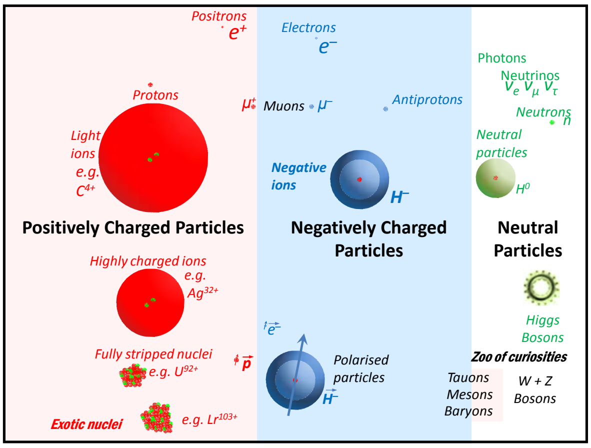
Particle Sources

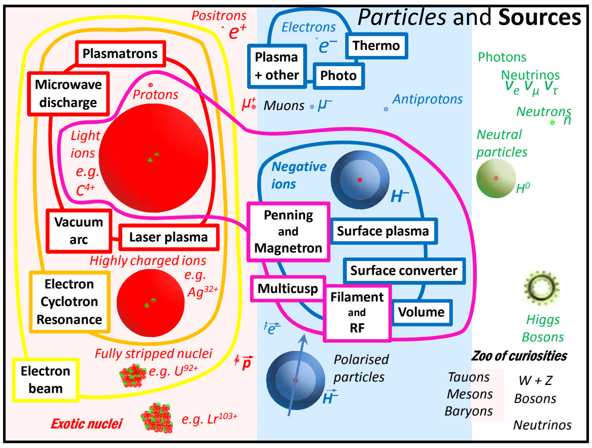
Dan Faircloth

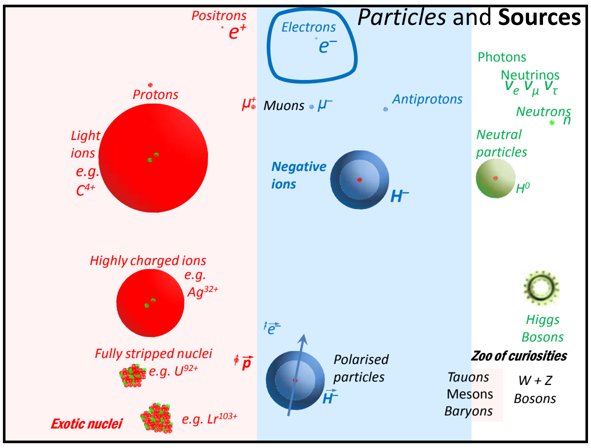
Rutherford Appleton Laboratory

CERN Accelerator School

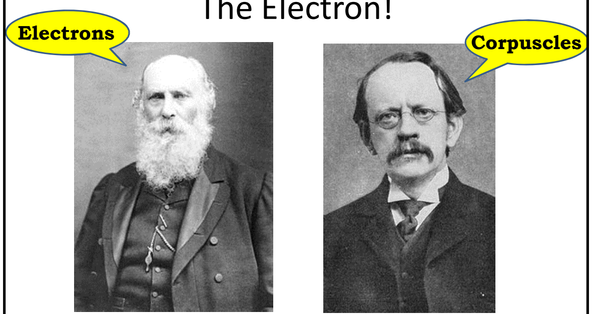
13 October 2016







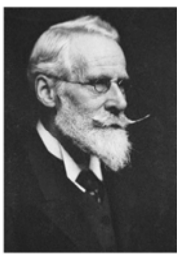
The Electron!



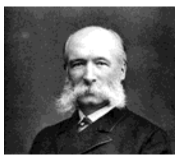
George Johnstone Stoney 1894

J. J. Thomson 1897

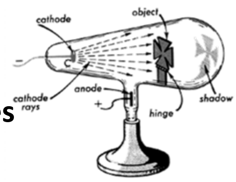
Early 1870's

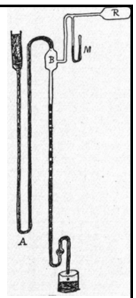


William Crookes



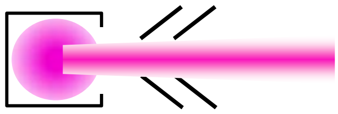
Hermann Sprengel



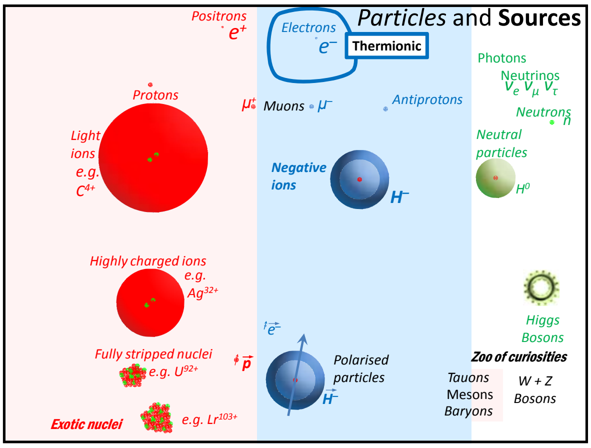


Improved mercury pump 10^{-5} mBar

Particle sources/guns consist of:

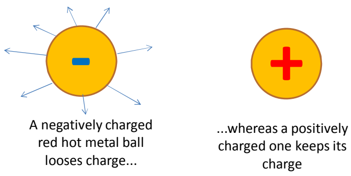


Something to make the particles + An extraction system to create and accelerate a beam



Fredrick Guthrie

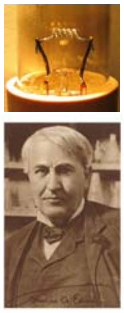
British scientific writer and professor



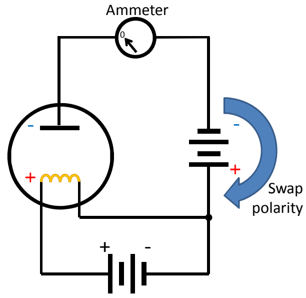
Elements of Heat in 1868

First experimental observation of thermionic emission

Thermionic Emission

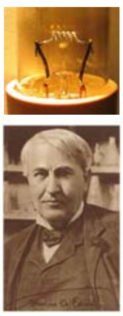


1880 Thomas Edison

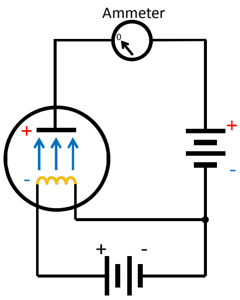


The “Edison effect”

Thermionic Emission

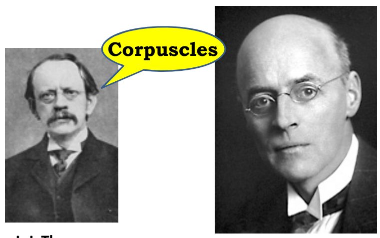


1880 Thomas Edison



The “Edison effect”

Thermionic Emission



J. J. Thomson 1897

1901 Owen Richardson

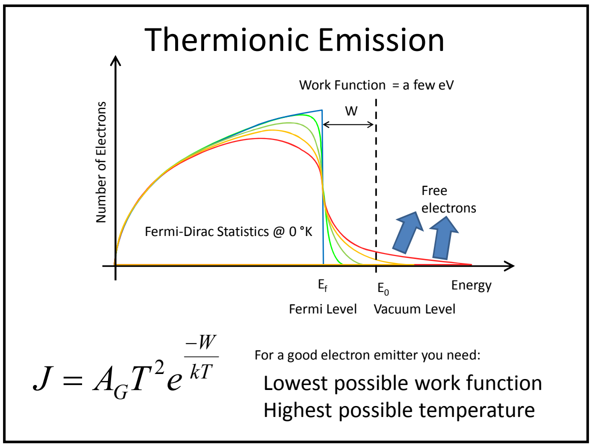
Cambridge University

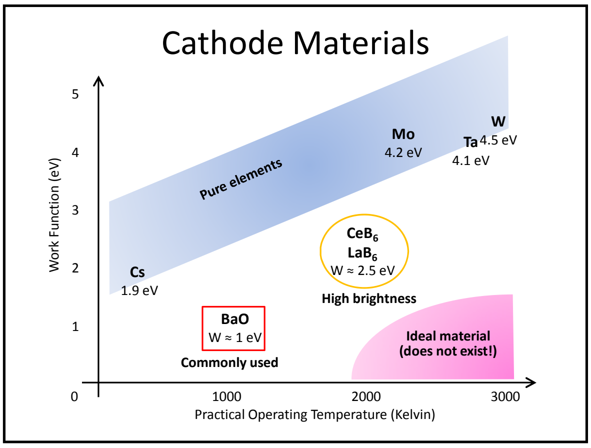
$$J = A_G T^2 e^{\frac{-W}{kT}}$$

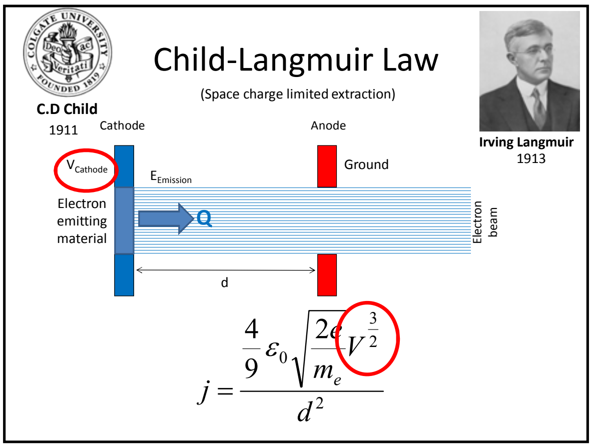
Richardson’s Law

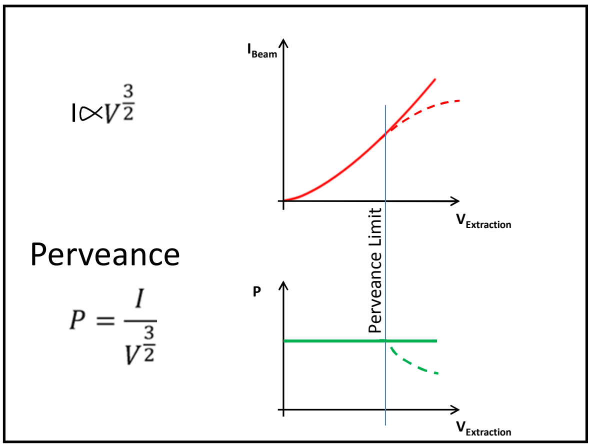
Same form as the Arrhenius equation

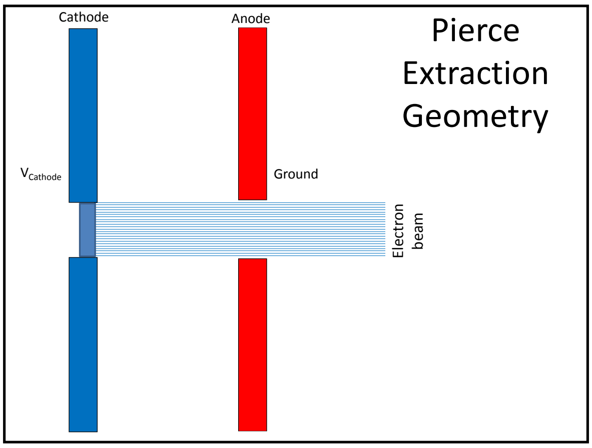
Current increases exponentially with temperature

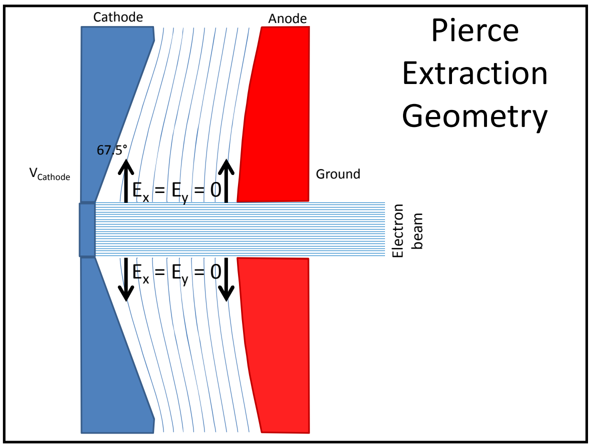

Thermionic Emission
Work Function = a few eV
W
Number of Electrons
Fermi-Dirac Statistics @ 0 °K
Free electrons
E_f
E_0
Energy
Fermi Level
Vacuum Level
$J = A_G T^2 e^{\frac{-W}{kT}}$
For a good electron emitter you need:
Lowest possible work function
Highest possible temperature

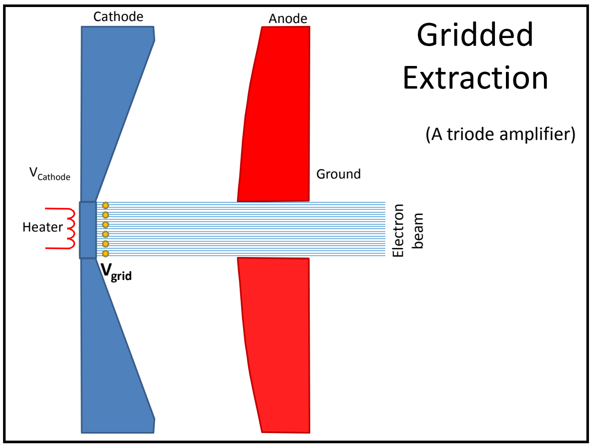

Cathode Materials
Work Function (eV)
5
4
3
2
1
0
Pure elements
Mo
4.2 eV
W
Ta 4.5 eV
4.1 eV
CeB_6
LaB_6
W ≈ 2.5 eV
High brightness
Cs
1.9 eV
BaO
W ≈ 1 eV
Commonly used
Ideal material
(does not exist!)
1000
2000
3000
Practical Operating Temperature (Kelvin)

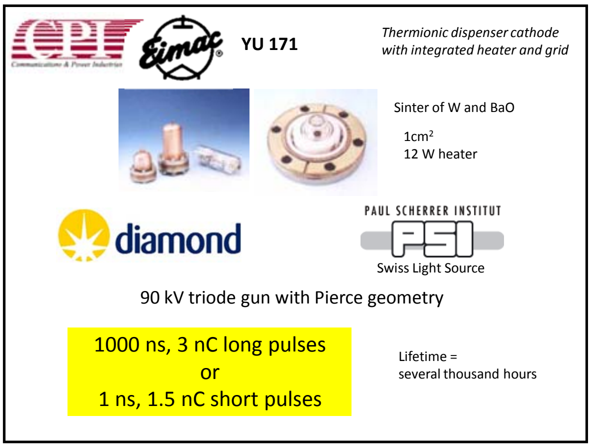

Child-Langmuir Law
(Space charge limited extraction)
C.D Child
1911
Irving Langmuir
1913
Cathode
Anode
$V_{Cathode}$
Ground
$E_{Emission}$
Electron emitting material
Q
Electron beam
d
$j = \frac{\frac{4}{9}\varepsilon_0 \sqrt{\frac{2e}{m_e}} V^{\frac{3}{2}}}{d^2}$

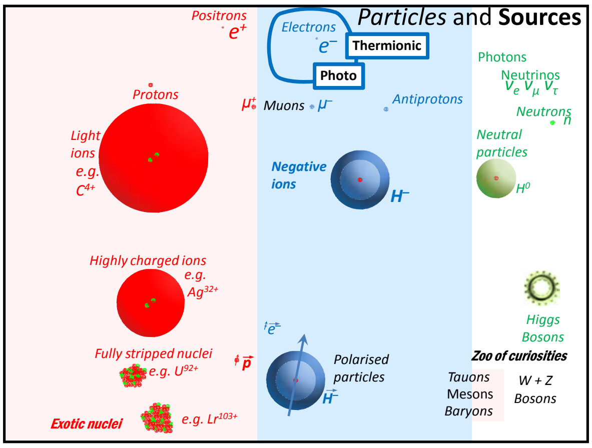

$I \propto V^{\frac{3}{2}}$
I_{Beam}
$V_{Extraction}$
Perveance
$P = \frac{I}{V^{\frac{3}{2}}}$
P
Perveance Limit
$V_{Extraction}$


Cathode
Anode
Pierce Extraction Geometry
$V_{Cathode}$
Ground
Electron beam


Cathode
Anode
Pierce Extraction Geometry
67.5°
$V_{Cathode}$
$E_x = E_y = 0$
Ground
Electron beam
$E_x = E_y = 0$


Gridded Extraction
(A triode amplifier)
Cathode
Anode
V Cathode
Ground
Heater
V grid
Electron beam


YU 171
Thermionic dispenser cathode with integrated heater and grid
Sinter of W and BaO
1cm²
12 W heater
diamond
PAUL SCHERRER INSTITUT
Swiss Light Source
90 kV triode gun with Pierce geometry
1000 ns, 3 nC long pulses
or
1 ns, 1.5 nC short pulses
Lifetime =
several thousand hours


Particles and Sources
Positrons
Electrons
Thermionic
Photo
Protons
Muons
Antiprotons
Photons
Neutrinos
Neutrons
Neutral particles
Light ions e.g. C4+
Negative ions
Highly charged ions e.g. Ag32+
Higgs Bosons
Fully stripped nuclei e.g. U92+
Polarised particles
Zoo of curiosities
Tauons
Mesons
Baryons
W + Z Bosons
Exotic nuclei e.g. Lr103+

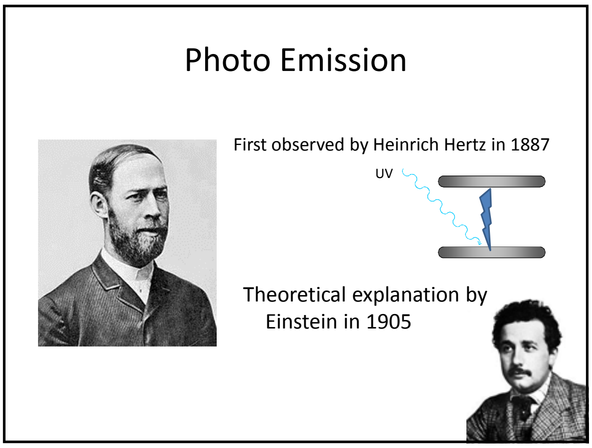


Photo Emission
First observed by Heinrich Hertz in 1887
UV
Theoretical explanation by Einstein in 1905

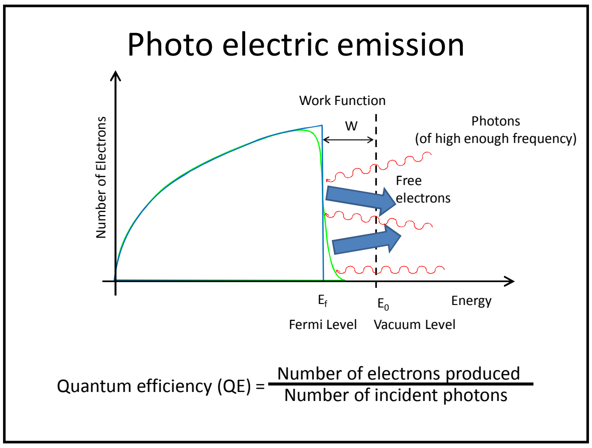


Photo electric emission
Number of Electrons
Work Function
W
Photons
(of high enough frequency)
Free electrons
Ef
E0
Energy
Fermi Level
Vacuum Level
Quantum efficiency (QE) = Number of electrons produced / Number of incident photons

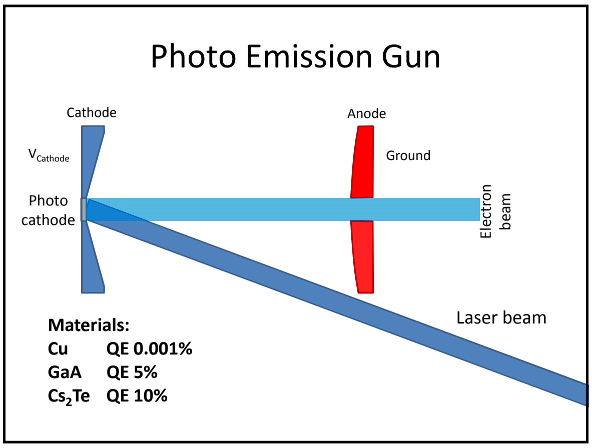
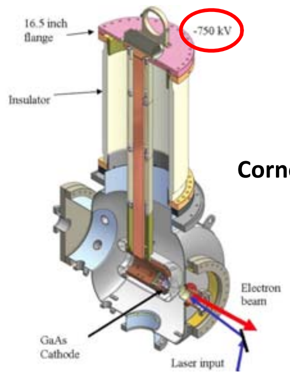


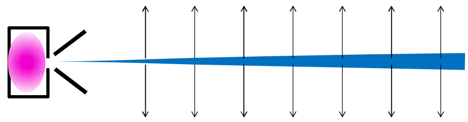
Photo Emission Gun
Cathode
Anode
V Cathode
Ground
Photo cathode
Electron beam
Laser beam
Materials:
Cu QE 0.001%
GaA QE 5%
Cs2Te QE 10%



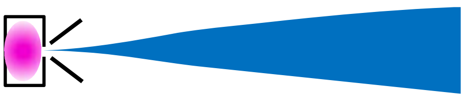
Cornell DC Photoemission gun

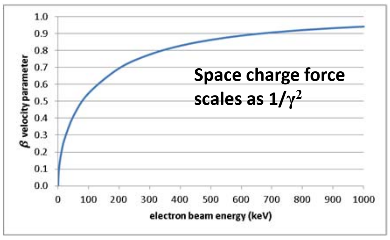
20 mA average current at 250kV

Space Charge



Space Charge





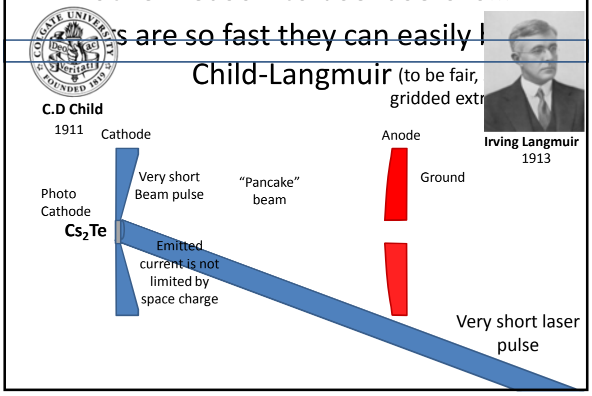
At 500 keV electron $\gamma = 2$

(940 MeV proton $\gamma = 2$)

Another reason to use lasers is…

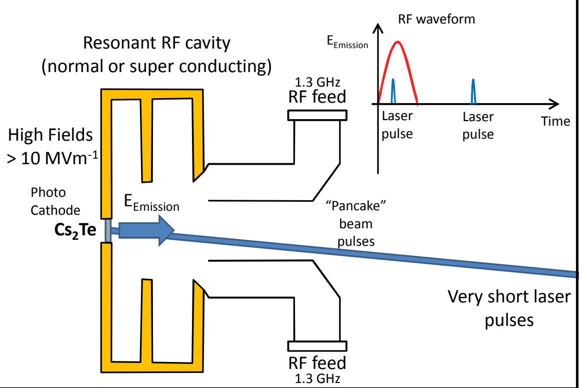
…s are so fast they can easily l…

Child-Langmuir (to be fair, gridded extr…



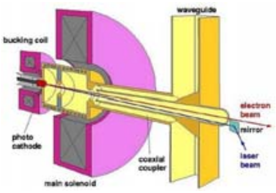
RF Photemission Source

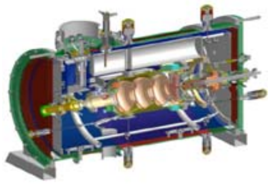
RF Photemission Source



Normally conducting

Super conducting

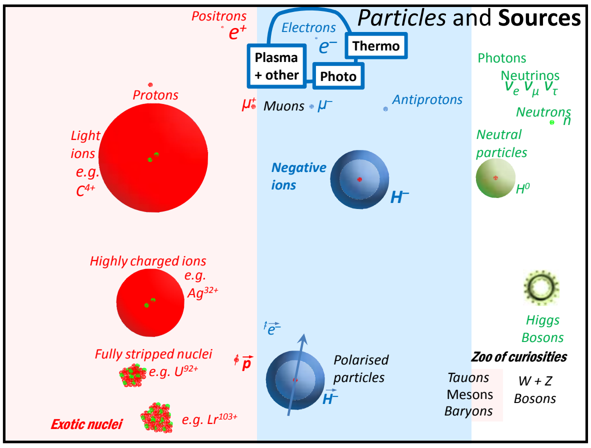




20 ps, 1 nC pulses
(50 A pulse)

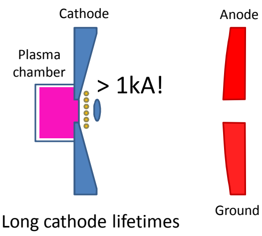
15 ps, 1 nC pulses
(67 A pulse)

High brightness low emittance guns for FEL



Plasma Cathode

Very high electron currents can be extracted from plasma cathode electron sources



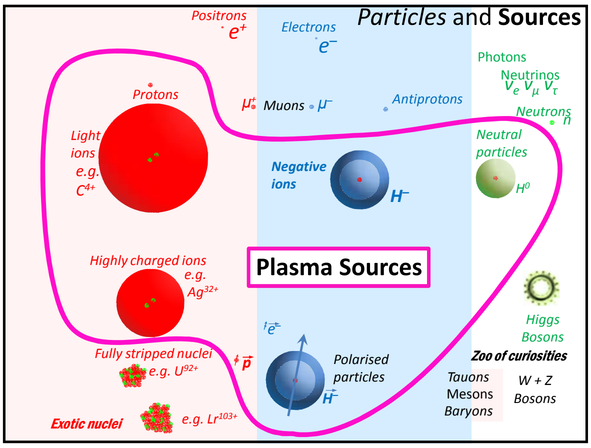
Long cathode lifetimes

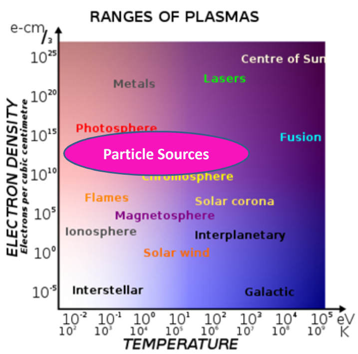
Other electron sources:

Combinations of those already mentioned e.g. photo-thermionic

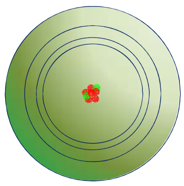
Rarely used in accelerators:

Field emission from needle arrays
Diamond amplifiers
Etc...





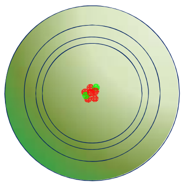
Ionisation



Neutral Atom

Most sources rely on electron impact ionisation

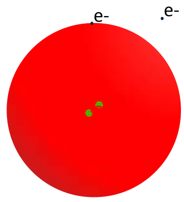
Ionisation



Neutral Atom

Most sources rely on electron impact ionisation

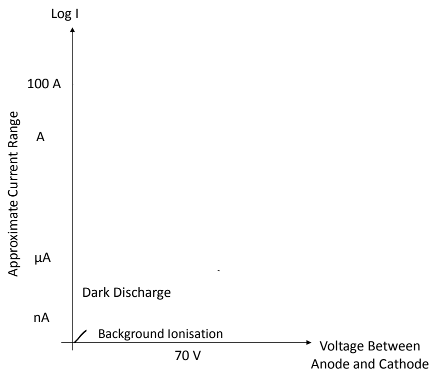
Ionisation

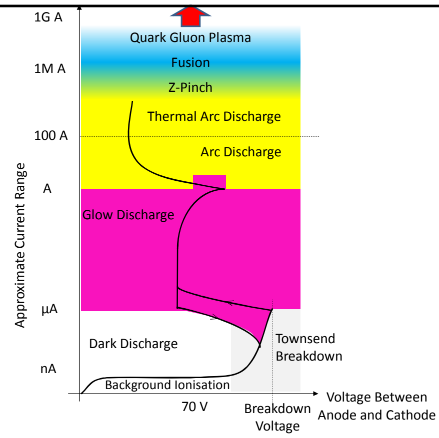


Positive Ion

Most sources rely on electron impact ionisation

Electrical Discharges





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

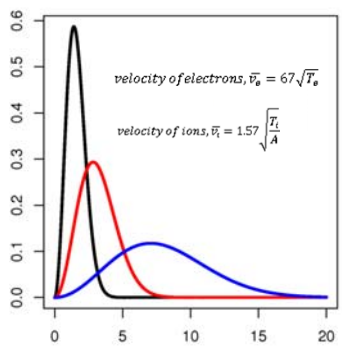
11600°K = 1 eV

Temperature Distribution

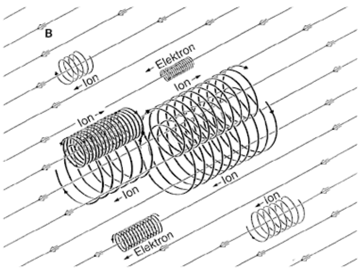
If thermalised velocity distributions should follow Maxwell Boltzmann statistics

However, in magnetic fields:

$v_x \neq v_y \neq v_z$

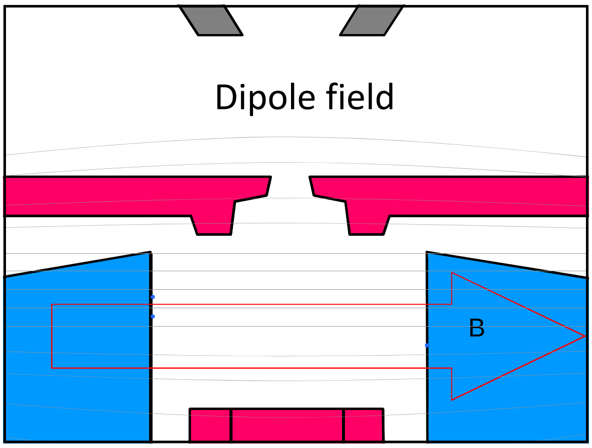


Magnetic Confinement

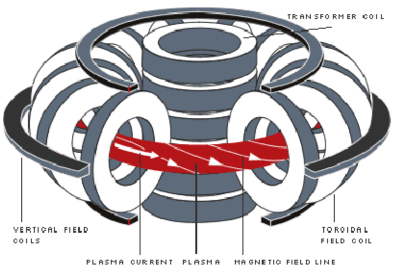


Particles spiral along magnetic field lines

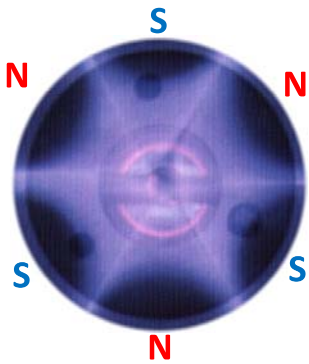
Dipole field



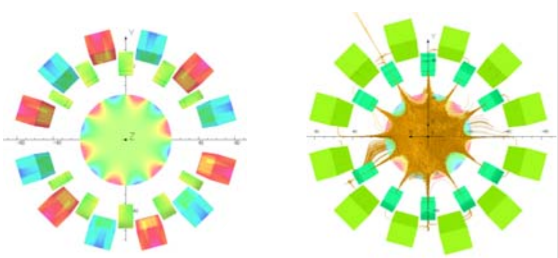
Solenoid field



Hexapole



Multicusp Confinement

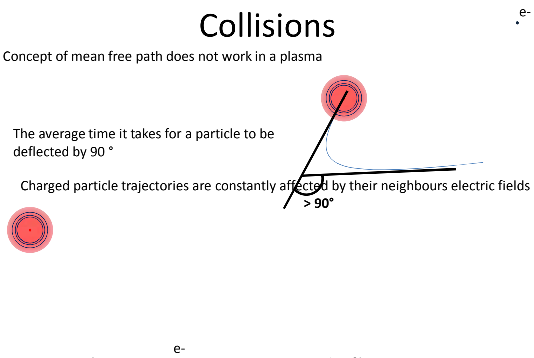


Collisions

Concept of mean free path does not work in a plasma

The average time it takes for a particle to be deflected by 90 °

Charged particle trajectories are constantly affected by their neighbours electric fields



Relaxation time = 90° deflection time

Percentage Ionisation

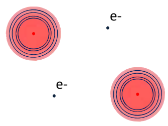
$$\frac{n_i}{n_i + n_n}$$

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

Quasi Neutrality

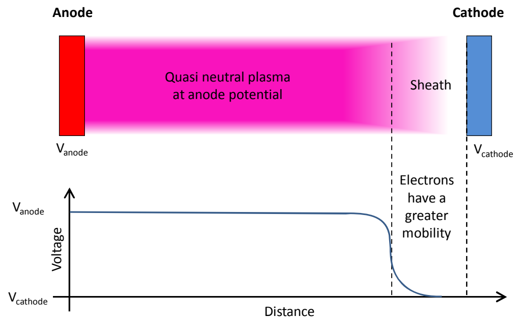
$$\sum q_i\, n_i = n_e$$

Debye Length



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

Cathode Sheath



Plasma Pioneers

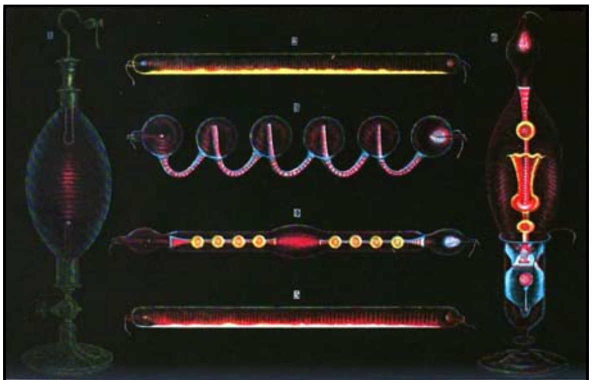
Heinrich Geißler

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

Julius Plücker

Mid 1850's University of Bonn

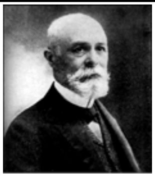
magnetism could move the glow discharge

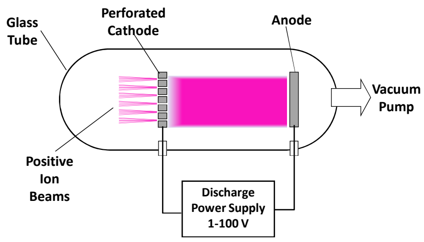


Drawing of Geissler tubes from 1860's French physics book

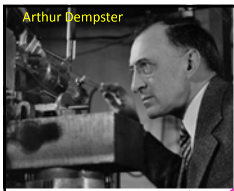
Canal Ray Source

In 1886 Eugen Goldstein discovered canal rays

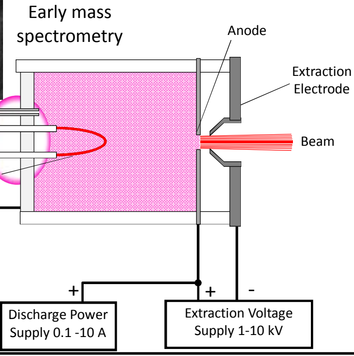


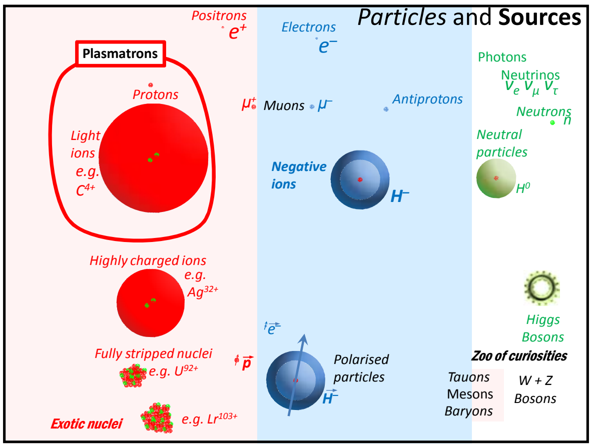


Electron Bombardment Source (1916)

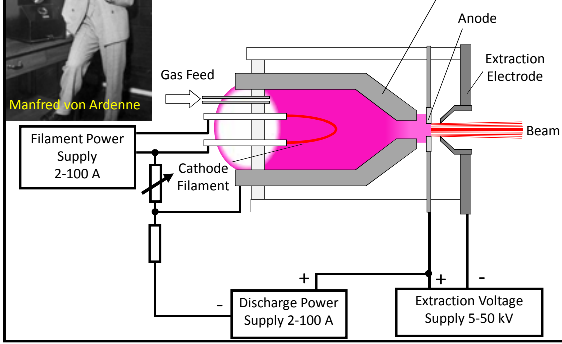


Early mass spectrometry

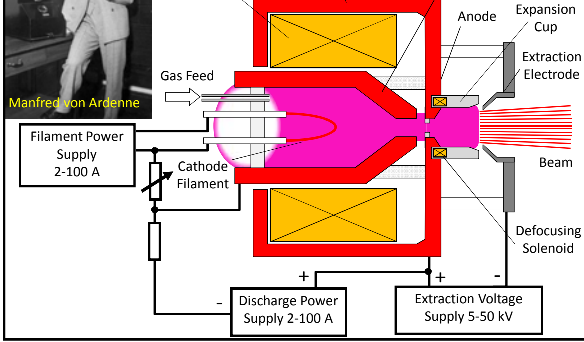




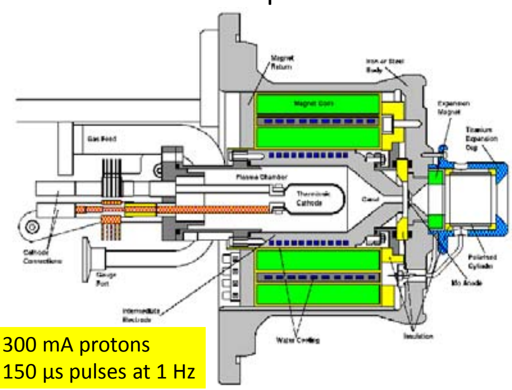
Plasmatron (late 1940s)



Duoplasmatron (1956)

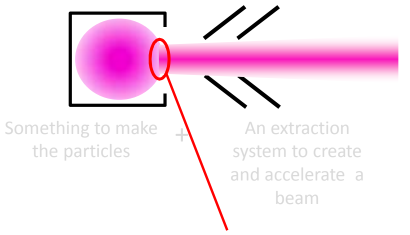


CERN Duoplasmatron



300 mA protons
150 µs pulses at 1 Hz

Particle sources/guns consist of:



The emission "surface" is critical to the quality of the beam

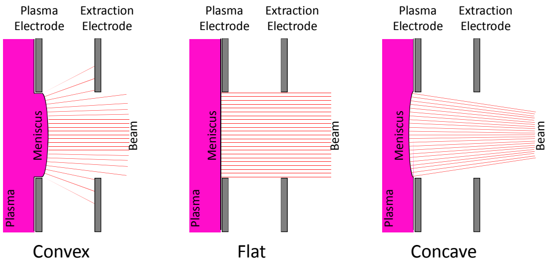
Plasma Mencius

...is not actually a surface

because of Debye length, it has a thickness,

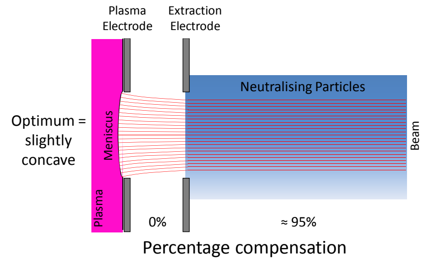
but it is a useful concept when considering the optics of extraction...

Plasma Mencius

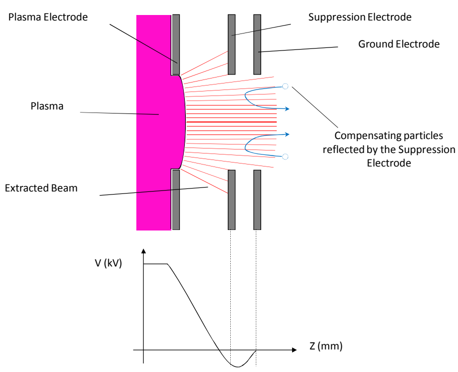


Not including space charge effects

Space Charge



Suppressor Electrode

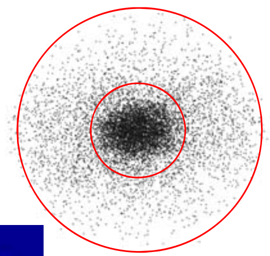


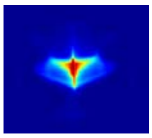
Emittance of Real Beams

Halo Effect

- Plasma boundary
- Fringe fields

How big is this beam?

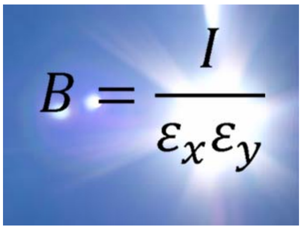




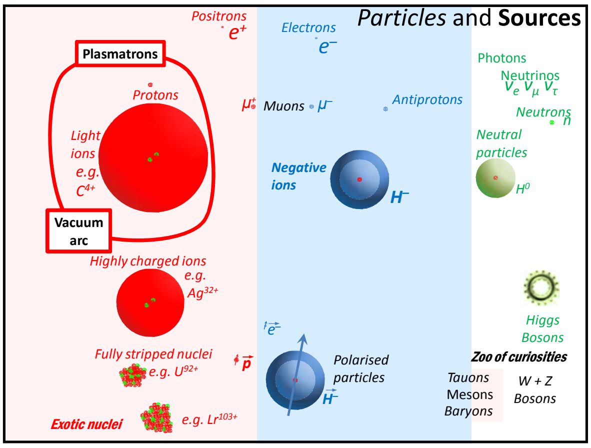
95% emittance

rms emittance

Brightness

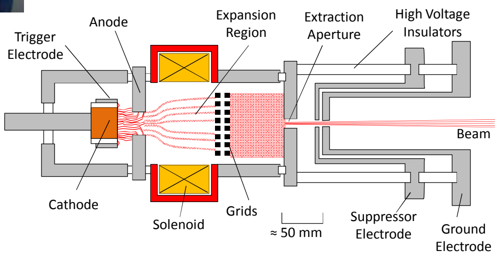


Be careful- Some definitions include factors of 2, 8 and π
Are the emittances normalised?



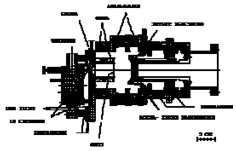
Vacuum Arc Ion Sources

1980s - Ian Brown LBNL and others

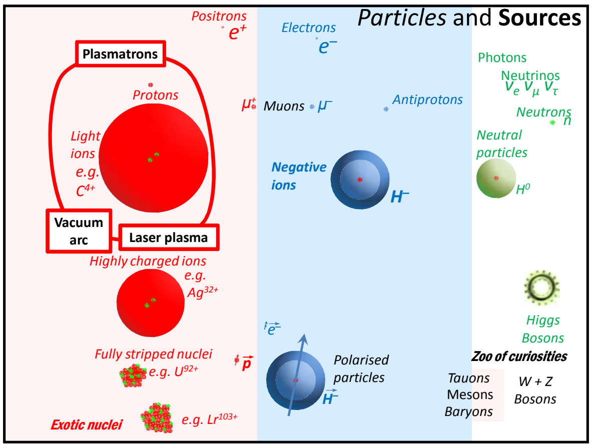


Lawrence Berkley Lab MEVVA

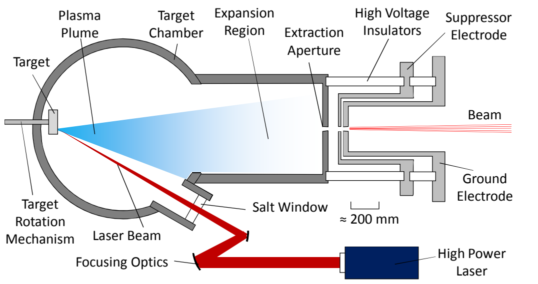
GSI MEVVA



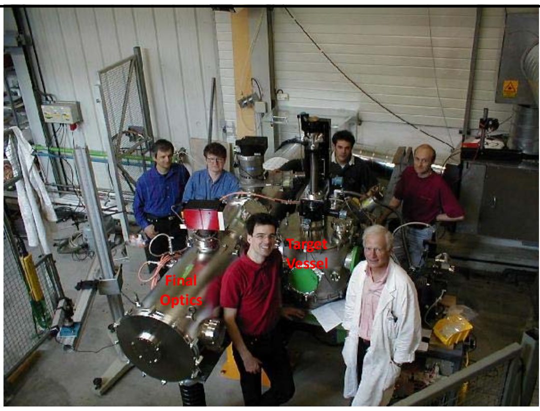
15 mA of U^{4+} ions



Laser Plasma Ion Sources



1 -100 Joules per pulse!



ITEP Laser source at CERN

ITEP Laser source at CERN

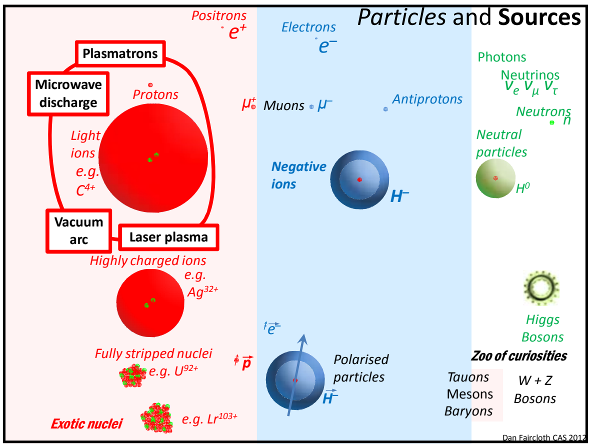
TWAC at ITEP Moscow

7 mA, 10 µs pulses of C^{4+}

BNL and RIKEN

Masahiro Okamura has demonstrated
Direct Plasma Injection into an RFQ

Particles and **Sources**



Microwave Ion Sources

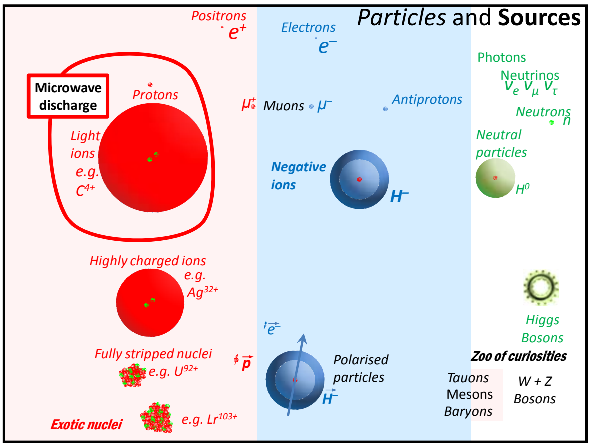
Off resonance

= Microwave discharge ion sources

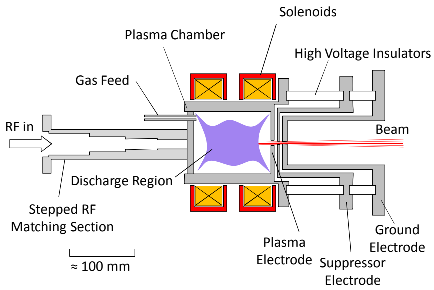
On resonance

= Electron Cyclotron Resonance (ECR) sources

Particles and **Sources**

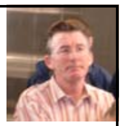


Microwave Discharge Ion Source

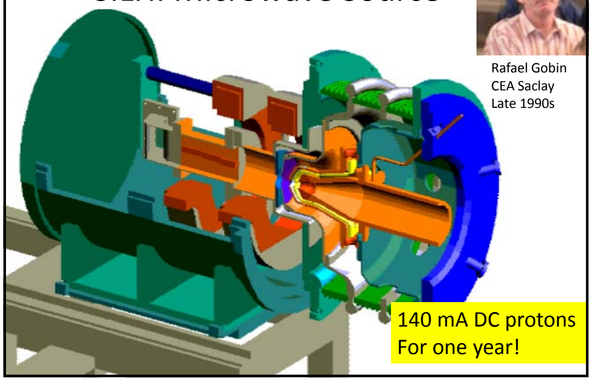


2.45 GHz commonly used

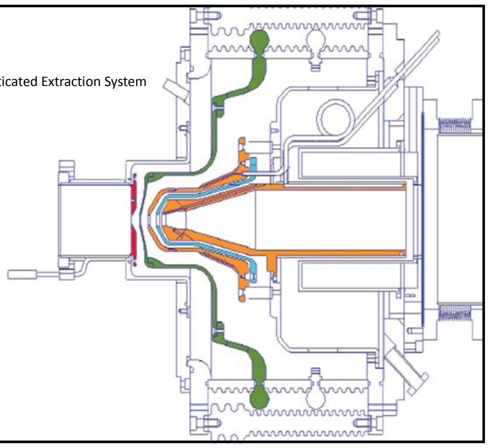
SILHI Microwave Source

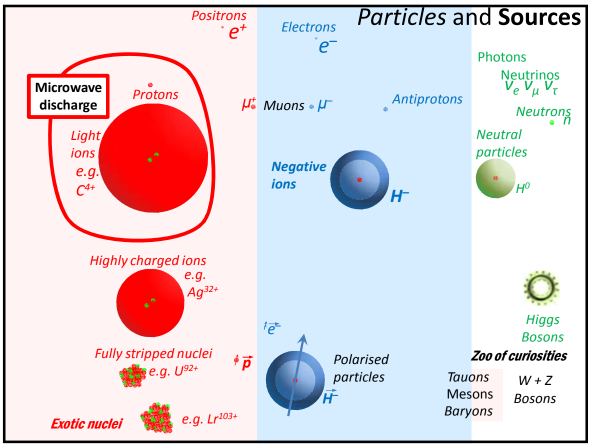


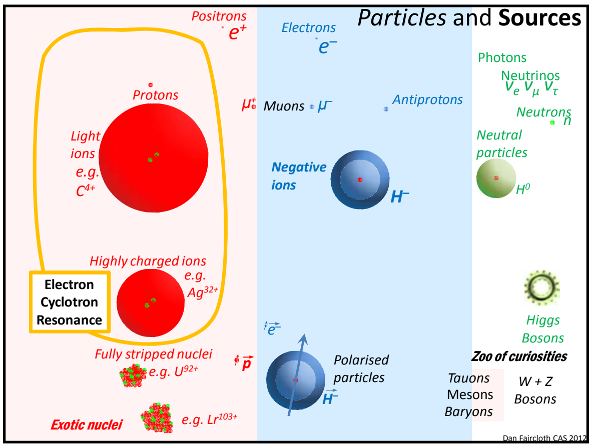
Rafael Gobin
CEA Saclay
Late 1990s



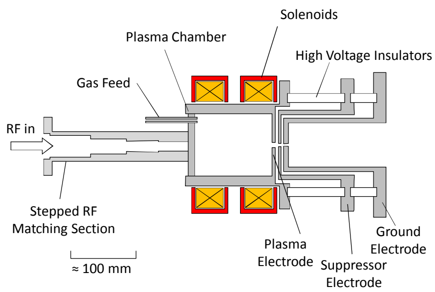
Sophisticated Extraction System



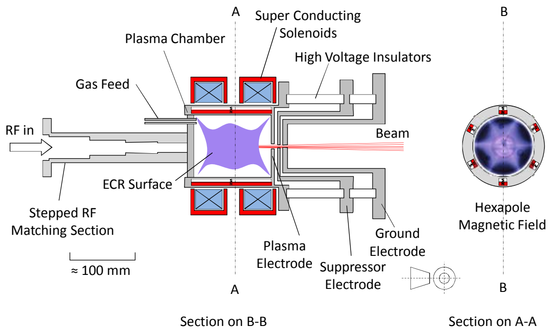




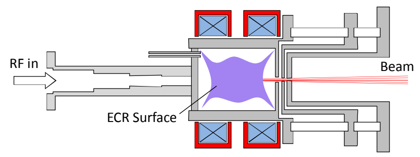
Microwave Discharge Ion Source



ECR Ion Source



ECR Surface



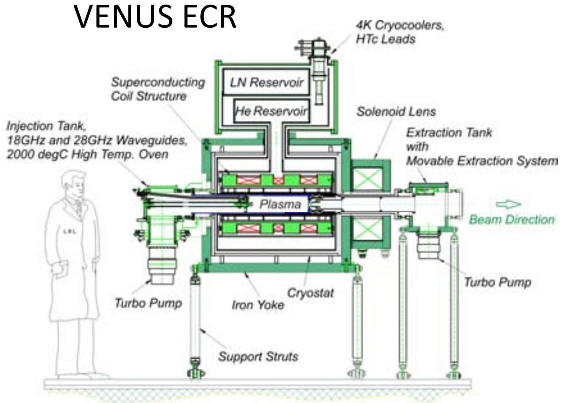
$$\omega_{ECR} = 2\pi f_{ECR} = \frac{eB}{m}$$

28 GHz superconducting VENUS ECR

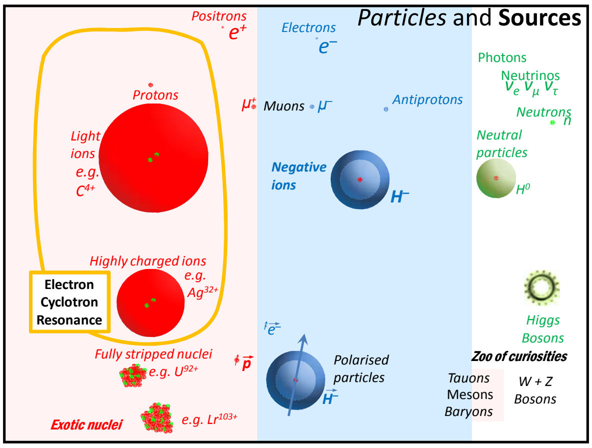
Daniela Leitner
LBNL
Late 2000s

200 eμA U^{34+} ions
4.9 eμA U^{47+} ions

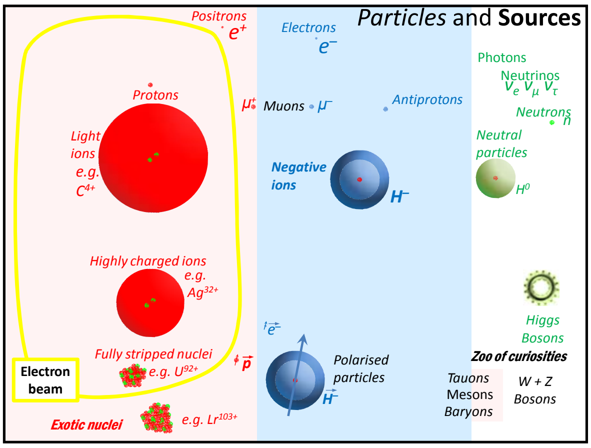
VENUS ECR



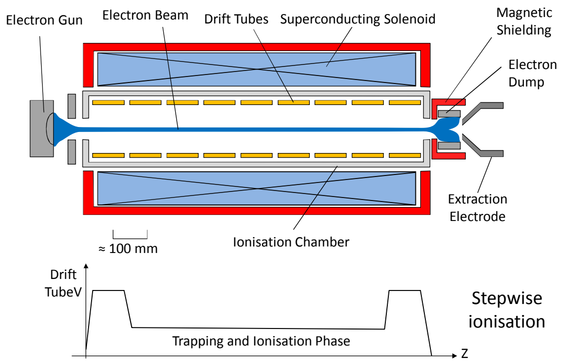
Particles and Sources



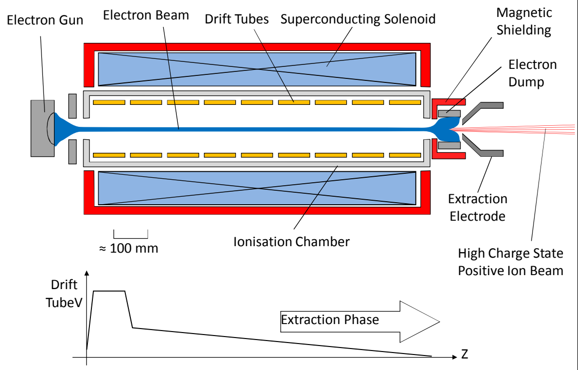
Particles and Sources



Electron Beam Ion Sources



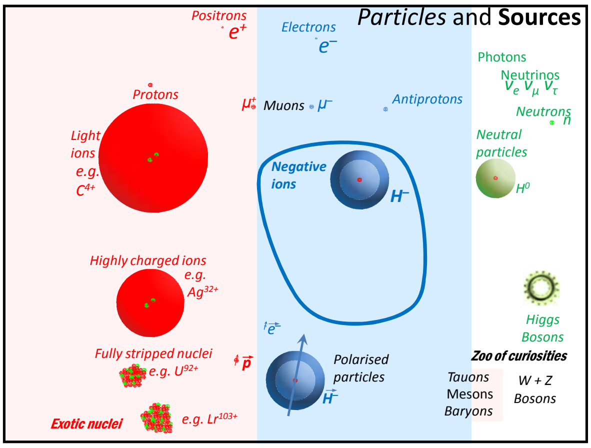
Electron Beam Ion Sources



Jim Alessi
BNL

1.7 emA, 10 μs, 5 Hz
Ag^{32+} ions

Fully stripped nuclei can be obtained in EBIT mode



Negative Ion Sources

Ripping electrons off is easy!

- It is much harder to add them on….

Not all elements will even make negative ions

Hydrogen has an electron affinity of 0.7542 eV

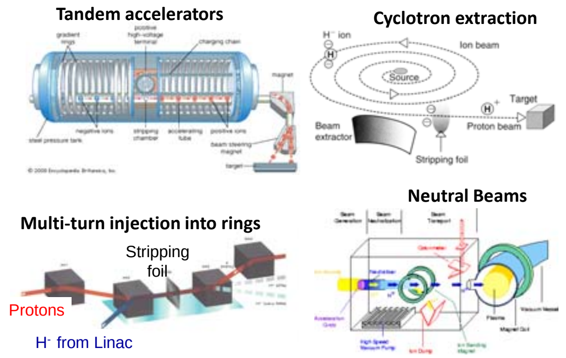
H^- has a much larger cross section than H^0

30 times for e^- collisions

100 times for H^+ collisions

H^- are very fragile!

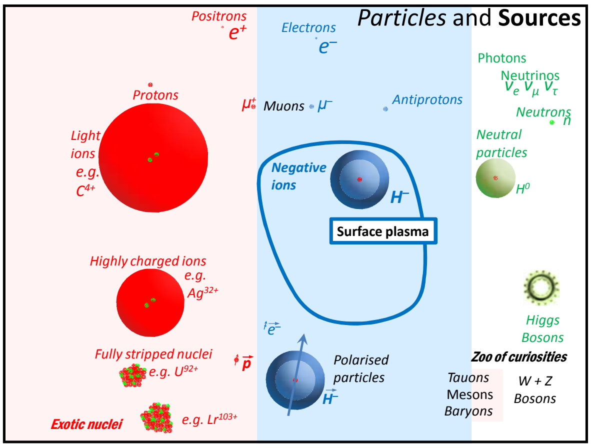
Applications



Early attempts at producing negative ion beams:

1. Charge exchange of positive beams in gas cells
   - very inefficient

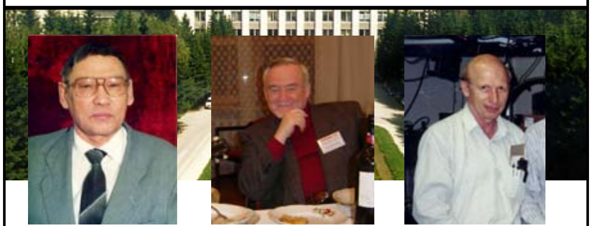
2. Extraction from existing ion sources



Early 1970s Budker Institute of Nuclear Physics Novosibirsk

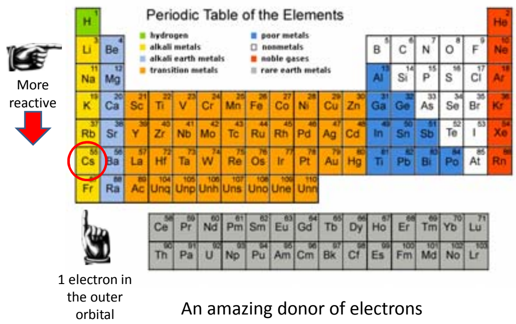
Production of H⁻ ions by surface ionisation with the addition of ceasium

Surface Plasma Sources (SPS)



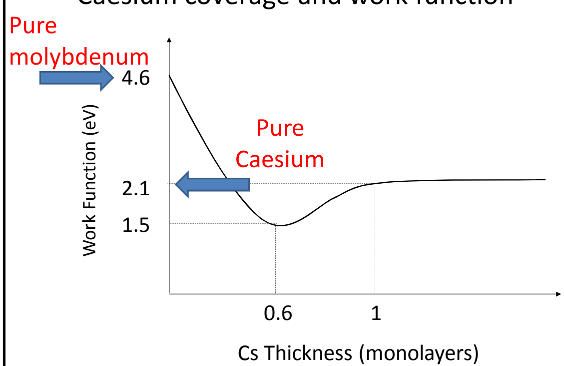
Gennady Dimov Yuri Belchenko Vadim Dudnikov

Caesium! – The magic elixir

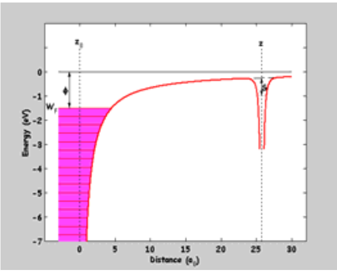


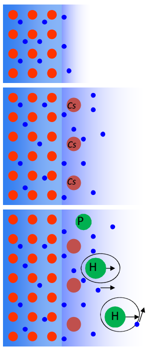
An amazing donor of electrons
= great for making negative ions

Caesium coverage and work function

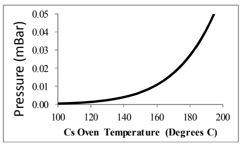


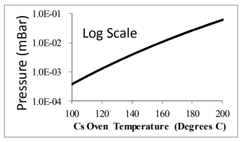
Fermilevels

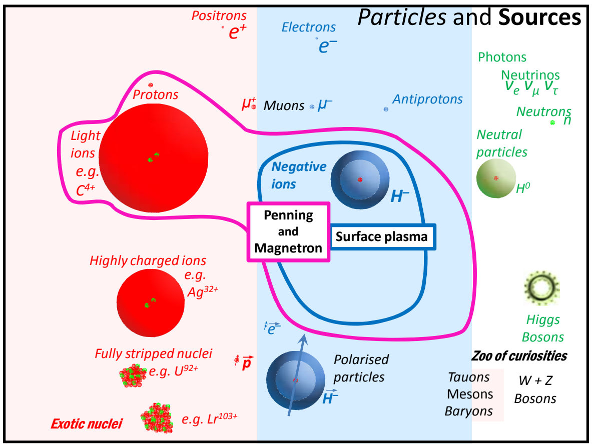




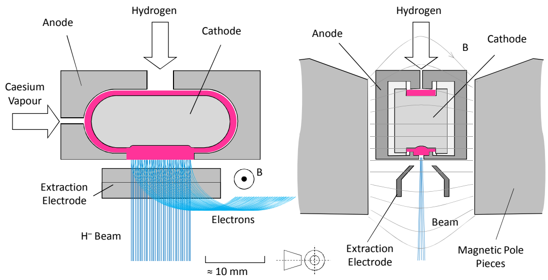
Caesium oven temperature → Caesium vapor pressure → Control caesium coverage



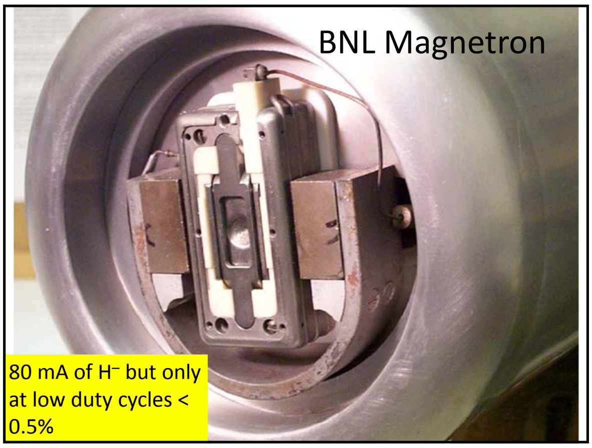




Magnetron SPS



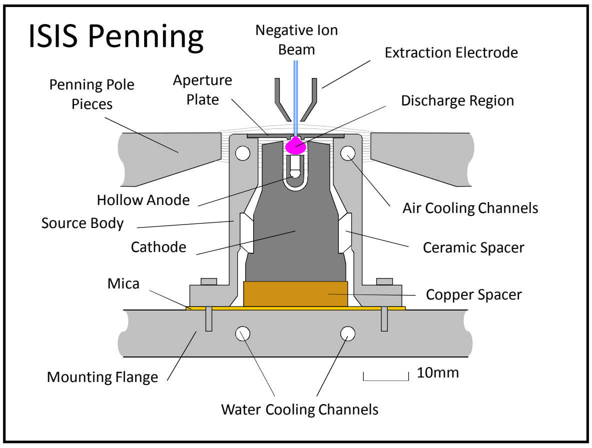
BNL Magnetron

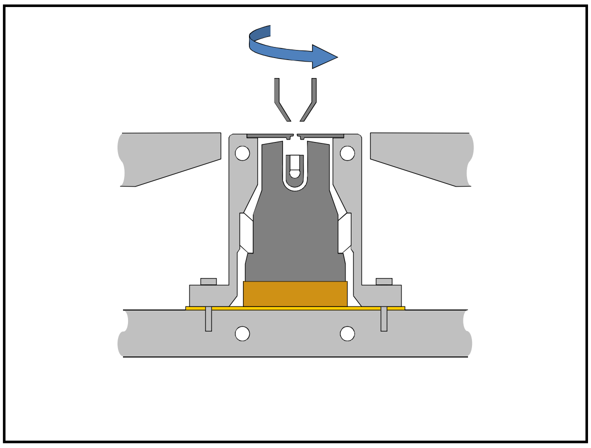


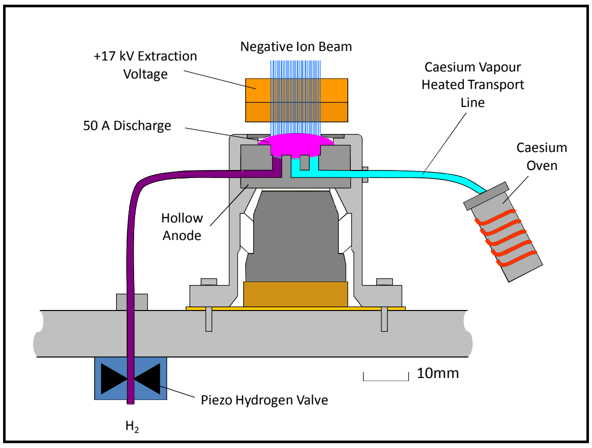
80 mA of H⁻ but only at low duty cycles < 0.5%

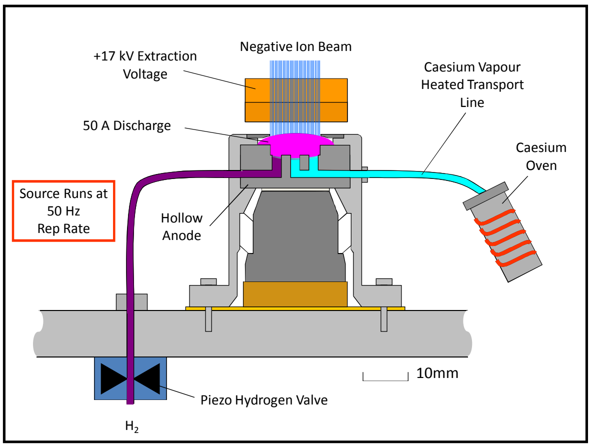
Penning SPS

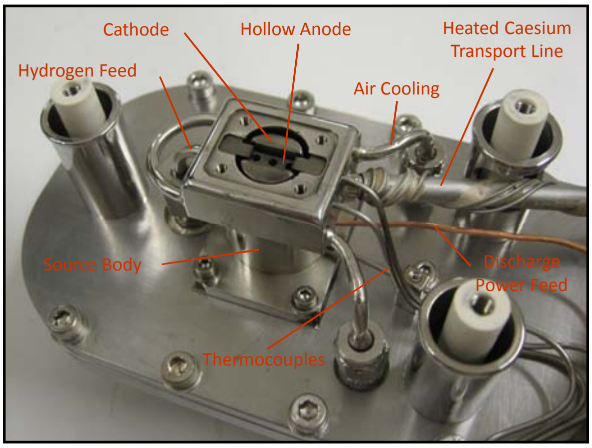
- Invented by Dudnikov in the 1970's
- Very high current density > 1 Acm^{-2}
- Low noise
- Does not work without ceasium

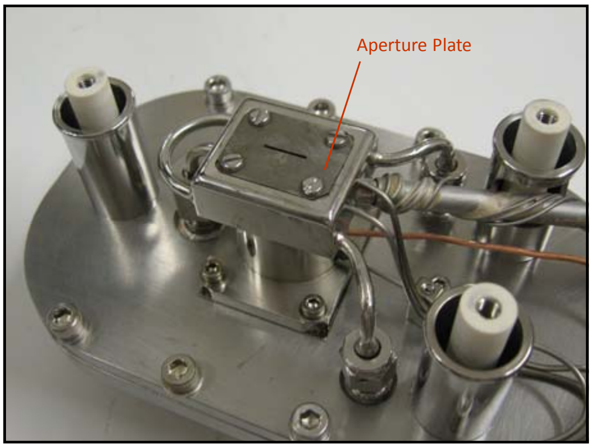

ISIS Penning
Negative Ion Beam
Extraction Electrode
Penning Pole Pieces
Aperture Plate
Discharge Region
Hollow Anode
Air Cooling Channels
Source Body
Cathode
Ceramic Spacer
Mica
Copper Spacer
Mounting Flange
10mm
Water Cooling Channels

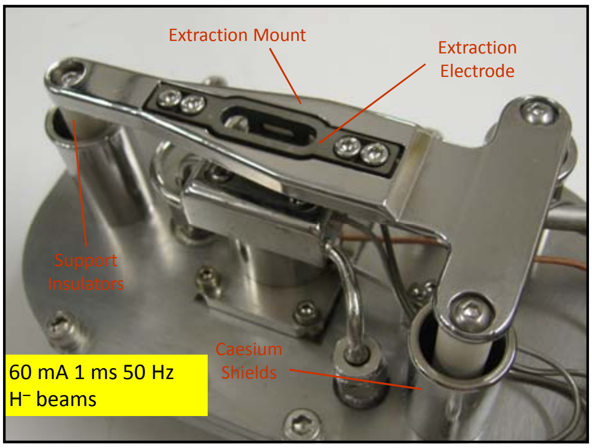


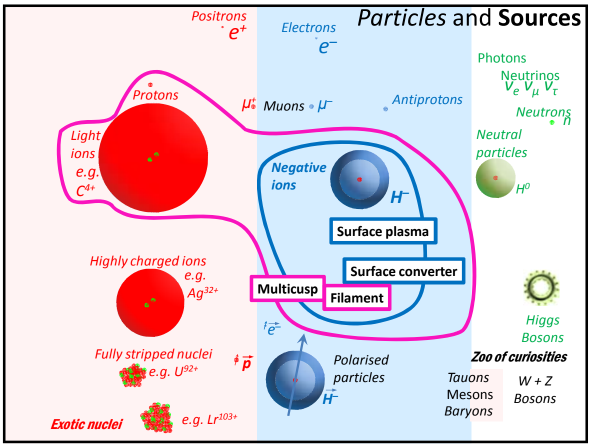

+17 kV Extraction Voltage
Negative Ion Beam
Caesium Vapour Heated Transport Line
50 A Discharge
Caesium Oven
Hollow Anode
10mm
Piezo Hydrogen Valve
H_2


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

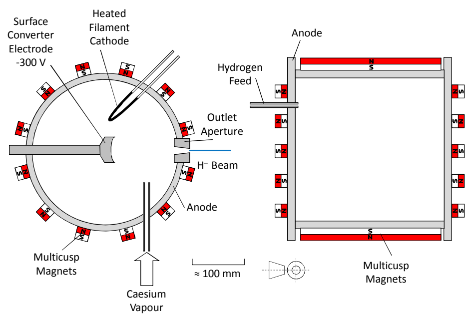

Cathode
Hollow Anode
Heated Caesium Transport Line
Hydrogen Feed
Air Cooling
Source Body
Discharge Power Feed
Thermocouples

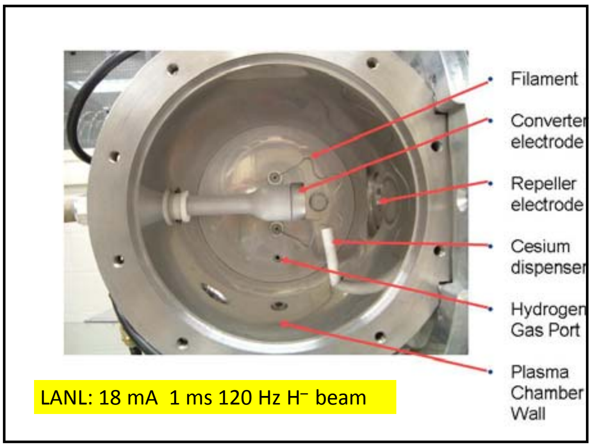

Aperture Plate

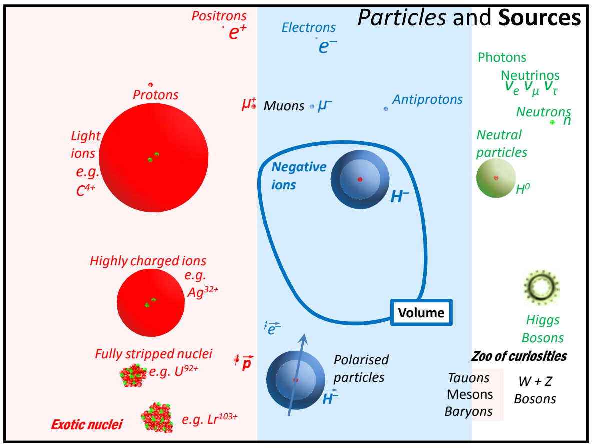




Filament Cathode Multicusp Surface Converter Source







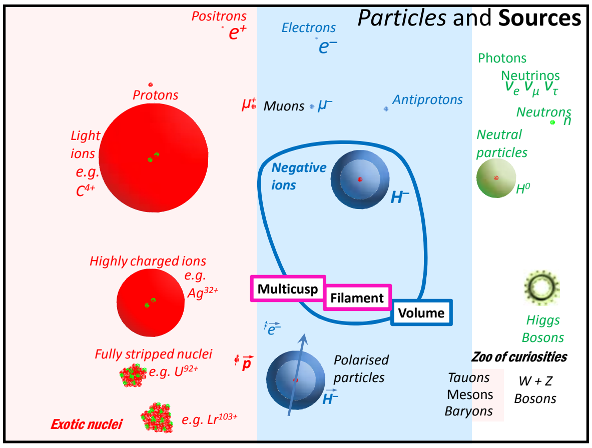
Volume Production

Marthe Bacal
Ecole Polytechnique
mid 1970's

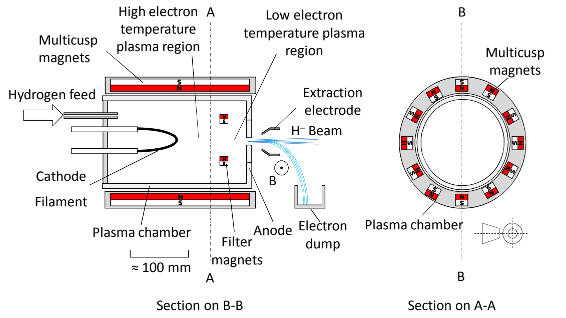
$H_2^* + e\ (\leq 1\ eV) \rightarrow H^- + H^0$

Dissociative attachment of low energy electrons to rovibrationally excited H_2 molecules

Developed by Ehlers + Leung at LBNL

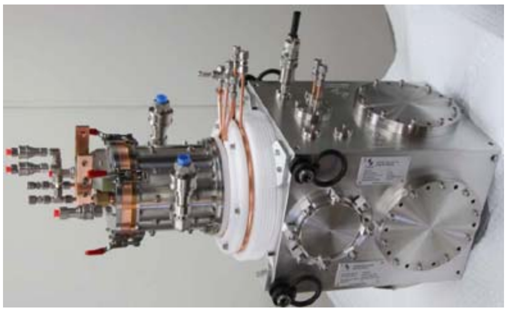


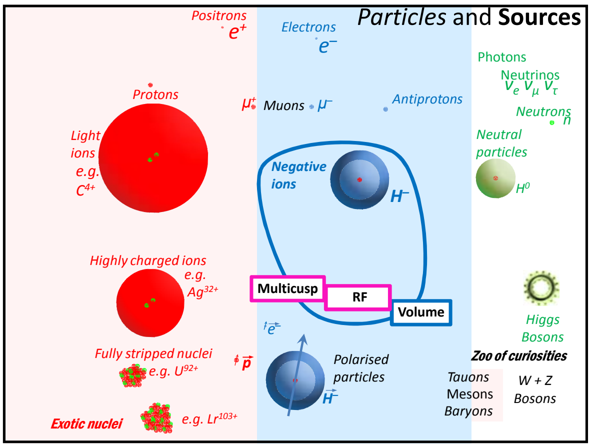
Multicusp Filament Volume Source

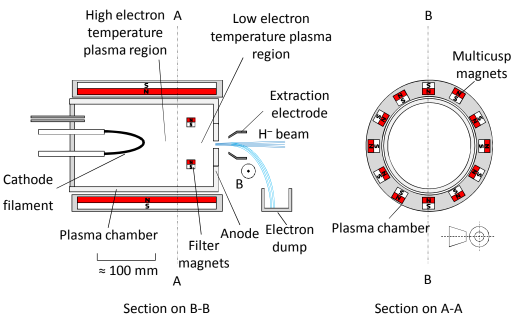


Many Variations: e.g. JPARC use a LaB_6 cathode

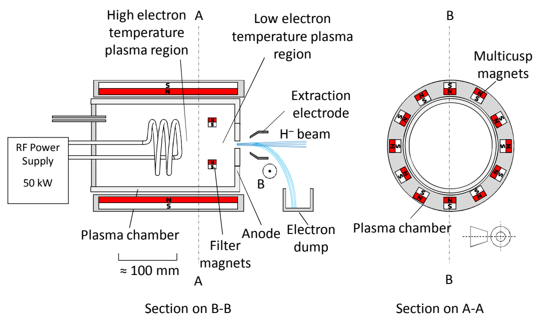
D-Pace 15 mA DC H⁻ Multicusp Volume Source



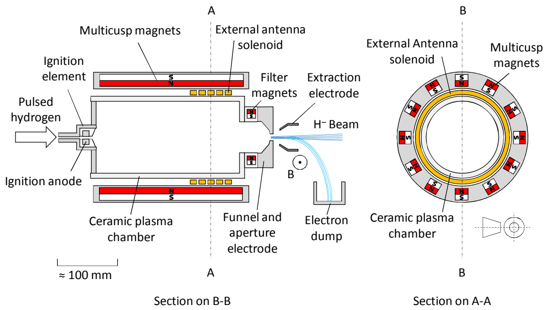




Internal RF Solenoid Antenna Volume Source

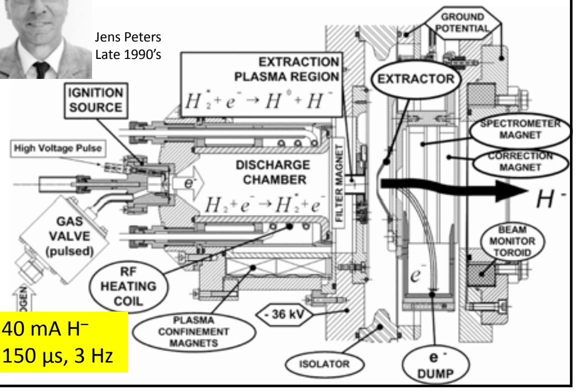


External RF Antenna Multicusp Source

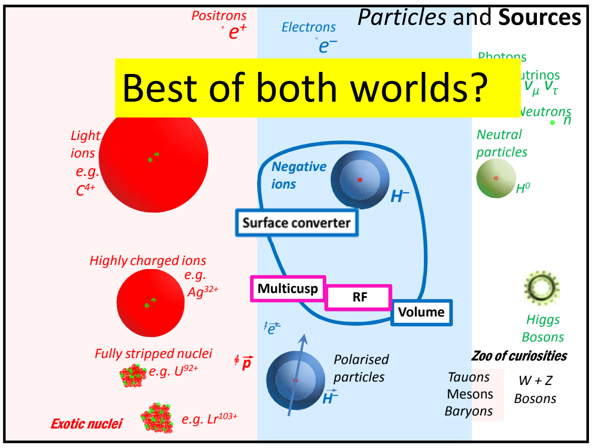


DESY Source

Jens Peters
Late 1990's

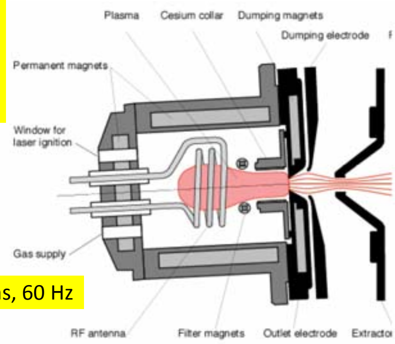


40 mA H⁻
150 µs, 3 Hz

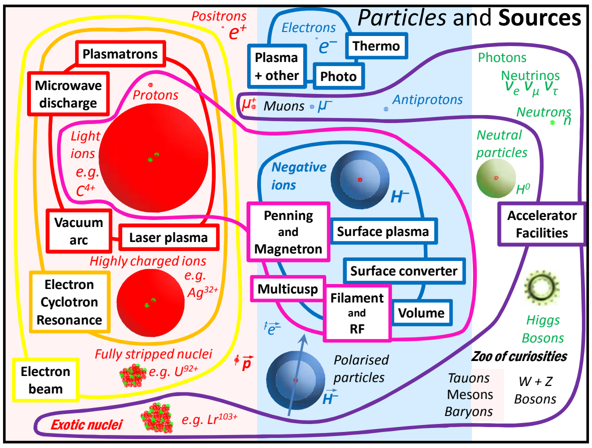


CERN are developing a ceasiated external antenna source for LINAC4

SNS ion source



38 mA H⁻ 1 ms, 60 Hz



Which Source?

- Type of particle
- Current, duty cycle, emittance
- Lifetime
- Expertise available
- Money available
- Space available

Reliability – is King!

- Operational sources should deliver >98% availability
- Lifetime compatible with operating schedule
- Ideally quick and easy to change
- Short start-up/set-up time

cryogenic systems
timing systems
machine interlocks
communication systems

Reliability also depends on:

low voltage power supplies

Everything Else!

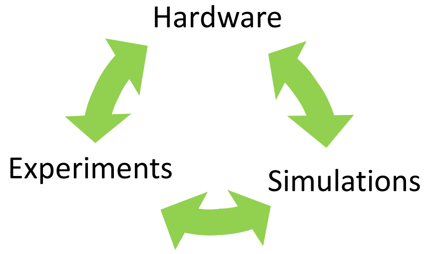
cooling water
human error
hydrogen
vacuum systems
temperature controllers
high voltage power supplies
compressed air supplies
control systems
mains power
personnel interlocks
material purity
laser systems

Developing Sources

Driven by demand for
- Increases in current, duty cycle and lifetime
- Improvements in beam quality

Development strategy
- Simulations
- Test stands
- Diagnostics

The Development Cycle



Summary

- Particle sources are a huge interesting subject
- A perfect mixture of engineering and physics
- We have only scratched the surface

Thank you for listening