Imperial College
London

Sourcery

or

The Art to build Particle sources for Accelerators

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Advanced School on Accelerator Optimization 06th – 11th July 2014 RHUL

Overview

The following topics will be covered:

- Electron sources
- Sources for single charged ions
- Sources producing high charge states
- Source for negatively charged ions
- Sources for secondary and tertiary particles

Electron sources

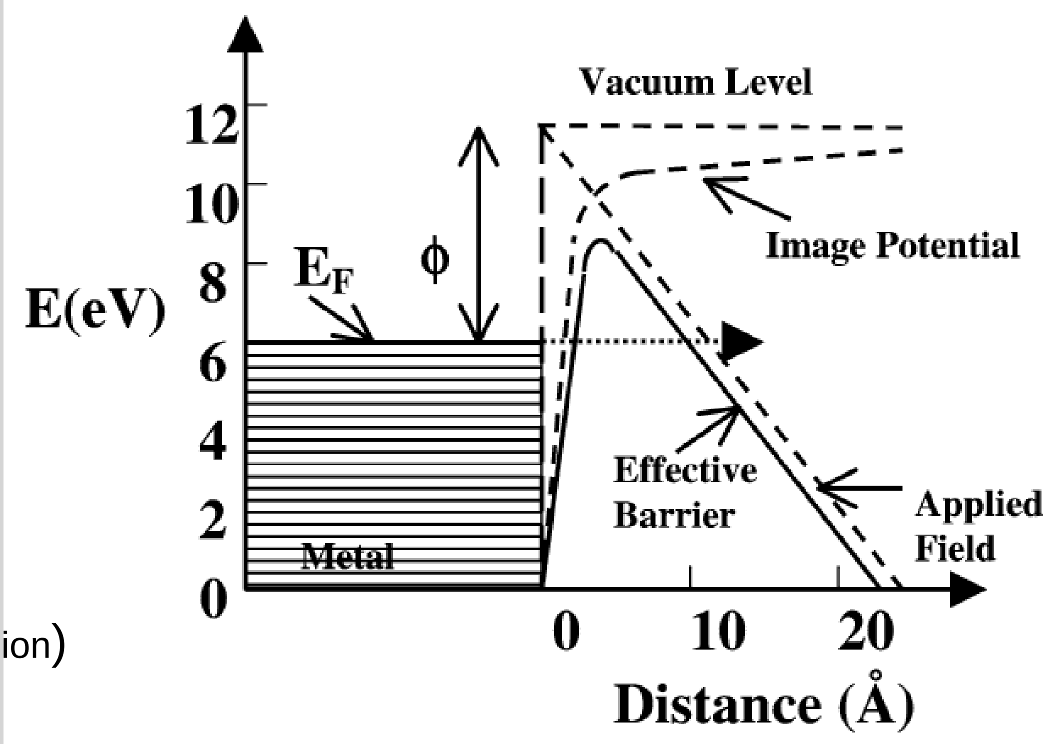
Electrons

Only very little energy is necessary to free electrons from the bound state or the upper levels of the "electron gas" in solids. This can be done by :

1) **Thermionic emission**
   The heated electron must have an energy higher than the workfunction

2) **Photoemission**
   The photon energy must exceed the work function

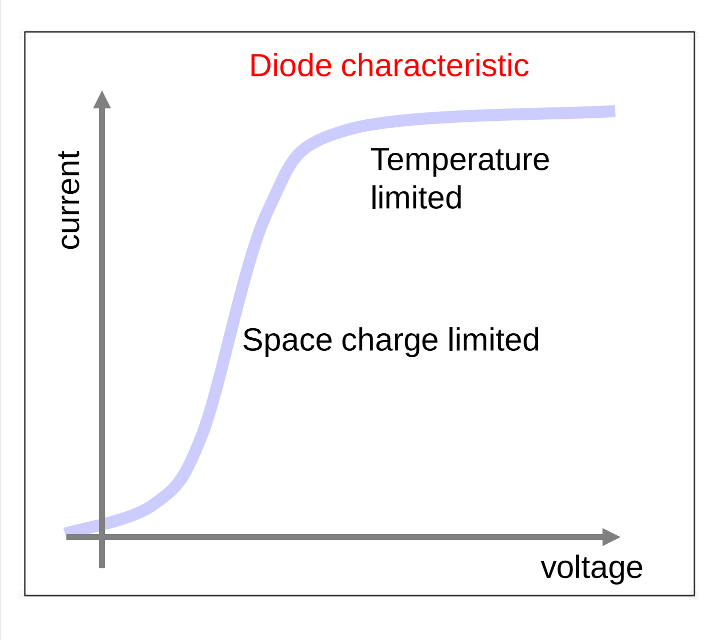
3) **Field emission** (ferroelectric emission)
   high external electric fields alter the potential barrier, and allow electrons to be extracted by the tunnel effect.

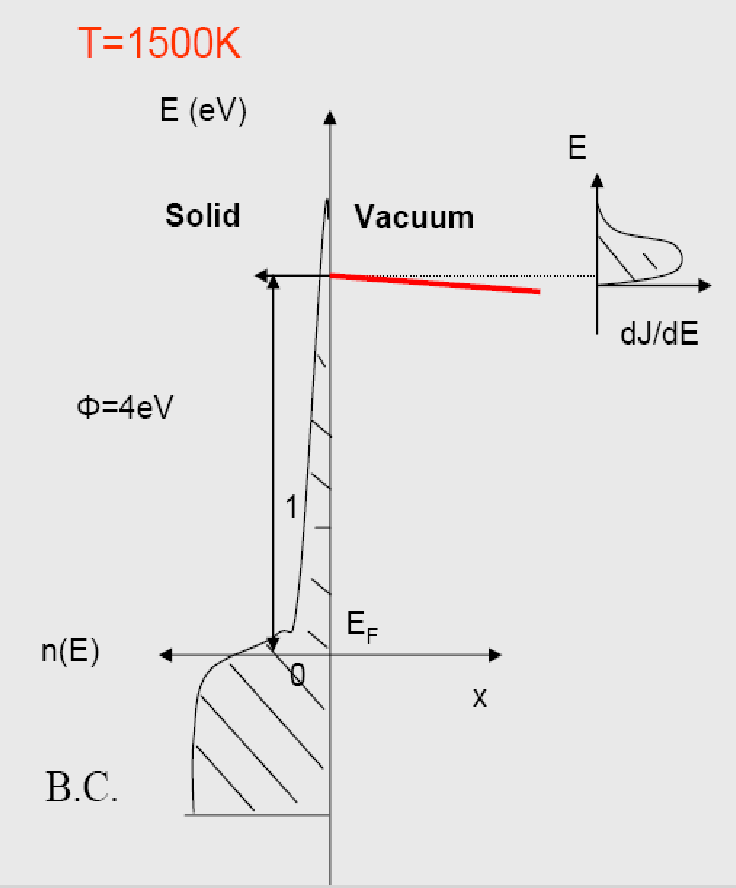


Current density as a function of Binding energy and temperature

Richardson-Dushman equation :

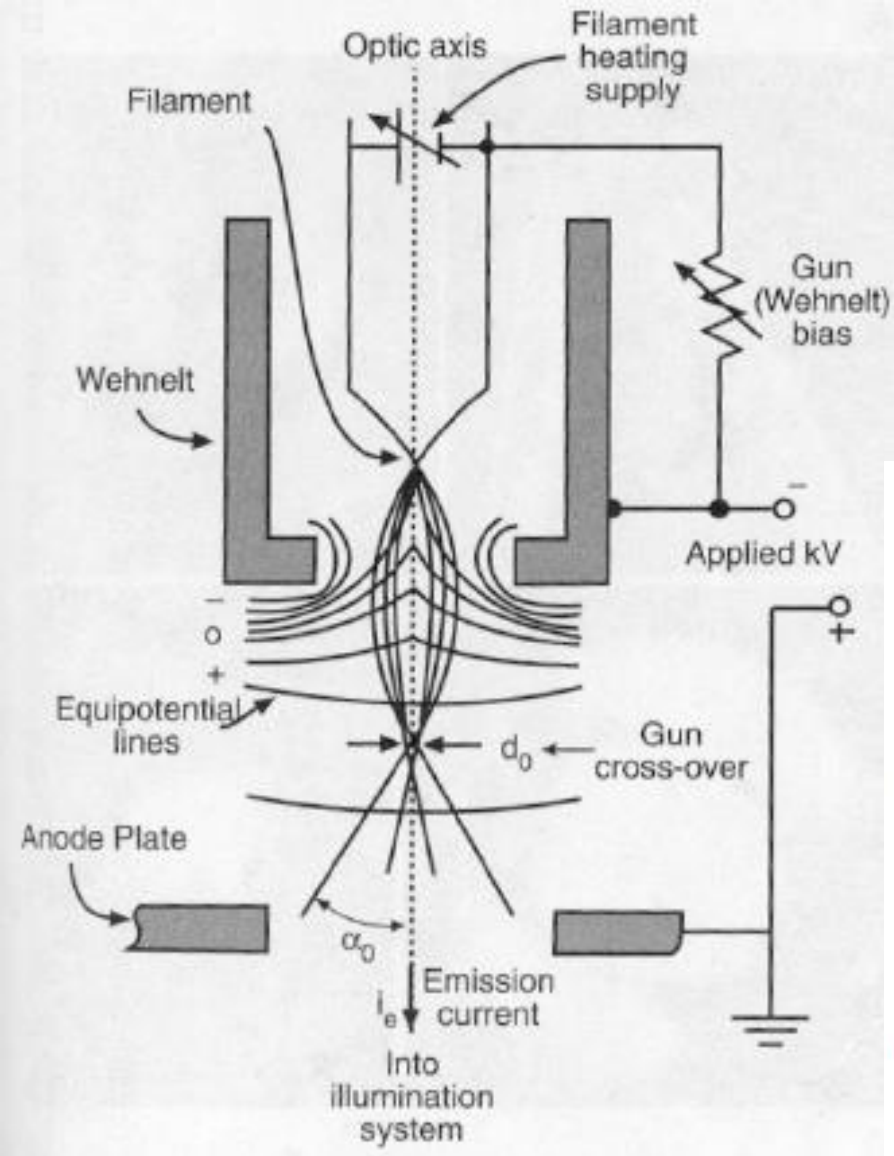
$$J = A \cdot T^2 \cdot e^{-\left[\frac{\phi_o}{kT}\right]}$$

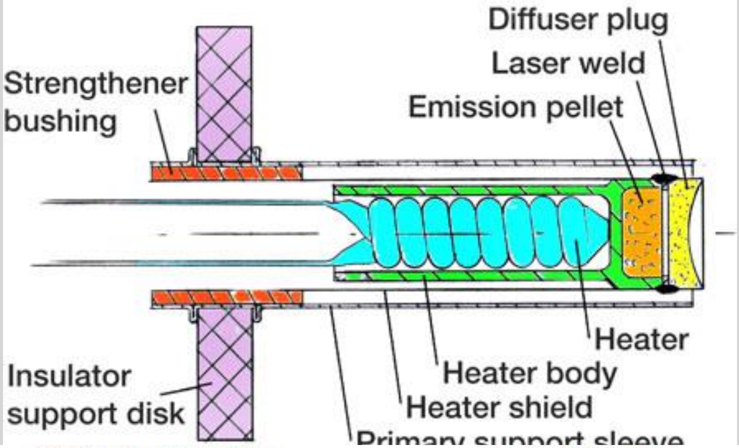




Material	A	Φ(eV)	Temp (° K)	J (A/cm^2)
Tungsten	60	4.54	2500	0.3
Thoriated W	3	2.63	1900	1.16
Tantalum	60	3.38	2500	2.38
Cs/O/W	0.003	0.72	1000	0.35

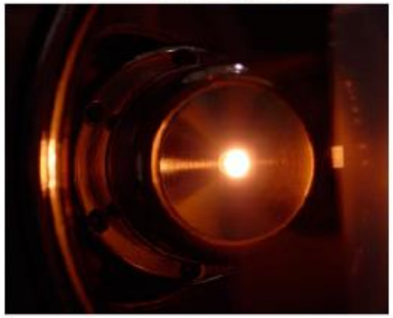
Thermionic guns

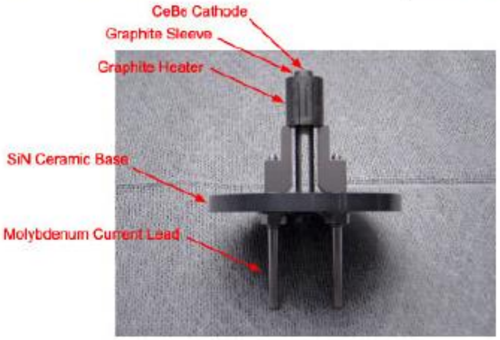


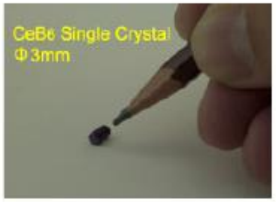


Cathode Assembly

Heated Cathode





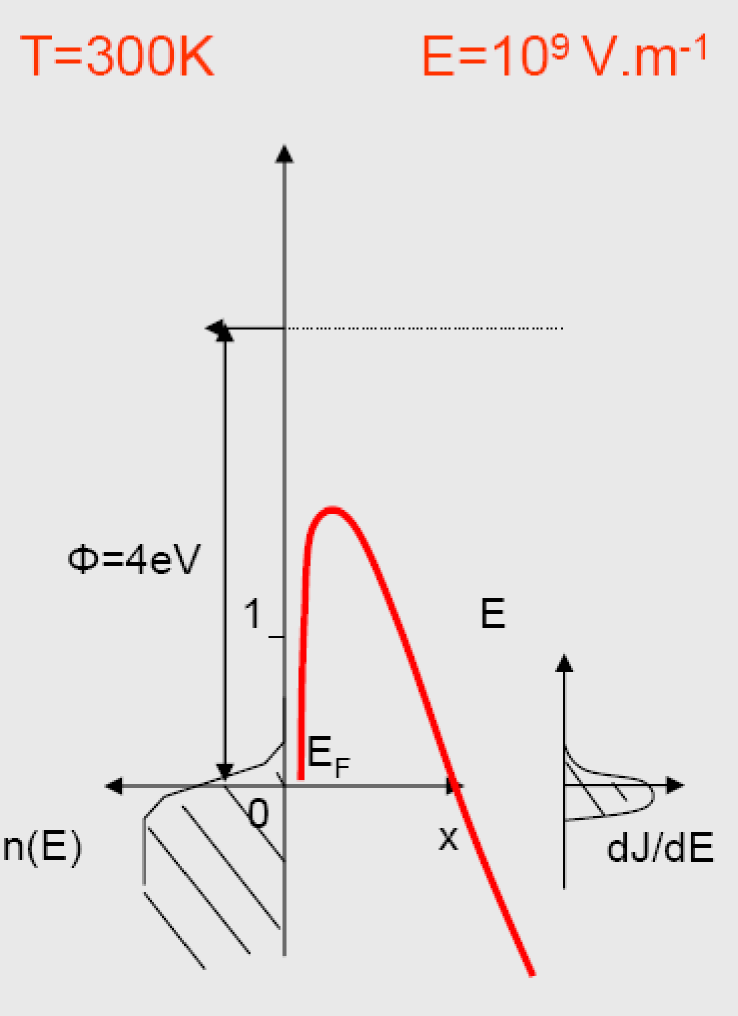


Field emission of electrons from surfaces

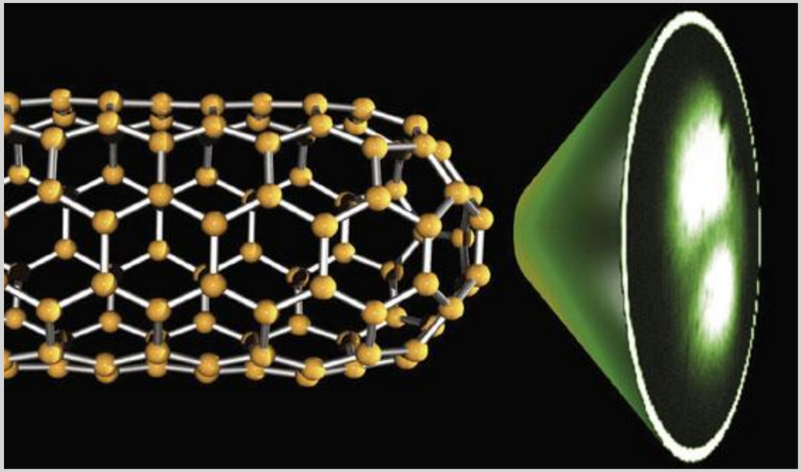
Fowler Nordheim
Equation:

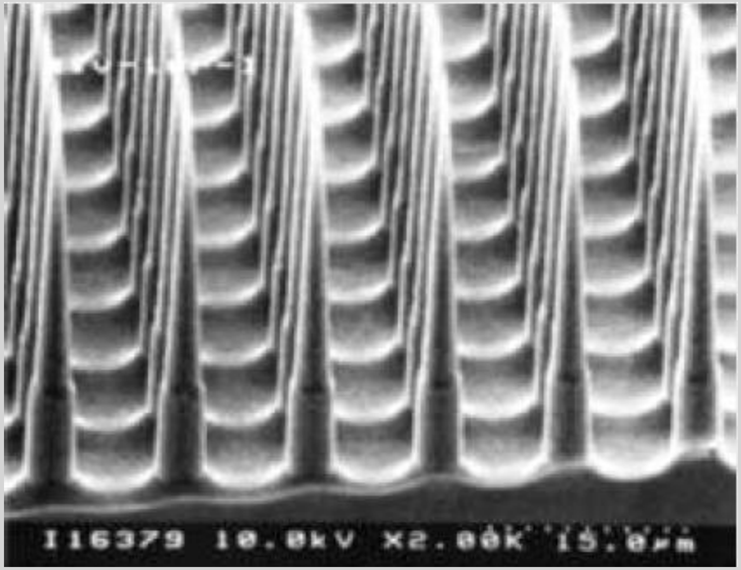
$$J = B \cdot E^2 \cdot e^{-\left[6.8 \cdot 10^7 \frac{\phi_0^{1.5}}{E}\right]}$$

J: emission current density (A/cm^2)
B: field-independent constant [A/V^2]
E: applied field (V/cm)
Φ_0: work function (eV)

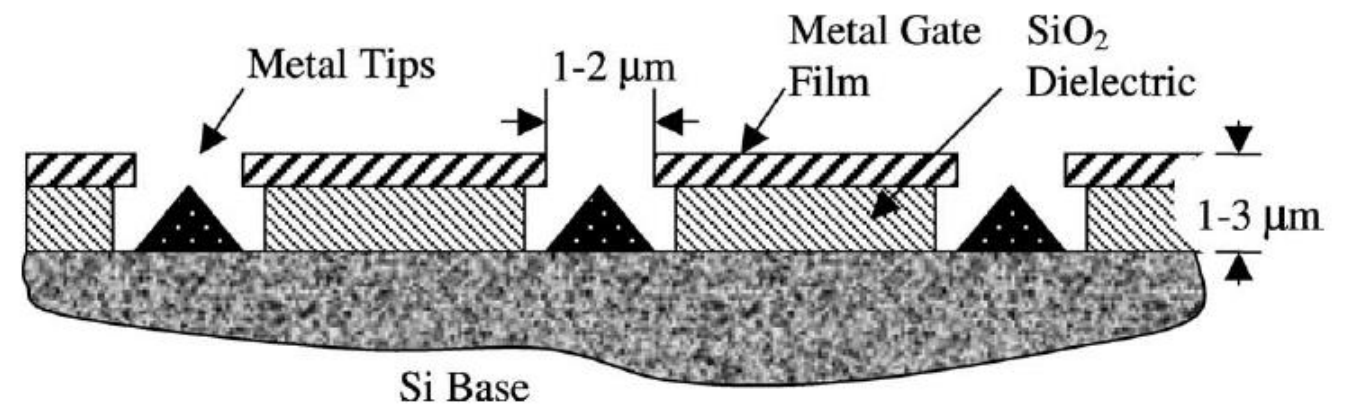


Field emission of electrons from surfaces





Single carbon nano tube (CNT) and CNT arrays for the production of high brightness electron beams

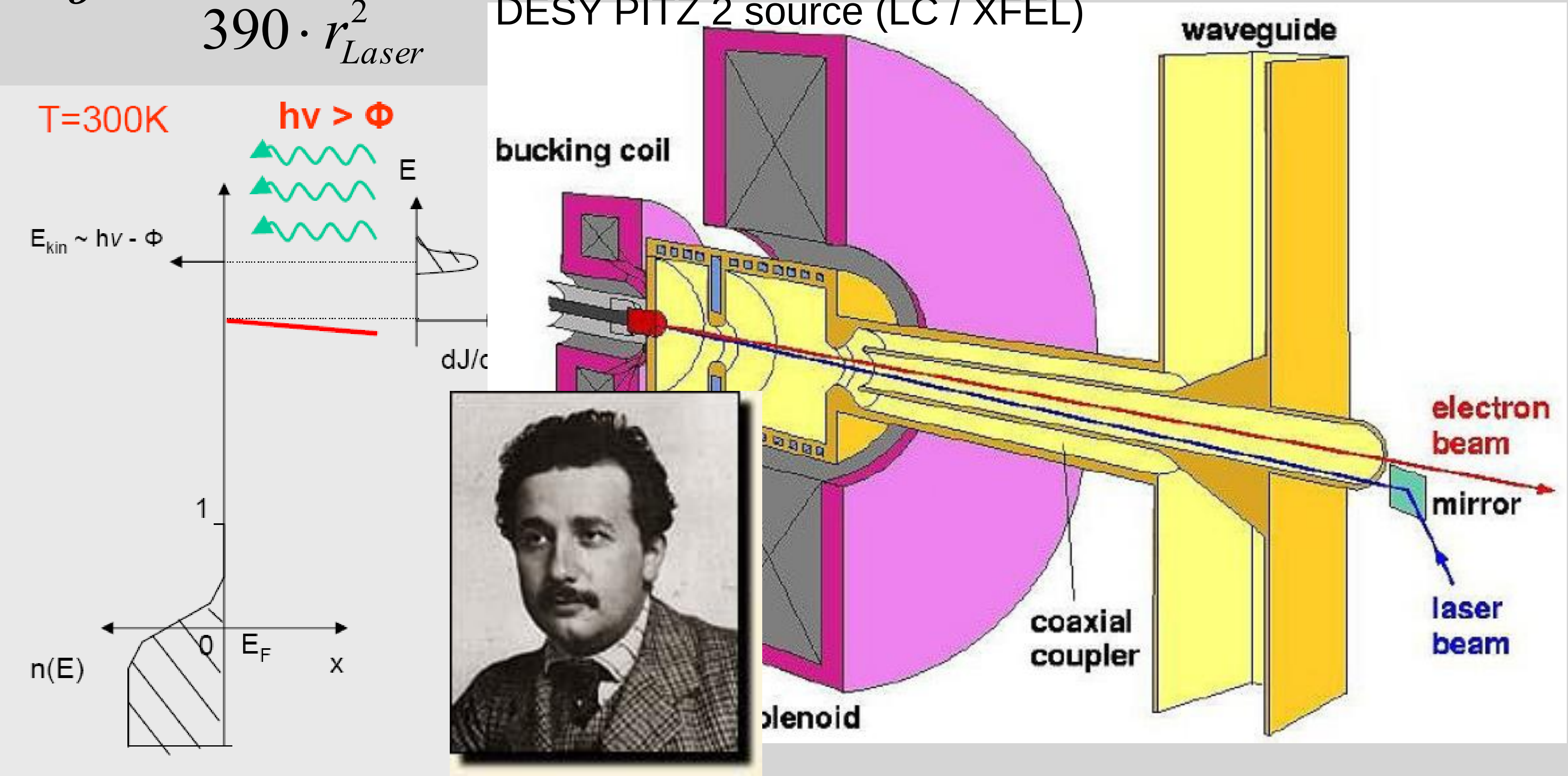


Field emitter arrays, designed for the production of large panel plasma screens

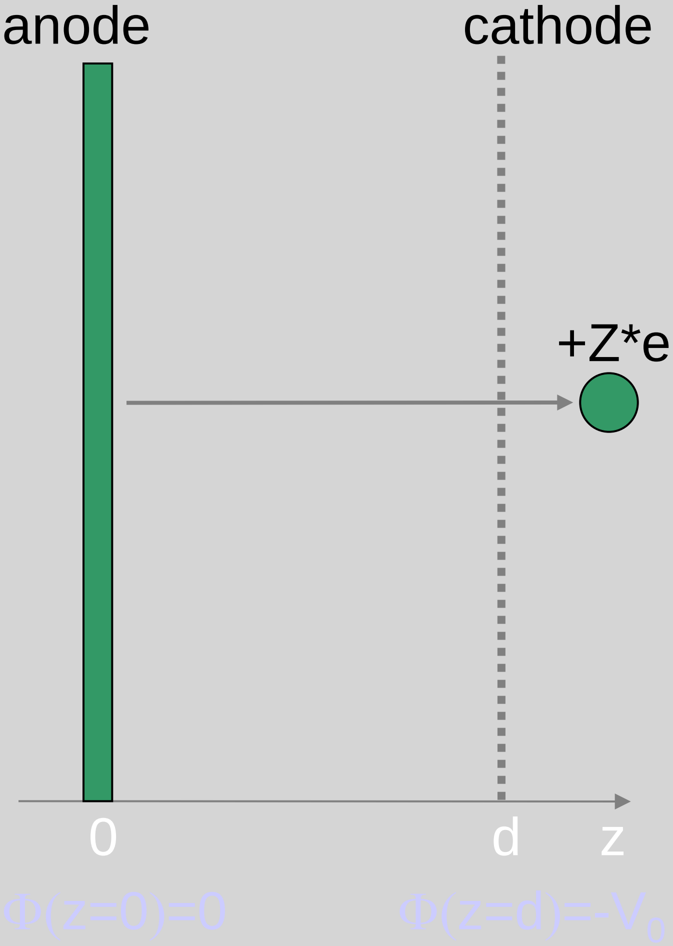
Photo effect and laser electron sources

$$E_{photon} = h \cdot f_{light} = \frac{h \cdot c}{\lambda_{light}} = E_{pot.} + E_{kin.} = \Phi_0 + \frac{1}{2} m_{electron} v^2$$

$$J = \frac{\lambda \cdot P_{Laser} \cdot QE}{390 \cdot r_{Laser}^2}$$


DESY PITZ 2 source (LC / XFEL)

The space charge limit and Child-Langmuir law



$$\frac{1}{2} m v_z^2 = -\zeta \cdot e \cdot \Phi(z)$$

$$\nabla^2 \Phi(z) = -\frac{\varphi(z)}{\varepsilon_0}$$

$$J = v \cdot \varphi = const.$$

$$\left(\frac{d^2\Phi}{dz^2} \right) = -\frac{J}{\varepsilon_0 \sqrt{\frac{2\zeta e \Phi}{m}}}$$

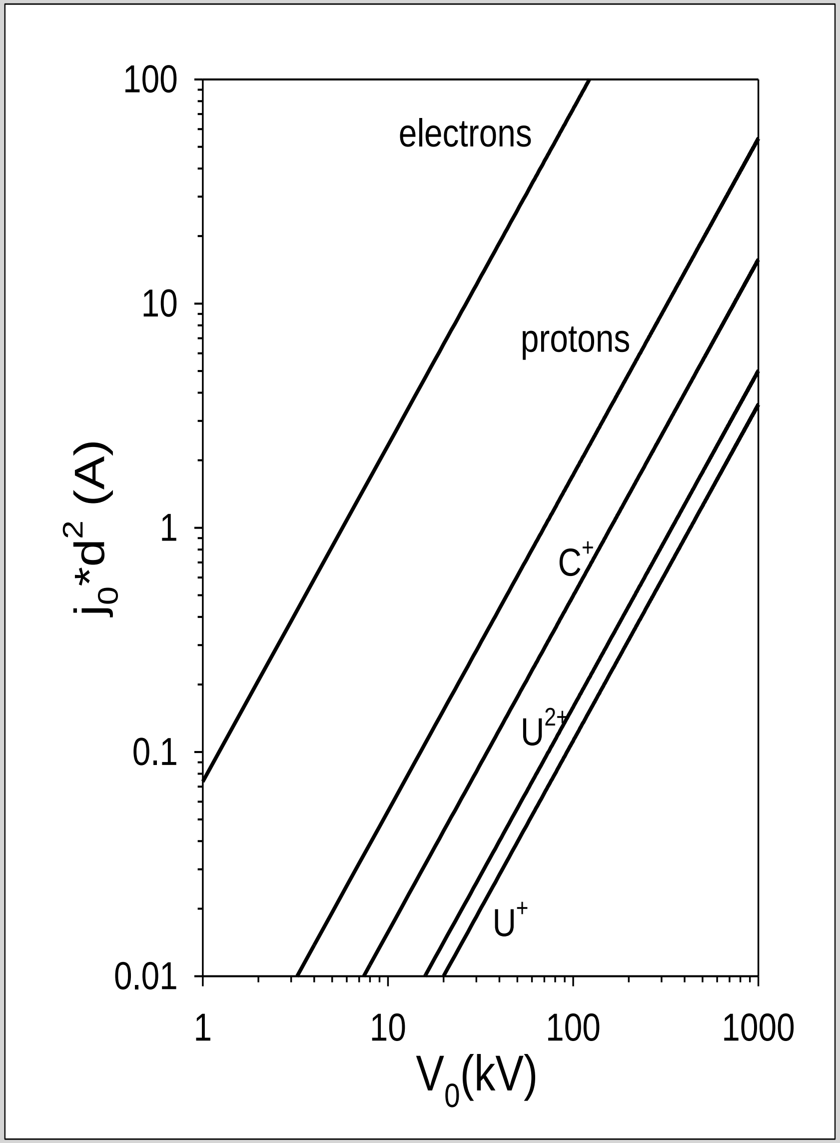
(Poisson equation)

Space charge limit for current density :

$$J_{SC} = \frac{4}{9} \varepsilon_0 \sqrt{\frac{2\zeta e}{m}} \frac{\Phi(z)^{3/2}}{d^2}$$

$$\Phi(z) = -V_0 \left(\frac{z}{d} \right)^{4/3}$$

Current limits given by the Child-Langmuir law



The total current extractable from an ion source is given by :

- The area covered by the extraction aperture (~ d^2)
- Extraction voltage ($U^{3/2}$)
- Mass of particles $(1/m)^{1/2}$
- Charge state $(\zeta)^{1/2}$
- The distance between the electrodes (d^2)

Under the assumption that the particle source is able to produce this current. For electron sources this is usually valid, for ion sources in general not !

Beam extraction, high voltage break down **limit** and aspect ratio

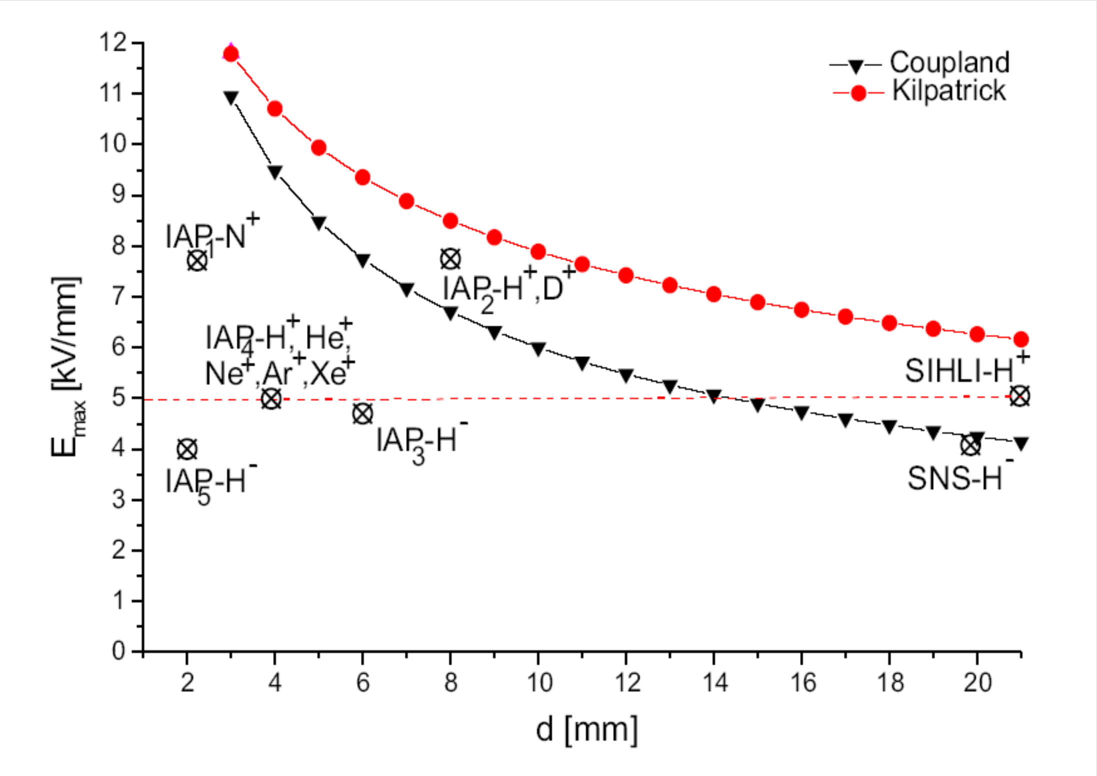
$$J_{SC} = \frac{4}{9}\varepsilon_0\sqrt{\frac{2qe}{m}}\,\frac{U^{3/2}}{d^2}$$

$$U = E \cdot d$$

$$J_{SC} = \frac{4}{9}\varepsilon_0\sqrt{\frac{2qe}{m}}\,\frac{E^2}{\sqrt{U}}$$

$$S = \frac{r}{d}$$

$$J_{SC} = \frac{4}{9}\varepsilon_0\sqrt{\frac{2qe}{m}}\sqrt{\frac{S}{r}}\,E^{3/2}$$

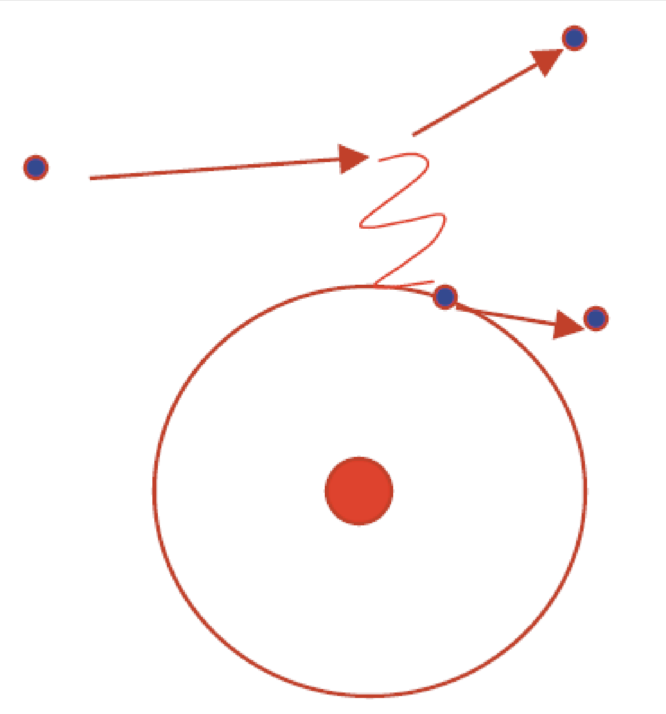


Break down law:

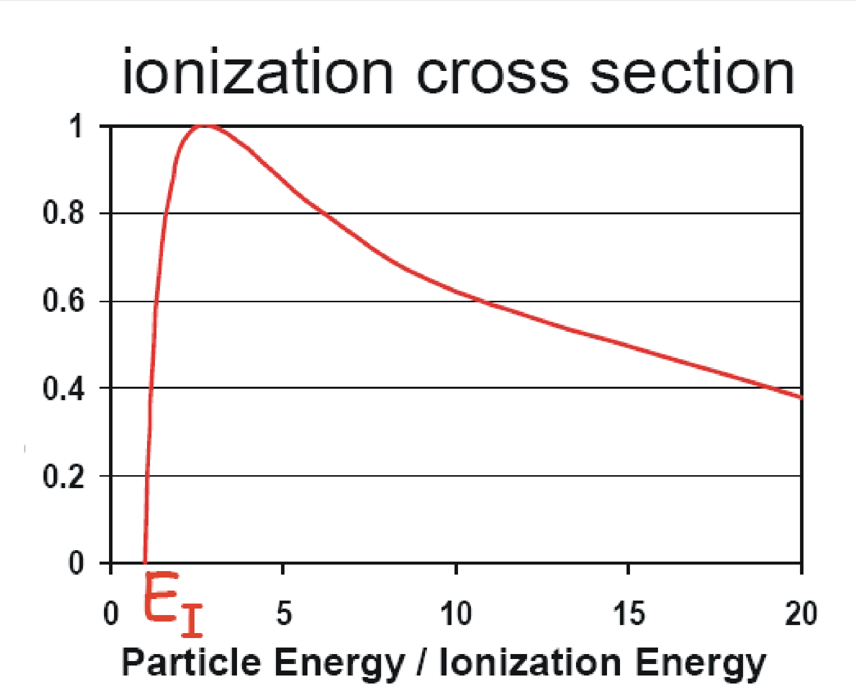
Kilpatrick	$U_{max} = 1.7 \cdot 10^6 d^{\frac{2}{3}}$	$\frac{(-1 + 3 \cdot S^2)}{(1 + 3 \cdot S^2)^2}$	$S_0 = 0.577$
Coupland	$U_{max} = 6 \cdot 10^5 \sqrt{d}$	$S^{\left(\frac{1}{4}\right)} \cdot \frac{(-5 + 9 \cdot S^2)}{(1 + 3 \cdot S^2)^2}$	$S_0 = 0.745$
Linear	$U_{max} = 5kV \cdot d$	$\frac{(9 \cdot S^2 - 1)}{\left[(1 + 3 \cdot S^2)^2 \cdot (\sqrt{R} \cdot \sqrt{S})\right]}$	$S_0 = 1/3$

maximum current density for aspect ratio of :

Production of charged Ions

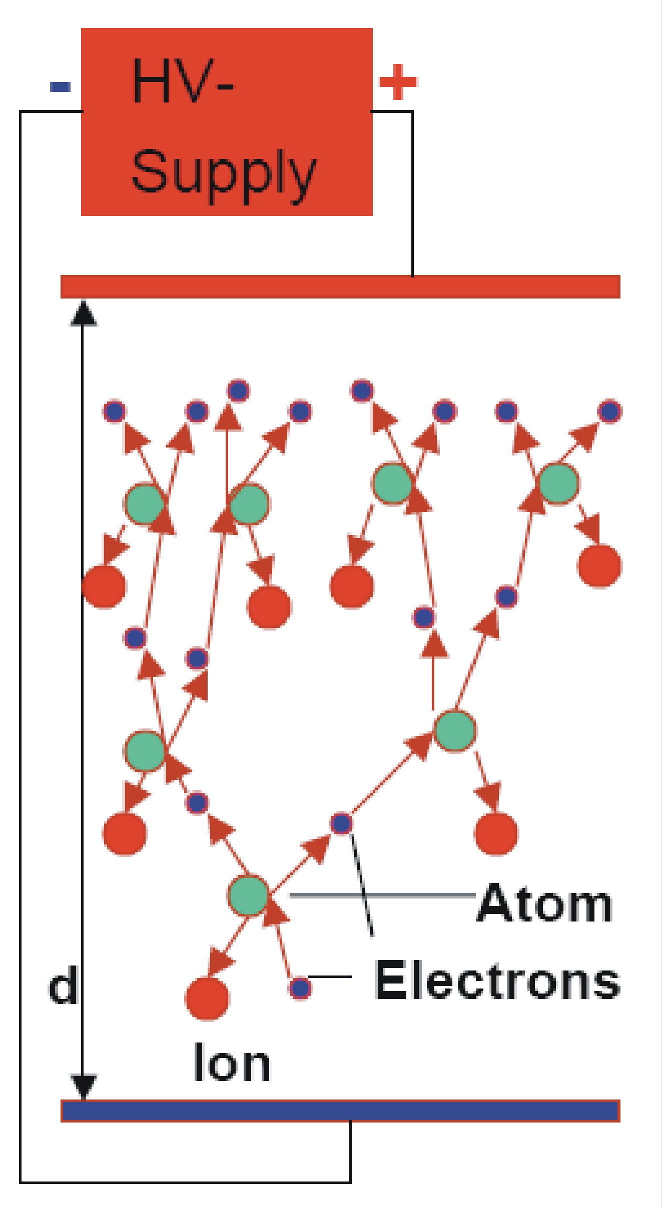


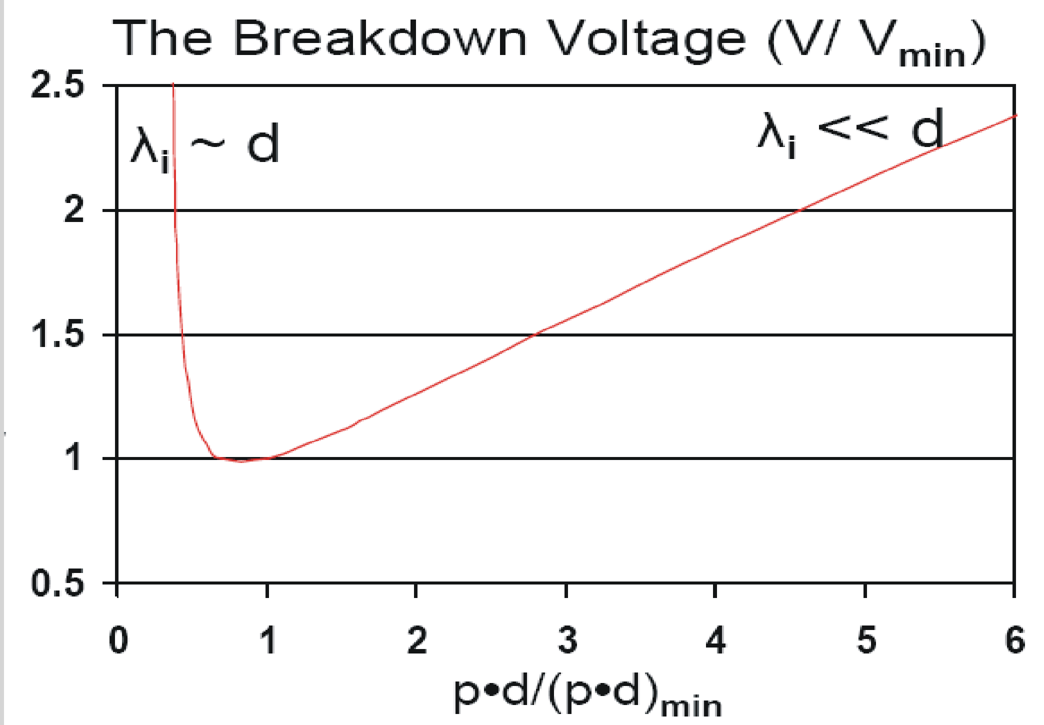
The impact of electron with gaseous atoms is mostly used for the production of ion beams.



For efficient ion production the electron energy should be appr. 2-4 times the ionization energy of the ion.

Production of charged Ions





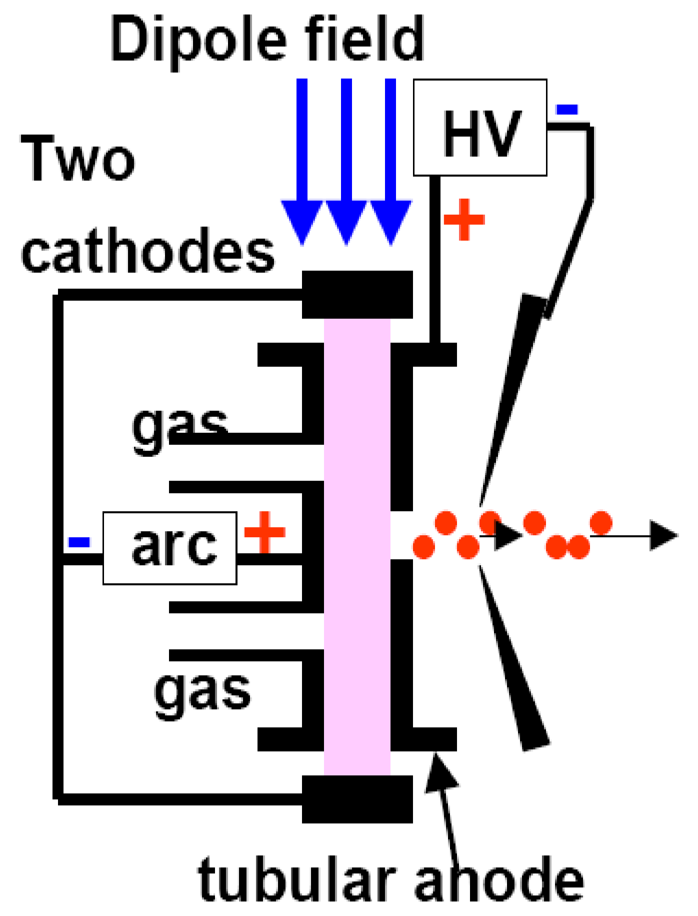
A Townsend gas discharge using an avalanche effect is an very effective way to produce a high amount of ions. Therefore the Paschen criteria has to be fulfilled. To improve the gas discharge and to enhance plasma confinement magnetic fields are used.

Penning sources

The Penning Ion Source or PIG source (Philips Ionization vacuum Gauge) invented by Penning in 1937 uses a a dipole field for plasma confinement .

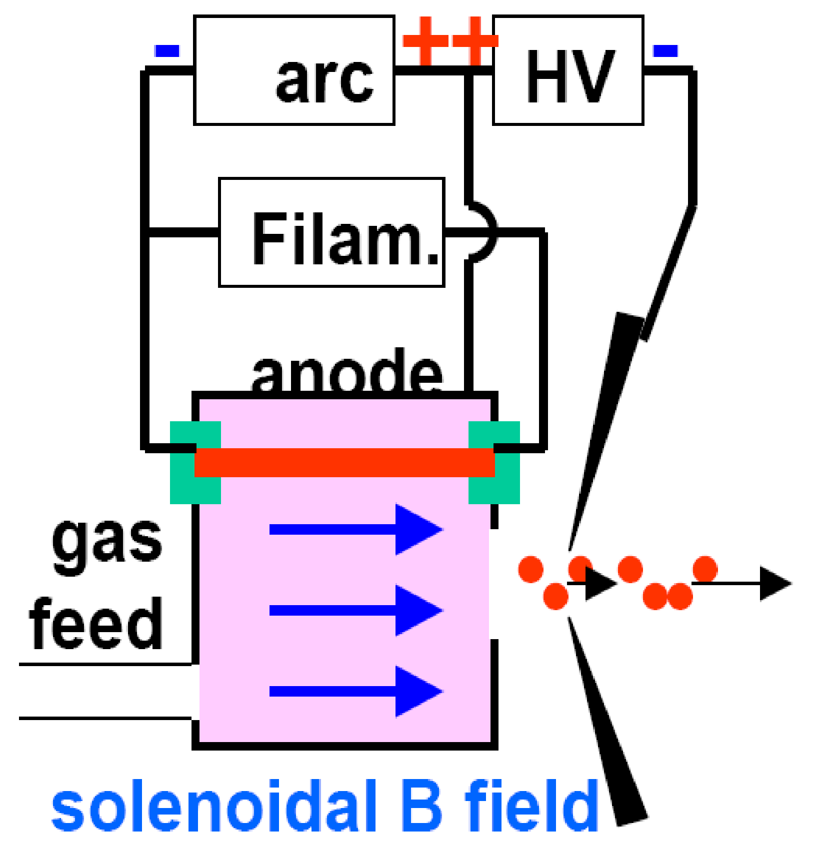
The strong magnetic dipole field gives high efficiency as electrons oscillate inside the hollow anode between the two cathodes at each end.

The Lifetime of the source limited by ***sputtering*** *of the cathodes, especially for highly charged, heavy ion operation.*



Magnetron sources

The Magnetron ion source which was first presented by Van Voorhis in 1934 uses a solenoidal magnetic field for plasma confinement The field of ~ 0.1 T is generated with an external solenoid surrounding the ion source. The chamber wall serves as anode, while the cathode provides electrons through thermionic emission. The filament mounted parallel to the magnetic field forces the electrons to spiral. As with Penning sources the Lifetime of the source limited by ***sputtering*** *of the cathodes, especially for highly charged, heavy ion operation*.



Hot cathode sources

Filament Ion Source

Discharge in the plasma chamber is driven by the electrons delivered by the filament.

Single charged ions up to 100 mA

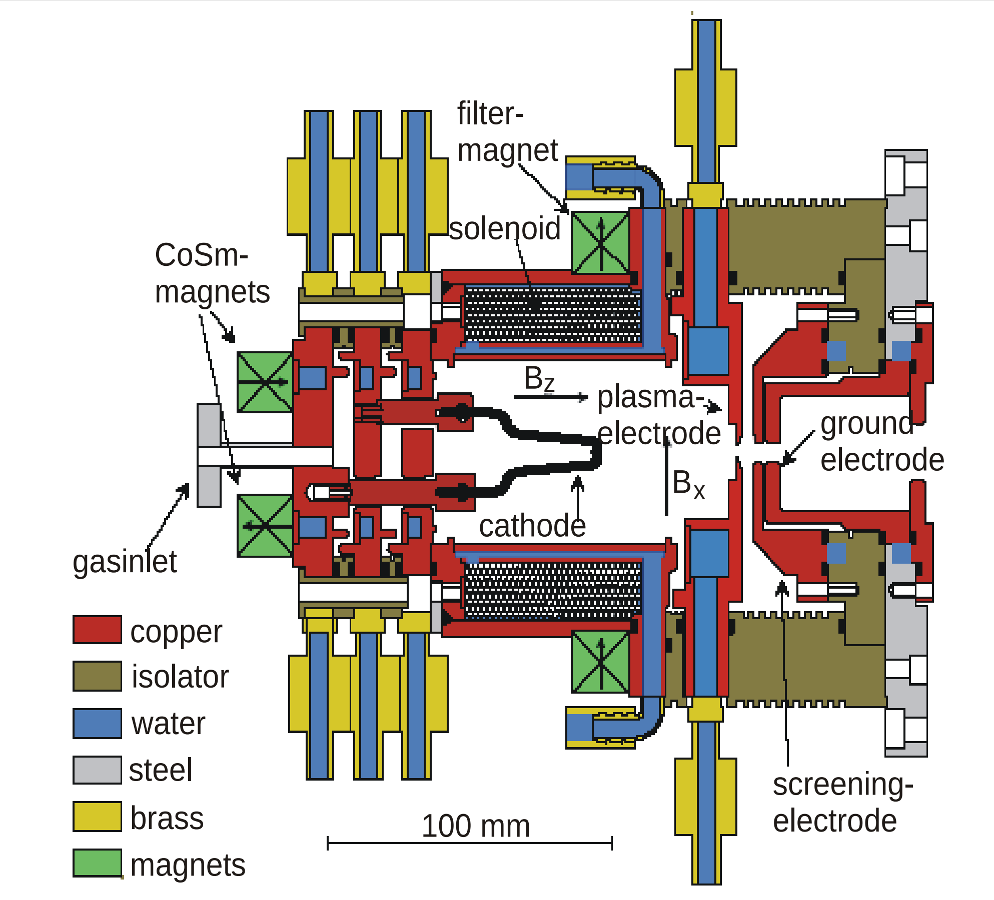
Plasma enclosure by magnets.

Pressure range 10^{-1} - 10^{-3} mbar.

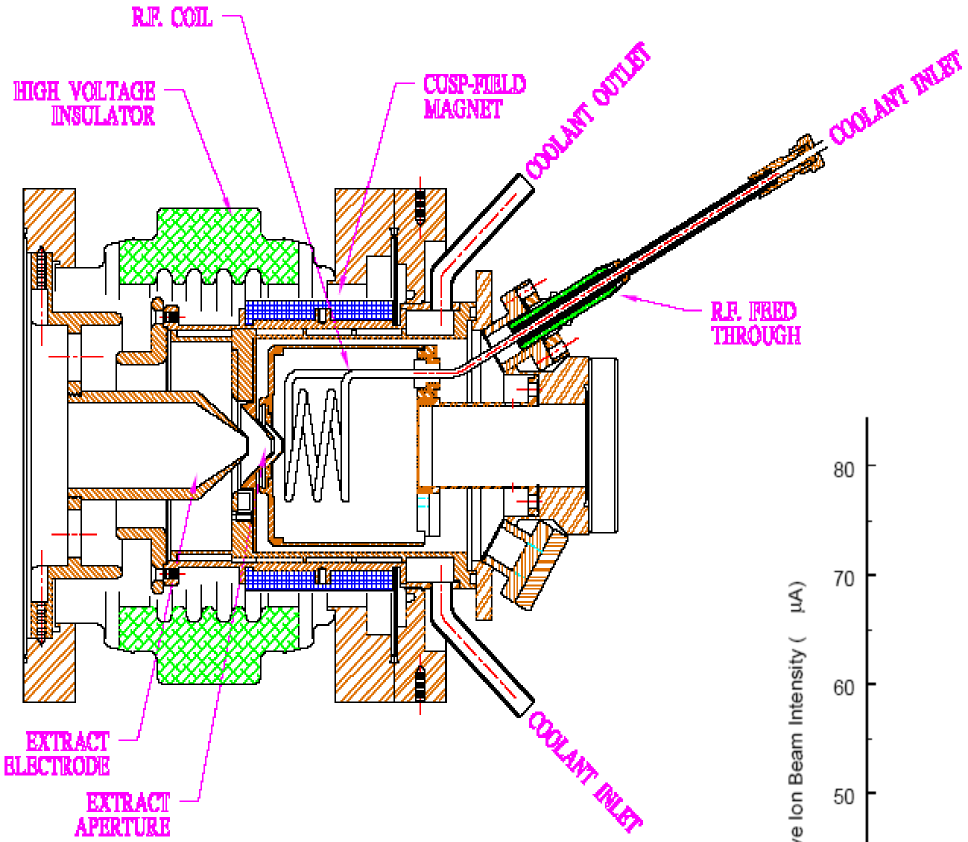
Discharge voltage 20 - 200 V

(depending on ionization voltage)

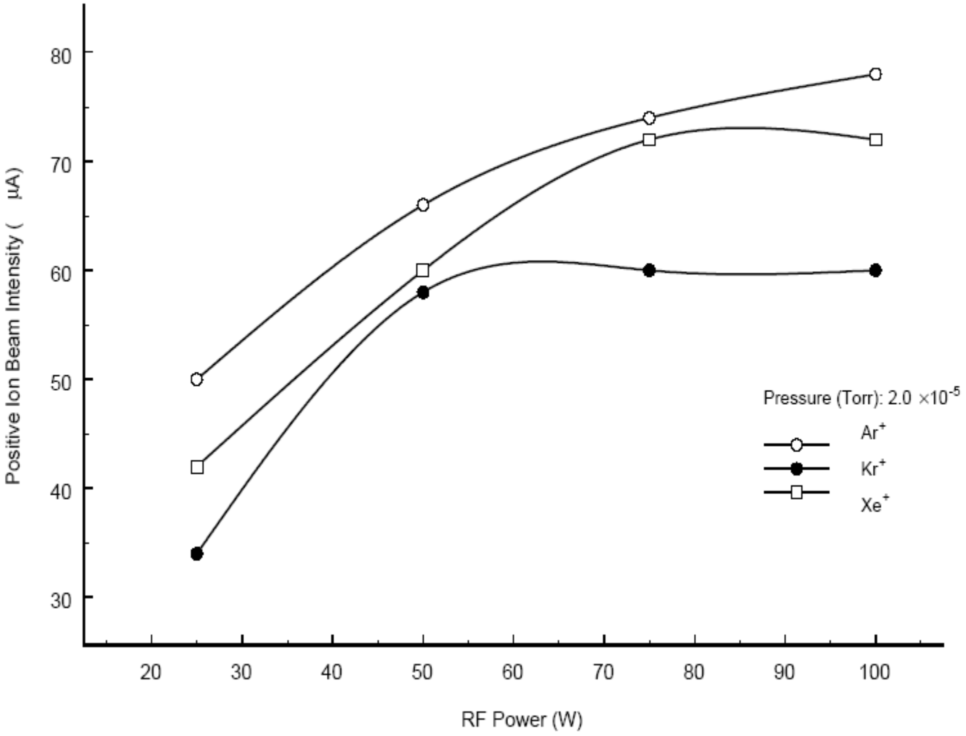
Discharge current 10 - 500 A



RF sources

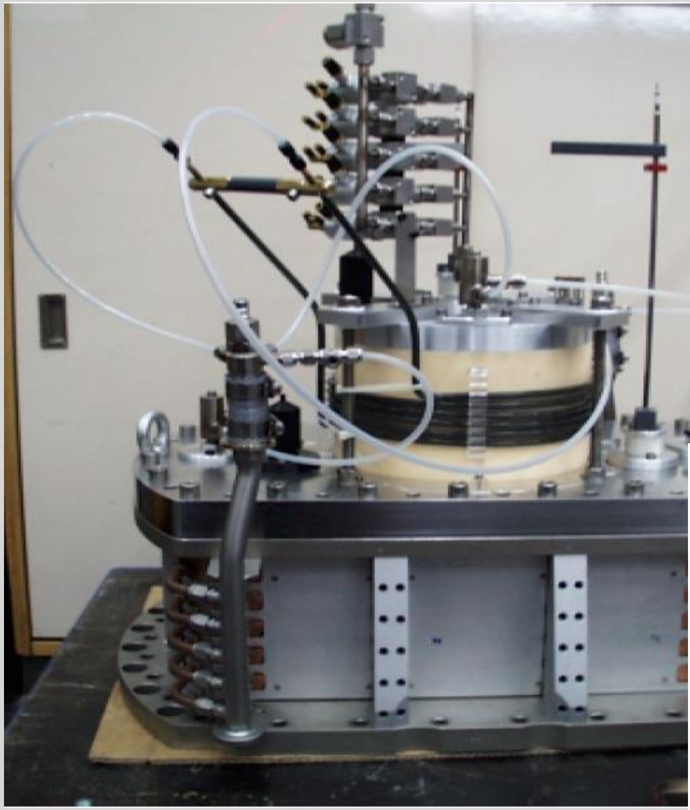


Non resonant excitation of plasma by RF. Only lower charge states available (low electron energy) but high beam currents possible.



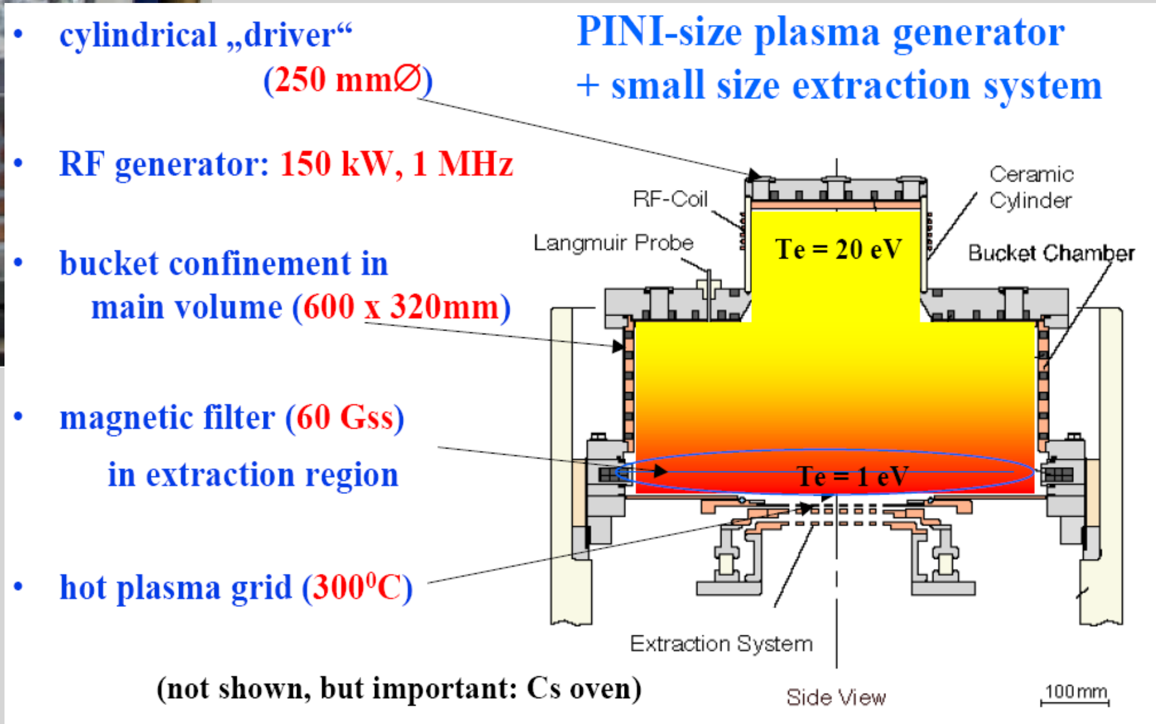
Internal antenna to feed RF power into plasma => limited lifetime of antenna due to sputtering, strong coupling of RF into plasma and good plasma confinement.

RF sources



Production of large ion currents (I>1 A) of single charged ions for surface treatment or plasma heating (tokamaks).

Multiaperture extraction therefore difficult to feed beam into conventional accelerator structure.



PINI-size plasma generator
+ small size extraction system

- **cylindrical „driver“ (250 mm∅)**
- **RF generator: 150 kW, 1 MHz**
- **bucket confinement in main volume (600 x 320mm)**
- **magnetic filter (60 Gss) in extraction region**
- **hot plasma grid (300^0C)**

(not shown, but important: Cs oven)

External antenna to feed RF power into plasma => Long lifetime of antenna, but chamber has to be of non conducting material.

Production of high charge state ions

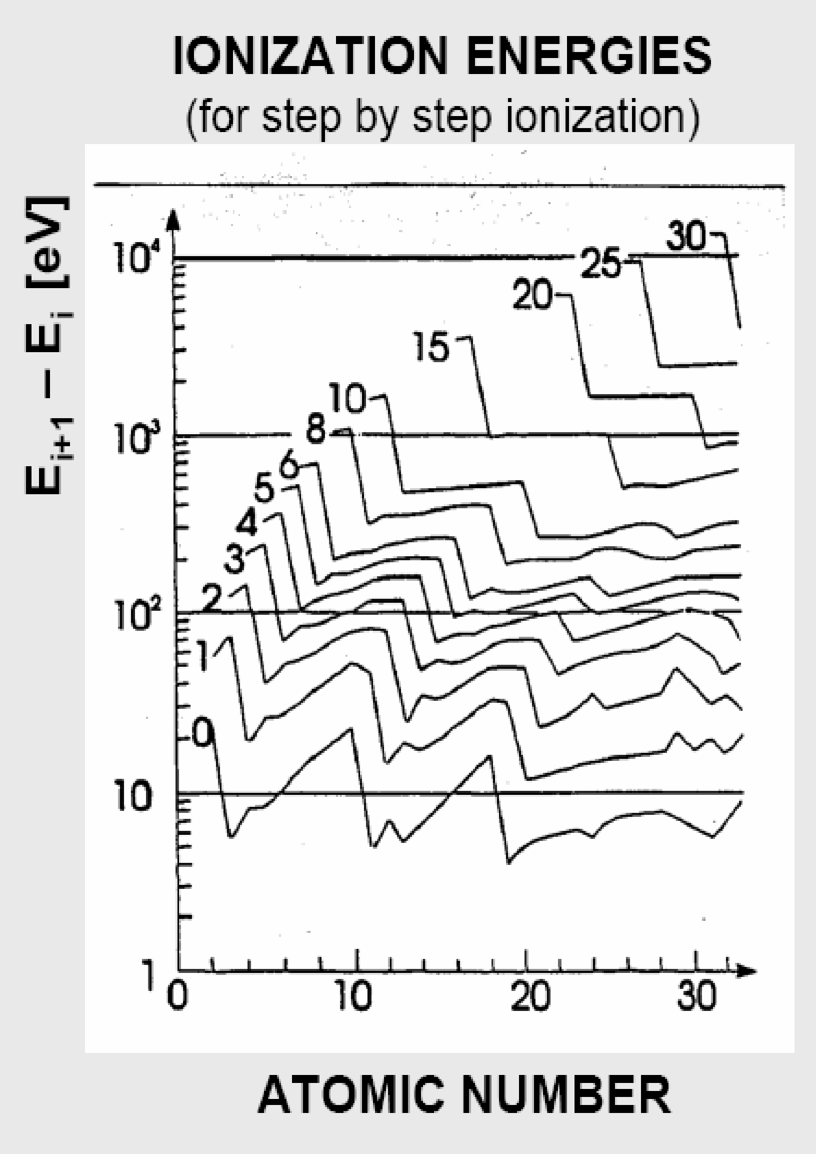
The **PLASMA** created is increased in density by electron bombardment. The maximum charge state that will be obtained depends on the incident electron energy.

$$e + X = X^{+} + 2e$$

For multi-charge states

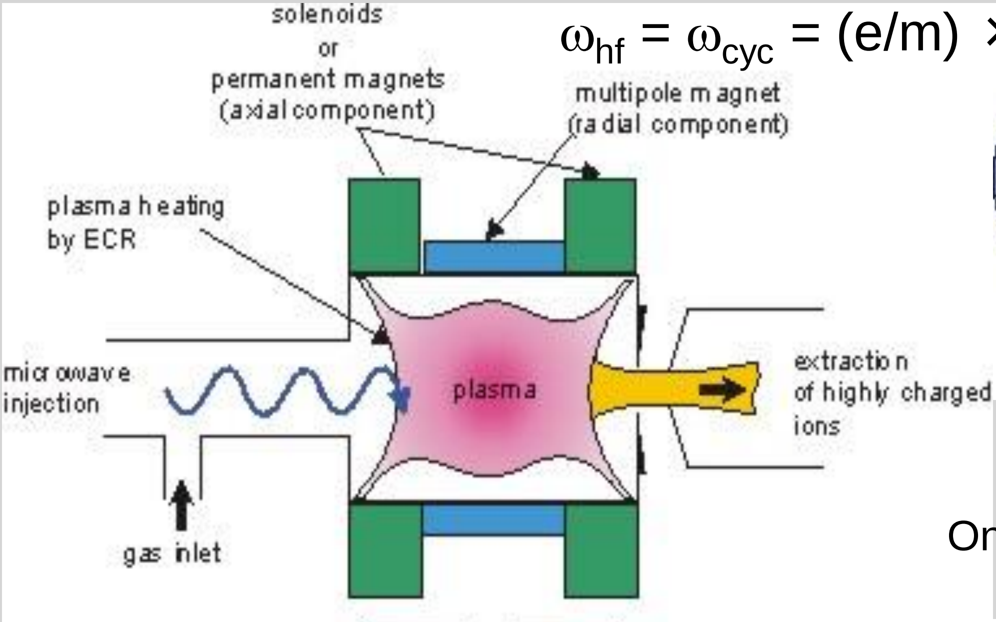
$$e + X^{i+} = X^{(i+1)+} + 2e$$

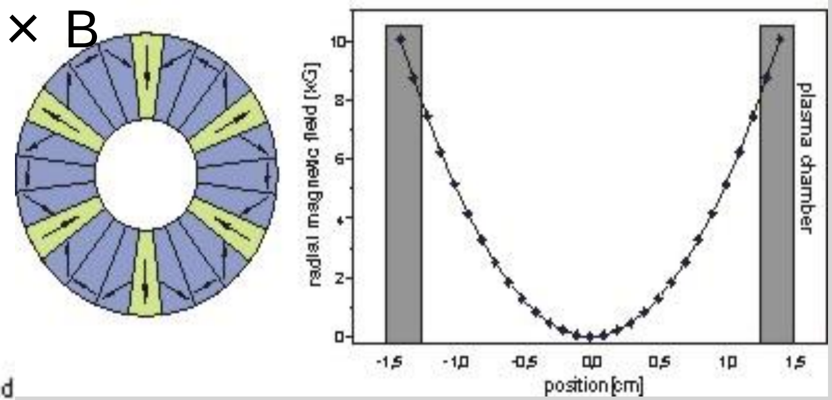
higher electron energies are required since electrons have to be removed from inner shells. The maximum charge state is limited by the incident electron energy.



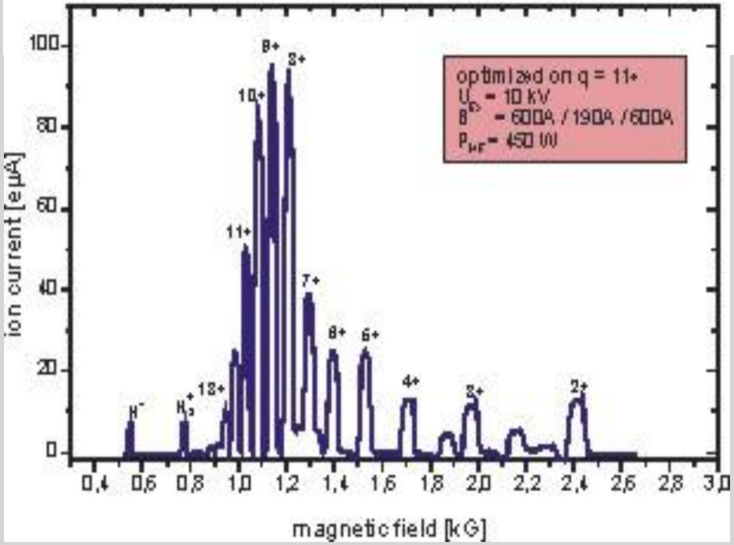
Electron Cyclotron Resonance Source

$$\omega_{hf} = \omega_{cyc} = (e/m) \times B$$

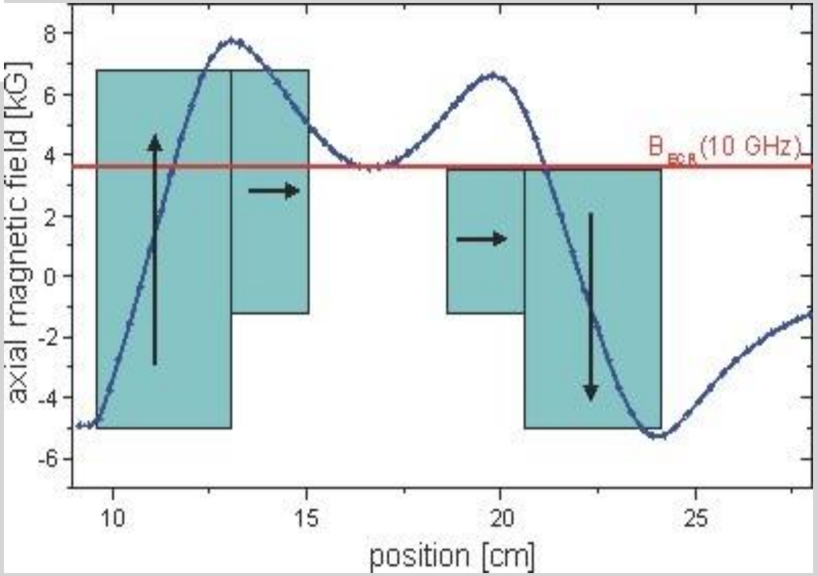




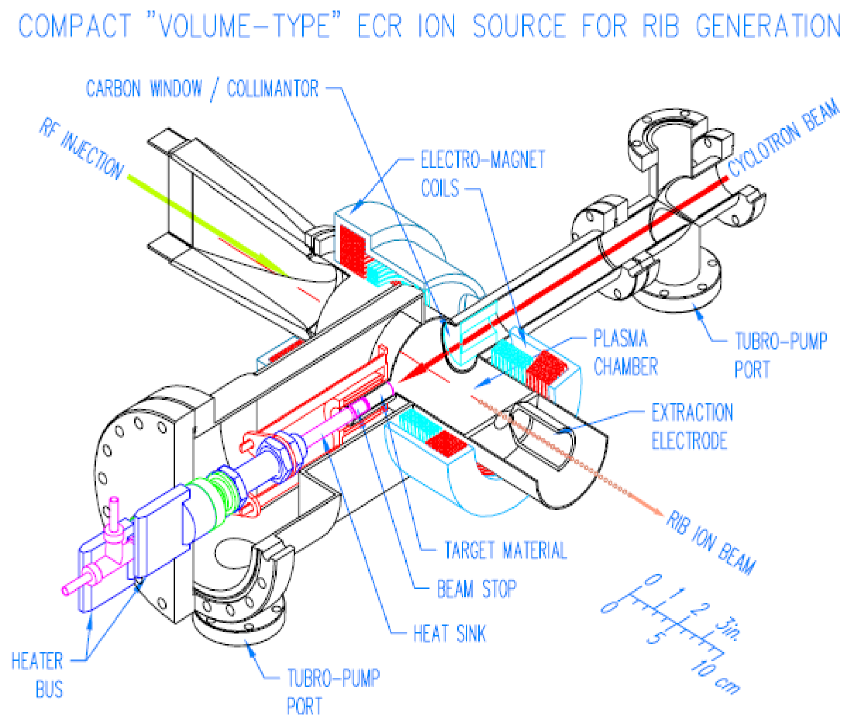
Radial and axial magnetic field distribution for the confinement of the source plasma. Only at the centre of the source the cyclotron condition for the electrons is full filled.



ion currents for different charge states of Argon

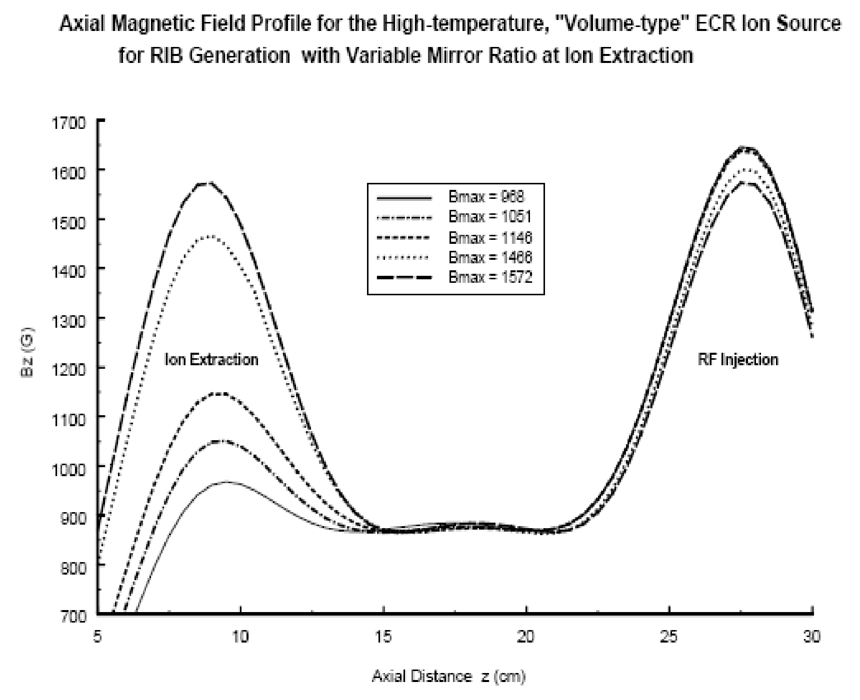


Electron **C**yclotron **R**esonance source



COMPACT "VOLUME-TYPE" ECR ION SOURCE FOR RIB GENERATION

Schematic layout of an ECR source for the production of radioactive ion beams



Axial Magnetic Field Profile for the High-temperature, "Volume-type" ECR Ion Source for RIB Generation with Variable Mirror Ratio at Ion Extraction

By variation of the longitudinal enclosing magnetic mirror configuration the charge distribution can be influenced.

Electron Beam Ion Source

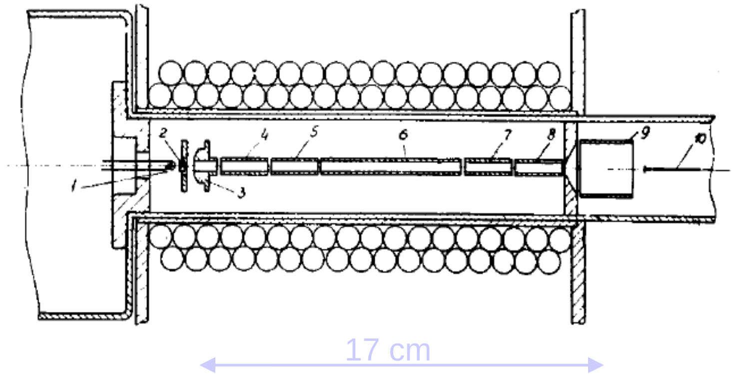
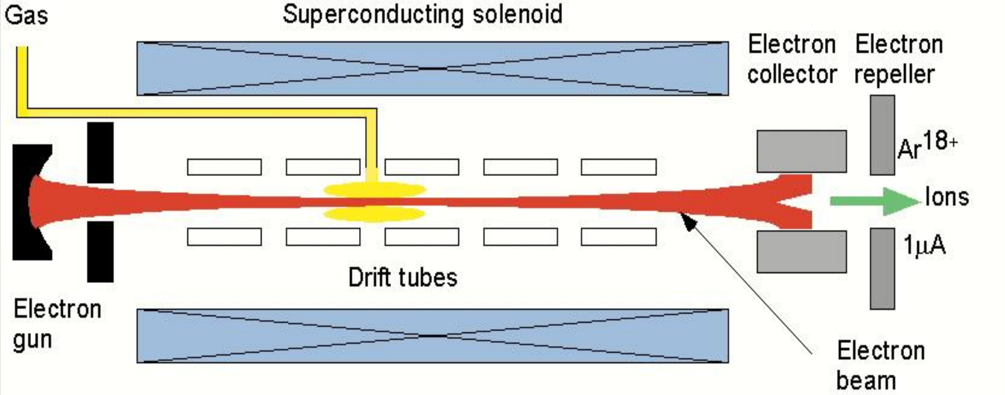
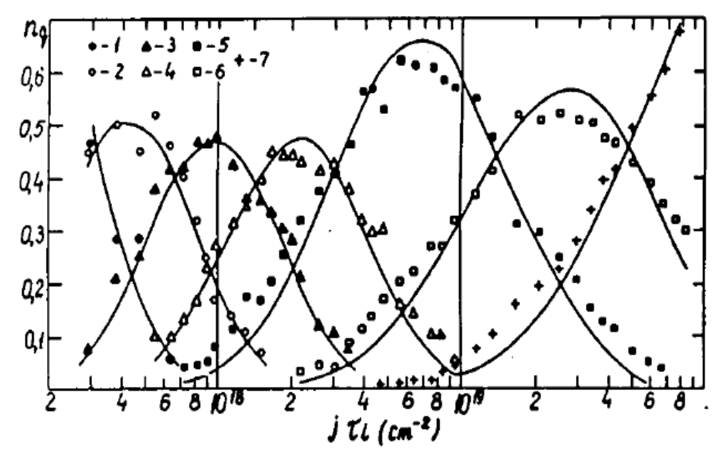


FIG. 1. Schematic diagram of the first EBIS IEL-1: 1,2,3—electron gun; 4,5,6,7,8—drift tube structure; 9—electron collector; 10—ion collector (Ref. 5).

CRYogenic Stockholm Ion Source



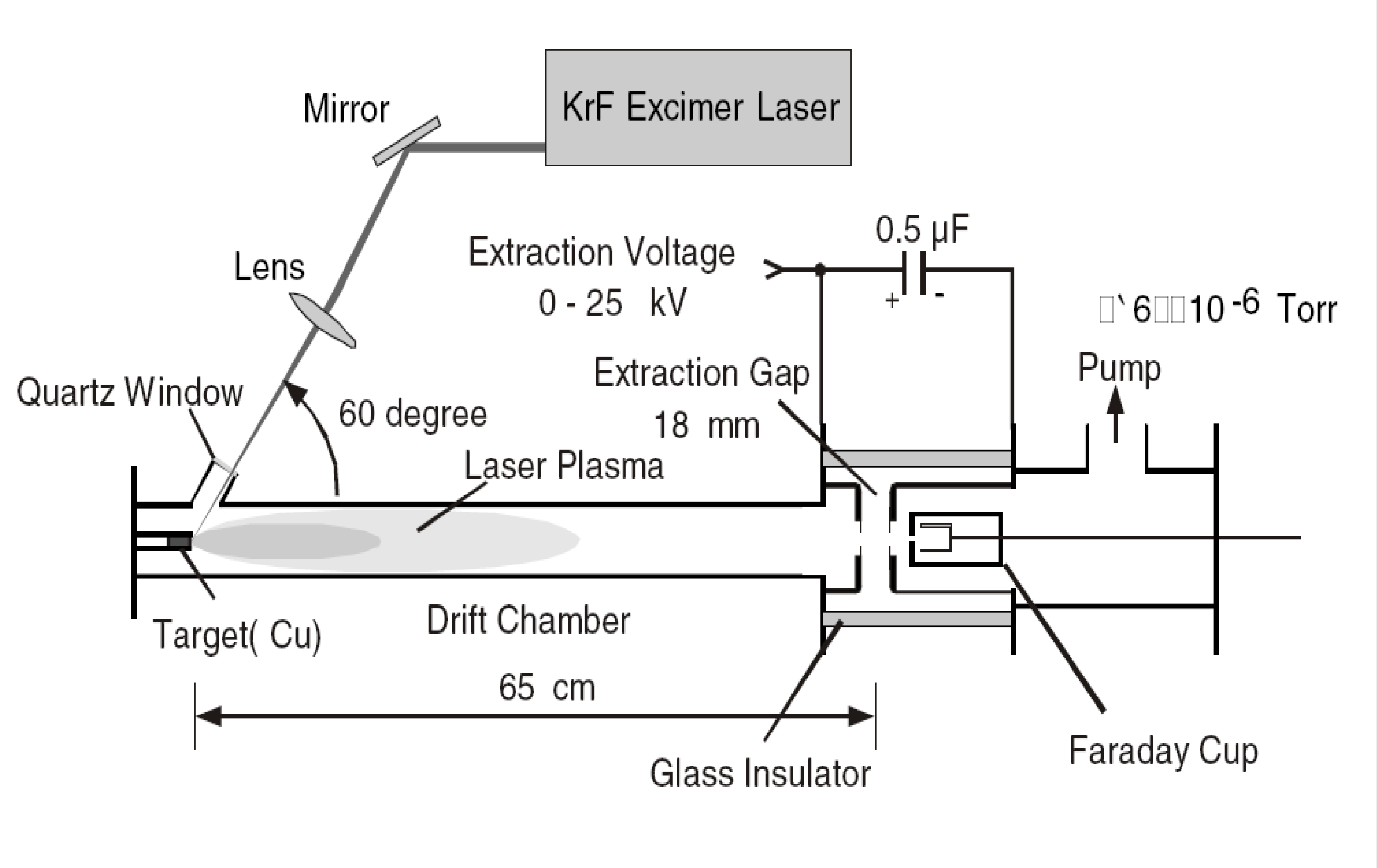
Upper: First EBIS IEL-1 build by Donets in 1968, lower : Evolution of charge state distribution of nitrogen ions at E_e=5.45 keV



Parameters of CRYSIS

	nominal values	max values	units
electron beam current	350	1300	mA
electron beam energy	20	27.5	keV
trap length	1.2	-	m
magnetic field	1.5	5	T
charge per pulse	1-2	4	nC
ion pulse length	0.05-100	-	µs
containment time	20-2000	-	ms

Laser Ion Sources



Schematic drawing of the experimental set up of a laser ion source. By the impact of the laser with the target, a plasma is created which expands in the drift chamber and then is accelerated in the extraction gap.

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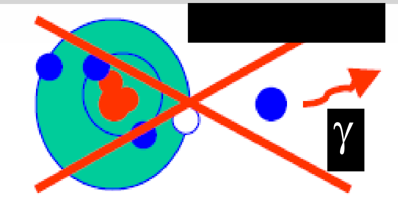
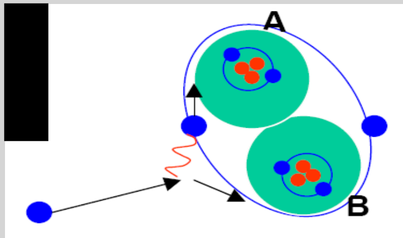
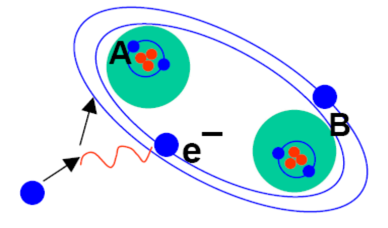
Production of negatively charged ion beams


[redacted]

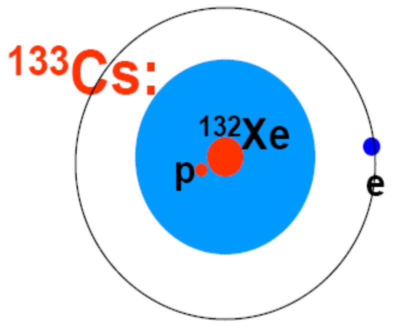
Conserving energy when forming a negative ion through direct electron attachment, the excess energy has to be dissipated through a photon. $A + e = A^- + \gamma$. *But radiative Capture is rare* ($5 \bullet 10^{-22} cm^2$ *for* H_2).


[redacted]

Higher cross sections ($\sim 10^{-20} cm2$ *for* H_2 *and* $E_e > 10$ *eV*) *can be realized when the excess energy can be transferred to a third particle,* $M + e = A + B + e$ *and sometimes* $= A + B^-$



Even better are processes which excite a molecule to the edge of breakup (vibrationally excited $4<n<12$*) and then dissociated by a slow electron*

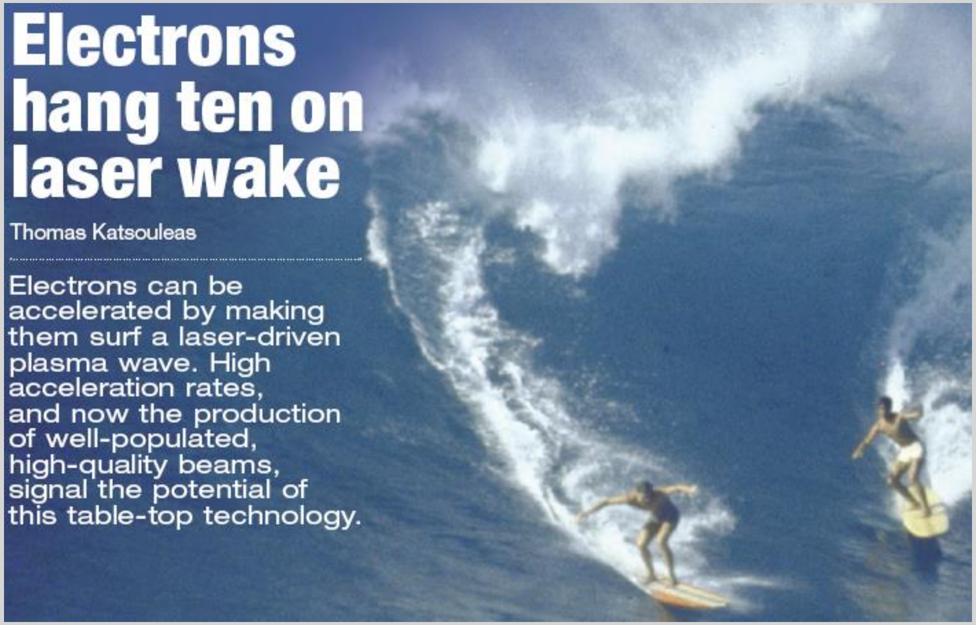


Cs can be used as an electron donator, but the ionisation energy of 3.9 eV is much higher than the 0.75 eV electron affinity of H^-
=> Surface treatment

Three Types of H^- Ion Sources are in use

- Surface conversion sources
- Volume production sources
- Hybrid production sources

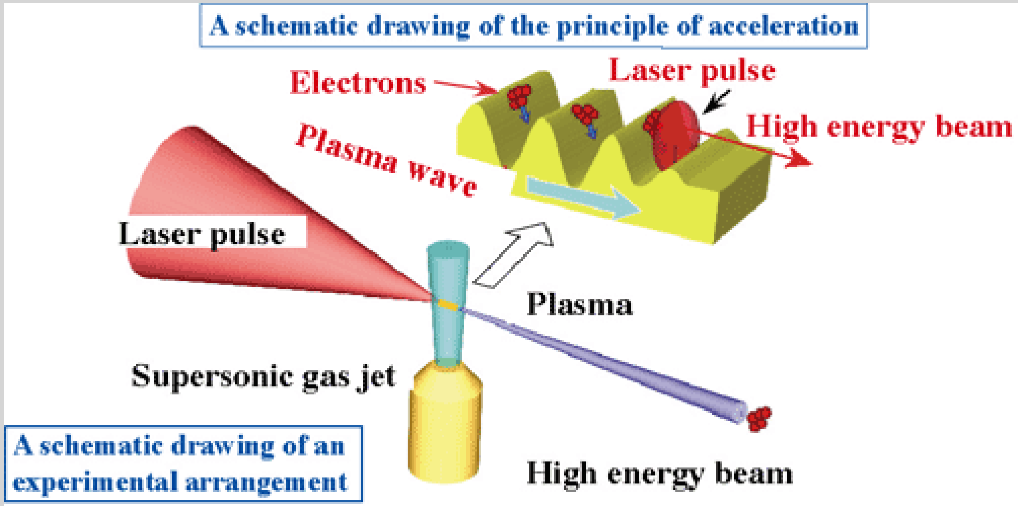
Laser accelerator ....also an Ion source

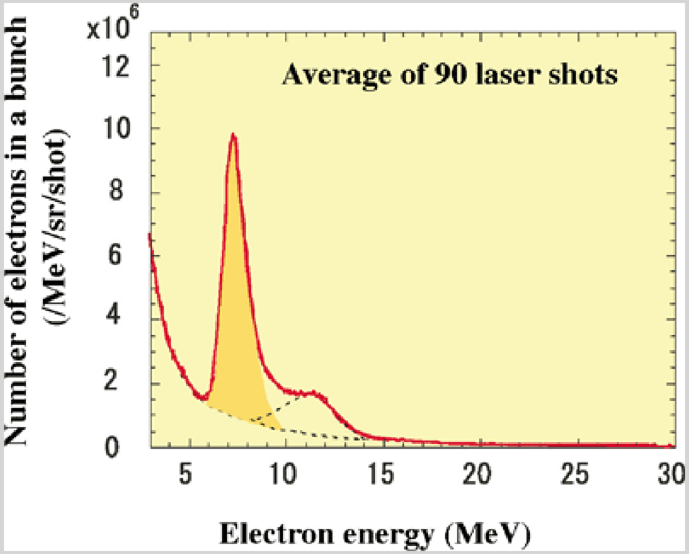


Electrons hang ten on laser wake

Thomas Katsouleas

Electrons can be accelerated by making them surf a laser-driven plasma wave. High acceleration rates, and now the production of well-populated, high-quality beams, signal the potential of this table-top technology.





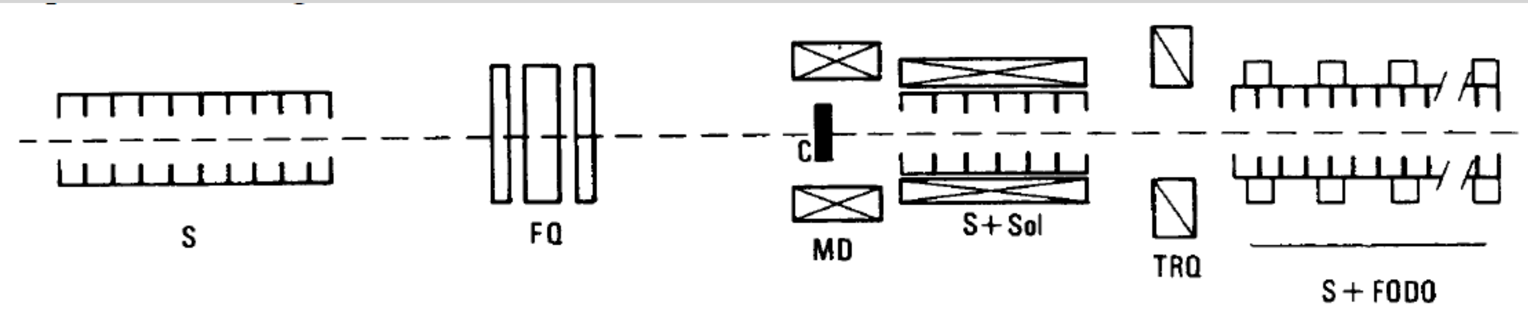
Secondary particle sources - Positrons

From radioactive decay:

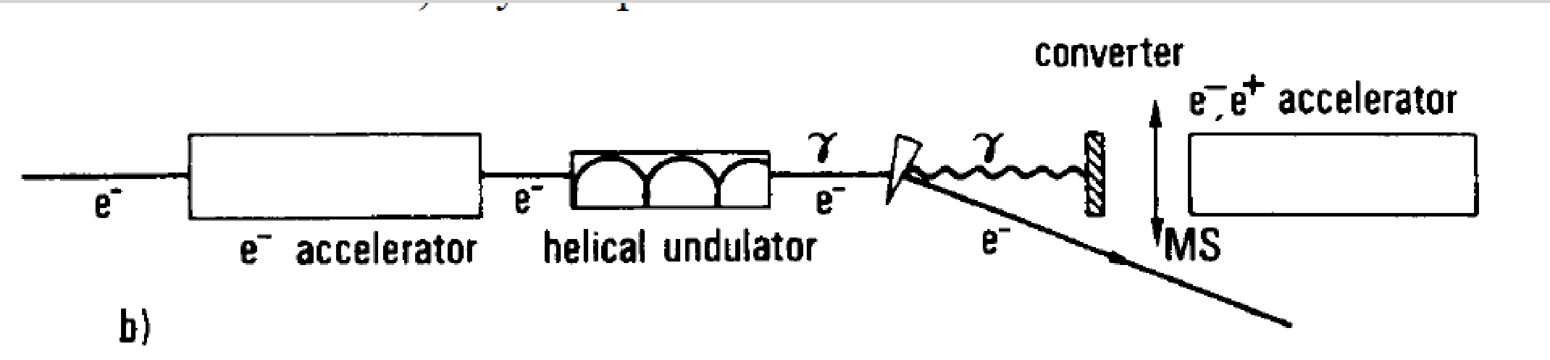
$$\mathrm{Cu}^{63} + \mathrm{n} \rightarrow \mathrm{Cu}^{64} + \gamma$$

$$\mathrm{Cu}^{64} \rightarrow \mathrm{N}_{\mathrm{i}}^{64} + \beta^{+} + \nu,$$

By the use of high energy electrons

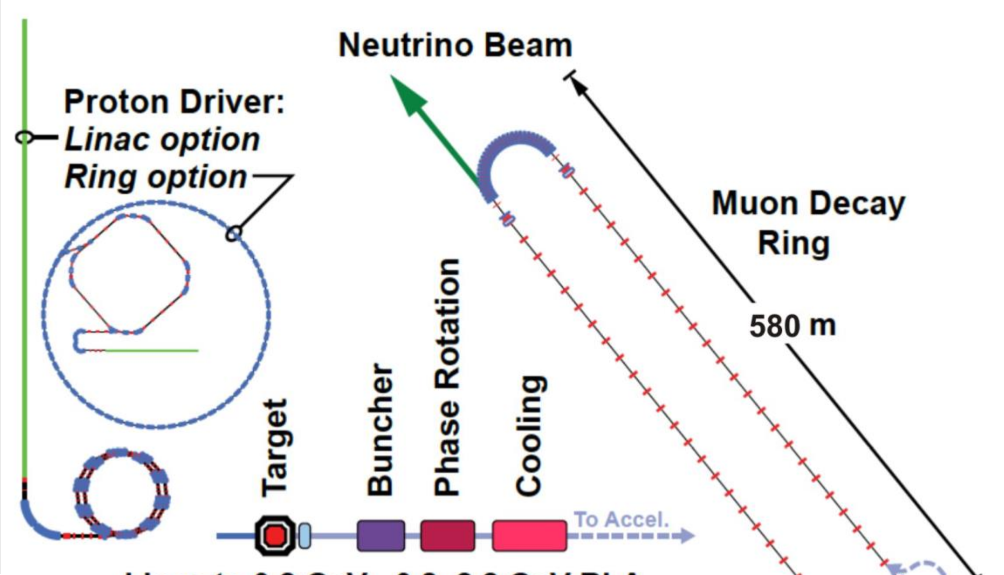


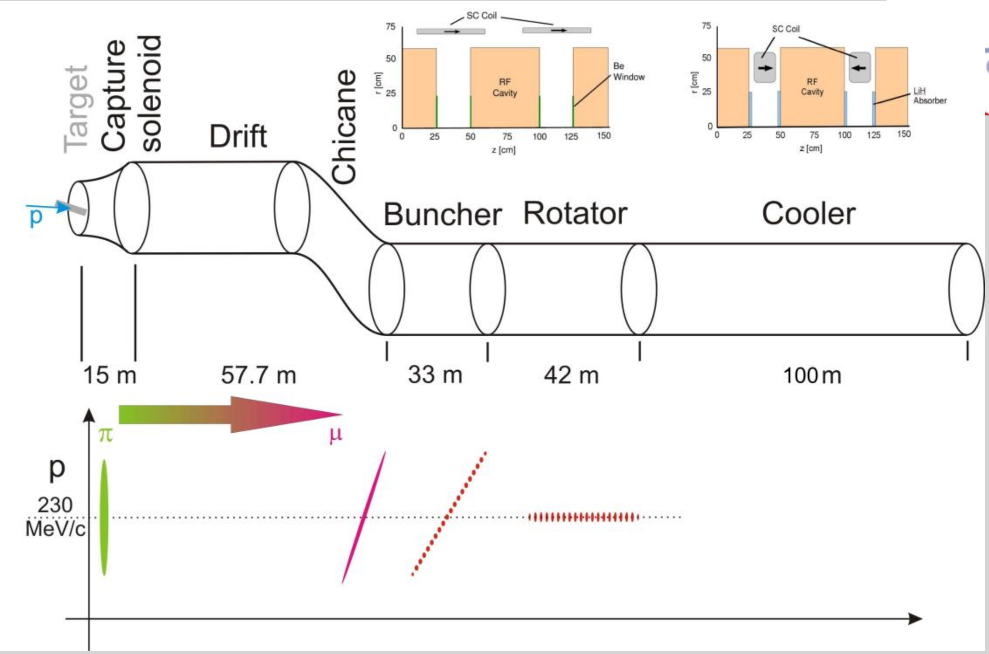
By the use of high energy photons



Secondary particle sources – Pions, Muons, Neutrinos

In a Neutrino factory the Neutrinos are produced by the decay of Muons which are the decay product of pions produced by the interaction of an high energy proton beam with a target. As the beam emittance is very high an cooling section is required to allow for efficient acceleration.





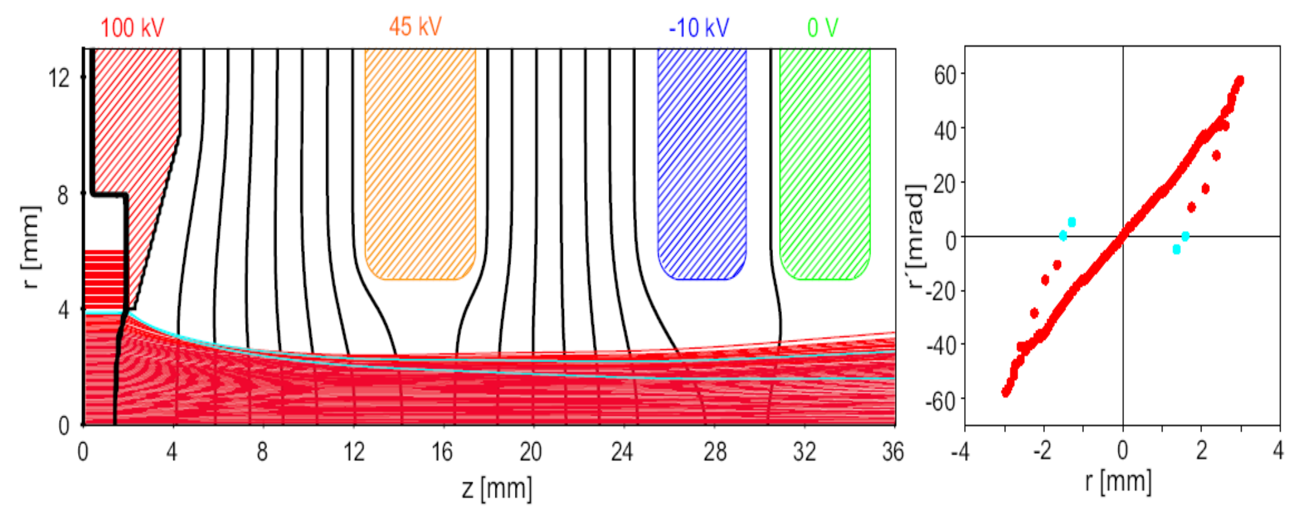
Summary

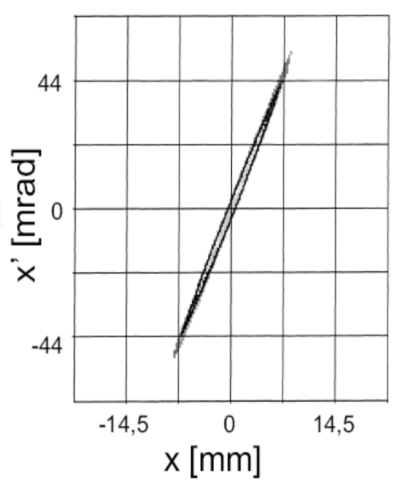
Particle sources for Accelerators covering a wide field of techniques depending on the specific particles, currents and the beam quality required.

While sources for electrons and single charged ions are wide spread, the production of highly charged ions, negatively chargde ions and secondary / tertiary particles require specific techniques and might need beam cooling to reach the required performance.

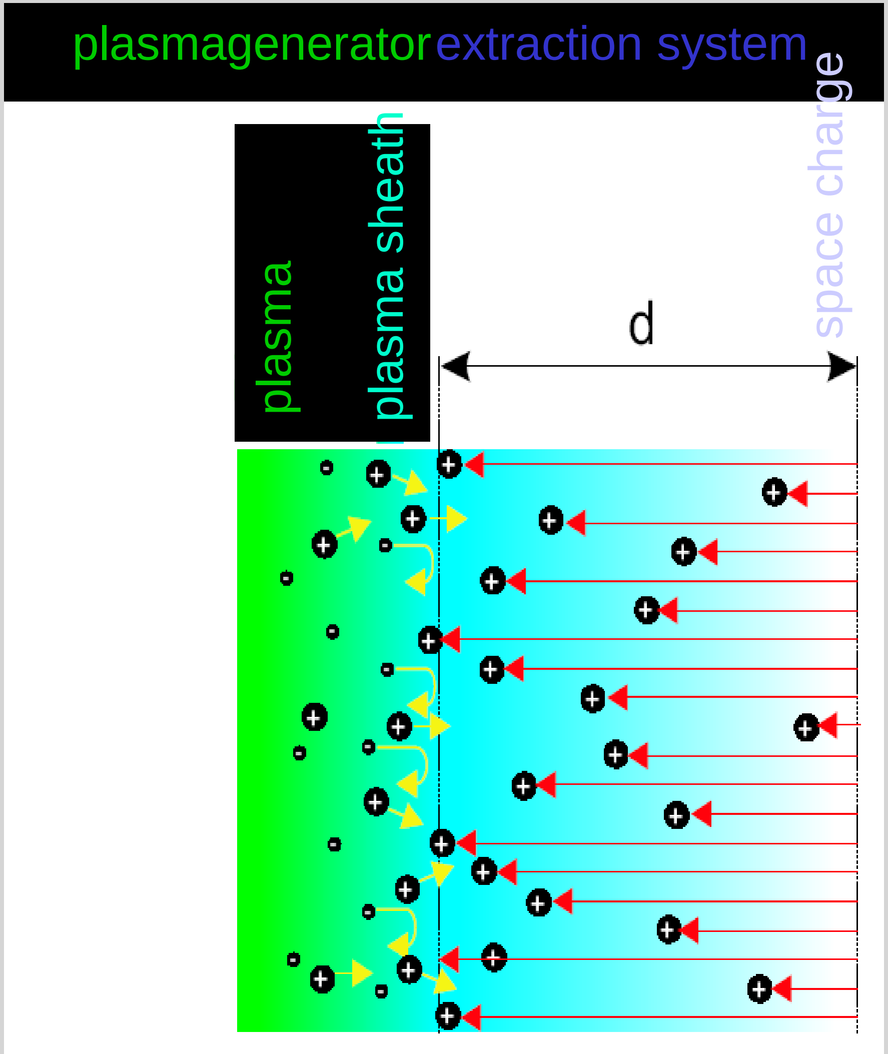
Additional information on Beam formation / Beam extraction

Initial Emittance : Numerical simulation of the extraction of a D^+ beam for IFMIF using IGUN and comparison with measured data





Ion beam extraction from a plasma



The extractable current from an ion source is limited by :

- Space charge forces in the extraction region
- Plasma density in the source
- Production speed of ions in the plasma
- Diffusion speed of ions from the plasma into the plasma sheath

Plasma sheath : While within the plasma the charges neutralize each other, the plasma itself is biased in respect to the walls to keep an equilibrium of losses between the fast electrons and slow ions. A thin boarder area (plasma sheath) separates the plasma from the outside by an electric field.

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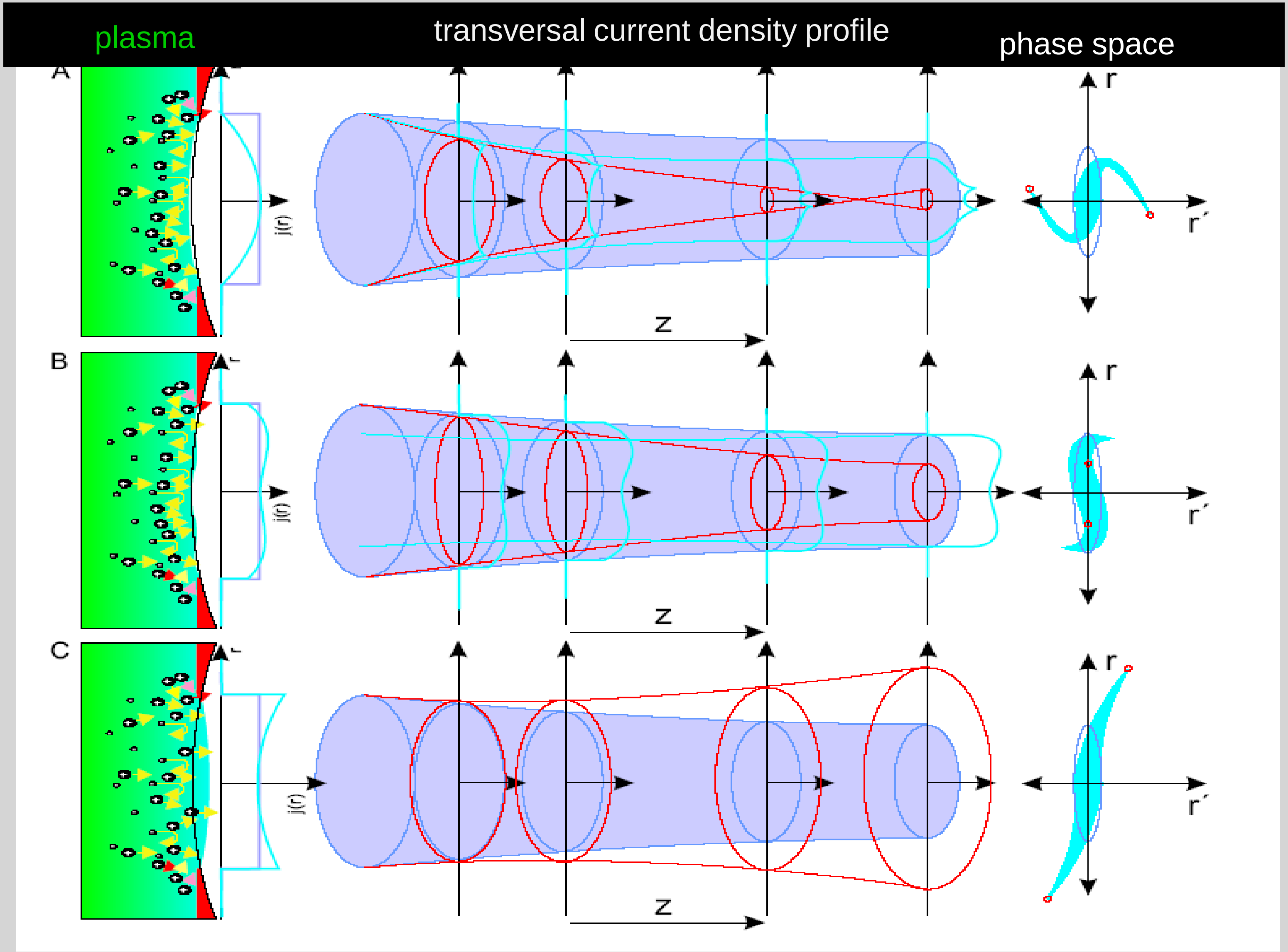
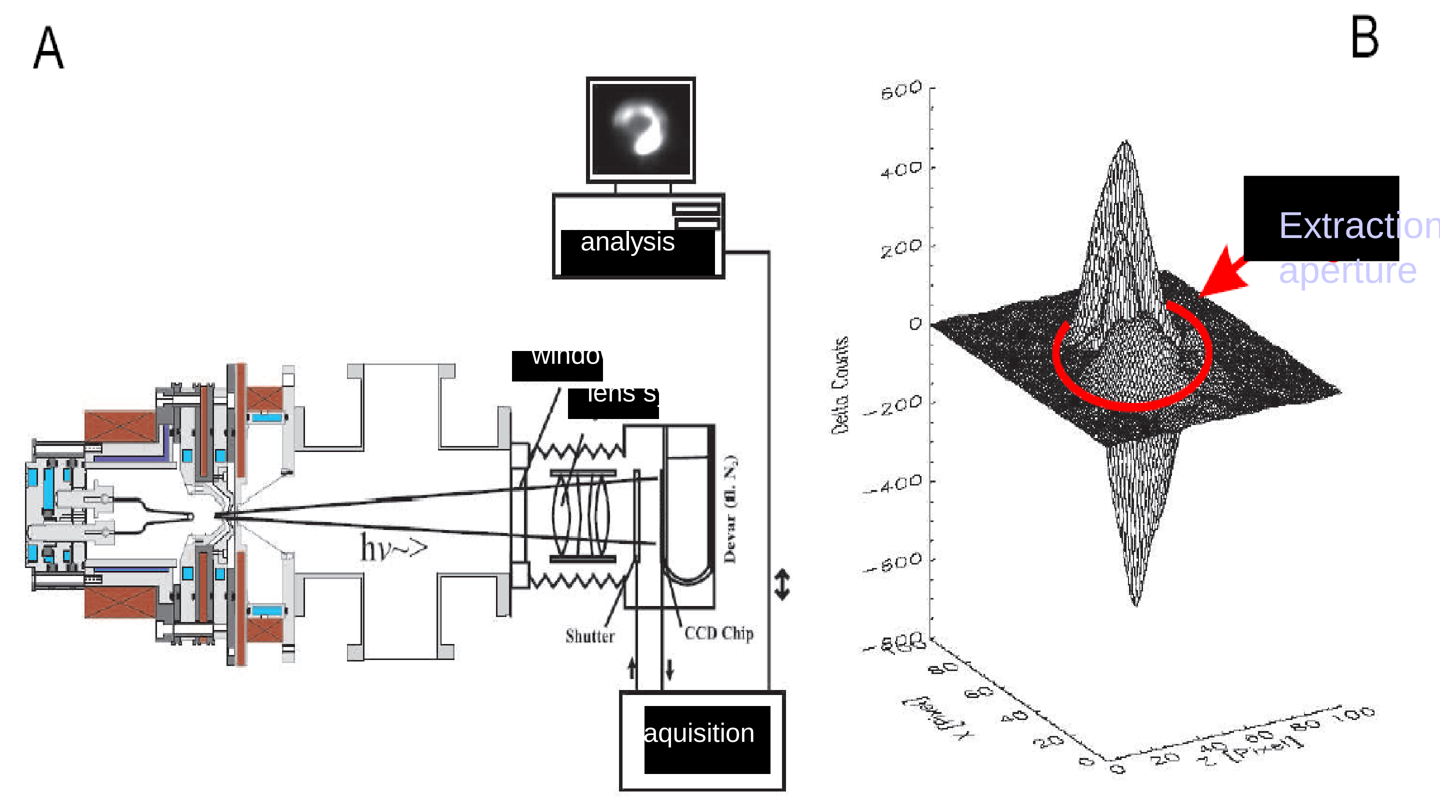
Influence of particle density distribution at the extraction aperture on initial phase space distribution

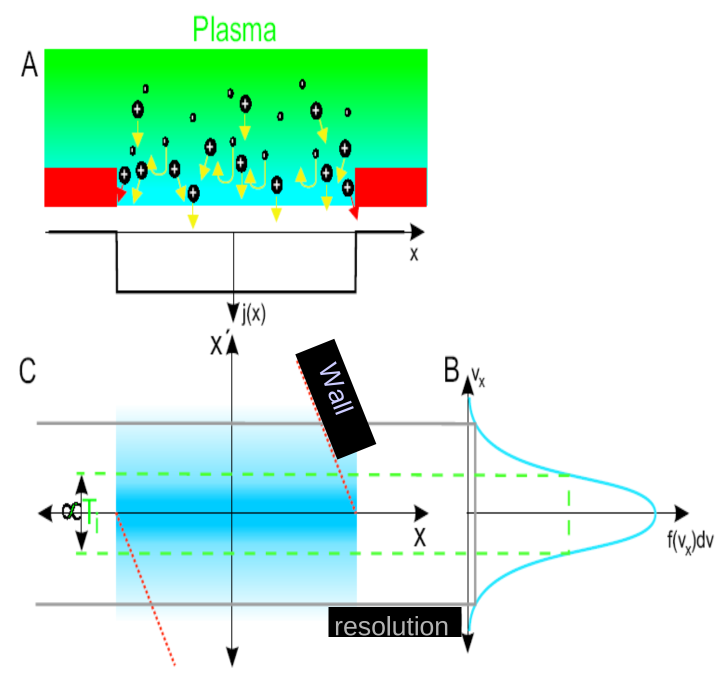


Plasma density distribution at extraction aperture

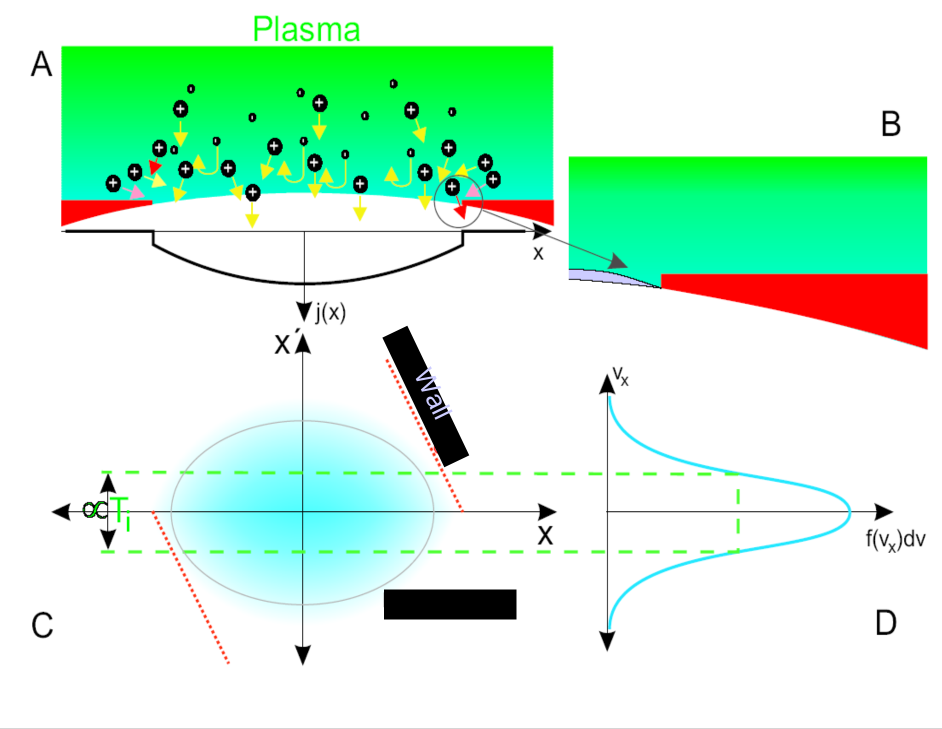


In praxis the particle density at the extraction aperture is not homogeneous. This will lead to non linear space charge forces within the beam transport. Redistributions of the beam particles within the beam cause growth of the effective (RMS) beam emittance.

The temperature of the source plasma, the potential depression in the plasma sheath and wall effects (losses of particles) are influencing the beam emittance.

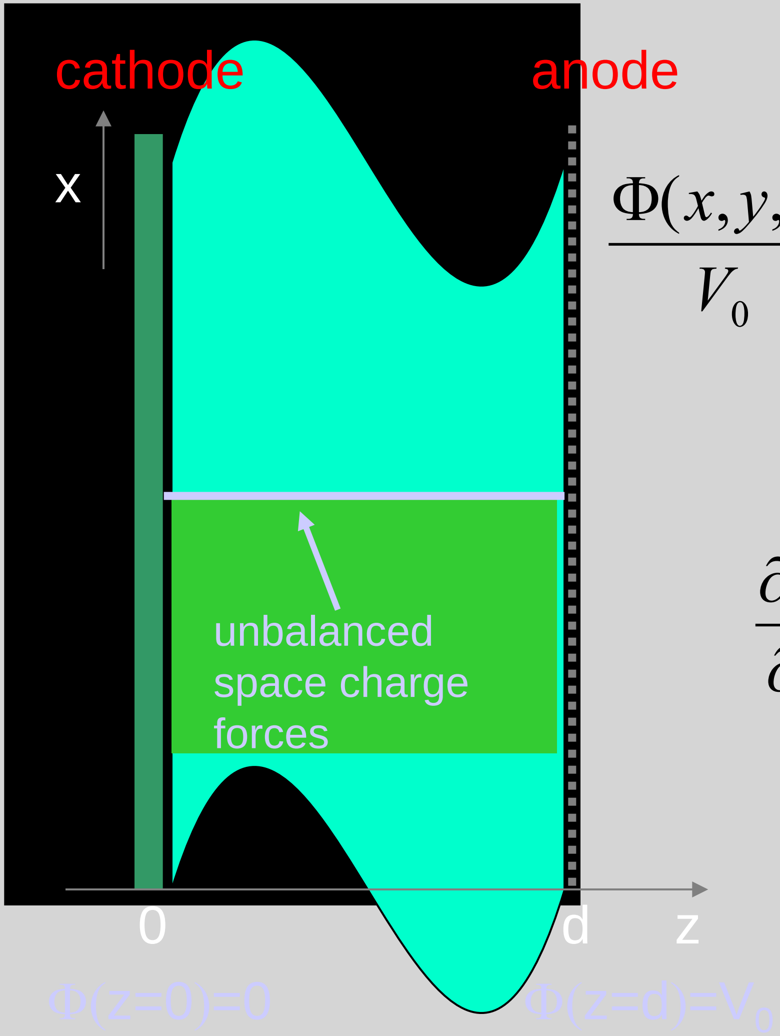


The transversal (and longitudinal) energy distribution of the beam ions is defined by the plasma temperature and the plasma potential (electric field in the plasma sheath)



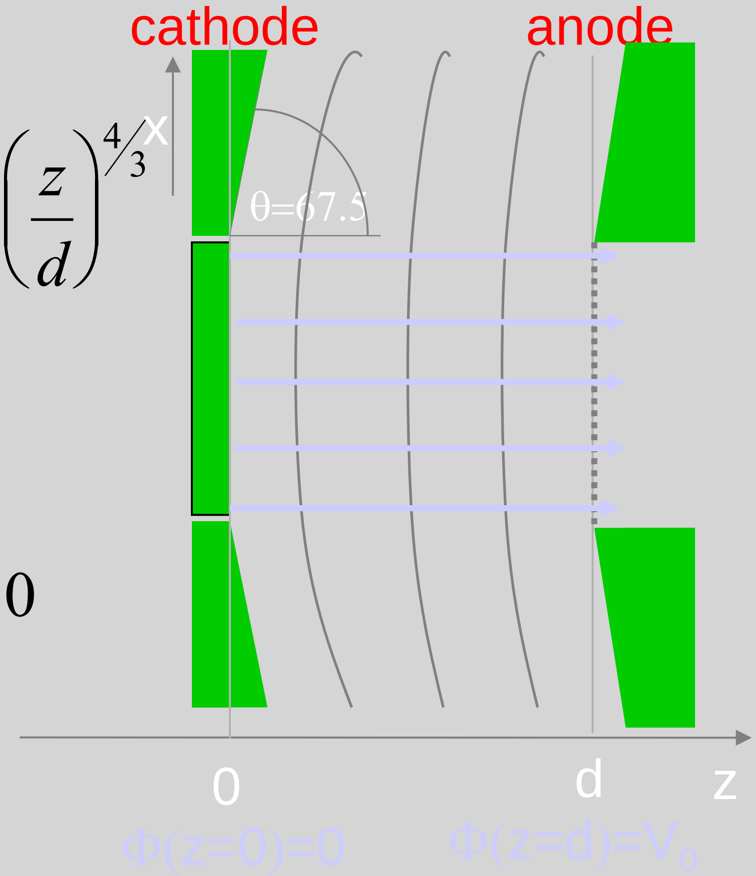
Losses of beam ions at the extraction electrode further reduces the number of ions to be extracted.

The Pierce method for the design of the extraction electrodes



$$\frac{\Phi(x,y,z)}{V_0} = \left(\frac{z}{d}\right)^{4/3}$$

$$\frac{\partial \Phi}{\partial x} = 0$$



Numerical simulation of H^- extraction and transport in the LEBT for SNS using PBGUN and comparison with measured data