Mexican Particle Accelerator School 2015

PARTICLE SOURCES

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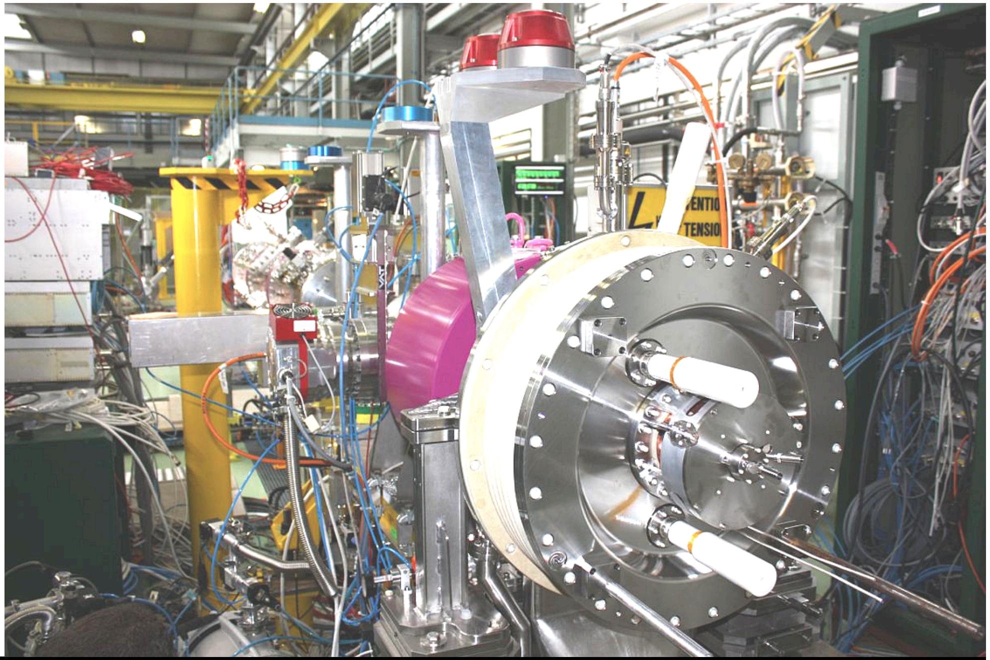
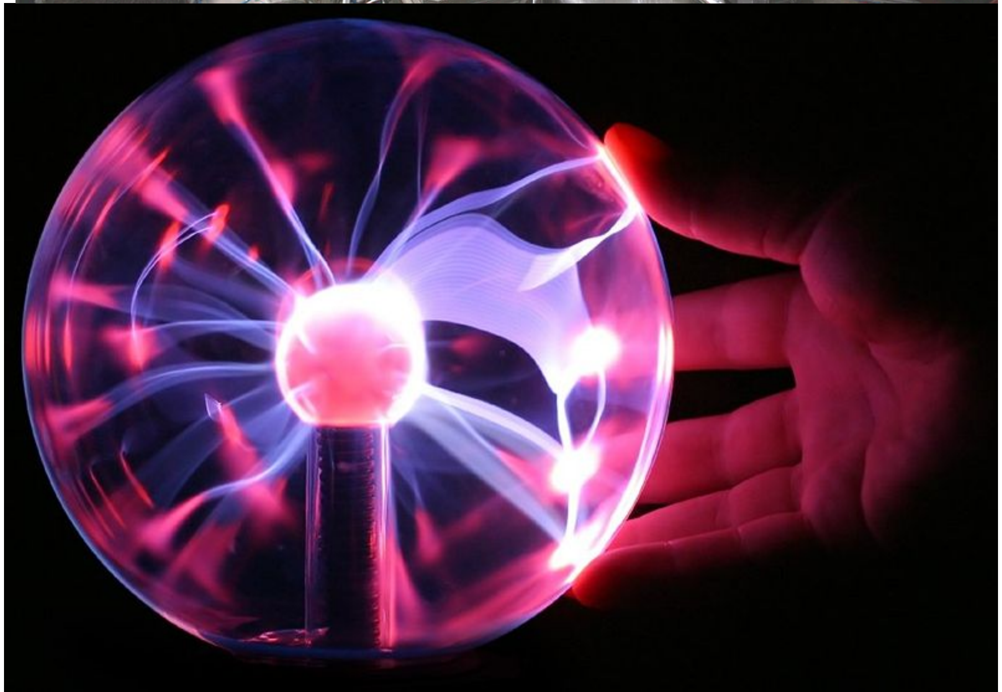
Particle Sources

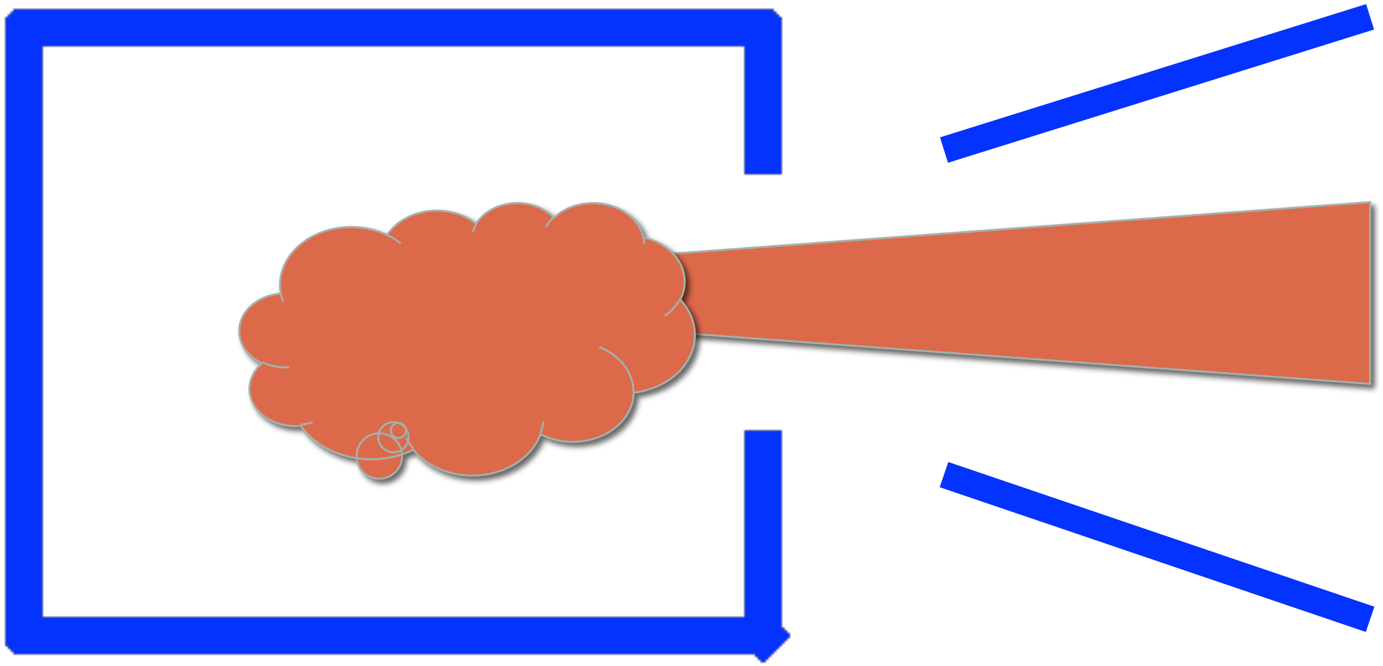
- Basic Definition
- Source Parameters
- Extraction systems
- Space charge
- Electron sources
- Ion sources





Definition

The Most important device!!

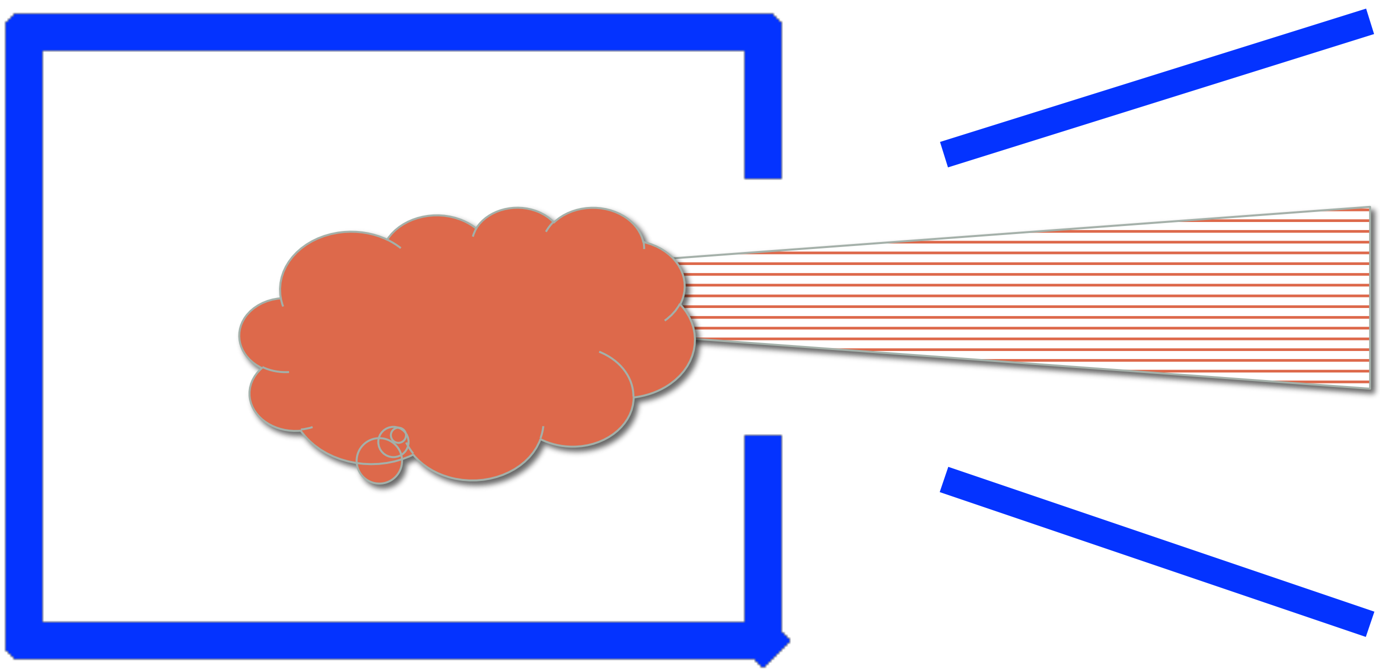


Place where the charged particles are created

A extraction system to create the beam

Definition

The Most important device!!



The beam can be created in bunches

Place where the charged particles are created

A extraction system to create the beam

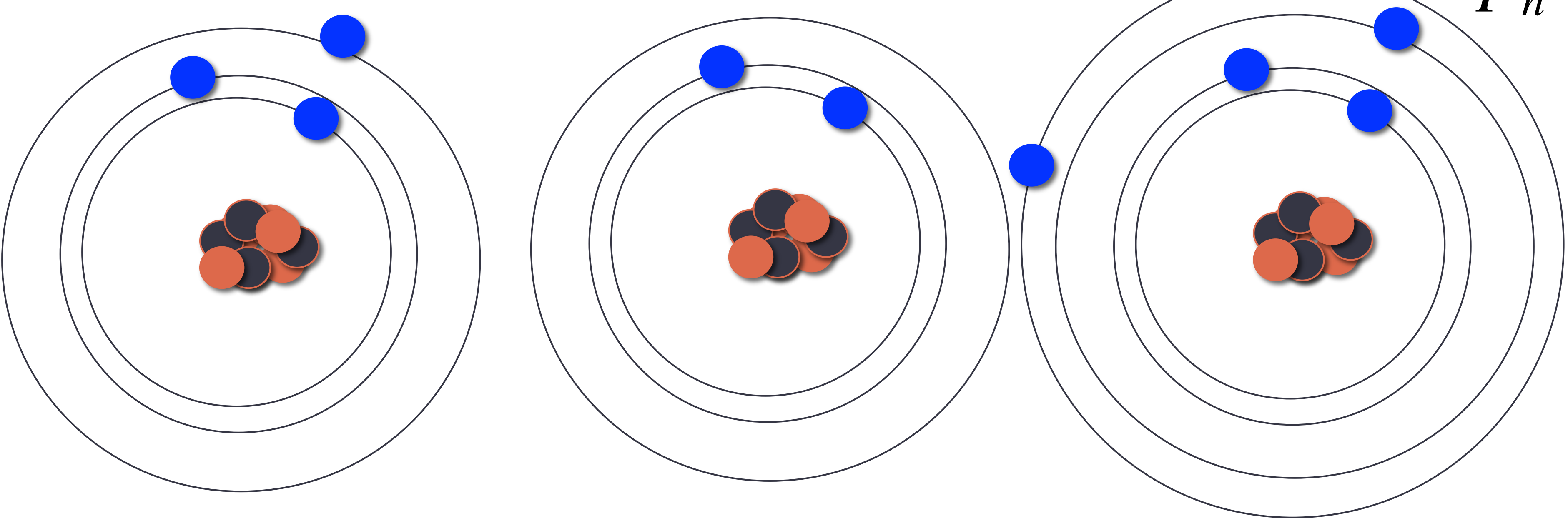
Ionization

Neutral state

Positive Ions :
1 o more electrons are removed

Negative Ions :
A extra electron Is attached

$${}^{A}p_{n}^{q+}$$



Particles sources

The generated particles can be ions or electrons, where the ions are defined as

$$^{A}p_{n}^{q+}$$

The mechanism to generate and extract the particles will depend of the type of particle

The desire type of particle to be extracted from the source will determinates the accelerator shape

- The particle sources in accelerator physics push to the limits the beam generated by an Ion source

Time structure

The beam time structure is also an important parameter in the particles source

- Beam pulse length is defined as

$$T_{pulse}$$

- The repetition rate is defined by the number of pulses in a second

$$\frac{1}{T_{rep}}$$

- The duty factor is defined as

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

Source Intensity

- The source intensity is measured in terms of
  - beam current.
  - Total charge taking in to account beam pulse time structure
  - Number of particles in the beam

$$I_{beam} = \frac{qeN_{ions}}{t}$$

q= particle charge

e= electron charge

Source pressure

- The ion sources operate in a wide range of pressures from 1^{-10} mbar to 1 mbar
- We need to inject gas inside the source

High pressures inside the sources can lead to **problems**:
Recombination and striping losses

- The electron sources operate in lower pressures from 1^{-11} mbar to 1^{-8} mbar
- The cathode need to be clean for optimum conditions

Carlos Hernandez talk tomorrow about vacuum

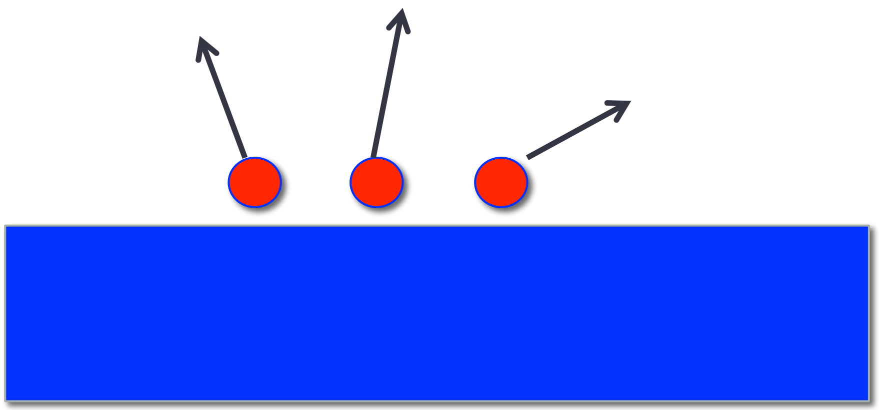
Reliability

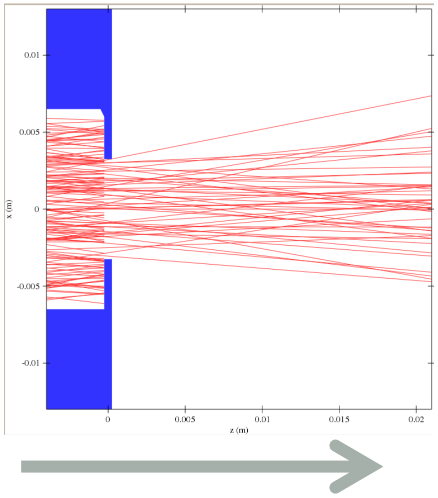
- Without source there is no beam !!
- 100% reliability is always the desire
- Really difficult or impossible to achieve in some cases

- Some electron and ion sources need a constant maintenance o replacement

Energy Spread

- When the particles are created, every particle has a different energy

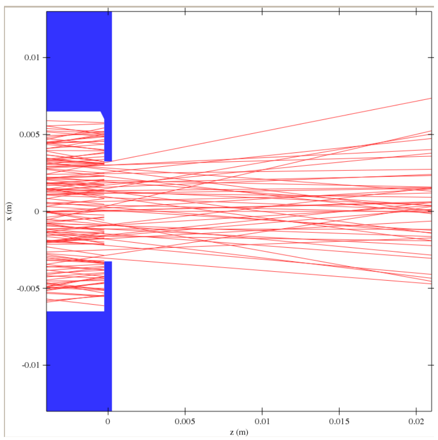


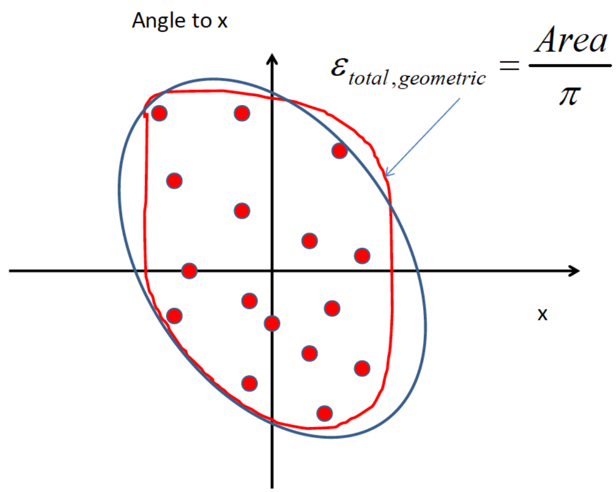


- The particles have 3 momentum components $p_x \ p_y \ p_z$

Emittance

- The region in phase space that the particles in a beam occupy is called the beam emittance





- Mm.mrad? mrad from p_x/p_z
- The goal in every accelerator is to have the lower beam emittance achievable

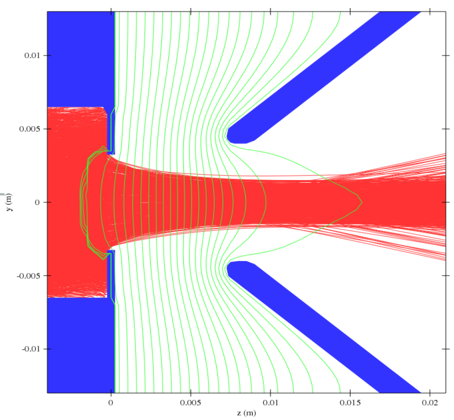
$$\varepsilon = \frac{r}{2c}\sqrt{\frac{kT}{m}} \propto T^{1/2} \qquad Brigthness \propto \frac{I}{\varepsilon_y \varepsilon_x}$$

Source energy

The beam energy is calculated by the diference of potential

Ground **Extracto**

Plasma



Ion Beam

Potential lines(green)
Electrodes (blue)
Ions (Red)

$$Energy = qe(V_{source} - V_{ground})$$

In the case of ions we can define the energy per nucleon as

$$\frac{Energy}{Nucleon} = \frac{qe(V_{source} - V_{ground})}{A}$$

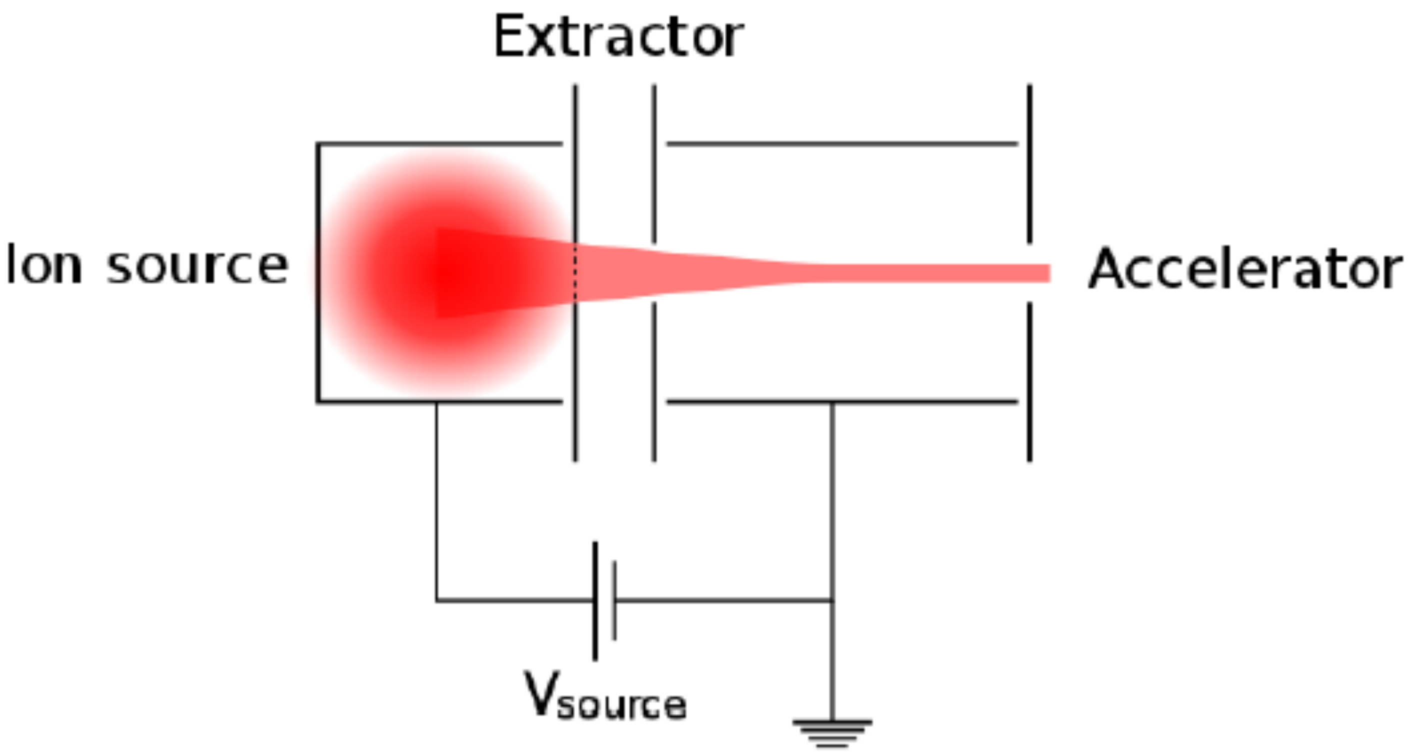
Ion and electron generation

Particles	Generation form
Ions	Surface production Plasma production
Electrons	Photo emission Thermal emission

- Quantum dynamics is necessary to understand and improve the particles production.
- Electrons usually arise from a surface(cathode)

$$\frac{M_p}{M_e} = \frac{937mev}{.511mev} \approx 1836$$

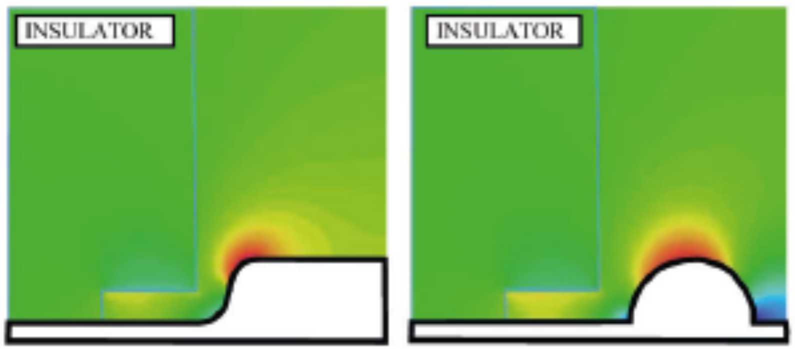
Extraction system



The extractor takes the particles and form a beam

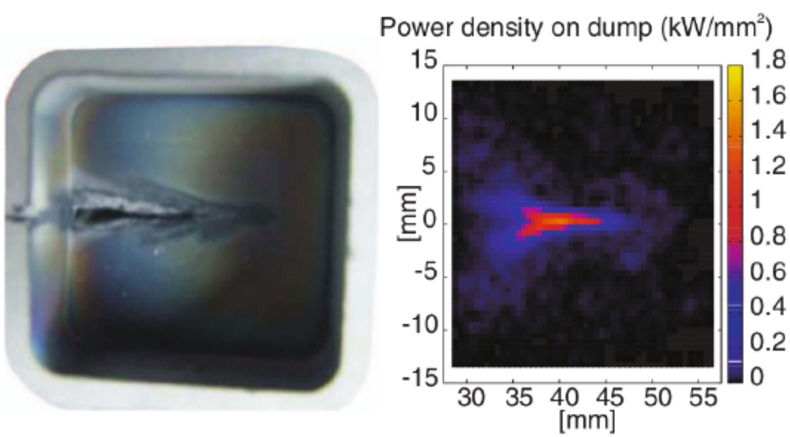
Taneli kalvas picture

Easy ?



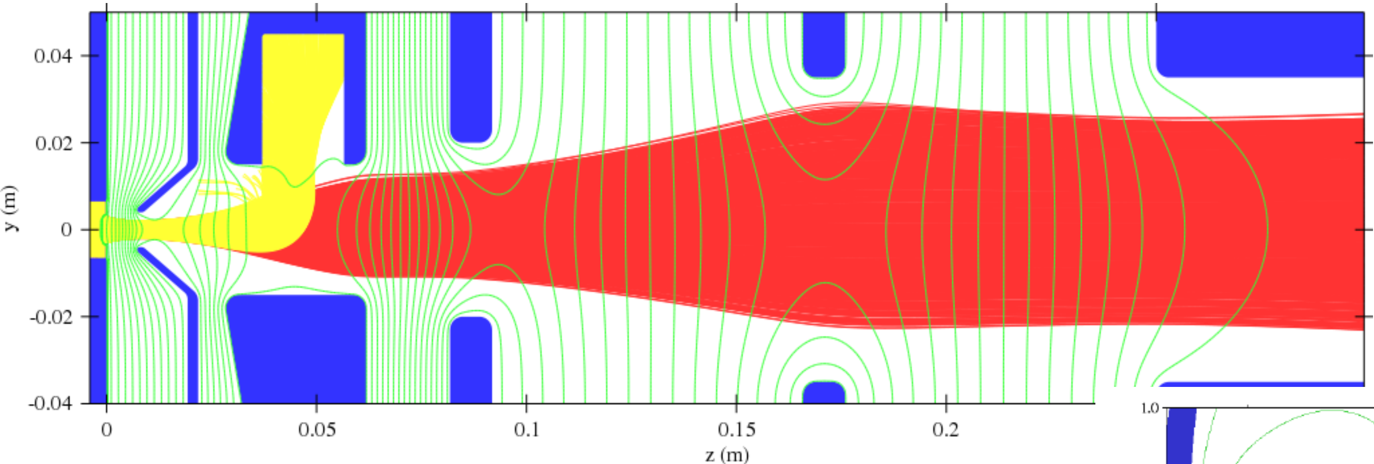
High voltage simulation hot spot

Breakdown by water leak

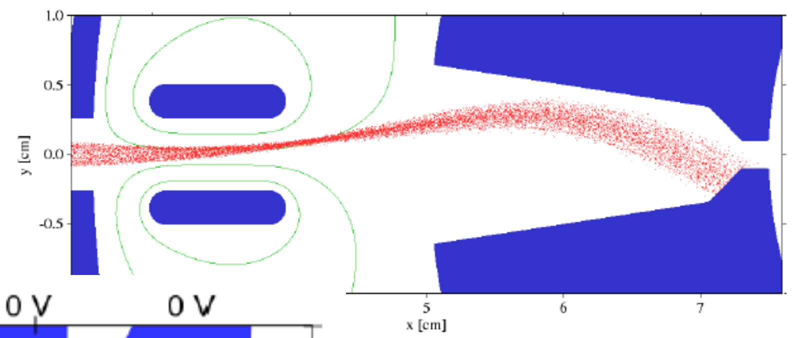


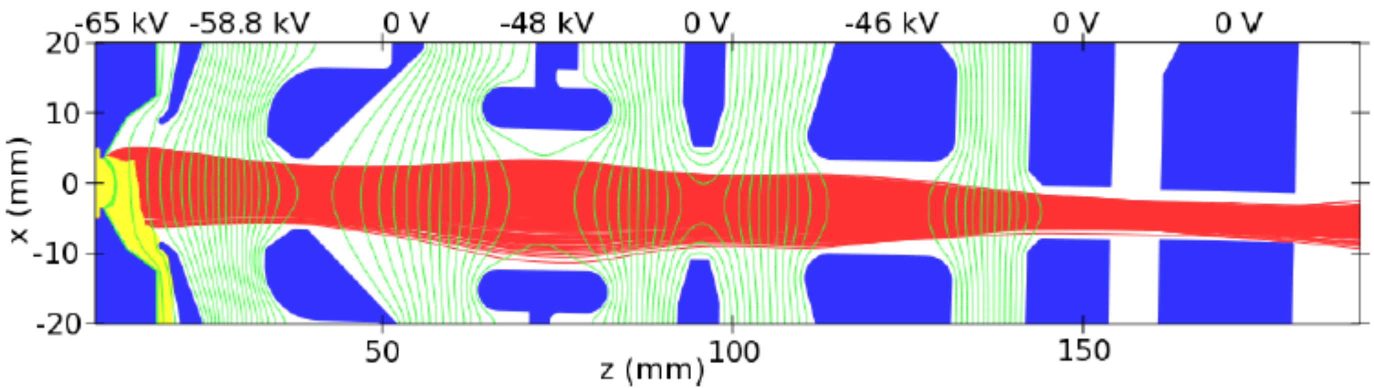
Real and electron dump simulation heat load

Extraction system shape



Negative ion extraction

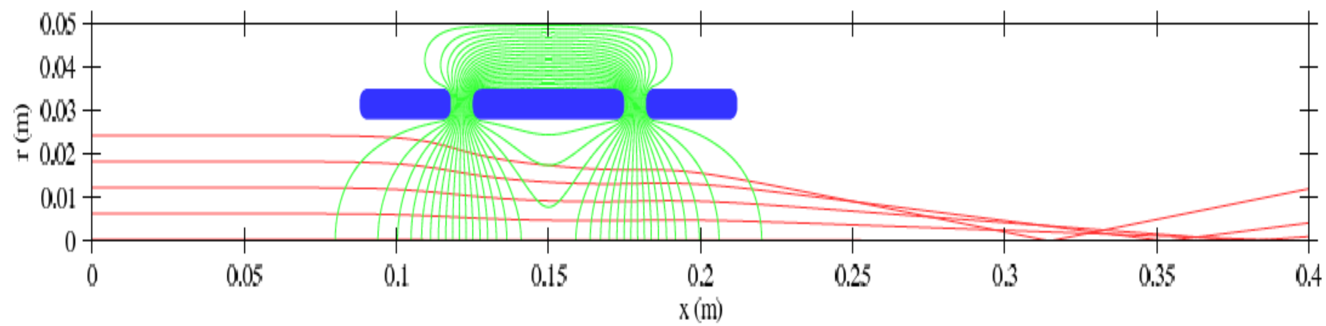


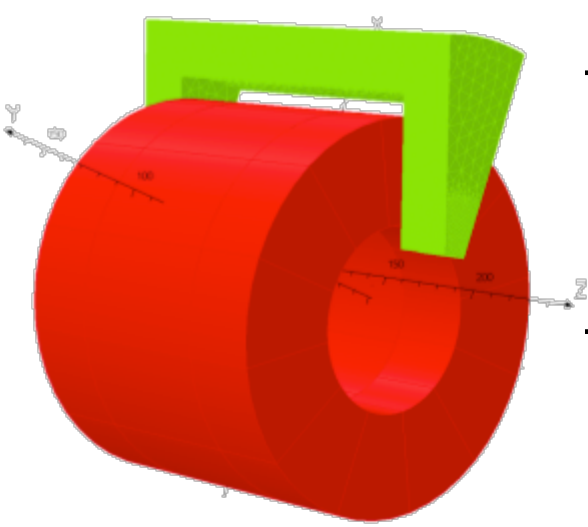


Focusing devices

- Einzel lens
- Solenoids
- E-Dipoles
- E-Quadrupoles

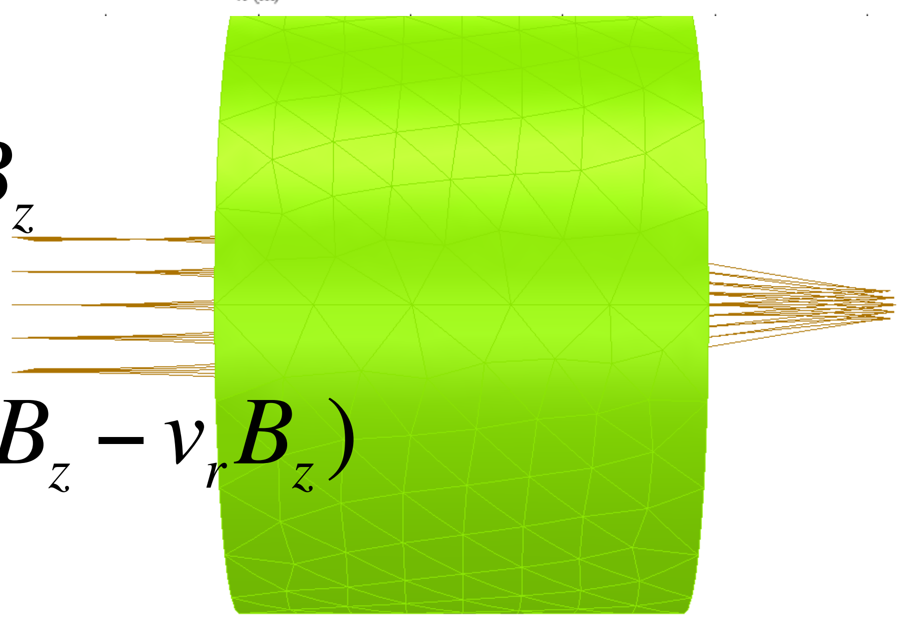
$$\frac{1}{f_{ein}} = \frac{V_{ein} - V_0}{4LV_{ein}V_0}$$



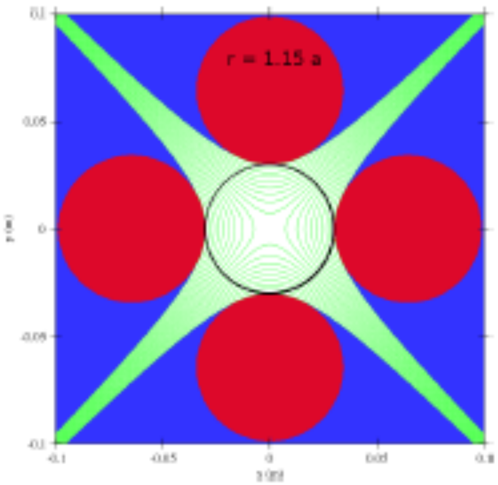


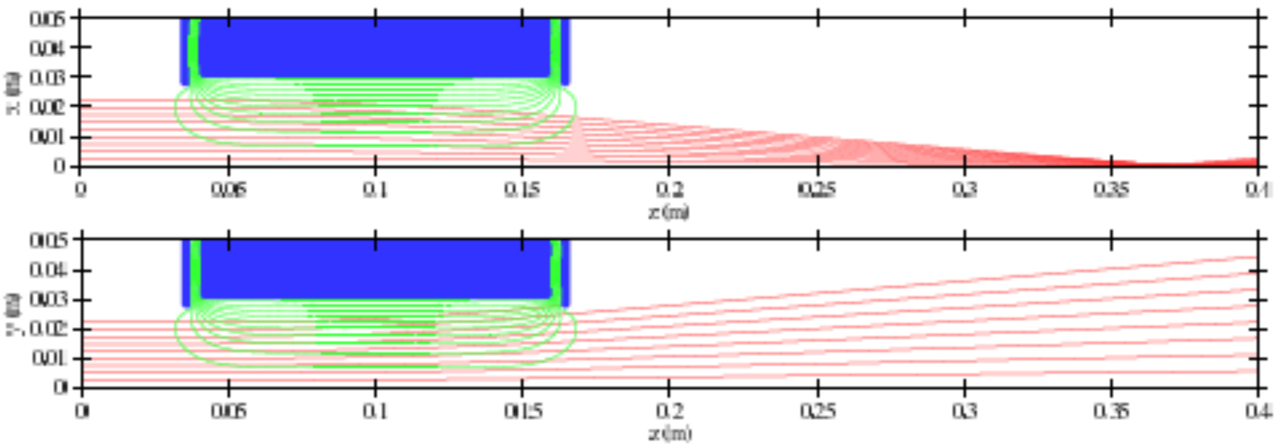
$$\frac{dp_r}{dt} = qv_\phi B_z$$

$$\frac{dp_\phi}{dt} = q(v_z B_z - v_r B_z)$$



Quadrupole electrostatic lens

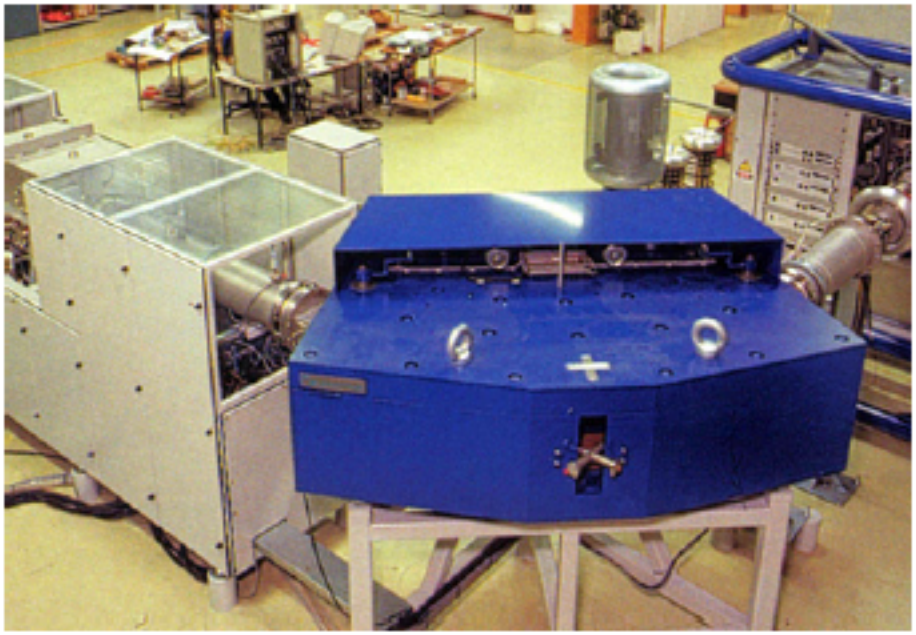


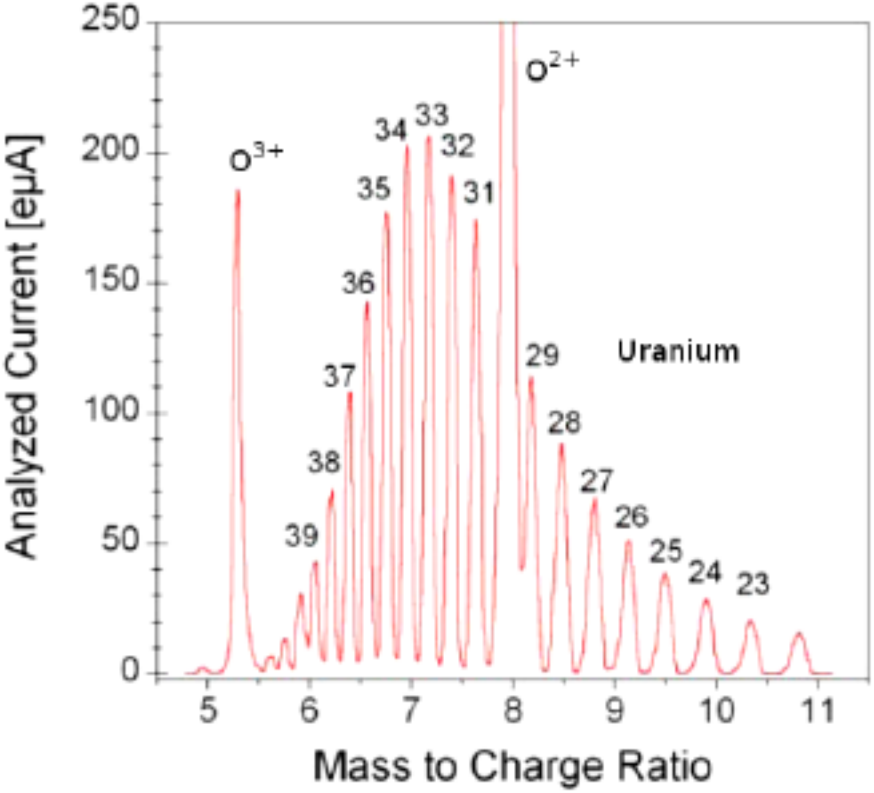


$$1/f_x = k\tan(kw)$$

$$1/f_y = -k\tanh(kw)\text{ ,where } k^2 = \frac{V_{\text{quad}}}{G_0 V_{\text{acc}}}$$

Multi species ion beam



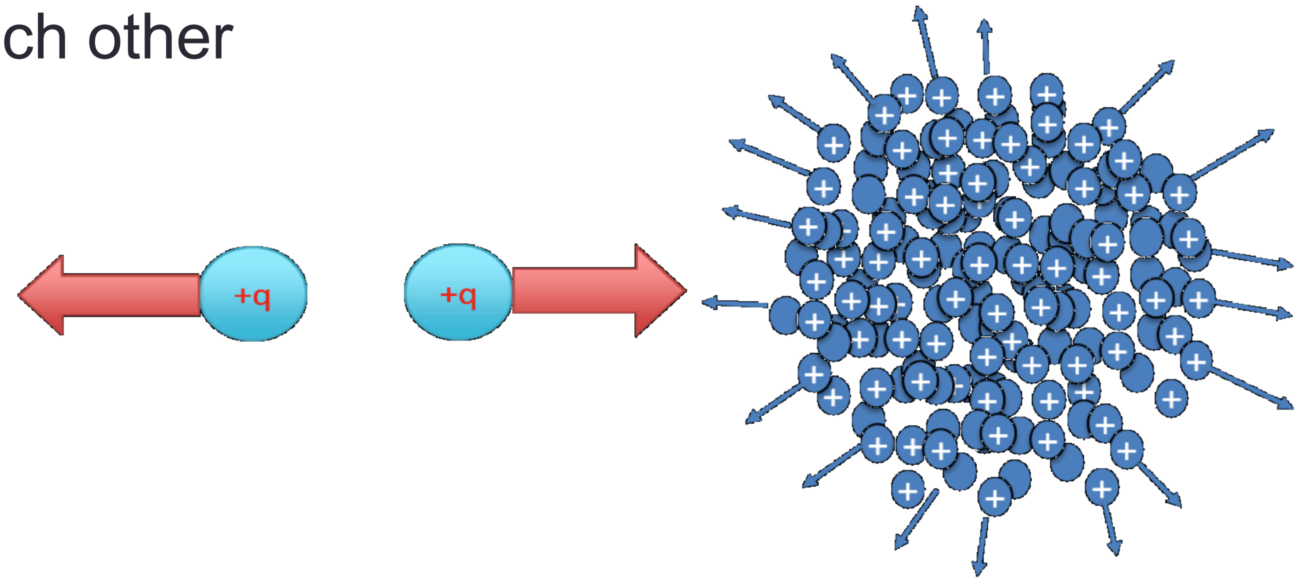


Dipoles can separate the different ion beam particles

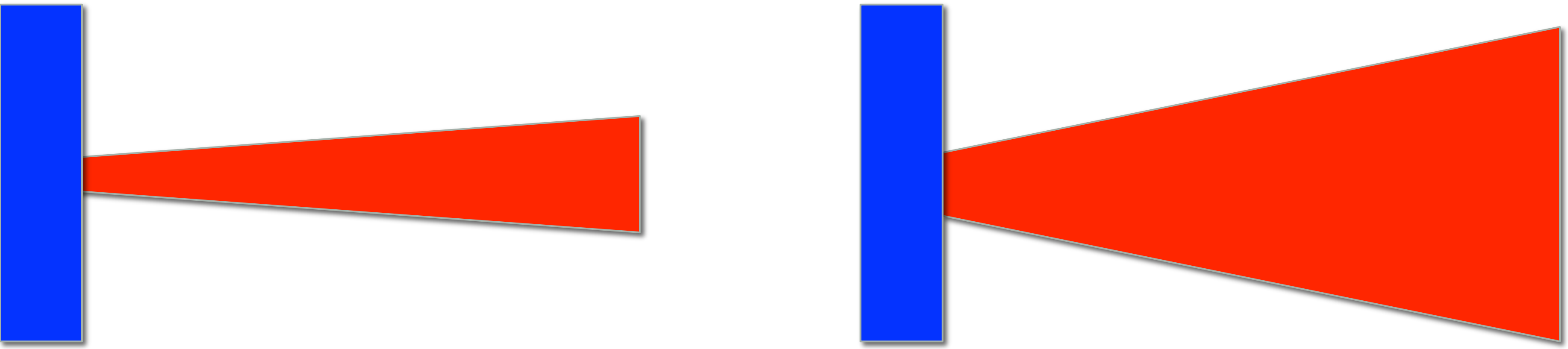
$$r = \frac{mv_z}{qB}$$

Space charge

- When the beam is created same charge particles are forced to be together
- Coulomb´s force separate the same charge particles from each other



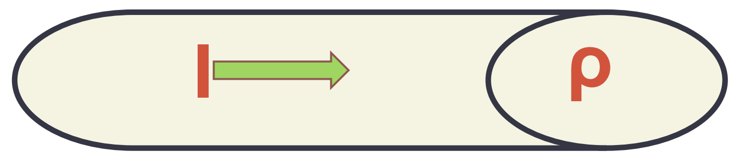
Space charge



The space charge can affect the beam size

Space charge

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



Consider a longitudinally cylindrical beam with constant charge density ρ and current I.

The magnetic field creates an opposite force to the electric field

$$E_r = \frac{\rho r}{2\varepsilon_0} \qquad J = \frac{I}{\pi a^2} \qquad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$B_\theta = \frac{\mu_0 J r}{2} = \frac{\mu_0 I r}{2\pi a^2} = \frac{\beta E_r}{c}$$

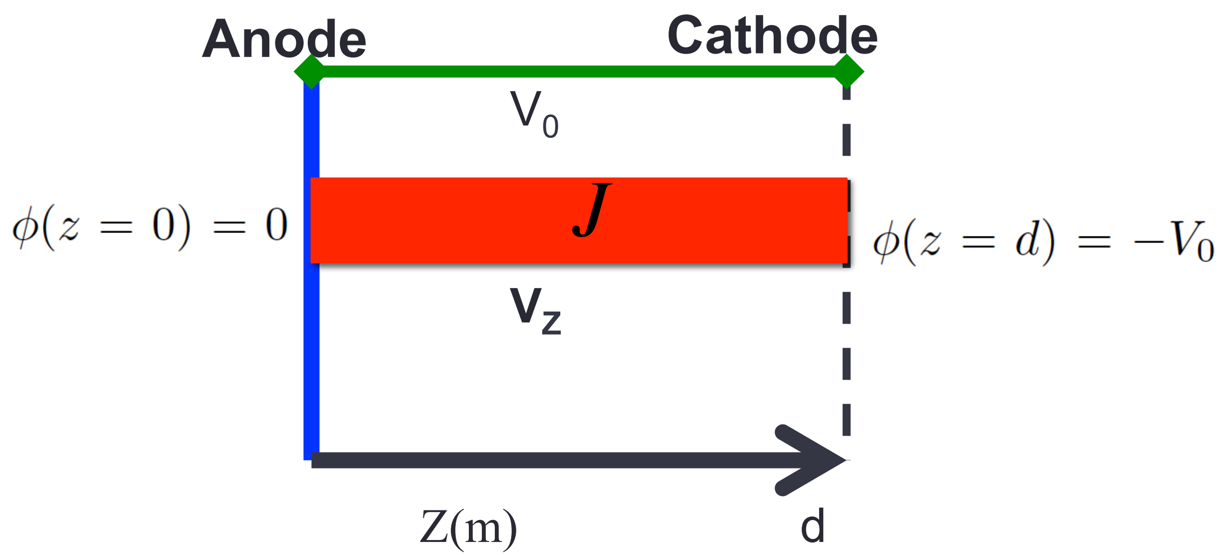
$$F = q(E - \frac{v\beta E}{c})$$

$$= q(E - \beta^2 E) = q\frac{E}{\gamma^2}$$

Energy	γ (protons)	γ (electrons)
45Kev	1.00004	1.088
50 Mev	1.05328	98.084
160 MeV	1.17052	314.112
1 Gev	2.06574	1957.145
1 TeV	1066.7889	1956952.375

The Child–Langmuir law

- There is a limit to the maximum current that can be extracted from a surface applying a voltage



The generated beam has a constant density.

The external applied electric potential is constant in time.

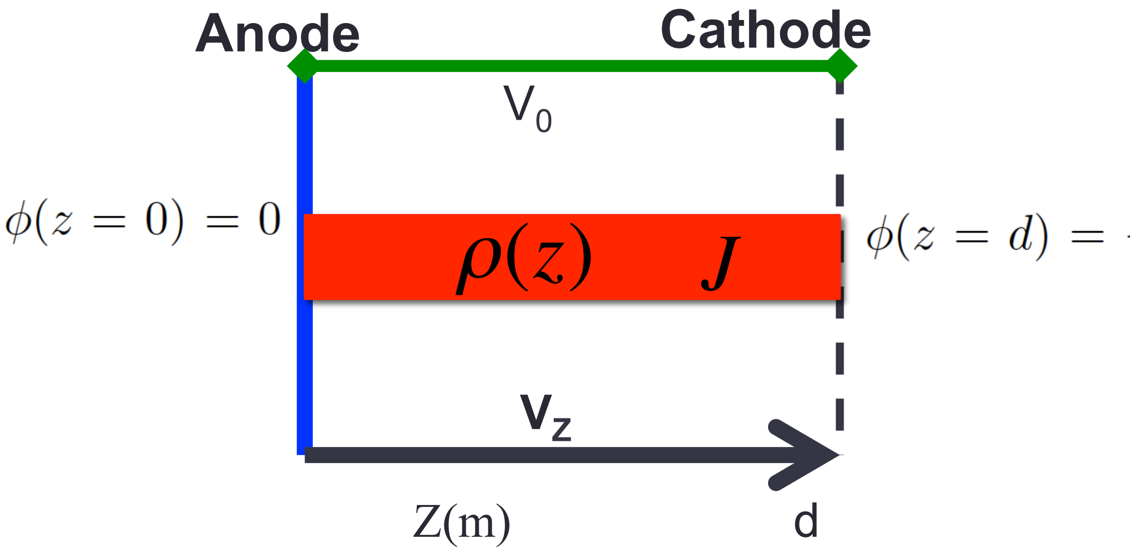
The Child–Langmuir law

The voltage applied set the particle speed

$$v_z = \sqrt{\frac{2q\phi}{m}}$$

We can use the beam current and particle speed to define the beam density

$$\rho(z) = \frac{J_0}{v_z}$$



$$\rho(z) = \frac{J_0}{\sqrt{\frac{2q\phi}{m}}}$$

We assume a beam with constant density

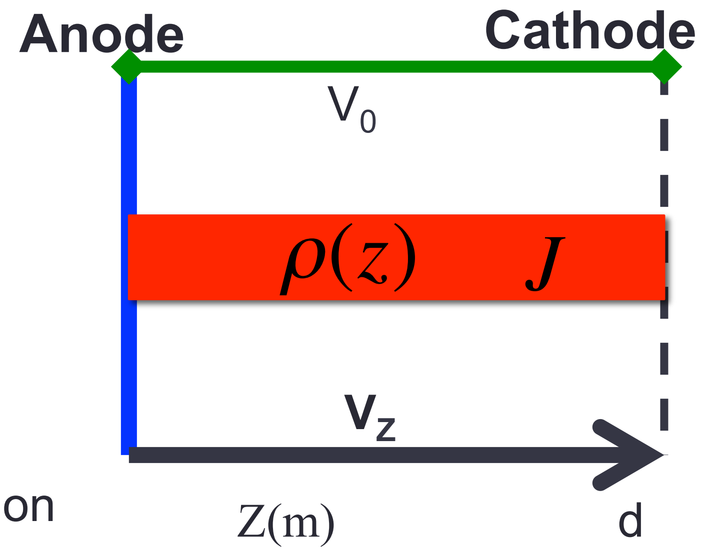
The Child–Langmuir law

The one-dimensional Poisson equation can be written as:

$$\nabla^2\phi = \frac{\partial^2\phi}{\partial z^2} = \frac{\rho(z)}{\epsilon_0}$$

$$\frac{\partial^2\phi(z)}{\partial z^2} = \frac{J_0}{\epsilon_0\sqrt{\frac{2q\phi}{m}}}$$

$$\frac{\partial^2\phi(z)}{\partial z^2} = \frac{\kappa}{\sqrt{\phi}}$$



To simplify the notation

$$\kappa = J_0/\epsilon_0\sqrt{\frac{2q}{m}}$$

Is possible a direct integration simply by multiplying by $d\phi/dz$

$$\frac{\partial\phi(z)}{\partial z}^2 = 4\kappa\sqrt{\phi} + C$$

The Child–Langmuir law

Using the condition $d\phi(0)/dz = 0$.

We solve the equation and the result is

$$\phi(z) = \left(\frac{3}{2}\right)^{4/3} \left(\frac{J_0}{\epsilon_0}\right)^{2/3} \left(\frac{m}{2q}\right)^{1/3} z^{4/3} + C_2$$

And using the boundary conditions C_2=0 the resulting equation is

$$\phi(z = 0) = 0$$

Now re arranging the terms to obtain the current

$$J = \left(\frac{4}{9}\right) \epsilon_0 \left(\frac{2q}{m}\right)^{1/2} \frac{V_0^{3/2}}{d^2}$$

The Child–Langmuir law

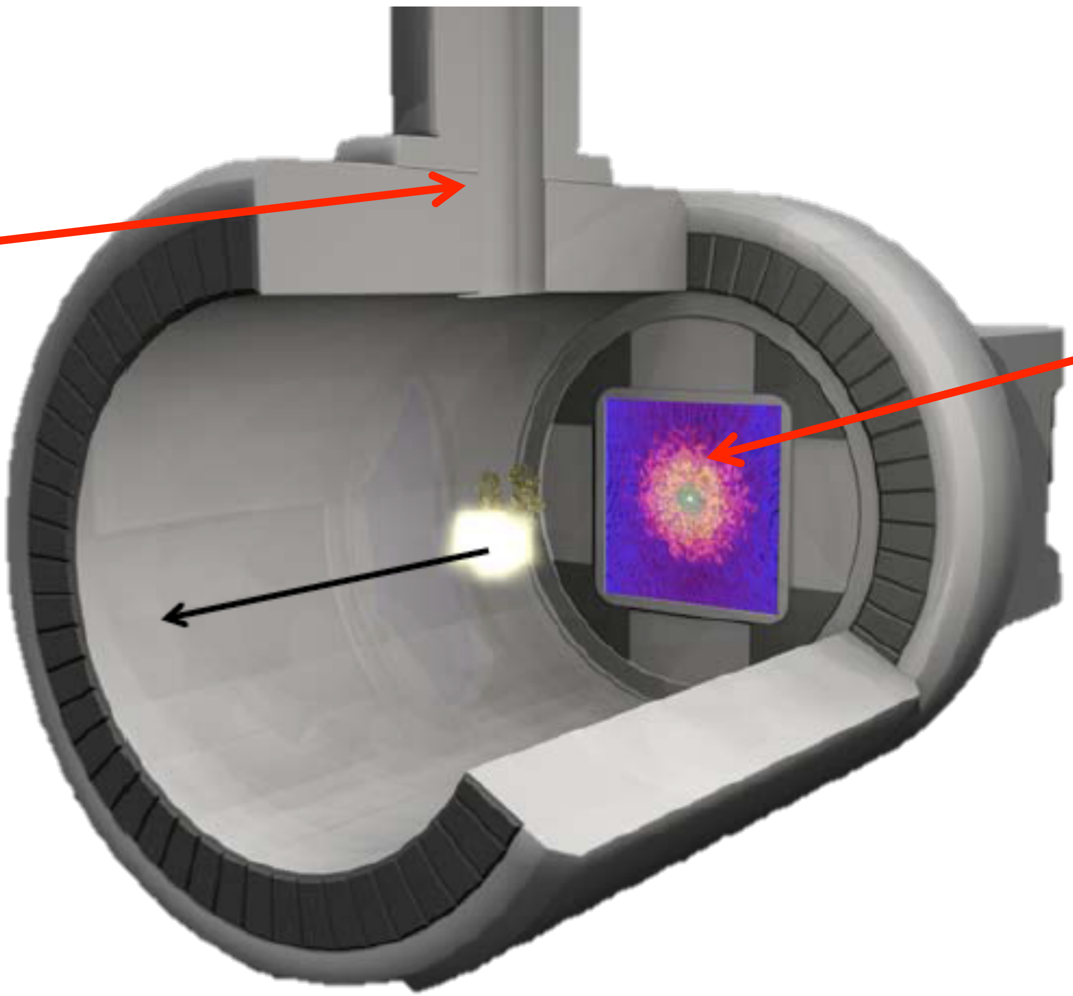
$$J = \left(\frac{4}{9}\right)\epsilon_0\left(\frac{2q}{m}\right)^{1/2}\frac{V_0^{3/2}}{d^2}$$

This equation sets the maximum current that can be extracted from the cathode by a determined anode voltage and is called the "Child-Langmuir law".

What happened if after create the beam we decrease the beam energy below this limit ?

Electron gun

Input power to create the accelerating voltage



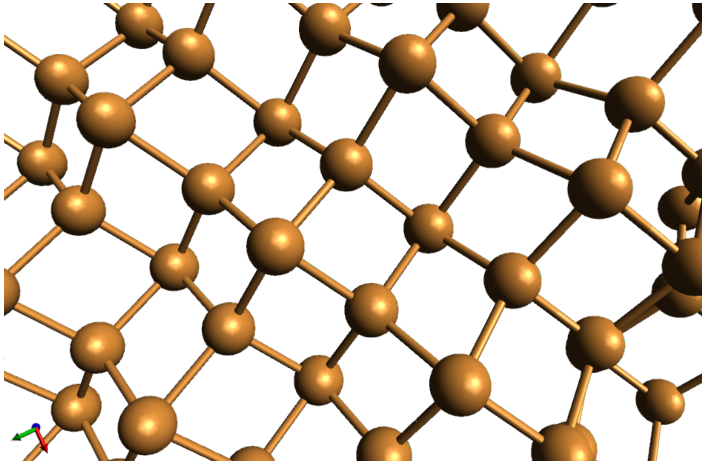
Surface where the electrons are extracted

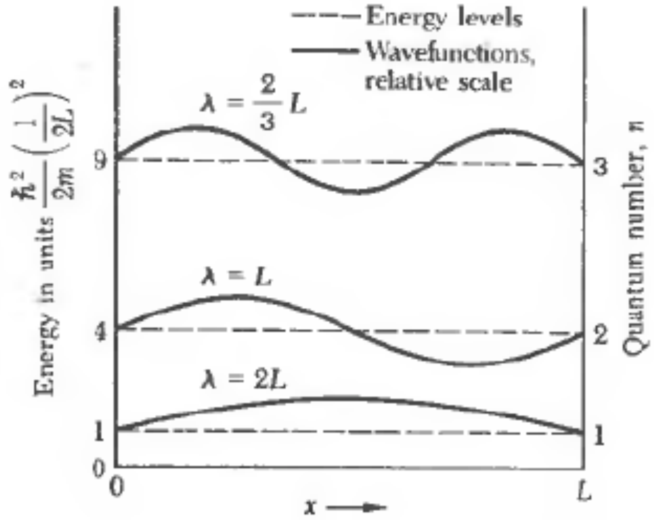
Free electron Fermi gas

- The valence electrons of the material atoms become conductivity electrons and move freely in all the material
- The topmost energy of the atoms is defined by ε_f

$$\varepsilon_f = \frac{h^2}{2m}\left(\frac{3\pi^2 N}{V}\right)^{2/3}$$

Solid state research is necessary here



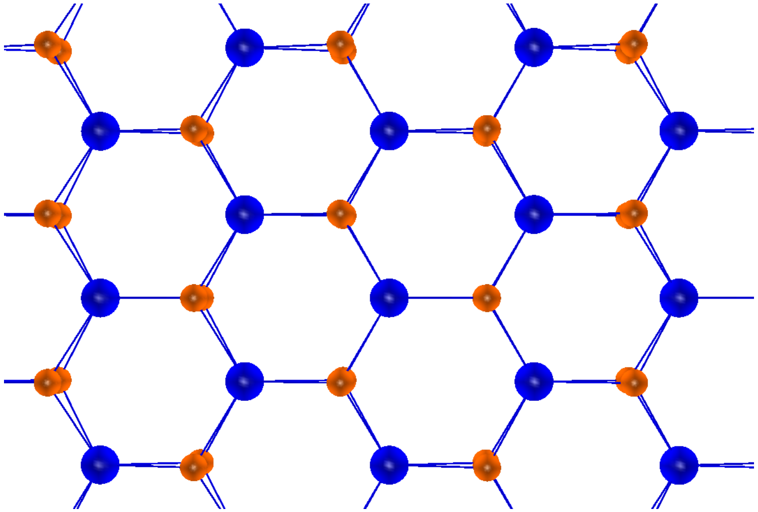


Work function

- The minimum energy needed to remove an electron from a solid

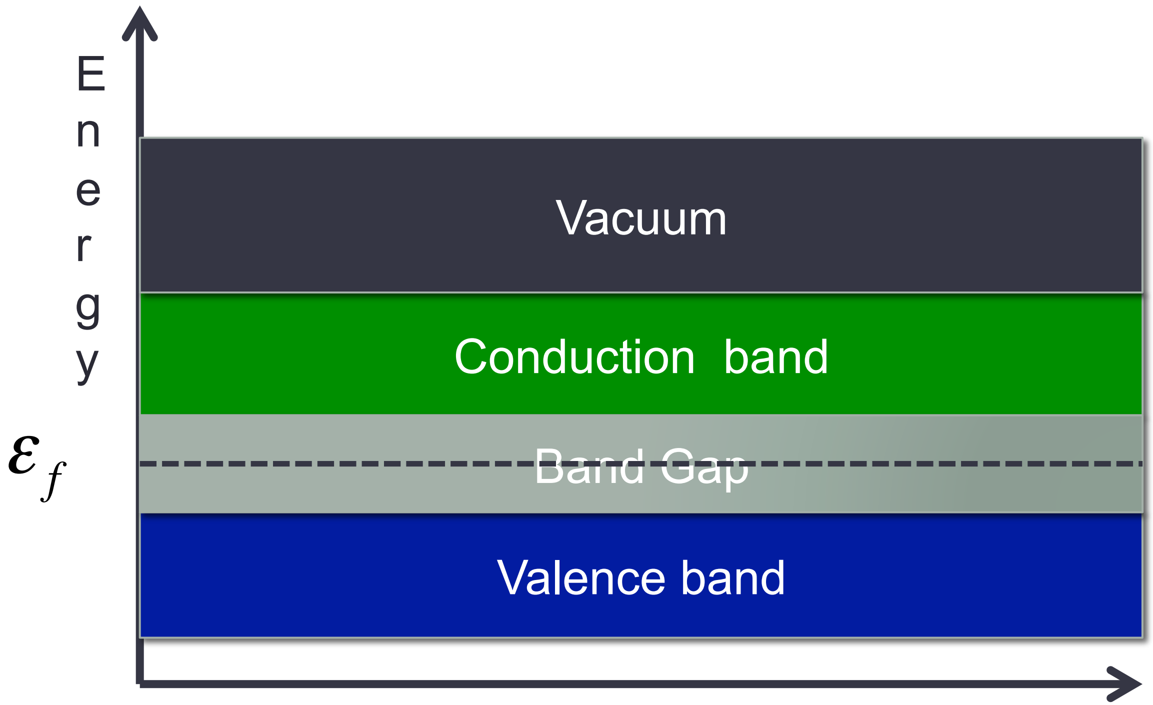
- There are several ways to remove the electrons form the surfaces (thermal emission, photo emission, etc)

$$w = q\phi - E_f$$



Band Gap

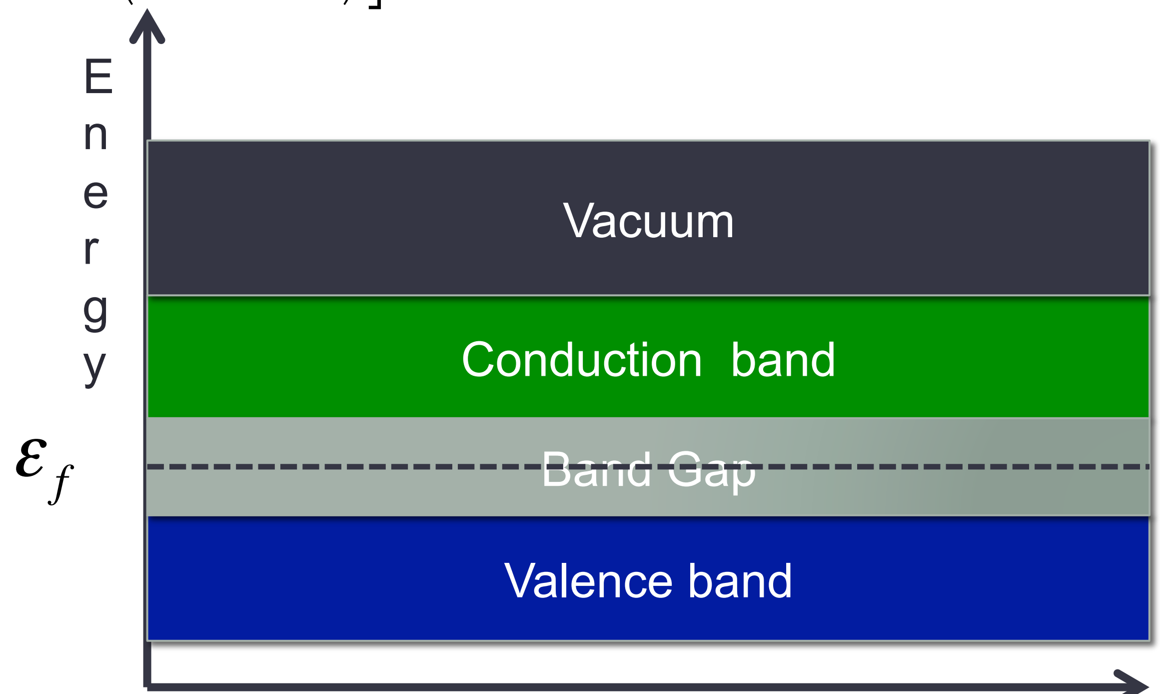
- The electrons are in the valence band they need to over come the band gap to pass to the conduction band
- Insulator has a bigger band gap than semiconductors



Thermionic Emission

- The material Is heated to increase the electron energy above the work function

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



Thermionic Emission

- 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.

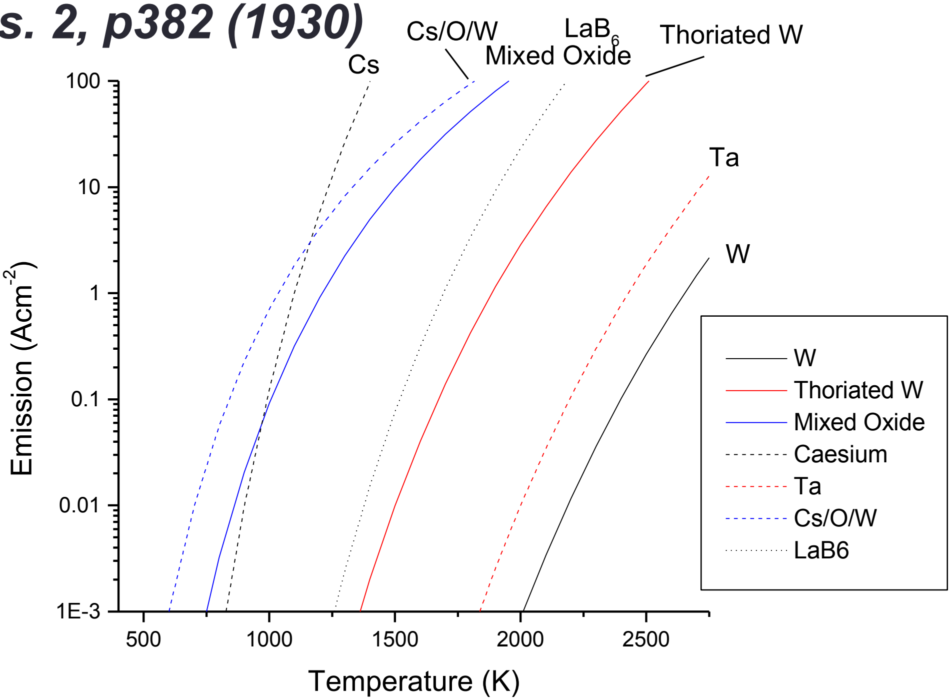
$$J = nve$$

Richardson-Dushmann equation
Rev. Mod. Phys. 2, p382 (1930)

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

Richardson constant
Impossible to achieve

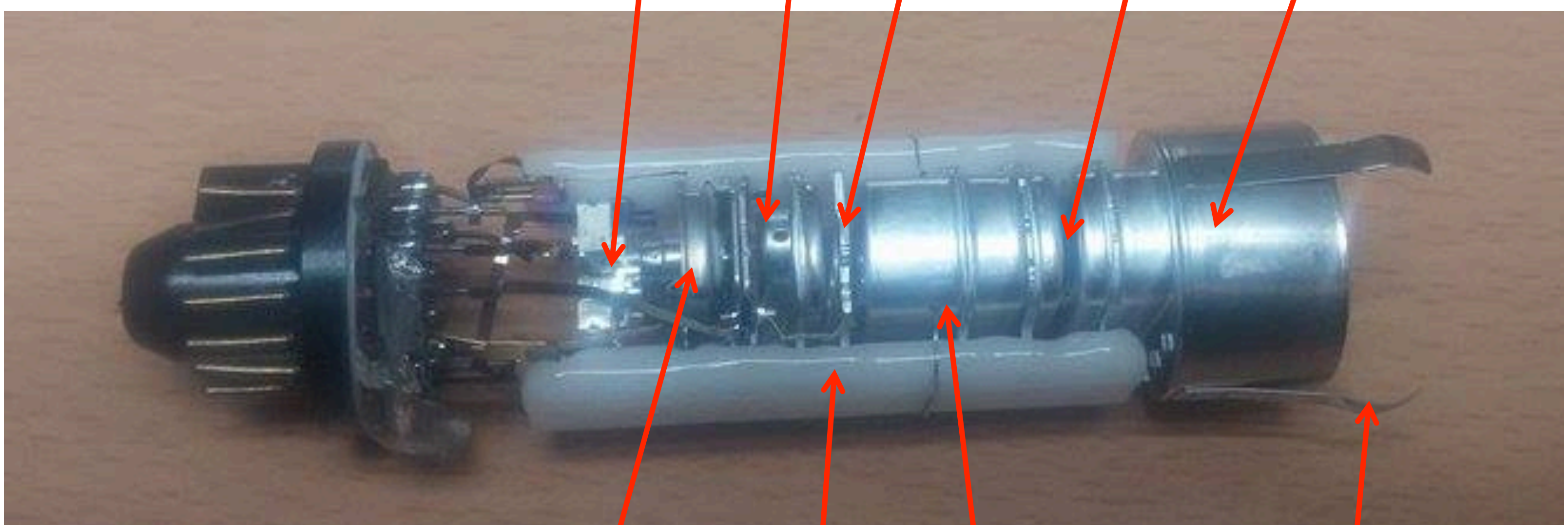
$$A = \frac{4\pi e m_e k^2}{h^3} \approx 1.2\times10^6\,\mathrm{Am^{-2}}K^{-2}$$



Richard scrivens, CERN CAS 2015 picture

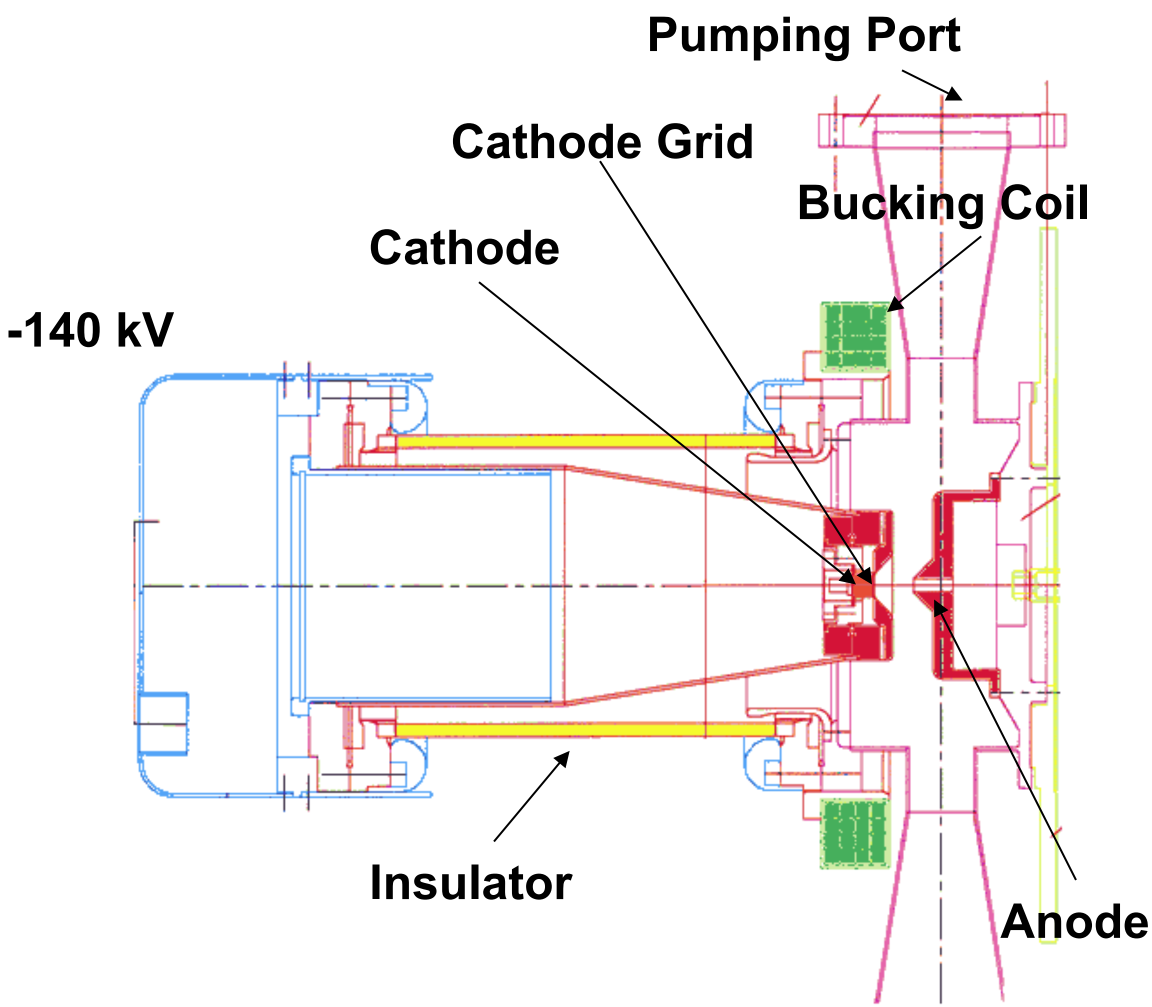
Famous Ion sources

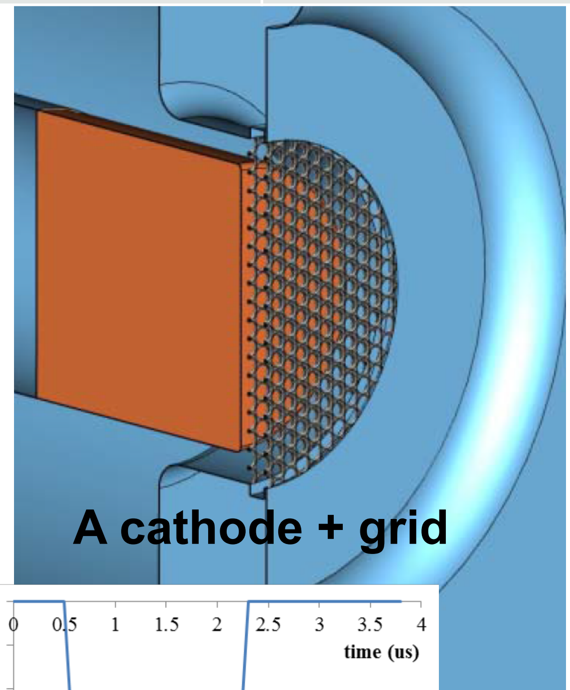
- This source was behind every TV before the fancy plasma TV

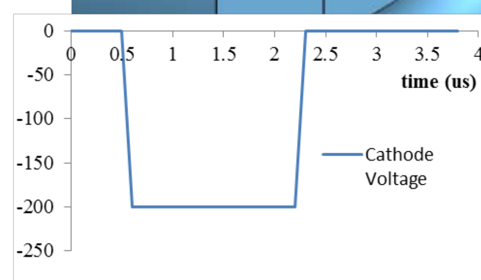


CERN CTF3 Thermionic Gun

Electron Current	5 A
Electron Energy	140 keV
Emittance	15-20 mm.mrad
Pulse	1.4us @ 5 Hz

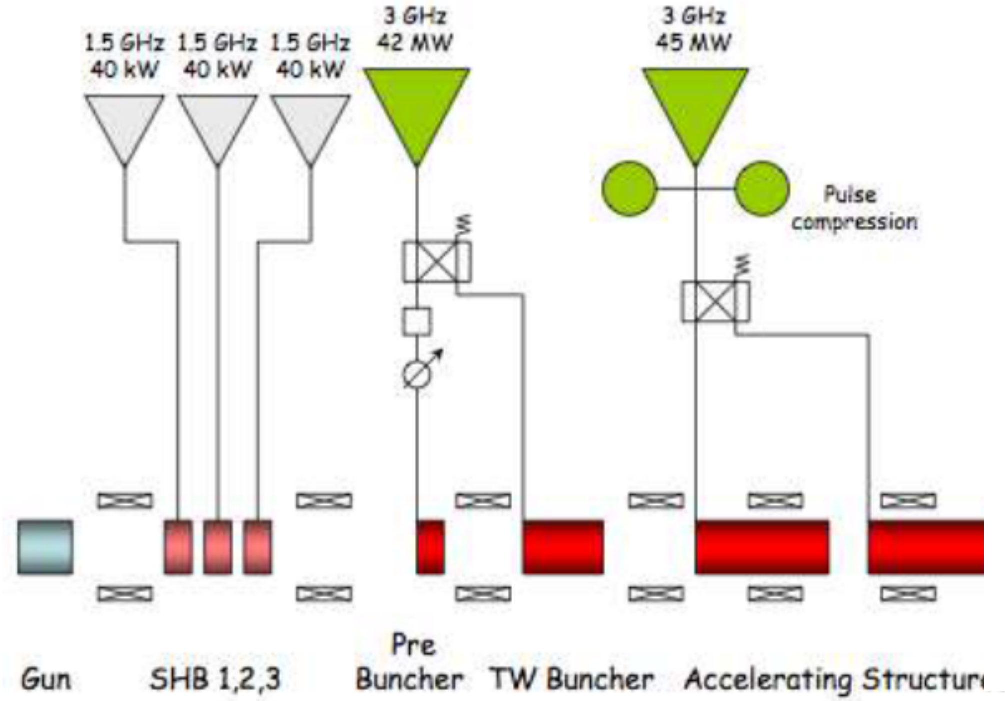


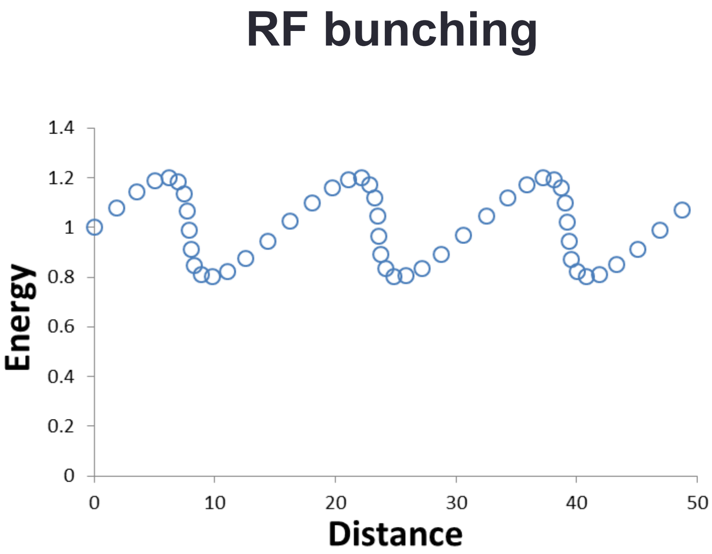




Disclaimer: These are not actual CTF3 systems

CTF3 Thermionic Gun – bunching the beam





- The thermionic gun produces a pulse.
- RF cavities are then used to produce bunches.
- It is not a very clean bunch structure, lots of satellite bunches.

Photo emission

- We can use photons to increase the electrons energy above the vacuum level
- Quantum efficiency

$$QE = \frac{N_{electrons}}{N_{photons}}$$

GaAsCs=17% ,
CsTe =12.4%
K2CsSb=29%
Cu~0.01%

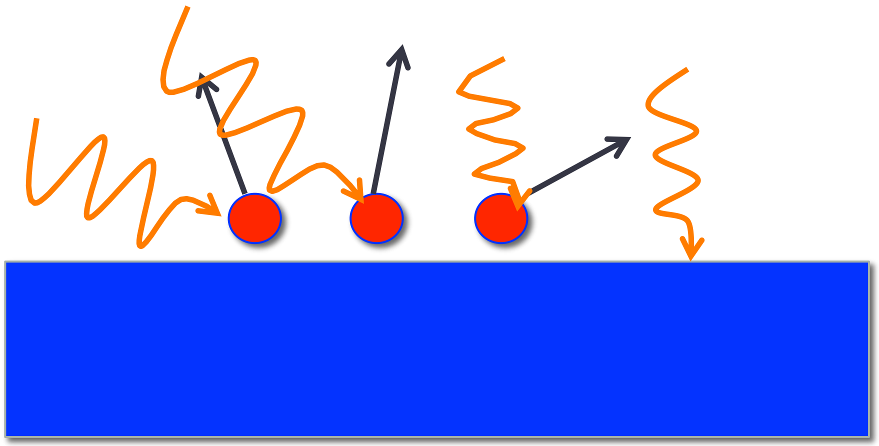
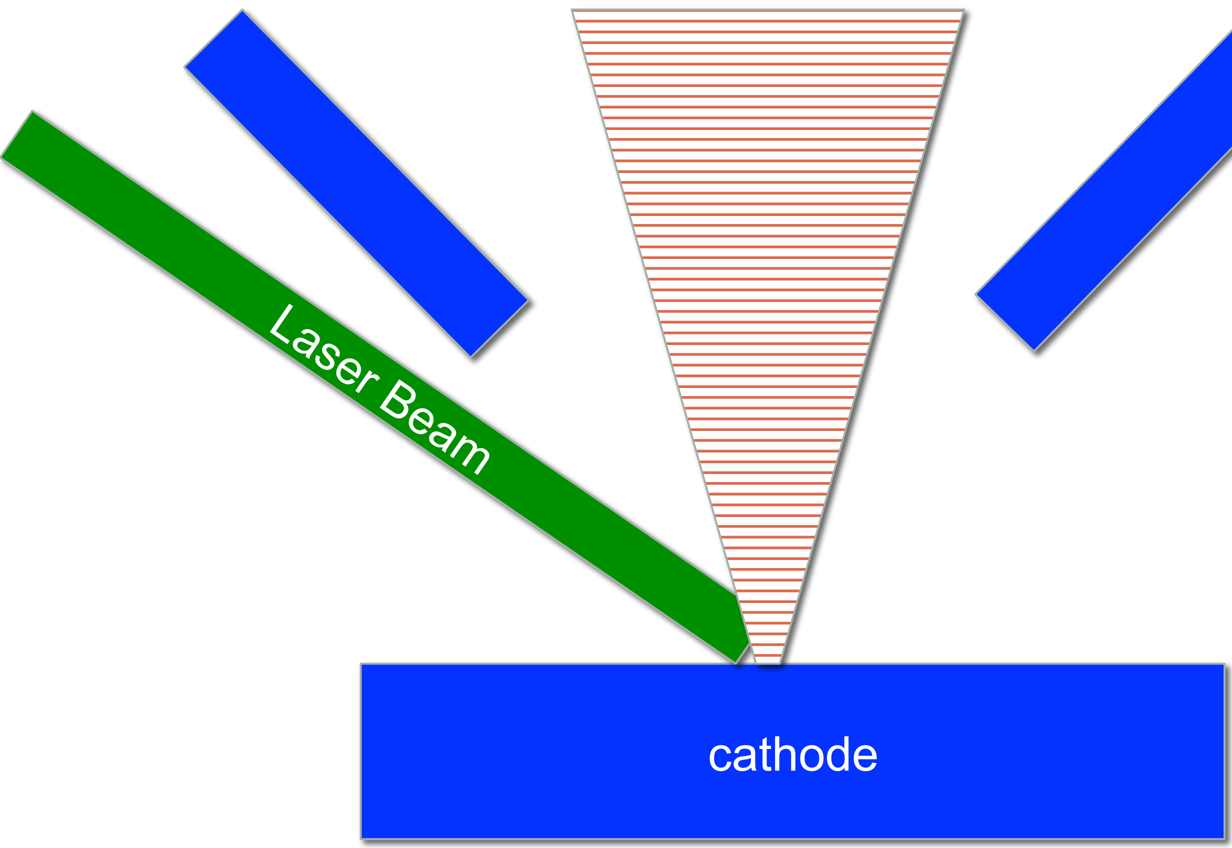


Photo emission



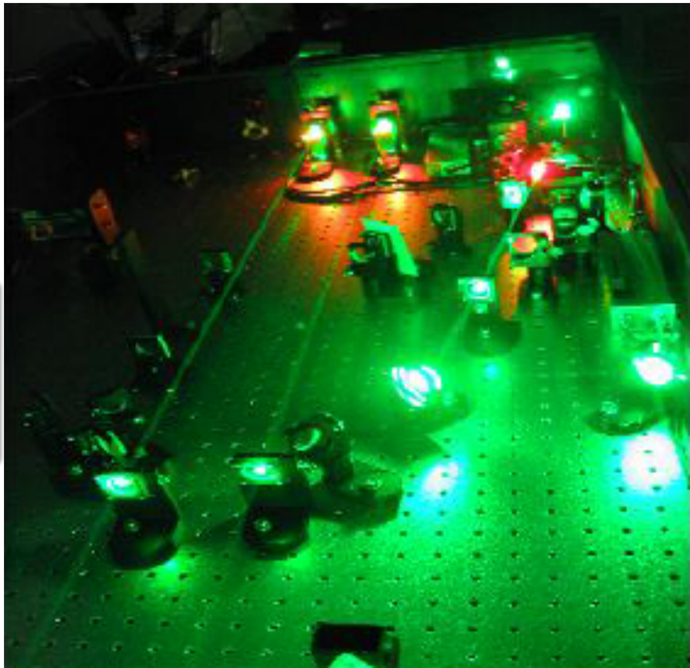
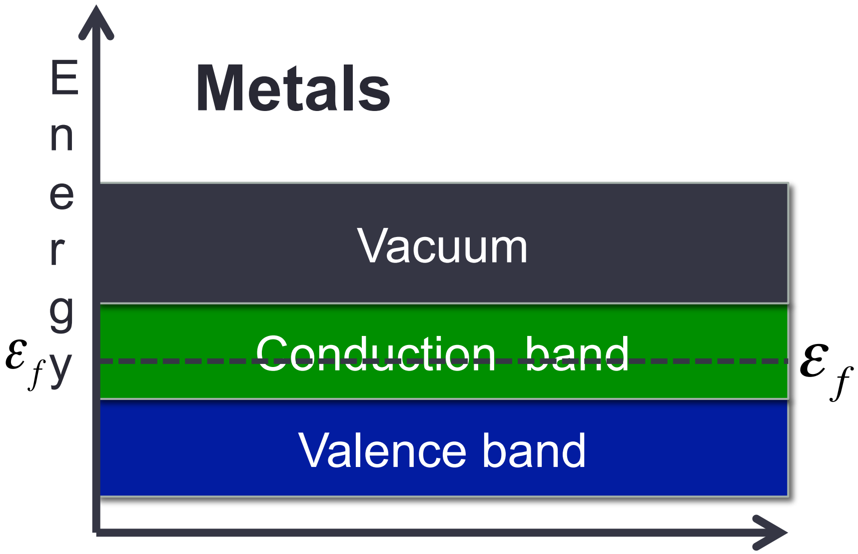
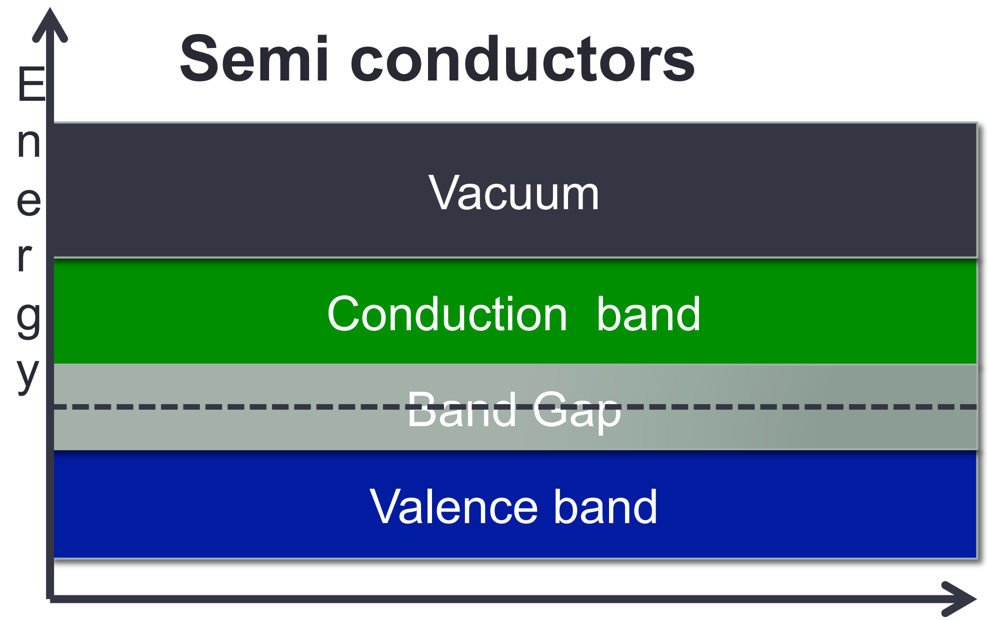


Photo emission





$$\lambda_c = \frac{hc}{ew} = \frac{1239.8}{w}$$

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

$$\lambda_c = \frac{hc}{e(E_{GAP} + E_{cb})} = \frac{1239.8}{E_{GAP} + E_{cb}}$$

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

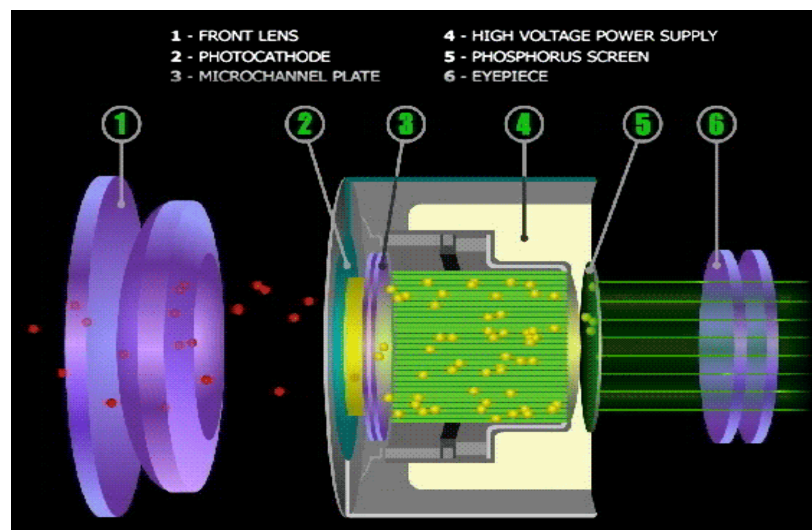
Photo emission

- Semiconductors
  - Is possible to find materials with optical wavelengths with high Q.E
  - GaAs.Cs has high QE at 532nm
  - They need constant treatments
- METALS
  - The quantum efficiency is low
  - Very reliable in operation

Particle source introduction

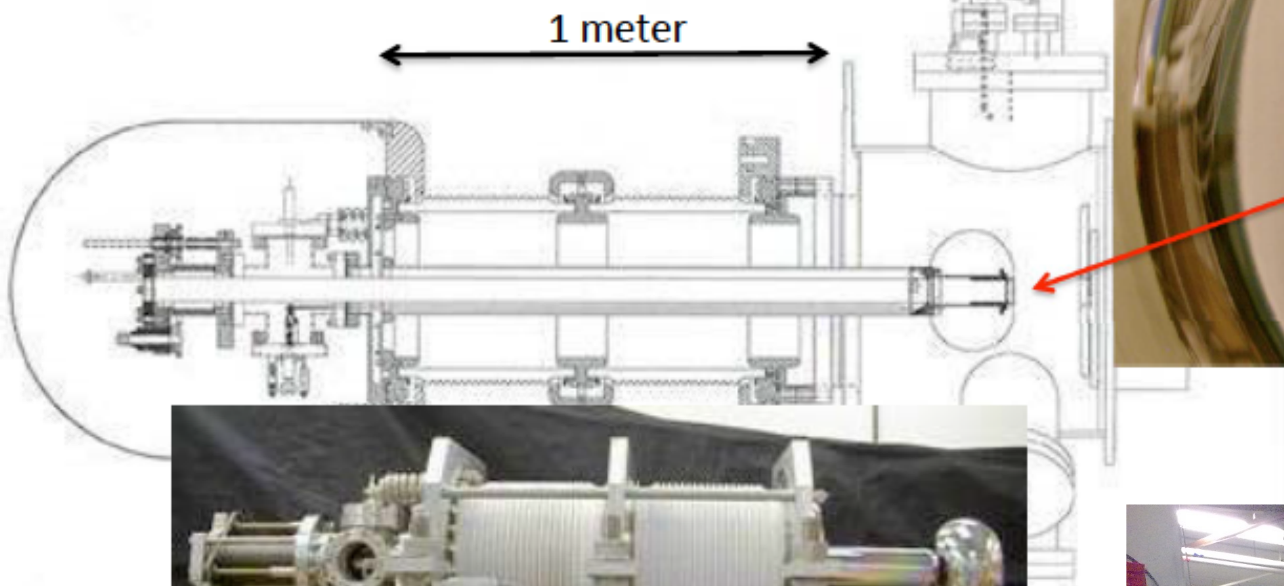
The particles need to be generated and introduced in to the accelerator chain

The ion sources are present in many device and strange places..
The imagination is the limit to the shape of the ion sources

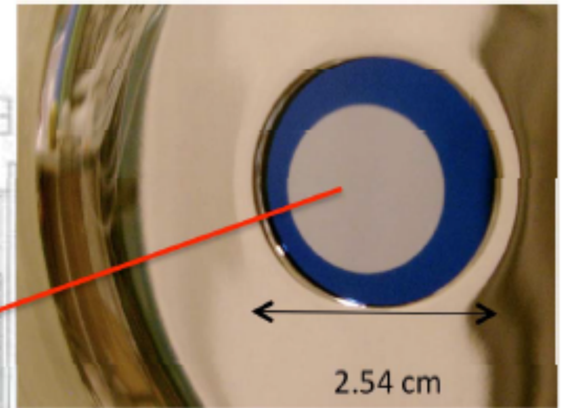


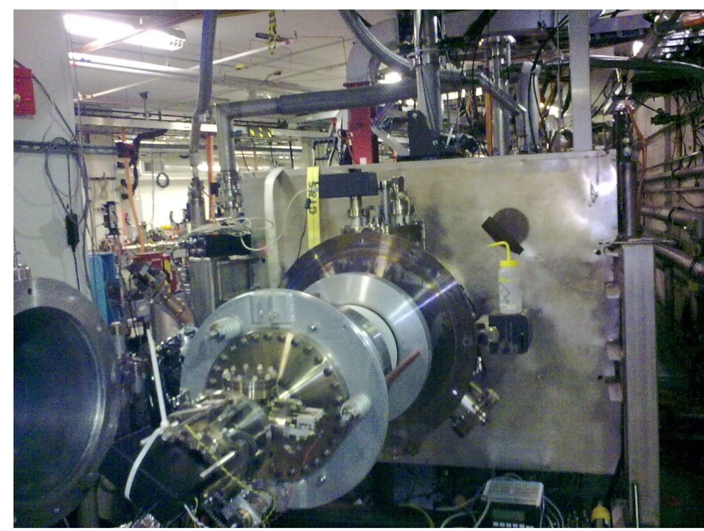
- **Are those heavy? Then they're expensive, put them back...**
- **- Jurassic Park**
- If you do not understand the reference, you are too young !!

- This is the Jlab FEL DC photoemission gun

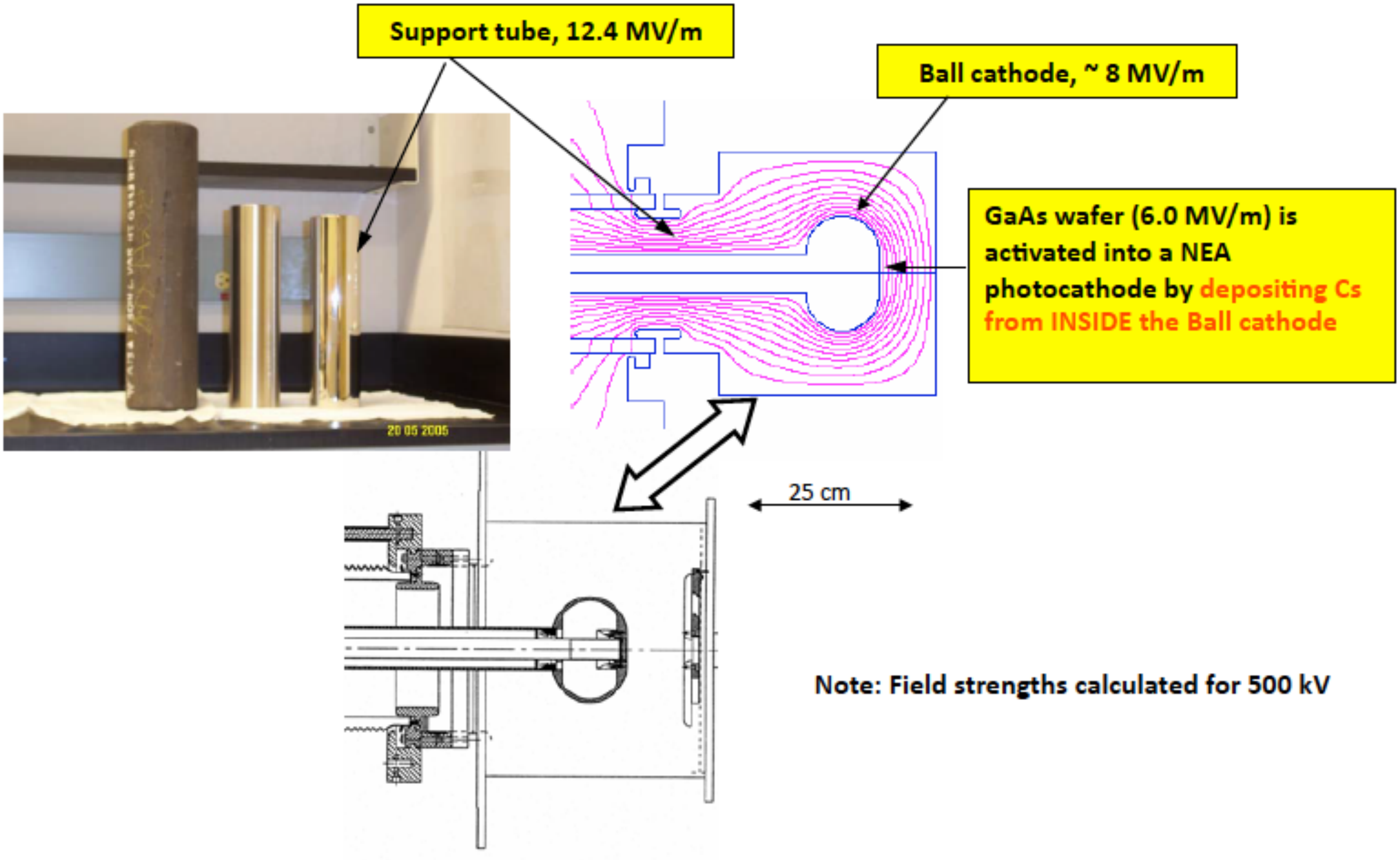


Anodized GaAs photocathode





Carlos hernandez, JLAB slide

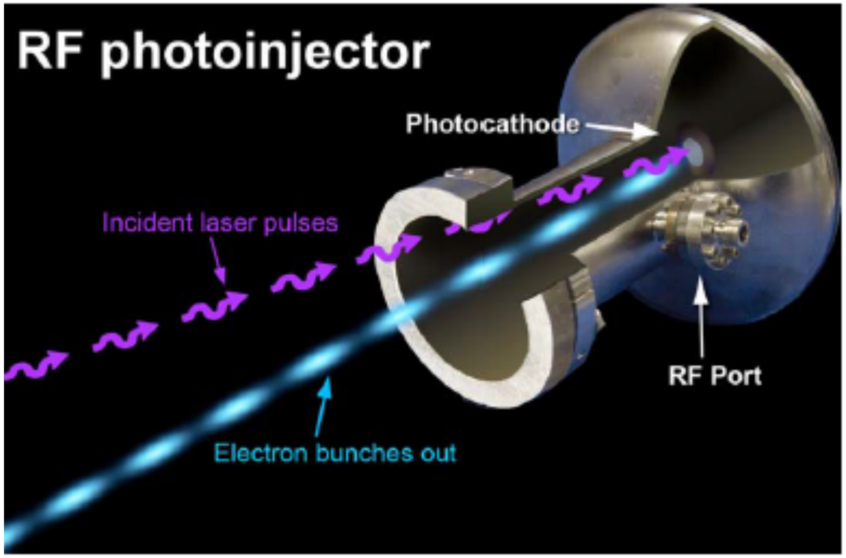


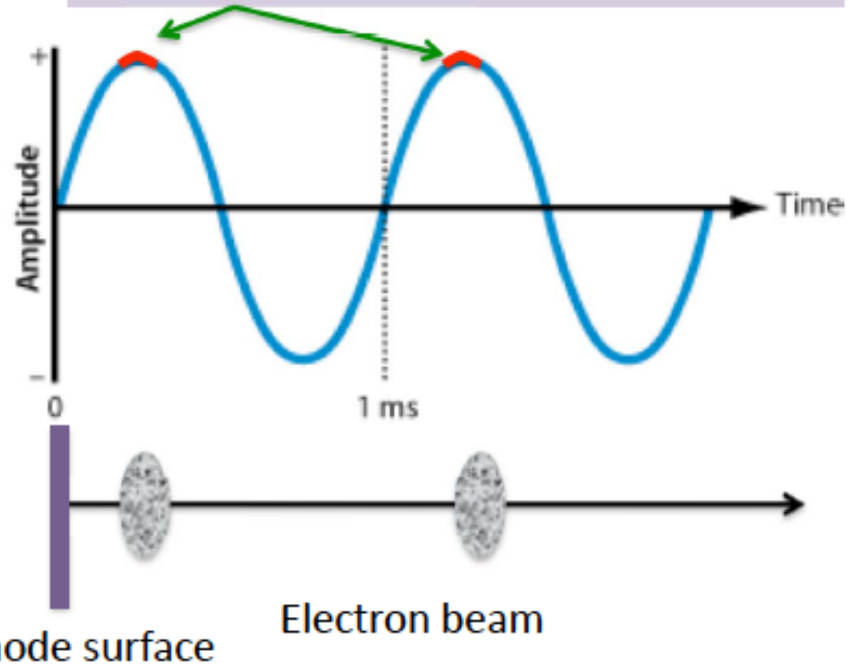
Carlos hernandez, JLAB slide

– If the photocathode is biased with an oscillating field, the device is called a radio frequency photo injector.

Photons are the energy source to excite the electrons above the photocathode vacuum level.

Laser pulses are fired in sync with the RF waveform to generate ps long electron bucnhes

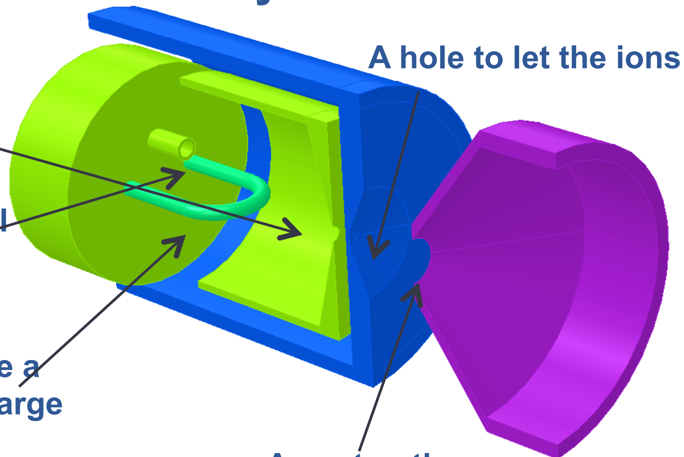




Carlos hernandez, JLAB slide

Ion Source

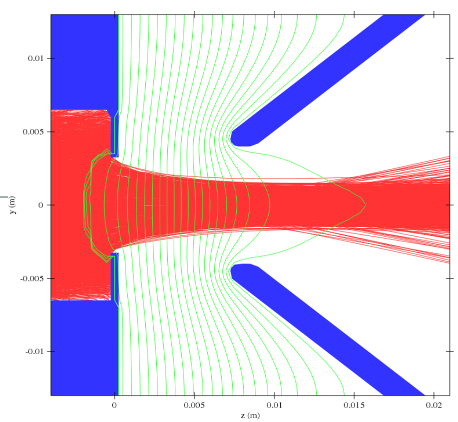
The beam is formed by the particles in the plasma taken by the extractor



Plasma extraction potential (meniscus)

Ground

Extracto



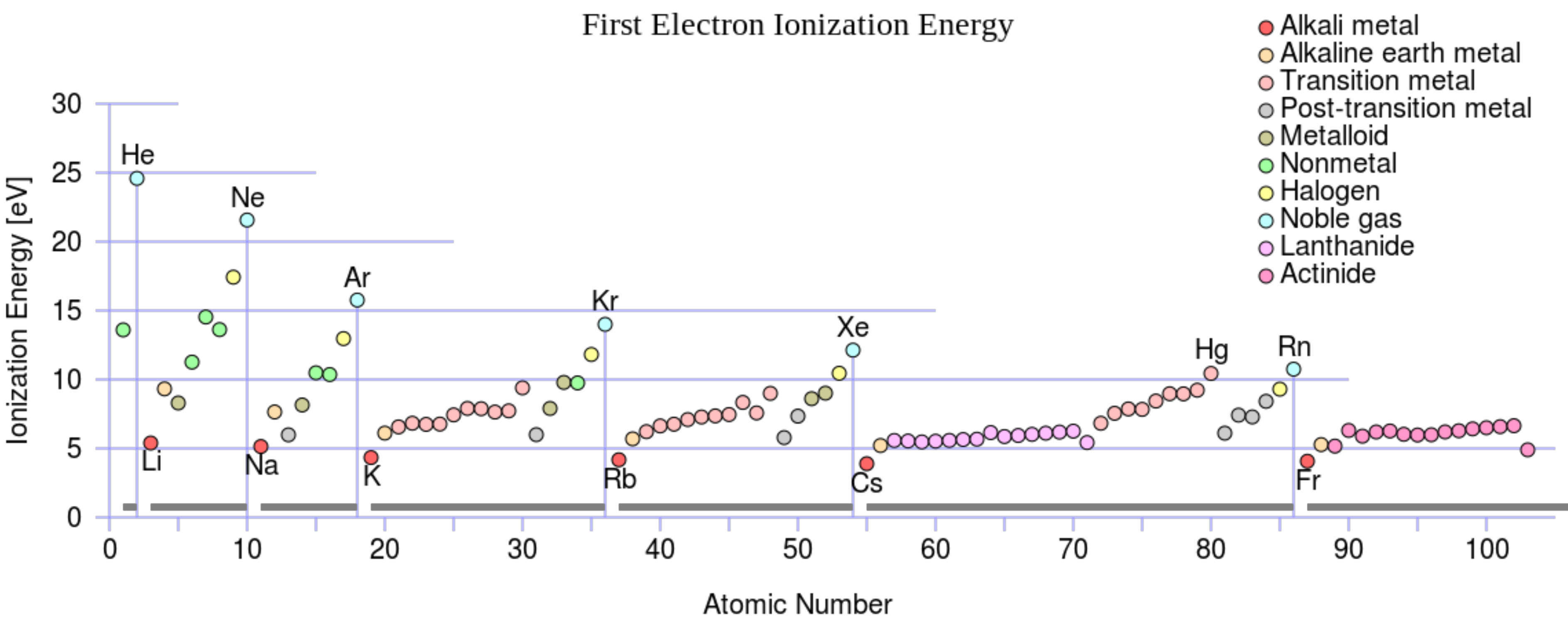
$$E = q(V_{source} - V_{ground})$$

Potential lines(green)
Electrodes (blue)

Ions (Red)

Ionization work function

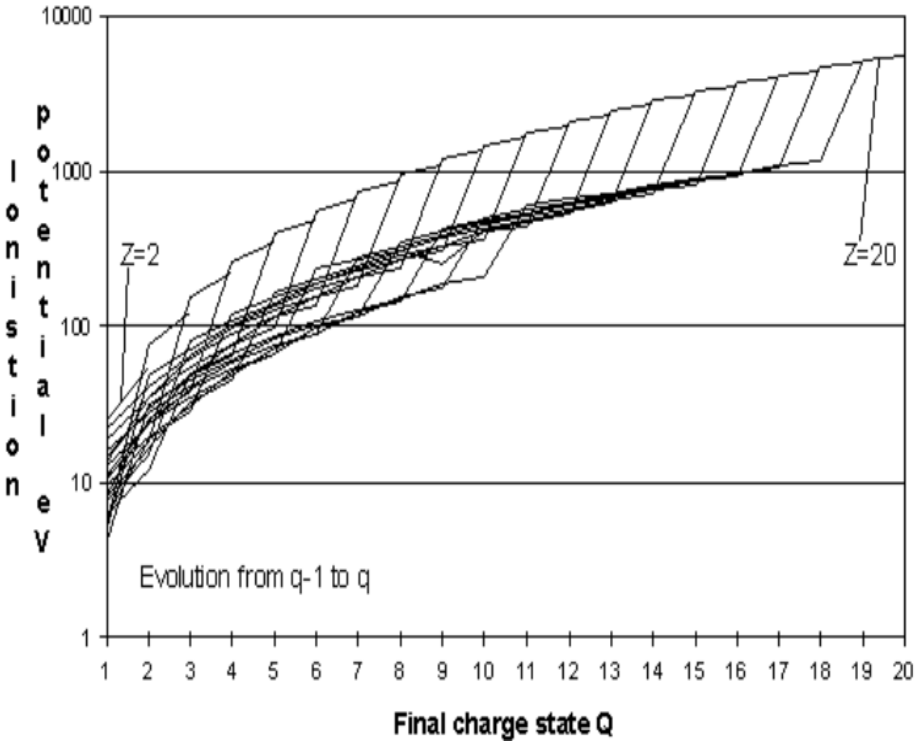
- How hard is to remove a electron from the atom?
- The minimum required energy to separate the electron from the free atom is called ionization energy



High Charge states

$$^{A}p_{n}^{q+}$$

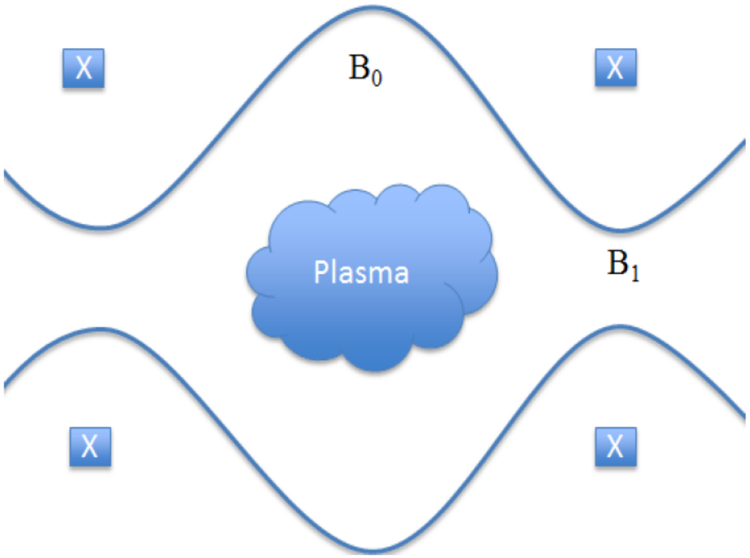
Chrage state	Ionization Energy (ev)
Oxygen 5+ to 6+	138.1
Oxygen 0+ to 6+	433.1
Lead 26+ to 27+	874
Lead 0+ to 27+	9200
Lead 81+ to 82+	91400



Ion Sources - Basics

- Plasma Processes
  - Electron heating
  - Plasma confinement (electric and magnetic)
  - Collisions (e-e, e-ions, ions-e, ions-iions + residual gas)
  - Atomic processes (ionization, excitation, disassociation, recombination)
  - Surface physics (coatings + desorption, 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.

Plasma confinement



$$\mu = \frac{1}{2}\frac{mv_0^2}{B_0} = \frac{1}{2}\frac{mv_1^2}{B_1}$$

$$\sin(\theta) = \frac{v_{o\perp}}{v_o}$$

This define the minimum angle of the particle to be reflected, particles with smaller angles will not be reflected, this can be seen like an imperfection of the magnetic confinement but in practice is a tool to select the particles

$$\theta = \sin^{-1}\left(\frac{B_0}{B_1}\right)$$

Plasma parameters

$$n_x = \frac{\text{Total of positive particles}}{\text{Volume}}$$ =particle density

Quasi neutrality

$$n_i = n_e$$

For multiple ion charge

$$n_i = \sum Q_z n_z$$

Ionization degree

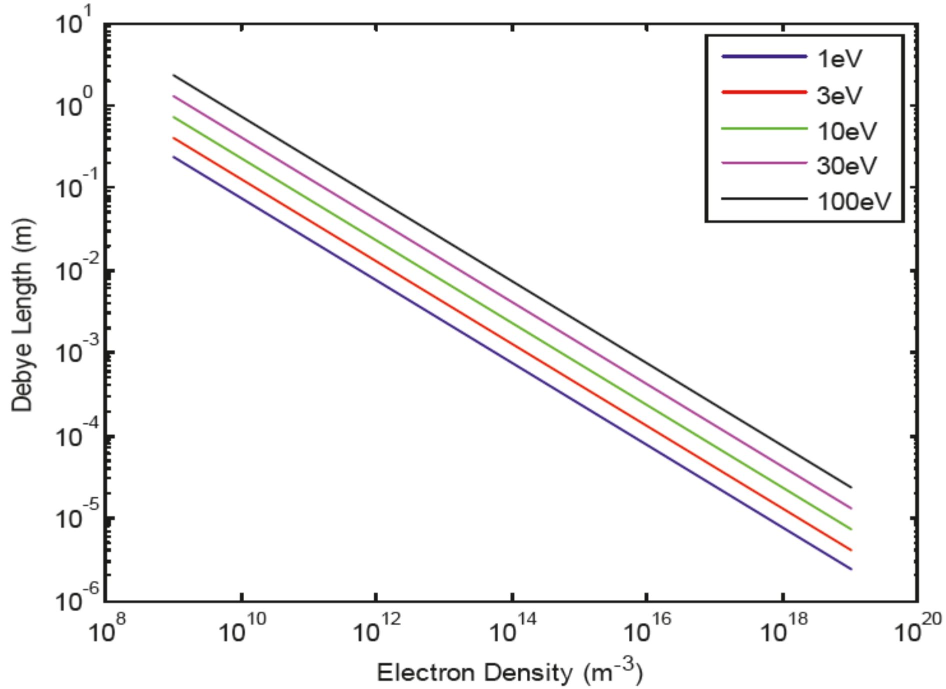
$$\eta_i = \frac{\sum Q_z n_z}{\sum Q_z n_z + n_n}$$

Debye length

$$\lambda = \frac{1}{n\sigma_i(E)}$$

Debye length

- How long it takes to a particle to interact with each other



$$\lambda = \frac{1}{n\sigma_i(E)}$$

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

In plasma we can define another Debye length

$$\Lambda = \sqrt{\frac{\varepsilon_l k_b T_e}{ne^2}}$$

Is necessary to improve the collisions between particles

Ionization degree

- **Before create the plasma gas is neutral**

Quasi neutrality

$$n_i = n_e$$

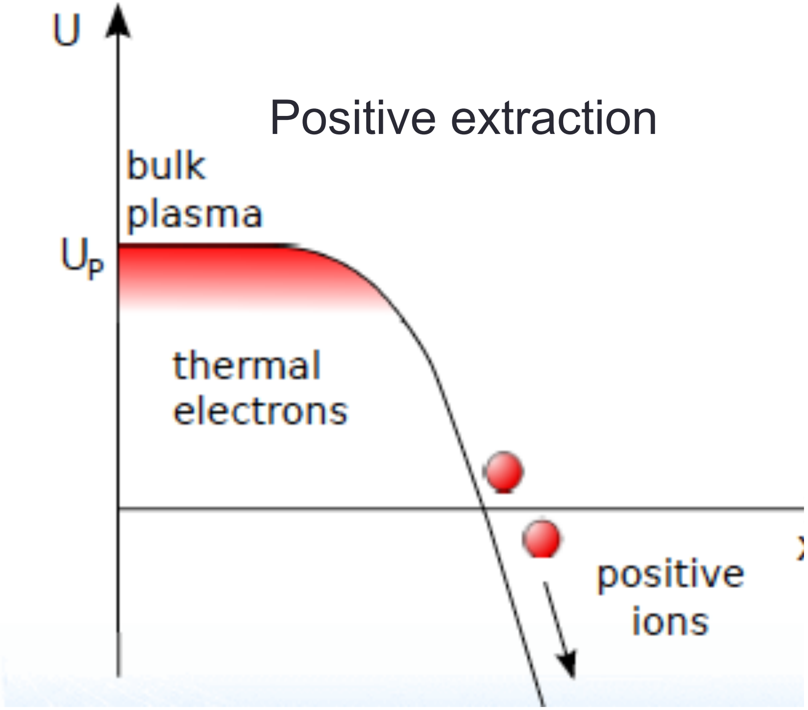
$$\eta_i = \frac{\sum Q_z n_z}{\sum Q_z n_z + n_n}$$

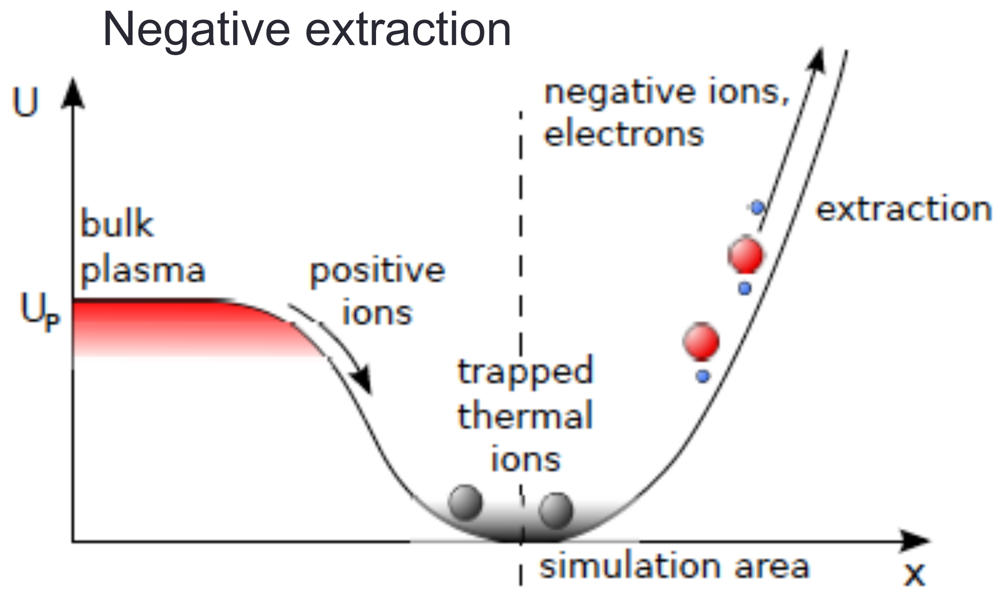
$$\eta_i < 1\%$$ **Weakly ionizated**

$$\eta_i > 10\%$$ **Highly**

The beam is a extreme case where we have 100%

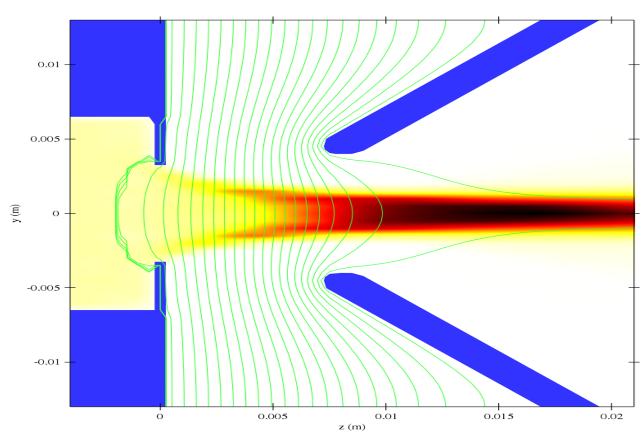
Plasma Boundary

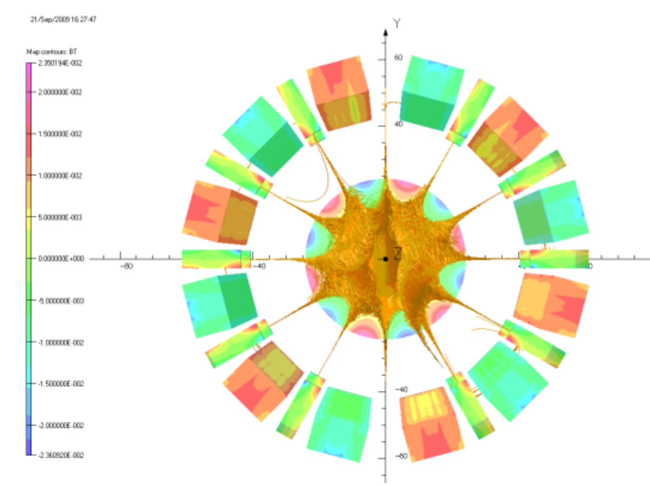




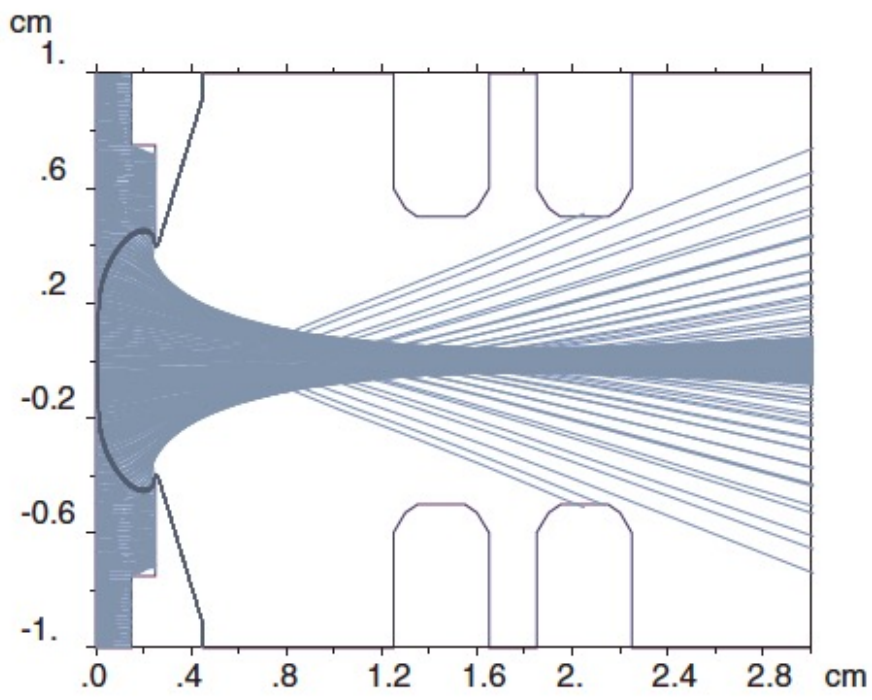
There is strong not linear effects is this region

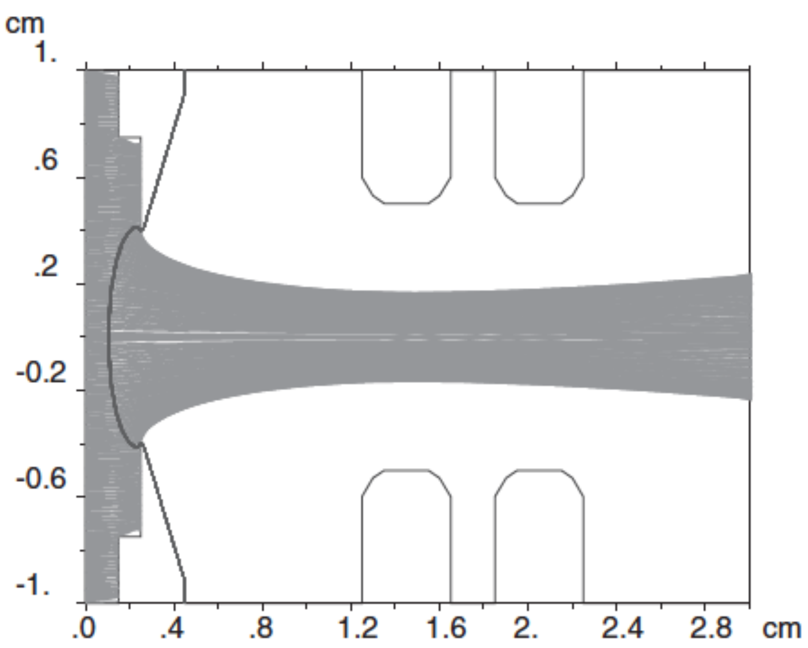
This boundary defines the extraction electrode shape and voltage





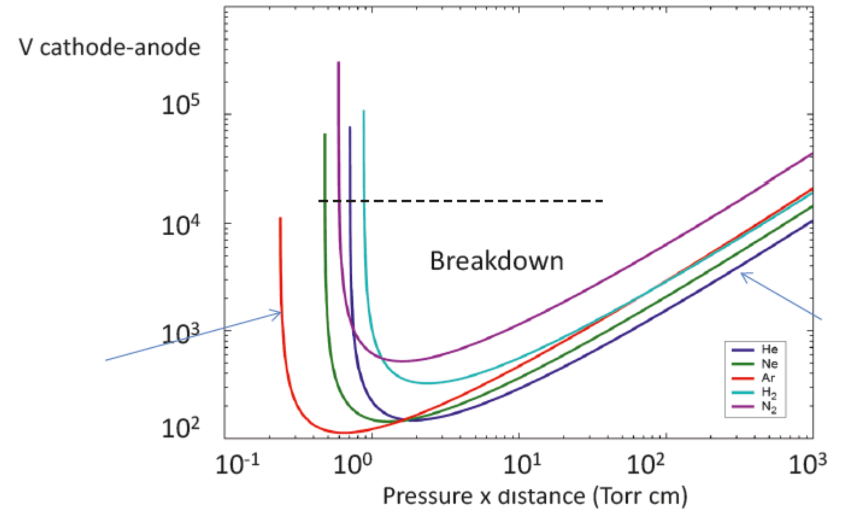
Plasma Boundary effect

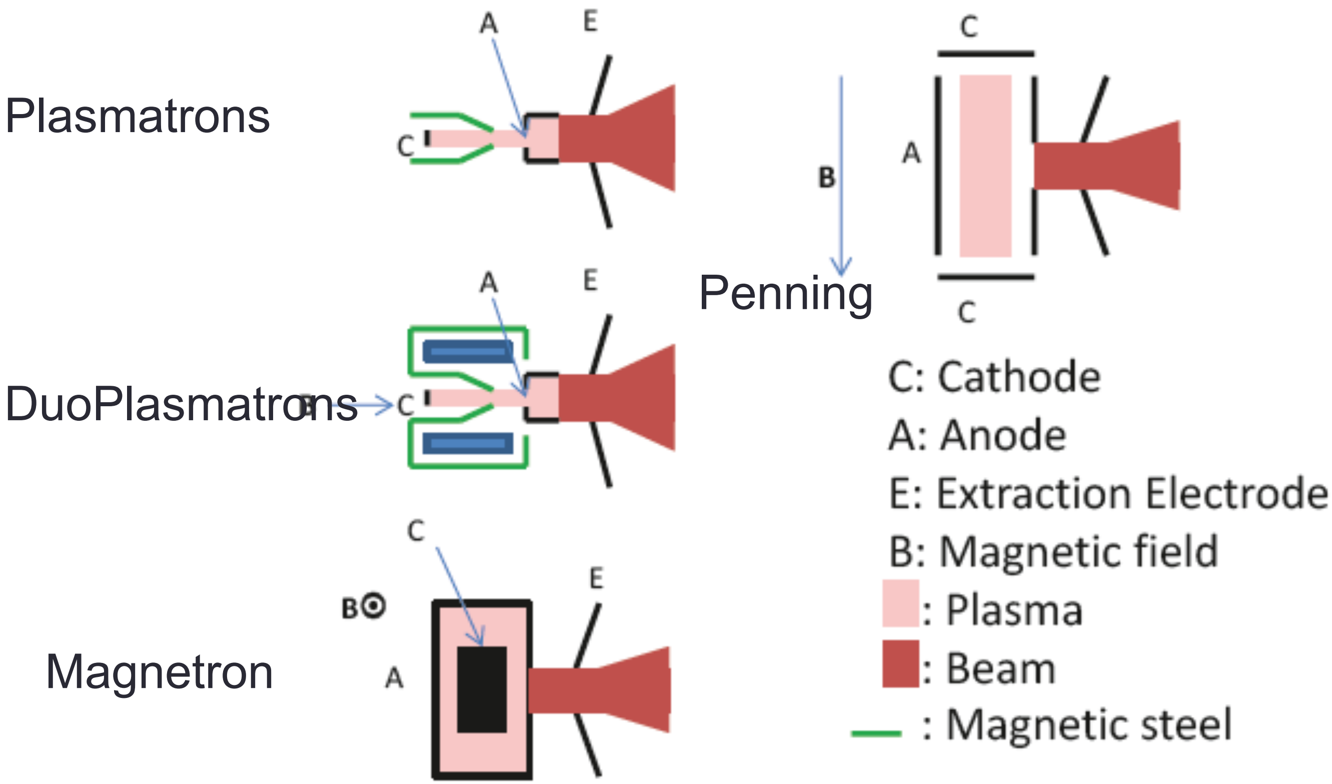




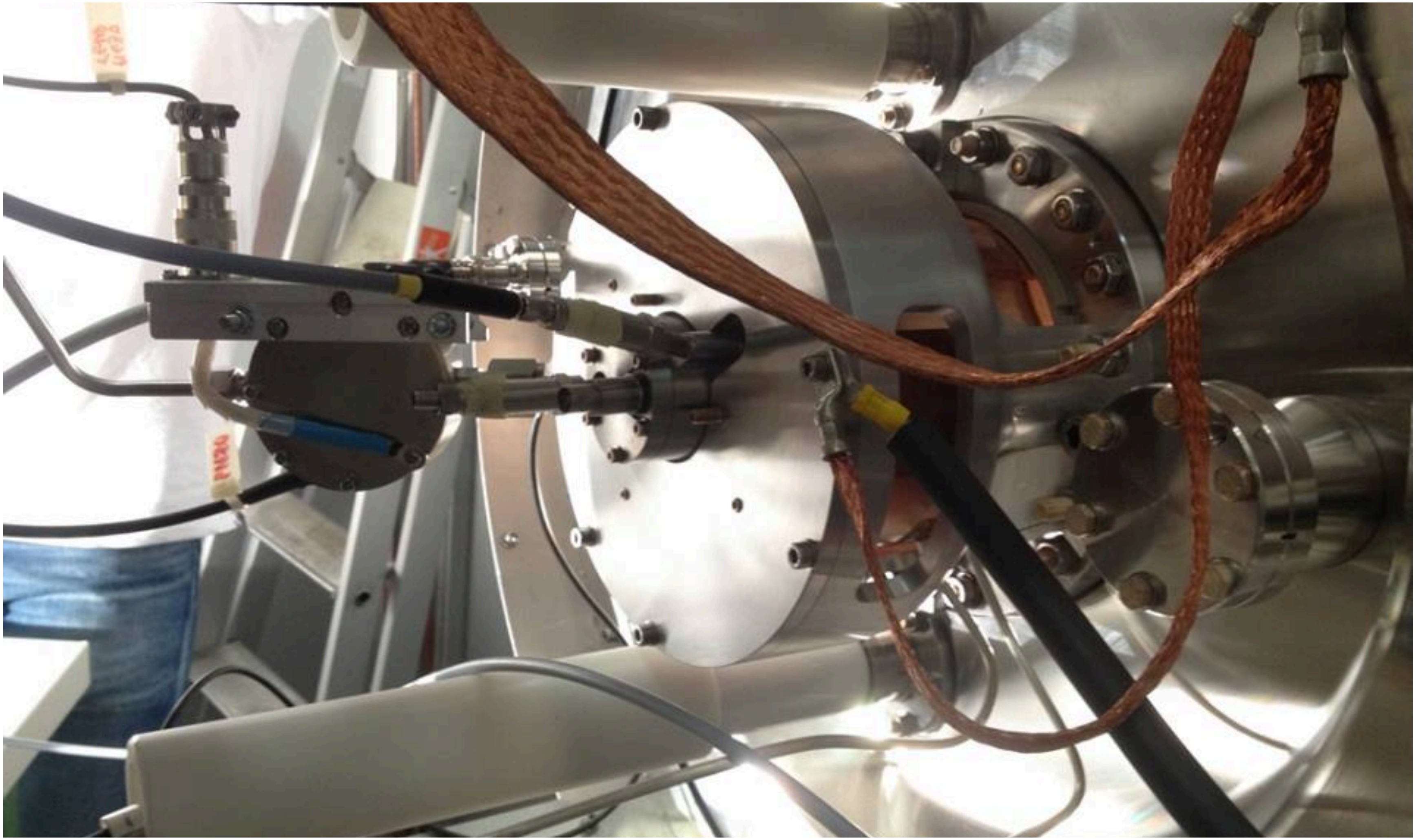
Ion source discharge

- Discharge ion sources
- They use a cathode to generate electrons and create plasma

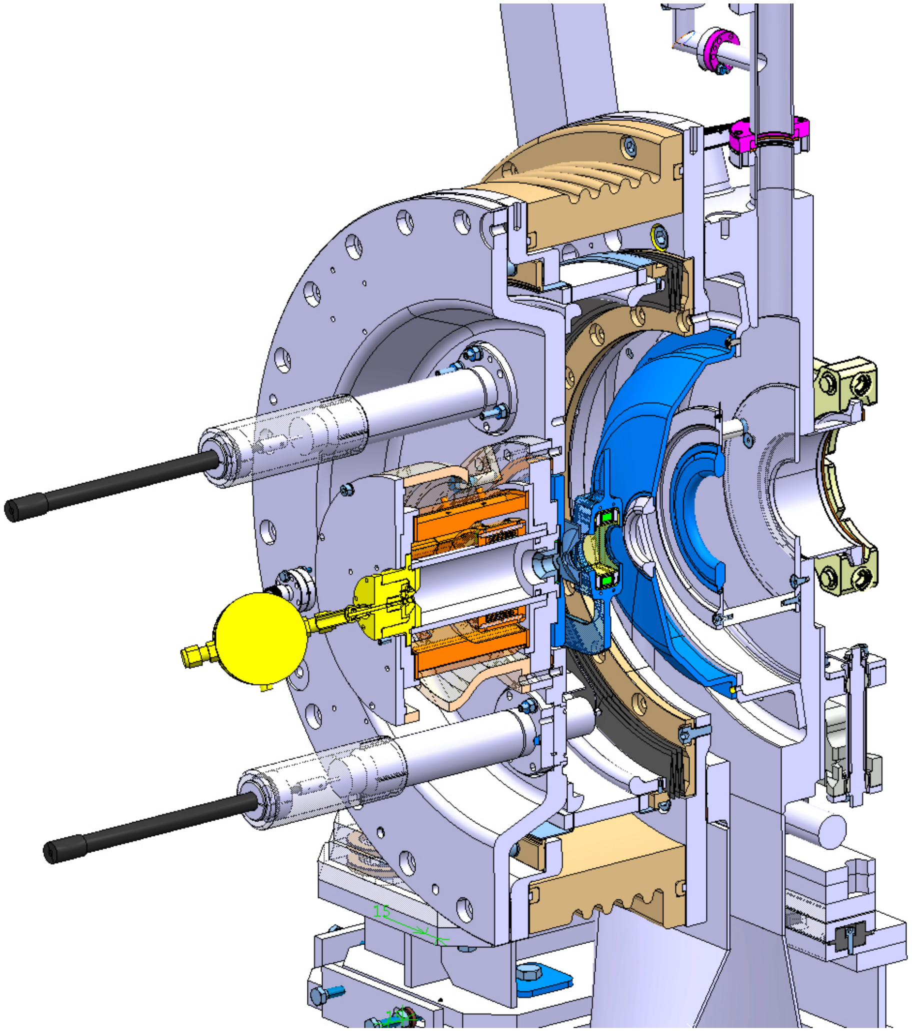


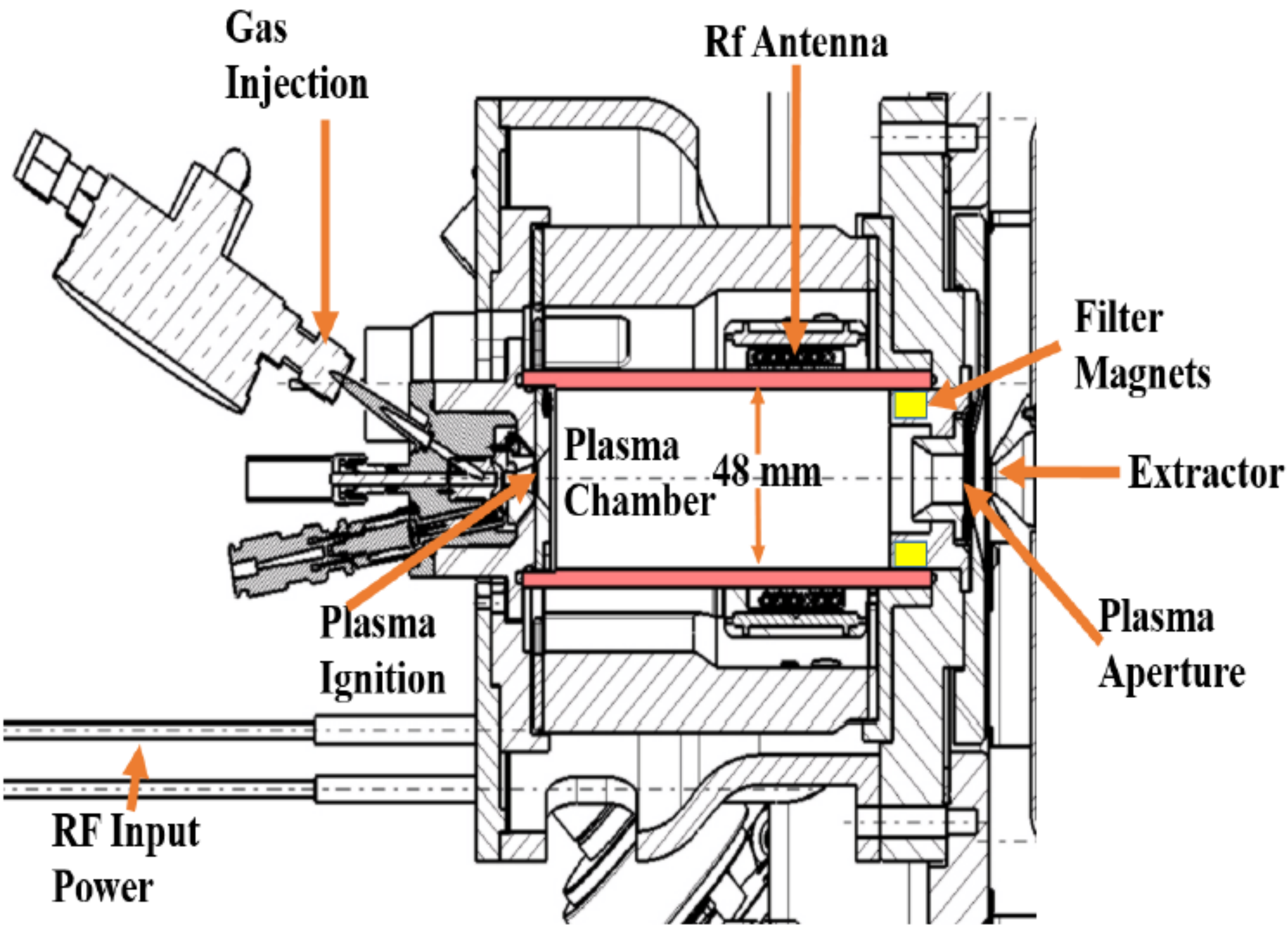


LInac4
Duoplasmatron cesiated ion source

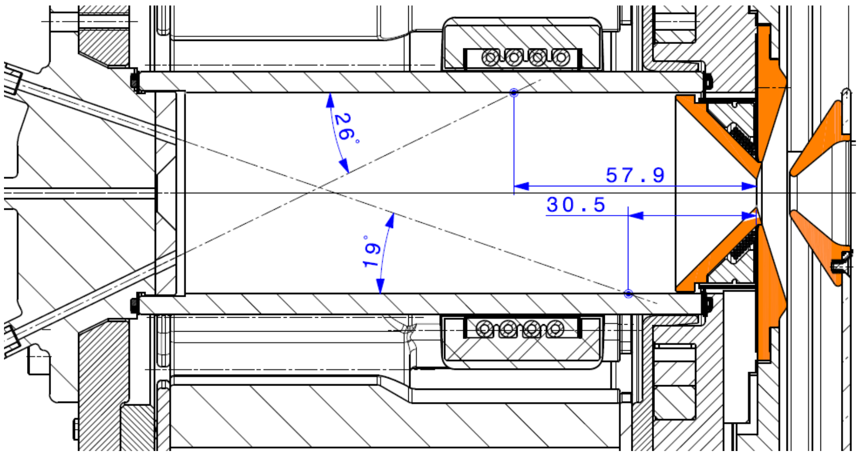


LInac4 Ion Source

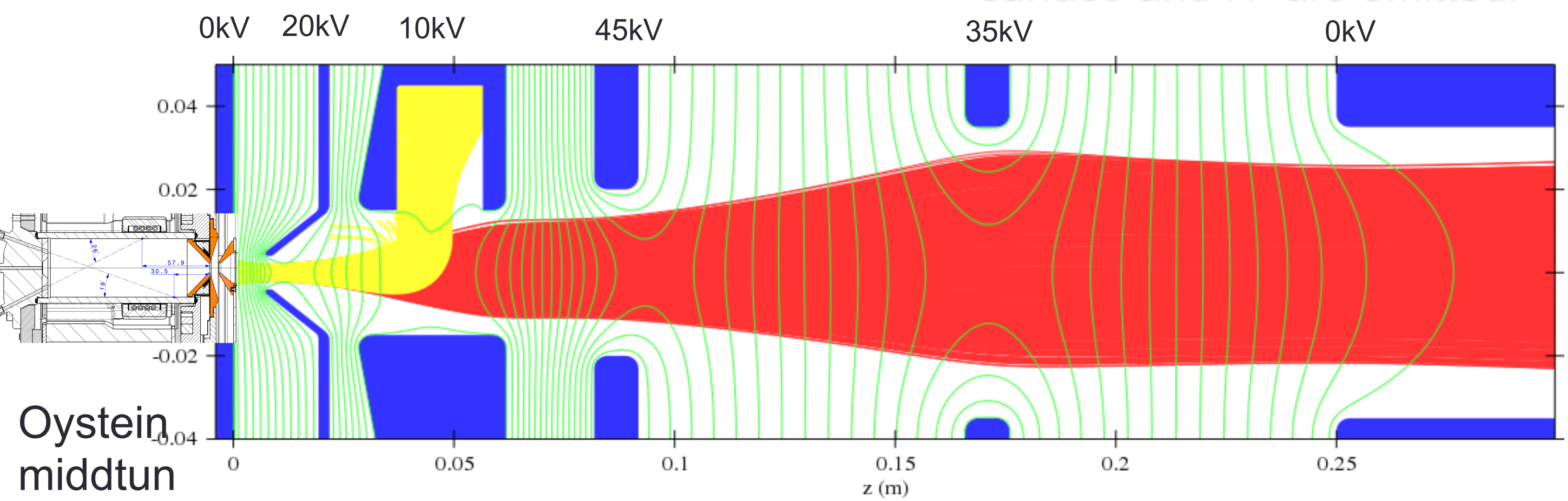



Gas
Injection
Rf Antenna
Filter
Magnets
Plasma
Chamber
48 mm
Extractor
Plasma
Ignition
Plasma
Aperture
RF Input
Power

Linac4 Ion Source and extraction system



- Plasma is created using 2MHz RF in a solenoid coil.
- The H- is produced in the plasma volume and surfaces
- A surface near the extraction is coated with cesium, evaporated from an oven at the back of the source.
- The plasma ions strike the cesium surface and H- are emitted.



Oystein middtun

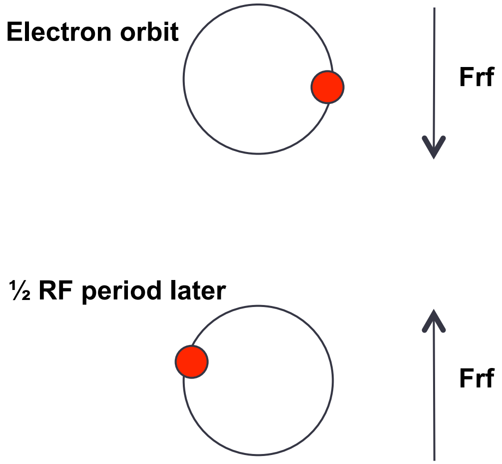
- Electrons (yellow) are extracted along with negative ions (red).

Electron cyclotron resonance(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 mili-seconds allowing mutliple ionization.
- The solenoid magnetic field still allows losses on axis – these ions make the beam.

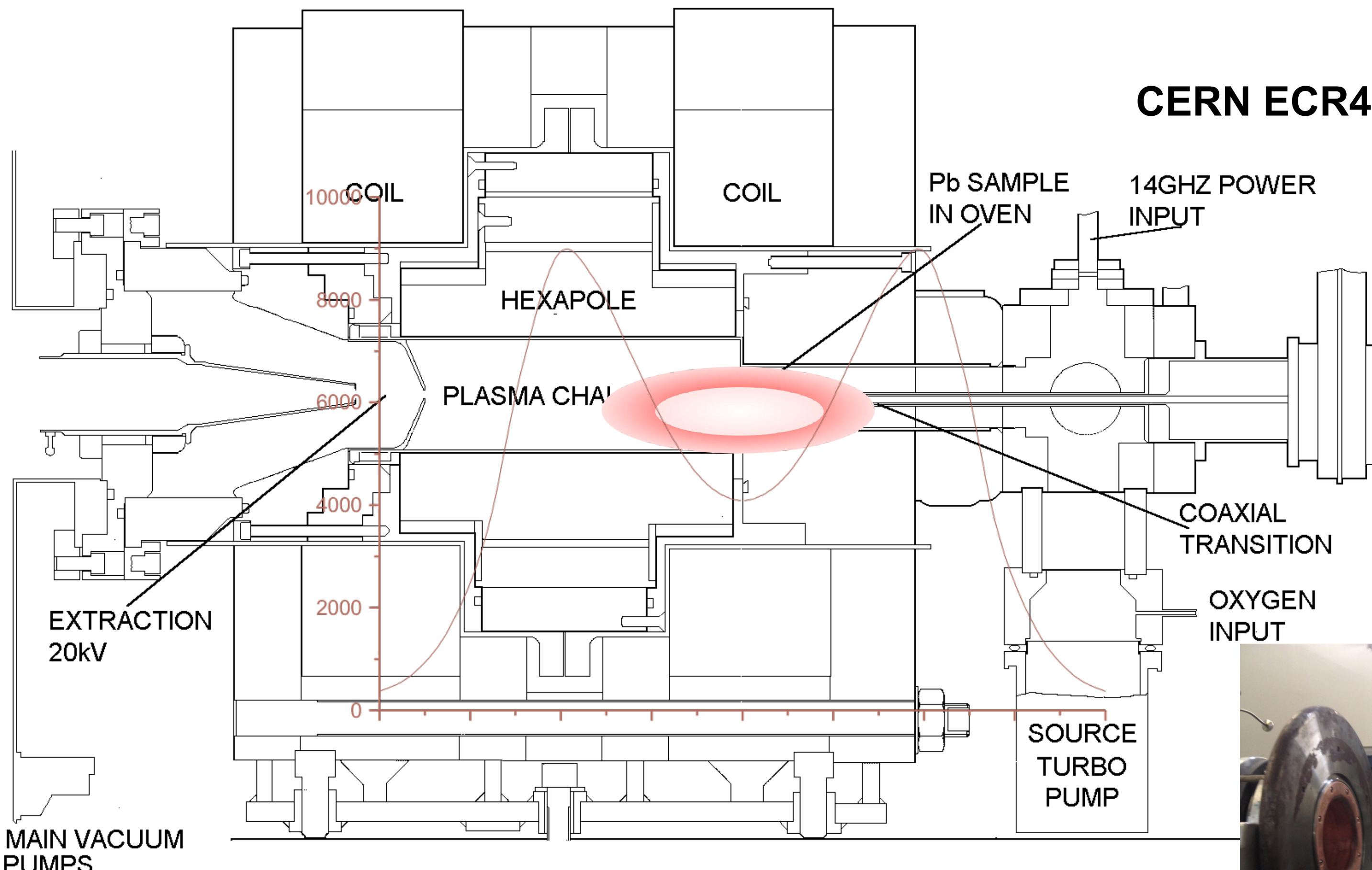
$$\omega_{ecr} = \frac{eB}{m}$$

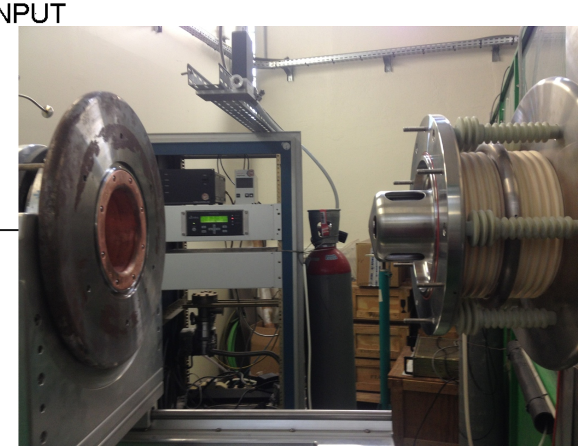
$$f_{ce}[\mathrm{GHz}] = 28 \times B[\mathrm{T}]$$



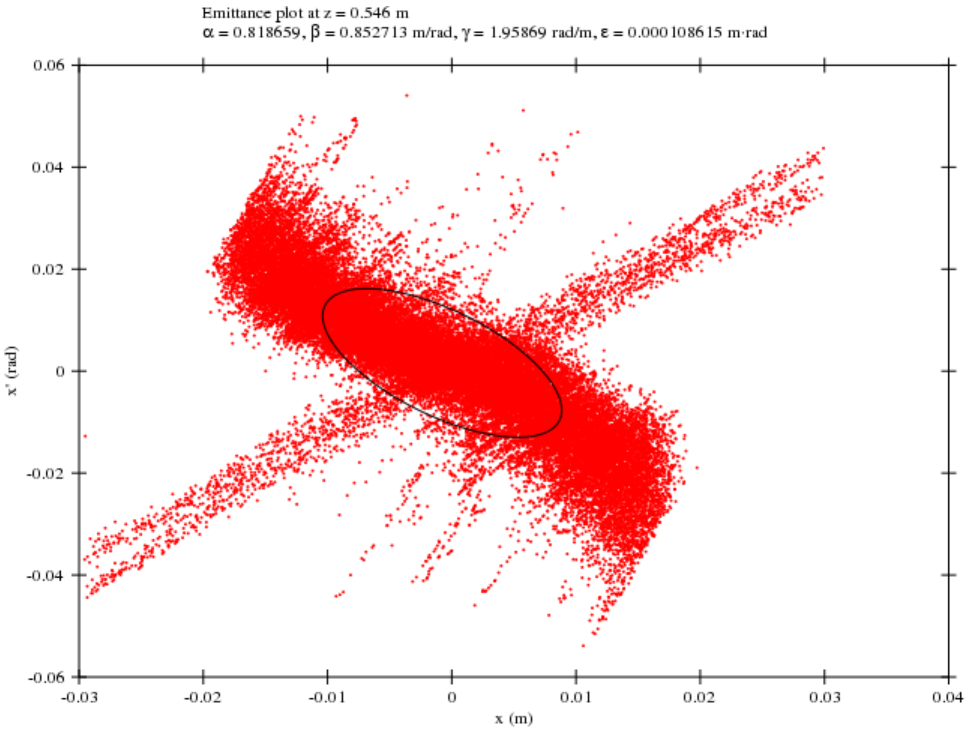
ECR Ion Source

CERN ECR4 – Built by GANIL





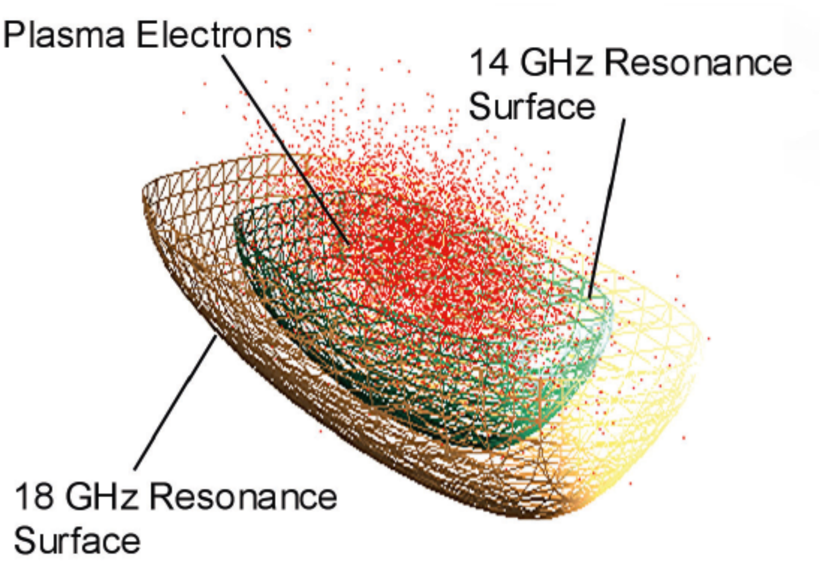
Emittance?



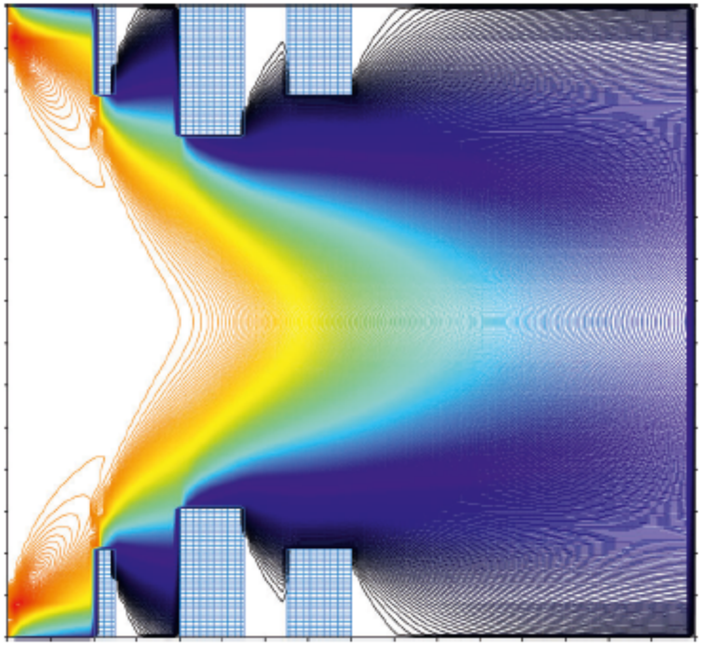
Emittance from a proton extraction system

Source codes

- The source simulations need to include more physics process than standard accelerator codes



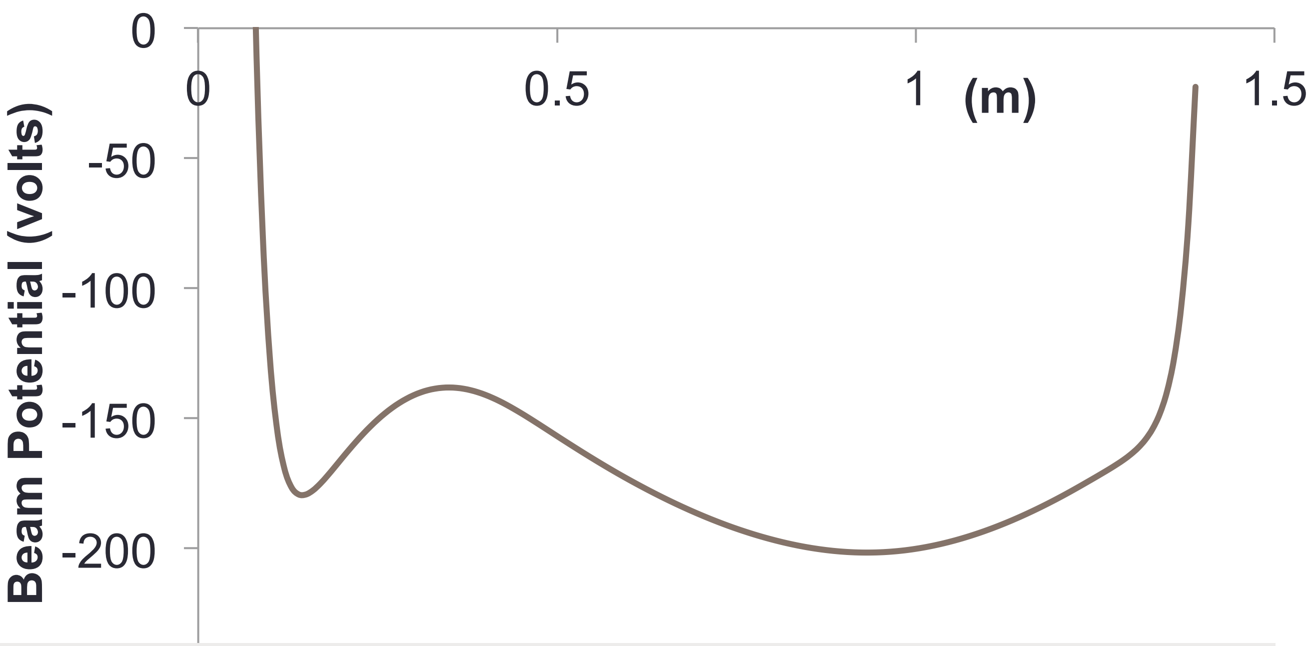
ECR Ion source plasma simulation

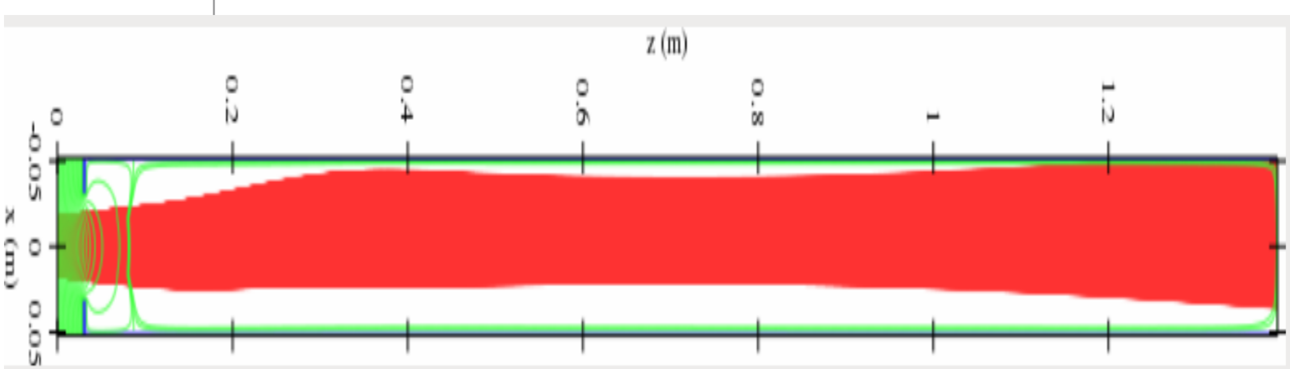


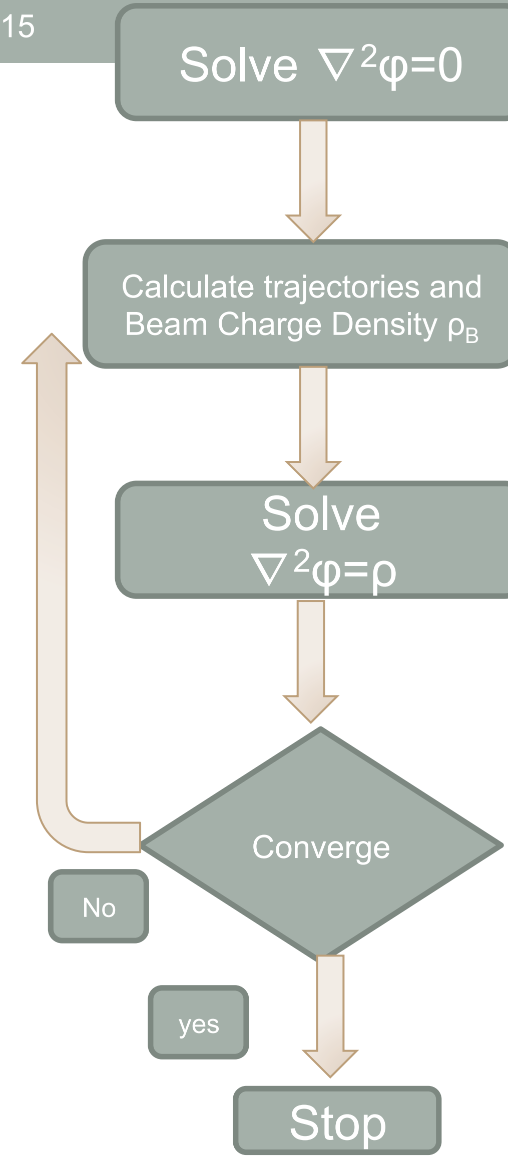
Neutral gas pressure flow simulation

Some Simulations of microseconds in the plasmas takes around 1 month

Ray tracing codes

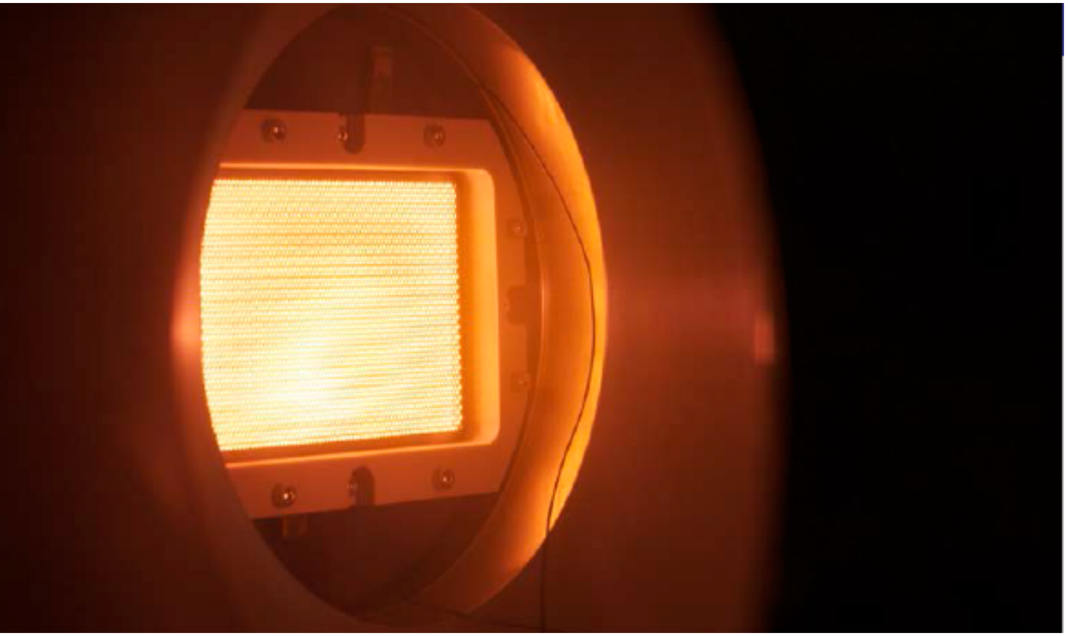




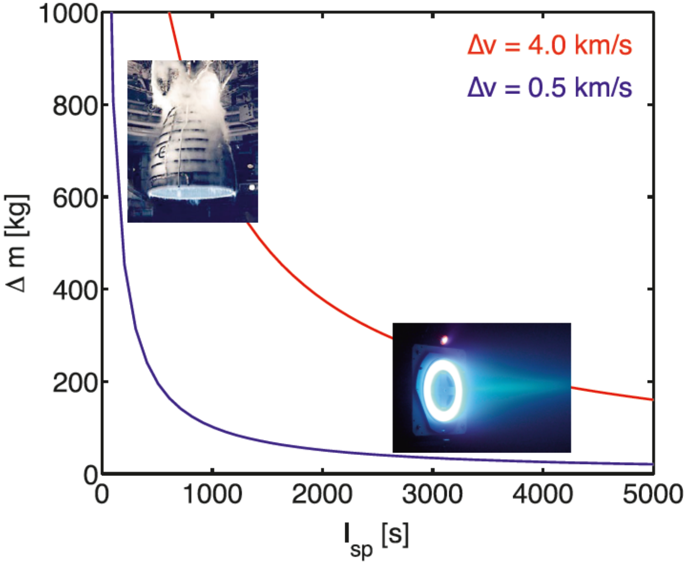


- **Is more accurate but the simulation time and resource consumption is higher**

Ion beam propulsion



The electronic propulsion is more efficient, but space charge limit the power



Challenges

Vacuum

Radio frequency

High voltage

Reliability

Magnet design

Complicate Simulations

Gas injection

Space charge

Beam losses

Instrumentations

Secondary Electrons

Users always want more

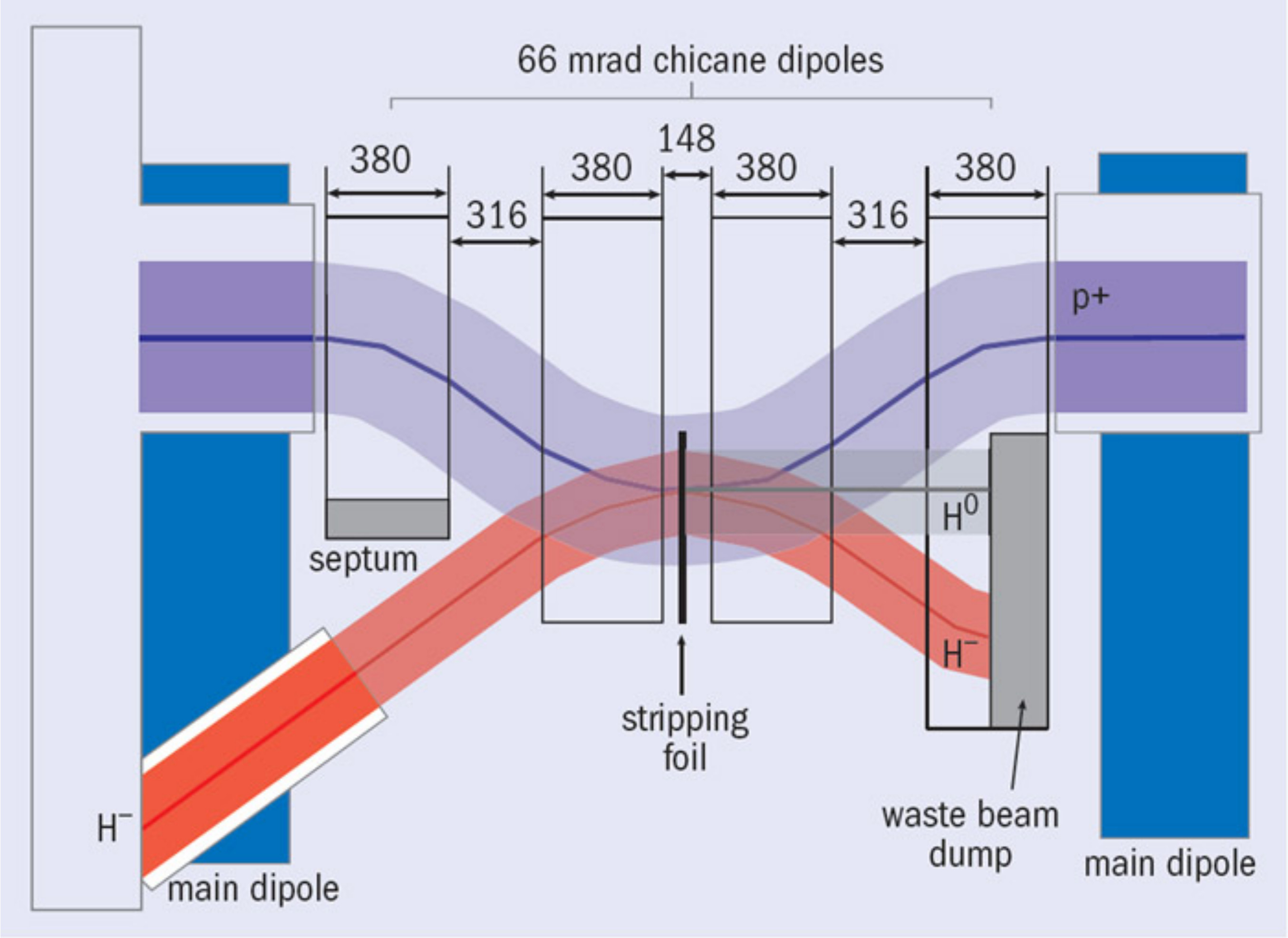
Summary

- There are many ways to create the beam, thermionic, photo cathode with different types, there are at least 14 species of ions sources.
- Always is necessary to create new type of beams
- There is plenty of scope for scientists to make a impact in the field
- Balance between physics and engineering
- And every accelerator will always need a particle source

Why H^-?

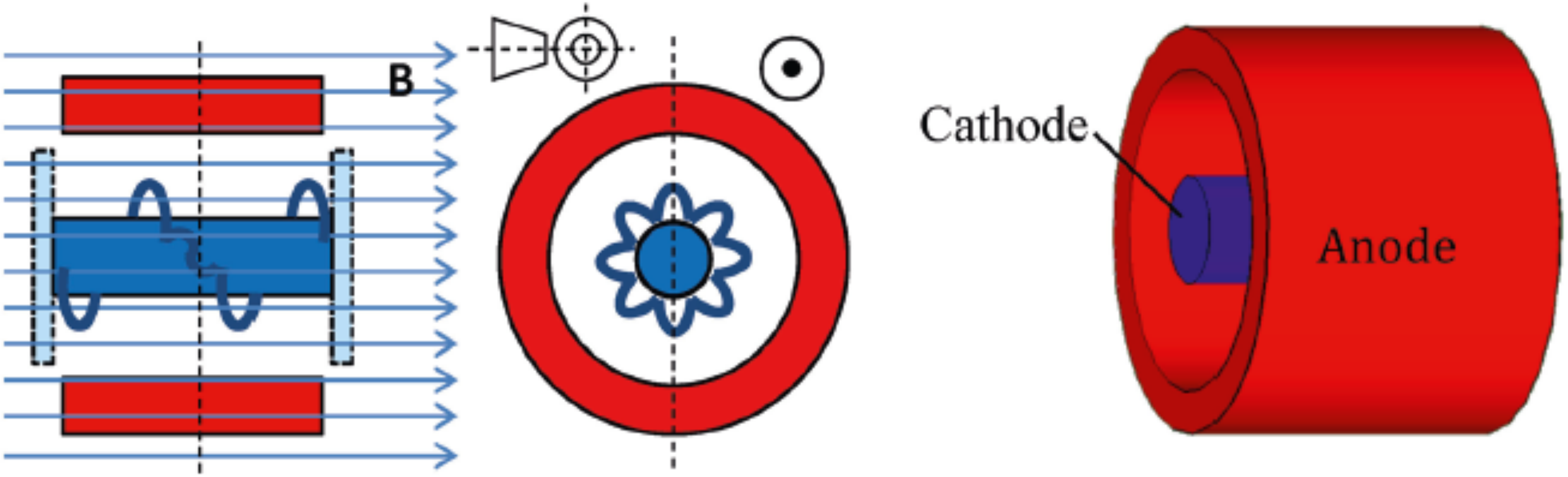
- Because the Space charge repulsion is easier to insert a negative beam inside a positive beam
- In therory the efficiency will be 99% in transform the H^- in to protons

Schematic of H^- injection into a circular machine.

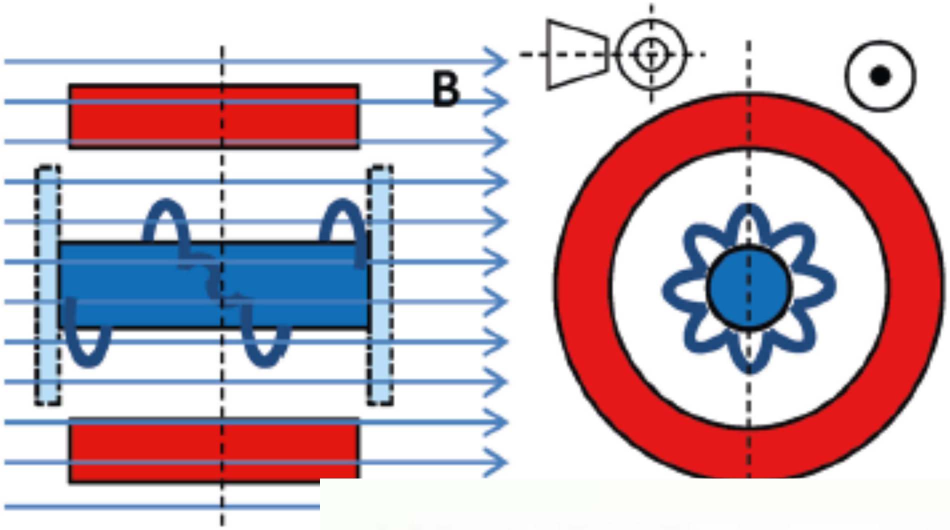


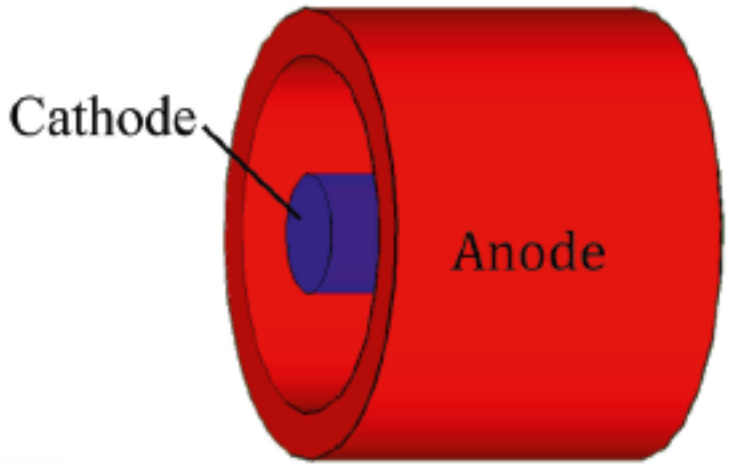
[1] CERN Courier, Sep 2012.

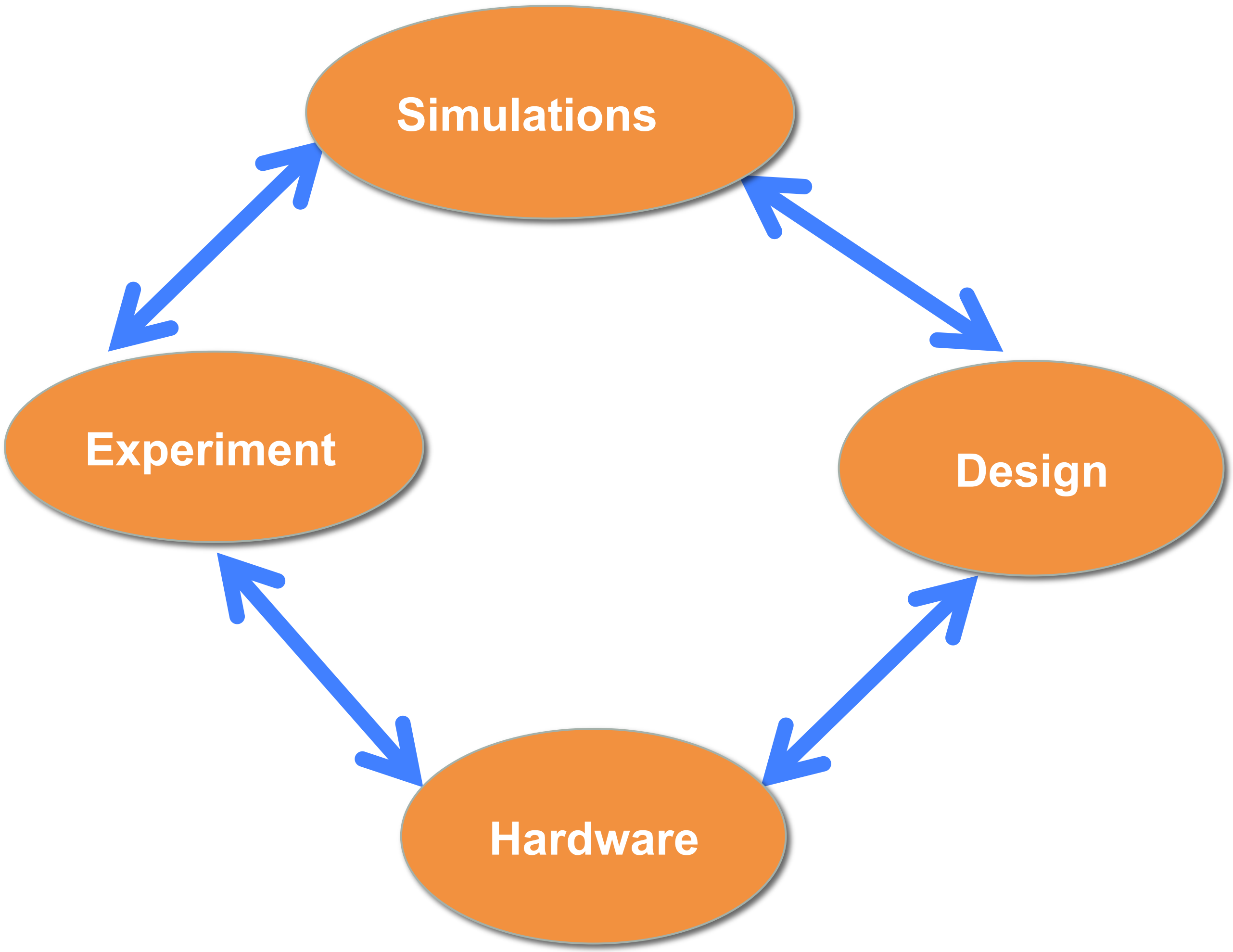
magnetron



magnetron






Simulations
Experiment
Design
Hardware