Ion Sources for High Power Hadron Accelerators

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William Whewell
Cambridge Polymath

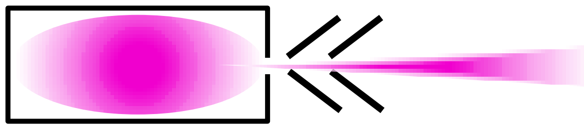
and prolific namer of things
Including "Scientist"!

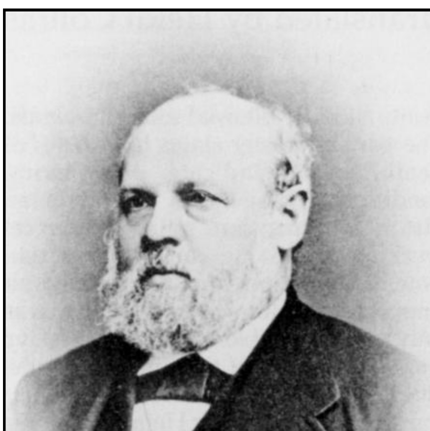
Ion: Greek ιον, meaning "going."

1834 ***Ion***- a charged particle that moves towards the electrode of opposite charge

Michael Faraday
Royal Institution Professor
Electrolysis

All ion sources consist of:





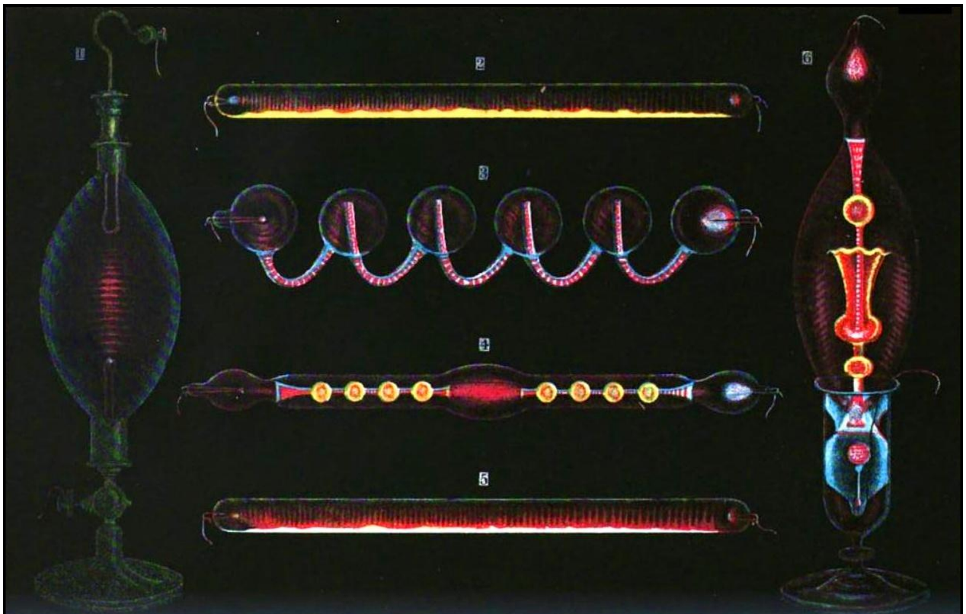
Heinrich Geißler

Gas discharge tube and mercury displacement pump just less than 1 mBar

Julius Plücker

Mid 1850's University of Bonn

magnetism could move the glow discharge



Drawing of Geissler tubes from 1860's French physics book

Fredrick Guthrie

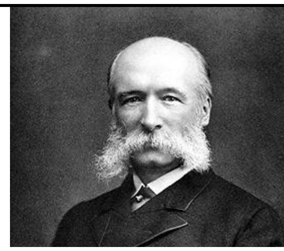
British scientific writer and professor

Elements of Heat in 1868

First experimental observation of thermionic emission

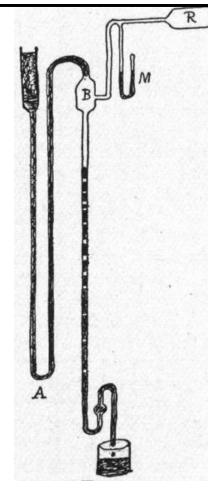
William Crookes

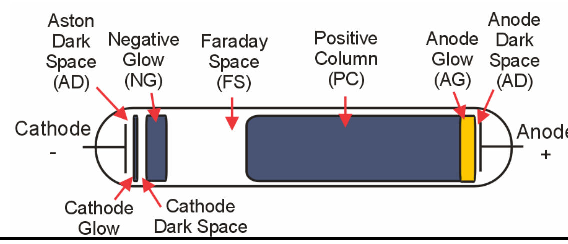
Early 1870's

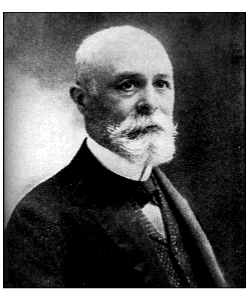


Hermann Sprengel

Improved mercury pump
10^{-6} mBar

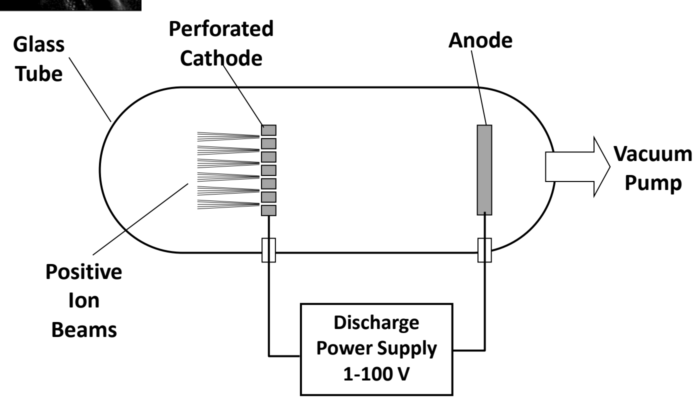


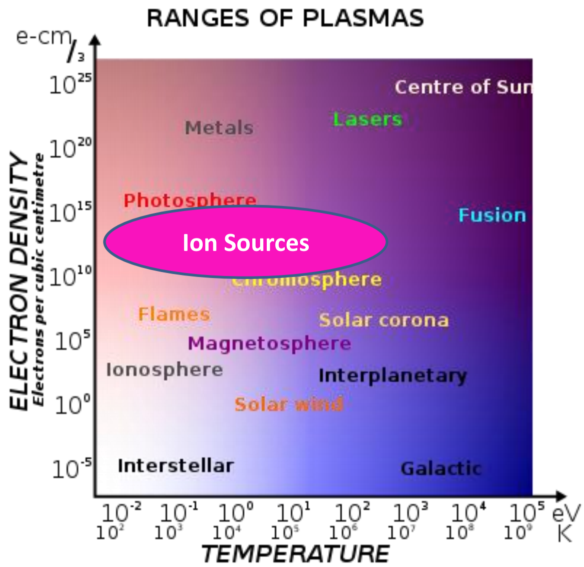




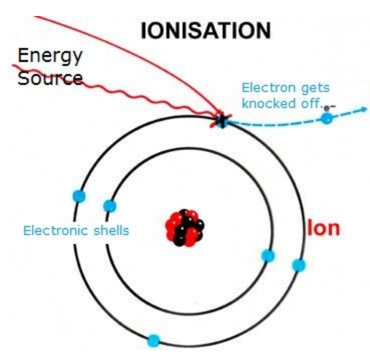
Canal Ray Source

In 1886 Eugen Goldstein discovered canal rays



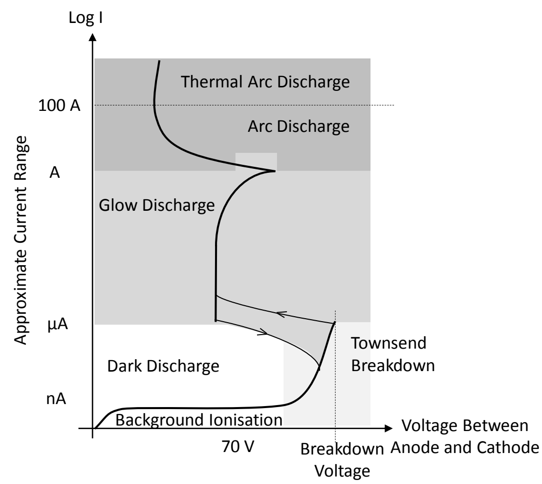


Ionisation

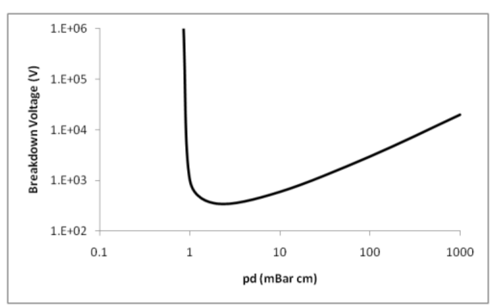


Most sources rely on electron impact ionisation

Electrical Discharges



Paschen Curve



Friedrich Paschen 1889

Basic Plasma Properties

Density, *n (per cm³)*

n_e = density of electrons

n_i = density of ions

n_n = density of neutrals

Charge State, *q*

H^+ → $q = +1$

Pb^{3+} → $q = +3$

H^- → $q = +1$

Temperature, *T* (eV)

T_e = temperature of electrons

T_i = temperature of ions

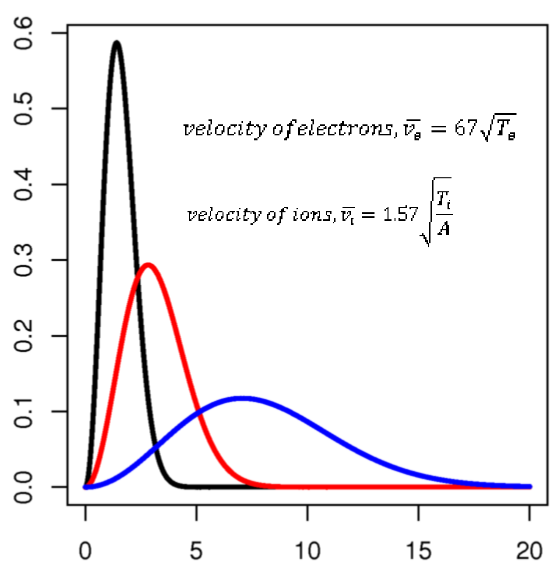
T_n = temperature of neutrals

Temperature Distribution

Maxwell Boltzmann statistics

In magnetic fields:

$v_x \neq v_y \neq v_z$



Quasi Neutrality

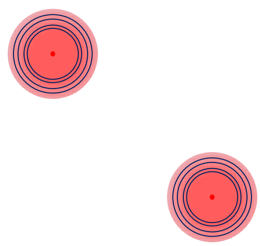
$$\Sigma\, q_i\, n_i = n_e$$

Percentage Ionisation

$$\frac{n_i}{n_i + n_n}$$

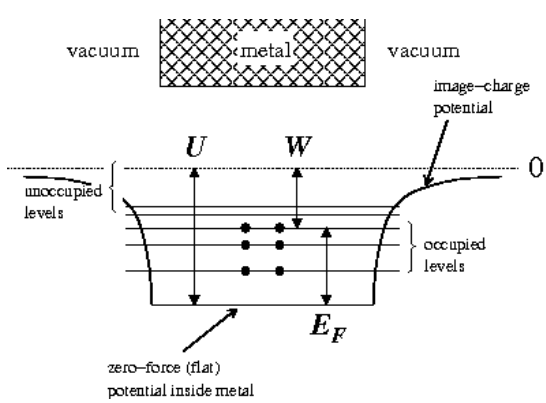
> 10 % → Highly Ionised
< 1 % → Weakly Ionised

Collisions

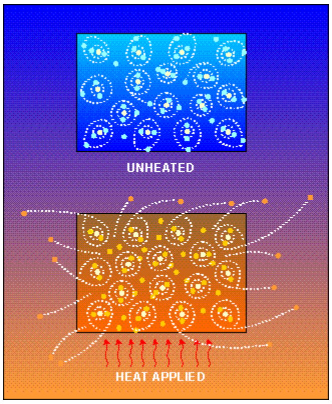


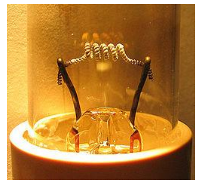
Relaxation time = 90° deflection time

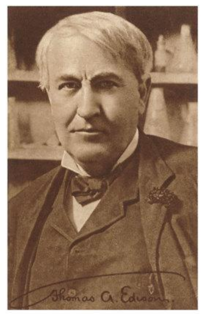
Work Function



Thermionic Emission







1880 Thomas Edison

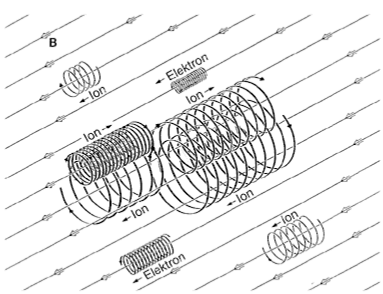
1901 Owen Richardson

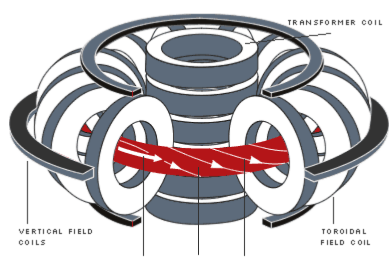
$$J = A_{\mathrm{G}} T^2 \mathrm{e}^{\frac{-W}{kT}}$$

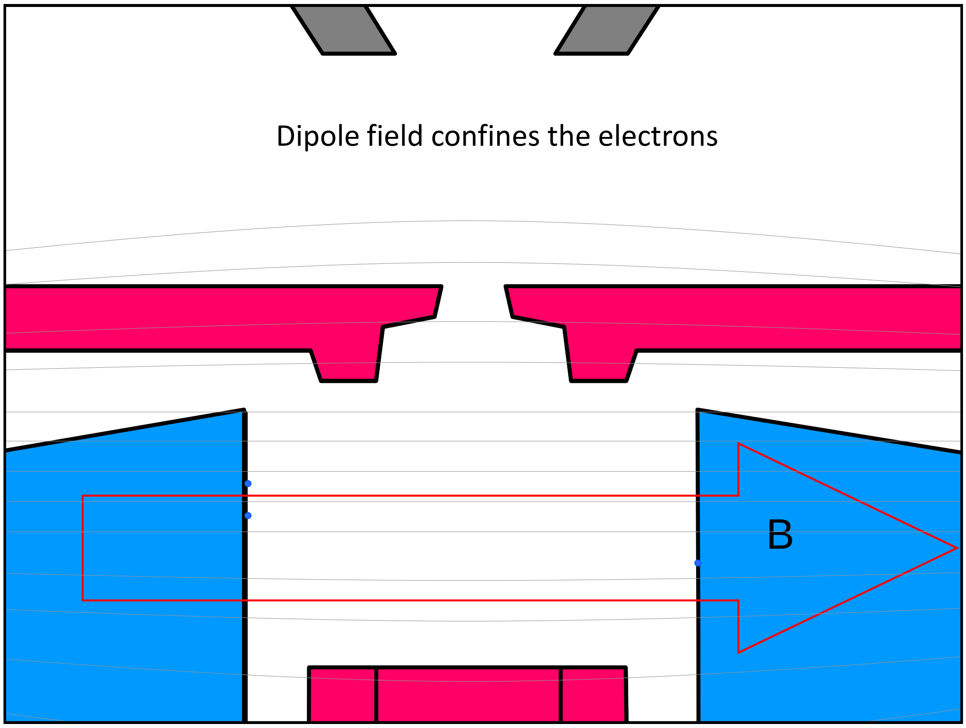
$$A_{\mathrm{G}} = \lambda_{\mathrm{R}} A_0$$

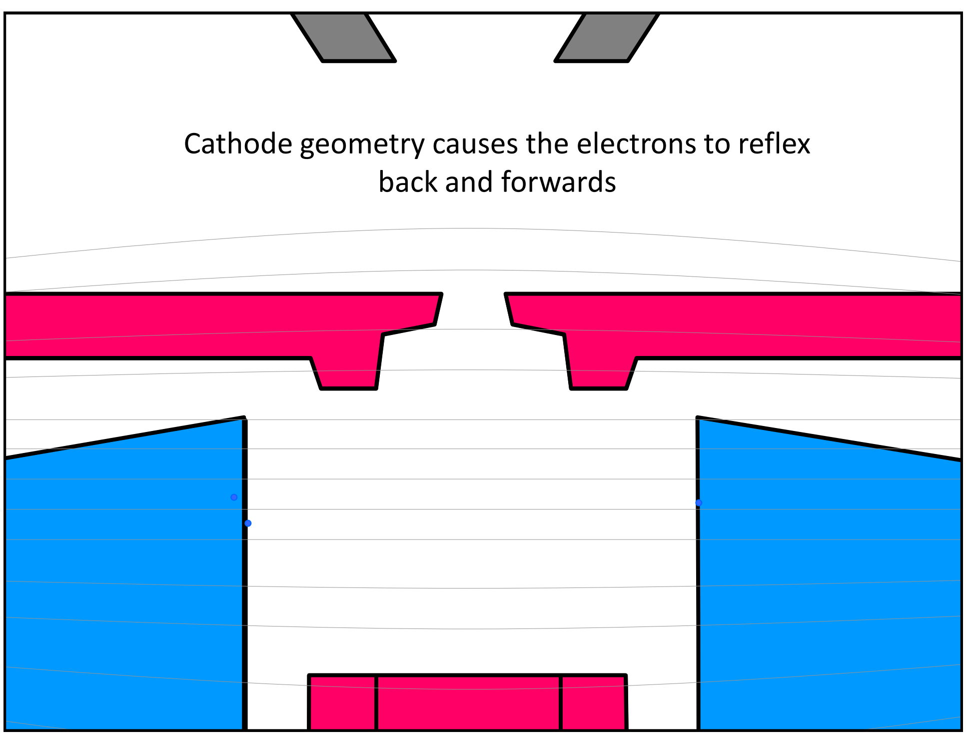
$$A_0 = \frac{4\pi m k^2 e}{h^3} = 1.20173 \times 10^6 \,\mathrm{A\,m^{-2}\,K^{-2}}$$

Magnetic Confinement

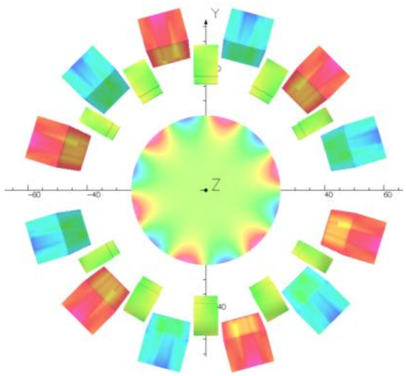


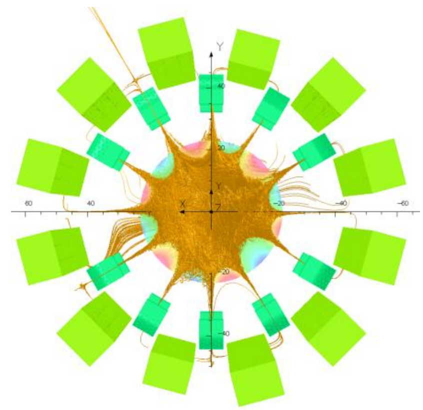



Dipole field confines the electrons
B

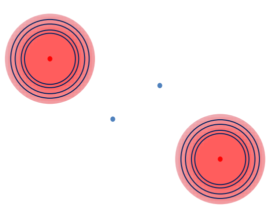

Cathode geometry causes the electrons to reflex back and forwards

Multicusp Confinement



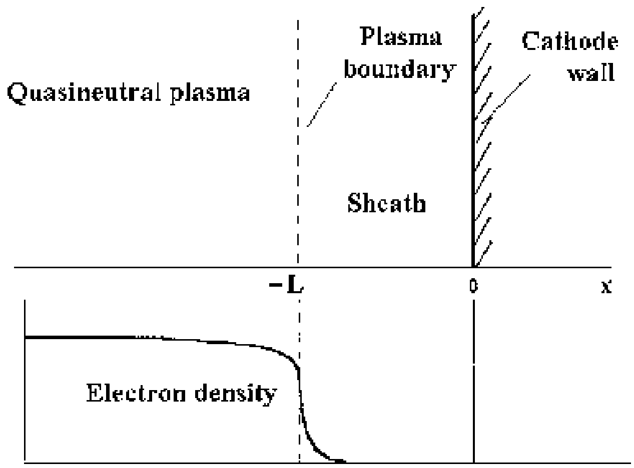


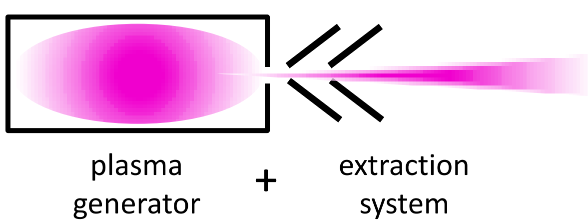
Debye Length



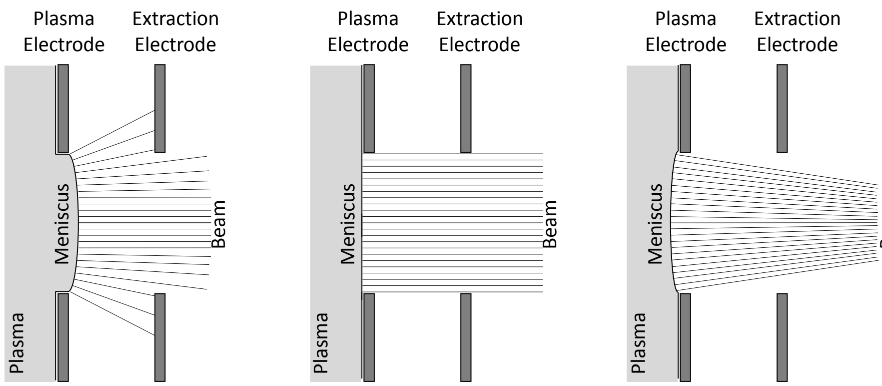
$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e {q_e}^2}}$$

Plasma Sheath

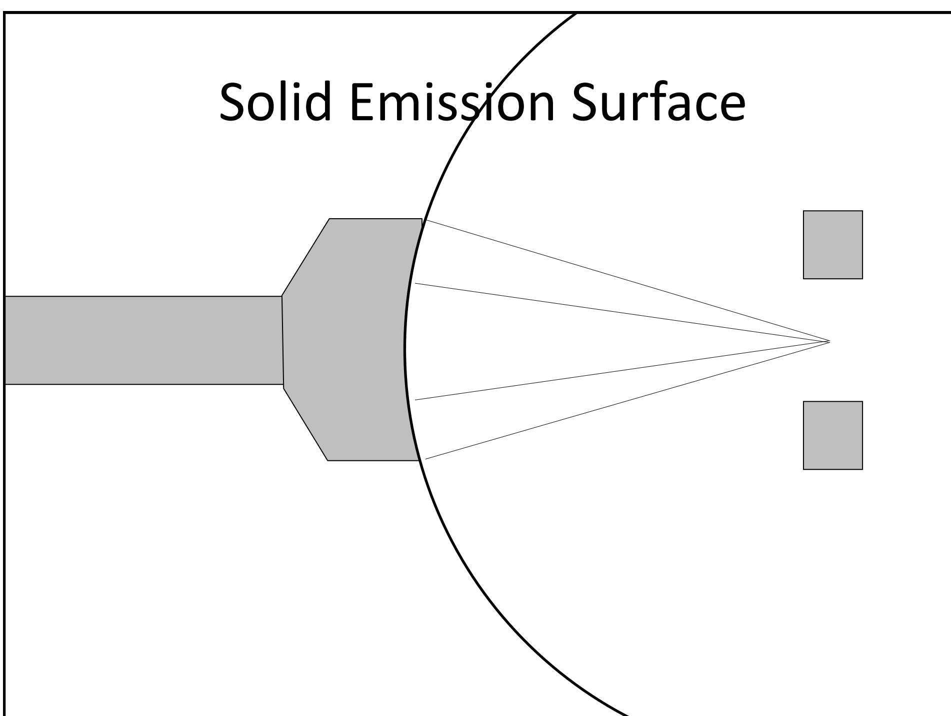




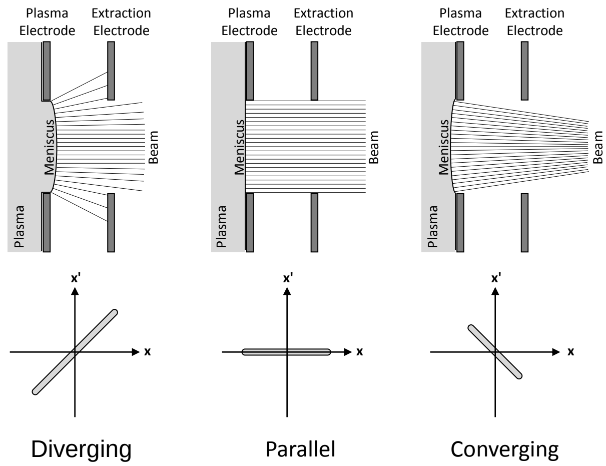
Plasma Mencius



Solid Emission Surface



Emittance

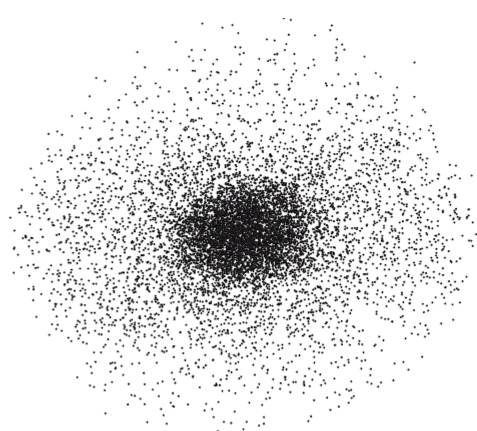


Emittance of Real Beams

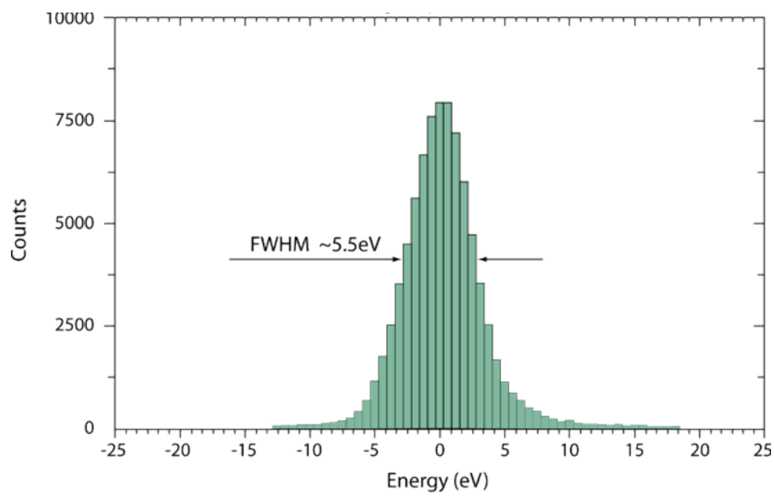
Halo Effect

95% emittance

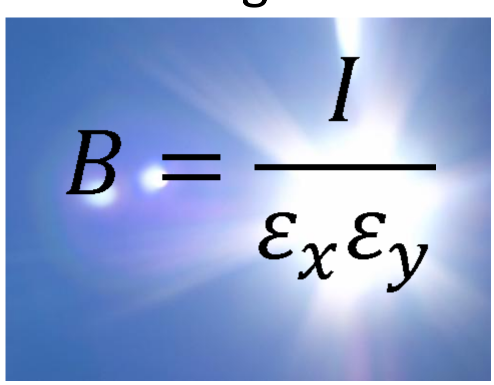
rms emittance



Energy Spread



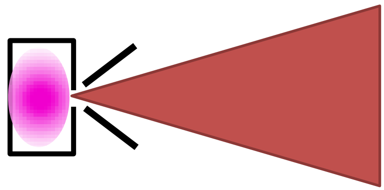
Brightness



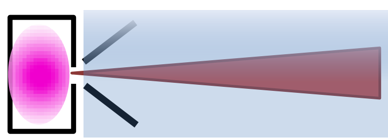
$$B = \frac{I}{\varepsilon_x \varepsilon_y}$$

Be careful- Some definitions include factors of 2, 8 and π
Are the emittances normalised?

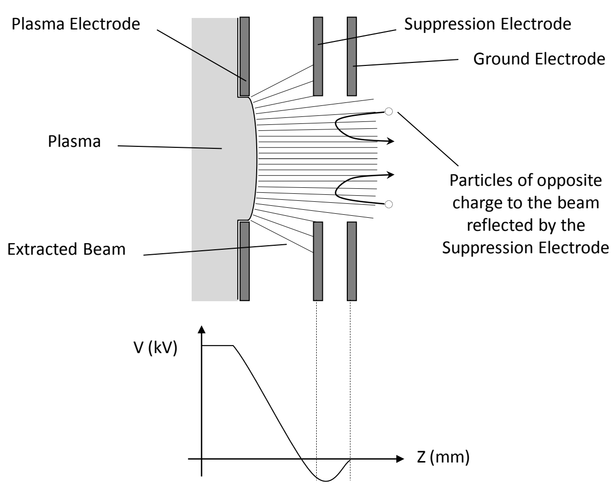
Space Charge



Space Charge Compensation



Suppressor Electrode



Child-Langmuir Law

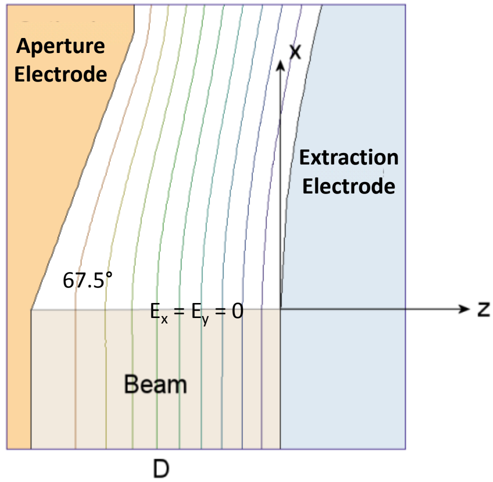
$$j = \frac{\frac{4}{9}\epsilon_0 \sqrt{\frac{2q_i}{m_i}} V^{\frac{3}{2}}}{d^2}$$

$$j = \frac{1.72 \sqrt{\frac{q}{A}} V^{\frac{3}{2}}}{d^2}$$

Perveance

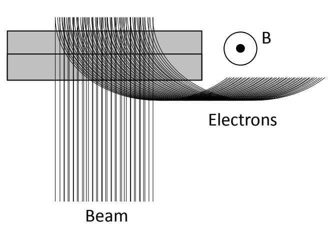
$$P = \frac{I}{V^{\frac{3}{2}}}$$

Pierce Extraction

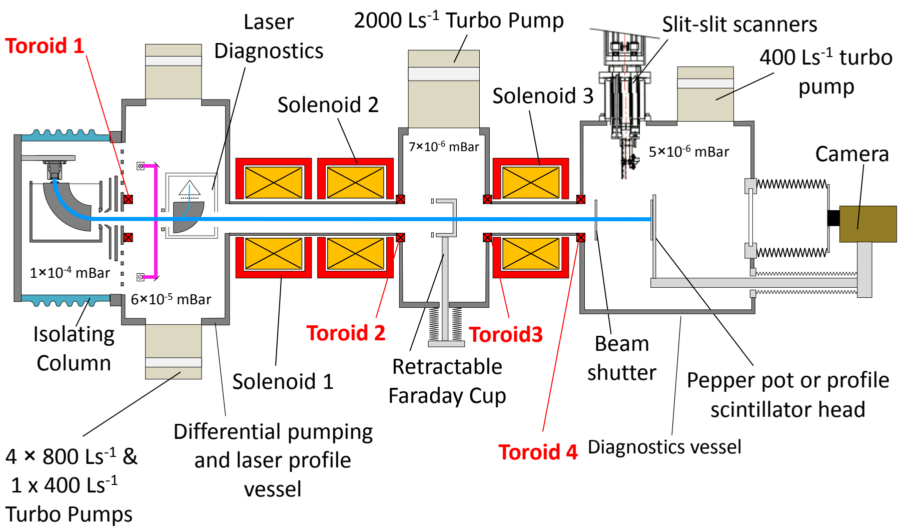


Negative Ion Extraction

- Electrons will be extracted as well
- Up to 1000 times the H^- current!
- Best about 0.5 times H^- current



Low Energy Beam Transport



Ion Sources

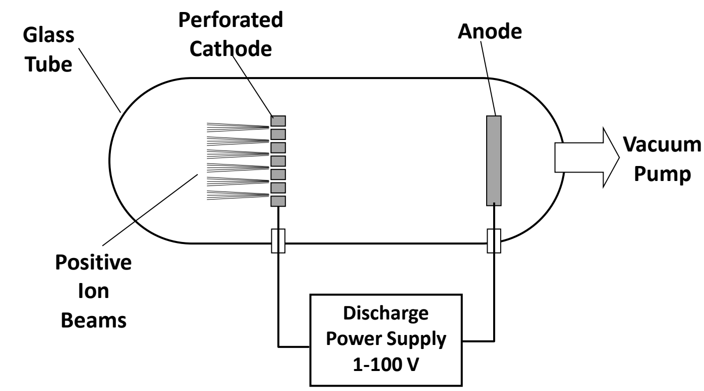
- Bayard-Alpert type ion source
- Electron Bombardment ion source
- Hollow Cathode ion source
- Reflex Discharge Multicusp source
- Cold- & Hot-Cathode PIG
- Electron Cyclotron Resonance ion source (ECR)
- Electron Beam Ion Source (EBIS)
- Surface Contact ion source
- Cryogenic Anode ion source
- Metal Vapor Vacuum Arc ion source (MEVVA)
- Sputtering-type negative ion source
- Plasma Surface Conversion negative ion source
- Electron Heated Vaporization ion source
- Hollow Cathode von Ardenne ion source
- Forrester Porus Plate ion source
- Multipole Confinement ion source

- EHD-driven Liquid ion source
- Surface Ionization ion source
- Charge Exchange ion source
- Inverse Magnetron ion source
- Microwave ion source
- XUV-driven ion source
- Arc Plasma ion source
- Capillary Arc ion source
- Von Ardenne ion source
- Capillaritron ion source
- Canal Ray ion source
- Pulsed Spark ion source
- Field Emission ion source
- Atomic Beam ion source
- Field Ionization ion source
- Arc Discharge ion source
- Multifilament ion source
- RF plasma ion source
- Freeman ion source

- Liquid Metal ion source
- Beam Plasma ion source
- Magnetron ion source
- Nier ion source
- Bernas ion source
- Nielsen ion source
- Wilson ion source
- Recoil ion source
- Zinn ion source
- Duoplasmatron
- Duopigatron
- Laser ion source
- Penning ion source
- Monocusp ion source
- Bucket ion source
- Metal ion source
- Multicusp ion source
- Kaufman ion source
- Flashover ion source
- Calutron ion source
- CHORDIS

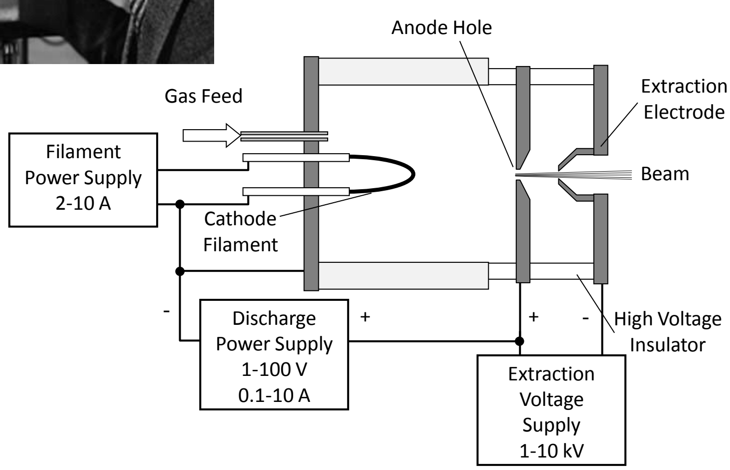
To name but a few!

1886 Canal Ray Source

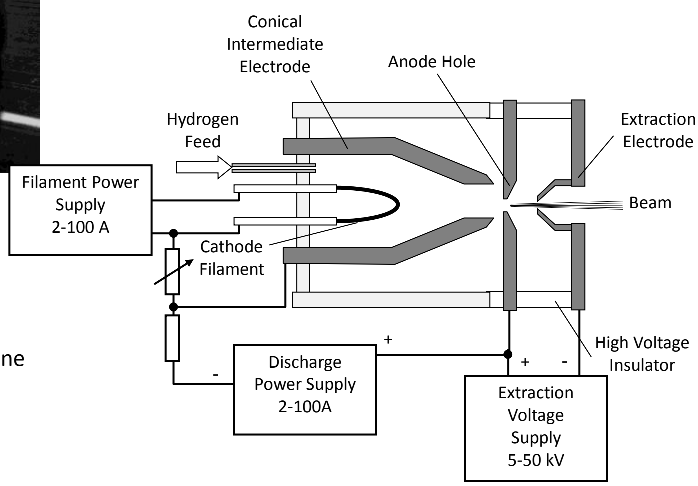


Arthur Dempster

Electron Bombardment Source 1916

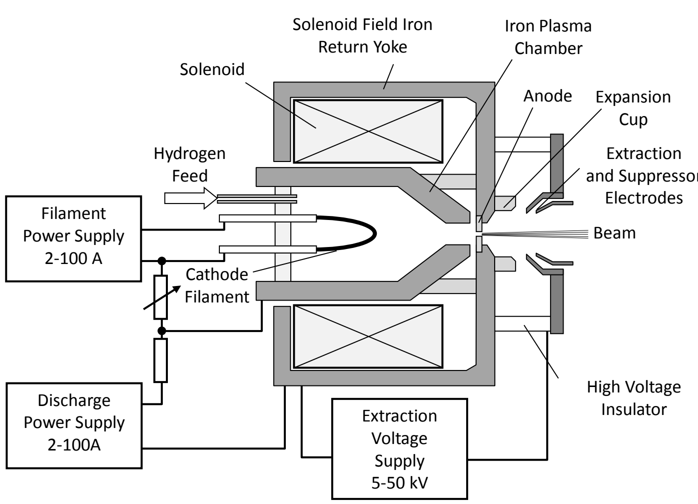


Plasmatron (late 1940's)

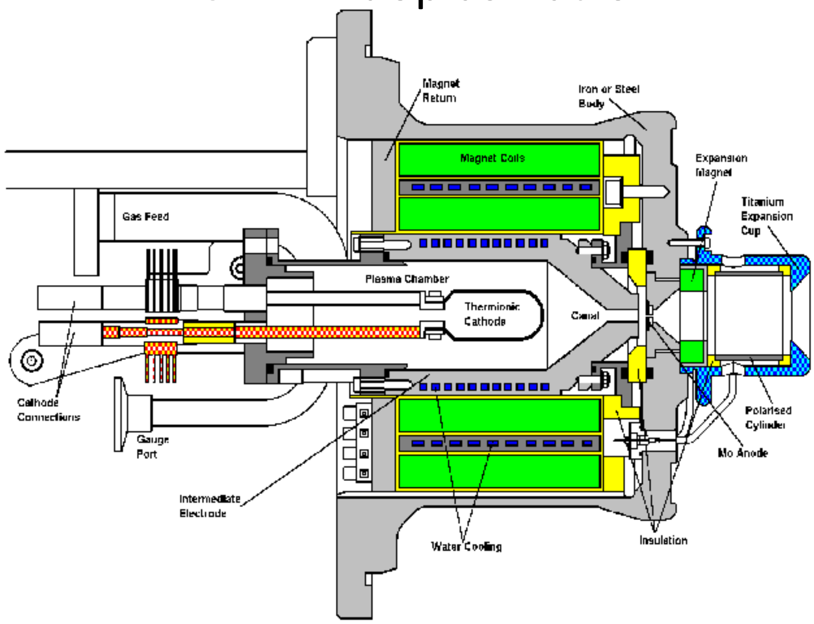


Manfred von Ardenne

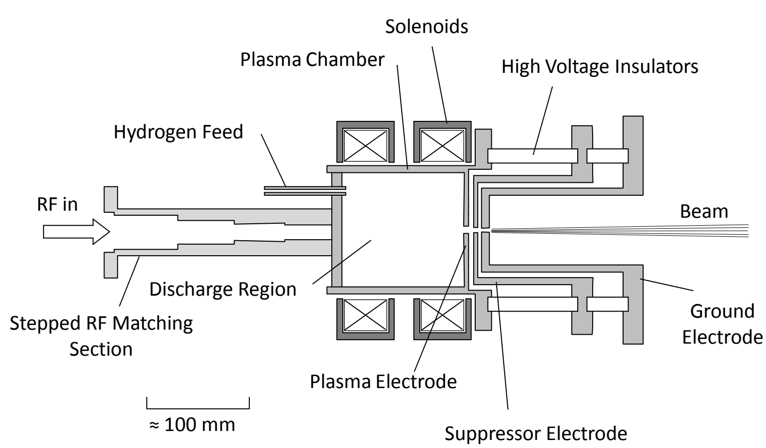
Duoplasmatron (1956)



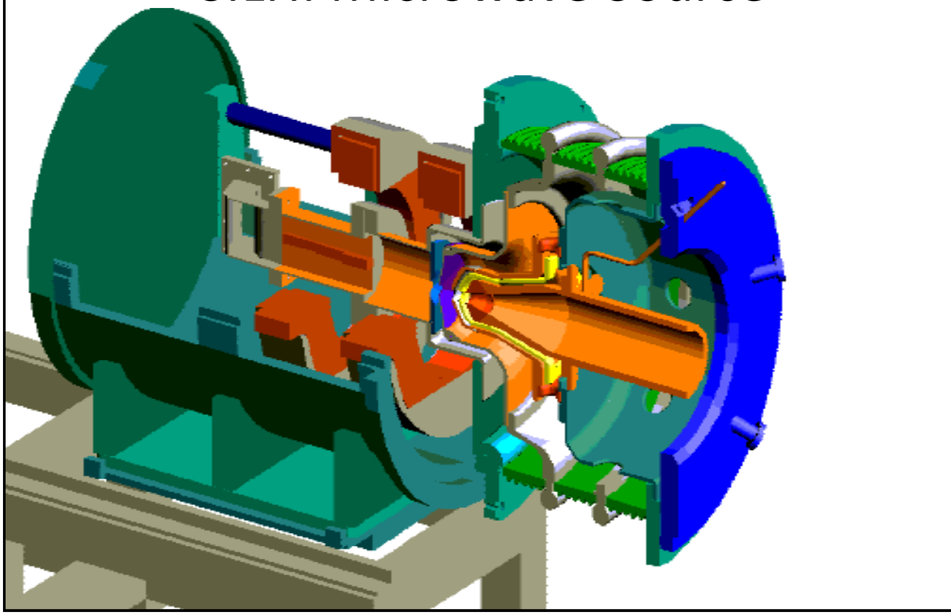
CERN Duoplasmatron

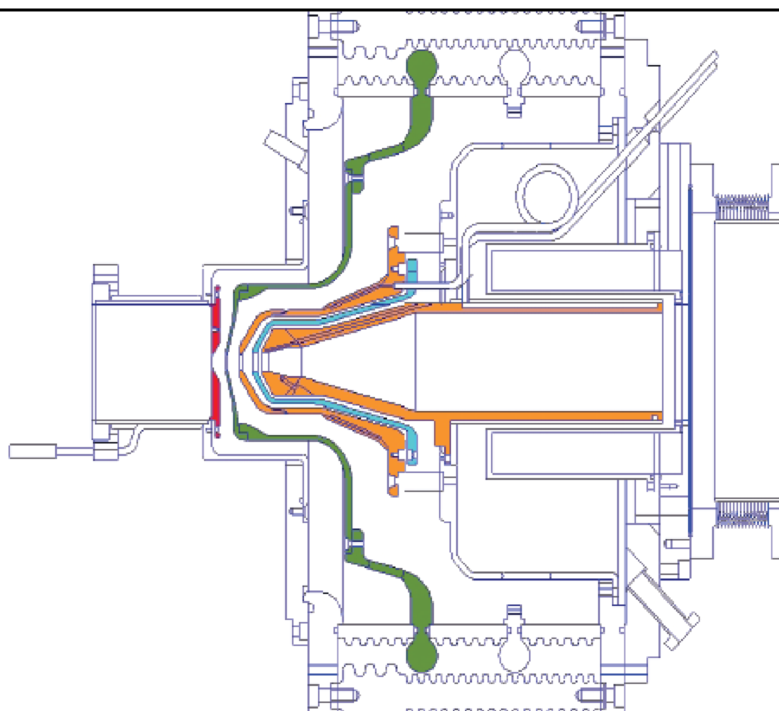


Microwave Ion Source



SILHI Microwave Source





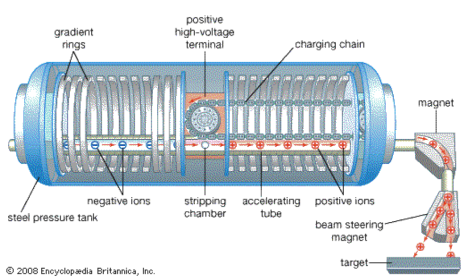
Negative Ion Sources

- Ripping electrons off is easy!
  - It is much harder to add them on

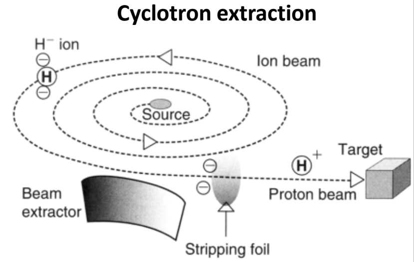
Not all elements will even make negative ions

Applications

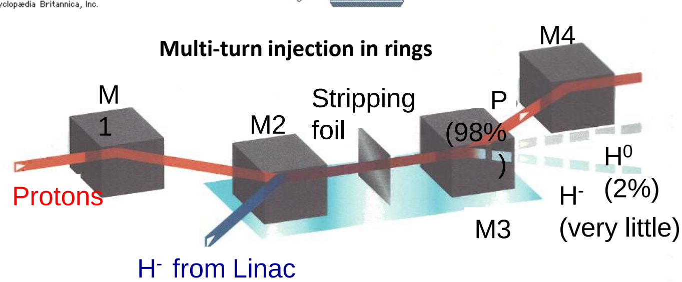
Tandem accelerators



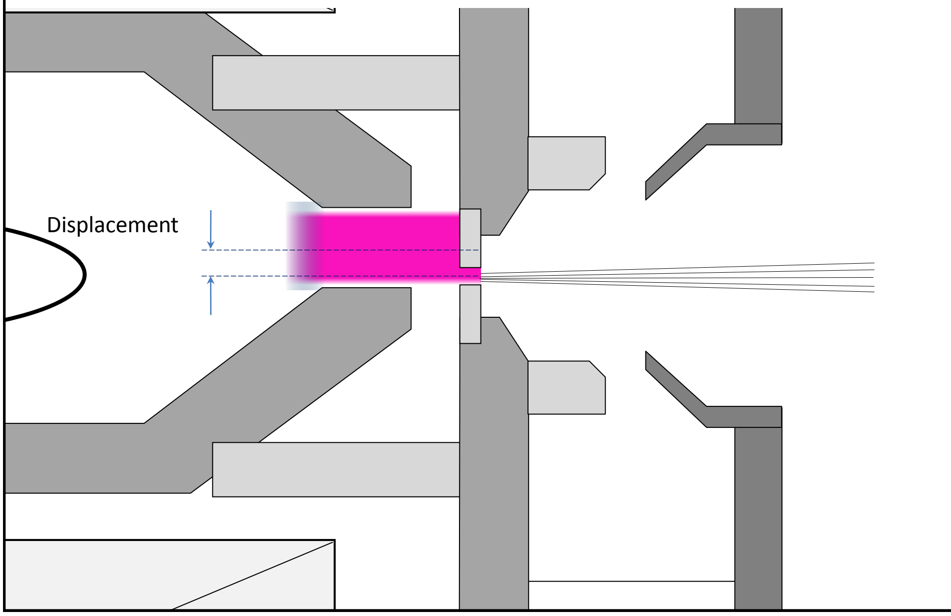
Cyclotron extraction



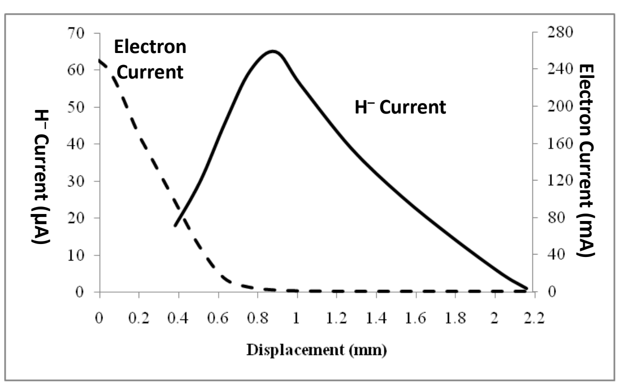
Multi-turn injection in rings



Off Axis Extraction

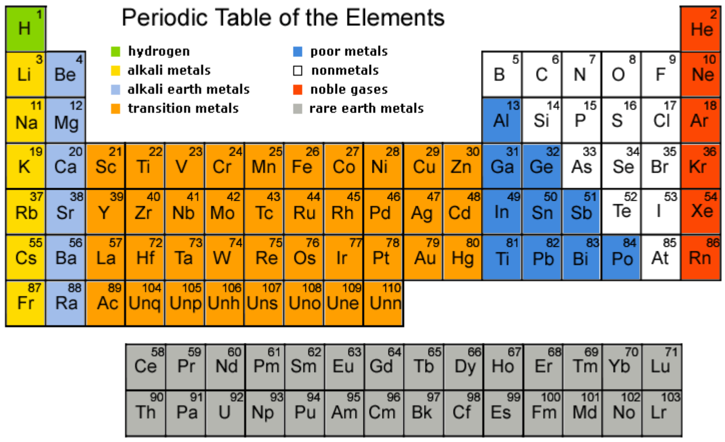


Off Axis Duoplasmatron Extraction

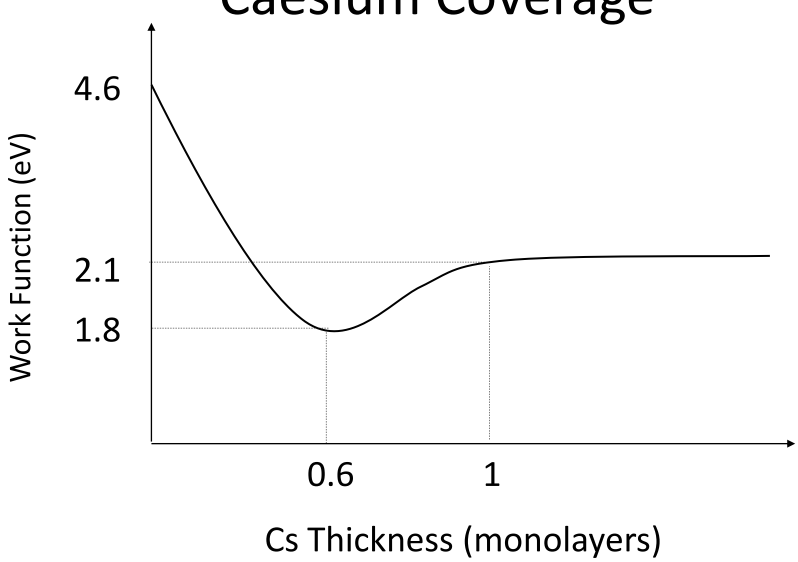


Yuri Belchenko , Vadim Dudnikov, G. I. Dimov Early 1970's Budker Institute of Nuclear Physics

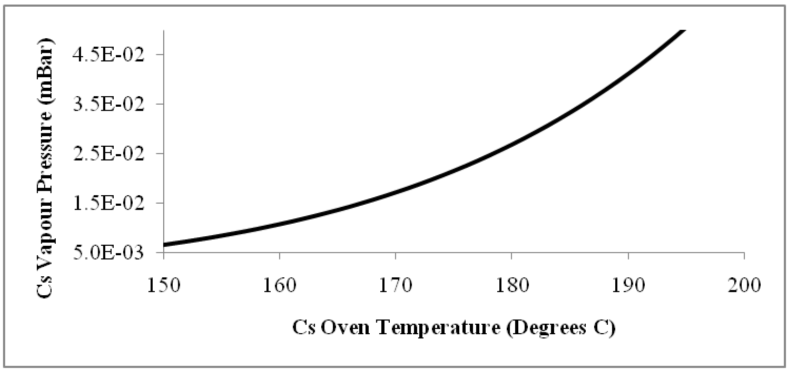
Production of H^- ions by surface ionisation



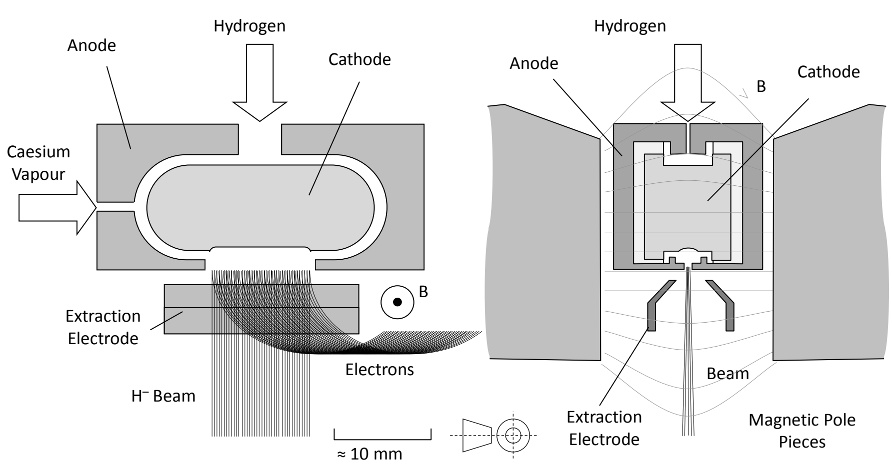
Caesium Coverage

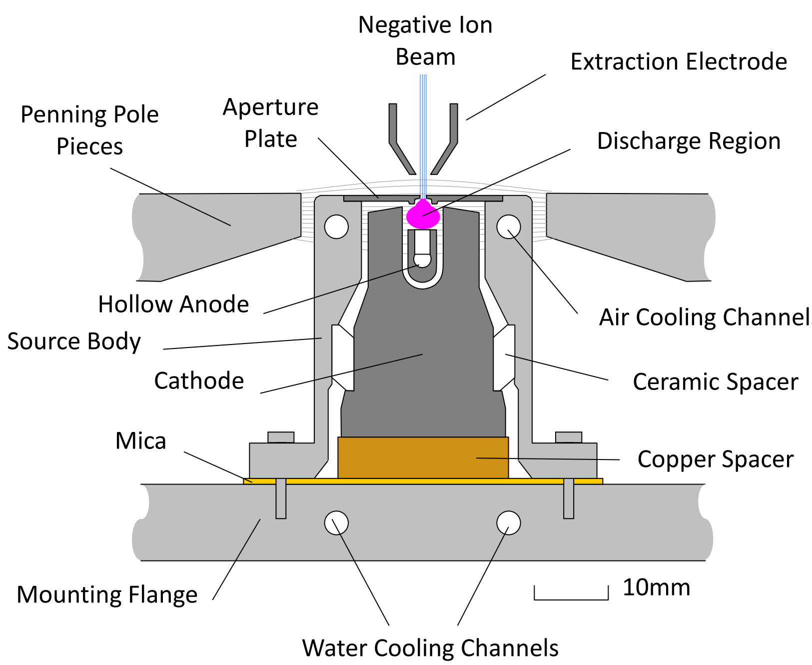


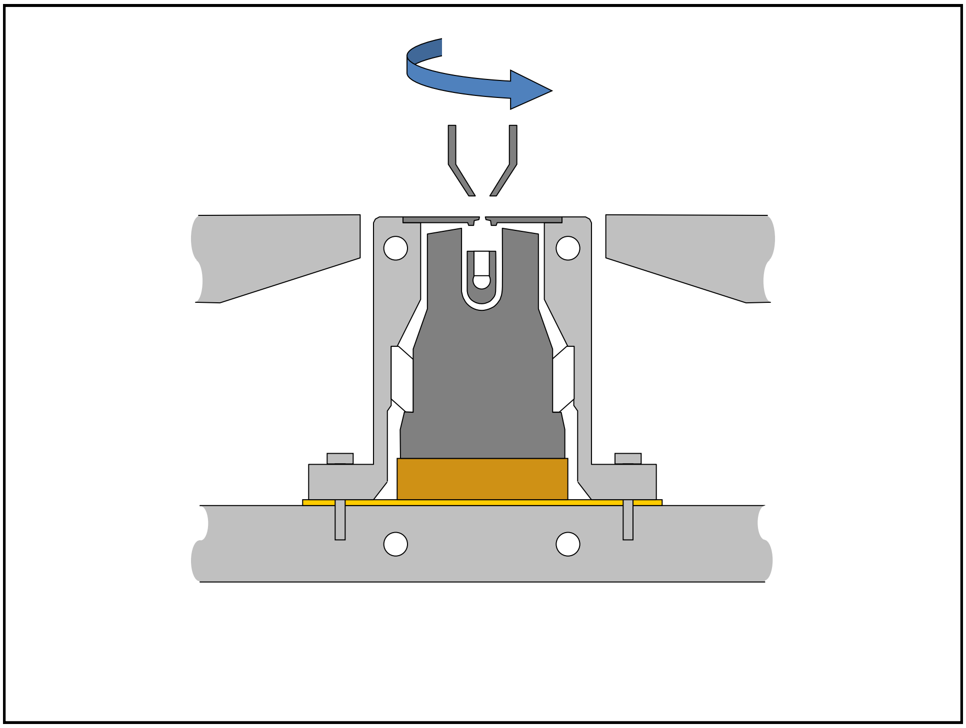
Caesium Vapour Pressure

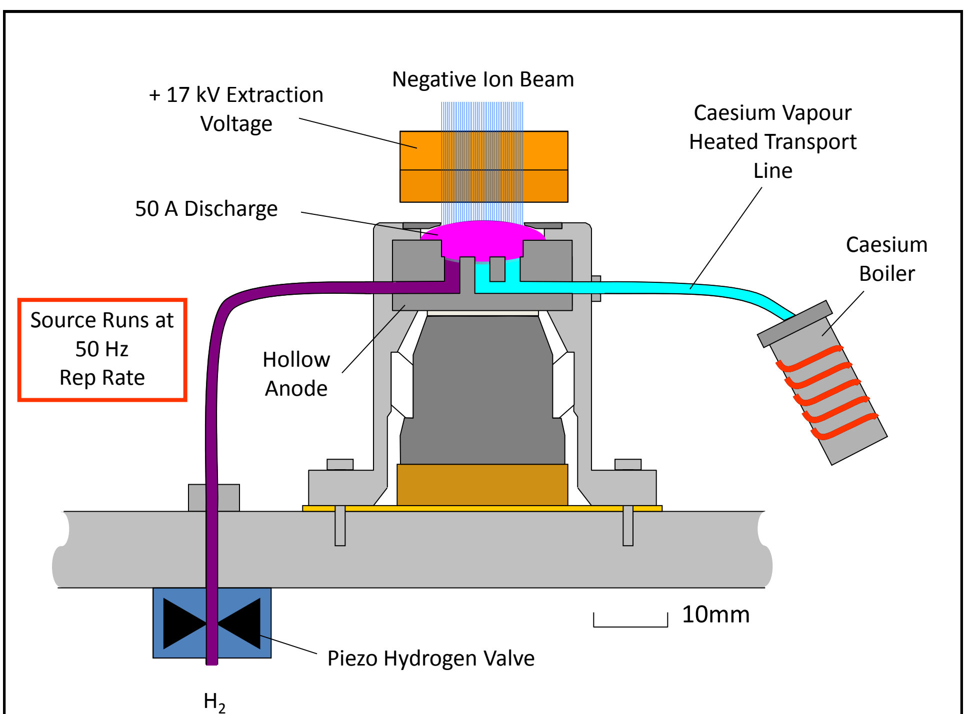


Magnetron Source



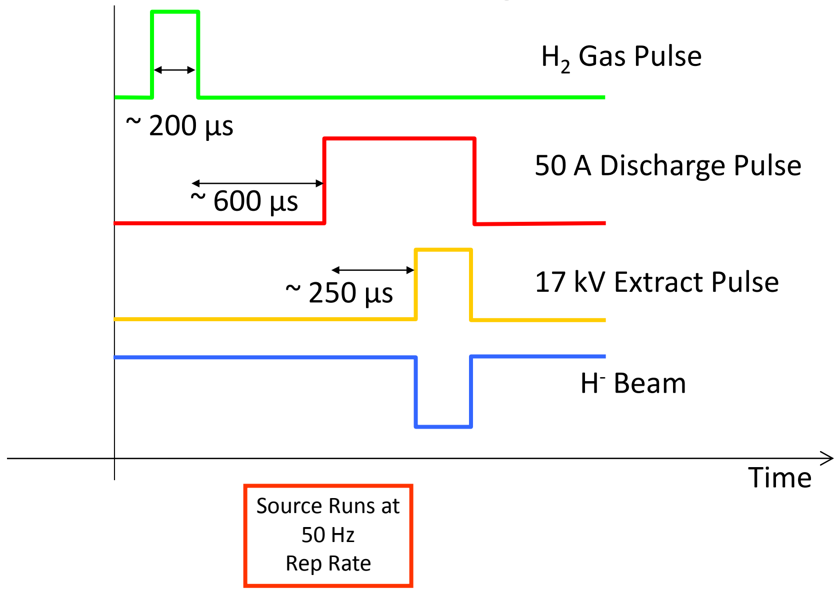

Negative Ion Beam
Extraction Electrode
Penning Pole Pieces
Aperture Plate
Discharge Region
Hollow Anode
Air Cooling Channels
Source Body
Cathode
Ceramic Spacer
Mica
Copper Spacer
Mounting Flange
10mm
Water Cooling Channels

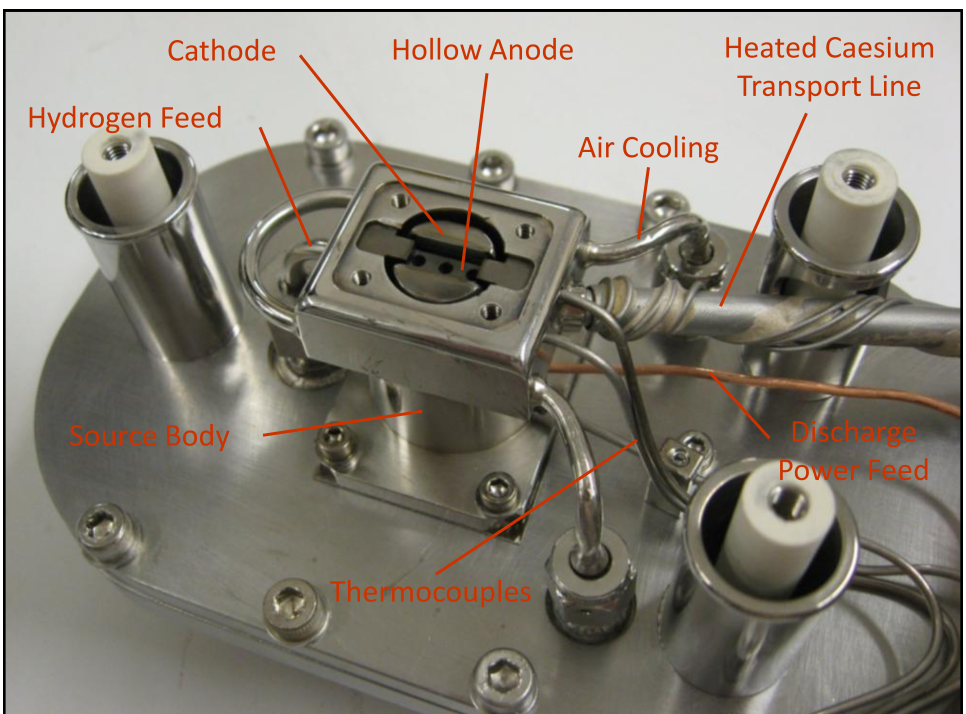


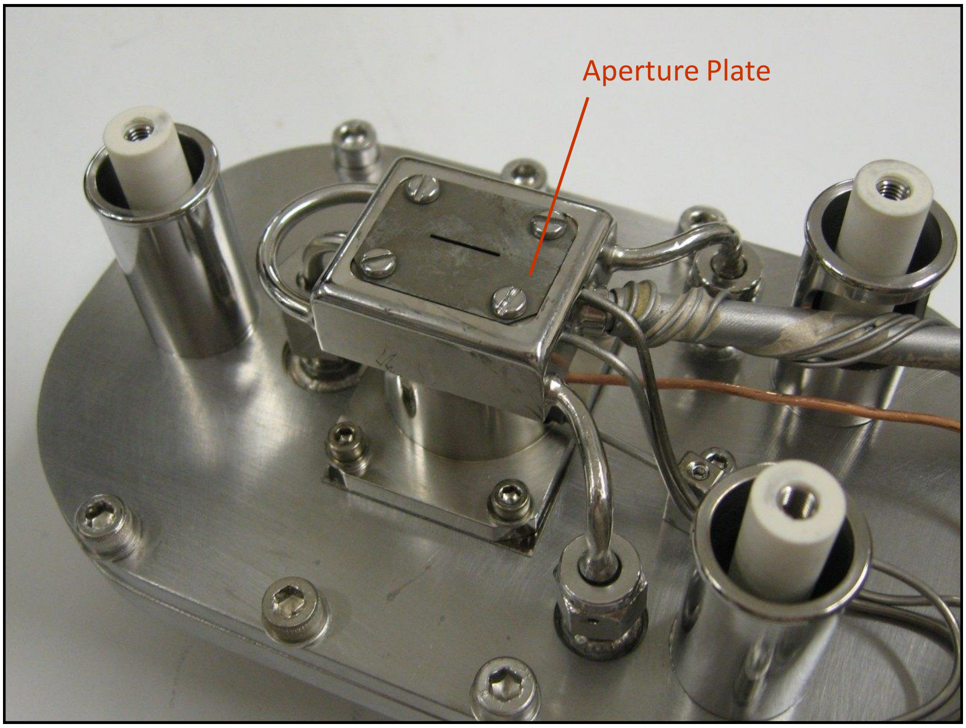


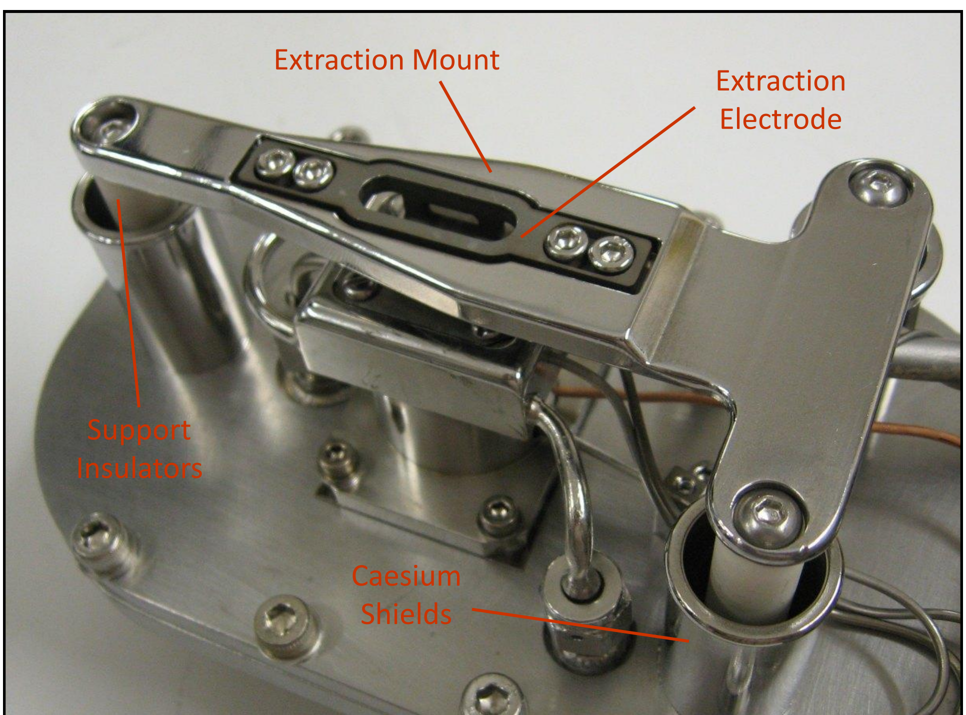
Negative Ion Beam
+ 17 kV Extraction Voltage
Caesium Vapour Heated Transport Line
50 A Discharge
Caesium Boiler
Source Runs at 50 Hz Rep Rate
Hollow Anode
10mm
Piezo Hydrogen Valve
H_2

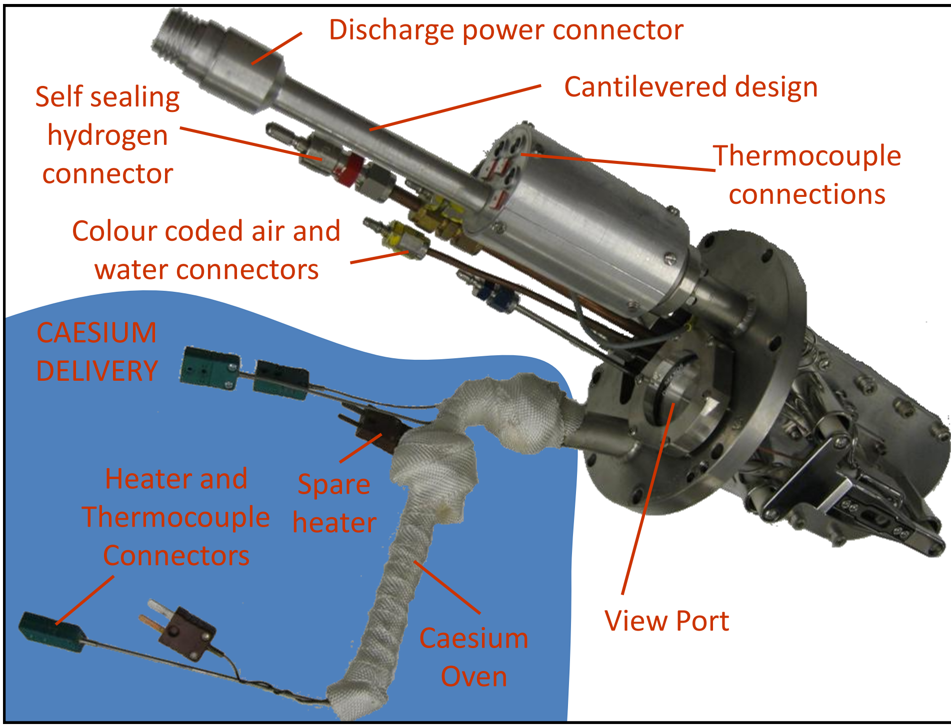
Timing


H_2 Gas Pulse
~ 200 µs
50 A Discharge Pulse
~ 600 µs
17 kV Extract Pulse
~ 250 µs
H^- Beam
Time
Source Runs at
50 Hz
Rep Rate

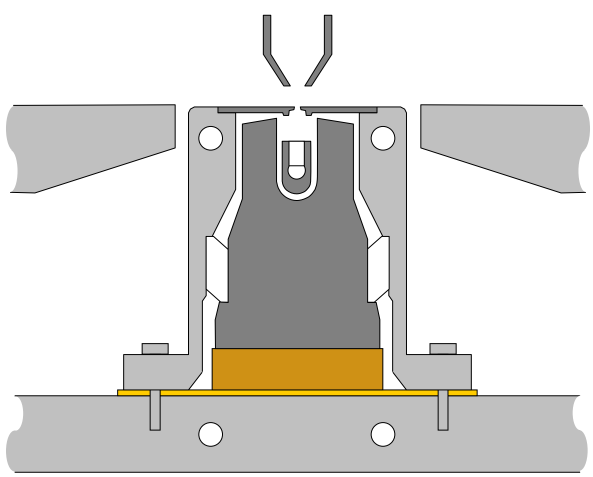

Cathode
Hollow Anode
Heated Caesium
Transport Line
Hydrogen Feed
Air Cooling
Source Body
Discharge
Power Feed
Thermocouples

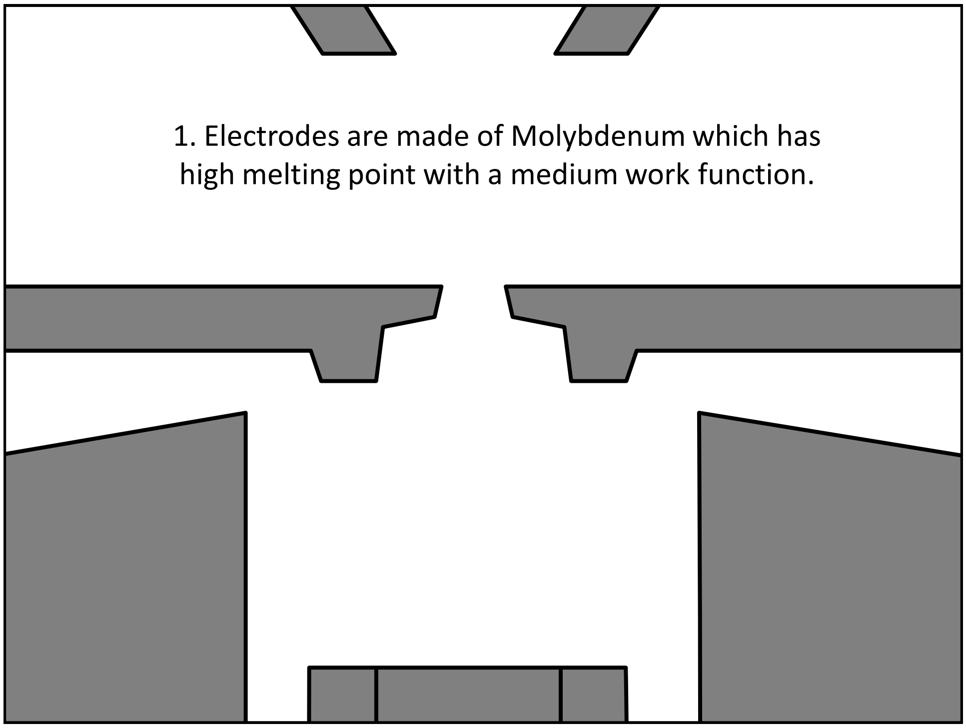

Aperture Plate

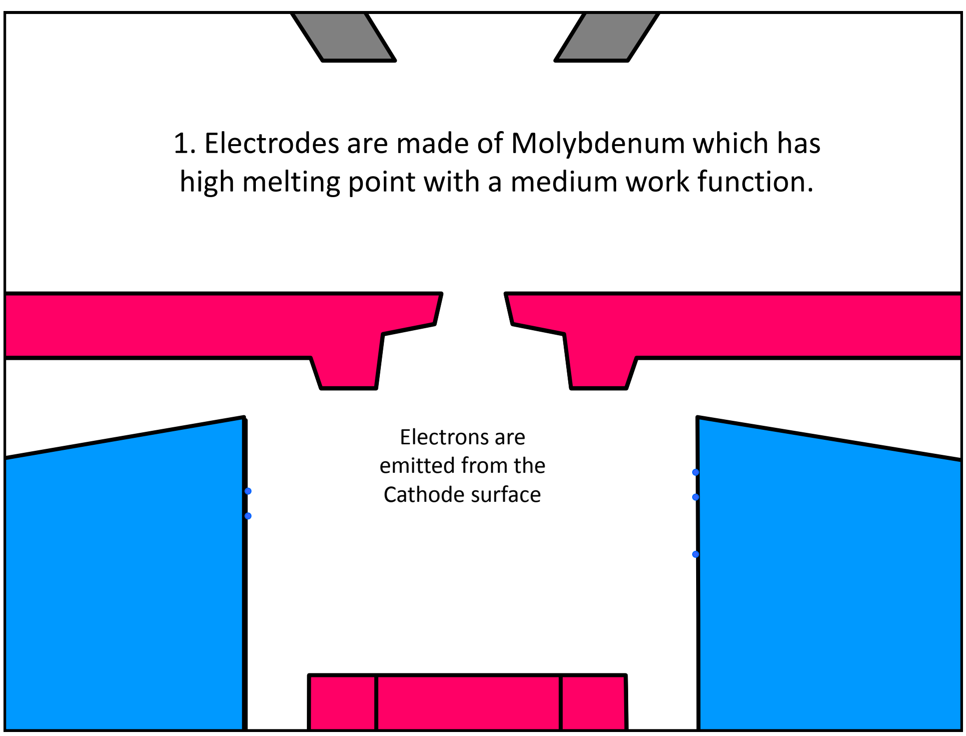

Extraction Mount
Extraction
Electrode
Support
Insulators
Caesium
Shields

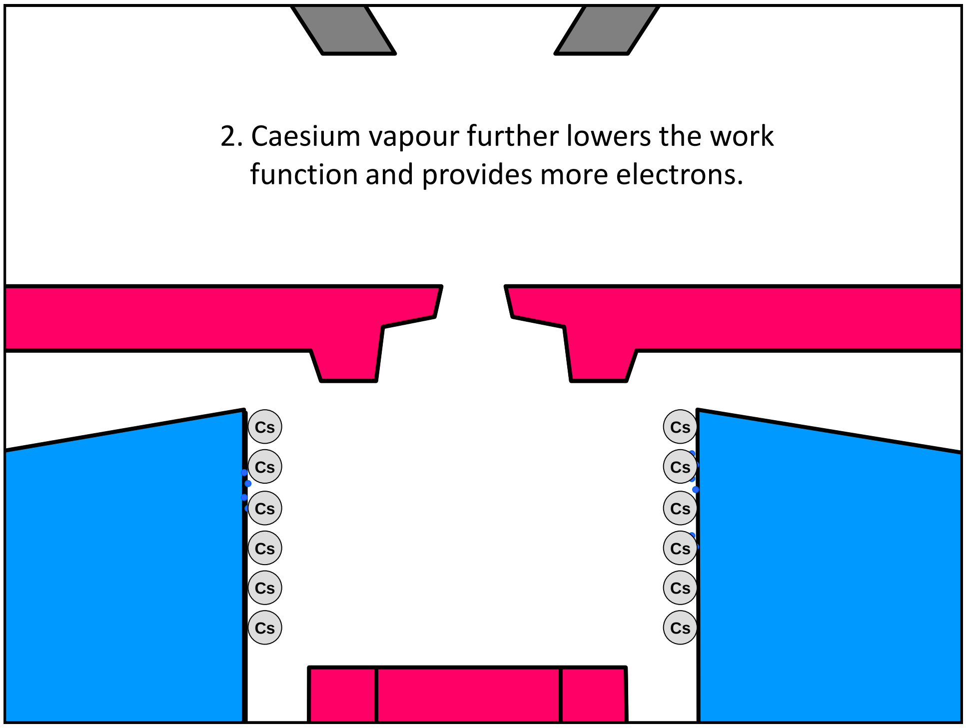


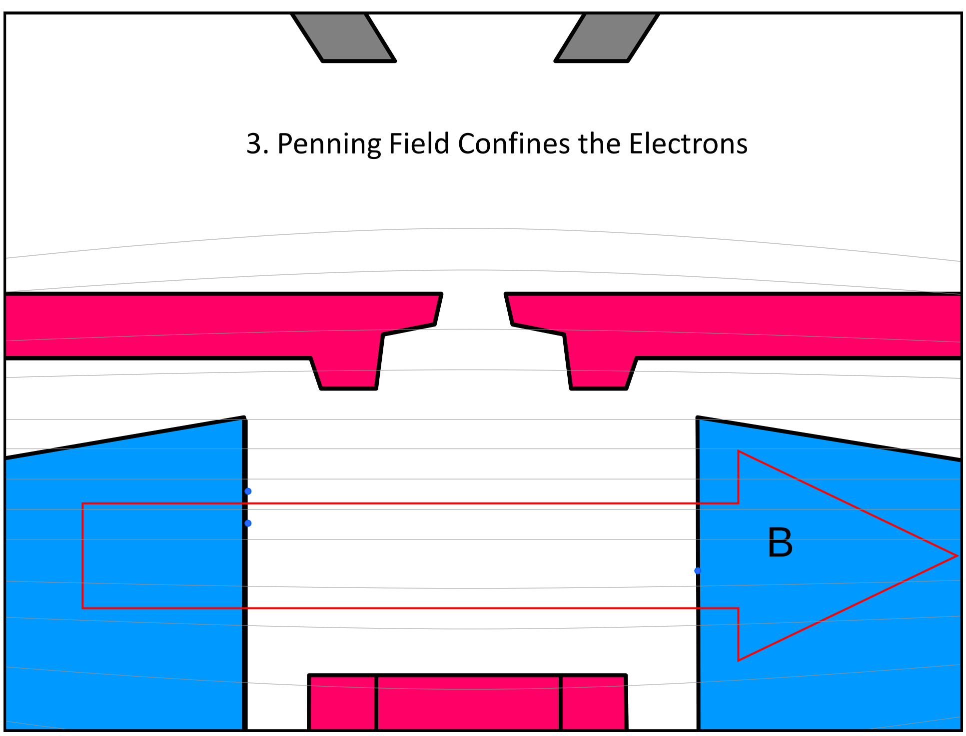
Key Design Points for H^- Production

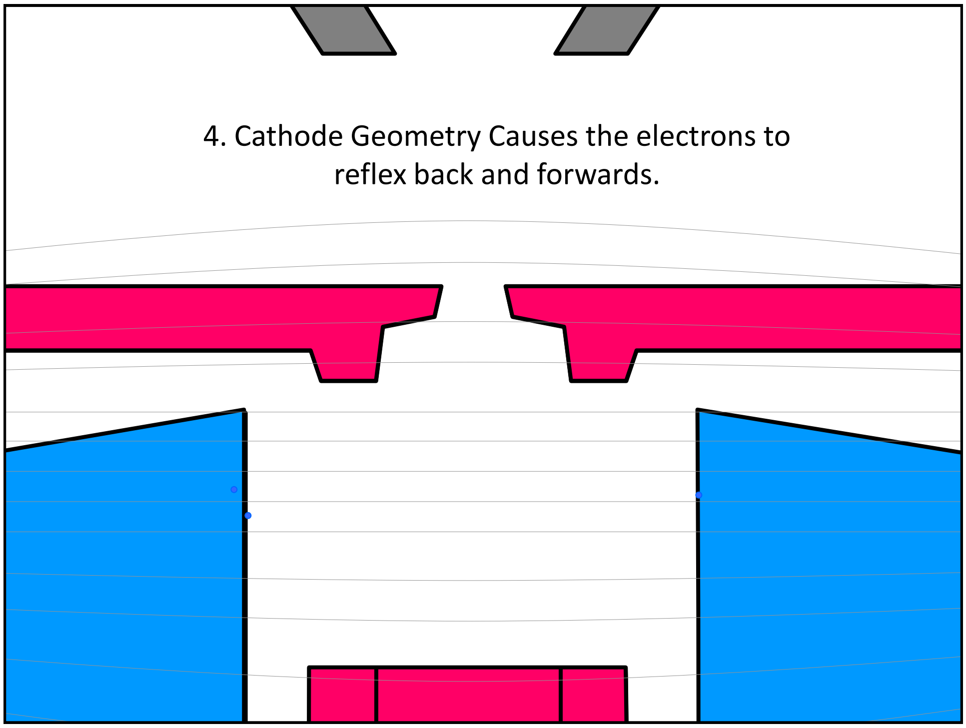


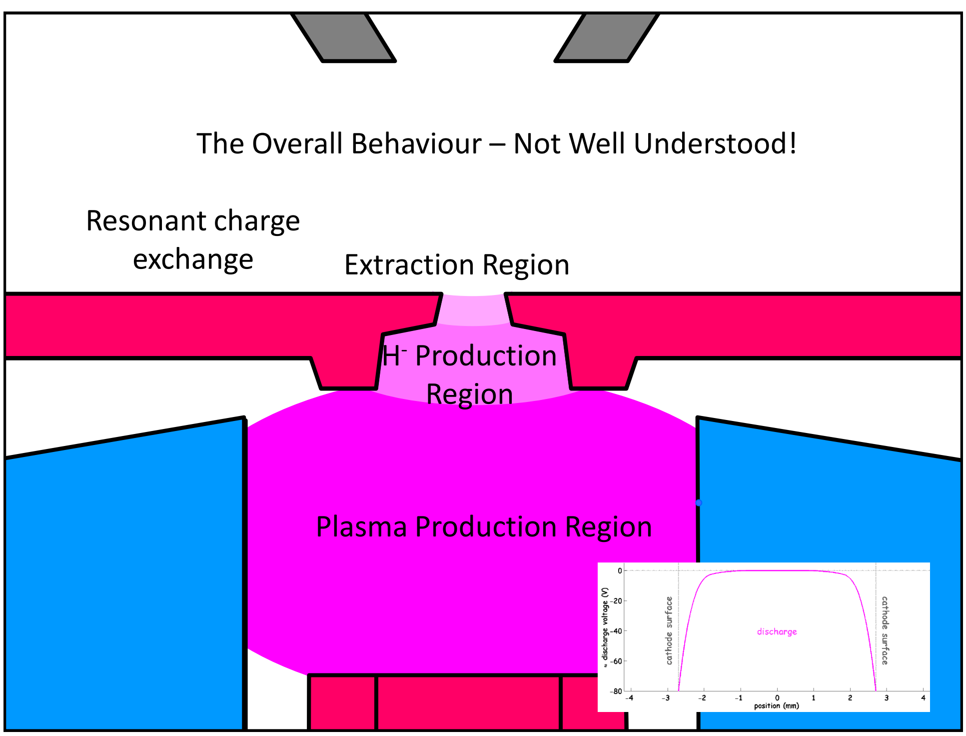

1. Electrodes are made of Molybdenum which has high melting point with a medium work function.


1. Electrodes are made of Molybdenum which has high melting point with a medium work function.
Electrons are emitted from the Cathode surface


2. Caesium vapour further lowers the work function and provides more electrons.
Cs
Cs
Cs
Cs
Cs
Cs
Cs
Cs
Cs
Cs
Cs
Cs


3. Penning Field Confines the Electrons
B


4. Cathode Geometry Causes the electrons to reflex back and forwards.


The Overall Behaviour – Not Well Understood!
Resonant charge exchange
Extraction Region
H- Production Region
Plasma Production Region
0
-20
-40
-60
-80
≈ discharge voltage (V)
cathode surface
discharge
cathode surface
-4
-3
-2
-1
0
1
2
3
4
position (mm)

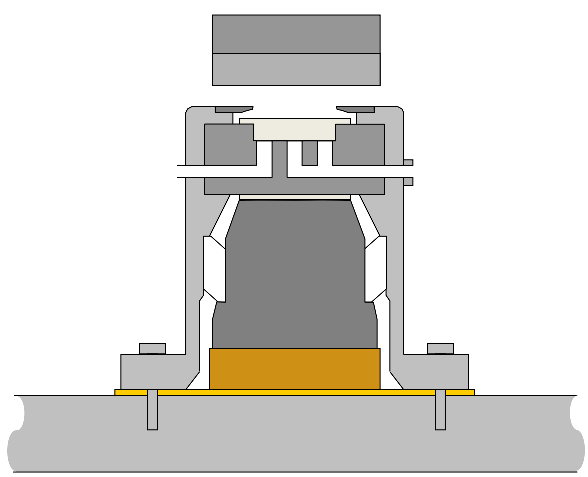
Resonant Charge Exchange in the Extraction Region

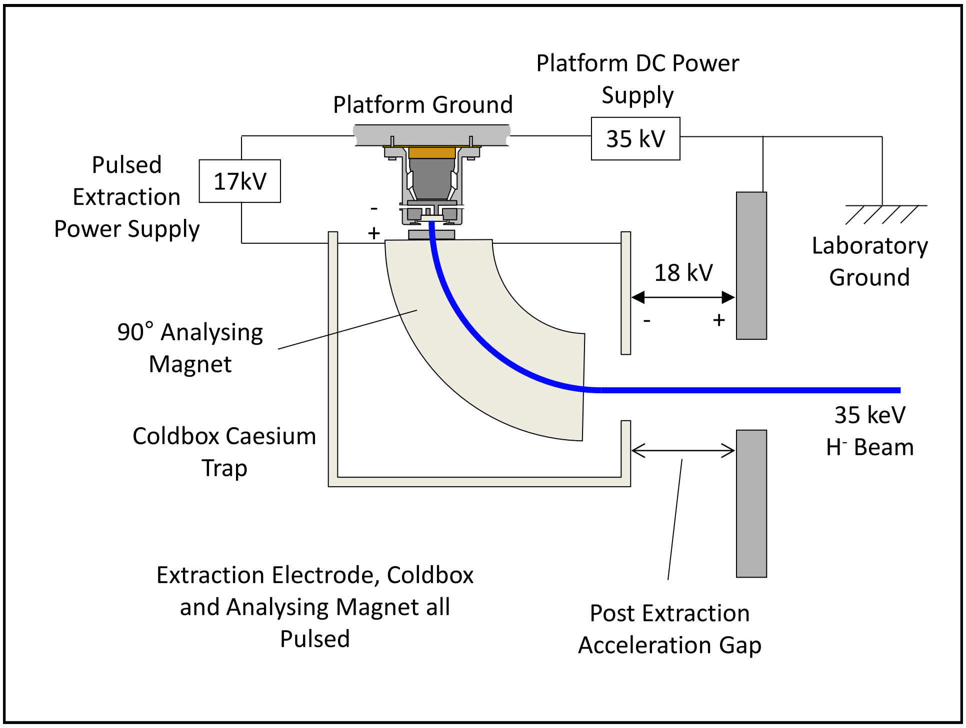
Leaving a slow H^-

Slow thermal H^0

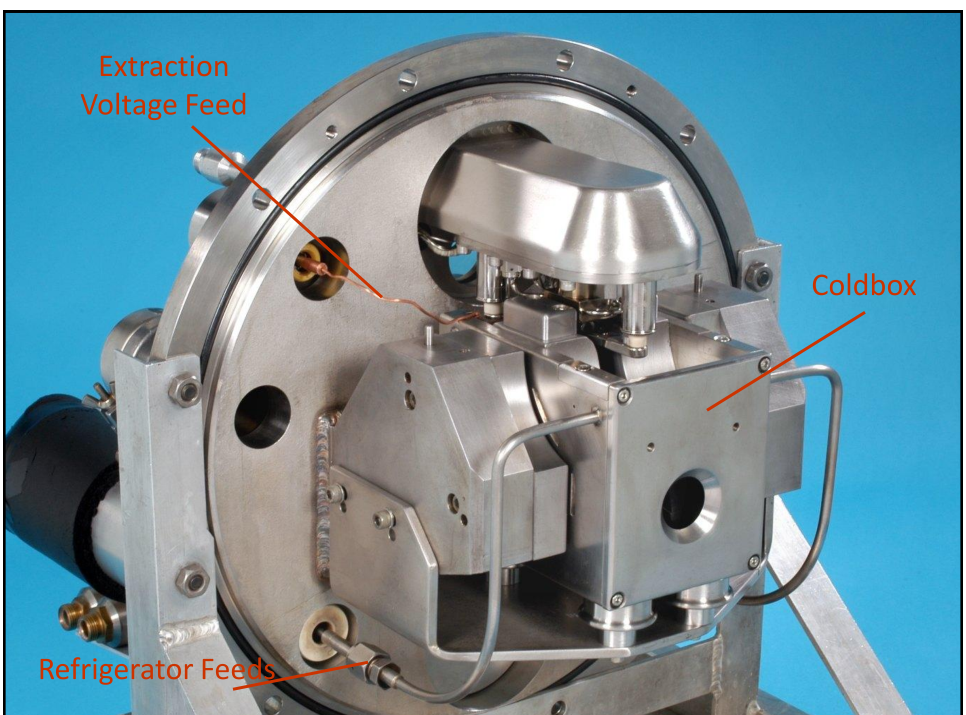
Ready for Extraction

Can undergo resonant charge exchange with fast H^-

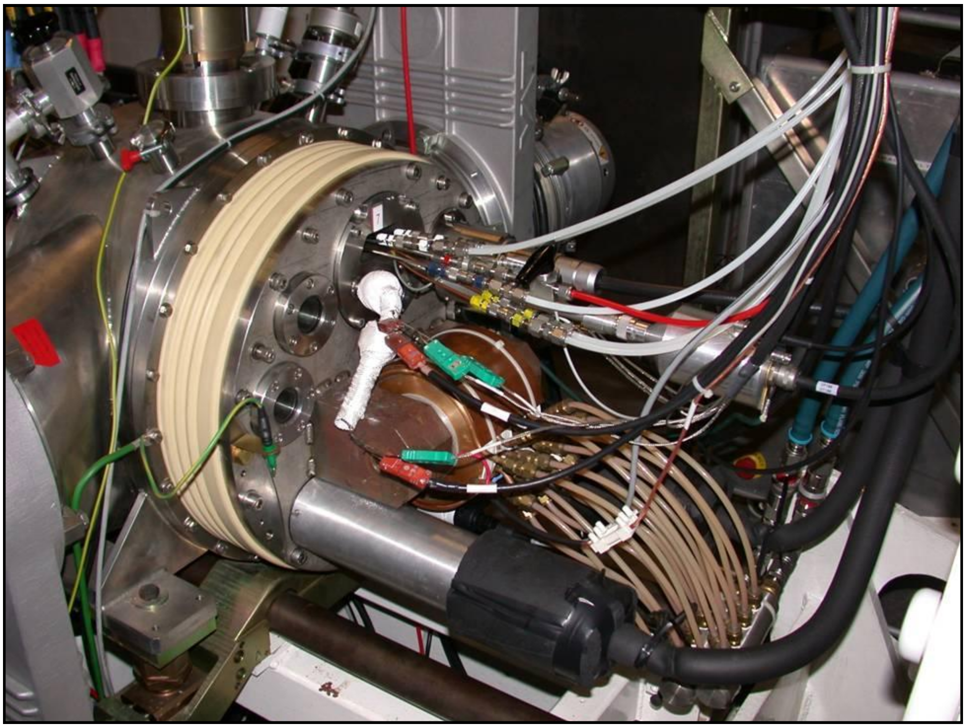




Platform DC Power Supply
Platform Ground
35 kV
Pulsed Extraction Power Supply
17kV
-
+
18 kV
-
+
Laboratory Ground
90° Analysing Magnet
35 keV
H- Beam
Coldbox Caesium Trap
Extraction Electrode, Coldbox and Analysing Magnet all Pulsed
Post Extraction Acceleration Gap



Extraction Voltage Feed
Coldbox
Refrigerator Feeds



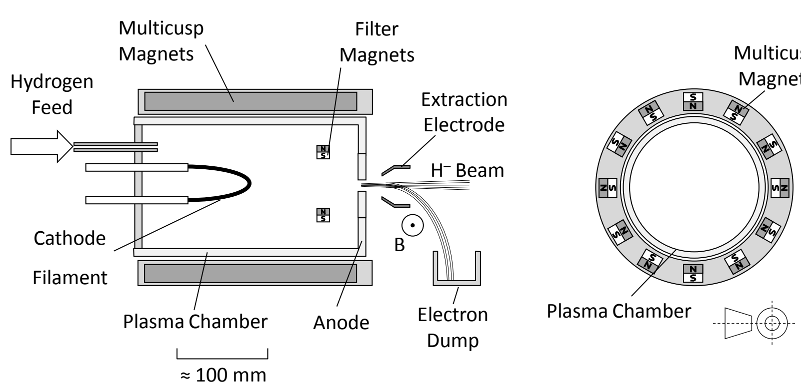
Volume Production

Marthe Bacal Ecole Polytechnique mid 1970’s

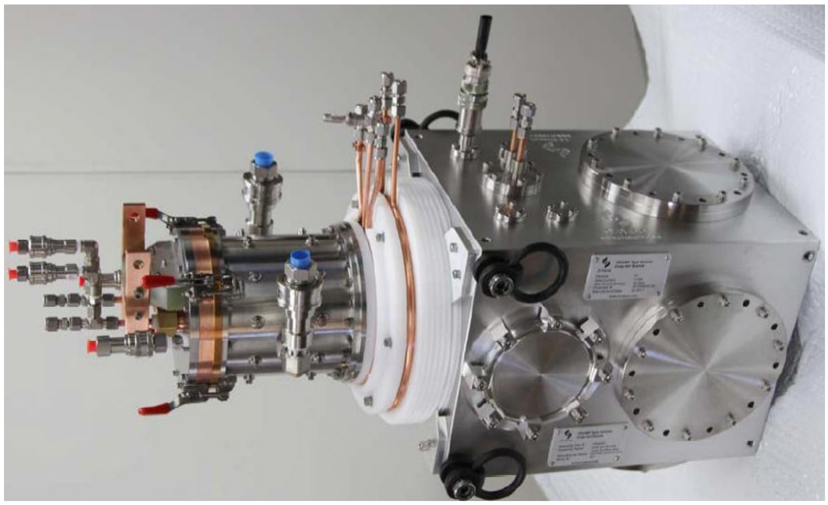
$$H_2^* + e\ (\leq 1\ \text{eV}) \rightarrow H^- + H^0$$

Dissociative attachment of low energy electrons to rovibrationally excited H_2 molecules

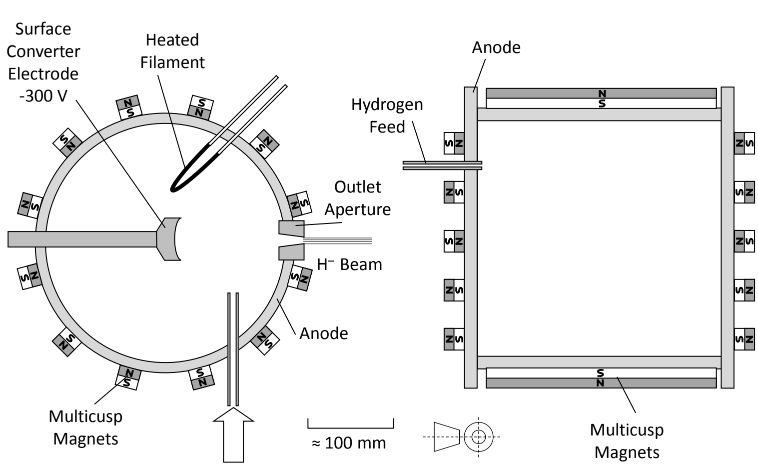
Multicusp Filament Volume Source

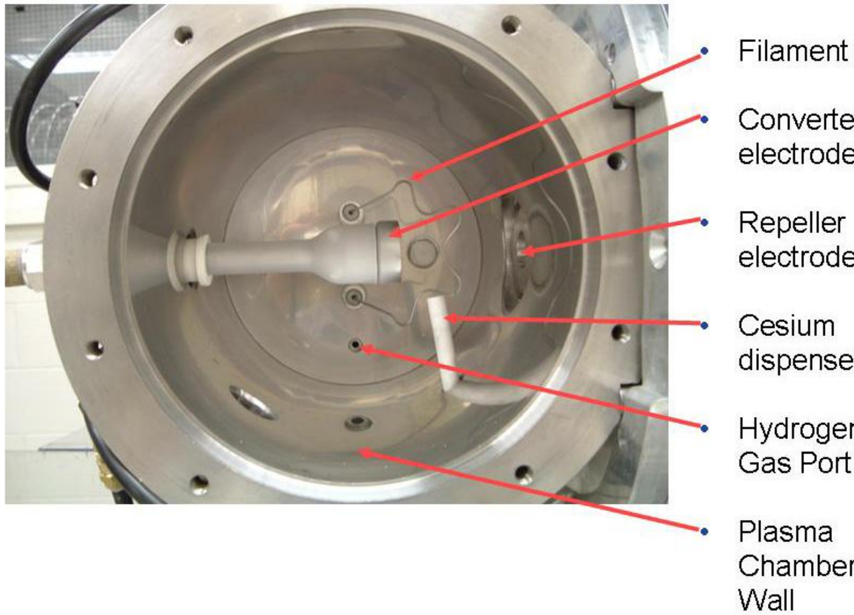


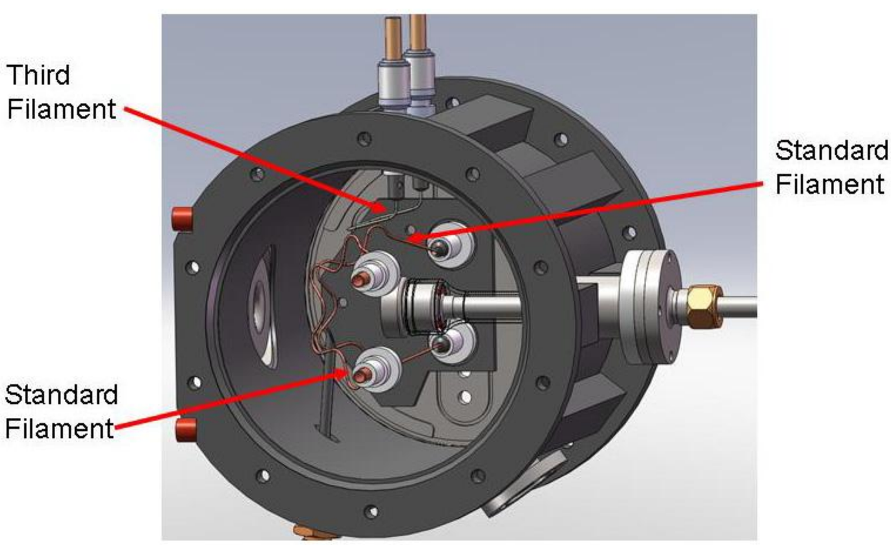
D-Pace 15 mA DC Multicusp Volume Source



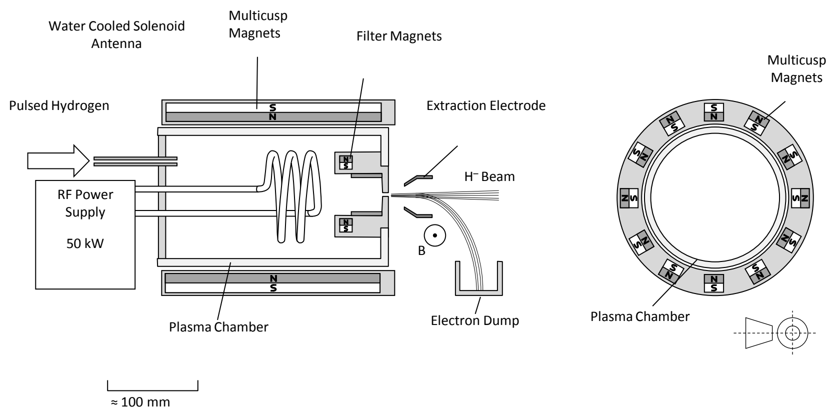
Filament Cathode Multicusp Surface Converter Source



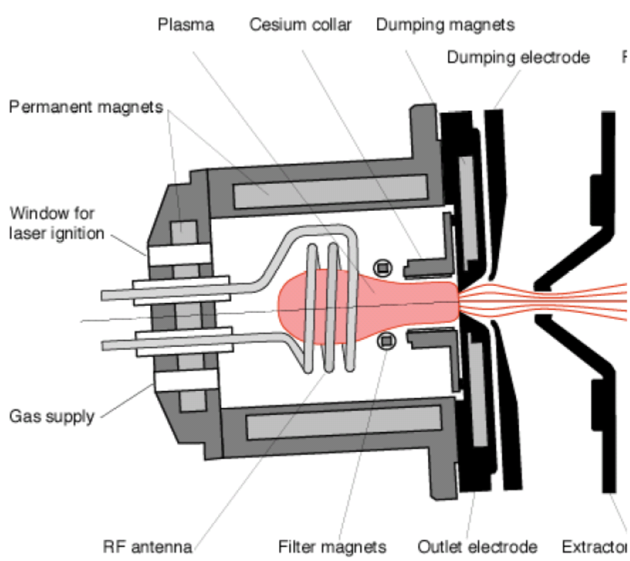

Filament
Converter electrode
Repeller electrode
Cesium dispenser
Hydrogen Gas Port
Plasma Chamber Wall


Third Filament
Standard Filament
Standard Filament

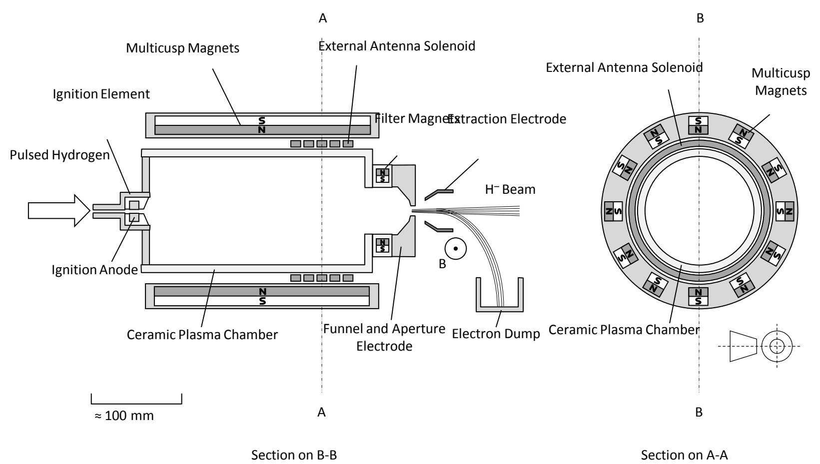
Internal RF Solenoid Antenna Multicusp Source



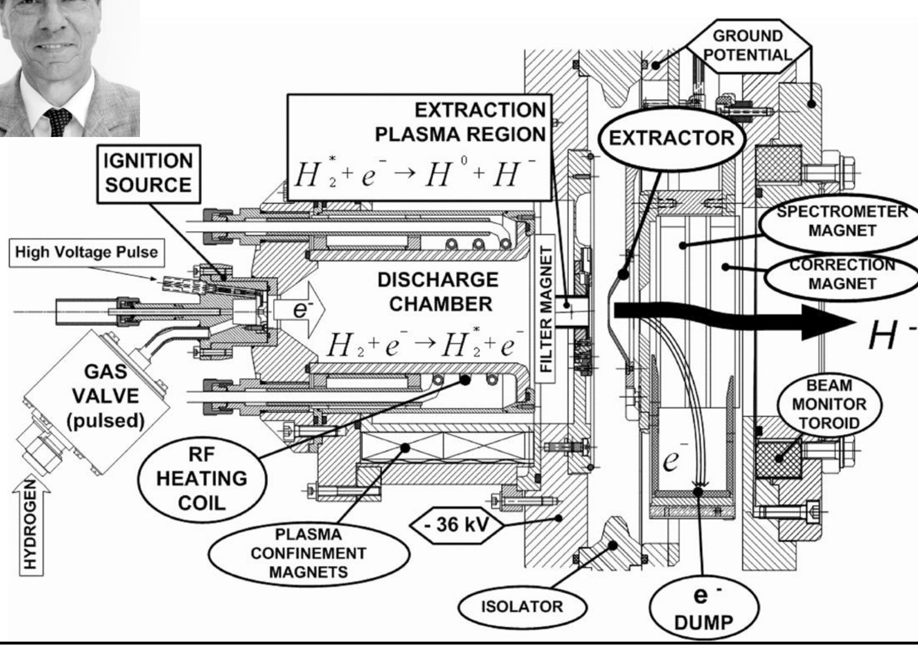
SNS ion source

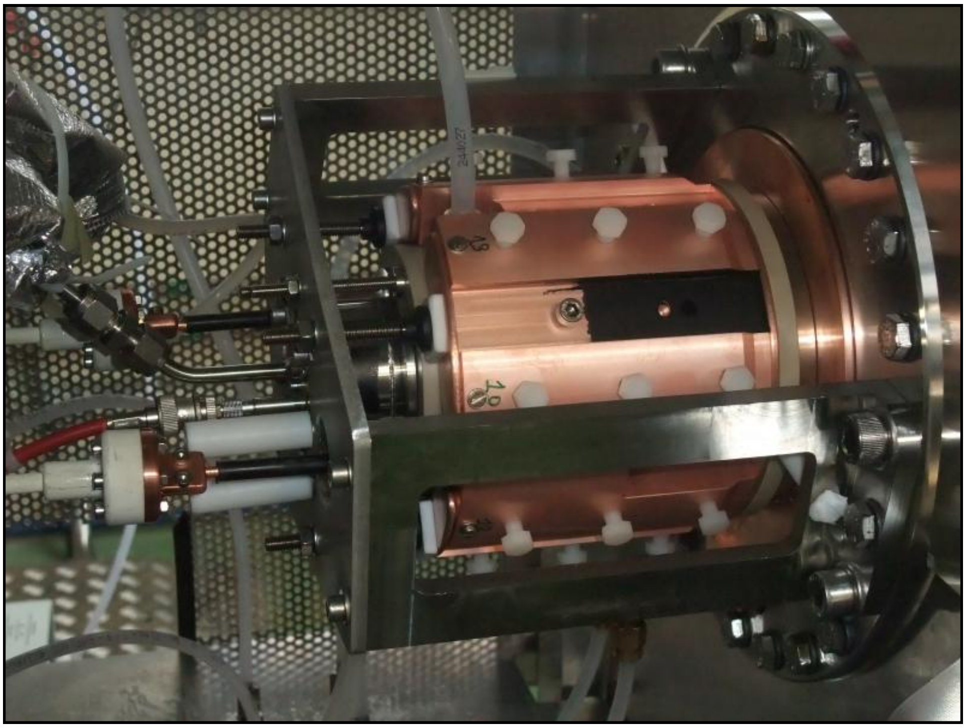


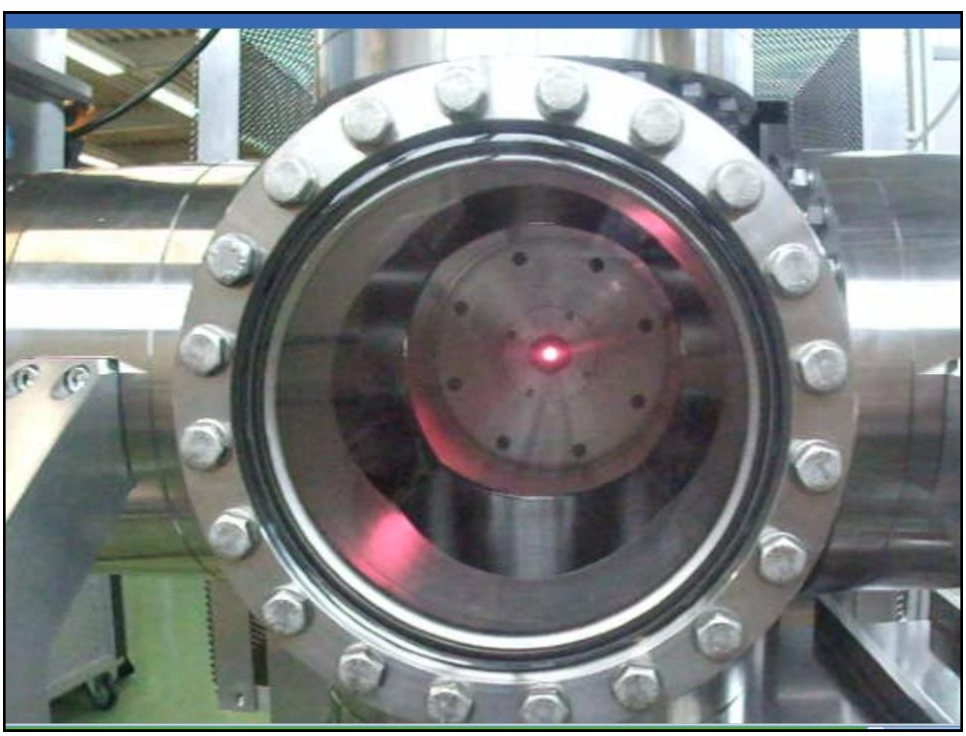
External RF Antenna Multicusp Source

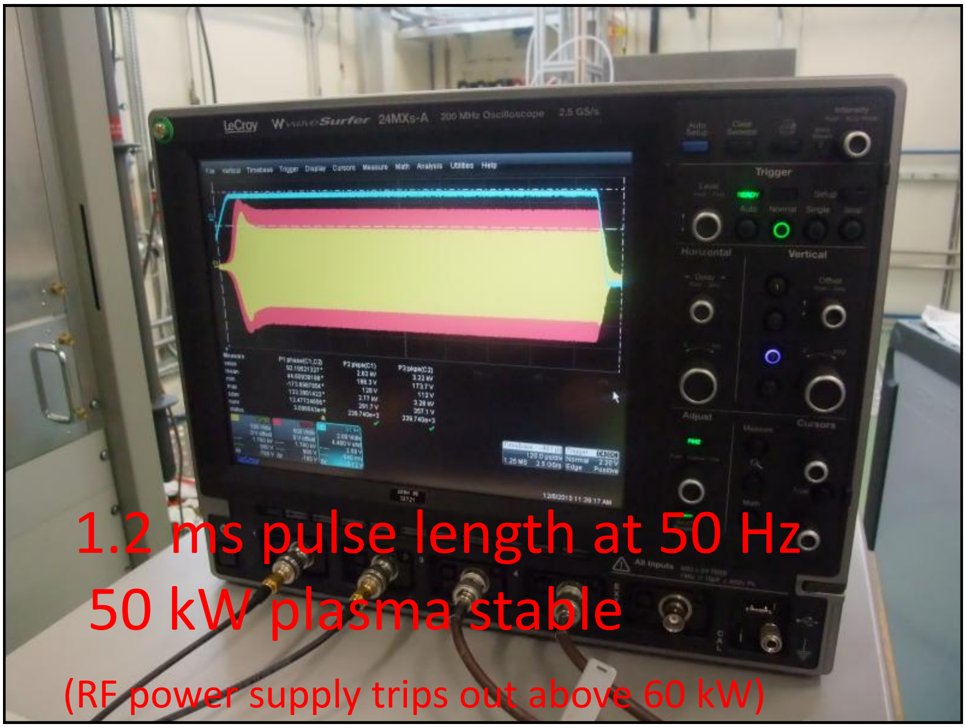


DESY Source









Which Source?

- Type of particle required
- Current, duty cycle
- Lifetime
- Expertise available

Diagnostics for Developing Sources

- Beam current e.g. toroids, faraday cups.
- Emittance e.g. slit-grid, pepperpot, slit-slit, Alison electric sweep scanner.
- Profile e.g. scintillator, wire scanner, laser wire scanner.
- Energy Spread e.g. retarding potential energy analyser.

Thank you to everyone whose images I have used