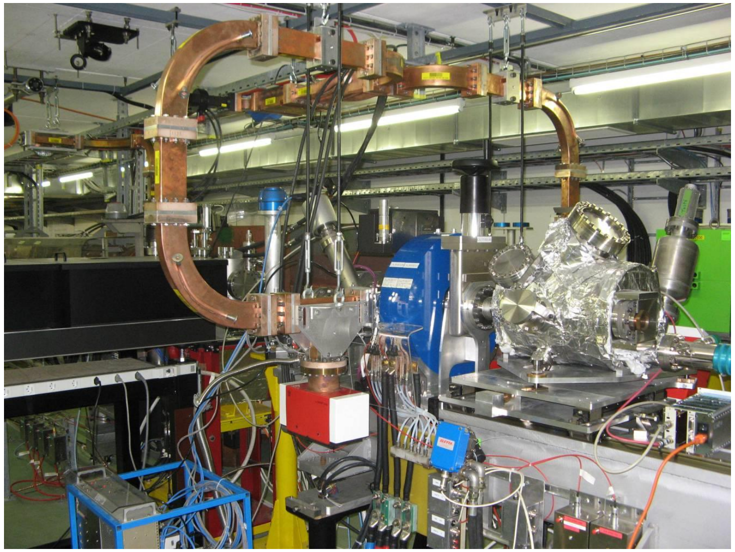
Electron and Ion Sources

Layout

- **Electron Sources**
  - Thermionic
  - Photo-Cathodes
- **Ion Sources**
  - Particle motion in plasmas
  - Protons
  - Negative Ions
  - ECR Ion Source

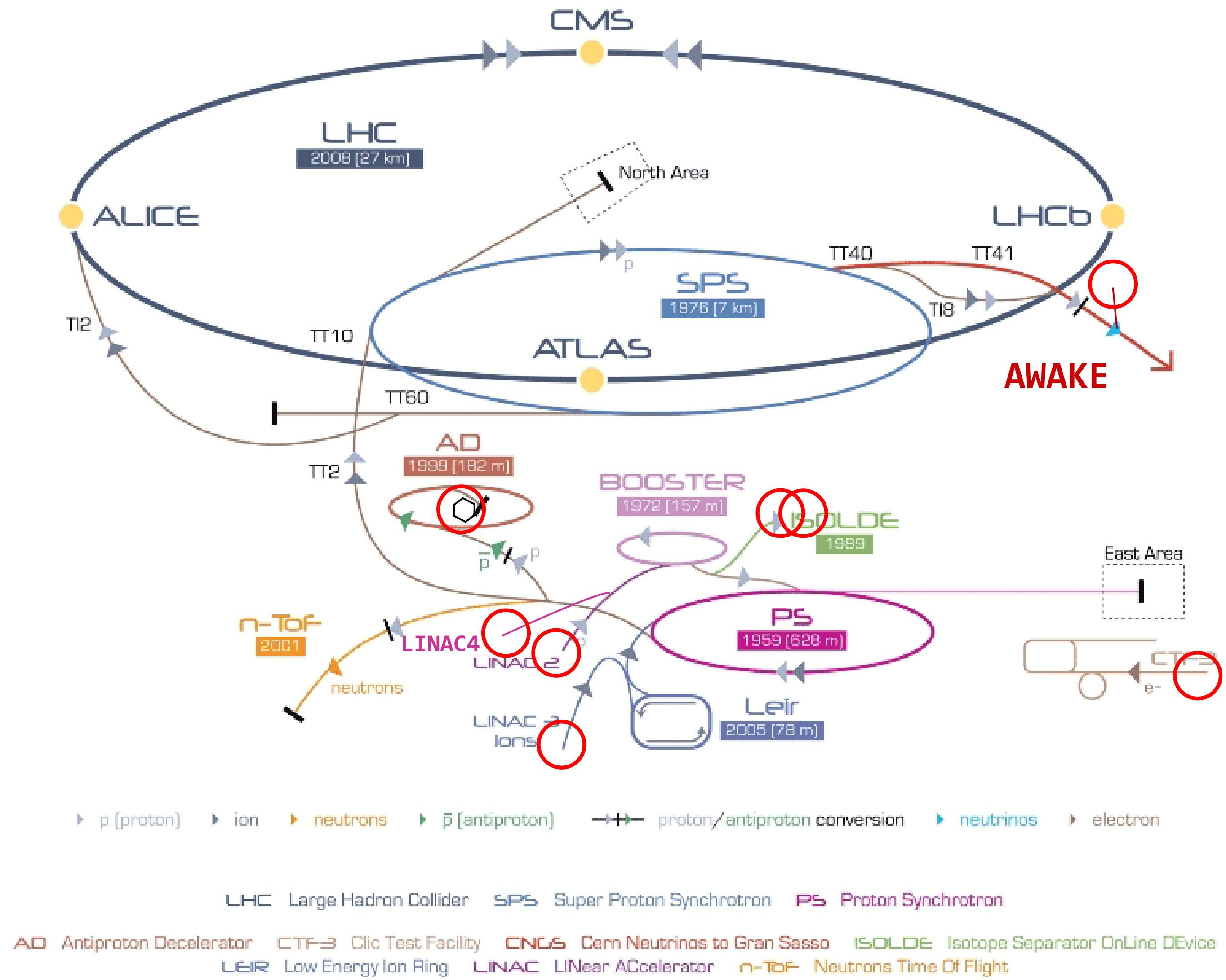


Richard Scrivens, BE Dept, CERN.

CAS@CERN, October 2019

Electron and Ion Sources

Every accelerator chain needs a source!



Electron and Ion Sources

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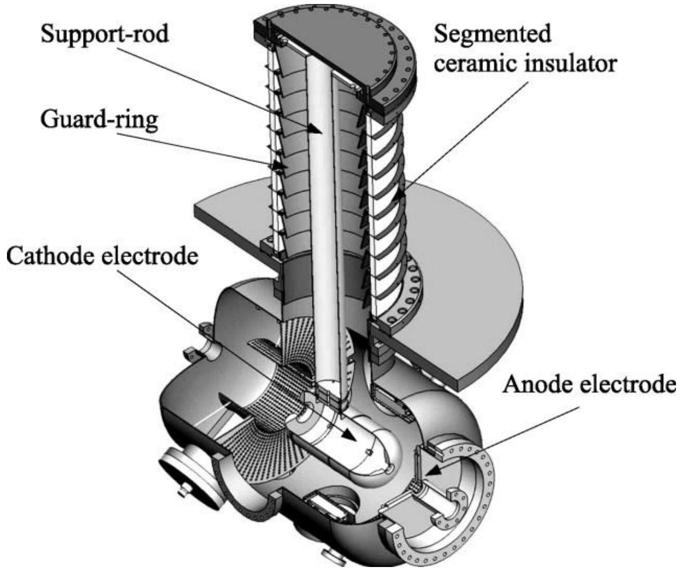
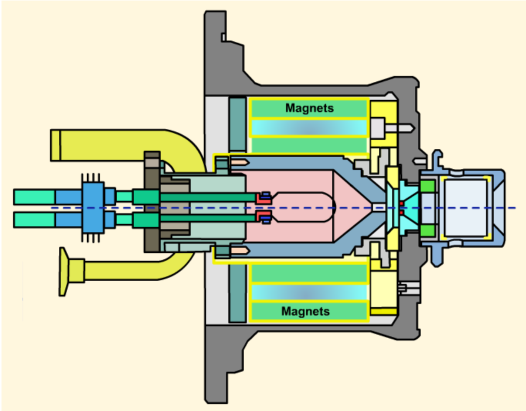
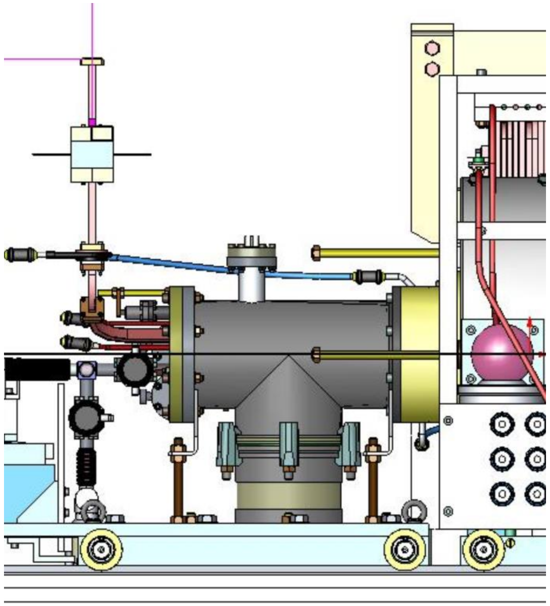






Protons

Ions

Principles of the electron guns, with thermionic and photo cathodes

Principles of ion sources, and the types used at CERN.

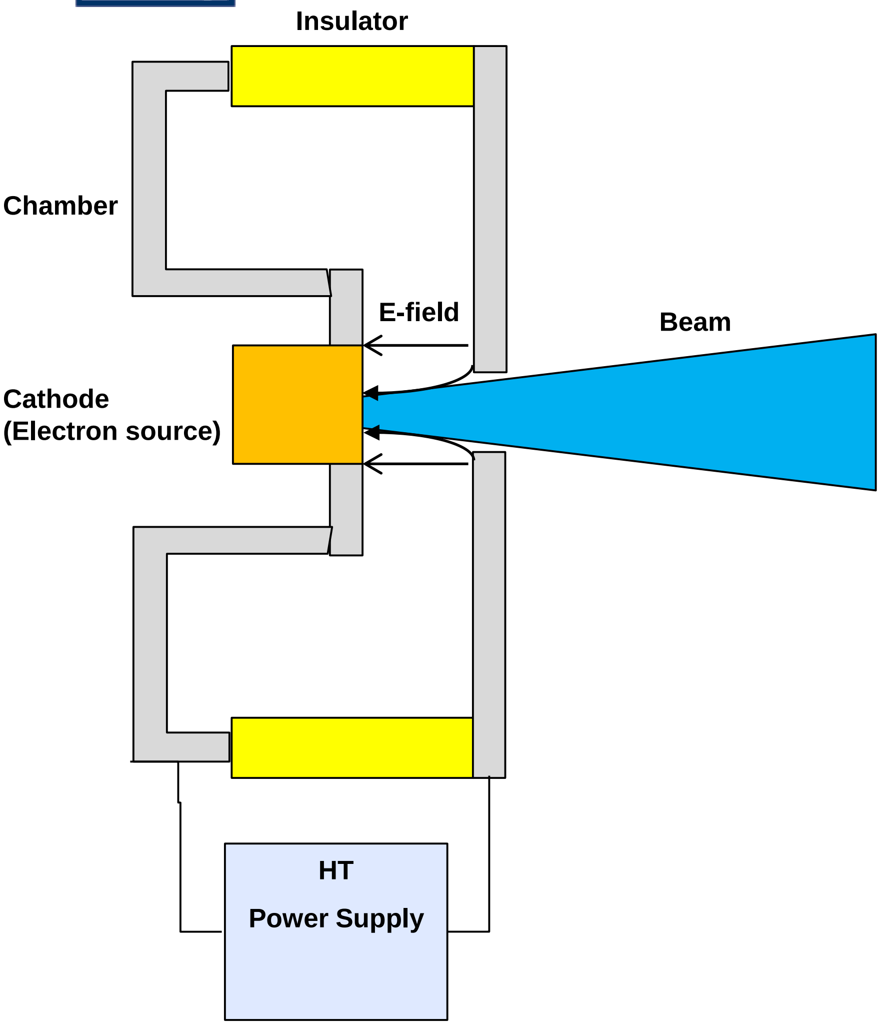
Electron and Ion Sources

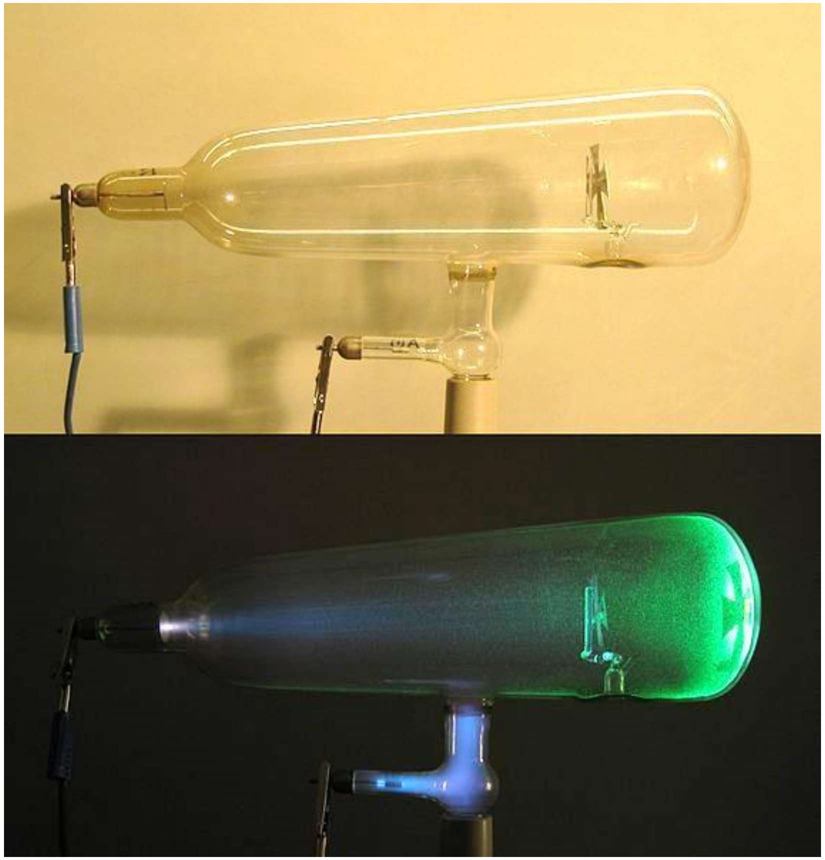
- **Electron Sources**
  - Thermionic
  - Photo-Cathodes

- **Ion Sources**
  - Particle motion in plasmas
  - Protons
  - Negative Ions
  - ECR Ion Source
  - Radioactive Ions

Electron and Ion Sources

Electron Sources - Basics





The classic Cathode Ray Experiment
Crookes Tube

Electron and Ion Sources

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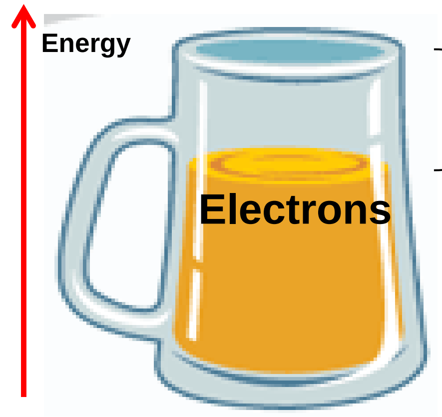
Electron and Ion Sources

Electrons – Thermionic Emission

Electrons within a material are heated to energies above that needed to escape the material.

Cathode emission is dominated by the Richardson Dushmann equation.



Energy difference between highest energy electron and vacuum

Work Function ϕ_s

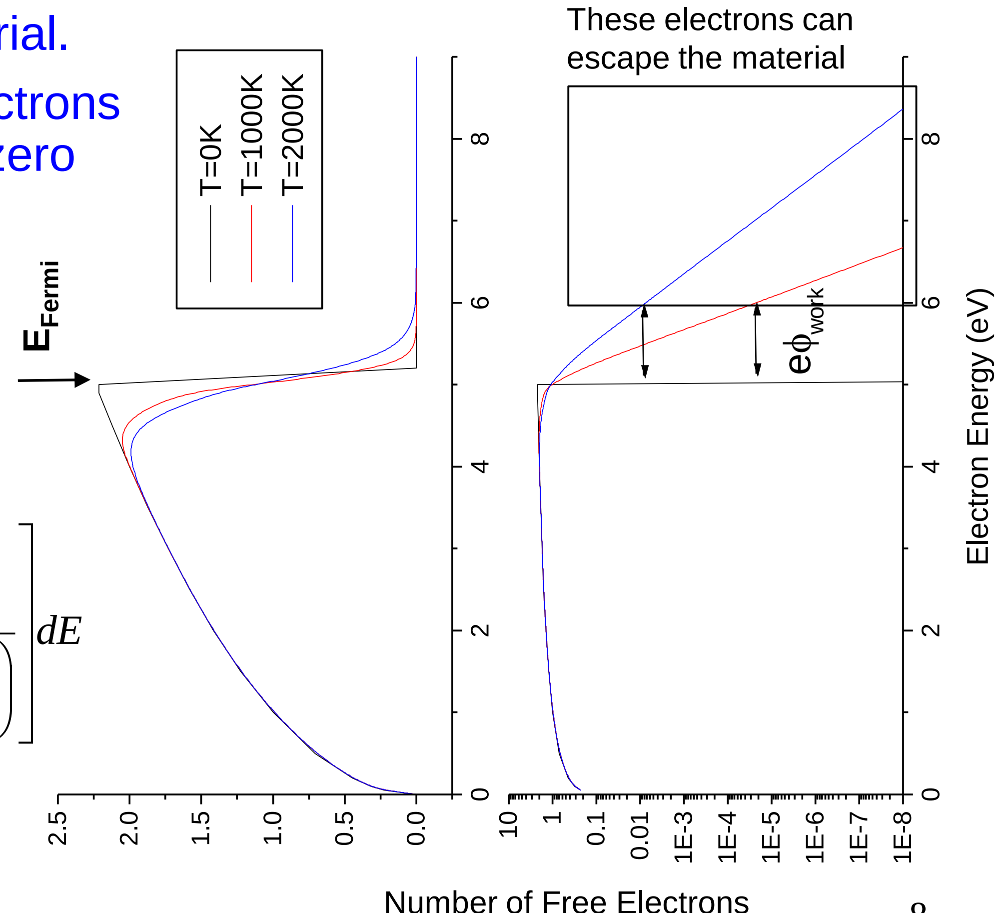
Material

Electrons – Thermionic Emission (the maths)

Conducting materials contain free electrons, who follow the Fermi-Dirac energy distribution inside the material.

When a material is heated, the electrons energy distribution shifts from the zero temperature Fermi distribution.

$$n(E)dE = \left[\frac{4\pi(2m_e)^{3/2}}{h^3}\right]\left[\frac{\sqrt{E}}{1+\exp\left(\frac{E-E_{Fermi}}{kT}\right)}\right]dE$$



Electrons – Thermionic Emission (the maths)

Therefore at high temperatures there is an ELECTRON CLOUD around the material. The current density can then be found by integrating the available electrons and their energy.

$$J = nev$$

$$J = A \cdot T^2 \exp\left(\frac{-eU_{work}}{kT}\right)$$

This electron current is available to be pulled off the surface… Richardson-Dushmann equation *Rev. Mod. Phys. 2, p382 (1930)*

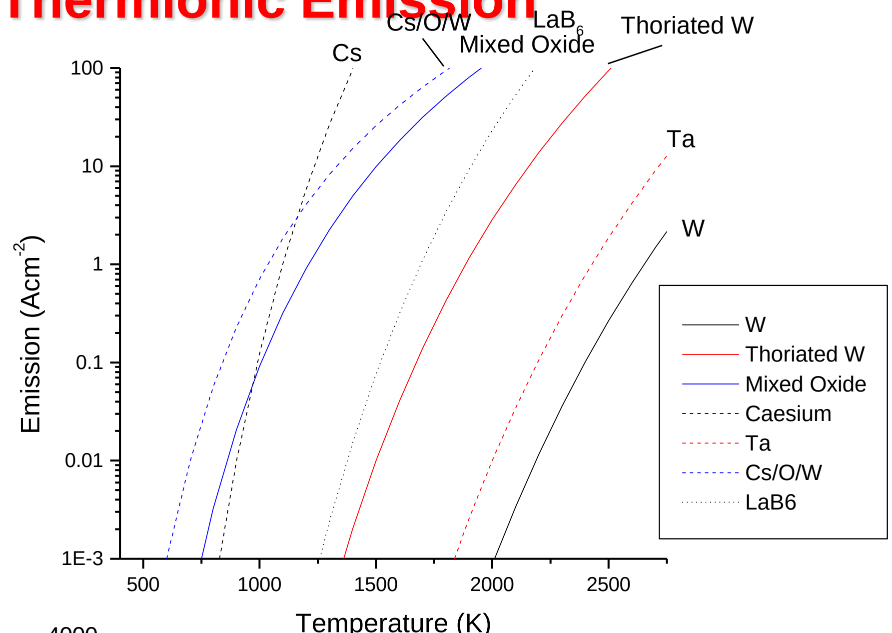
$$A = \frac{4\pi e m_e k^2}{h^3} \approx 1.2 \times 10^6 \,\mathrm{Am}^{-2} K^{-2}$$

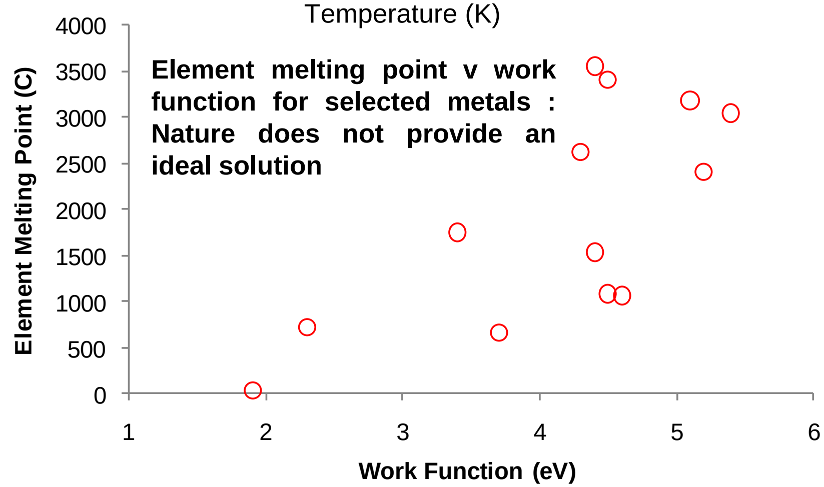
This factor *A* is not achieved in practice (some electrons are reflected from the inner surface)

Electron and Ion Sources

Electrons – Thermionic Emission

	A $Acm^{-2}K^{-2}$	U_{work} eV
W	60	4.54
W Thoriated	3	2.63
Mixed Oxide	0.01	1
Cesium	162	1.81
Ta	60	4.12
Cs/O/W	0.003*	0.72*
LaB_6	29	2.66





*- A and work function depend on the Cs/O lay

Thickness and purity

Electron and Ion Sources

- **Electron Sources**
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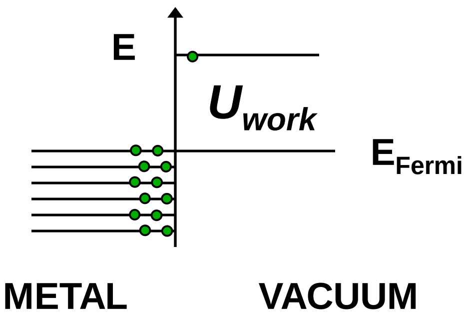
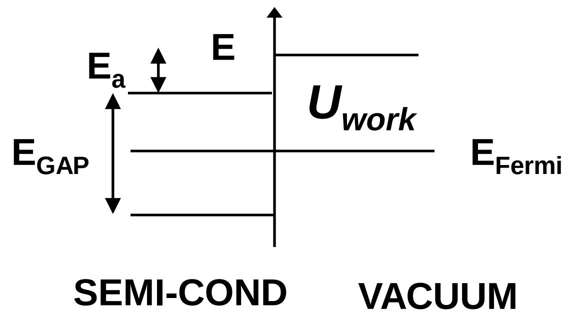
Electron and Ion Sources

Electrons – Photo Emission

The energy of an electron in a material can be increased above the vacuum energy by absorbing photons - photoelectric effect.





$$\text{Photon Energy} = \frac{hc}{\lambda}$$

$$\lambda_c = \frac{hc}{eU_{work}} = \frac{1239.8}{U_{work}}$$

$$\lambda_c = \frac{hc}{E_{GAP} + E_a} = \frac{1239.8}{E_{GAP} + E_a}$$

	U_{work} (eV)	λ_c (nm)
W	4.5	275
Mg	3.67	340
Cu	4.65	267

	E_g+E_a (eV)	λ_c (nm)
GaAs	5.5	225
Cs_2Te	~3.5	350
K_2CsSb	2.1	590

Electron and Ion Sources

Electrons – Photo Cathodes

- METALS
  - Lower quantum efficiency ($<4 \times 10^{-4}$) requires high power lasers.
  - But at high optical powers, a plasma is formed.
  - Very robust and simple to use cathode material.
- SEMICONDUCTORS
  - Can find materials optical wavelengths with high quantum efficiency (cf Photo Cathode Tubes).
  - Difficult to use in a high radiation area of an electron-gun (x-rays and ions cause decomposition and surface damage).
  - Cs2Te (Cesium Telluride) – High Quantum efficiency but needs UV lasers.

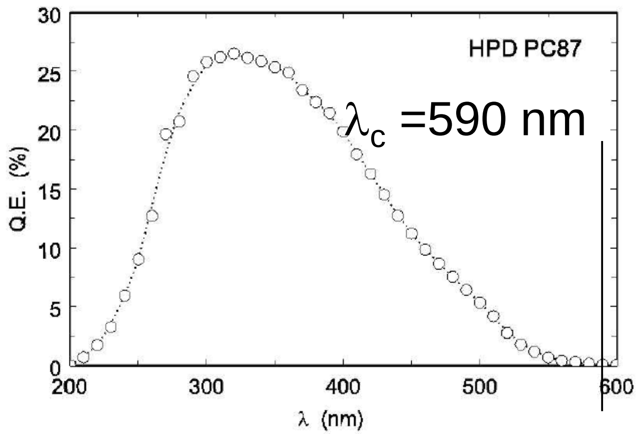
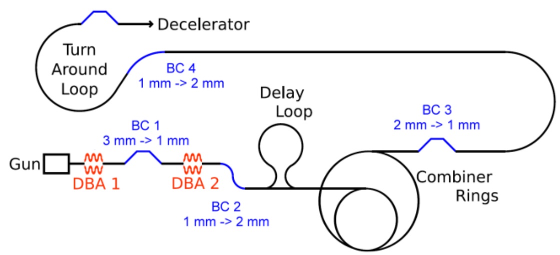
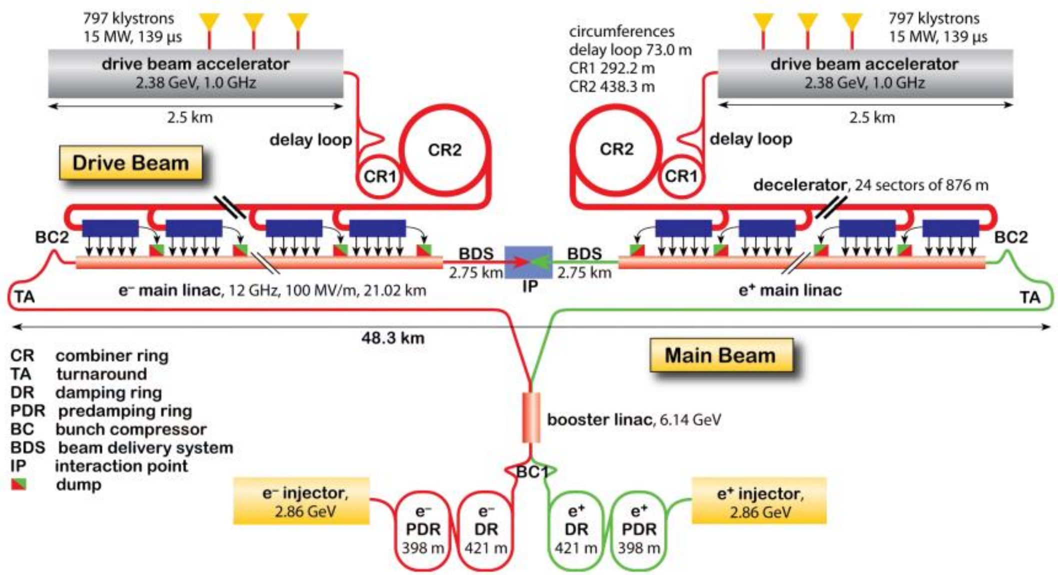


Figure 6. Quantum efficiency of a K_2CsSb photocathode produced on a UV extended HPD glass window.

Electron and Ion Sources

CLIC – Electron Guns



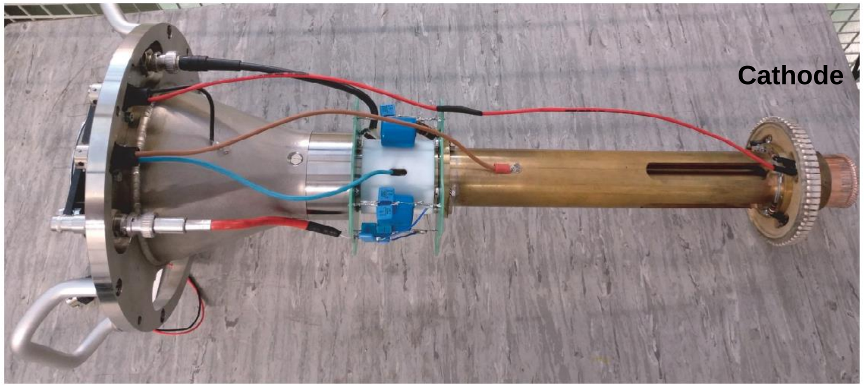


CTF3 has three electron guns.

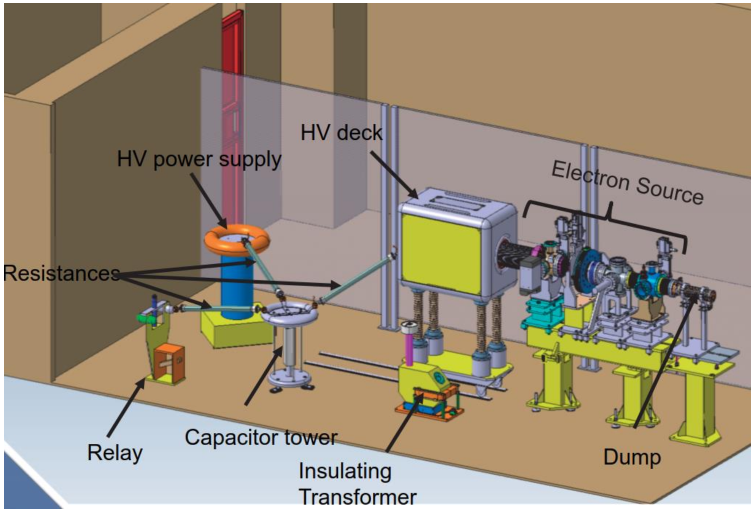
1. **A thermionic Gun for the drive beam generation**
2. **A test photo-emission and RF gun as a test facility for the drive beam.**
3. **A photo-emission and RF gun for the probe beam.**

Electron and Ion Sources

CLIC Drive Beam Thermionic Gun



Cathode System

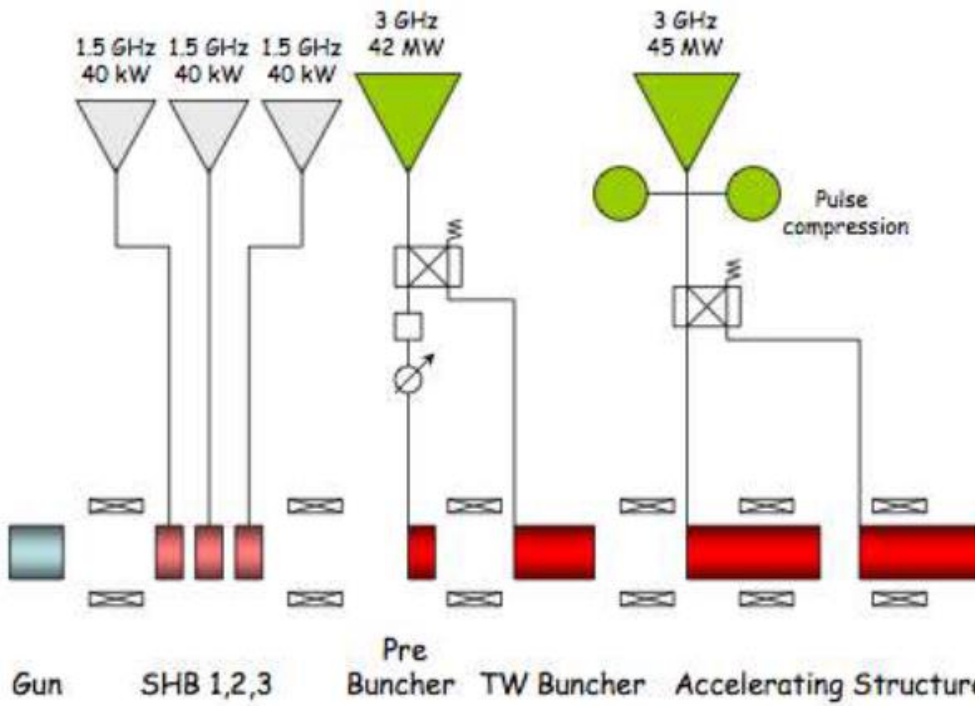


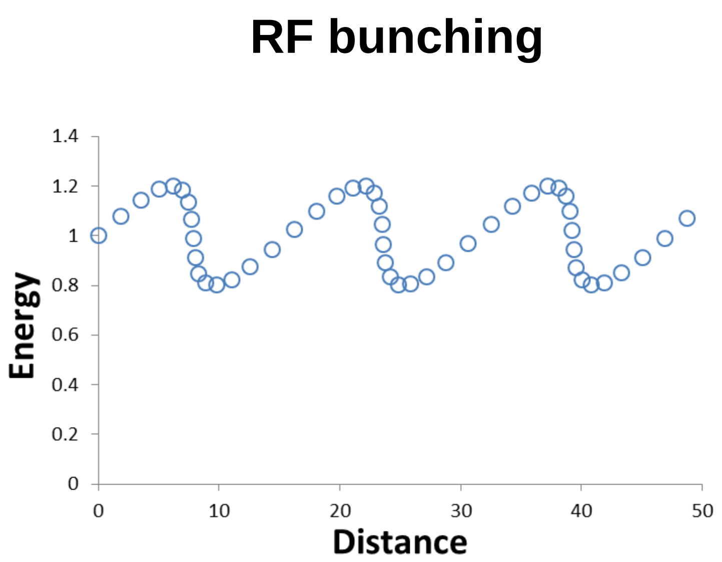
Test Stand

The CLIC Drive Beam Electron Gun is a Thermonic Gun.

Electron and Ion Sources

CTF3 Thermionic Gun – bunching the beam



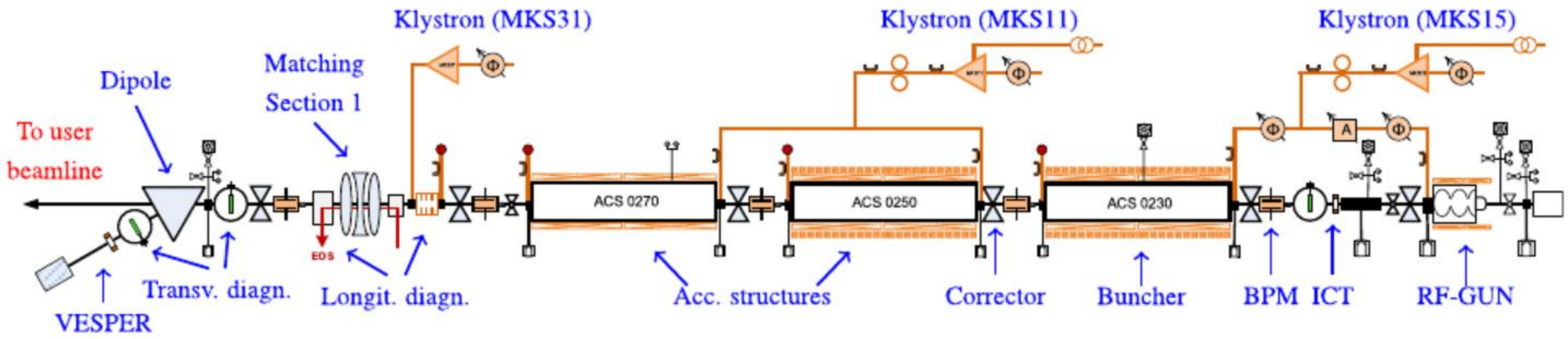


- The thermionic gun produces a 1.5us pulse of electrons.
- RF cavities are then used to produce bunches, which can lead to transverse emittance growth.

Electron and Ion Sources

CLEAR – Electron Gun

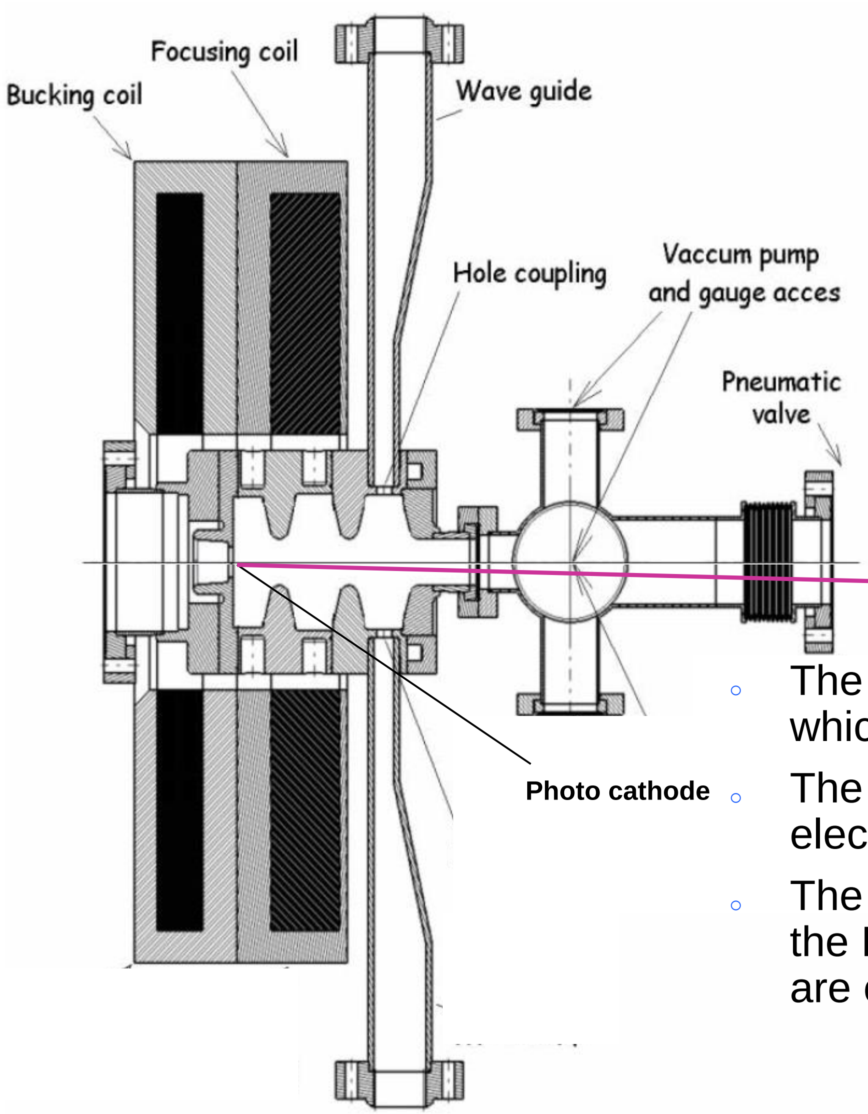
CLEAR uses the PHIN Photo Cathode RF Gun.

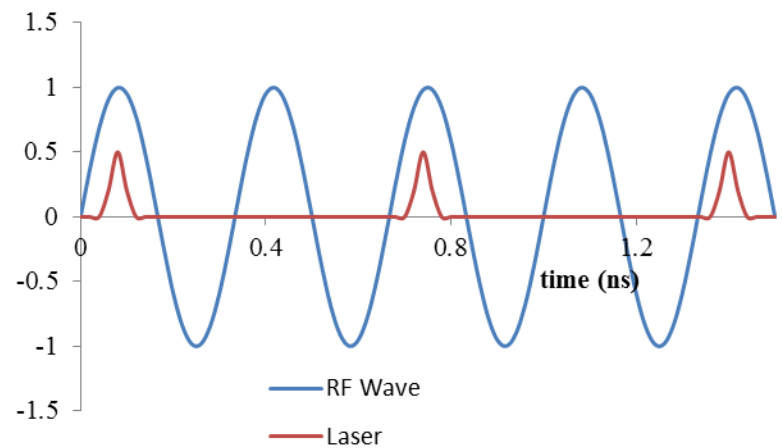


The CTF3 facility is now converted to CLEAR – as a facility for users.
It uses a photo cathode RF gun for the electron source.

Electron and Ion Sources

CTF3 – CALIFES – probe beam photo gun



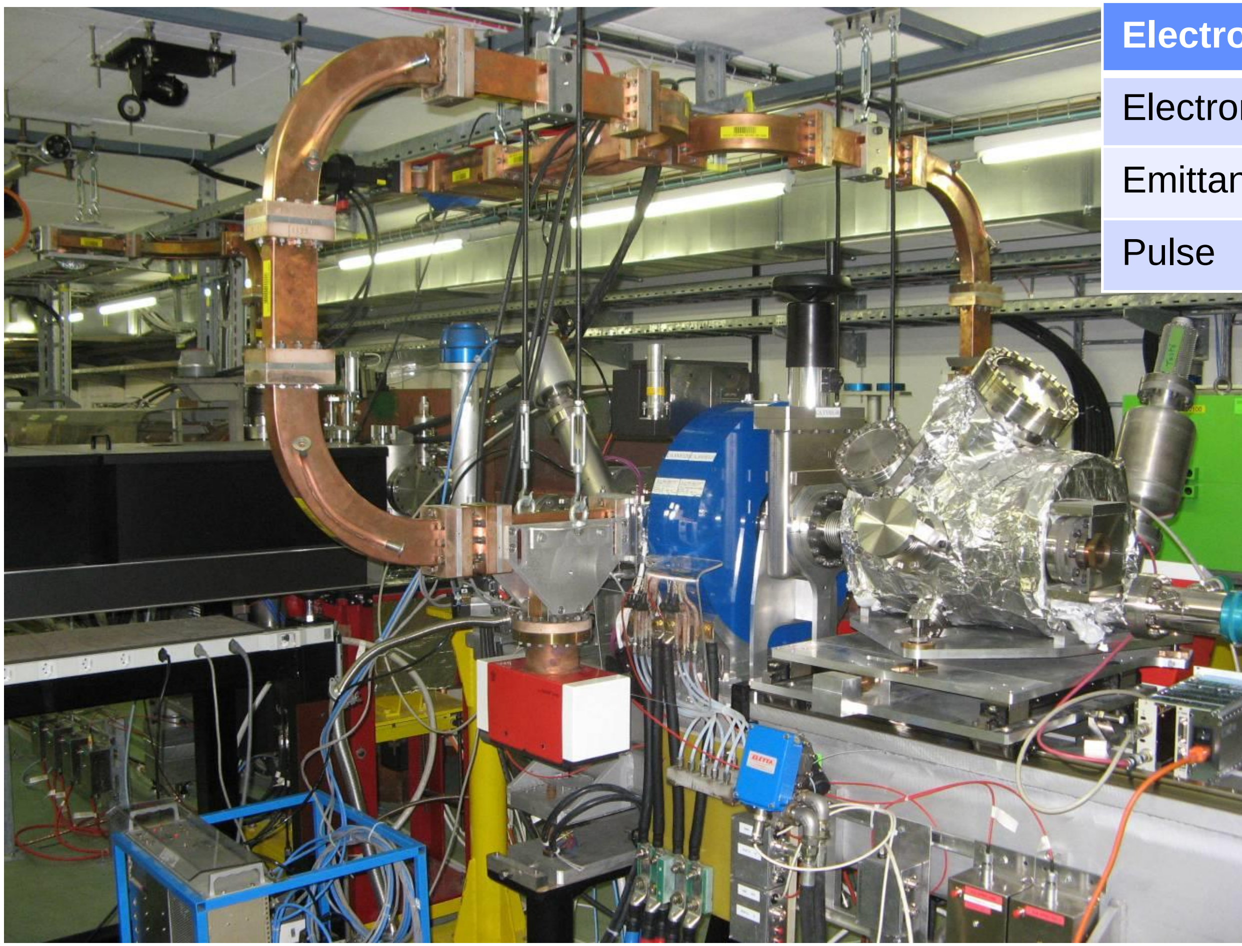


Nd:YLF – 4x frequency -> UV

- The RF gun accelerates to 5MeV in ~15cm, which combats space charge forces.
- The short laser pulses (~6ps) generate short electron bunches from the CsTe photo cathode.
- The laser can pulse at a different harmonic of the RF system. 1.5GHz laser-electron bunches are created, using RF 3GHz acceleration.

Electron and Ion Sources

CTF3 – CALIFES – RF Photo injector

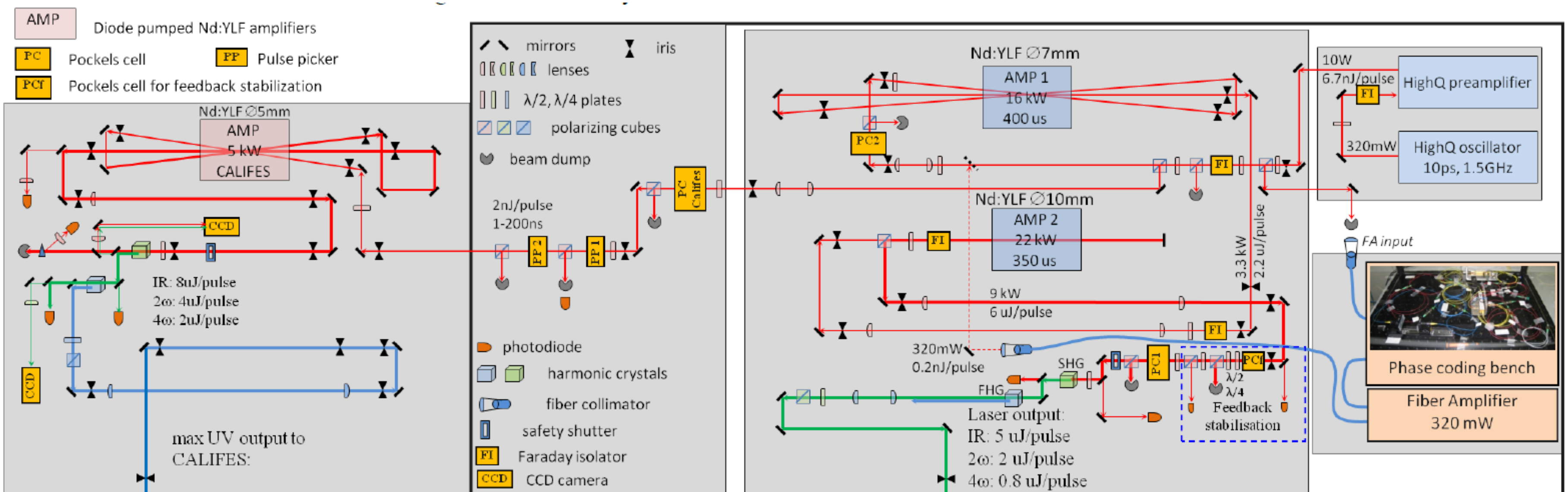


Electron Current	0.9 A
Electron Energy	5-6 MeV
Emittance	20 mm.mrad
Pulse	150ns @ 5 Hz

Electron and Ion Sources

CTF3 – Photo Emission

- … and you need a laser…



To CALIFES

To PHIN

Electron and Ion Sources

- Electron Sources
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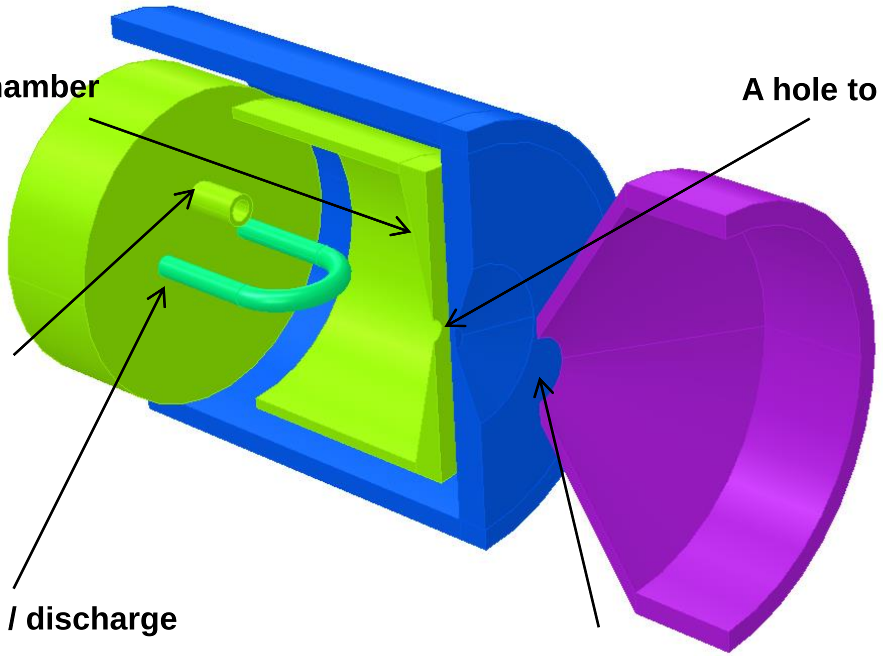
- Ion Sources
  - Particle motion in plasmas
  - Protons
  - Negative Ions
  - ECR Ion Source
  - Radioactive Ions

Electron and Ion Sources

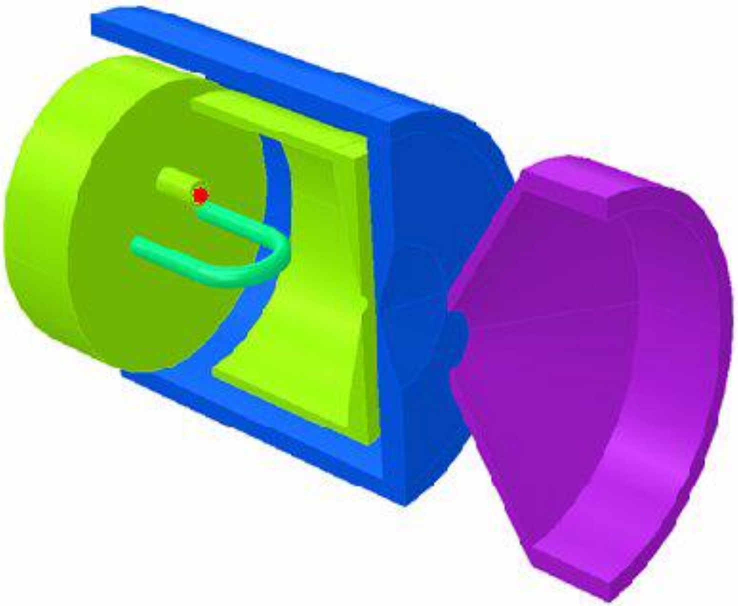
Ion Sources - Basics

- An Ion Source requires an “ion production” region and an “ion extraction” system.
- In most (but not all) cases, ion production occurs in a plasma.



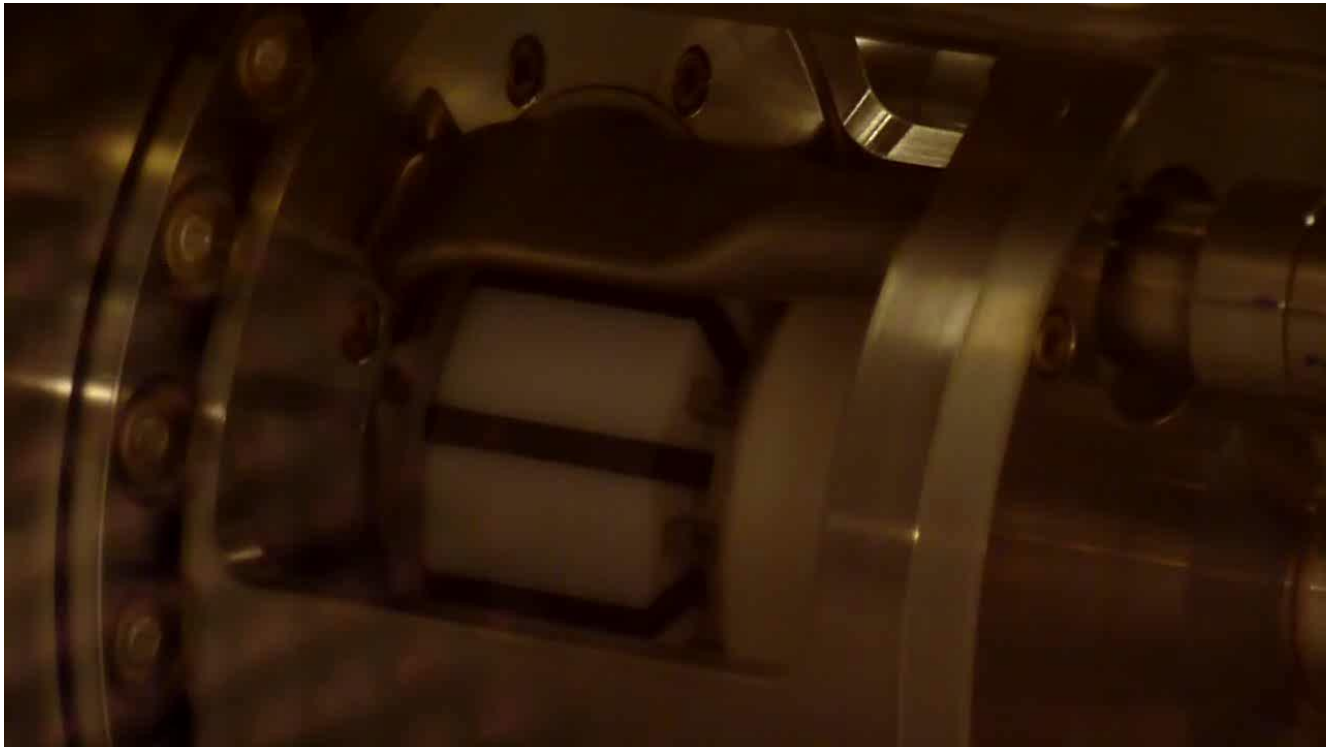
Electron and Ion Sources

Ion Sources - Basics



Electron and Ion Sources

Ion Sources - Basics



- Hydrogen plasma (for protons or H-) from an RF source.
- Hydrogen plasma emits a pink light from an atomic transition.

Electron and Ion Sources

Ion Sources - Basics

- Plasma Processes
  - Electron heating
  - Plasma confinement (electric and magnetic)
  - Collisions (e-e, e-i, i-e, i-i + residual gas)
  - Atomic processes (ionisation, excitation, disassociation, recombination)
  - Surface physics (coatings + desorbtion, e-emission)
  - Mechanical processes (chamber heating+cooling, erosion)
- Ion Source Goal -> Optimise these processes to produce the required ion type and pulse parameters.
- AND maximize reliability, minimize emittance, power and material consumption.

Electron and Ion Sources

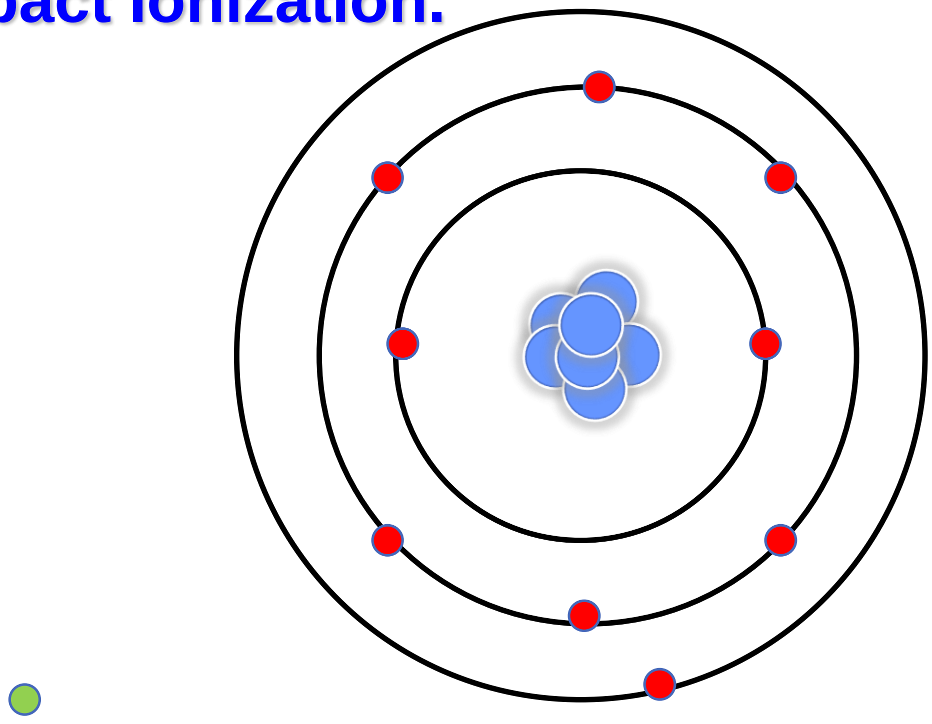
- Electron Sources
  - Thermionic
  - Photo-Cathodes

- Ion Sources
  - **Plasmas and their particle's motion**
  - Protons
  - ECR Ion Source
  - Negative Ions
  - Radioactive Ions

Electron and Ion Sources

How to make ions in an ion source

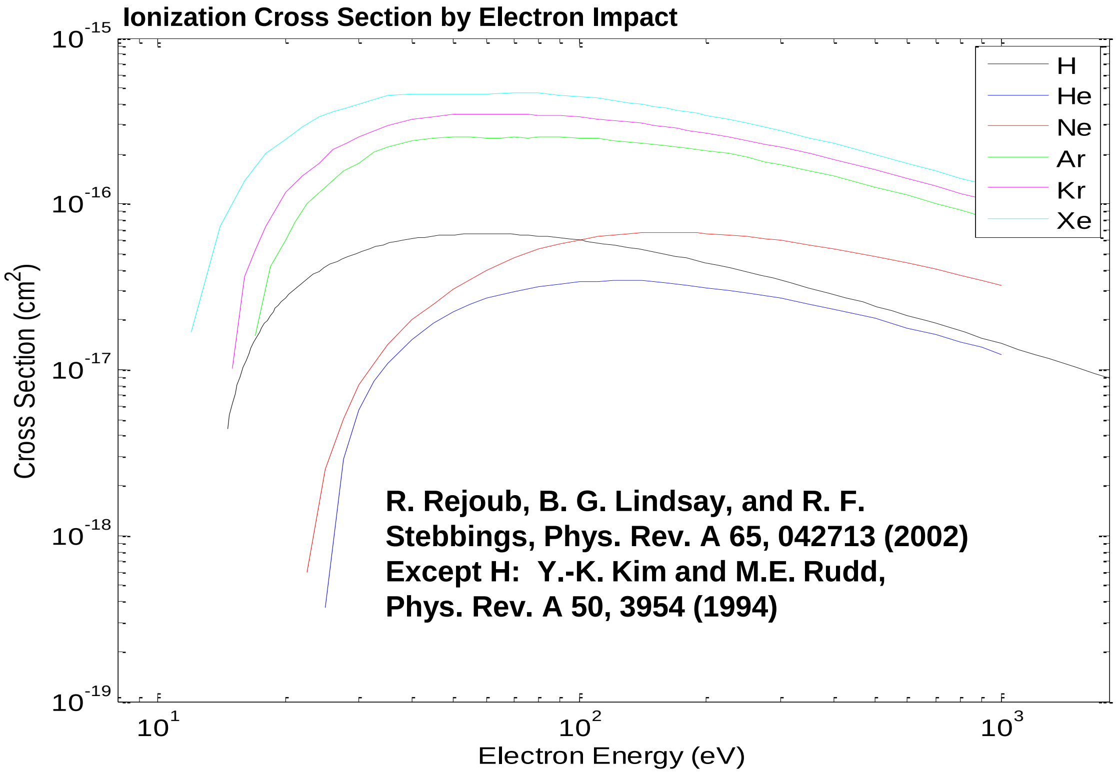
- The most common way to make ion is by Electron Impact Ionization.



Electron and Ion Sources

The recipe for ions

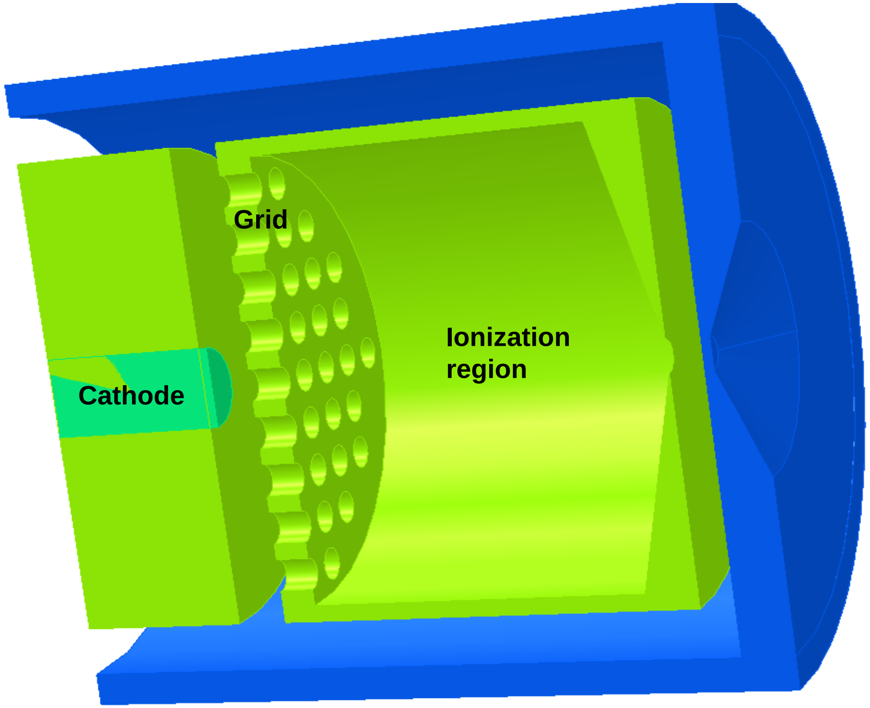
- We need to create electrons, accelerate them to a few times the ionization potential of the material, and get them to interact with atoms.
- Highest probability is at ~3x the ionization potential.



Electron and Ion Sources

The recipe for ions

- A simple source can produce electrons from a cathode, accelerate them to ~100eV, and let them strike atoms in a gas.

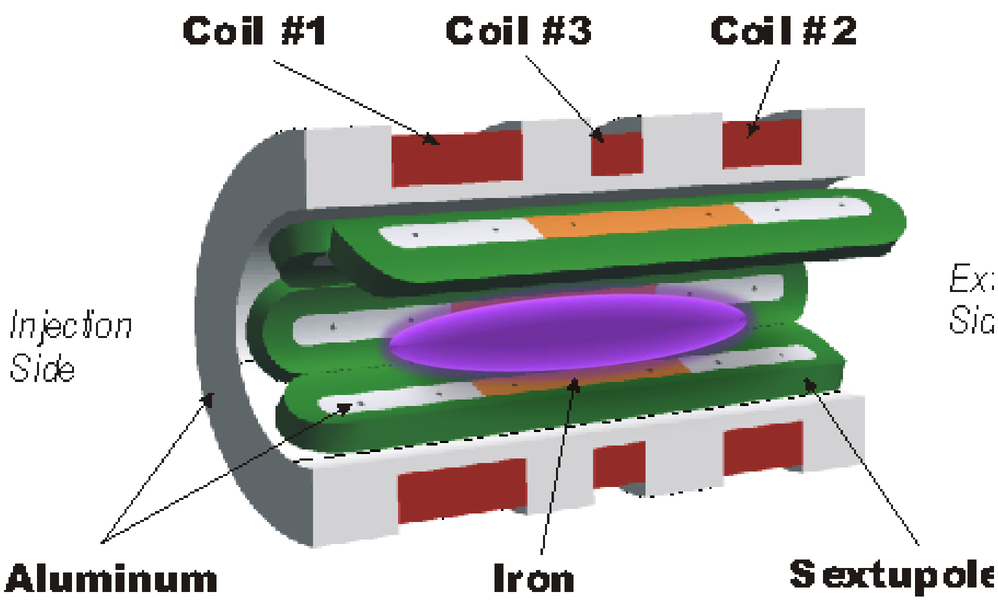


R.L. Gill, A. Piotrowski, NIM A, Vol 234 (2), p213, 1985.
http://dx.doi.org/10.1016/0168-9002(85)90907-6

Electron and Ion Sources

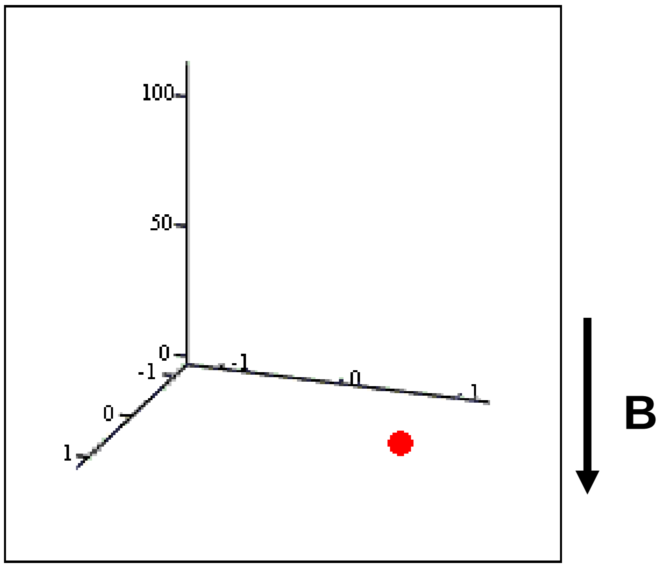
Controlling the ions

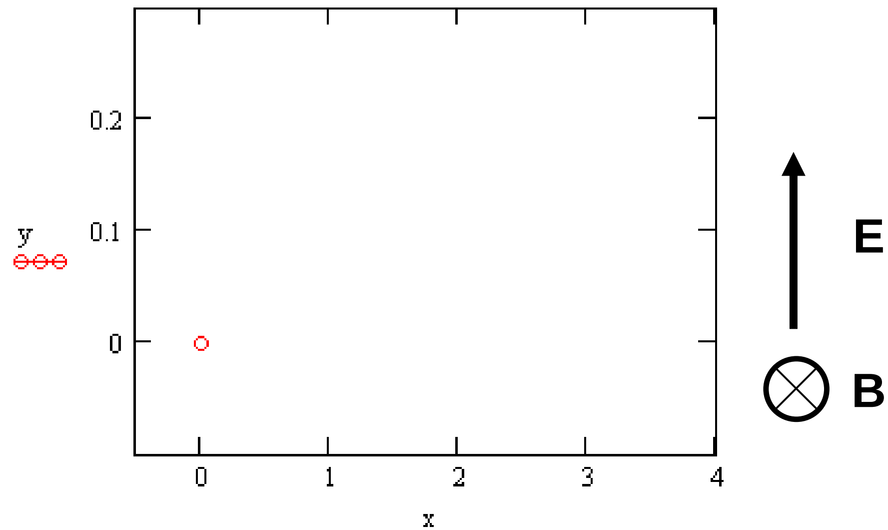
- In order to control the electrons and ions, we make use of magnetic and electric fields to alter their paths.



Electron and Ion Sources

Plasma Particle Motion





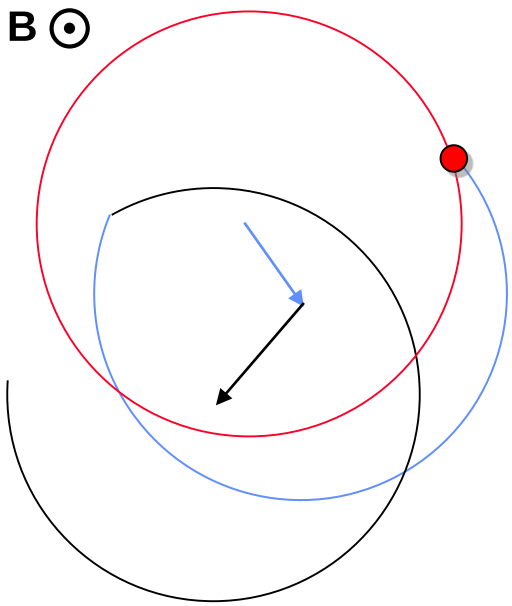
$$\rho_c = \frac{\sqrt{2mE_\perp}}{eB}, \omega_c = \frac{eB}{m}$$

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

Electron and Ion Sources

Plasma Particle Motion

$$D \sim \rho_c{}^2 \upsilon_c \sim \left(\frac{\sqrt{2 m_p E_\perp}}{eB} \right)^2 \frac{1}{T^{3/2}} \left(\frac{m_e}{m_p} \right)^{1/2} \sim \frac{m_p^{1/2}}{T^{1/2}}$$



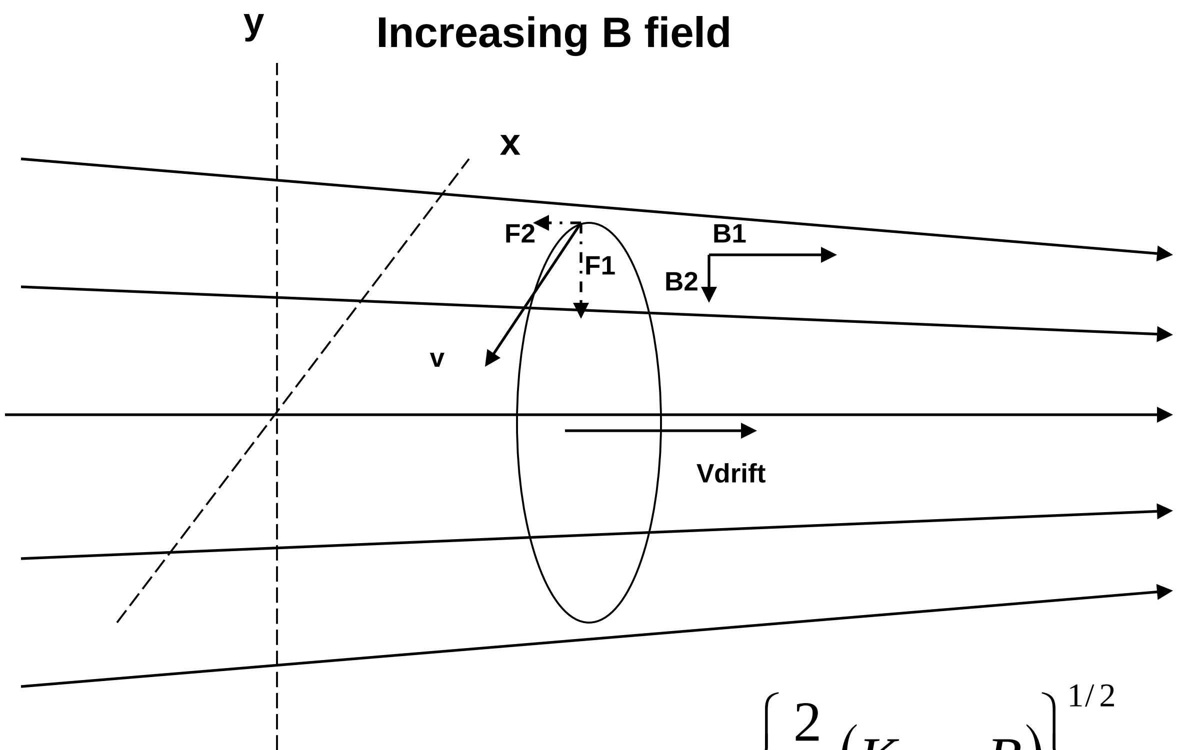
cf: opposite to classical energy – velocity equation !

$$v = \left(\frac{2E}{m} \right)^{1/2}$$

Electron and Ion Sources

ECR Source – Magnetic Mirror

A force acts in the opposite direction to the Increasing B field



Energy is transferred from Vdrift to Vecr

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

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

μ = magnetic moment

K = total kinetic energy

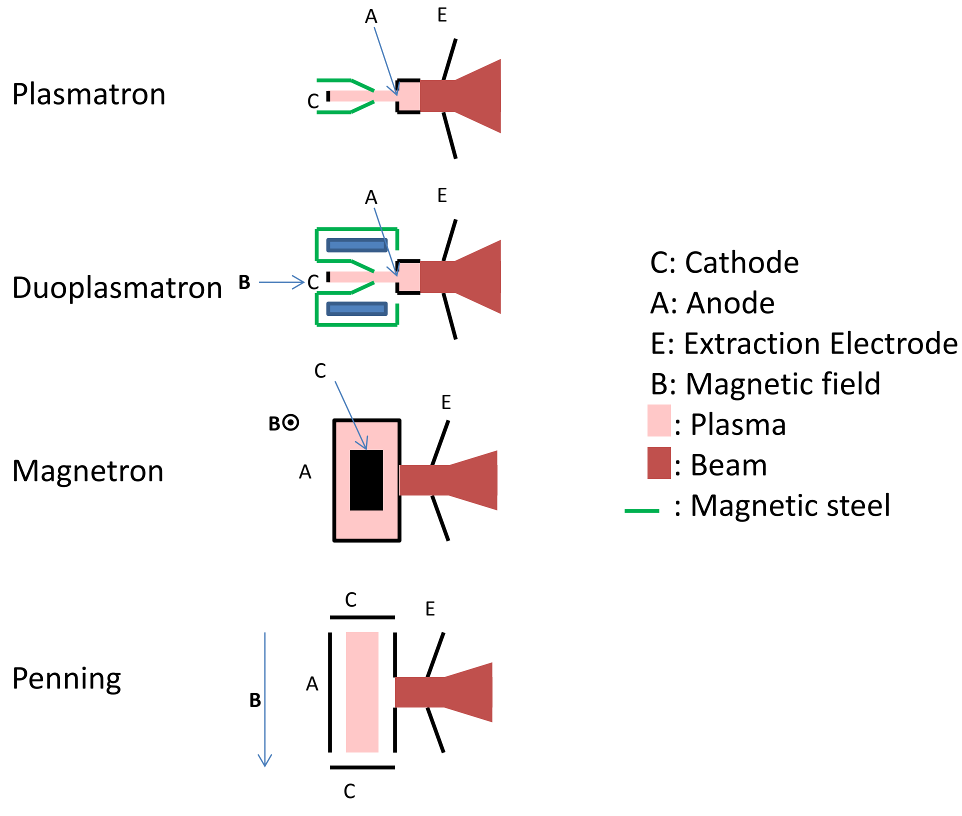
Electron and Ion Sources

Ion Source – Gas Discharge

- Many sources work on the principle of a cathode – anode gas discharge
- The gas can be a compound form (e.g. Carbon from CO) or from a vapour (e.g. lead vapour from an oven).
- Electrons from a hot cathode are accelerated into the gas by a cathode to anode voltage, and ionize the gas atoms/molecules with electron impact ionization.
- At low gas pressures, most electrons do not cause ionization and the ion density remains low.
- At higher pressures, the electrons cause ionization, which also leads to new electrons to be accelerated and cause ionization.

Electron and Ion Sources

By applying an magnetic field, electrons can have longer path lengths inside the source, and the chance of ionization is increased.



Electron and Ion Sources

Ion Sources - Basics

- **Ion Sources at CERN.**
  - Linac2 – Protons - Dupolasmatron
  - Linac3 – Ions (Pb, O, Ar) – ECR
  - ISOLDE – Radioactive ions – Surface, laser, Electron Bombardment.
  - Linac4 – Negative Hydrogen – RF

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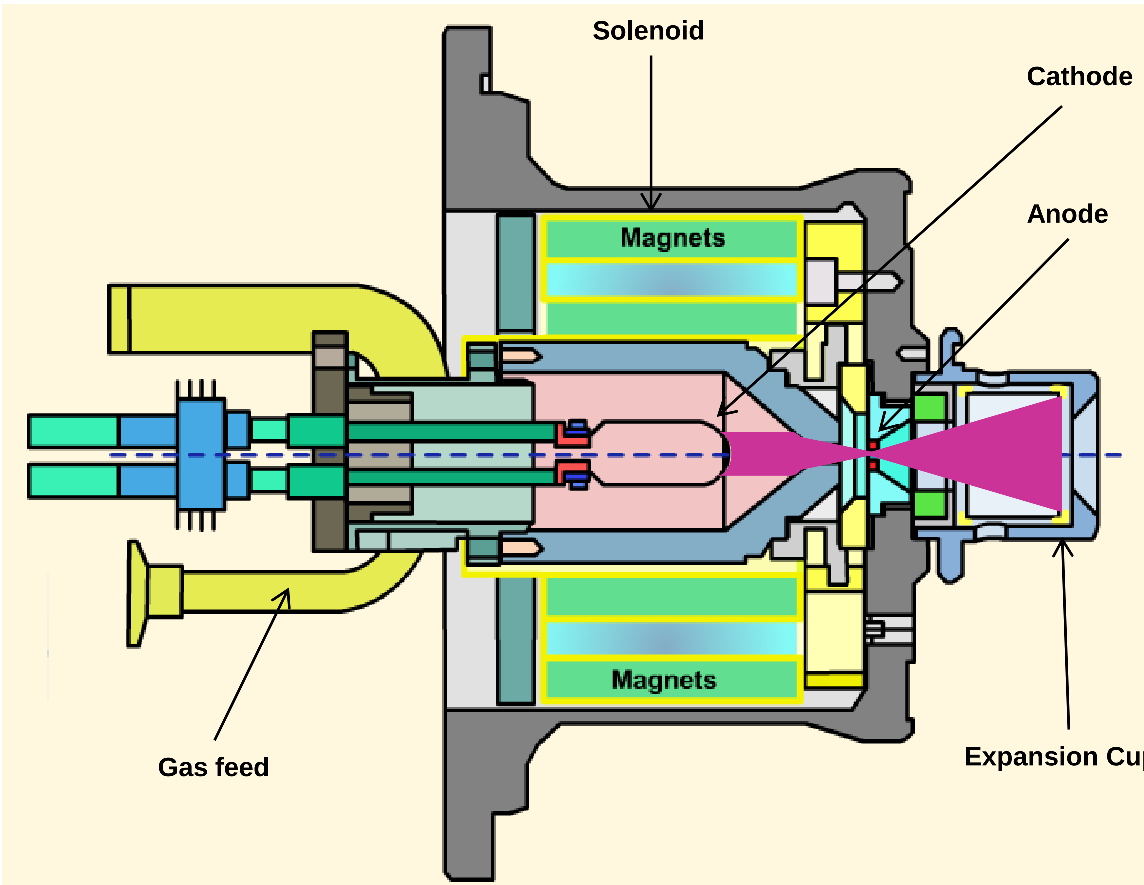
Electron and Ion Sources

Ion Source – Duoplasmatron – Linac2



Proton Current	200 mA
Proton Energy	90 keV
Emittance	~0.4 mm.mrad
Pulse for LHC	20us @ 1 Hz
# protons / pulse	2.5×10^{13}
# LHC bunches	~24 *

*** Creation of LHC bunches is a complicated process, this is an example for 50ns LHC bunches**

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Electron and Ion Sources

Ion Sources – Negative Ions

- Negative ion sources allow:
  Charge exchange injection into synchrotrons.
  Charge exchange extraction from cyclotrons.
  Tandem accelerators.

	Electron Affinity (eV)
H	0.7542
He	<0
Li	0.6182
Be	<0
B	0.277
C	1.2629
N	<0
O	1.462
F	3.399

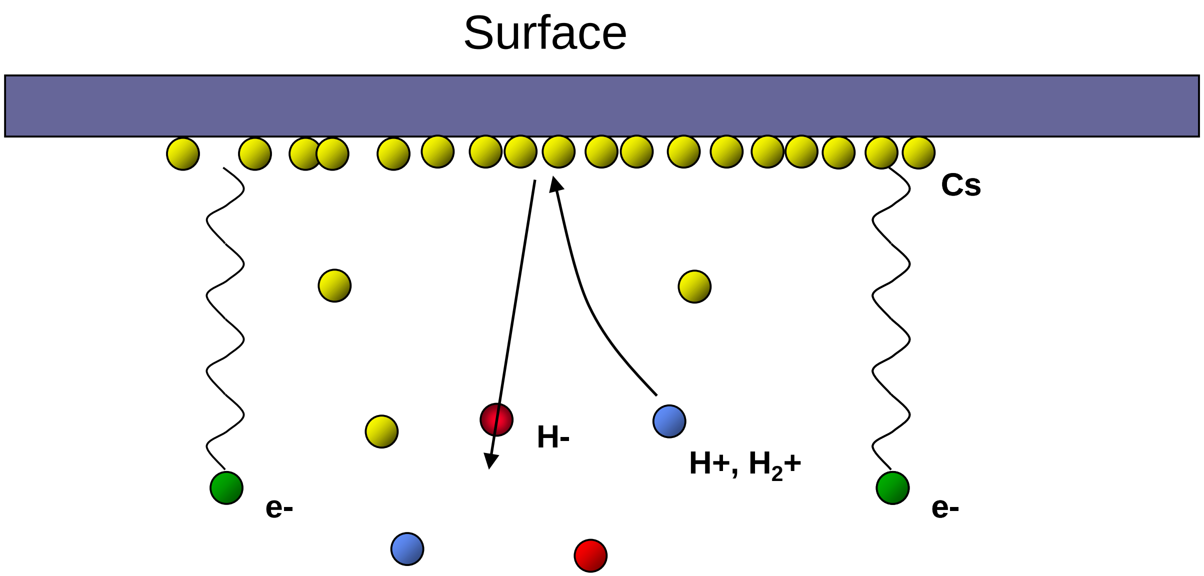
- The bonding energy for an electron onto an atom is the Electron Affinity.
- Ea < 0 for Noble Gases
- Large Ea for Halogens
- Two categories of negative ion sources
  - Surface – an atom on a surface can be desorbed with an extra electron (whose wave-function overlapped the atom).
  - Volume – Through collisions, e-capture and molecular dissociation, negative ions can be formed.

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

$\mathbf{AB^* + e \rightarrow A^- + B}$ $\quad$ $A^+ + B \rightarrow A^- + B^{2+}$

Electron and Ion Sources

H- Surface Ion Production

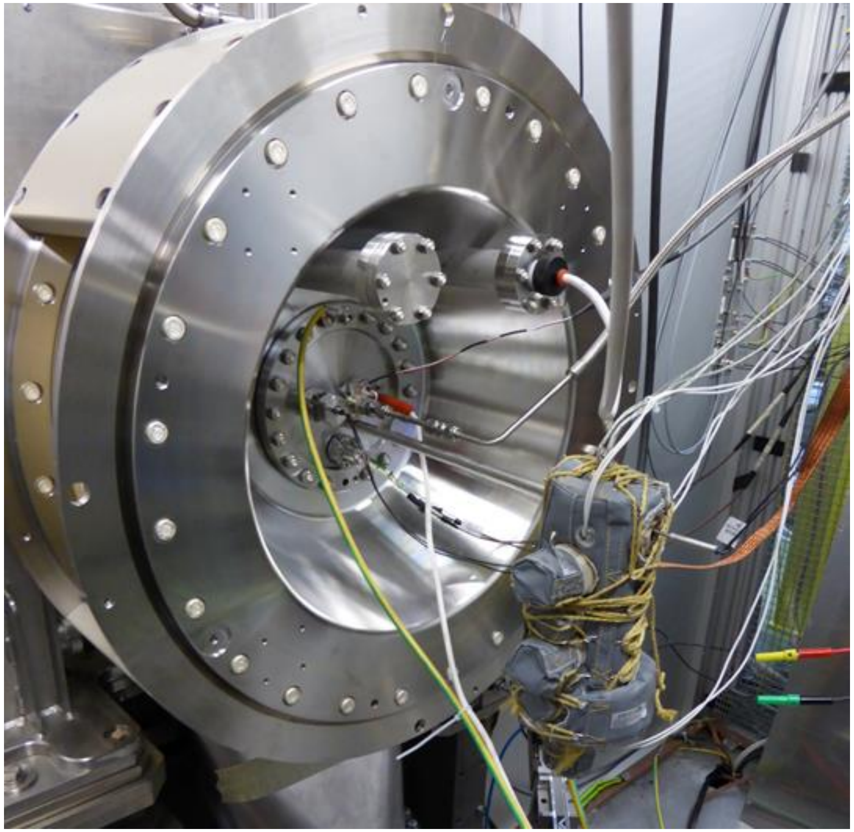


- Protons from the plasma are accelerated to the cathode, which has a coating of caesium.
- The protons desorbed from the low work function surface, with an additional electron.
- The plasma must not be too hot, to avoid ionising the H-.
- Penning, Magnetron, etc, sources produce H this way.

Electron and Ion Sources

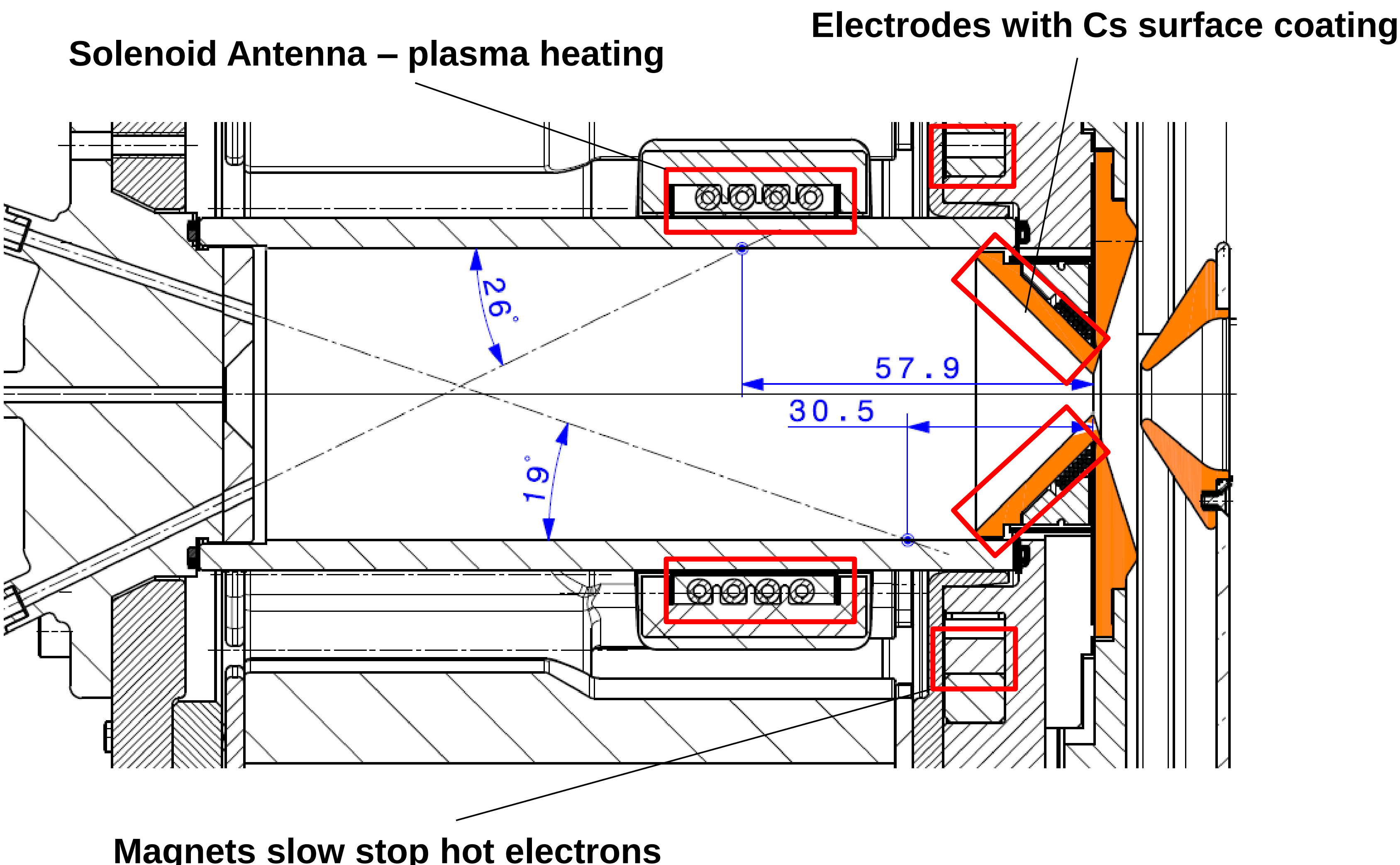
Ion Sources – Negative Ions – Linac4

- **Linac4 Ion Source uses a 2MHz RF driven plasma**



Electron and Ion Sources

Ion Sources – Negative Ions – Linac4



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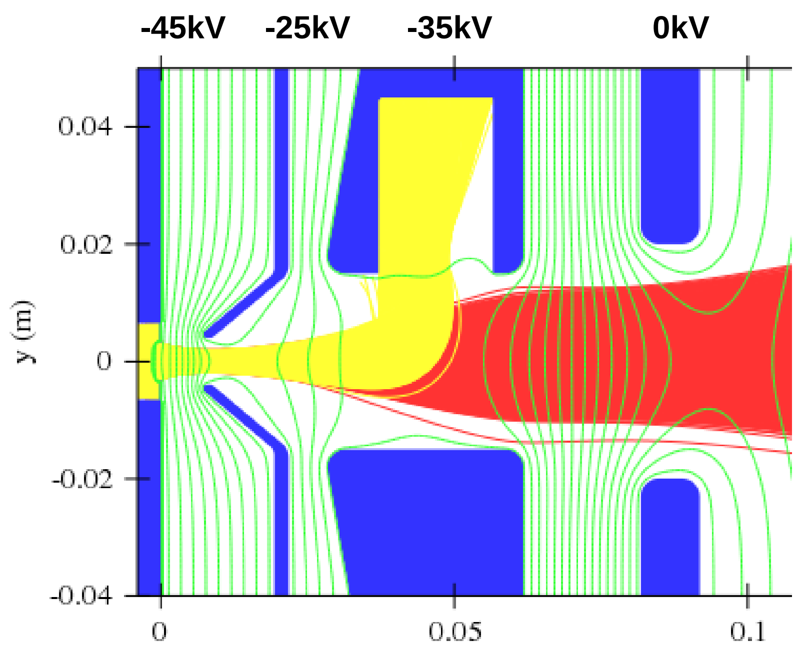
Electron and Ion Sources

Ion Sources – Negative Ions – Linac4

- Electrons (yellow) are extracted along with negative ions (red).
- Electrons can be separated with a dipole B field in extraction.
- In the Linac4 RF source electron current is:
  - >1 A without caesium
  - ~ 50mA with caesium



Electron and Ion Sources

- Electron Sources
    - Thermionic
    - Photo-Cathodes

- Ion Sources
    - Particle motion in plasmas
    - Protons
    - Negative Ions
    - ECR Ion Source
    - Radioactive Ions

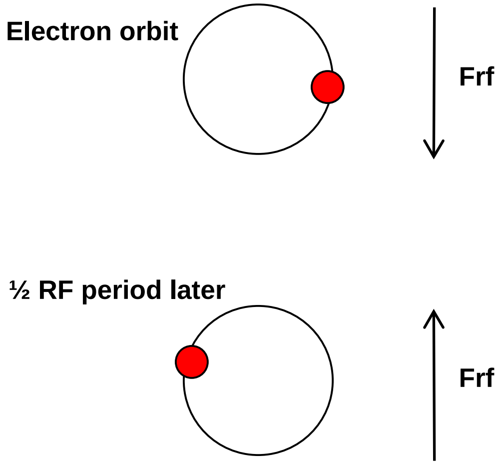
Electron and Ion Sources

Ion Source – ECR – Linac3

- Electron Cyclotron Resonance Ion Source (ECR)
  - For a given magnetic field, non-relativistic electrons have a fixed revolution frequency.
  - The plasma electrons will absorb energy at this frequency (just as particles in a cyclotron).
  - If confined in a magnetic bottle, the electrons can be heated to the keV and even MeV range.
  - Ions also trapped by the charge of the electrons, but for milli-seconds allowing mutliple ionisation.
  - The solenoid magnetic field still allows losses on axis – these ions make the beam.

$$\omega_c = \frac{eB}{m}$$

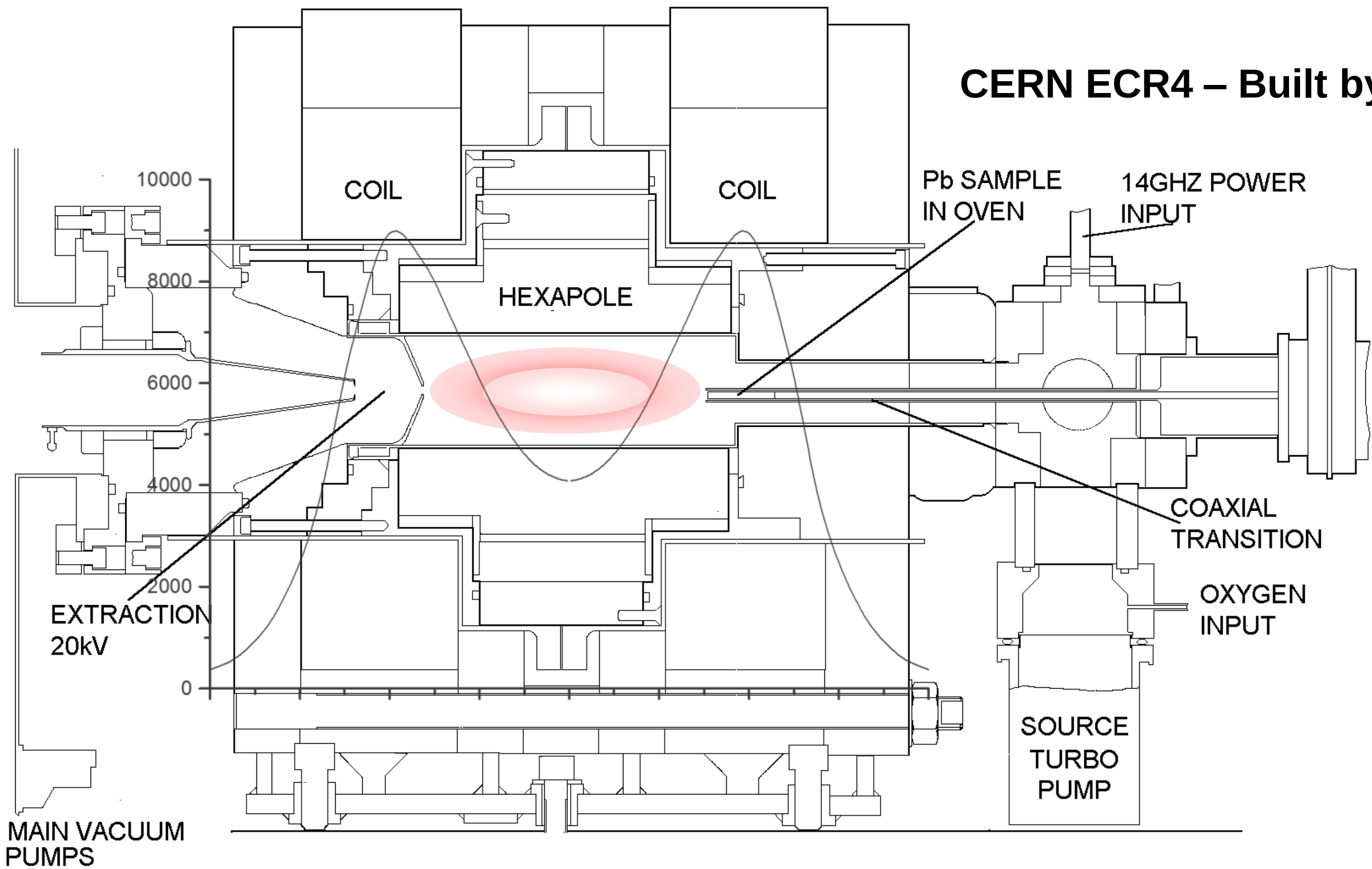
$$f_c[\mathrm{GHz}] = 28 \times B[\mathrm{T}]$$



Electron and Ion Sources

Ion Source – ECR

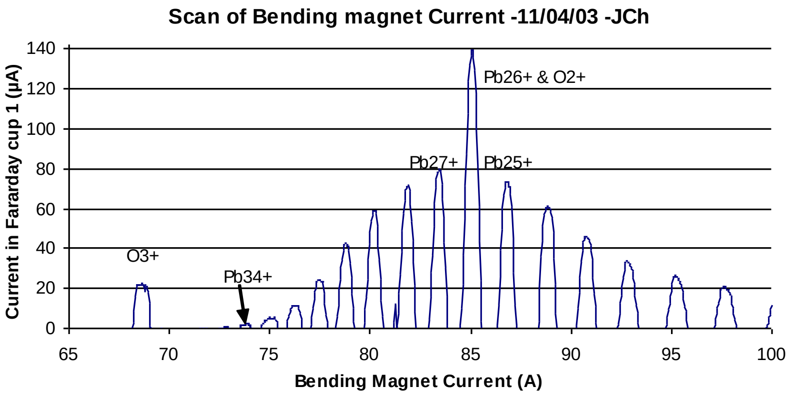
CERN ECR4 – Built by GANIL

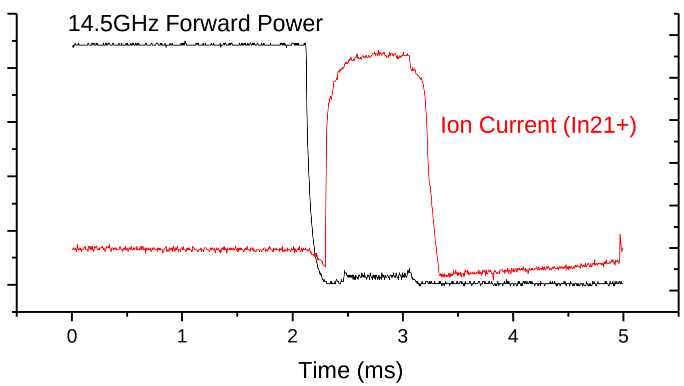


Electron and Ion Sources

Ion Source – ECR – High charge states

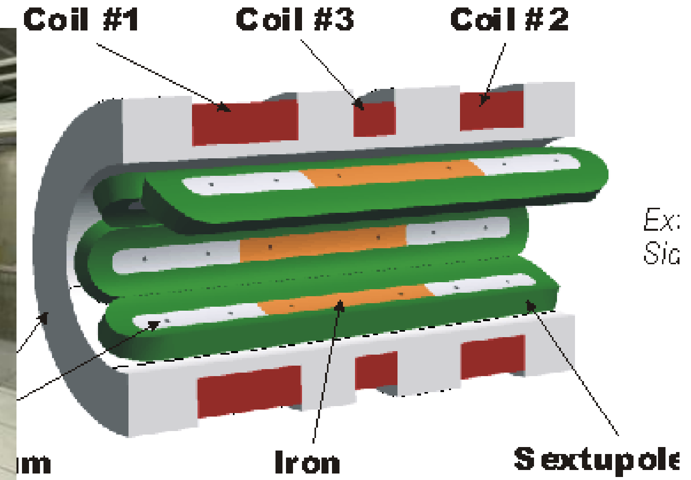
- No filament is needed, greatly increasing the source lifetime.
- Singly, multiply and highly charged ions can be produced by these sources (although the source construction will influence this).
  A → A+ → A2+ → A3+
  Stepwise ionisation.
- Gaseous ions are easily made. Metallic ions come from an OVEN or from a compound gas (e.g UF6 for uranium).
- In the afterglow mode, the ion intensity increases AFTER switching off the micro-waves.





Electron and Ion Sources

Ion Source – ECR – High charge states + industry solutions

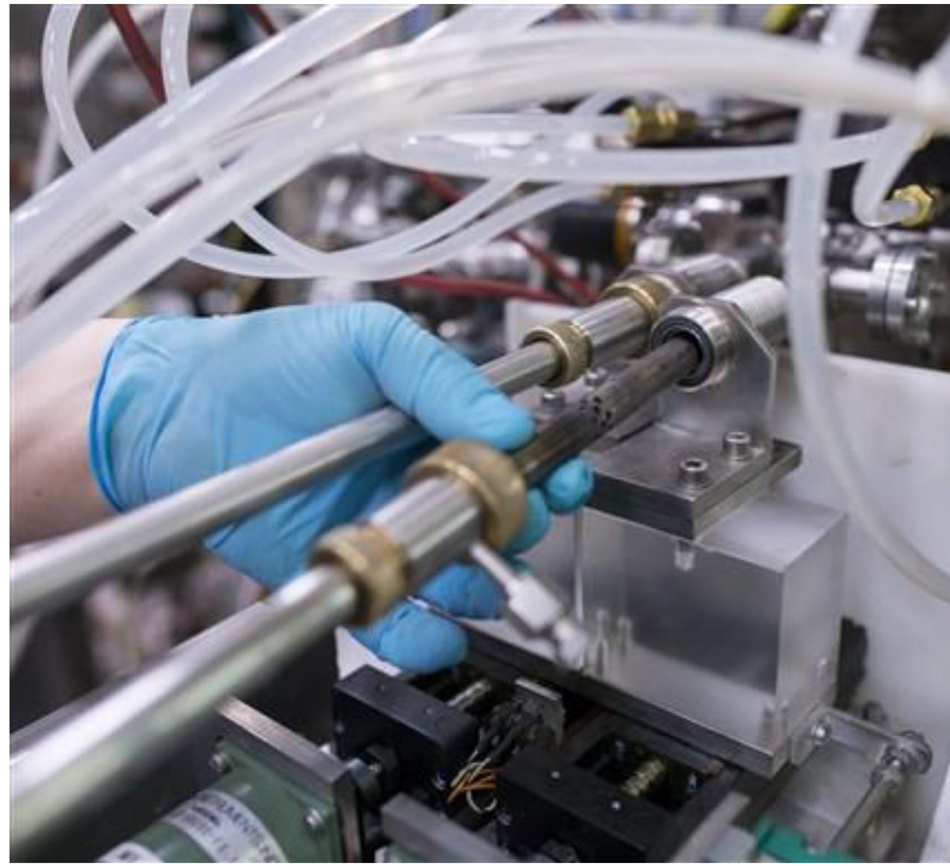


- Plasma density increases with frequency and associated magnetic field.
- Example: VENUS source and Berkeley, Ca, uses superconducting solenoid and sextapole magnets.

- Industry can now provide turnkey solutions for ECR ions sources, usually using permanent magnets.

Electron and Ion Sources

Lead (Pb) is evapourated from a micro oven in the source

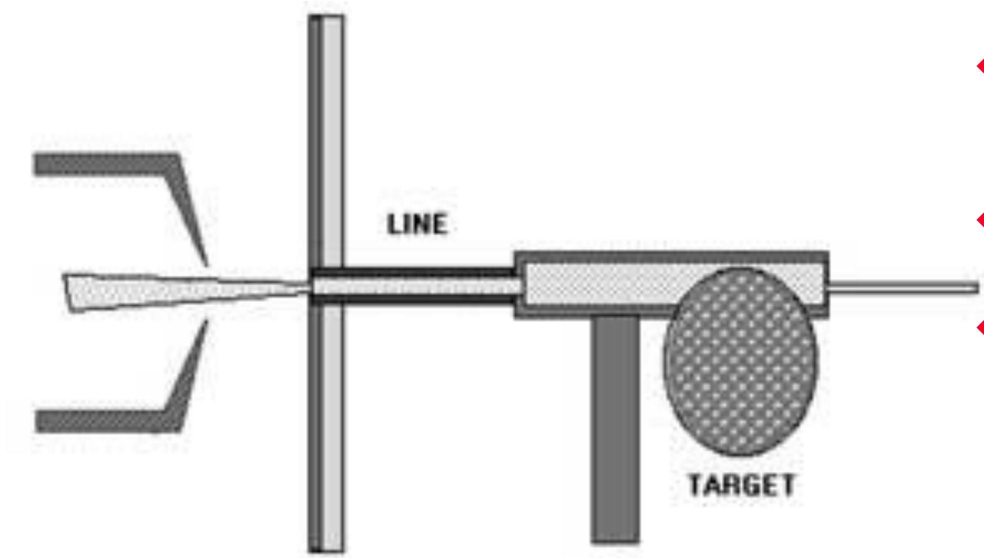


Electron and Ion Sources

- Electron Sources
  - Thermionic
  - Photo-Cathodes
- Ion Sources
  - Particle motion in plasmas
  - Protons
  - ECR Ion Source
  - Negative Ions
  - Radioactive Ions

Electron and Ion Sources

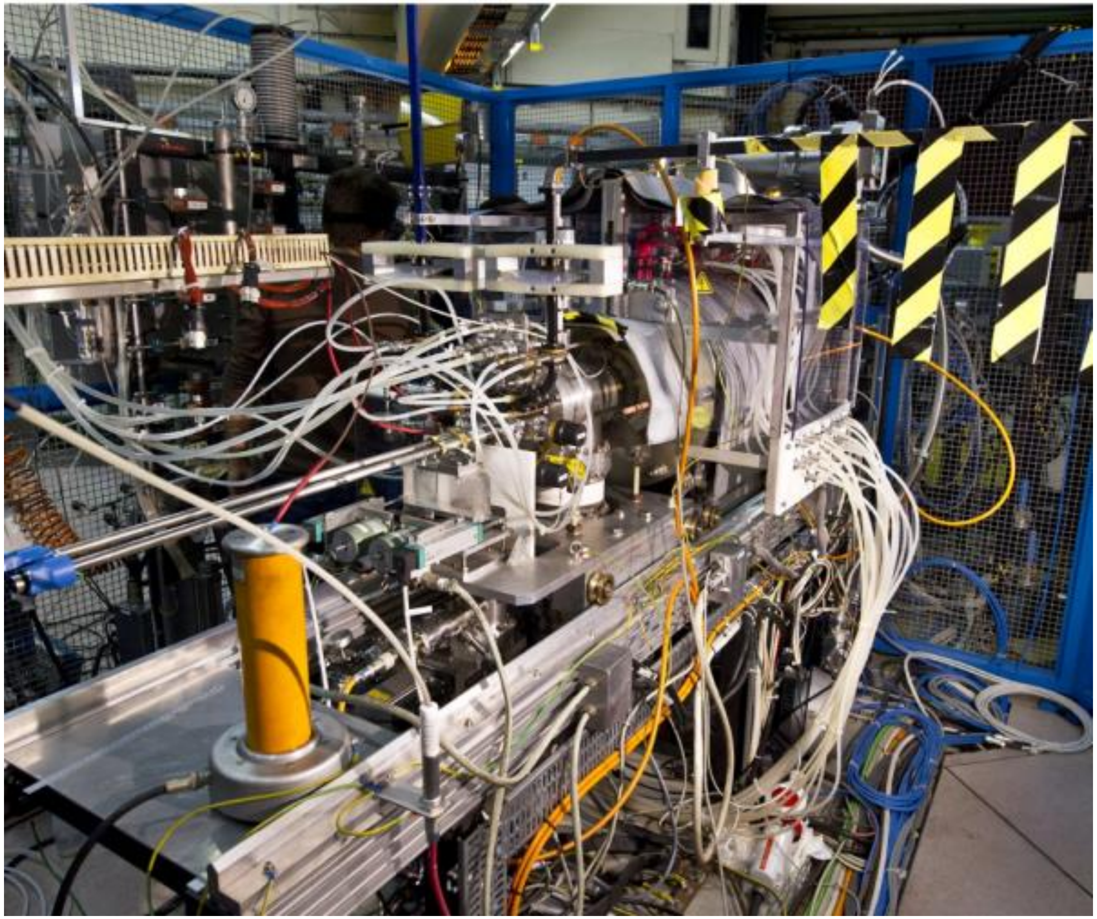
Ion Source – Radioactive Ions – ISOLDE



- A gas/vapour of new isotopes is produced from 1.4GeV protons onto a target.
- The ion source is used to ionize the gas.
- The ions will be mass selected in an ion spectrometer.

- An important goal is to have a high conversion rate of the desired gas to ions.
- The sources must be robust to work in the extreme radiation environment. For example minimize use of any organic compounds.
- The sources can help to reduce the contamination (i.e. stable/other isotopes of the same mass) through some selective process (e.g. using lasers to selectively ionize the atom of interest).

Electron and Ion Sources



- For sources, all we have seen so far is the ion generation.
- You still have to add the high voltage systems, pumping, cooling, power convertors, controls…

Electron and Ion Sources

Summary

- Electron Source Summary
  - Thermionic Source. Some thermal electrons are above the Work-Function.
  - Use low work-function or high melting point materials to obtain the most electrons
  - Photo-cathodes – Use photons above the work-function or E_g+E_a.
  - Metals – Stable but have a low quantum efficiency
  - Semiconductors – high Q, but can be unstable and degrade in use.

- Ion Source Summary
  - Plasmas are a common production method for ions.
  - There are many ways to produce, heat and confine a plasma, leading to many source types.
  - CERN already uses quite an array of these types.

Electron and Ion Sources

Further Reading

- Handbook of Ion Source, B. Wolf, Boca Raton, FL: CRC Press, 1995
- Ion Sources, Zhang Hua Shun, Berlin: Springer, 1999.
- The Physics and Technology of Ion Source, I. G. Brown, New York, NY: Wiley, 1989
- Large Ion Beams: Fundamentals of Generation and Propagation, T. A .Forrester, New York, NY: Wiley, 1988
- CAS – 5th General School (CERN 94-01) and Cyclotrons, Linacs… (CERN-96-02)

Thank you for your attention.

Electron and Ion Sources

A: Richardson-Dushman constant
B: Magnetic field
D: Diffusion rate

E: Particle Kinetic Energy
E: Electric field
J: Current density
m: Particle Mass
n: Particle density
T: Temperature
U,V: Voltage
v: Particle velocity
v_{drift}: Particle drift velocity

β: Relativistic beta
γ: Relativistic gamma
ϕ_s: Work Function (Voltage)
ν: Collision Frequency
ρ_c: Cyclotron Radius
ω_c: Cyclotron Frequency