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

Dan Faircloth

Ion Source Section Leader

Rutherford Appleton Laboratory

Positrons e^+

Electrons e^-

Photons

Neutrinos ν_e ν_μ ν_τ

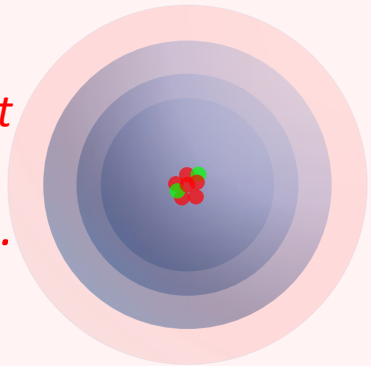
Protons

μ^+ Muons μ^-

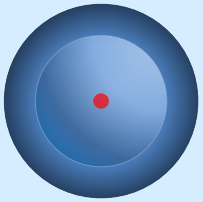
Antiprotons

Neutrons n

Light ions e.g. C^{4+}



Negative ions



H^-

Neutral particles

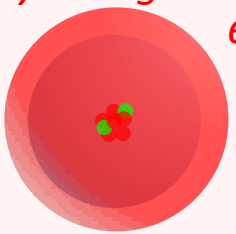
H^0

Positively Charged Particles

Negatively Charged Particles

Neutral Particles

Highly charged ions e.g. Ag^{32+}

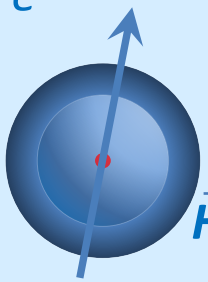


Higgs Bosons

$\vec{e}^-$

Fully stripped nuclei e.g. U^{92+}

$\vec{p}$



Polarised particles

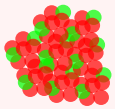
$\vec{H}^-$

Zoo of curiosities

Tauons
Mesons
Baryons

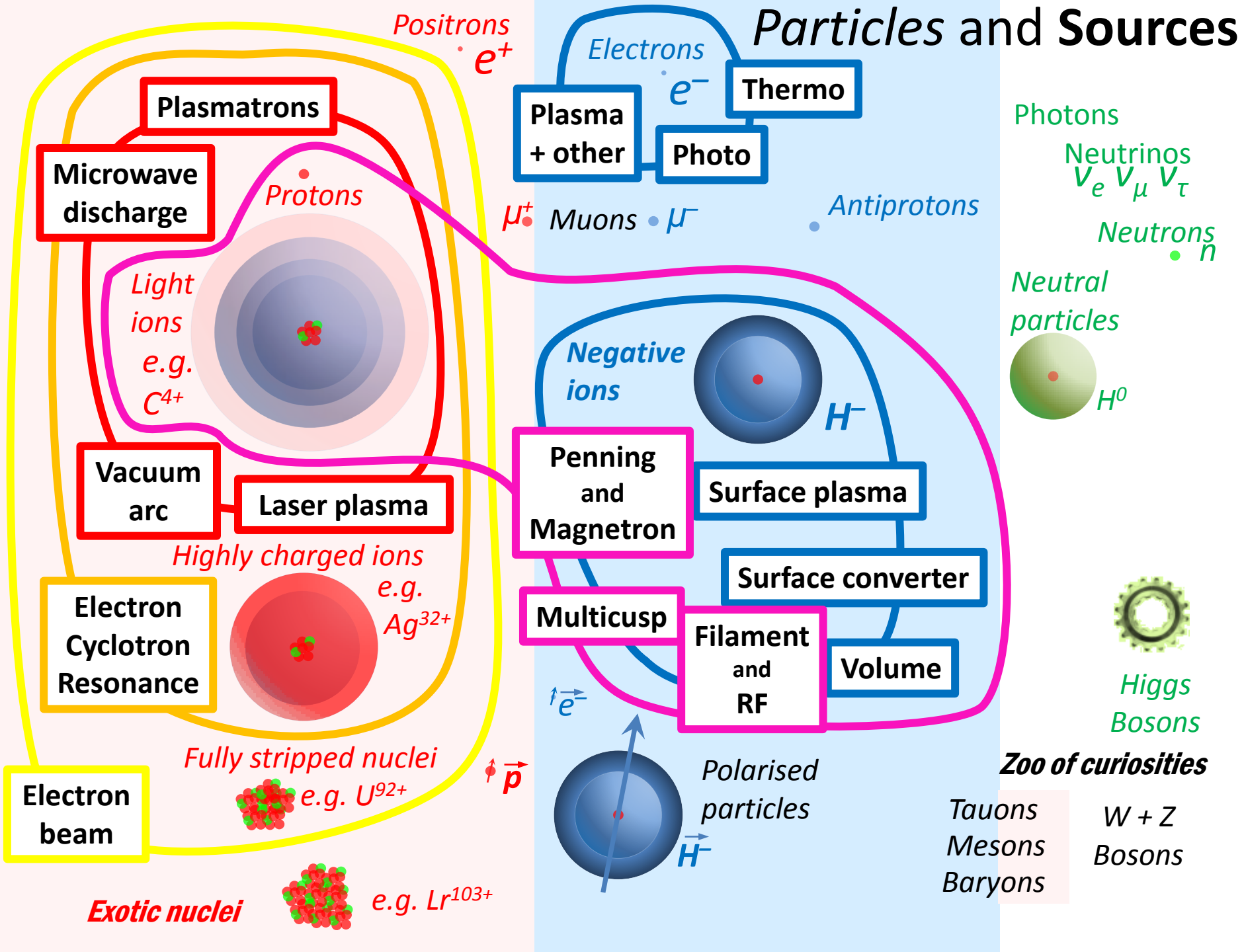
$W + Z$ Bosons

Exotic nuclei



e.g. Lr^{103+}

Particles and **Sources**



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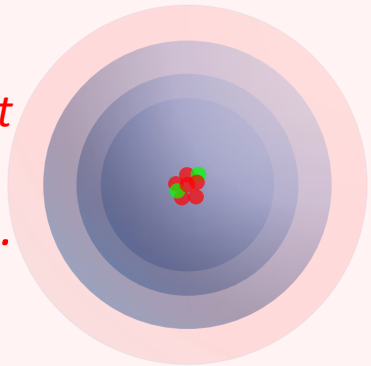

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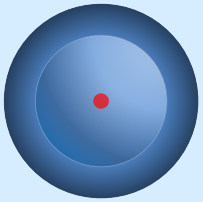

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H^0

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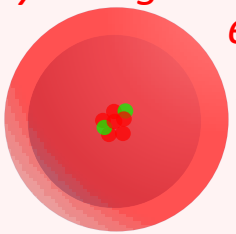

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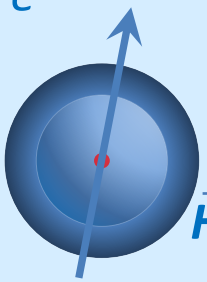

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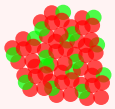
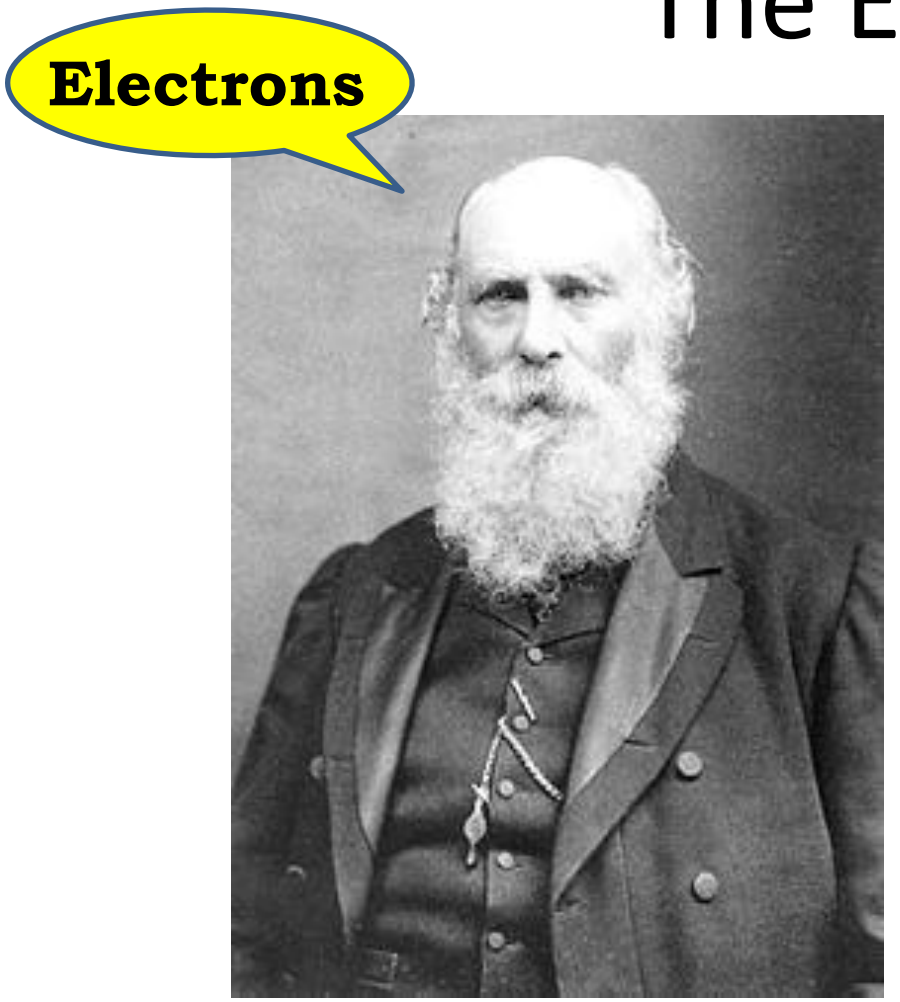


e.g. Lr^{103+}

The Electron!

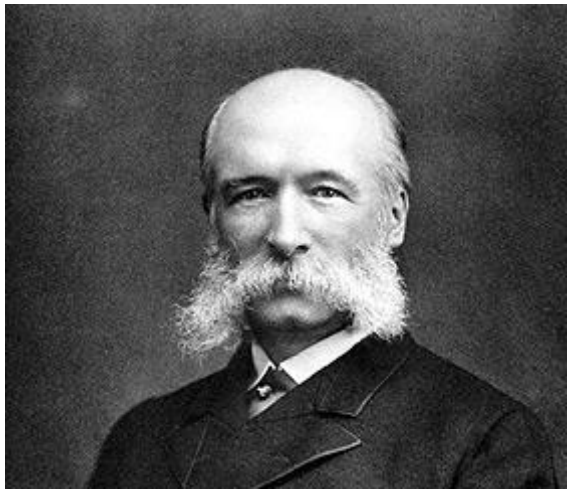


George Johnstone Stoney
1894

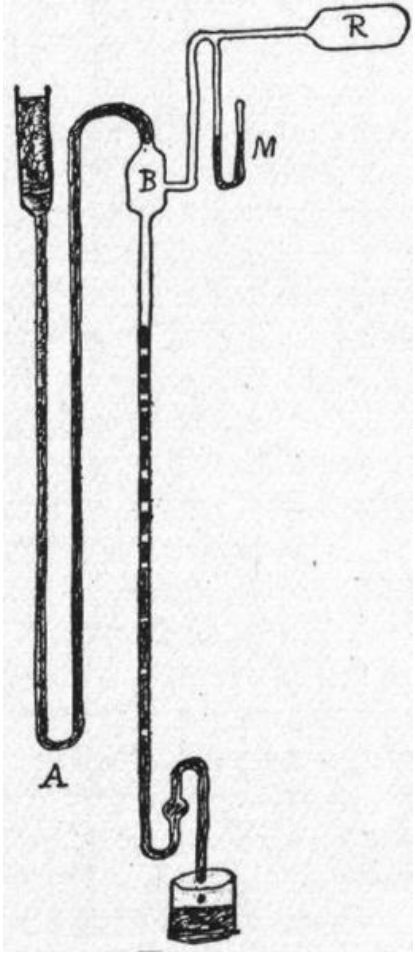
J. J. Thomson
1897

Early 1870's

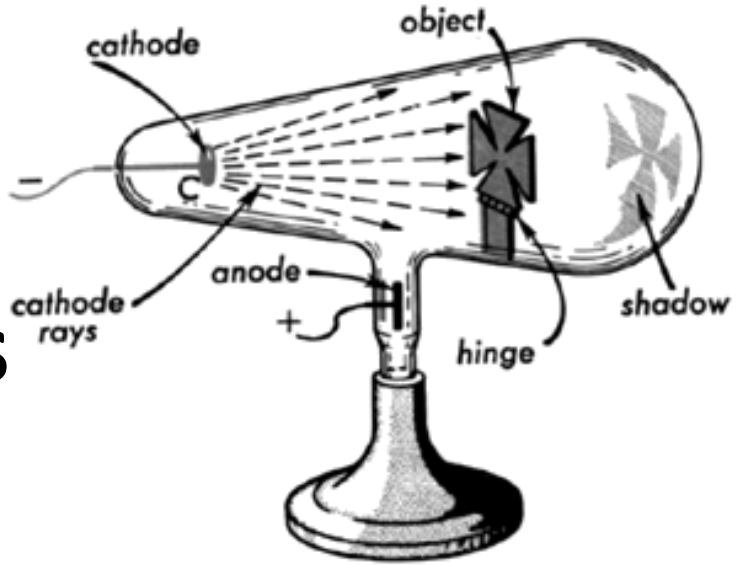
William Crookes



Hermann Sprengel



Improved mercury pump 10^{-5} mBar



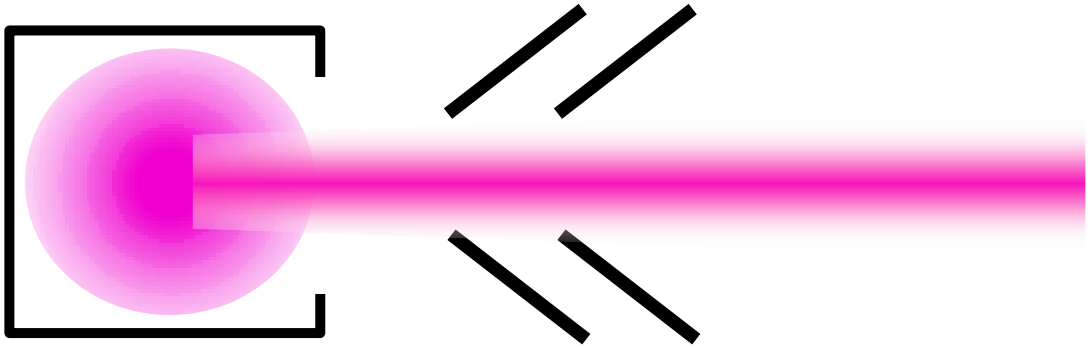
Electron Guns

Inferiority complex…
Because they're so small!

?

Ion Sources

Particle sources/guns consist of:



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

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Electrons e^-

Thermionic

Photons

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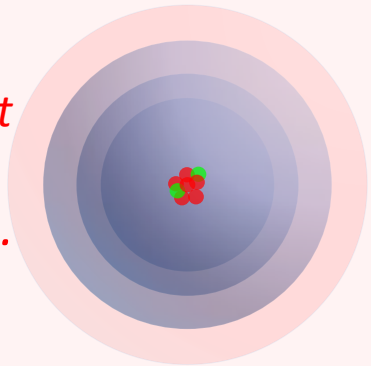

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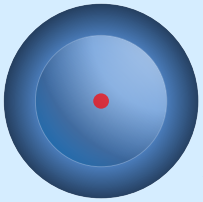

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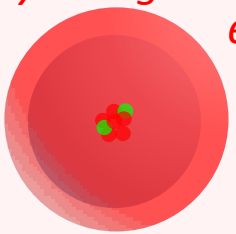

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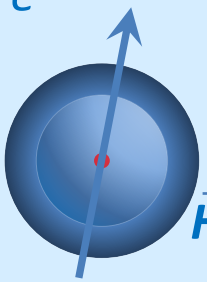

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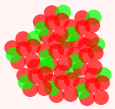
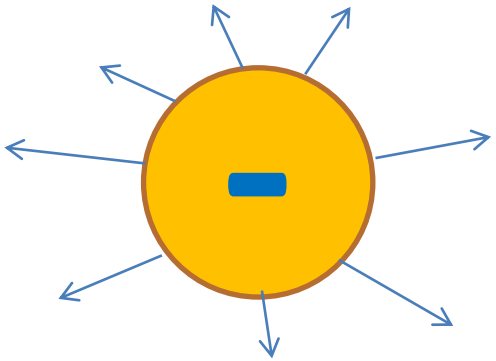


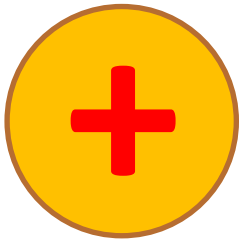
e.g. Lr^{103+}

Fredrick Guthrie

British scientific writer and professor



A negatively charged red hot metal ball looses charge...

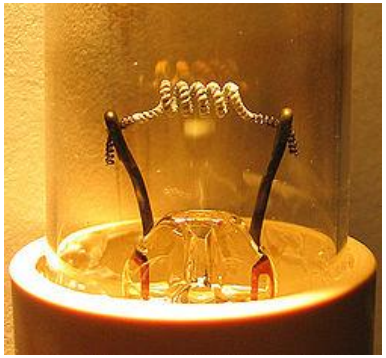


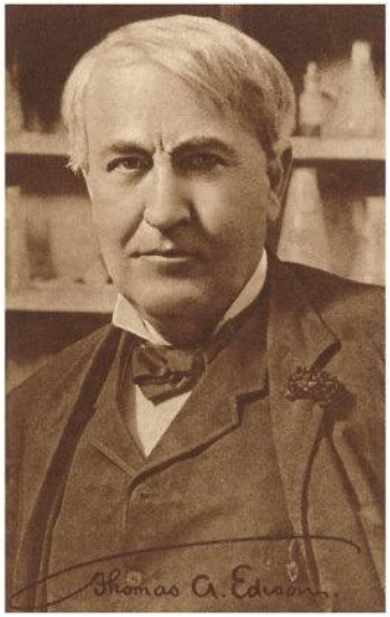
...whereas a positively charged one keeps its charge

Elements of Heat in 1868

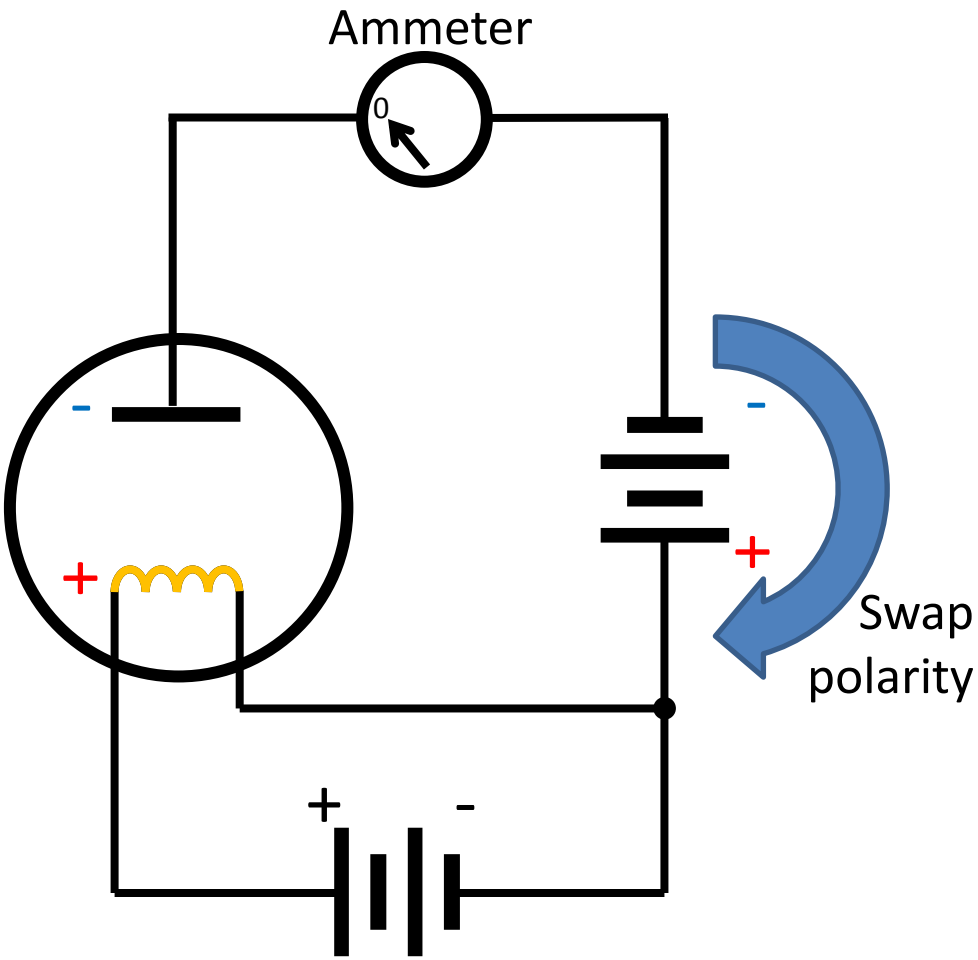
First experimental observation of thermionic emission

Thermionic Emission



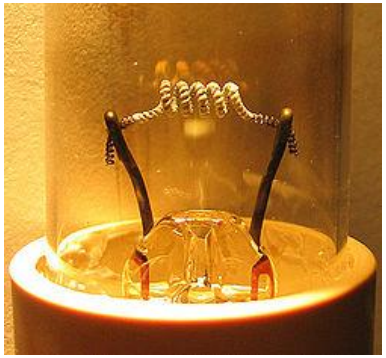


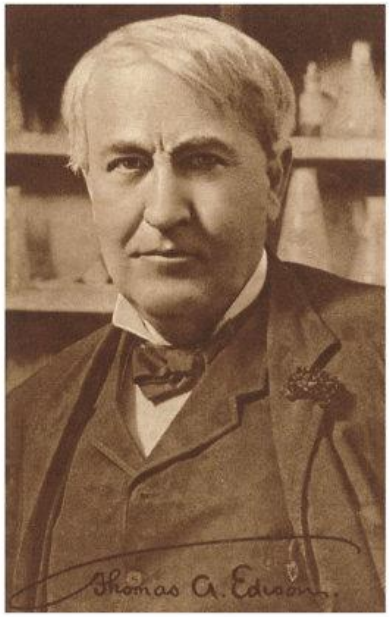
1880 Thomas Edison



The “Edison effect”

Thermionic Emission





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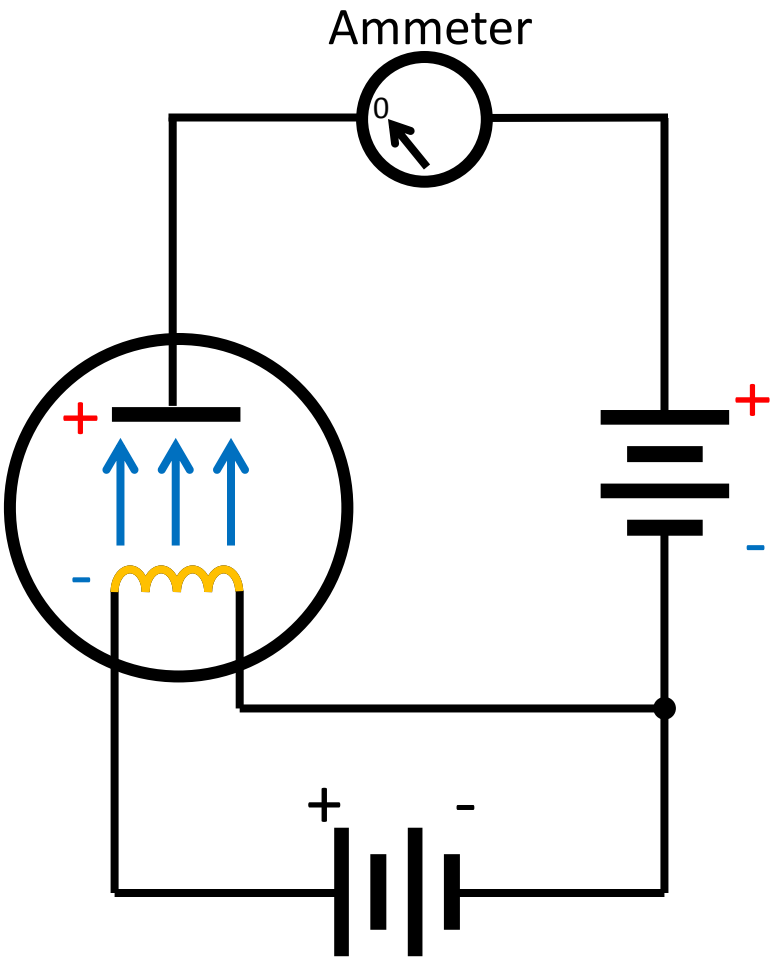

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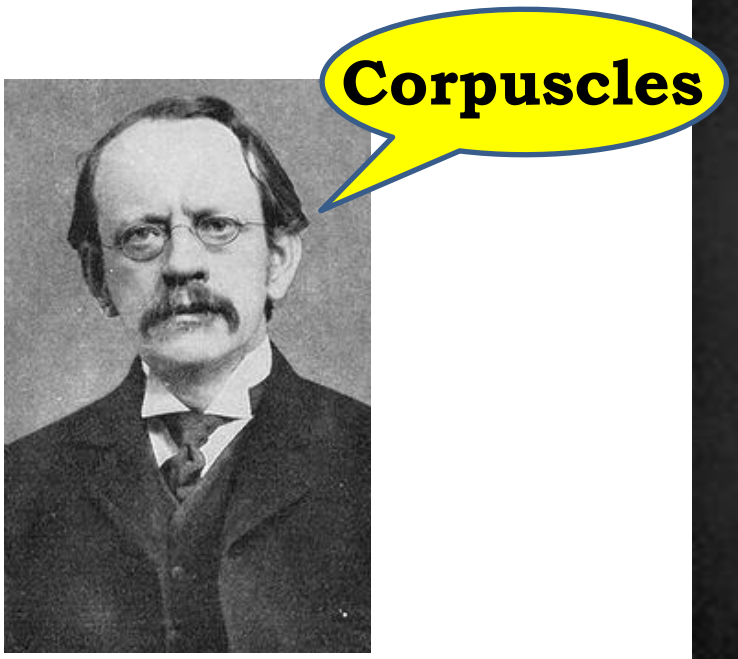


J. J. Thomson
1897

1901 Owen Richardson

Cambridge University

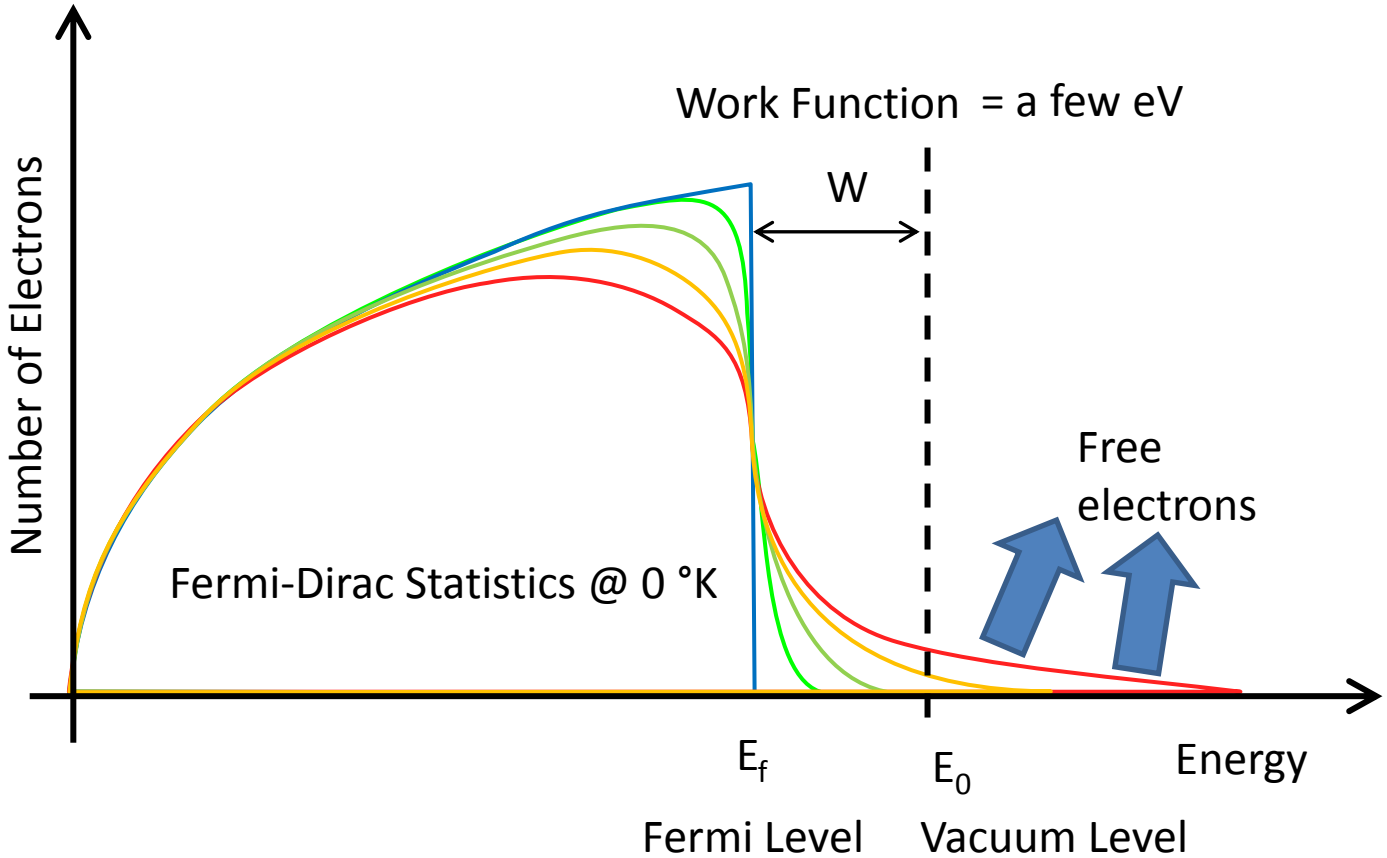
$$J = A_G T^2 e^{\frac{-W}{kT}}$$

Richardson's Law

Same form as the Arrhenius equation

Current increases exponentially with temperature

Thermionic Emission



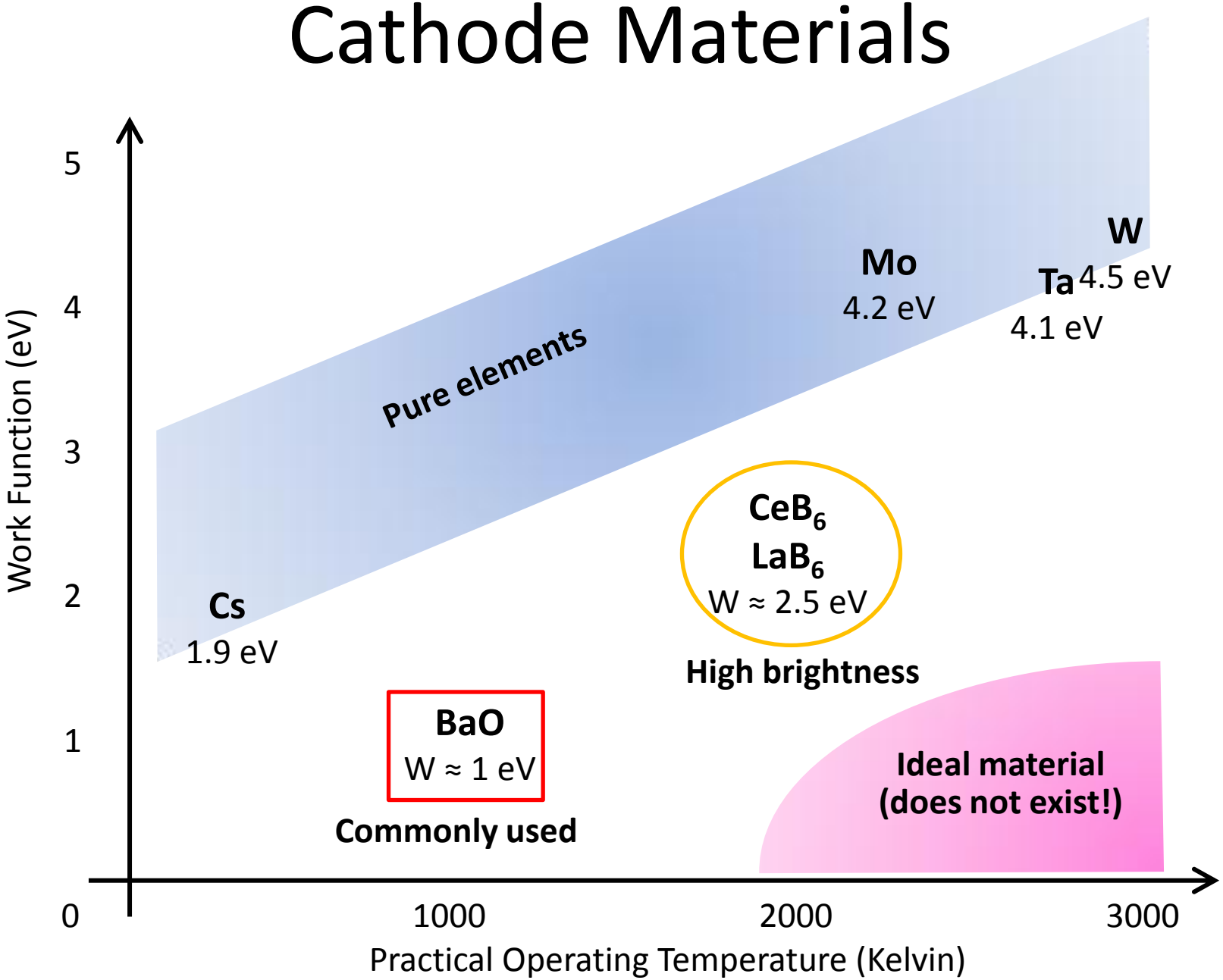
$$J = A_G T^2 e^{\frac{-W}{kT}}$$

For a good electron emitter you need:

Lowest possible work function

Highest possible temperature

Cathode Materials

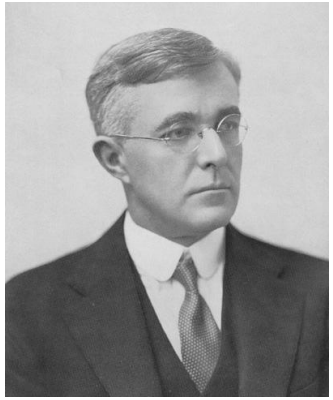


Child-Langmuir Law

(Space charge limited extraction)

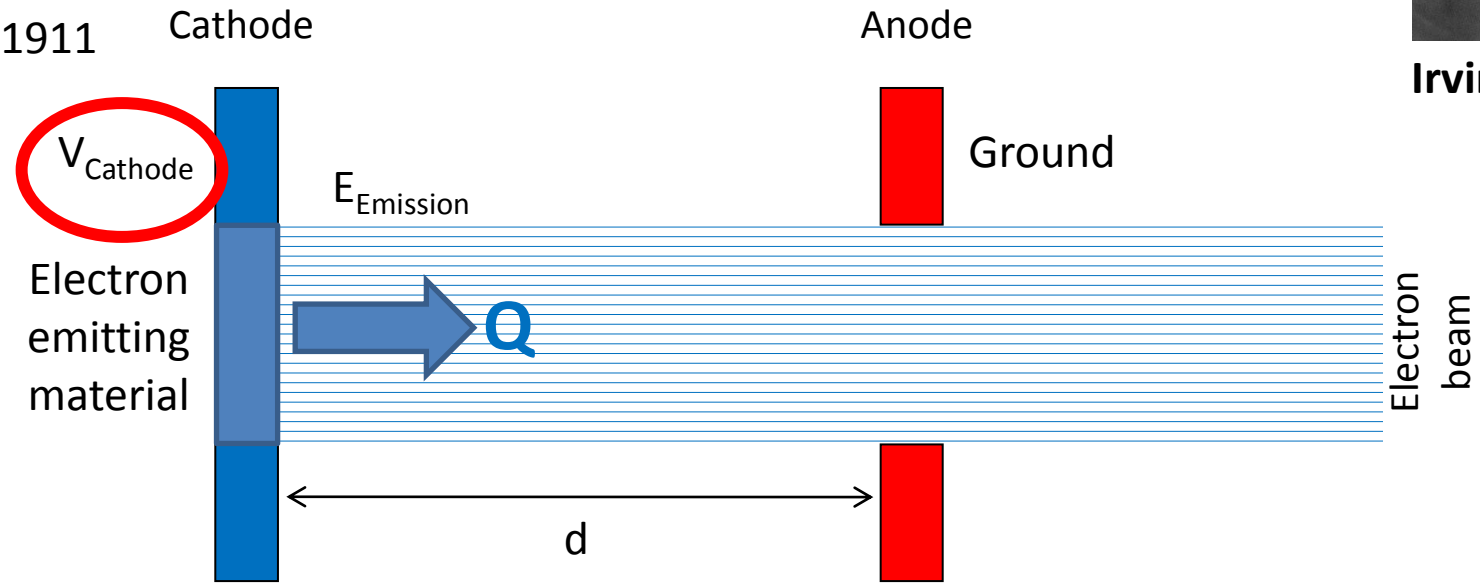
C.D Child

1911



Irving Langmuir

1913

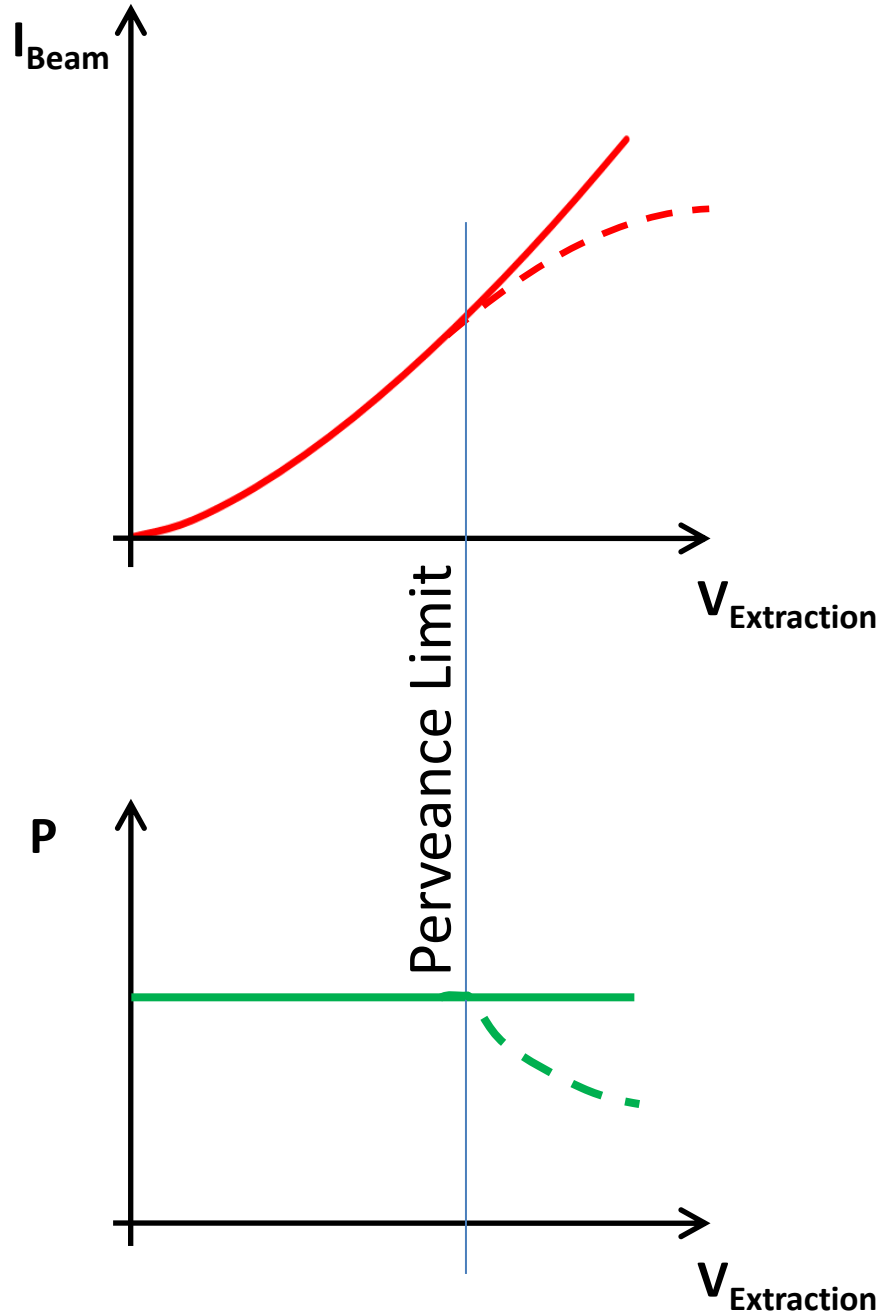


$$j = \frac{\frac{4}{9}\varepsilon_0 \sqrt{\frac{2e}{m_e}} V^{\frac{3}{2}}}{d^2}$$

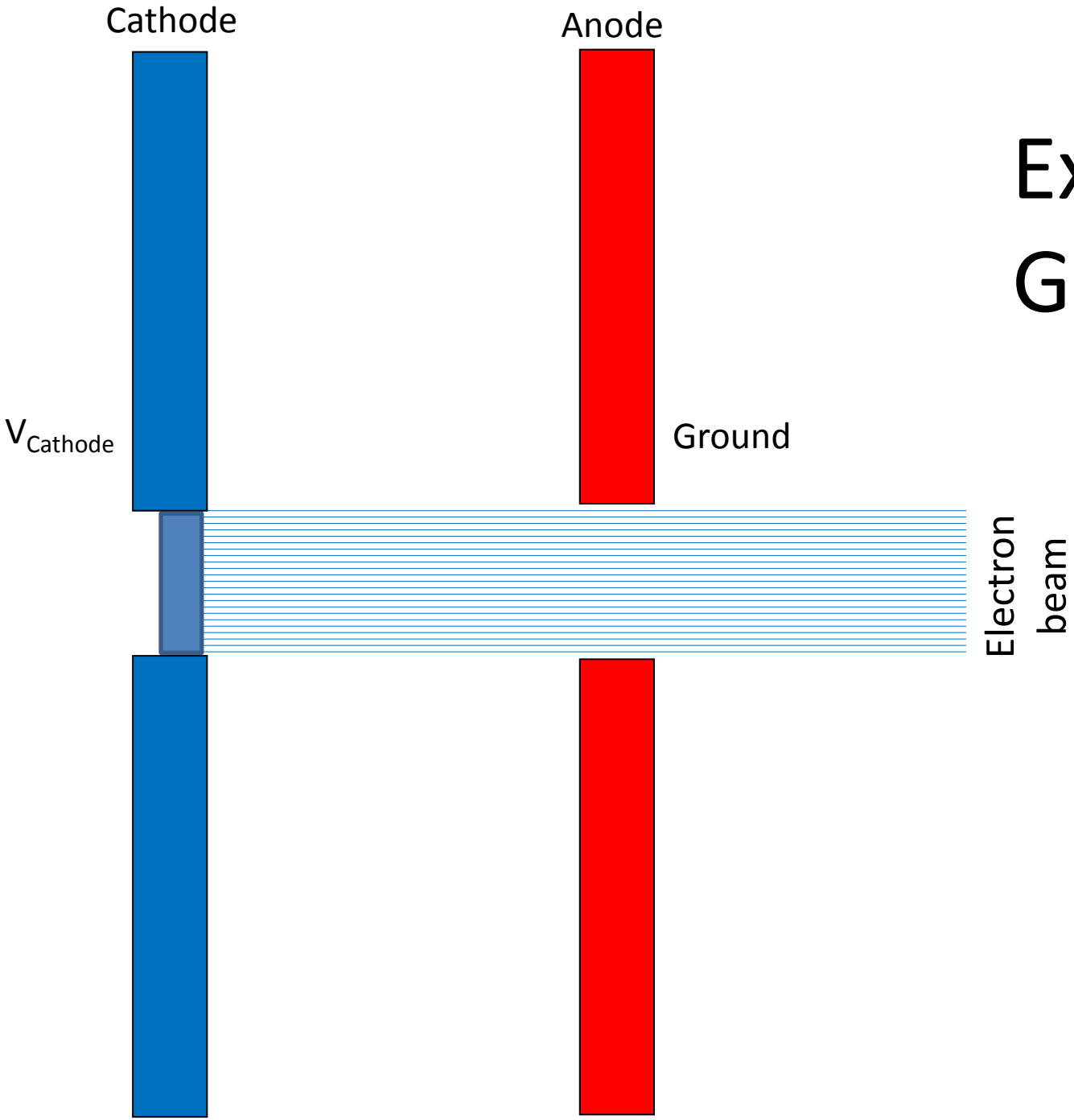
$$I \propto V^{\frac{3}{2}}$$

Perveance

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



Pierce Extraction Geometry



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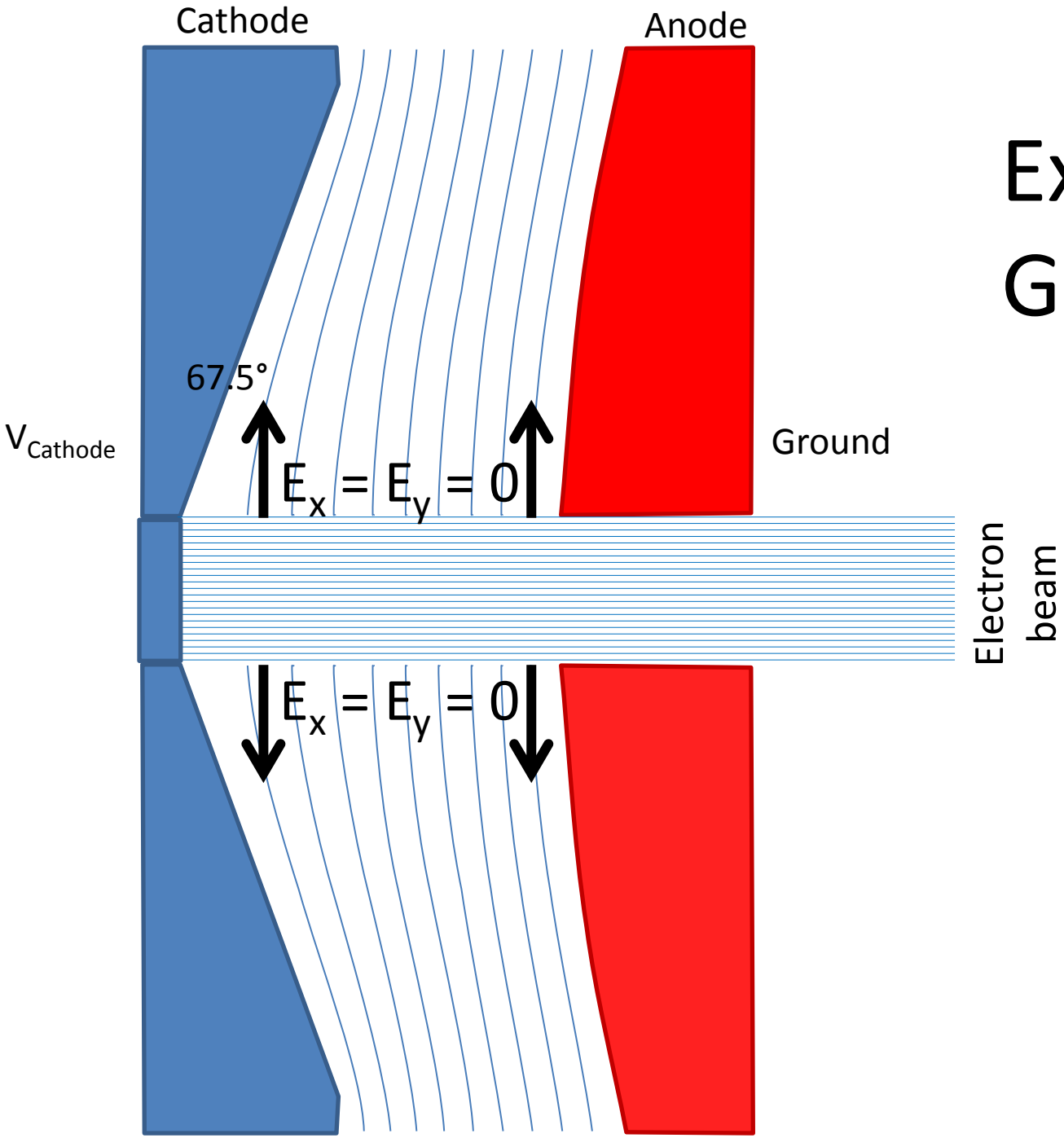
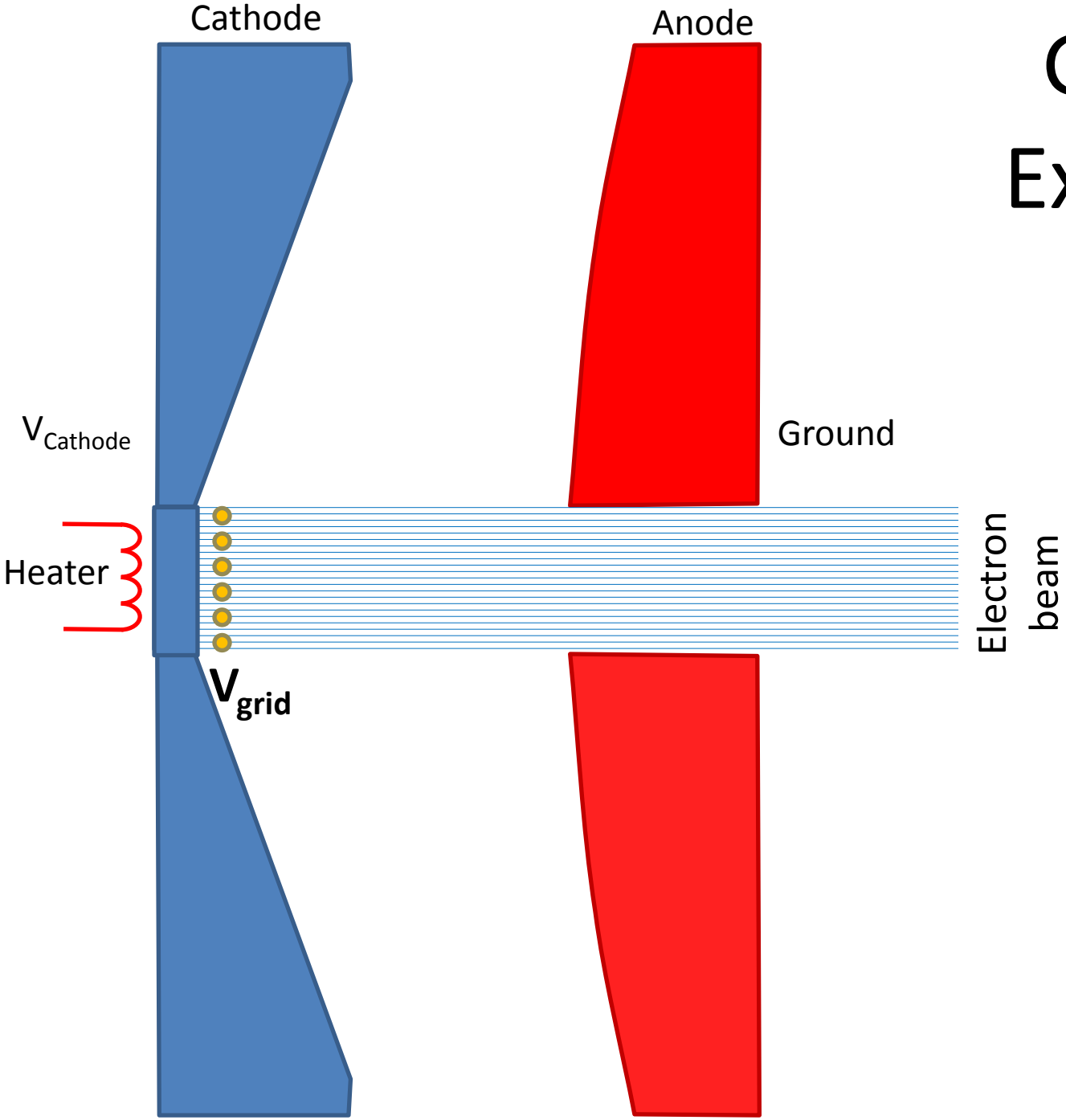


Gridded Extraction

(A triode amplifier)



Communications & Power Industries

Eimac

YU 171

Thermionic dispenser cathode with integrated heater and grid

Sinter of W and BaO

$1cm^2$
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

Particles and **Sources**

Positrons e^+

Electrons e^-

Thermionic

Photo

Photons

Neutrinos $\nu_e\ \nu_\mu\ \nu_\tau$

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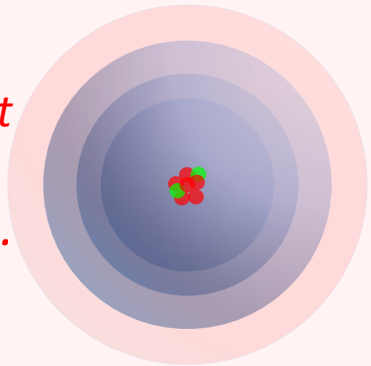
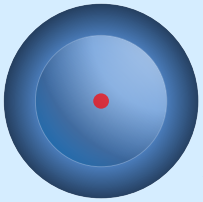


Negative ions



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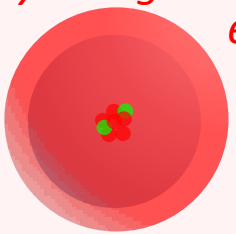

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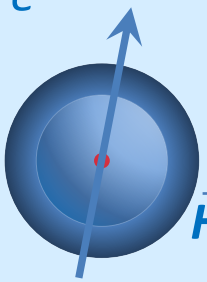

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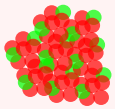
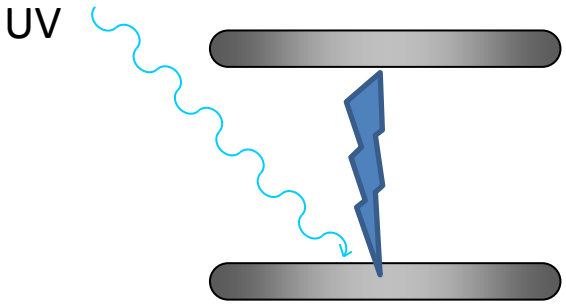


e.g. Lr^{103+}

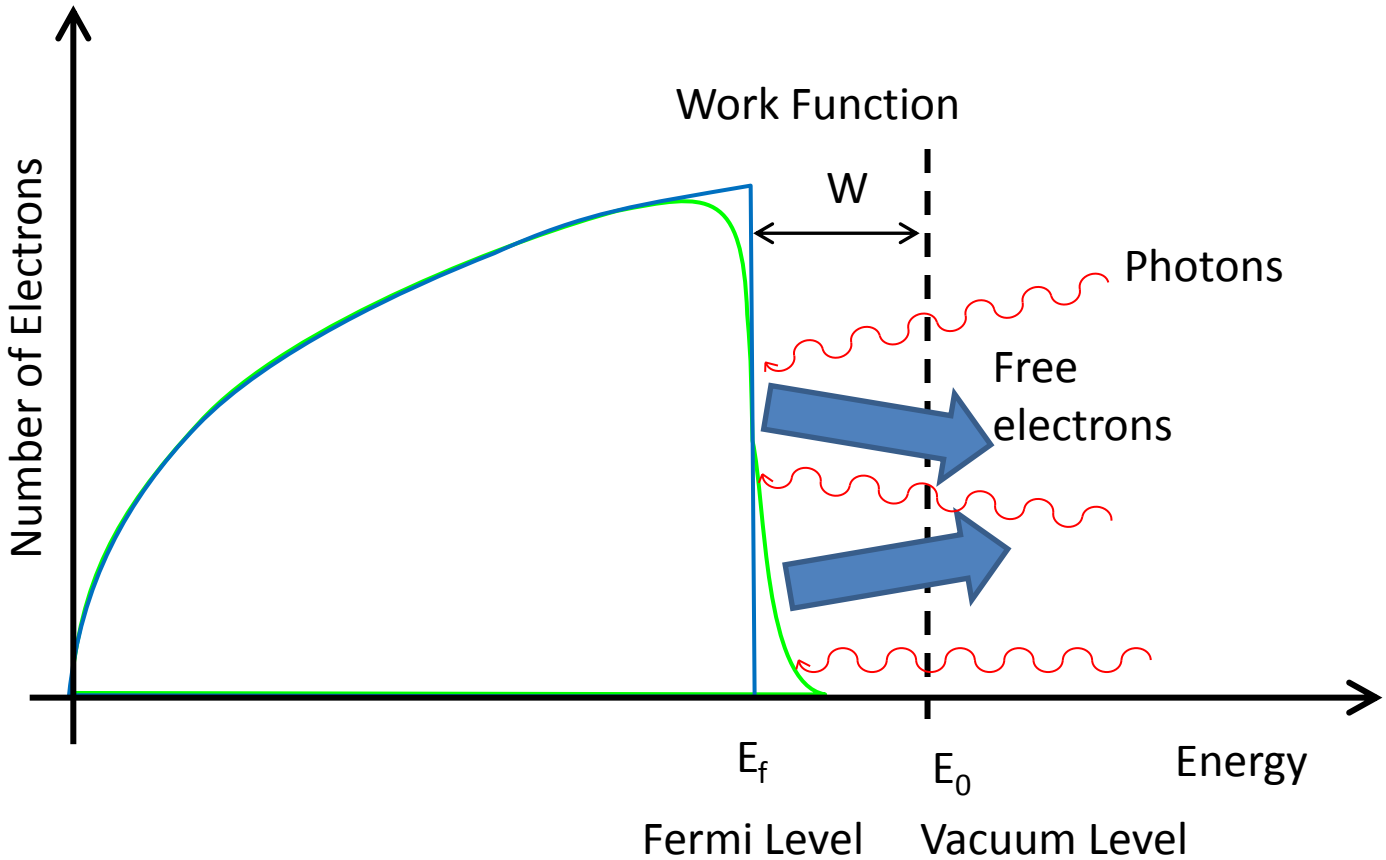
Photo Emission

First observed by Heinrich Hertz in 1887



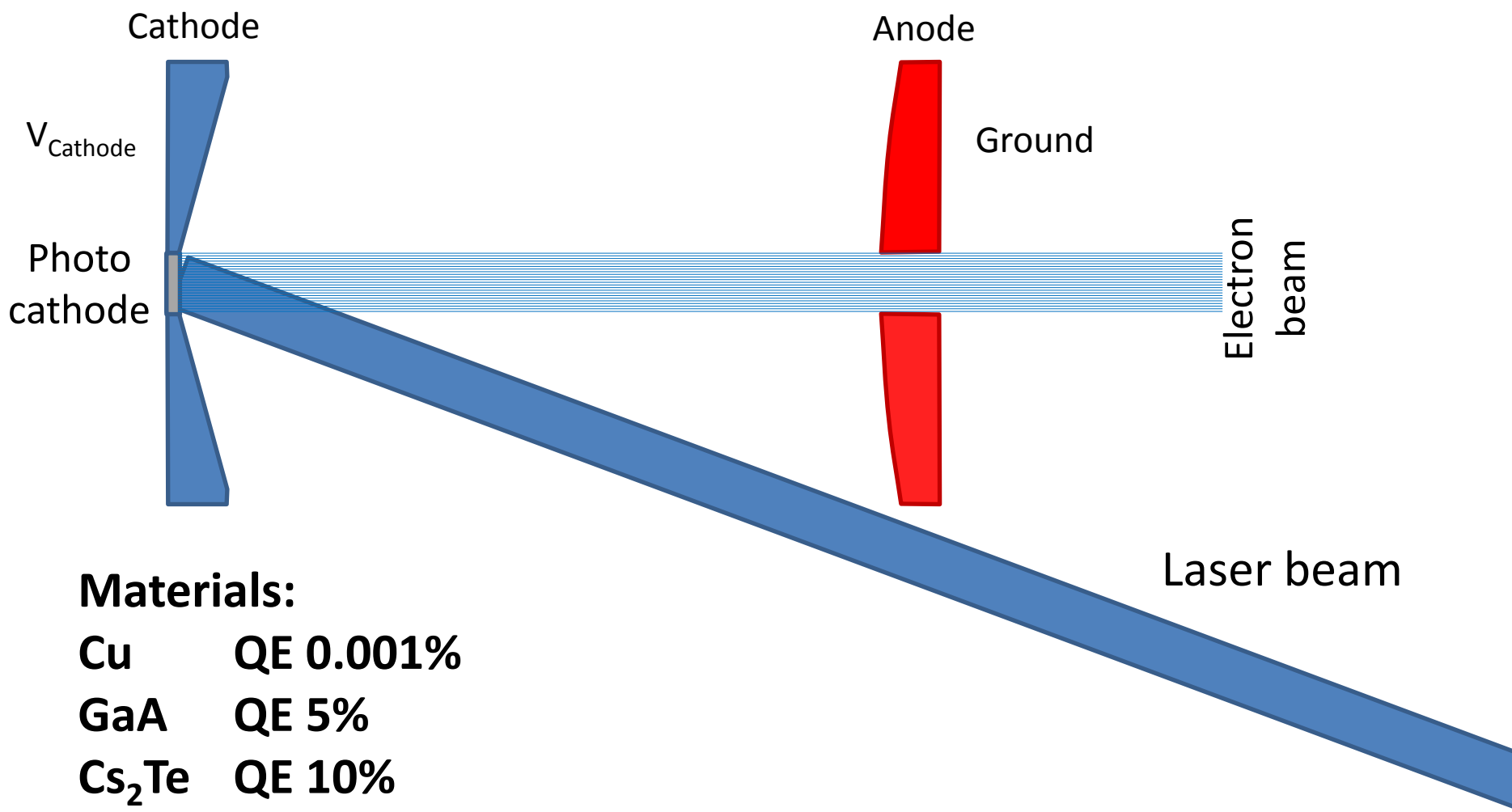
Theoretical explanation by Einstein in 1905

Photo electric emission



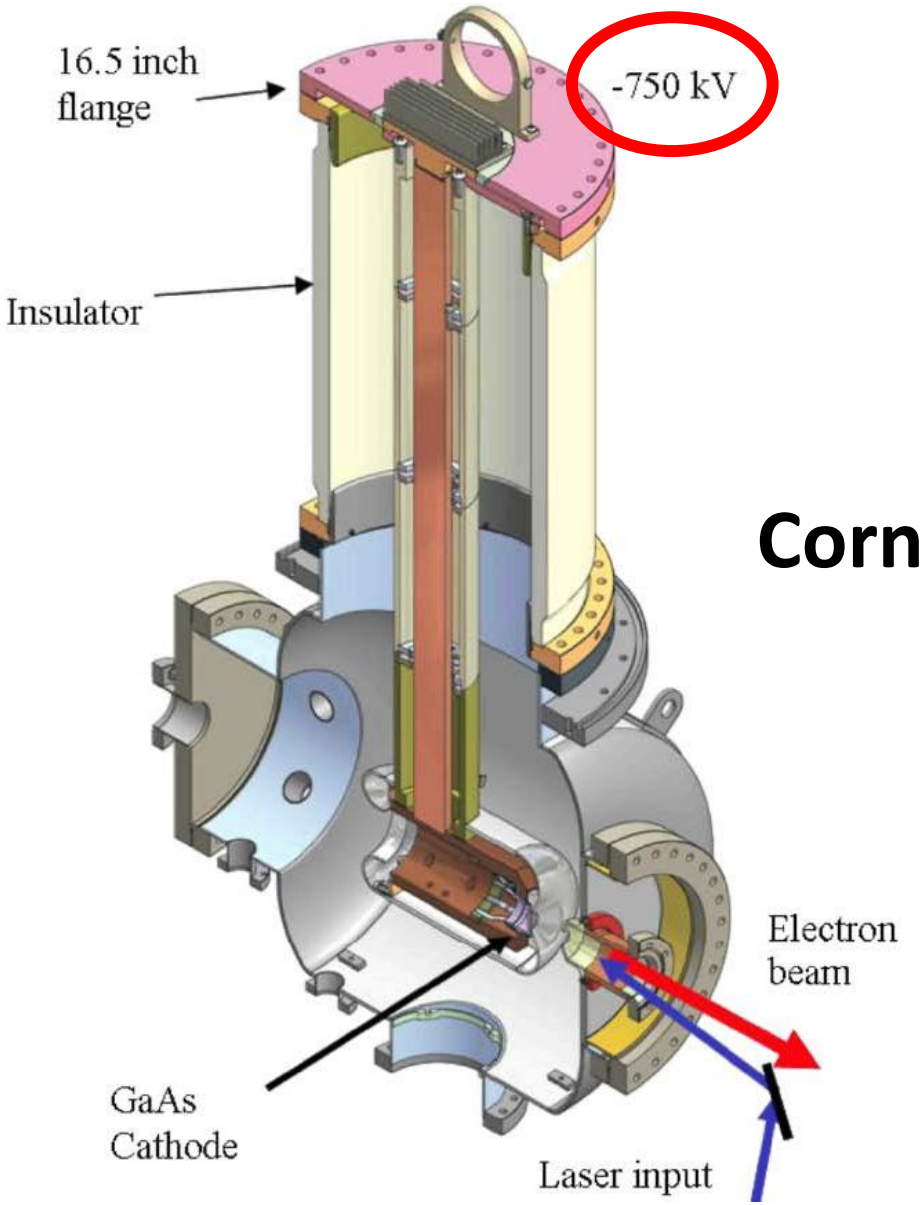
$$\text{Quantum efficiency (QE)} = \frac{\text{Number of electrons produced}}{\text{Number of incident photons}}$$

Photo Emission Gun



Materials:

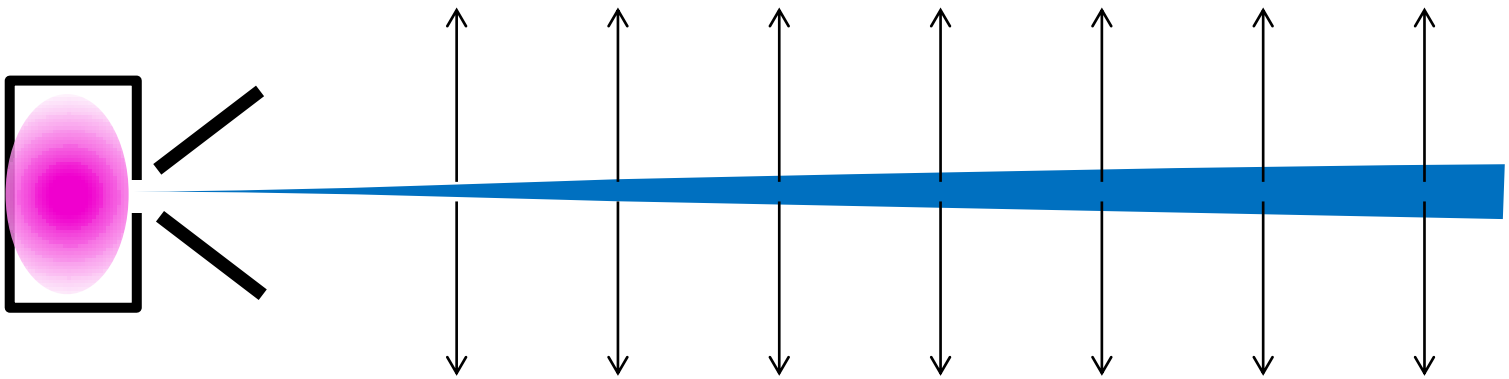
Cu	**QE 0.001%**
GaA	**QE 5%**
Cs_2Te	**QE 10%**



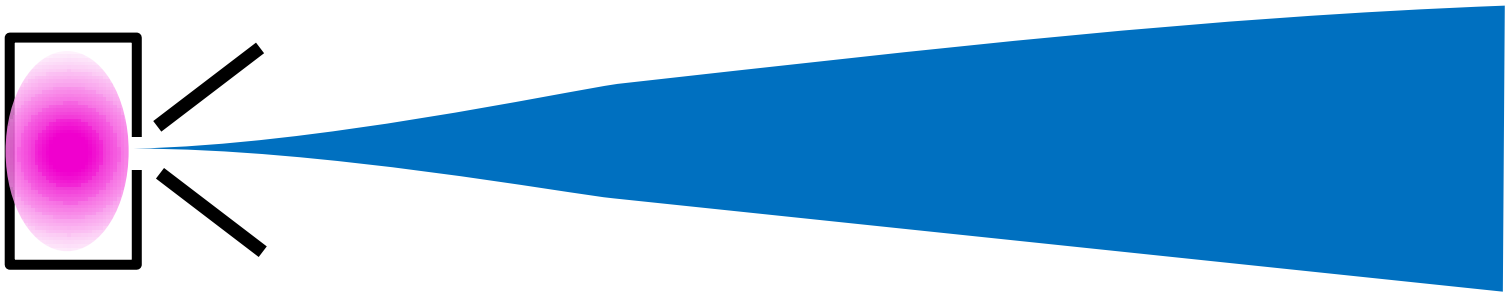
Cornell DC Photoemission gun

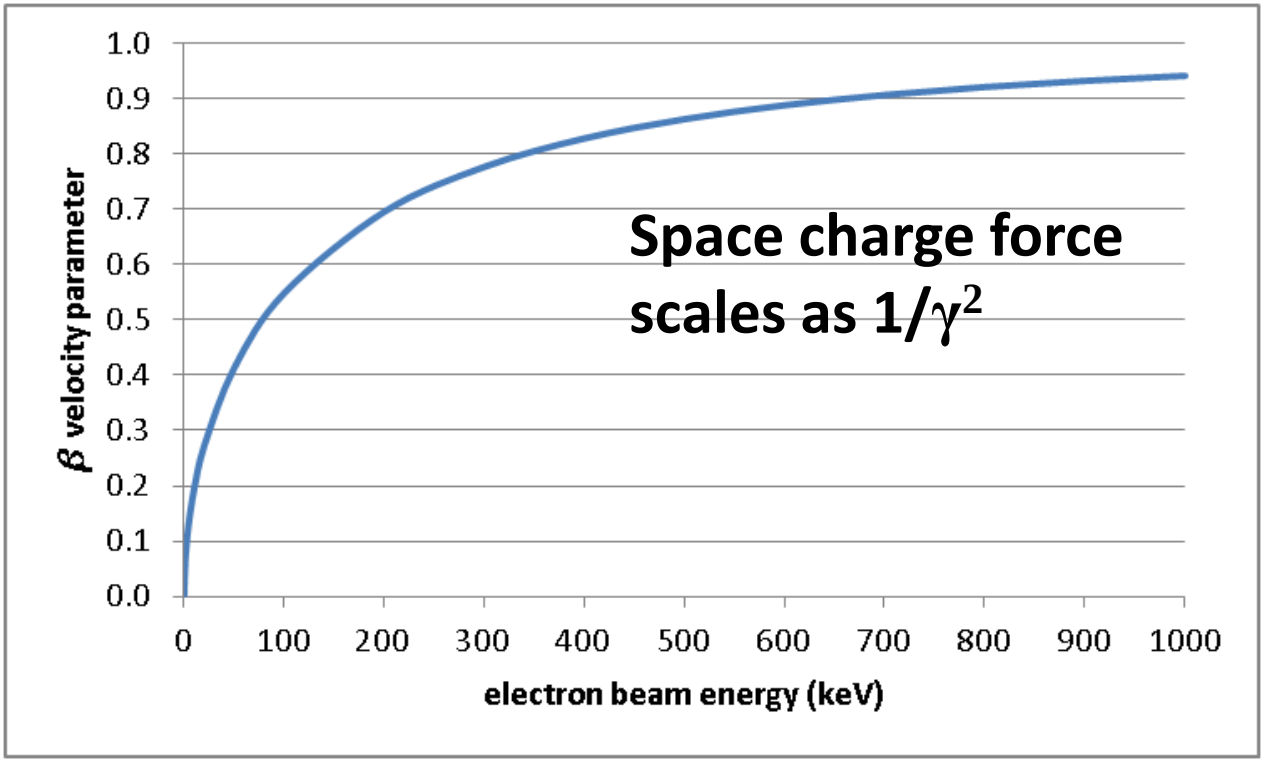
20mA average current
at 250kV

Space Charge



Space Charge



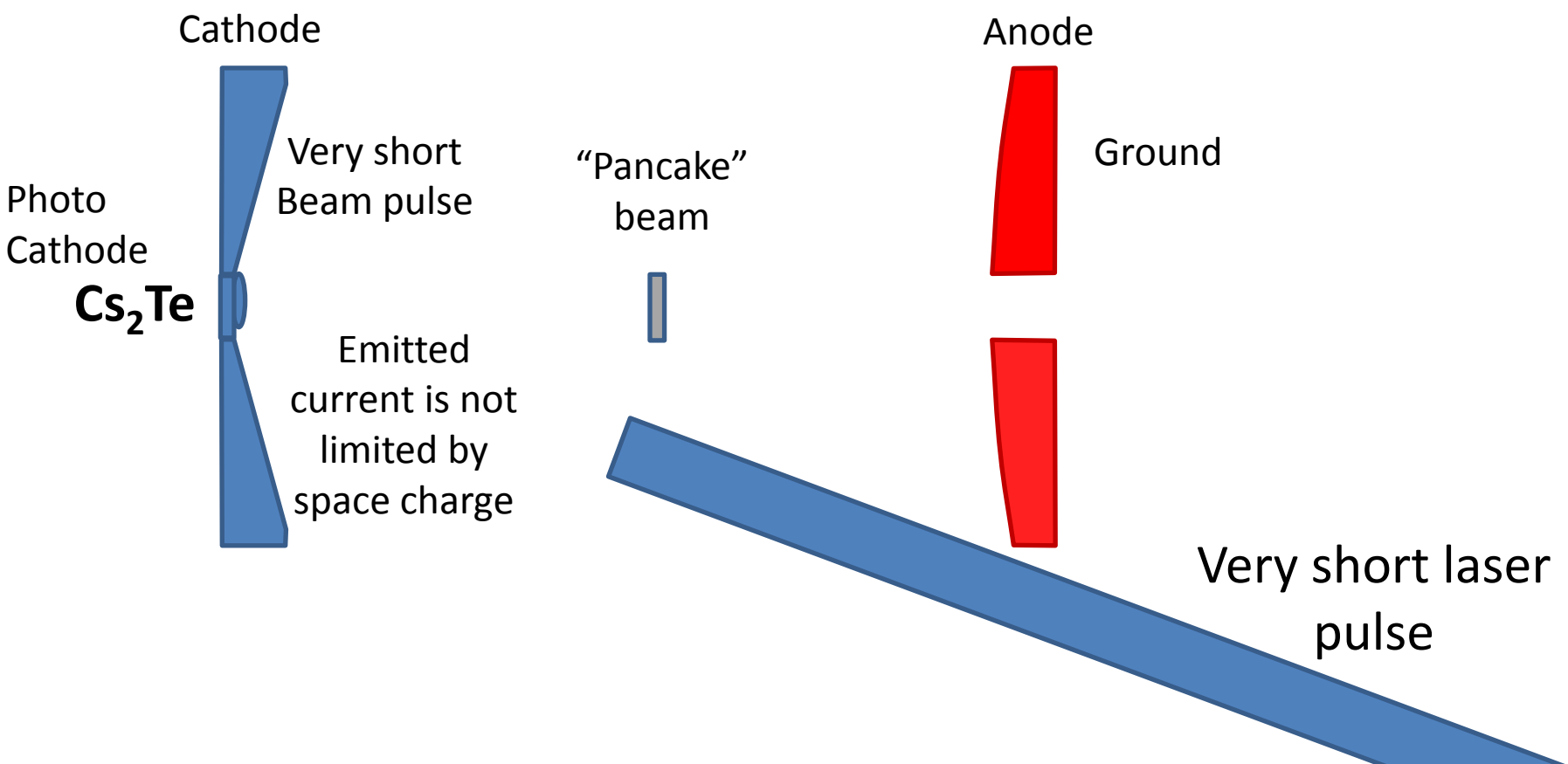


At 500 keV electron $\gamma = 2$

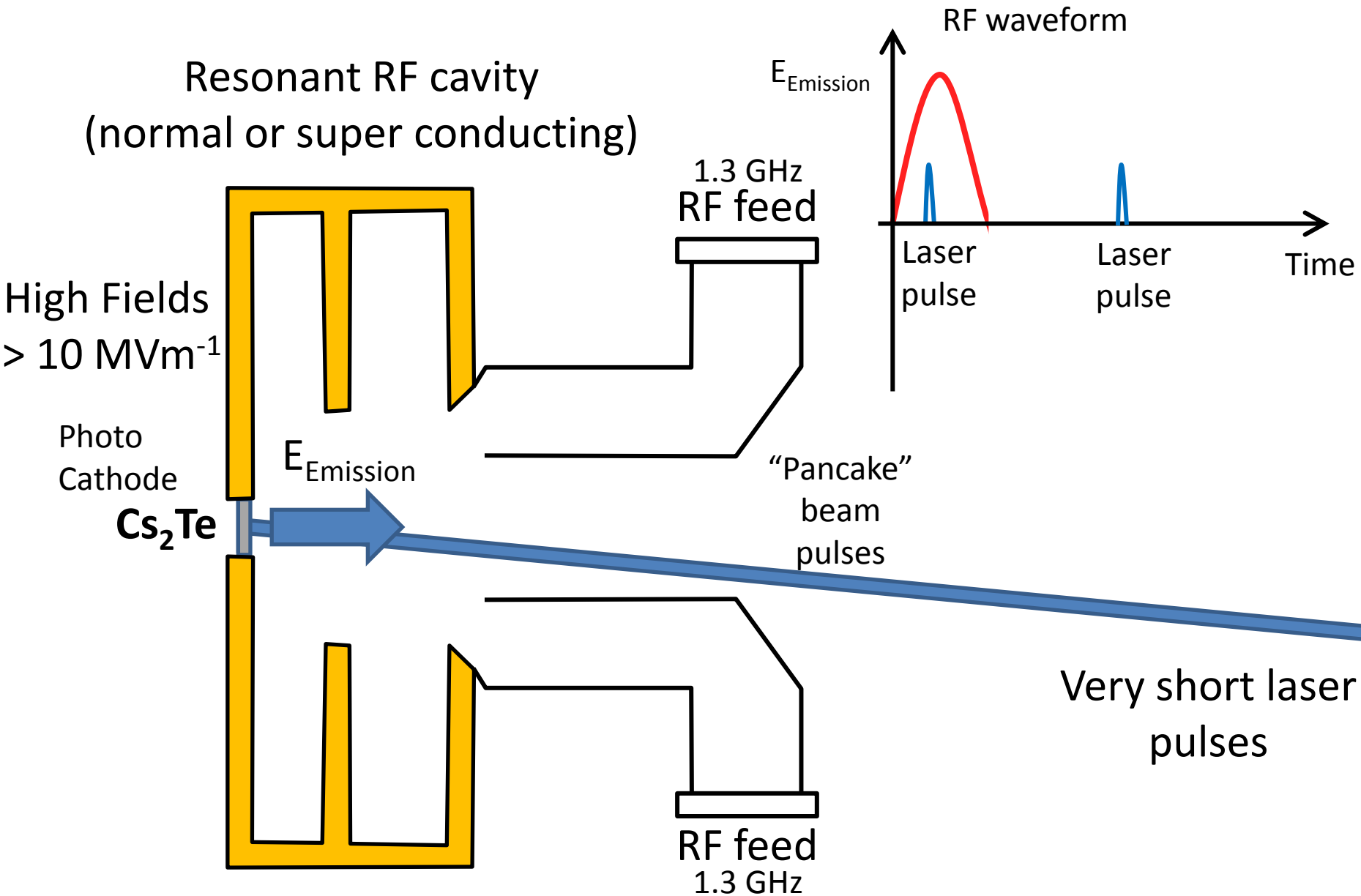
(940 MeV proton $\gamma = 2$)

Another reason to use lasers is…

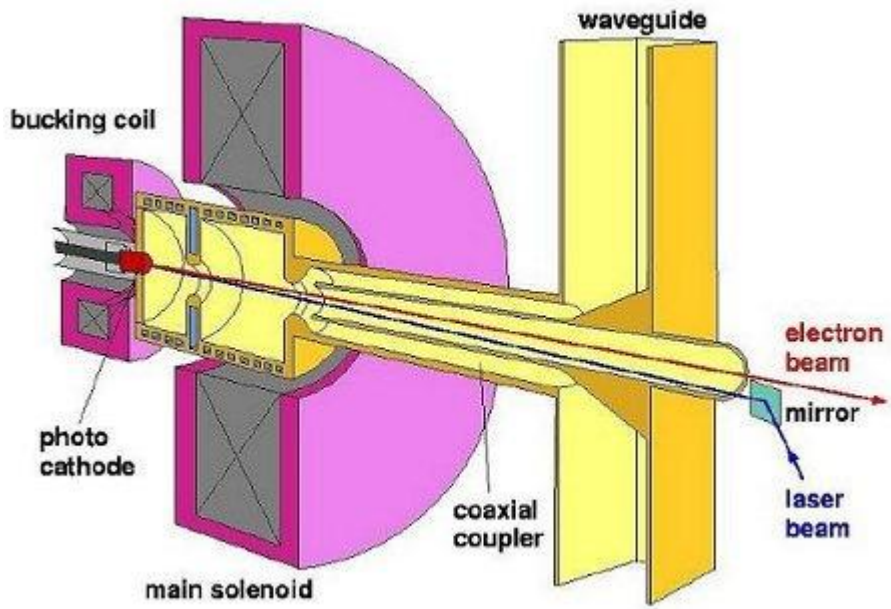
Lasers are so fast they can easily beat Child-Langmuir (to be fair, so can gridded extraction)



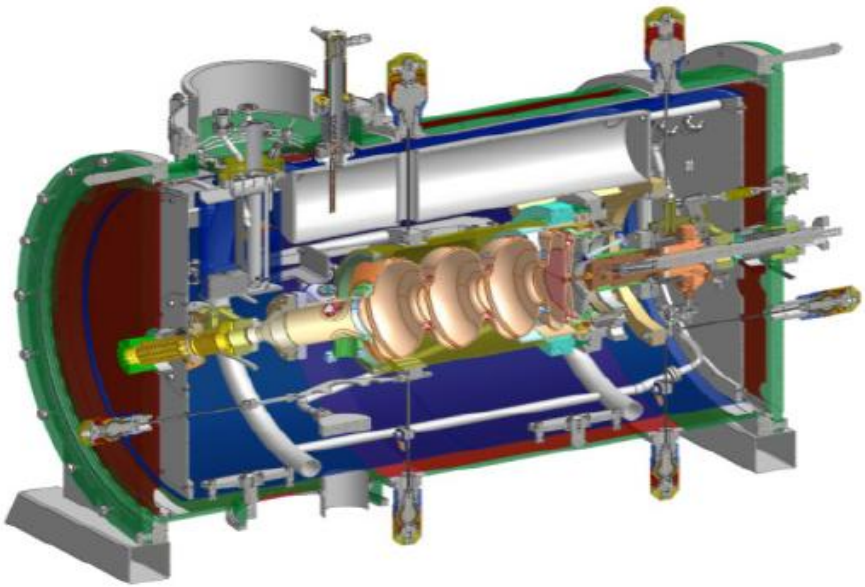
RF Photemission Source



Normally conducting



Super conducting

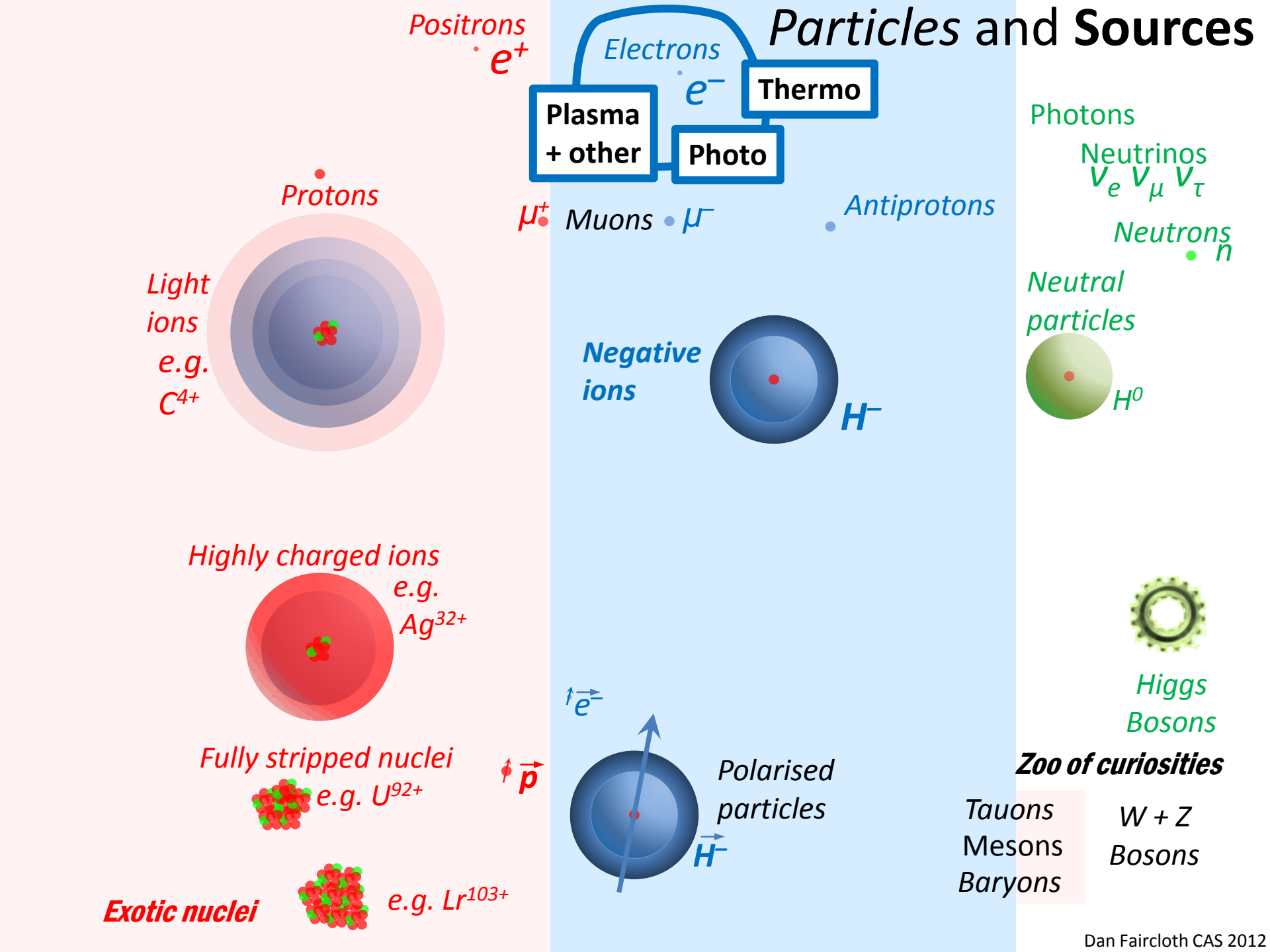


20 ps, 1 nC pulses
(50 A pulse)

15 ps, 1 nC pulses
(67 A pulse)

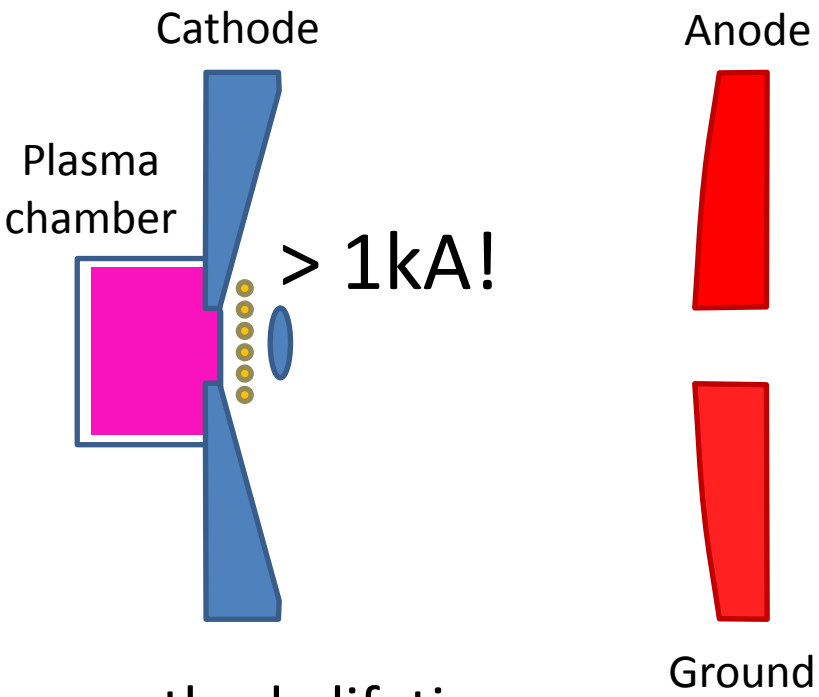
High brightness low emittance guns for FEL

Particles and **Sources**



Plasma Cathode

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



Long cathode lifetimes

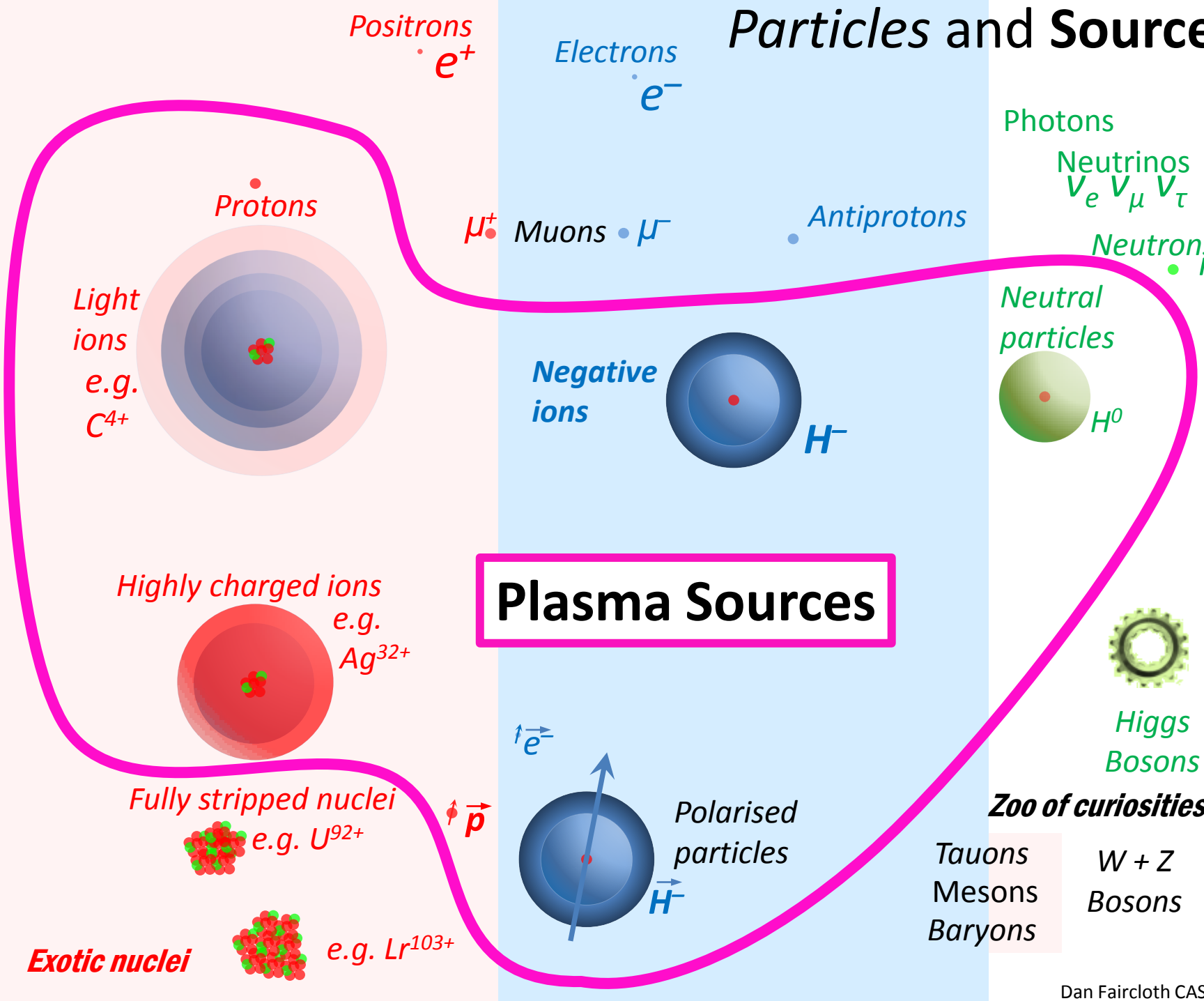
Other electron sources:

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

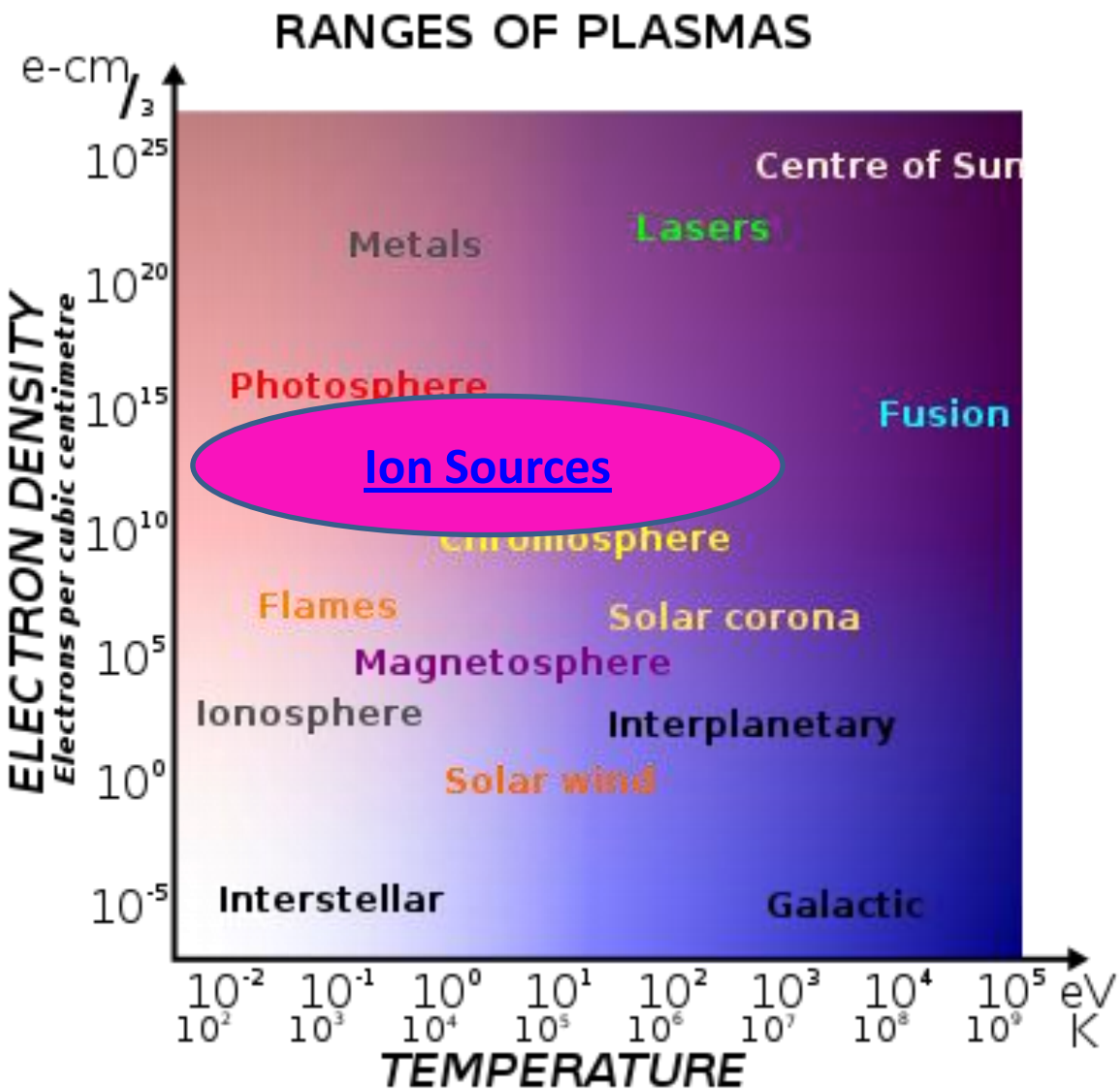
Rarely used in accelerators:

Field emission from needle arrays
Diamond amplifiers
Etc...

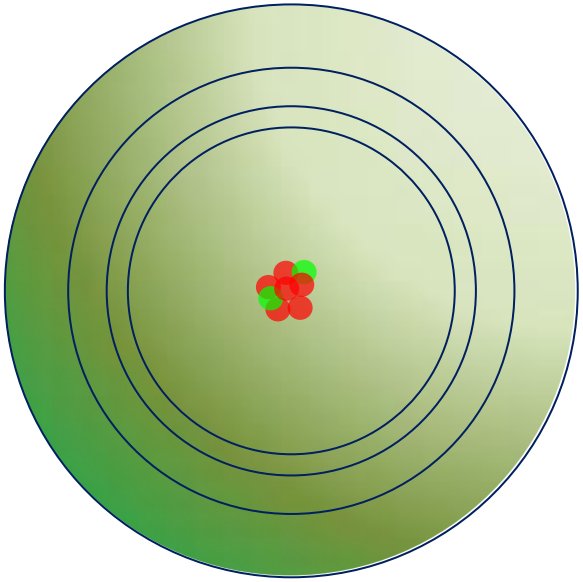
Particles and **Sources**



Dan Faircloth CAS 2012


RANGES OF PLASMAS
e-cm/3
ELECTRON DENSITY
Electrons per cubic centimetre
10^25
10^20
10^15
10^10
10^5
10^0
10^-5
Centre of Sun
Lasers
Metals
Photosphere
Fusion
Ion Sources
Chromosphere
Flames
Solar corona
Magnetosphere
Ionosphere
Interplanetary
Solar wind
Interstellar
Galactic
10^-2 10^-1 10^0 10^1 10^2 10^3 10^4 10^5 eV
10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 K
TEMPERATURE

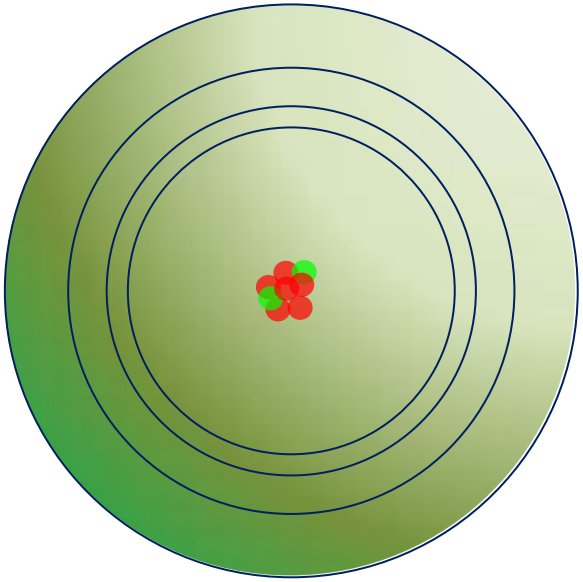
Ionisation



Neutral Atom

Most sources rely on electron impact ionisation

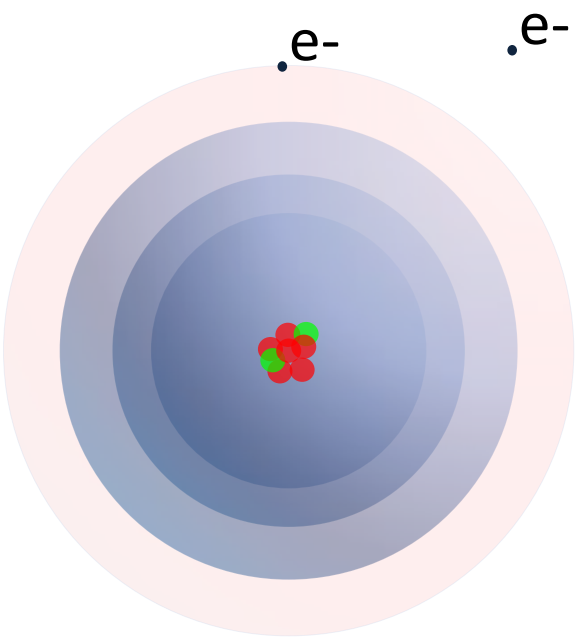
Ionisation



Neutral Atom

Most sources rely on electron impact ionisation

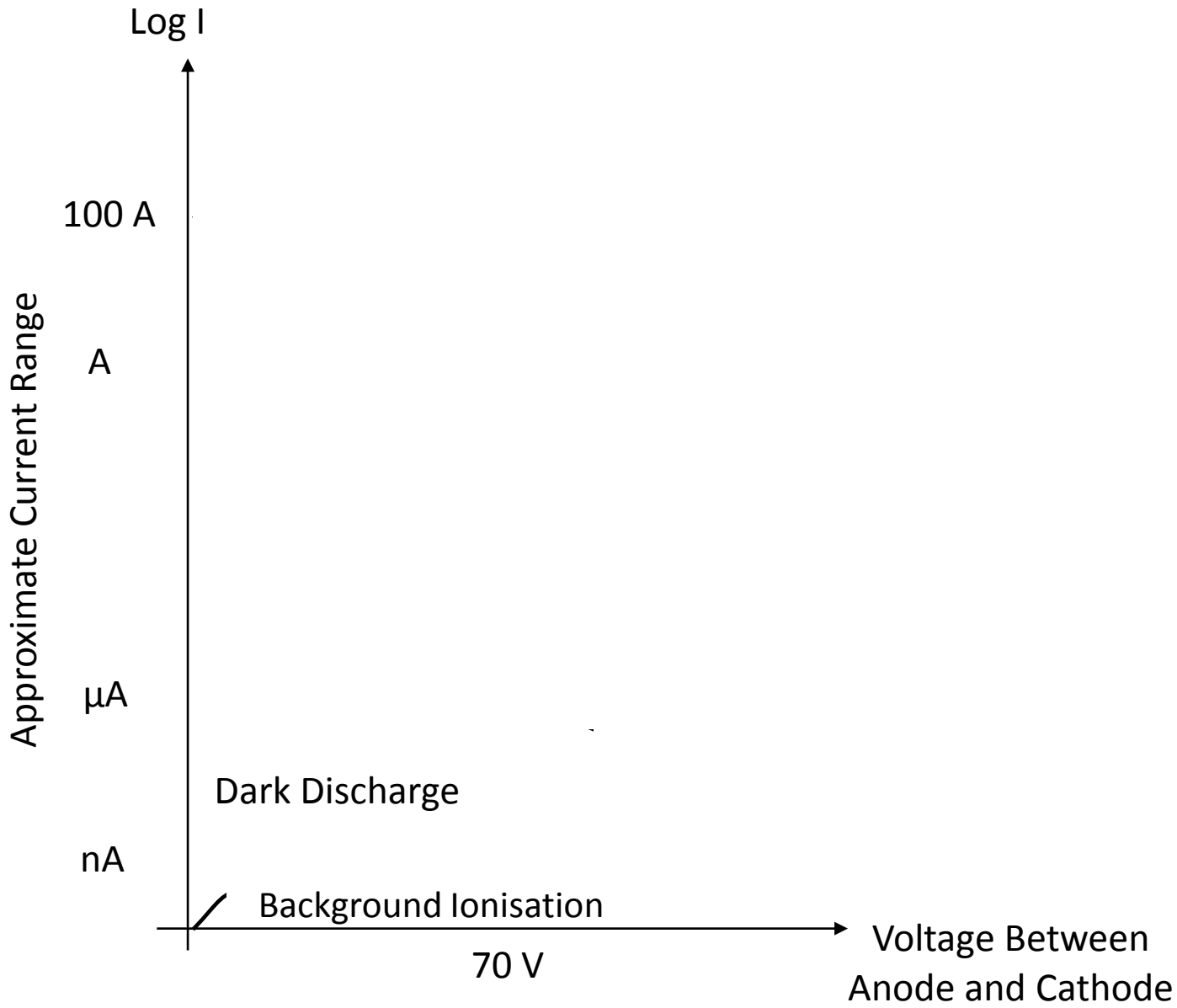
Ionisation

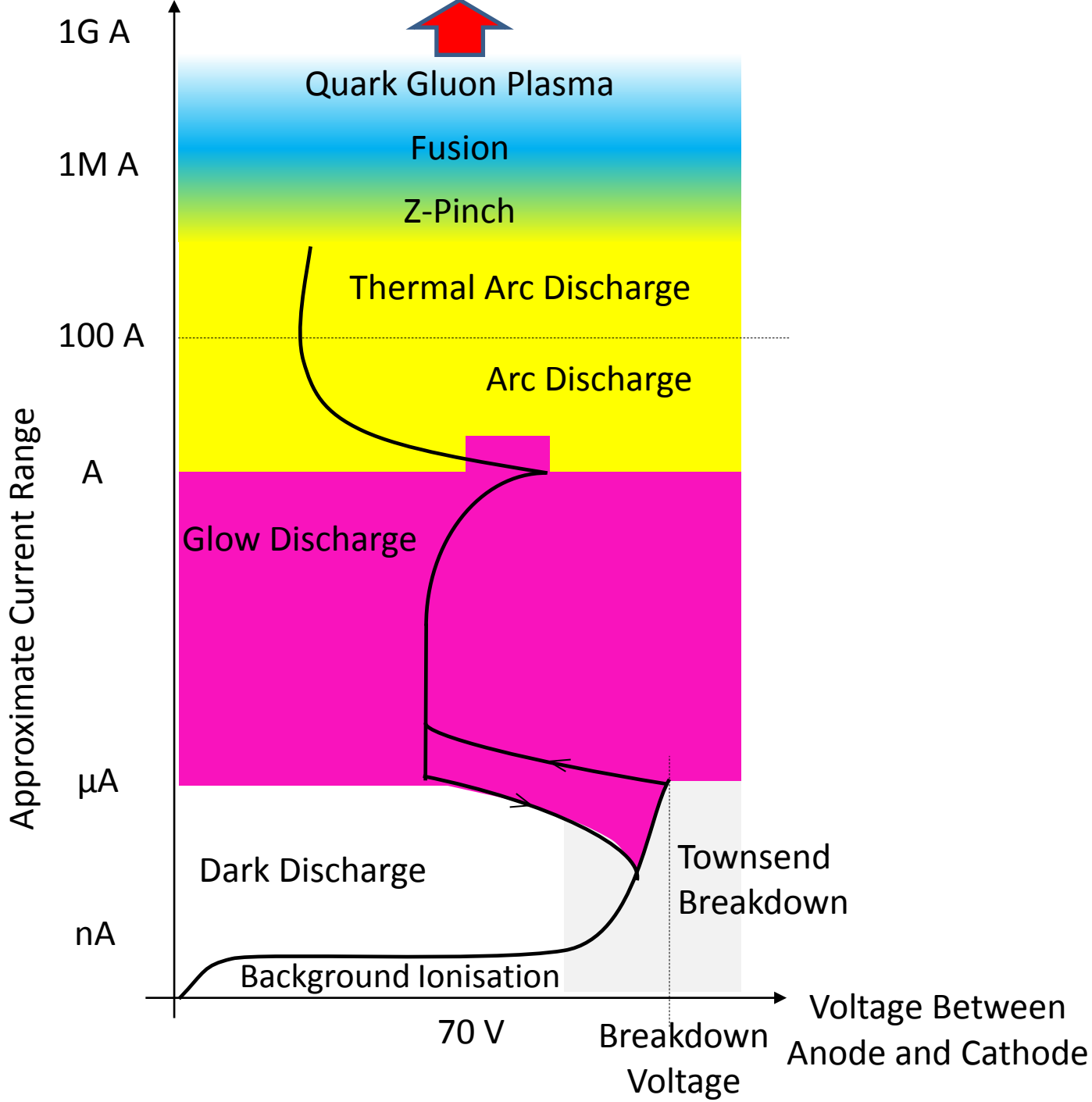


Positive Ion

Most sources rely on electron impact ionisation

Electrical Discharges




1G A
1M A
100 A
A
µA
nA
Approximate Current Range
Quark Gluon Plasma
Fusion
Z-Pinch
Thermal Arc Discharge
Arc Discharge
Glow Discharge
Dark Discharge
Townsend Breakdown
Background Ionisation
70 V
Breakdown Voltage
Voltage Between Anode and Cathode

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*

$H^+ \rightarrow q = +1$

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

$H^- \rightarrow q = -1$

Temperature, *T* (eV)

T_e = temperature of electrons

T_i = temperature of ions

T_n = temperature of neutrals

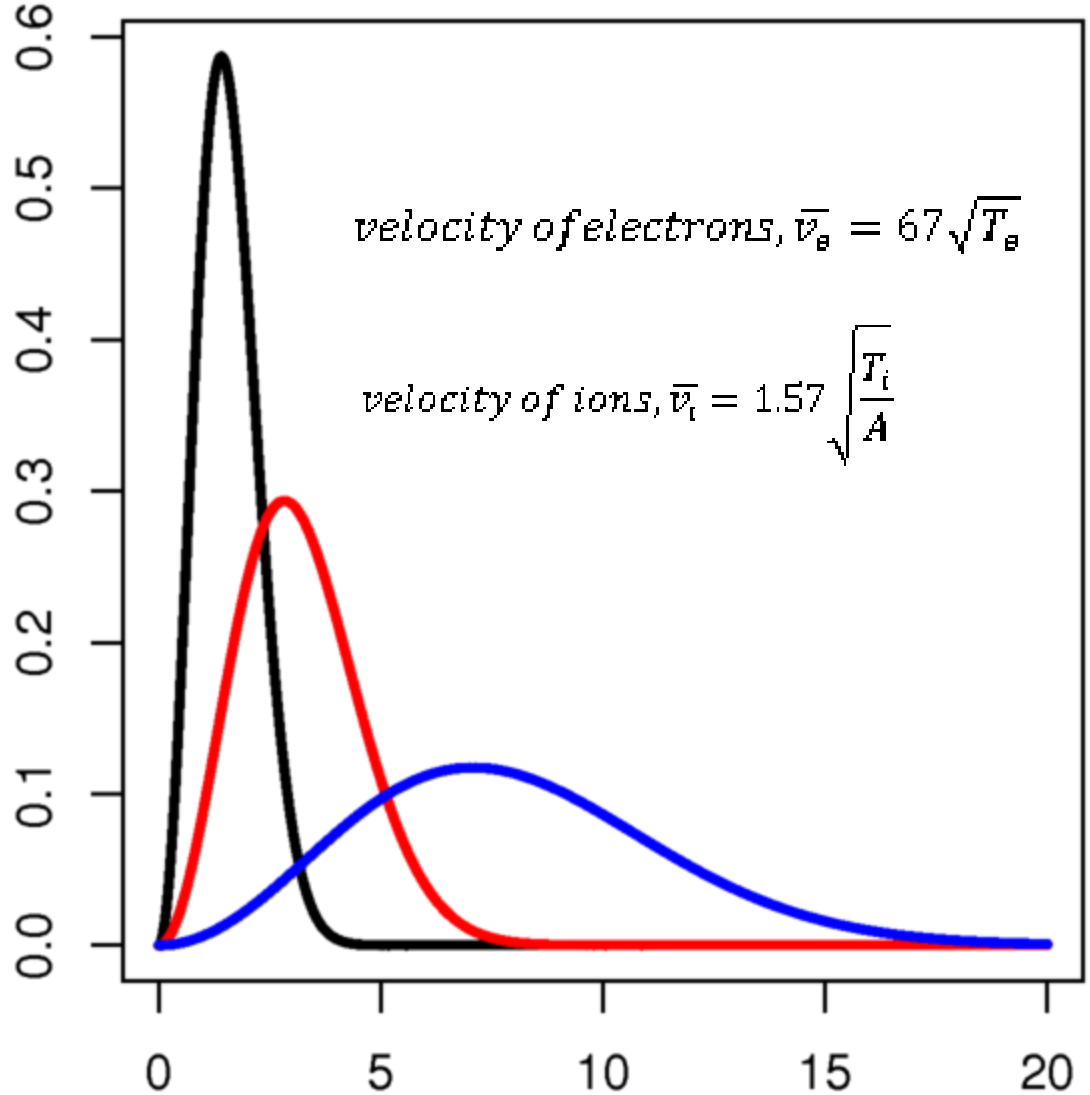
11600°K = 1 eV

Temperature Distribution

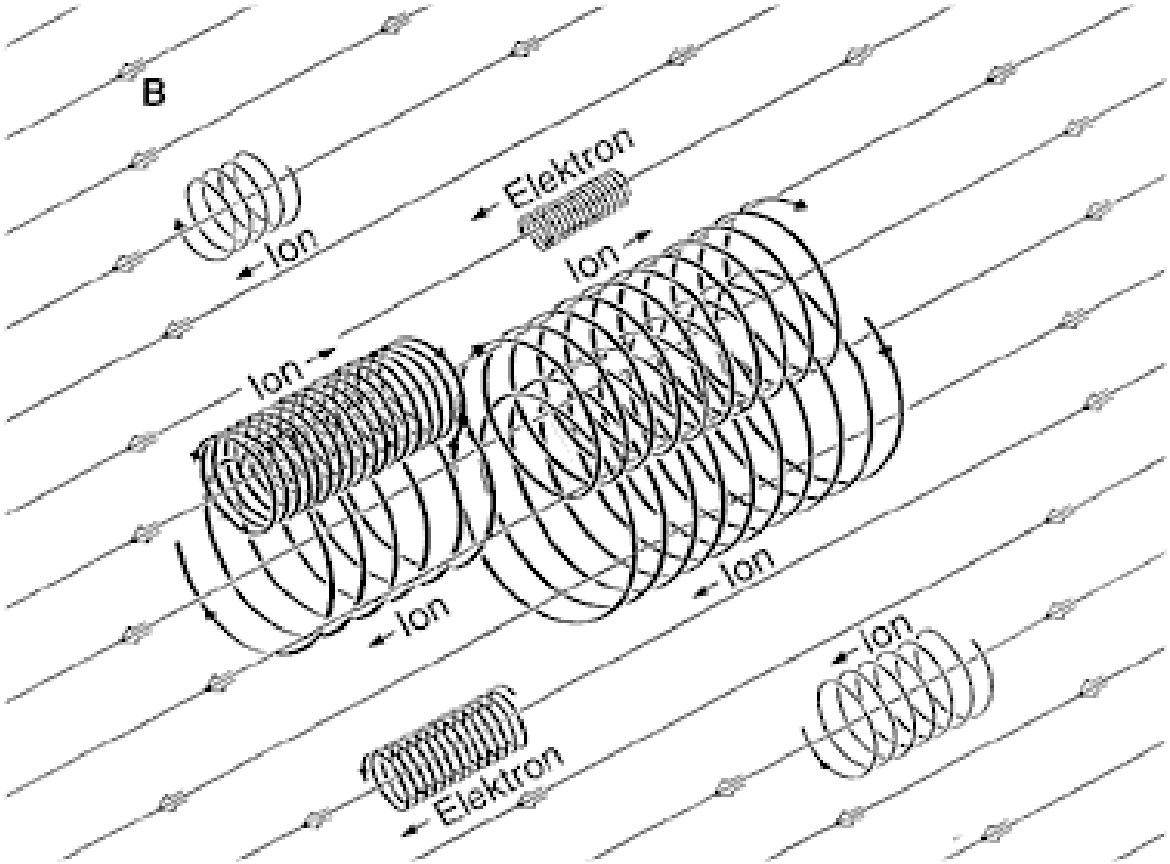
If thermalised velocity distributions should follow Maxwell Boltzmann statistics

However, in magnetic fields:

$$v_x \neq v_y \neq v_z$$

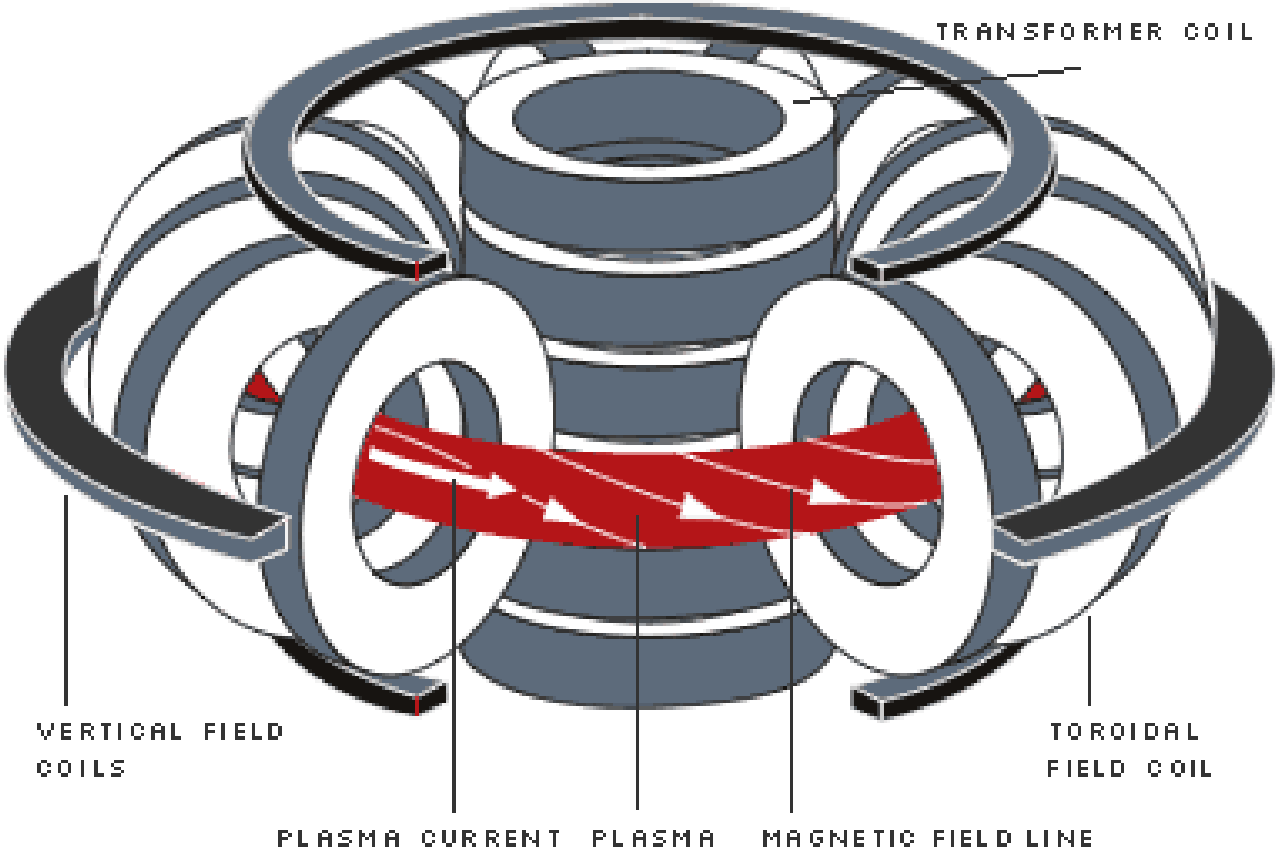


Magnetic Confinement

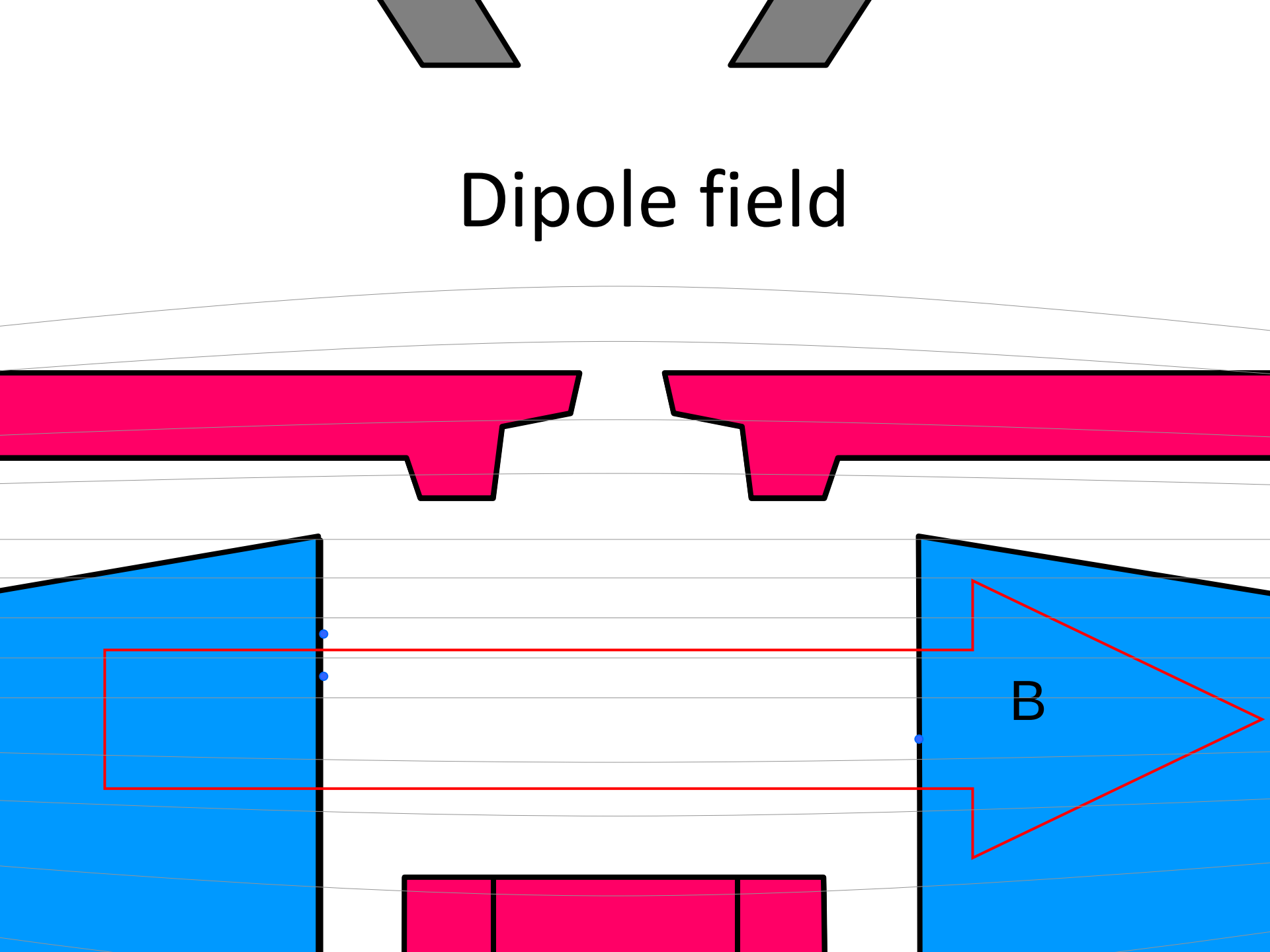


Particles spiral along magnetic field lines

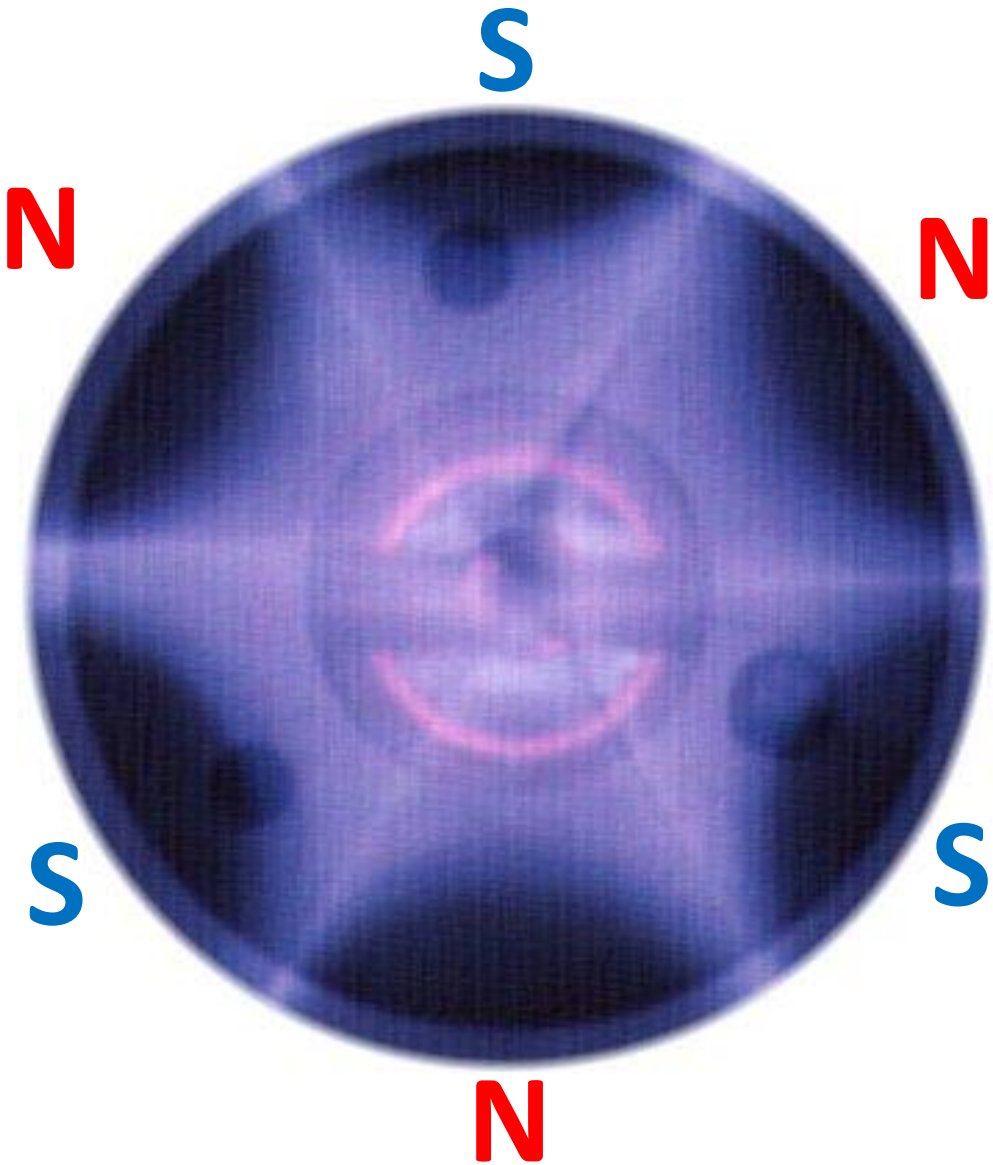
Solenoid field



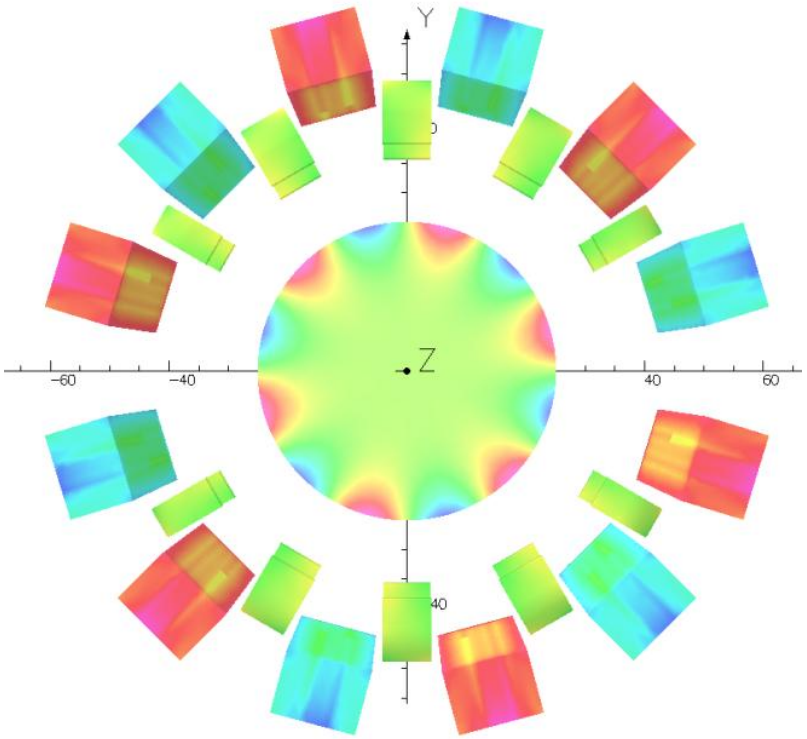
Dipole field

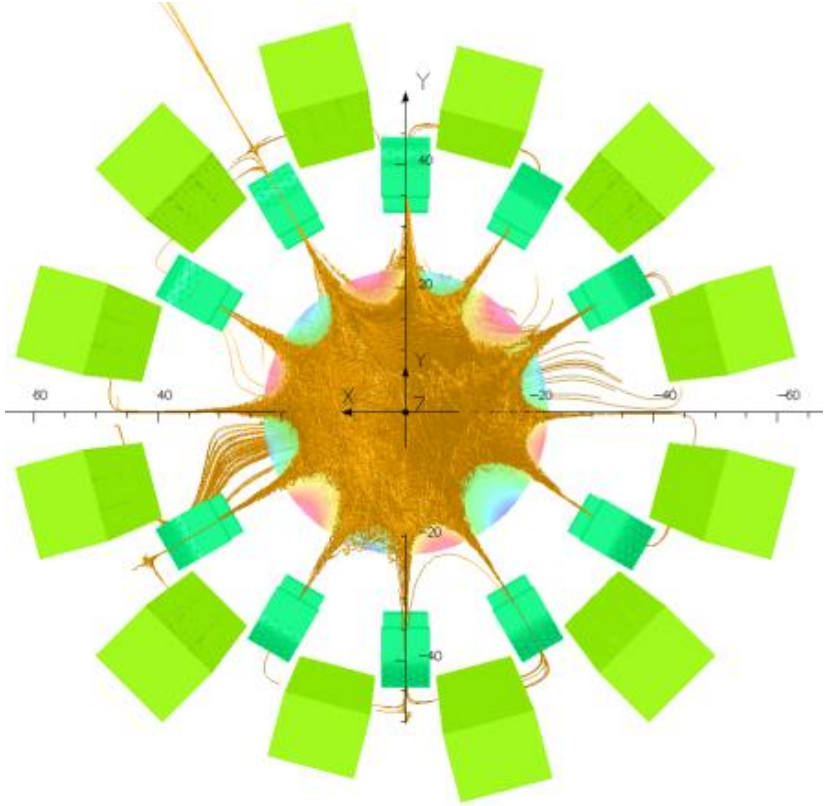


Hexapole



Multicusp Confinement



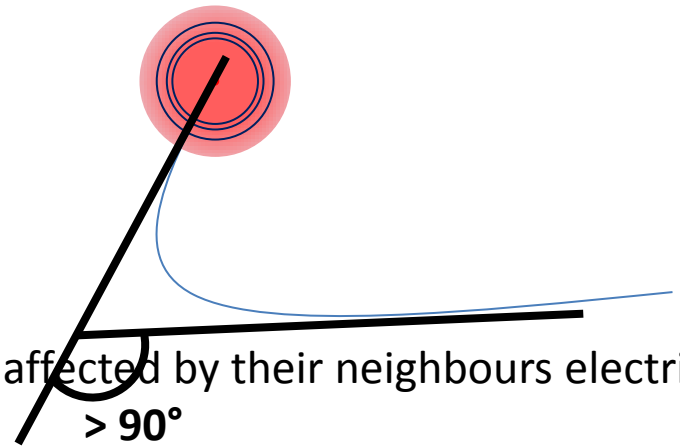


Collisions

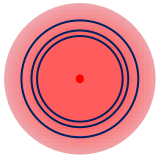
e-

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



e-

Relaxation time = 90° deflection time

Percentage Ionisation

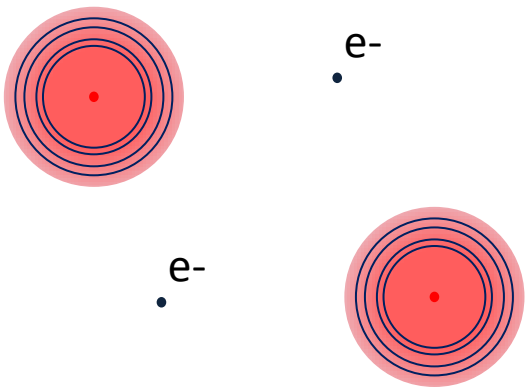
$$\frac{n_i}{n_i + n_n}$$

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

Quasi Neutrality

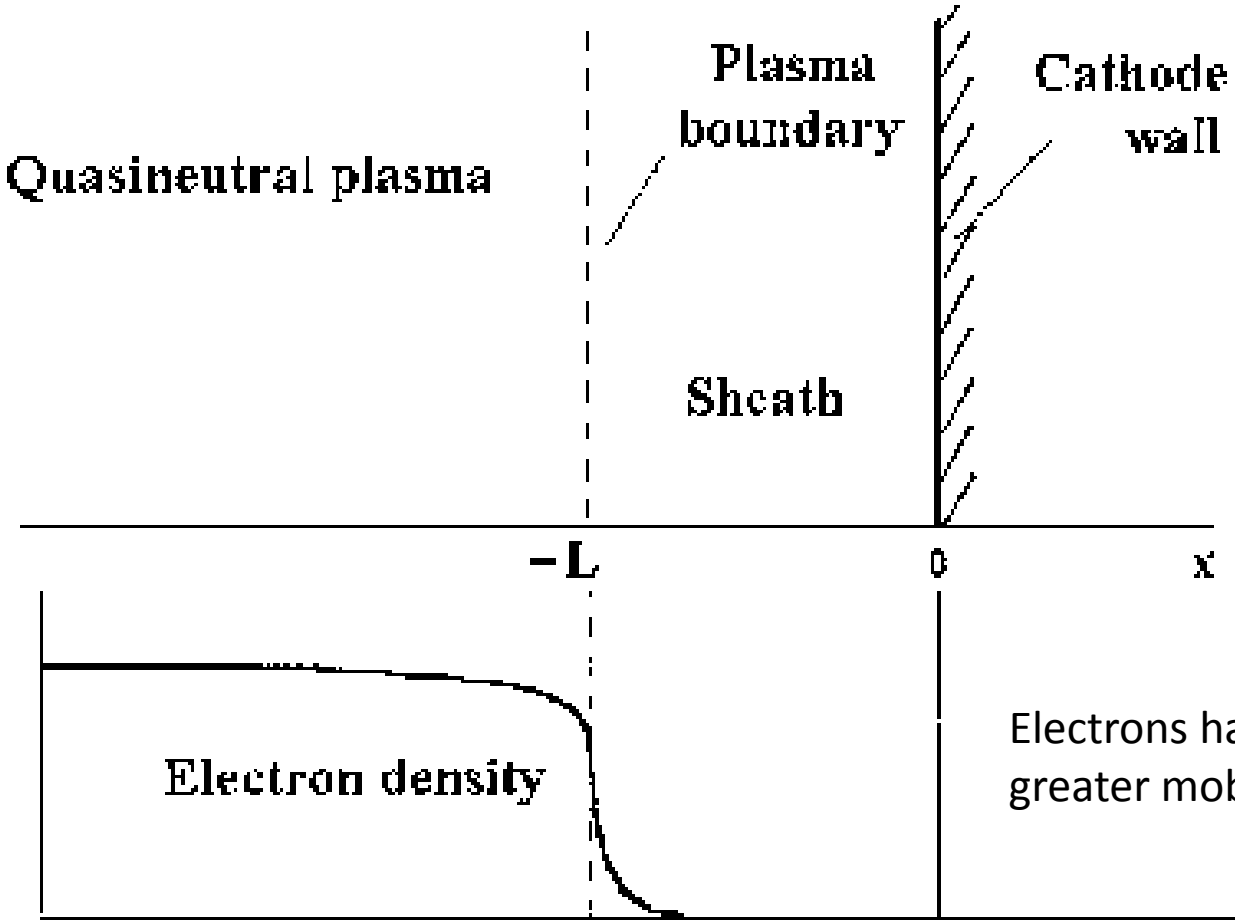
$$\sum q_i \, n_i = n_e$$

Debye Length



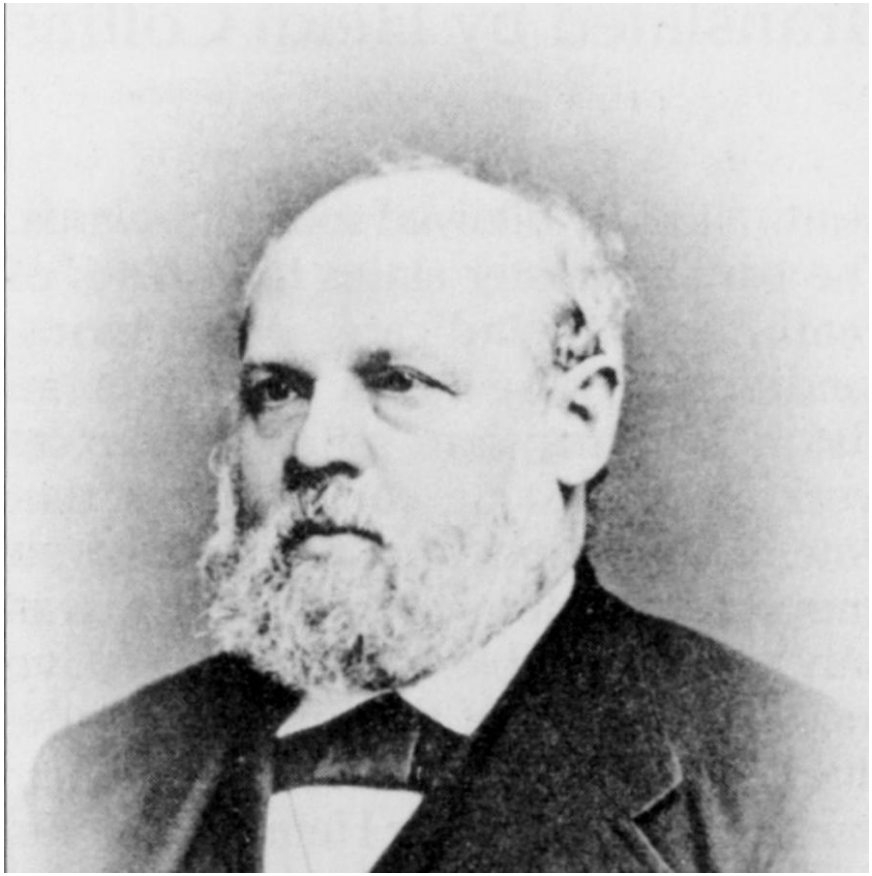
$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e q_e{}^2}}$$

Plasma Sheath



Electrons have a greater mobility

Plasma Pioneers



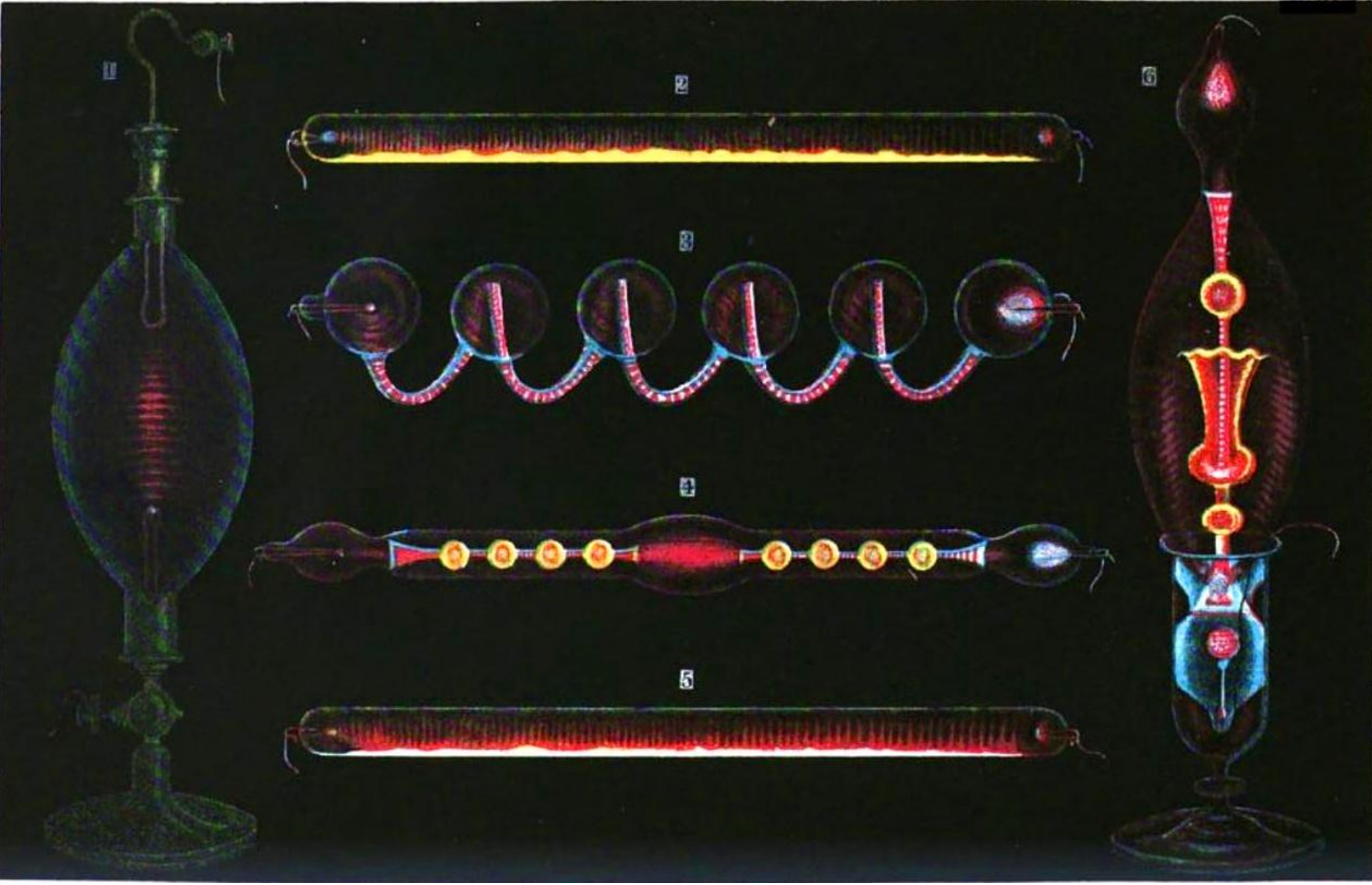
Heinrich Geißler

Julius Plücker

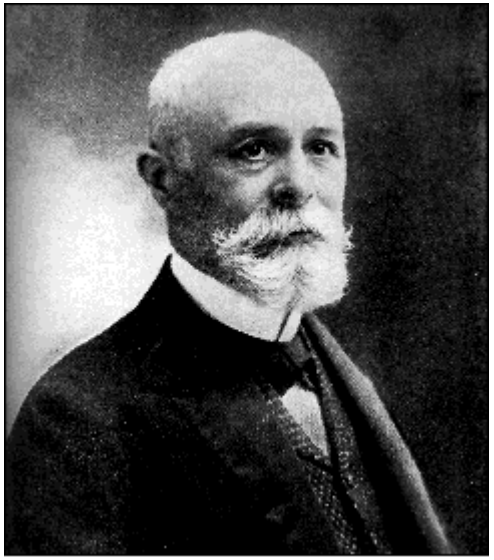
Gas discharge tube and
mercury displacement pump
just less than 1 mBar

Mid 1850's University of Bonn

magnetism could move the glow discharge

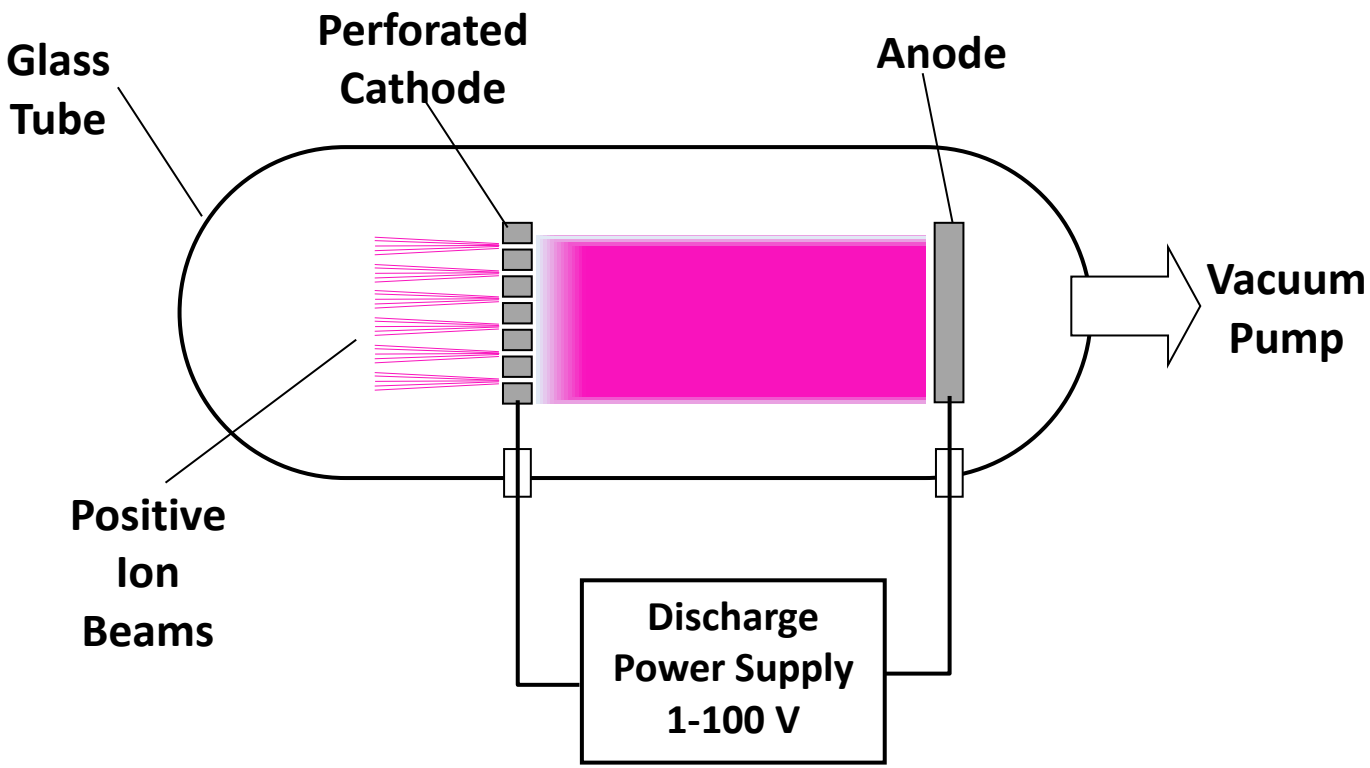


Drawing of Geissler tubes from 1860’s French physics book

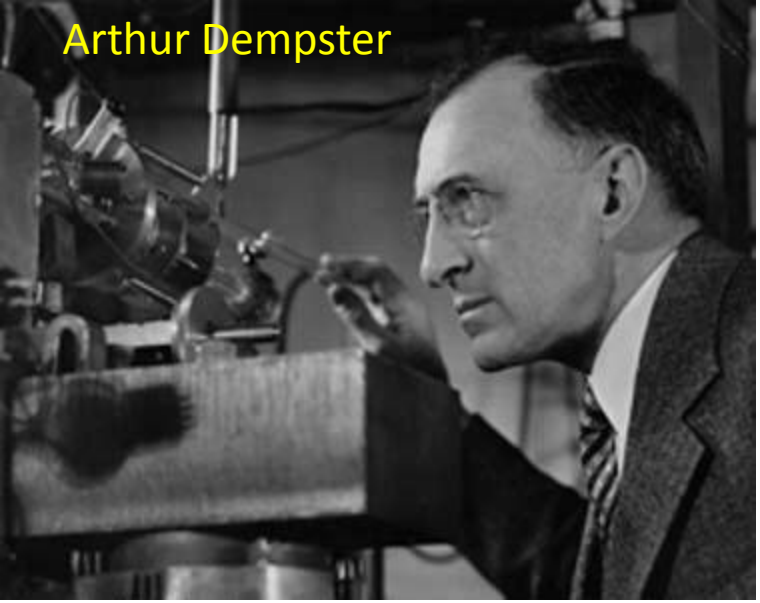


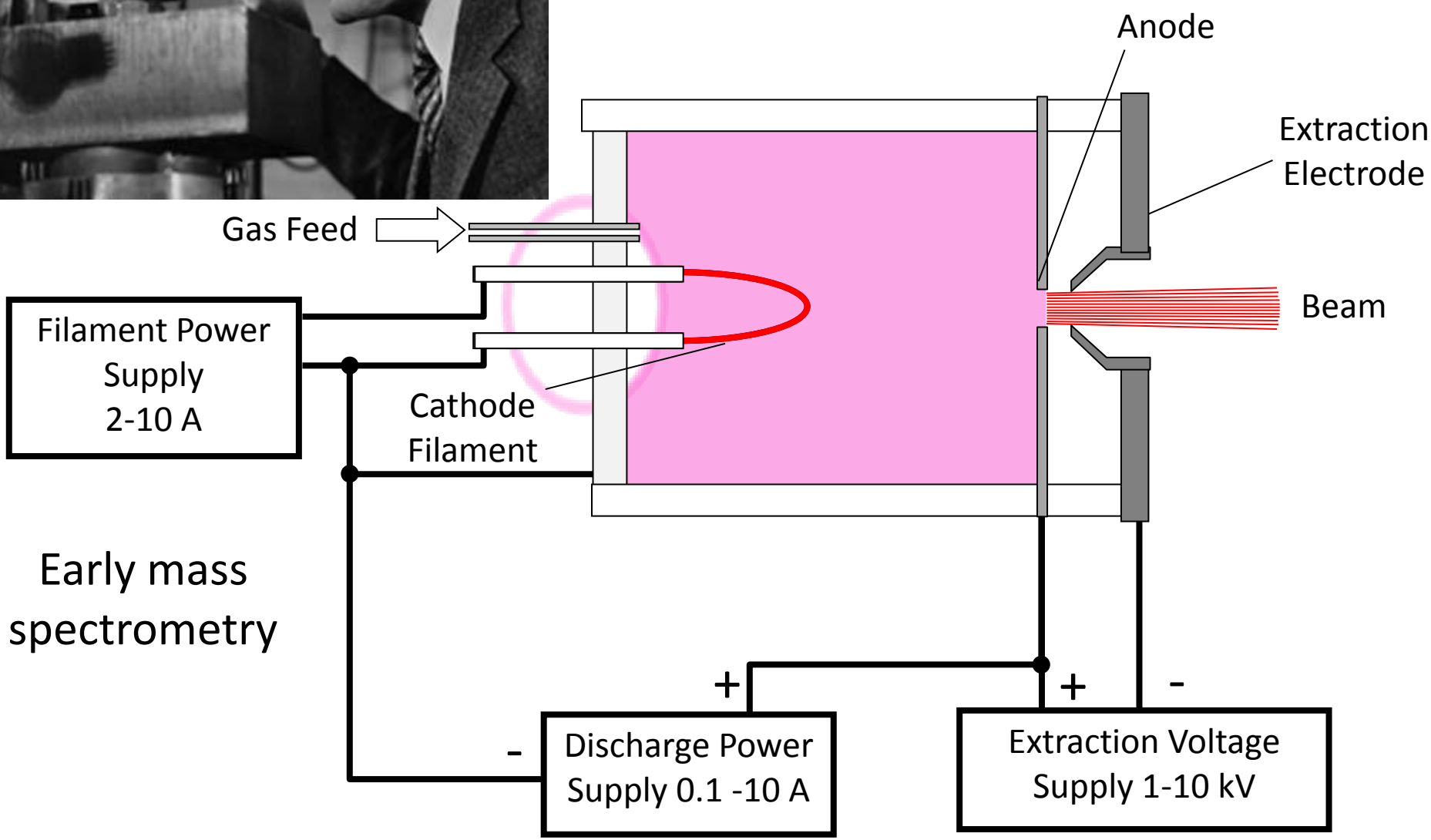
Canal Ray Source

In 1886 Eugen Goldstein discovered canal rays



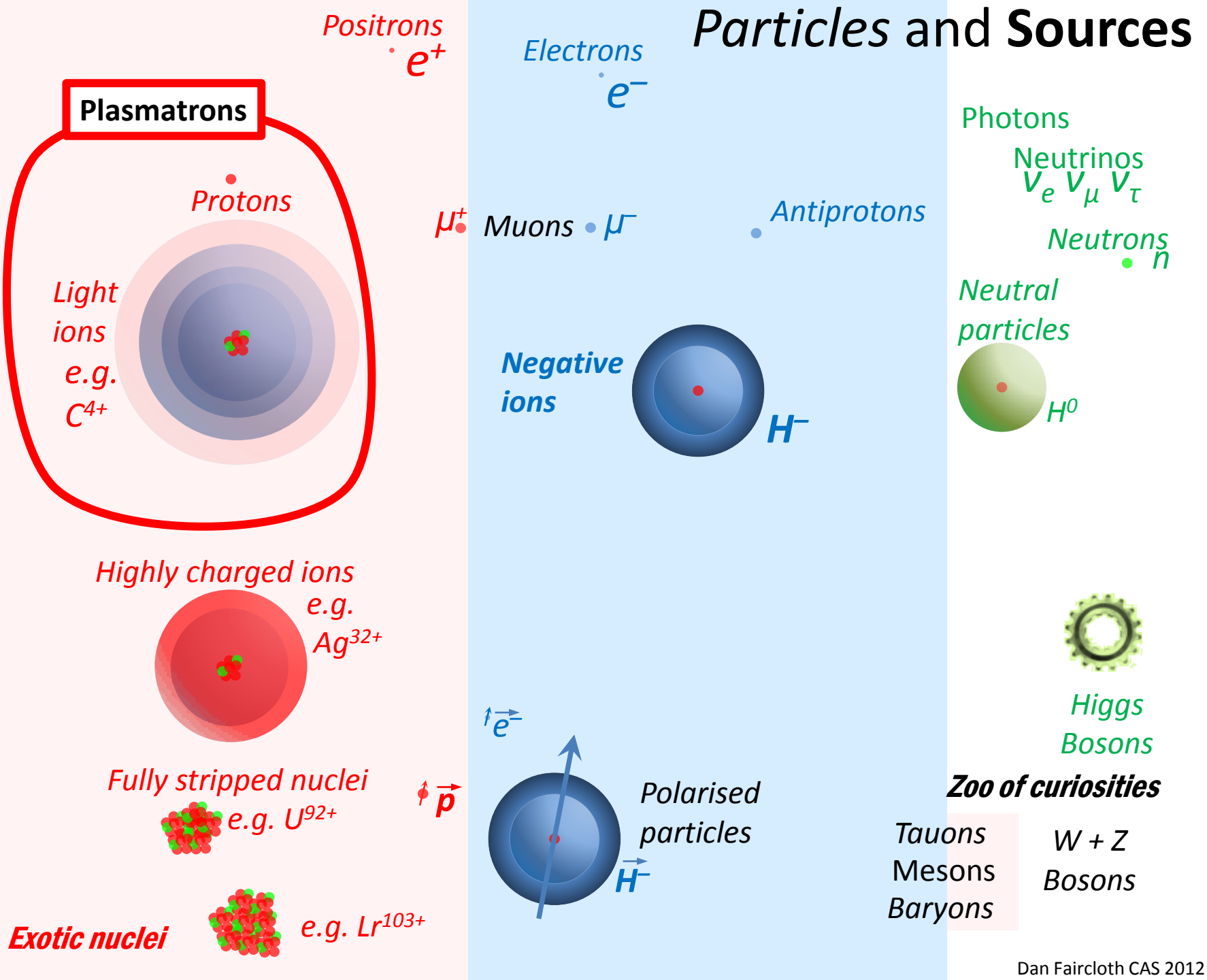
Electron Bombardment Source (1916)



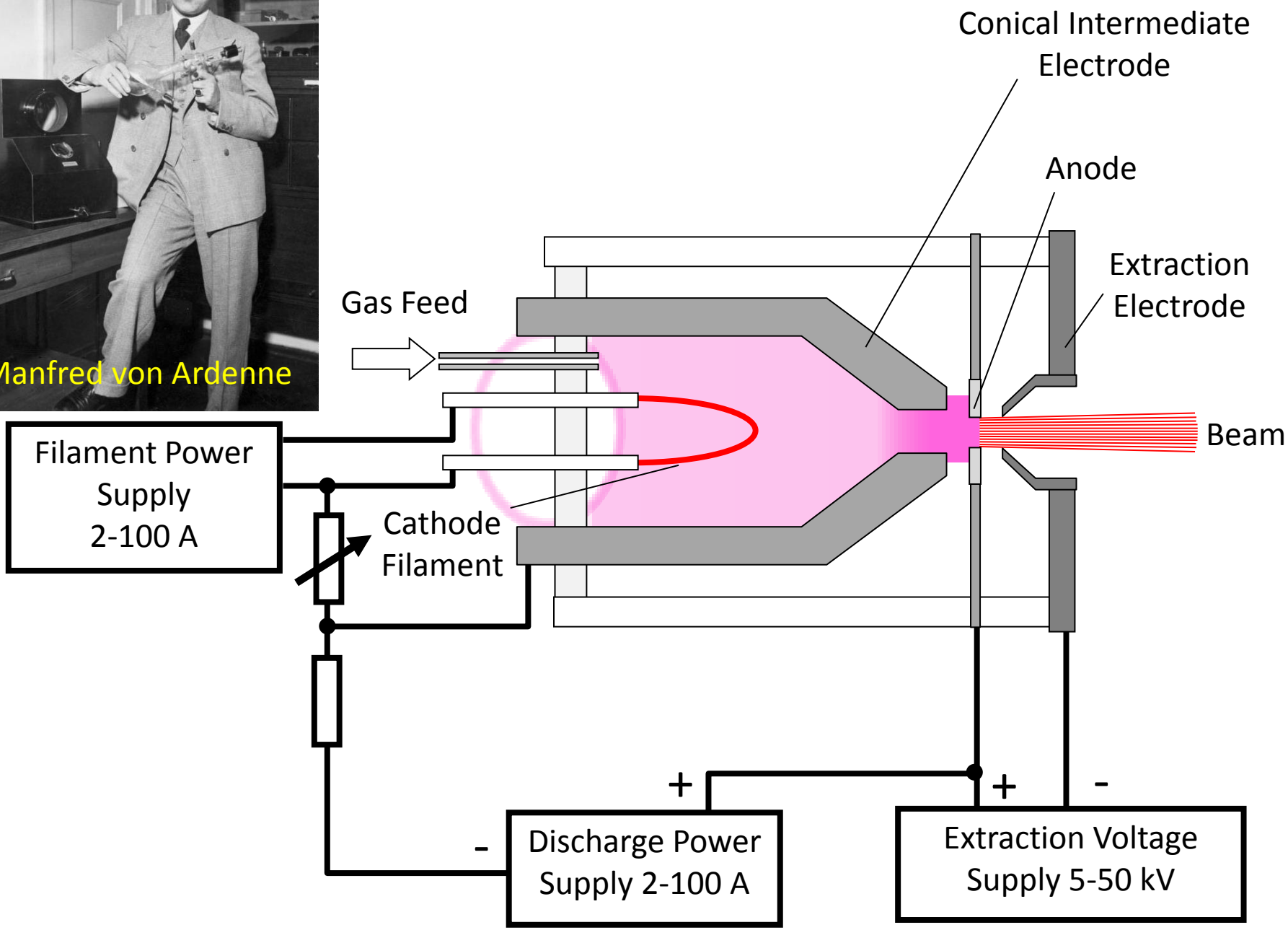


Early mass spectrometry

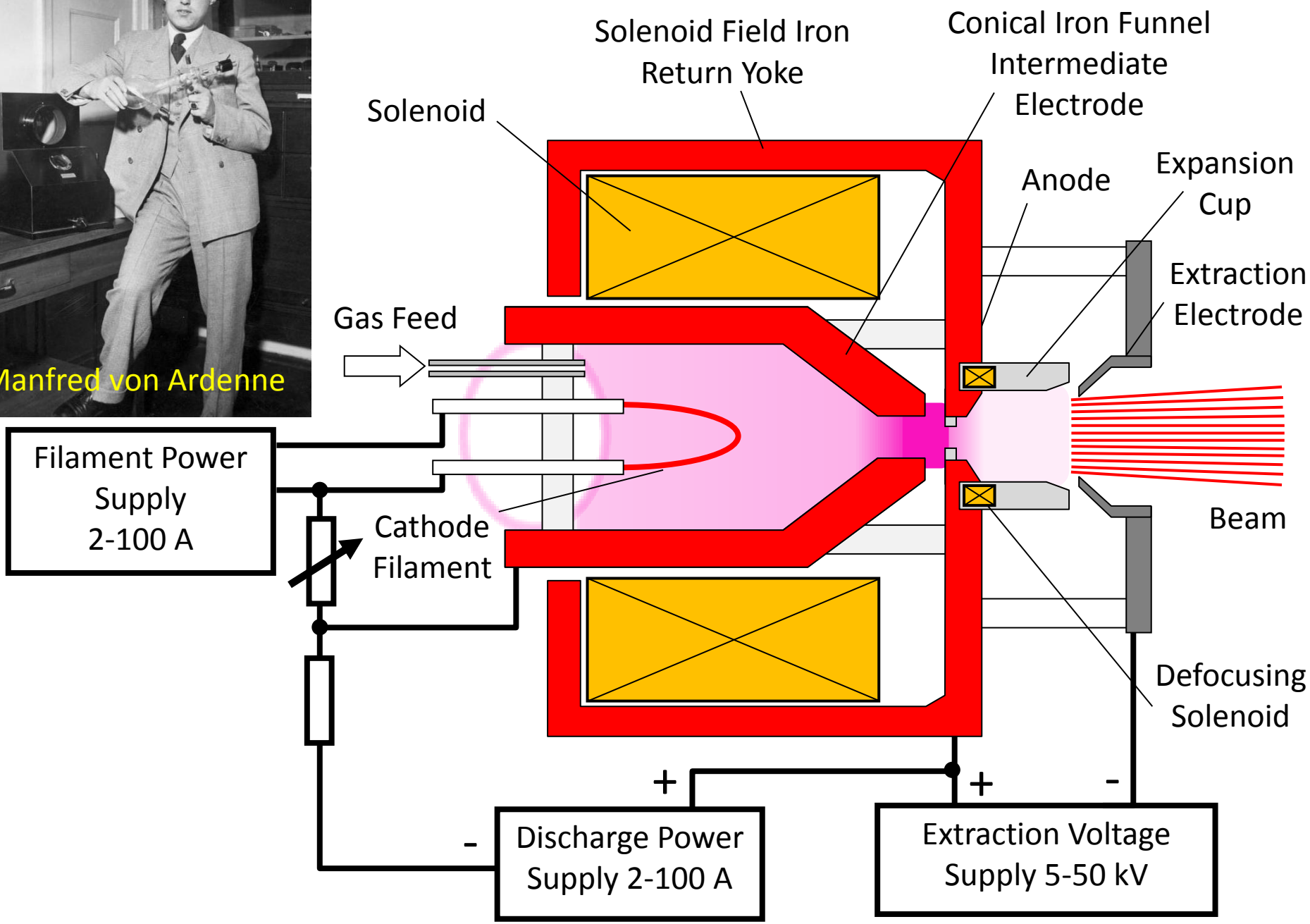
Particles and **Sources**



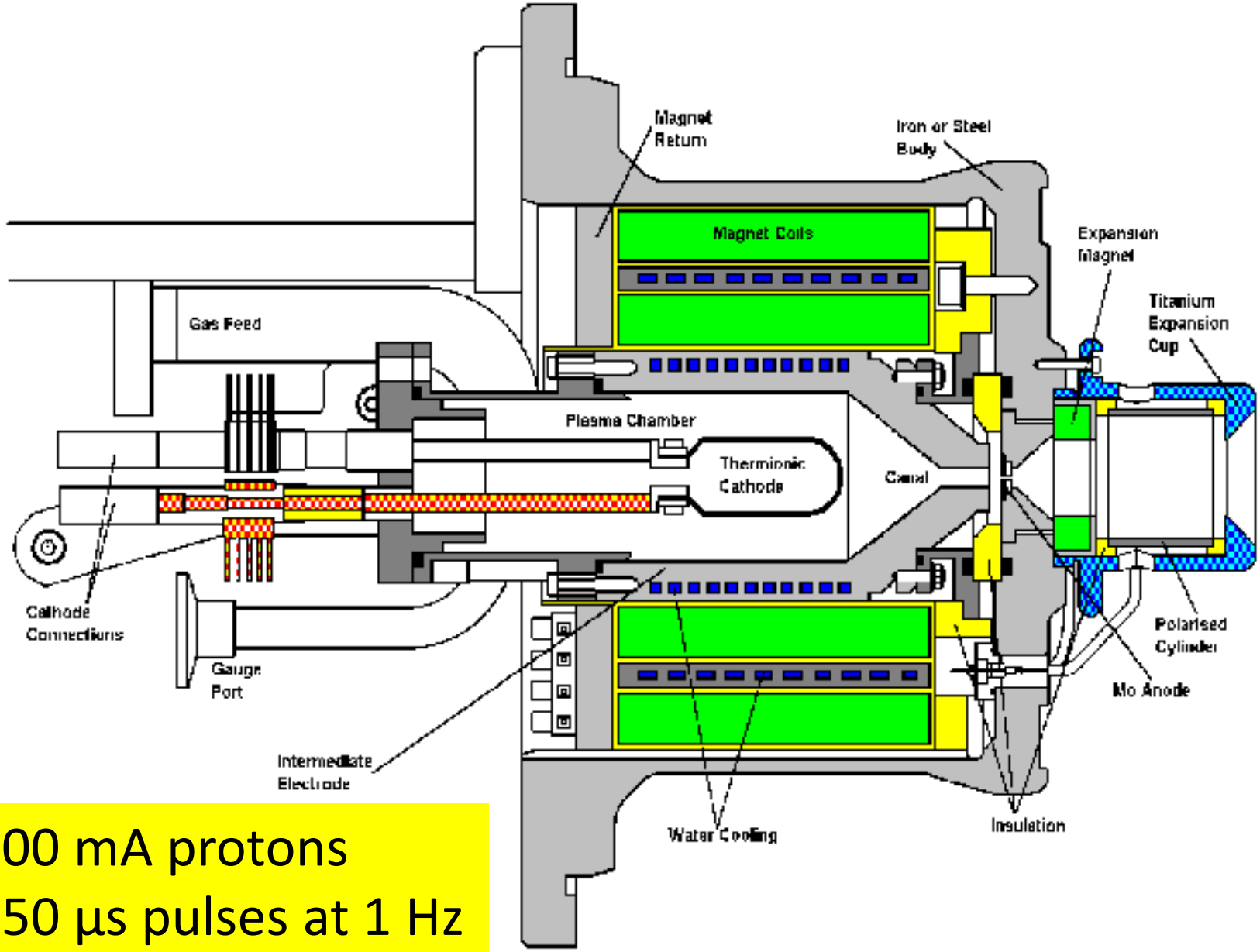
Plasmatron (late 1940s)



Duoplasmatron (1956)

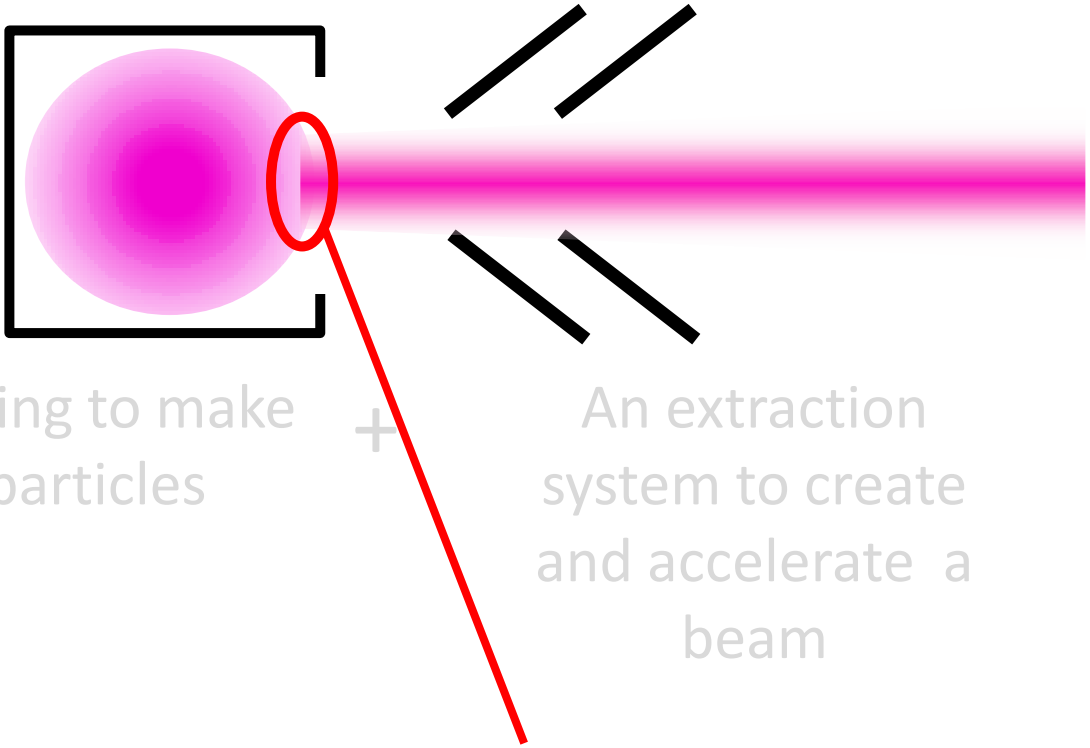


CERN Duoplasmatron



300 mA protons
150 µs pulses at 1 Hz

Particle sources/guns consist of:



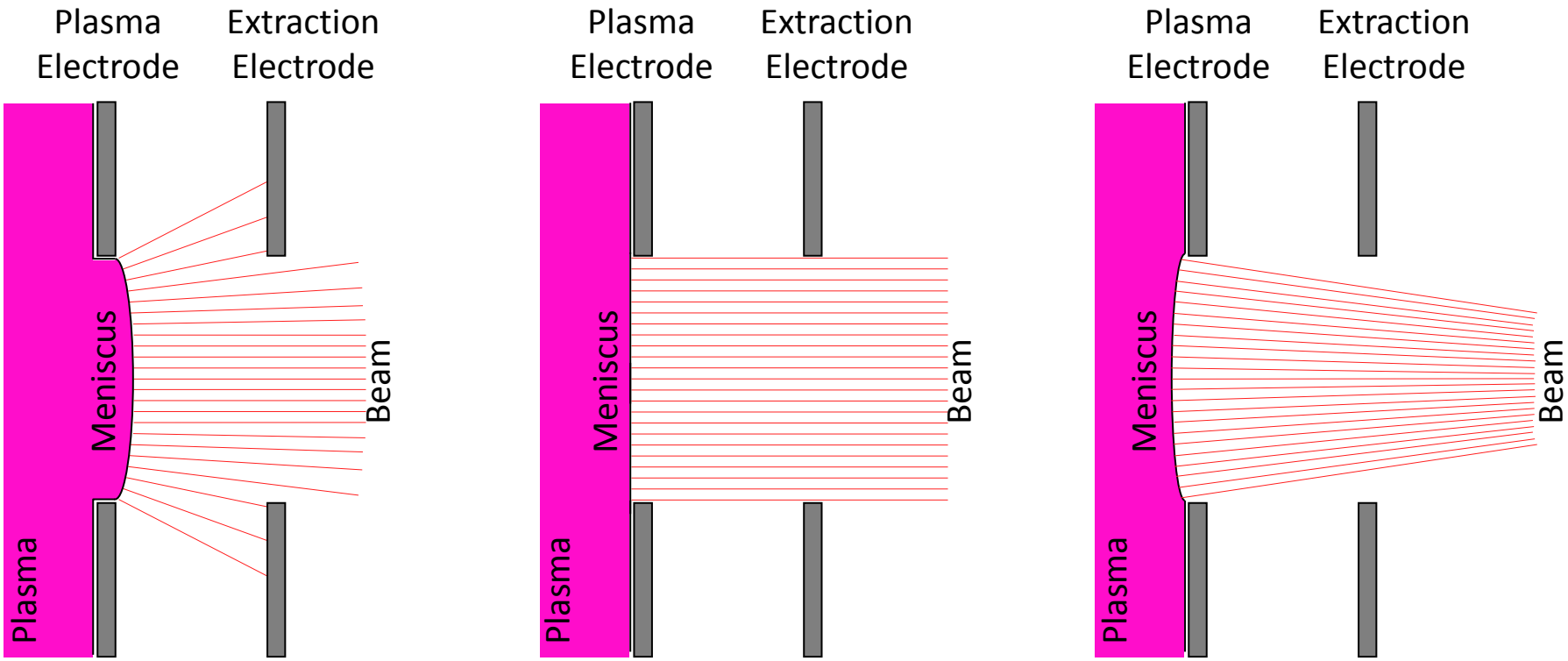
Something to make the particles

+

An extraction system to create and accelerate a beam

The emission surface is critical to the quality of the beam

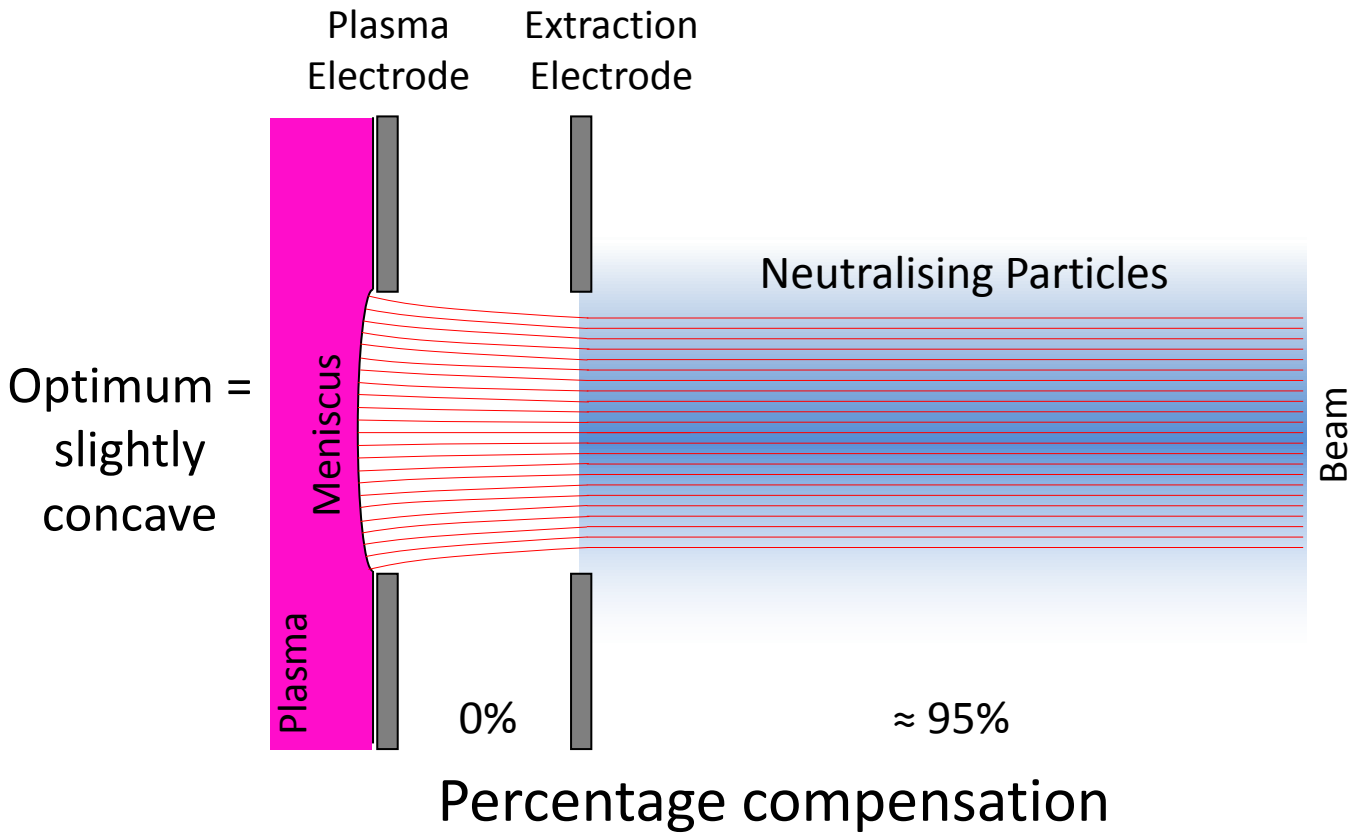
Plasma Mencius



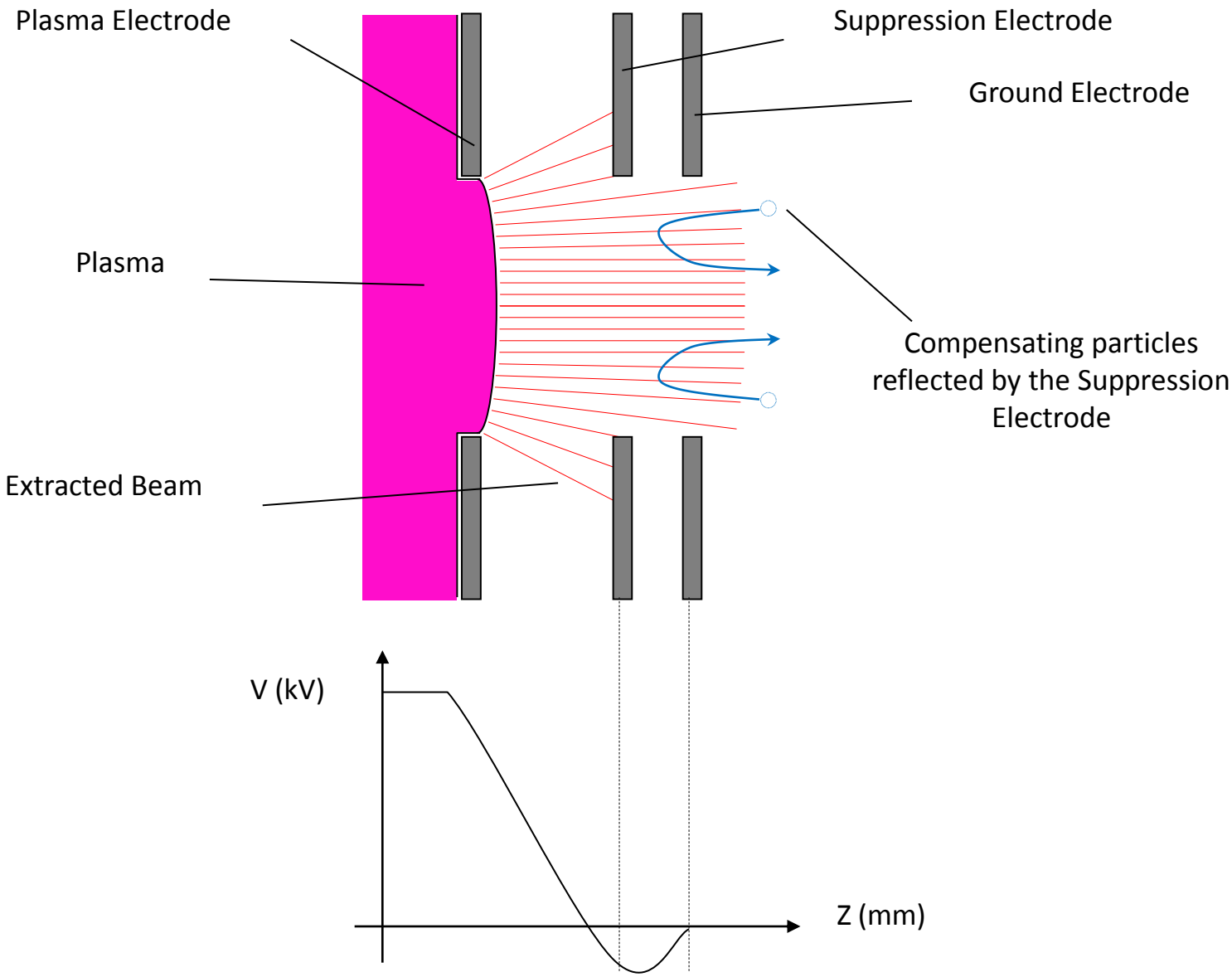
Convex Flat Concave

Not including space charge effects

Space Charge



Suppressor Electrode

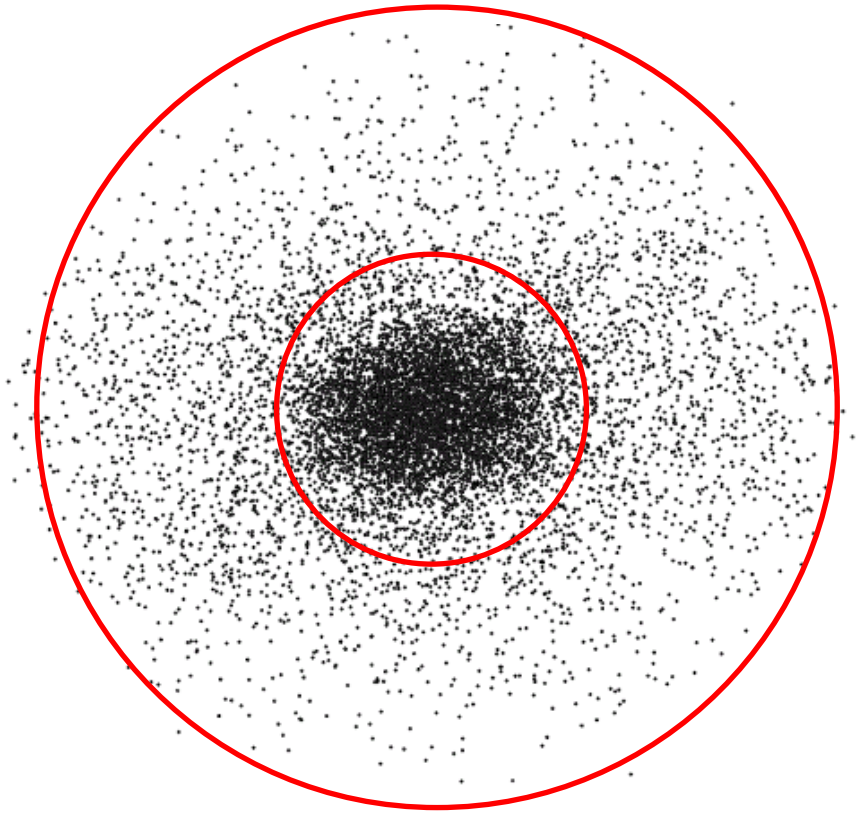


Emittance of Real Beams

Halo Effect

- Plasma boundary
- Fringe fields

How big is this beam?



95% emittance

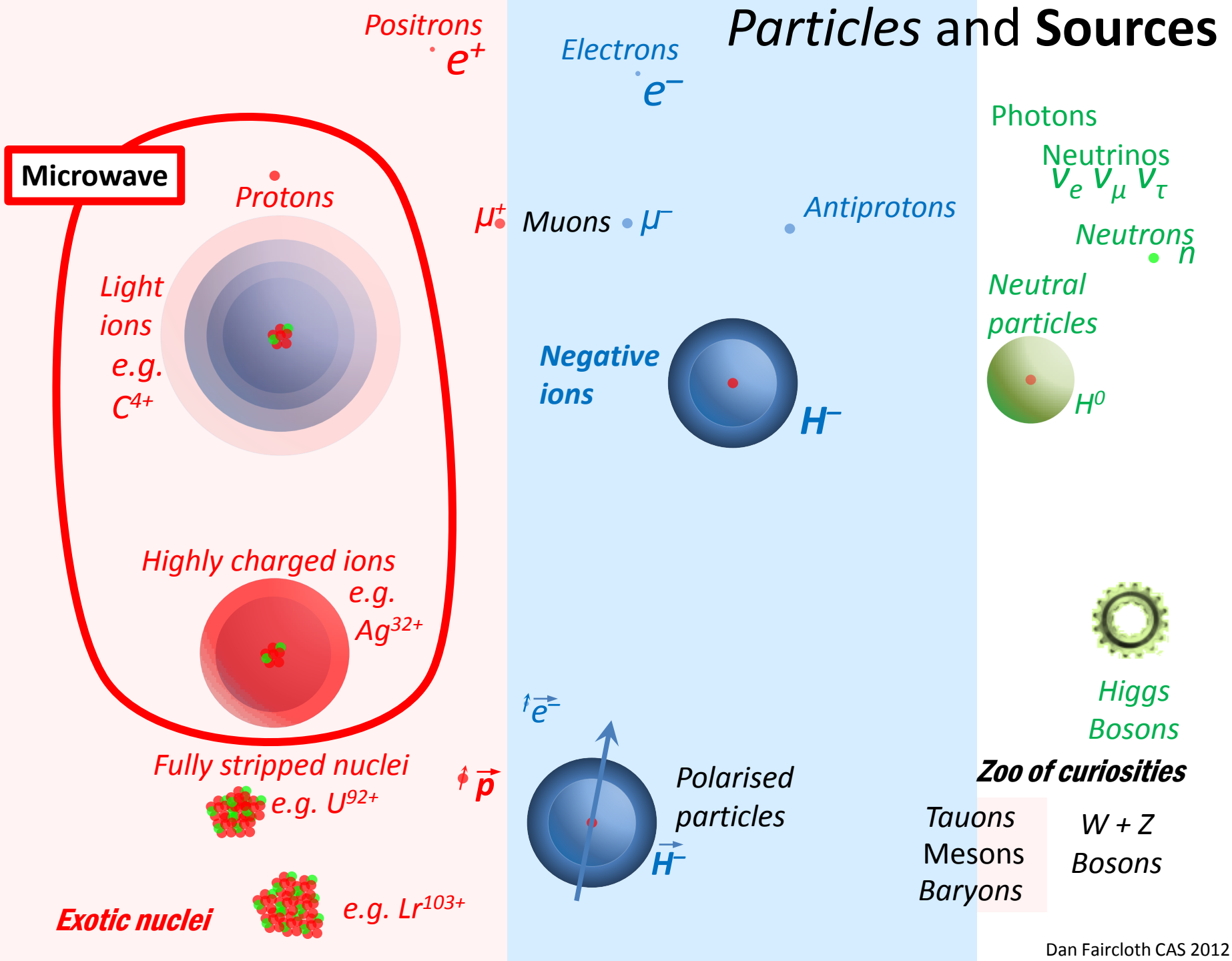
rms emittance

Brightness

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

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

Particles and **Sources**



Microwave Ion Sources

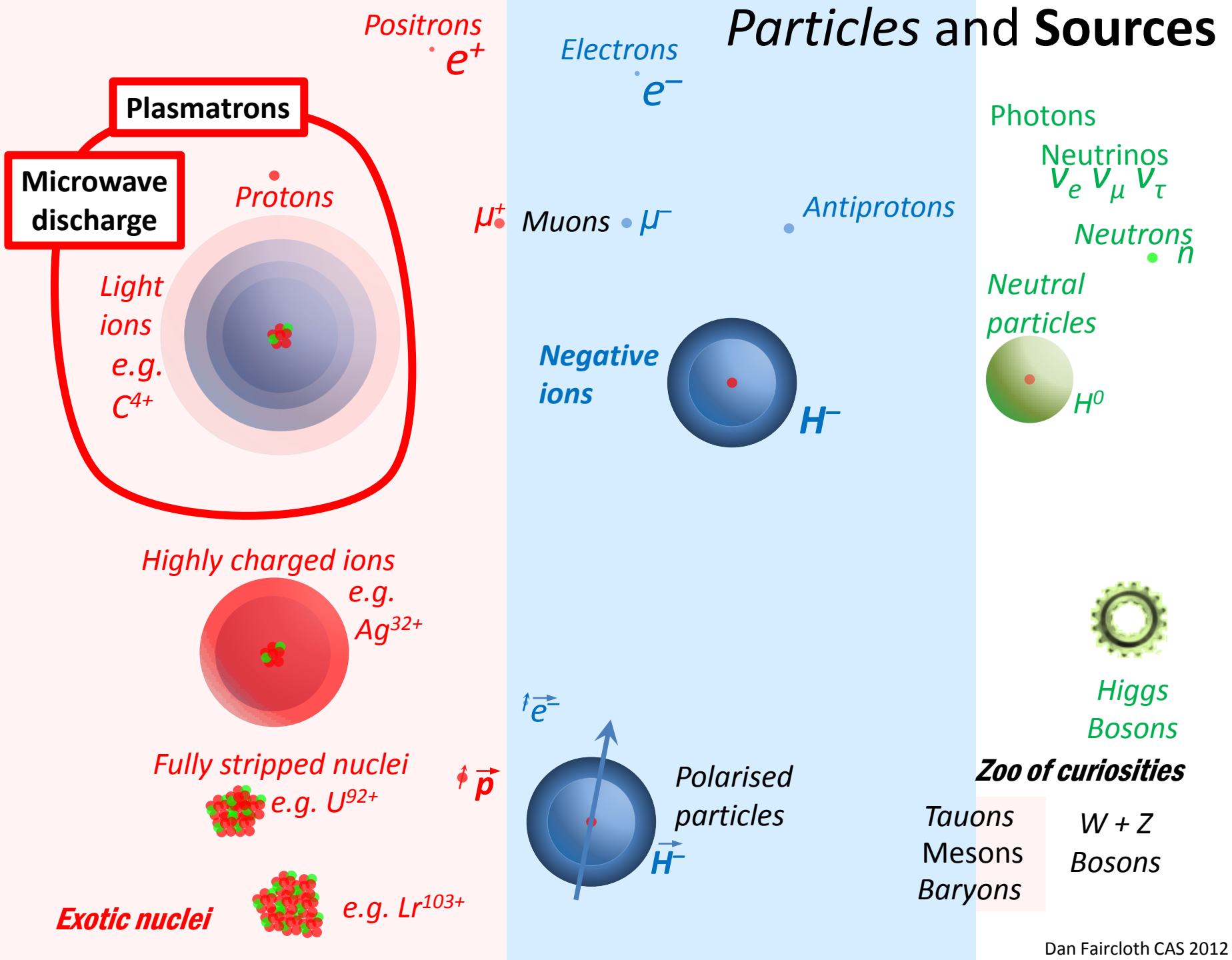
Off resonance

= Microwave discharge ion sources

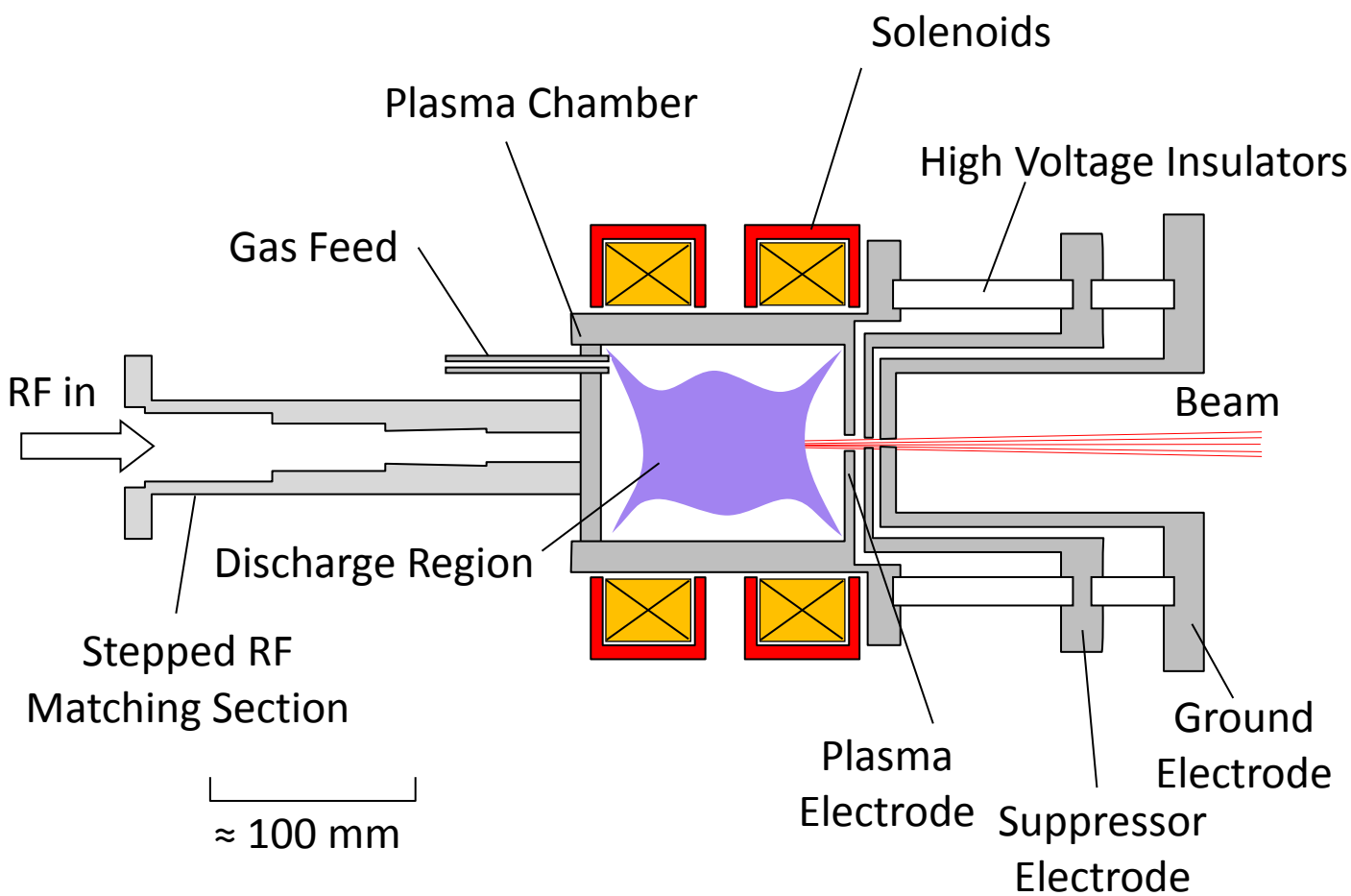
On resonance

= Electron Cyclotron Resonance (ECR) sources

Particles and **Sources**

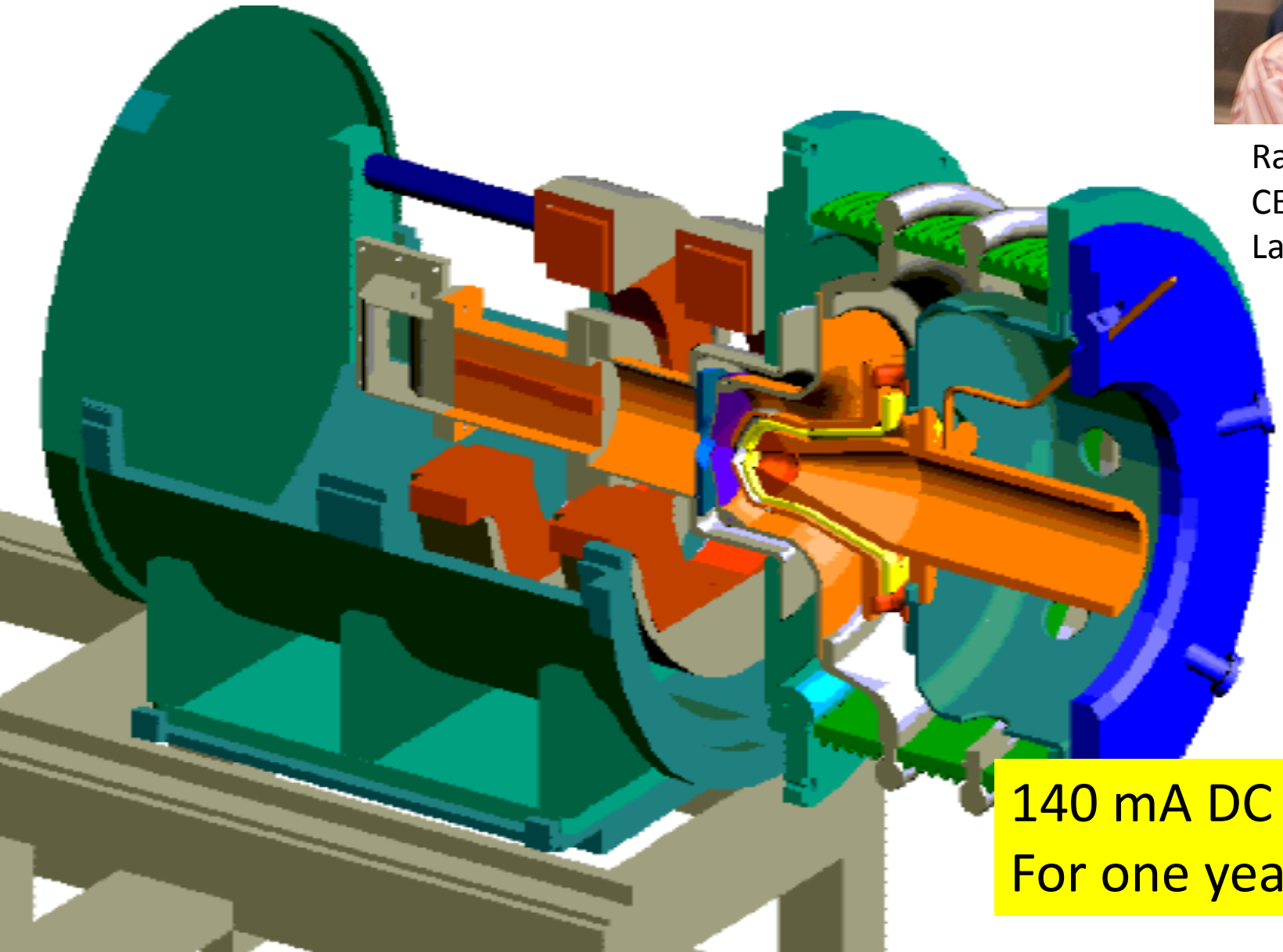


Microwave Discharge Ion Source



2.45 GHz commonly used

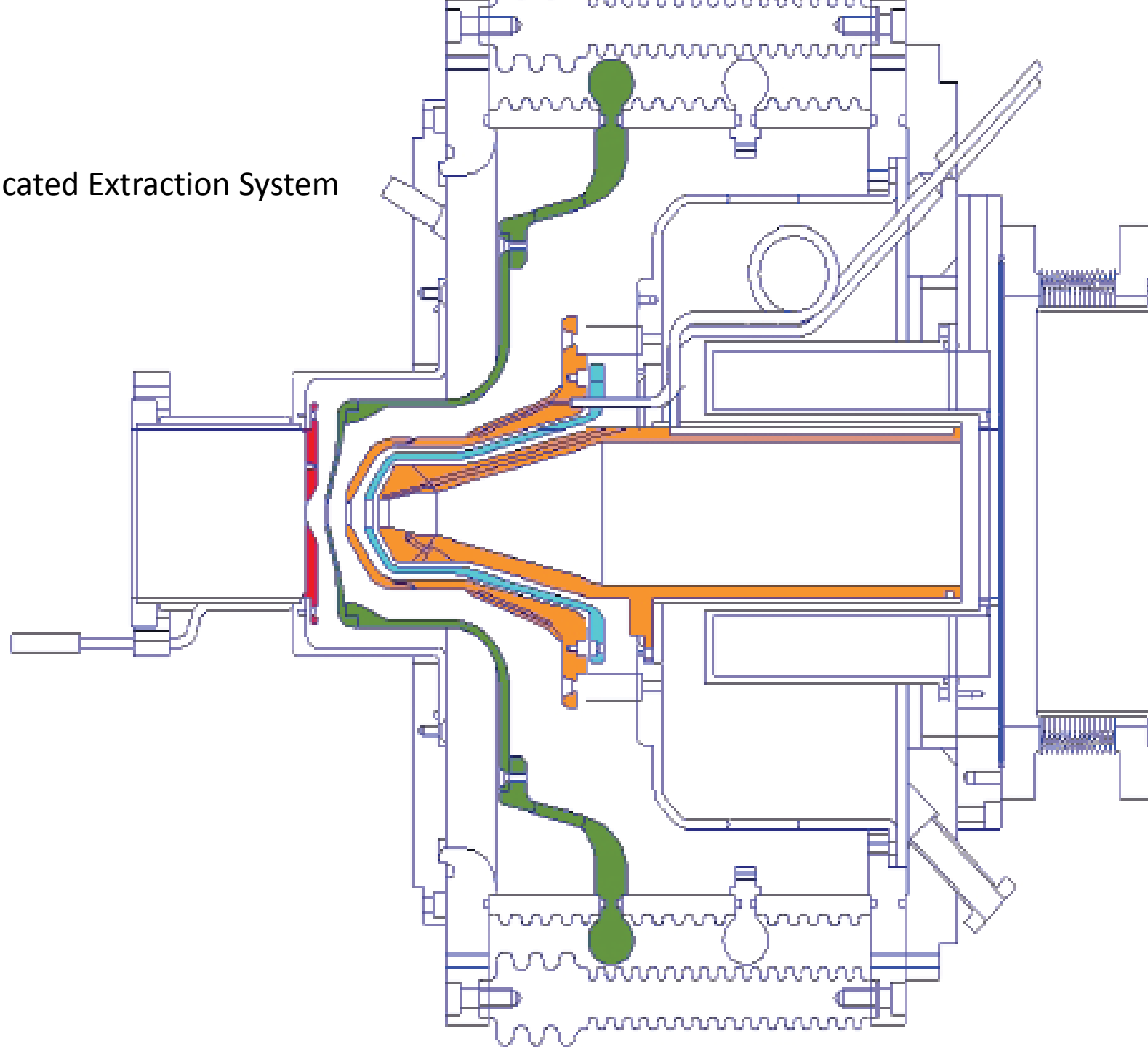
SILHI Microwave Source



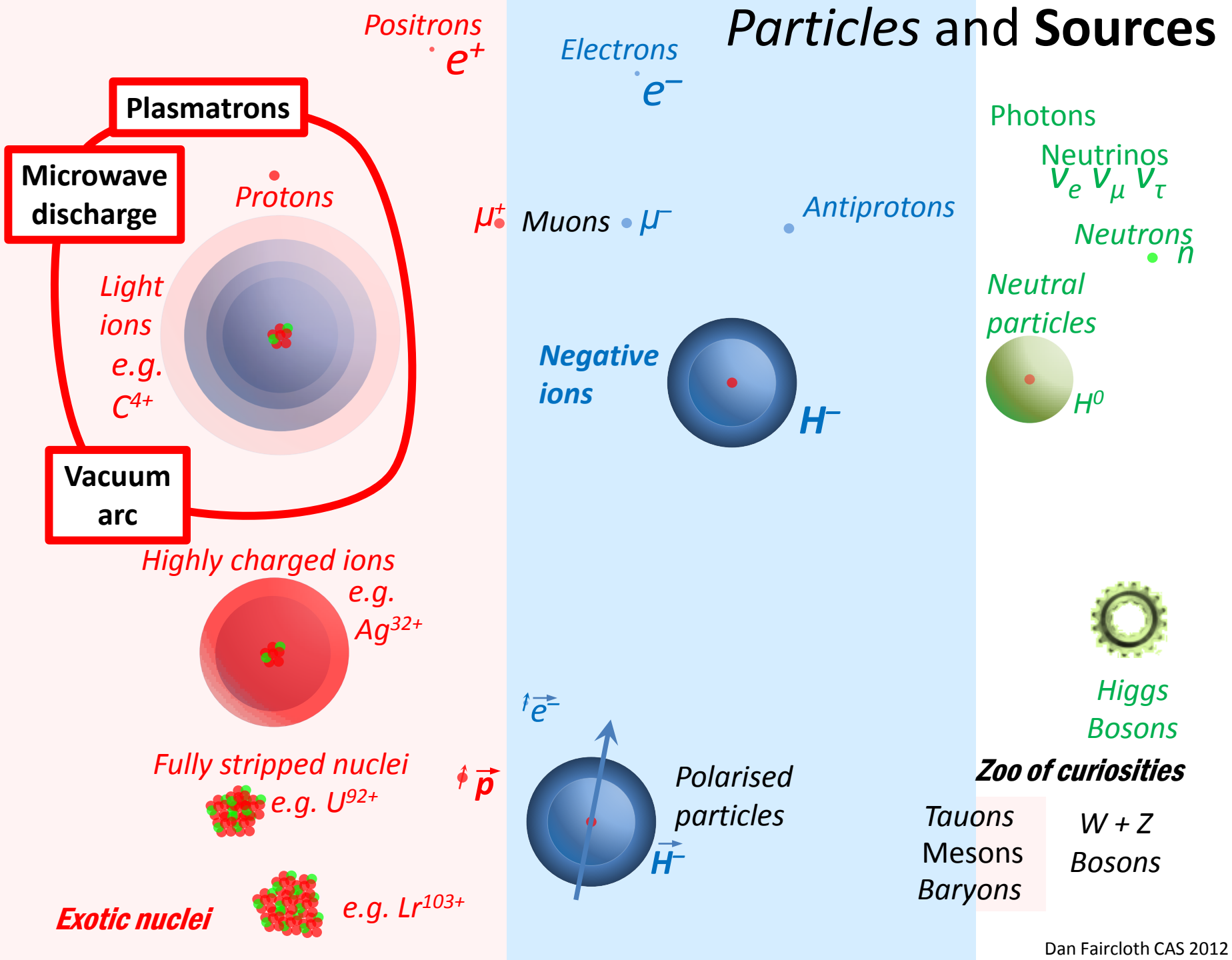
Rafael Gobin
CEA Saclay
Late 1990s

140 mA DC protons
For one year!

Sophisticated Extraction System

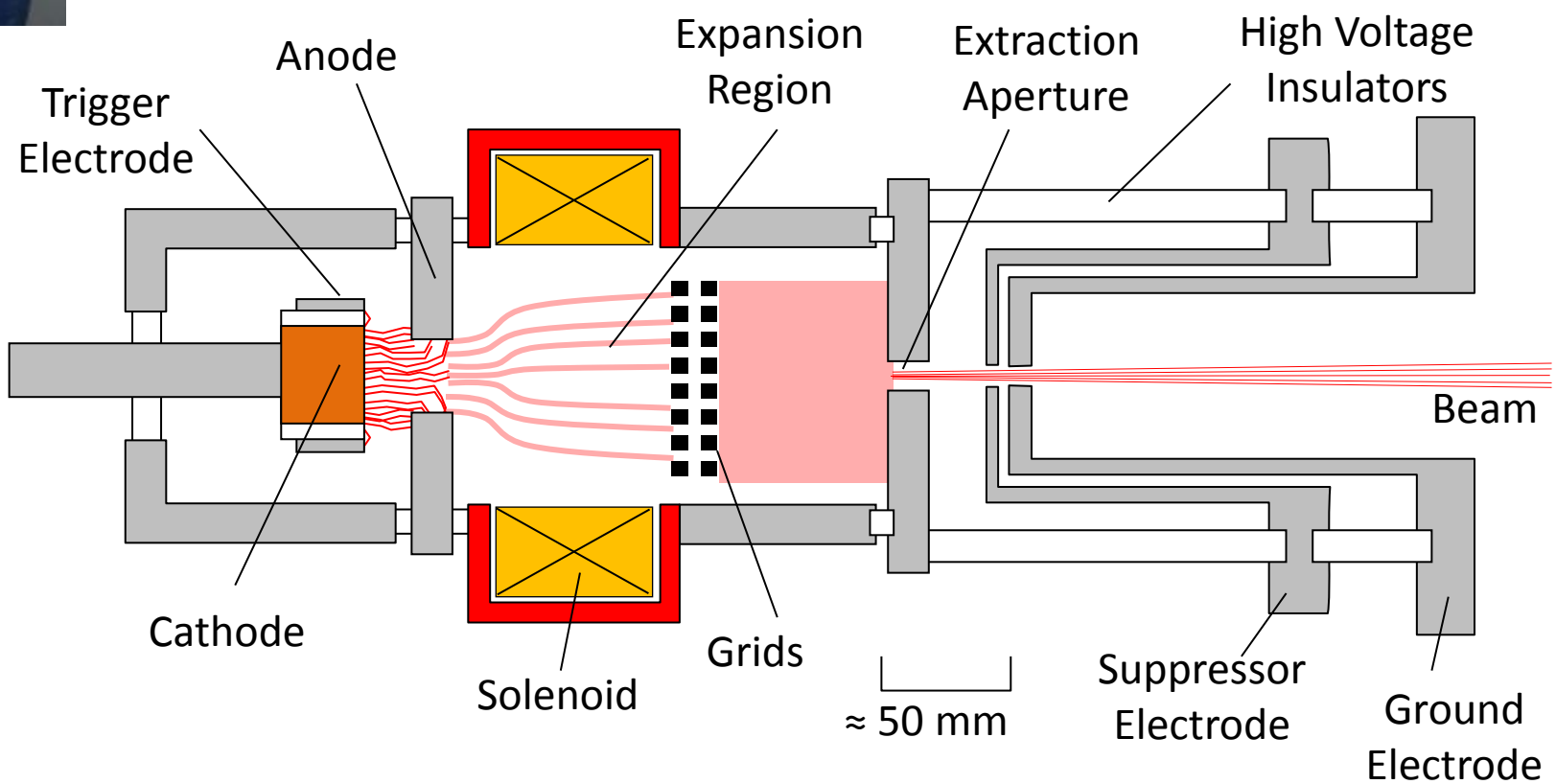


Particles and **Sources**



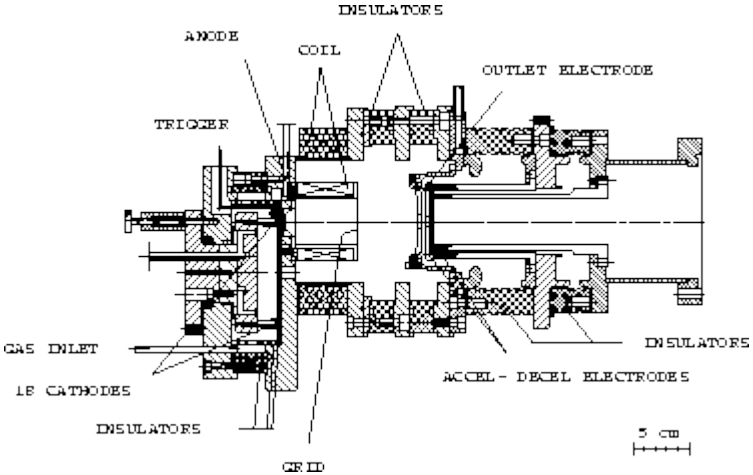
Vacuum Arc Ion Sources

1980s - Ian Brown and others



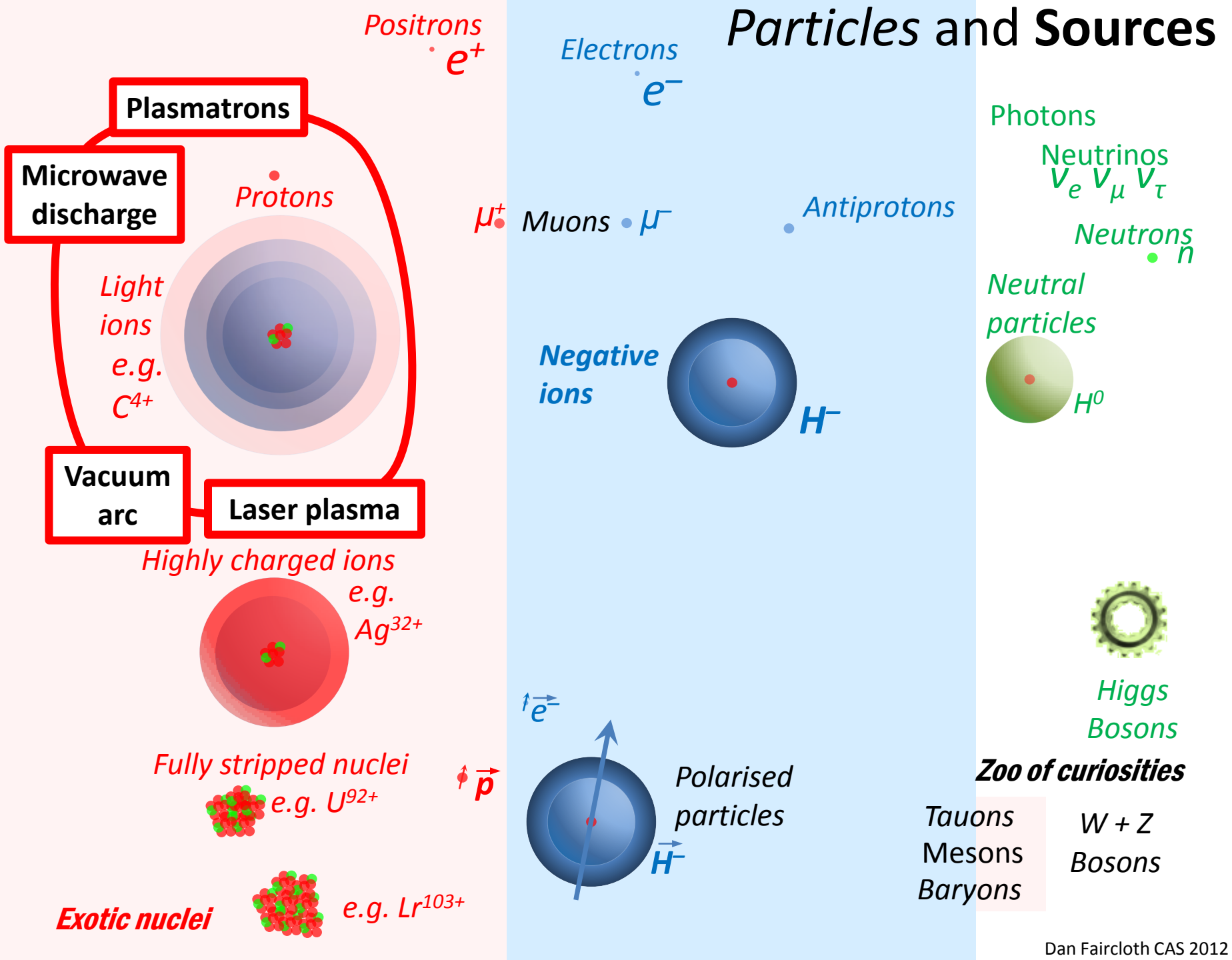
Lawrence Berkley Lab MEVVA

GSI MEVVA

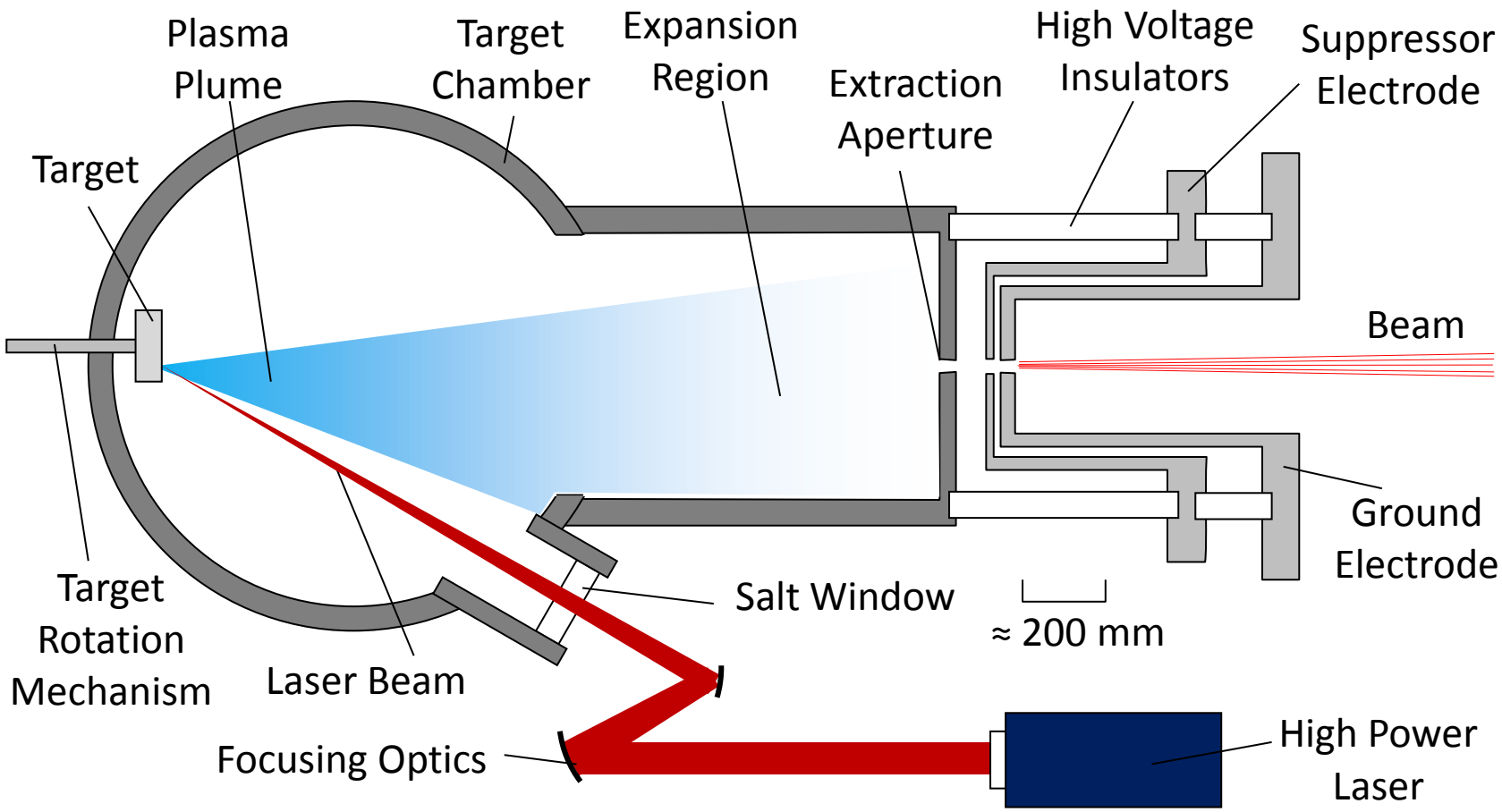


15 mA of U^{4+} ions

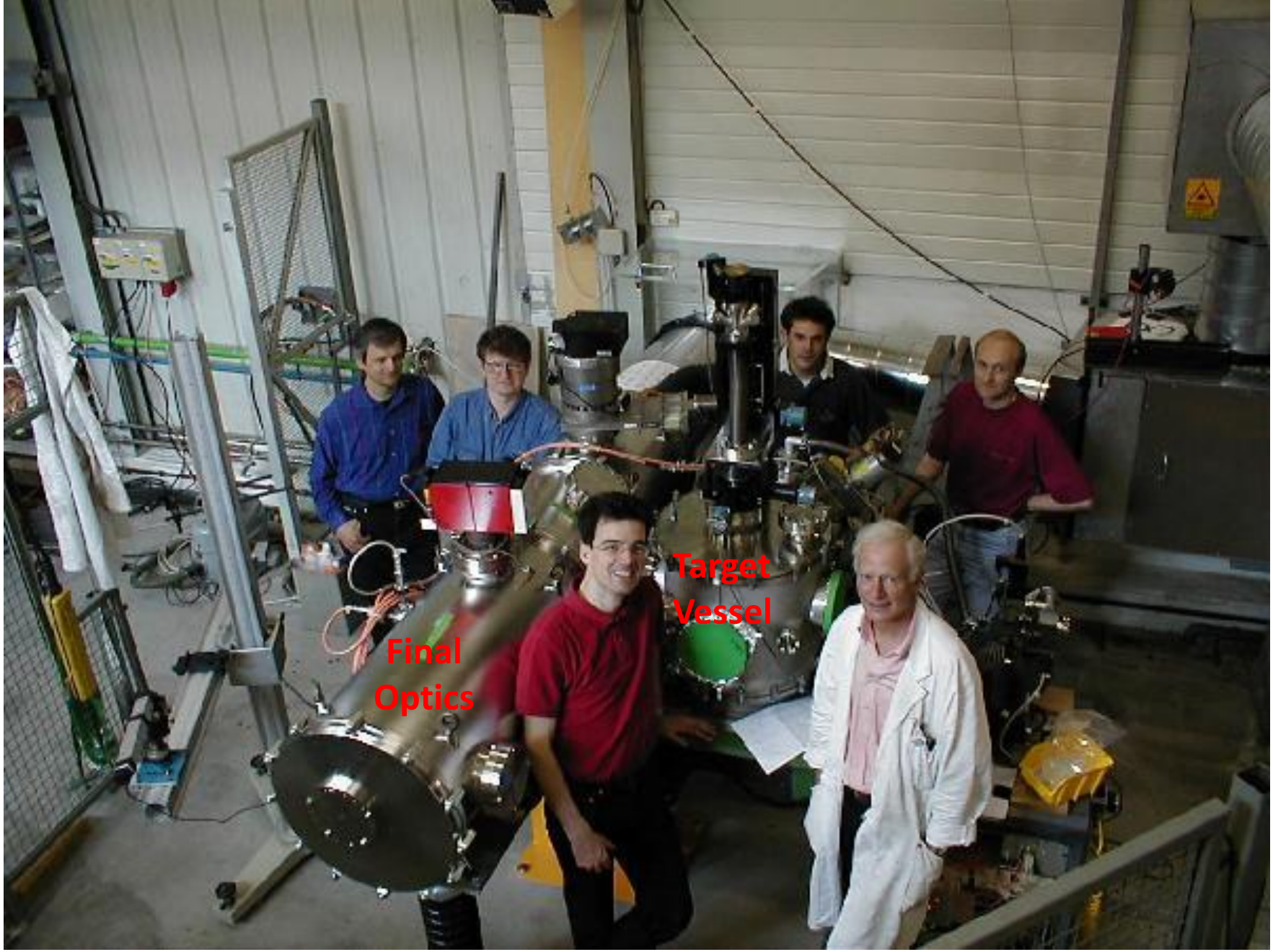
Particles and **Sources**



Laser Plasma Ion Sources



1 -100 Joules per pulse!



ITEP Laser source at CERN

ITEP Laser source at CERN

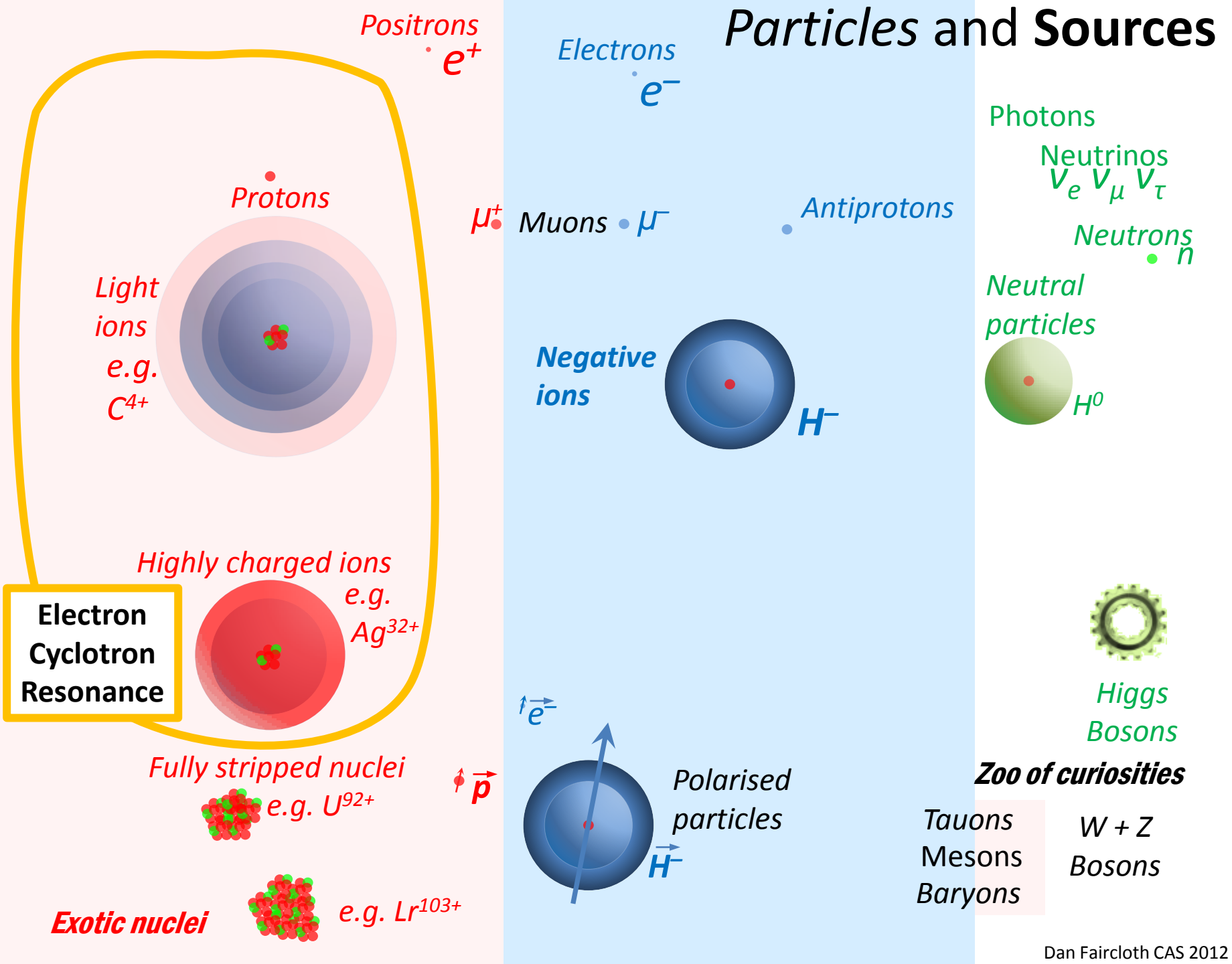
TWAC at ITEP Moscow

7 mA, 10 μs pulses of C^{4+}

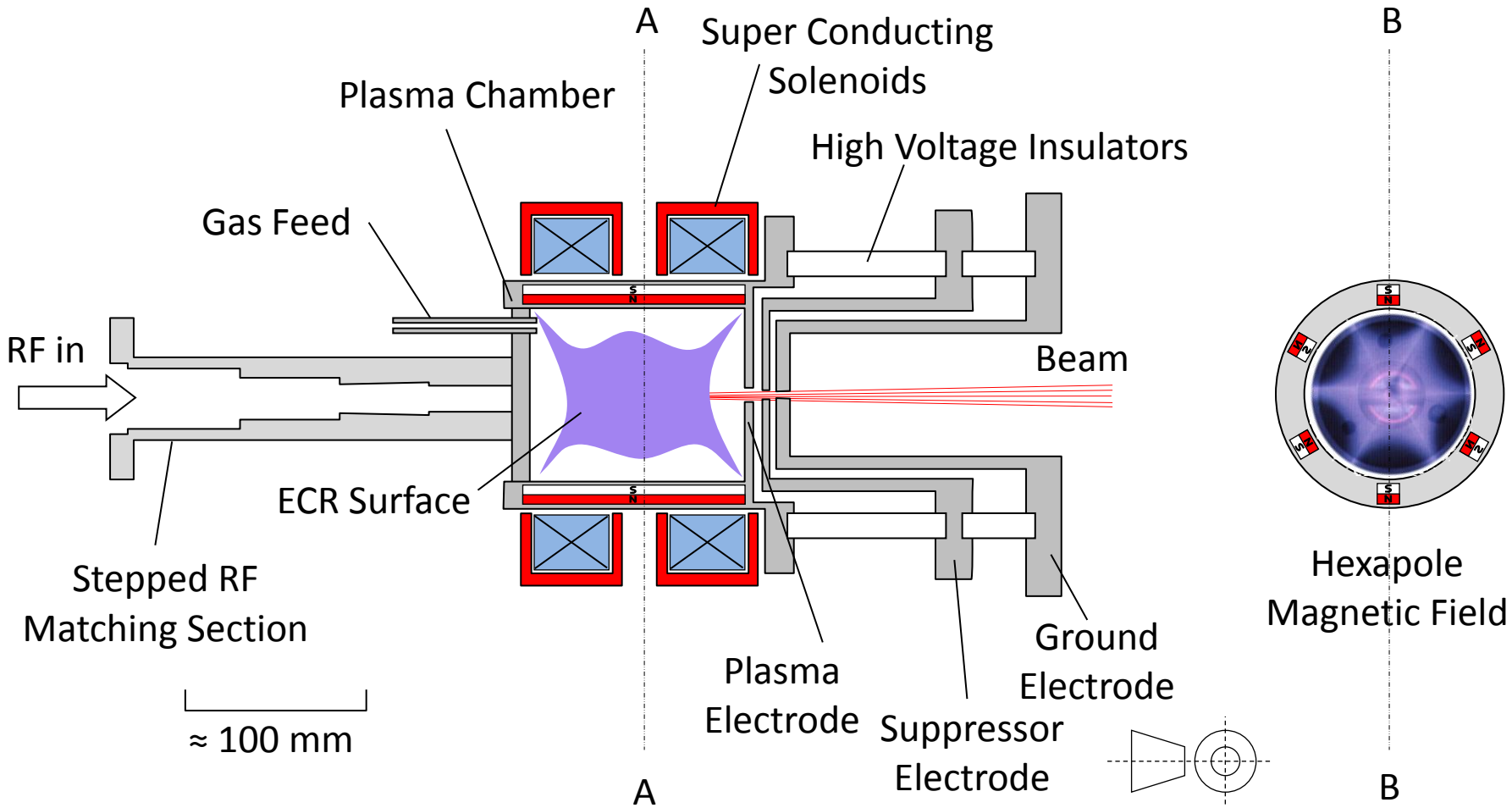
Very Recently

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

Particles and **Sources**



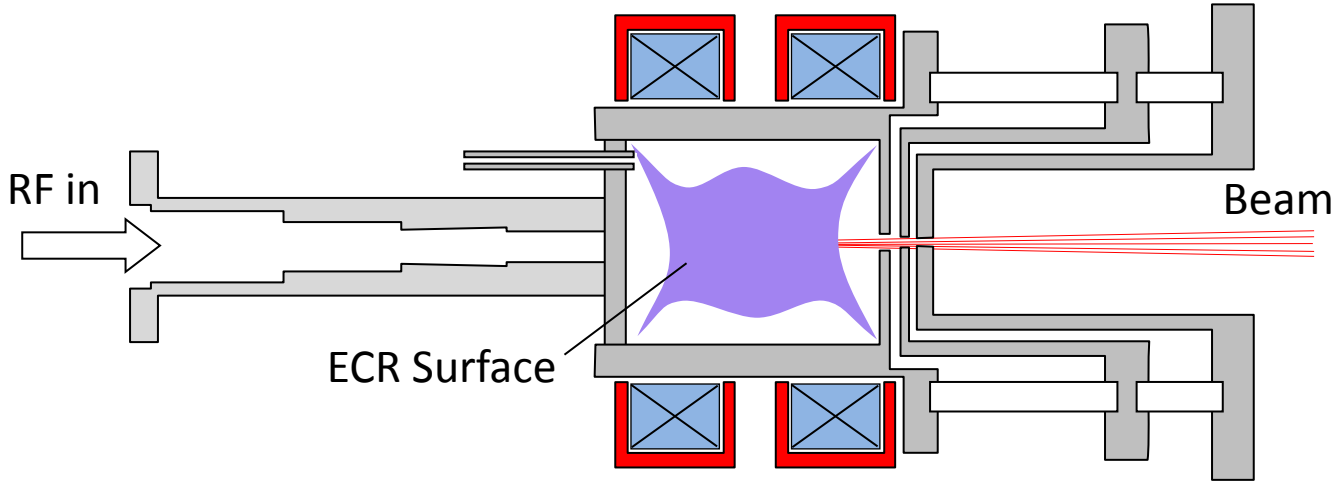
ECR Ion Source



Section on B-B

Section on A-A

ECR Surface



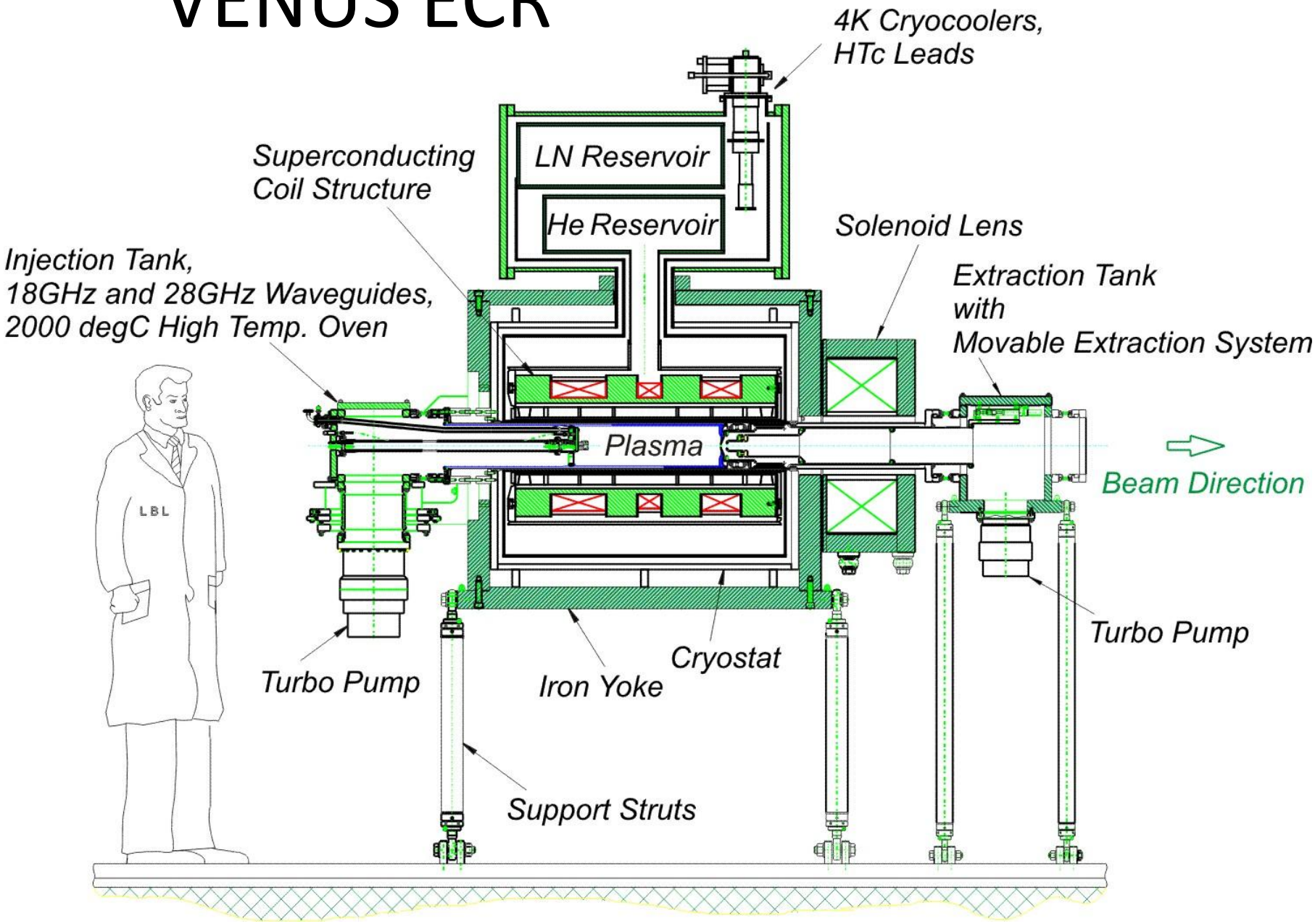
$$\omega_{ECR} = 2\pi f_{ECR} = \frac{eB}{m}$$

28 GHz superconducting VENUS ECR

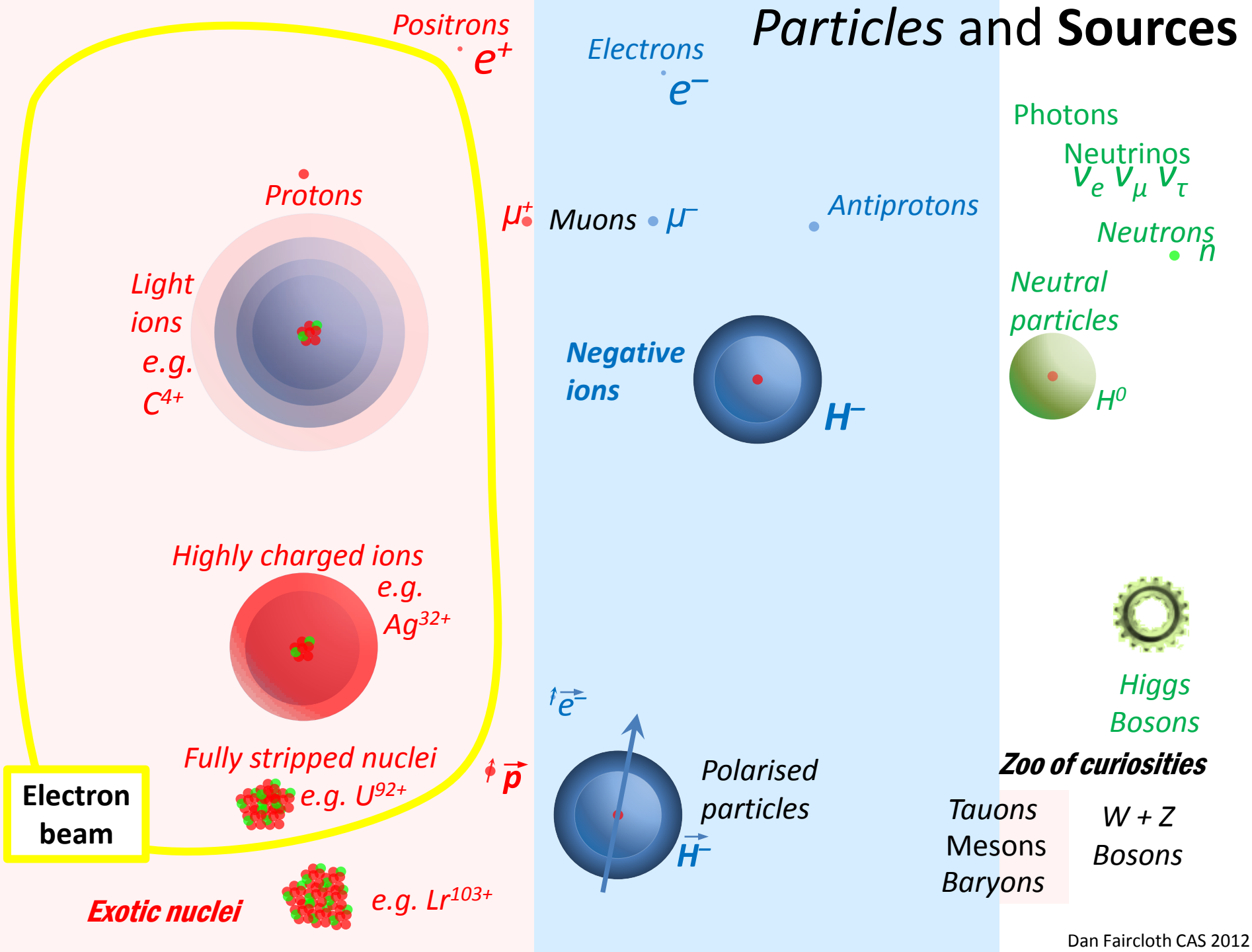
Daniela Leitner
LBNL
Late 2000s

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

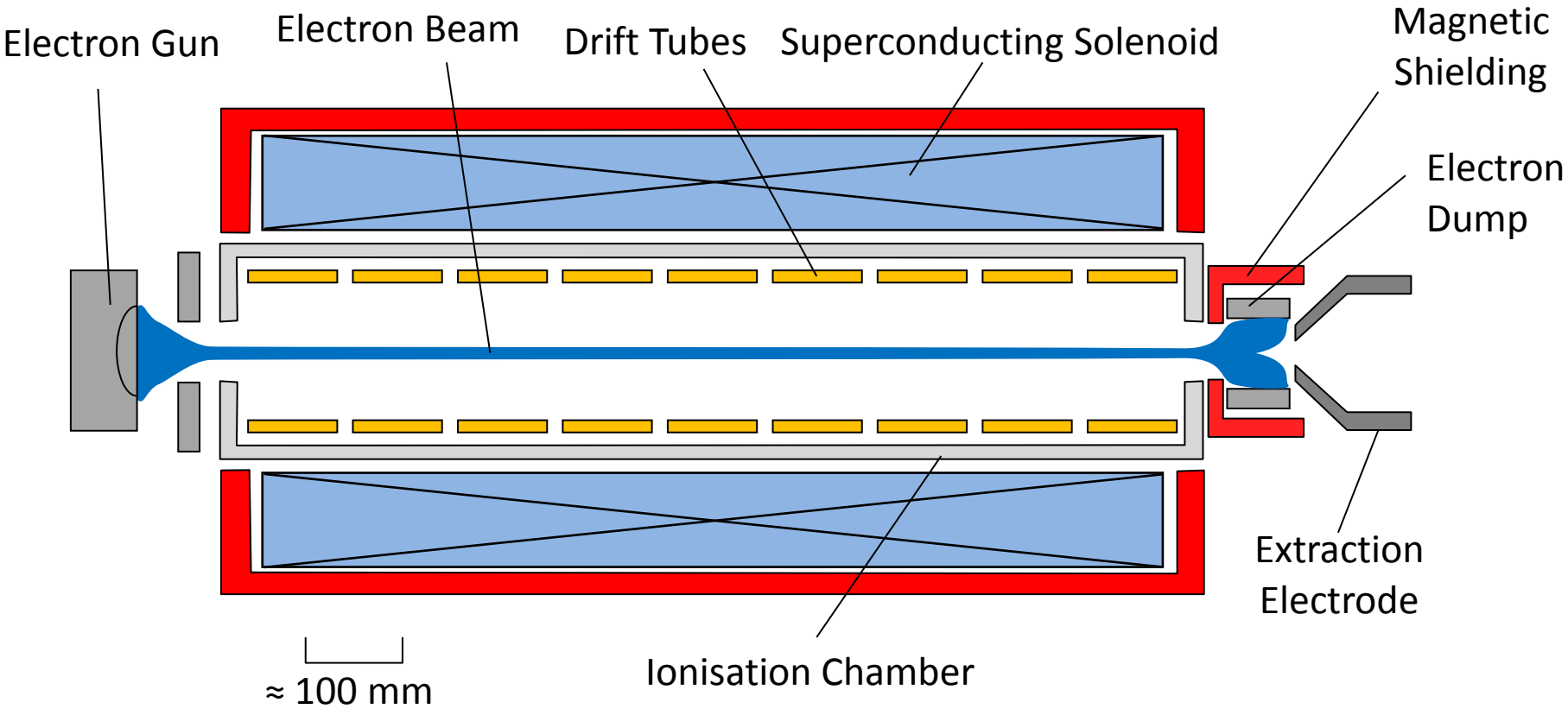
VENUS ECR

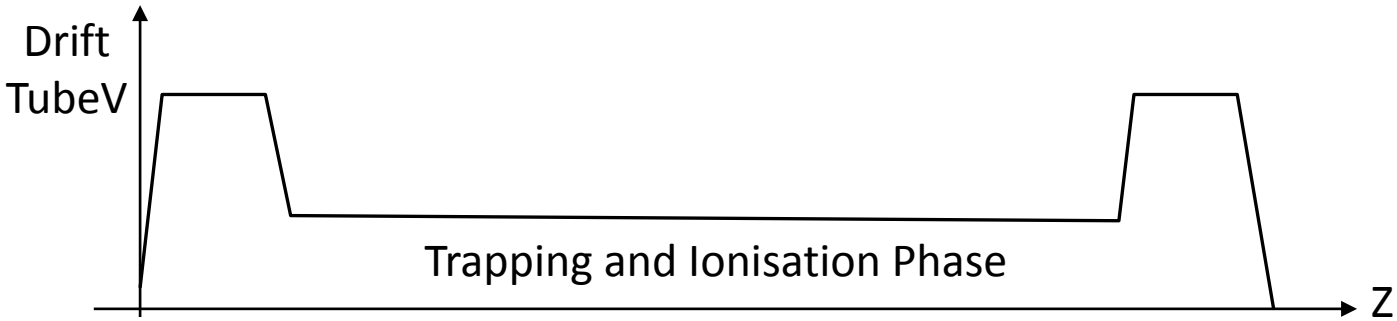

4K Cryocoolers,
HTc Leads
LN Reservoir
He Reservoir
Superconducting
Coil Structure
Solenoid Lens
Injection Tank,
18GHz and 28GHz Waveguides,
2000 degC High Temp. Oven
Extraction Tank
with
Movable Extraction System
Plasma
Beam Direction
LBL
Turbo Pump
Turbo Pump
Cryostat
Iron Yoke
Support Struts

Particles and **Sources**



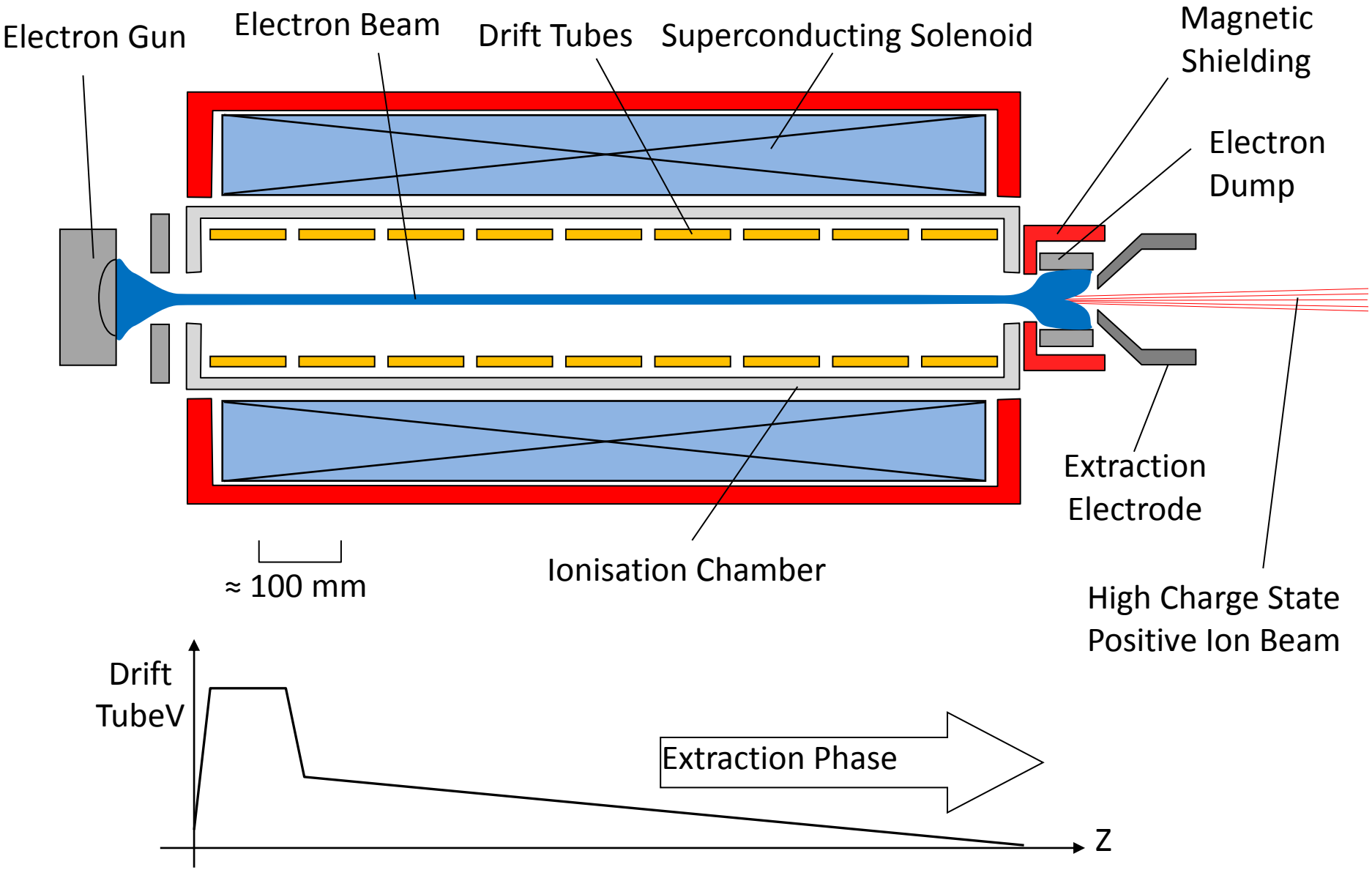
Electron Beam Ion Sources

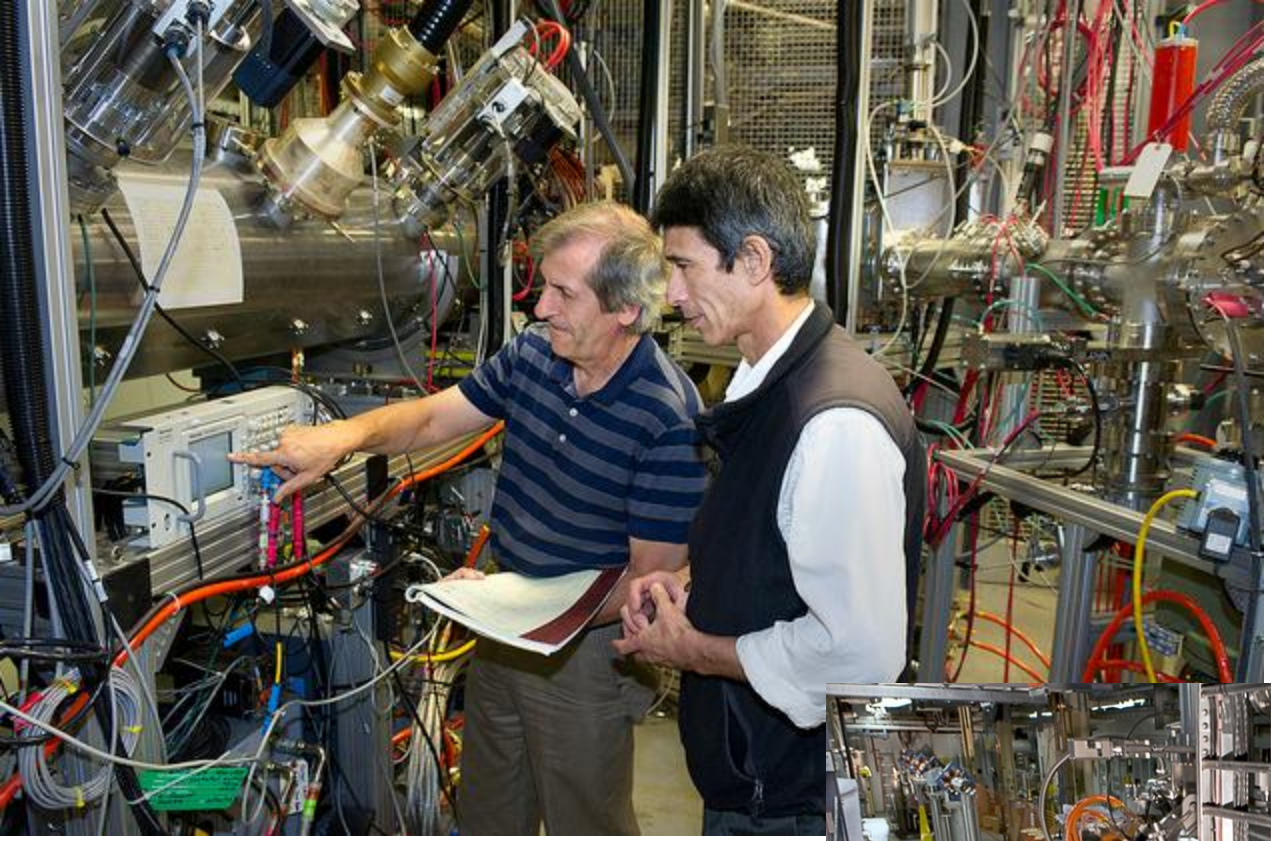




Stepwise ionisation

Electron Beam Ion Sources



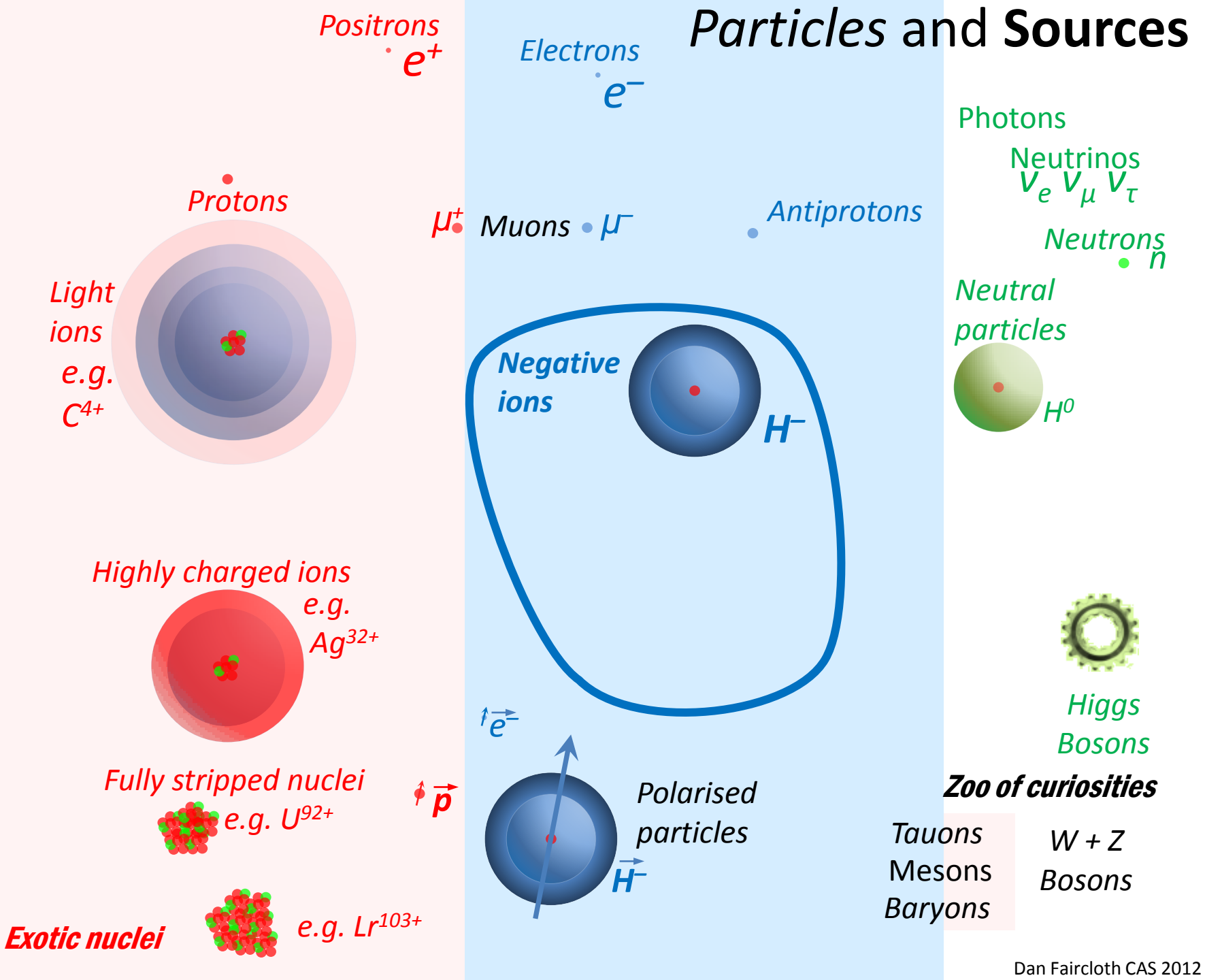


Jim Alessi
BNL

1.7 emA, 10 µs, 5 Hz
Ag^{32+} ions

Fully stripped nuclei can be obtained in EBIT mode

Particles and **Sources**



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

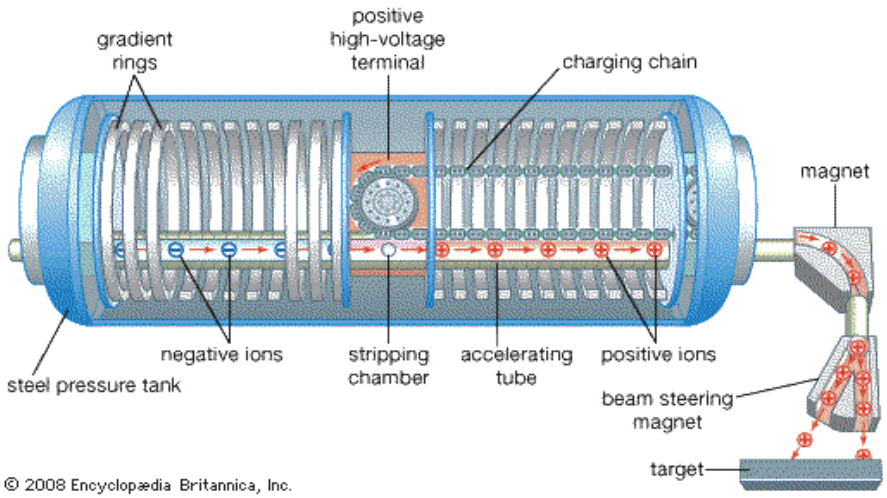
30 times for e^- collisions

100 times for H^+ collisions

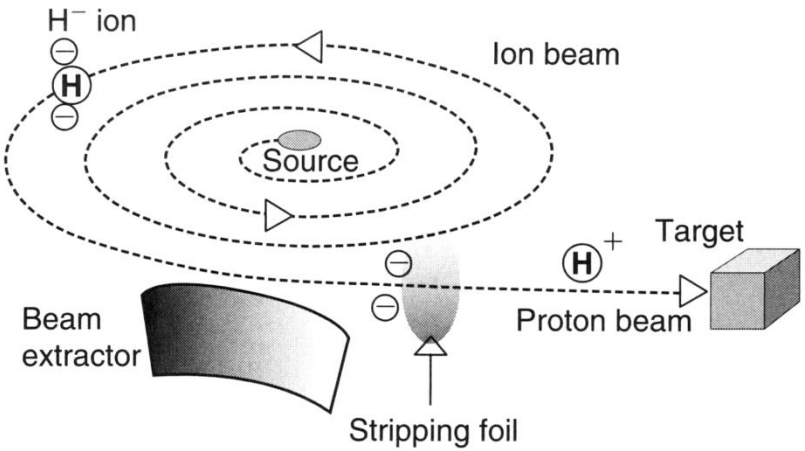
H^- are very fragile!

Applications

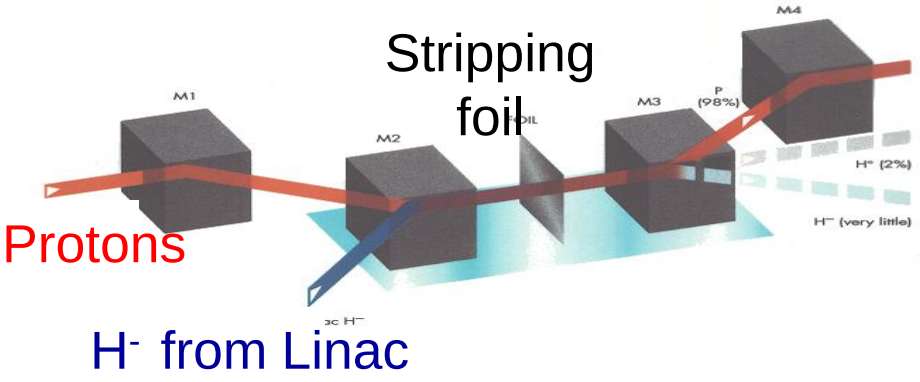
Tandem accelerators



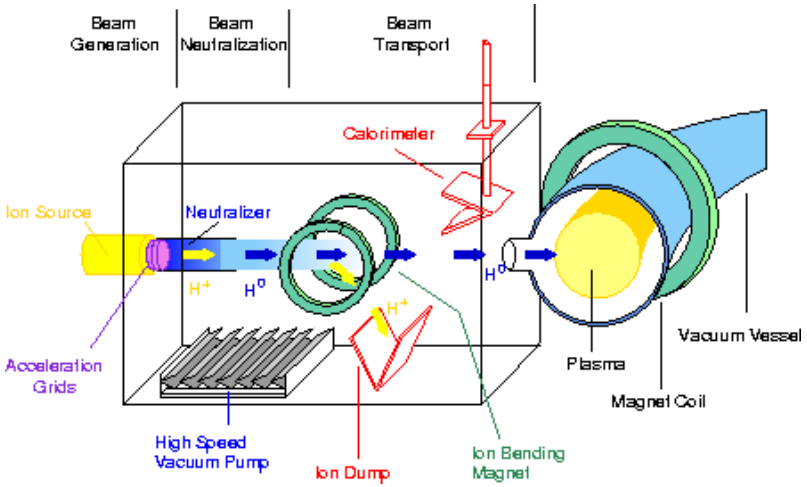
Cyclotron extraction



Multi-turn injection into rings



Neutral Beams

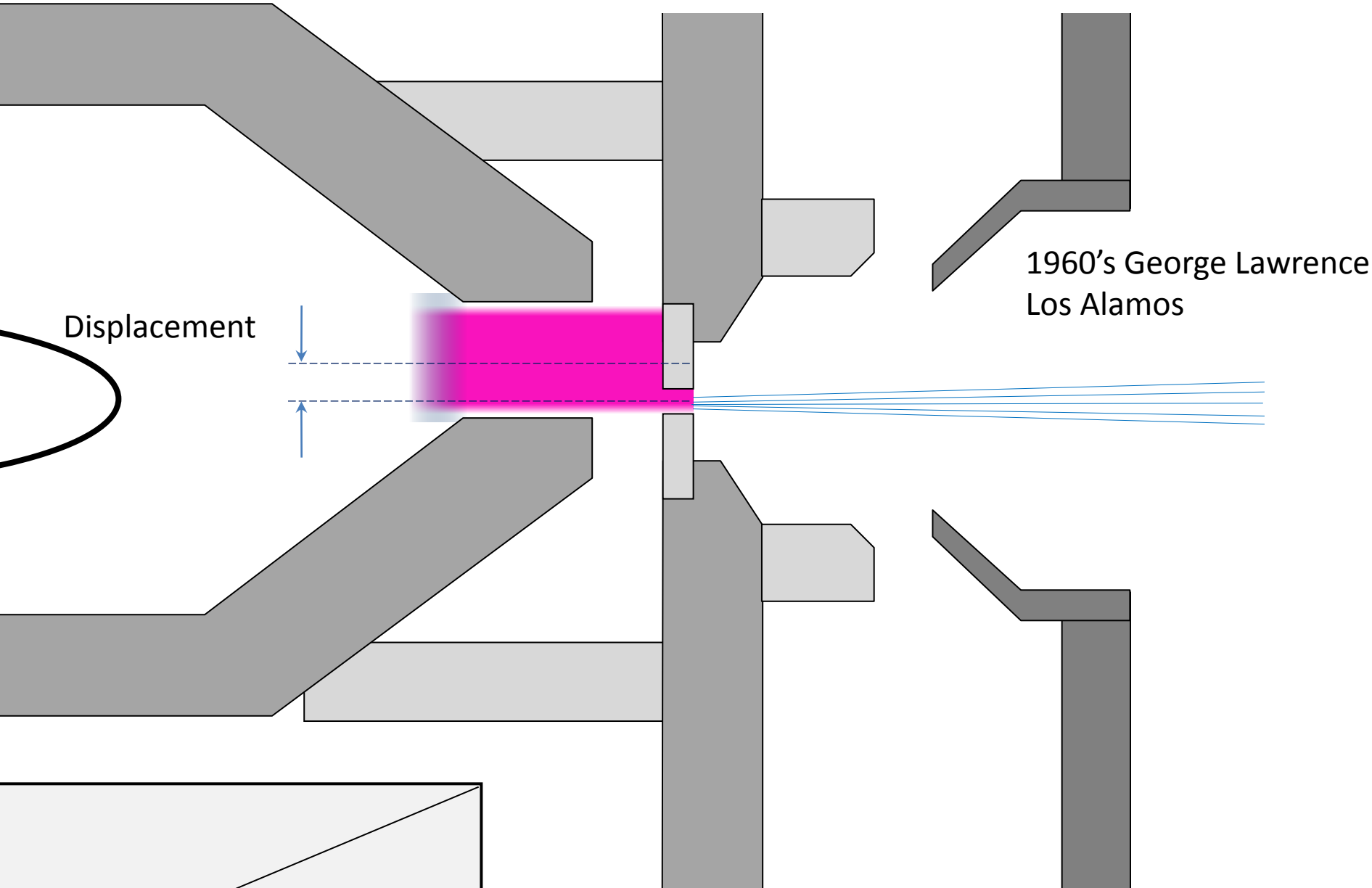


Early attempts at producing negative ion beams:

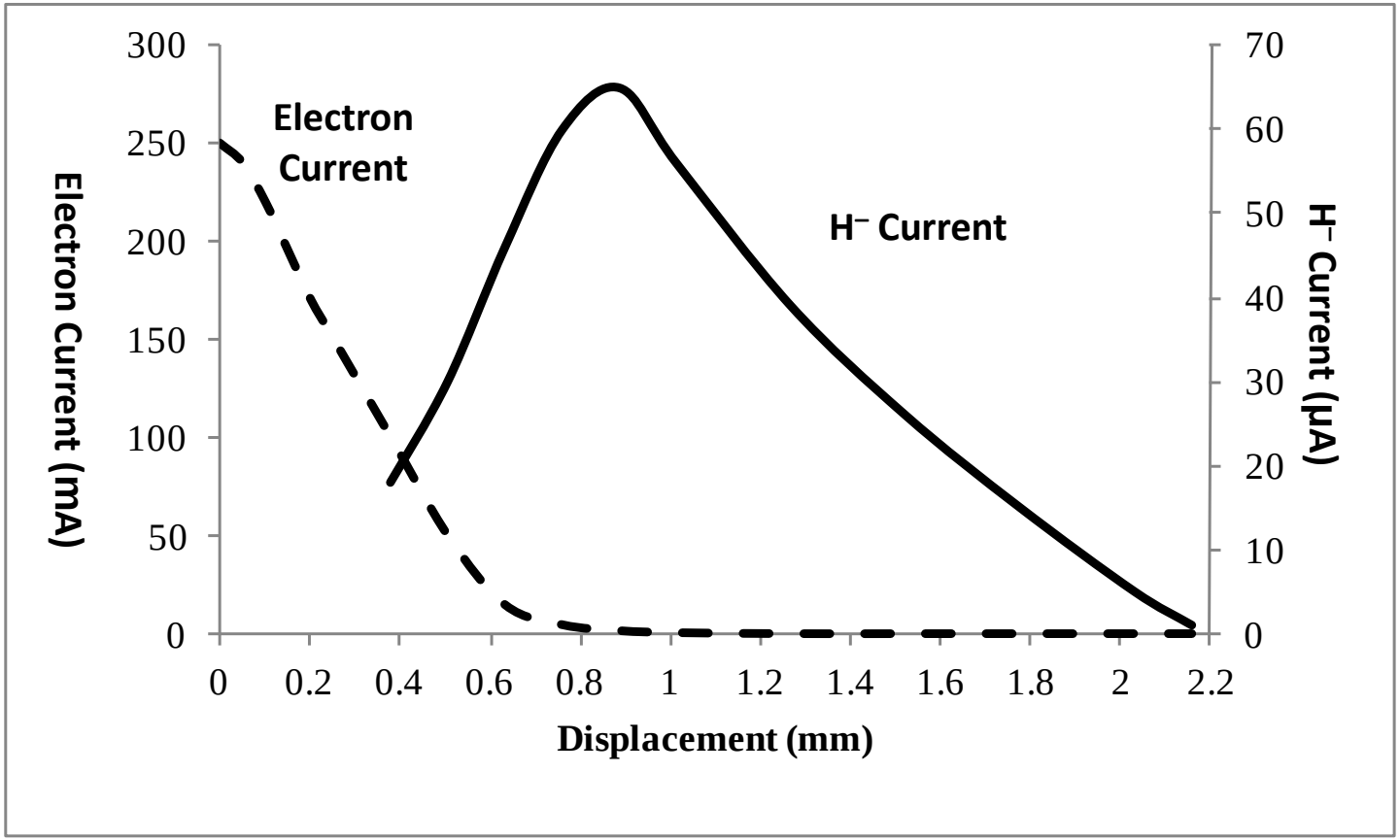
1. Charge exchange of positive beams in gas cells
    - very inefficient

2. Extraction from existing ion sources

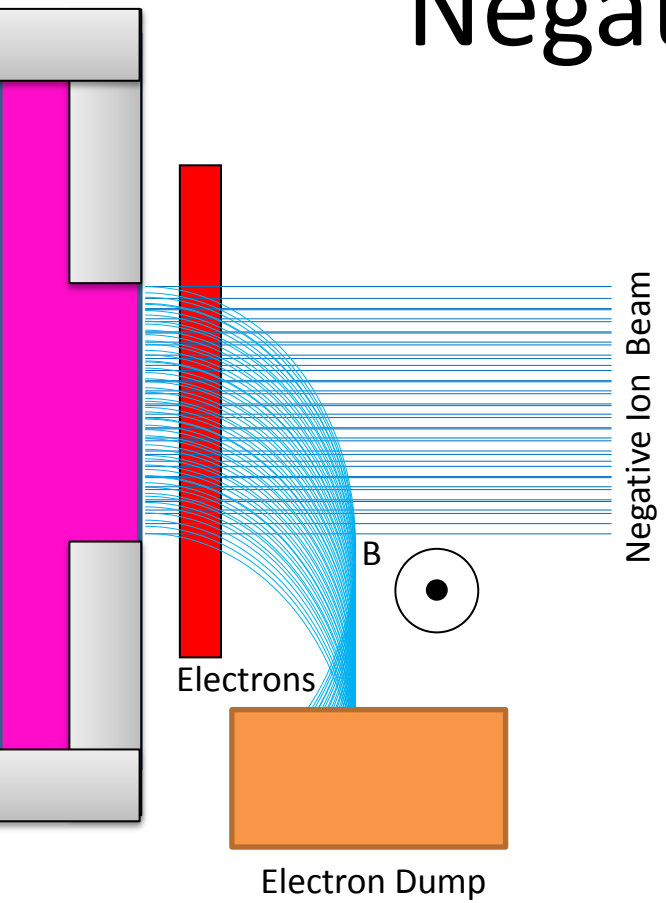
Off Axis Duoplasmatron Extraction



Off Axis Duoplasmatron Extraction



Negative Ion Extraction



Electrons will also be extracted

Up to 1000 times the H^- current!

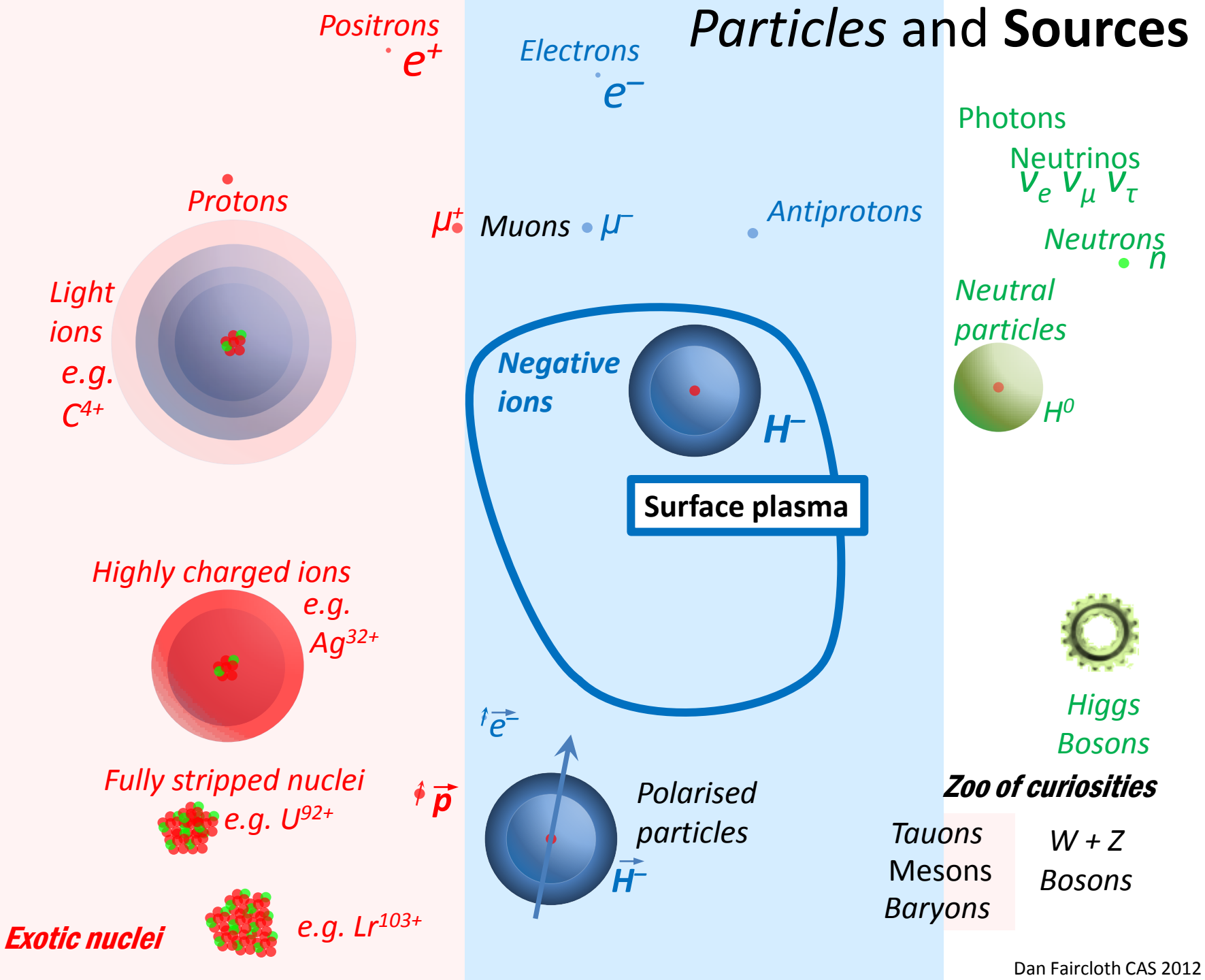
Use a magnetic field

Dump must be properly designed

Best sources:

only 0.5 times H^- current

Particles and **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


5 g Caesium
Ampoule

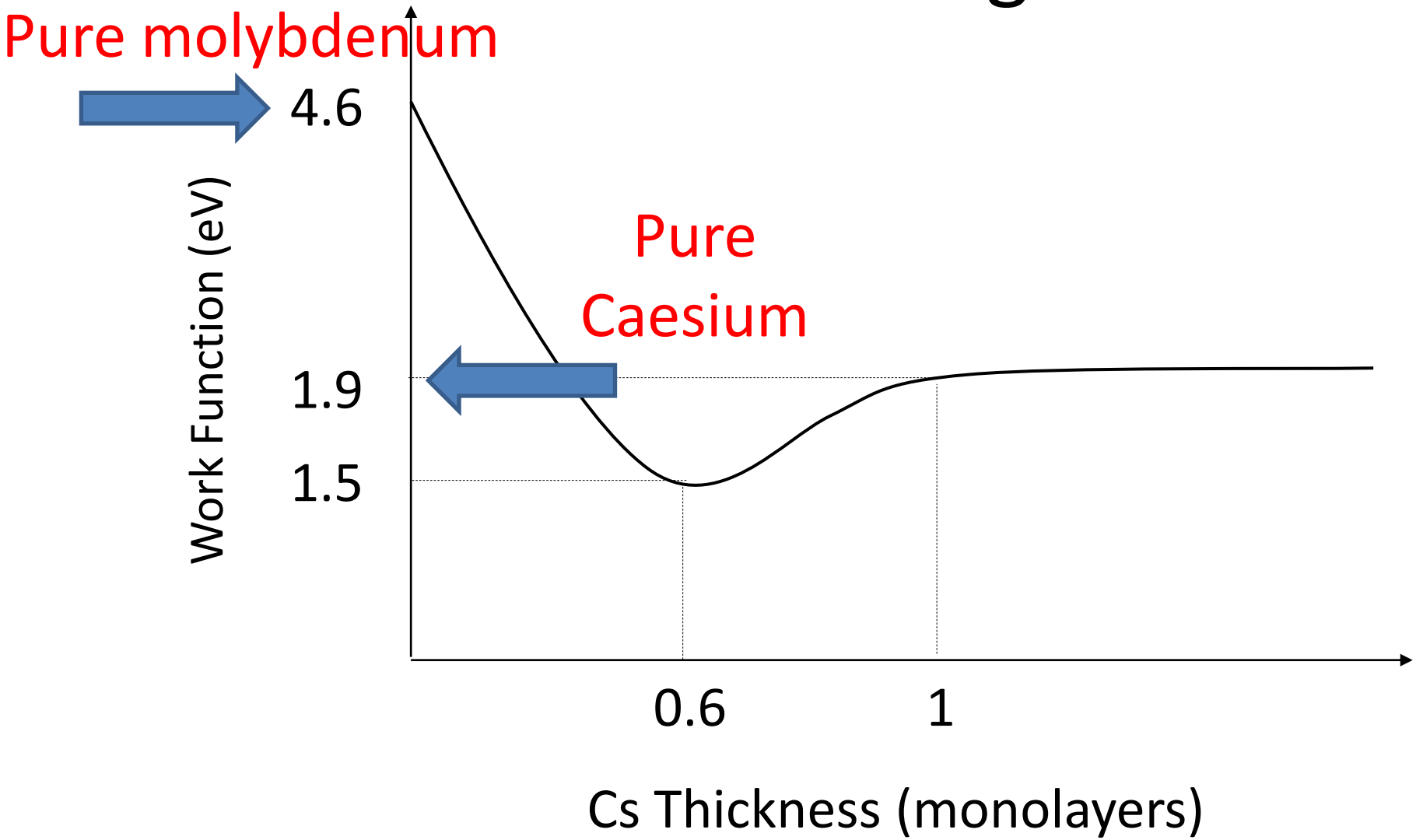
Periodic Table of the Elements

- hydrogen
- alkali metals
- alkali earth metals
- transition metals
- poor metals
- nonmetals
- noble gases
- rare earth metals

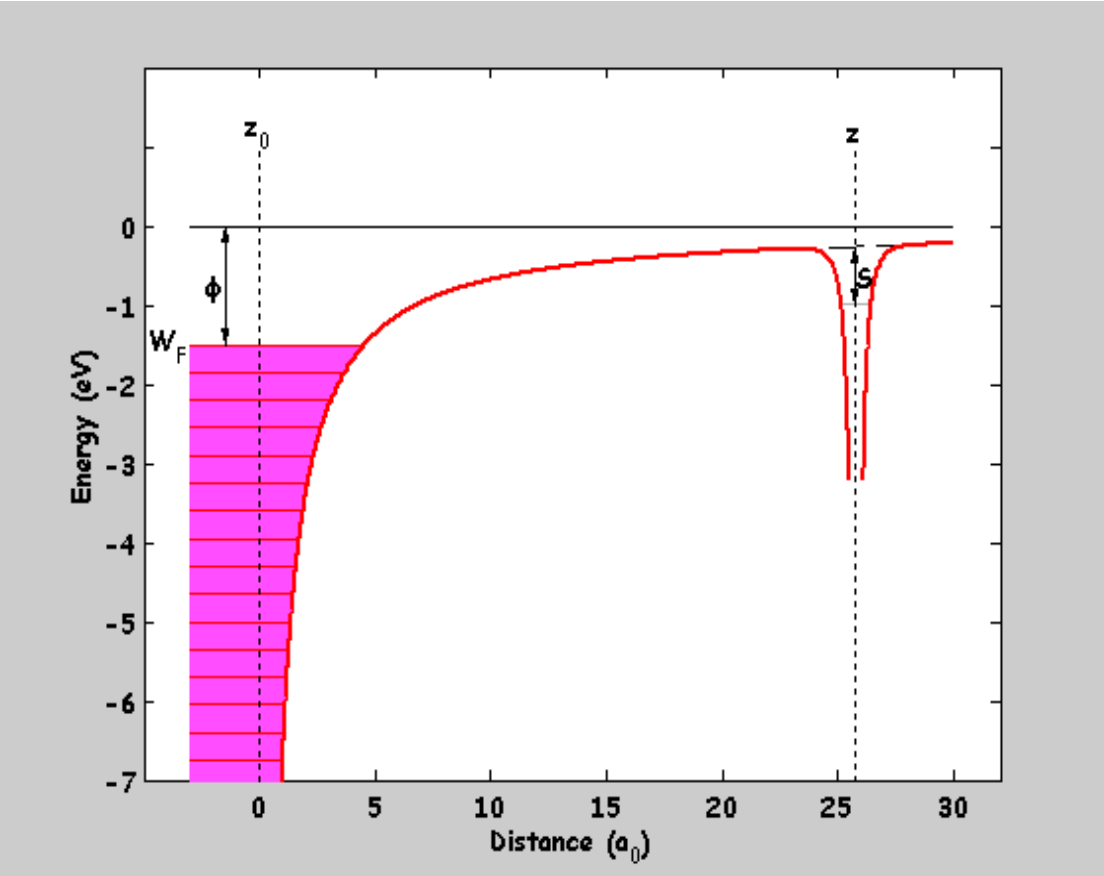
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Ti	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

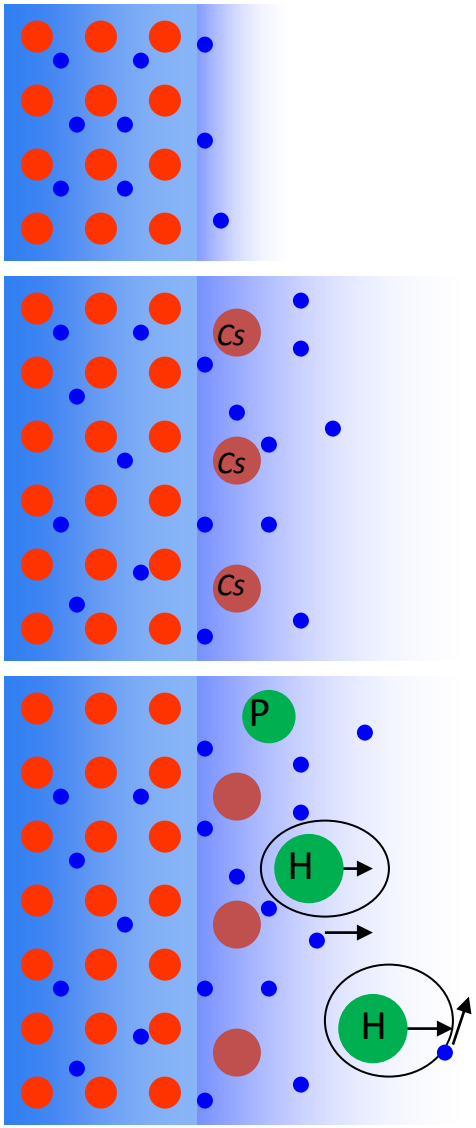
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Caesium Coverage

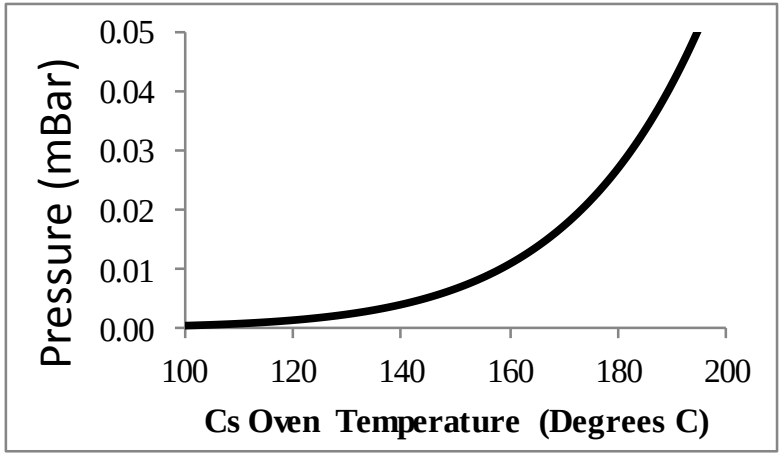


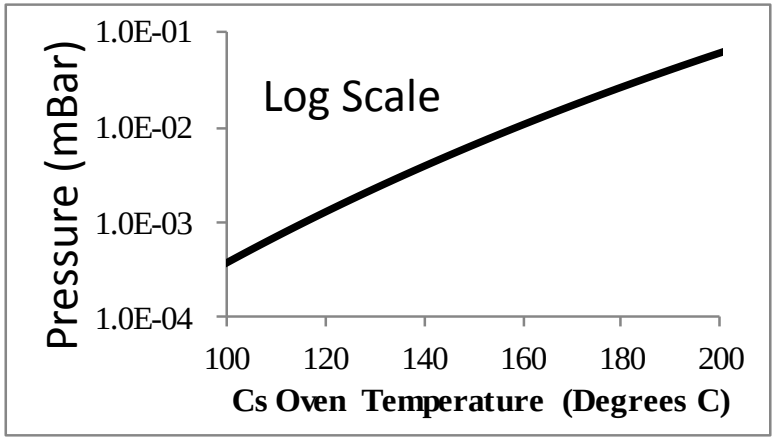
Fermilevels



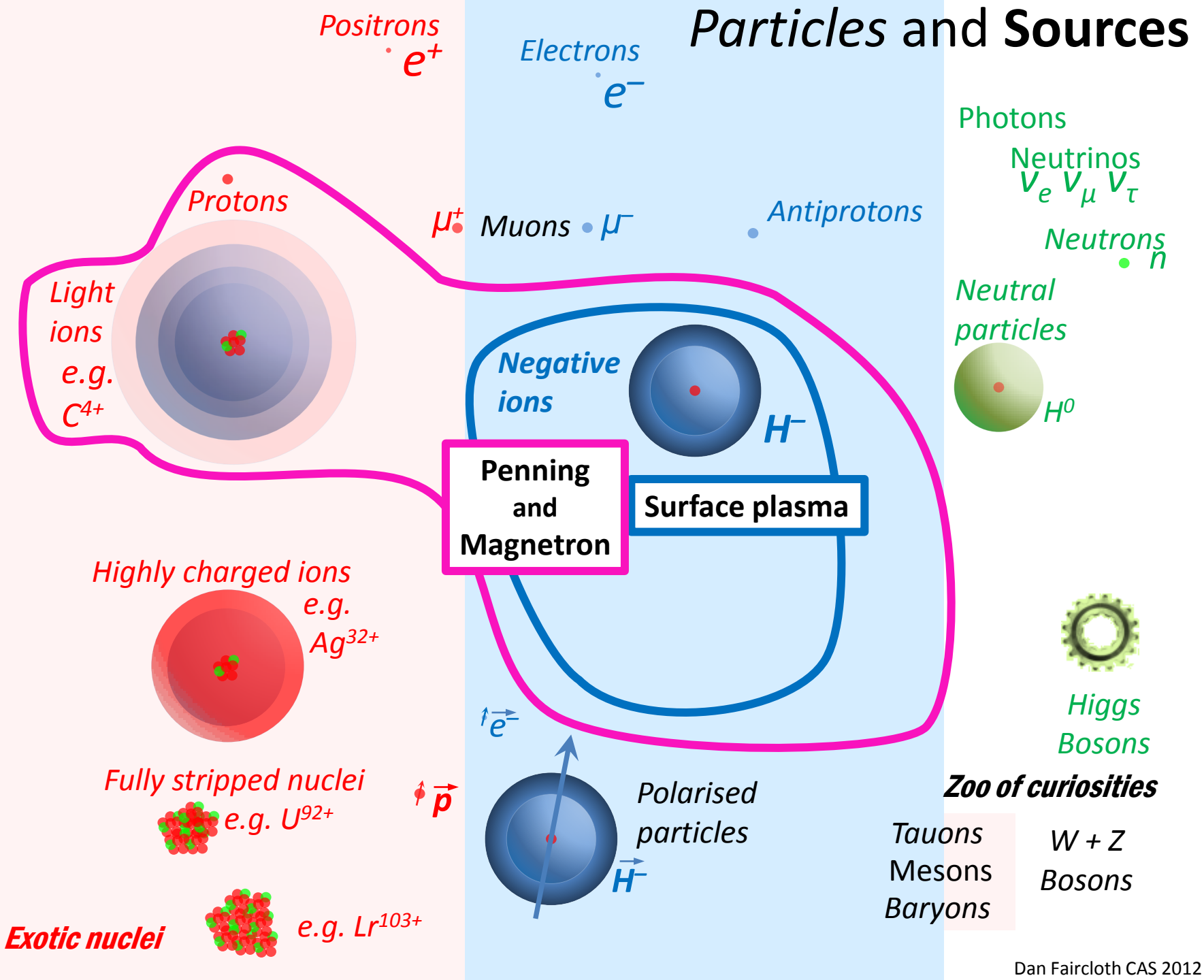


Control caesium oven temperature to vary caesium vapour pressure to control caesium coverage



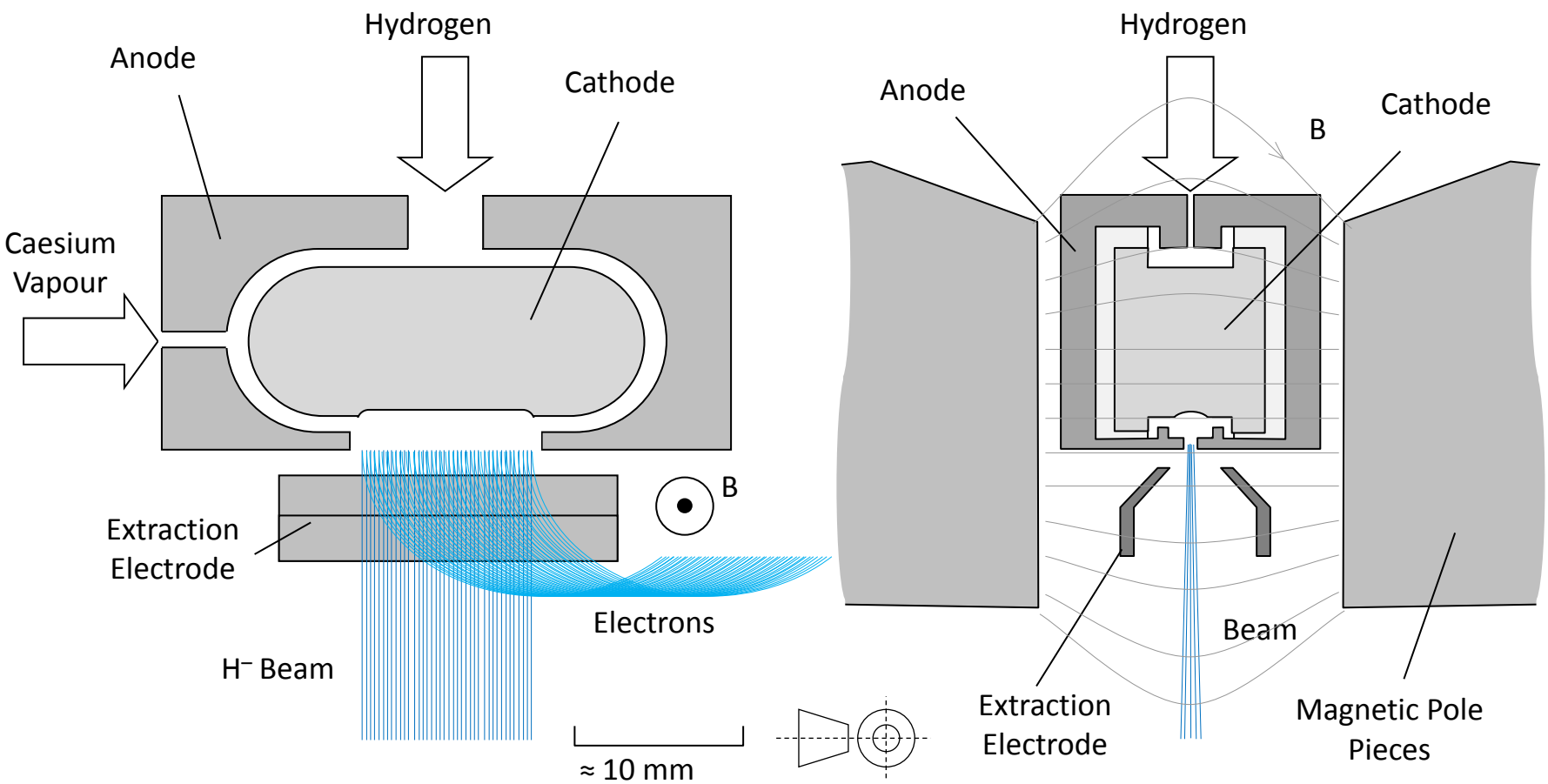


Particles and **Sources**

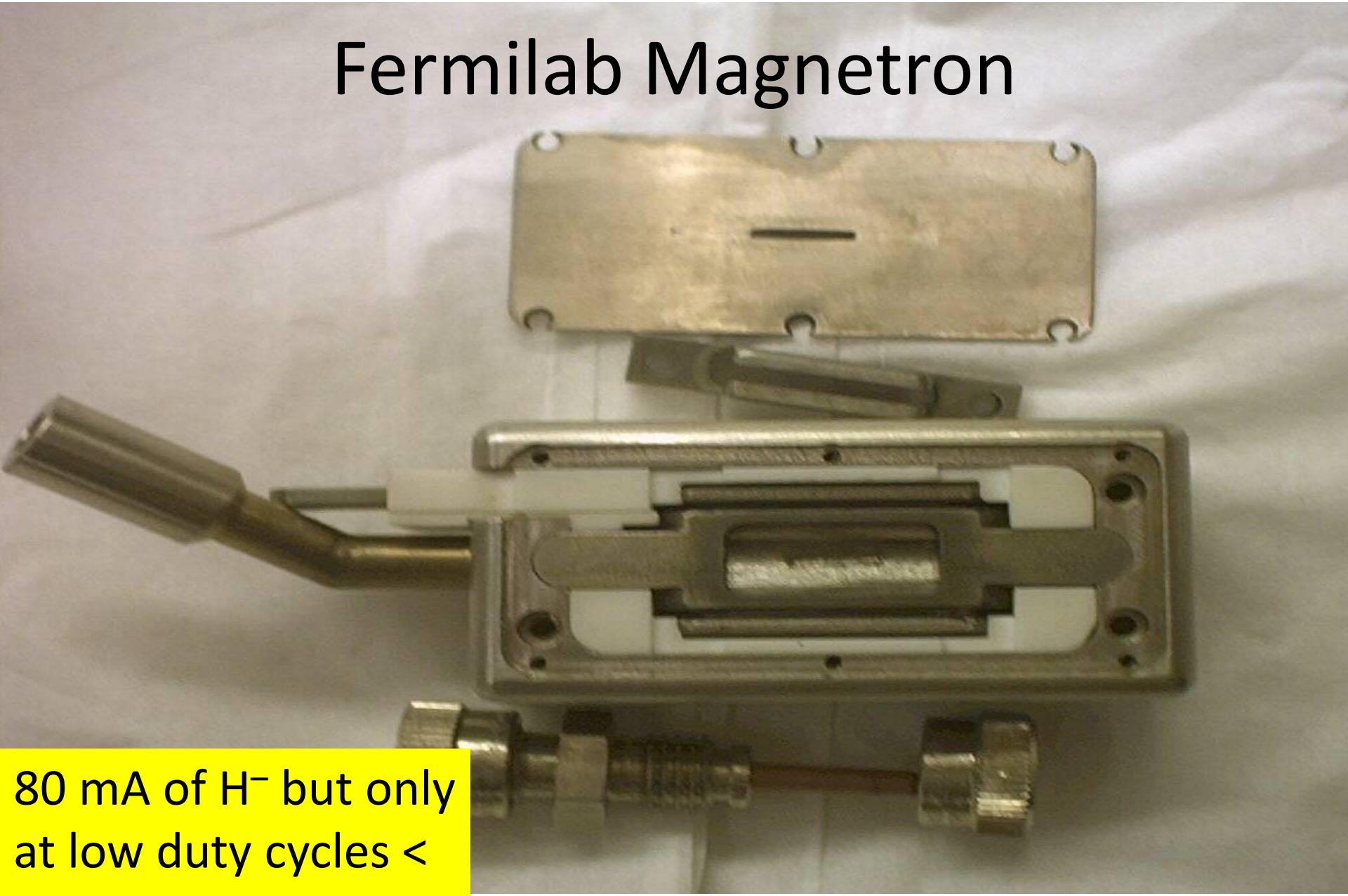


Dan Faircloth CAS 2012

Magnetron Source



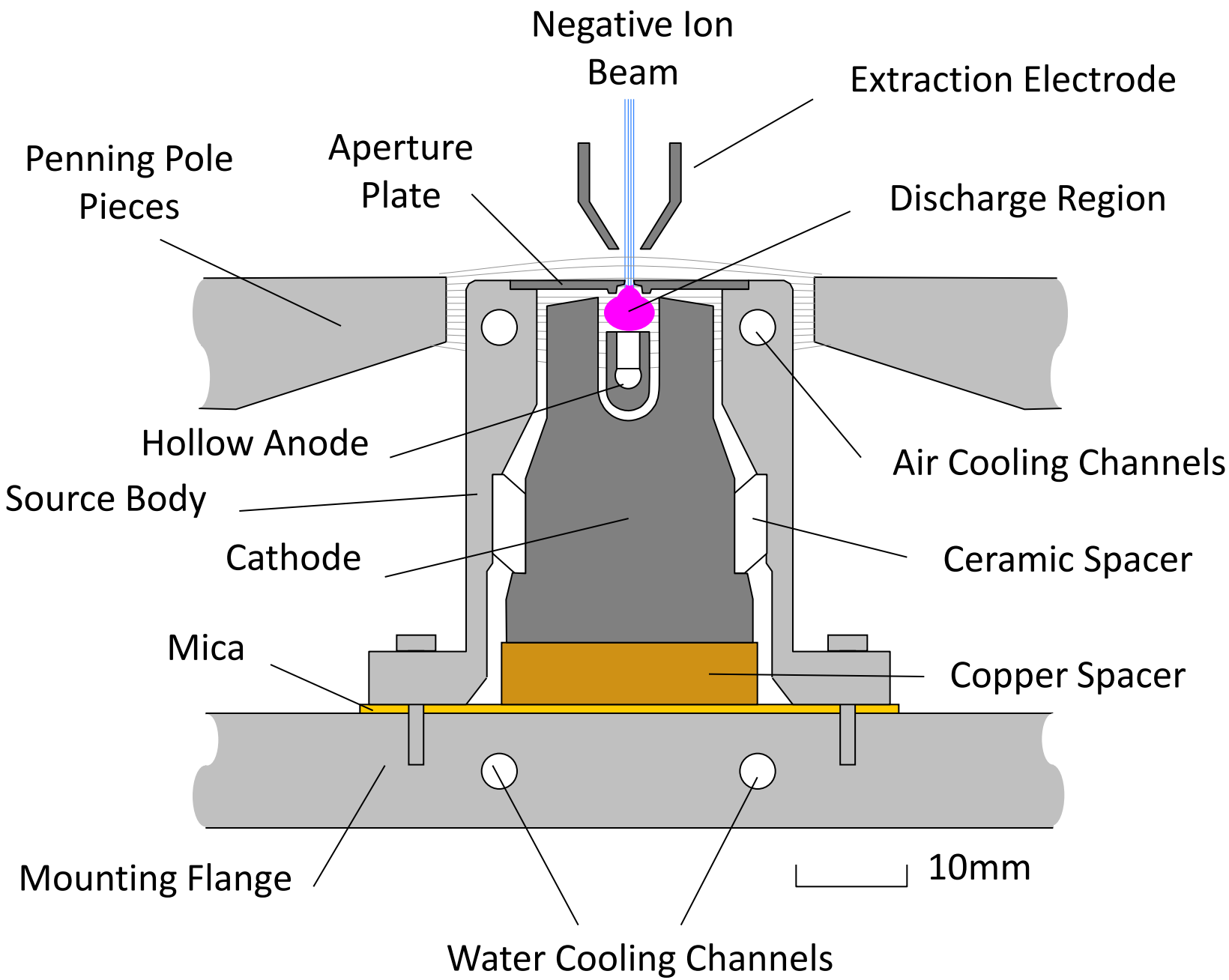
Fermilab Magnetron

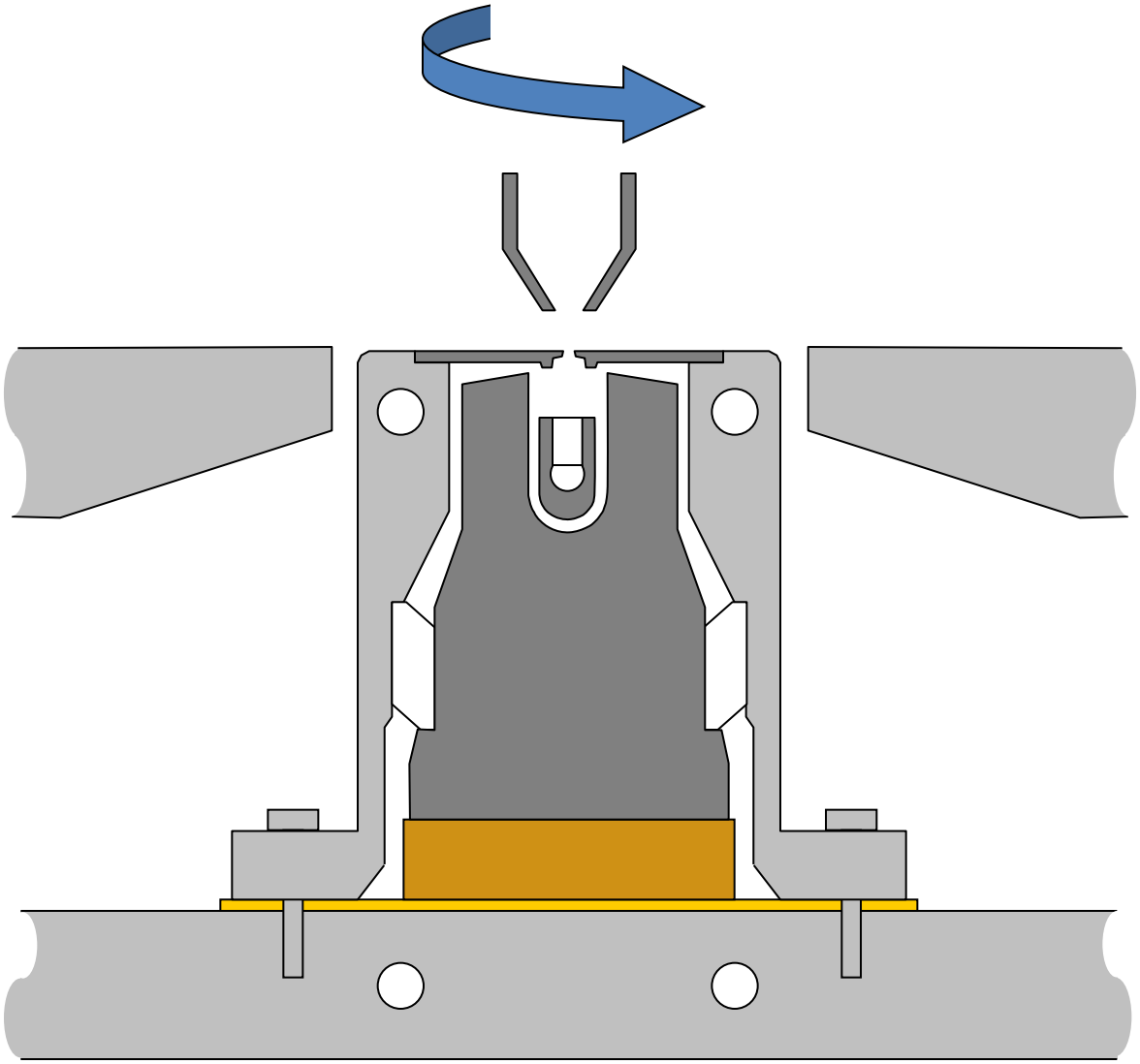


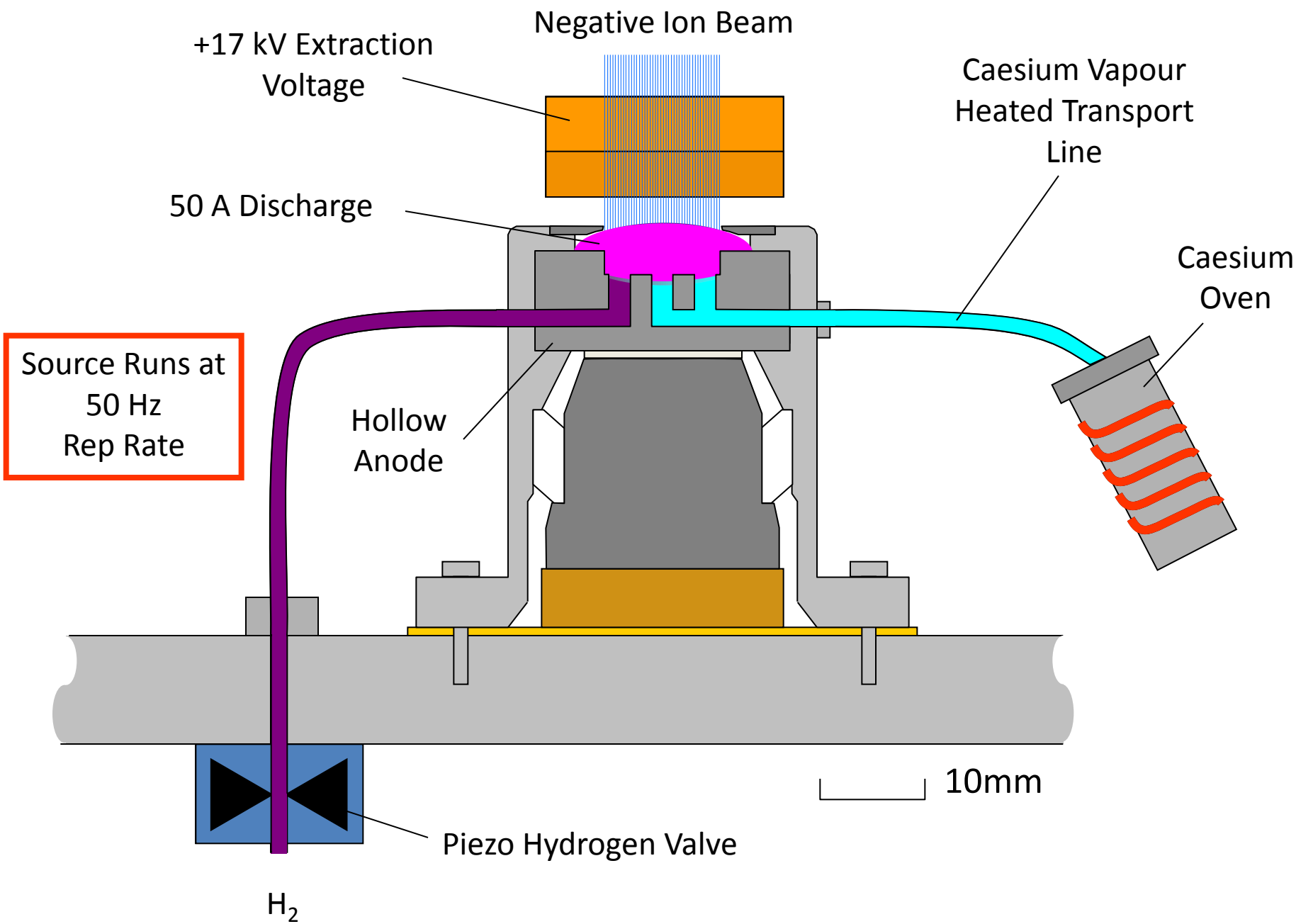
80 mA of H^- but only at low duty cycles < 0.5%

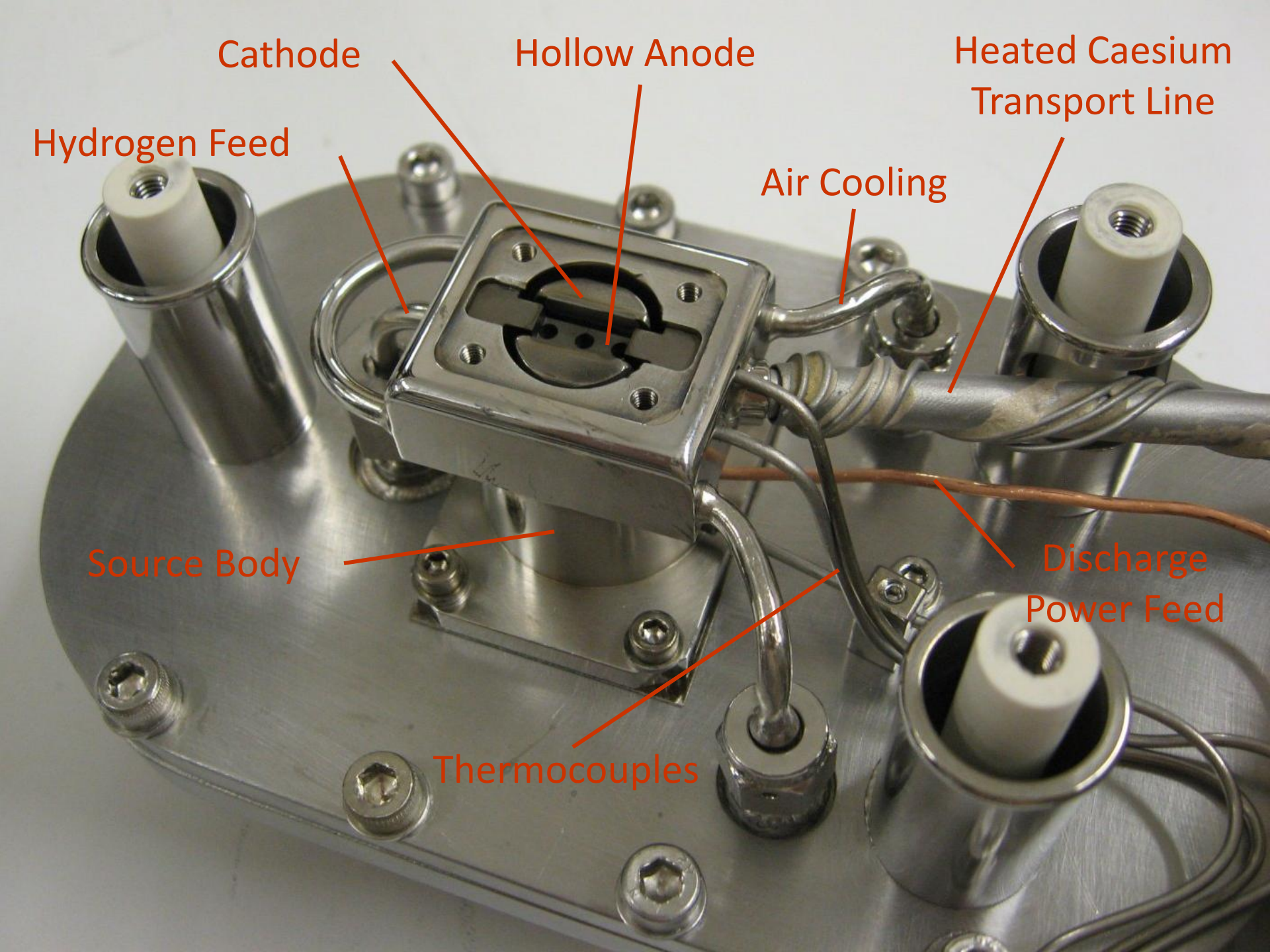
Penning SPS Ion Sources

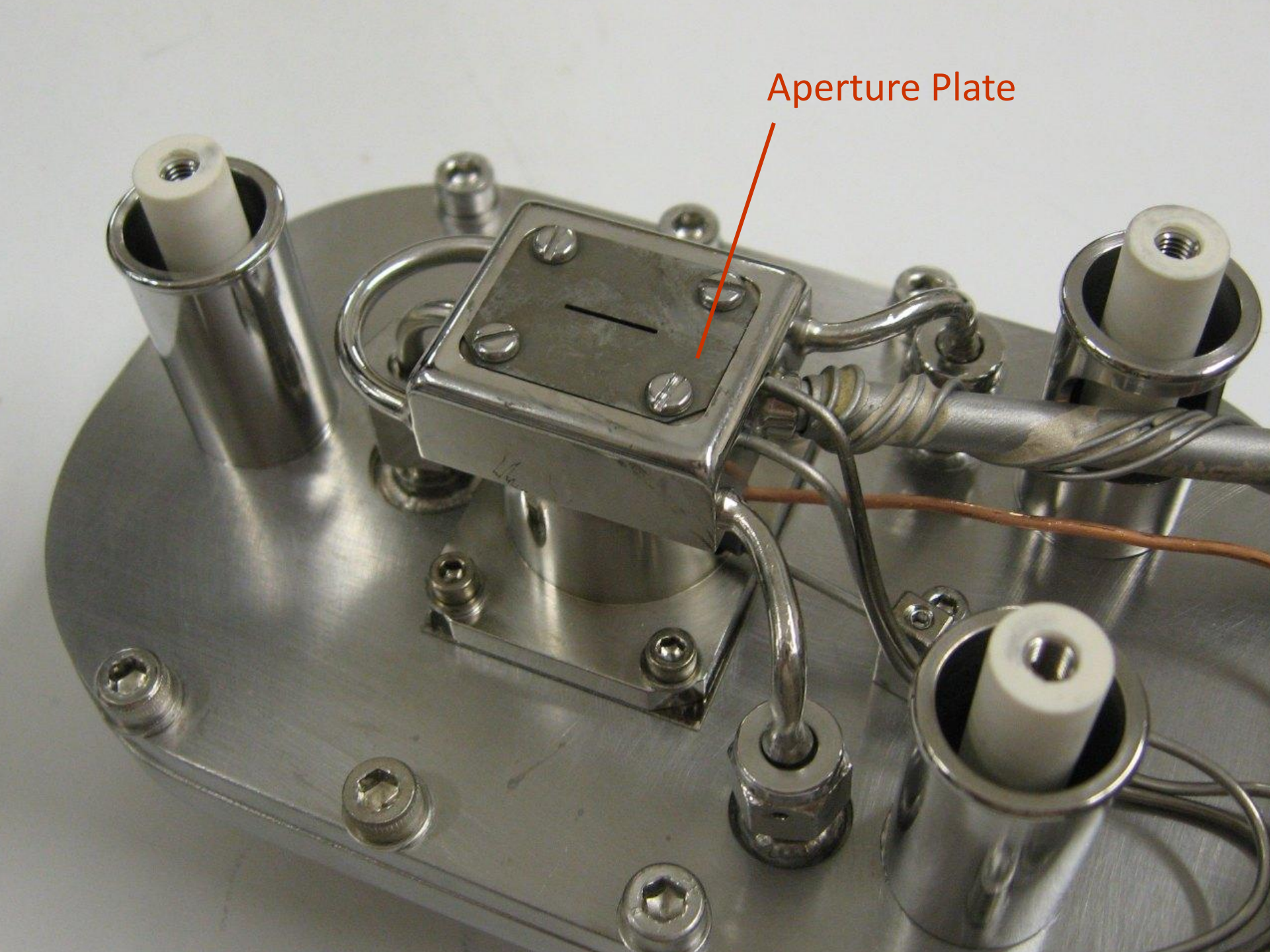
- Invented by Dudnikov in the 1970's
- Very high current density > 1 Acm^{-2}
- Low noise
- Does not work without ceasium

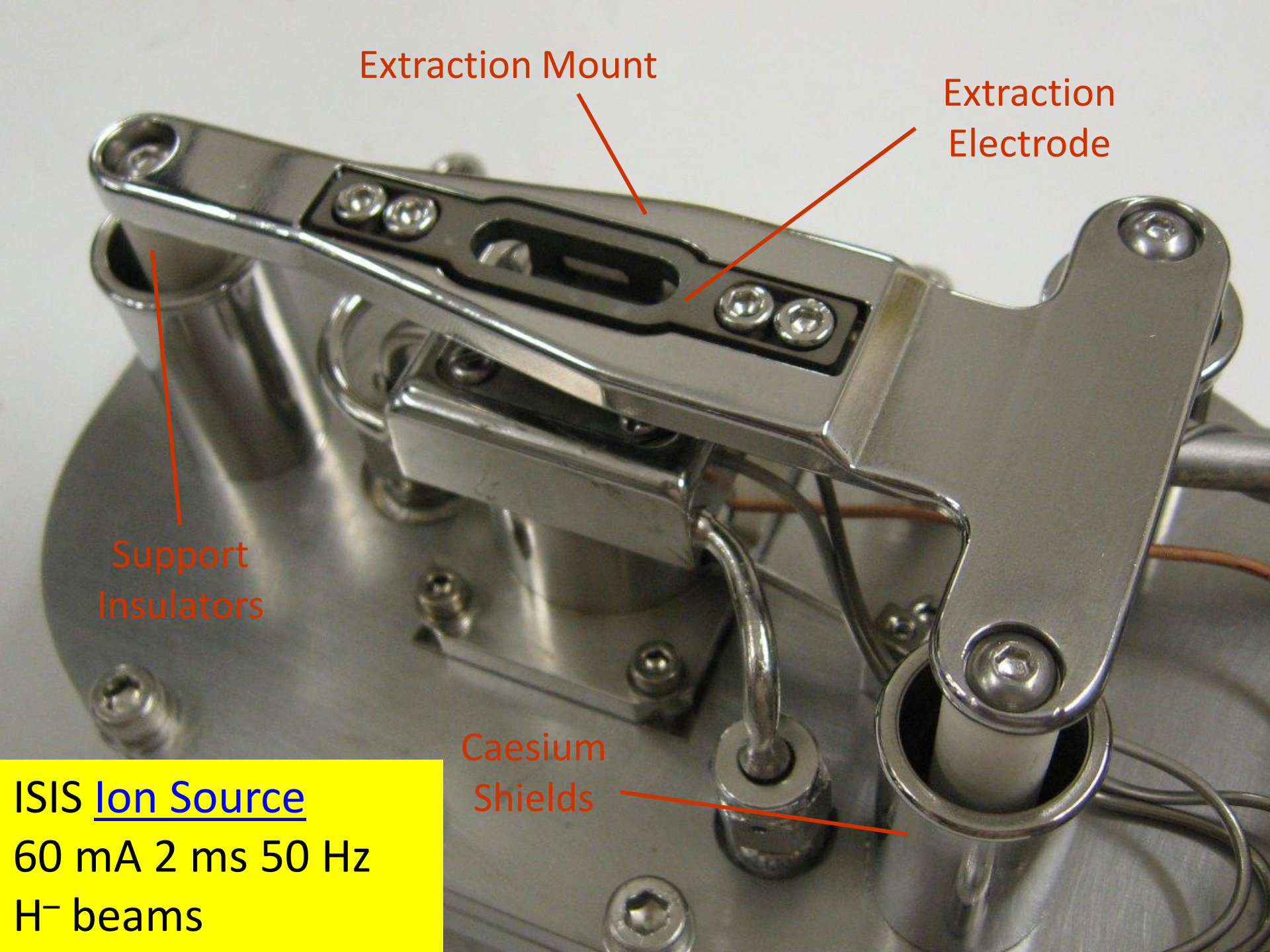

Negative Ion Beam
Extraction Electrode
Penning Pole Pieces
Aperture Plate
Discharge Region
Hollow Anode
Air Cooling Channels
Source Body
Cathode
Ceramic Spacer
Mica
Copper Spacer
Mounting Flange
10mm
Water Cooling Channels




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

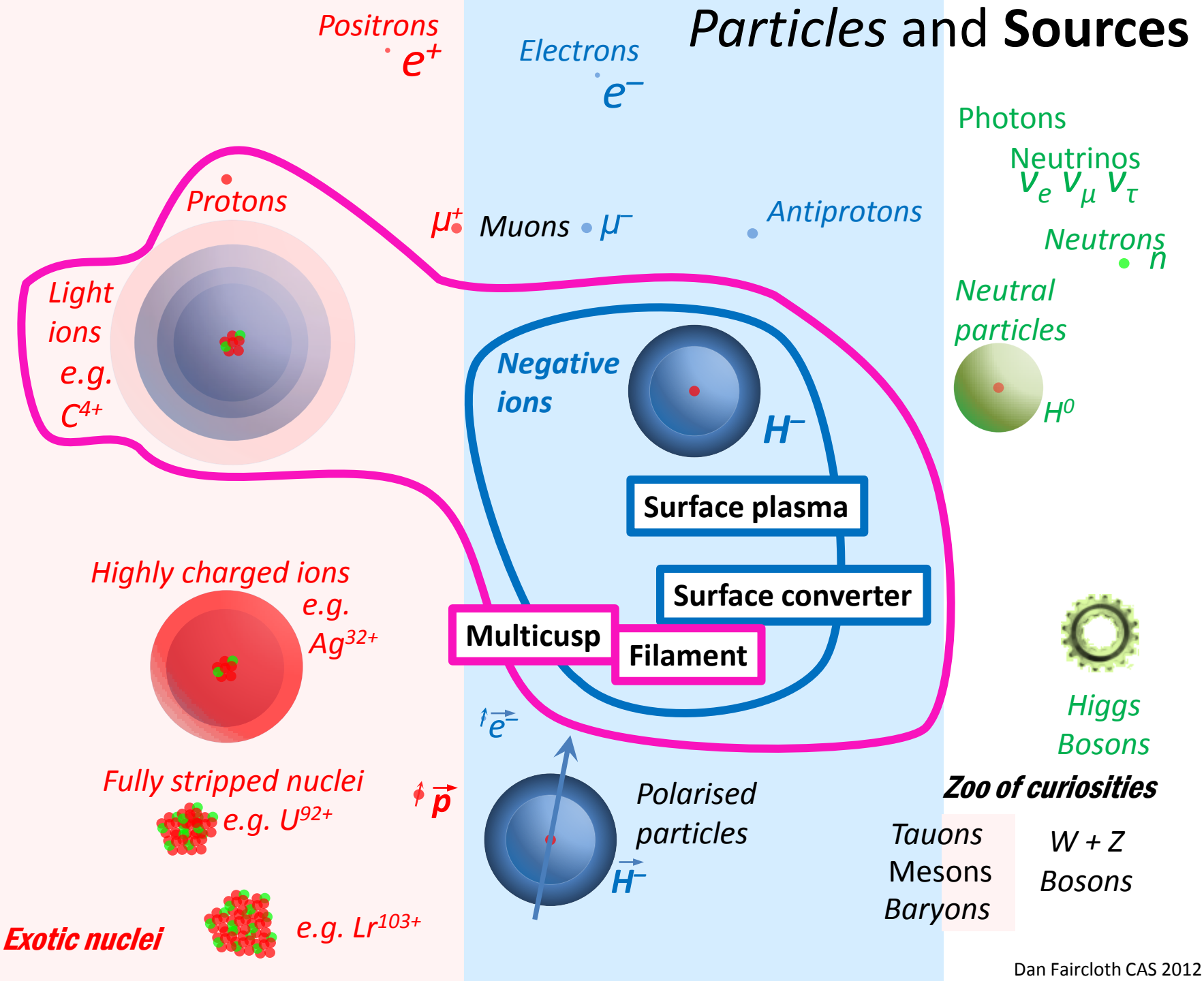

Cathode
Hollow Anode
Heated Caesium
Transport Line
Hydrogen Feed
Air Cooling
Source Body
Discharge
Power Feed
Thermocouples


Aperture Plate

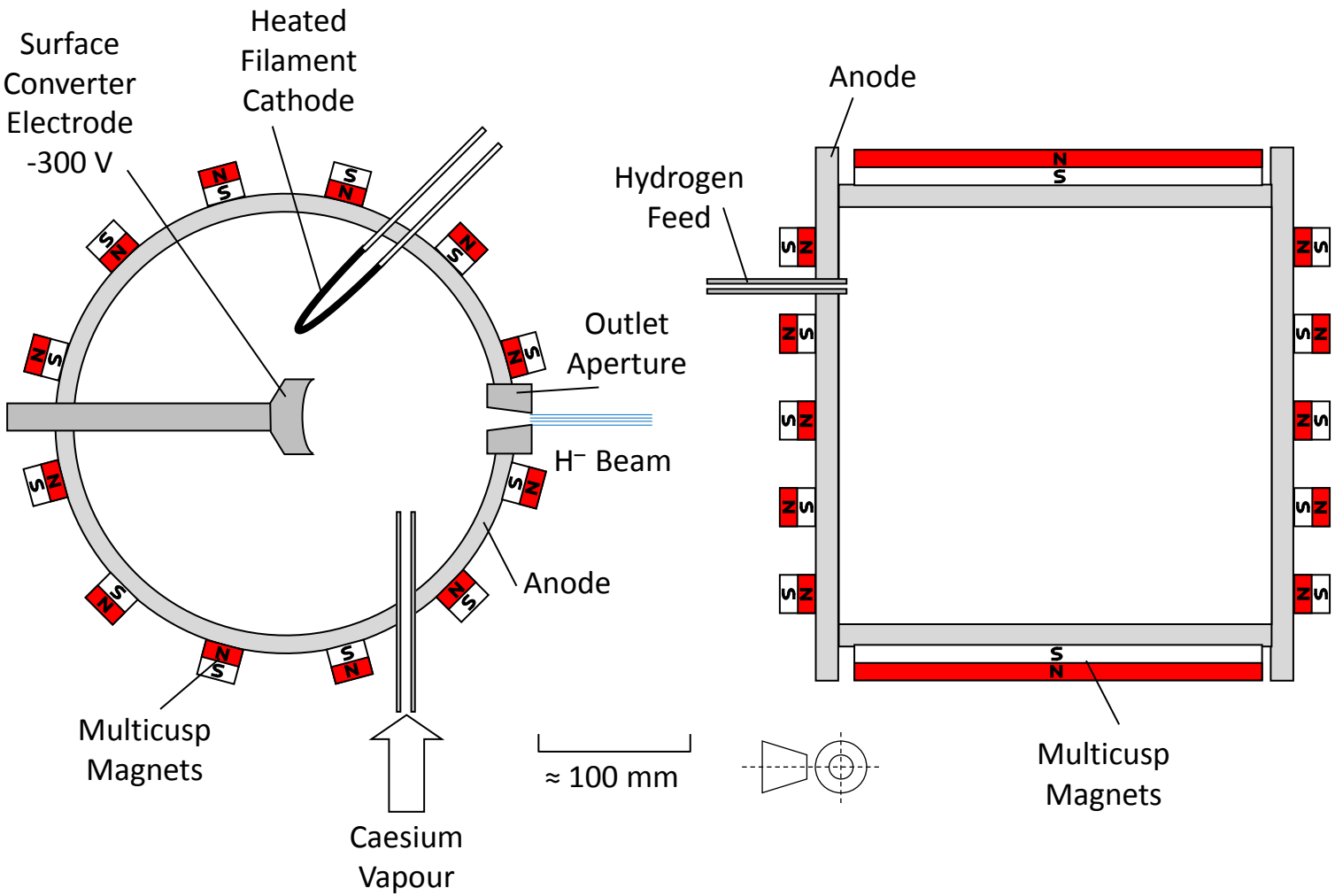


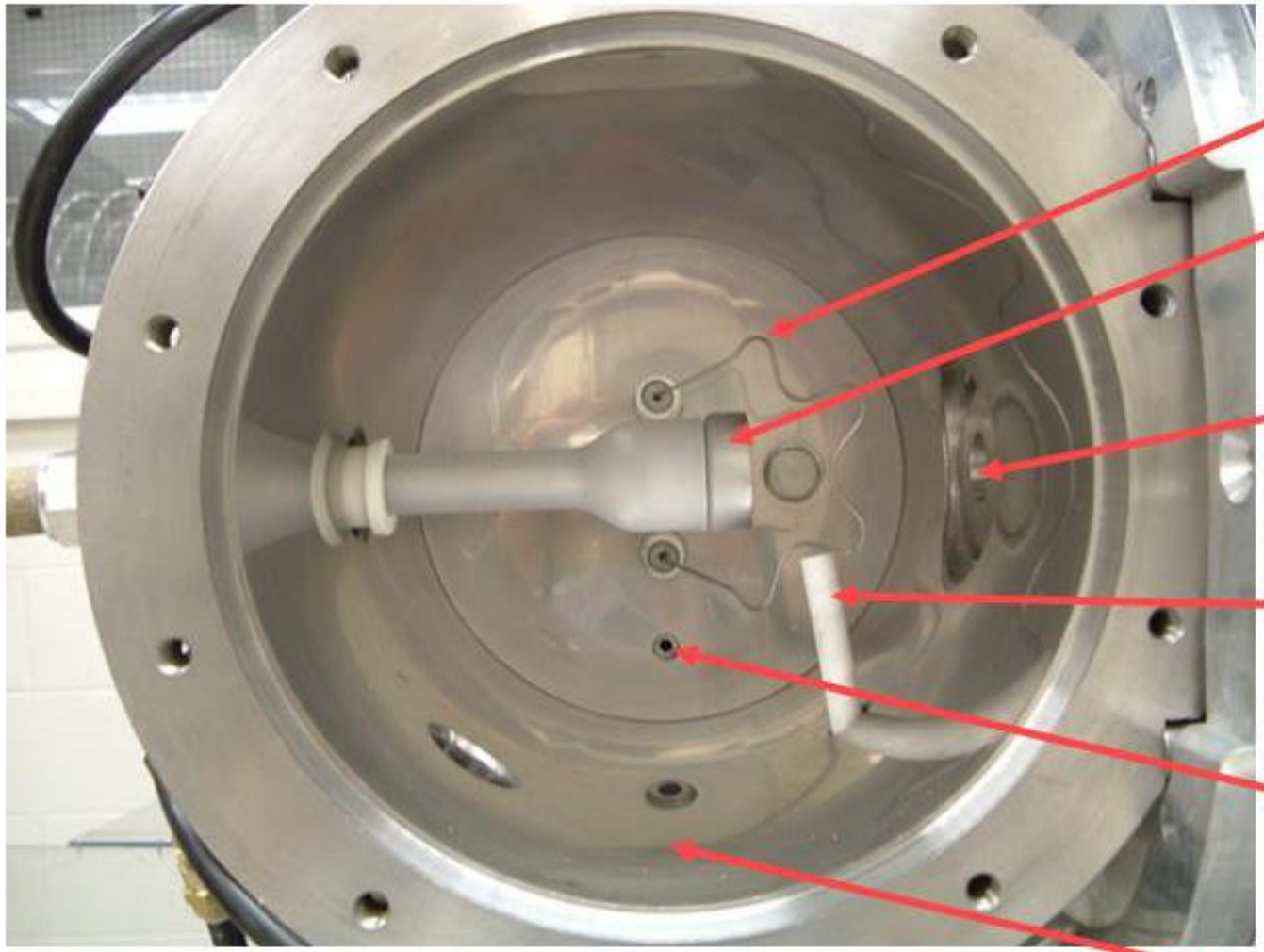
ISIS Ion Source
60 mA 2 ms 50 Hz
H^- beams

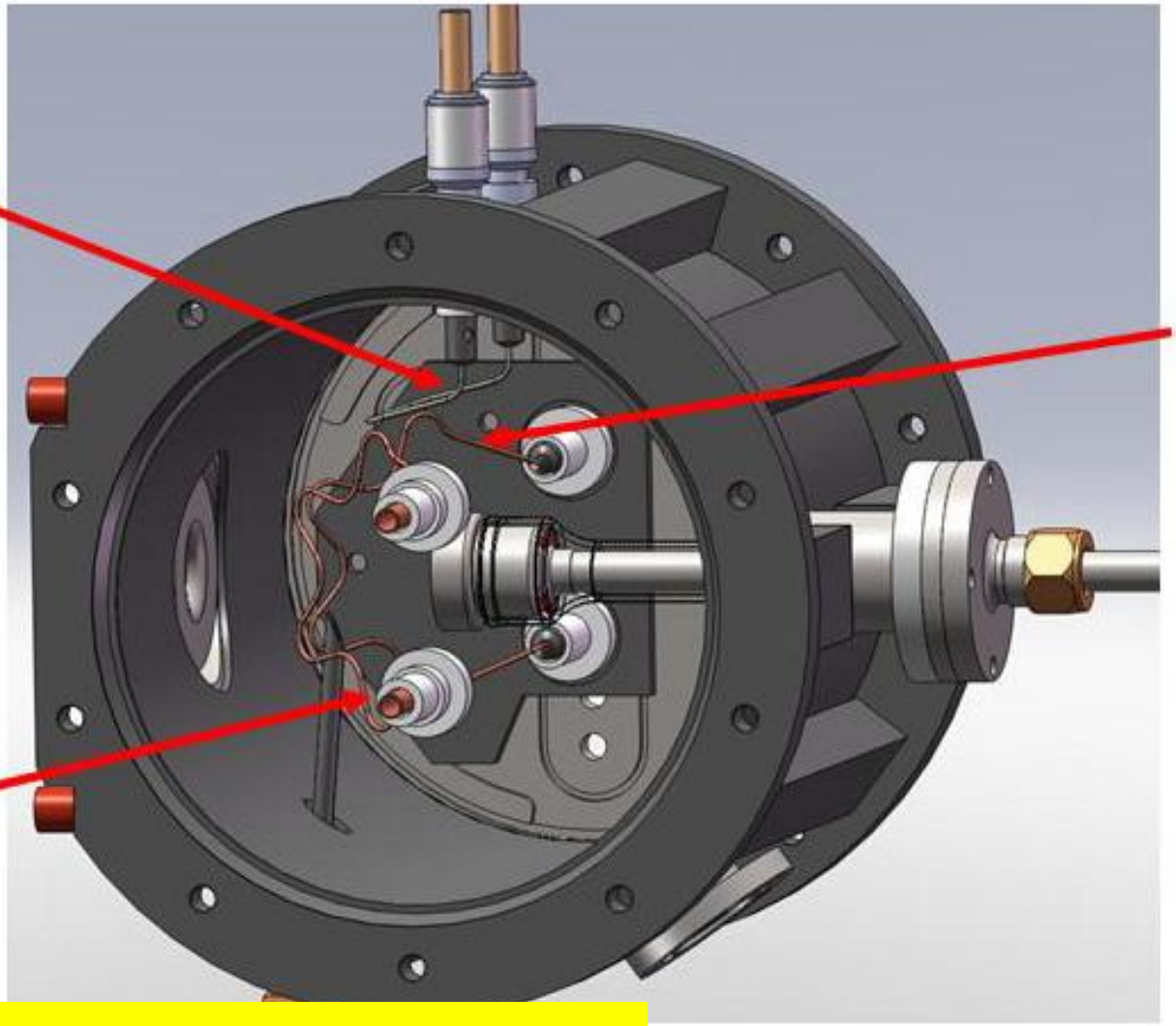
Particles and **Sources**



Filament Cathode Multicusp Surface Converter Source

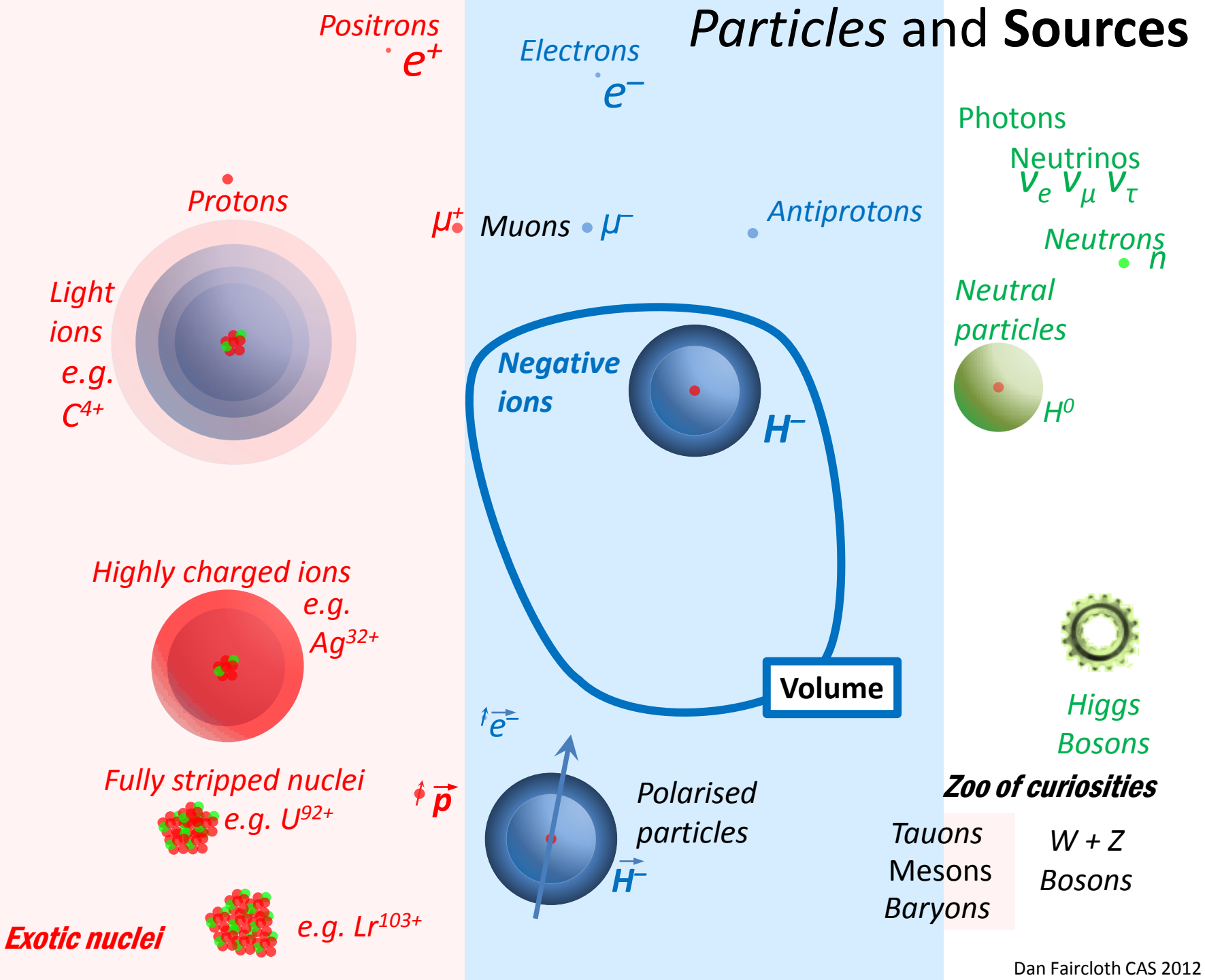



Filament
Converter electrode
Repeller electrode
Cesium dispenser
Hydrogen Gas Port
Plasma Chamber Wall



LANL with multiple filaments:
1 A of H^-

Particles and **Sources**



Marthe Bacal
Ecole Polytechnique
mid 1970's

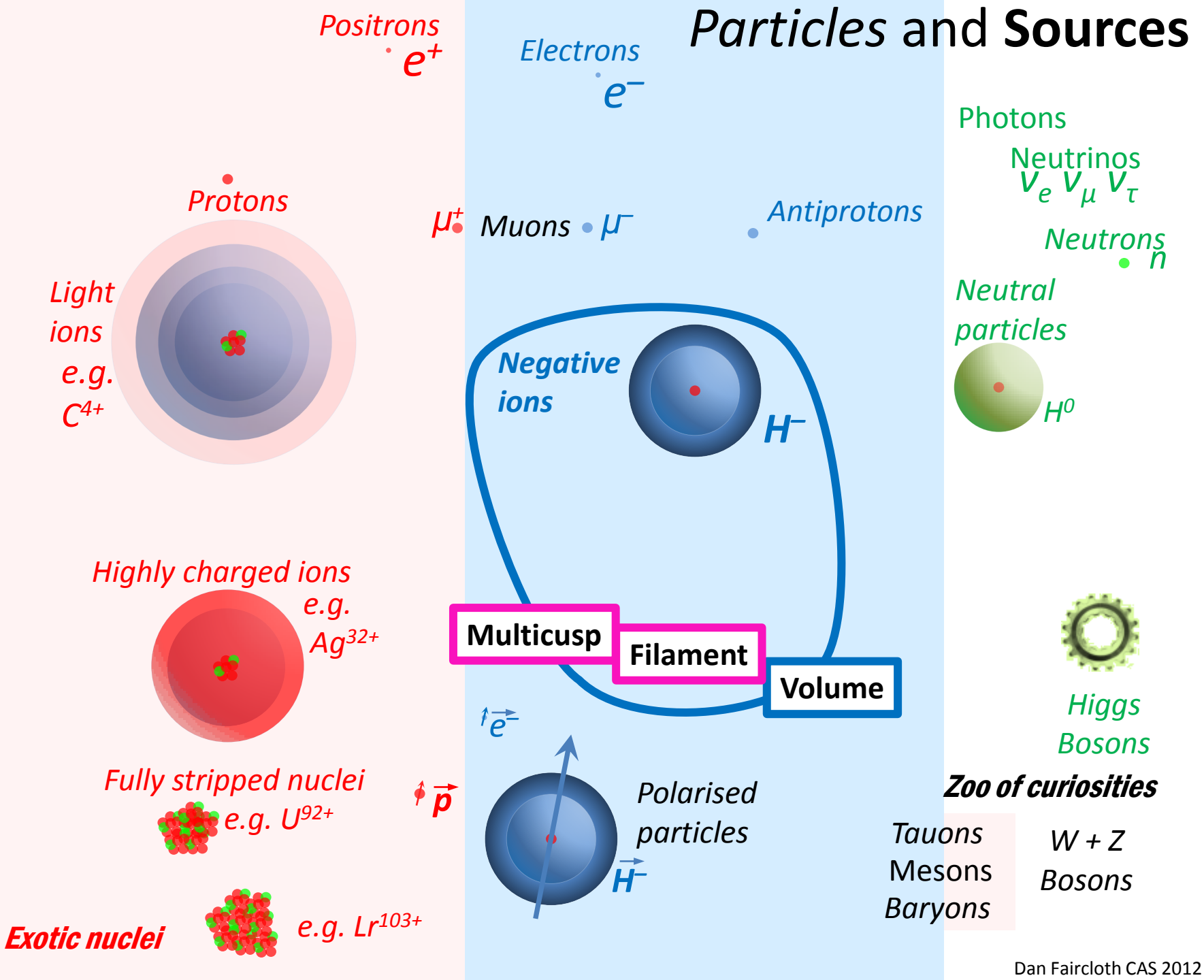
Volume Production

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

Dissociative attachment
of low energy electrons
to rovibrationally excited
H_2 molecules

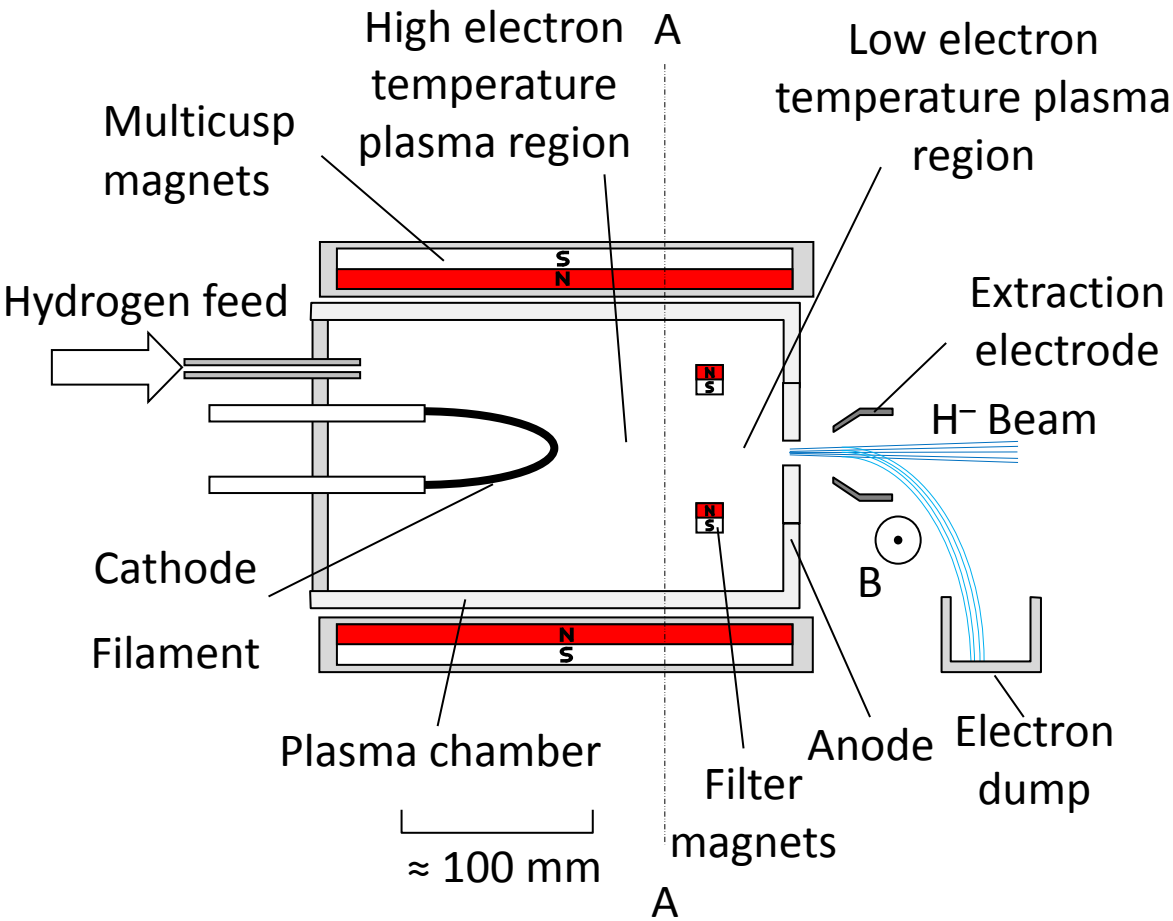
Developed by Ehlers + Leung at LBNL

Particles and **Sources**

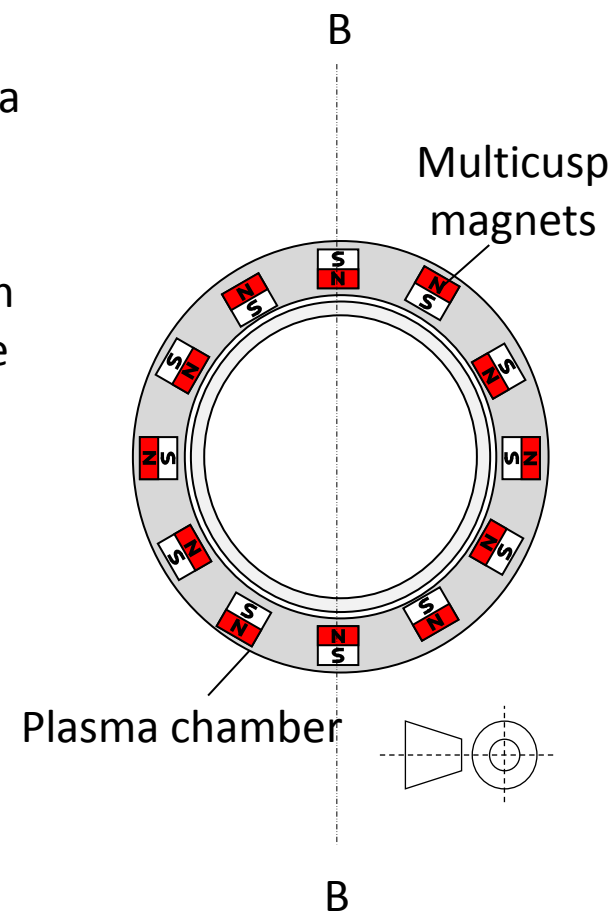


Dan Faircloth CAS 2012

Multicusp Filament Volume Source



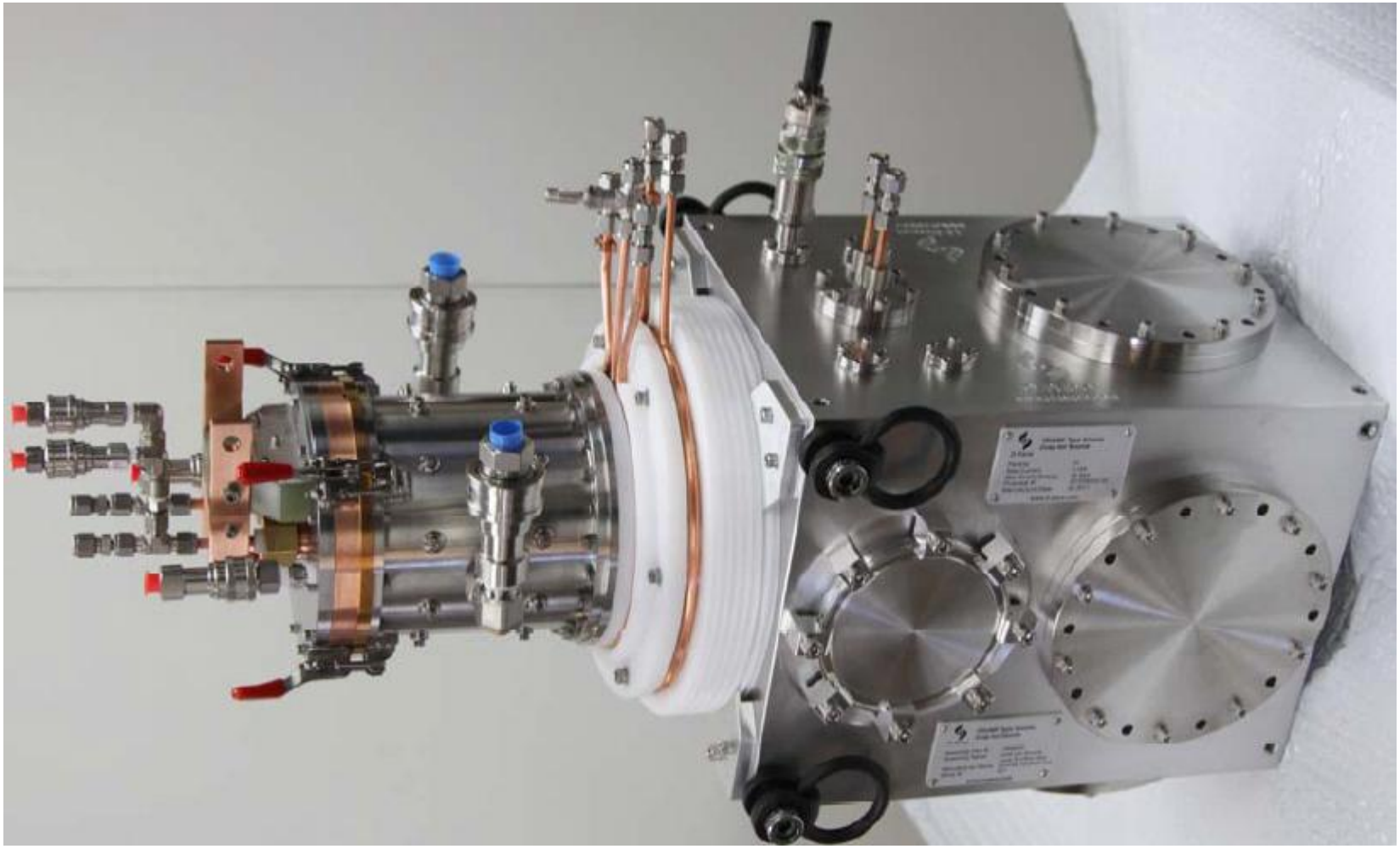
Section on B-B



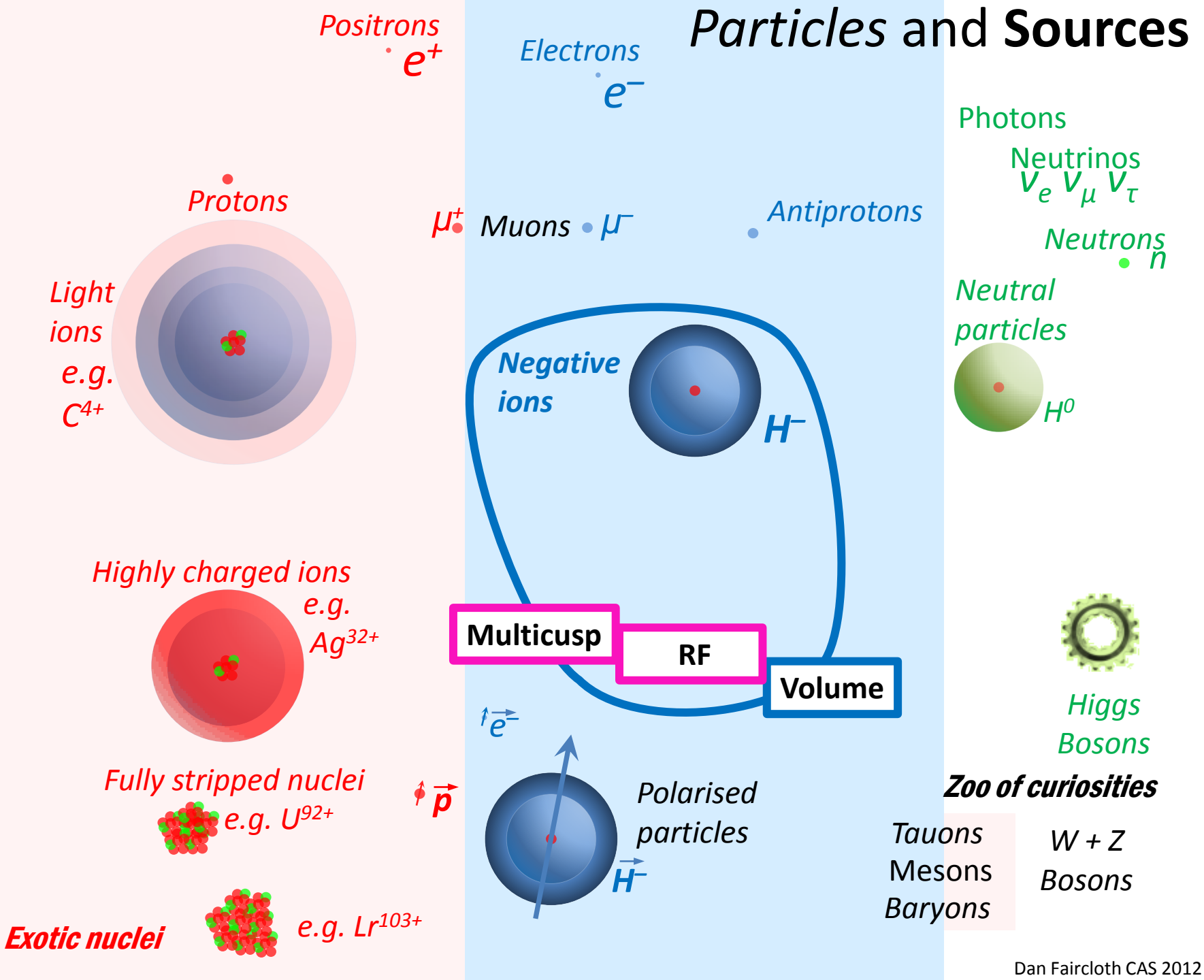
Section on A-A

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

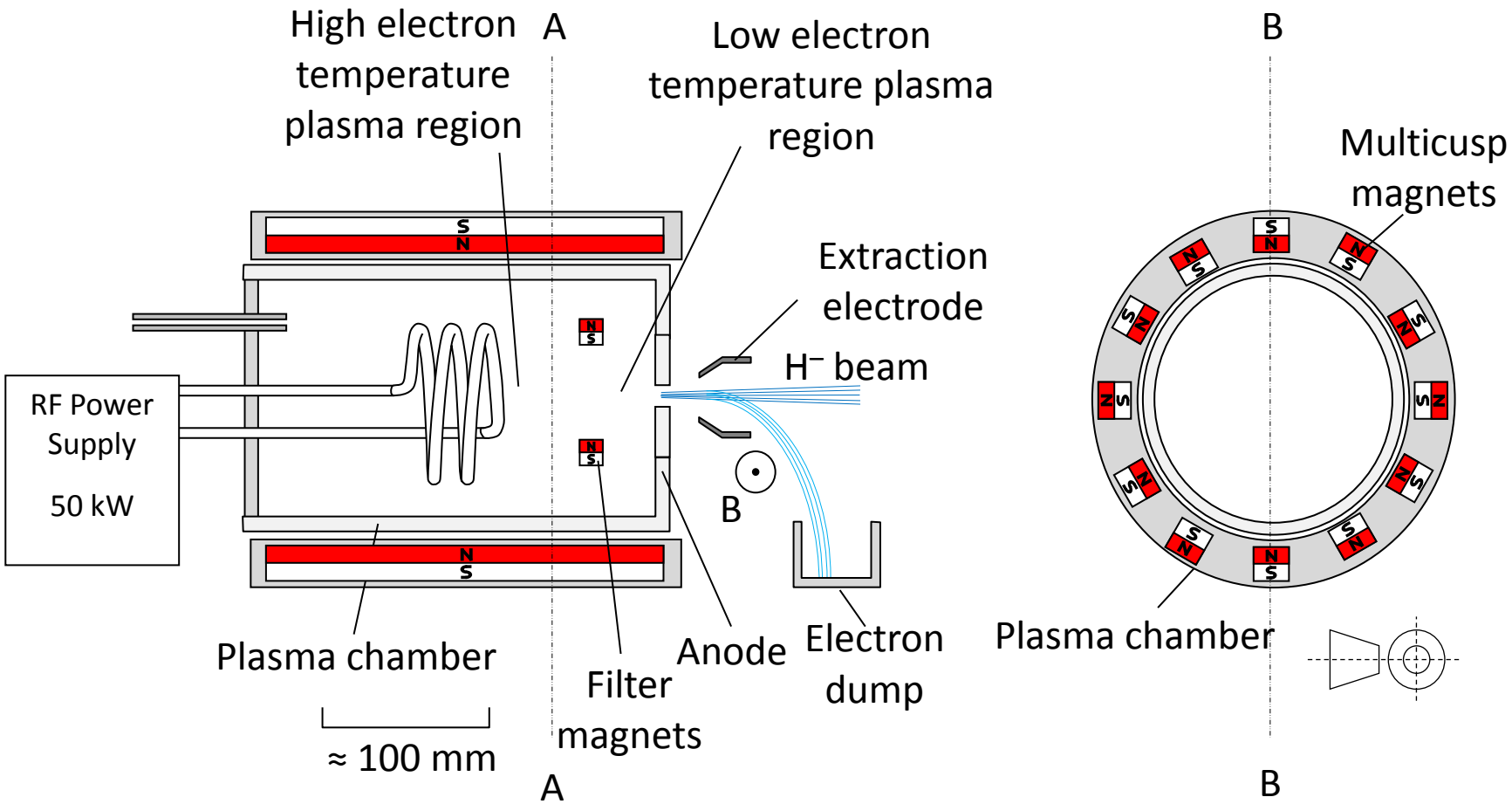
D-Pace 15 mA DC H^- Multicusp Volume Source



Particles and **Sources**



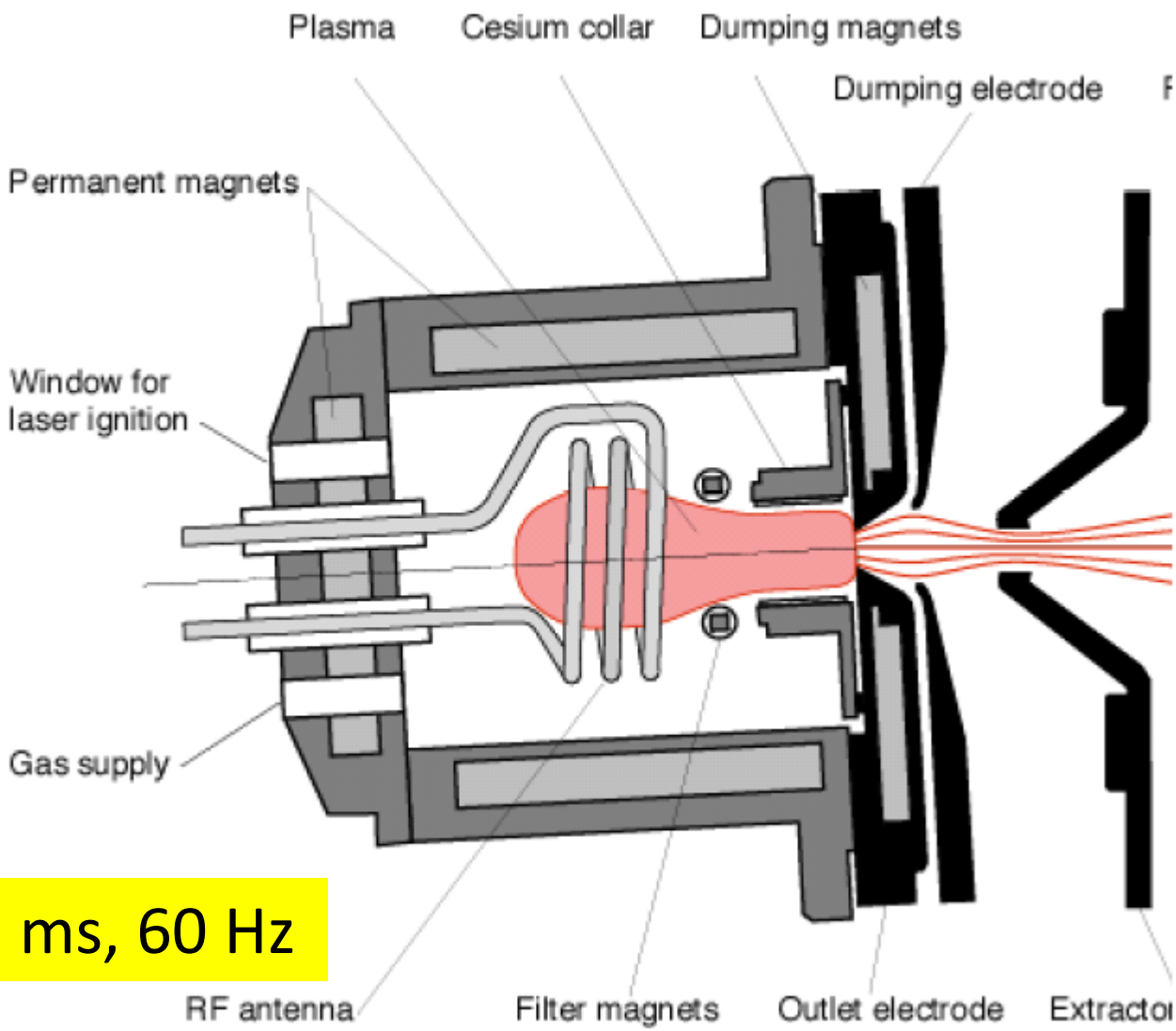
Internal RF Solenoid Antenna Volume Source



Section on B-B

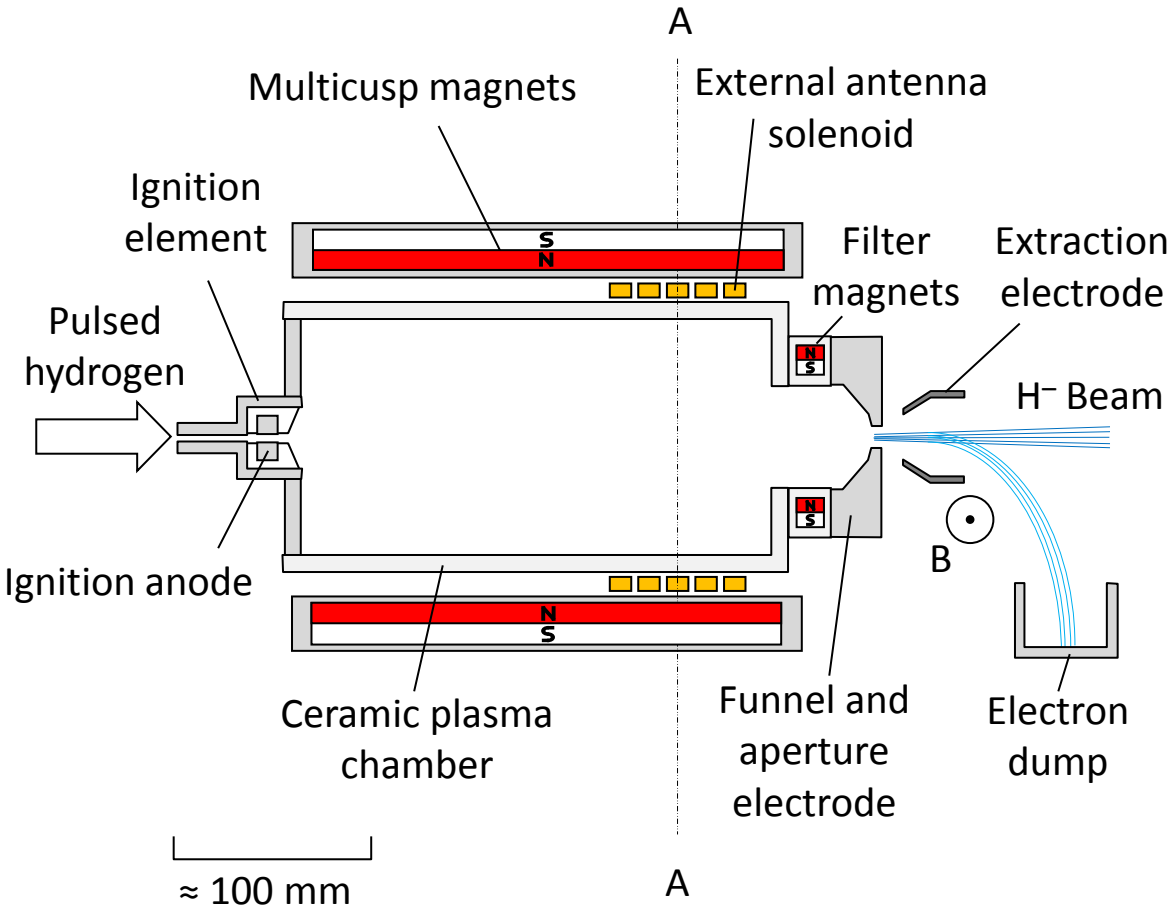
Section on A-A

SNS ion source

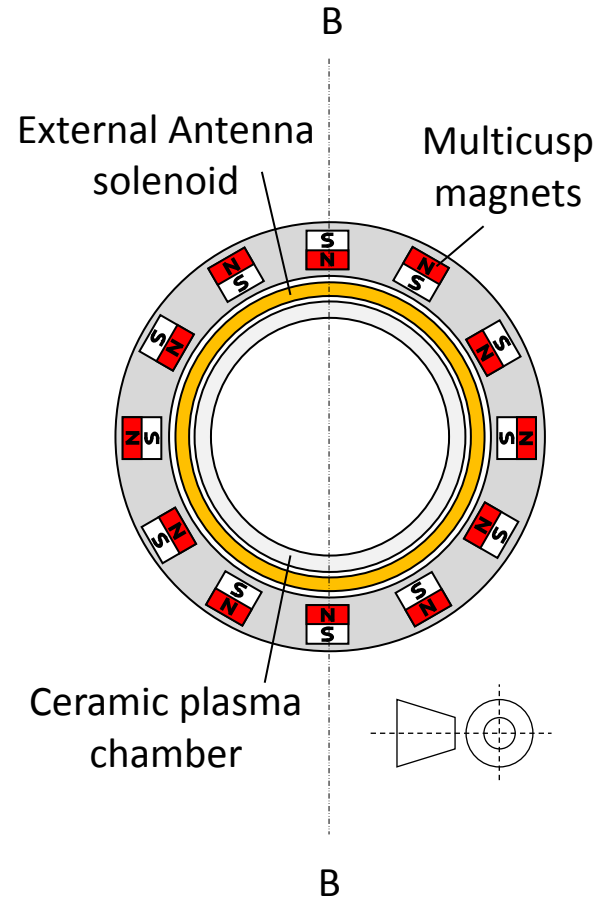


38 mA H^- 1 ms, 60 Hz

External RF Antenna Multicusp Source



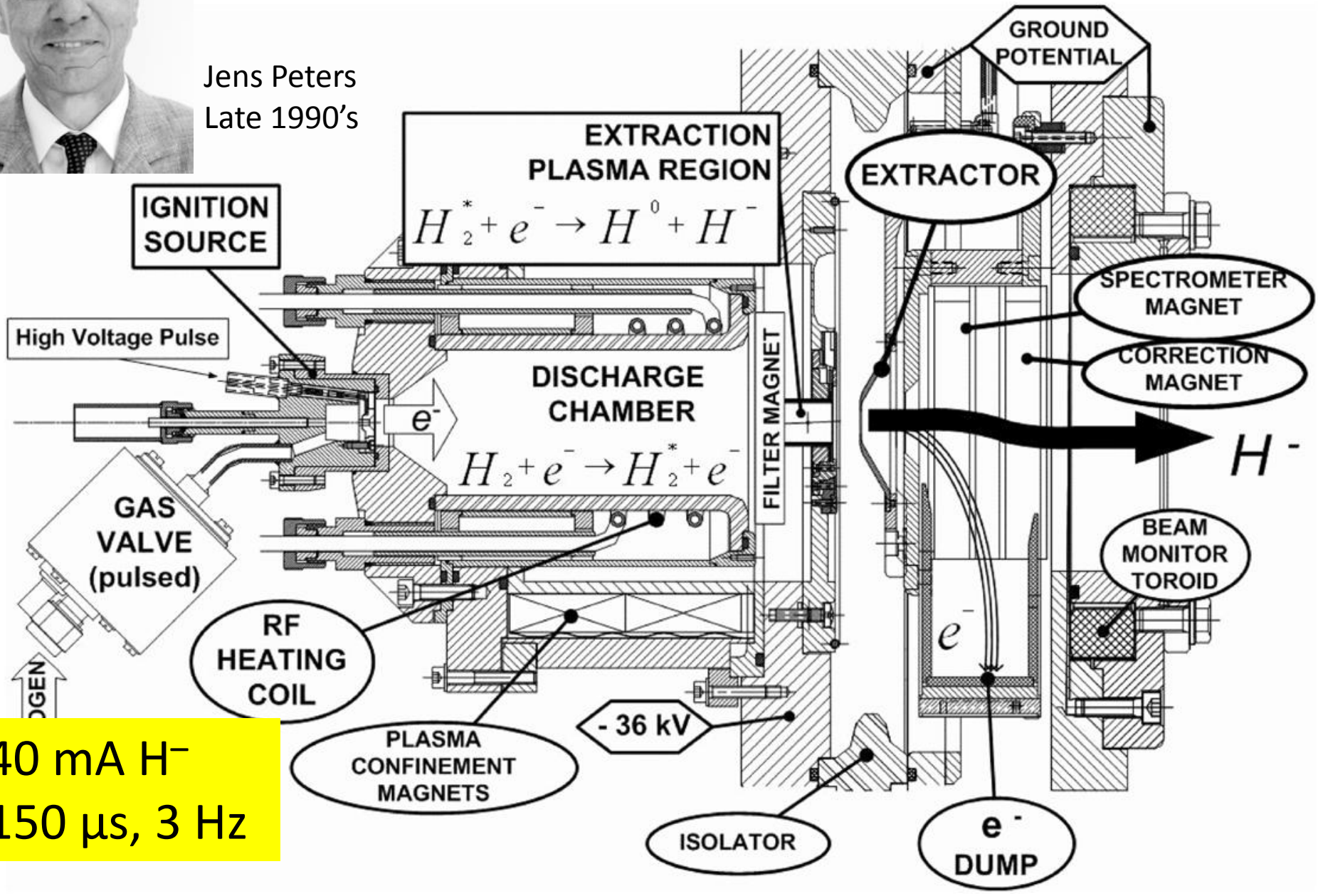
Section on B-B



Section on A-A

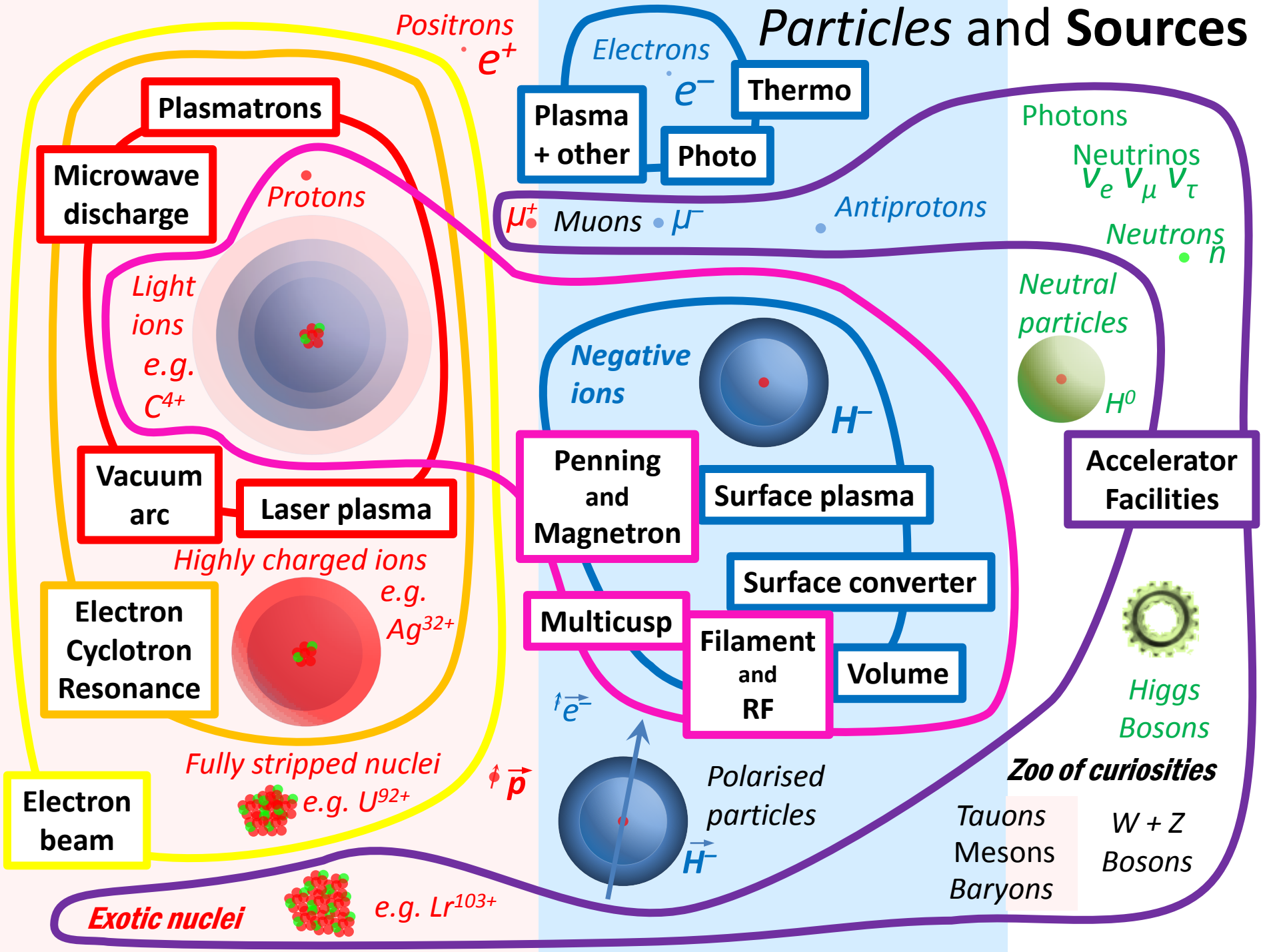
DESY Source

Jens Peters
Late 1990's



40 mA H^-
150 µs, 3 Hz

Particles and **Sources**



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

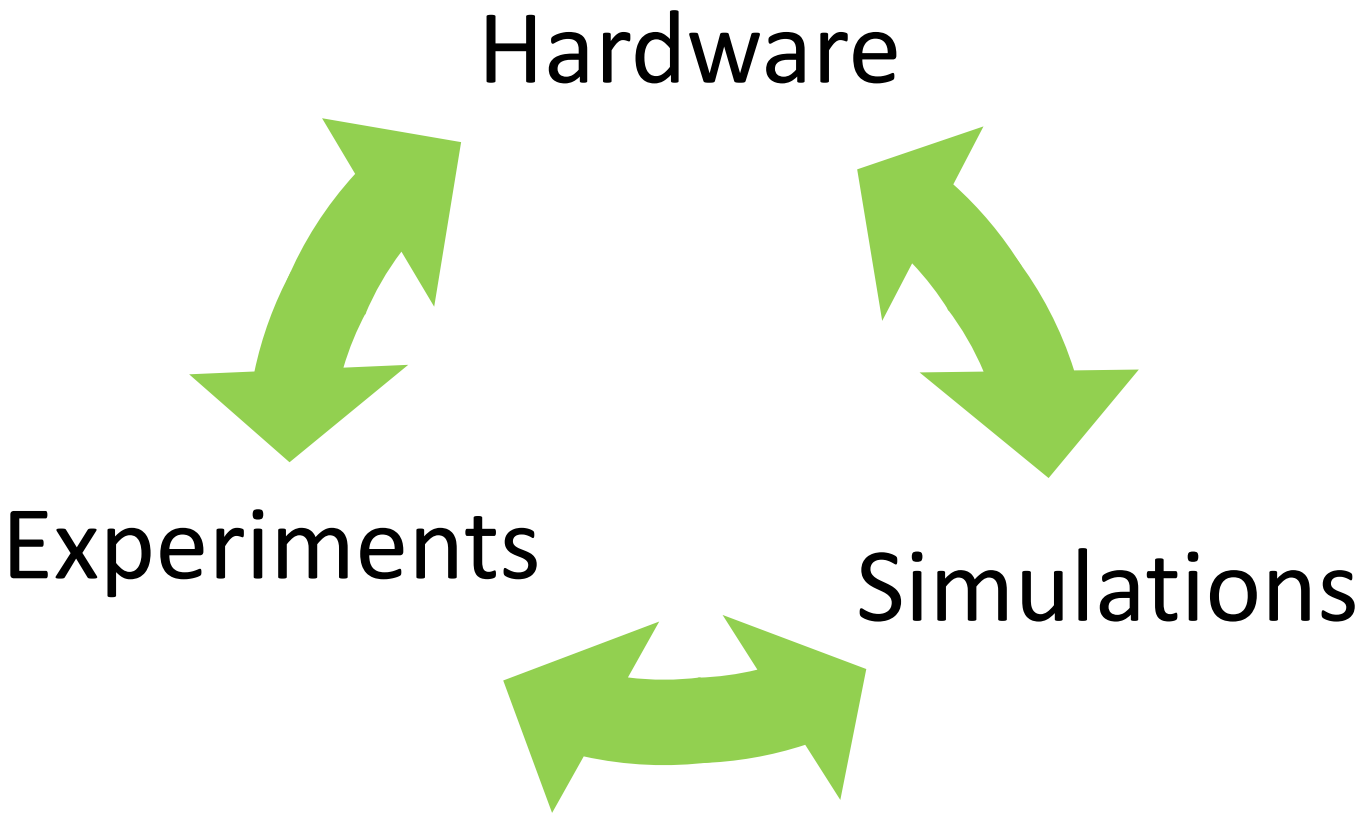
Driven by demand for

- 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