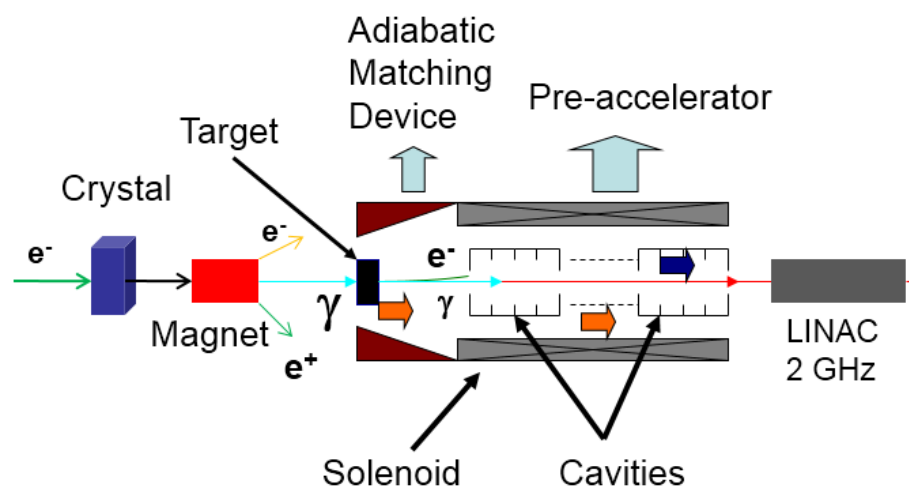
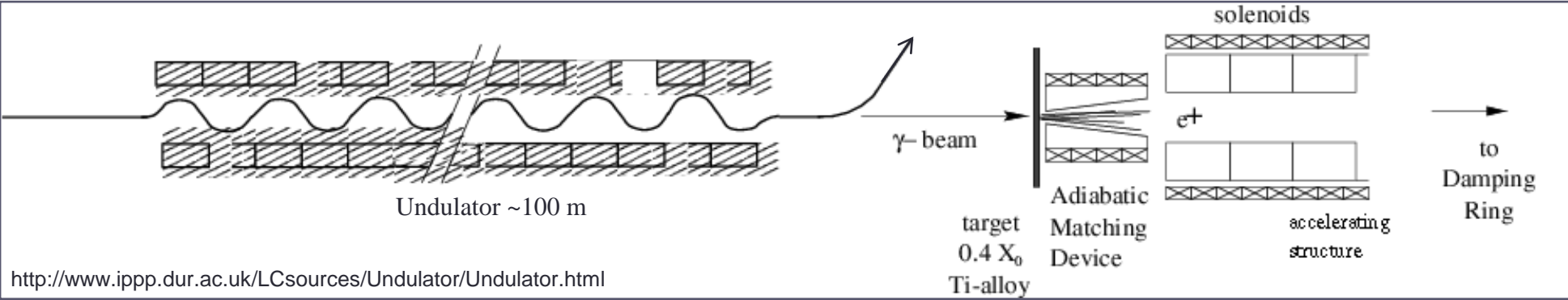
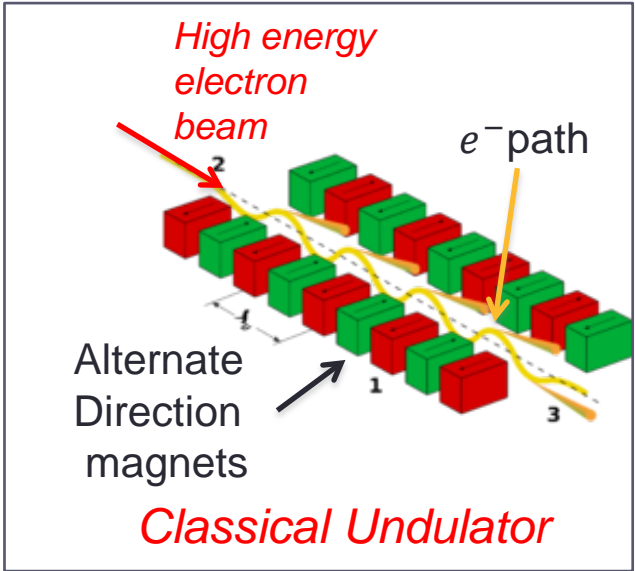
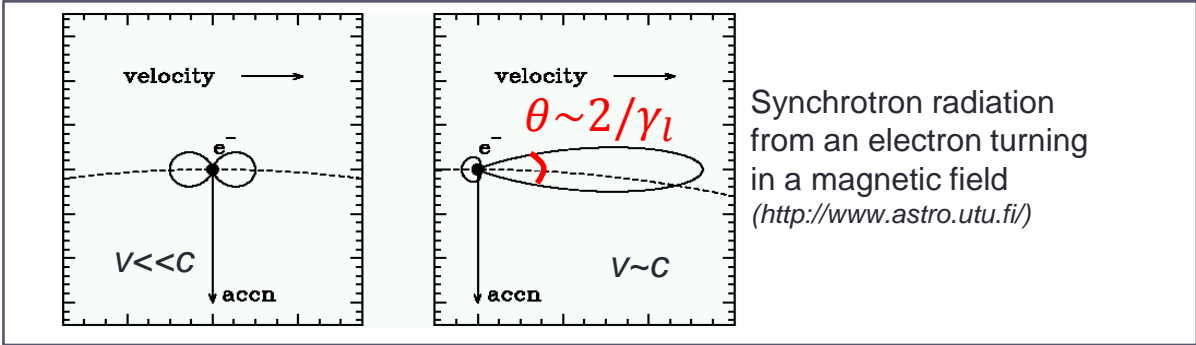


Figure from: A. Vivoli, CLIC Positron Source, POSIPOL 2009, LYON

Possible schemes to produce positrons for CLIC (2/3)

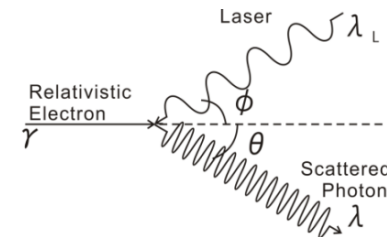
- Scheme B: Undulator based γ -radiation:
 - γ photons can be produced by synchrotron radiation from a high energy e^- beam
 - Any charged particle radiates photons when it accelerates
 - An electron placed in a magnetic field radiates synchrotron light
 - The higher the Lorentz factor γ_l , the higher the photon collimation
 - The longer the undulator, the higher the γ photon intensity
- This process suppresses the use of the scheme A crystal target



Possible schemes to produce positrons for CLIC (3/3)

• Scheme C: Compton back-scattering

- A 1 GeV electron beam interacts with a circularly polarized laser beam
- Circularly polarized γ photons are emitted via Compton backscattering
- The polarized γ photons generate polarized e^+ via pair production in target



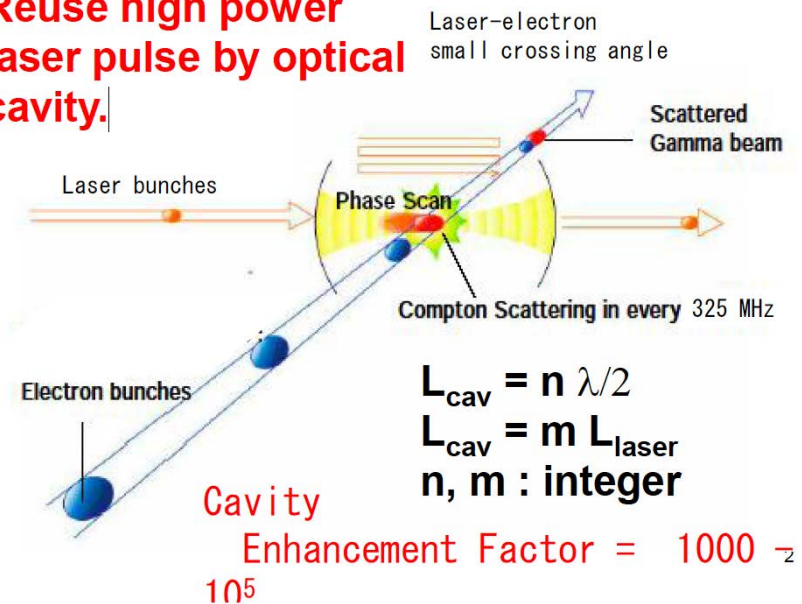
• Advantages:

- Suppresses the crystal target
- Higher collider reaction cross section with polarized e^+ and polarized e^- beams

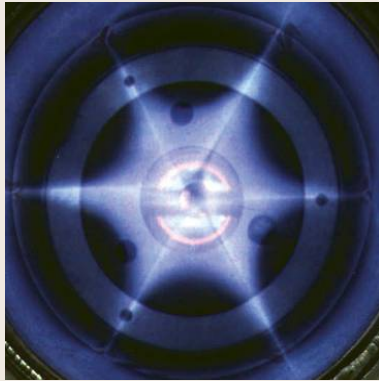
• Inconvenient:

- Requires electron and laser bunch intensities which are not available today

Reuse high power laser pulse by optical cavity.



The CLIC 3 scheme will require strong and active R&D!



ION SOURCES

An introduction to ion sources

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

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 developed 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 background physics necessary to understand how it works

Electronic configuration of atoms

- Each atom has a specific electronic cloud configuration
- Each electron has a spin number s up (\uparrow) or down (\downarrow)
- The electrons are splitted into shells defined by quantum numbers
- principle quantum number n :
 - $K (n = 1), L (n = 2), M (n = 3), \dots$
 - 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 l :
 - $0 < l < n$
 - 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 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: n, l, m, s

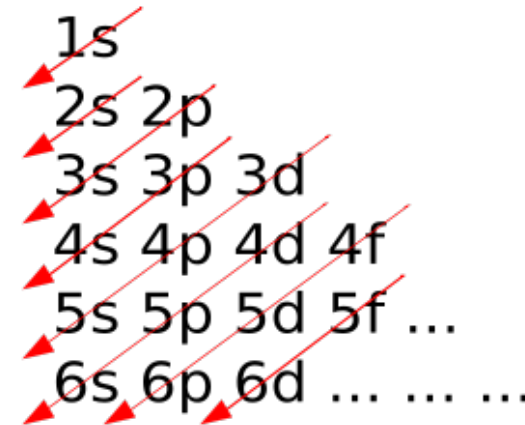


Kshell: $n = 1 \rightarrow l = 0 \rightarrow m = 0 \rightarrow s = \left\{ \begin{array}{c} \uparrow \\ \downarrow \end{array} \right\}$

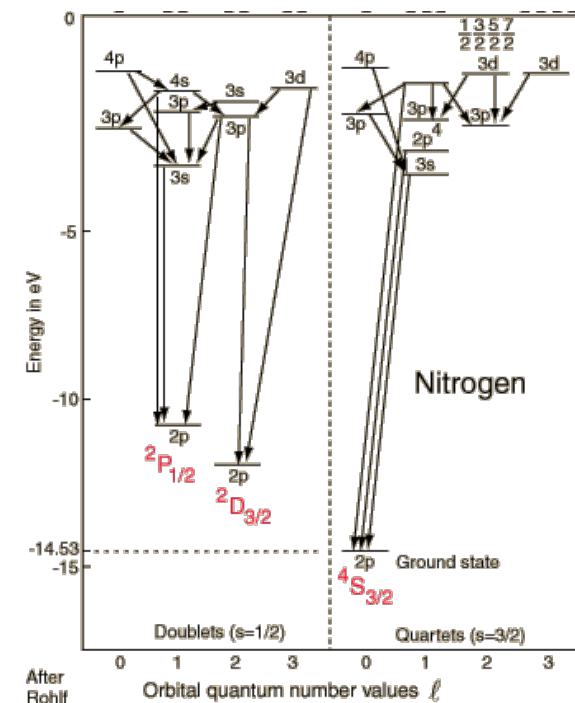
Lshell: $n = 2 \rightarrow l = \left\{ \begin{array}{l} 1 \rightarrow m = \left\{ \begin{array}{l} -1 \rightarrow s = \left\{ \begin{array}{c} \uparrow \\ \downarrow \end{array} \right\} \\ 0 \rightarrow s = \left\{ \begin{array}{c} \uparrow \\ \downarrow \end{array} \right\} \\ 1 \rightarrow s = \left\{ \begin{array}{c} \uparrow \\ \downarrow \end{array} \right\} \end{array} \right. \\ 0 \rightarrow m = 0 \rightarrow s = \left\{ \begin{array}{c} \uparrow \\ \downarrow \end{array} \right\} \end{array} \right.$

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: some exception exists
 - Ex.: Cr, Cu, Mo, Pd, Ag, La, Ce, Gd...



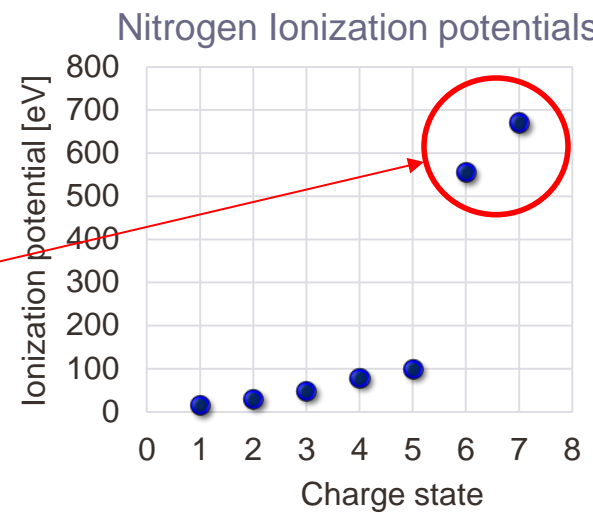
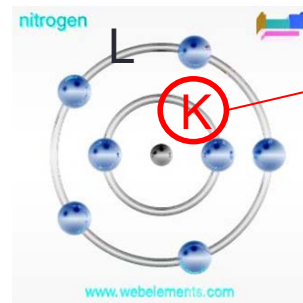
Klechkovski (Madelung) rule



Material compiled from H. Koivisto, JUAS12 lecture

Electrons binding energy in atoms

- Electrons are bound to the atom nucleus with energy which depends 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 needed to remove a second electron from the highest occupied subshell
 - A given n^{th} ionization energy decreases with the atom Z



	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

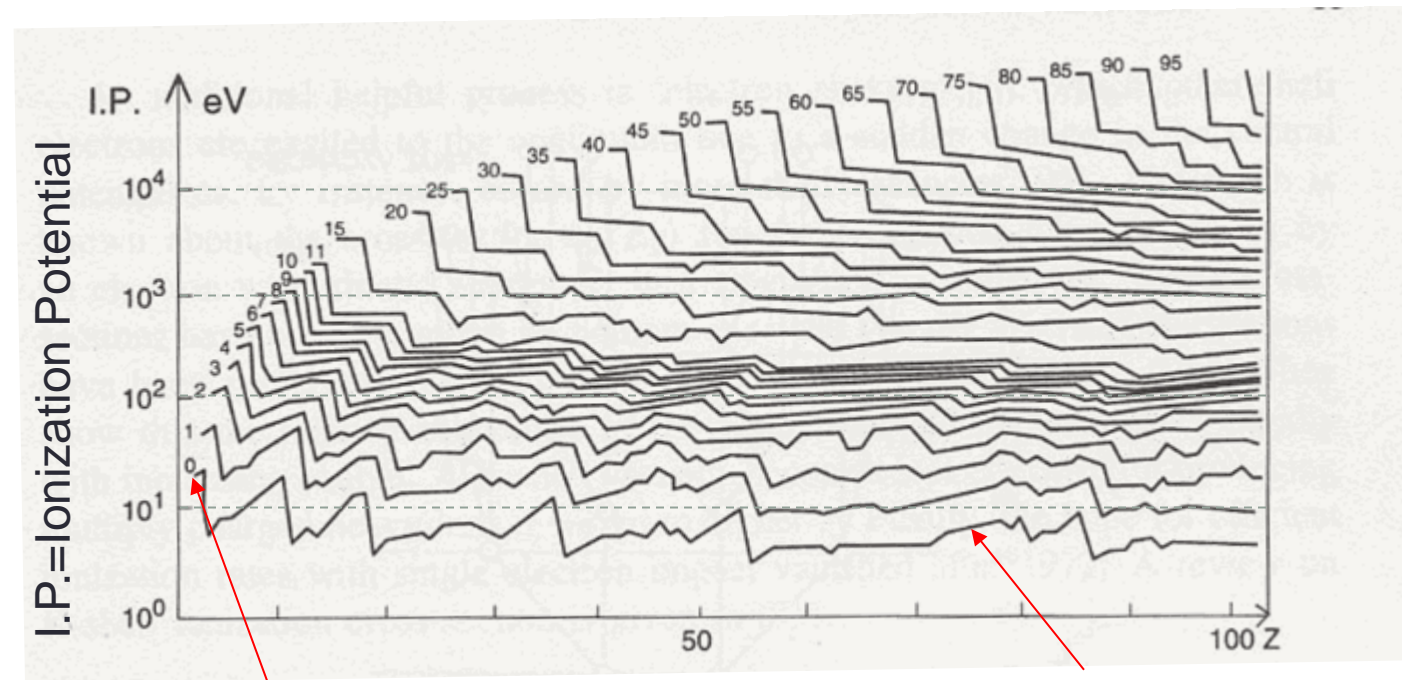
Material compiled from H. koivisto, JUAS12 lecture

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

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

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



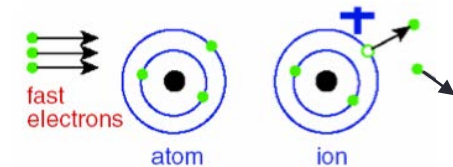
Initial ion charge state

1+ ion line

How to Ionize an atom

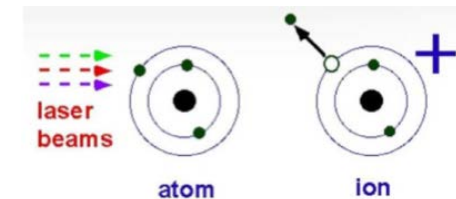
- **Electron Impact:** an energetic electron collide with an atom (ion) and expells one shell electron

- $e^- + A^{n+} \rightarrow A^{(n+1)+} + 2e^-$
- 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

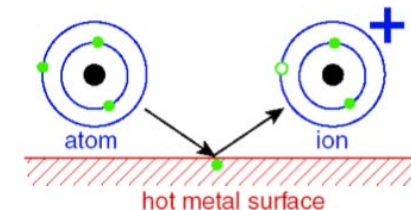
- $h\nu + A^{n+} \rightarrow A^{(n+1)+} + e^-$
- The photon disappears
- The photon ionization process is of interest for specific applications like ionizing atoms in a Radioactive Ion Beam facility.
 - In this case, a set of lasers are used to guide an electron from shell to shell until it is freed.



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 attract back electrons
- The main channels for an ion to loose 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
 - $A^{n+} + B^0 \rightarrow A^{(n-1)+} + B^{1+} + \text{radiative processes}$
 - Dominant process
 - $A^{n+} + B^{m+} \rightarrow A^{(n-1)+} + B^{(m+1)+} + \text{radiative processes}$
 - 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

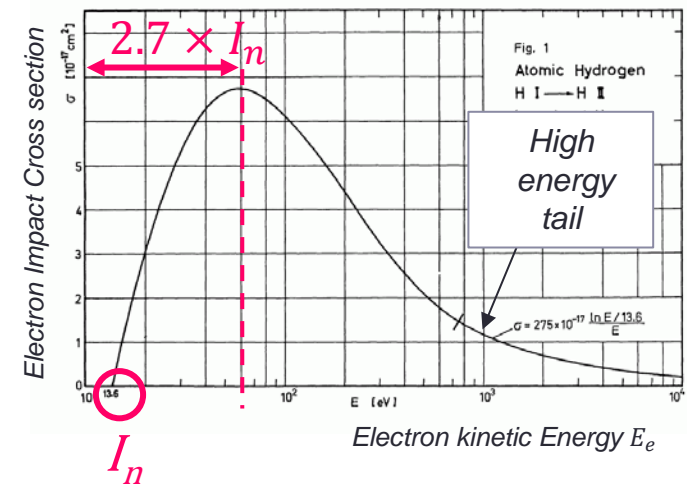


Cross-section and other microscopic processes

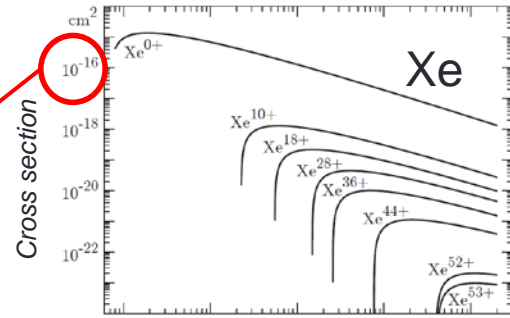
- Cross-section: σ (cm^2 or *barn*)
 - The cross section σ is the effective area which governs the probability of a specific physical interaction between two particles. Its unit is usually cm^2 or *barn* (10^{-24} cm^2)
- Collision rate: $n\sigma v$ (Hz or s^{-1})
 - The number of collision $N_{\text{col.}}$ between a single electron with a velocity v and a set of gaseous atoms targets with a density n during a time t is given by:
 - $N_{\text{col.}} = n\sigma v t$
 - σ is the cross section associated to this particular collision
 - $\sigma v t$ is the volume swept by the electron during a time t
 - The collision rate is $\frac{N_{\text{collision}}}{t} = n\sigma v$ in Hertz (s^{-1})
- 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 probability to have an interaction is proportional to the target density n (in cm^{-3}) and the cross-section σ . The probability to have a collision along a distance l is $P(l) = n\sigma l$. The MFP is such that $P(\lambda) = 1$. So $\lambda = \frac{1}{\sigma n}$

Electron Impact Ionization

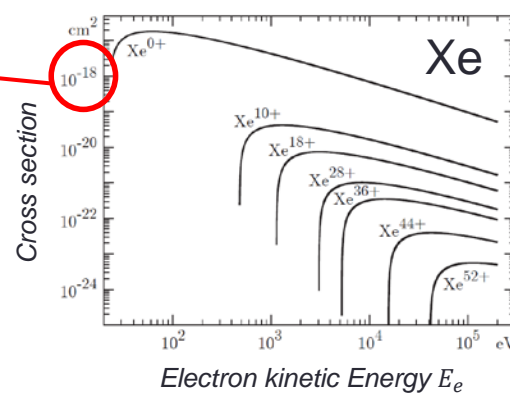
- Ions are produced through a direct collision between an atom and a free energetic electron
 - $e^- + A^{n+} \rightarrow A^{(n+1)+} + e^- + e^-$
 - single impact, most probable
 - $e^- + A^{n+} \rightarrow A^{(n+2)+} + 2e^- + e^-$
 - double impact, much less probable
- Kinetic energy threshold E_e of 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 electron can contribute significantly



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



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



Xe plots from F. Wenanders, CAS2012

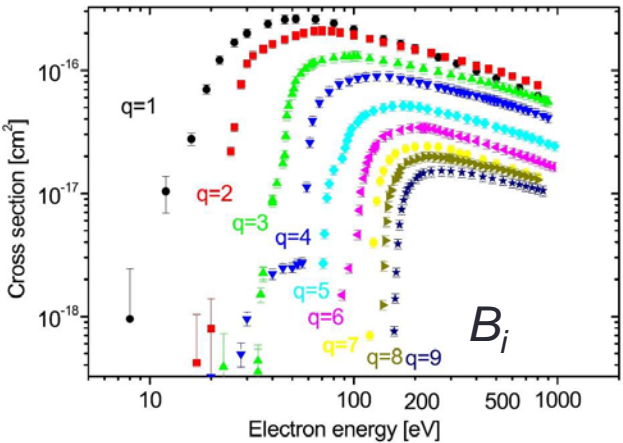
Electron Impact Ionization

- Electron impact ionization cross section can be estimated by the semi-empirical Lotz Formula:

- $\sigma_{n \rightarrow n+1} \sim 1.4 \times 10^{-13} \frac{\ln(\frac{E}{I_{n+1}})}{EI_{n+1}} (cm^2)$
 - E electron kinetic energy
 - I_{n+1} (n+1)th ionization potential
 - High charge state production requires hot electrons
 - $Max(\sigma_{n \rightarrow n+1}) \sim \frac{1}{I_{n+1}^2} \Rightarrow$ the higher the charge state, the lower the probability of ionization

Example for Bismuth

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



Charge-Exchange

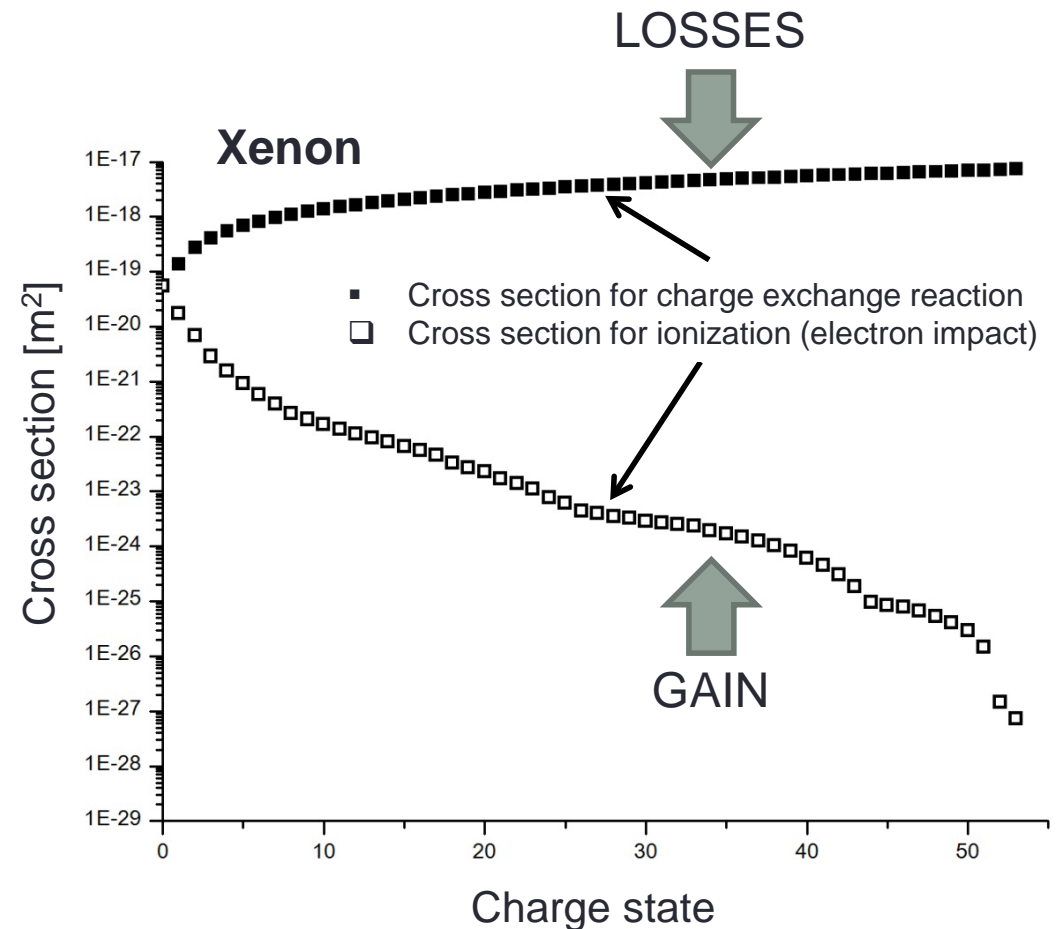
- The main process to reduce an ion charge state is through atom-ion collision
 - $A^{n+} + B^0 \rightarrow A^{(n-1)+} + B^{1+}$ (+radiative transitions)
 - Long distance interaction: the electric field of the ion sucks up an electron from the atom electron cloud
 - Any ion surface grazing signs the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

Example :
Bismuth with O₂

Z	1+	22+	54+	72+	82+
$\sigma_{CE} (cm^2)$	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:

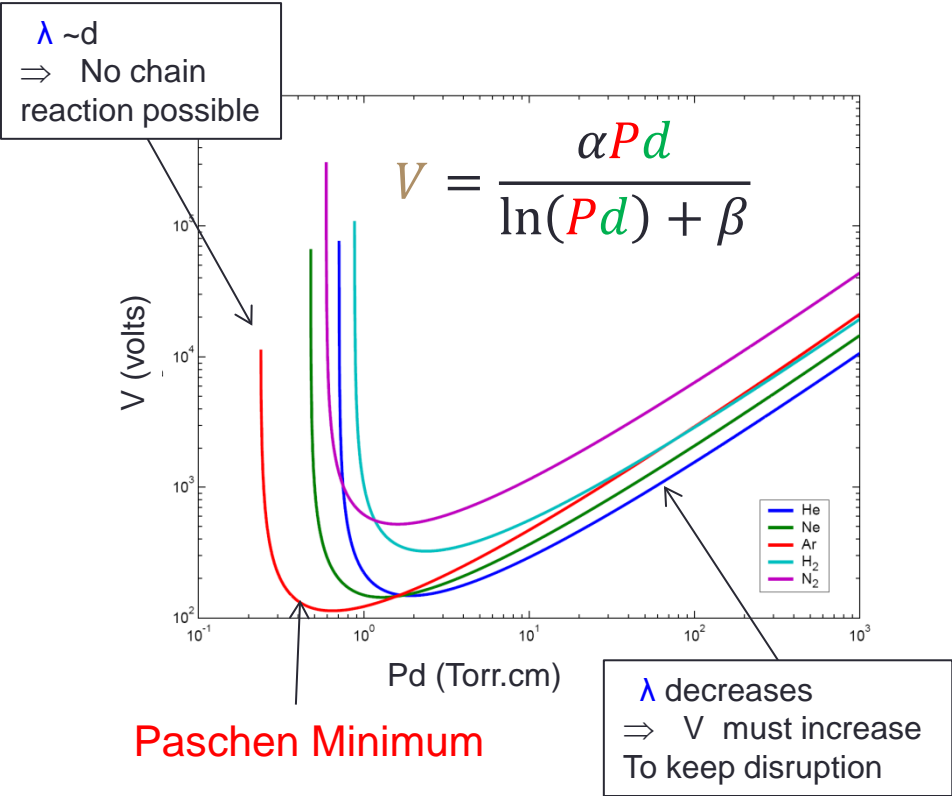
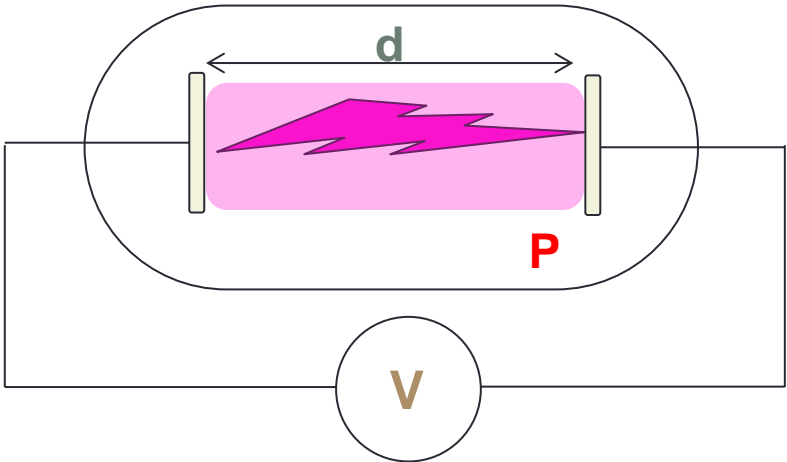
$$\frac{\partial n_i}{\partial t} = \underbrace{\sum_{j=j_{\min}}^{i-1} n_e n_j \langle \sigma_{j \rightarrow i}^{El} v_e \rangle + n_0 n_{i+1} \langle \sigma_{i+1 \rightarrow i}^{CE} v_{i+1} \rangle}_{\text{creation}} - \underbrace{n_0 n_i \langle \sigma_{i \rightarrow i-1}^{CE} v_i \rangle - \sum_{j=i+1}^{j_{\max}} n_e n_j \langle \sigma_{i \rightarrow j}^{El} v_e \rangle}_{\text{destruction}} - \underbrace{\frac{n_i}{\tau_i}}_{\text{Losses (ion extraction, wall...)}}$$

- 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

Losses
(ion extraction,
wall...)

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, $\lambda \sim d$ and no more chain reaction is possible, the avalanche breakdown is no more possible.



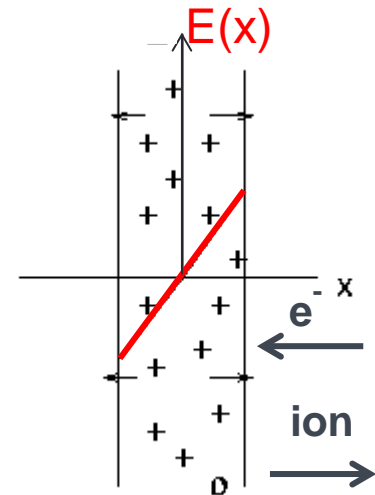
Basics of plasma physics - generalities

- 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 $T_i = T_e$ (T_i ion temperature, T_e electron temperature).
 - a Cold Plasma is such that the move of ions can be neglected with respect to electrons, so $T_e \gg T_i$. 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: $\text{div}(\vec{E}) = \frac{\rho}{\epsilon_0}$
- Let's consider a one dimension slab of plasma with a n_i excess
- $\frac{dE}{dx} = \frac{\rho}{\epsilon_0} \Rightarrow E(x) = \frac{\rho}{\epsilon_0} x$
- The resulting force $F_x(x) = (\pm e) \frac{\rho}{\epsilon_0} x$ expells ions and attracts nearby electrons, tending eventually to reduce the space charge
 $\rho = e(n_i - n_e) \rightarrow 0$



- So plasma is 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:

$$\frac{1}{2}mv^2 = \frac{3}{2}kT$$

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

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

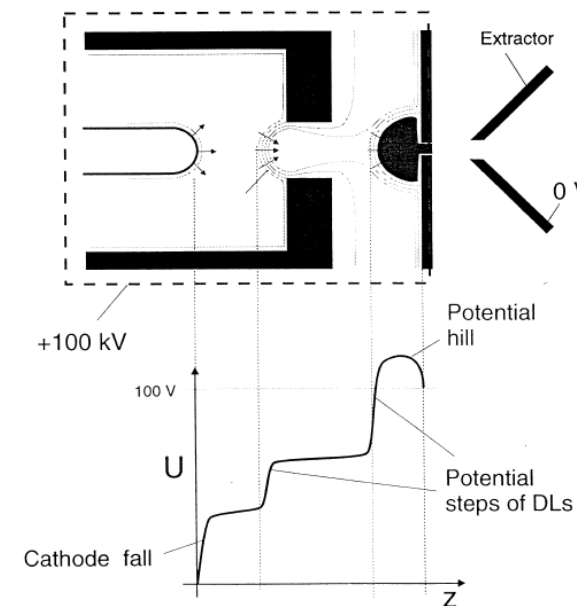
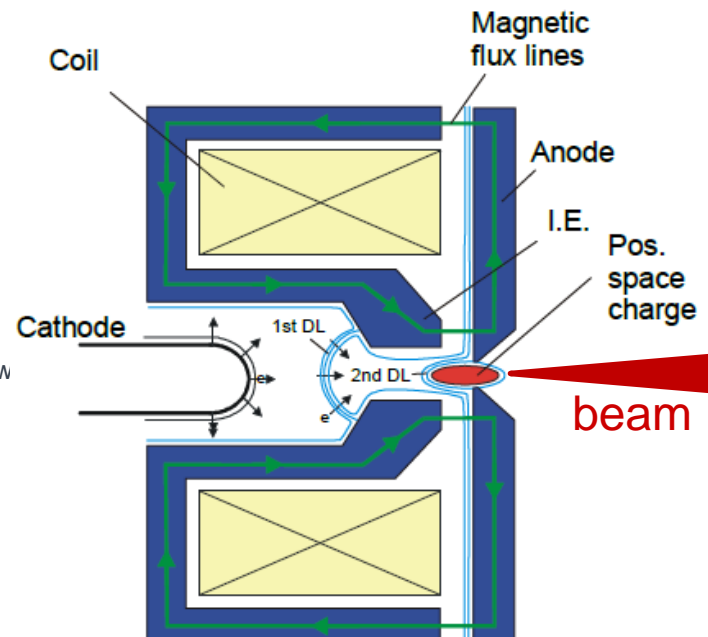
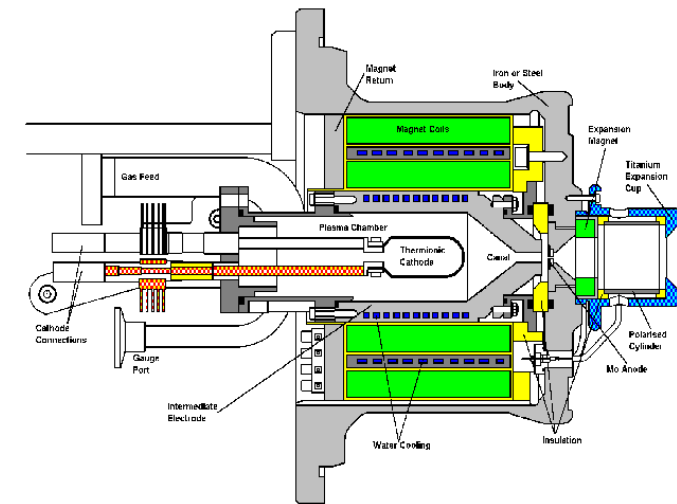
- Electrons are also more sensitive than ions to any electric field E :

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

- In a cold plasma with $T_e \gg T_i$, it is assumed that the movement 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 μ s) 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

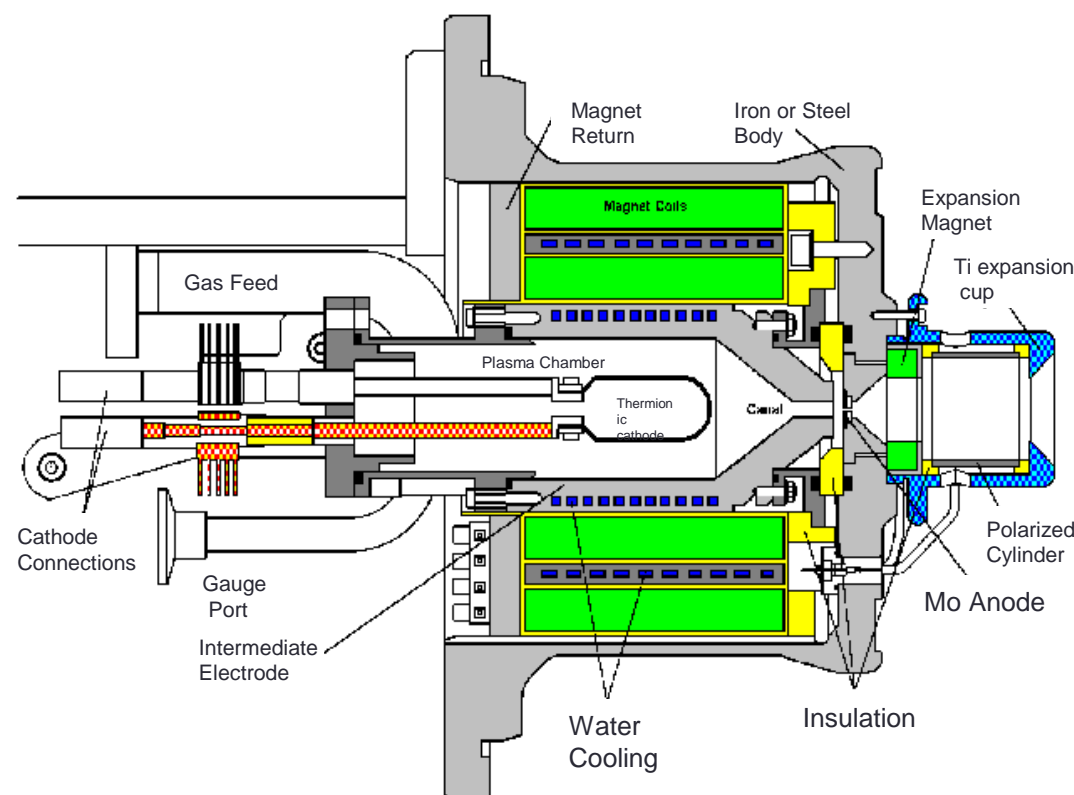


Extracted from, P. Sortais, JUAS 2006

CERN Duo Plasmatron

CERN DUOPLASMATRON

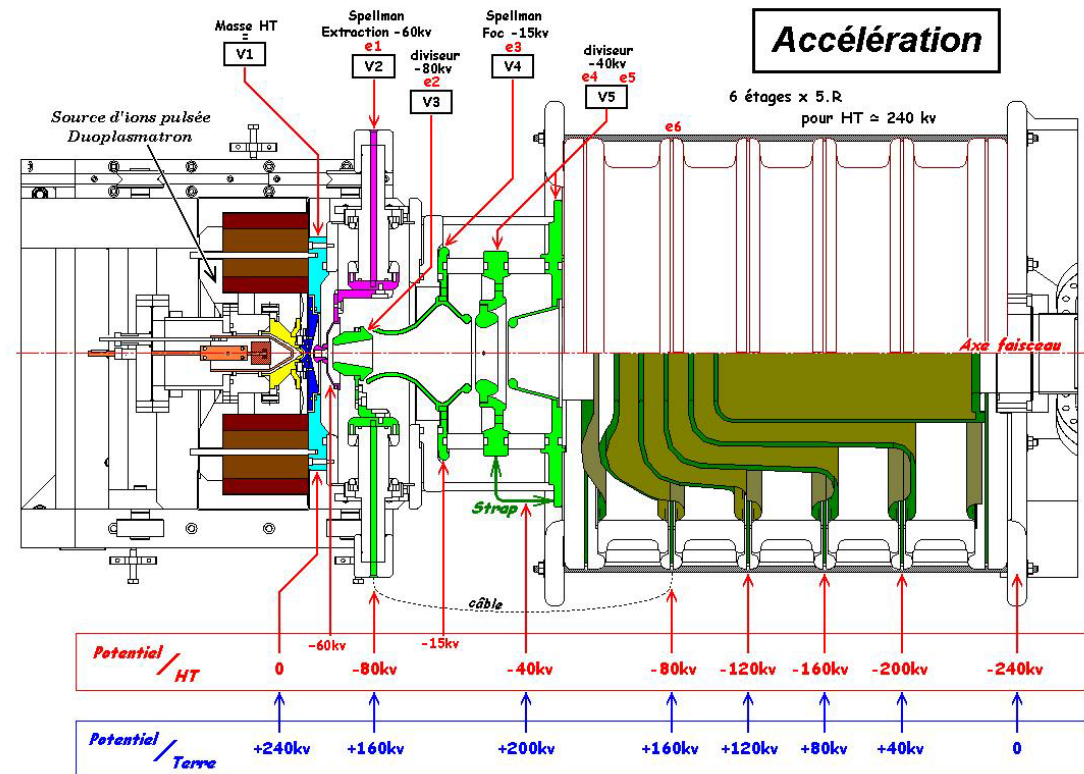
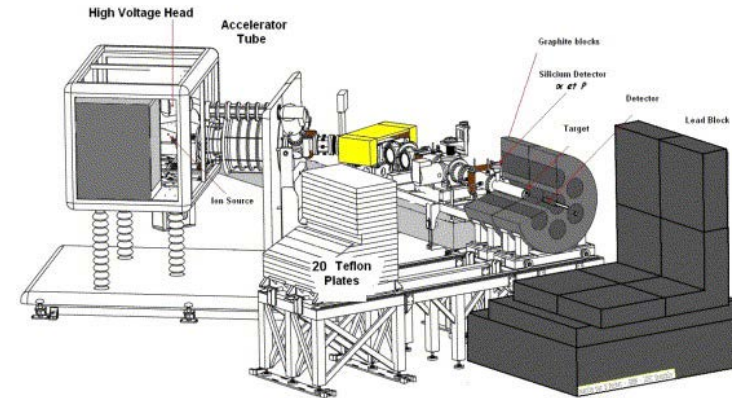
Type	Duoplasmatron with biased electrode in expansion cup
Source Body	Iron or mild steel acting as magnetic flux path
Intermediate electrode	Iron, water cooled. Forms cathode plasma chamber
I.E. Canal	5 mm. diameter, 12 mm. long
Cathode	Mixed oxide thermionic, hairpin, 16 mm. by 92 mm.
Heating current	50 A (150 W) via arc isolating transformer
Hydrogen flow	3 - 6 atm.cc/min (0.05 - 0.1 mbar l/s)
Plasma chamber pressure	0.7 - 2 mbar (estimated)
Main (compression magnet)	2 layer, water cooled, 10A (8750 A.T), iron return
Anode	1 mm. molybdenum in iron insert
Anode hole	Typically 0.6 mm
Arc supply	Current controlled connected to cathode
Arc voltage	500 - 1000 V ignition, 80 V during discharge
Arc current	50 - 60 A pulsed
Pulse length	20 - 150 us (by crowbar or delay line, user defined)
Repetition rate	1 Hz
Expansion magnet	Encapsulated, Kapton/BN3/epoxy insulated (600 A.T)
Expansion cup	Titanium with pseudo-Pierce angle, 20 mm. aperture
Polarised electrode	Stainless steel held at -40 V wrt. expansion cup
Extraction	By acceleration field, accel - decel
Extraction potential	92 kV (- 3kV on decel electrode)
Extraction gap	16.5 mm
Beam current	250 - 320 mA



<http://linac2.home.cern.ch/linac2/sources/source.htm>

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
- 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 $\vec{v}_{\perp} \cdot \vec{B} = 0$ 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 $\vec{e}_{\perp 2} = \vec{e}_{\parallel} \times \vec{e}_{\perp 1}$

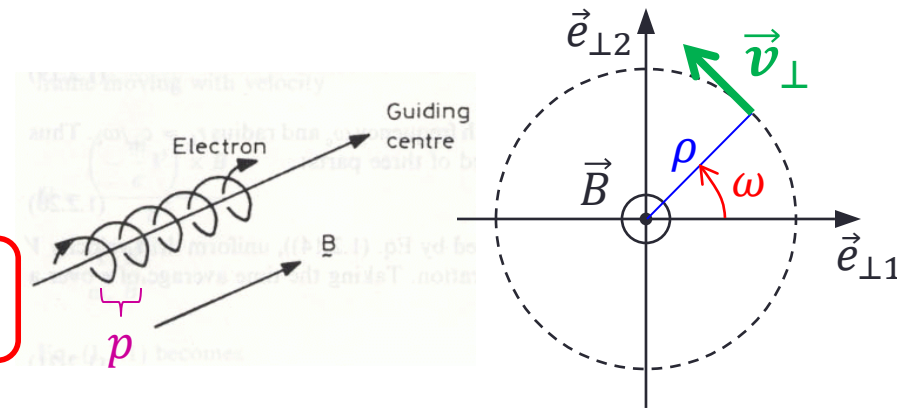
- General solution for the velocity is:

- $$\begin{cases} v_{\parallel} = \text{const} \\ \vec{v}_{\perp} = \rho \omega (\sin \omega t \cdot \vec{e}_{\perp 1} + \cos \omega t \cdot \vec{e}_{\perp 2}) \end{cases}$$

- $\omega = \frac{qB}{m}$ is the cyclotronic frequency

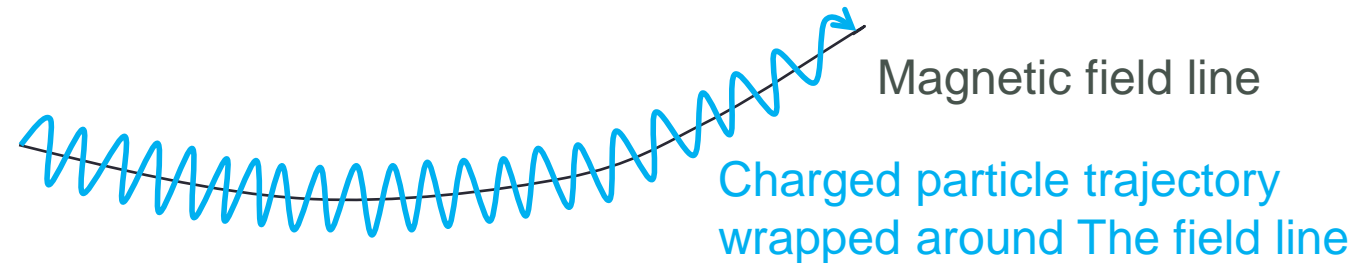
- ρ is the Larmor radius (constant)

- The particle trajectory is an helix with radius ρ and pitch $p = \frac{2\pi v_{\parallel}}{\omega}$

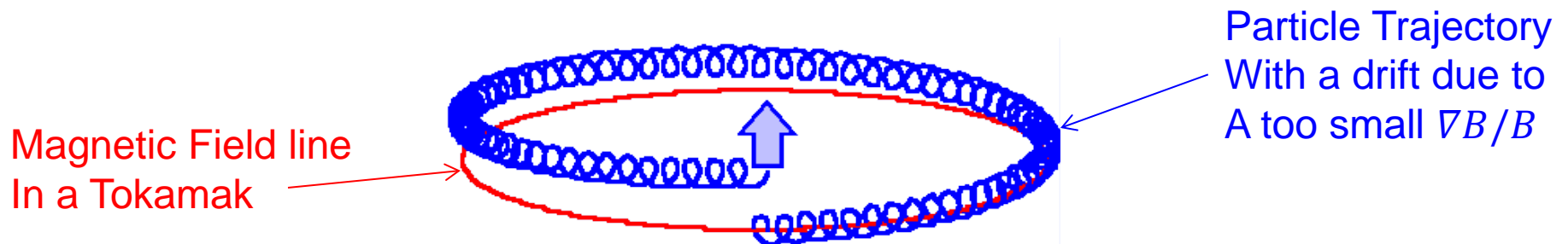


Motion of a particle in a non-uniform magnetic field

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



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



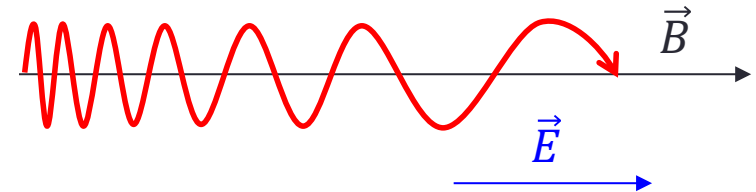
<http://www-fusion-magnetique.cea.fr>

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

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

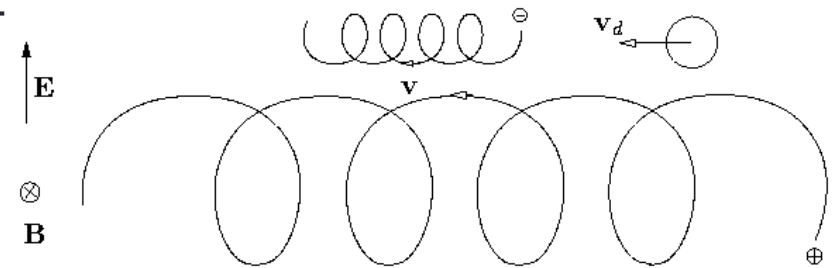
• Motion of a charged particle with $\vec{E} \parallel \vec{B}$

- v_{\parallel} increases linearly with time
- Helical trajectory with an increasing thread pitch



• Motion of a charged particle with $\vec{E} \perp \vec{B}$

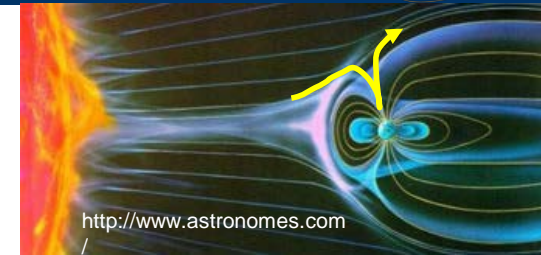
- Cycloidal trajectory
- No Mean acceleration due to E !
- Drift velocity : $\vec{v}_D = \frac{\vec{E} \times \vec{B}}{B^2}$



The Magnetic Mirror Effect

- When a charged particle propagates along z toward a higher magnetic field region, it may be reflected back

Solar wind
reflection by the
Earth
magnetosphere



- $T_{kin} = W_{\parallel} + W_{\perp} = \frac{1}{2}mv_{\parallel}^2 + \frac{1}{2}mv_{\perp}^2 = \text{const}$

- $\mu = \frac{mv_{\perp}^2}{2B} = \frac{W_{\perp}}{B} \sim \text{const}$ (magnetic moment)

- $T_{kin}(z) = \frac{1}{2}mv_{\parallel}^2(z) + \mu B(z) = \text{const}$

- When B increases, then the velocity is adiabatically transferred from v_{\parallel} to v_{\perp}

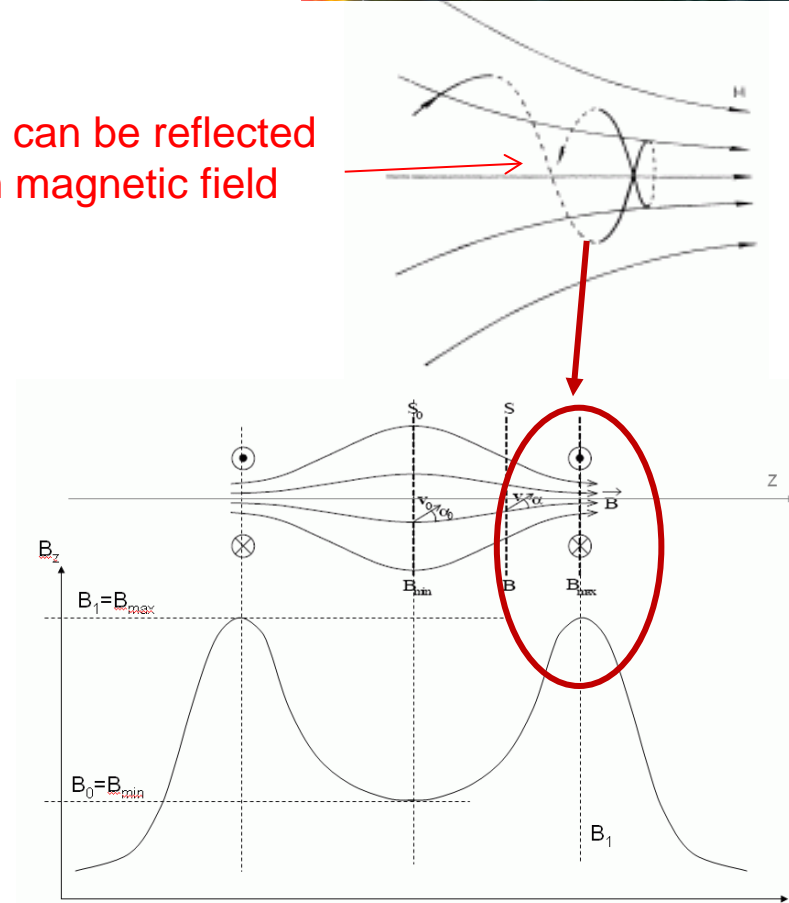
- The particle is stopped at $z = z_1$

where ($v_{\parallel} = 0$) and $B(z_1) = \frac{T_{kin}}{\mu}$

- $T_{kin}(z_1) = \frac{1}{2}mv_{\perp}^2$

- The particle is forced to go backward

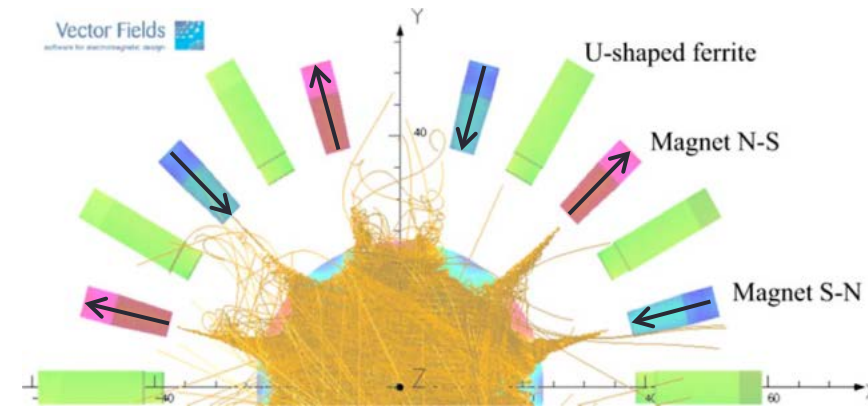
A particle can be reflected
By a high magnetic field
intensity



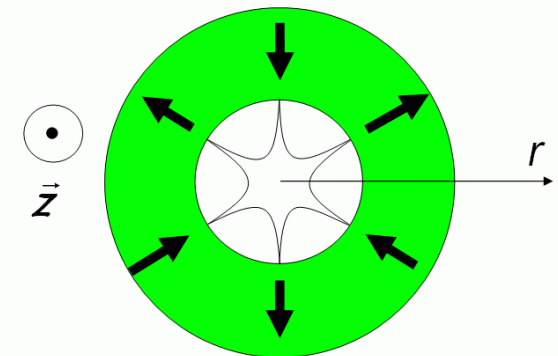
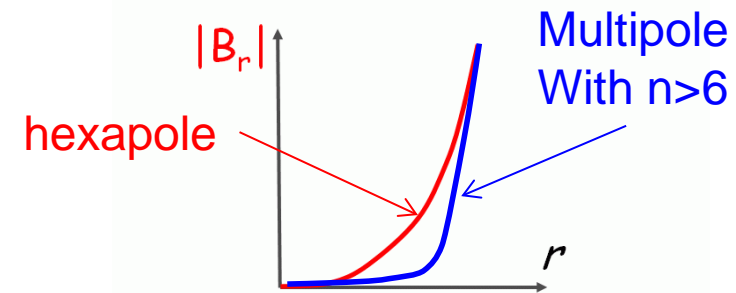
Axial magnetic mirror done with a set of 2 coils

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



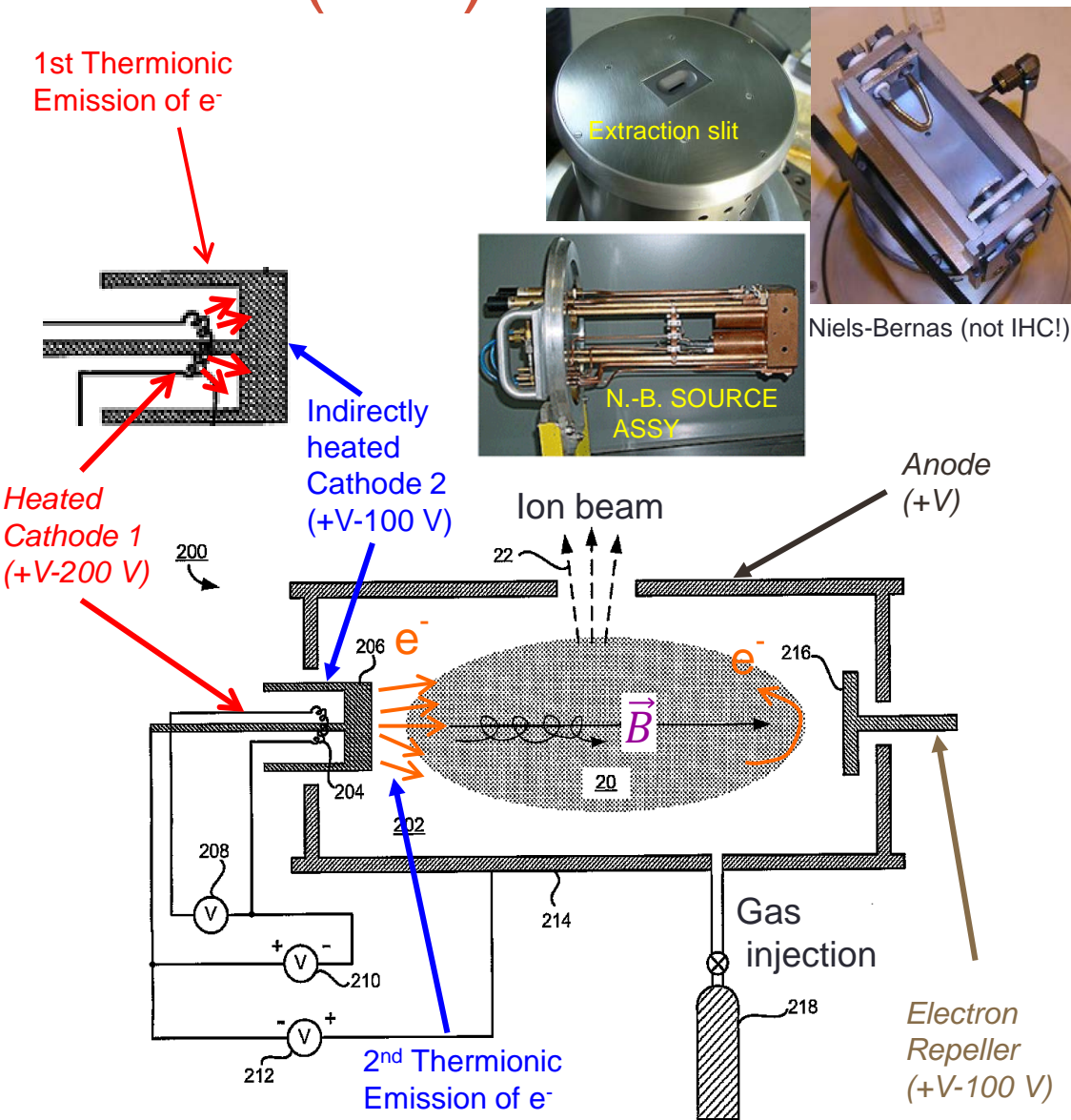
Trajectories of e^- in a CUSP magnetic structure (CERN), Rev. Sci. Instrum. 81, 02A723 (2010))



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 operation condition
- 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%

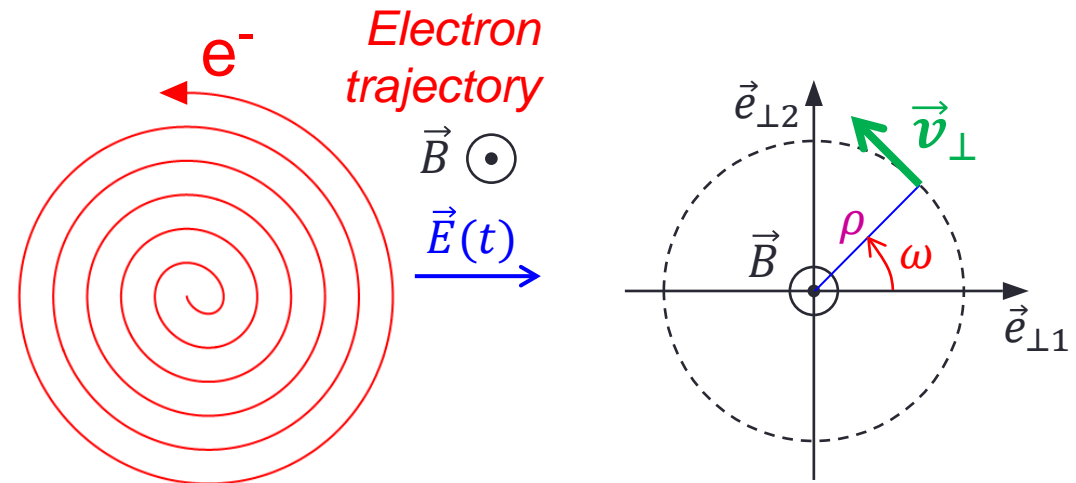


(introduction to) the Electron Cyclotron Resonance (ECR)

- When a particle is moving 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 particle 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:

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

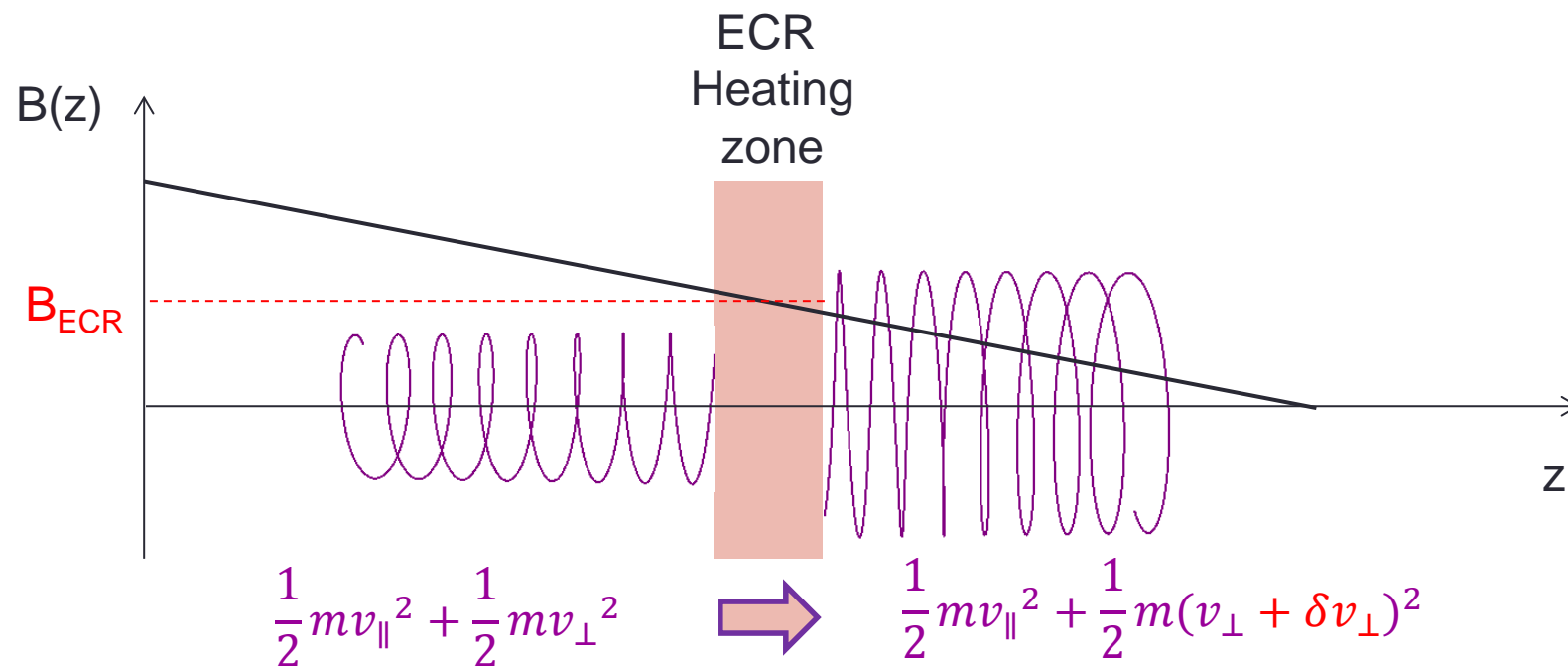


- Since the electric field turns at the same velocity as the particle (an electron here), the particle sees a constant electric field in its own framework => **constant acceleration**
- The particle describes a spiral and gains transverse energy:
 - $\vec{v} = \vec{v}_{\parallel} + \vec{v}_{\perp}$
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

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

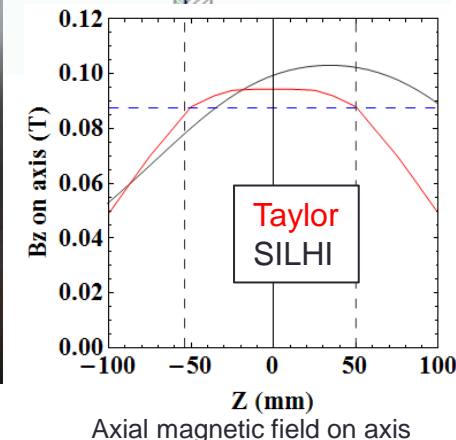
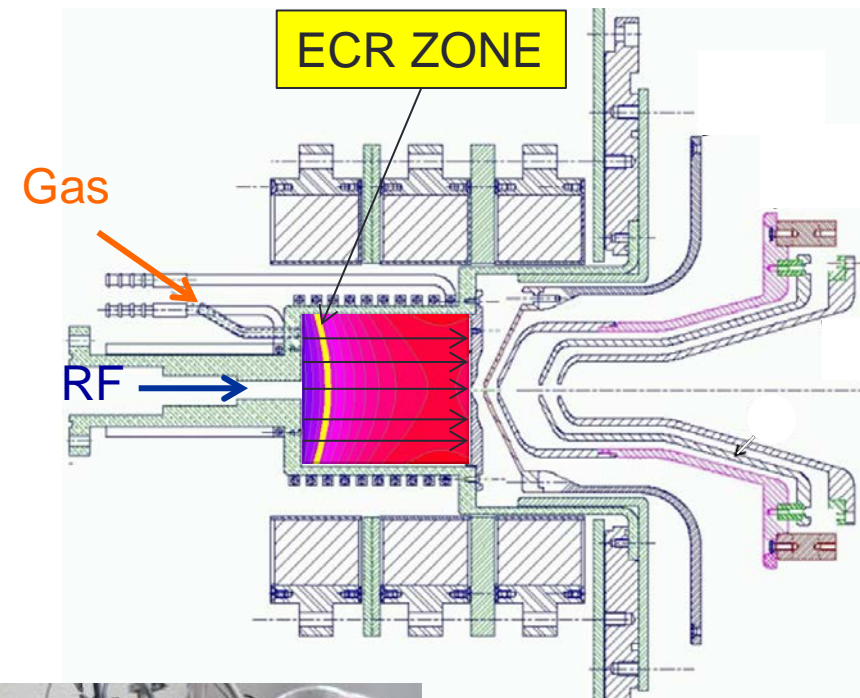
ECR Heating in a Magnetic Gradient

- 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

- 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

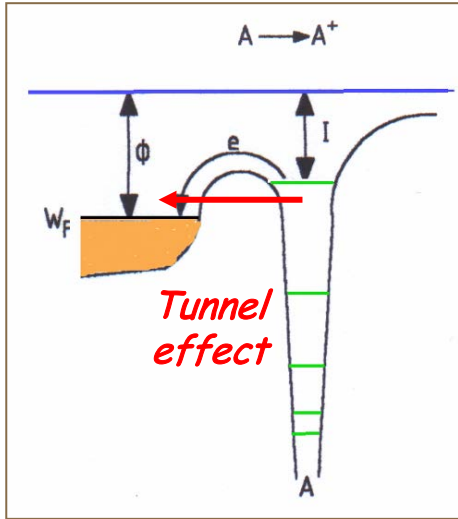
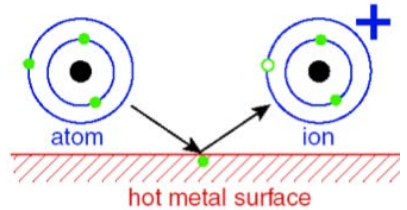


Ionization of atoms on surfaces

• A metal with a High Work Function can steal an electron to an adsorbed atom through Tunnel Effect

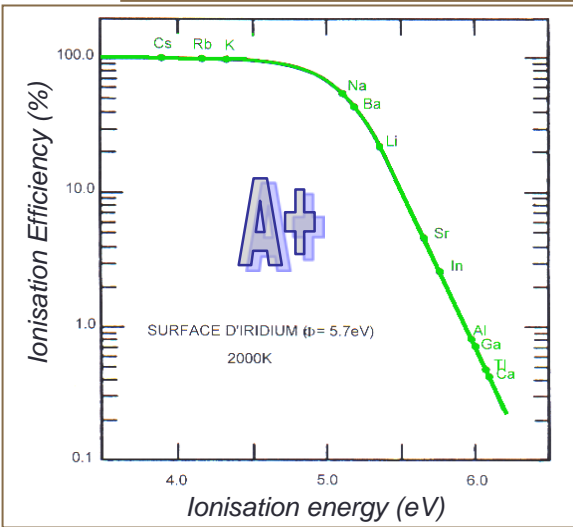
• The ion production efficiency is given by the **SAHA Formula**: $\frac{N^+}{N_0} = C^+ e^{\frac{\varphi - I}{kT}}$, provided $\varphi > I$

- I First Ionisation Potential of adsorbed atom
- φ metal work function
- T metal temperature



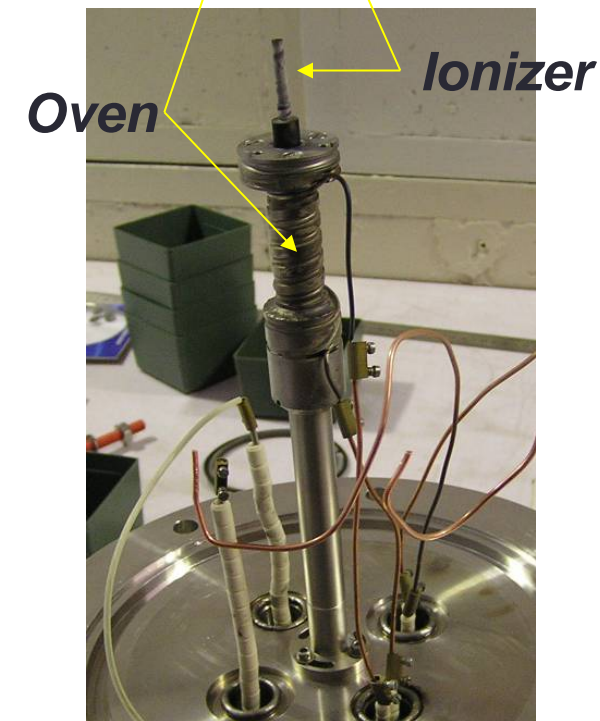
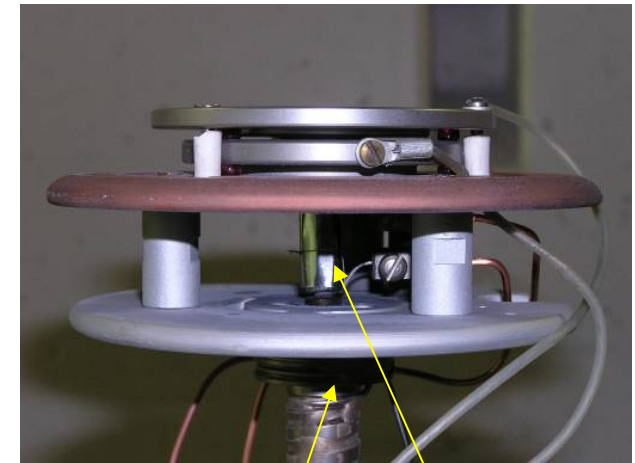
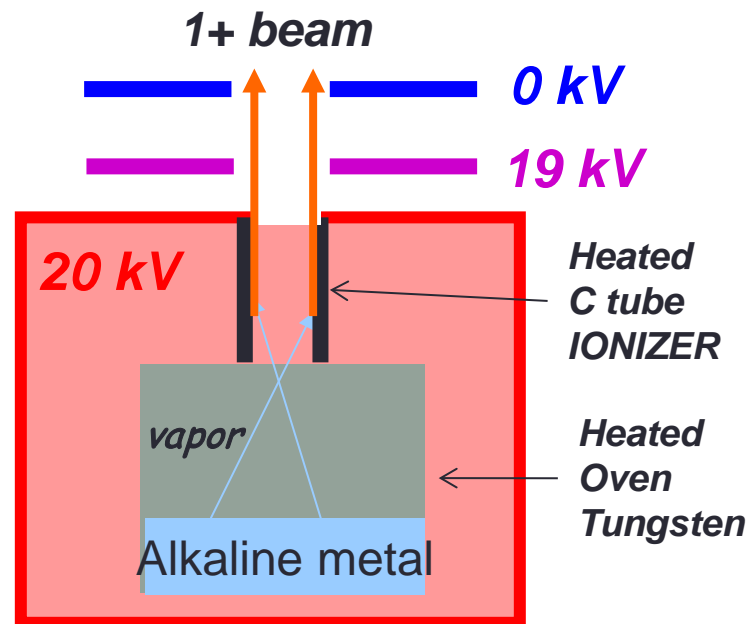
Works with High φ metals and low I atoms

- 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



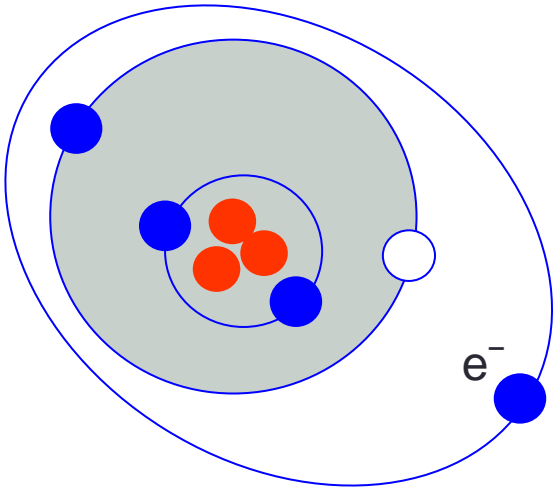
1+ Surface Ionization Source

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



Negative Ions- Electron Affinity

- 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).



3.6 eV for Cl ⁻																He	
H																0	
73																	
Li	Be											B	C	N	O	F	Ne
60	0											27	154	7	141	328	0
Na	Mg											Al	Si	P	S	Cl	Ar
53	0											43	134	72	200	349	0
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
48	2	18	8	51	64	0	16	64	112	118	0	29	119	78	195	325	0
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
47	5	27	41	86	72	53	101	110	54	126	0	29	107	103	190	295	0
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
45	14	50	0	31	79	14	106	151	205	223	0	19	35	91	183	270	0

Periodic table of **electronic affinity** in kJ/mol, actinids not represented

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 attachment:

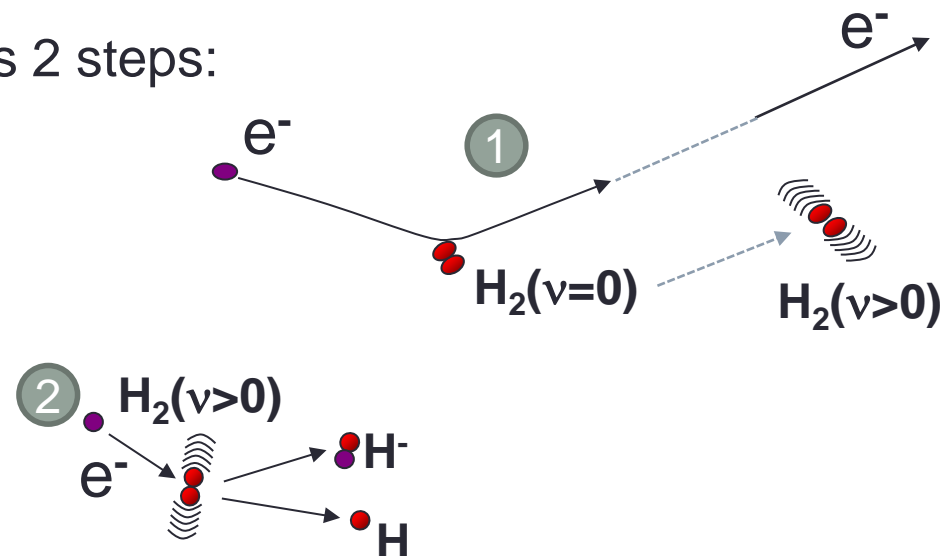
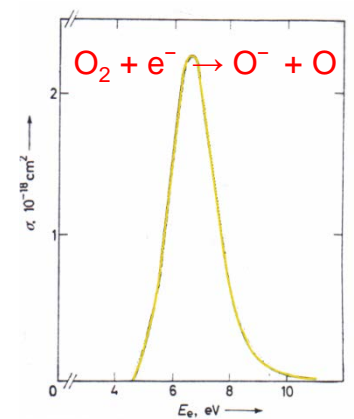
- the excess of energy is transferred to a third particle when dissociating a molecule
 - $AB + e^- \rightarrow A^- + B$ (rare event)

- 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 attachment
 - $H_2^v + e^- \rightarrow H^- + H$



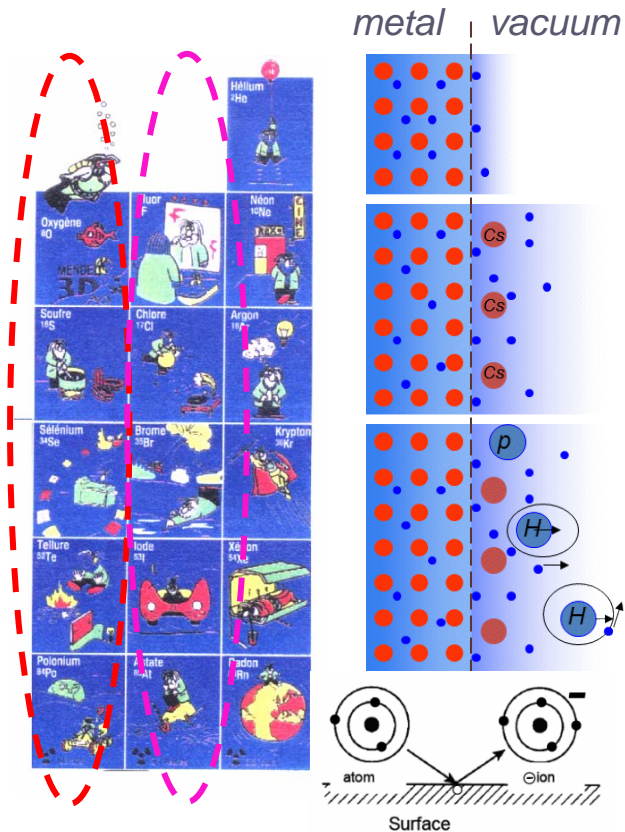
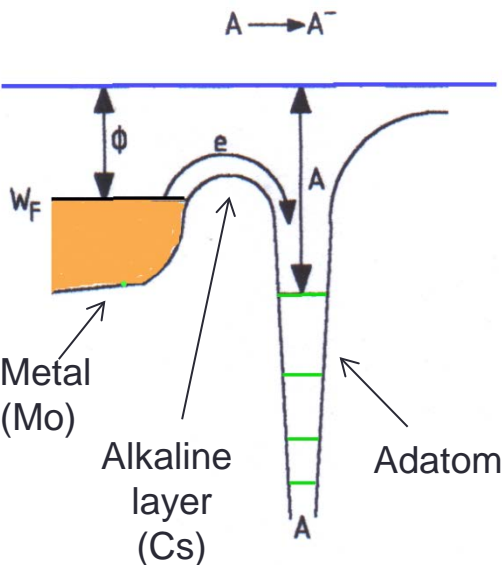
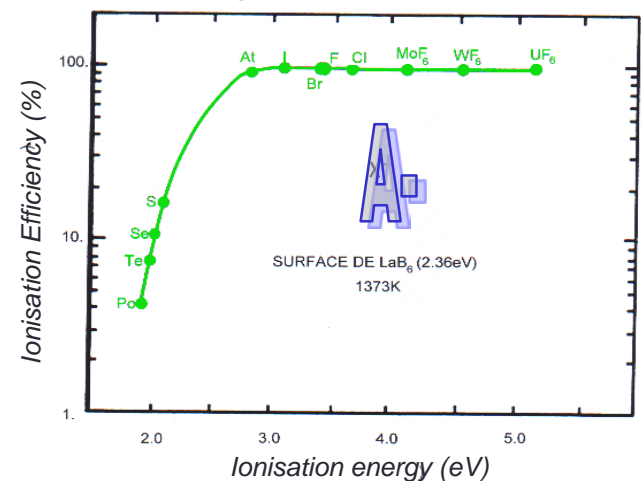
How to create a negative ion? (2/2)

- **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 $A > \phi$
- Surface ionization works efficiently with **Halogens** and **Chalcogens**

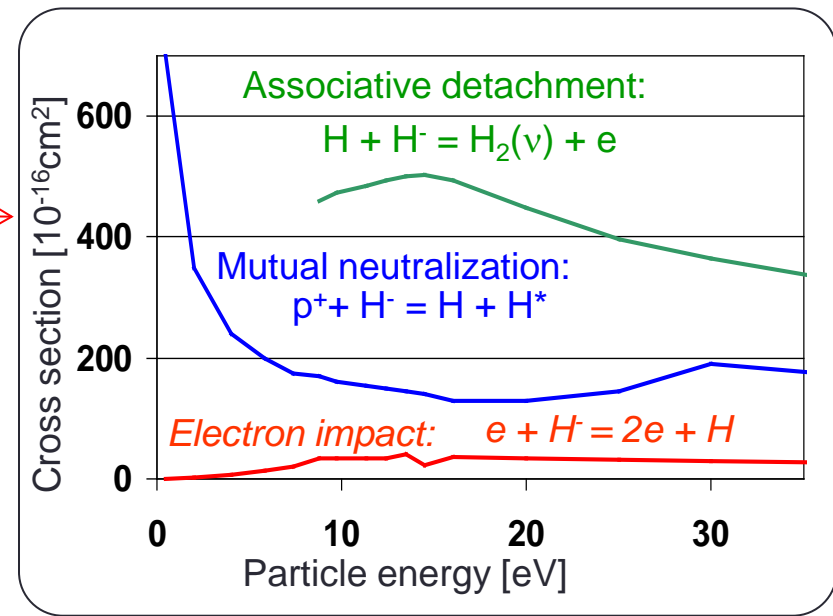
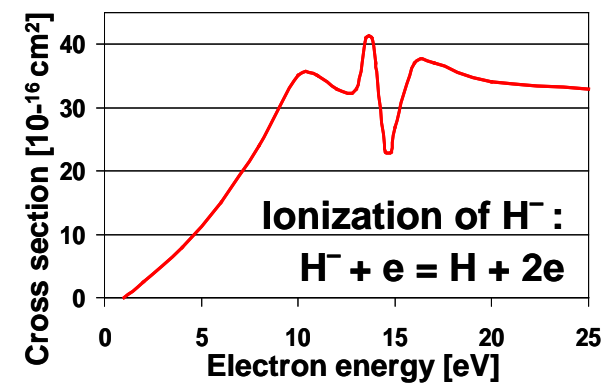
- Saha Formula: $\frac{N^-}{N_0} = C^- e^{\frac{A-\phi}{kT}}$

- High kT helps to desorb A^-



How to lose a negative ion?

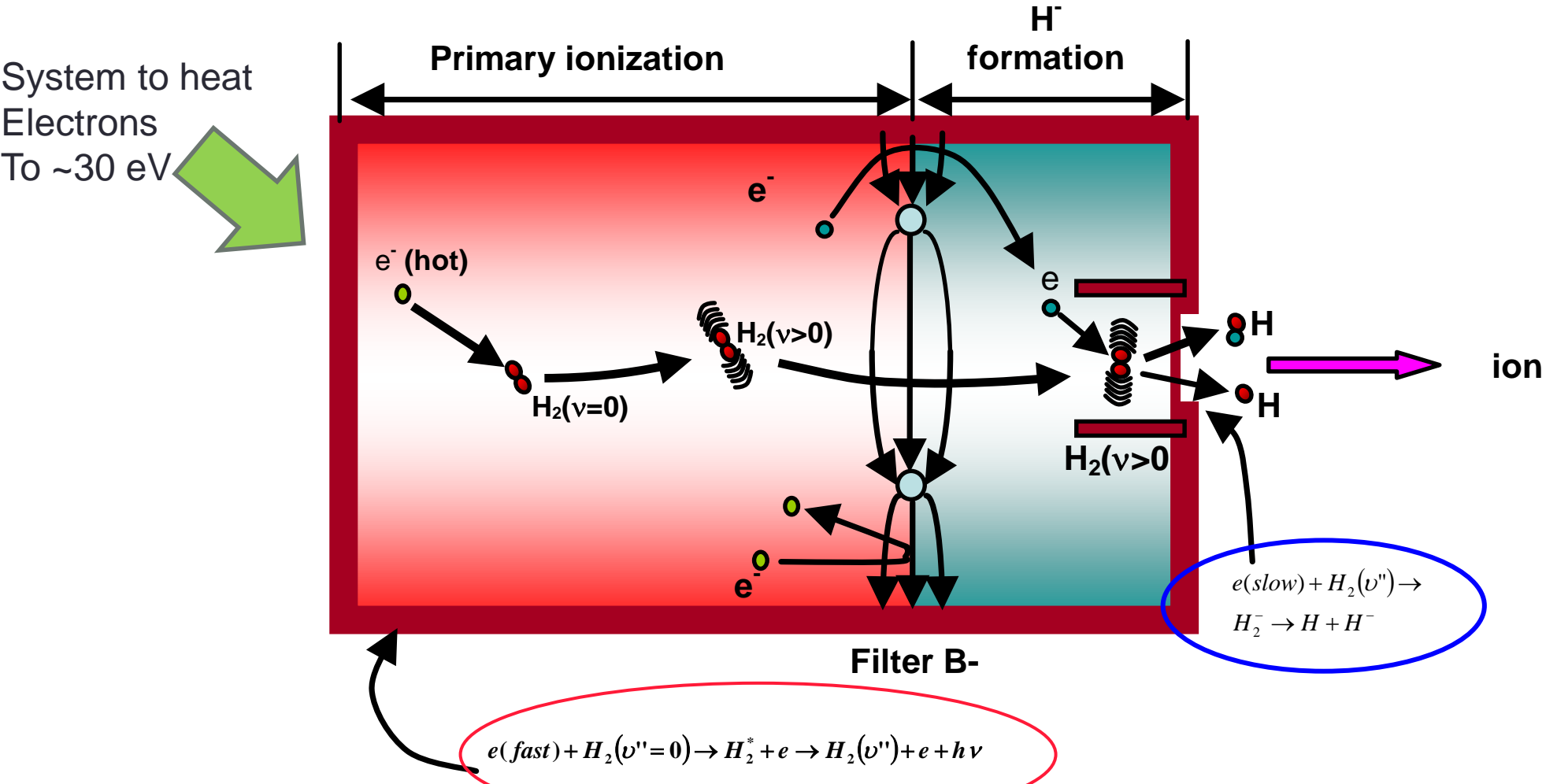
- Very very easily!
- Electron impact ionization:
 $A^- + e^- \rightarrow A + 2e^-$
- Mutual neutralisation (Recombination)
 $A^- + H^+ \rightarrow A + H$
- Collisional Detachment:
 $A^- + B \rightarrow A + B + e^-$
- Associative Detachment:
 $A^- + B \rightarrow AB + e^-$
- **Negative ions are totally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

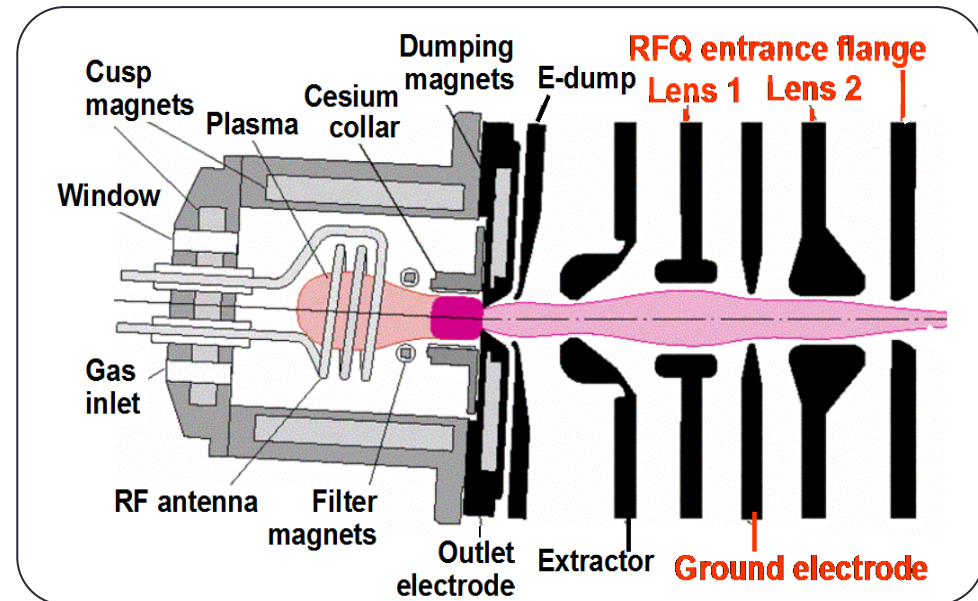
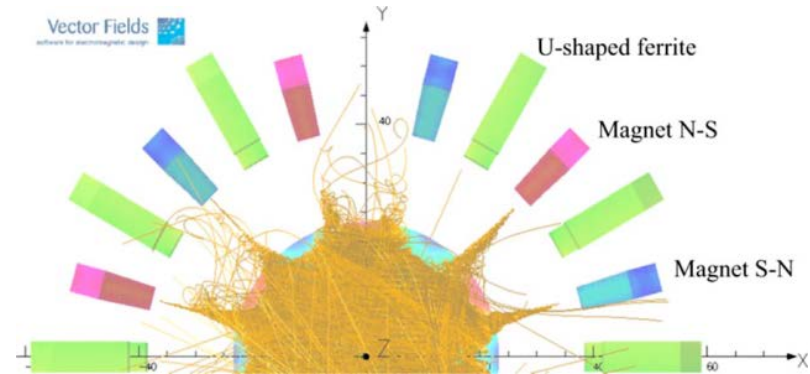


Radio-Frequency Negative Ion Source

• Example of the ORNL H^- Ion Source

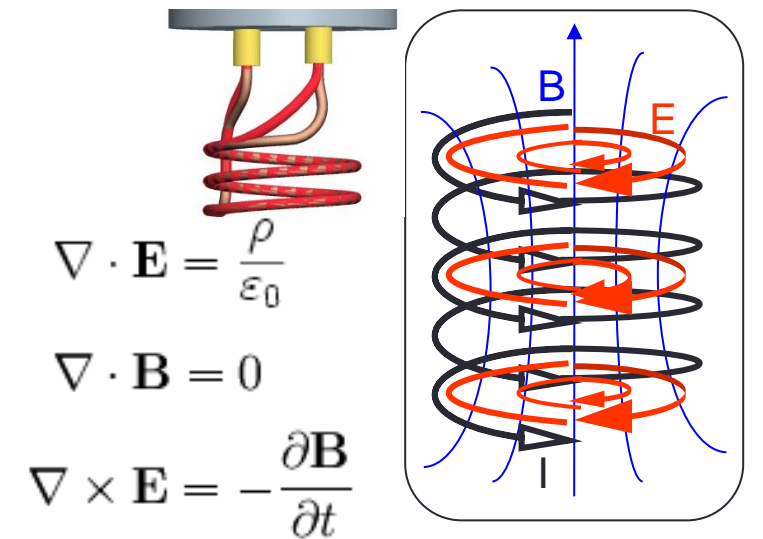
- A multicusp magnetic structure provides a radial plasma confinement
- H_2 gas is injected on the rear part
- A pulsed RF antenna under vacuum generates the plasma (see next slide) and ionizes hydrogen to produce H^+ , H_2^+ , e^-
- Two filter magnets (SmCo 200 Gauss) repel hot electrons generated by 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

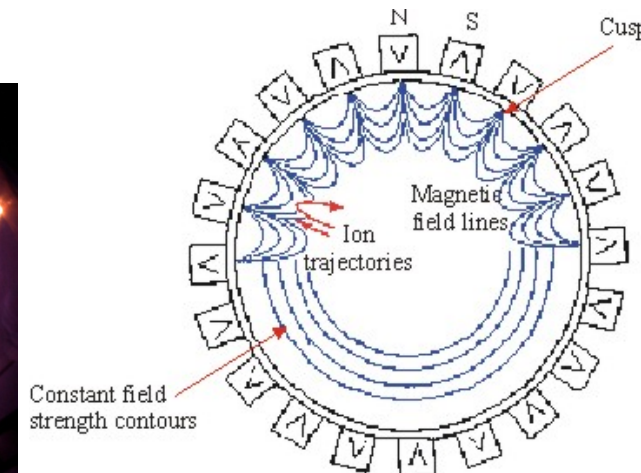


$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

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

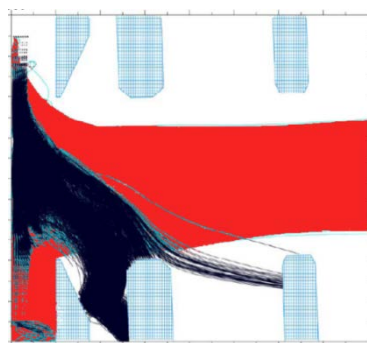
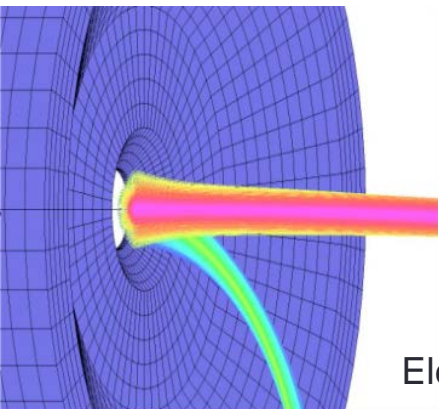
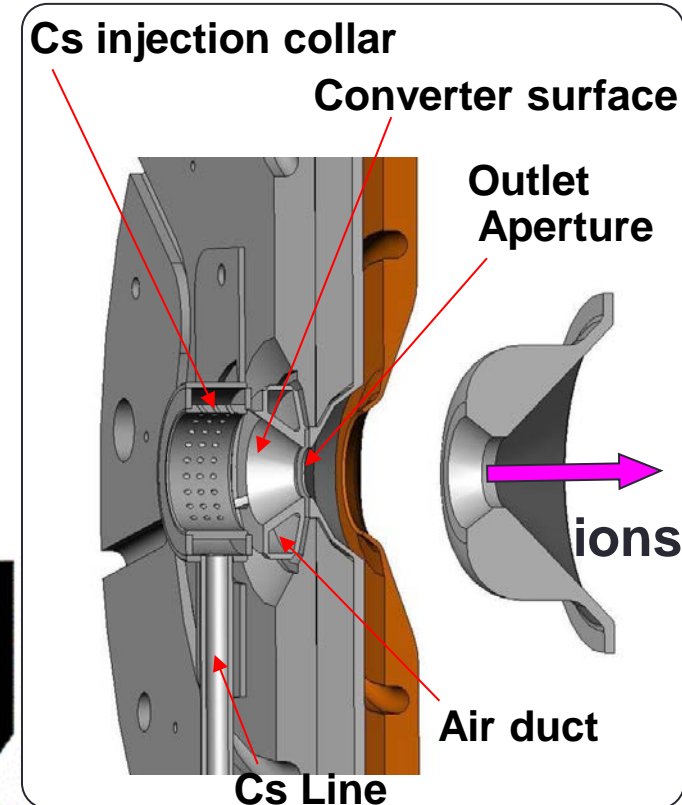
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

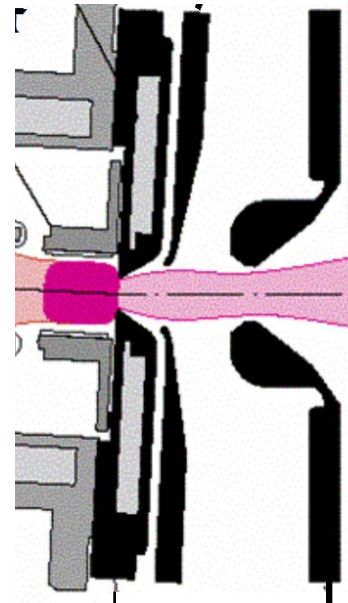


RF Negative Ion Source – Cesium System and Beam Extraction

- Cesium system:
 - The Cs flux is controlled by an external oven
 - Cs manipulation is tricky (pyrophoric, unusable once oxydised)
- Gain of H^- current:
 - 10 mA (no Cs) → 50 mA (Cs)
- H^- extraction
 - A dumping magnet is located in the extraction area to deviate the co-extracted electrons off-axis
 - The co-extracted electron beam is dumped on the intermediate electrodes
 - The source is tilted to have the H^- on the accelerator axis



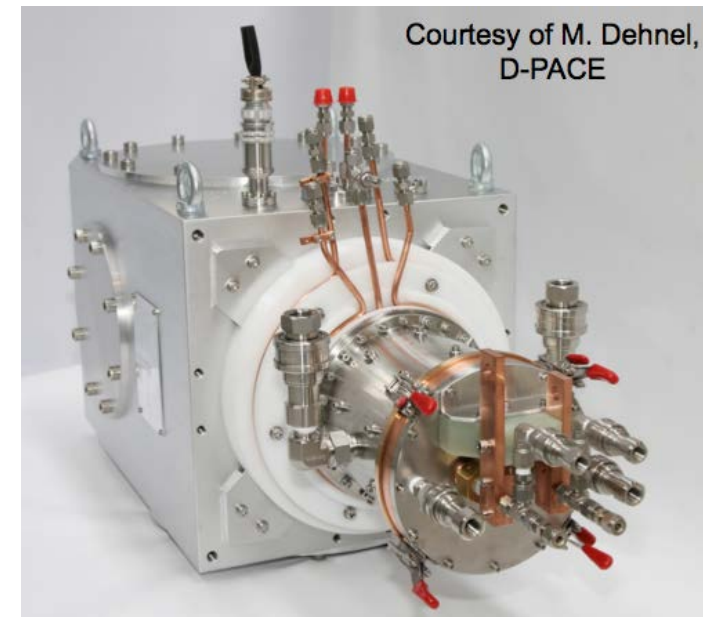
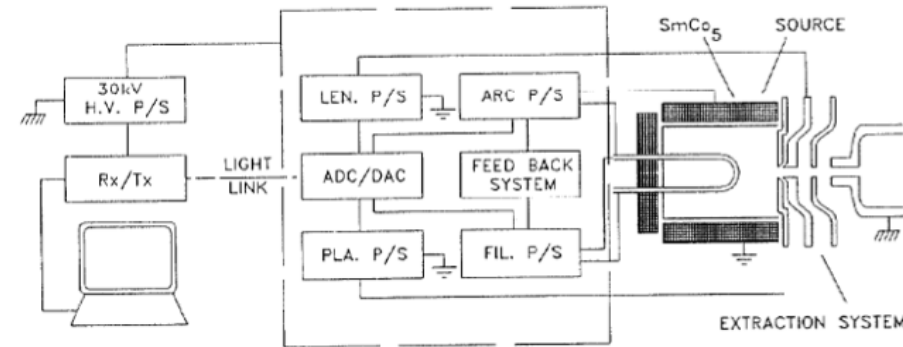
Electron deviation in the Extraction gap



Filament driven Triumf H- ion source: Volume production

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

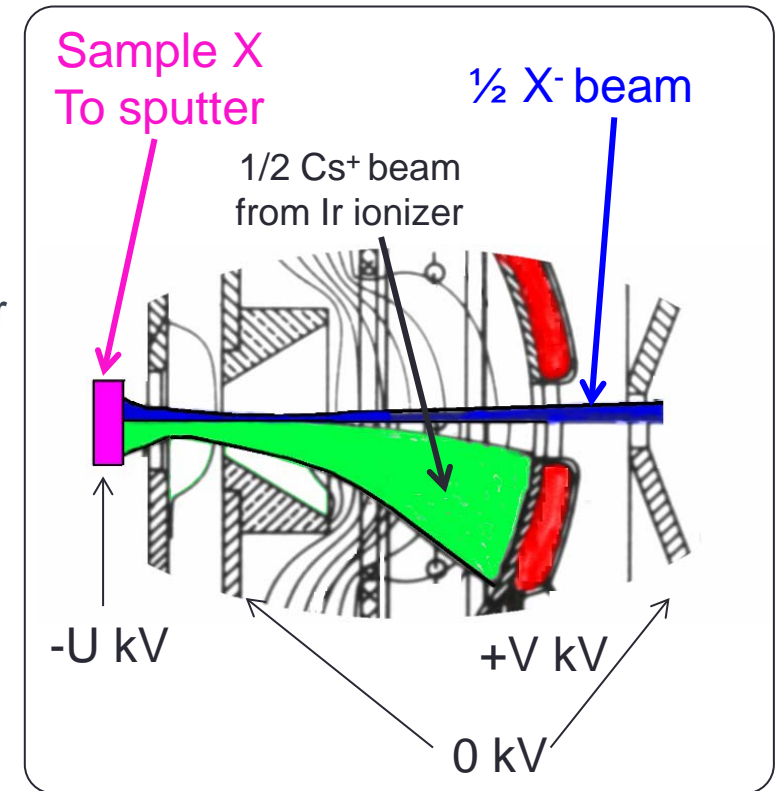
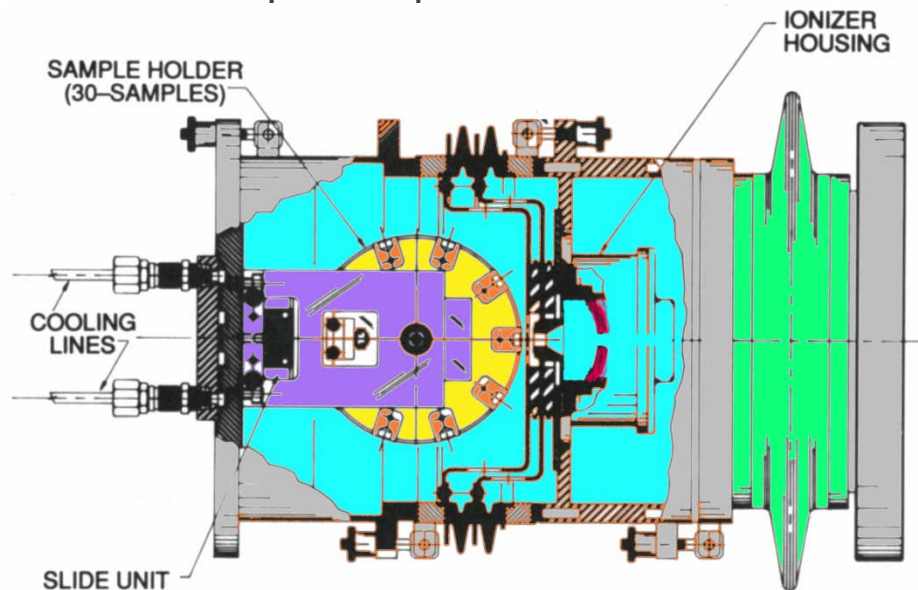
- The TRIUMF H- source was developed ~1990 to inject H- into the TRIUMF Cyclotron
- A filament driven plasma is confined by a multicusp field
- Filter field generated by two inverted cusp magnets near the outlet.
- Licensed to and sold by D- PACE at www.d-pace.com
 - Beam current: 15 mA continuous
 -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



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



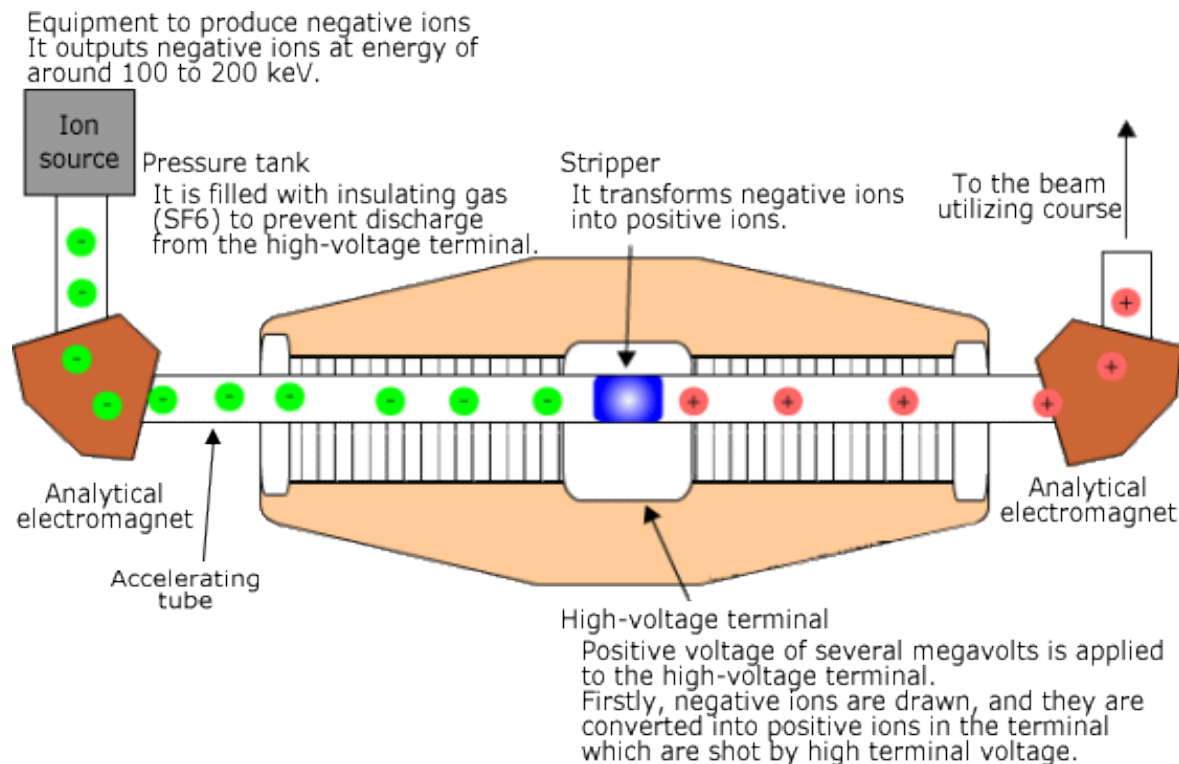
- Negative Metal Ions are produced (helped with high kT)
- Automatic Rotation of Sample to sputter to increase the beam time

Negative Ion Source Applications for TANDEM

• TANDEM Accelerator

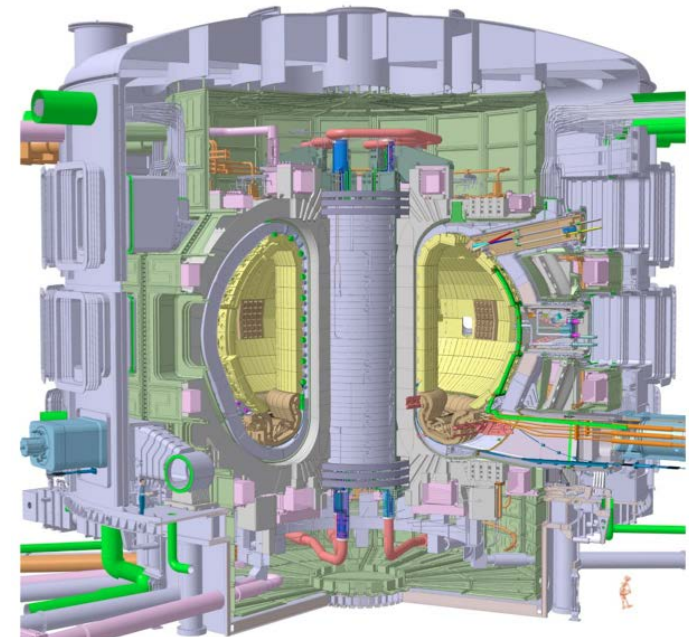
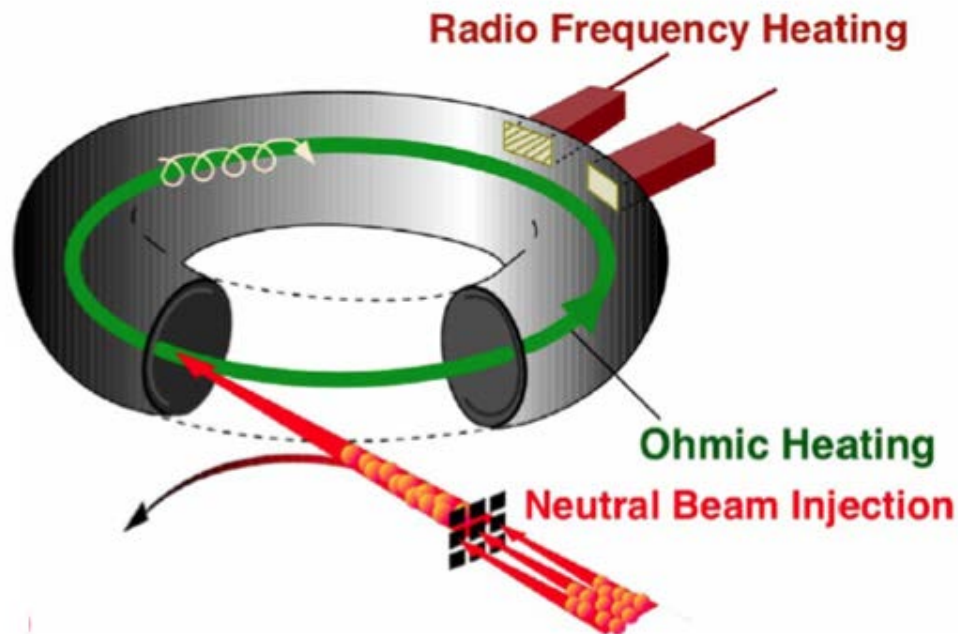
<http://www.werc.or.jp/english/reseadeve/activities/accelerator/accelerator/tandem/index.htm>

- 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.



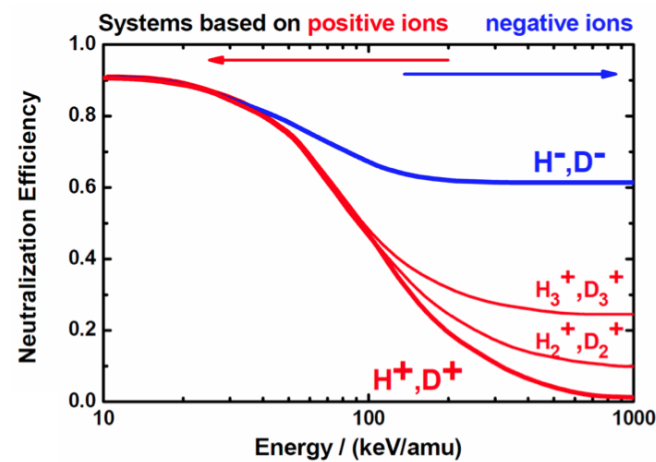
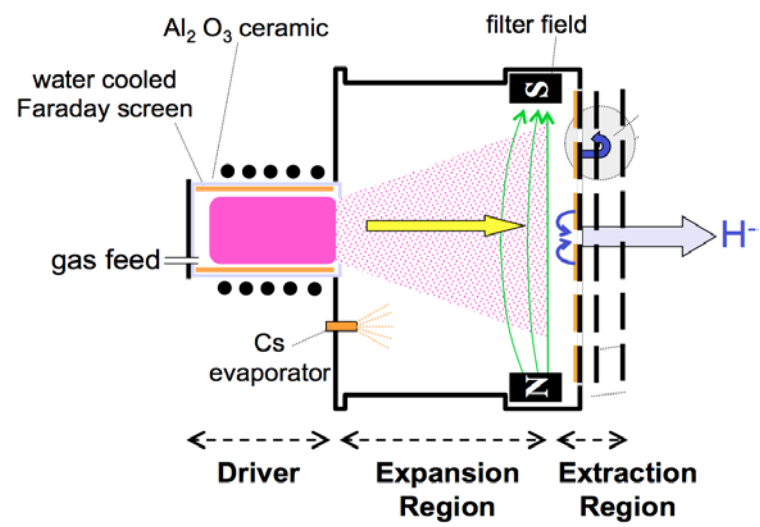
Negative Ion Application for TOKAMAK

- 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

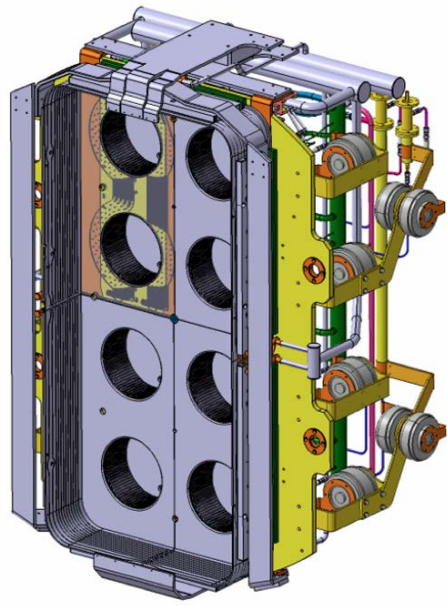
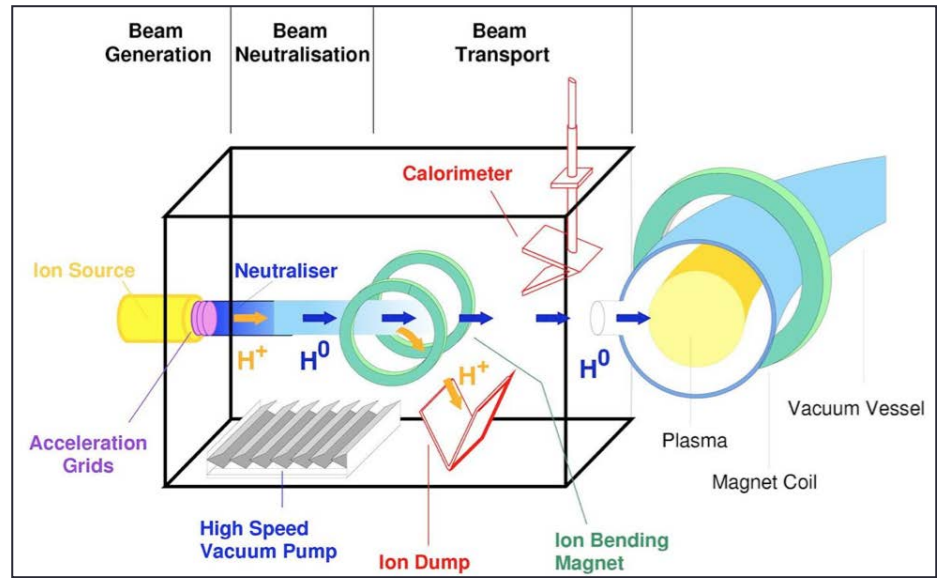


D⁻ Ion source for ITER

- 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



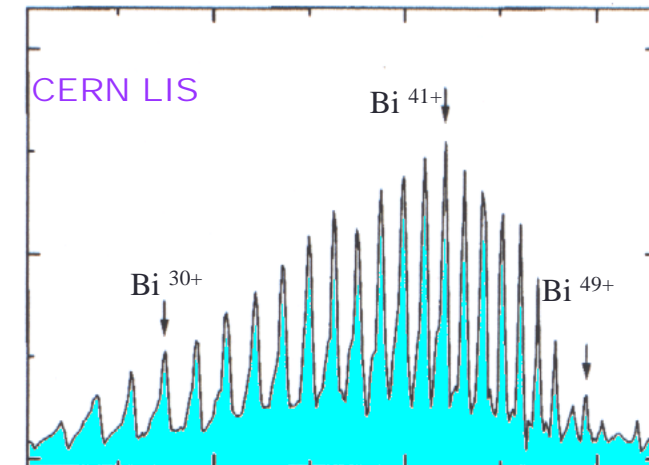
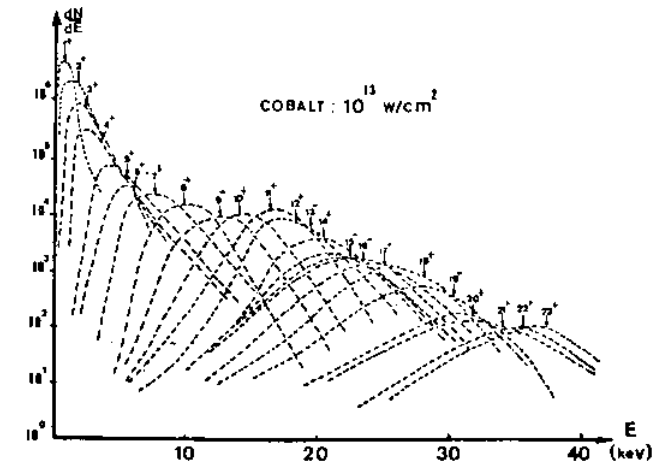
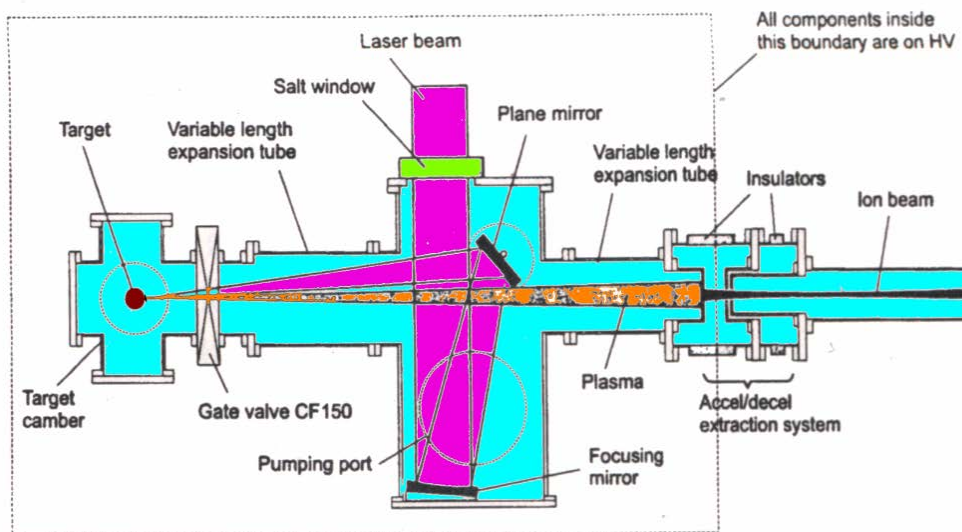
ITER source 1.9 x 0.9 m²



Material from CAS2012: W. Kraus

Laser Ion Source

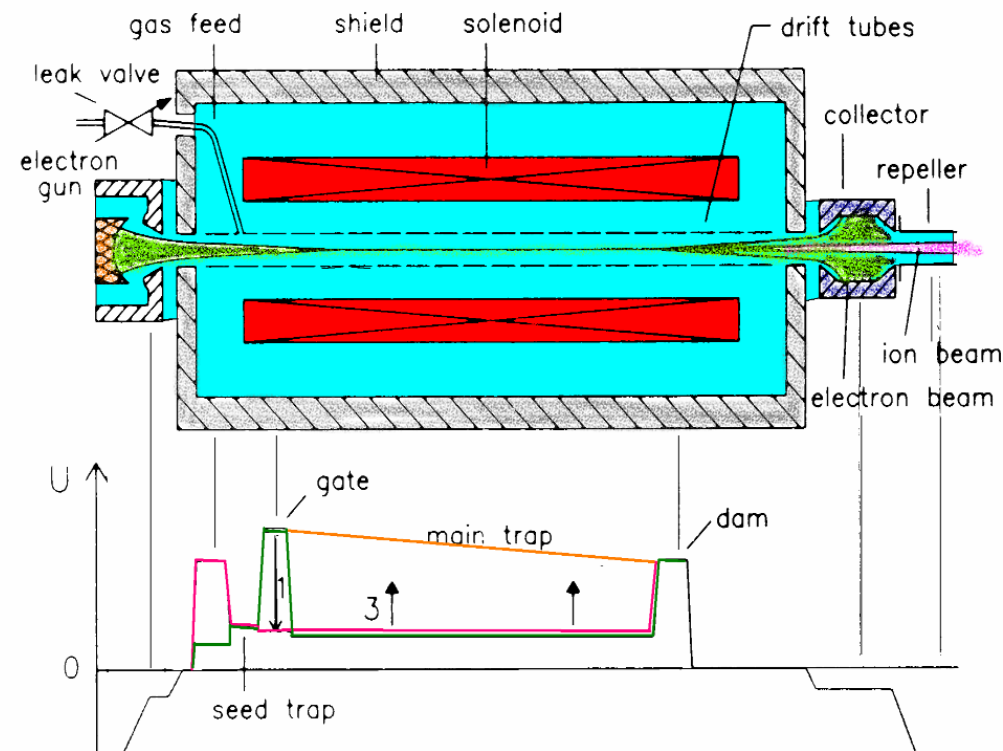
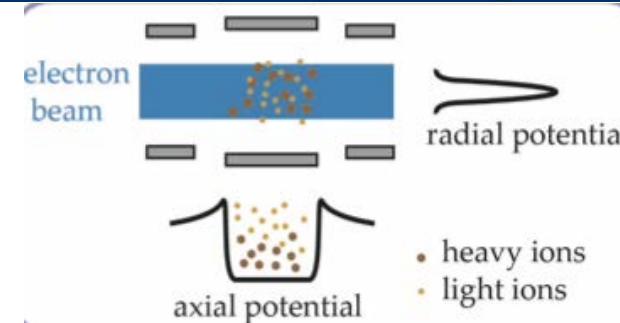
- A very strong power laser pulse evaporates solid matter and generates a medium to high charge state hot plasma
 - Very High density plasma
 - Complicated plasma physics behind
 - High charge state ions created
 - High currents
 - But Very Hot ions (KeV to MeV)
 - Complicated extraction and acceleration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



Specifications :
 $\text{CO}_2\text{-N}_2\text{-He}$ laser $100\text{J-}10^{13}\text{W.cm}^{-2}$
 pulses of 50ns at 1Hz
 $1.4 \cdot 10^{10} \text{ Pb}^{25+}$ per pulse

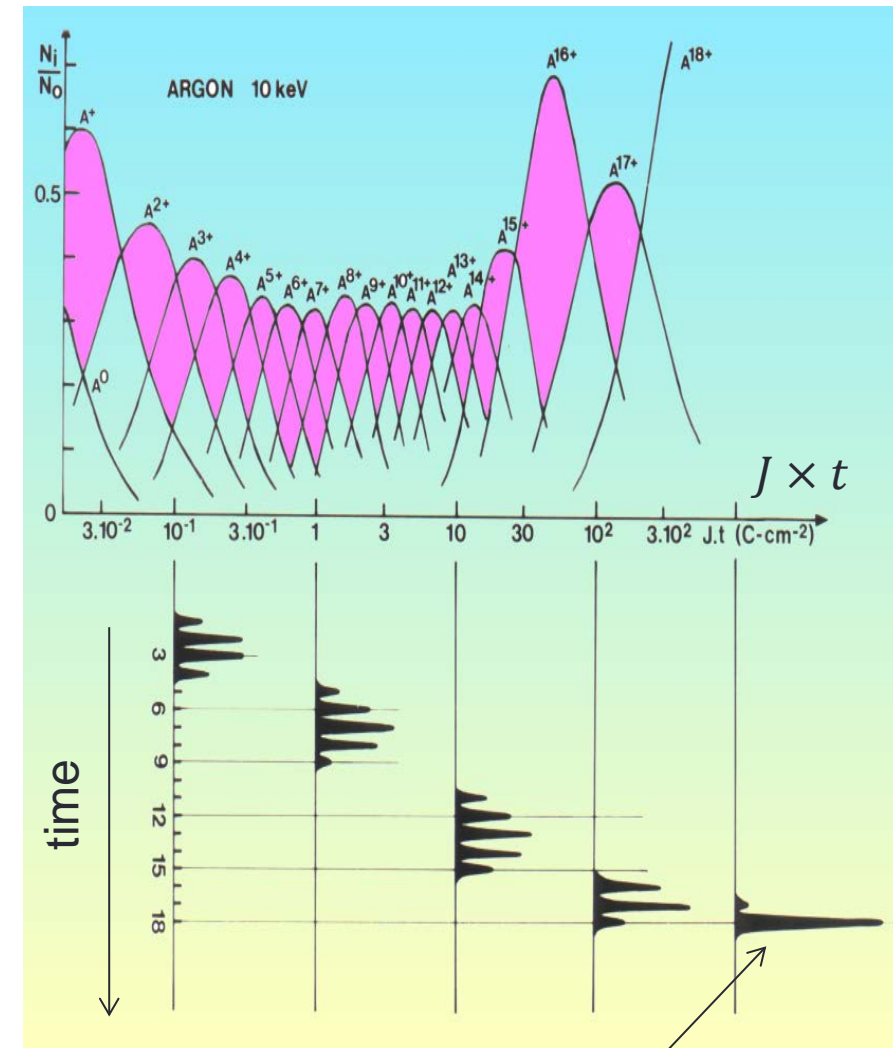
Electron Beam Ion Source (EBIS)

- 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

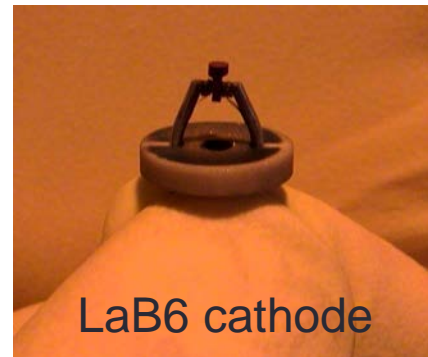


EBIS Performance

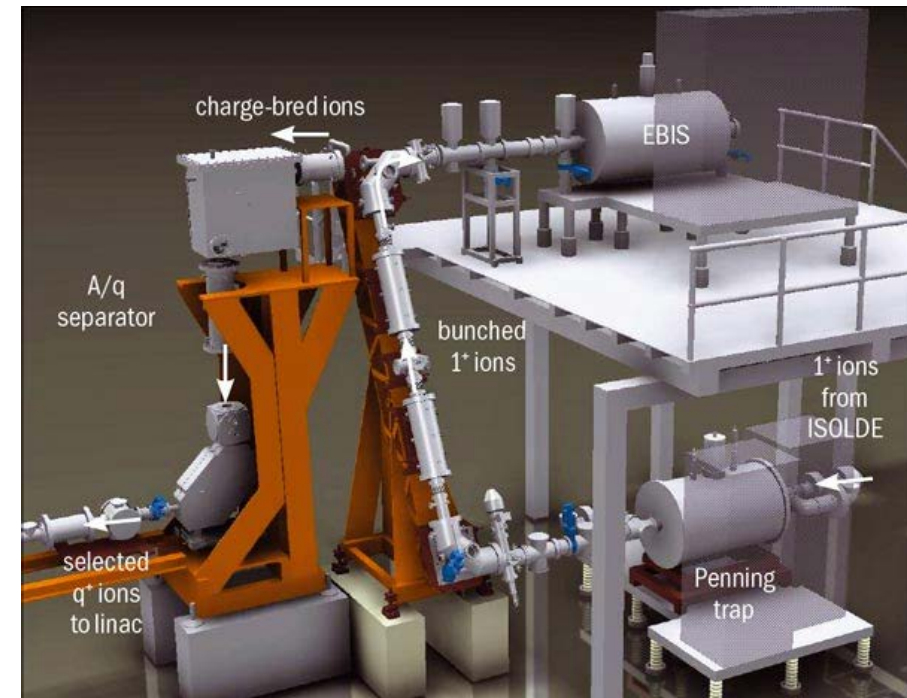
- Production of Very High Charge state
 - The Ions charge state distribution increase with the “cooking time”
 - Charge state distribution is narrow
 - Ultra high charge state achievable
- Limited pulse repetition rate
 - Long Cooking time (10-100 ms)
 - Suitable for LINAC & synchrotrons
- Limited beam 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



The REX-EBIS setup



- REX-EBIS specifications (CERN)
 - LaB6 cathode (thermal electron gun)
 - $j_{\text{cathode}} < 20 \text{ A/cm}^2$
 - $j_e = j_{\text{trap}} < 200 \text{ A/cm}^2$
 - $I_e = 460 \text{ mA}$ (normal operation 200 mA)
 - $E = 3.5\text{--}6 \text{ keV}$
 - 3 drift tubes $L = 200$ to 800 mm
 - Theoretical capacity $5 \cdot 10^{10}$ positive charges
 - Ultra-high vacuum $10^{-10}\text{--}10^{-11} \text{ mbar}$

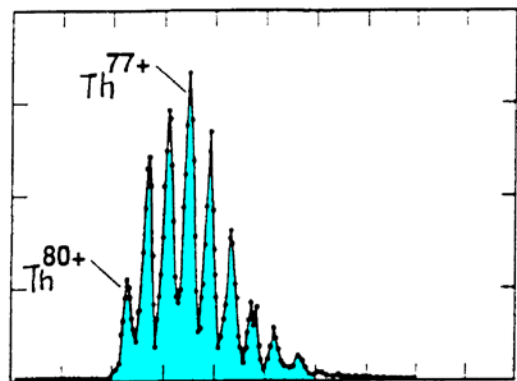


The charge state is selected with a mass separator of Nier-Spectrometer type

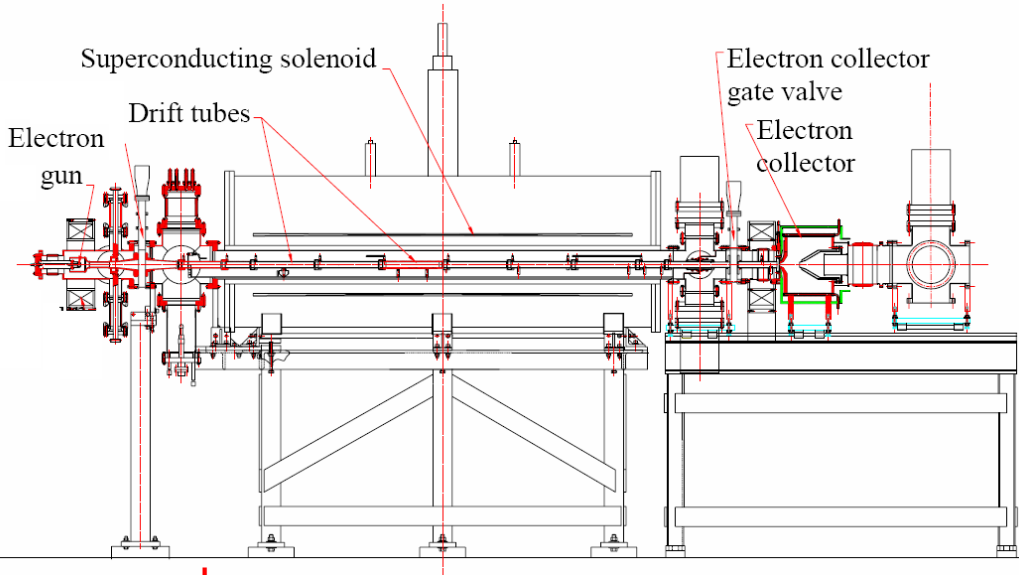
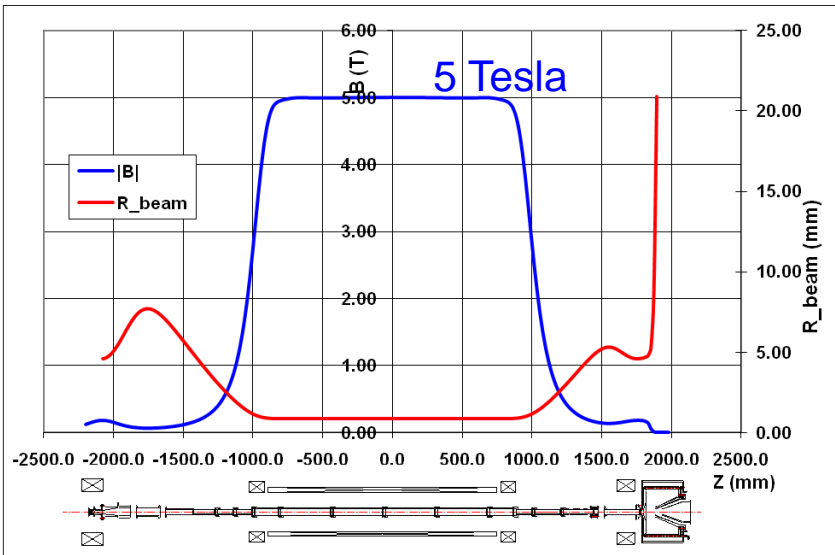
Performances: F. Wenander et al.,
Rev. Sci. Instrum. 77, 03B104 (2006)
ICIS 05 Proceedings

High Intensity EBIS at RHIC

- 1.7 mA – 10 μ s – 5 Hz

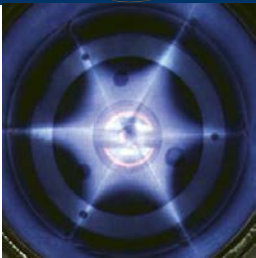


Narrow charge state distribution for Th beam

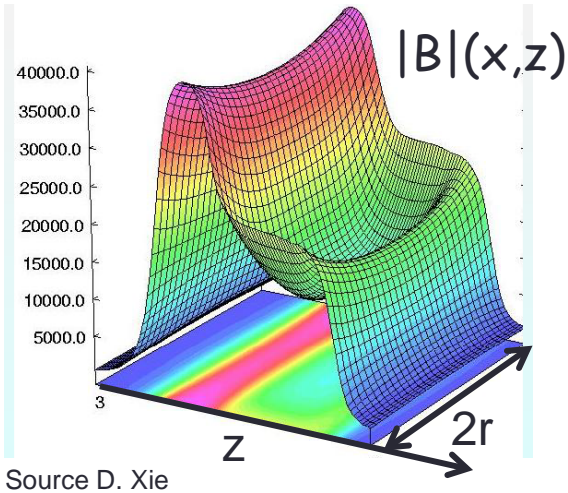
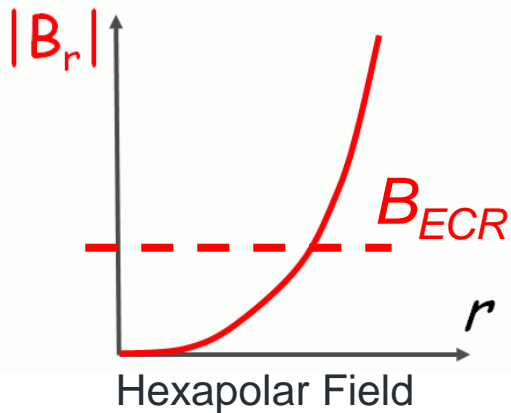
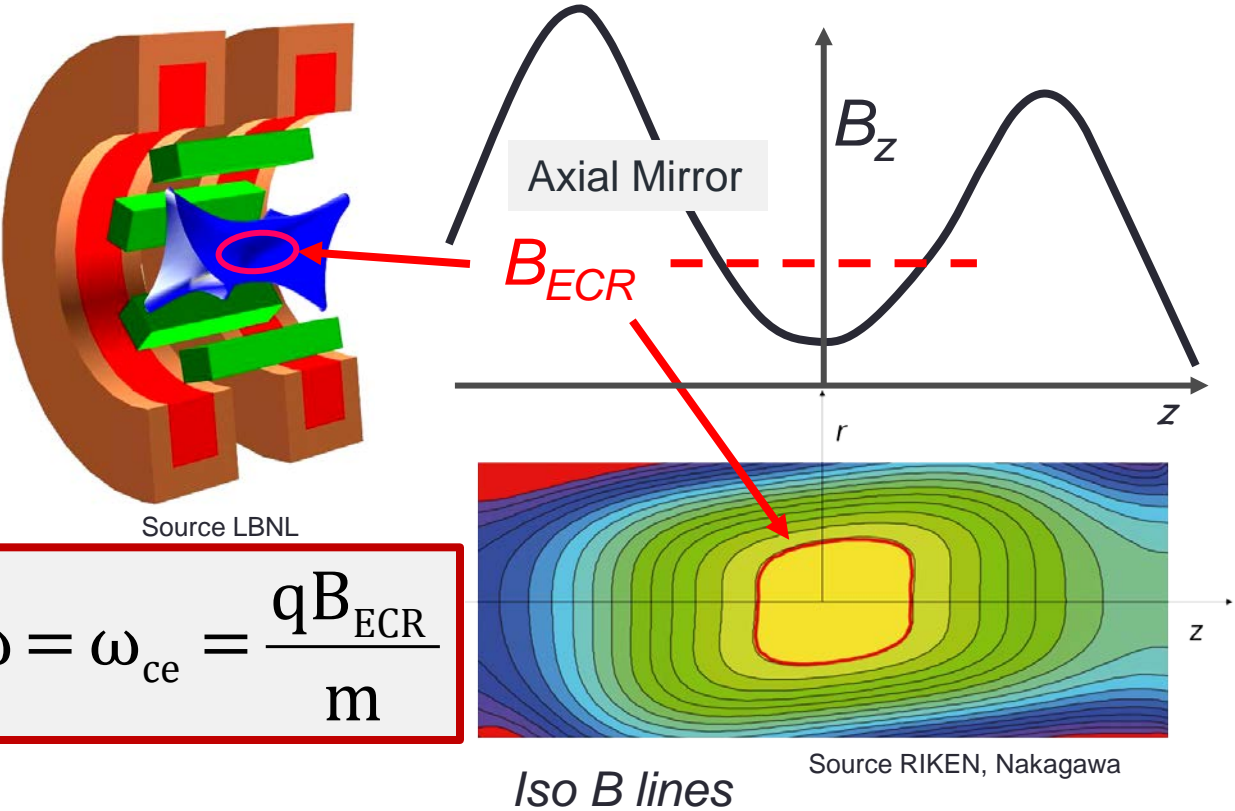


Magnetic field profile along the trap – Electron beam envelope

Electron Cyclotron Resonance Ion Source

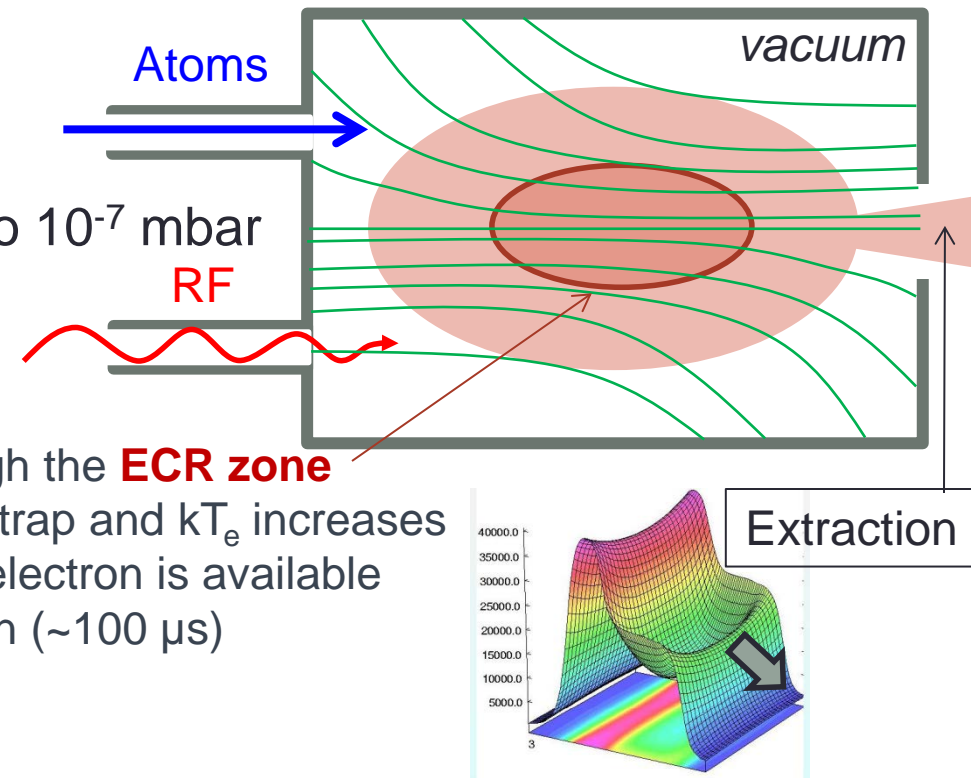


- ECR ion sources features a sophisticated magnetic field structure to optimize charged particle trapping
 - Superimposition of axial coils and hexapole coils
 - The ECR surface (place where $|B|=B_{ECR}$) is closed
 - ECR surface =place where the electrons are heated by a microwave



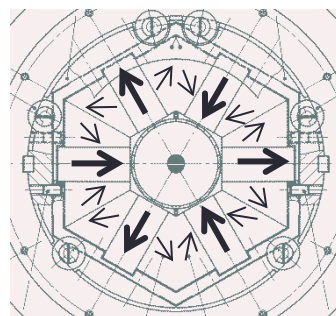
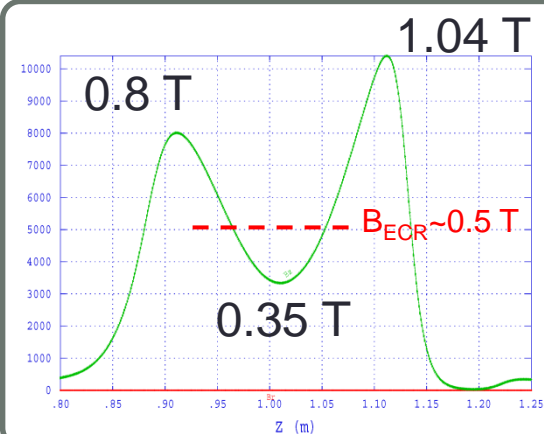
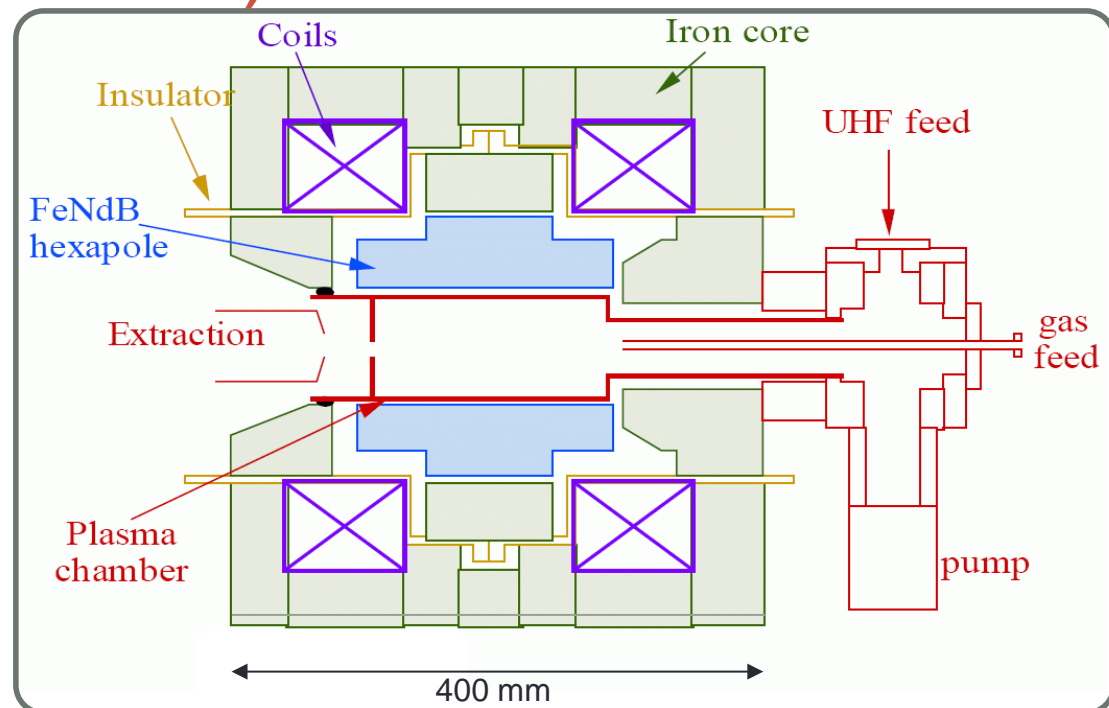
ECR Plasma build up

- Pumping & **Gas Injection** to reach $P \sim 10^{-6}$ 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 $kT_e > I_1^+$, a first ion is created and a new electron is available
 - Fast Amplification of electron and ion population ($\sim 100 \mu s$)
 - \Rightarrow plasma breakdown
- Multicharged ion build up
 - When T_e is established ($kT_e \sim 1-5$ keV), multicharged ions are continuously produced and trapped in the magnetic bottle
 - Ions remain cold in an ECR: $kT_i \sim 1/40$ eV, ($m_e \ll m_i$)
- Population of the loss cone through particle diffusion (coulombian interaction) \Rightarrow constant change in the particle trajectory \Rightarrow random redistribution of $\vec{v} = \vec{v}_{\parallel} + \vec{v}_{\perp}$
- \Rightarrow ion extraction through the magnetic **loss cone** on the side of the source presenting the minimum magnetic field intensity

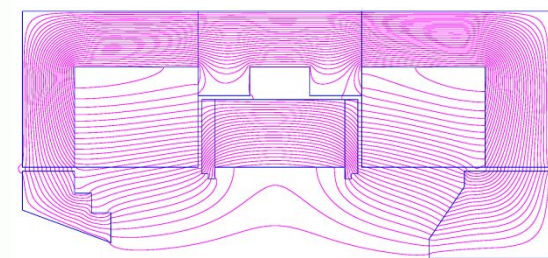
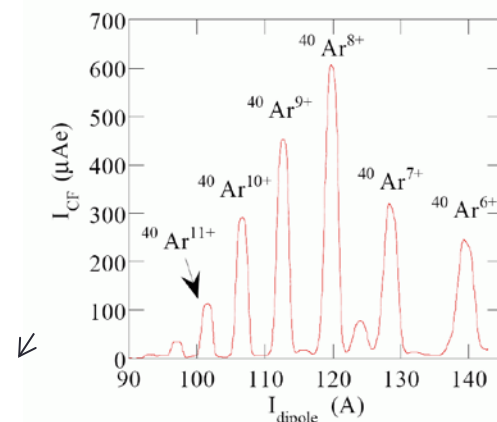


Example of ECR4 (GANIL)

- Microwave: $f=14.5$ GHz-1.5 kW ($B_{\text{ECR}}=0.64$ 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 ($\varnothing 64$ mm \times L200 mm) $V \sim 0.5$ liter
- Can produce any gas and many condensable beams



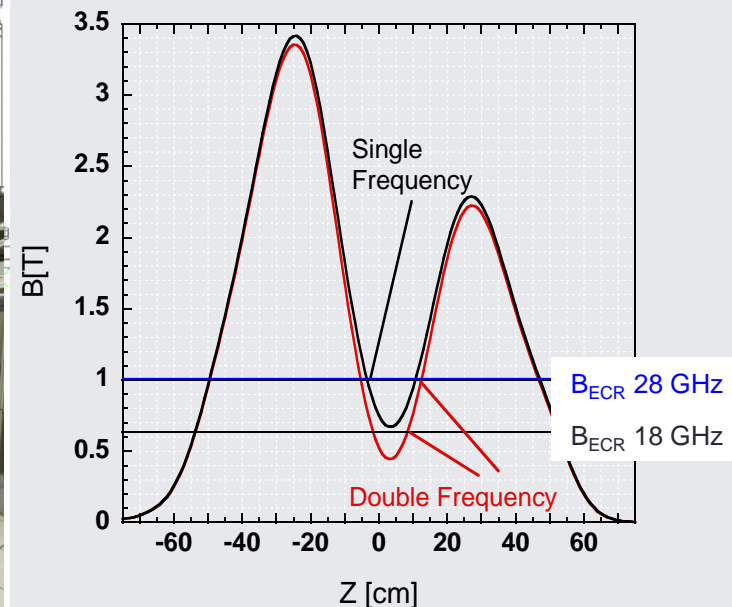
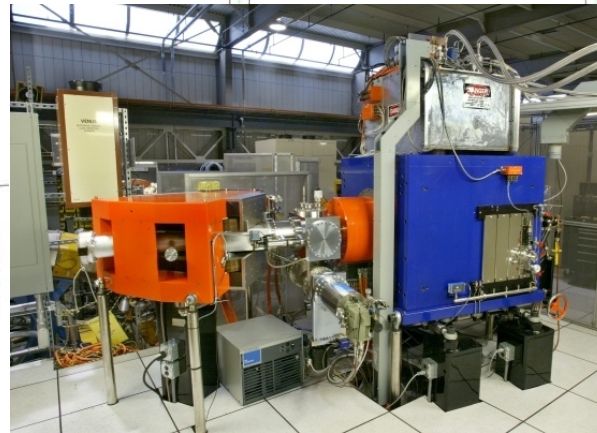
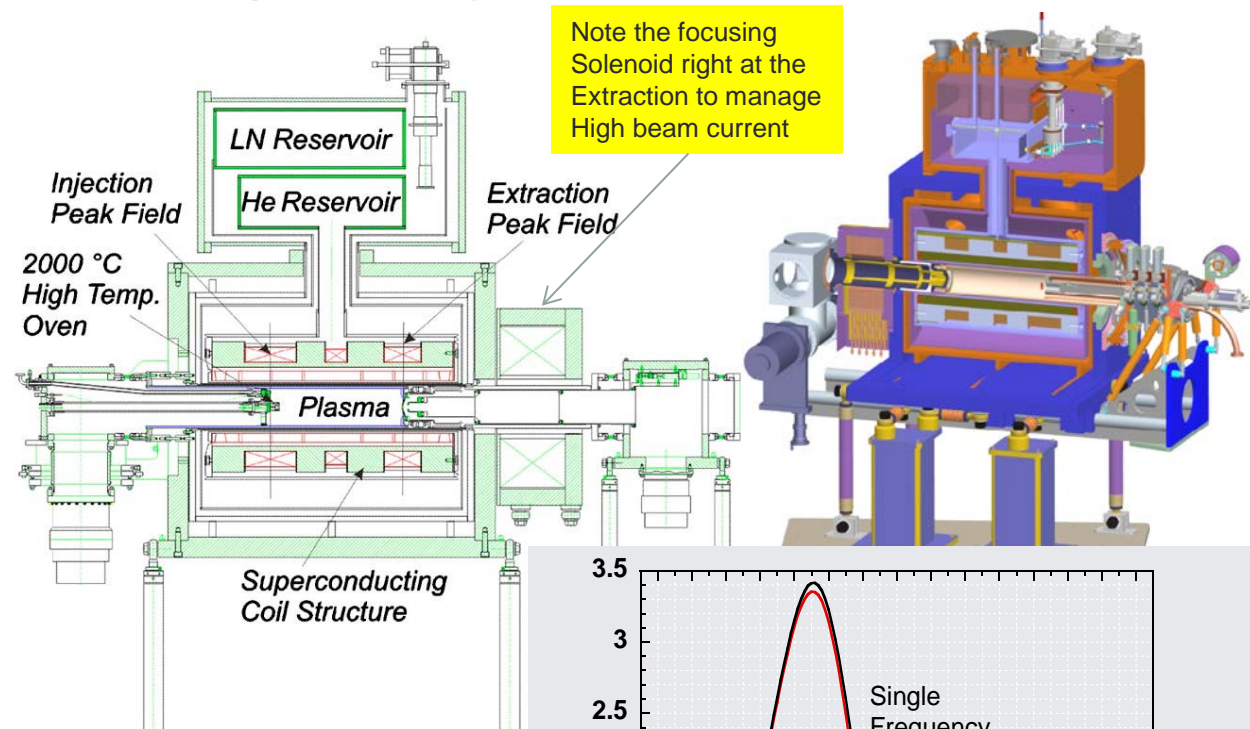
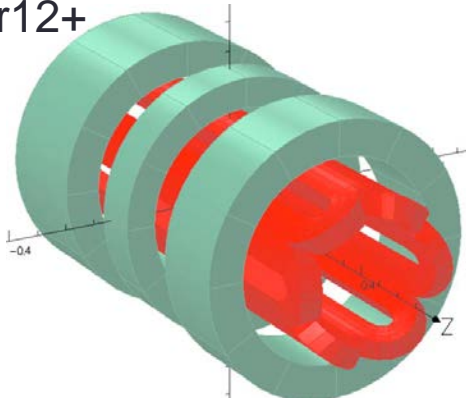
FeNdB hexapole



Axial Magnetic field lines (ECR4M)

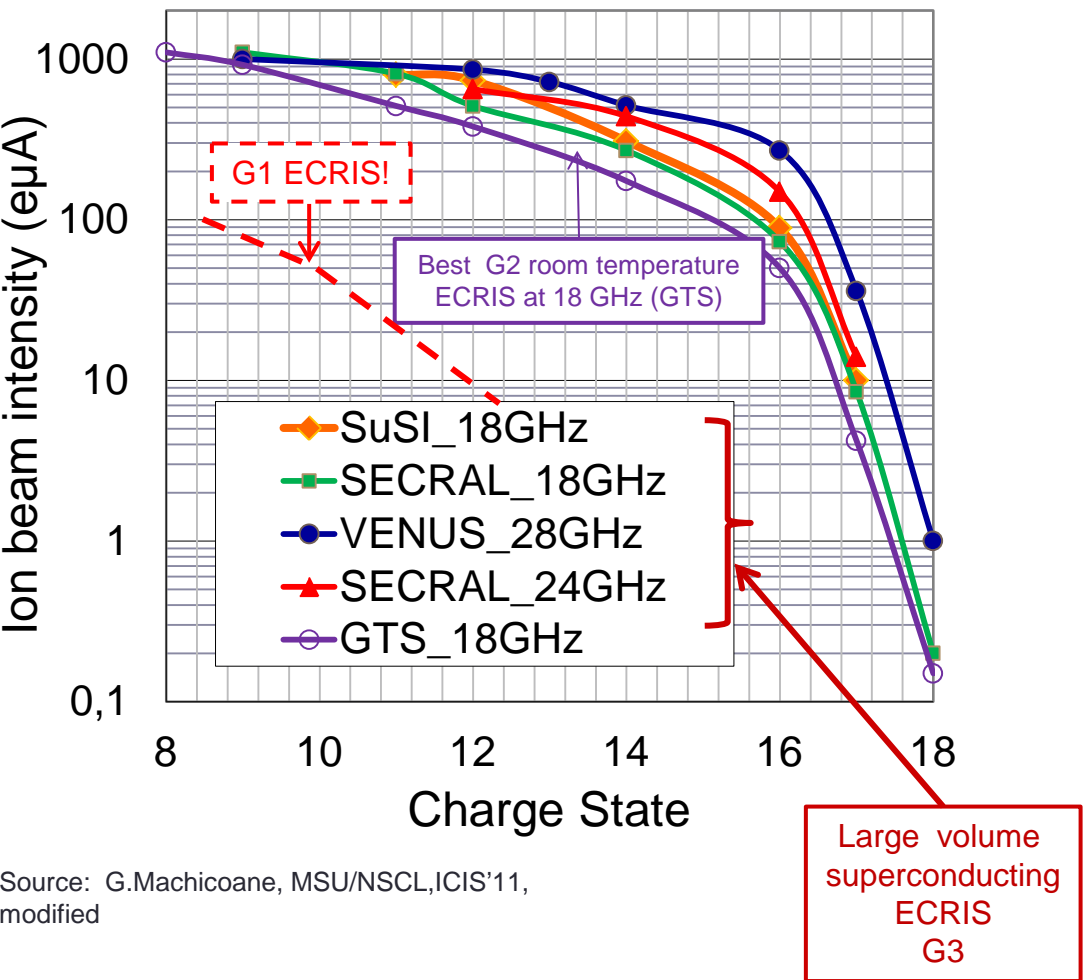
VENUS ECR Ion Source (LBNL)

- $f=18+28$ GHz - (2+6) kW
- $B_{\text{ECR}}=1$ 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 $B_r=2.2$ T
- Dedicated to very high intensity, very high charge state applied to cyclotron acceleration
- Plasma Chamber volume $V \sim 8.5$ liter
 - $\varnothing \sim 15$ cm , $L \sim 50$ cm
- $V \sim 25$ kV
- Typical beams: 3 mA O^{6+} , 0.86 mA Ar^{12+}

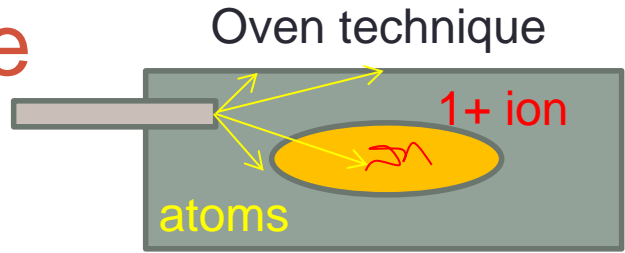


Example of Today ECR performance

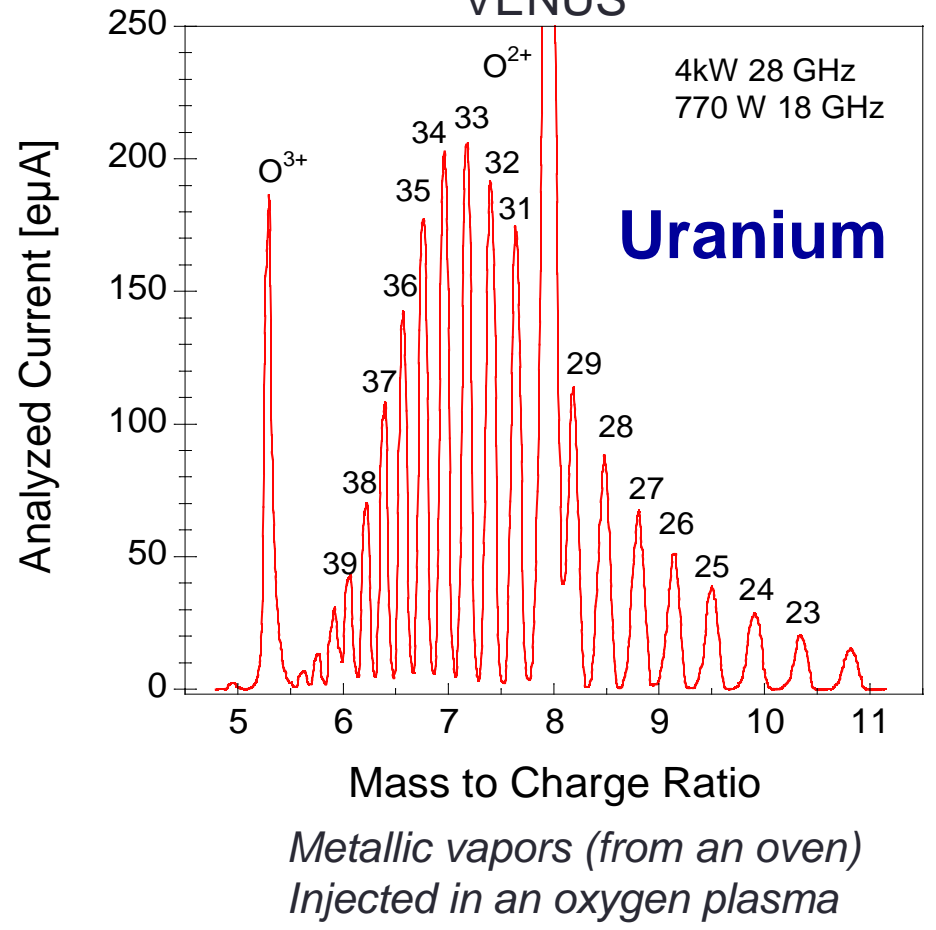
Argon



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

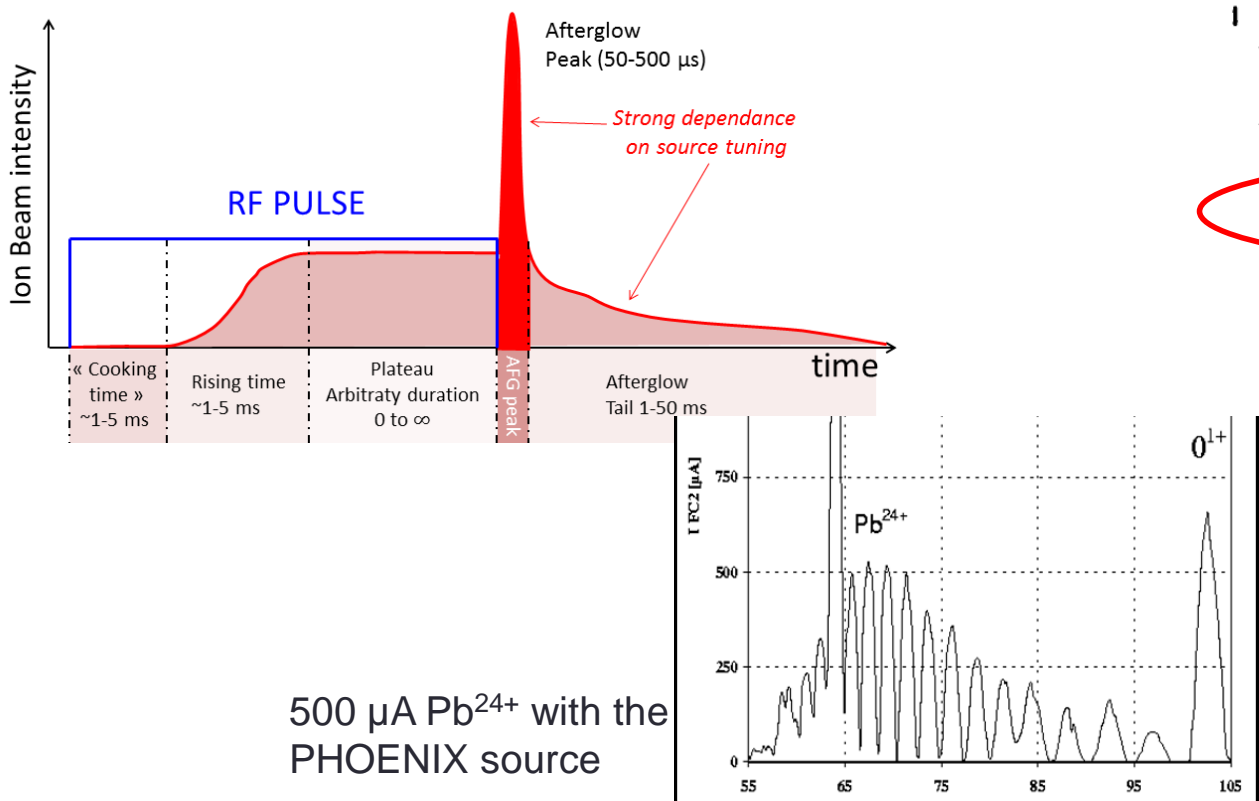


VENUS

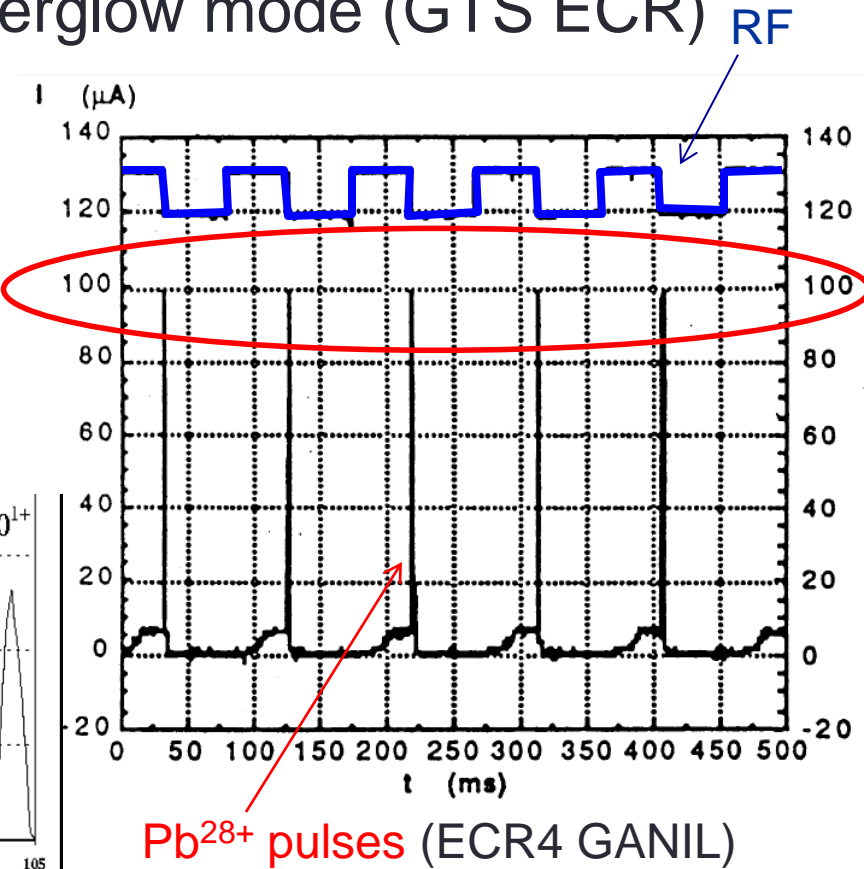


ECR Pulse Mode operation for Synchrotrons

- 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) RF

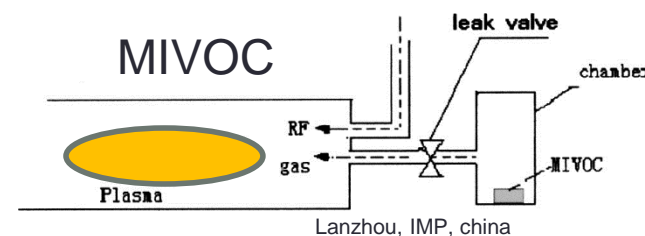
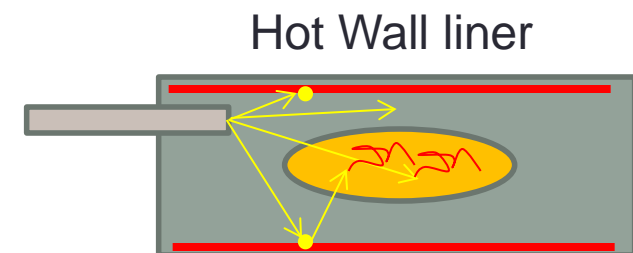
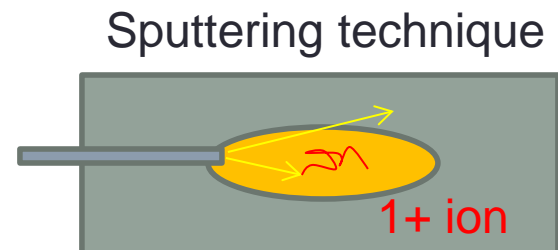
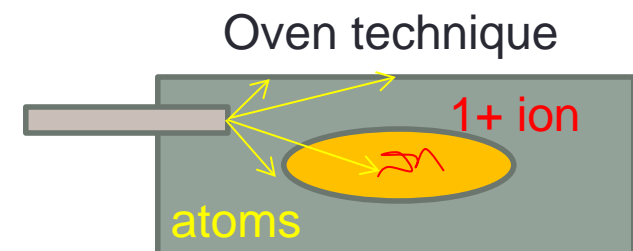


500 μA Pb^{24+} with the PHOENIX source



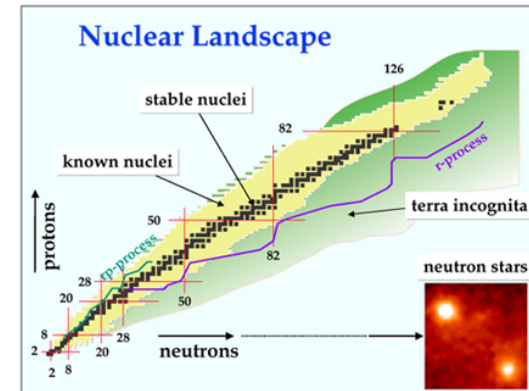
Condensable Ion Beam production in ECR Ion Sources

- The high plasma density of ECR ion Sources features a short mean free path for 1st ionization of atoms:
 $\lambda_{0 \rightarrow 1+} \sim 1 - 10 \text{ cm}$
- On flight ionization of condensable or refractory atom can be performed by several techniques in ECRIS
 - Oven technique:** A 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.

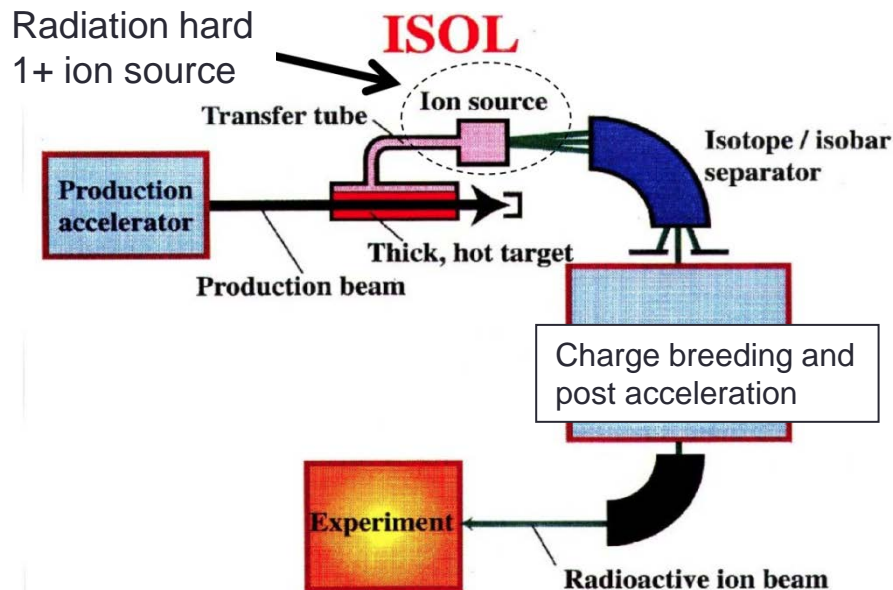


Ion Source for Radioactive Ion Beams (RIB) facilities

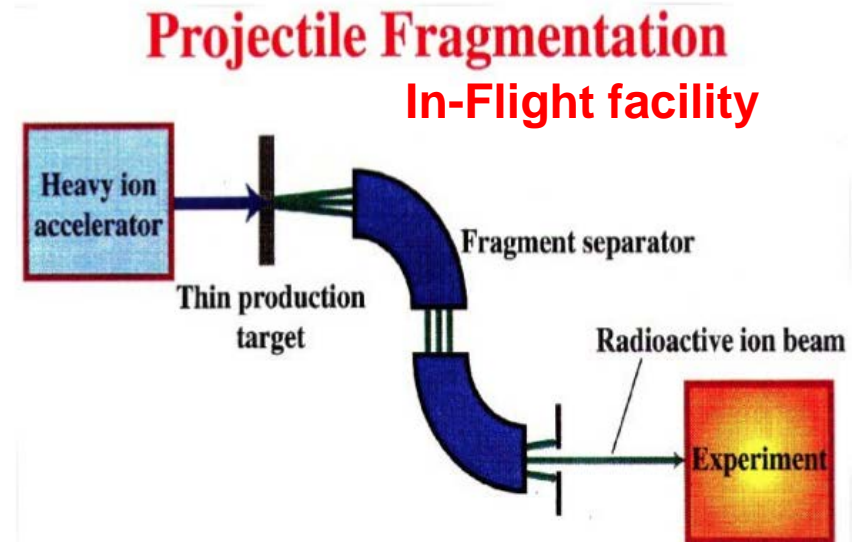
- Motivation: study exotic nuclei far from stability
- Two exotic RIB production method:
 - Isotope Separation On-Line (ISOL)
 - Projectile separation



<http://radchem.nevada.edu/>



EURISOL, HIE-ISOLDE, SPIRAL2, SPES,...



RIKEN RIBF, FAIR (Slide H. Koivisto, JUAS2013)

1+ Radioactive source for ISOL

- **Physics Requirement:** Exotic nuclides may have a short half-life. The radioactive atoms have to be ionized and transferred to the beam line as fast as possible.
- **Source Technical requirement:**
 - Radiation hard (even 1 MGy)
 - Compact
 - Simple and reliable in use (no maintenance access due to the strong radiation level)

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
	1A	2A	3B	4B	5B	6B	7B	8B			1B	2B	3A	4A	5A	6A	7A	8A	
Period																			
1	1 H																	2 He	
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg							
* Lanthanides			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
** Actinides			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

Ion source:

+

Surface

-

hotPlasmacool

Laser

CERN beams, T. Stora, CAS_2012 lectures

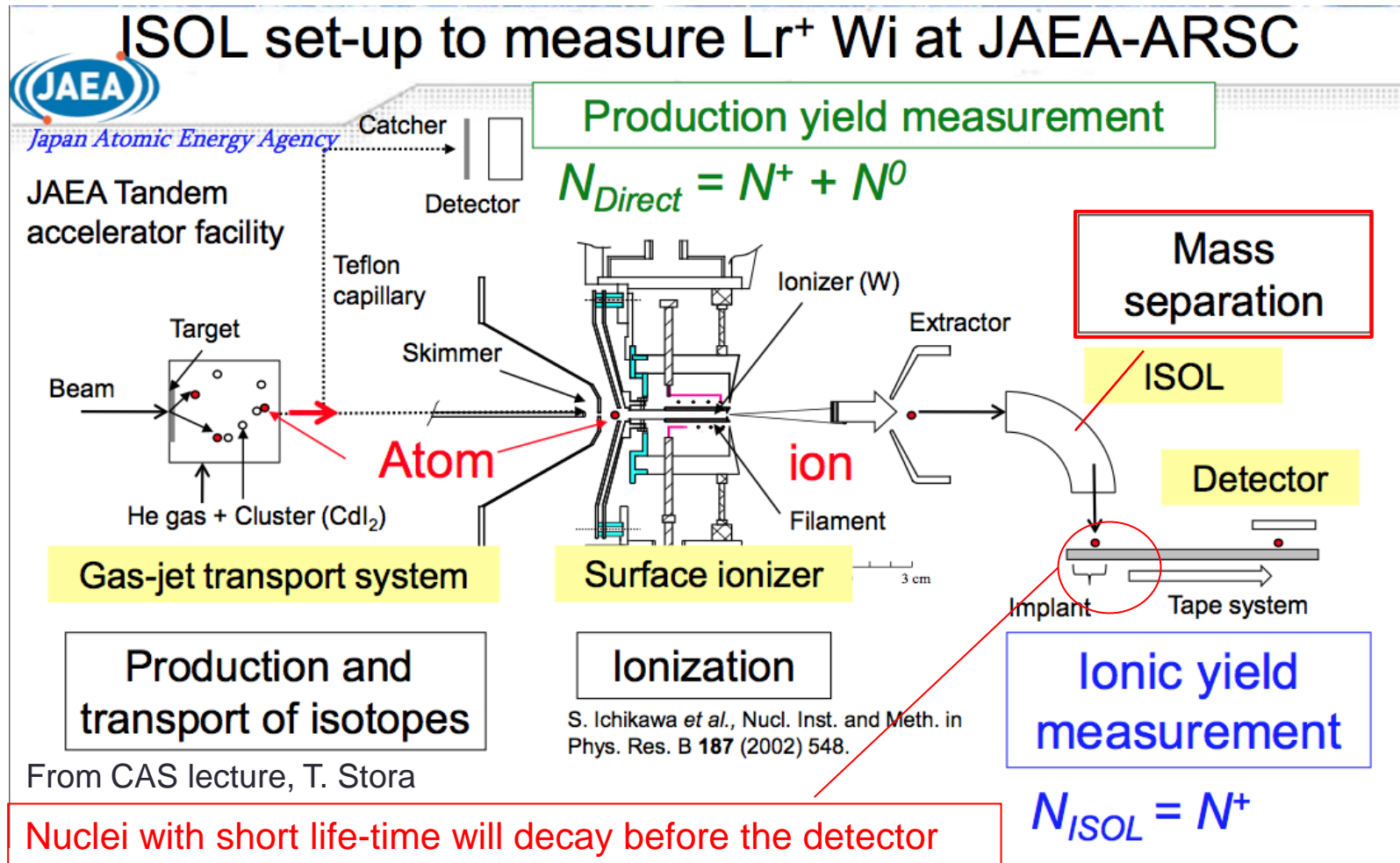
As an example: after the CERN production target following 1+ ion sources are mainly used:

1. Surface Ion Source (SIS) (see slide 72)
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

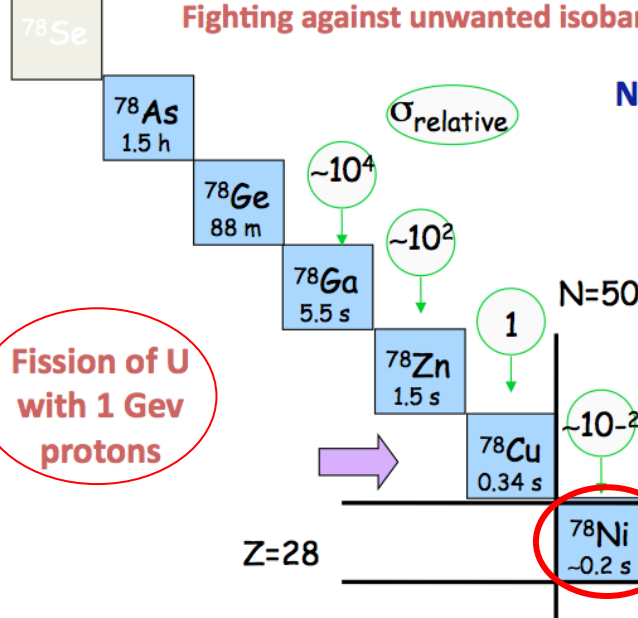


How to separate Iso-mass radioactive atoms?

- 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

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



Ni+:Ga+ ratio with surface ionization only:

$$\text{IP (Ga)} = 5.99 \text{ eV} \quad \text{IP (Ni)} = 7.63 \text{ eV}$$

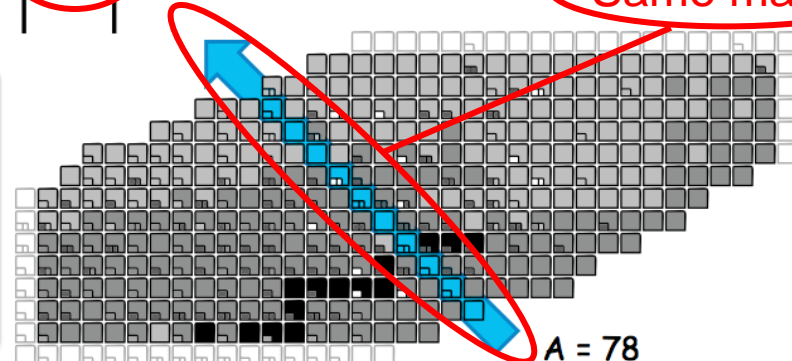
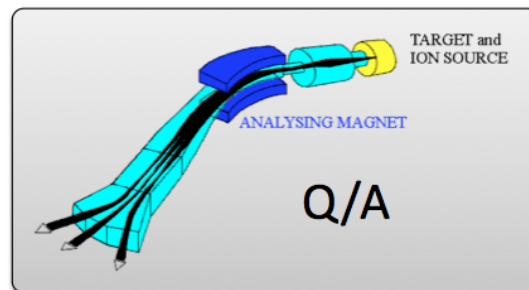
$$\alpha = \frac{n_i}{n_0} = \frac{\omega_i}{\omega_0} \exp\left(\frac{\Phi - W_i}{kT}\right)$$

$$\text{Ga}^+:\text{Ni}^+ > 10^6!$$

Need to selectively increase Ni ionization efficiency

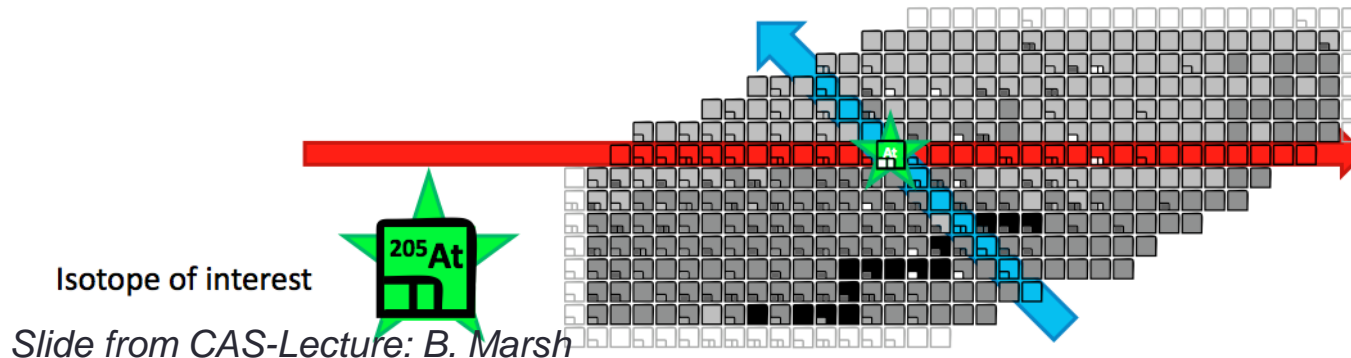
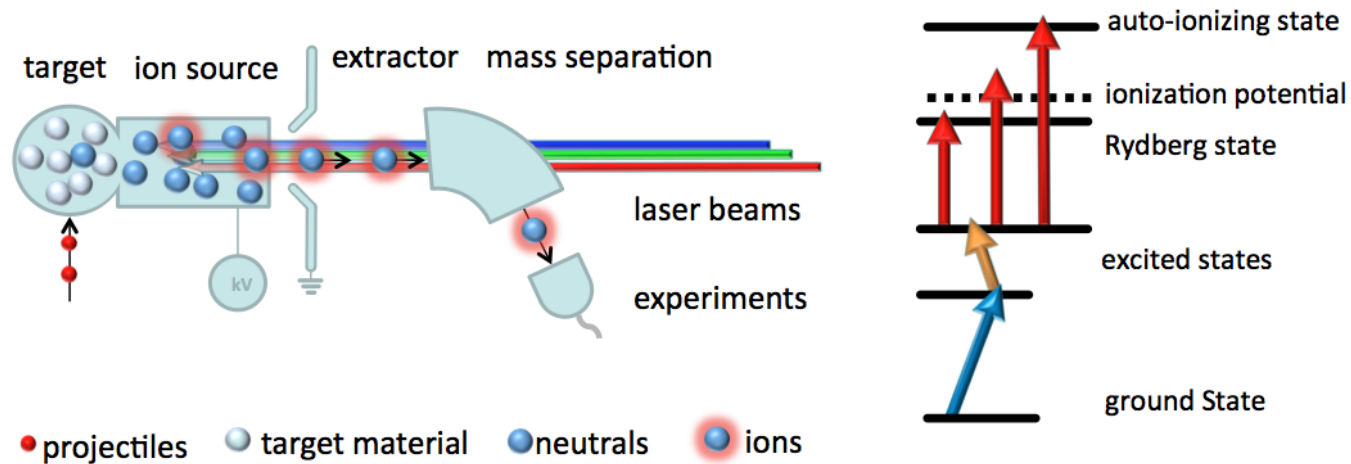
And/or suppress isobar (Cu, Zn, Ga) ionization efficiency

Same mass



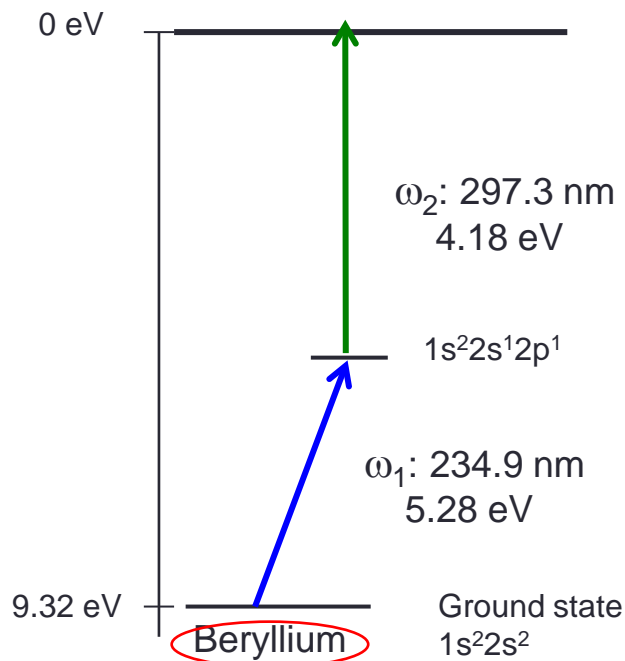
Resonance Ionization Laser Ion Source (RILIS)

- The co-produced iso-mass radioactive atoms have specific electronic level states
- Lasers can help selecting the atom of interest 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!**



Resonance Ionization example

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



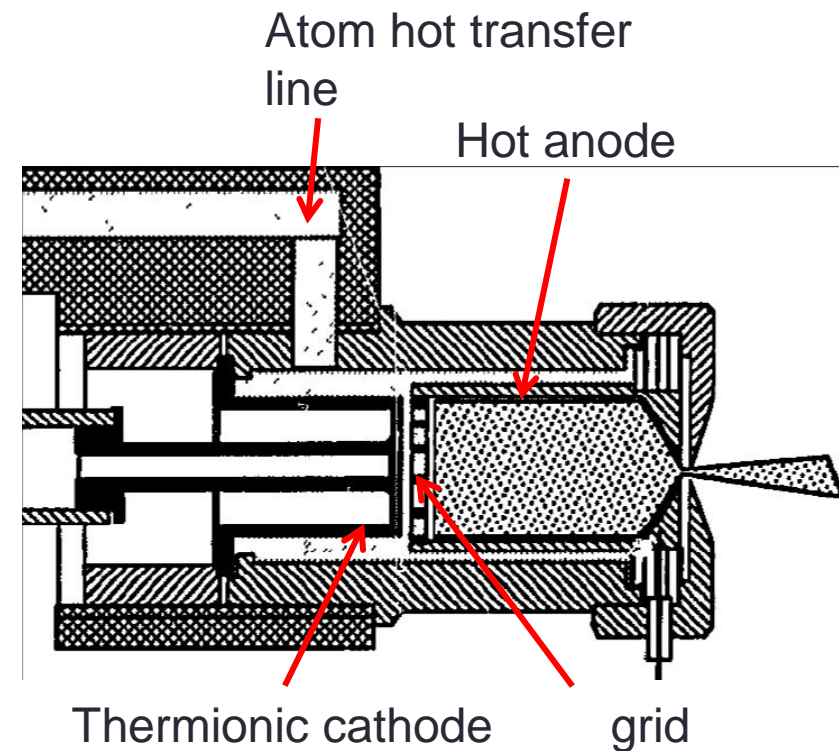
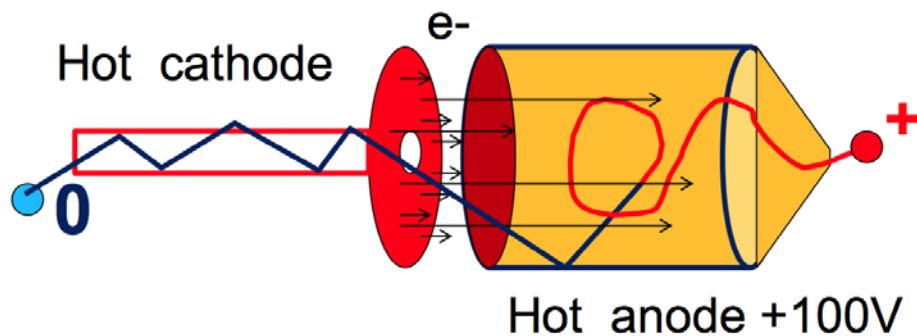
Excitation schemes used at the ISOLDE RILIS. λ_1 , λ_2 and λ_3 are the wavelengths of the first, second and third step excitation transition; E_i – atomic ionization energies; η_{ion} – values of ionization efficiency.

Element	E_i (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	$\simeq 9$	109–137
Tm	6.18	589.6	571.2	575.5	> 2	off-line
Yb	6.25	555.6	581.1	581.1	15	157–167

Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source

• FEBIAD are used for example at CERN and Triumf to produce radioactive 1+ beams at $\sim \mu\text{A}$ intensity level.

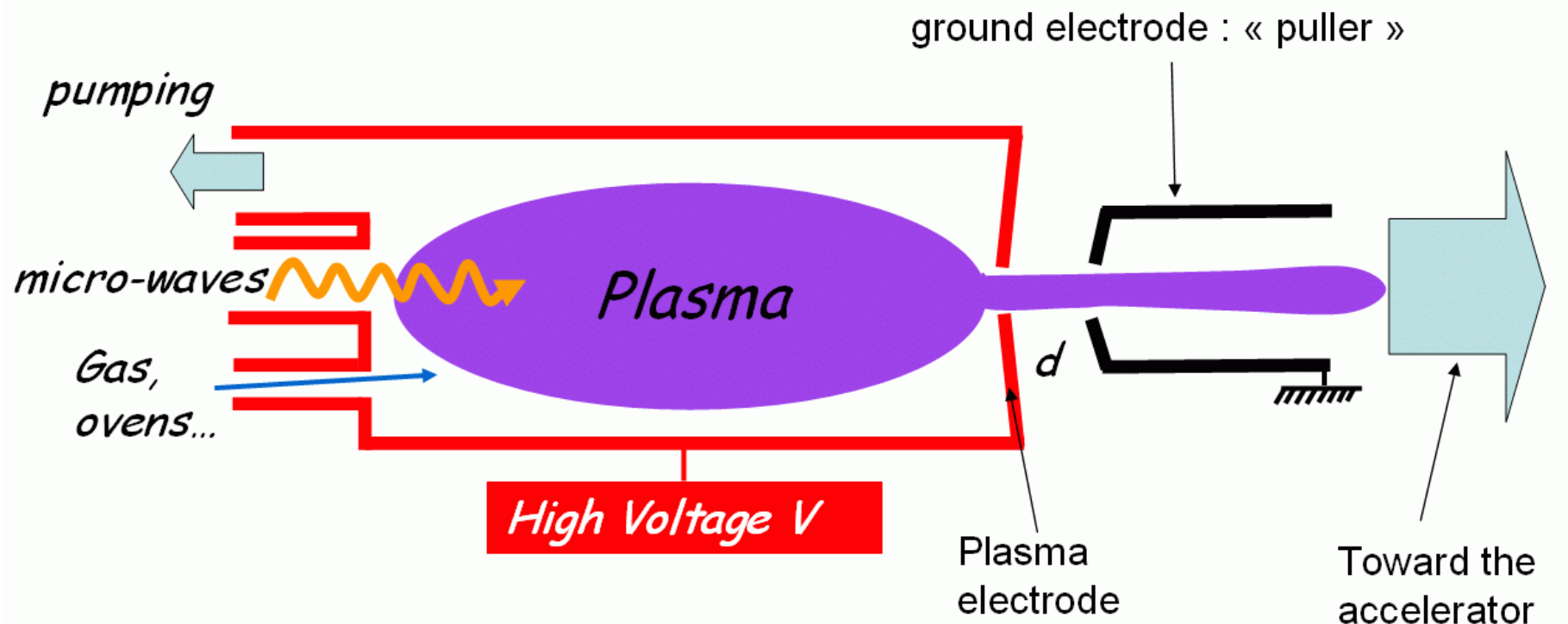
- the electrons are produced by a hot cathode
- electrons are accelerated through a grid
- Electron impact ionization of vapors emitted by the hot anode



APPENDIX

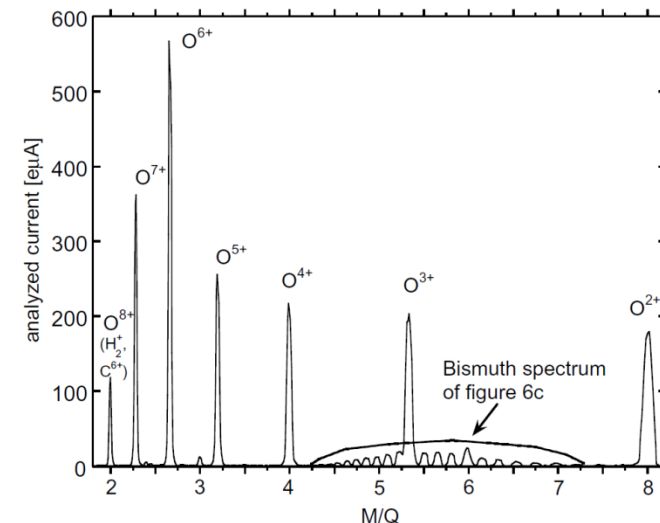
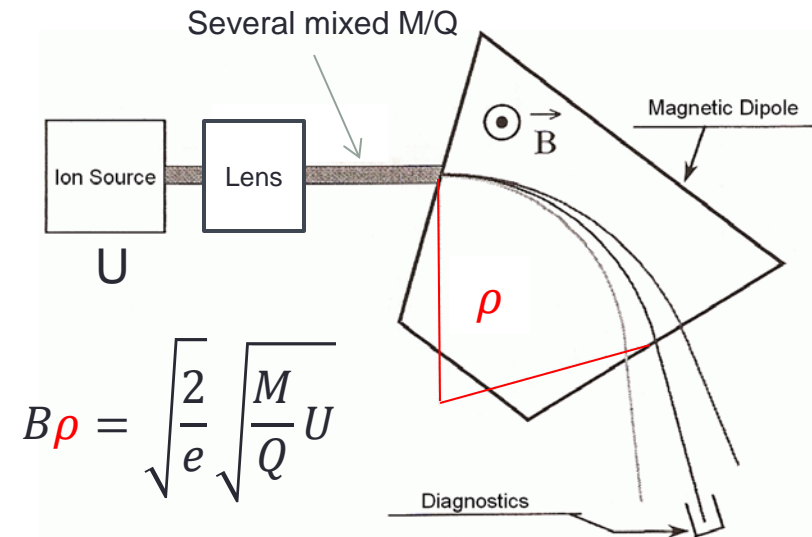
Beam Extraction

- The ion beam is extracted by setting the plasma chamber to high voltage $V_{HV} \sim 15\text{-}60\text{ kV}$
- A plasma electrode is closing the cavity on the extraction side, it is equipped with a circular hole with diameter $\varnothing \sim 5\text{-}13\text{ mm}$
- A puller electrode, set to ground potential, is placed in front of the plasma electrode
- The electric field in the gap d enables to accelerate the low energy ions from the plasma while hot electrons are repelled back to the source



Beam separation and transport

- The ion sources beams are usually composed of several charge states of several atomic species. These beams are extracted all together, and their number is in the range ~10-50. A bending magnet with a mass separation $M/\delta M \sim 100$ is necessary to cleanly separate the beam of interest from its M/Q neighbours.

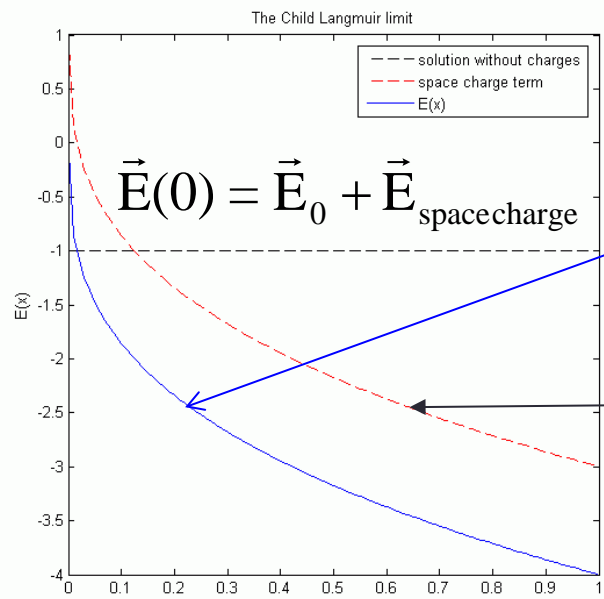


Example of an ion spectrum from VENUS, LBNL

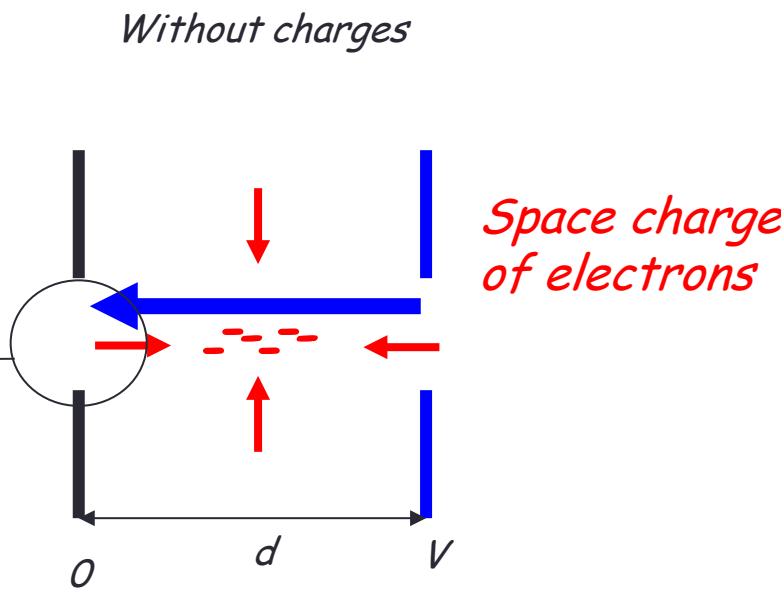
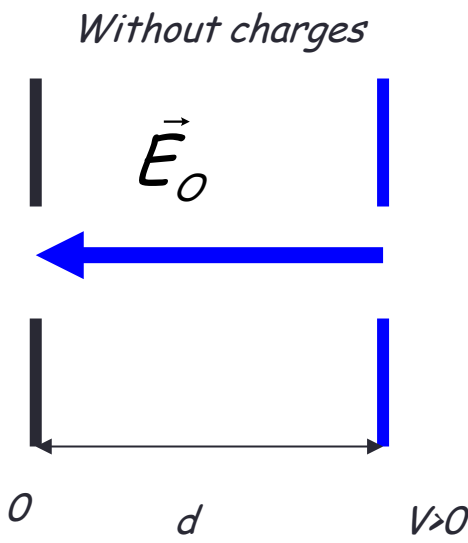
NIMB 235 (2005) 486–493

Beam space charge limitations

- The Child Langmuir Law (1/2)
 - The passage of CW beam in the extraction area creates a static space charge
 - The space charge creates an electric field which reduces the electric field applied at the exit of the source to extract beam
 - When the space charge is too high, there is no more electric field available to extract particle from the source!



Limit case when $E(0)=0 \Rightarrow$ Child Langmuir law



Beam space charge limitations

- The Child Langmuir Law (2/2)
 - Beam extraction with space charge limitation

- For electrons beam :

$$J \leq \frac{4\epsilon_0}{9} \sqrt{\frac{2e}{m}} \frac{V^{3/2}}{d^2}$$

- For ions beam :

$$J \leq \frac{4\epsilon_0}{9} \sqrt{\frac{2Ze}{Am_A}} \frac{V^{3/2}}{d^2}$$

J=current density extracted from the source

V=acceleration voltage

d= gap between electrodes

Z,A charge and atomic ion numbers

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