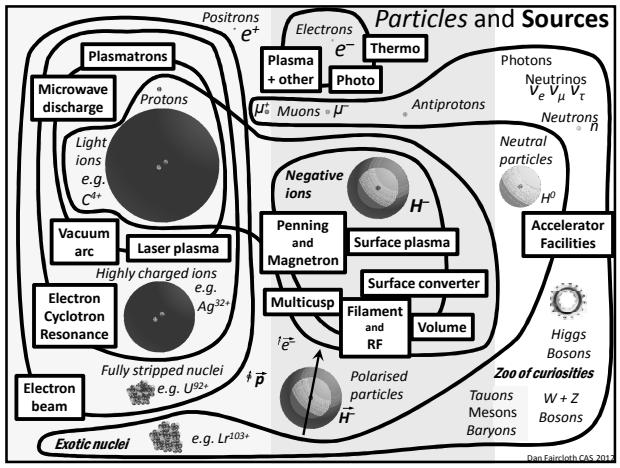
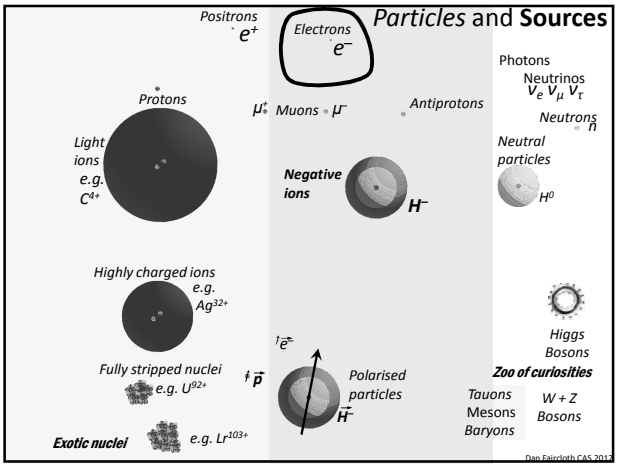
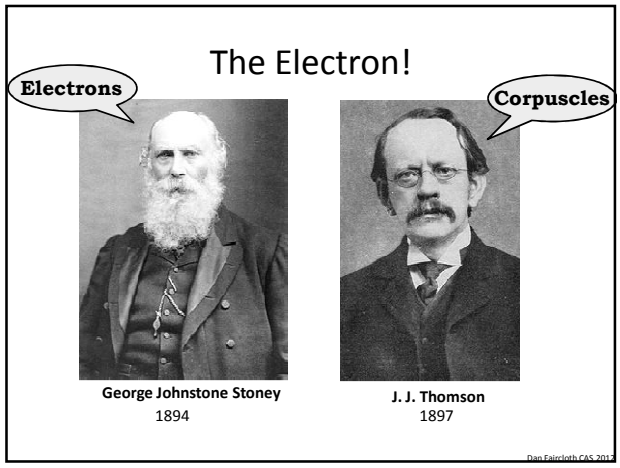
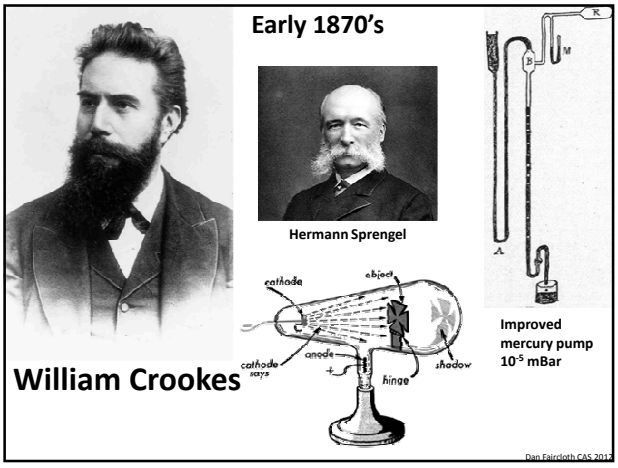
Particle Sources *-The most important part of the whole machine*

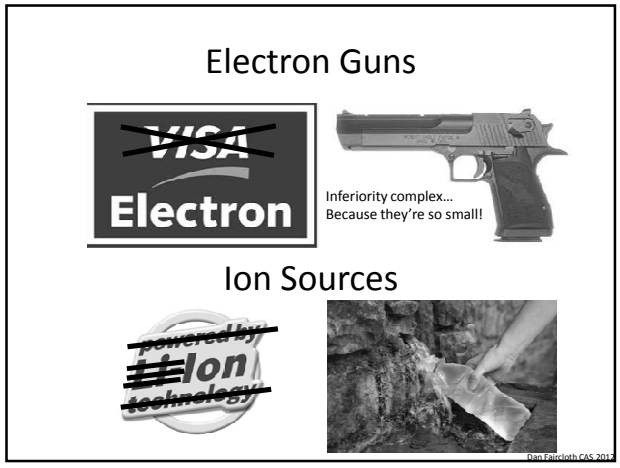
Dan Faircloth
Ion Source Section Leader
Rutherford Appleton Laboratory



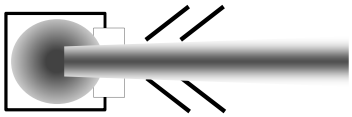






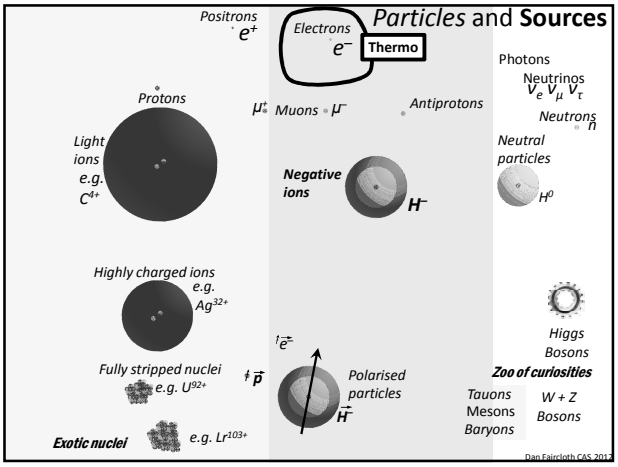


Particle sources/guns consist of:



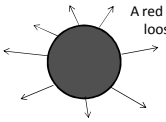
Something to make the particles + An extraction system to create and accelerate a beam

Dan Faircloth CAS 2012



Fredrick Guthrie

British scientific writer and professor

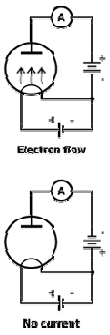


Elements of Heat in 1868

First experimental observation of thermionic emission

Thermionic Emission

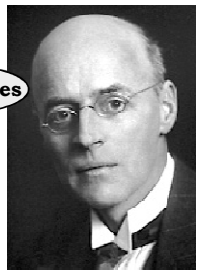
1880 Thomas Edison



The "Edison effect"

Thermionic Emission

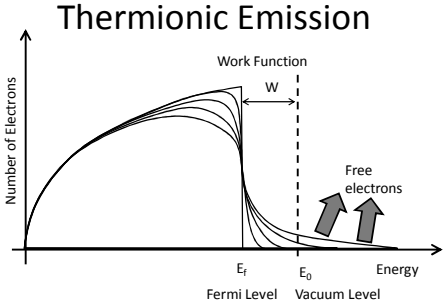
J. J. Thomson
1897



1901 Owen Richardson

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

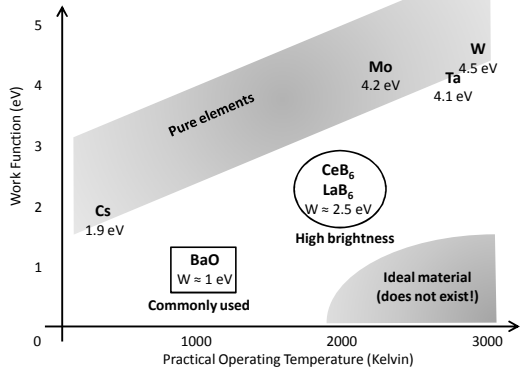
Thermionic Emission



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

Lowest possible work function
Highest possible temperature

Cathode Materials

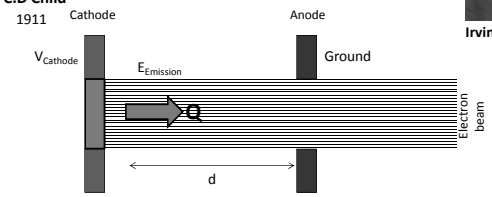


Child-Langmuir Law

(Space charge limited extraction)

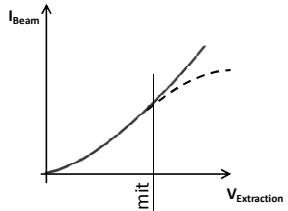
C.D Child
1911

Irving Langmuir
1913



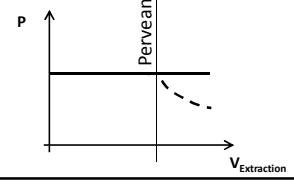
$$j = \frac{\frac{4}{9}\varepsilon_0\sqrt{\frac{2e}{m_e}}V^{\frac{3}{2}}}{d^2}$$

$$I \propto V^{\frac{3}{2}}$$

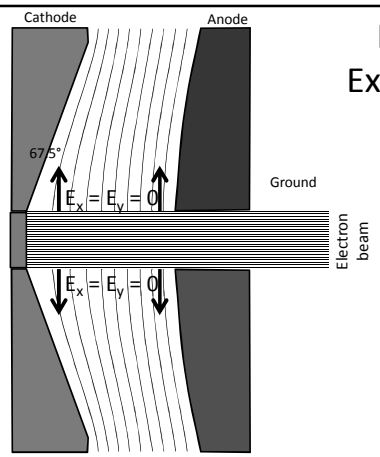


Perveance

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

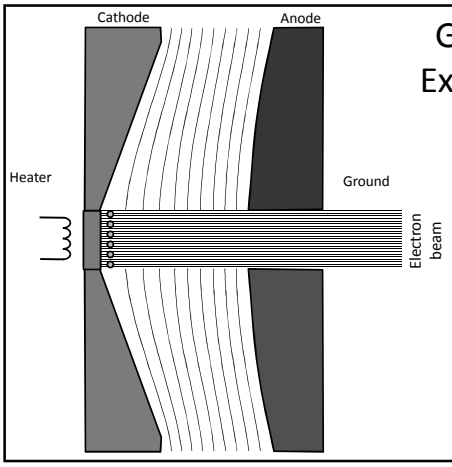


Pierce Extraction



Gridded Extraction

A triode amplifier!



EIMAC YU 171

Thermionic dispenser cathode with integrated heater and grid

Sinter of W and BaO

1cm²
12 W heater

diamond

PAUL SCHERRER INSTITUT
PSI
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

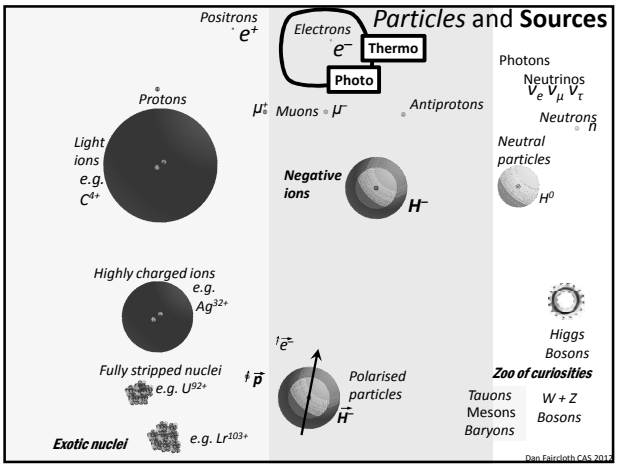
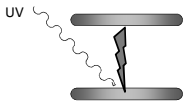


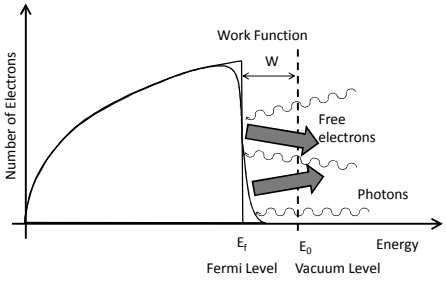
Photo Emission

First observed by Heinrich Hertz in 1887



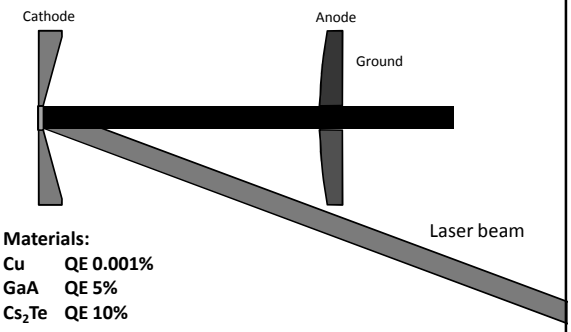
Theoretical explanation by Einstein in 1905

Photo electric emission



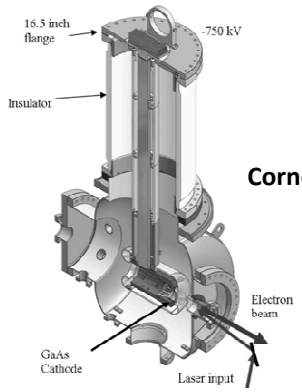
$$\text{Quantum efficiency (QE)} = \frac{\text{Number of electrons produced}}{\text{Number of incident photons}}$$

Photo Emission Gun



Materials:

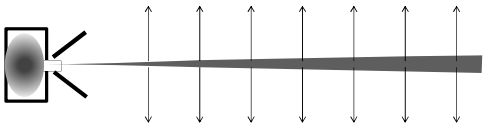
Cu	**QE 0.001%**
GaA	**QE 5%**
Cs_2Te	**QE 10%**



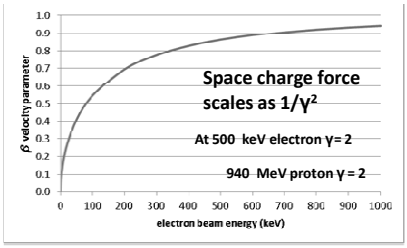
Cornell DC Photoemission gun

20mA average current at 250kV

Space Charge

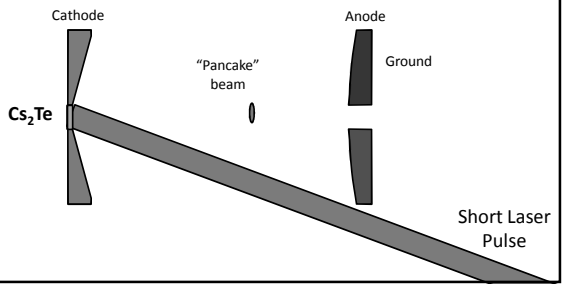


Space Charge

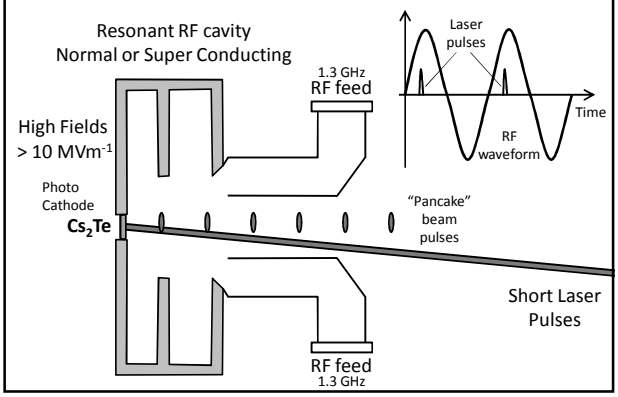


Another reason to use lasers is…

Lasers are so fast they can easily beat Child-Langmuir (and so can gridded extraction)

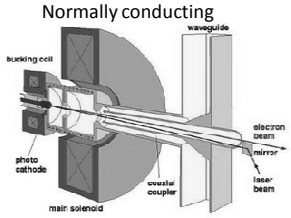


RF Photemission Source

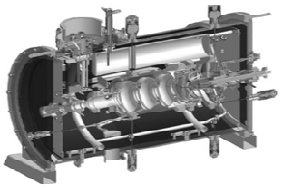


PITZ Photo Injector Test Facility (Zeuthen) | HELMHOLTZ GEMEINSCHAFT | DESY | HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Normally conducting



Super conducting

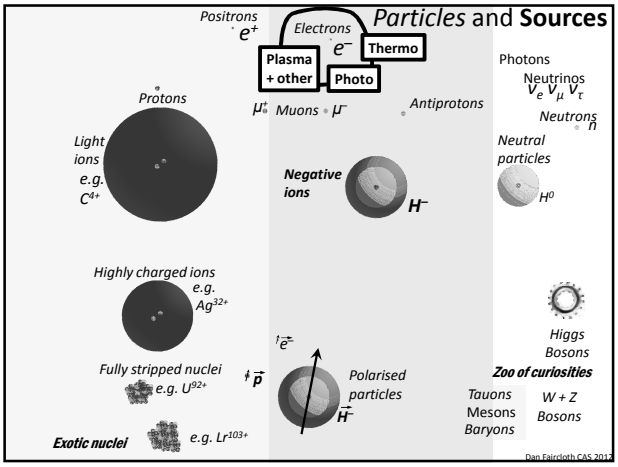


20 ps, 1 nC pulses

15 ps, 1 nC pulses

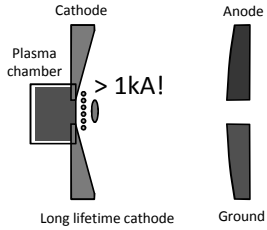
High brightness low emittance guns for FEL

Particles and **Sources**



Plasma cathode and other electron sources

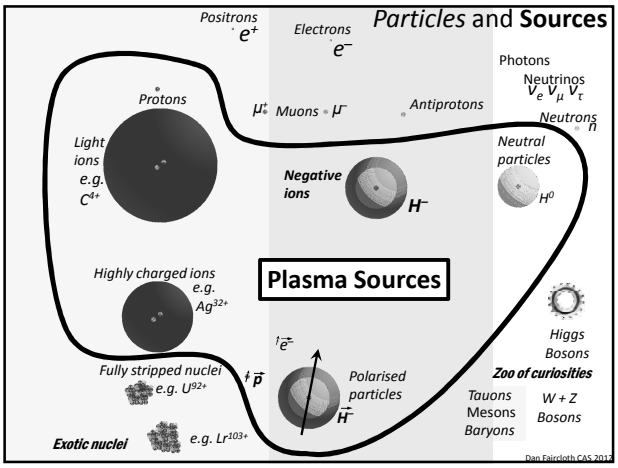
Very high electron currents can be extracted from plasma cathode electron sources

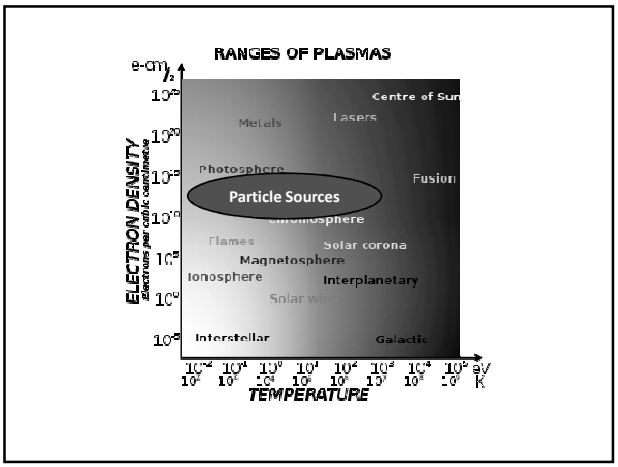


Combinations of those mentioned e.g. photo-thermionic

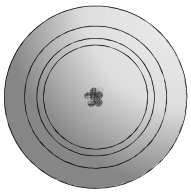
Rarely used in accelerators:

Field emission from needle arrays
Diamond amplifiers
Etc...





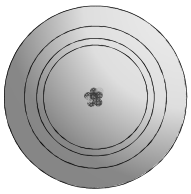
Ionisation



Neutral Atom

Most sources rely on electron impact ionisation

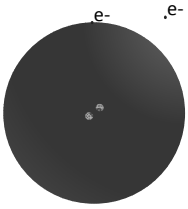
Ionisation



Neutral Atom

Most sources rely on electron impact ionisation

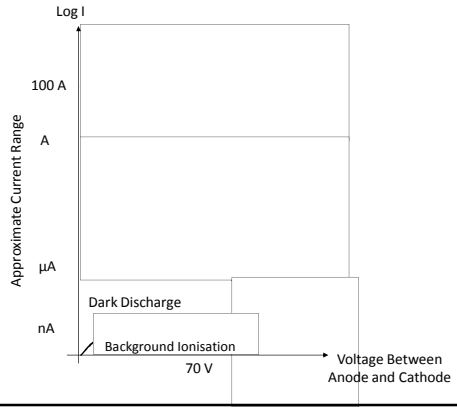
Ionisation

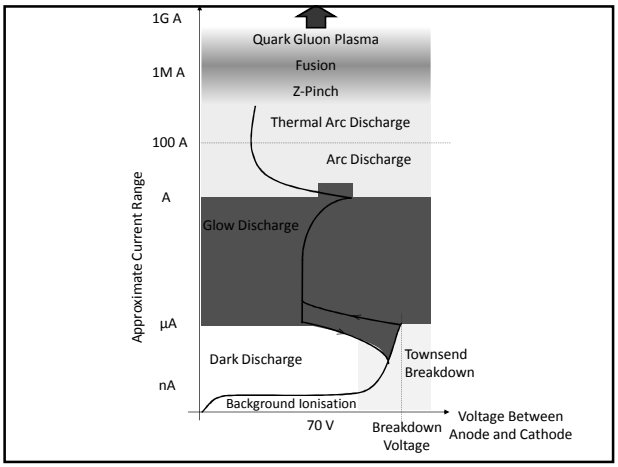


Positive Ion

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*

$H^+ \rightarrow q = +1$

$Pb^{3+} \rightarrow q = +3$

$H^- \rightarrow q = -1$

11600°K = 1 eV

Temperature, *T* (eV)

T_e = temperature of electrons

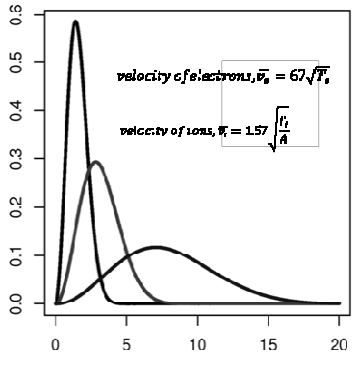
T_i = temperature of ions

T_n = temperature of neutrals

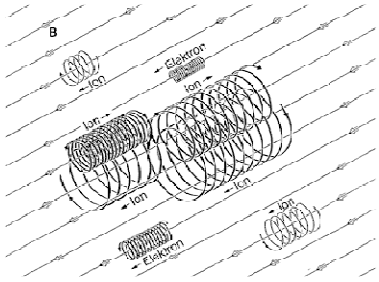
Temperature Distribution

Maxwell Boltzmann statistics

In magnetic fields: $v_x \neq v_y \neq v_z$

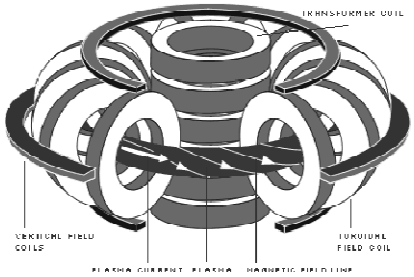


Magnetic Confinement

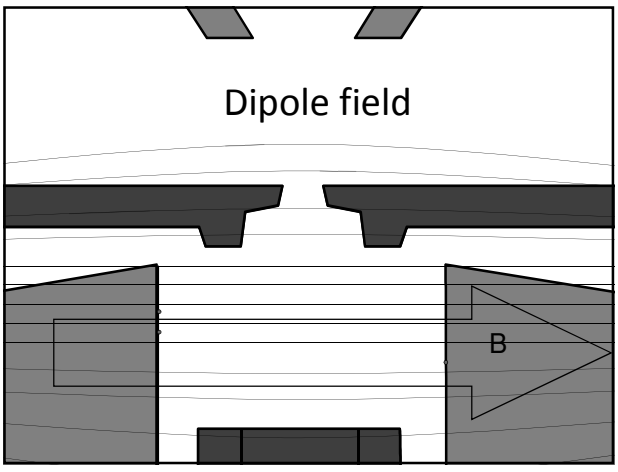


Particles spiral along magnetic field lines

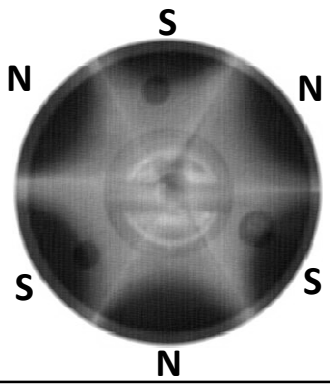
Solenoid field



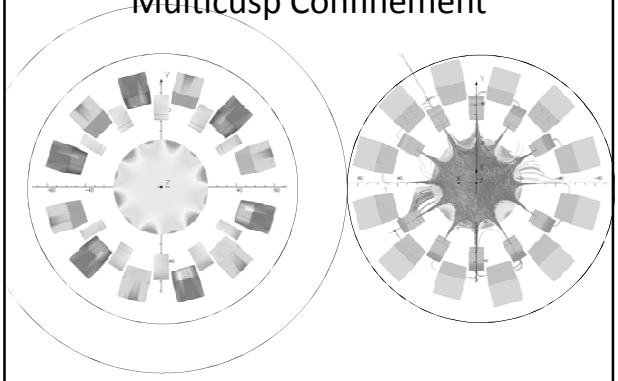
Dipole field



Hexapole



Multicusp Confinement

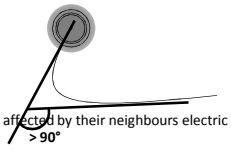


Collisions

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

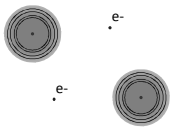
$$\frac{n_i}{n_i + n_n}$$

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

Quasi Neutrality

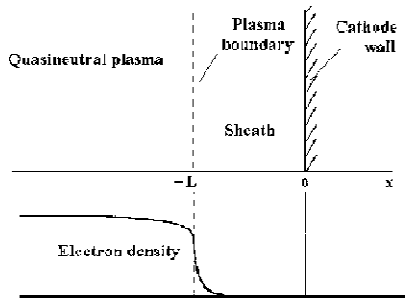
$$\sum q_i n_i = n_e$$

Debye Length

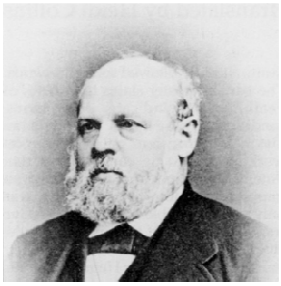


$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e q_e^2}}$$

Plasma Sheath



Plasma Pioneers

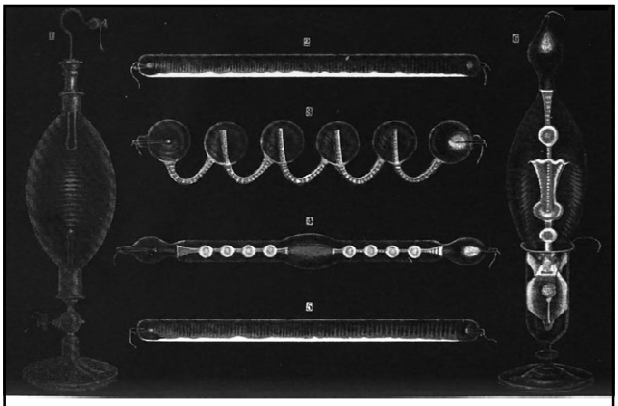


Heinrich Geißler **Julius Plücker**

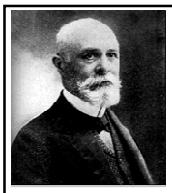
Gas discharge tube and mercury displacement pump just less than 1 mBar

Mid 1850's University of Bonn

magnetism could move the glow discharge

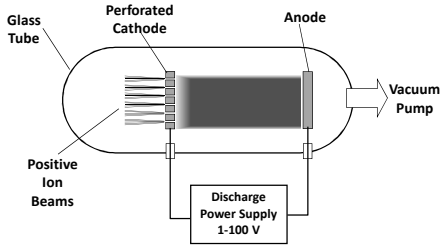


Drawing of Geissler tubes from 1860's French physics book

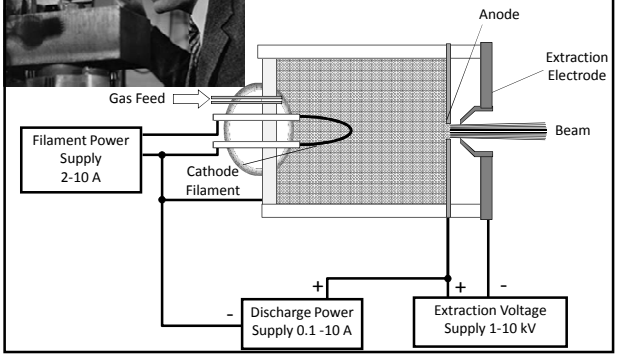


Canal Ray Source

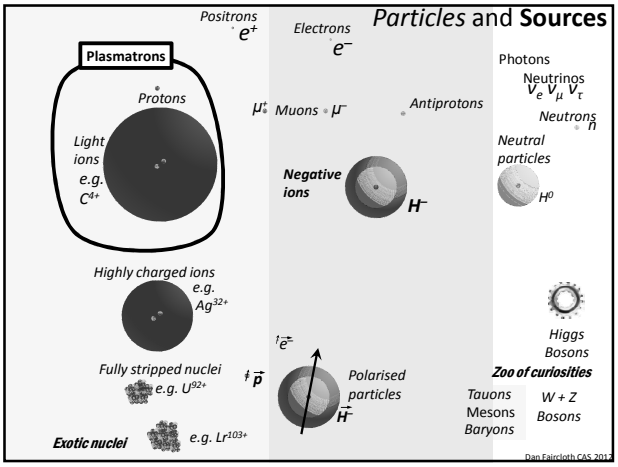
In 1886 Eugen Goldstein discovered canal rays



Electron Bombardment Source (1916)



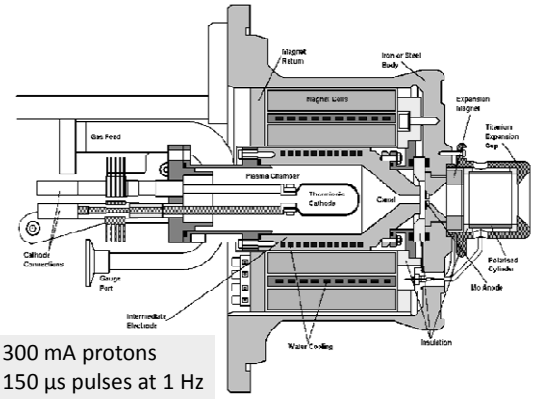
Particles and **Sources**



Plasmatron (late 1940s)

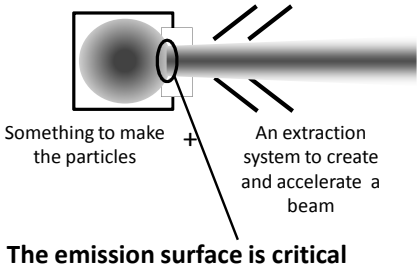
Duoplasmatron (1956)

CERN Duoplasmatron



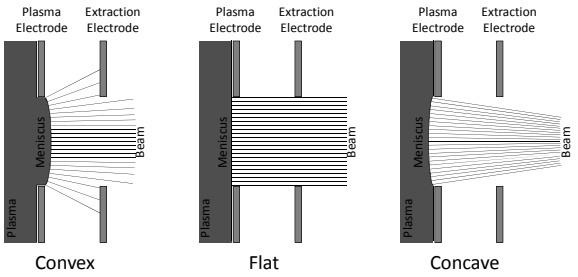
300 mA protons
150 µs pulses at 1 Hz

Particle sources/guns consist of:



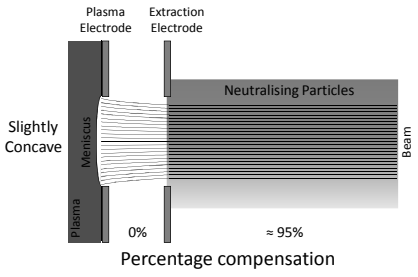
The emission surface is critical to the quality of the beam

Plasma Mencius



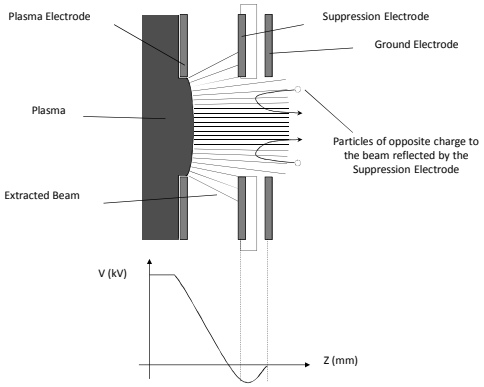
Not including space charge effects

Space Charge



Percentage compensation

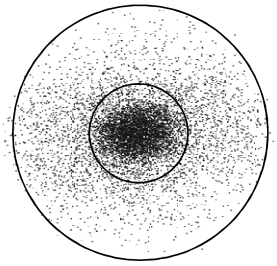
Suppressor Electrode



Emittance of Real Beams

Halo Effect
- Plasma boundary
- Fringe fields

How big is this beam?



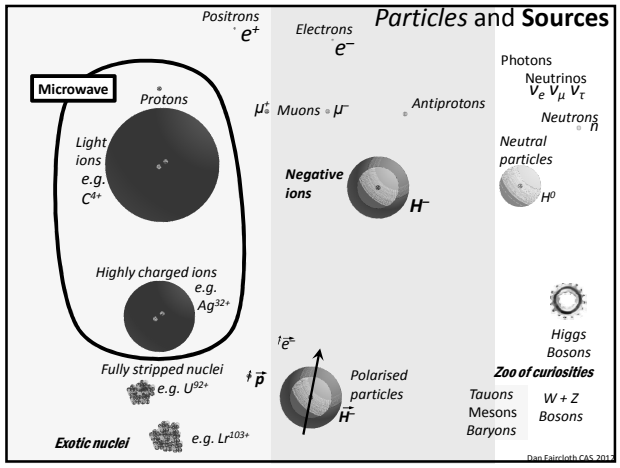
95% emittance

rms emittance

Brightness

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

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



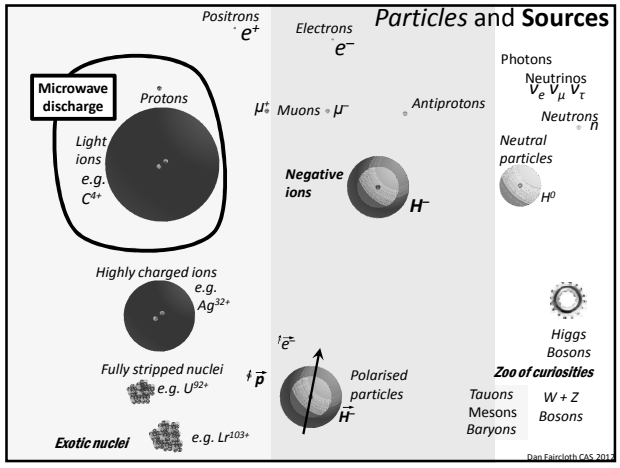
Microwave Ion Sources

Off Resonance

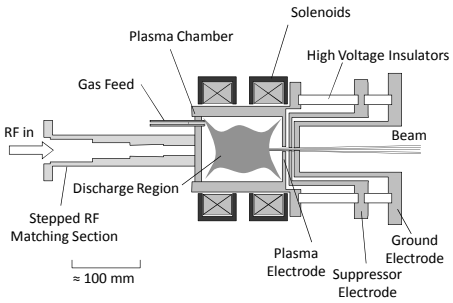
= Microwave Discharge Ion Sources

On Resonance

= Electron Cyclotron Resonance (ECR) Sources

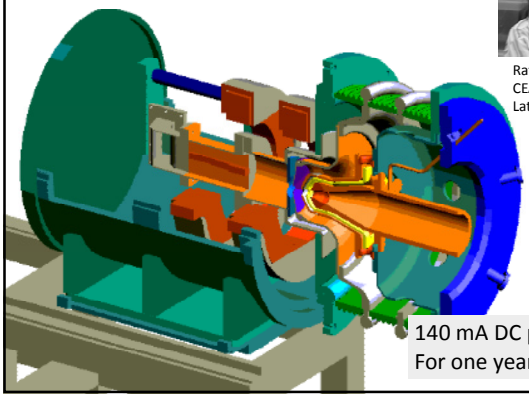


Microwave Discharge Ion Source



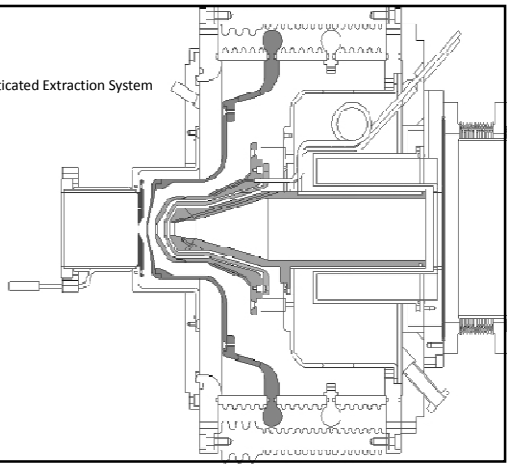
SILHI Microwave Source

Rafael Gobin
CEA Saclay
Late 1990s

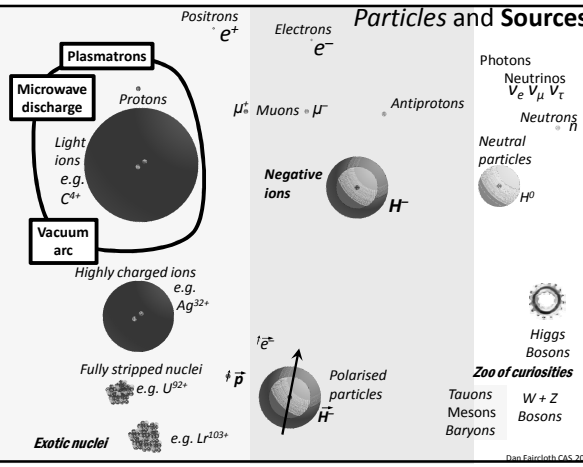


140 mA DC protons
For one year!

Sophisticated Extraction System

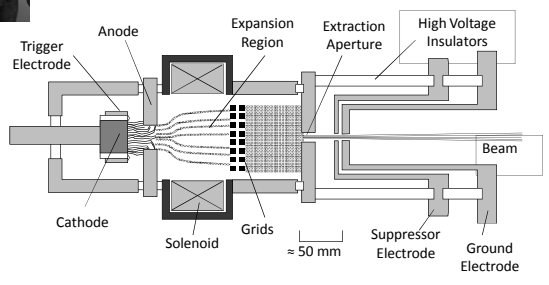


Particles and **Sources**



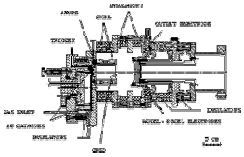
Vacuum Arc Ion Sources

1980s - Ian Brown and others

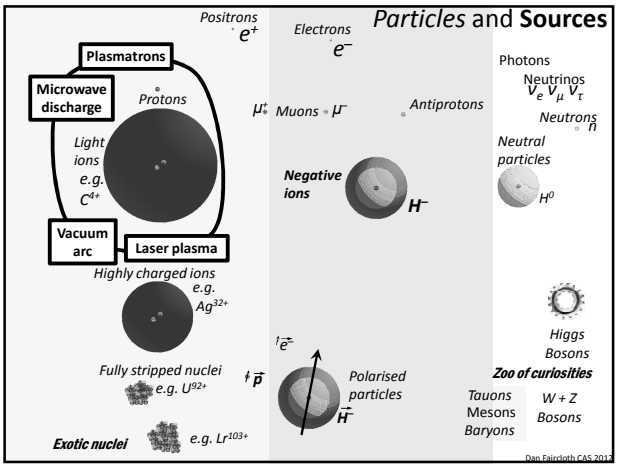


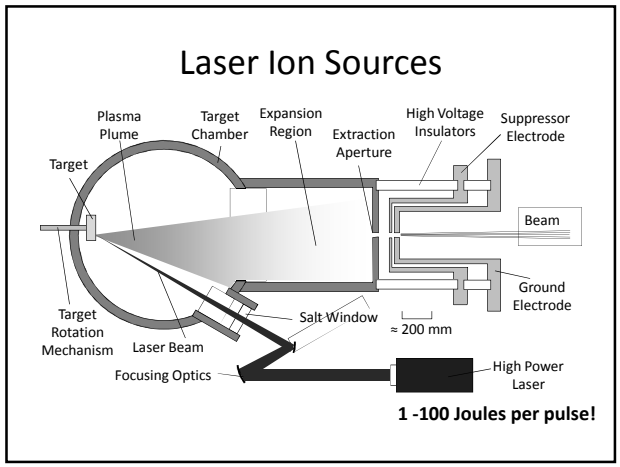
Lawrence Berkley Lab MEVVA

GSI MEVVA



15 mA of U^{4+} ions





ITEP Laser source at CERN

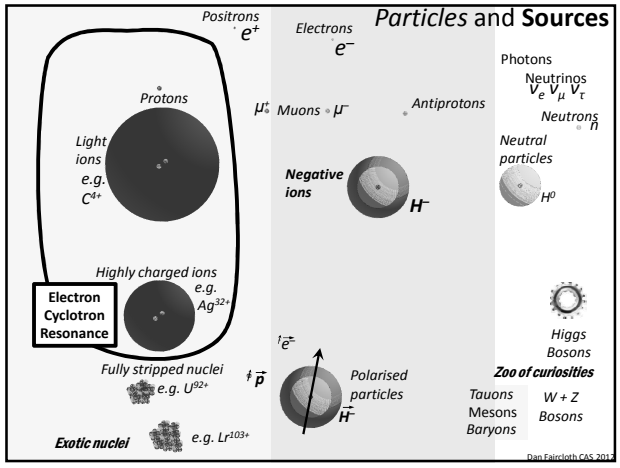
ITEP Laser source at CERN

TWAC at ITEP Moscow

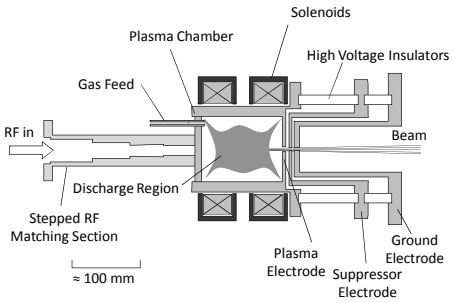
7 mA, 10 μs pulses of C^{4+}

Very Recently

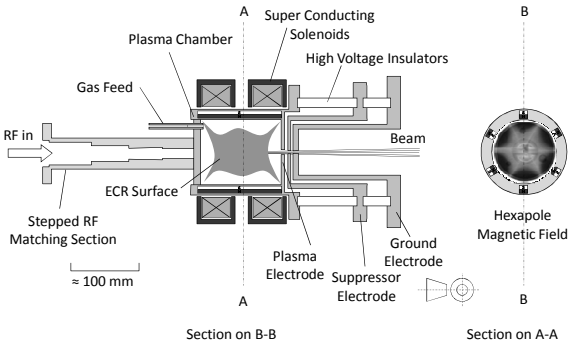
Masahiro Okamura, BNL and RIKEN demonstrated Direct Plasma Injection into an RFQ



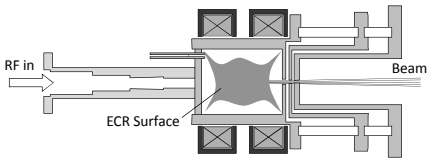
Microwave Discharge Ion Source



ECR Ion Source



ECR Surface



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

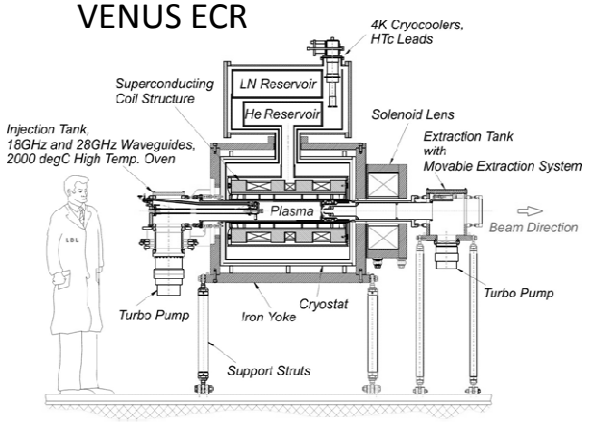
2.45 GHz
commonly used

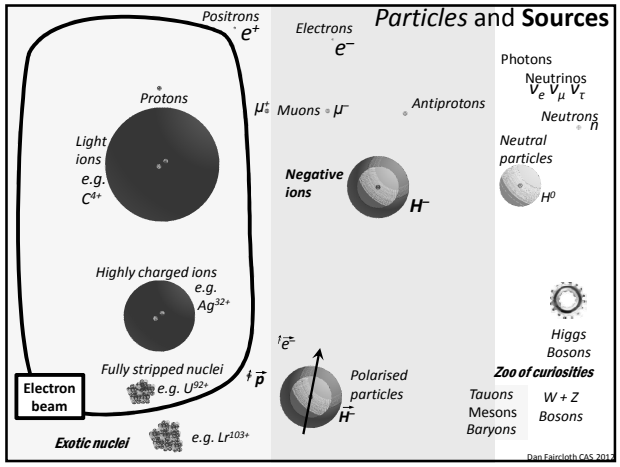
28 GHz superconducting VENUS ECR

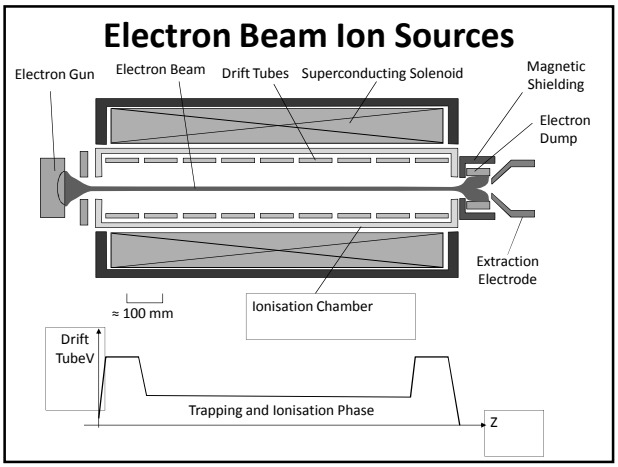
Daniela Leitner
LBNL
Late 2000s

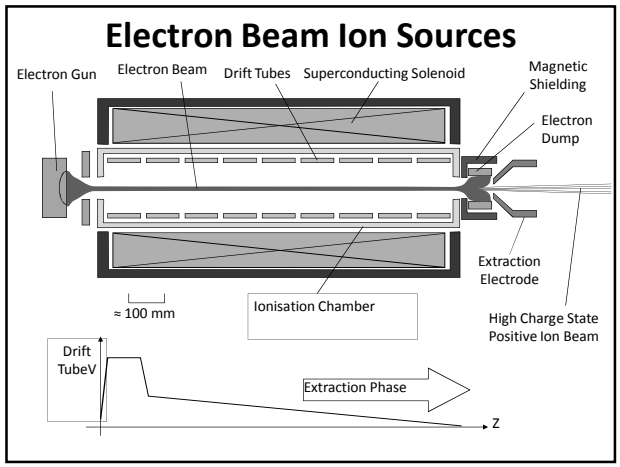
200 eμA U^{34+} ions
4.9 eμA U^{47+} ions

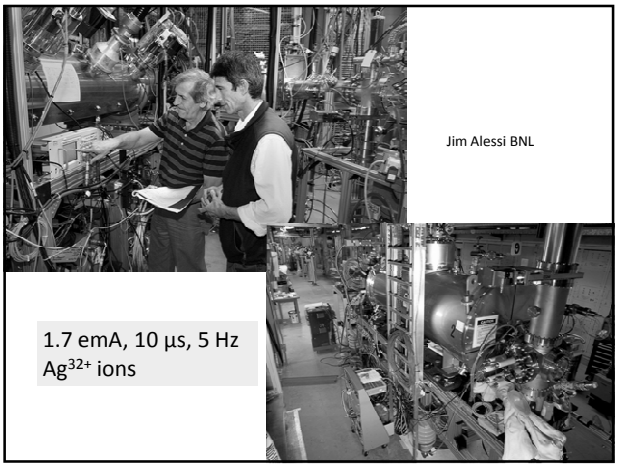
VENUS ECR

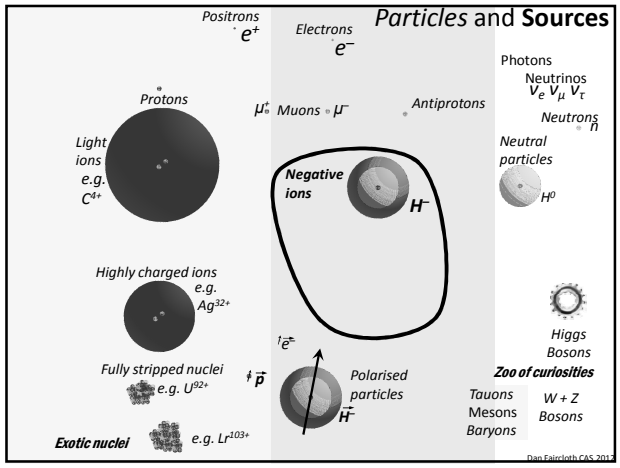












Negative Ion Sources

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

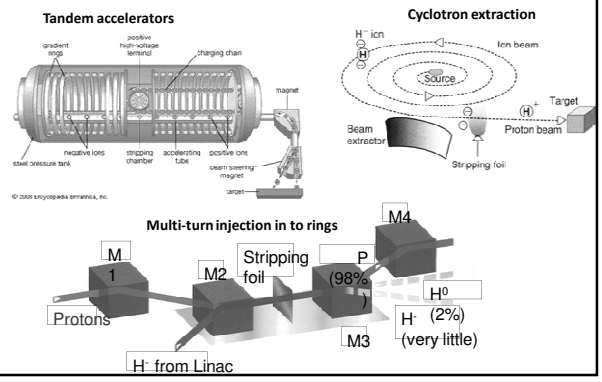
H^- has a much larger cross section than H^0

30 times for e^- collisions

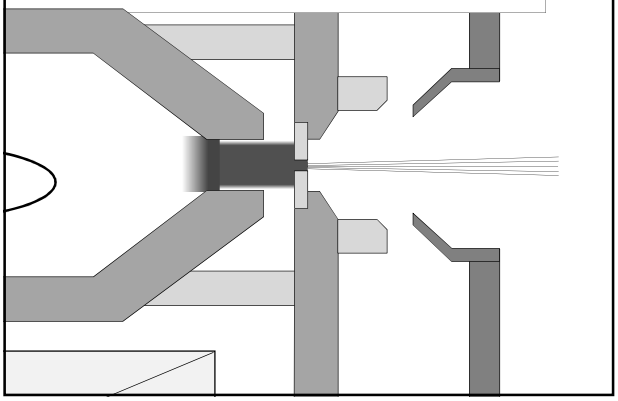
100 times for H^+ collisions

H^- are very fragile!

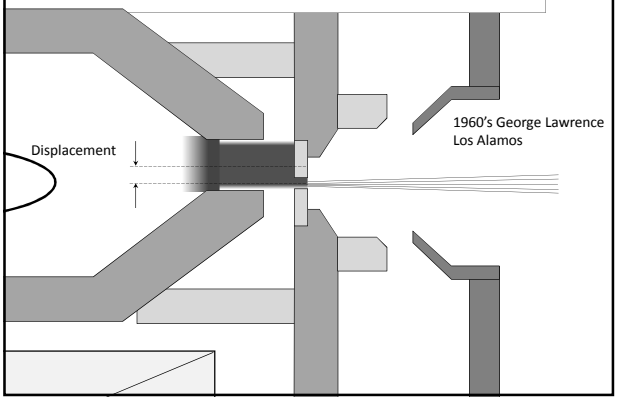
Applications



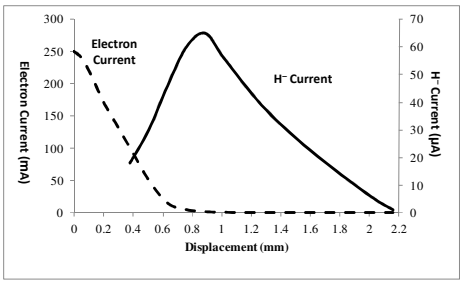
Off Axis Duoplasmatron Extraction



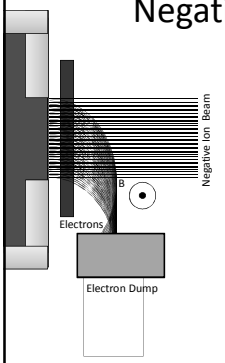
Off Axis Duoplasmatron Extraction



Off Axis Duoplasmatron Extraction

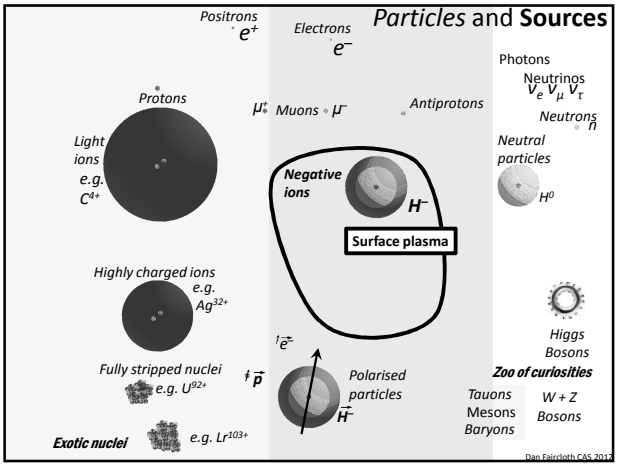


Negative Ion Extraction



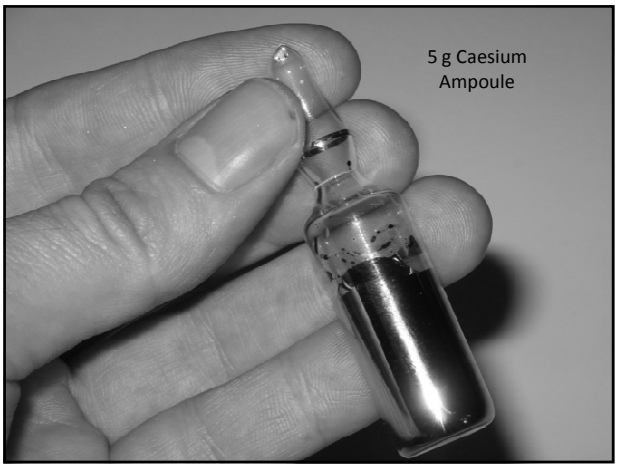
Electrons will also be extracted
Up to 1000 times the H^- current!
Use a magnetic field
Dump must be properly designed

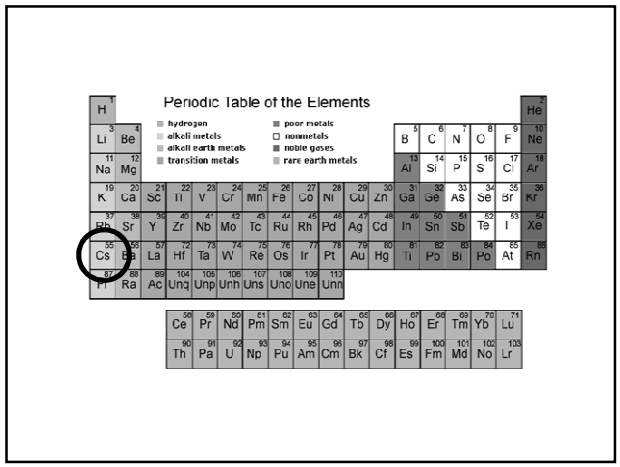
Best sources:
only 0.5 times H^- current

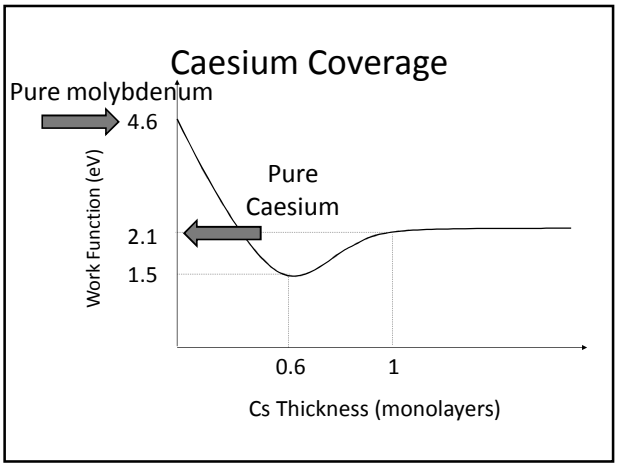


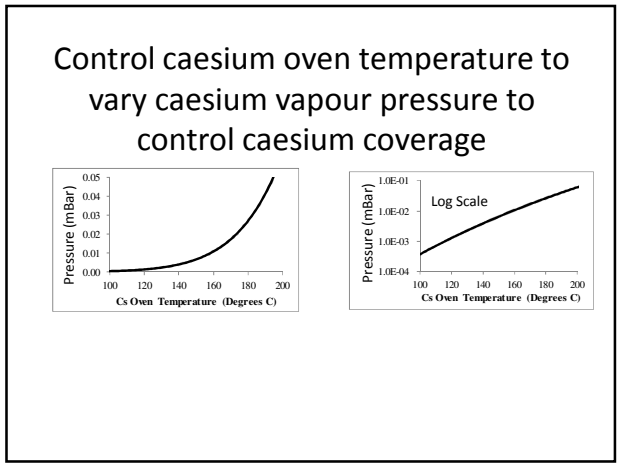
G. I. Dimov, Yuri Belchenko , Vadim Dudnikov
Early 1970's Budker Institute of Nuclear Physics

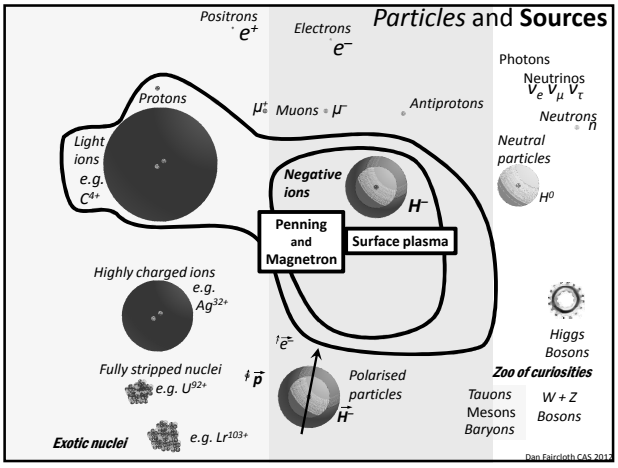
Production of H^- ions by surface ionisation with the addition of ceasium

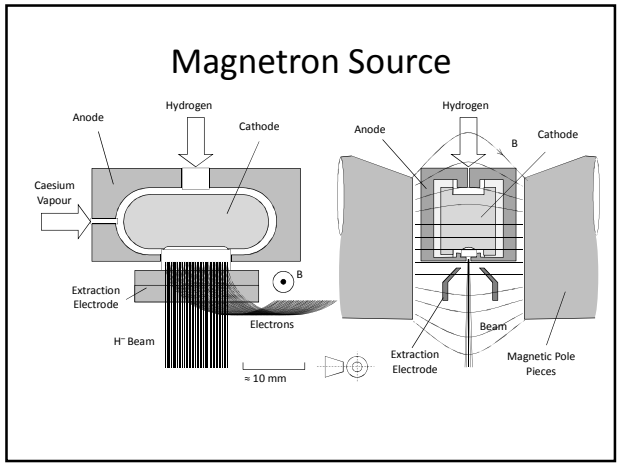

5 g Caesium
Ampoule


Periodic Table of the Elements
hydrogen
alkali metals
alkali earth metals
transition metals
poor metals
nonmetals
noble gases
rare earth metals

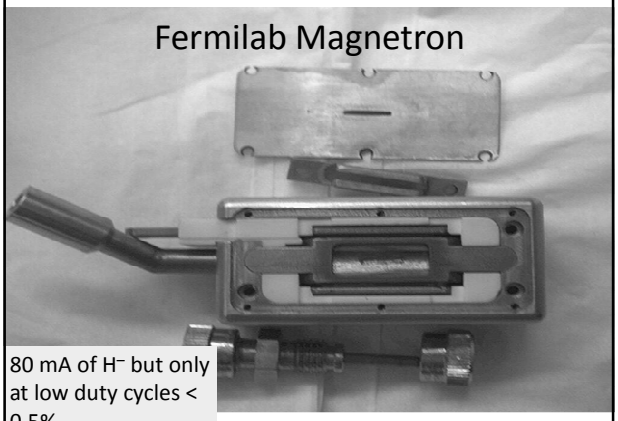

Caesium Coverage
Pure molybdenum
4.6
Pure
Caesium
2.1
1.5
Work Function (eV)
0.6
1
Cs Thickness (monolayers)


Control caesium oven temperature to vary caesium vapour pressure to control caesium coverage
Pressure (mBar)
Cs Oven Temperature (Degrees C)
Log Scale
Pressure (mBar)
Cs Oven Temperature (Degrees C)


Particles and Sources
Positrons
Electrons
Photons
Neutrinos
Protons
Muons
Antiprotons
Neutrons
Light ions e.g. C4+
Negative ions
Neutral particles
Penning and Magnetron
Surface plasma
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+
Dan Faircloth CAS 2012


Magnetron Source
Anode
Hydrogen
Cathode
Caesium Vapour
Extraction Electrode
H⁻ Beam
Electrons
B
≈ 10 mm
Beam
Magnetic Pole Pieces

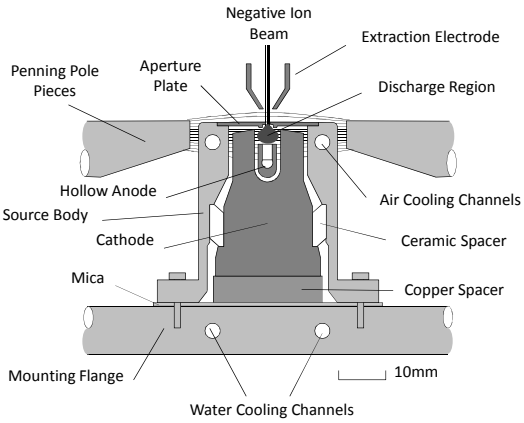
Fermilab Magnetron

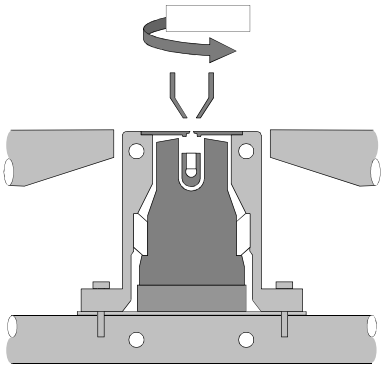


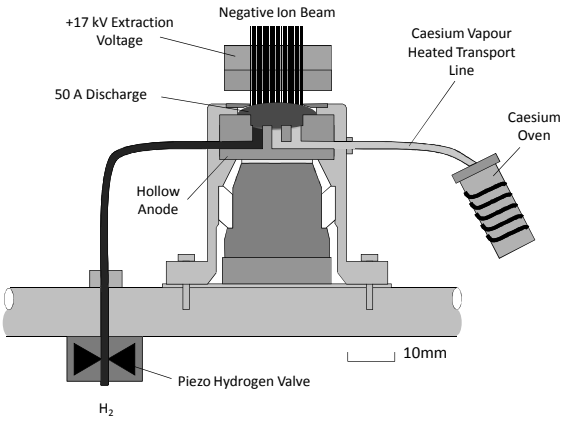
80 mA of H^- but only at low duty cycles < 0.5%

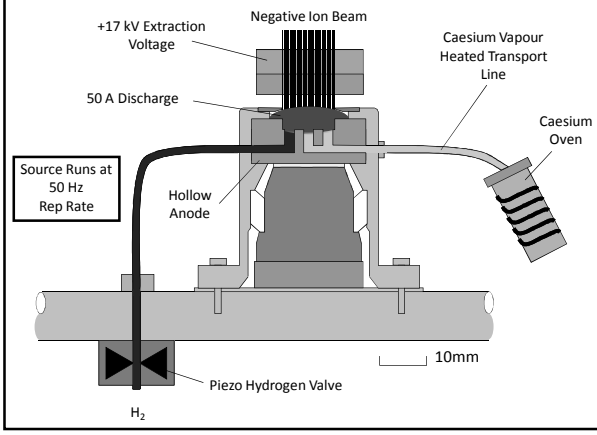
Penning Ion Sources

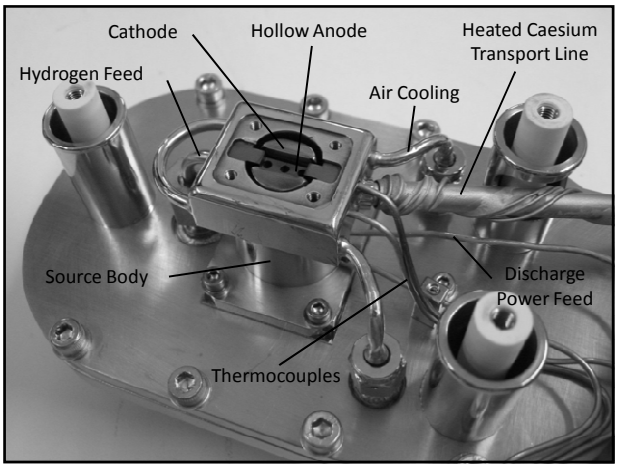
- Invented by Dudnikov in the 1970's
- Very high current density > 1 Acm^{-2}
- Low noise
- Does not work without ceasium

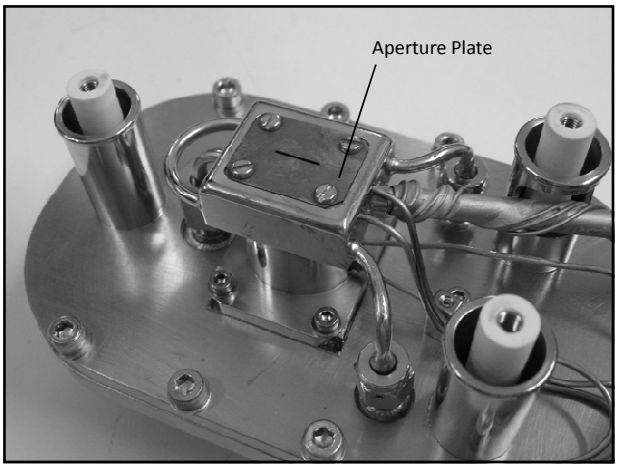


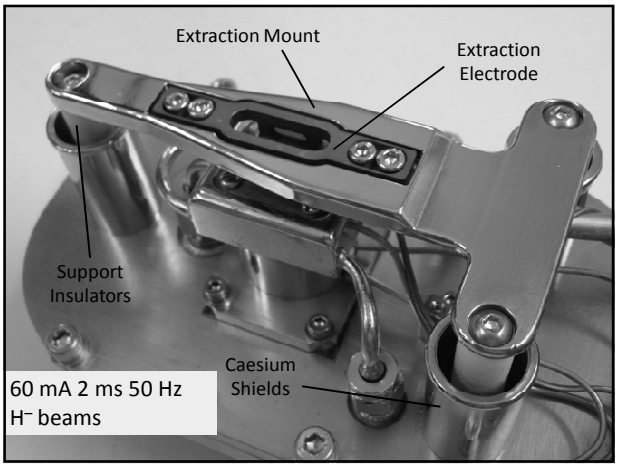


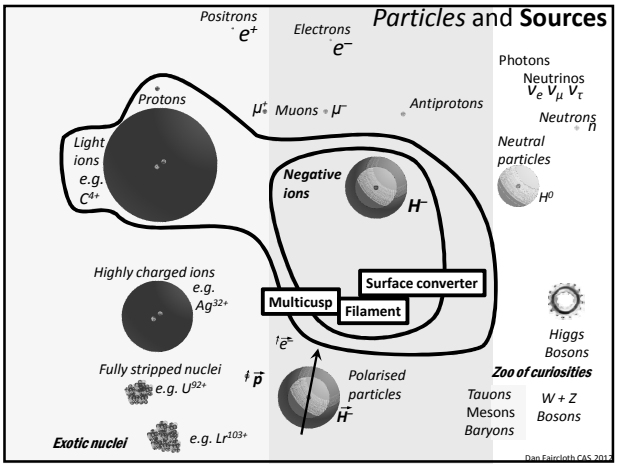




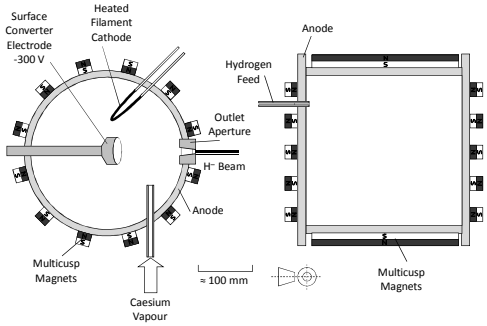


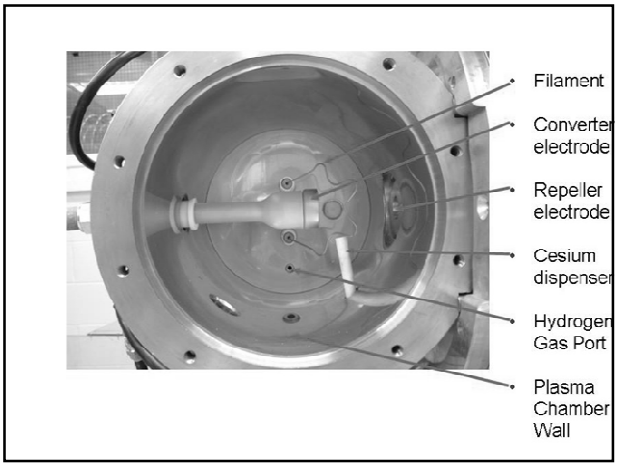


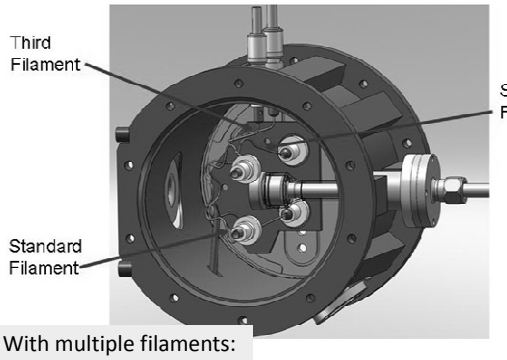




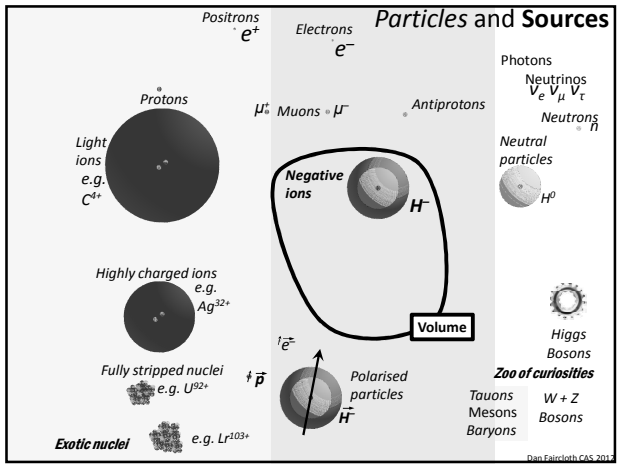
Filament Cathode Multicusp Surface Converter Source







With multiple filaments:
1 A of H^-

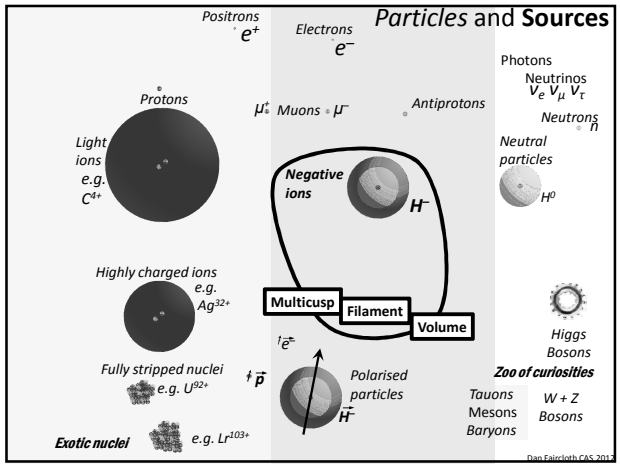


Marthe Bacal
Ecole Polytechnique
mid 1970's

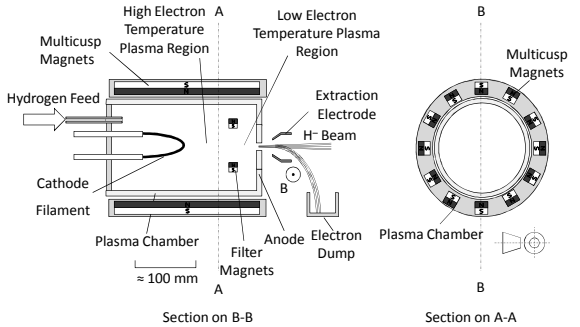
Volume Production

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

Dissociative attachment of low energy electrons to rovibrationally excited H_2 molecules

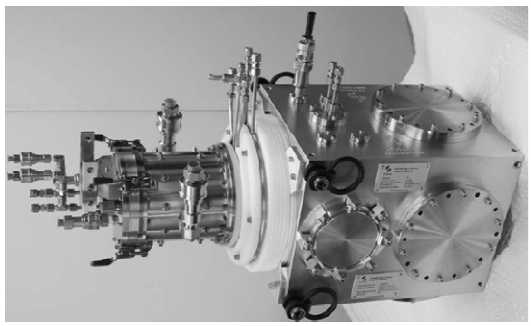


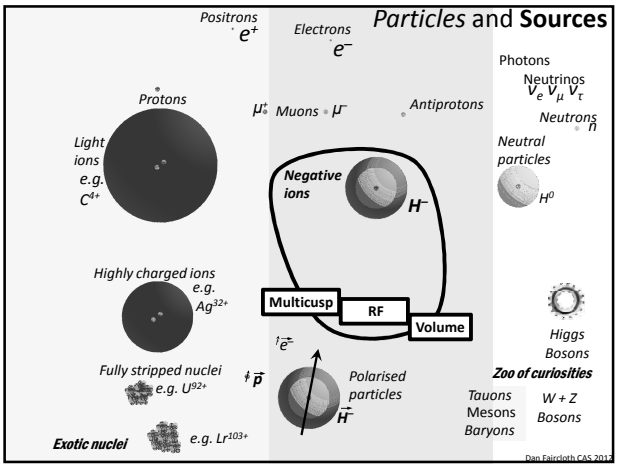
Multicusp Filament Volume Source

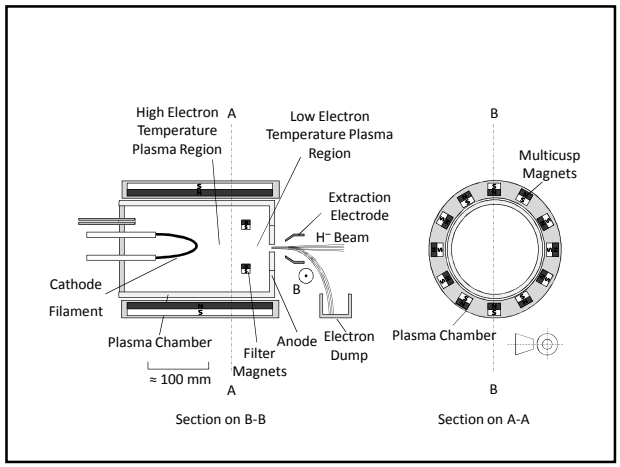


Many Variations: e.g. JPARC use a LaB_6 cathode

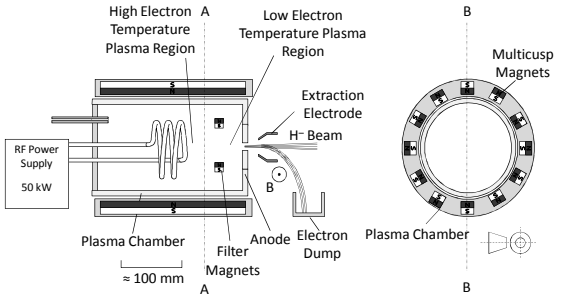
D-Pace 15 mA DC Multicusp Volume Source



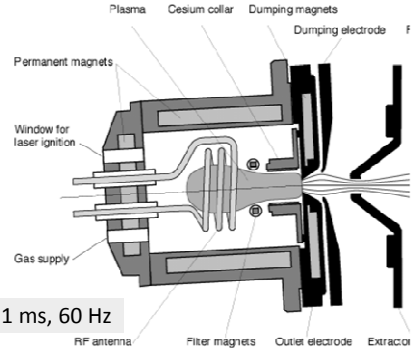




Internal RF Solenoid Antenna Volume Source

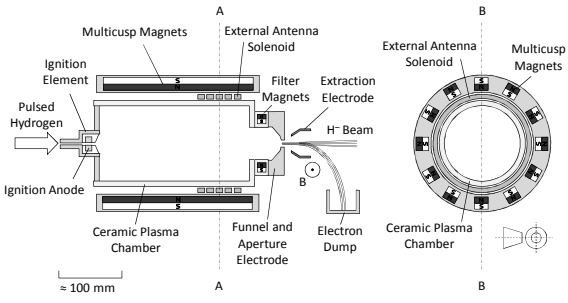


SNS ion source



38 mA H⁻ 1 ms, 60 Hz

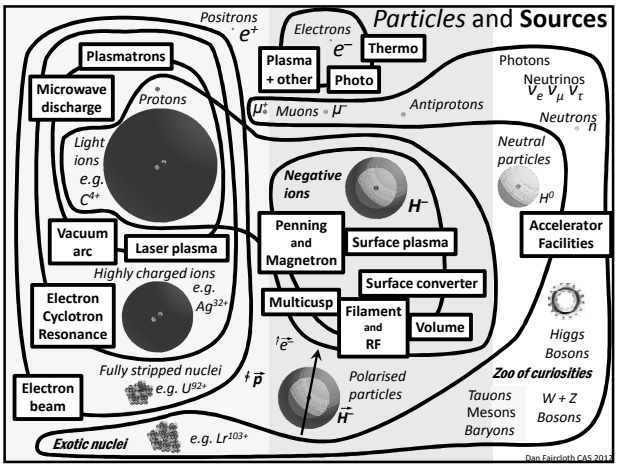
External RF Antenna Multicusp Source



DESY Source

Jens Peters
Late 1990's

40 mA H⁻
150 µs, 3 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

compressed air supplies

temperature controllers

high voltage power supplies

control systems

mains power

personnel interlocks

material purity

laser systems

Developing Sources

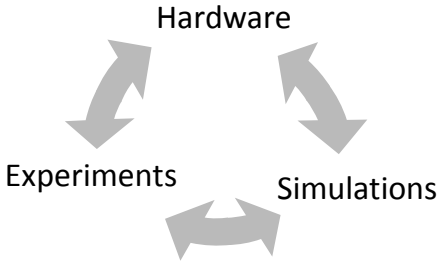
Driven by demand for

- 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