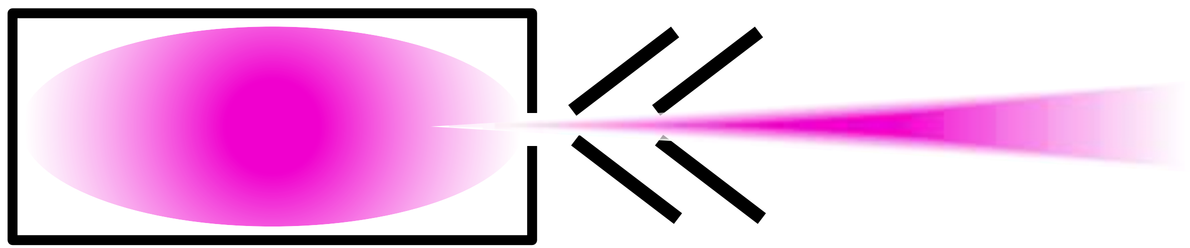
Ion Sources

Dr Dan Faircloth
Low Energy Beams Group Leader - ISIS
Rutherford Appleton Laboratory

Ion sources consist of:



Particle generator (plasma) + An extraction system

Plasma Pioneers

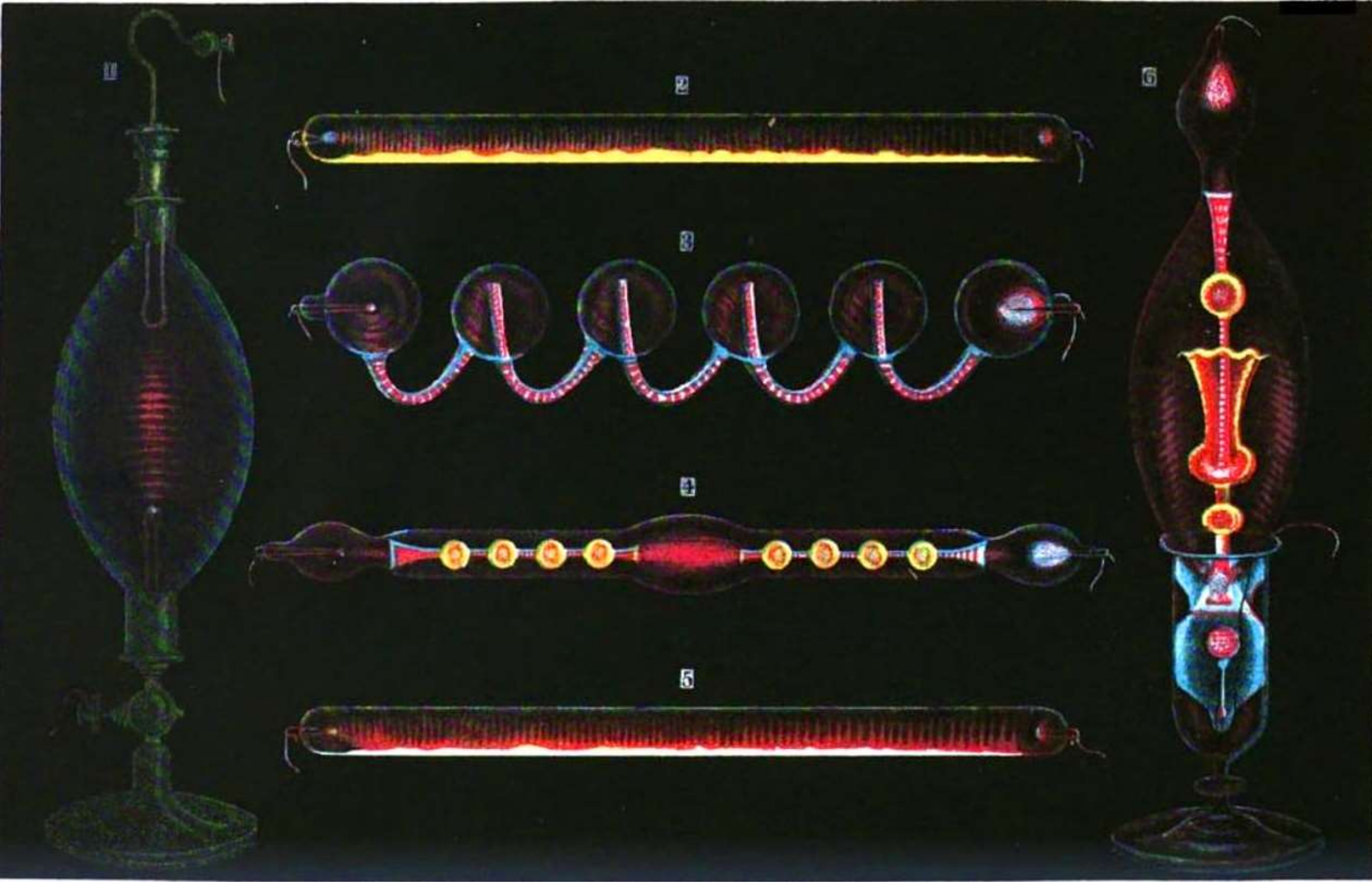
Heinrich Geißler

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

Julius Plücker

Mid 1850’s University of Bonn

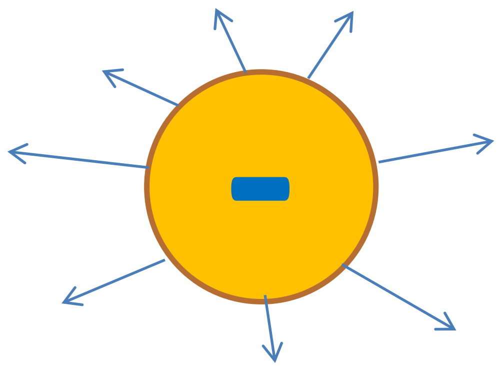
magnetism could move the glow discharge



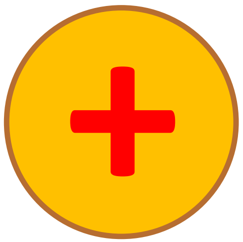
Drawing of Geissler tubes from 1860’s French physics book

Fredrick Guthrie

British scientific writer and professor



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



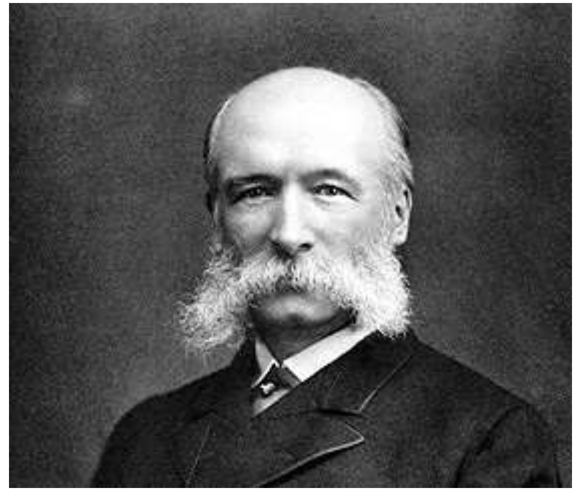
...whereas a positively charged one keeps its charge

Elements of Heat in 1868

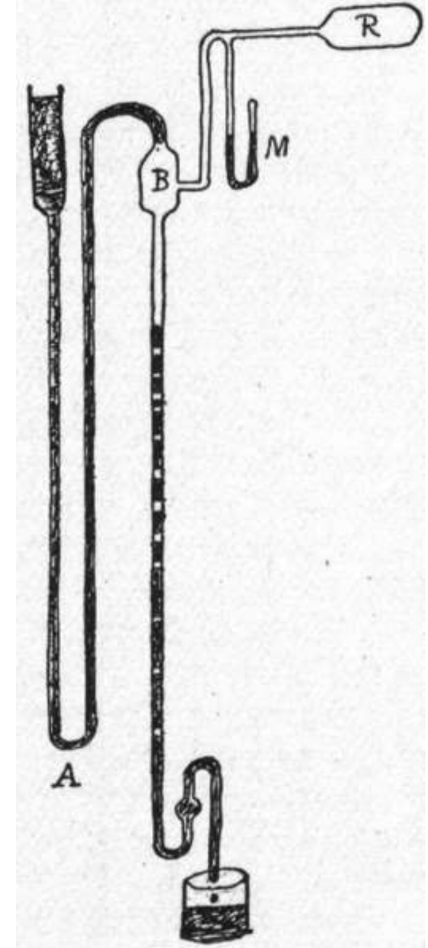
First experimental observation of thermionic emission

Early 1870's

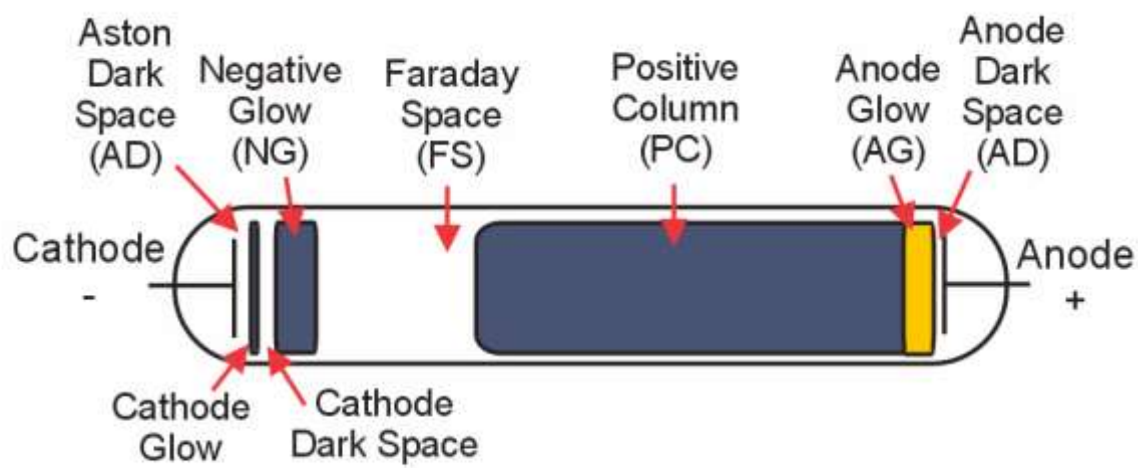
William Crookes



Hermann Sprengel

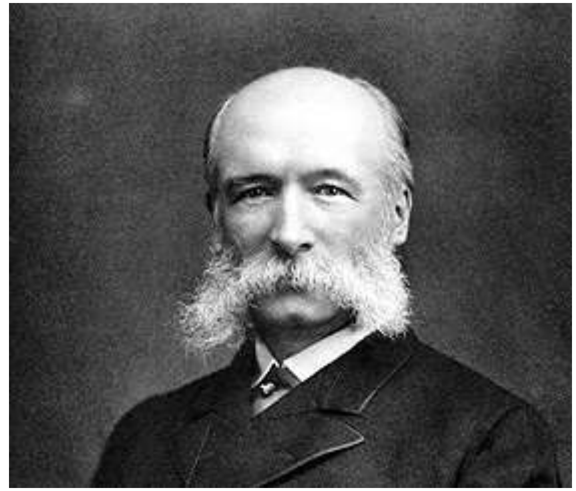


Improved mercury pump
10^{-5} mbar

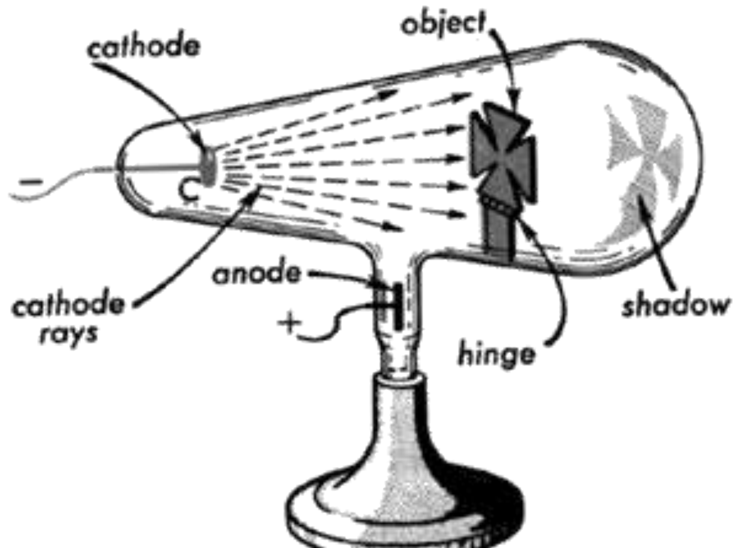


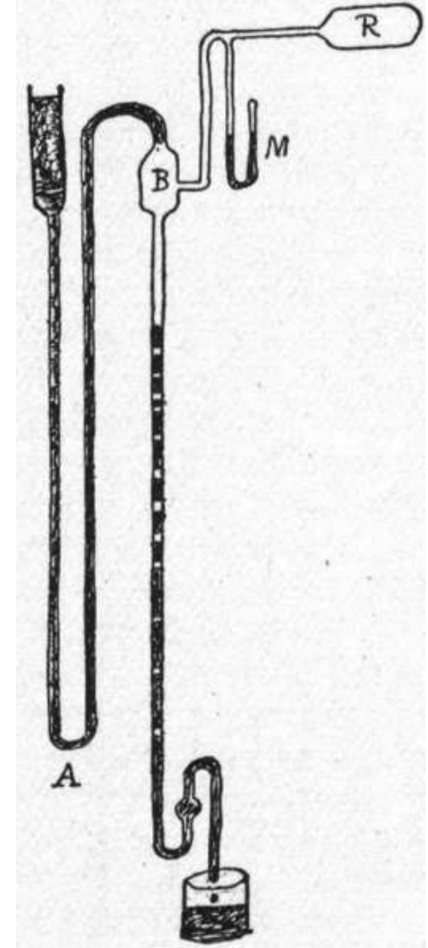
Early 1870's

William Crookes



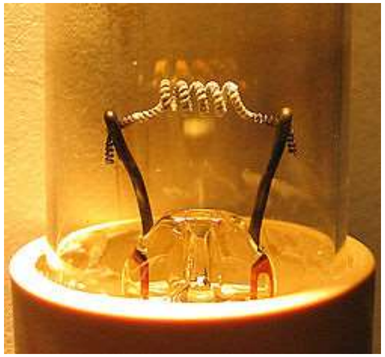
Hermann Sprengel



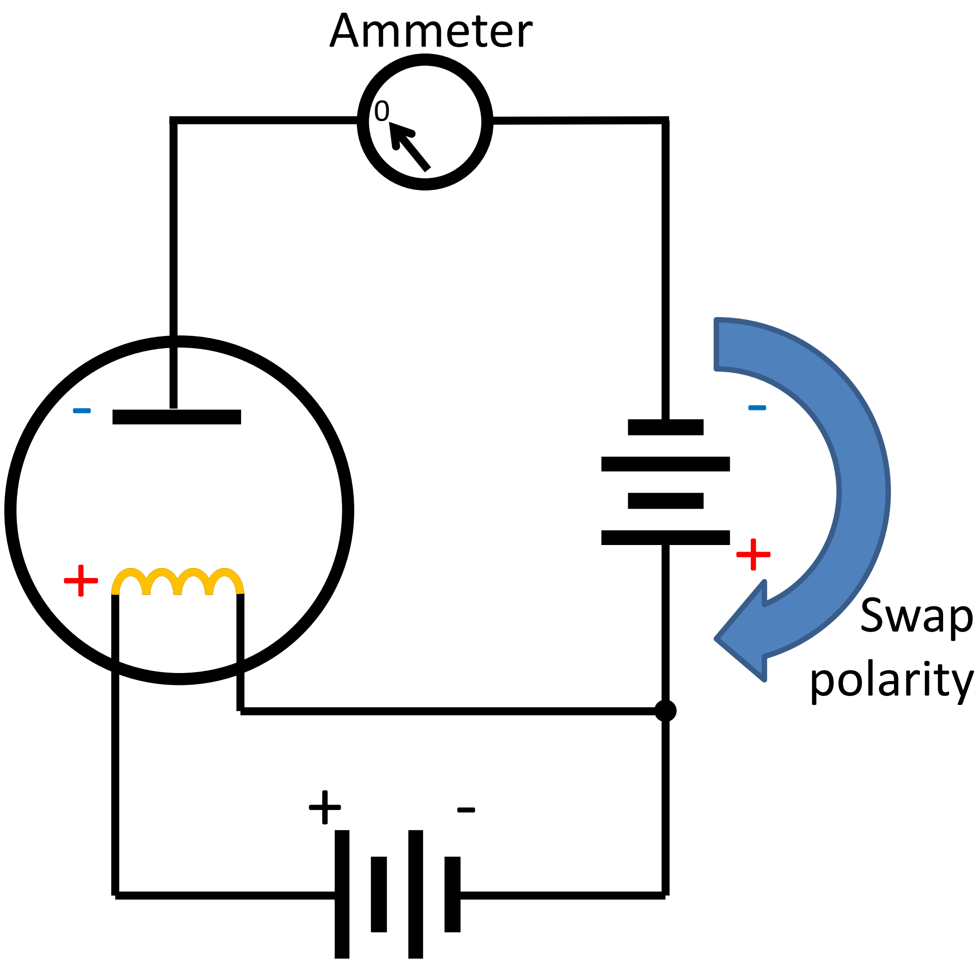


Improved mercury pump 10^{-5} mbar

Thermionic Emission

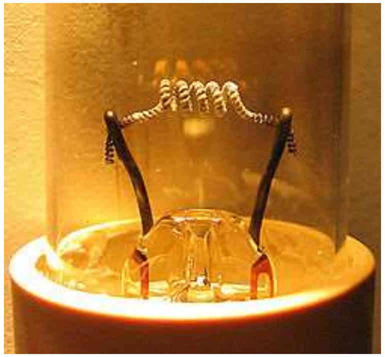


1880 Thomas Edison

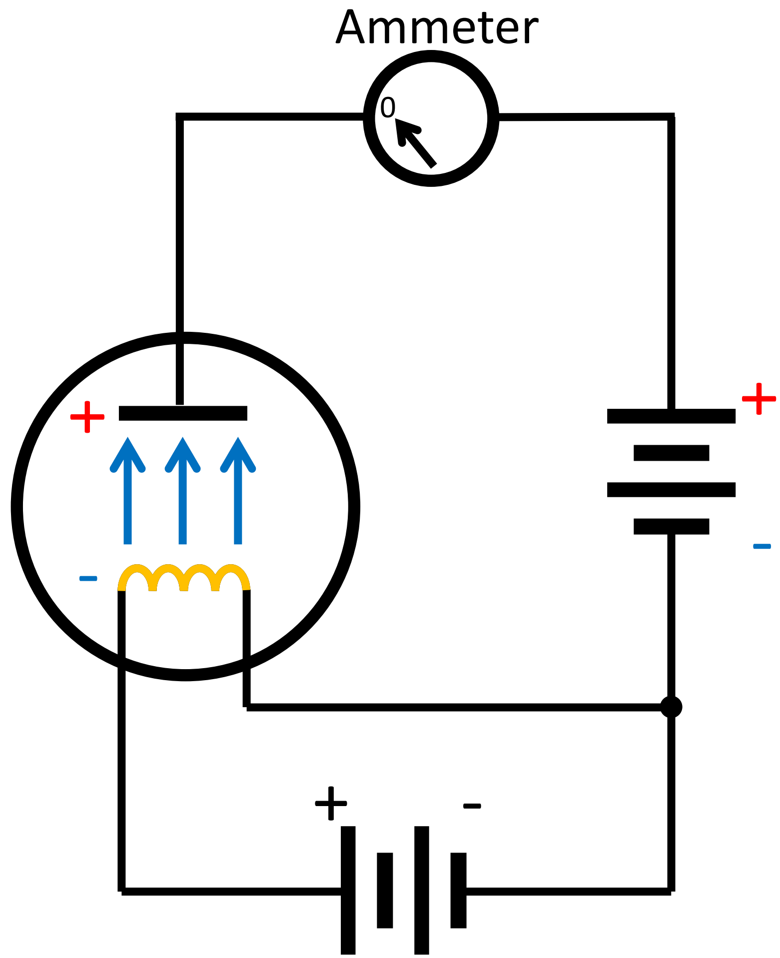


The "Edison effect"

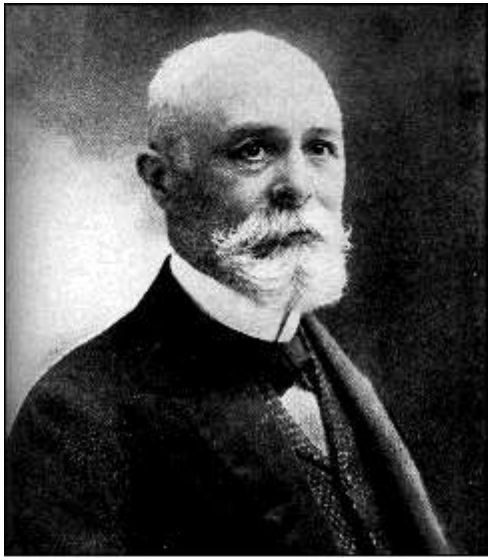
Thermionic Emission



1880 Thomas Edison

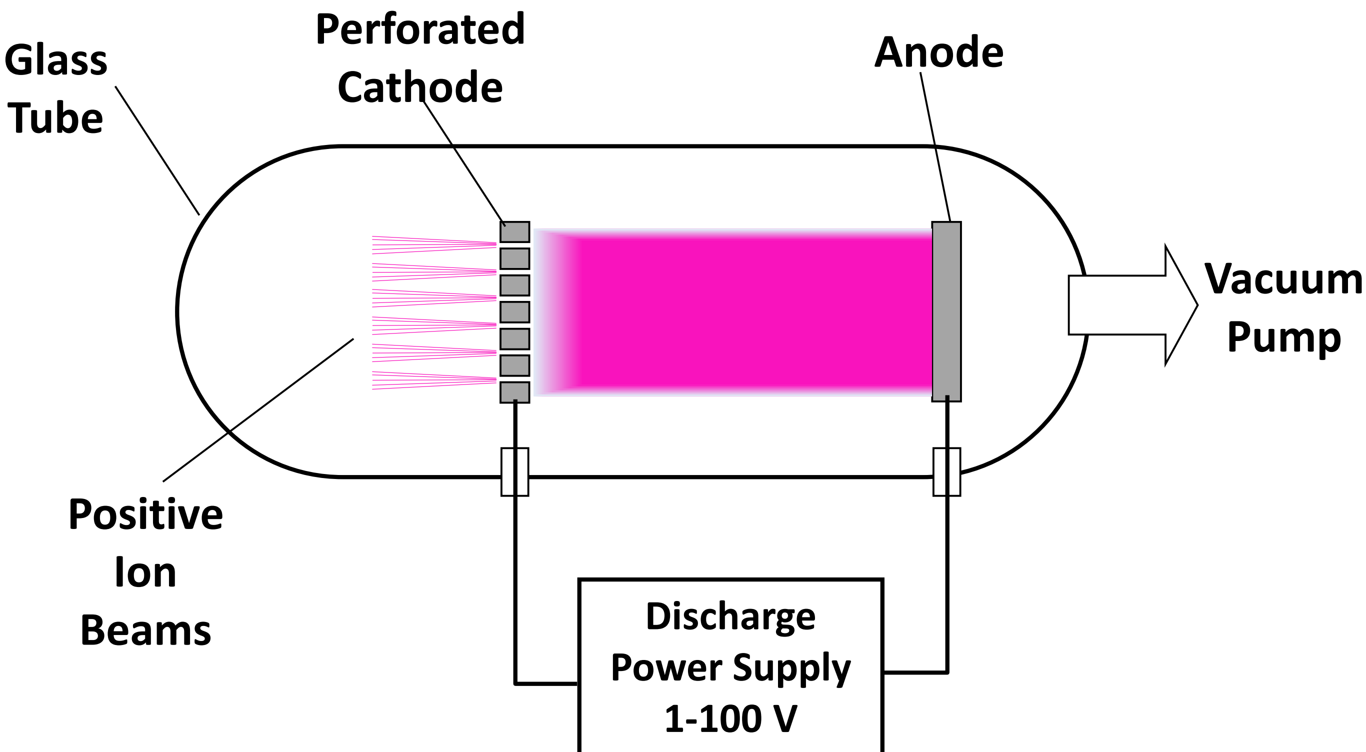


The “Edison effect”

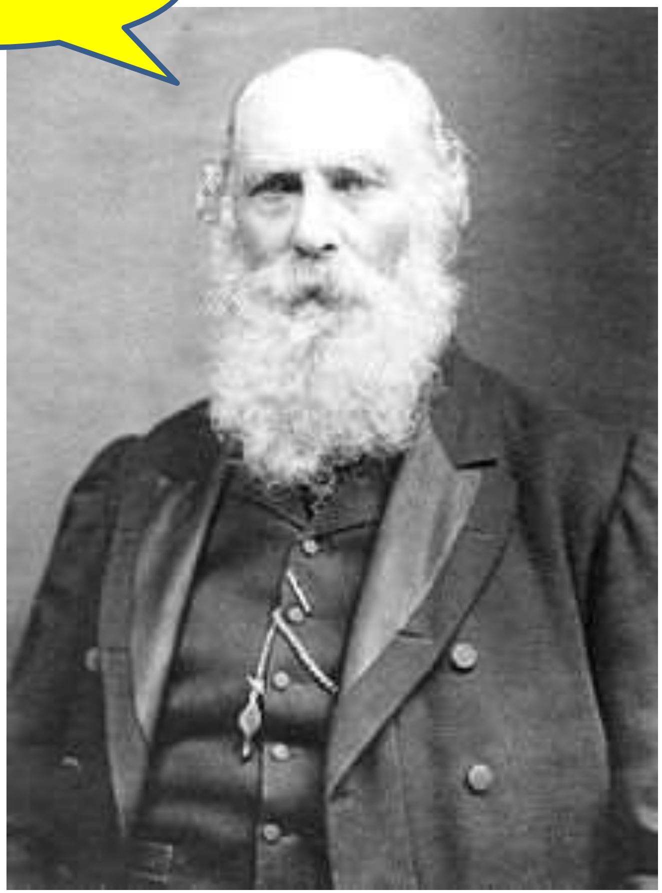


Canal Ray Source

In 1886 Eugen Goldstein discovered canal rays



“Discovery” of the Electron



George Johnstone Stoney
1894

J. J. Thomson
1897

Thermionic Emission

Corpuscles

J. J. Thomson
1897

1901 Owen Richardson

Cambridge University

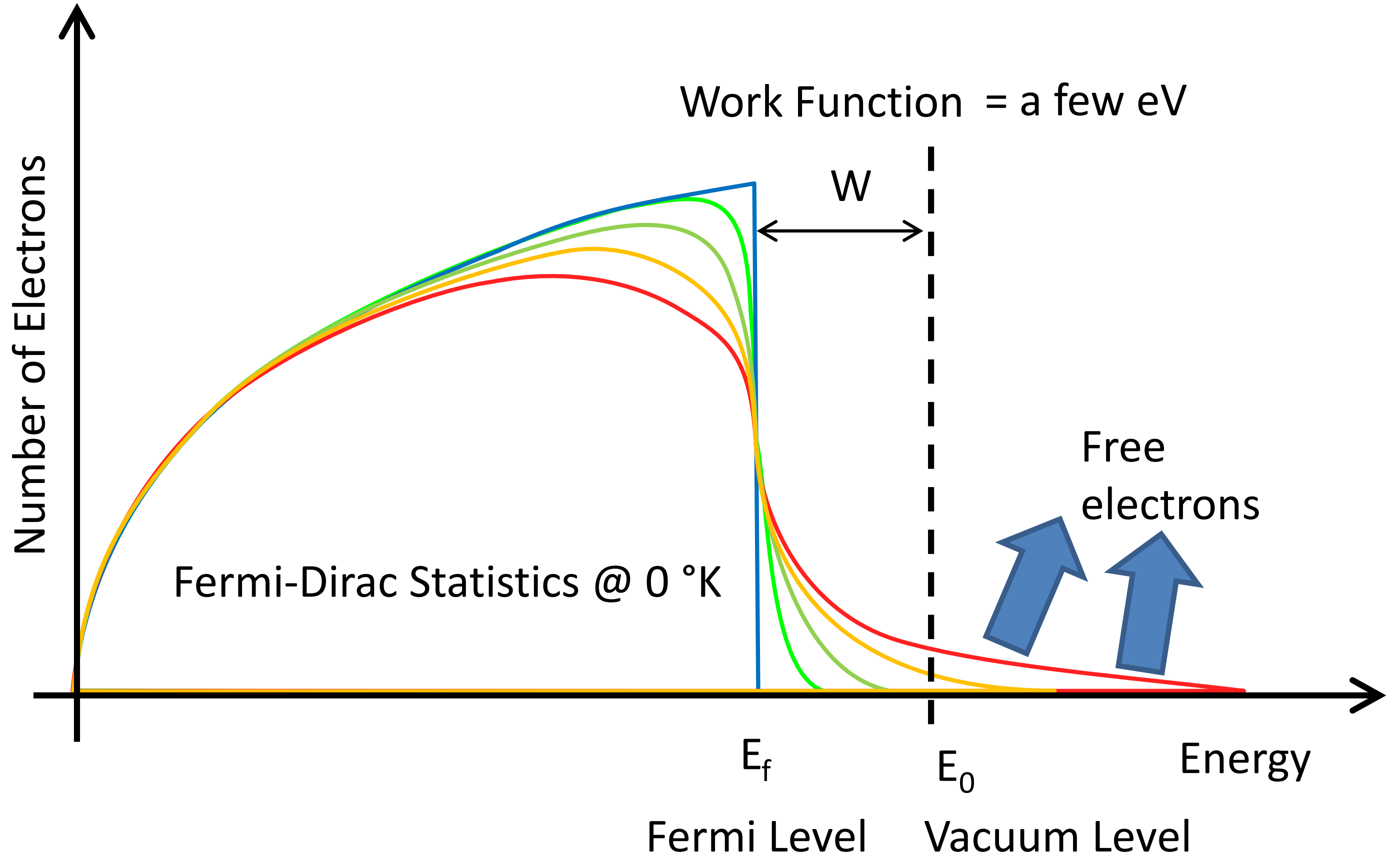
$$J = A_G T^2 e^{\frac{-W}{kT}}$$

Richardson's Law

Same form as the Arrhenius equation

Current increases exponentially with temperature

Thermionic Emission



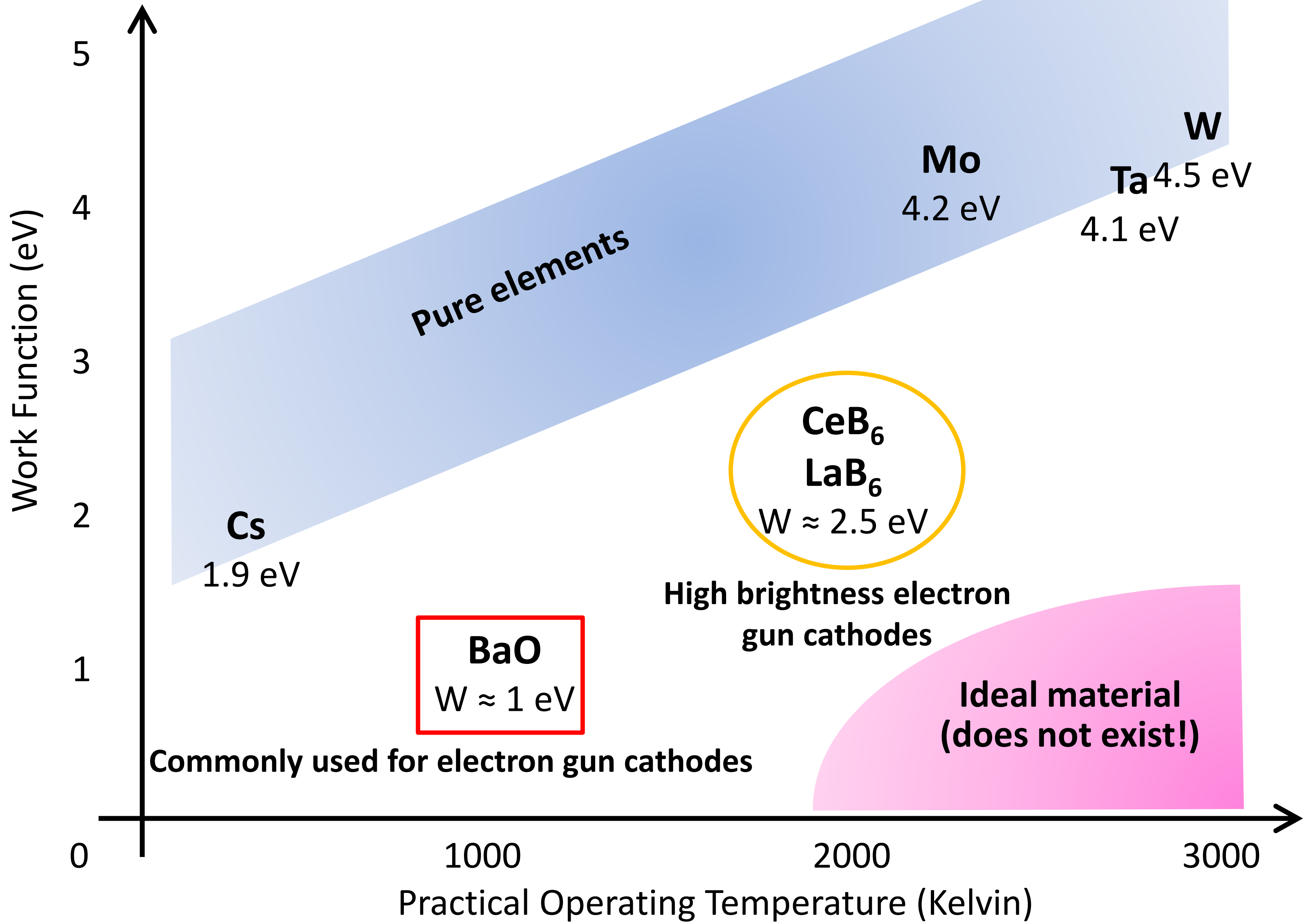
$$J = A_G T^2 e^{\frac{-W}{kT}}$$

For a good electron emitter you need:

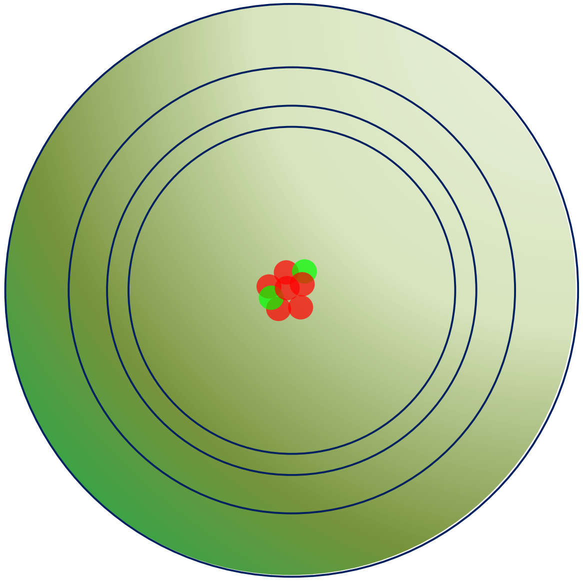
Lowest possible work function

Highest possible temperature

Electron emitting materials



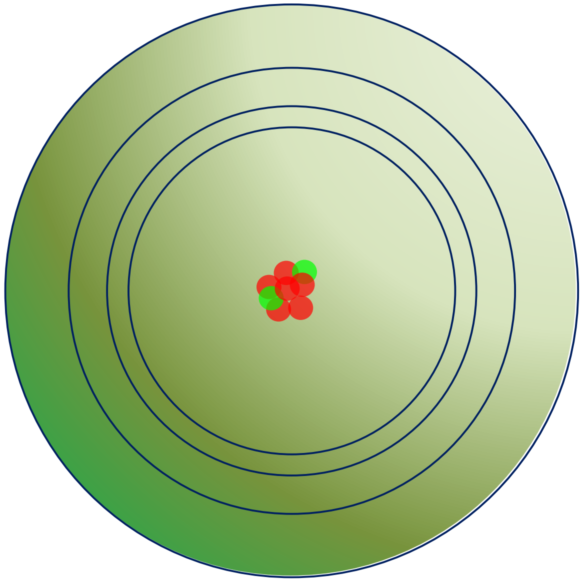
Ionisation



Neutral Atom

Most sources rely on electron impact ionisation

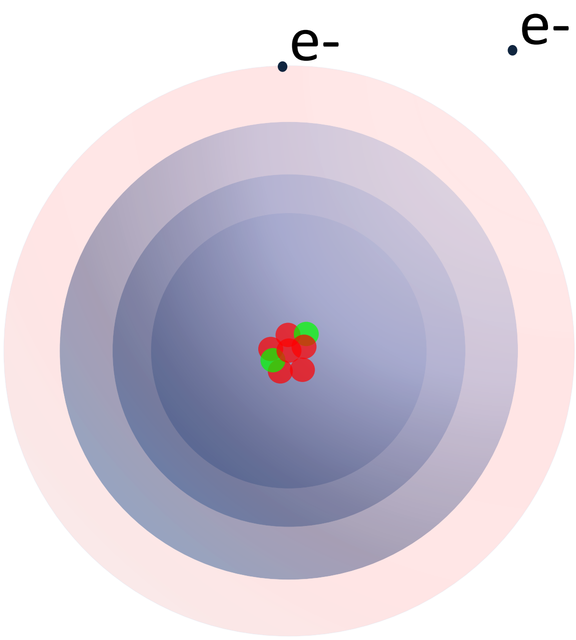
Ionisation



Neutral Atom

Most sources rely on electron impact ionisation

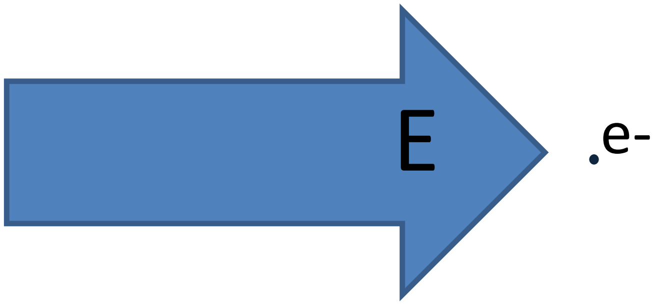
Ionisation



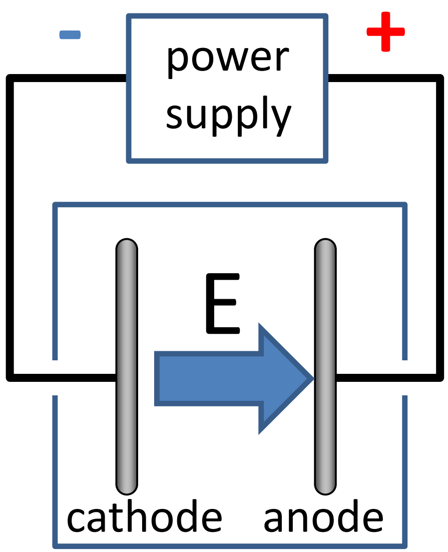
Positive Ion

Most sources rely on electron impact ionisation

Making electrons move

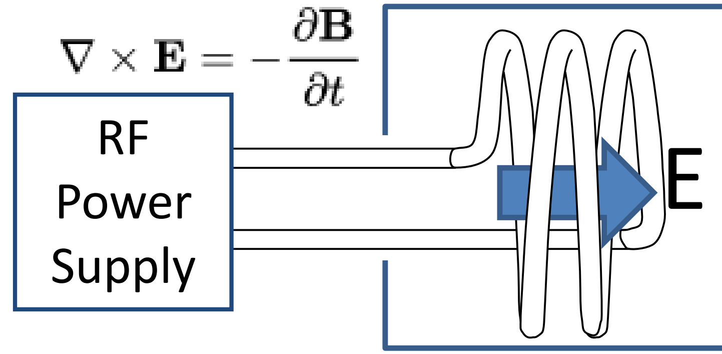


(a) Capacitively Coupled Plasma (CCP) = Voltage applied to electrodes creates electric field

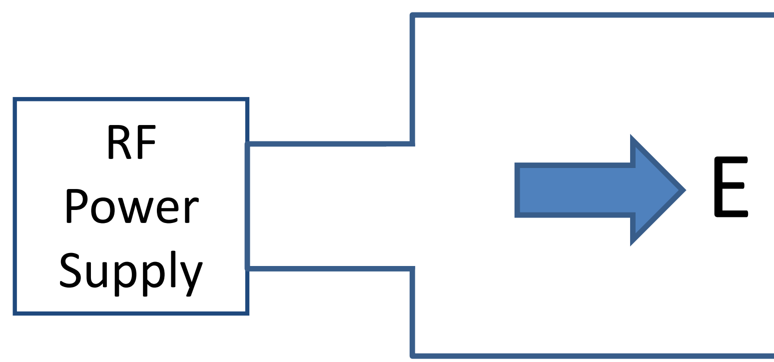


(b) Inductively Coupled Plasma (ICP) = Time varying current in a coil creates a magnetic field the induces a time varying electric field

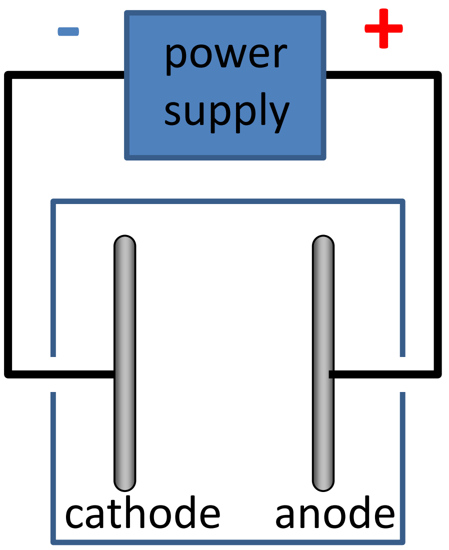
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$



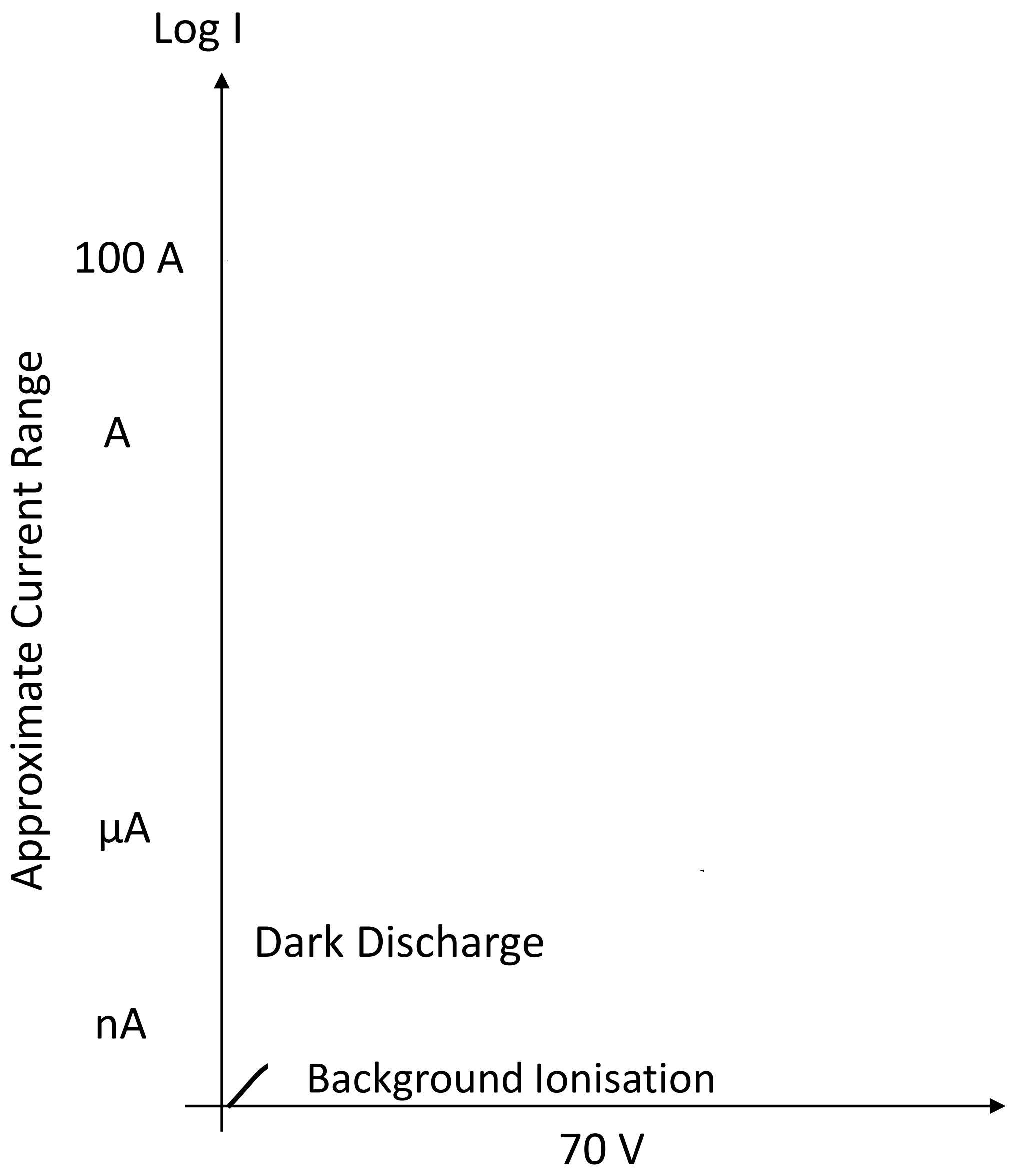
(c) The electric field component of an electromagnetic wave in a cavity

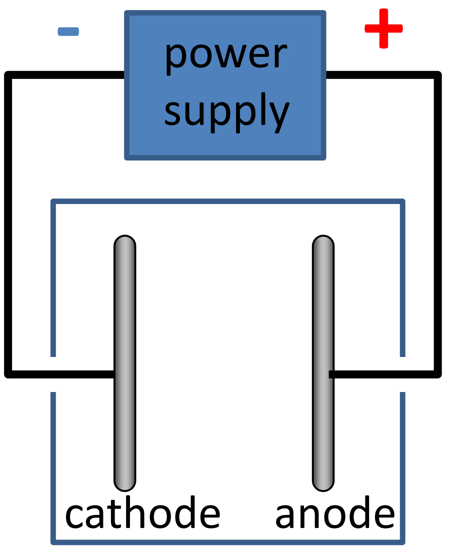


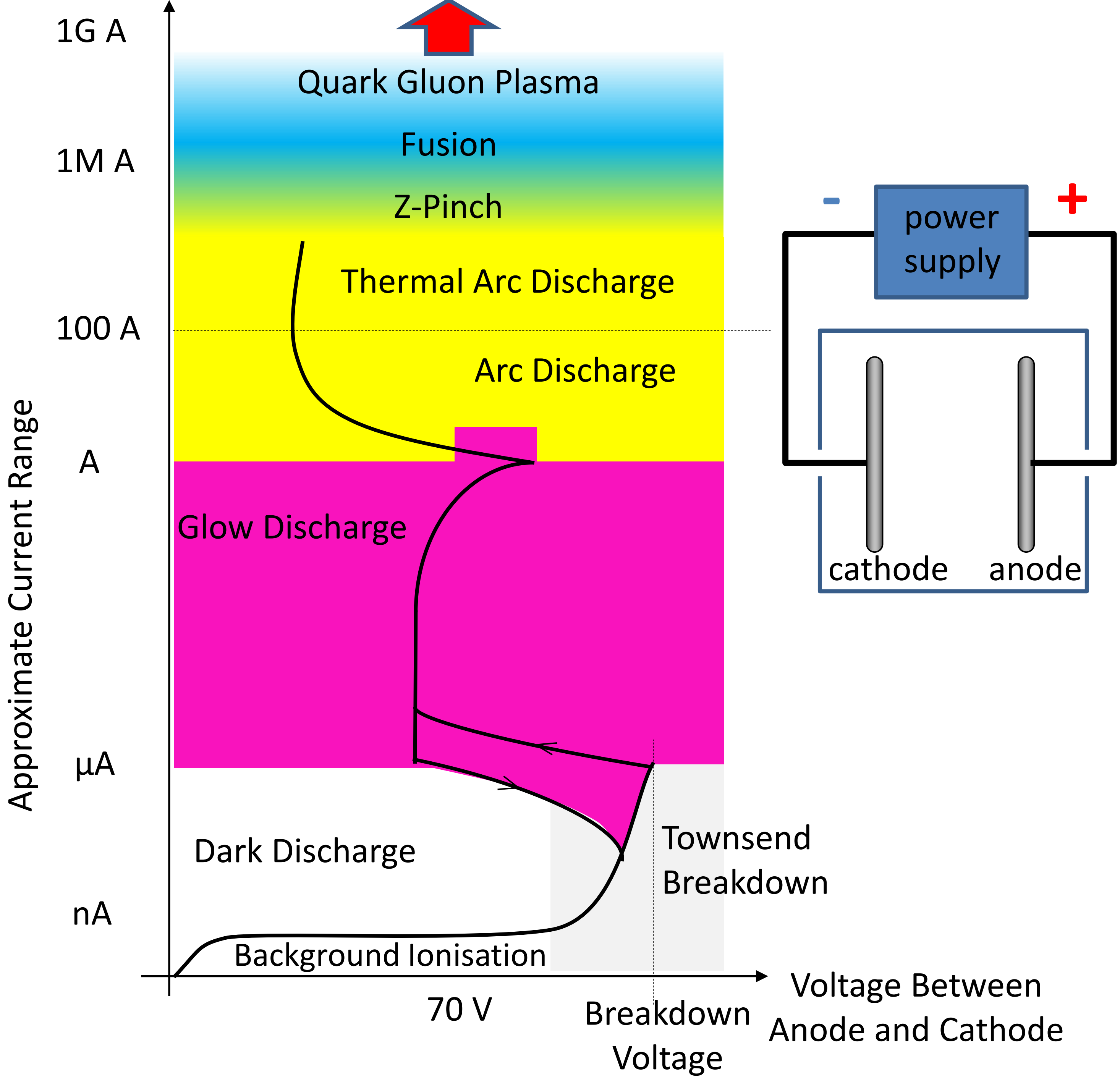
Electrical Discharges



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
-
power
supply
+
cathode
anode

Basic Plasma Properties

Density, n (per per m^3 or cm^3)

n_e = density of electrons

n_i = density of ions

n_n = density of neutrals

Charge State, q

$H^+ \rightarrow q = +1$

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

$H^- \rightarrow q = -1$

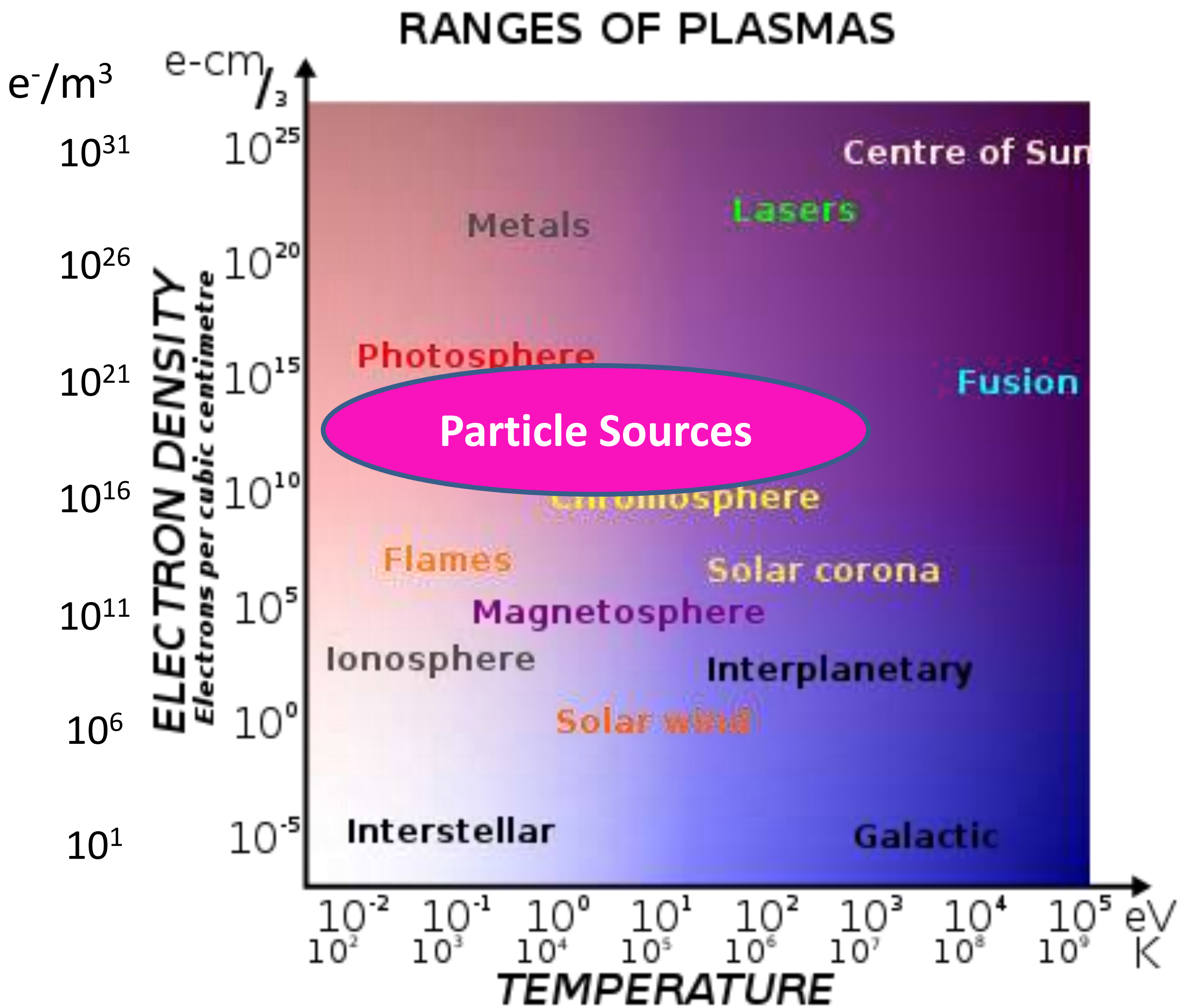
Temperature, T (eV)

T_e = temperature of electrons

T_i = temperature of ions

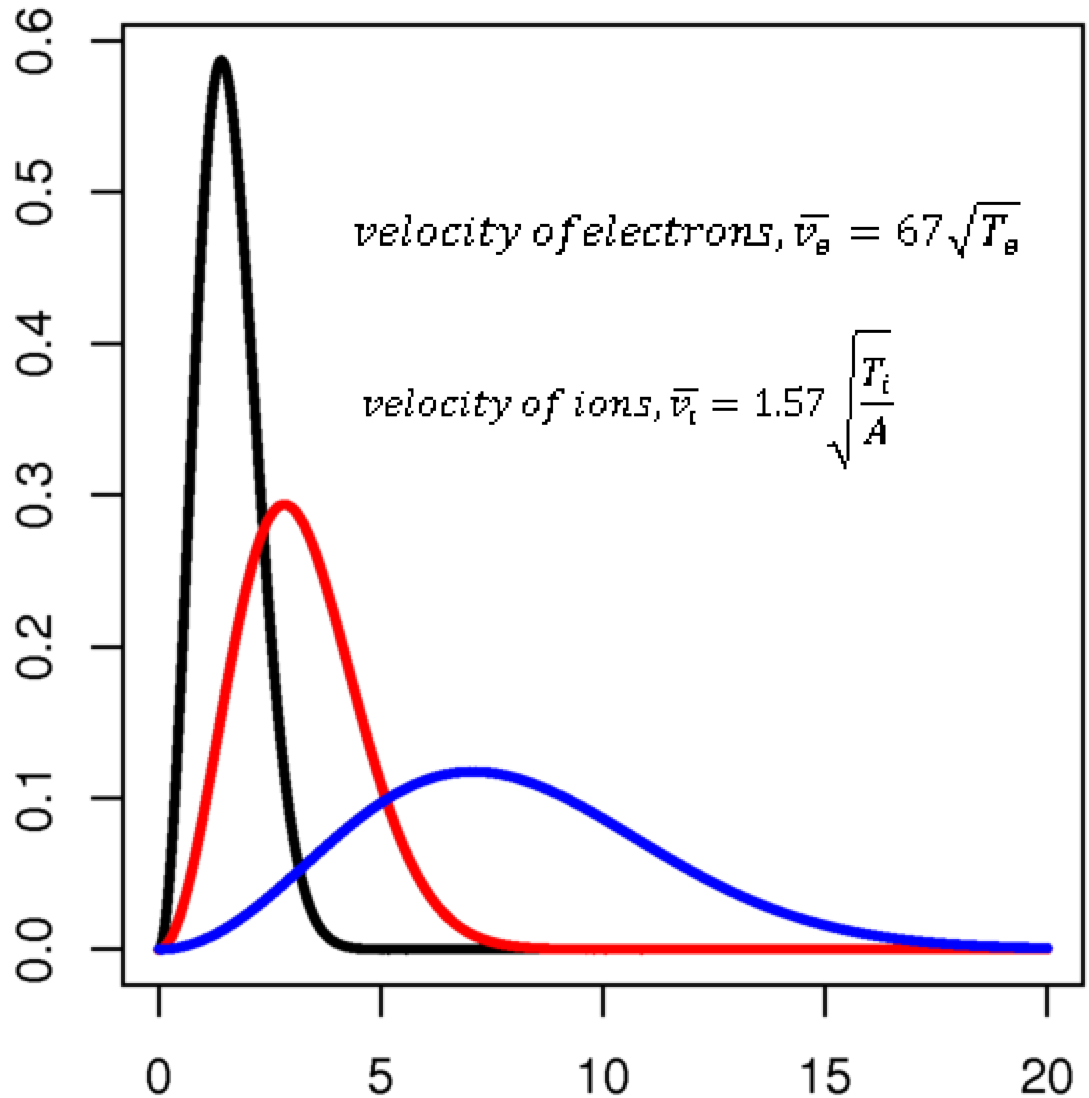
T_n = temperature of neutrals

11600°K = 1 eV


RANGES OF PLASMAS
e-/m3
e-cm/3
10^31
10^26
10^21
10^16
10^11
10^6
10^1
10^25
10^20
10^15
10^10
10^5
10^0
10^-5
ELECTRON DENSITY
Electrons per cubic centimetre
Centre of Sun
Lasers
Metals
Photosphere
Fusion
Particle Sources
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

Temperature Distribution

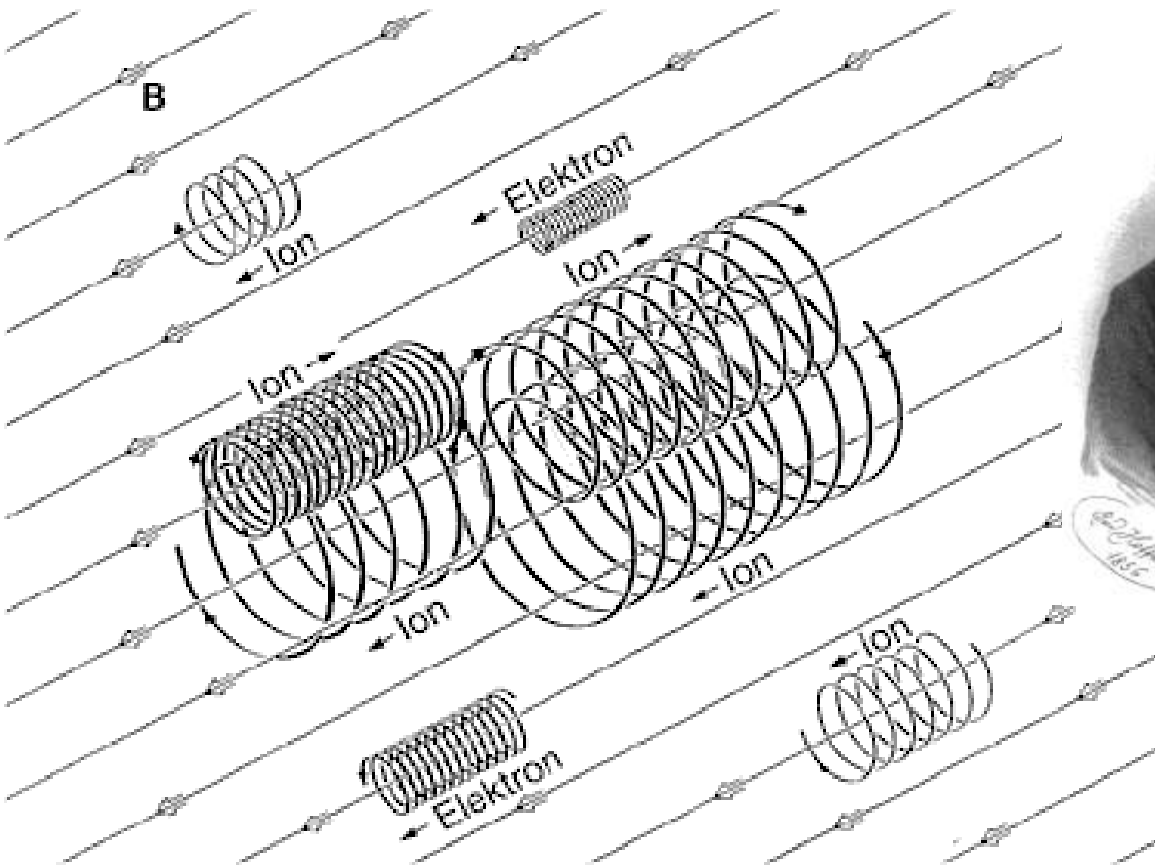
Maxwell Boltzmann statistics



In magnetic fields:

$$v_x \neq v_y \neq v_z$$

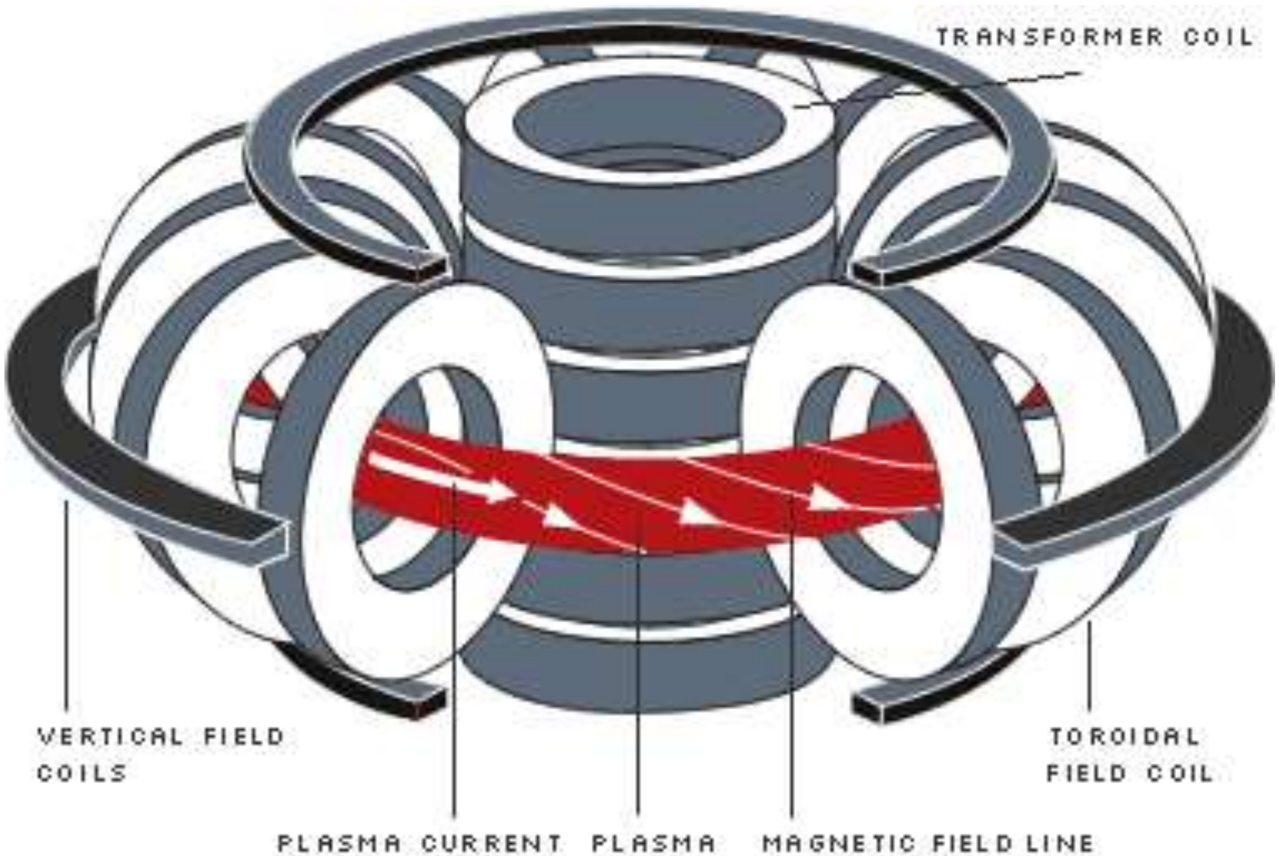
Magnetic Confinement



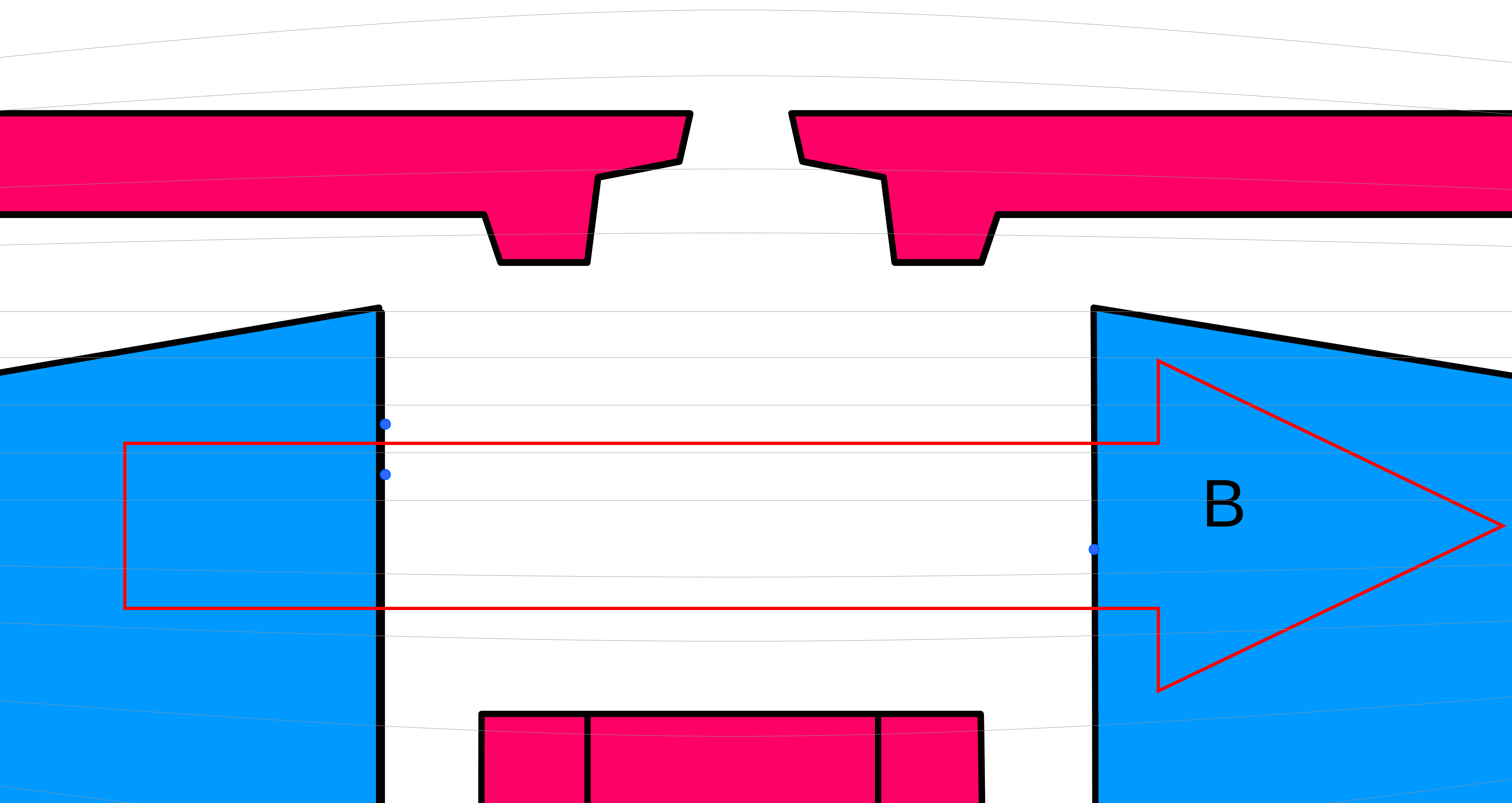
Julius Plücker

Particles spiral along magnetic field lines

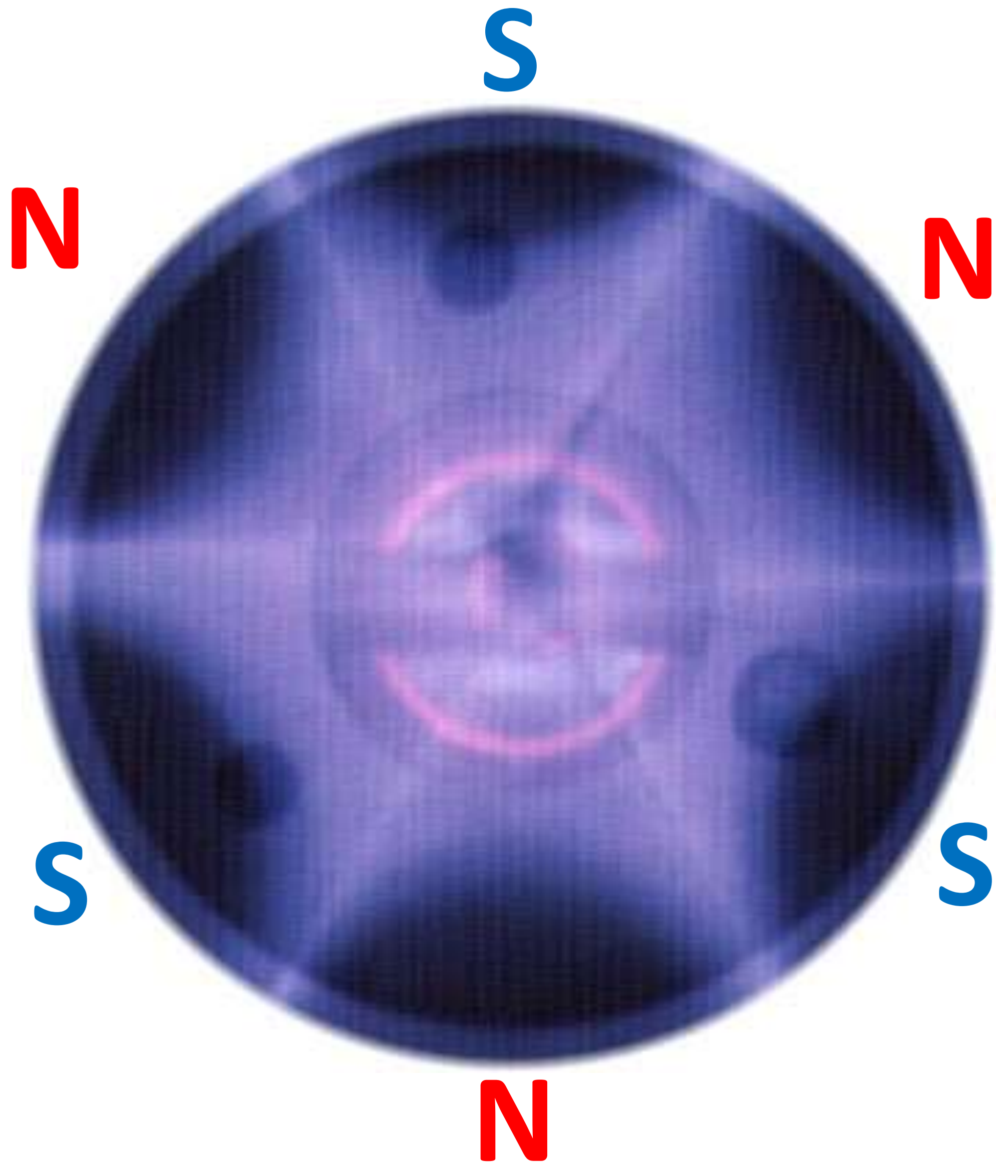
Solenoid field



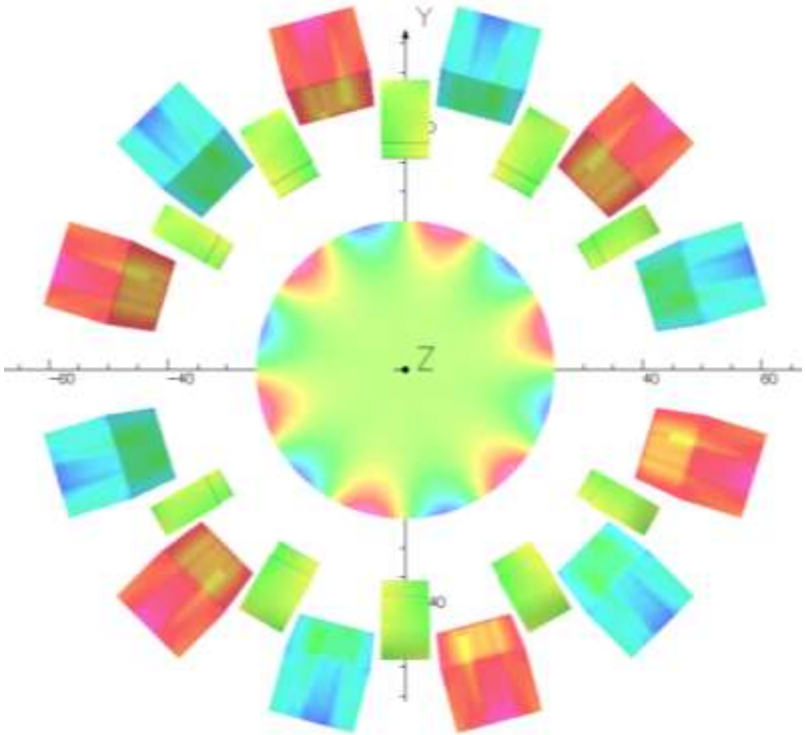
Dipole field

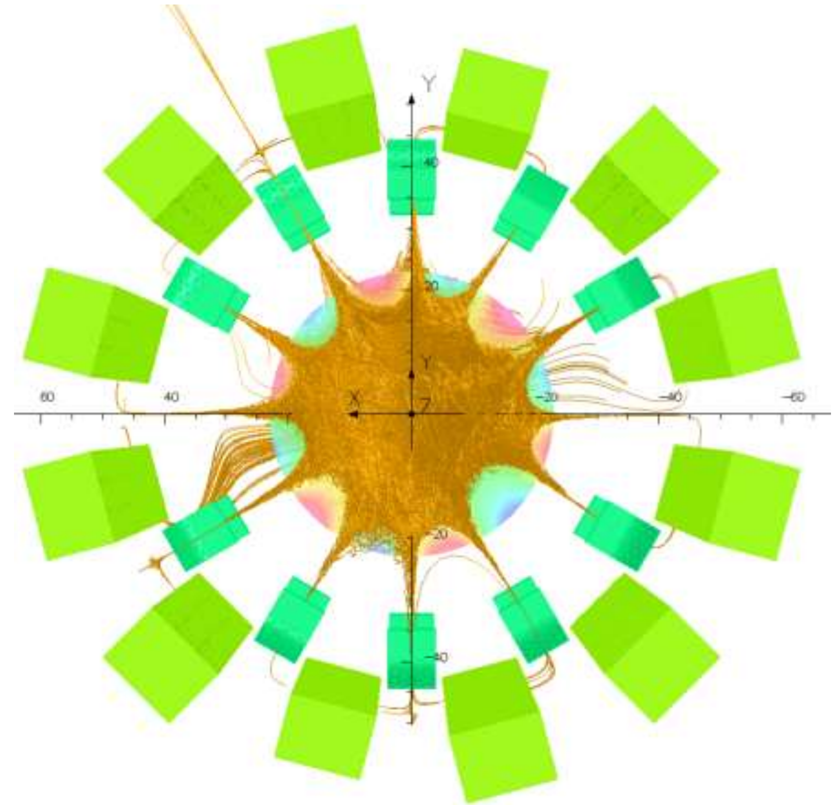


Hexapole



Multicusp Confinement





Percentage Ionisation

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

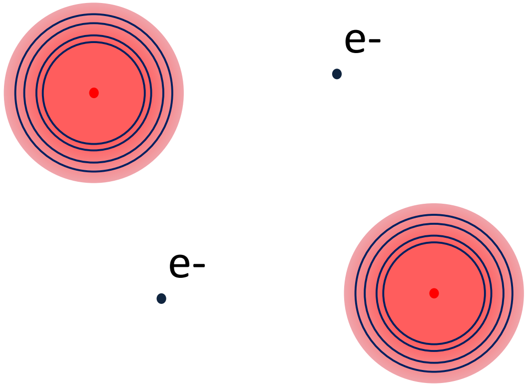
> 10 % → Highly Ionised

< 1 % → Weakly Ionised

Quasi Neutrality

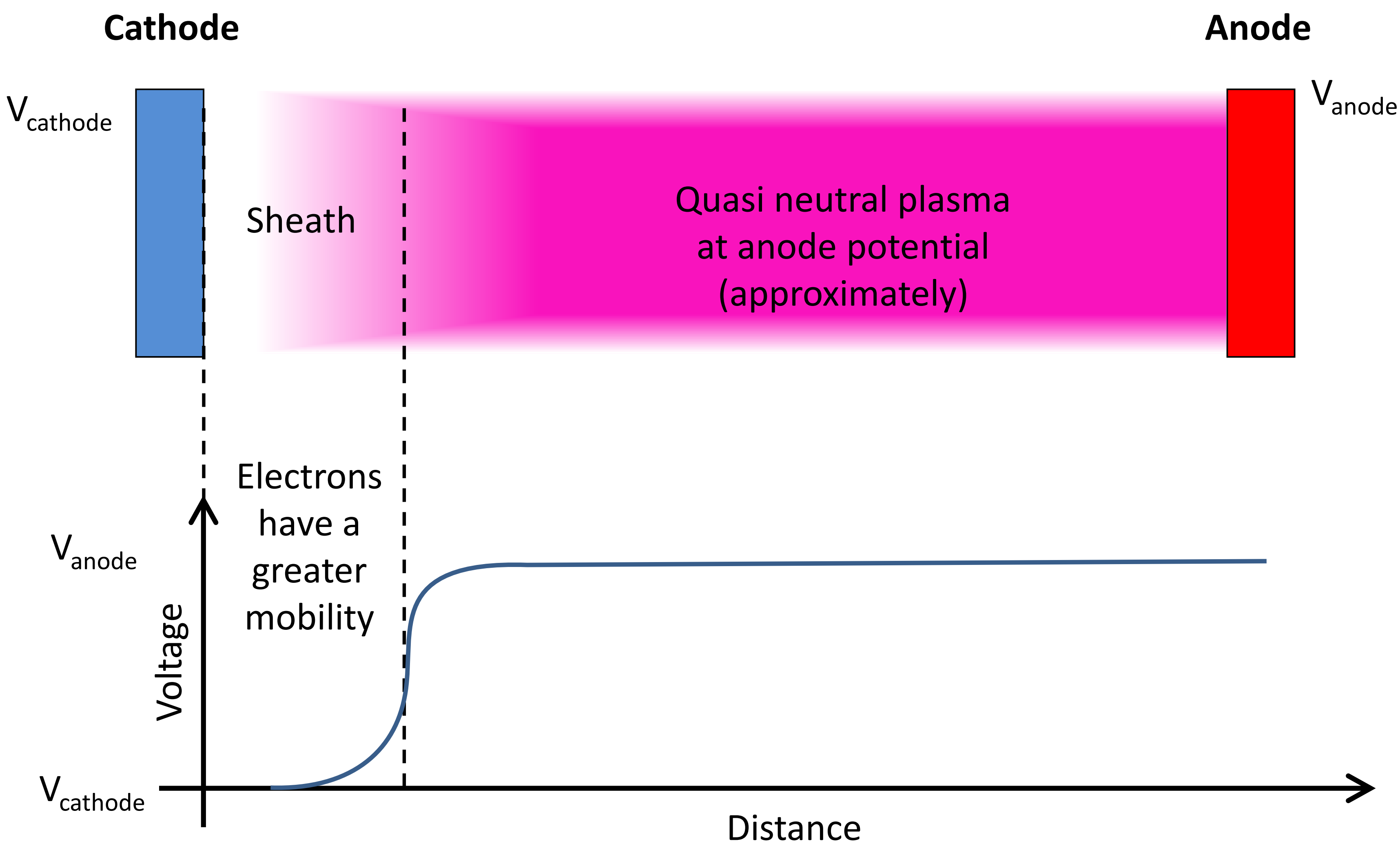
$$\sum q_i \, n_i = n_e$$

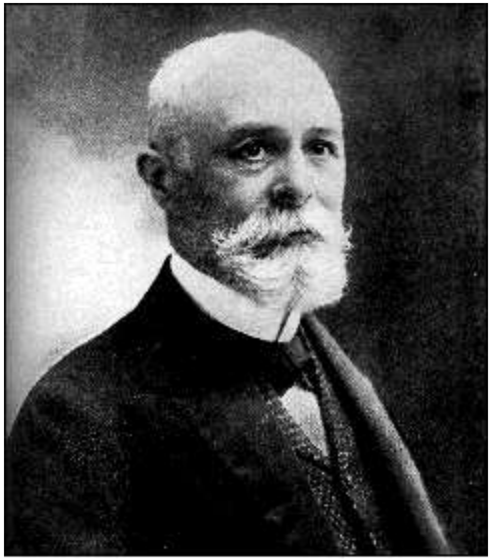
Debye Length



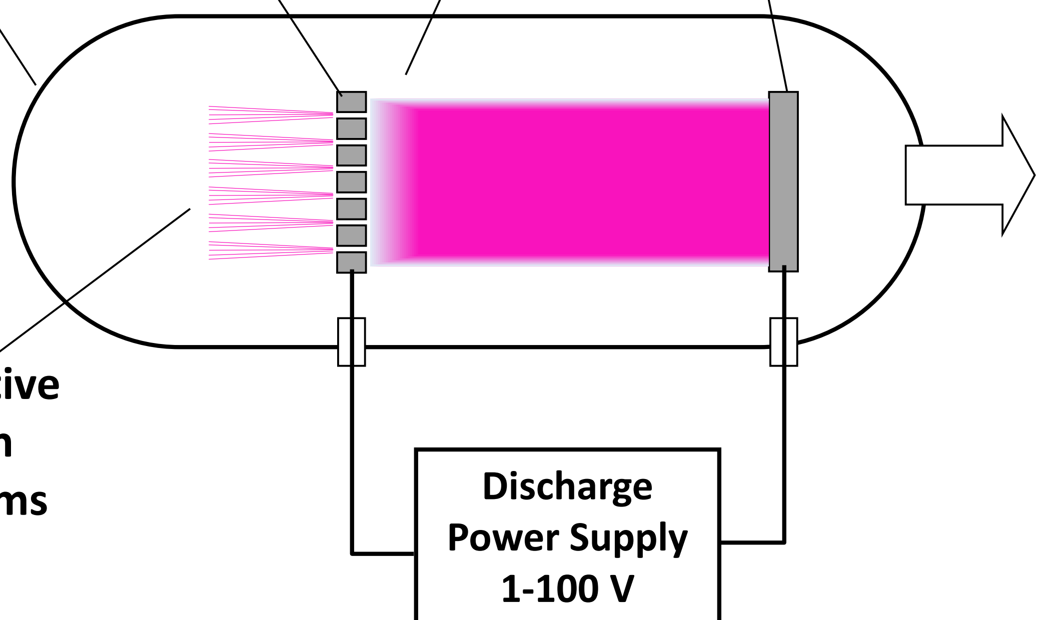
$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e {q_e}^2}}$$

Cathode Sheath



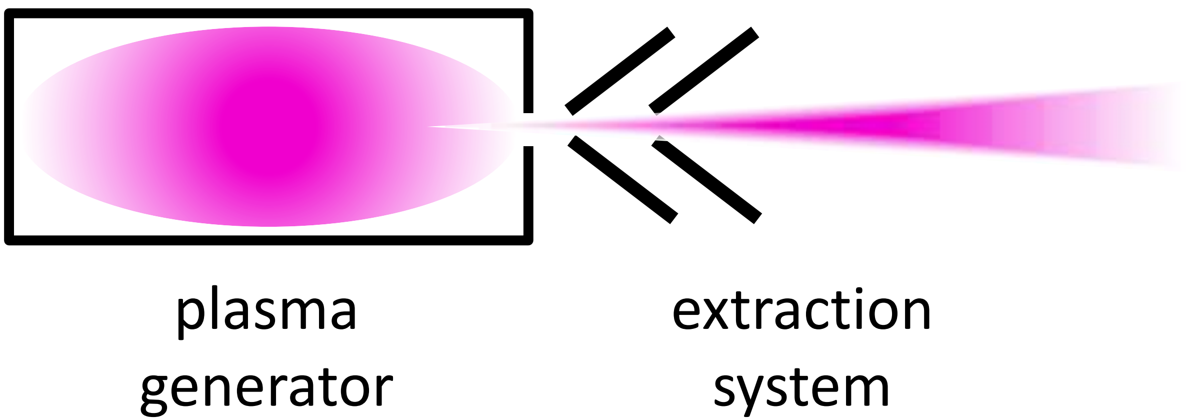


Canal Ray Source

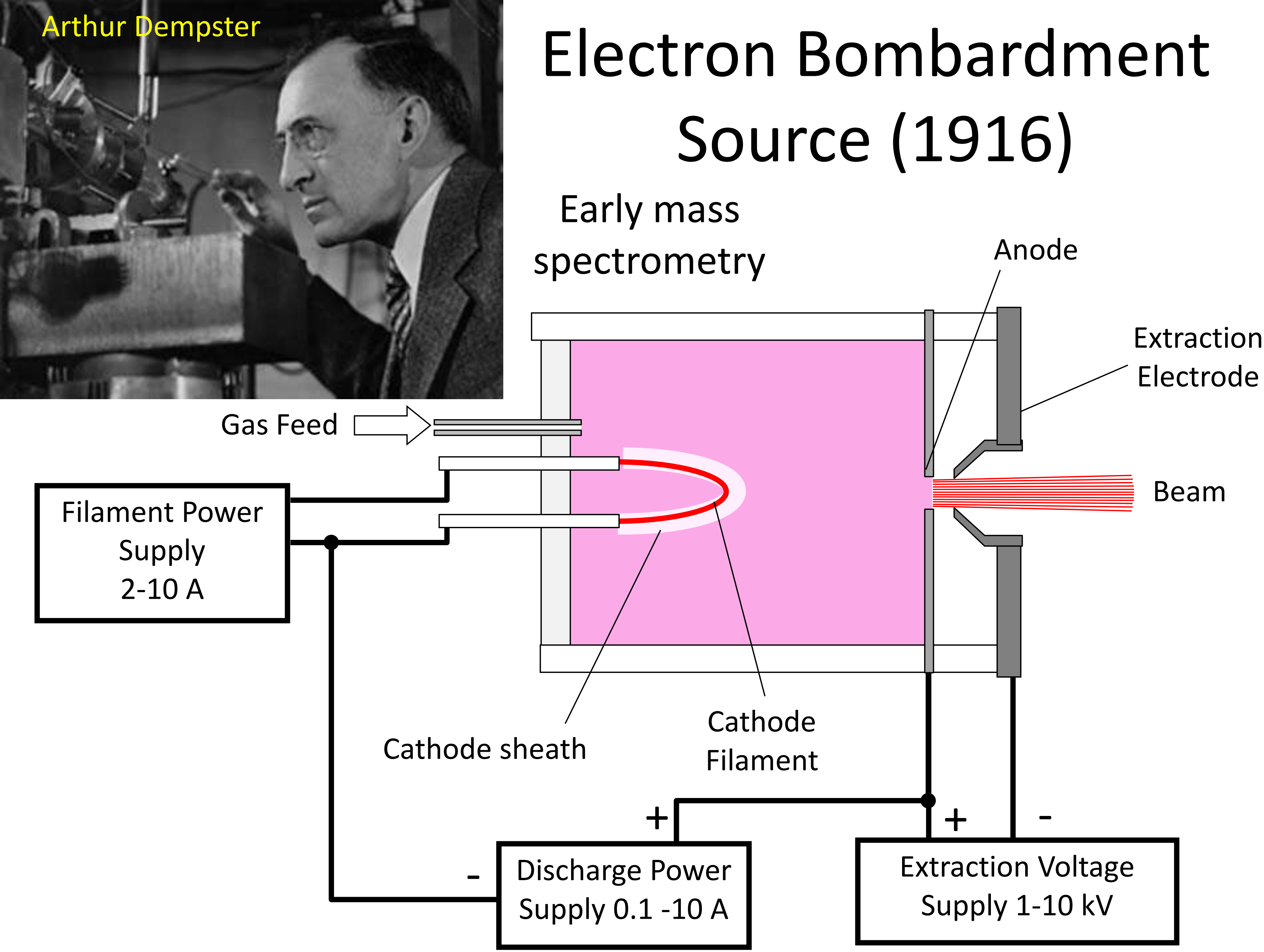


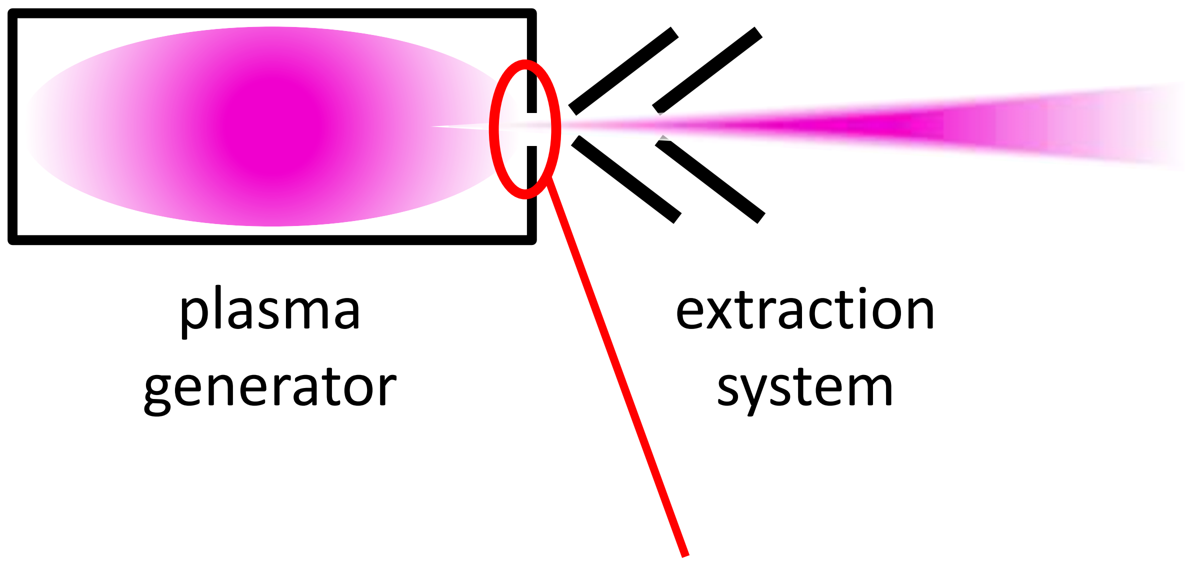
Large beam energy spread

Extraction



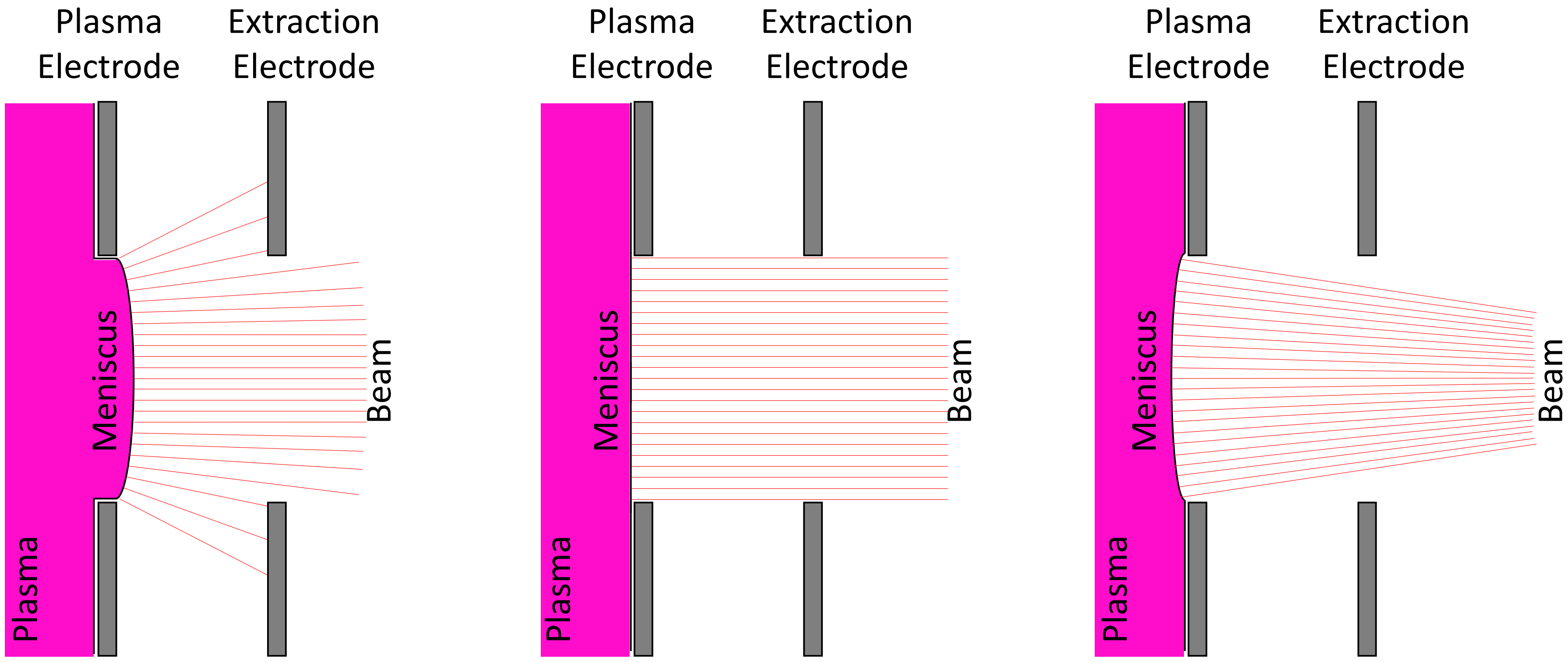
Electron Bombardment Source (1916)





The emission surface is critical to the quality of the beam

Plasma Mencius

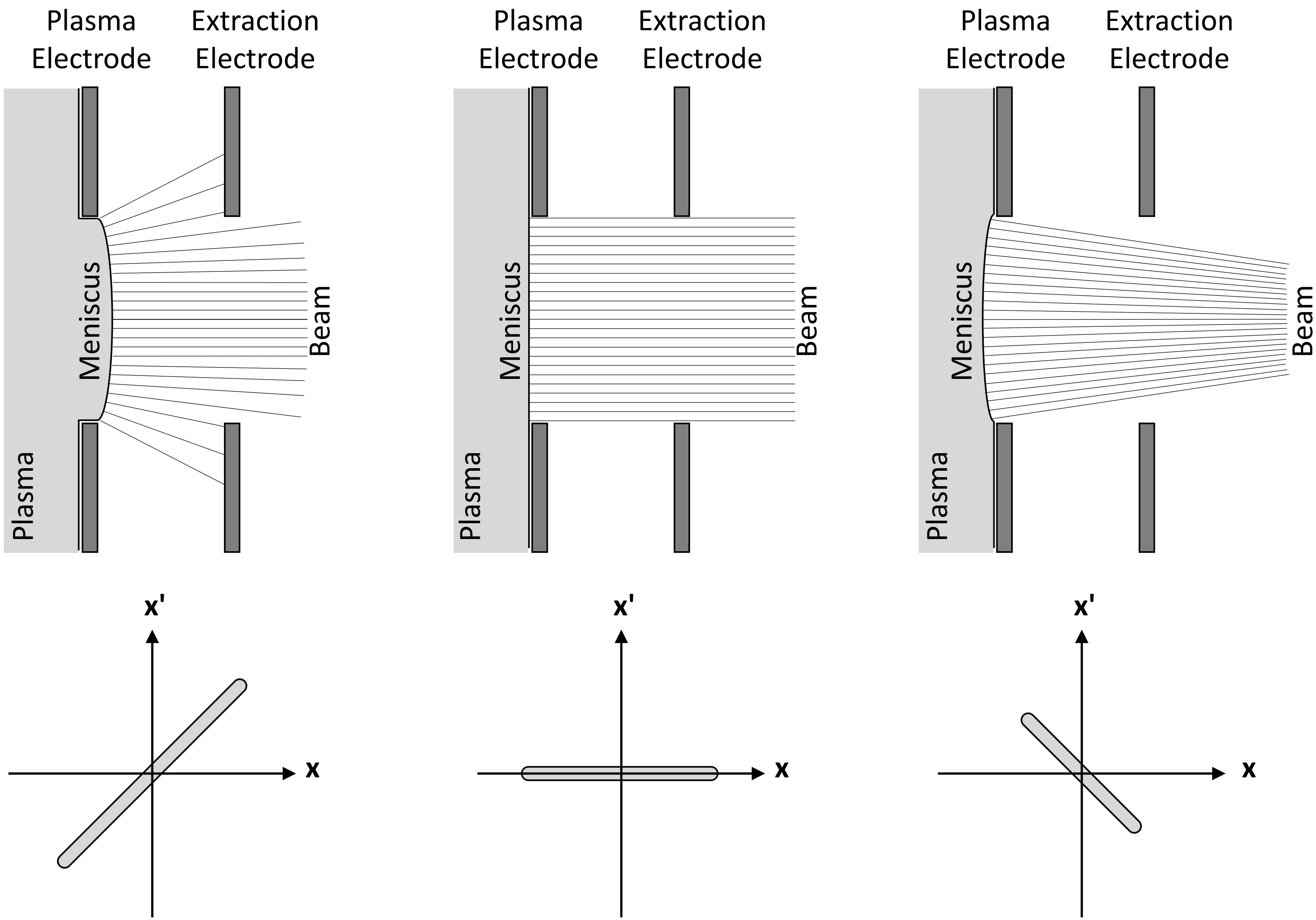


Convex Flat Concave

Not including space charge effects

Emittance

Measured in mm.mRads



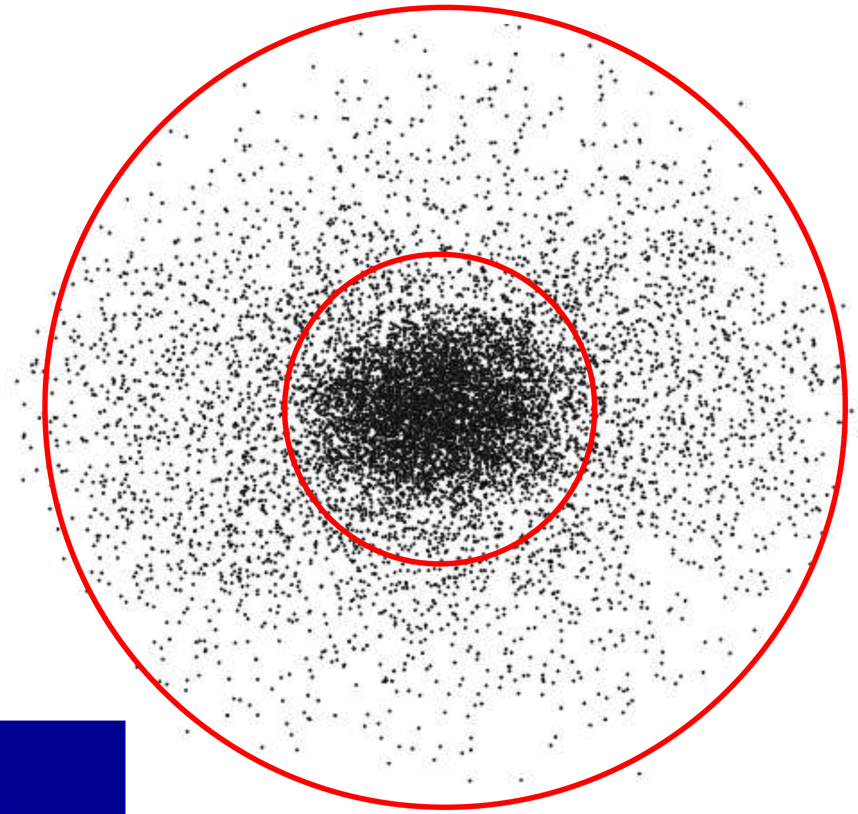
Diverging

Parallel

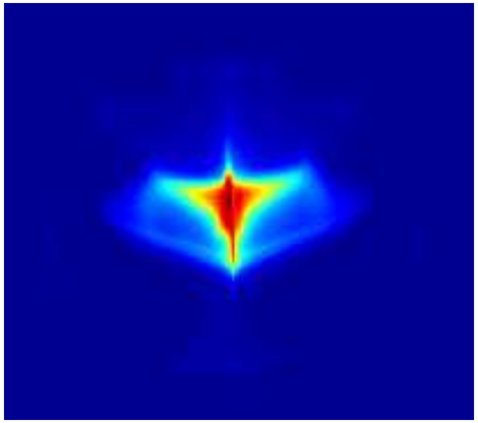
Converging

Emittance of Real Beams

Halo Effect
- Plasma boundary
- Fringe fields



How big is this beam?



95% emittance

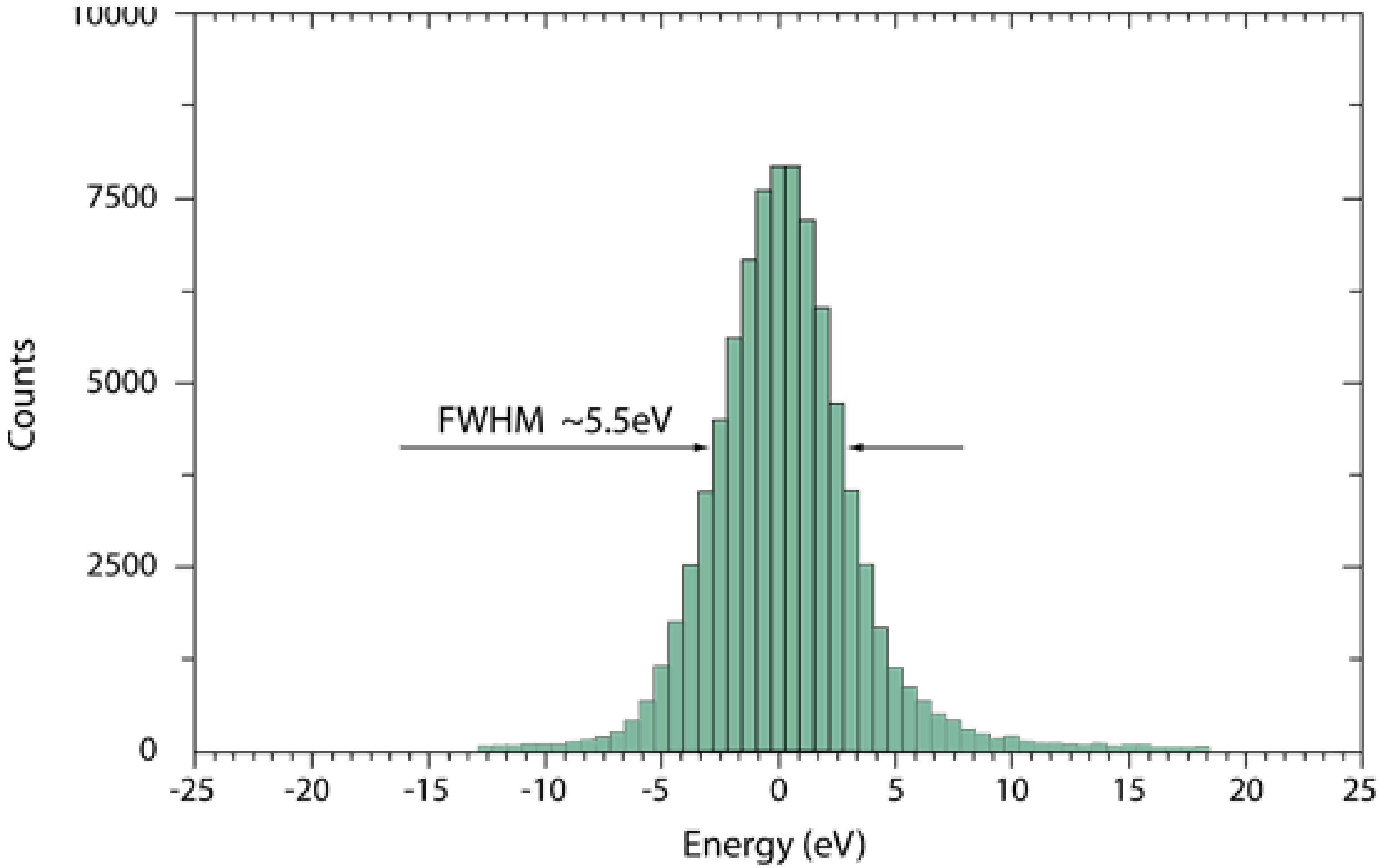
rms emittance

Brightness

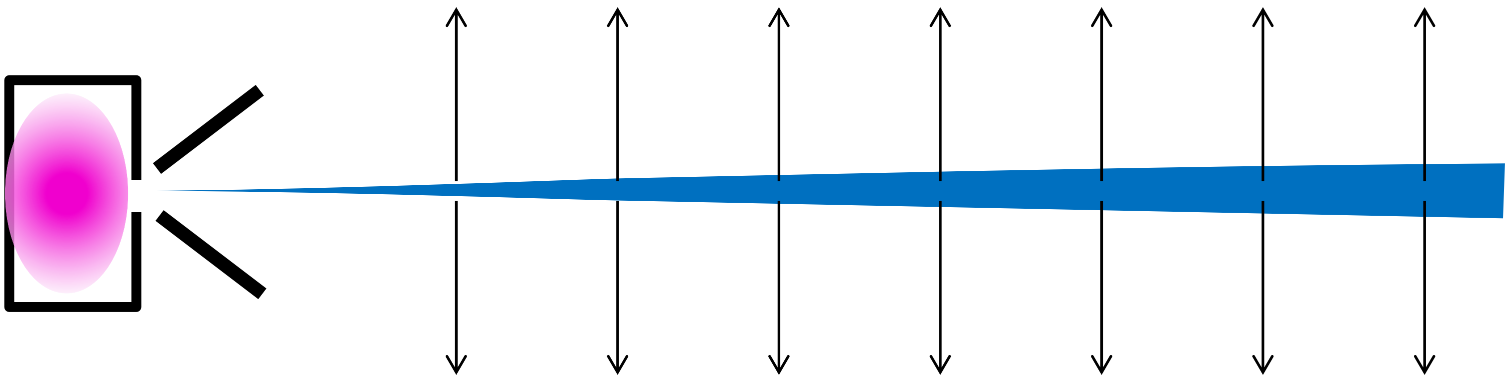
$$B = \frac{I}{\varepsilon_x \varepsilon_y}$$

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

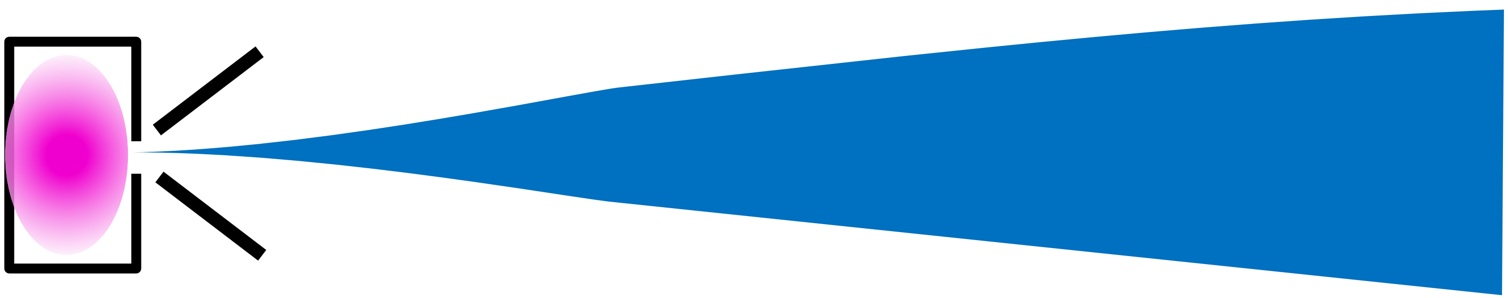
Energy Spread (Longitudinal Emittance)

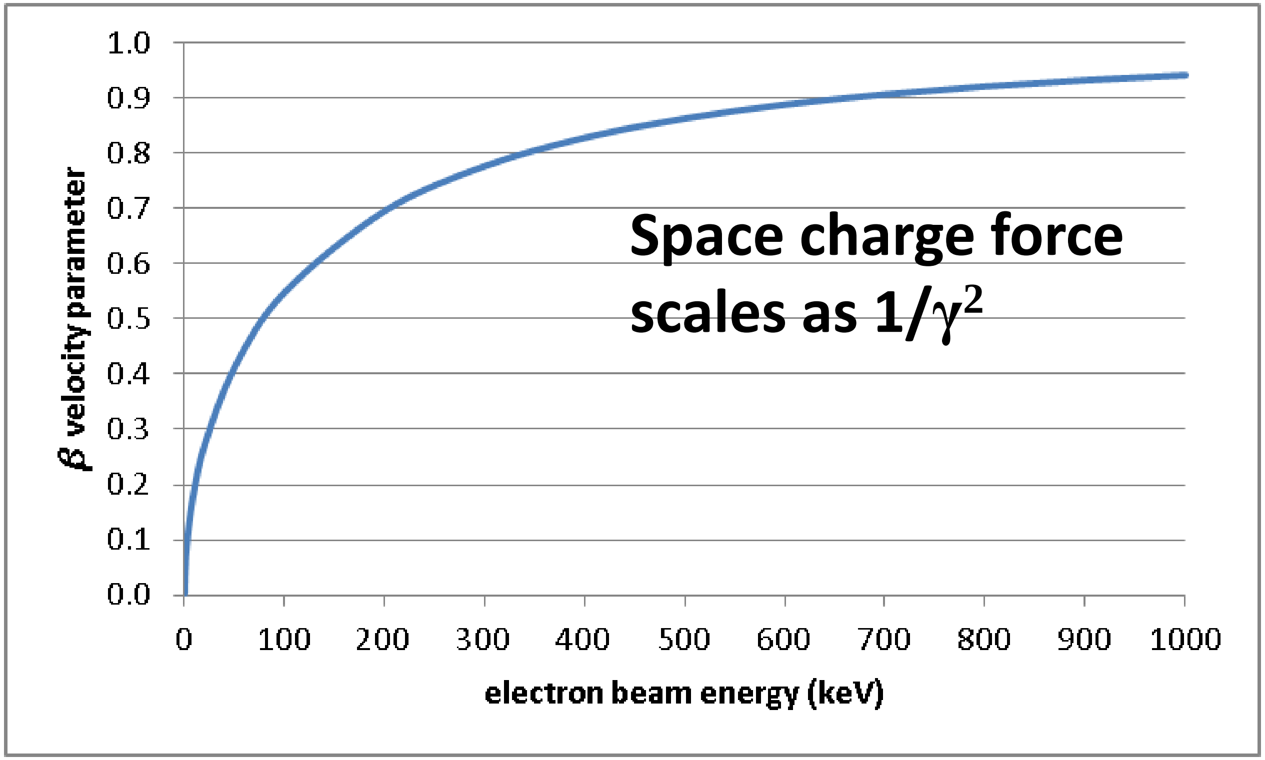


Space Charge



Space Charge

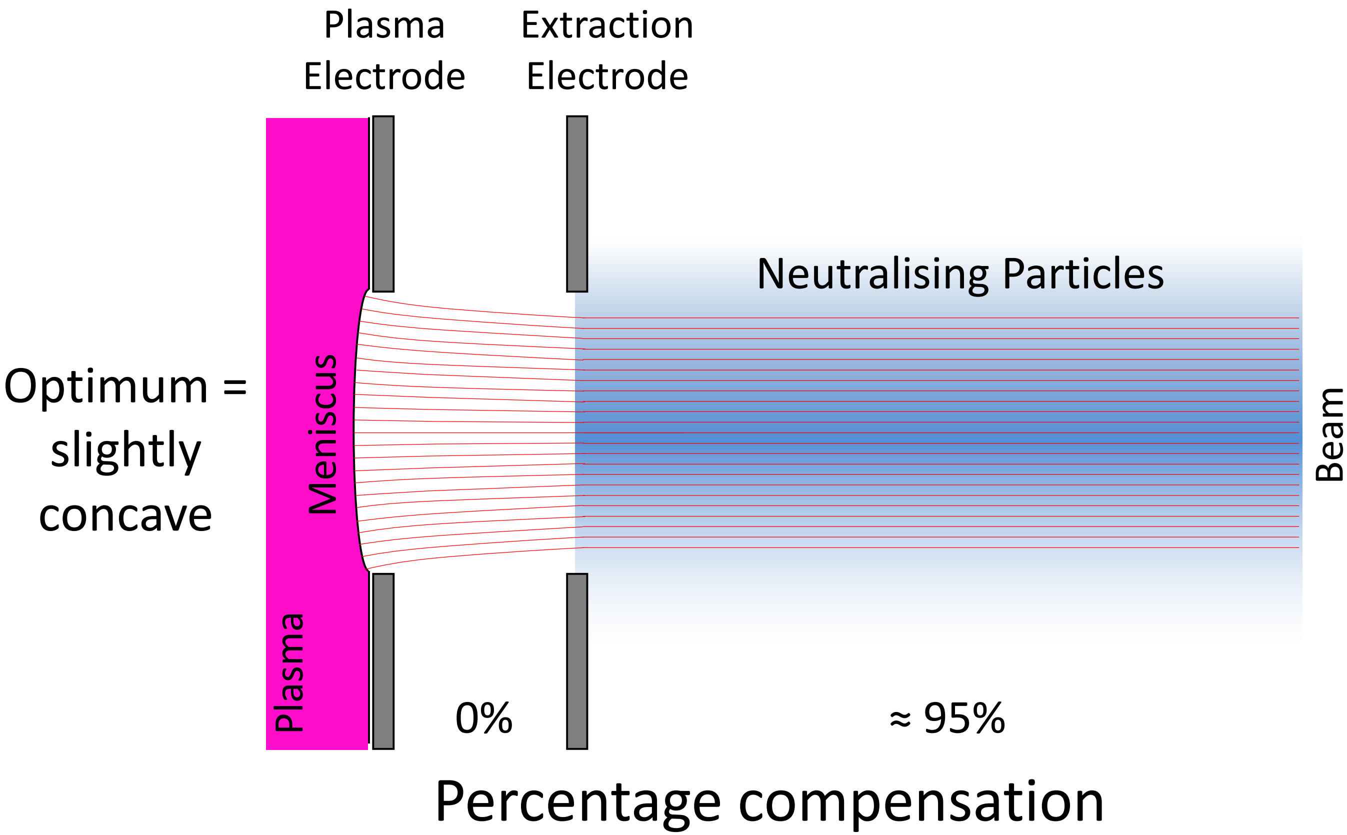




At 500 keV electron γ= 2

However it is not until 940 MeV proton γ = 2

Space Charge



Child-Langmuir Law

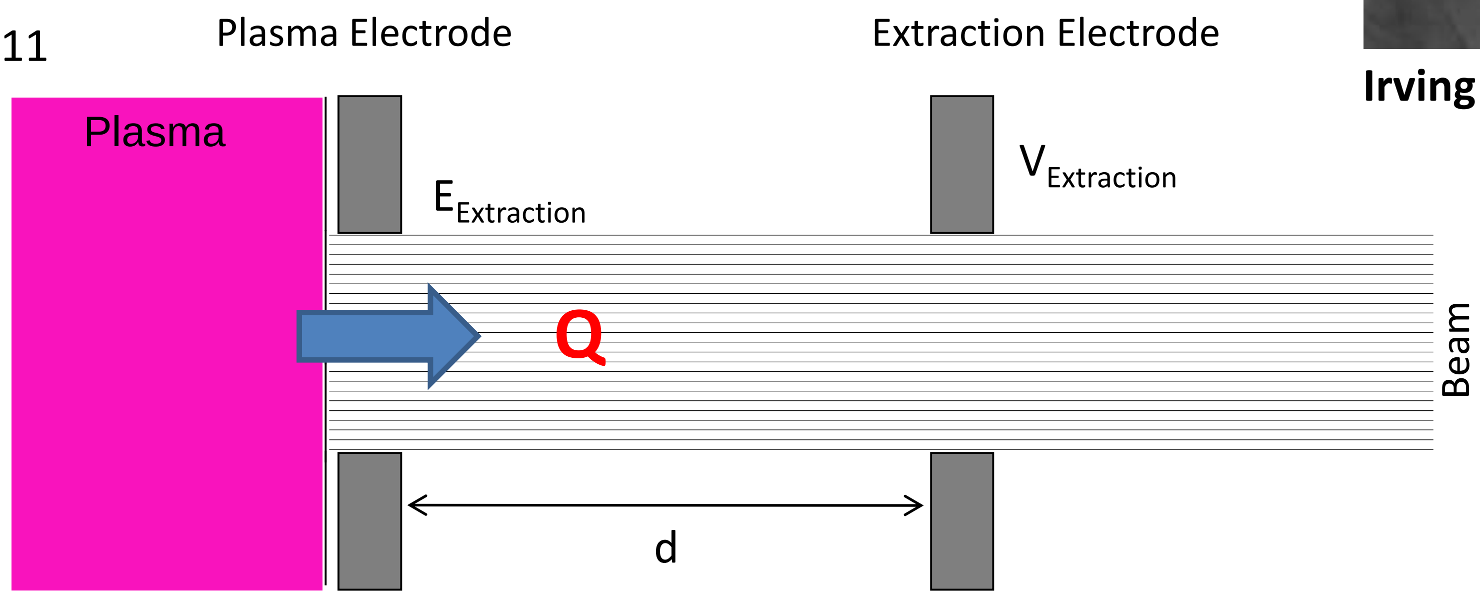
(Space charge limited extraction)

C.D Child

1911

Irving Langmuir

1913



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

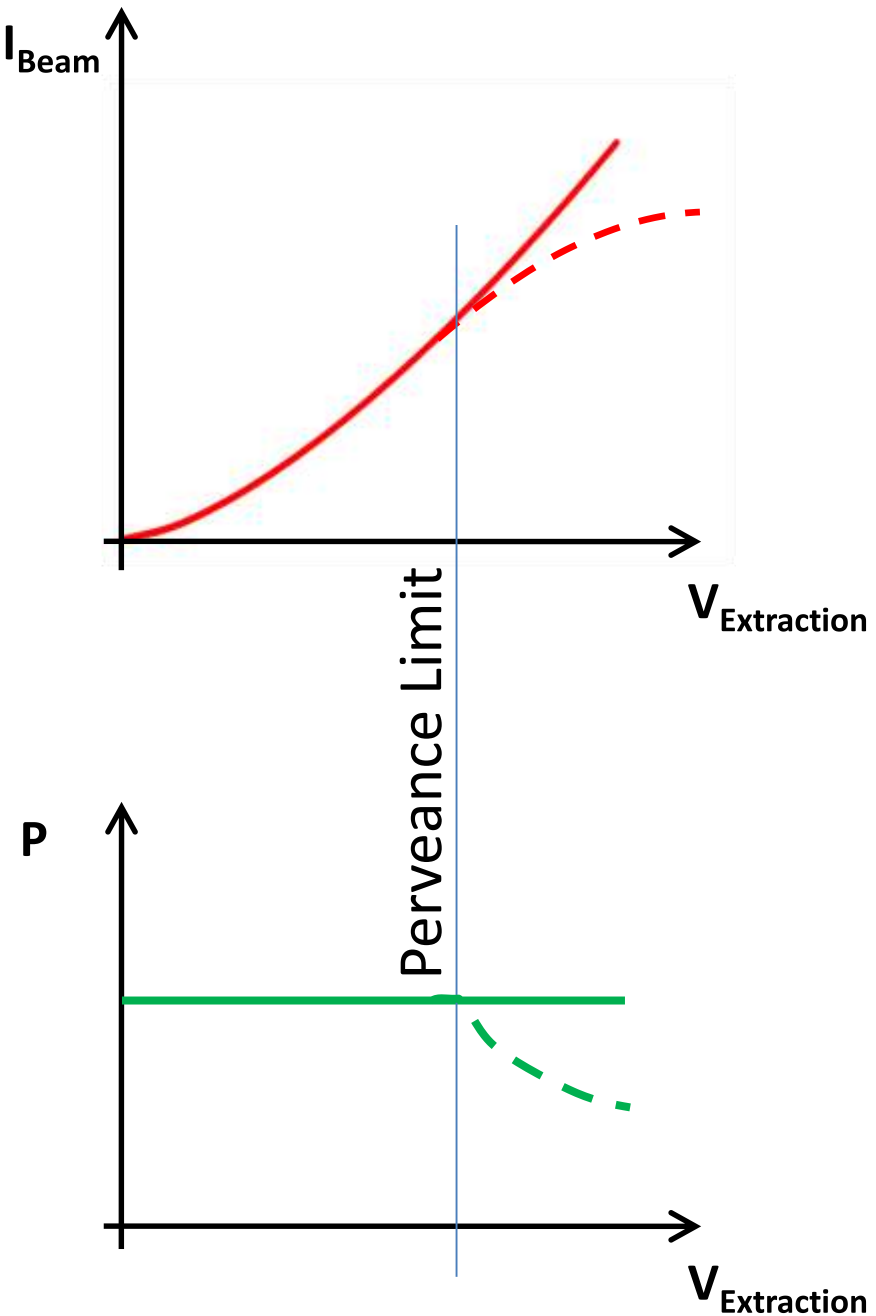
$$j = \frac{1.72\sqrt{\frac{q}{A}}V^{\frac{3}{2}}}{d^2}$$

This does not include geometric meniscus effects

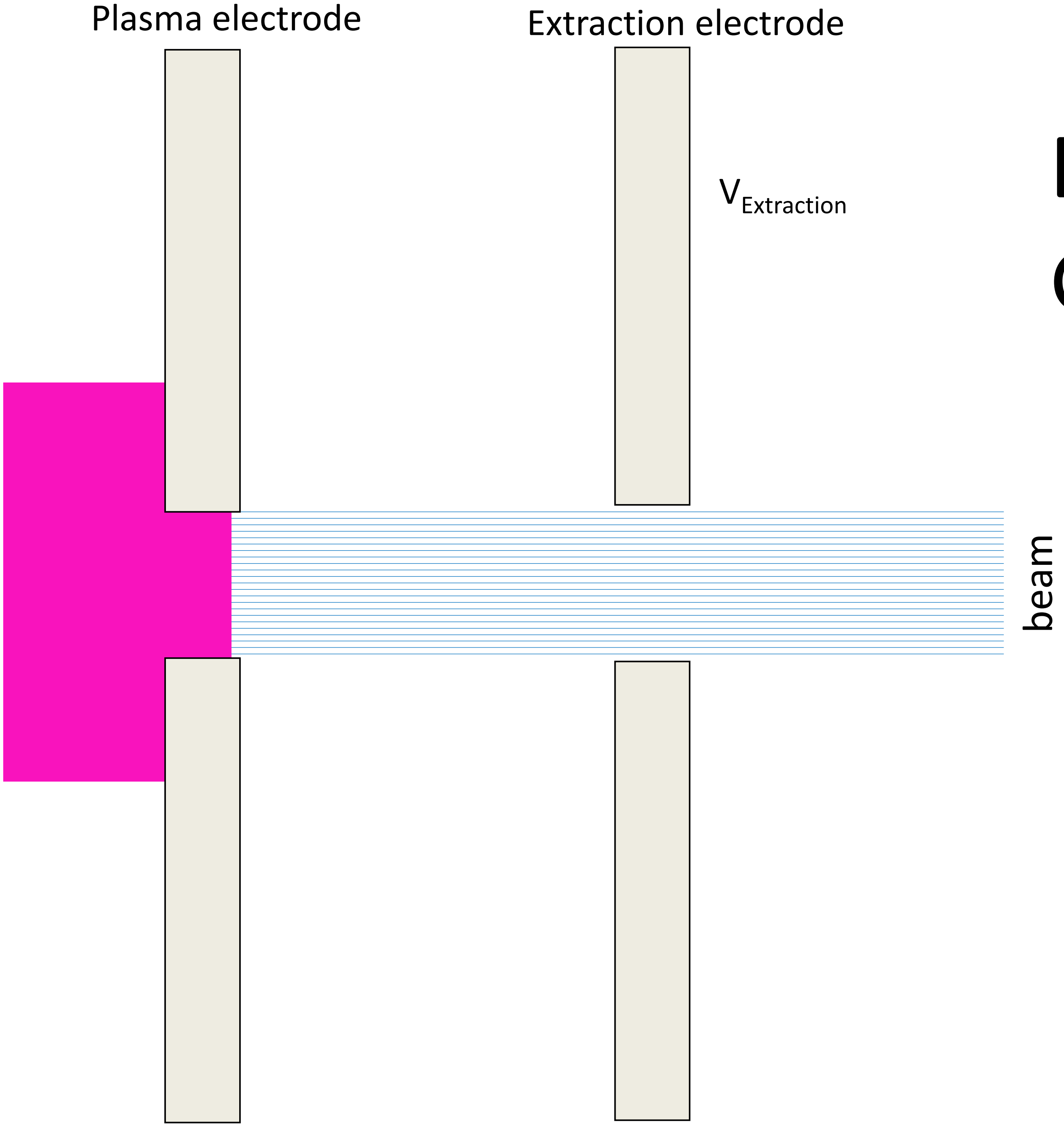
$$I \propto V^{\frac{3}{2}}$$

Perveance

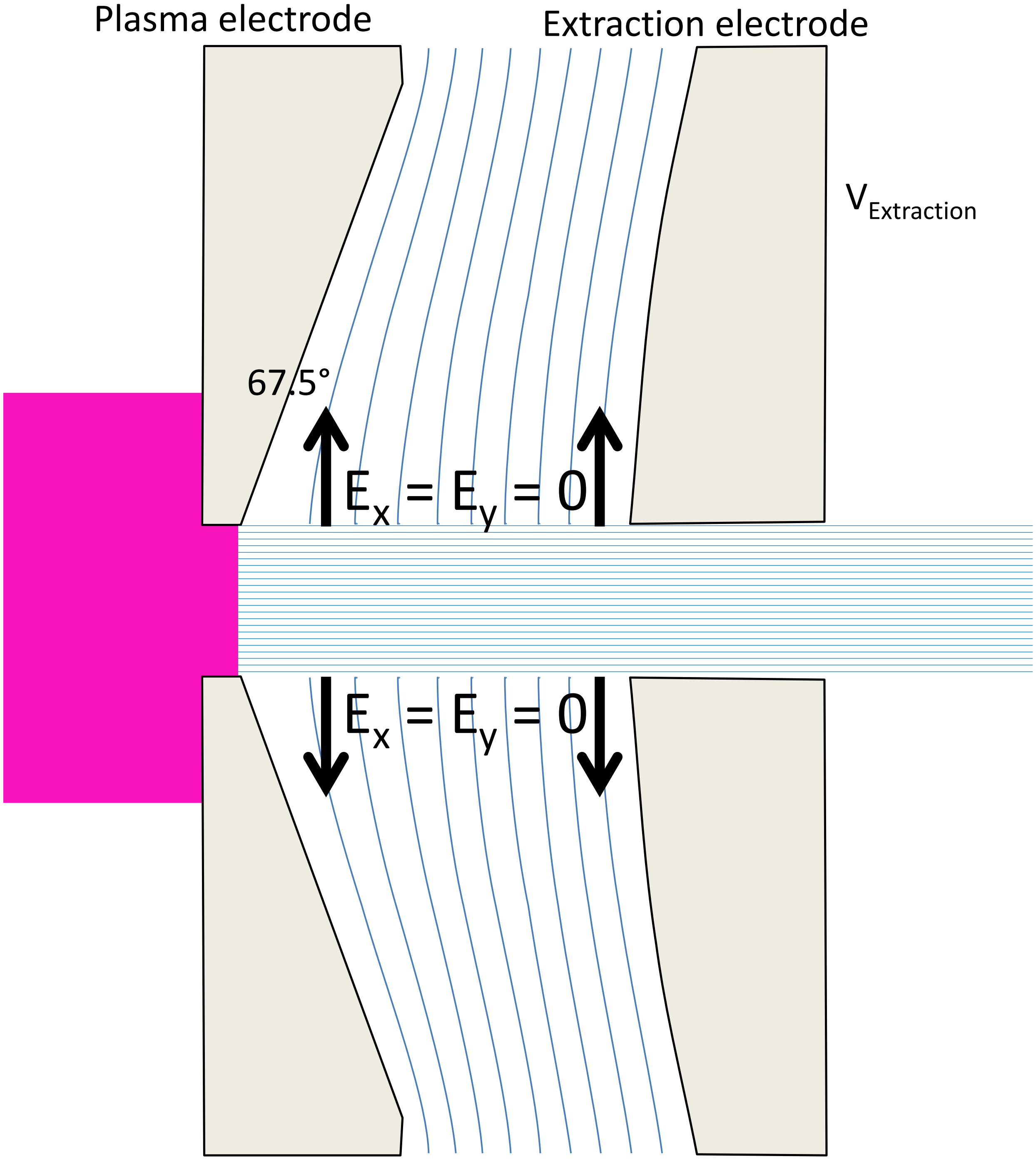
$$P = \frac{I}{V^{\frac{3}{2}}}$$



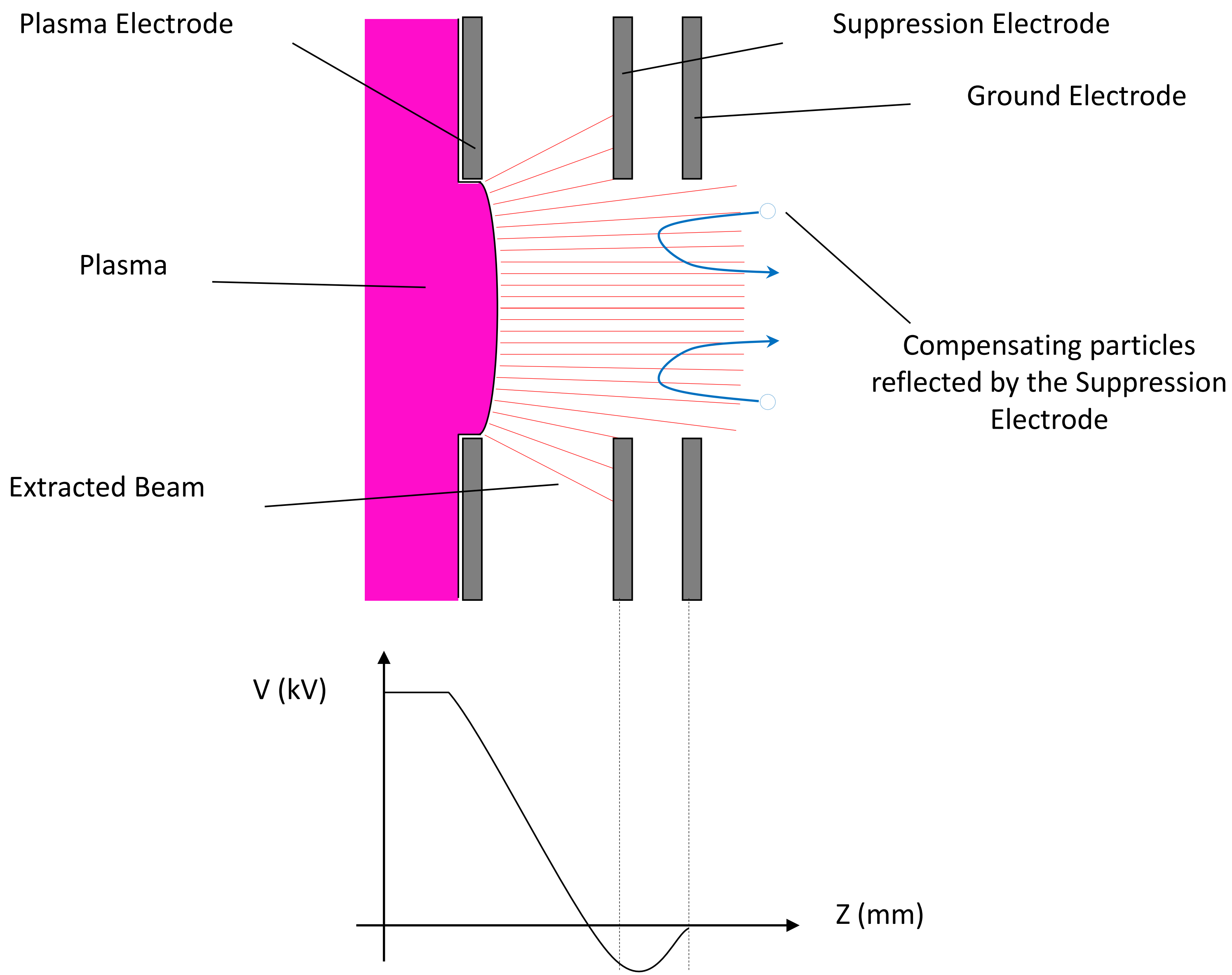
Pierce Extraction Geometry



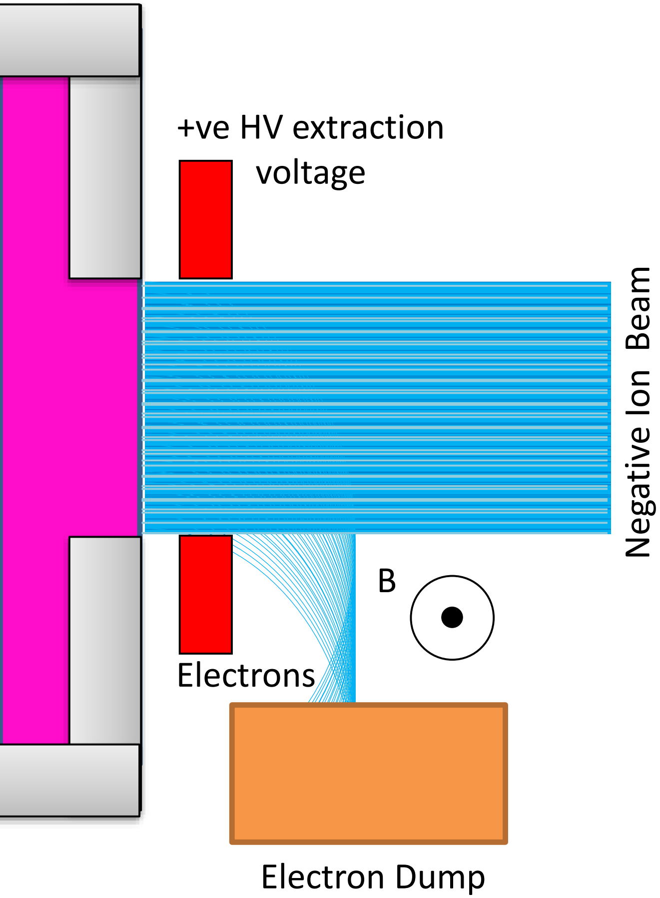
Pierce Extraction Geometry



Suppressor Electrode



Negative Ion Extraction



- Electrons will always be extracted
  up to 1000 times the H^- current!
  (Best sources: $e/H^- = 0.5$)

- Properly designed dump system
- Properly designed extraction power supply
- Design to minimize co-extracted electrons
- Space charge forces can be strong
- Properly designed extraction optics required to minimize emittance

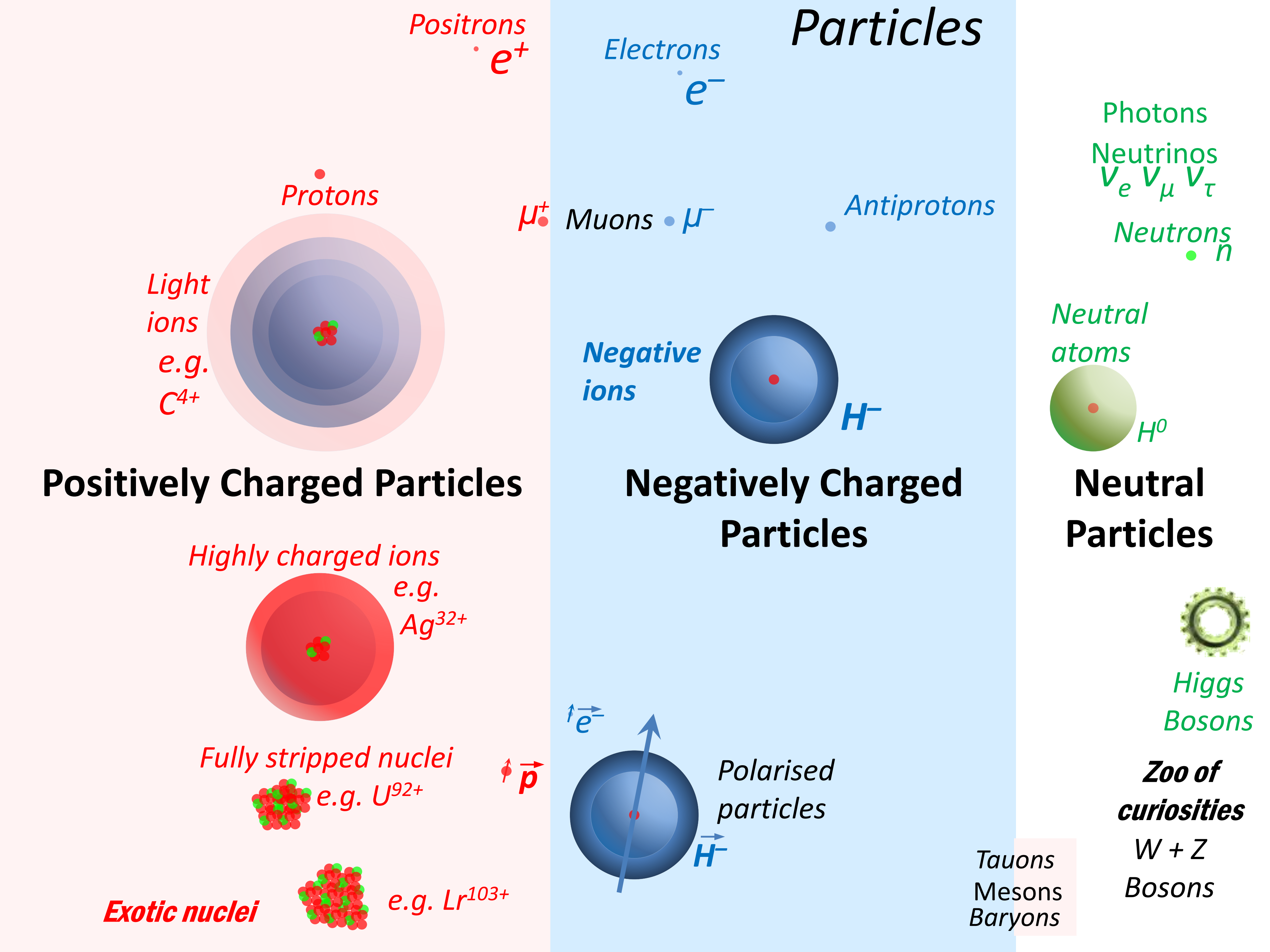
Ion Sources

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

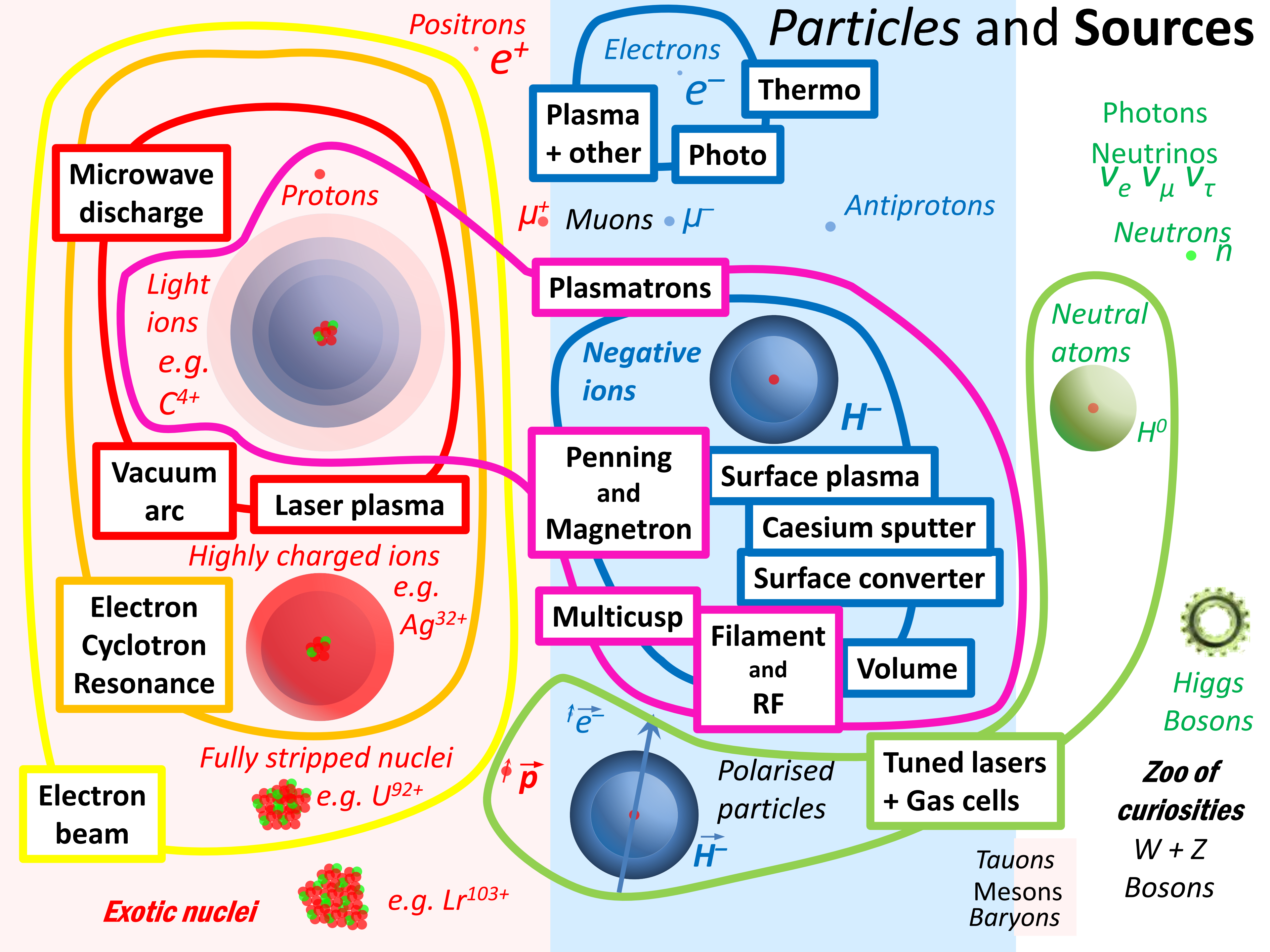
EHD-driven Liquid ion source
Surface Ionization ion source
Charge Exchange ion source
Inverse Magnetron ion source
Microwave ion source
XUV-driven ion source
Arc Plasma ion source
Capillary Arc ion source
Von Ardenne ion source
Capillaritron ion source
Canal Ray ion source
Pulsed Spark ion source
Field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

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

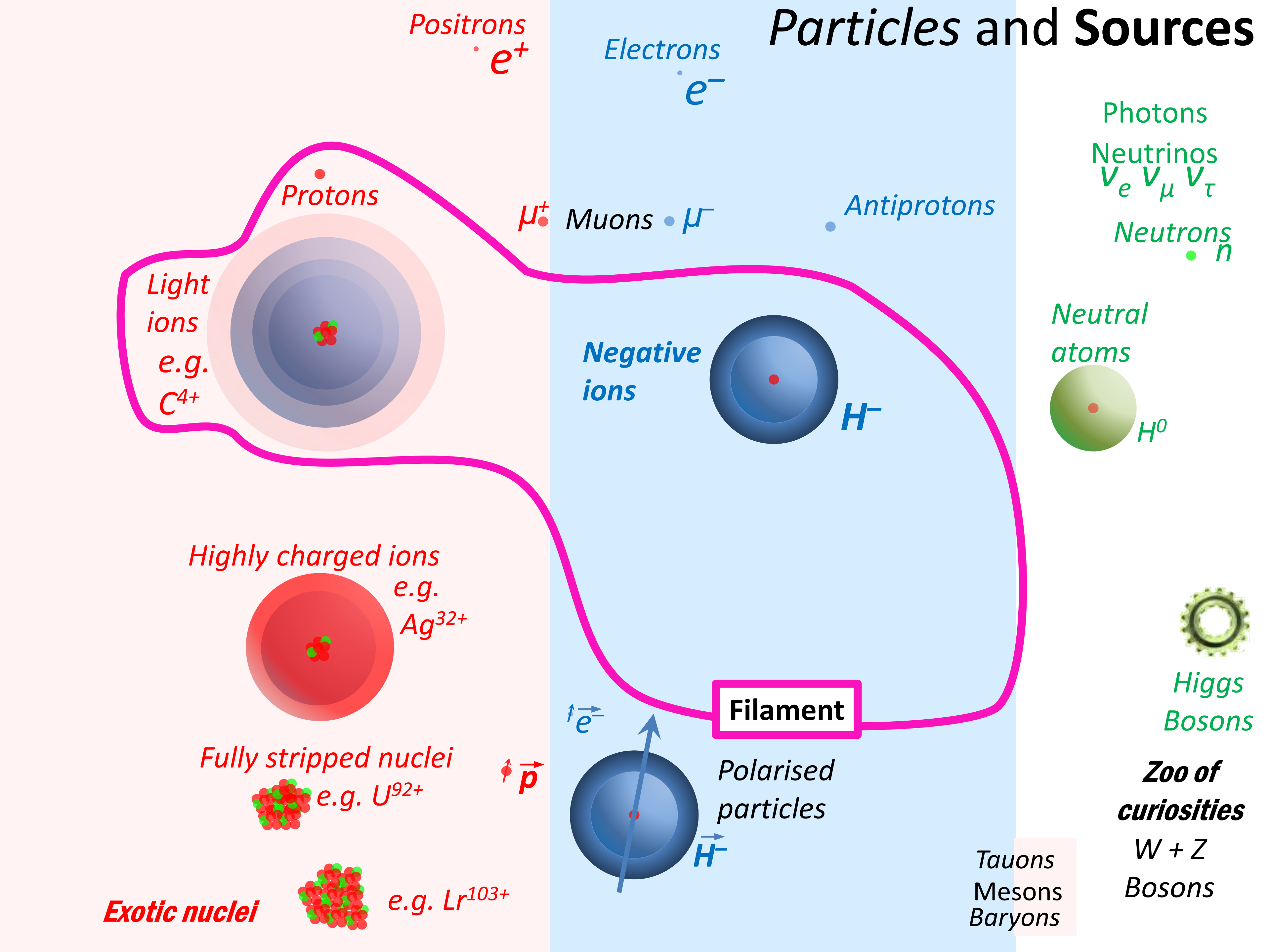
To name but a few!



Particles
Positrons
e^+
Electrons
e^-
Photons
Neutrinos
$\nu_e\ \nu_\mu\ \nu_\tau$
Protons
μ^+
Muons μ^-
Antiprotons
Neutrons
n
Light ions
e.g. C^{4+}
Negative ions
H^-
Neutral atoms
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
W + Z Bosons
Tauons
Mesons
Baryons
Exotic nuclei
e.g. Lr^{103+}



Particles and Sources
Positrons
e^+
Electrons
e^-
Plasma + other
Thermo
Photo
Microwave discharge
Protons
Light ions e.g. C^{4+}
μ^+ Muons μ^-
Antiprotons
Photons
Neutrinos
ν_e ν_μ ν_τ
Neutrons
n
Plasmatrons
Negative ions
H^-
Neutral atoms
H^0
Penning and Magnetron
Surface plasma
Caesium sputter
Surface converter
Vacuum arc
Laser plasma
Highly charged ions
e.g. Ag^{32+}
Electron Cyclotron Resonance
Multicusp
Filament and RF
Volume
Higgs Bosons
$\vec{e}^-$
$\vec{p}$
Polarised particles
$\vec{H}^-$
Tuned lasers + Gas cells
Fully stripped nuclei
e.g. U^{92+}
Electron beam
Zoo of curiosities
W + Z Bosons
Tauons
Mesons
Baryons
Exotic nuclei
e.g. Lr^{103+}



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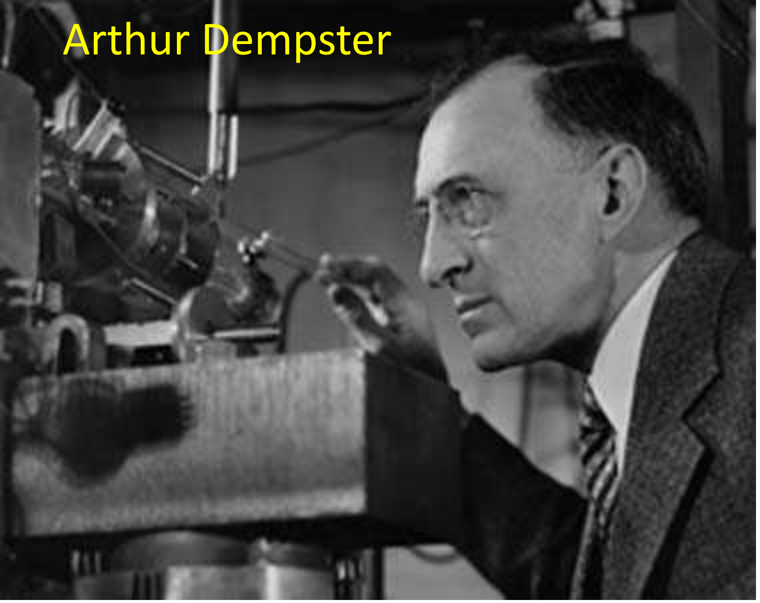
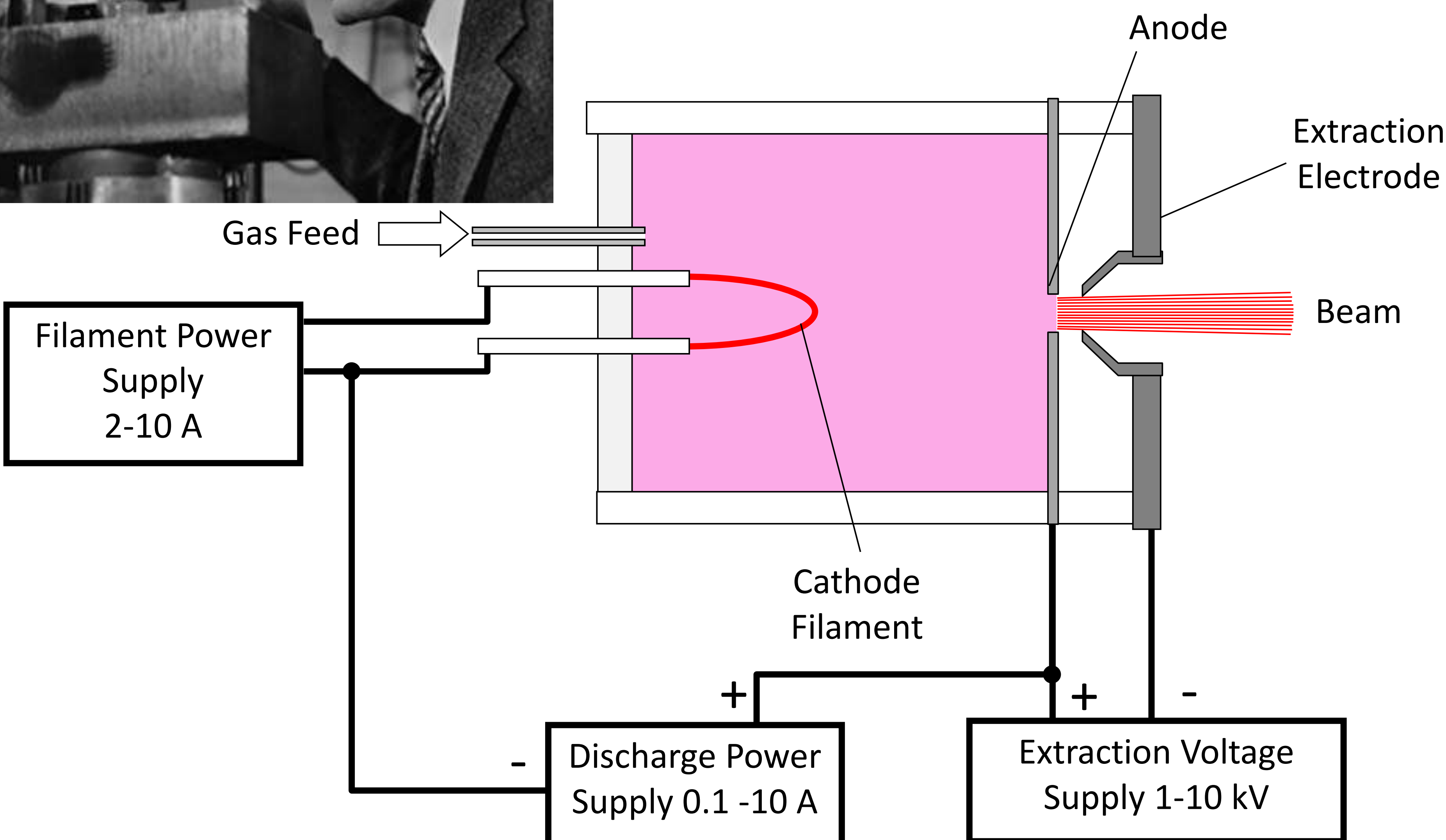
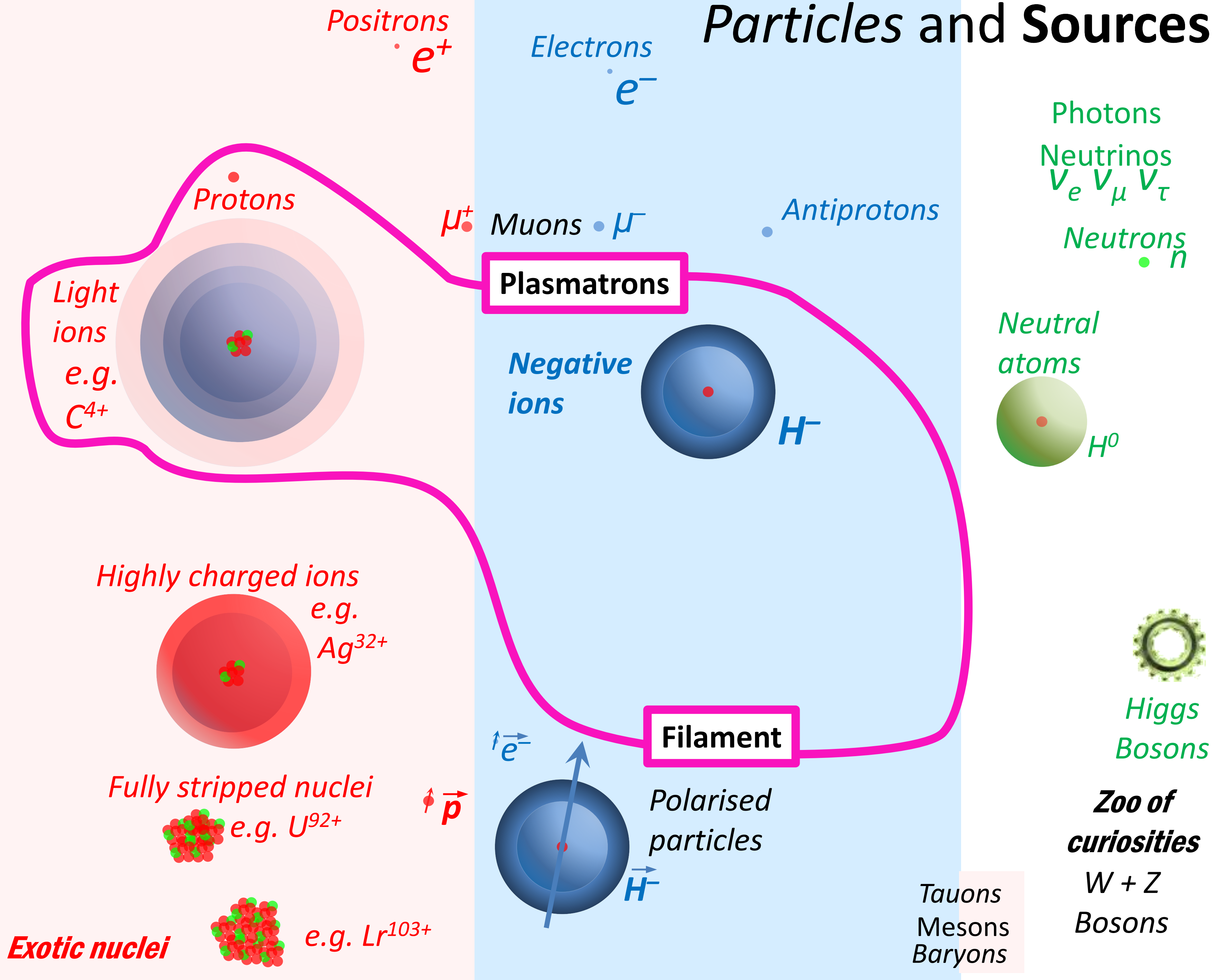


Filament Source

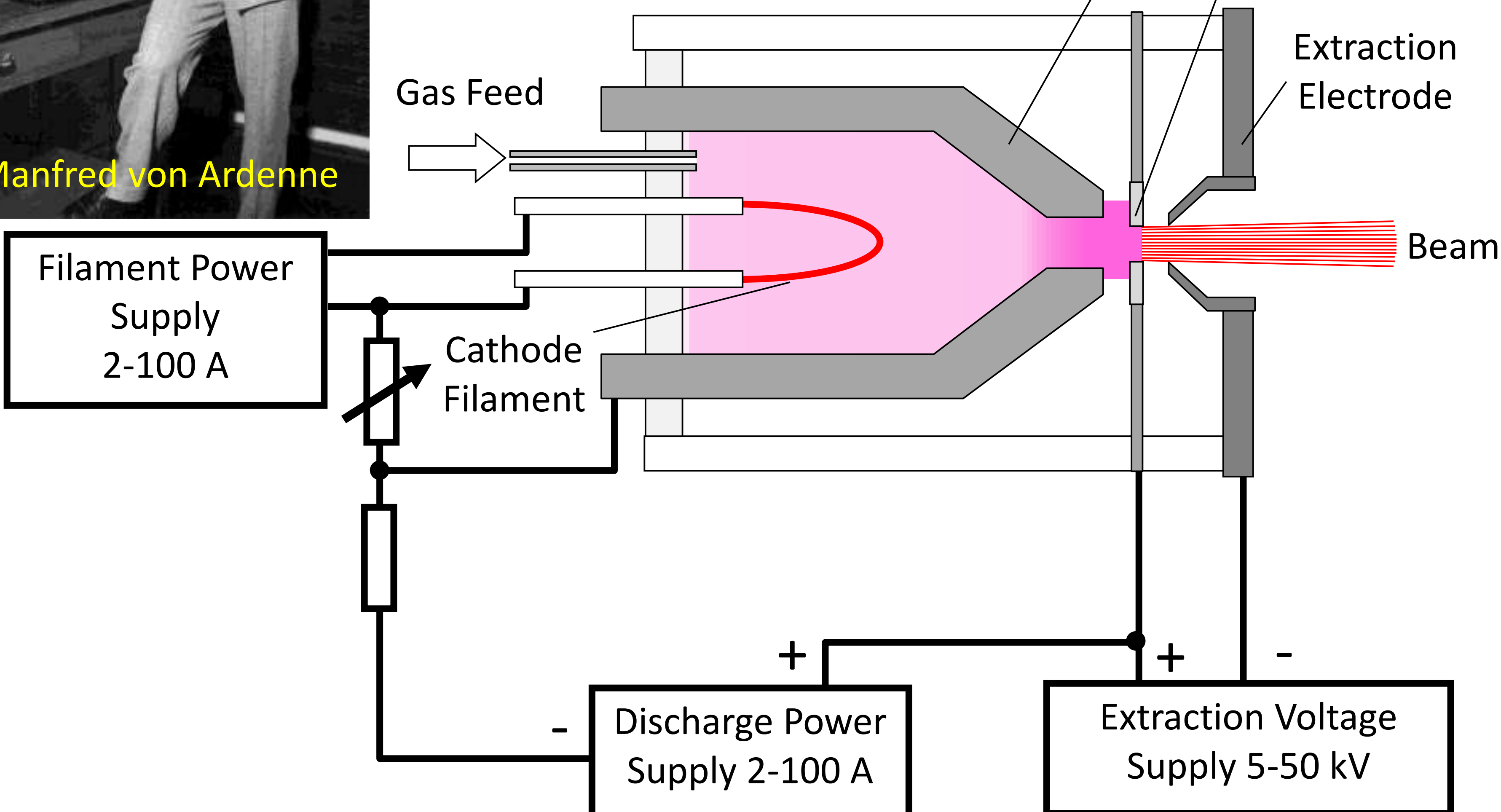
Electron Bombardment Source (1916)



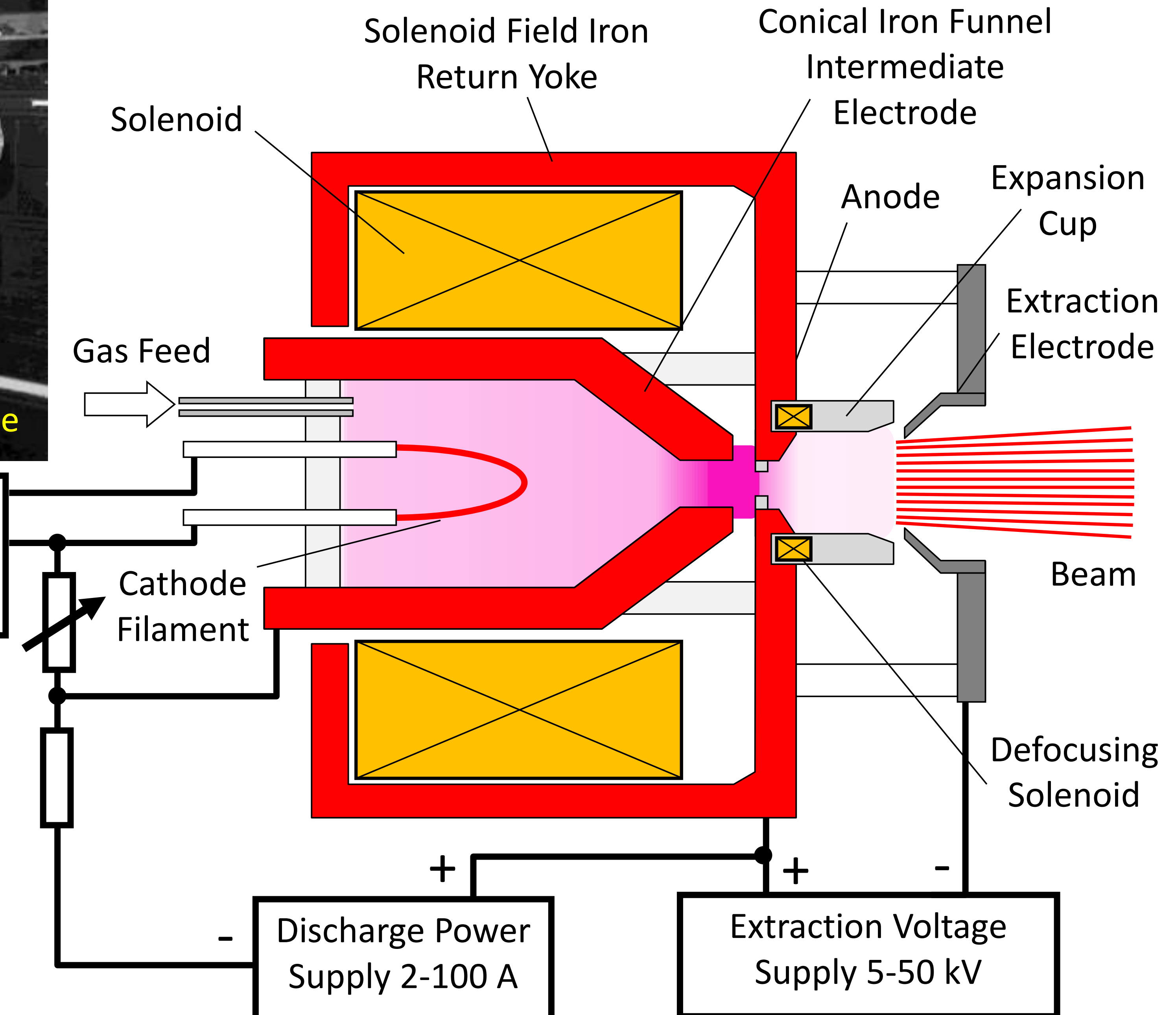
Particles and **Sources**



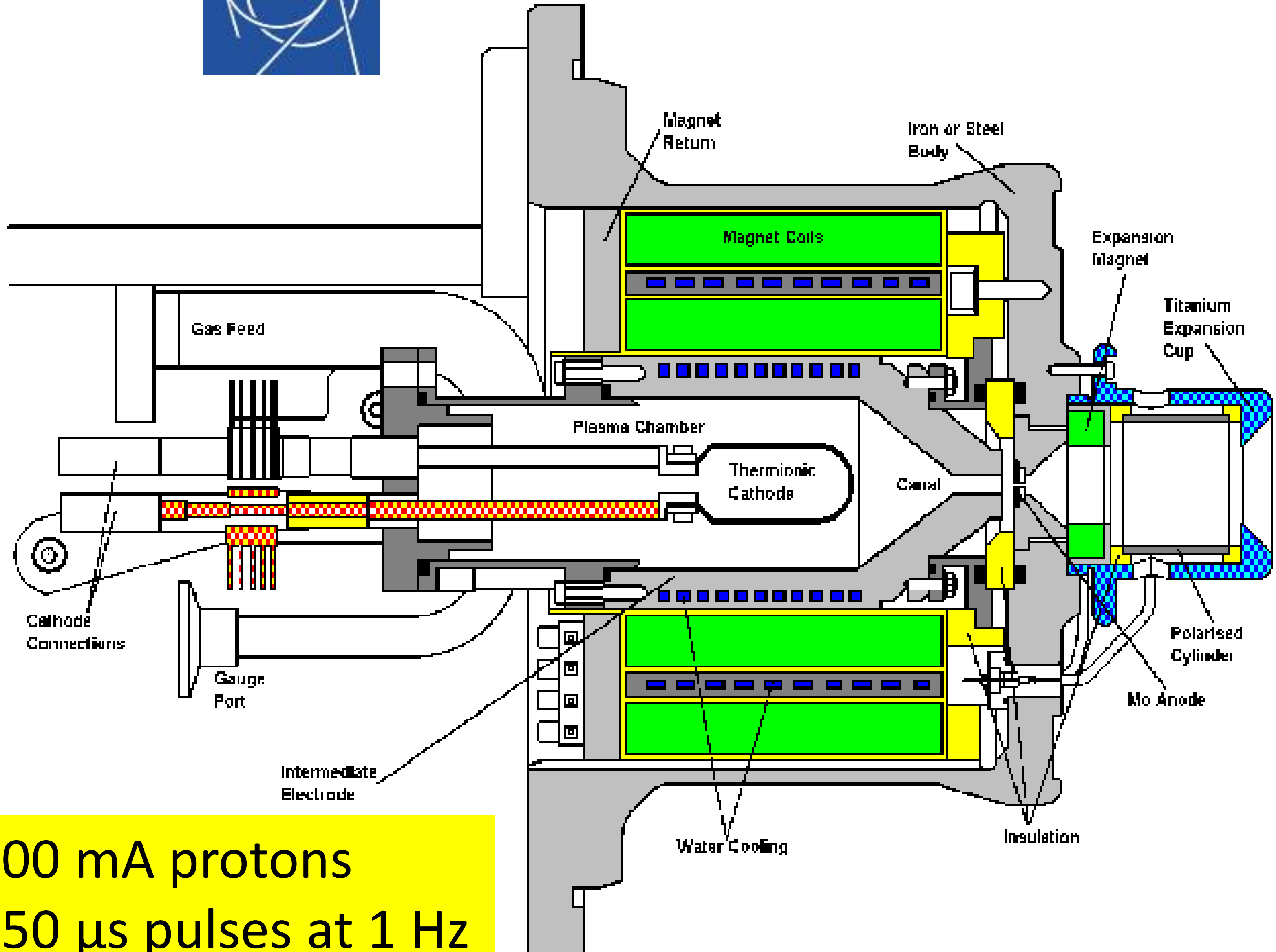
Plasmatron (late 1940s)



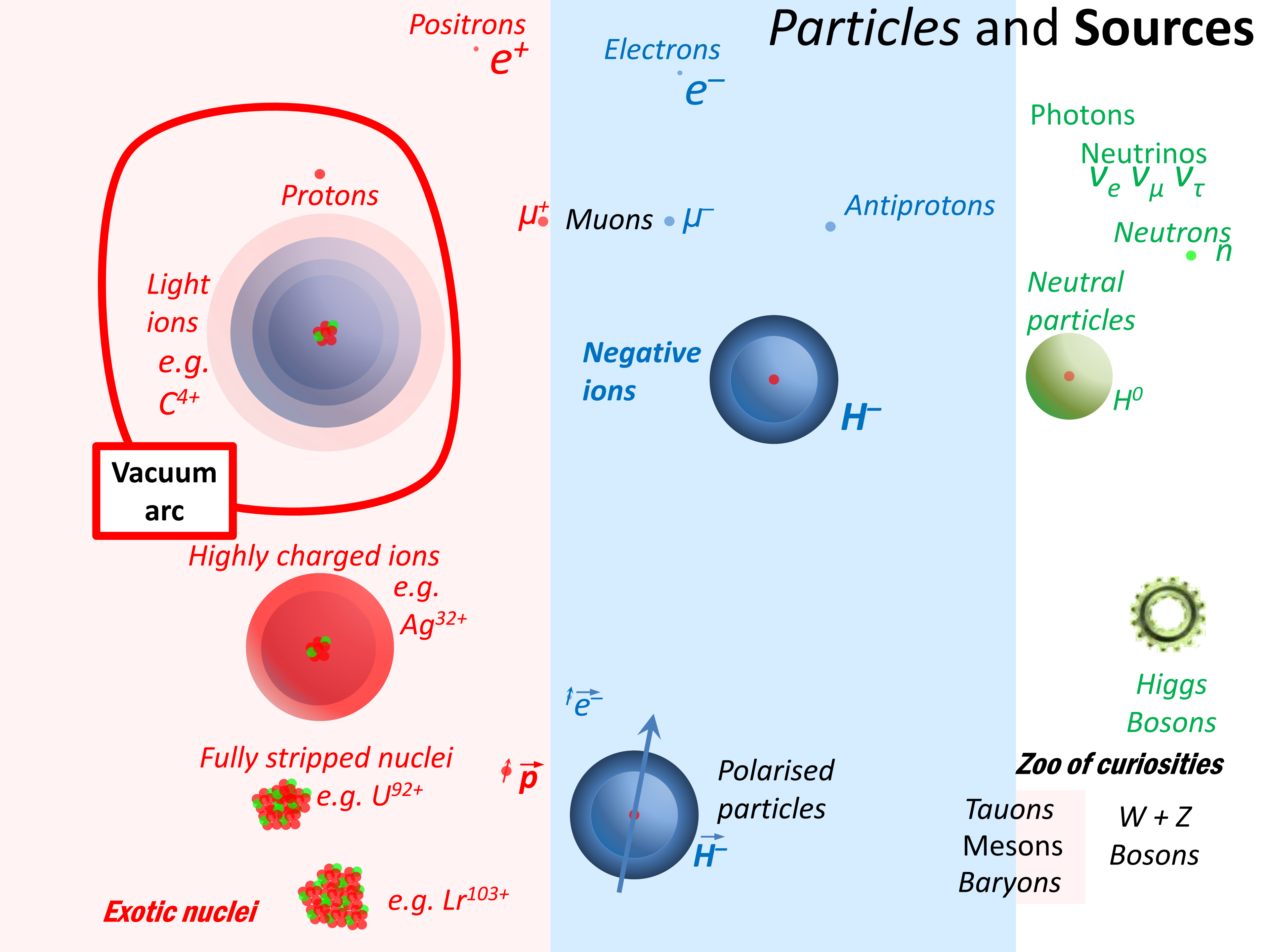
Duoplasmatron (1956)



Duoplasmatron



300 mA protons
150 µs pulses at 1 Hz



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Vacuum arc
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$\vec{p}$
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Zoo of curiosities
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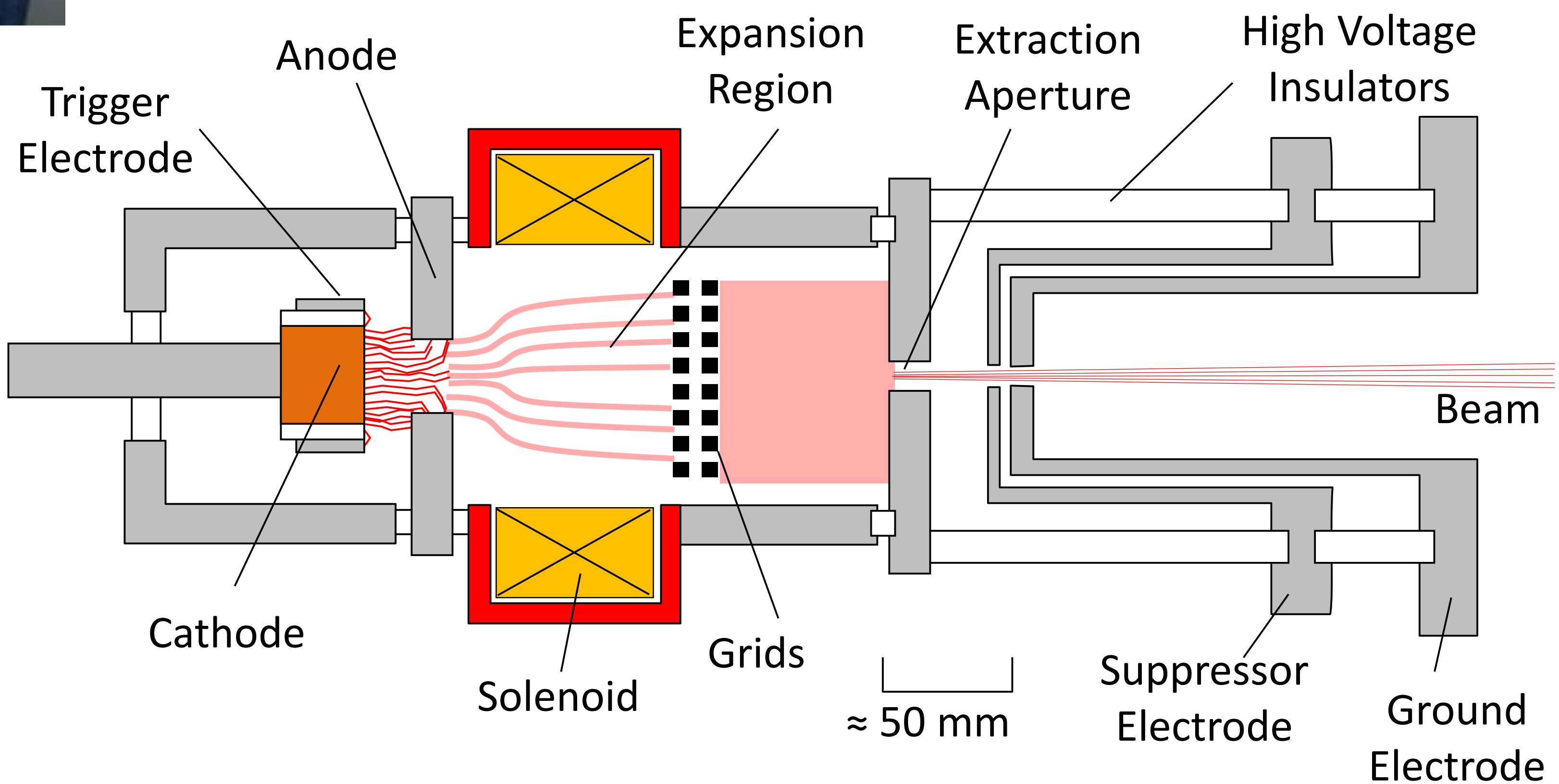
Baryons
W + Z Bosons
$\vec{H}^-$
Exotic nuclei
e.g. Lr^{103+}

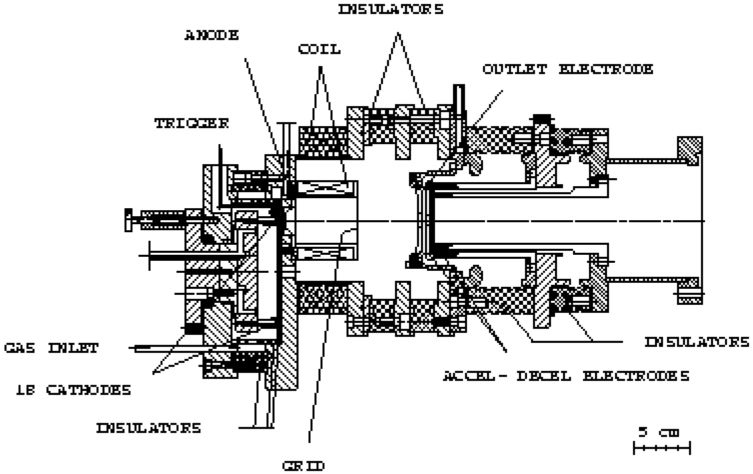
Vacuum Arc Ion Sources

1980s - Ian Brown at LBNL and others

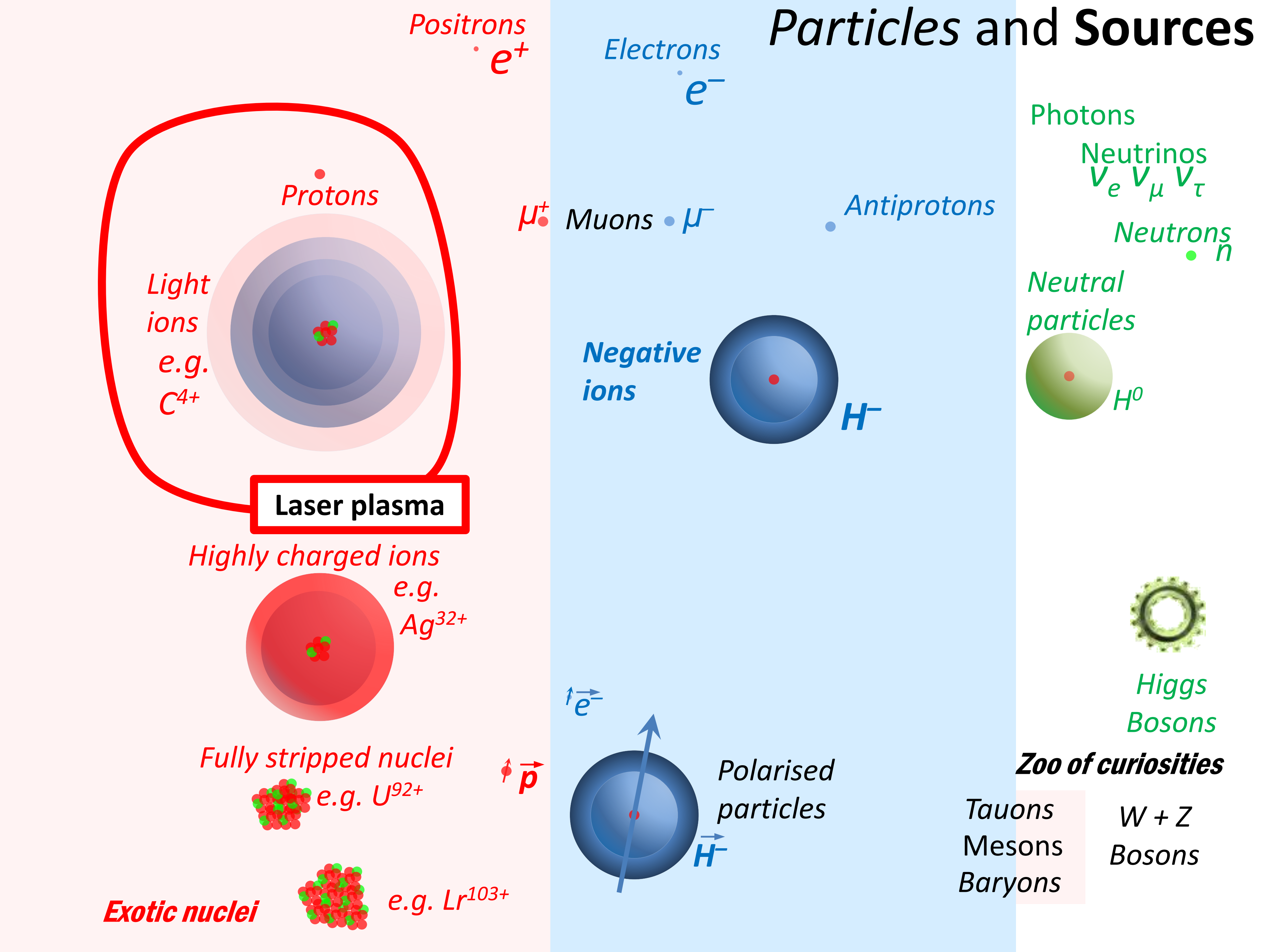


Lawrence Berkley Lab MEVVA

GSI MEVVA



15 mA of U^{4+} ions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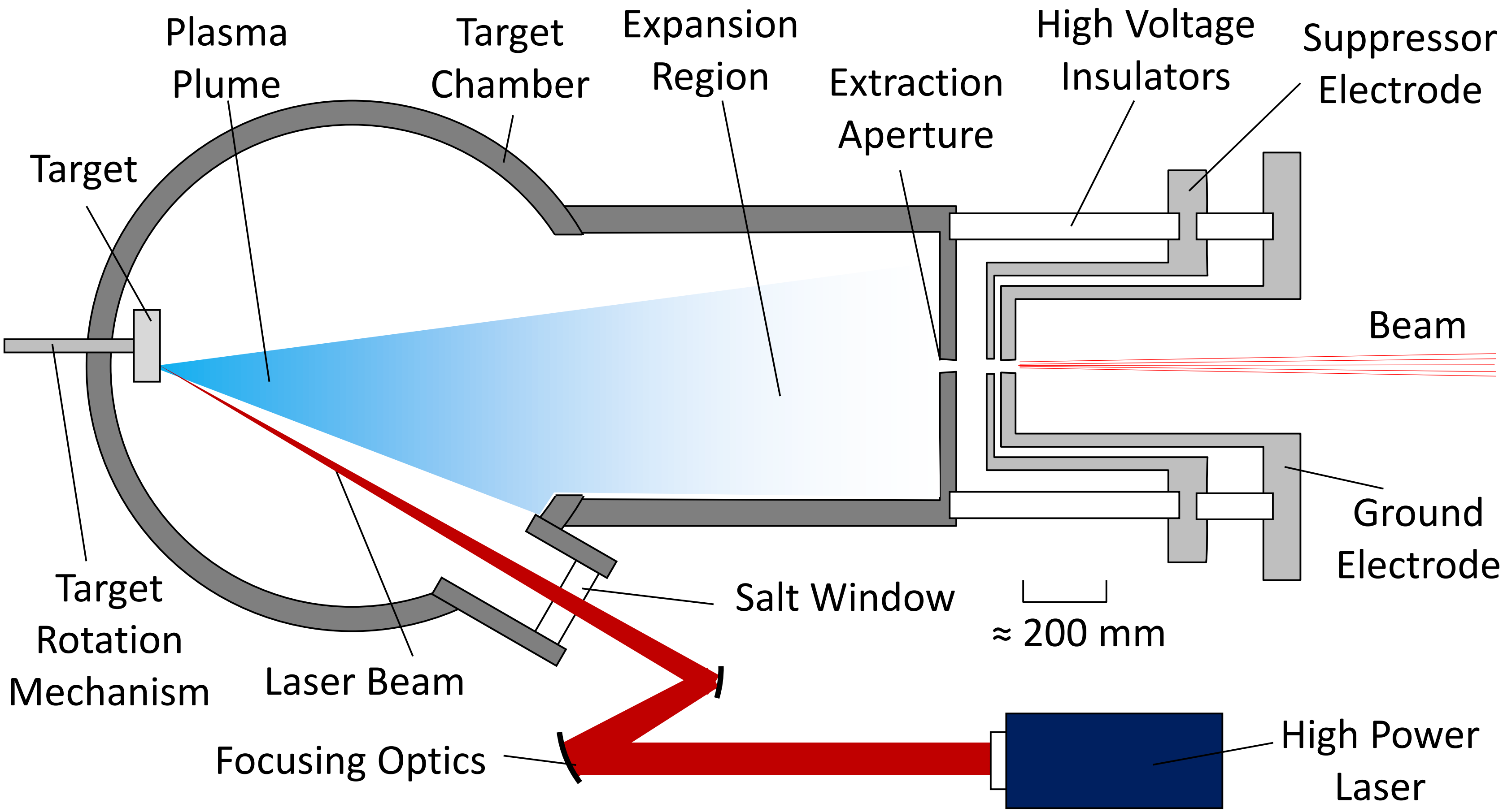
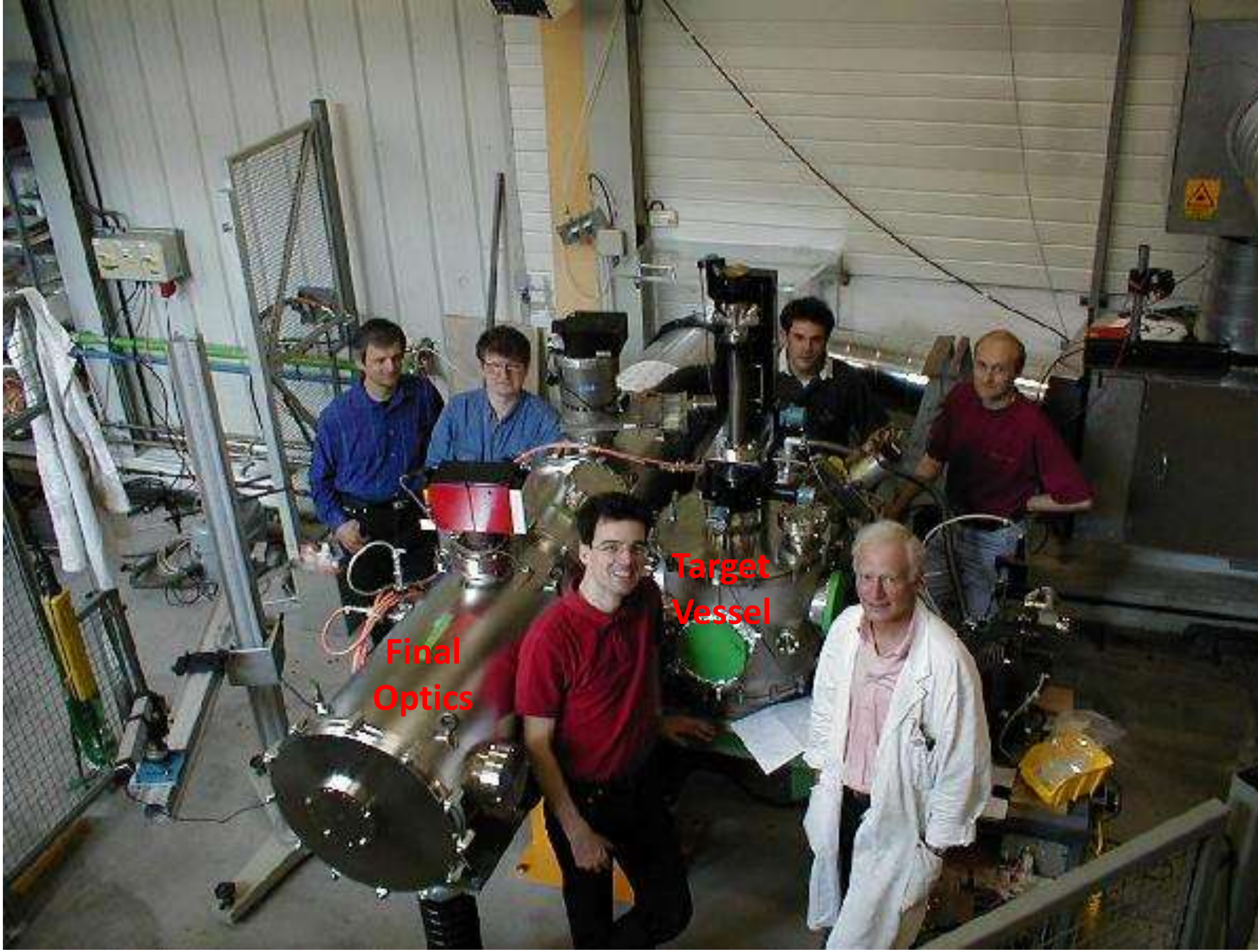
Laser Plasma Ion Sources



1 -100 Joules per pulse!



ITEP Laser source at CERN

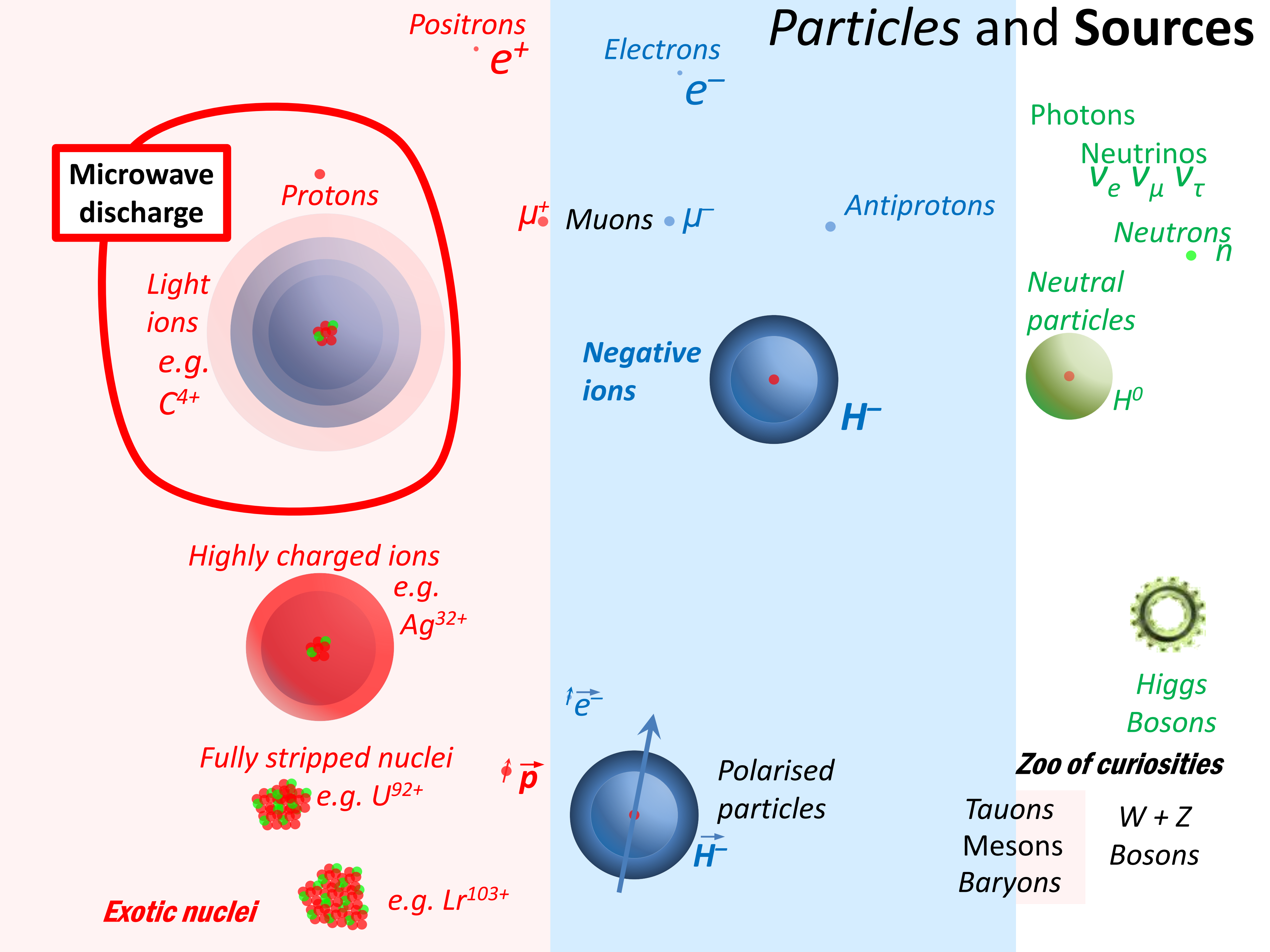
ITEP Laser source at CERN

TWAC at ITEP Moscow

7 mA, 10 μs pulses of C^{4+}

Further Developments

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

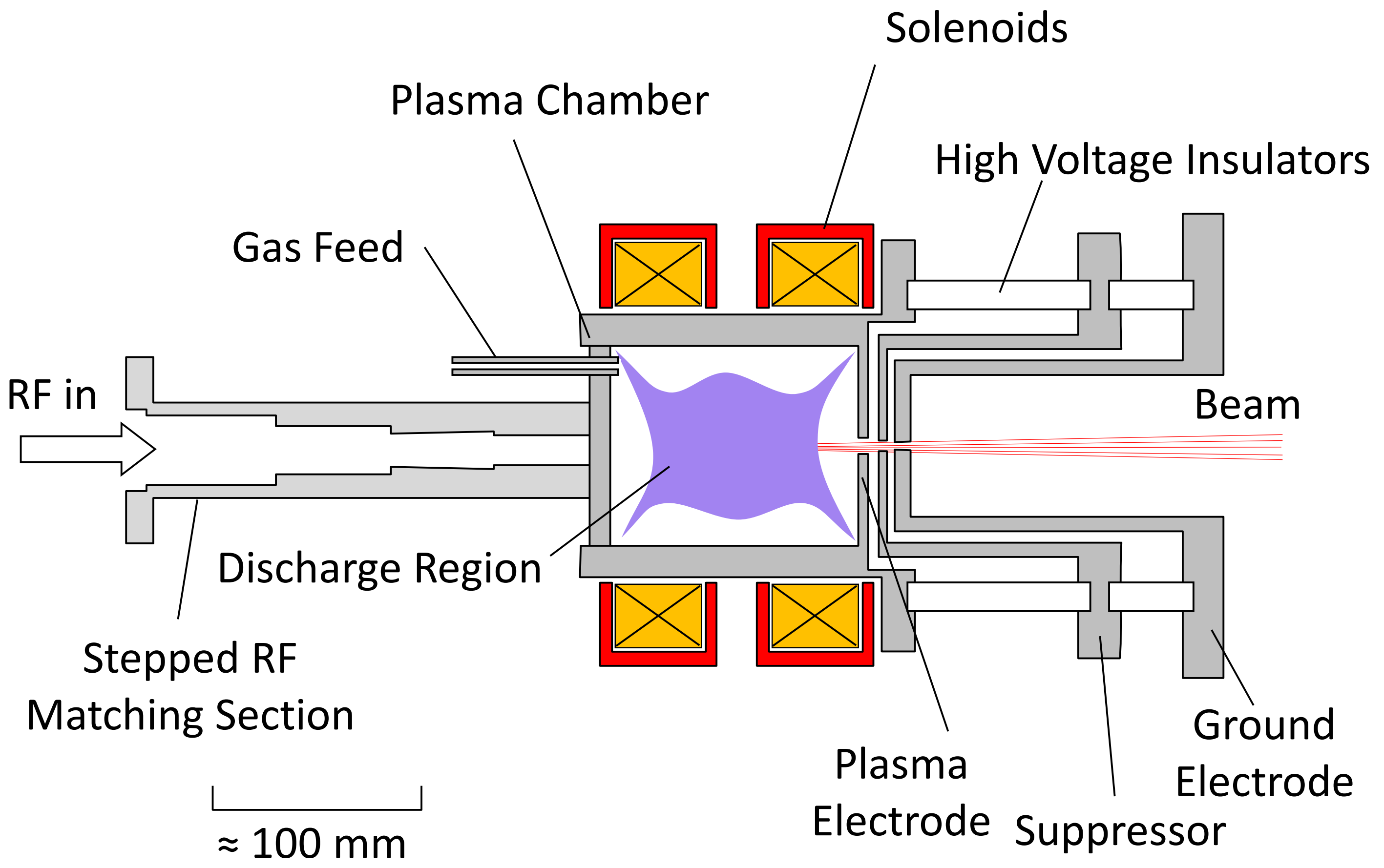
Off resonance

= Microwave discharge ion sources

On resonance

= Electron Cyclotron Resonance (ECR) sources

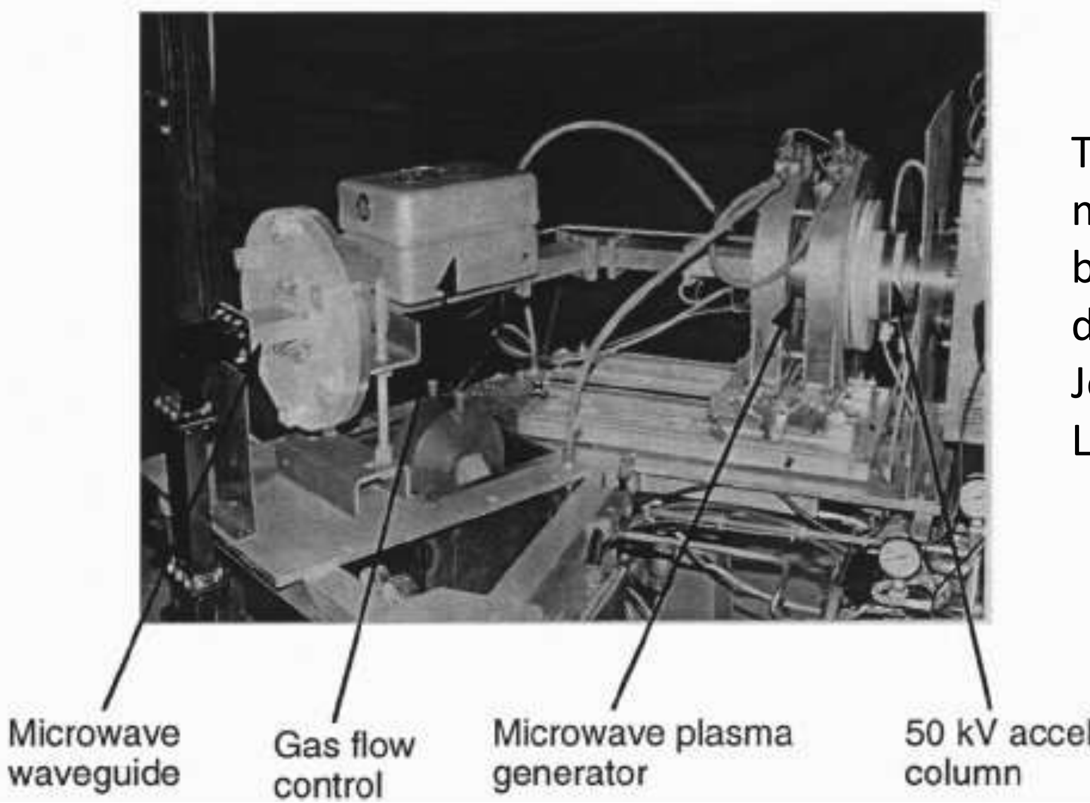
Microwave Discharge Ion Source



2.45 GHz commonly used

Microwave Discharge Ion Source

First developed in the late 1970s and early 1980s by: Noriyuki Sakudo at Hitachi
Junzo Ishikawa at Kyoto University

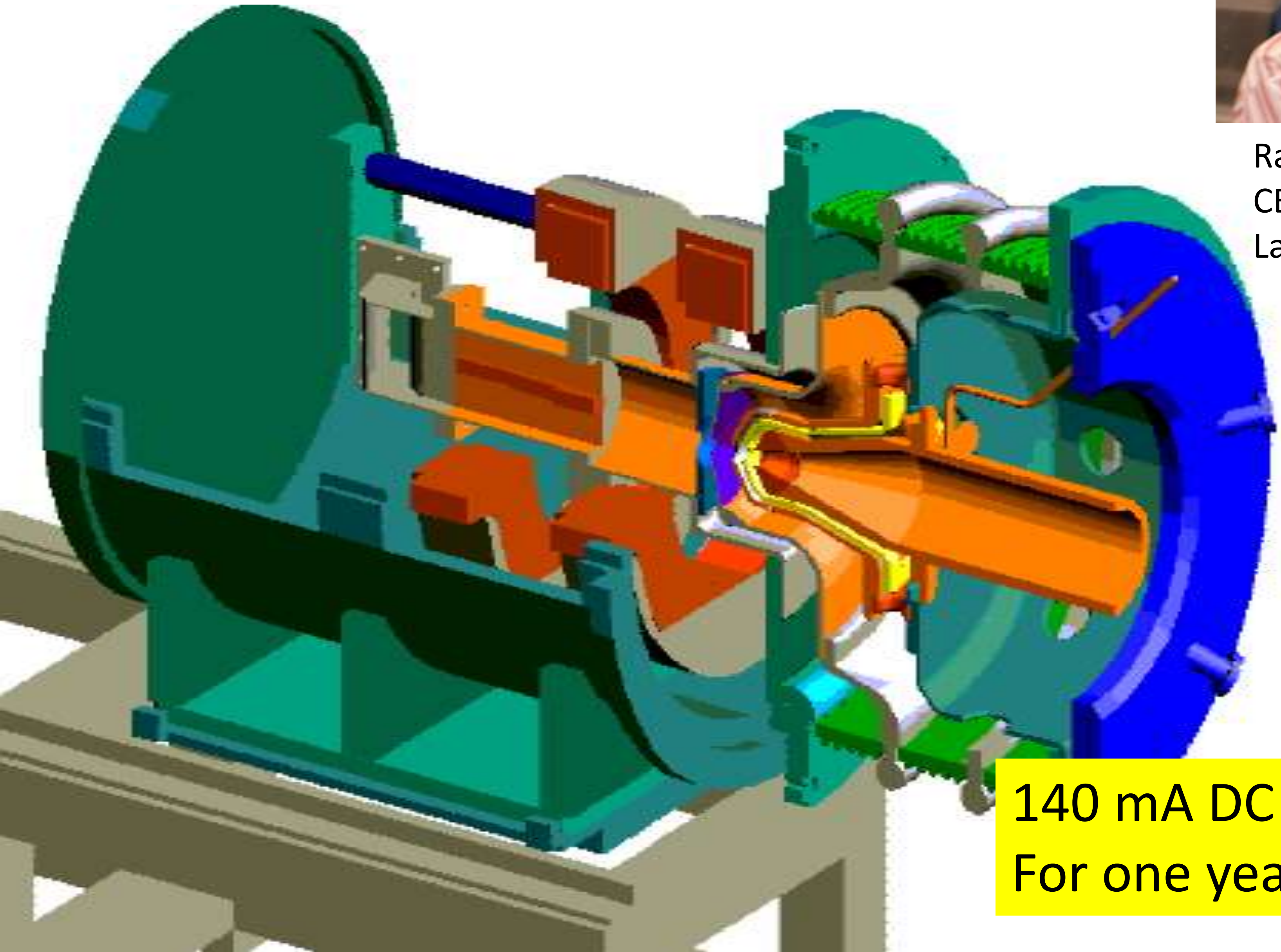


The basic design of all modern microwave discharge ion sources is based on the proton source developed by Terence Taylor and Jozef Mouris at Chalk River National Laboratory in the early 1990s

The Chalk River source at LANL developed by Joe Sherman

60 mA DC protons

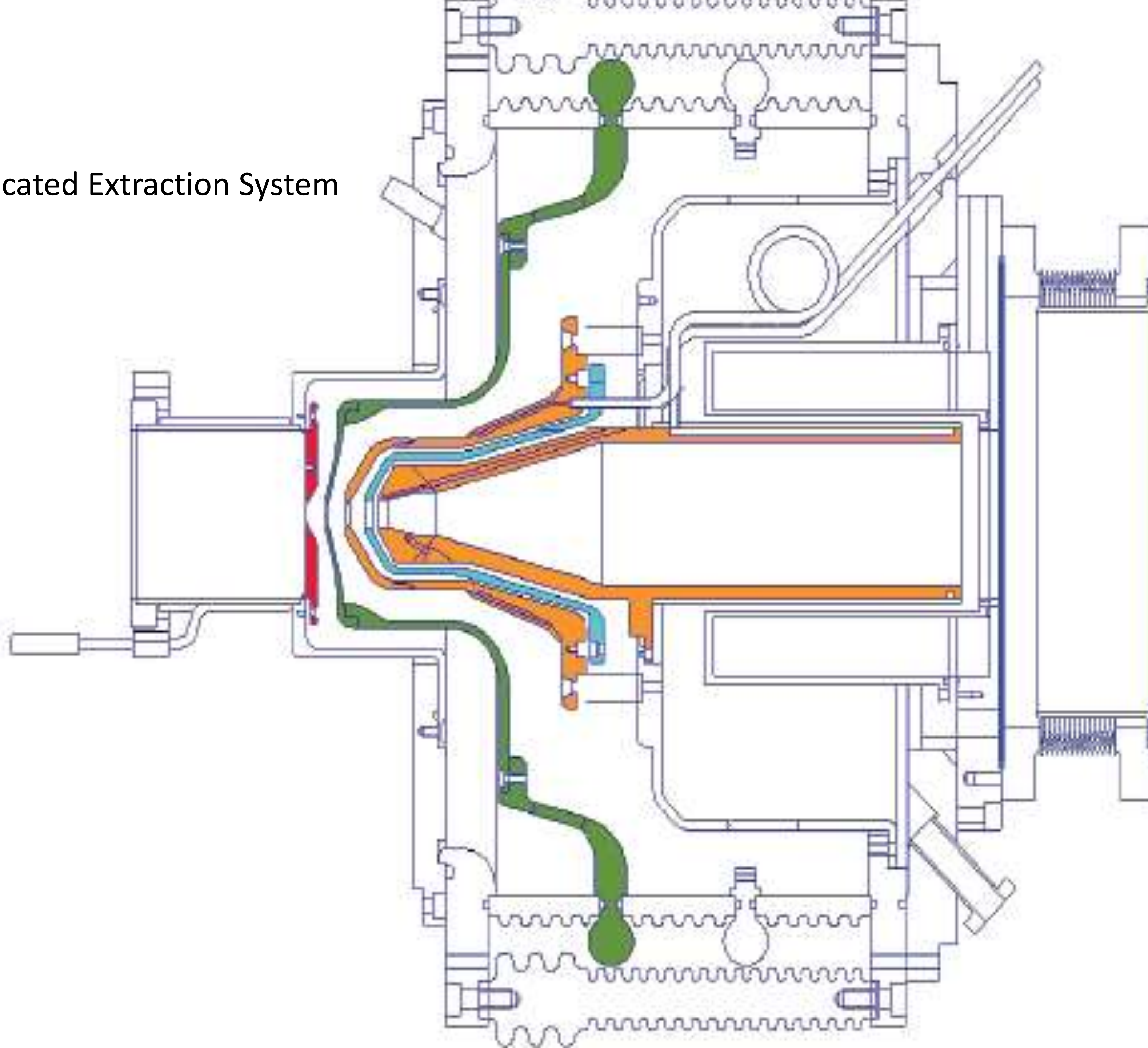
SILHI Microwave Source



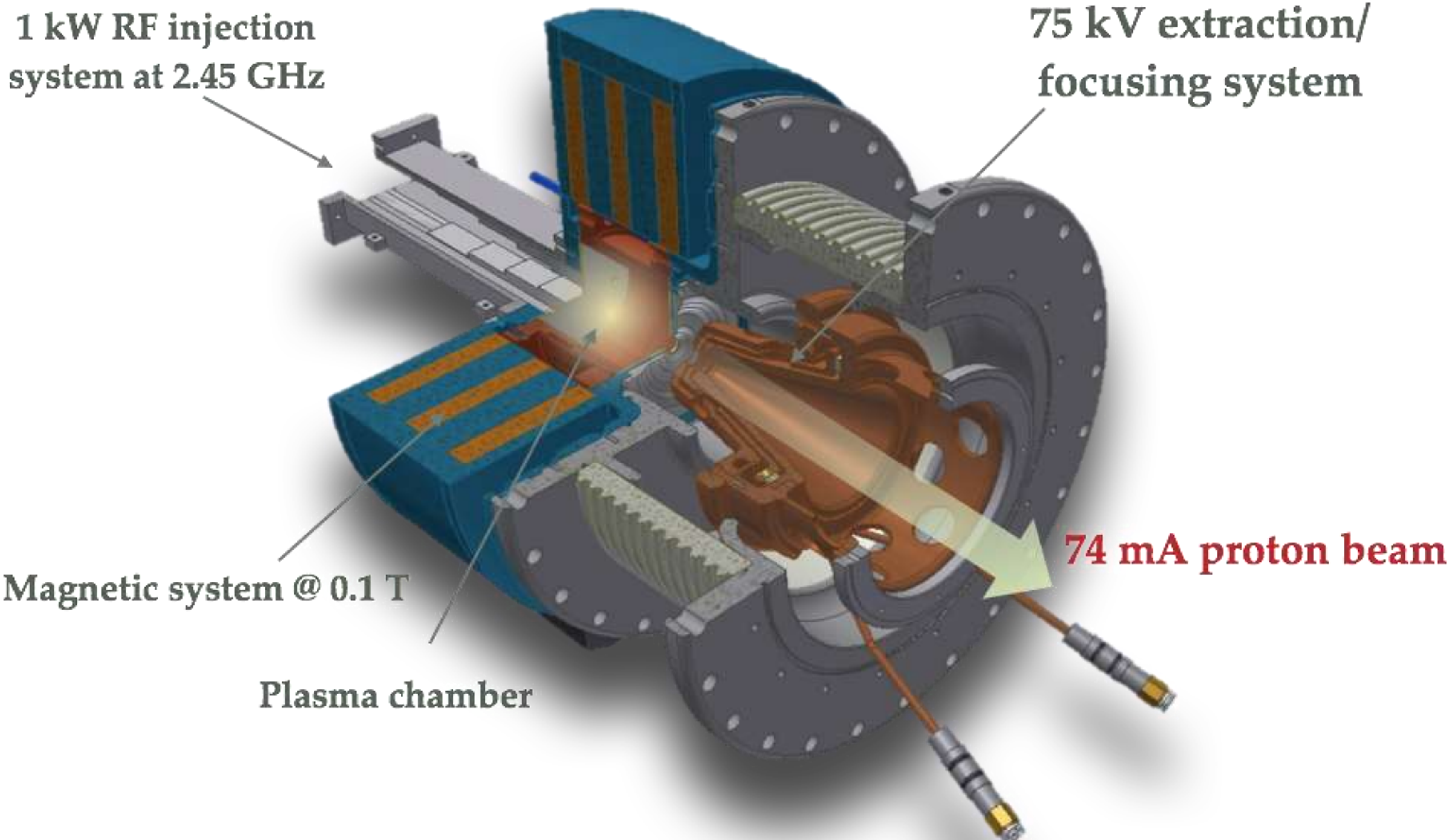
Rafael Gobin
CEA Saclay
Late 1990s

140 mA DC protons
For one year!

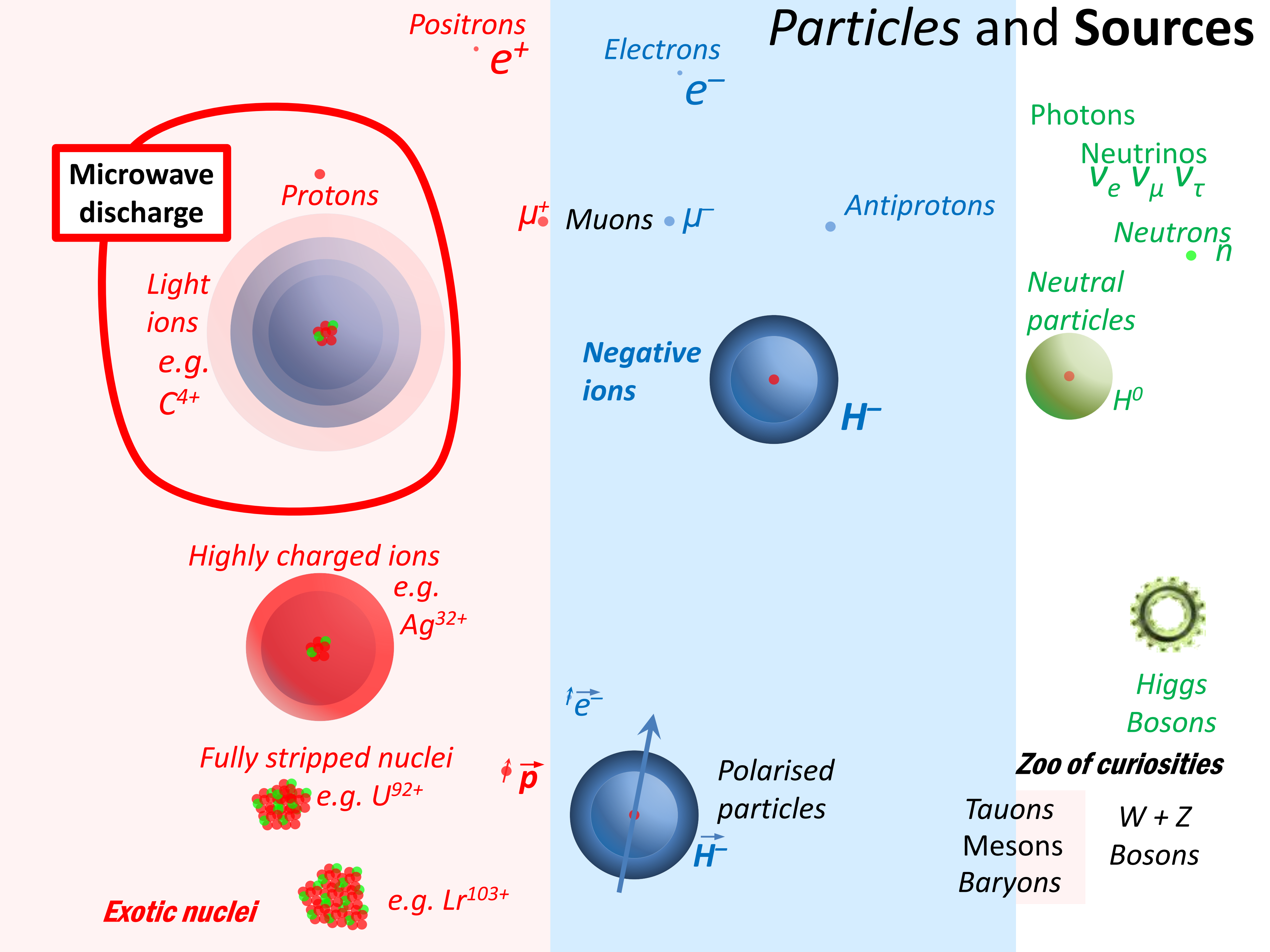
Sophisticated Extraction System



ESS Source



SILHI source via INFN


Particles and Sources
Positrons
e+
Electrons
e−
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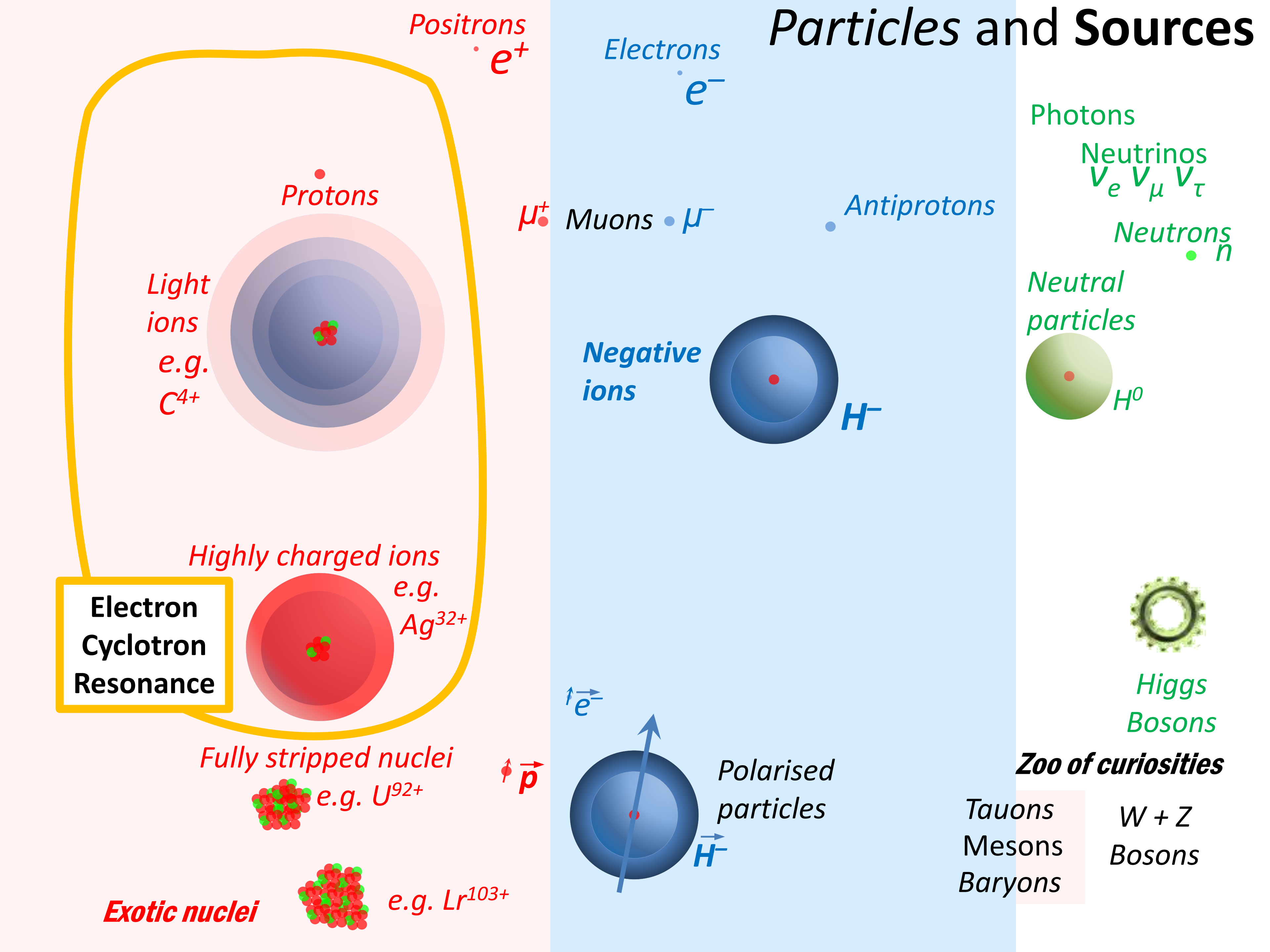
νe νμ ντ
Microwave discharge
Protons
μ+
Muons
μ−
Antiprotons
Neutrons
n
Light ions e.g. C4+
Neutral particles
Negative ions
H−
H0
Highly charged ions
e.g. Ag32+
Higgs Bosons
e−
Fully stripped nuclei
e.g. U92+
p
Polarised particles
Zoo of curiosities
Tauons
Mesons
Baryons
W + Z Bosons
H−
Exotic nuclei
e.g. Lr103+



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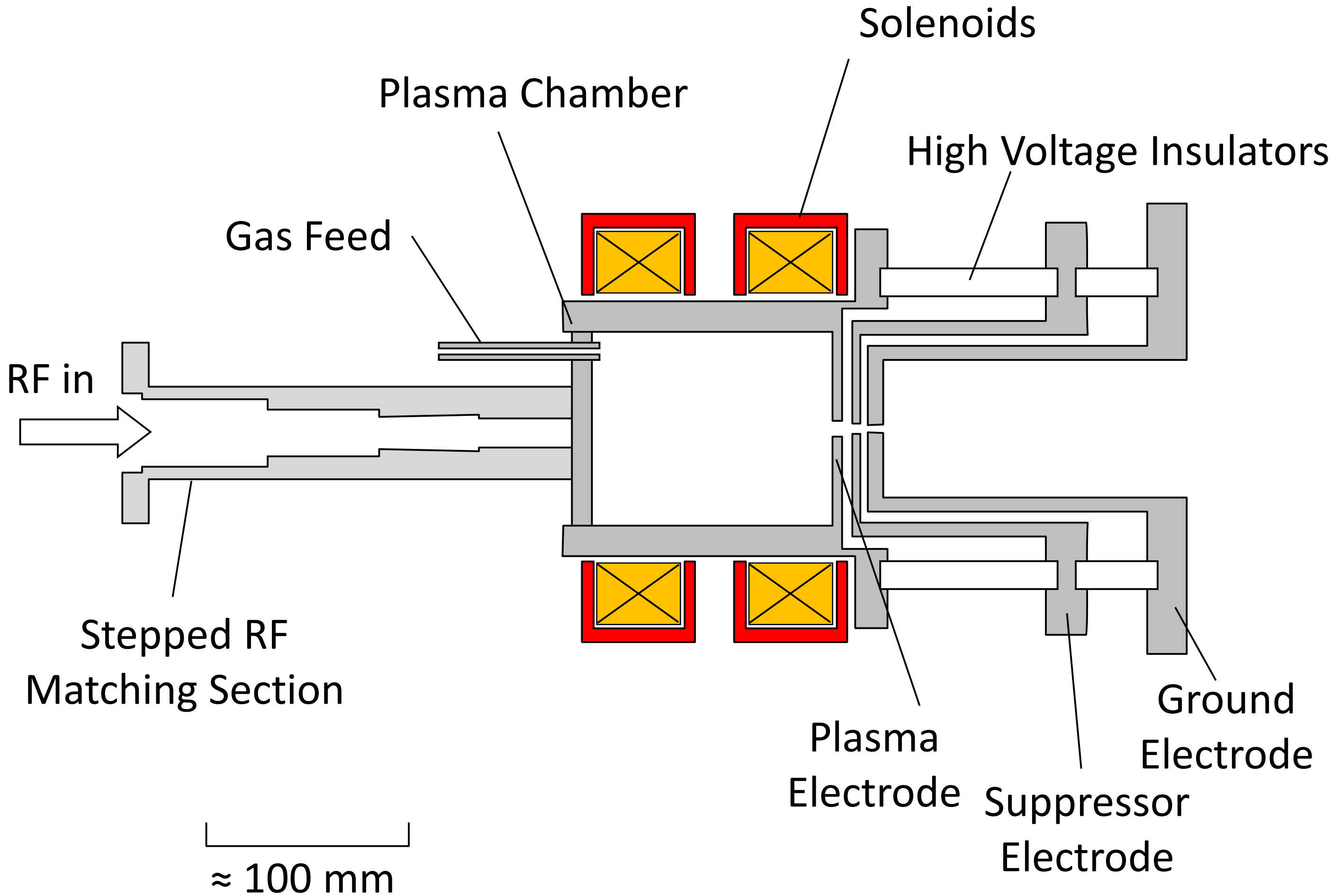
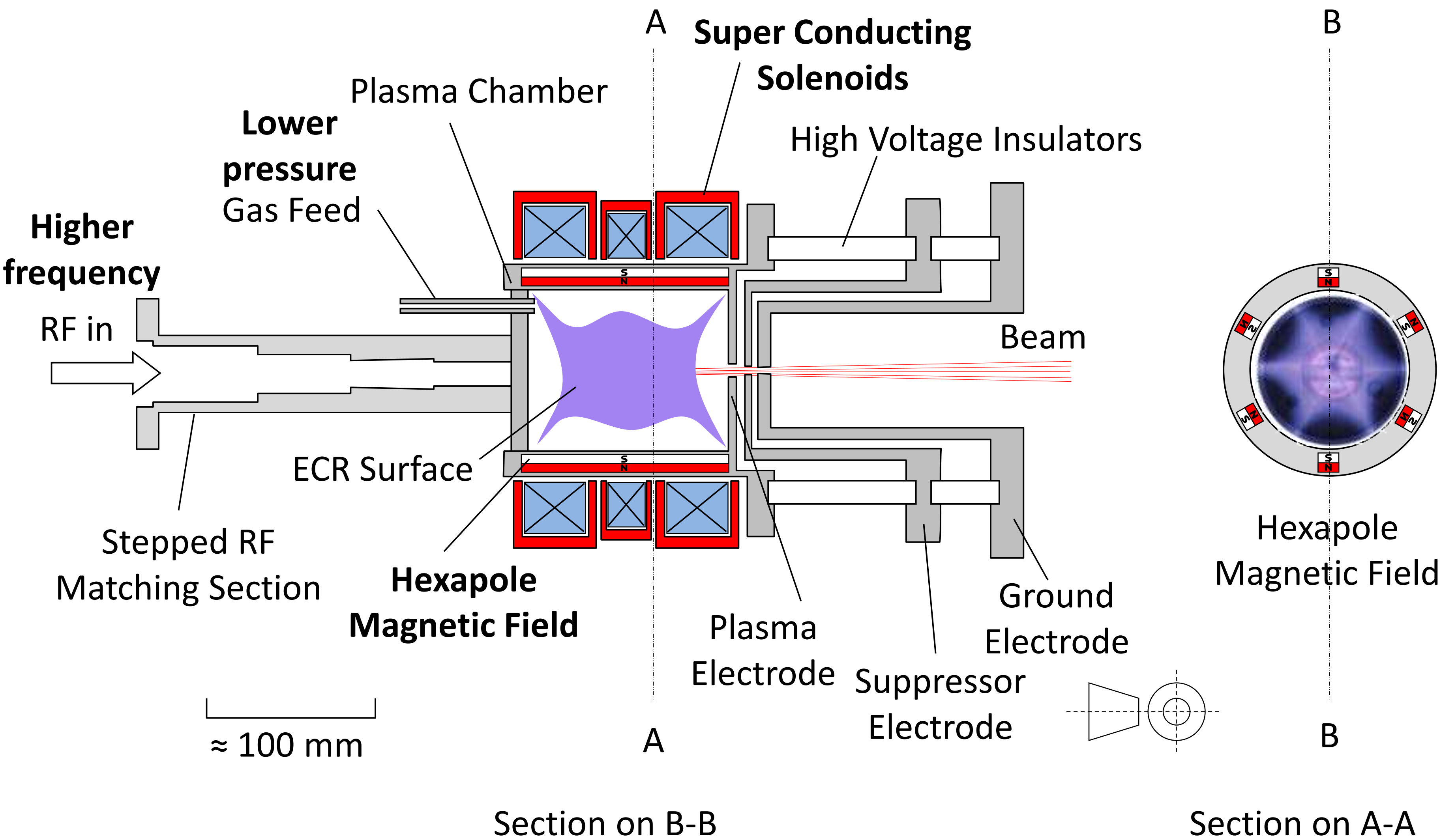
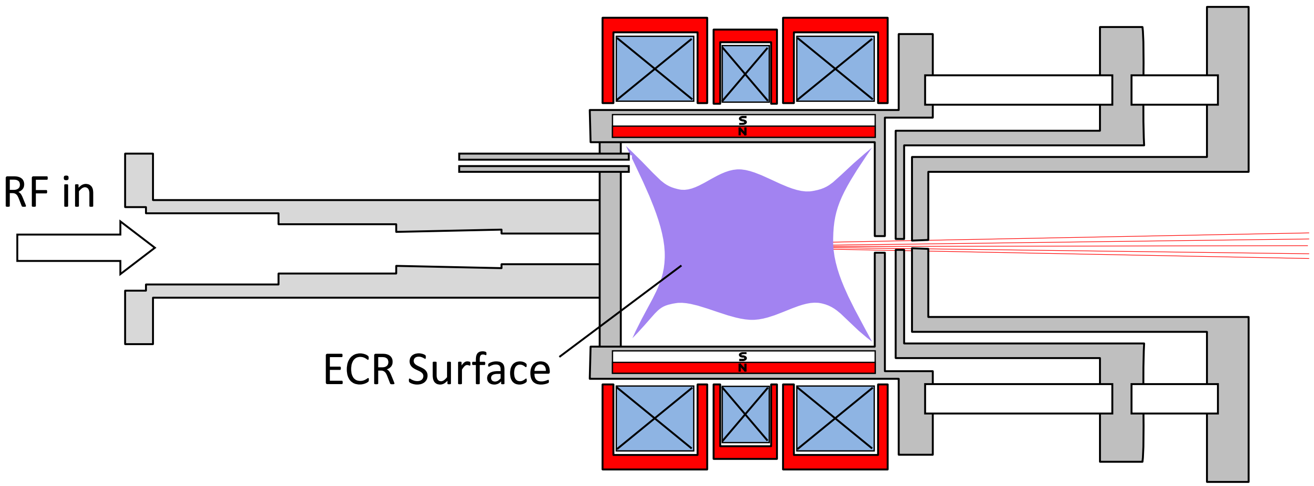
Microwave Discharge Ion Source

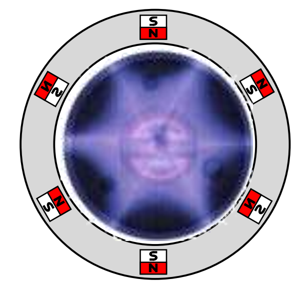


ECR Ion Source



ECR Ion Source





Hexapole
Magnetic Field

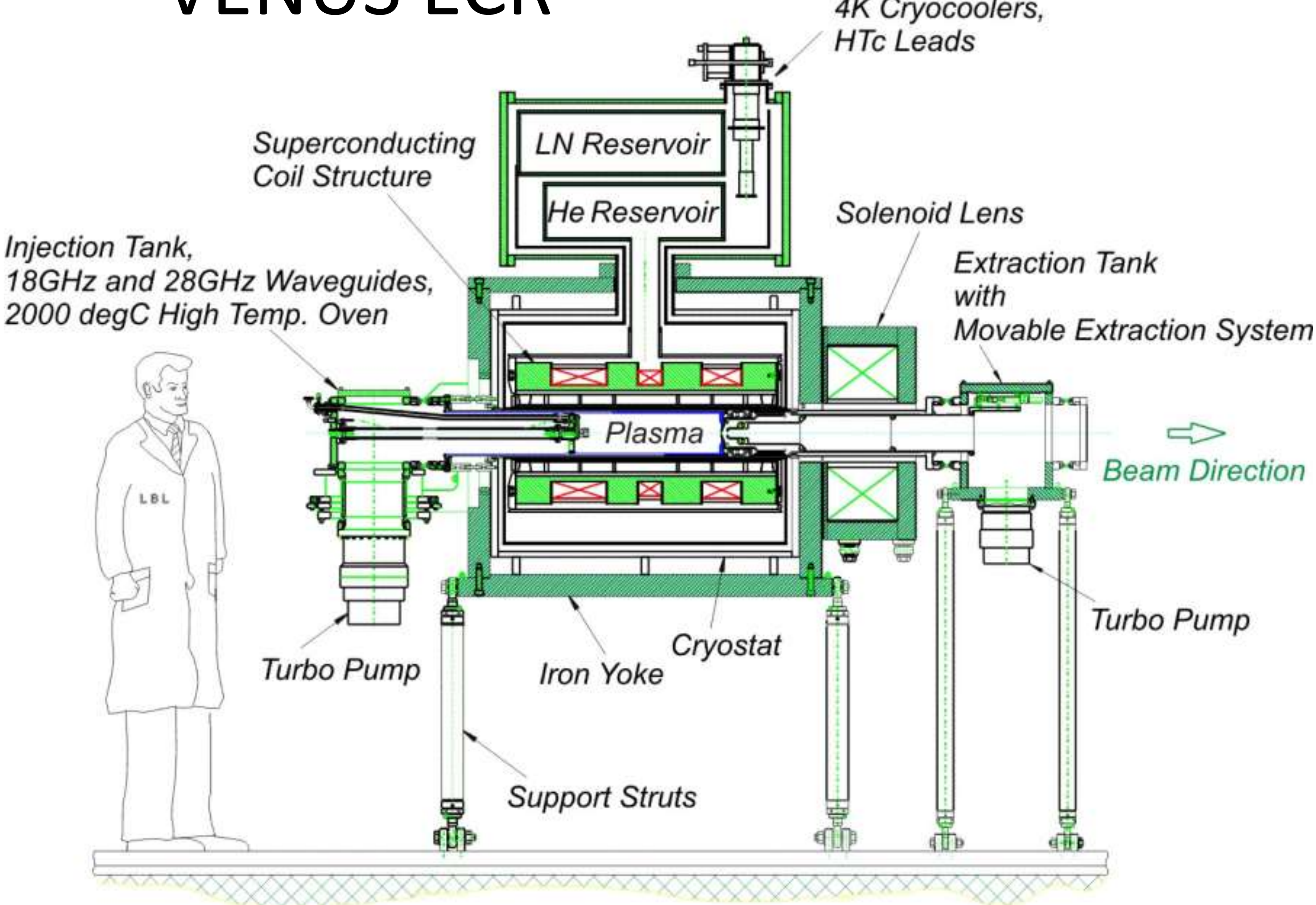
$$\omega_{ECR} = 2\pi f_{ECR} = \frac{eB}{m}$$

28 GHz superconducting VENUS ECR

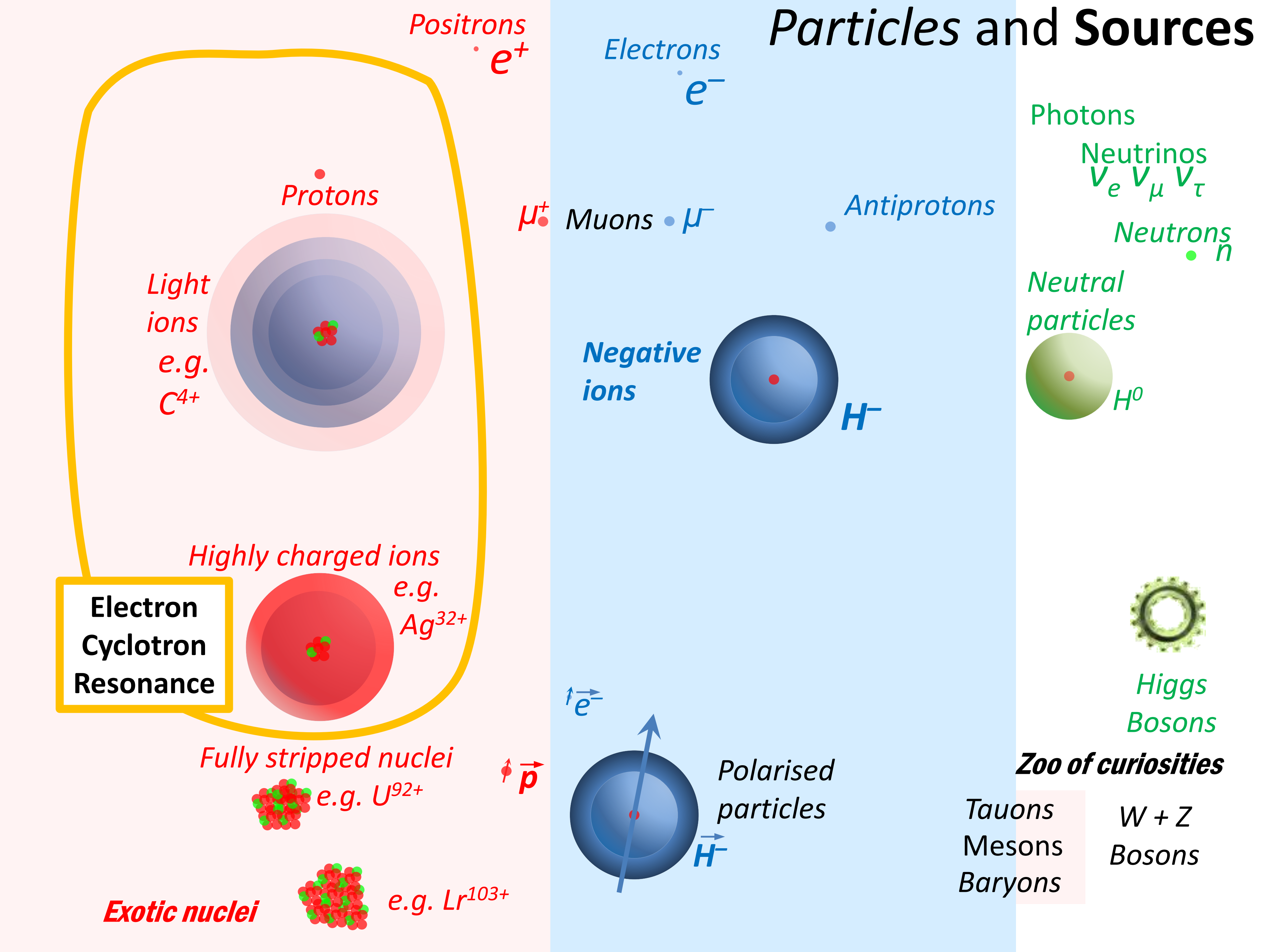
Daniela Leitner
LBNL
Late 2000s

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
LBL
Plasma
Beam Direction
Turbo Pump
Cryostat
Iron Yoke
Turbo Pump
Support Struts



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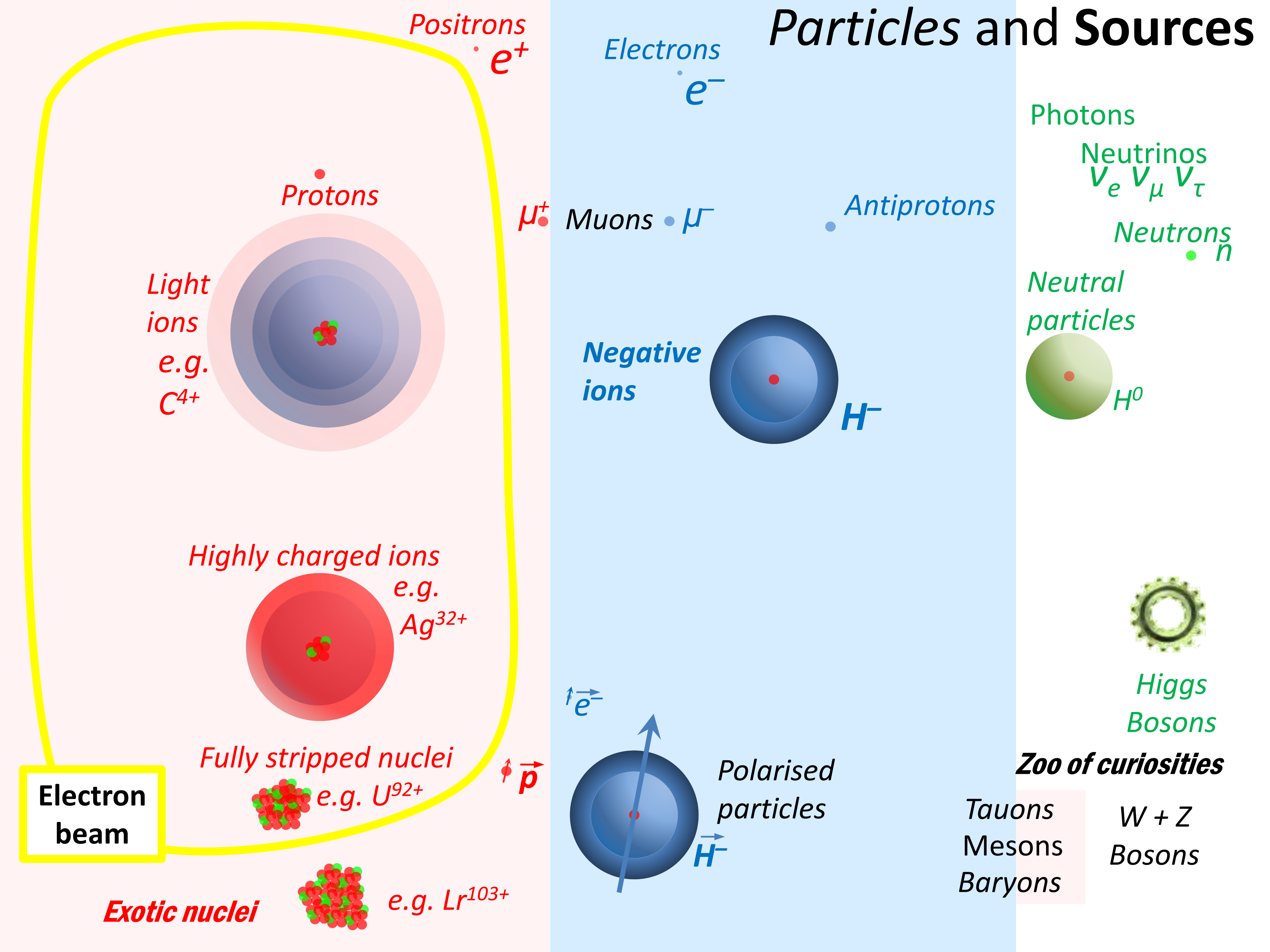
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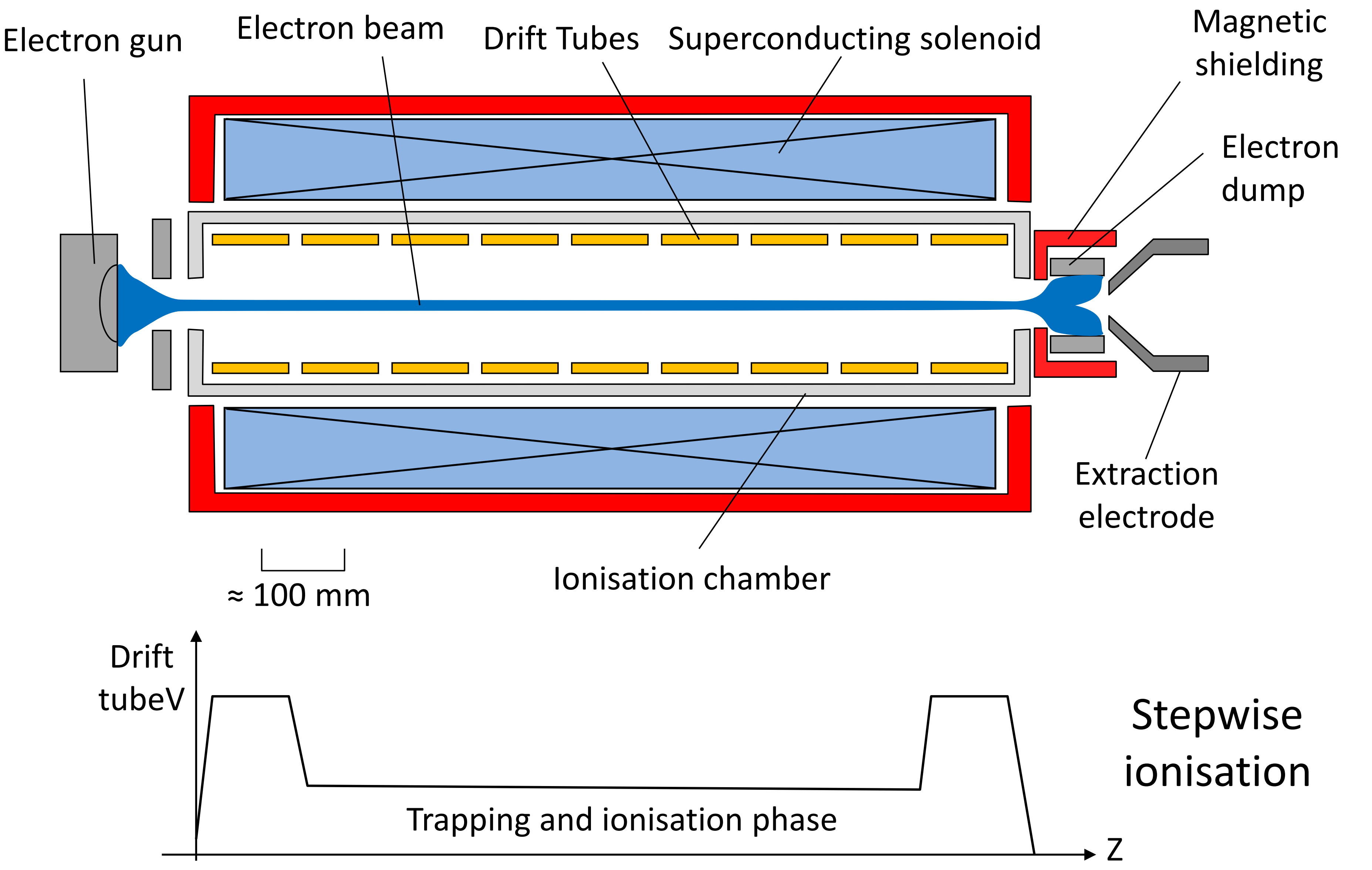
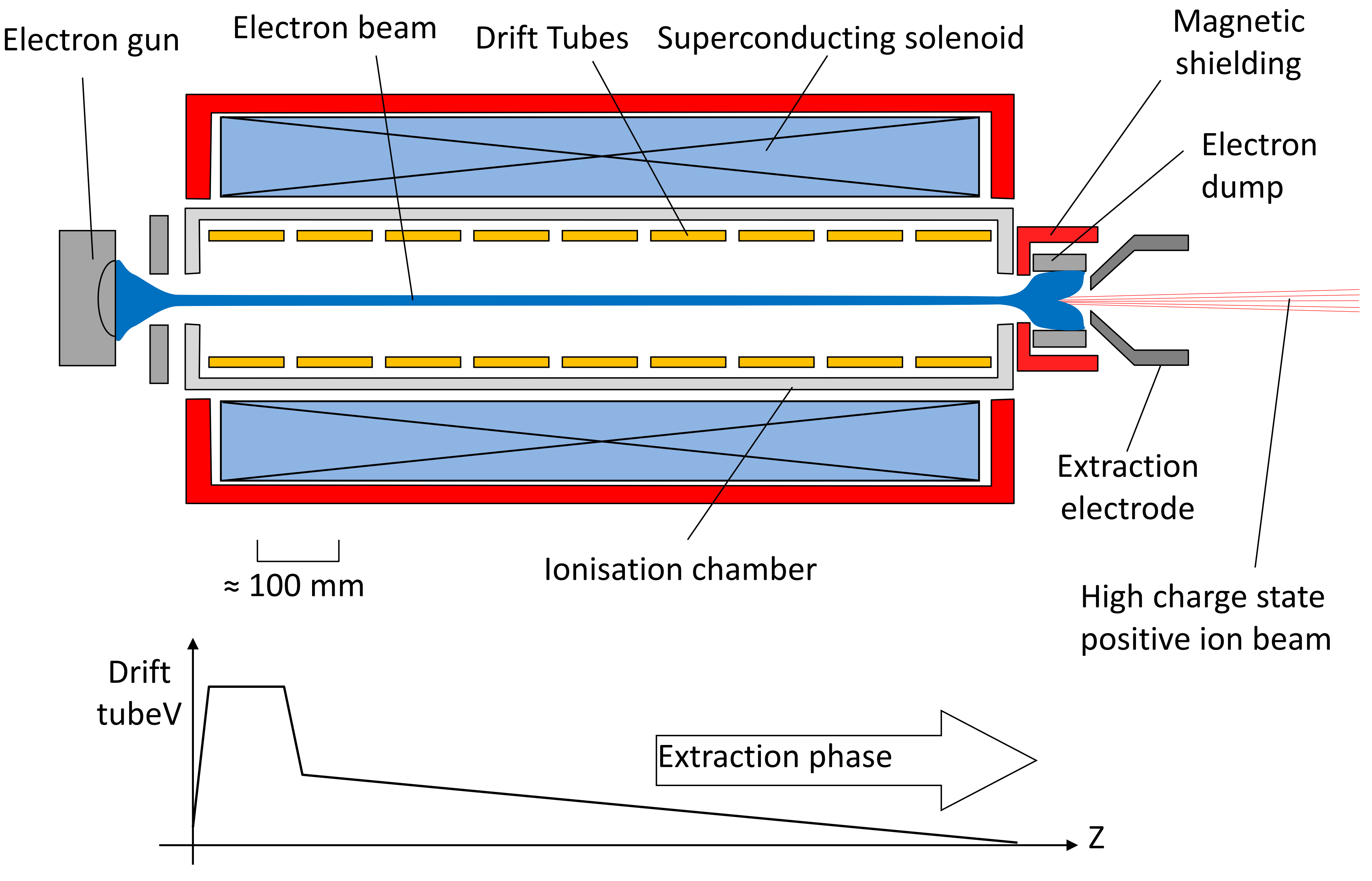
Electron Beam Ion Sources



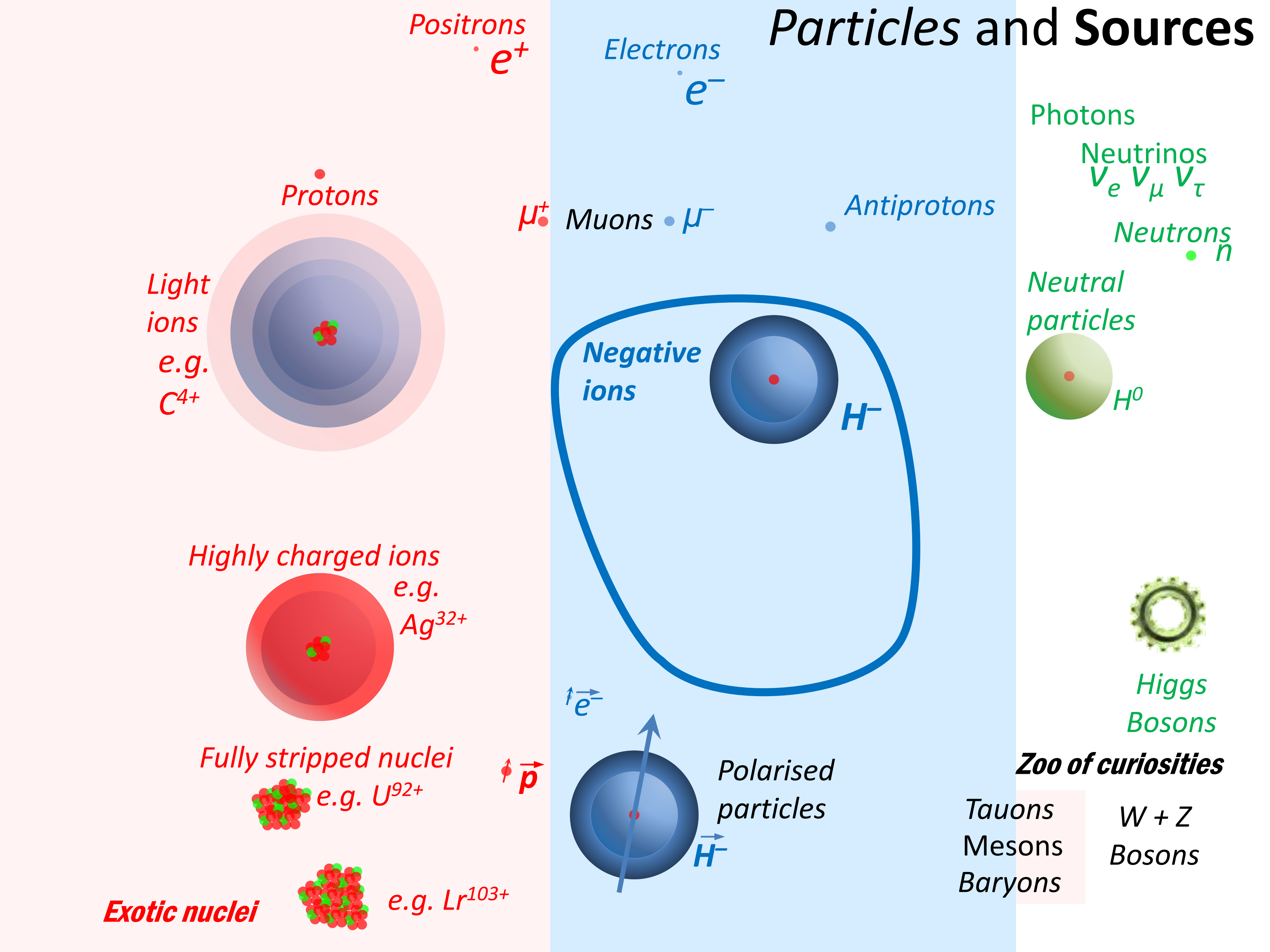
Electron Beam Ion Sources



Jim Alessi
BNL

1.7 emA, 10 μs, 5 Hz
Ag^{32+} ions

Fully stripped nuclei can be obtained in EBIT mode



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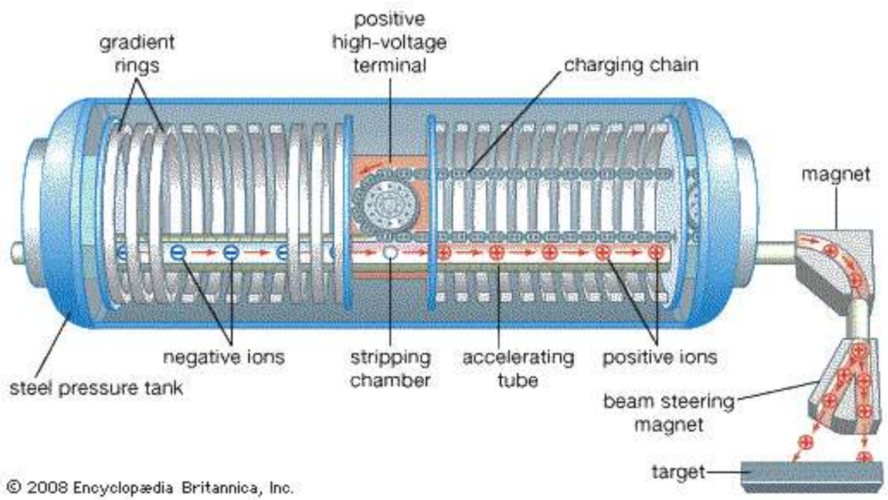
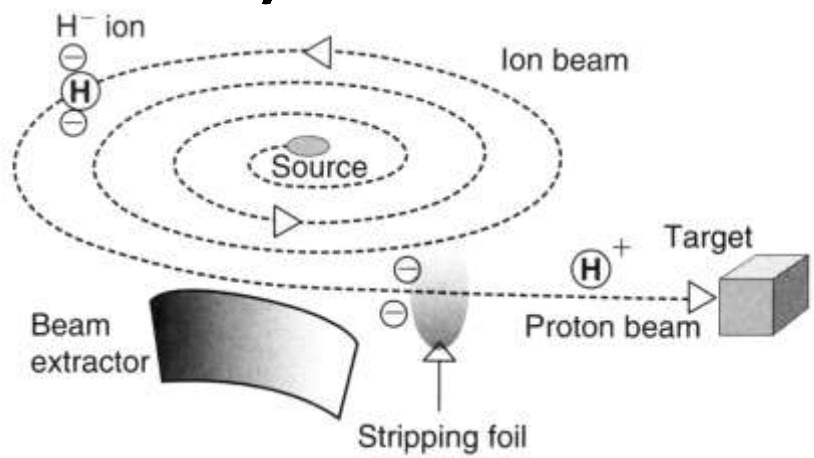
Applications

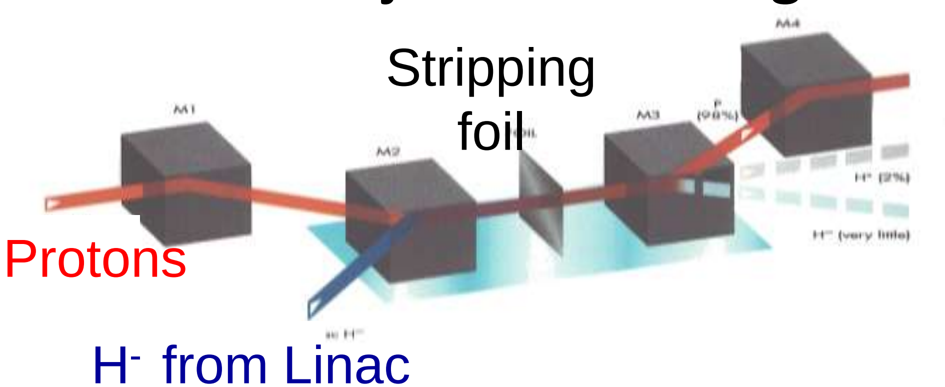
Tandem accelerators



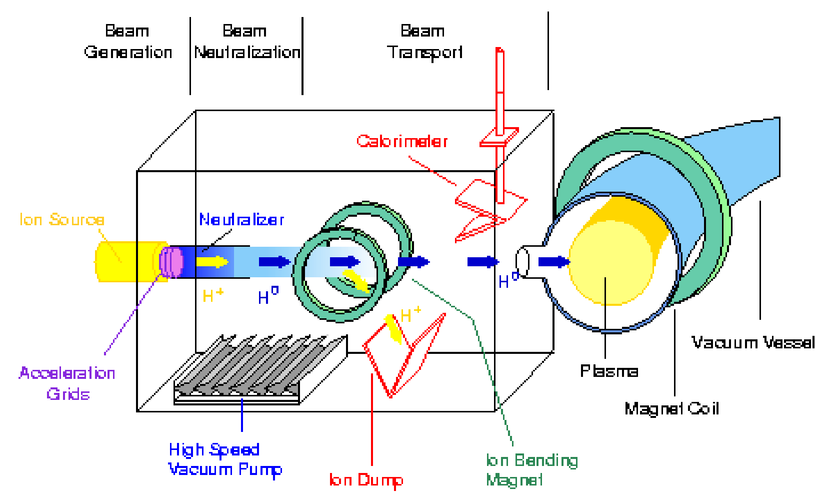
Cyclotron extraction



Multi-turn injection into rings



Neutral Beams



Negative Ion Sources

Ripping electrons off is easy!

- It is much harder to add them on….

Not all elements will even make negative ions

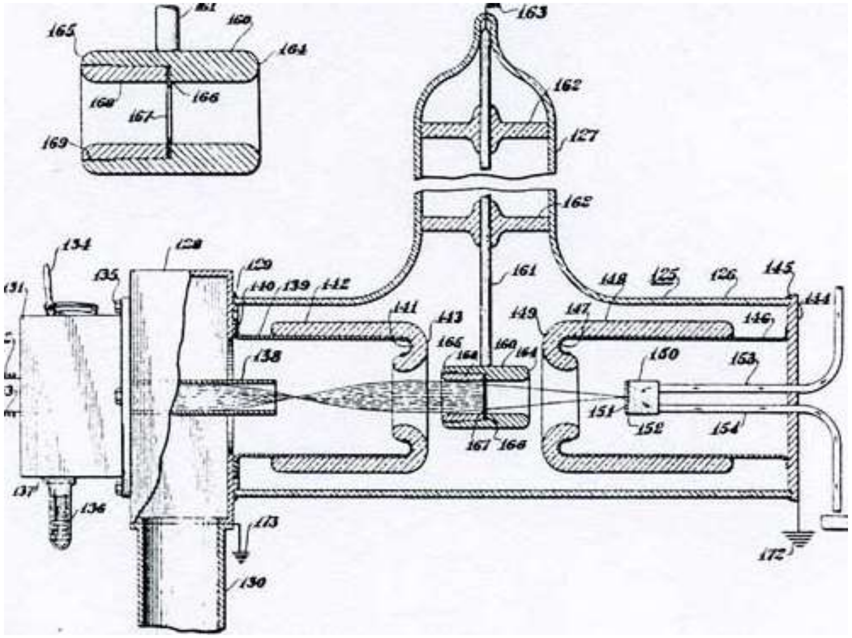
Hydrogen has an electron affinity of 0.7542 eV

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

30 times for e^- collisions

100 times for H^+ collisions

H^- are very fragile!



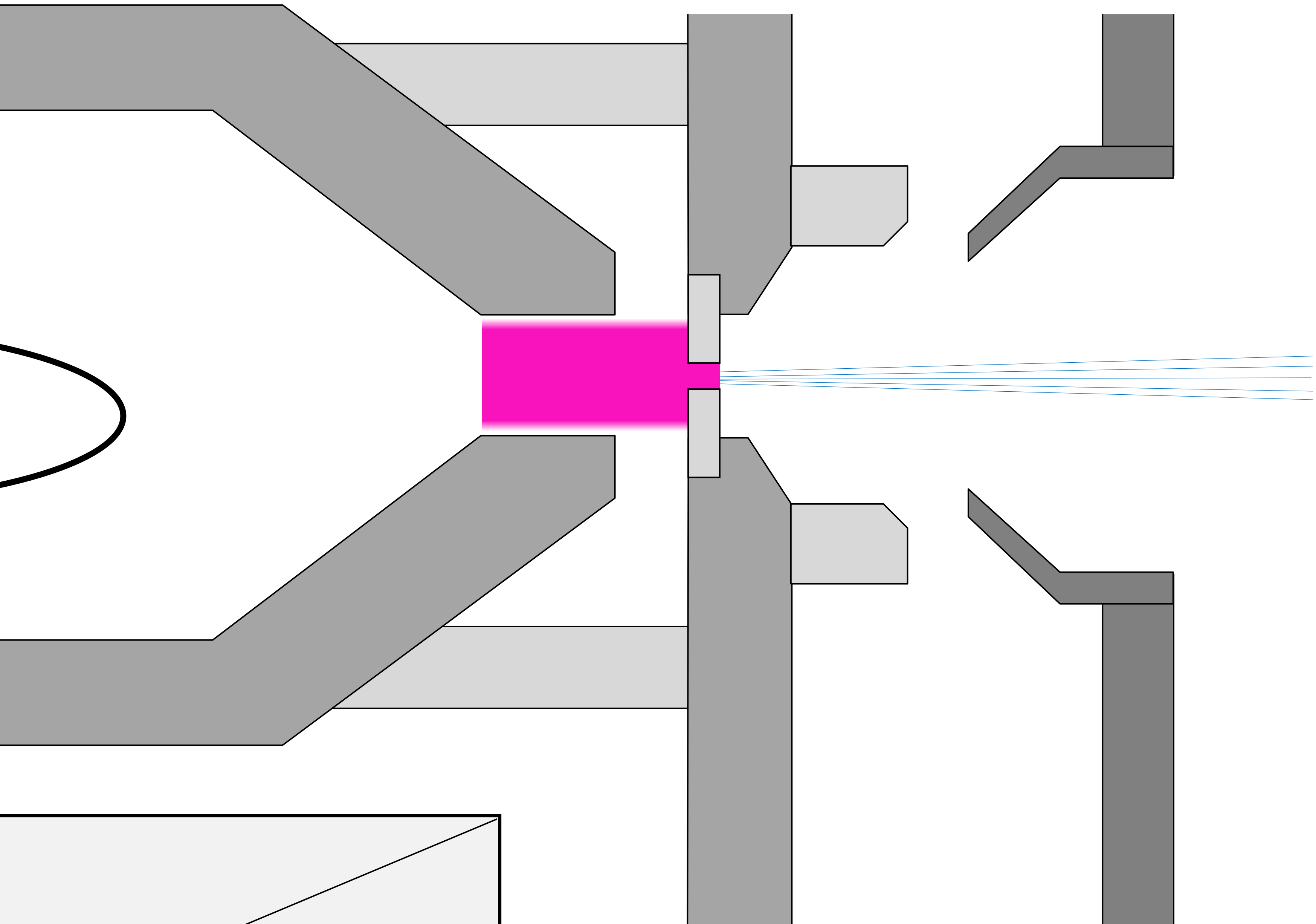
A 1937 tandem

Early attempts at producing negative ion beams:

- Charge exchange of positive beams
  stripper foils and gas cells
  - very inefficient <2%

- Extraction from existing ion sources…

Off Axis Duoplasmatron Extraction



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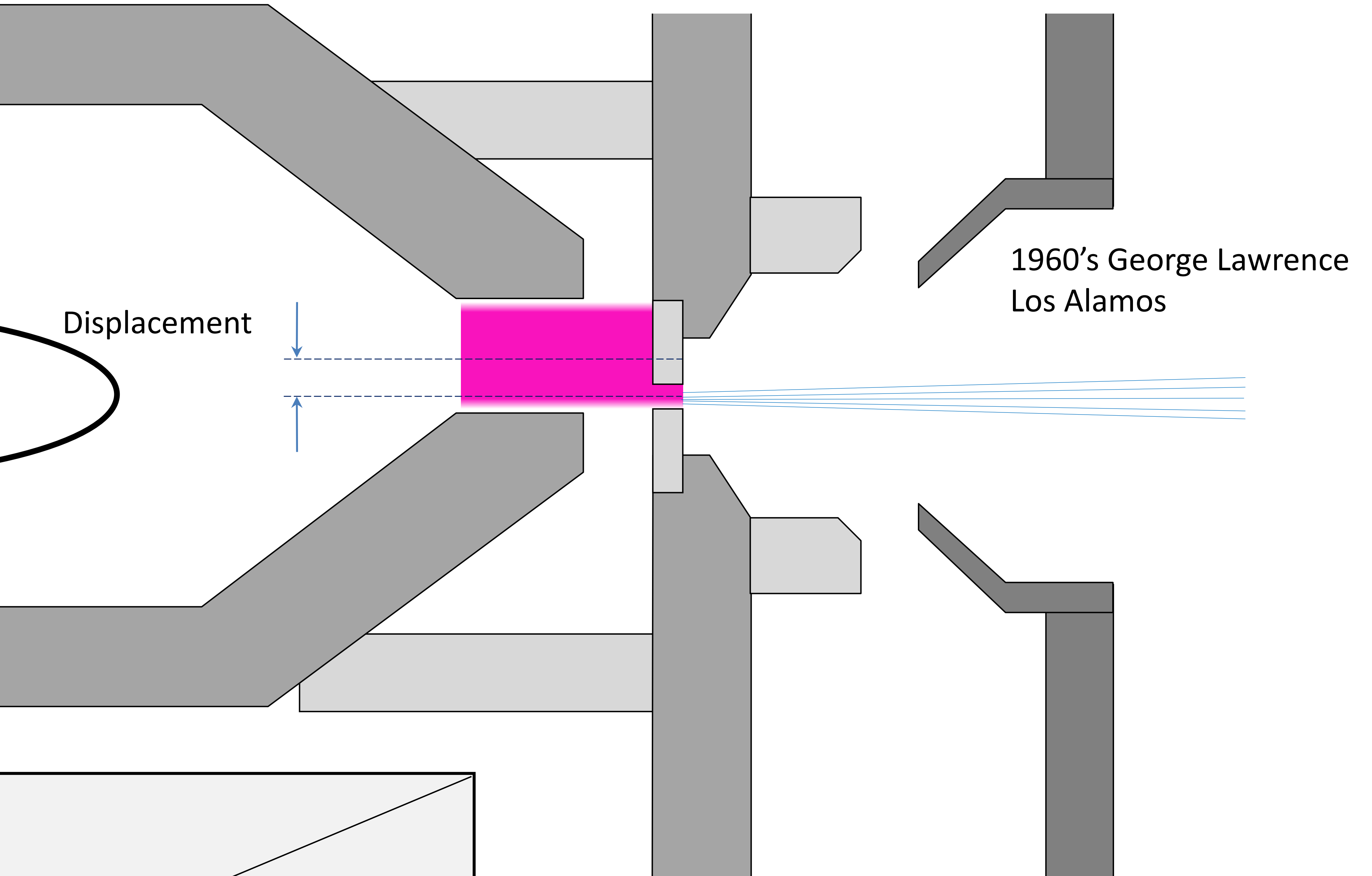
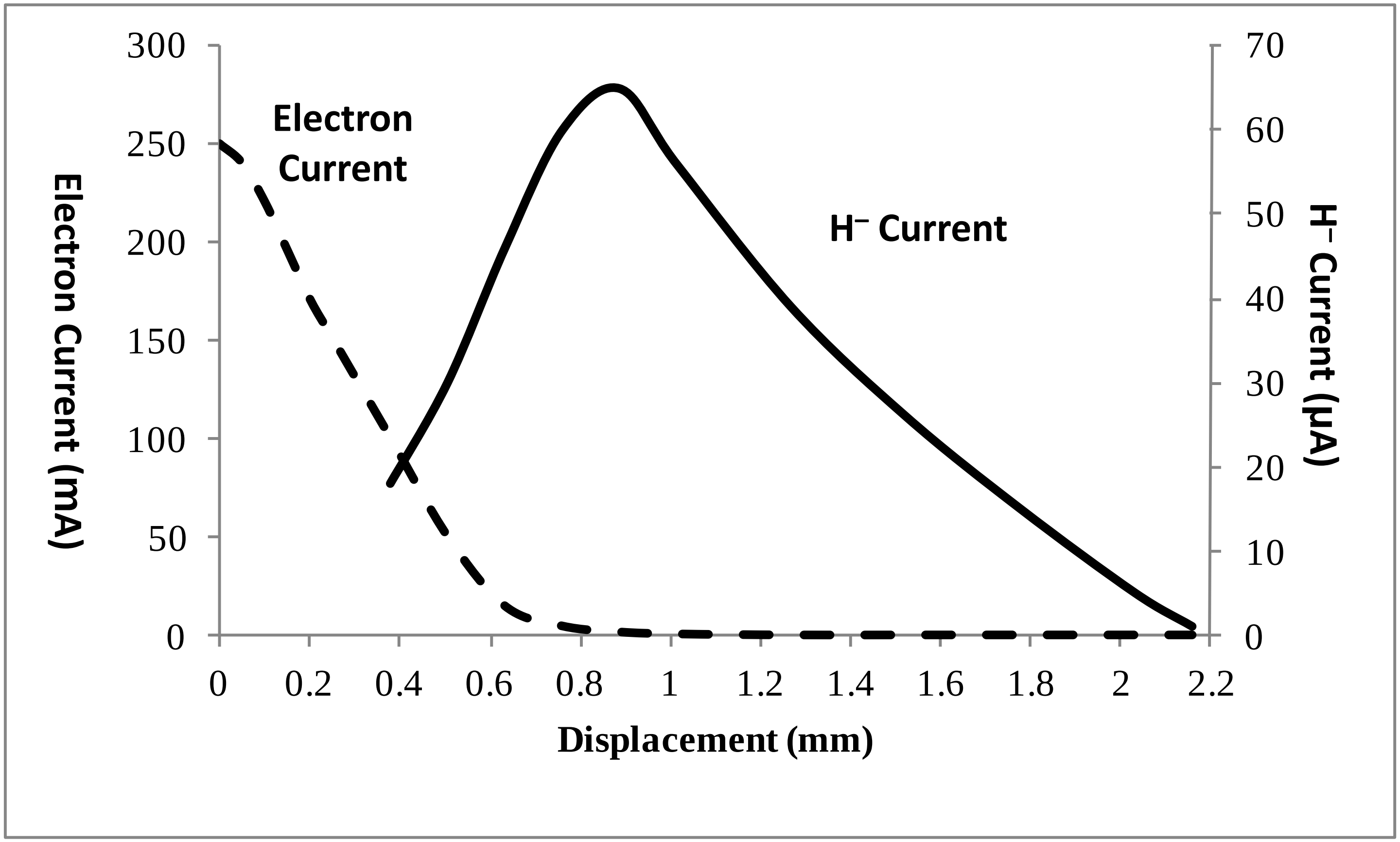


Off Axis Duoplasmatron Extraction



Off Axis Duoplasmatron Extraction

National Electrostatics Corp.

Direct Extraction Negative Ion Duoplasmatron

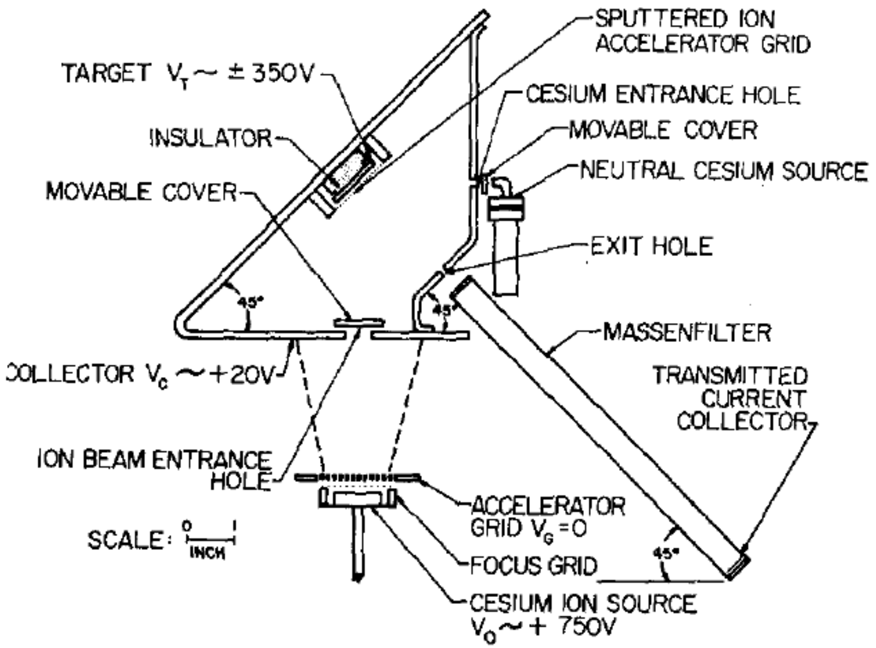
30 μA DC
H^- current

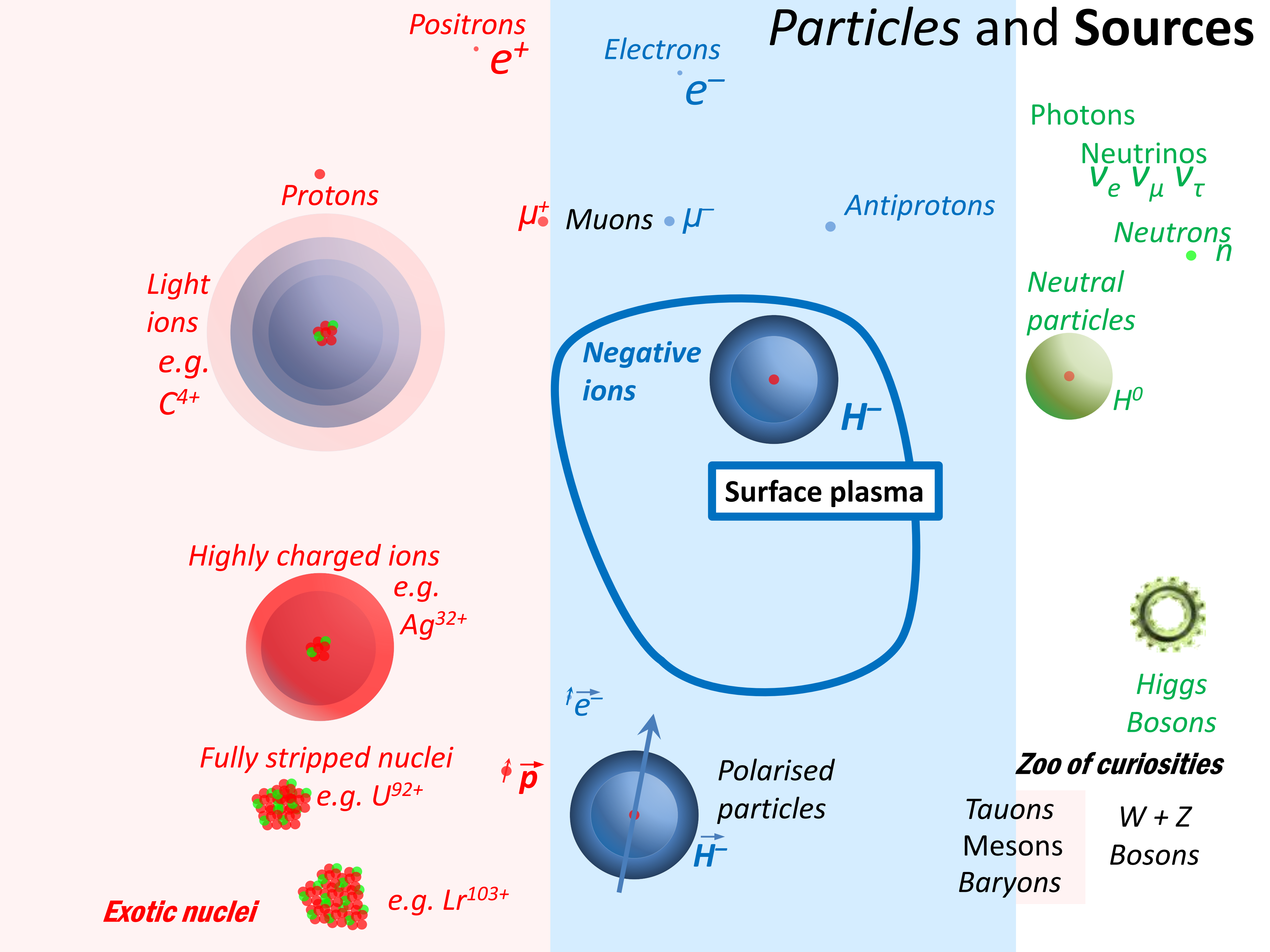
displaced
intermediate
electrode
duoplasmatron

1962 Victor Krohn

Space Technology Laboratories inc.
Redondo Beach, California

Cs^+ ions on a metal target
increase yield of sputtered
negative ions
by an order of magnitude




Particles and Sources
Positrons
e+
Electrons
e−
Photons
Neutrinos
νe νμ ντ
Protons
μ+
Muons
μ−
Antiprotons
Neutrons
n
Light
ions
e.g.
C4+
Negative
ions
H−
Neutral
particles
H0
Surface plasma
Highly charged ions
e.g.
Ag32+
Higgs
Bosons
e−
Fully stripped nuclei
e.g. U92+
p
Polarised
particles
H−
Zoo of curiosities
Tauons
Mesons
Baryons
W + Z
Bosons
Exotic nuclei
e.g. Lr103+

Early 1970s Budker Institute of Nuclear Physics

Novosibirsk

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

Surface Plasma Sources (SPS)

Gennady Dimov

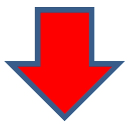
Yuri Belchenko

Vadim Dudnikov


5 g Caesium
Ampoule

Ceasium! – The magic elixir

More reactive



1 electron in the outer orbital

Periodic Table of the Elements

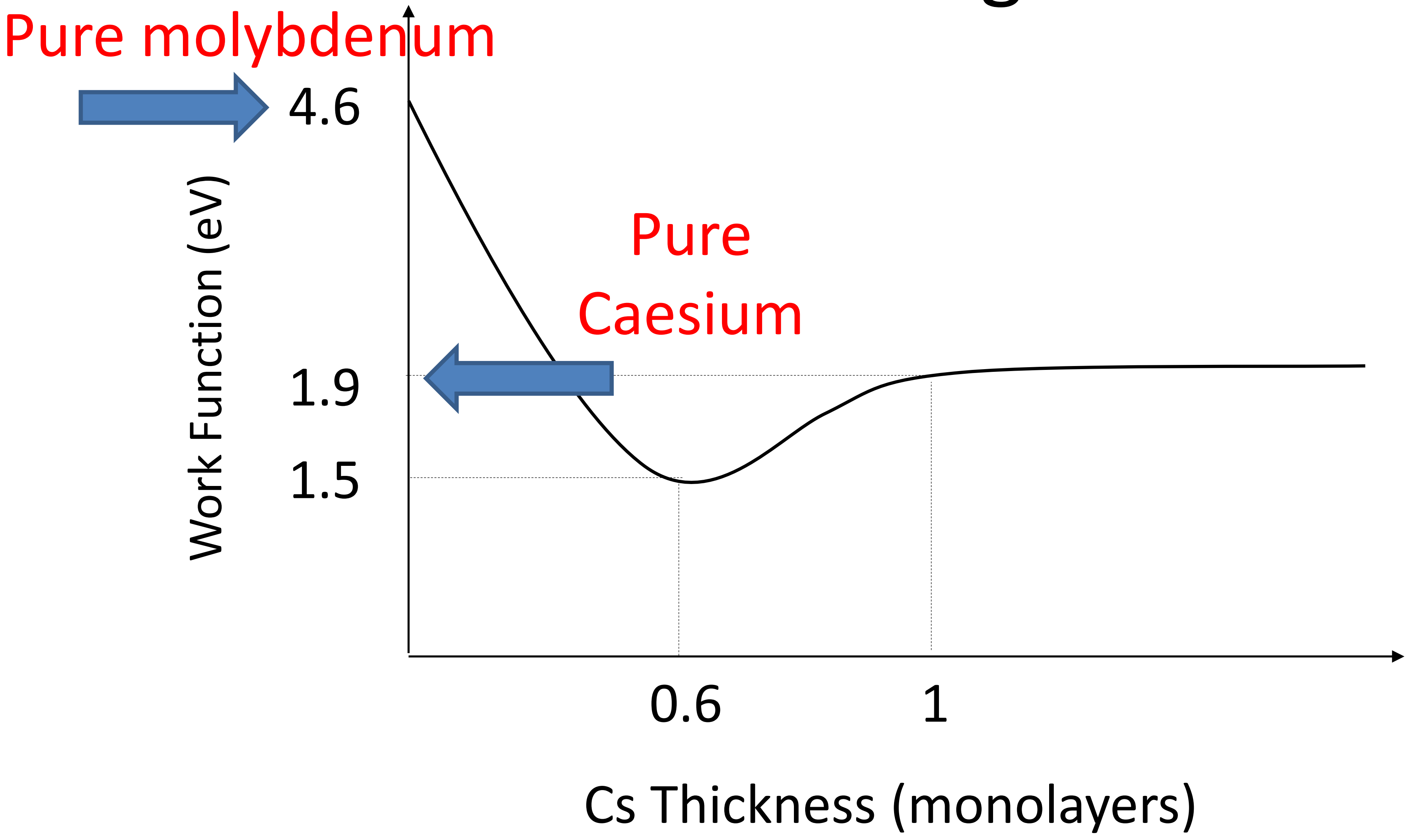
- hydrogen
- alkali metals
- alkali earth metals
- transition metals
- poor metals
- nonmetals
- noble gases
- rare earth metals

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								

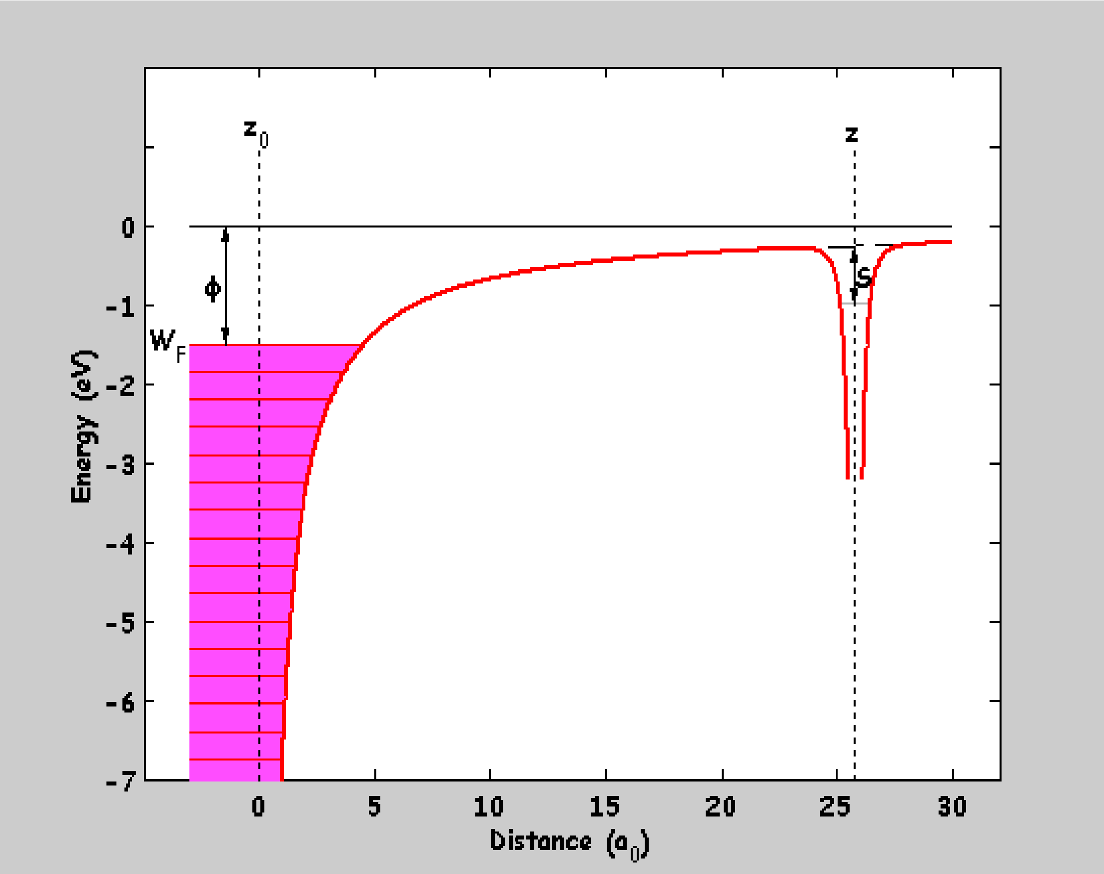
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

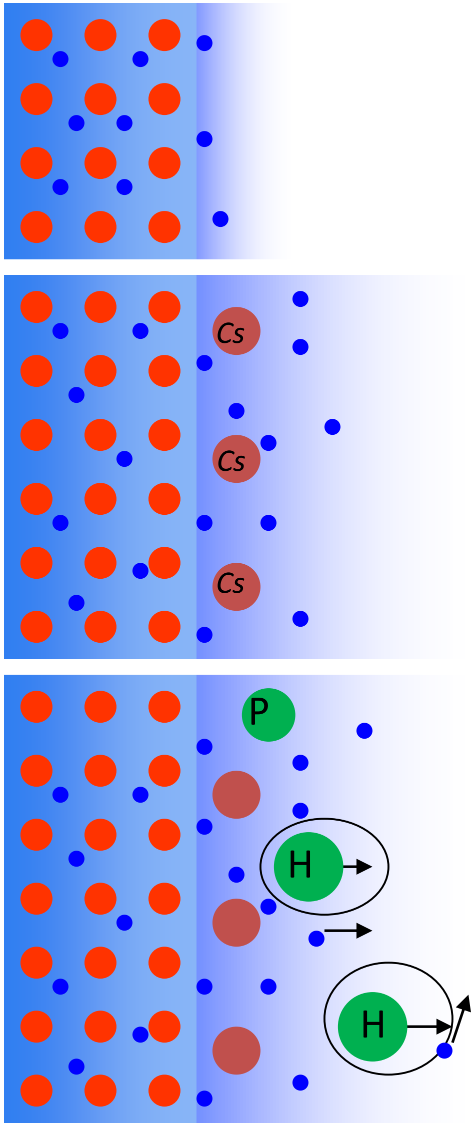
An amazing donor of electrons
= great for making negative ions

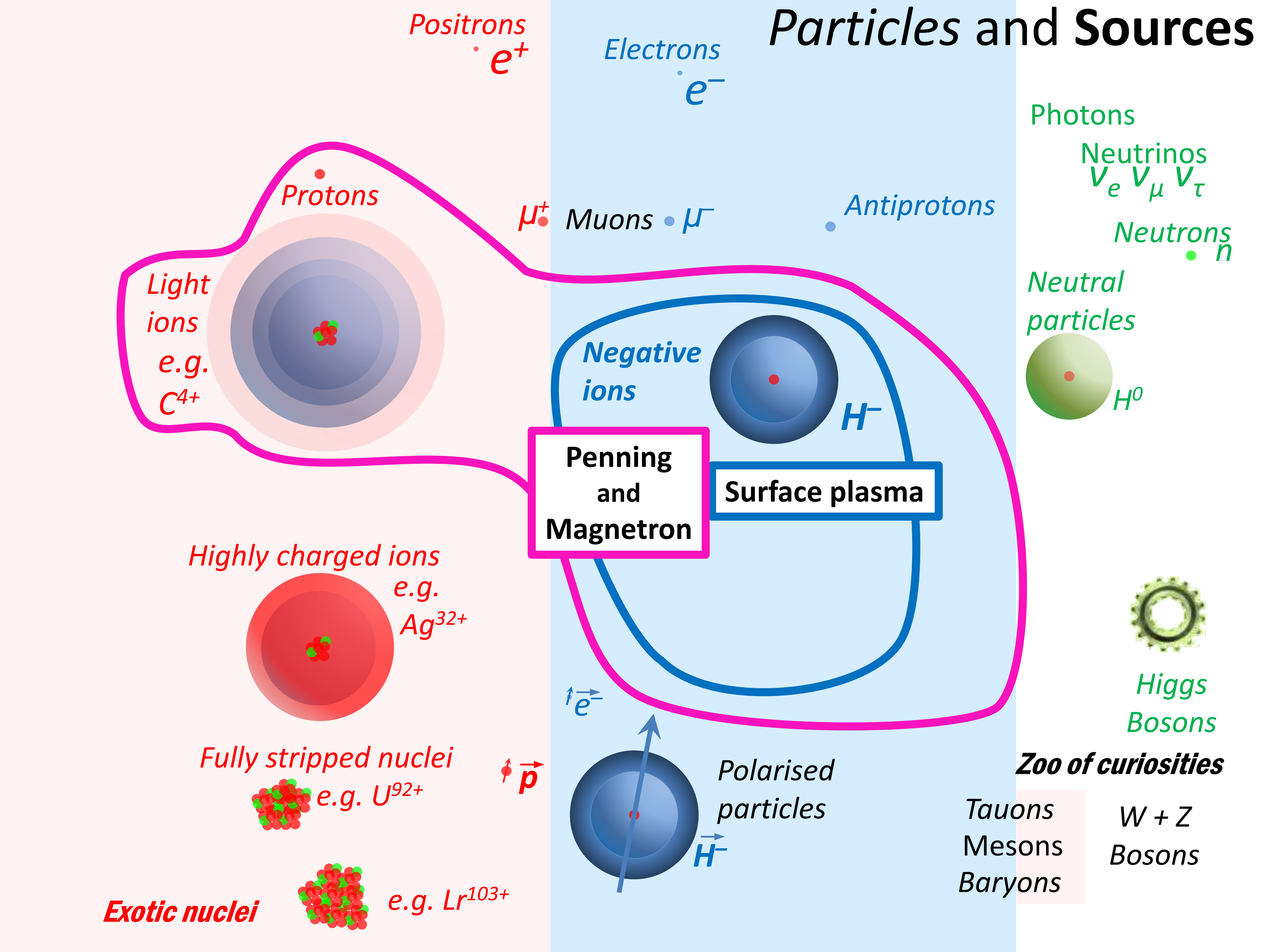
Caesium Coverage



Fermilevels

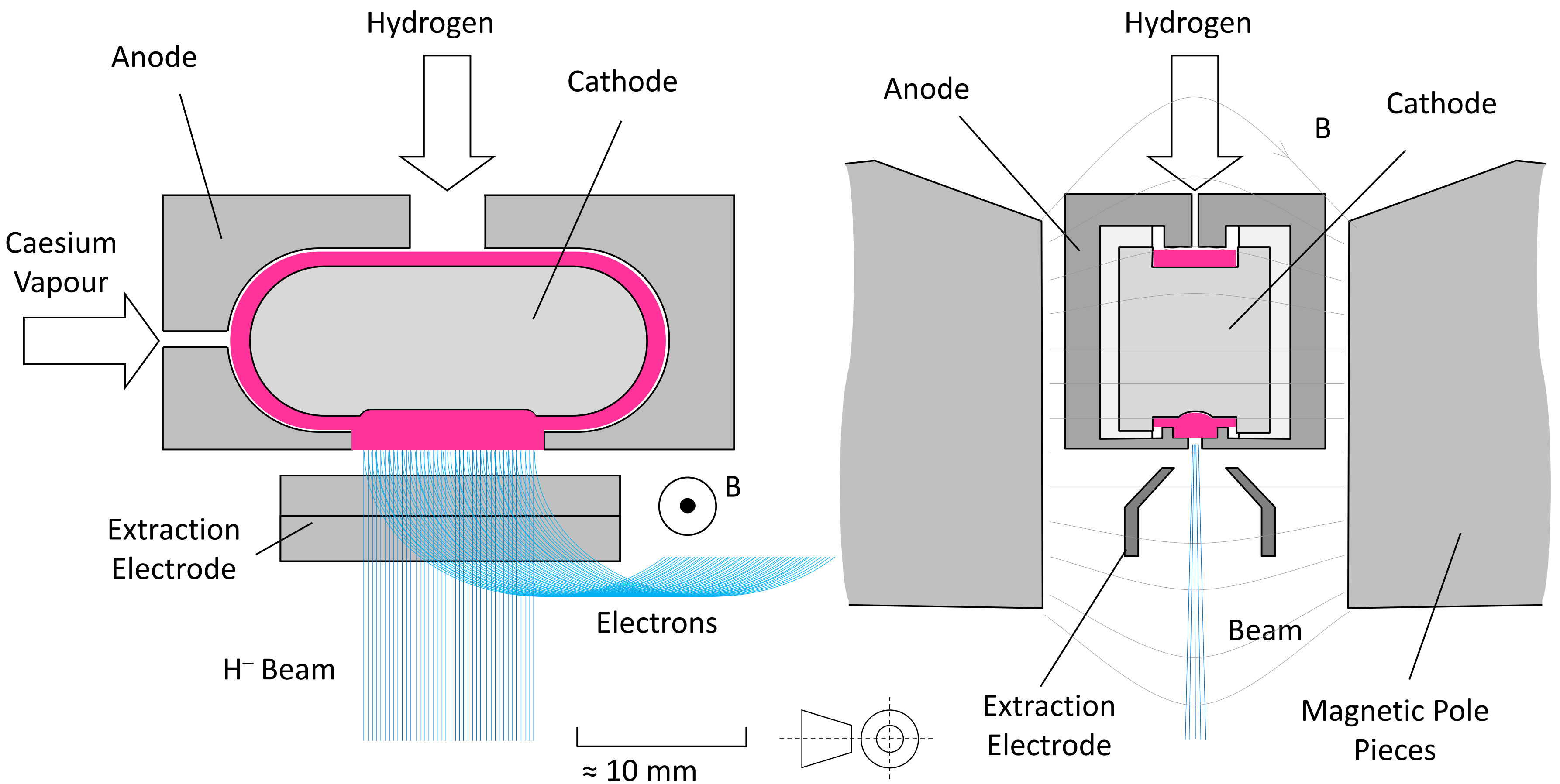




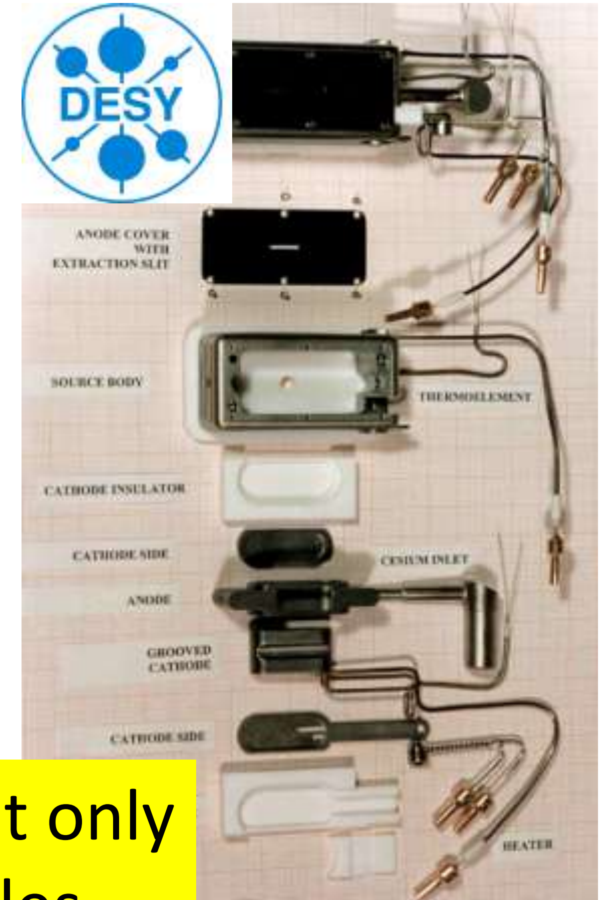


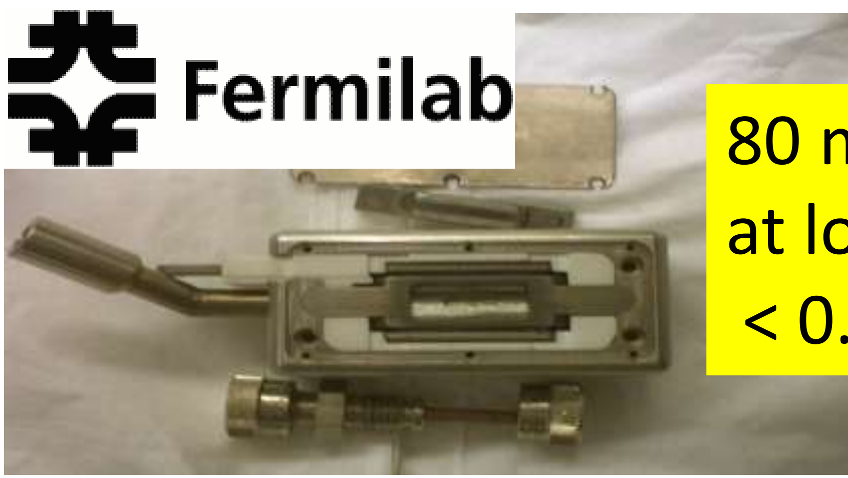
Particles and Sources
Positrons
e^+
Electrons
e^-
Photons
Neutrinos
$\nu_e\ \nu_\mu\ \nu_\tau$
Protons
μ^+
Muons
μ^-
Antiprotons
Neutrons
n
Light ions e.g. C^{4+}
Neutral particles
Negative ions
H^-
H^0
Penning and Magnetron
Surface plasma
Highly charged ions e.g. Ag^{32+}
Higgs Bosons
$\vec{e}^-$
Fully 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+}

Magnetron SPS



Magnetron is a popular source

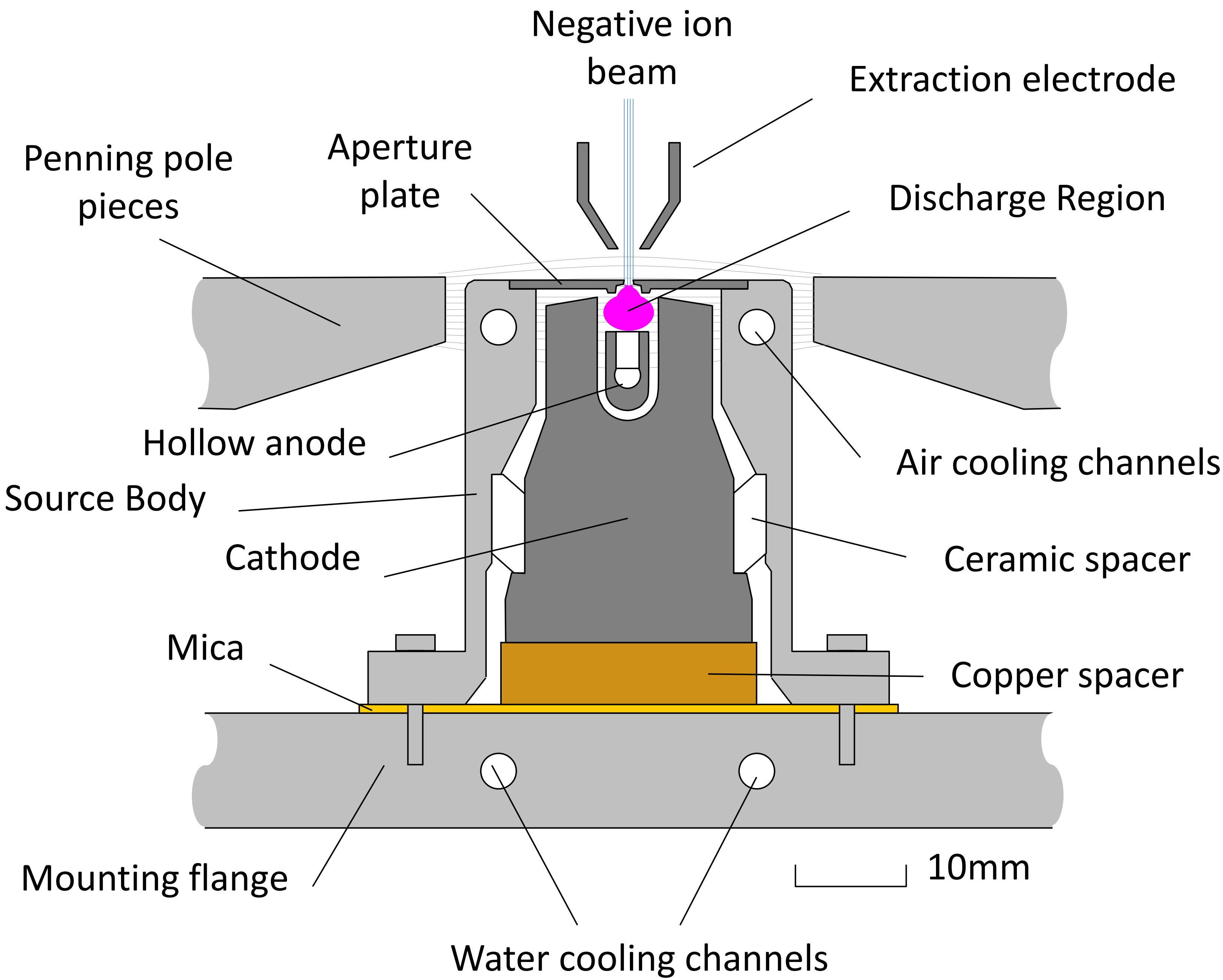


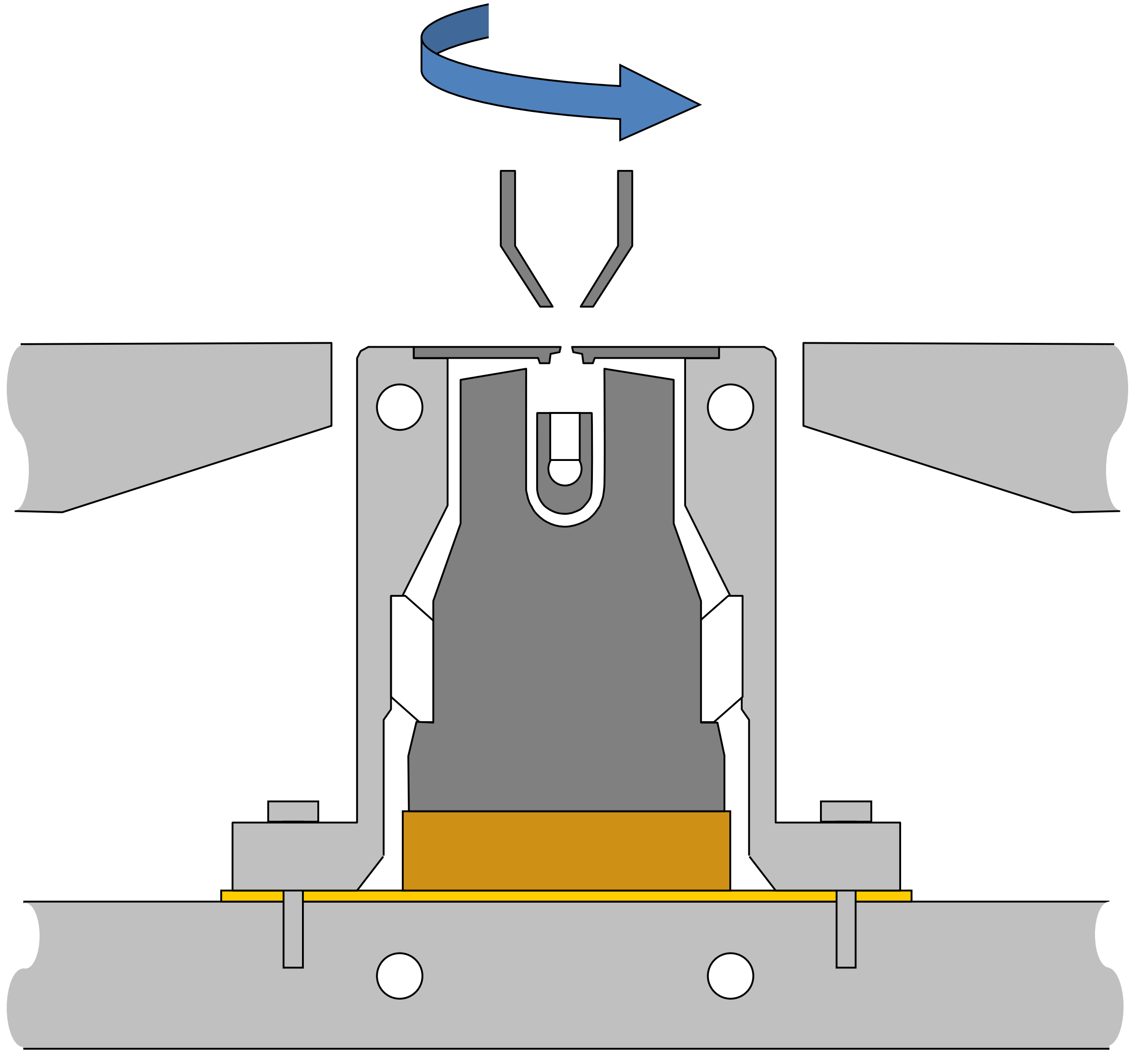


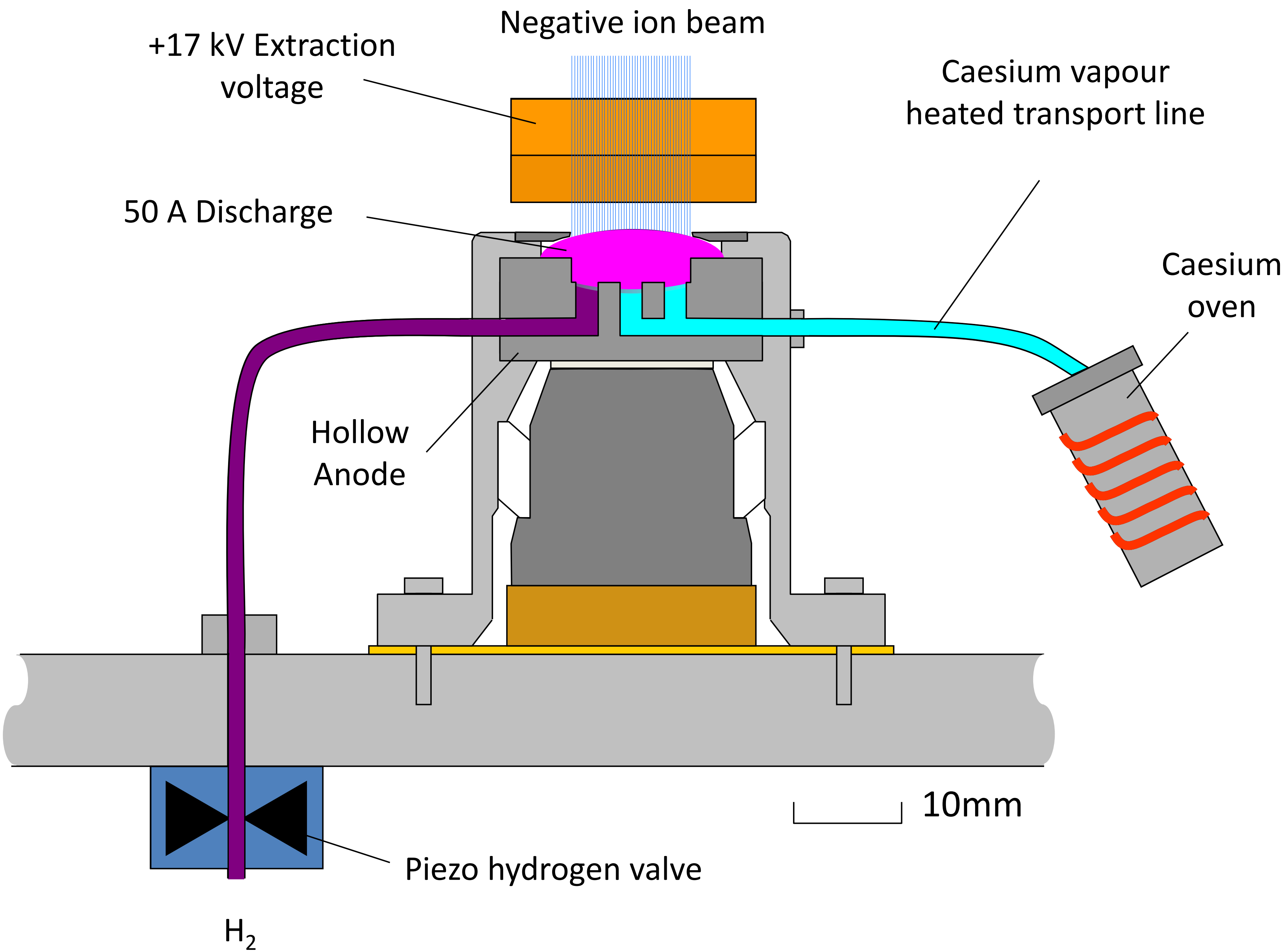
80 mA of H^- but only at low duty cycles < 0.5%

Penning SPS

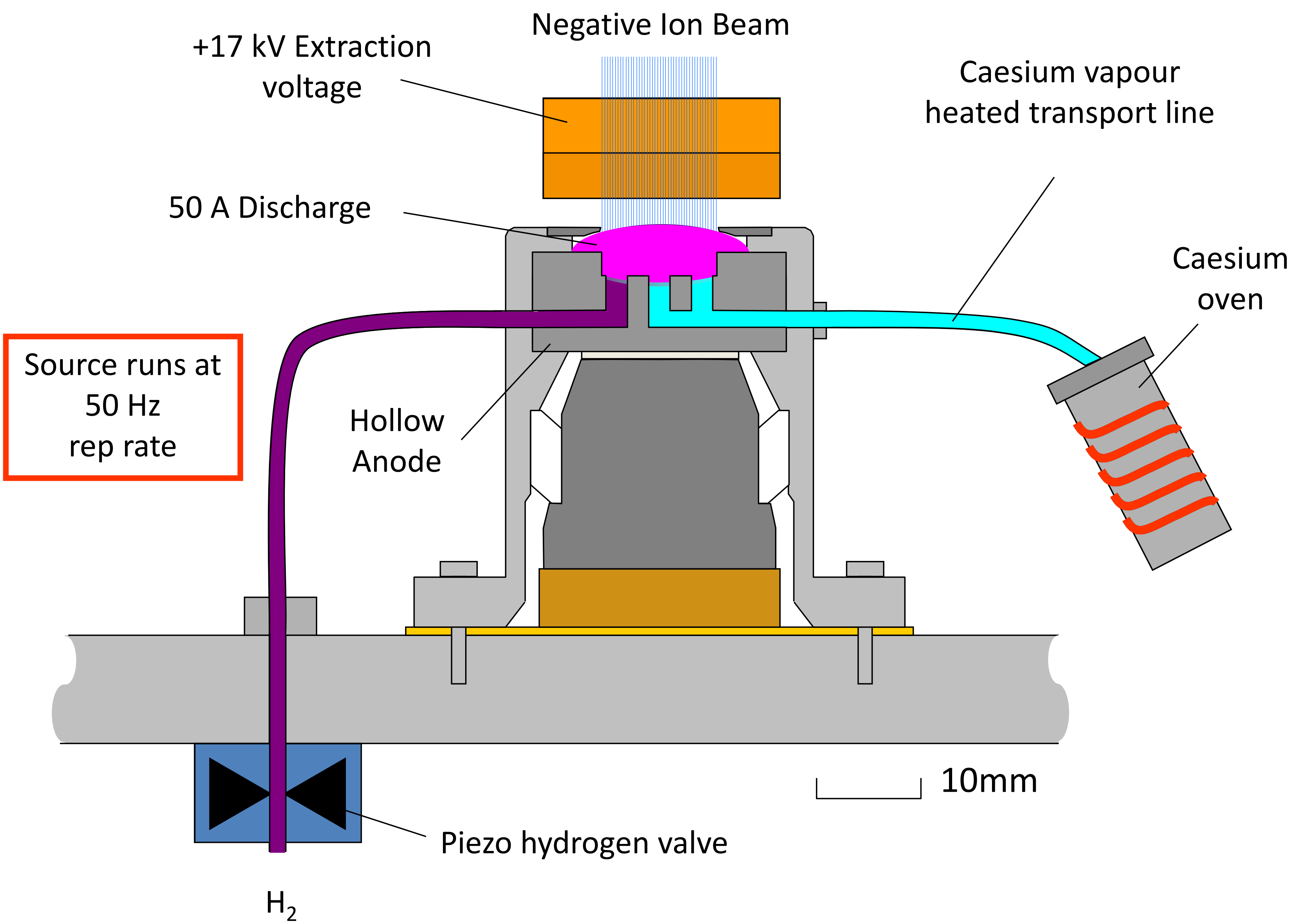
- Invented by Dudnikov in the 1970's
- Very high brightness and current density > 1 Acm^{-2}
- Low noise

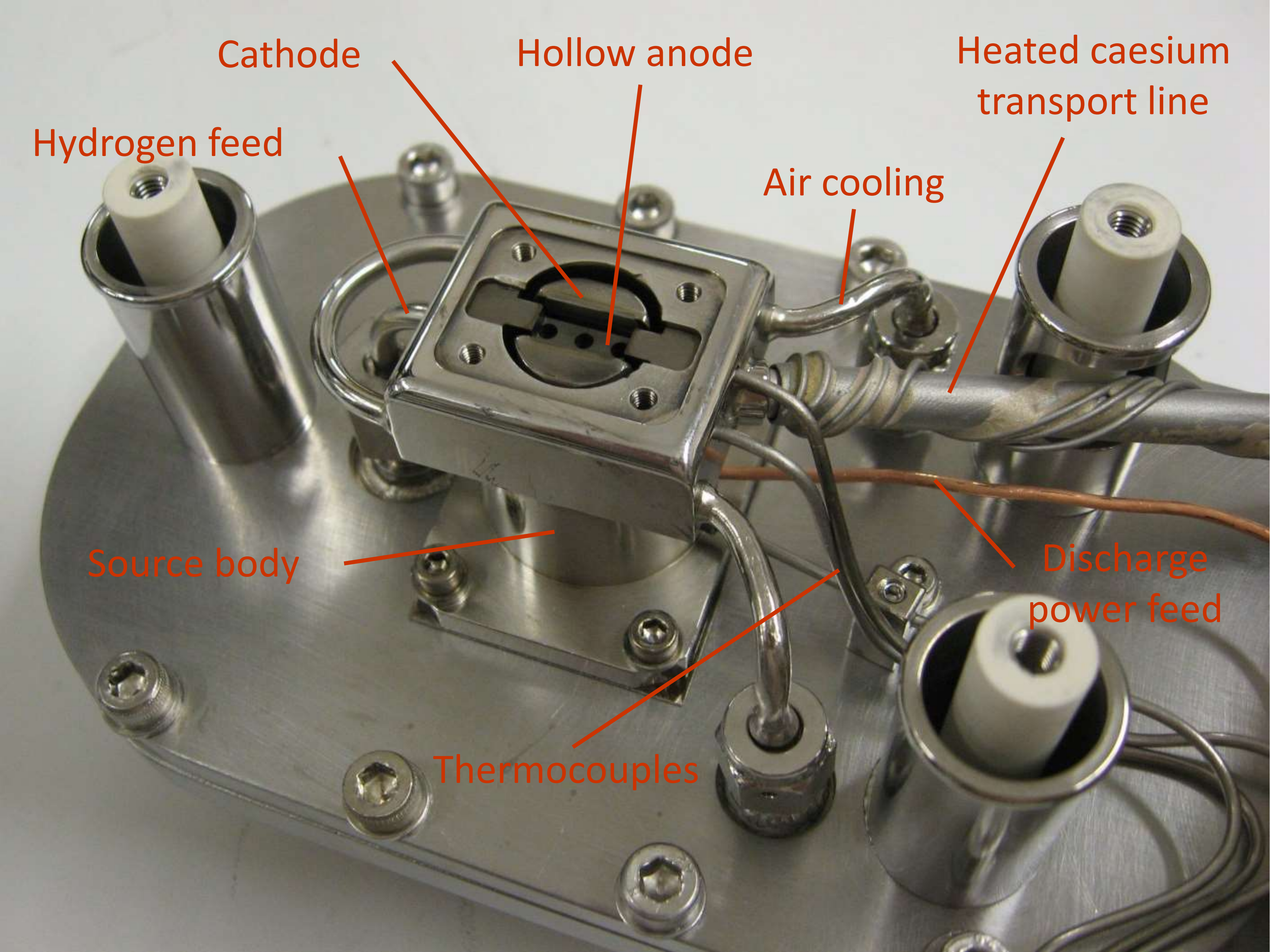

Negative ion beam
Extraction electrode
Aperture plate
Penning pole pieces
Discharge Region
Hollow anode
Air cooling channels
Source Body
Cathode
Ceramic spacer
Mica
Copper spacer
Mounting flange
10mm
Water cooling channels

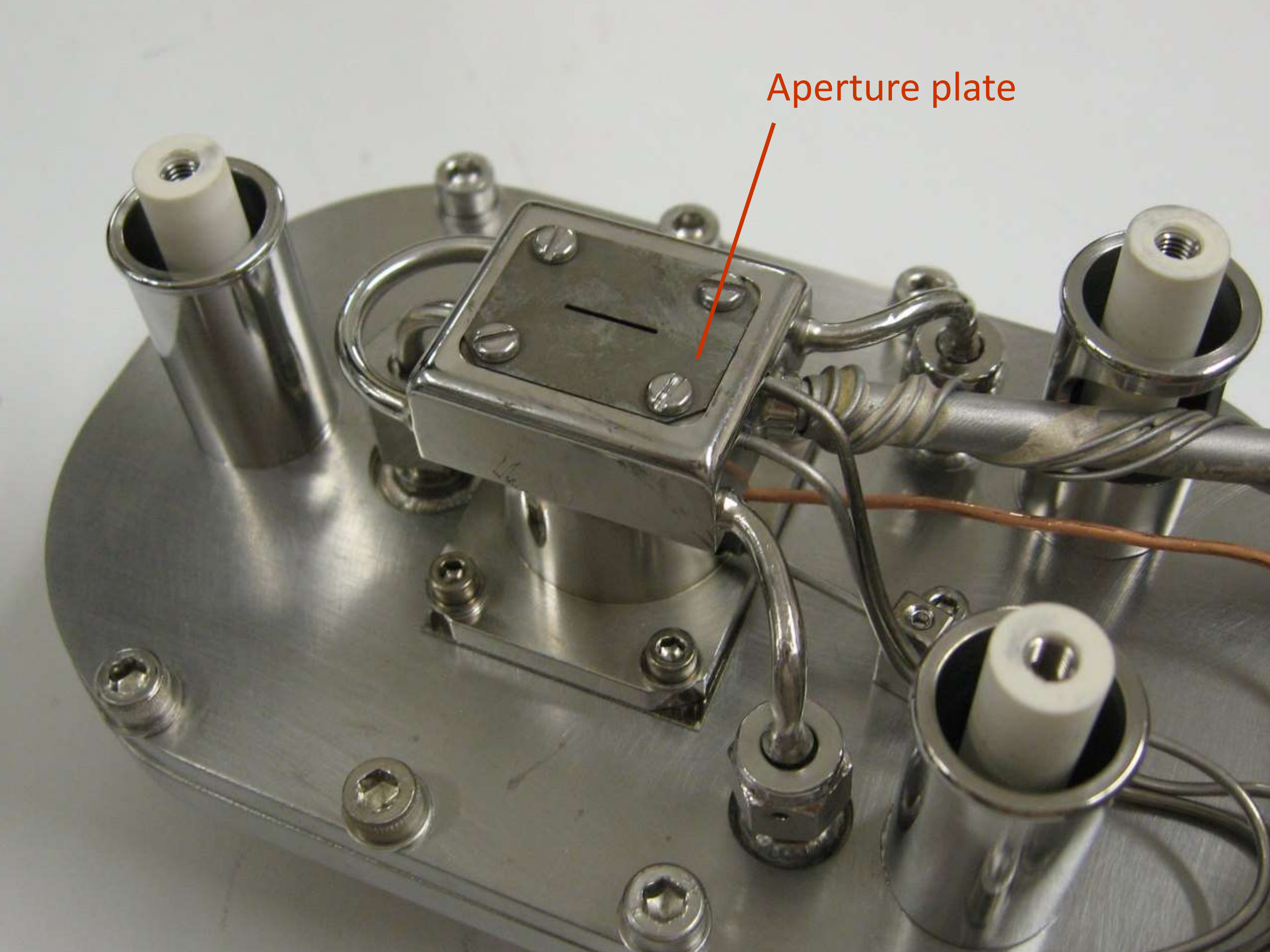


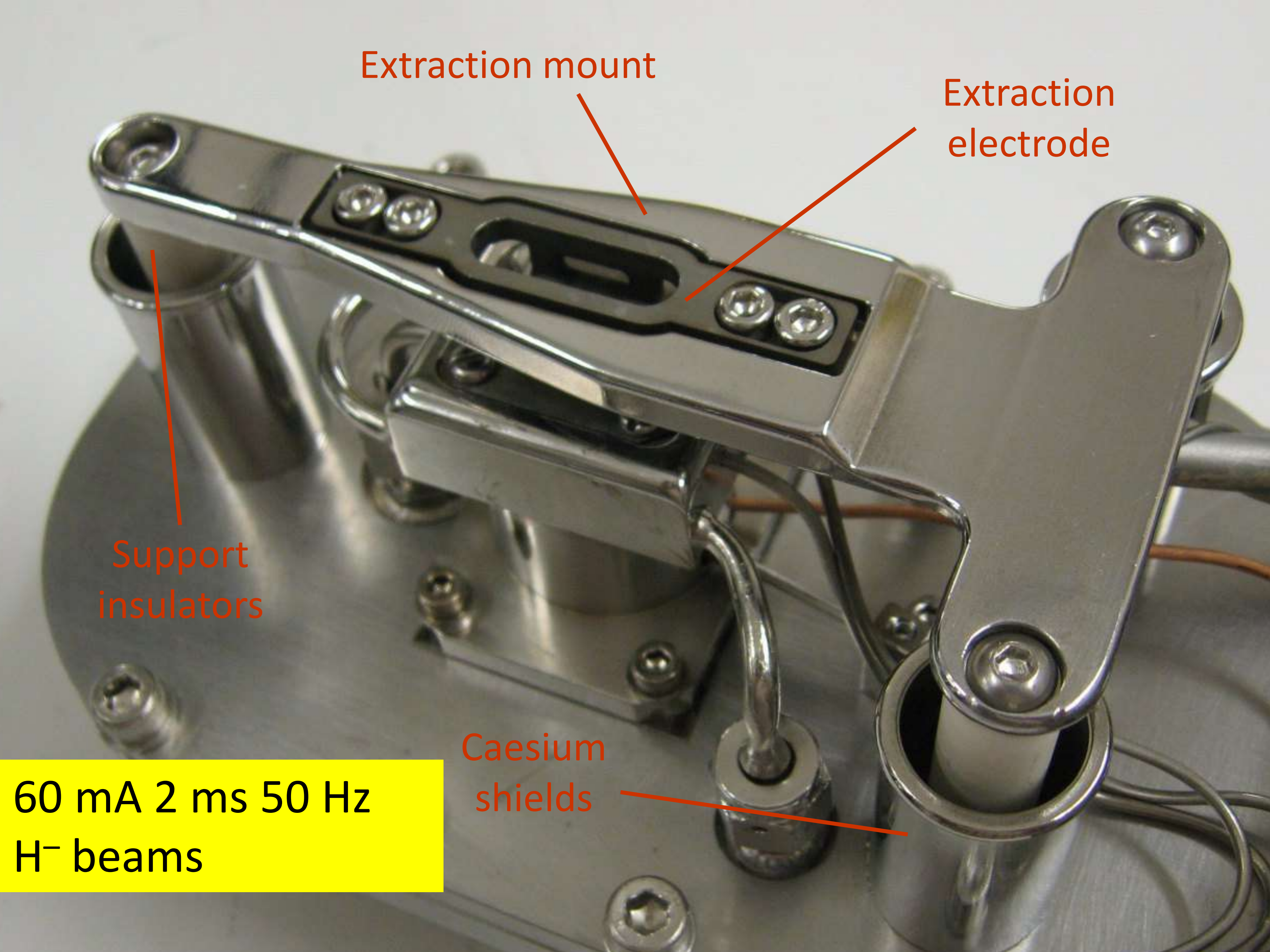


Negative ion beam
+17 kV Extraction voltage
Caesium vapour heated transport line
50 A Discharge
Caesium oven
Hollow Anode
10mm
Piezo hydrogen valve
H_2

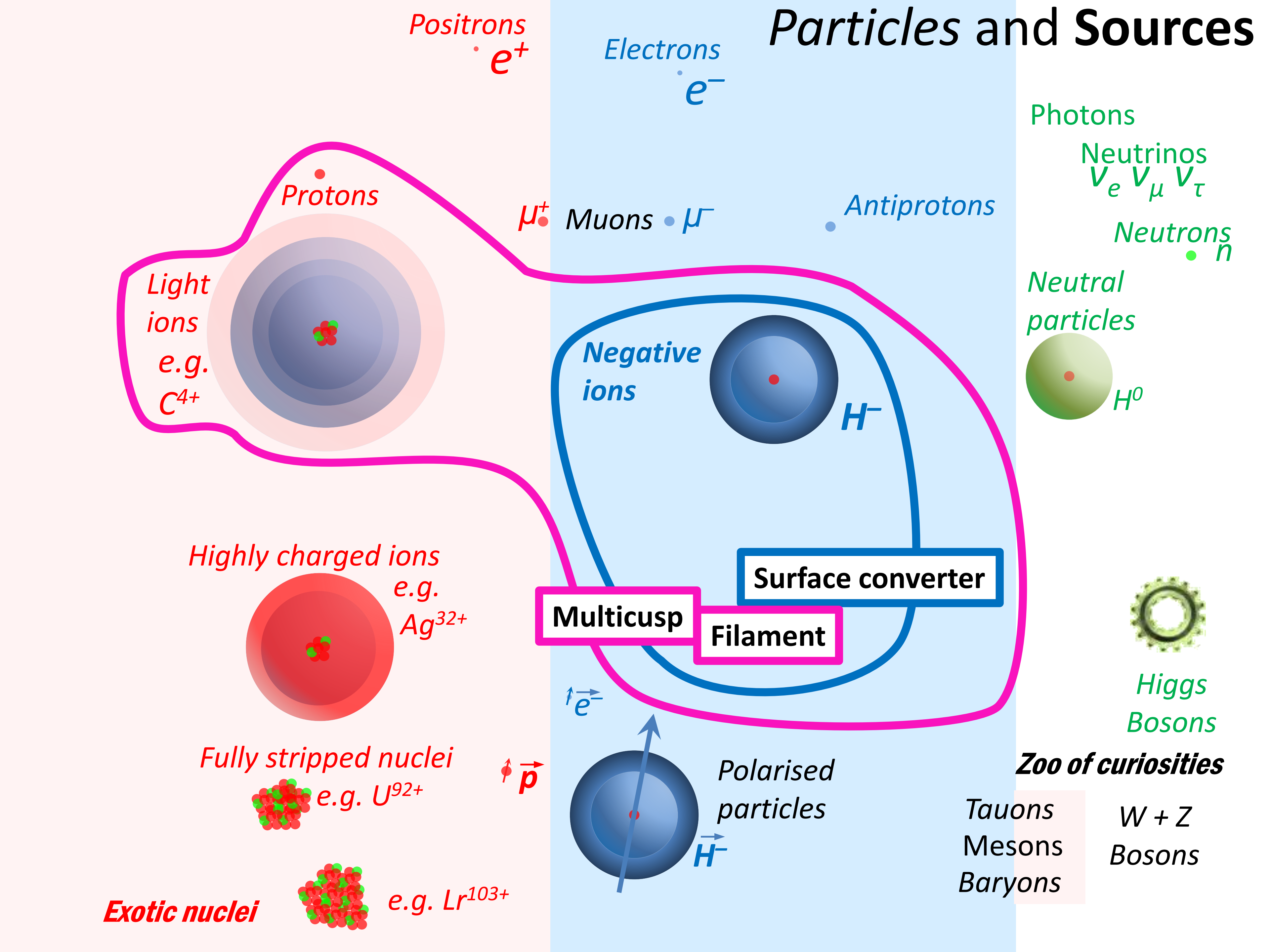

Negative Ion Beam
+17 kV Extraction voltage
Caesium vapour heated transport line
50 A Discharge
Caesium oven
Source runs at 50 Hz rep rate
Hollow Anode
10mm
Piezo hydrogen valve
H_2


Cathode
Hollow anode
Heated caesium transport line
Hydrogen feed
Air cooling
Source body
Discharge power feed
Thermocouples


Aperture plate



60 mA 2 ms 50 Hz
H^- beams


Particles and Sources
Positrons
e^+
Electrons
e^-
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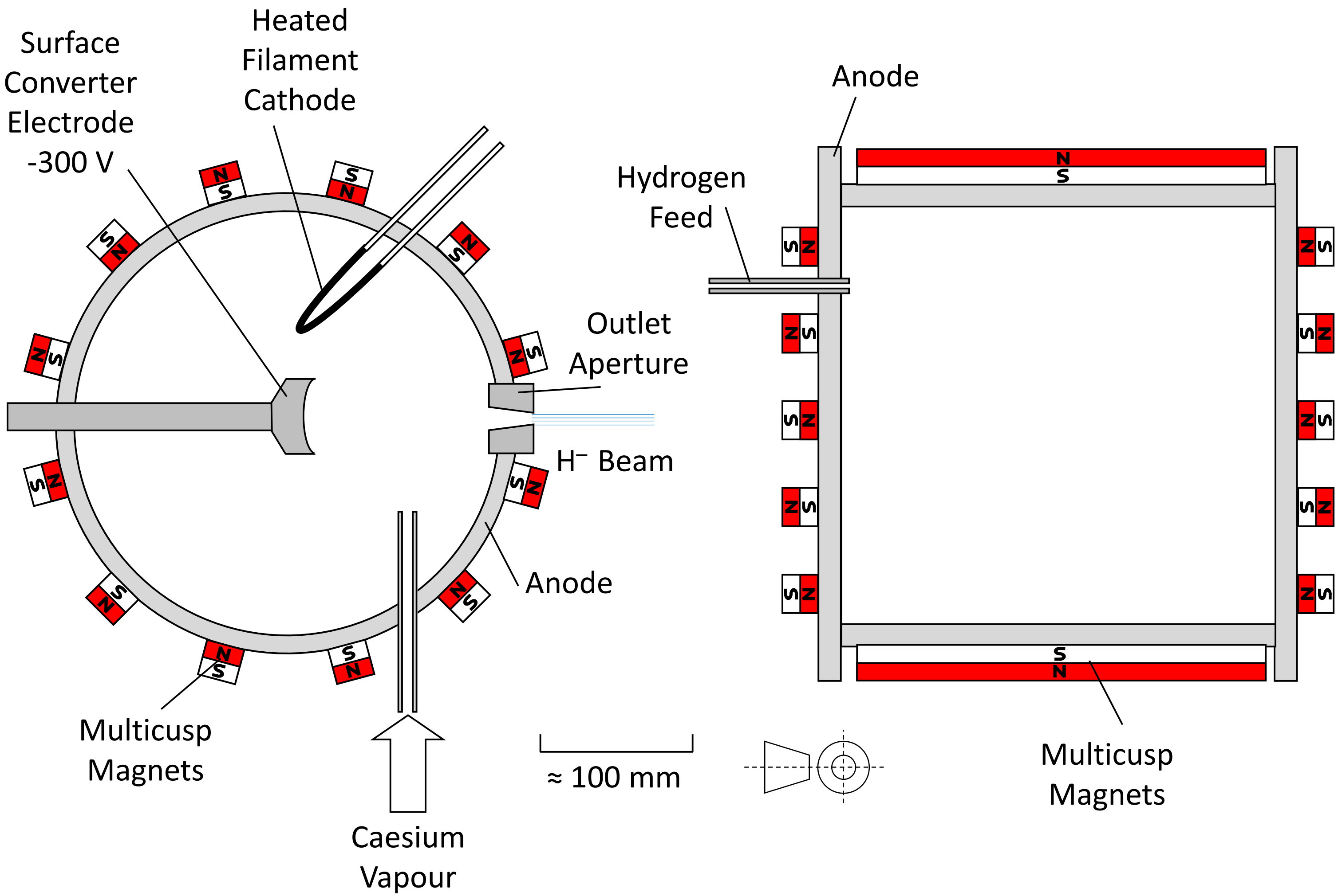
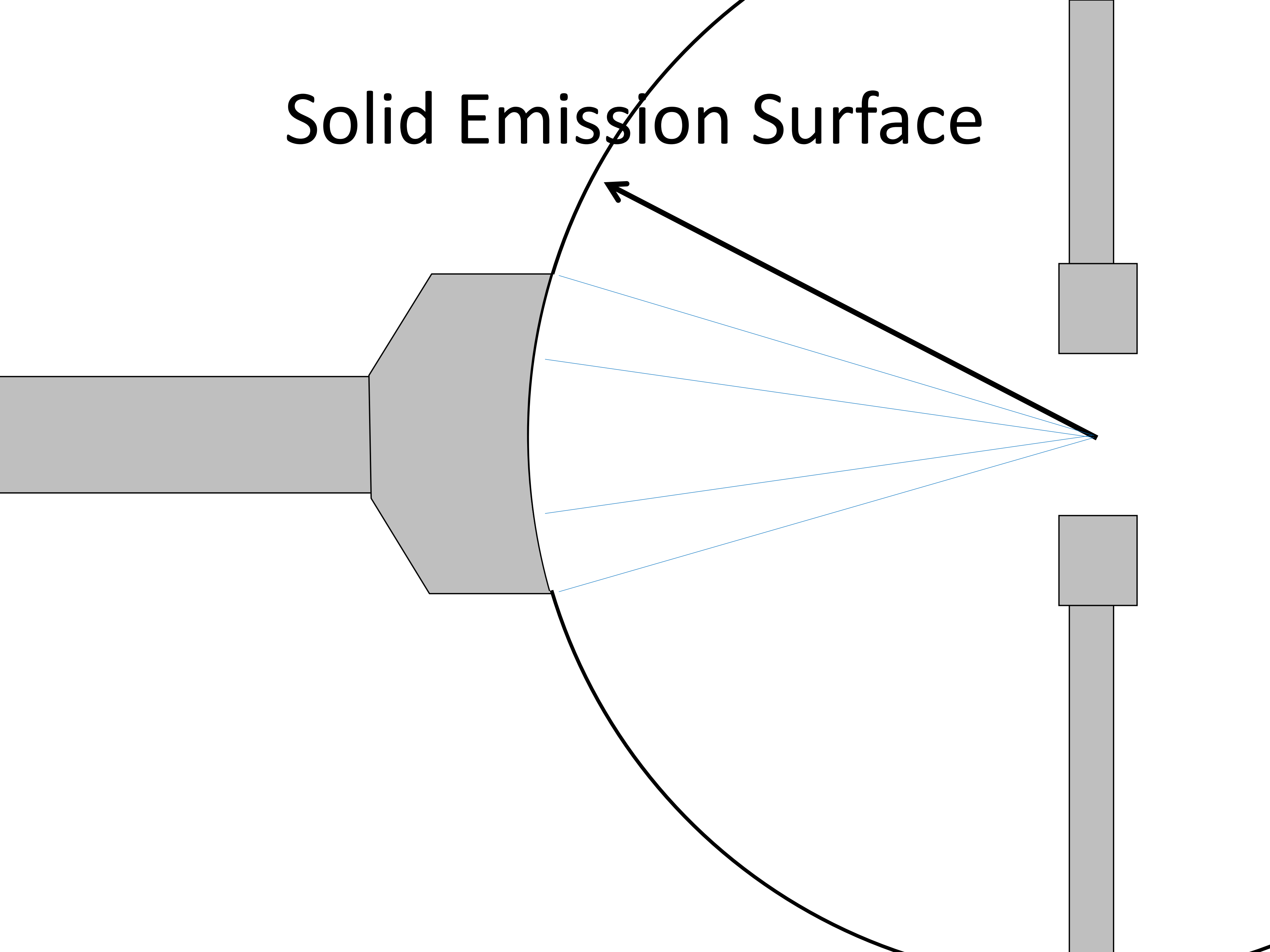
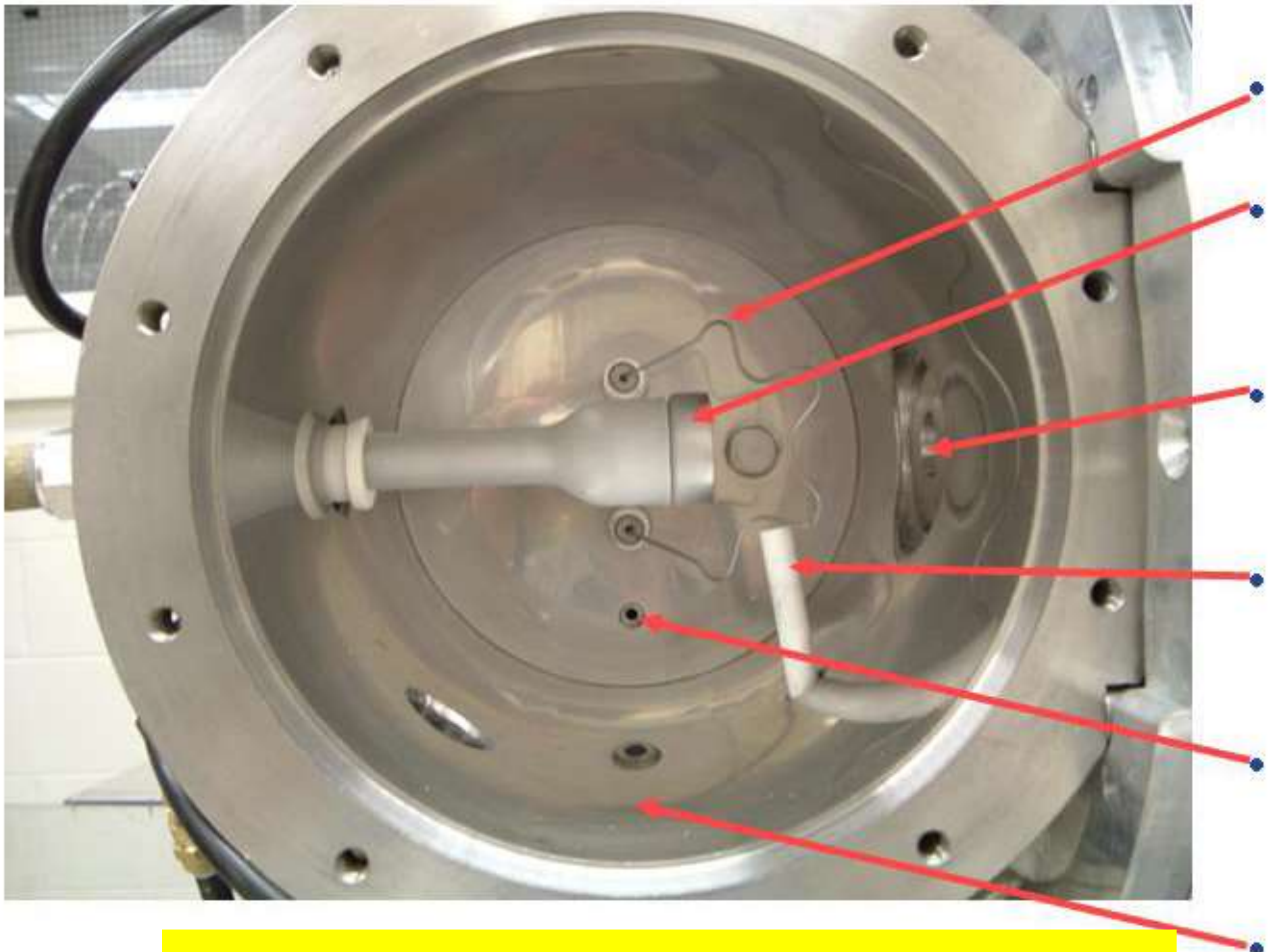
Neutrinos
$\nu_e\ \nu_\mu\ \nu_\tau$
Protons
μ^+
Muons
μ^-
Antiprotons
Neutrons
n
Light ions e.g. C^{4+}
Neutral particles
Negative ions
H^-
H^0
Highly charged ions e.g. Ag^{32+}
Surface converter
Multicusp
Filament
$\vec{e}^-$
Higgs Bosons
Fully stripped nuclei e.g. U^{92+}
$\vec{p}$
Polarised particles
Zoo of curiosities
Tauons
Mesons
Baryons
W + Z Bosons
$\vec{H}^-$
Exotic nuclei
e.g. Lr^{103+}

Filament Cathode Multicusp Surface Converter Source

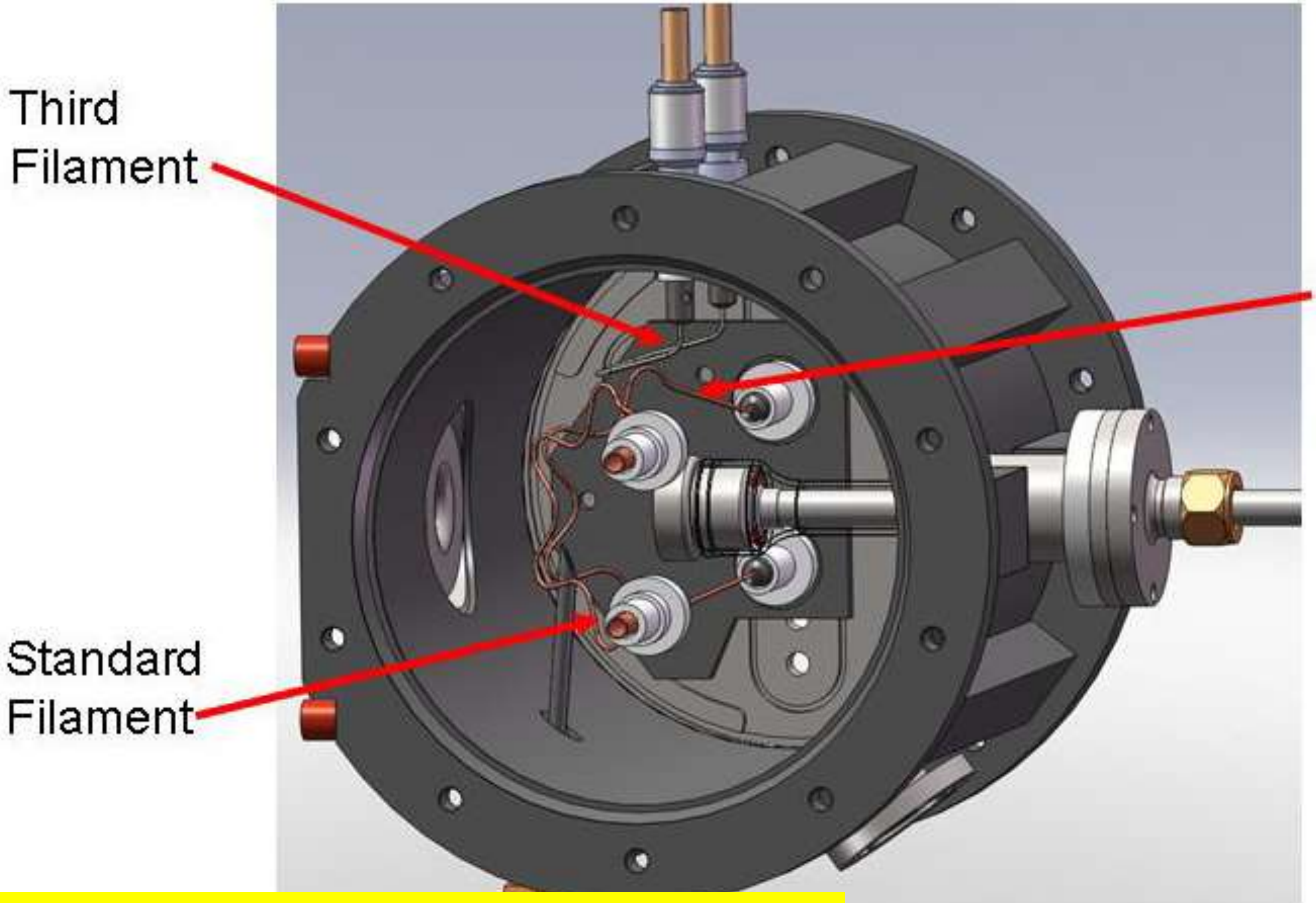



Solid Emission Surface

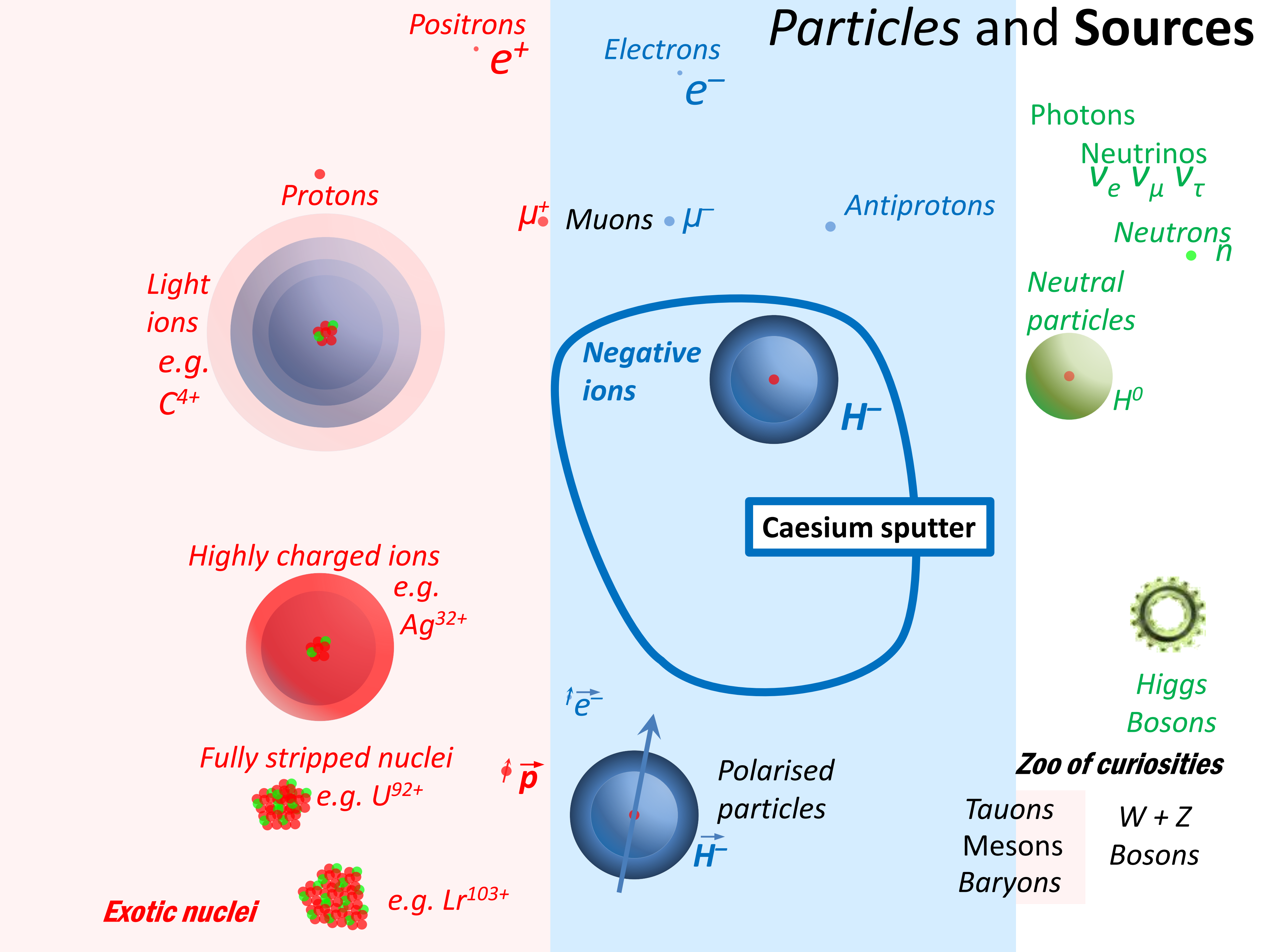
Filament Cathode Multicusp Surface Converter Source



16-18 mA 1 ms 120 Hz



LANL with multiple filaments:
1 A of H^-



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W + Z
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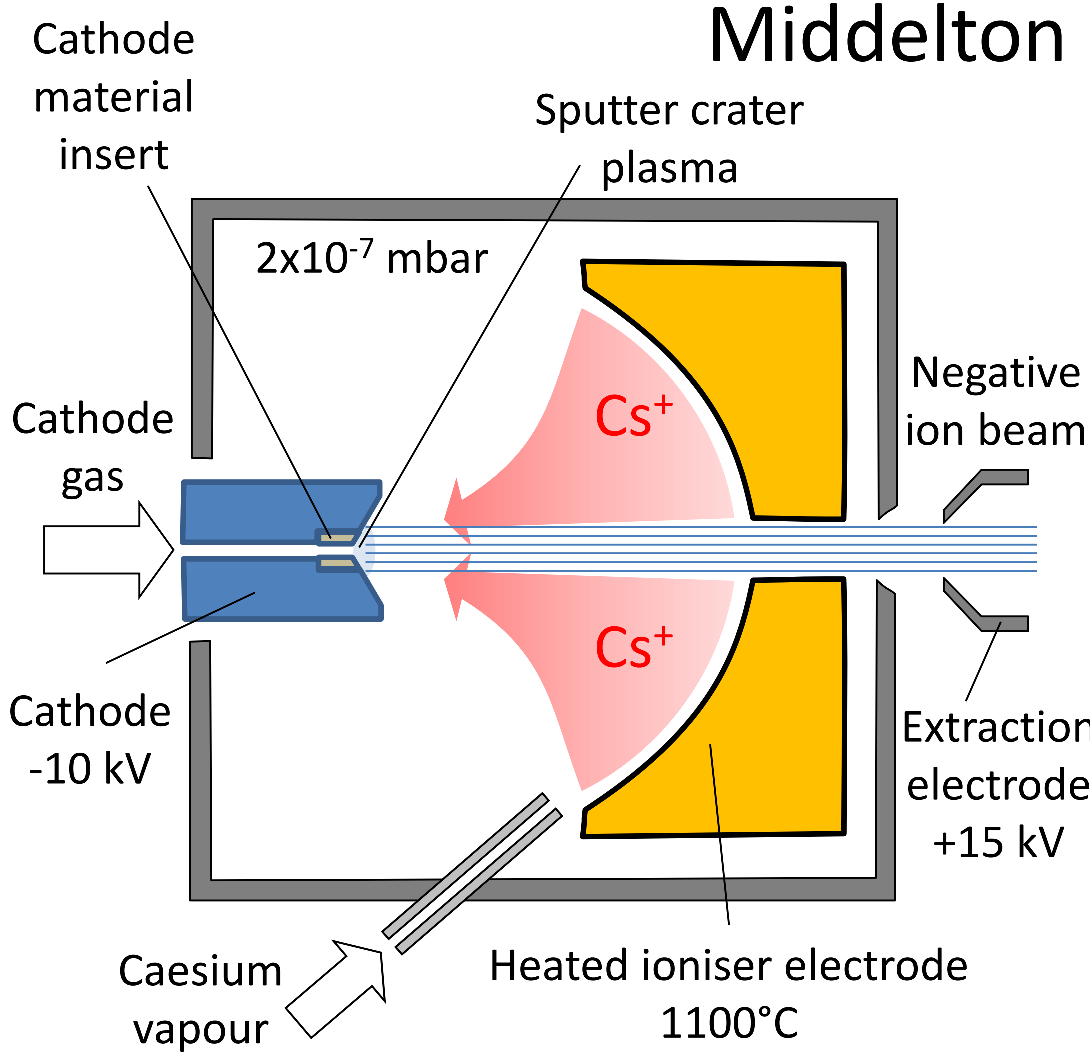
Exotic nuclei
e.g. Lr103+

SNICS (Source of Negative Ions by Cesium Sputtering) Middelton et al

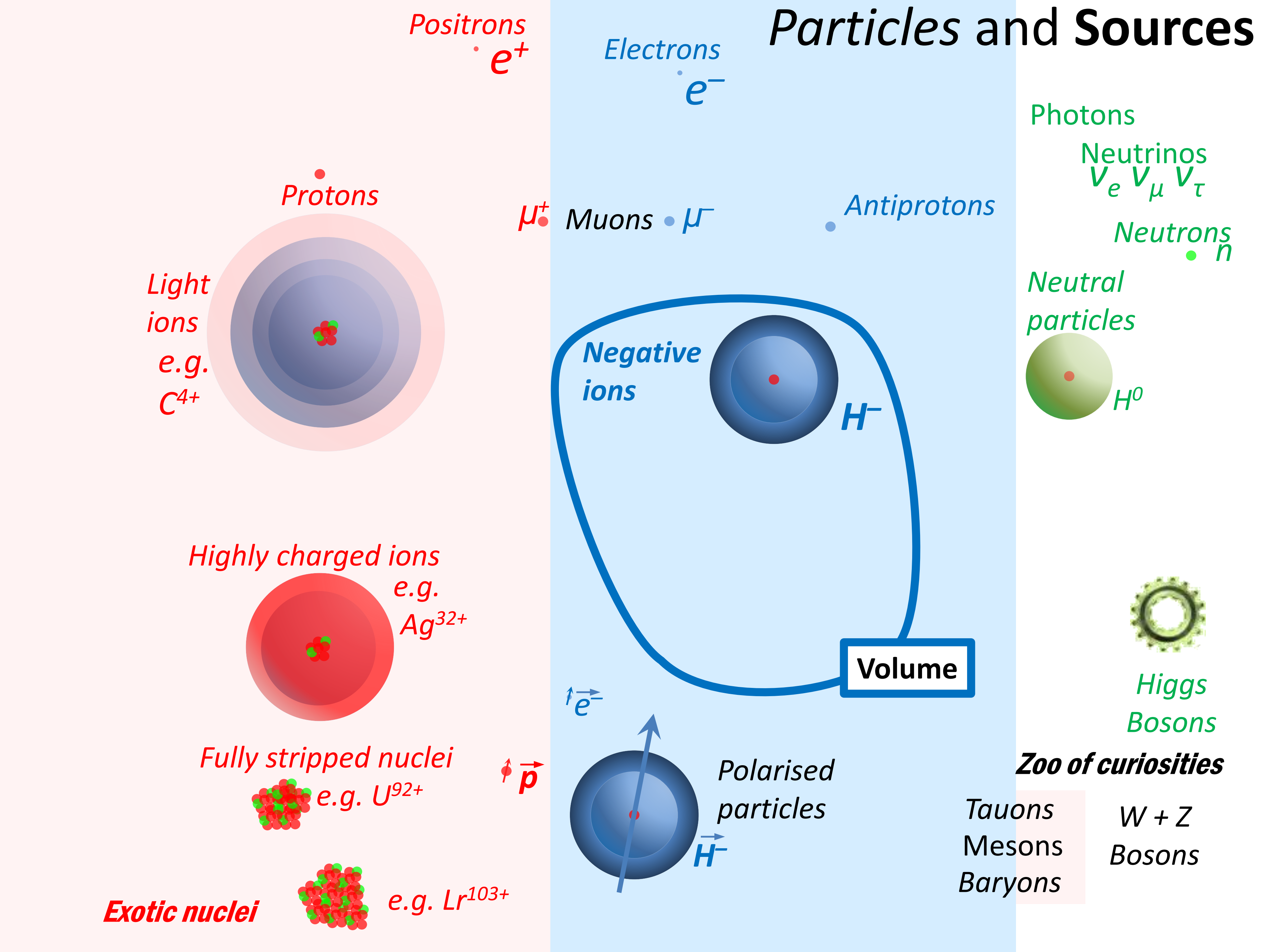


Currents in μA

H-130	Si– 430	As– 60	Cs– 1.5
D– 150	P– 125	Se– 10	CeO– 0.2
Li– 4	S– 100	Br – 40	NdO– 0.3
BeO– 10	Cl– 100	Sr – 1.5	EuO– 1.0
B– 60	CaH3– 0.8	Y– 0.66	ErO– 10
B2– 73	TiH– 10	Zr – 9.4	TmO– 1.0
C– 260	VH– 25	Nb– 7	YbO– 1.0
C2– 40	Cr– 5	Mo– 5	Ta– 9.5
CN– 12	MnO– 4	Rh– 5	TaO– 6
CN–(15N) 20	Fe– 20	Ag– 13	W– 2.5
O– 300	Co– 120	CdO– 7	Os – 15
F– 100	Ni– 80	InO– 20	Ir – 100
Na– 4.0	Cu– 160	Sn– 20	Pt – 250
MgH2– 1.5	ZnO– 12	Sb– 16	Au– 150
Al– 7	GaO– 7	Te– 20	PbO– 1
Al2– 50	Ge– 60	I– 220	Bi– 3.5

Produces a large range of different negative ions

National Electrostatics Corp.



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μ^+
Muons
μ^-
Antiprotons
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n
Light ions e.g. C^{4+}
Neutral particles
Negative ions
H^-
H^0
Highly charged ions e.g. Ag^{32+}
Volume
Higgs Bosons
$\vec{e}^-$
Fully stripped nuclei e.g. U^{92+}
$\vec{p}$
Polarised particles
Zoo of curiosities
Tauons
Mesons
Baryons
W + Z Bosons
$\vec{H}^-$
Exotic nuclei
e.g. Lr^{103+}

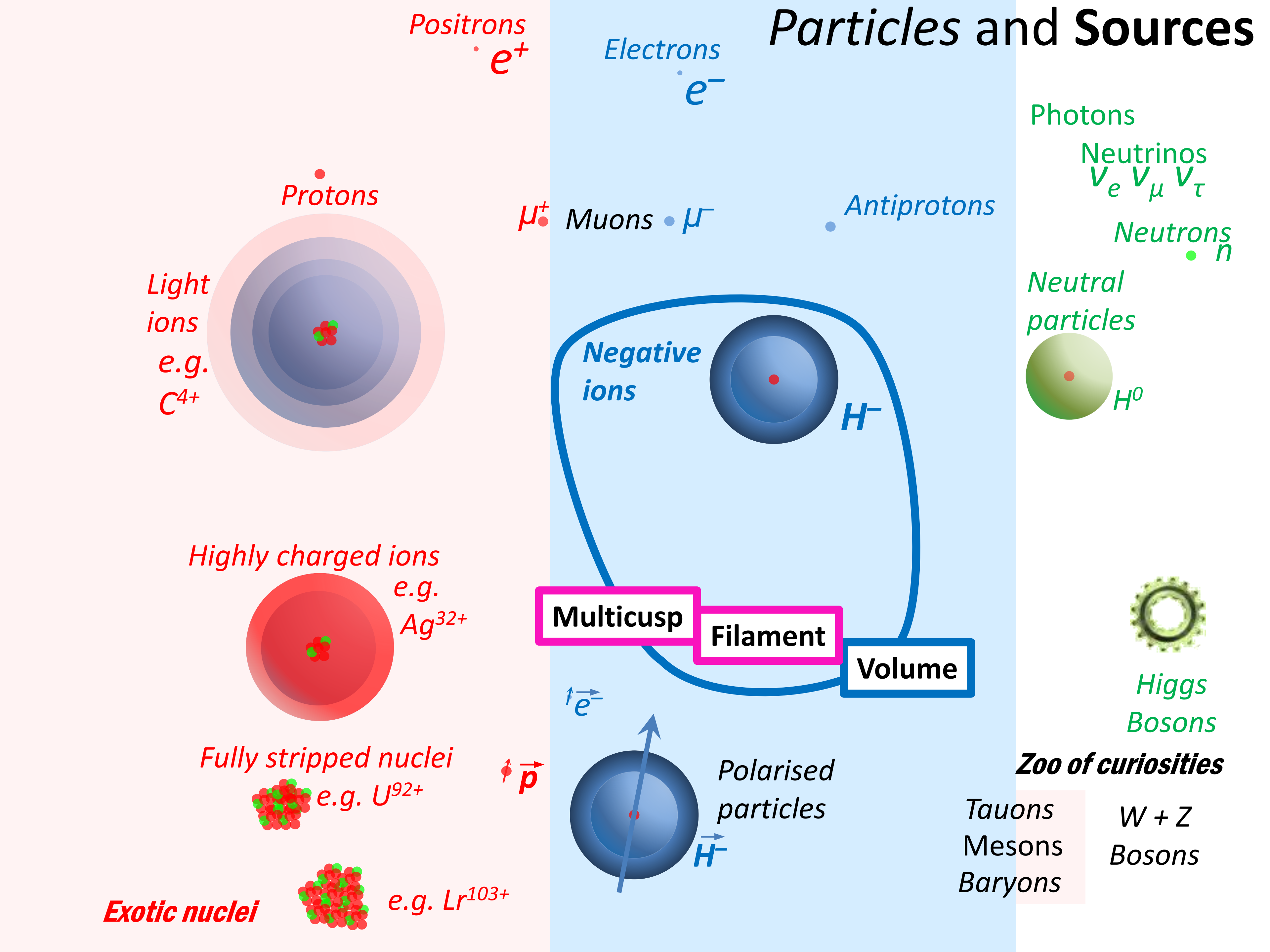
Marthe Bacal
Ecole Polytechnique
mid 1970's

Volume Production

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

Dissociative attachment
of low energy electrons
to rovibrationally excited
H_2 molecules

Developed by Ehlers + Leung at LBNL



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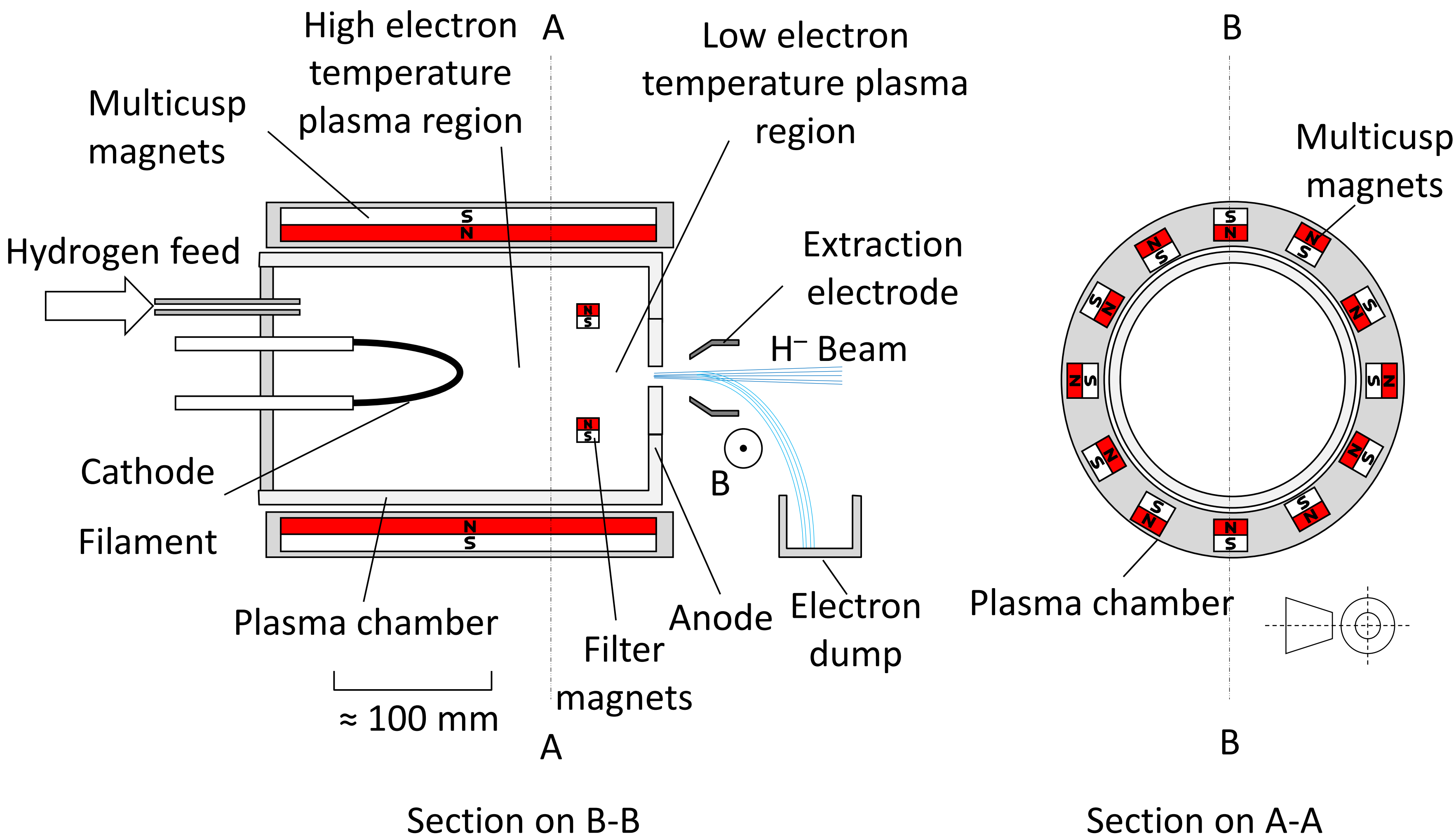
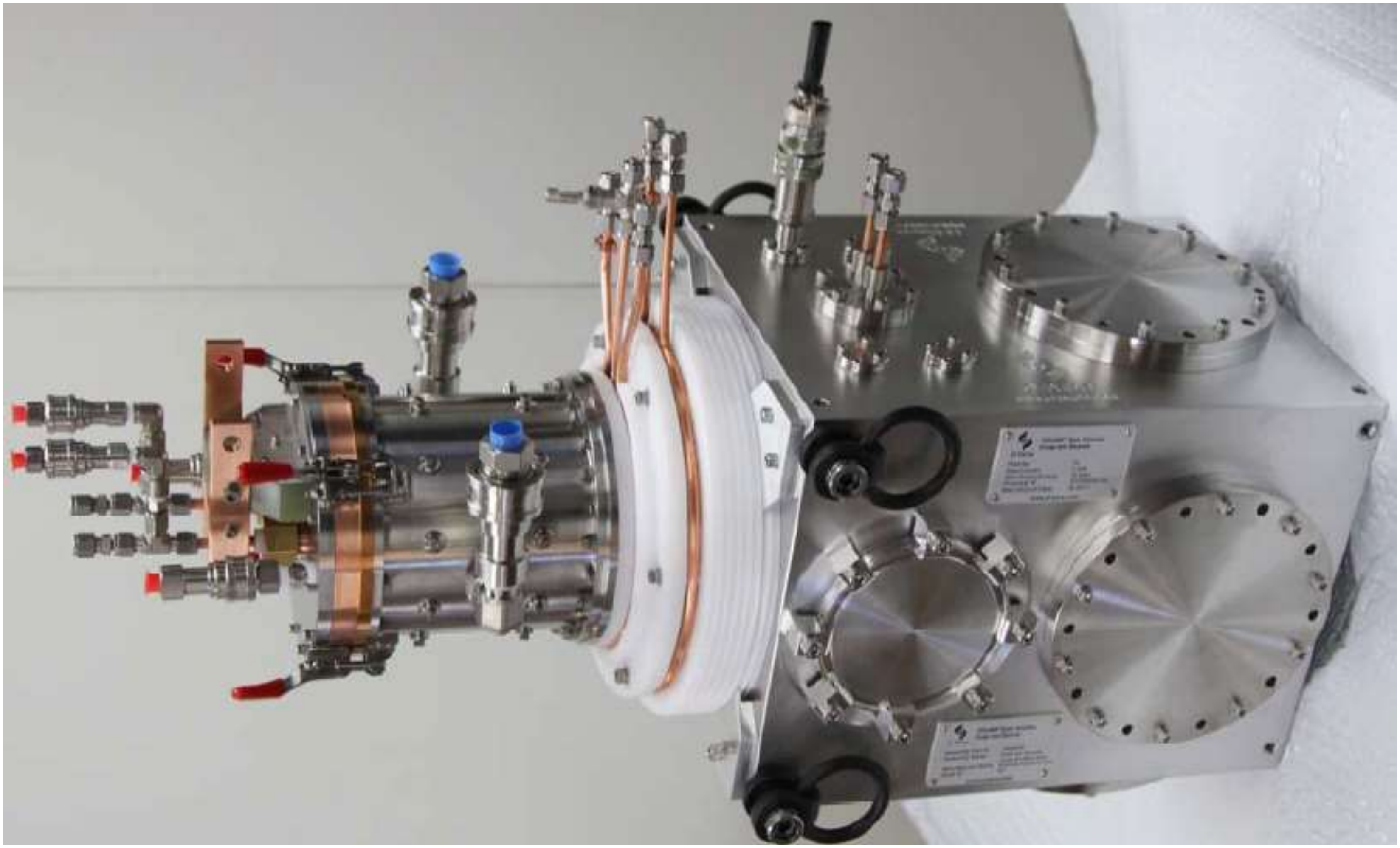
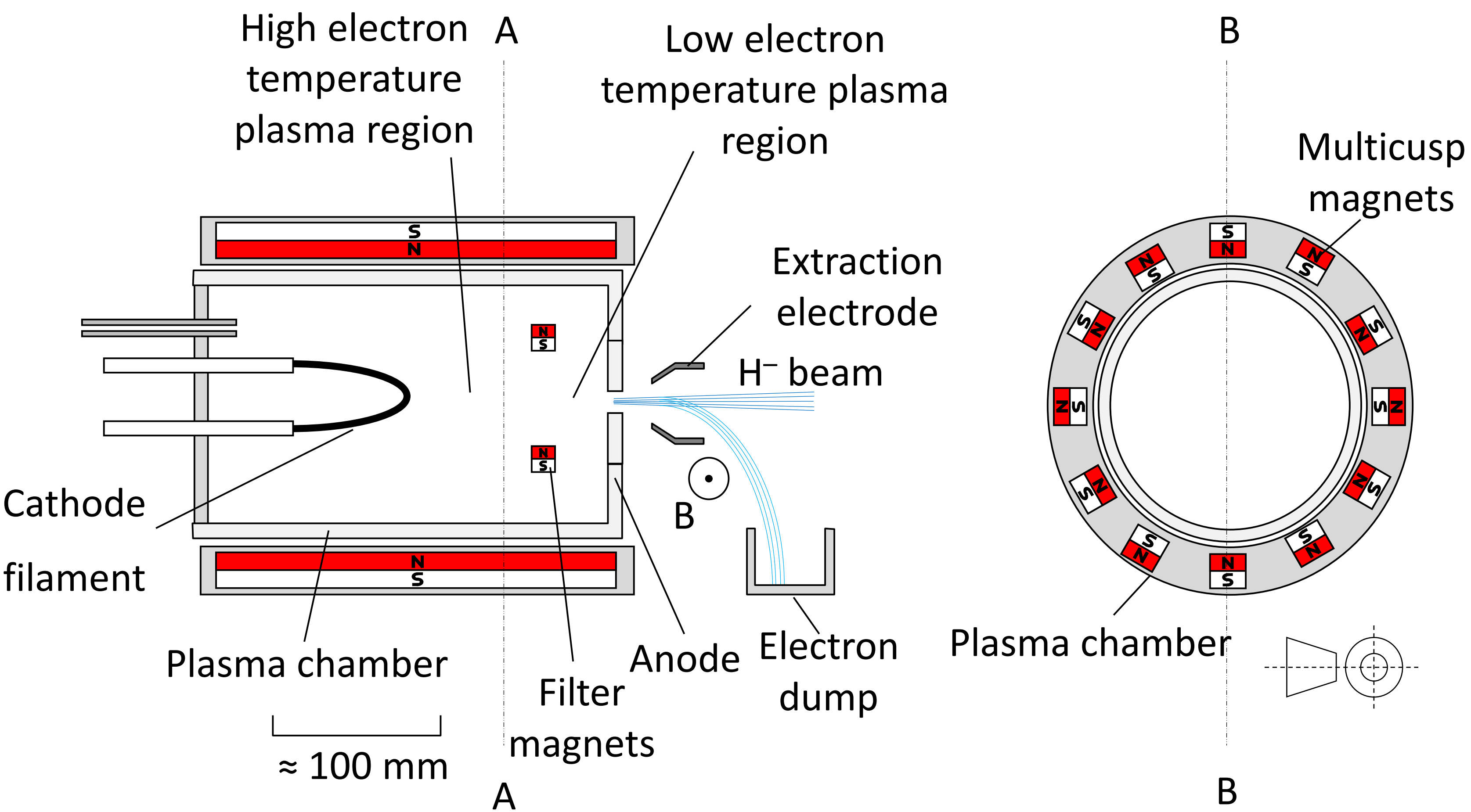
Exotic nuclei
e.g. Lr103+

Multicusp Filament Volume Source



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

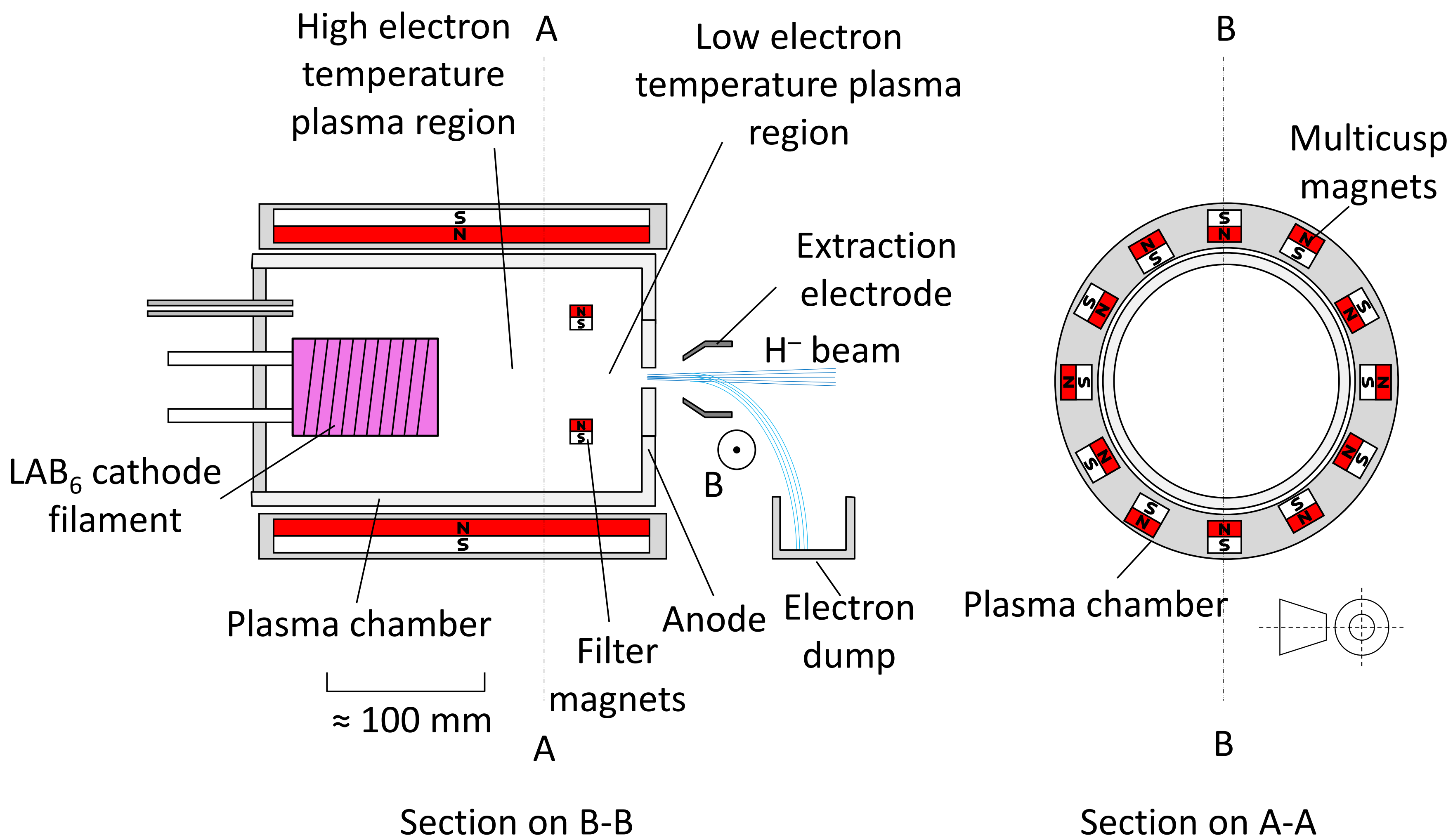




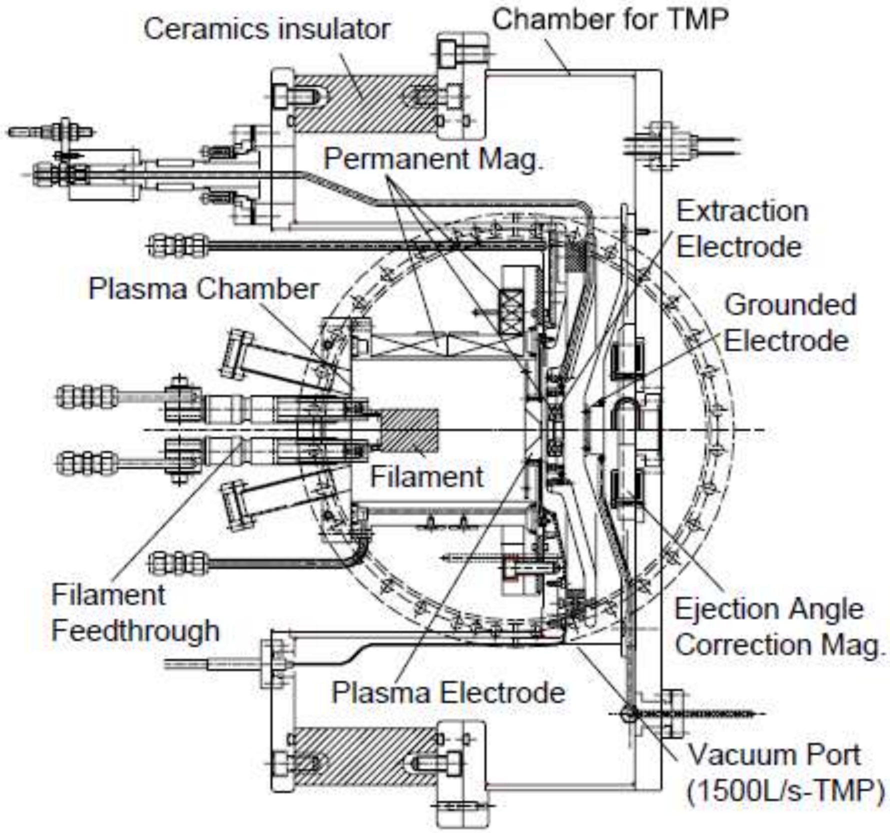
Section on B-B

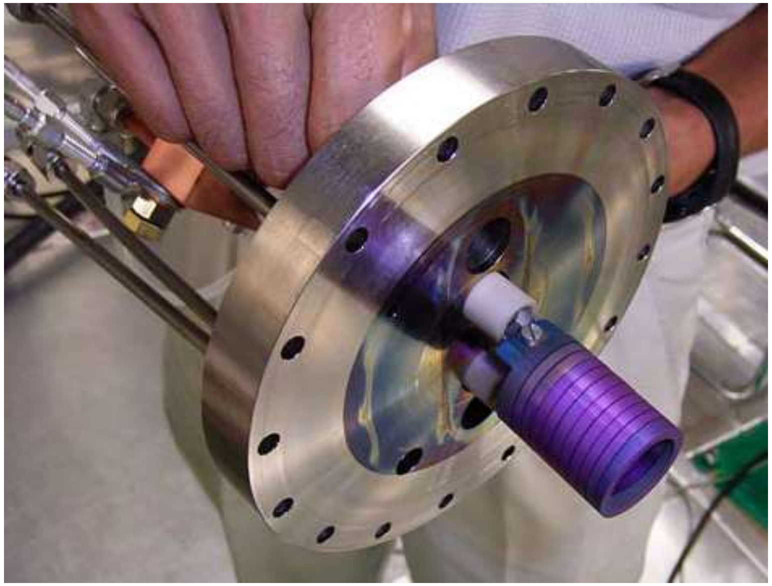
Section on A-A

LAB_6 Filament Volume Source

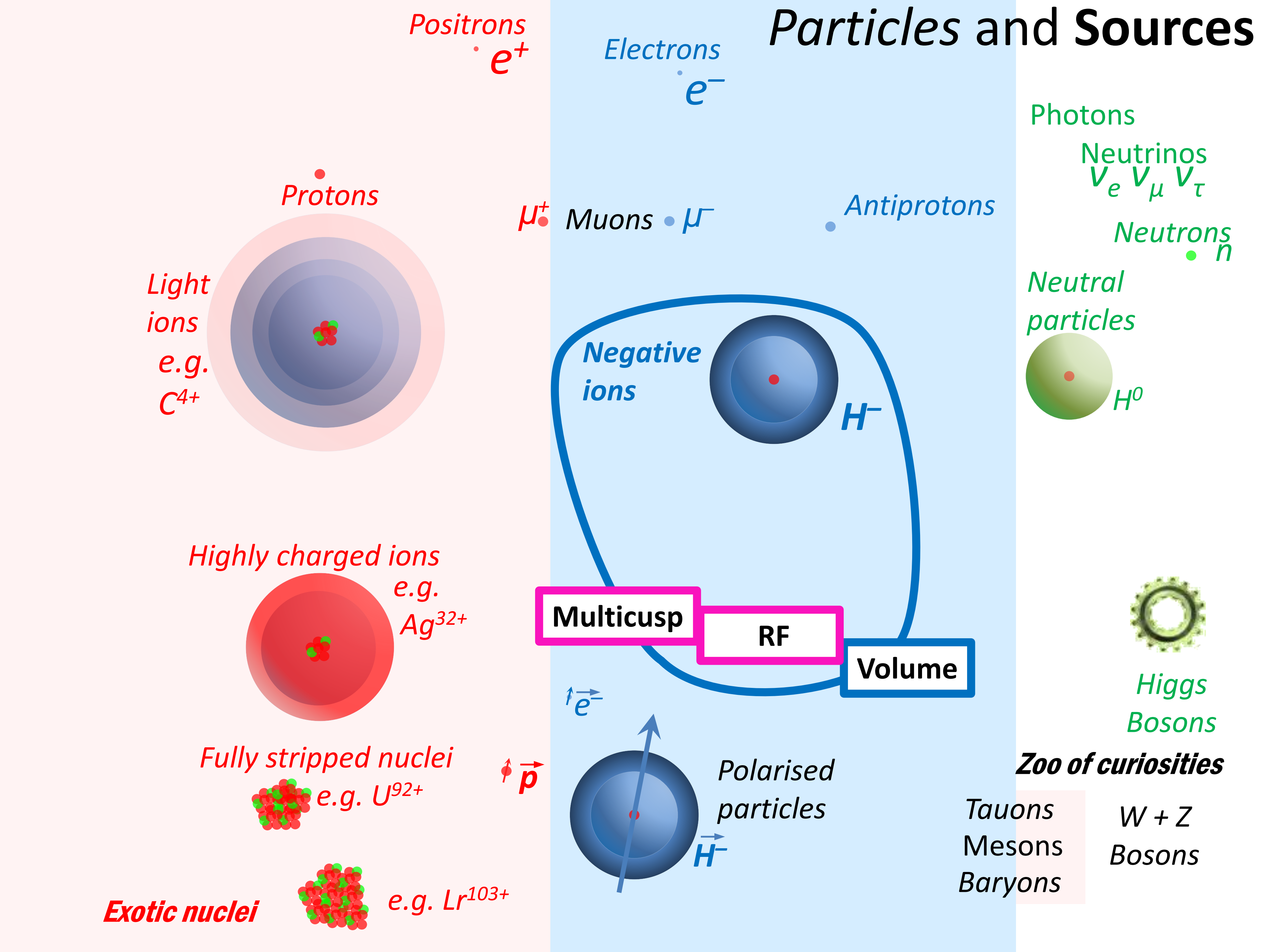


LAB_6 Filament Volume Source





36 mA @500 μs 25 Hz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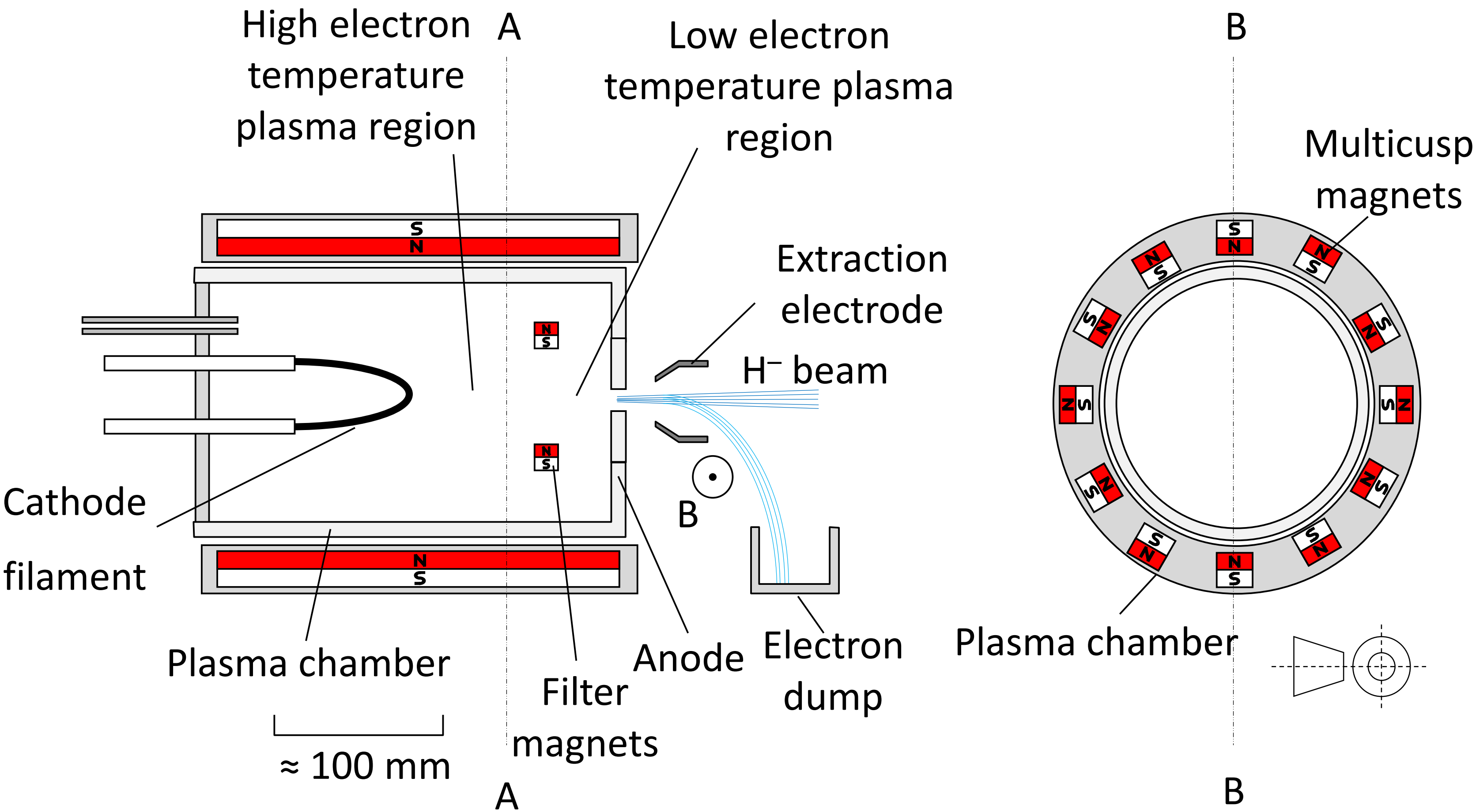
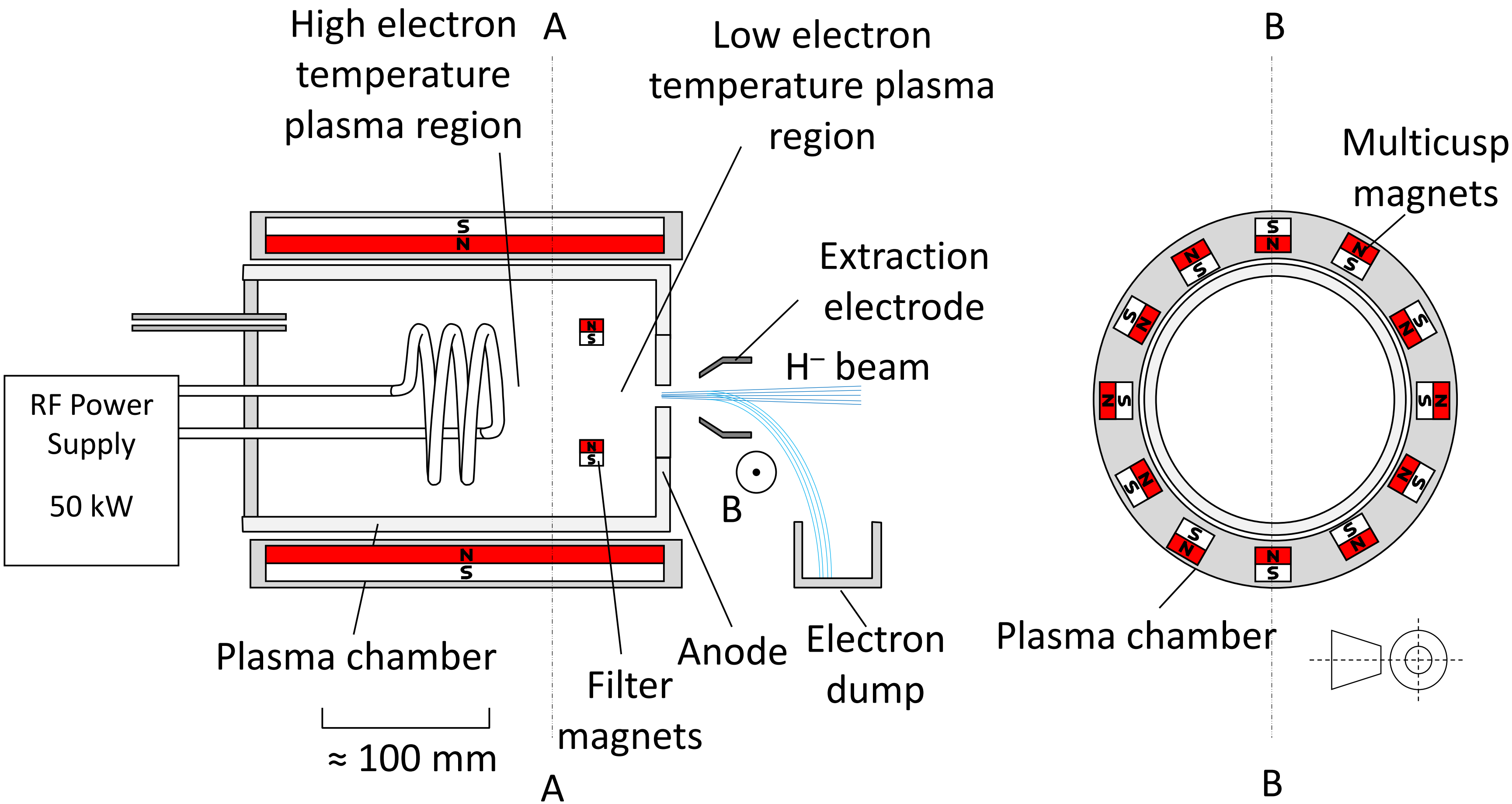


Section on B-B

Section on A-A

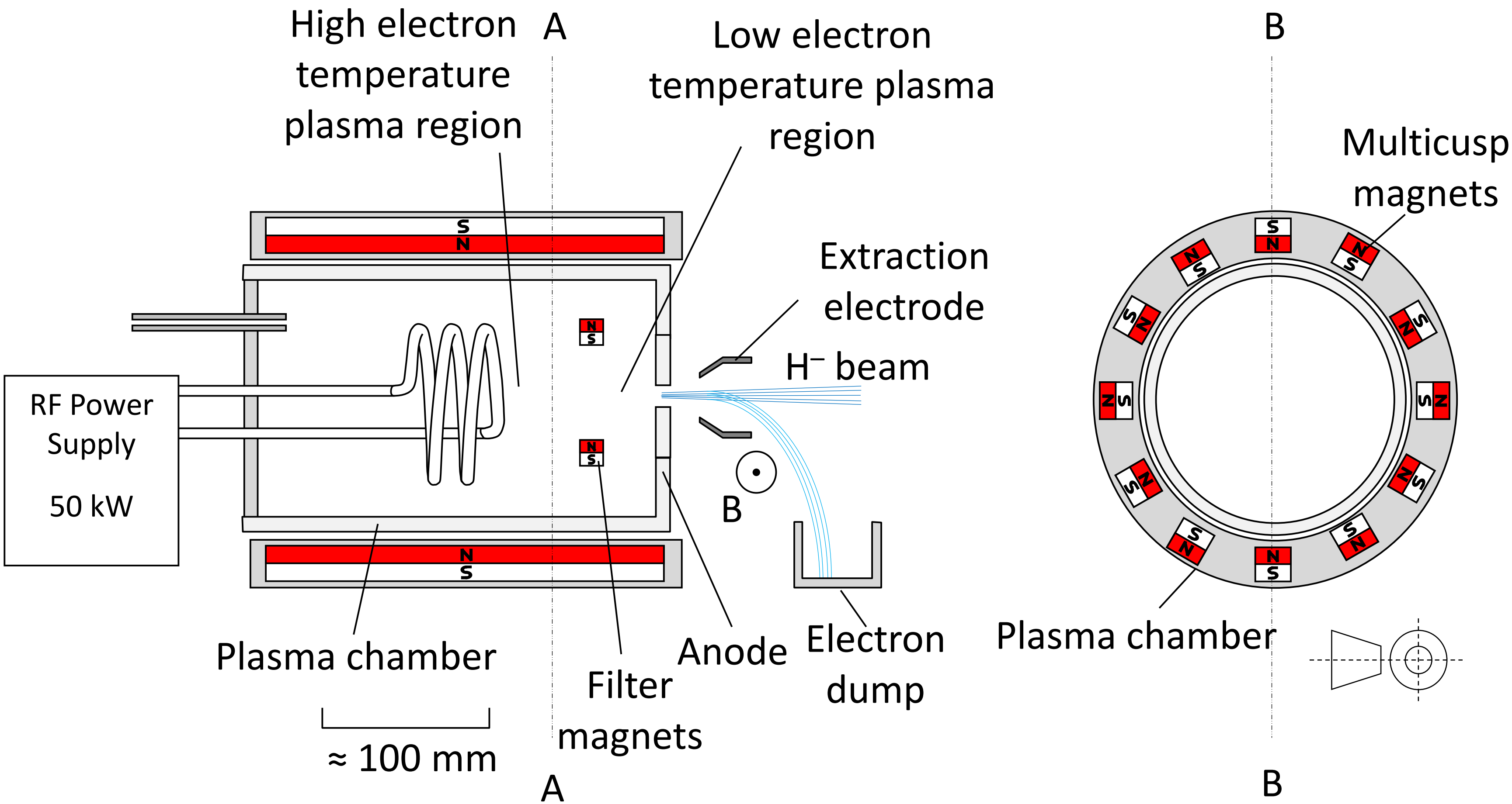
Internal RF Solenoid Coil Volume Source



Section on B-B

Section on A-A

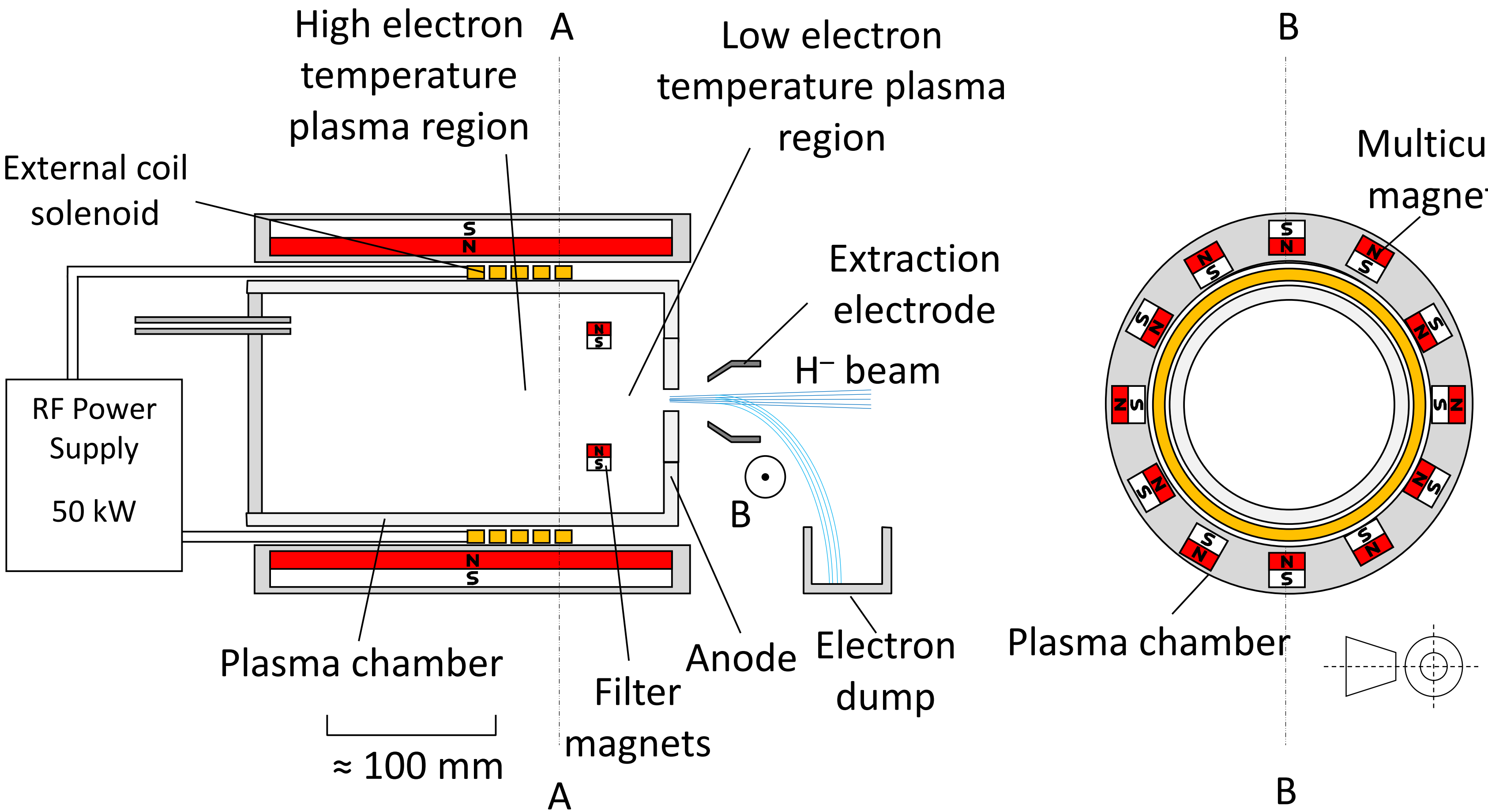
Internal RF Solenoid Coil Volume Source



Section on B-B

Section on A-A

External RF Solenoid Coil Volume Source

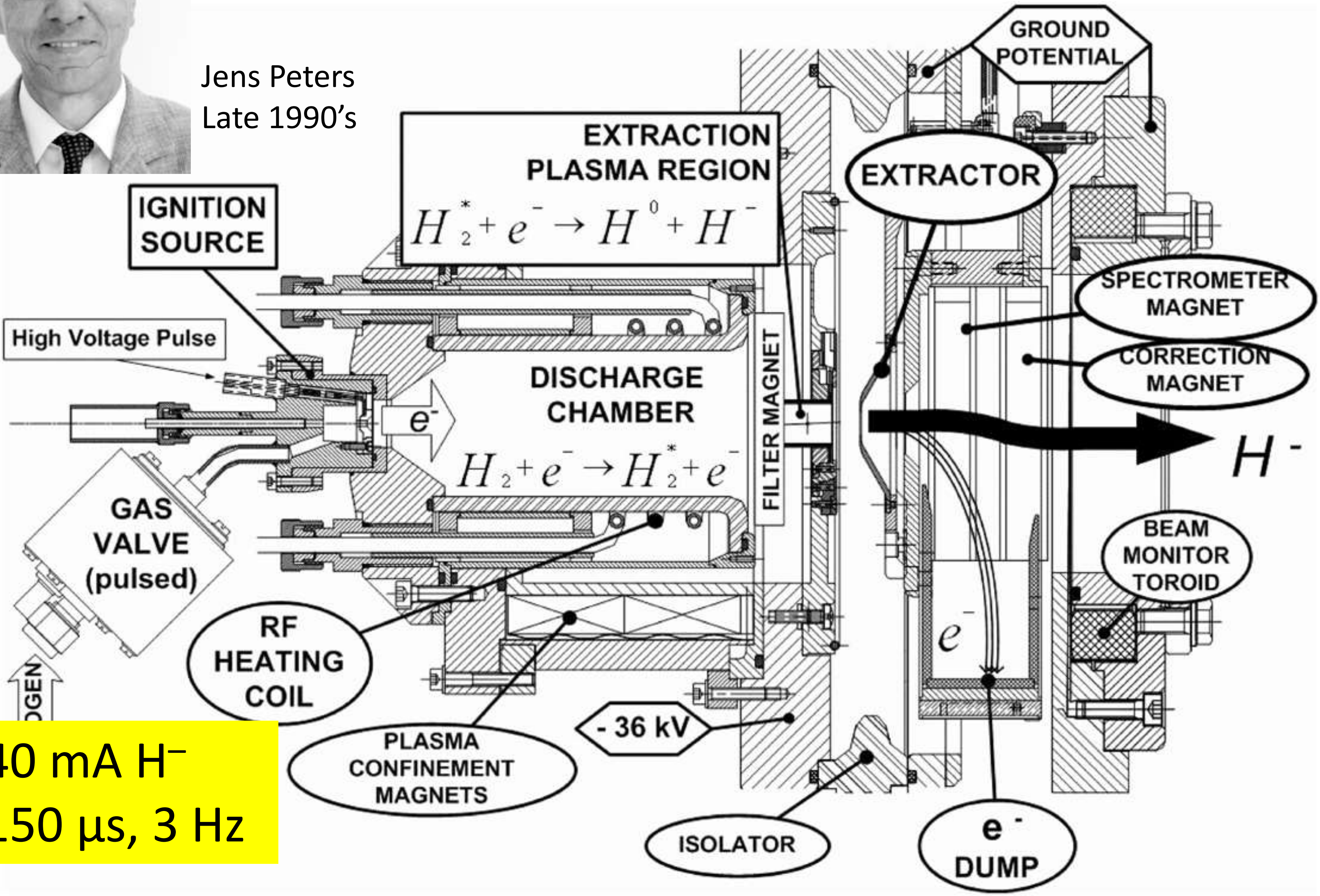


Section on B-B

Section on A-A

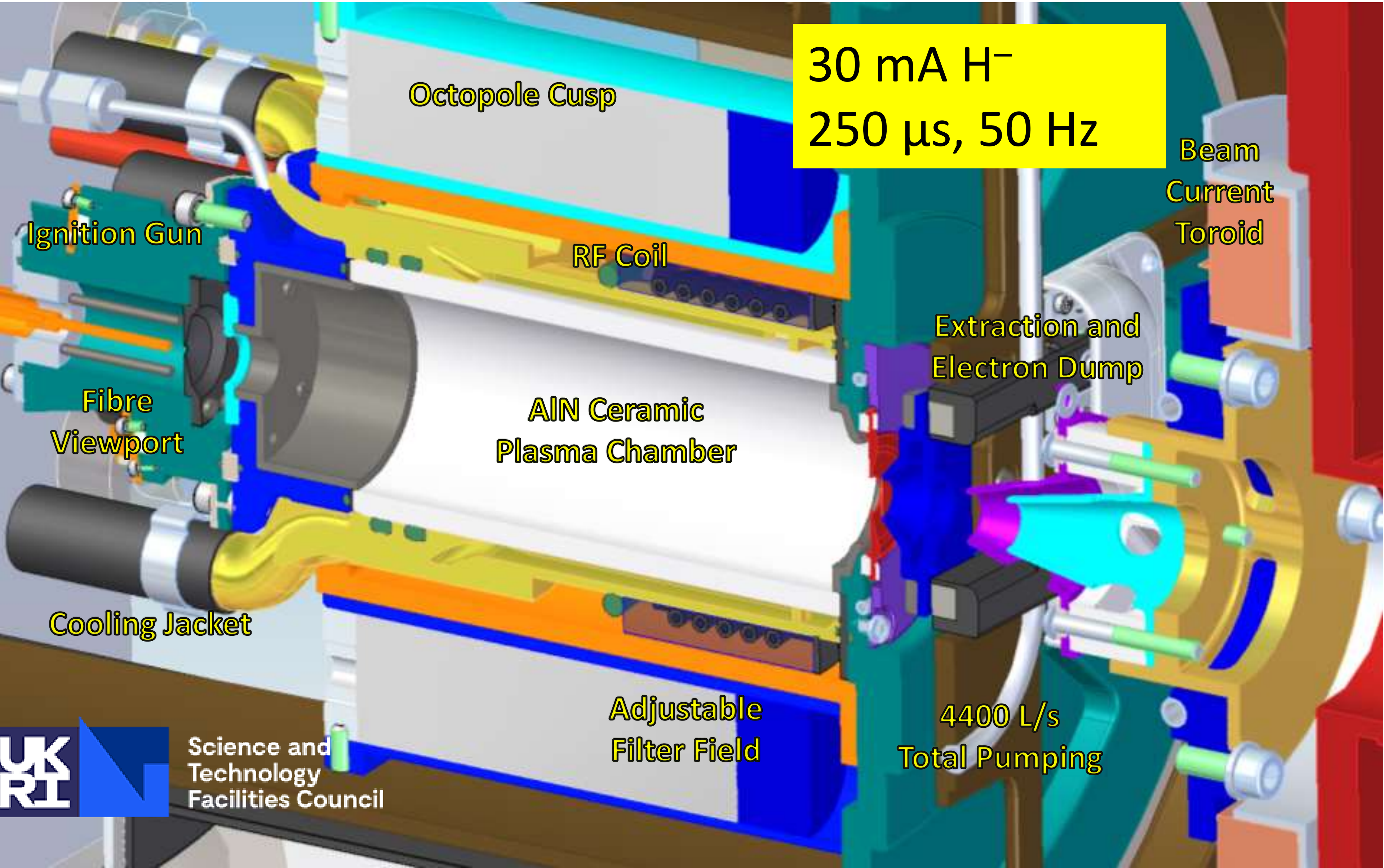
DESY Source

Jens Peters
Late 1990's



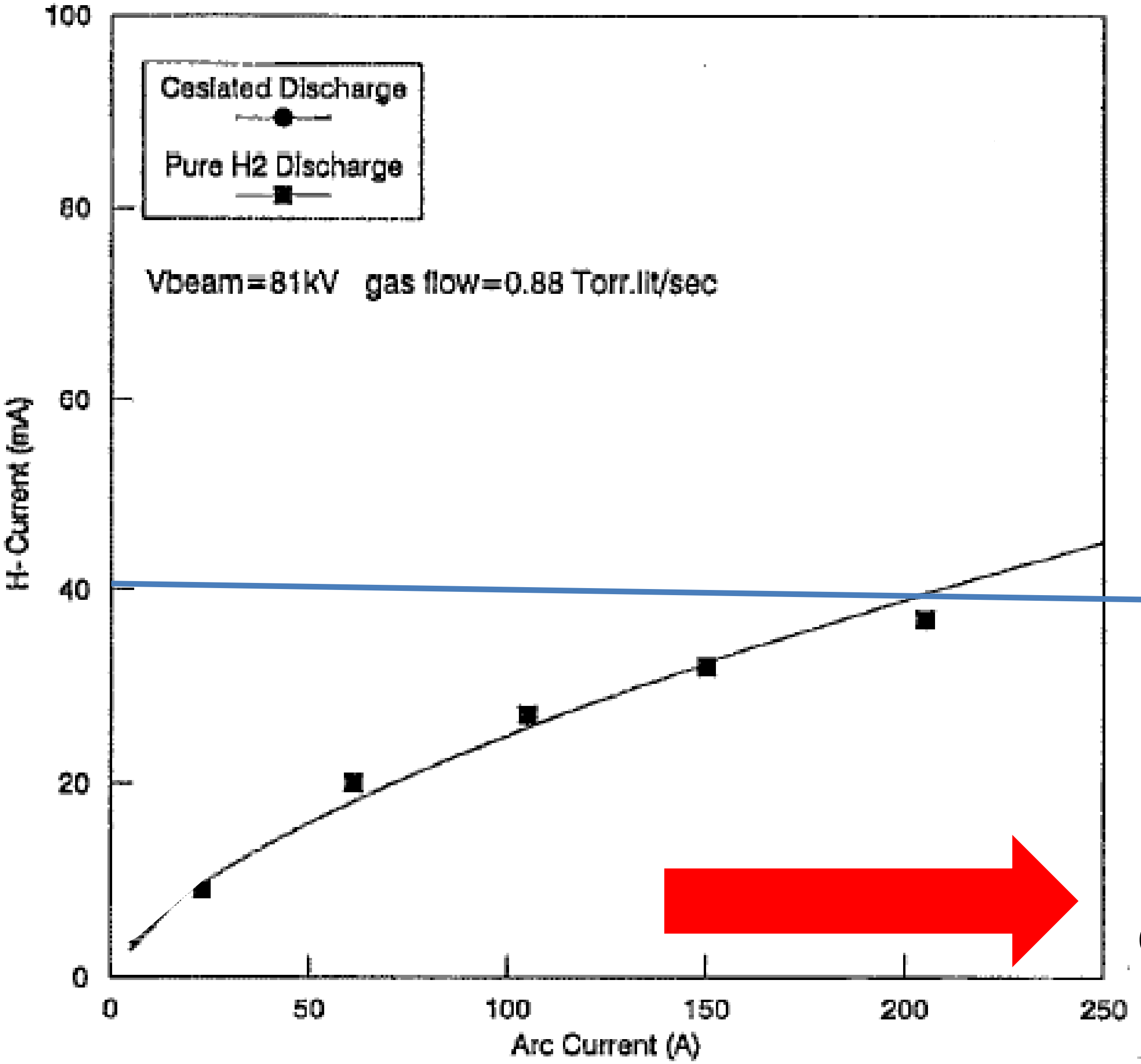
40 mA H⁻
150 µs, 3 Hz

ISIS RF H$^-$ Ion Source (under commissioning)



UKRI Science and Technology Facilities Council

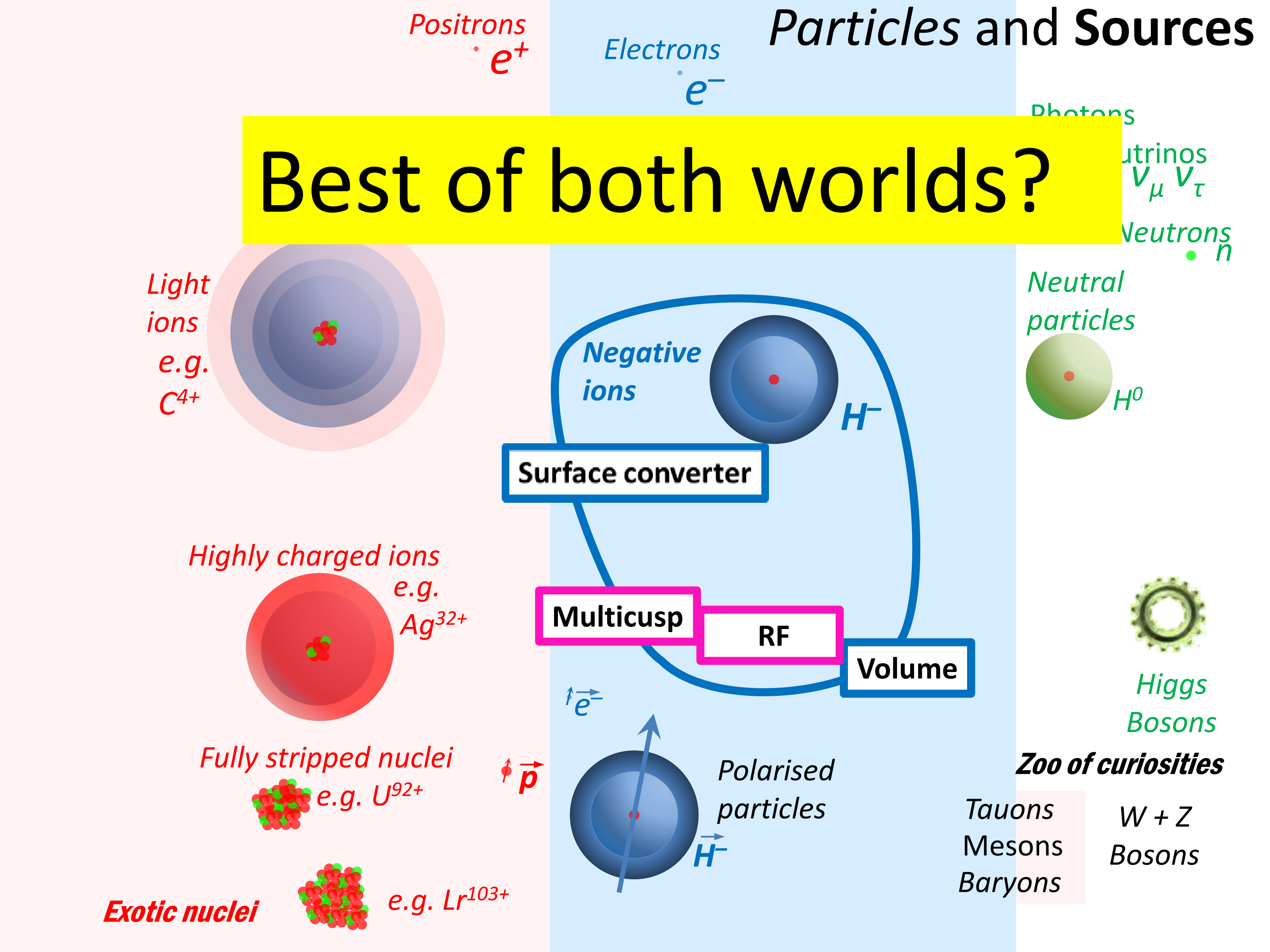
Holmes et. al. Culham UK



Add caesium

40 mA = apparent limit of the volume process

Destruction process dominate



Particles and Sources
Best of both worlds?
Positrons
e^+
Electrons
e^-
ν_μ ν_τ
n
Neutral particles
H^0
Light ions
e.g. C^{4+}
Negative ions
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Surface converter
Highly charged ions
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Higgs Bosons
$\vec{e}^-$
Fully stripped nuclei
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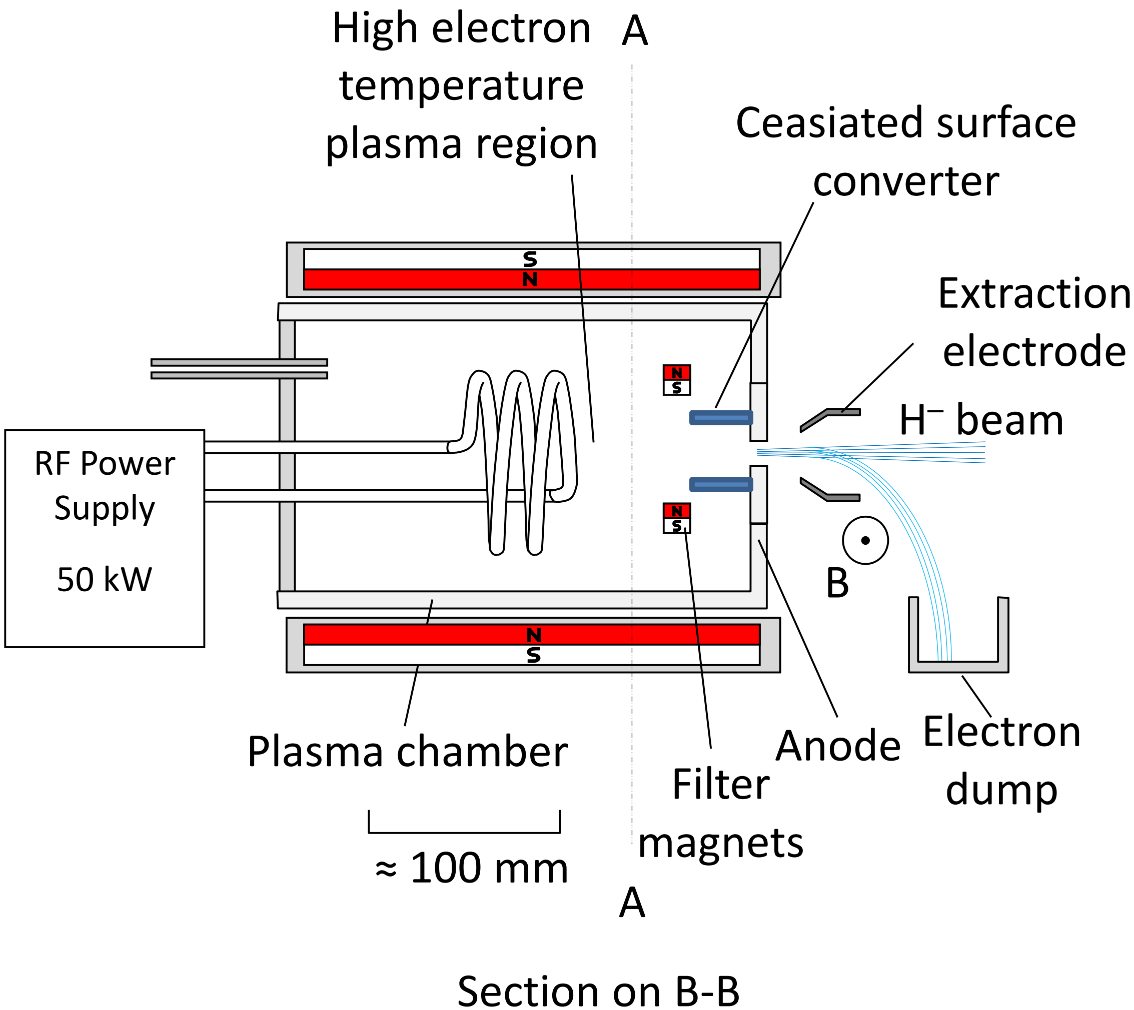
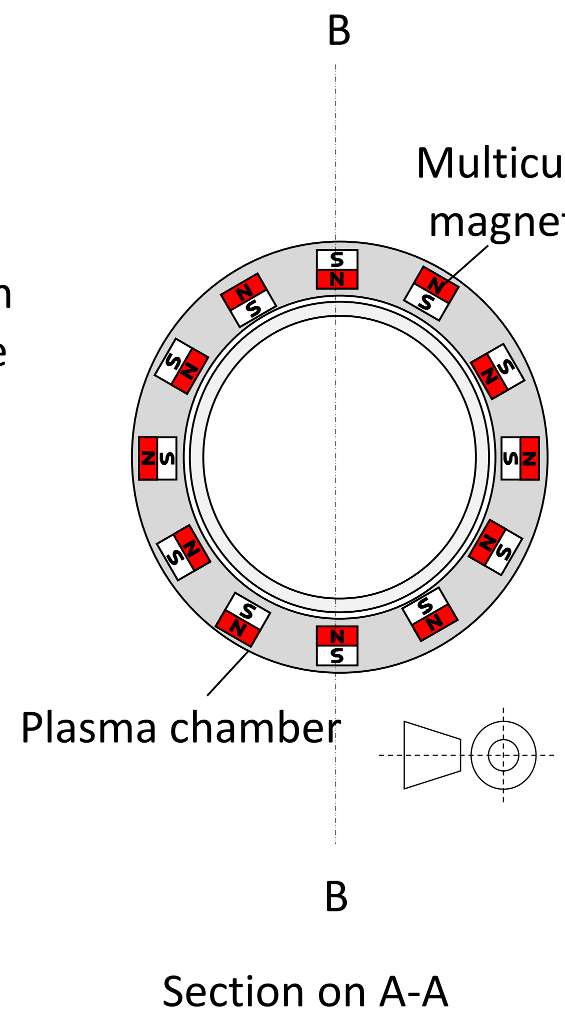
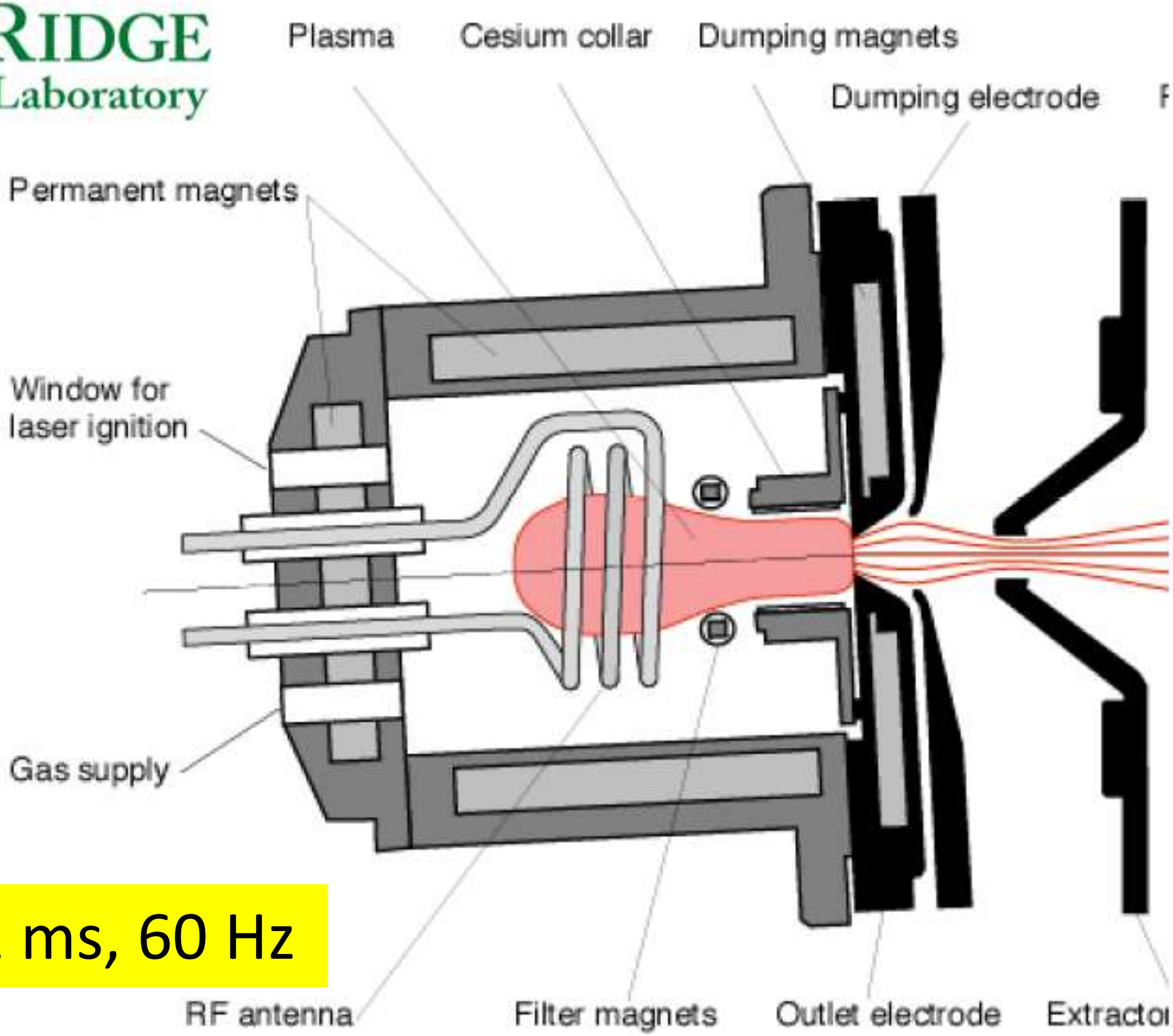
Polarised particles
$\vec{H}^-$
Zoo of curiosities
Tauons
Mesons
Baryons
W + Z
Bosons
Exotic nuclei
e.g. Lr^{103+}

Internal RF Solenoid Coil
Volume Source with Surface Converter





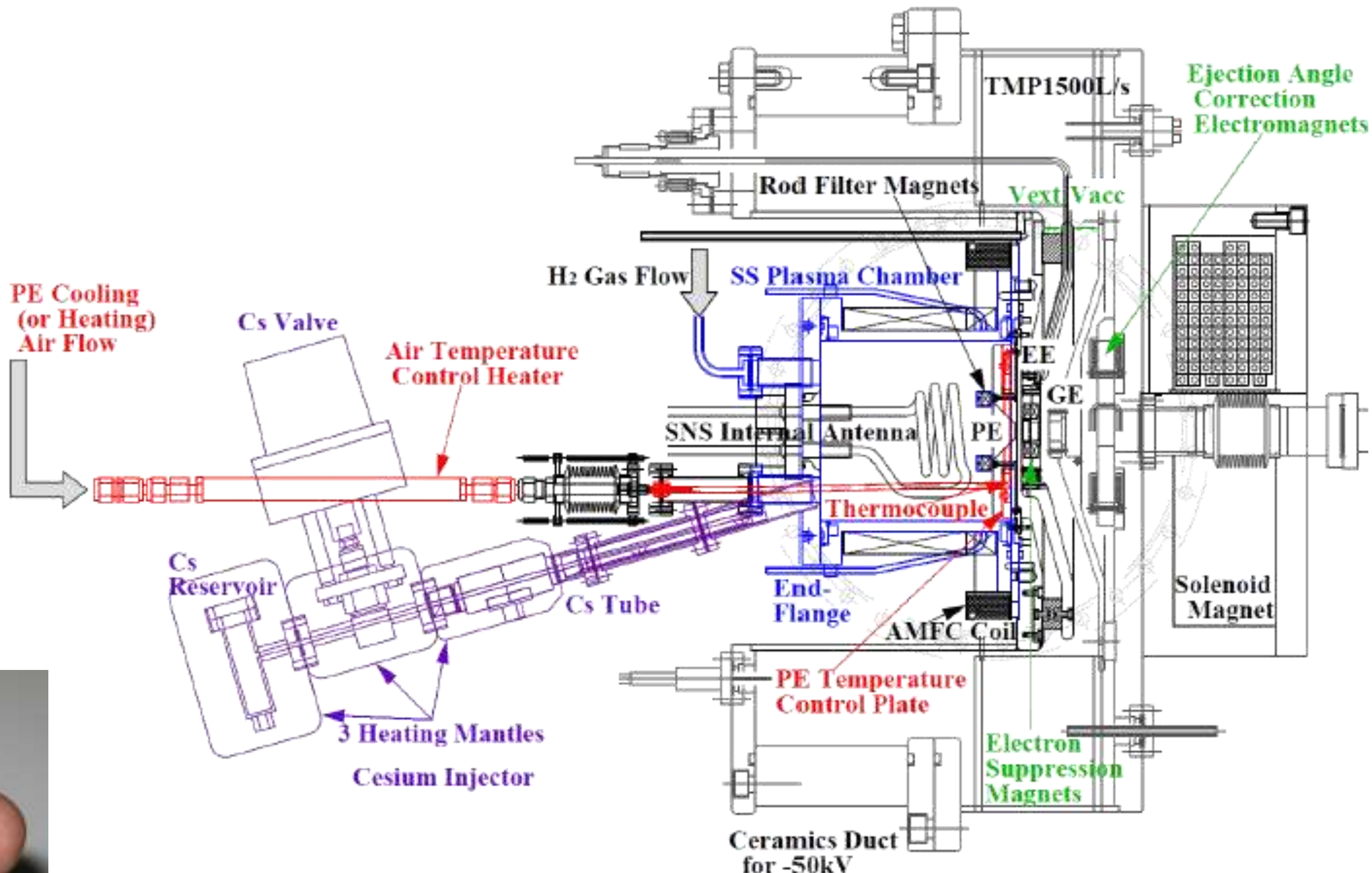
SNS Internal RF Solenoid Coil Volume Source with Surface Converter



Caesium Chromate Cartridges

60 mA H^- 1 ms, 60 Hz

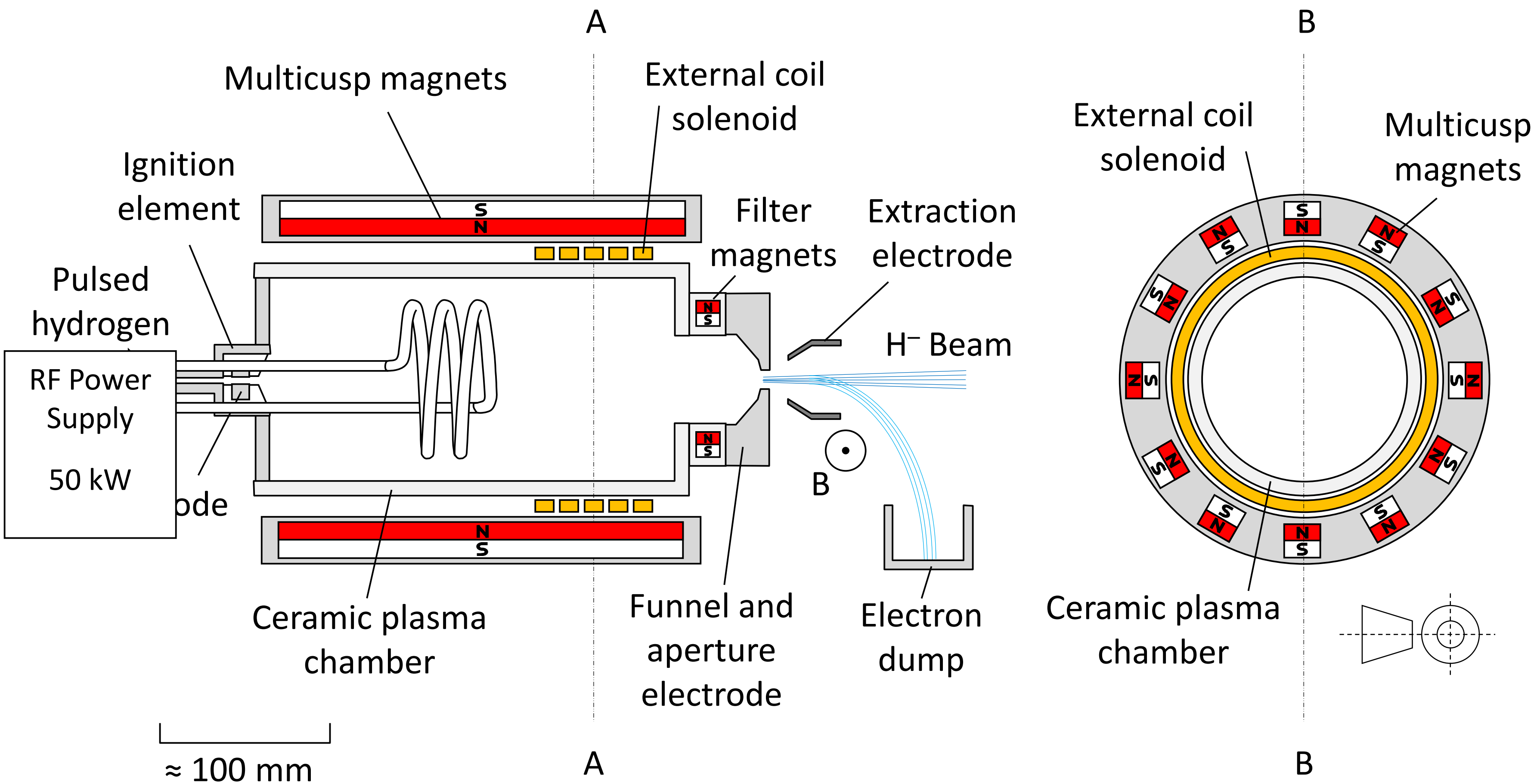
Ceasiated Internal RF Solenoid Coil Volume Source with Surface Converter



Elemental Cs

100 mA H^- 500 ms, 25 Hz

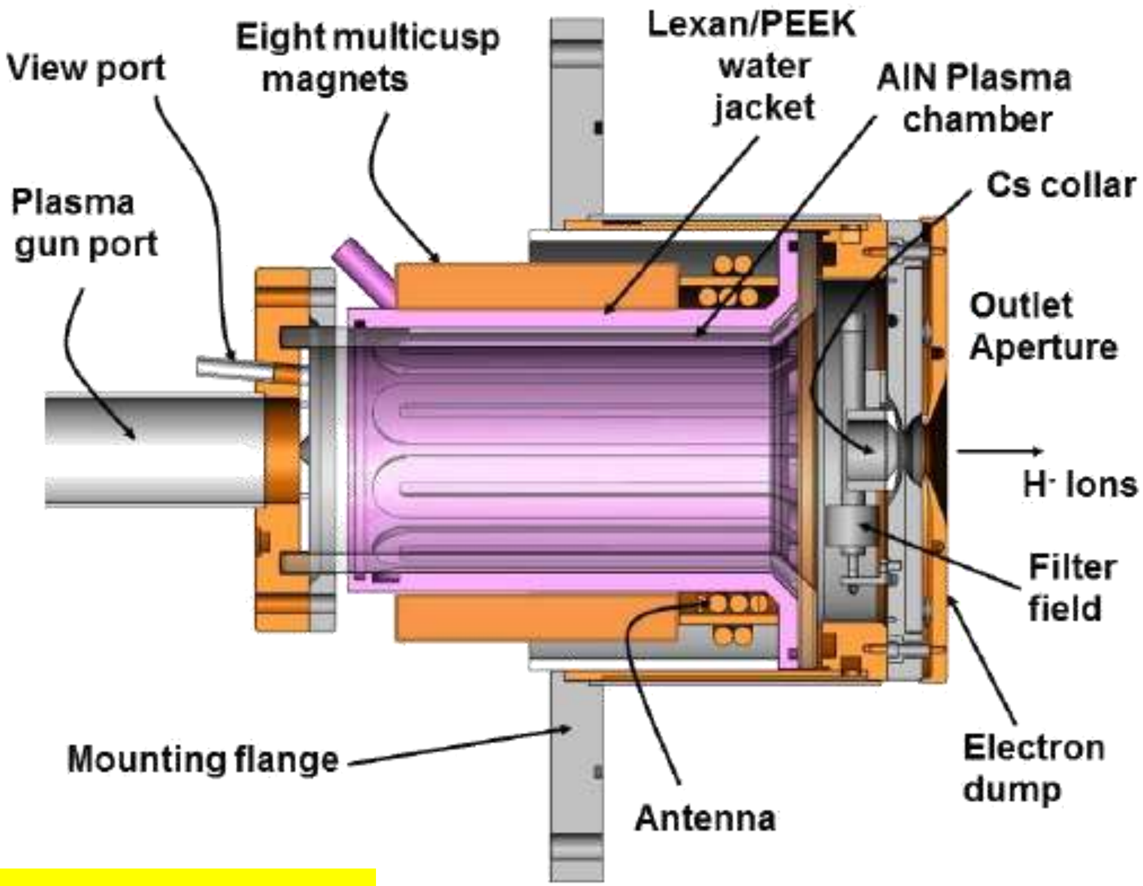
External RF Coil Multicusp Source



Section on B-B

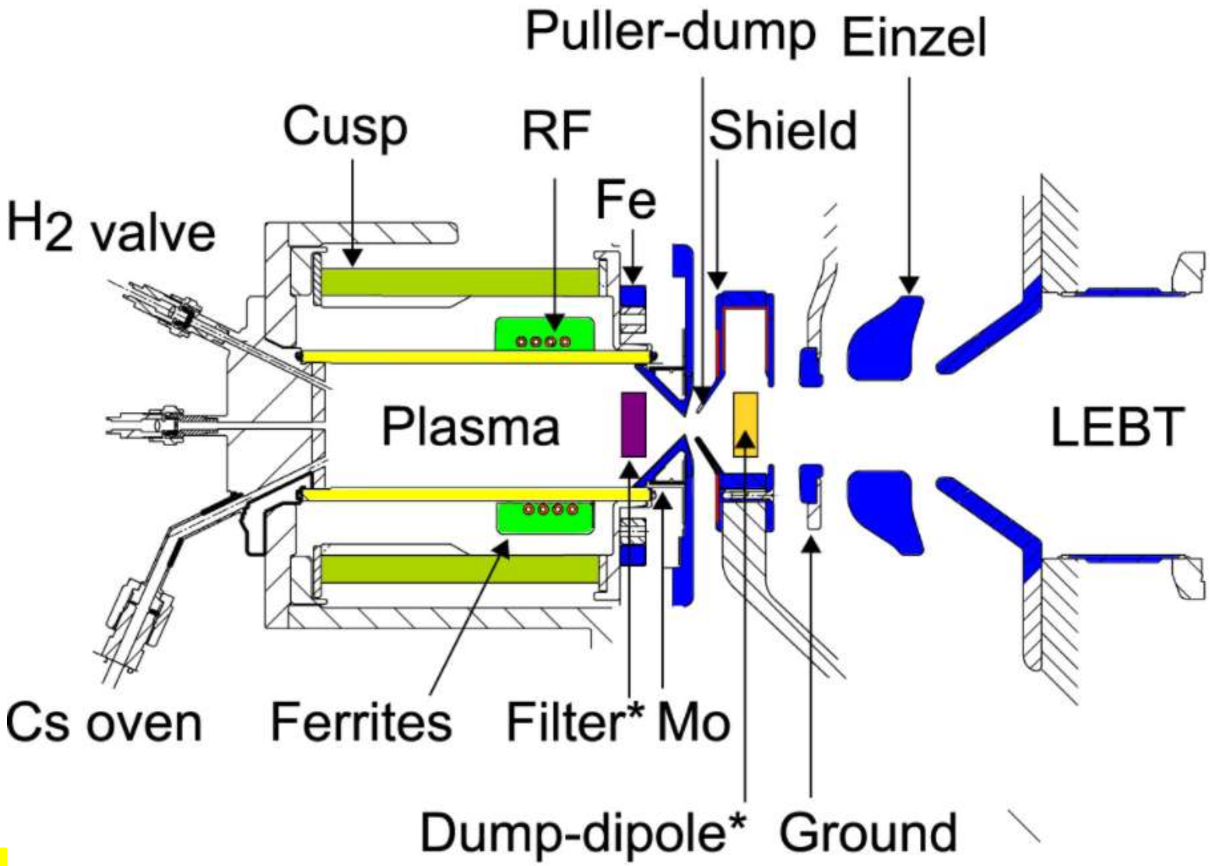
Section on A-A

Ceasiated External RF Solenoid Coil Multicusp Volume Source



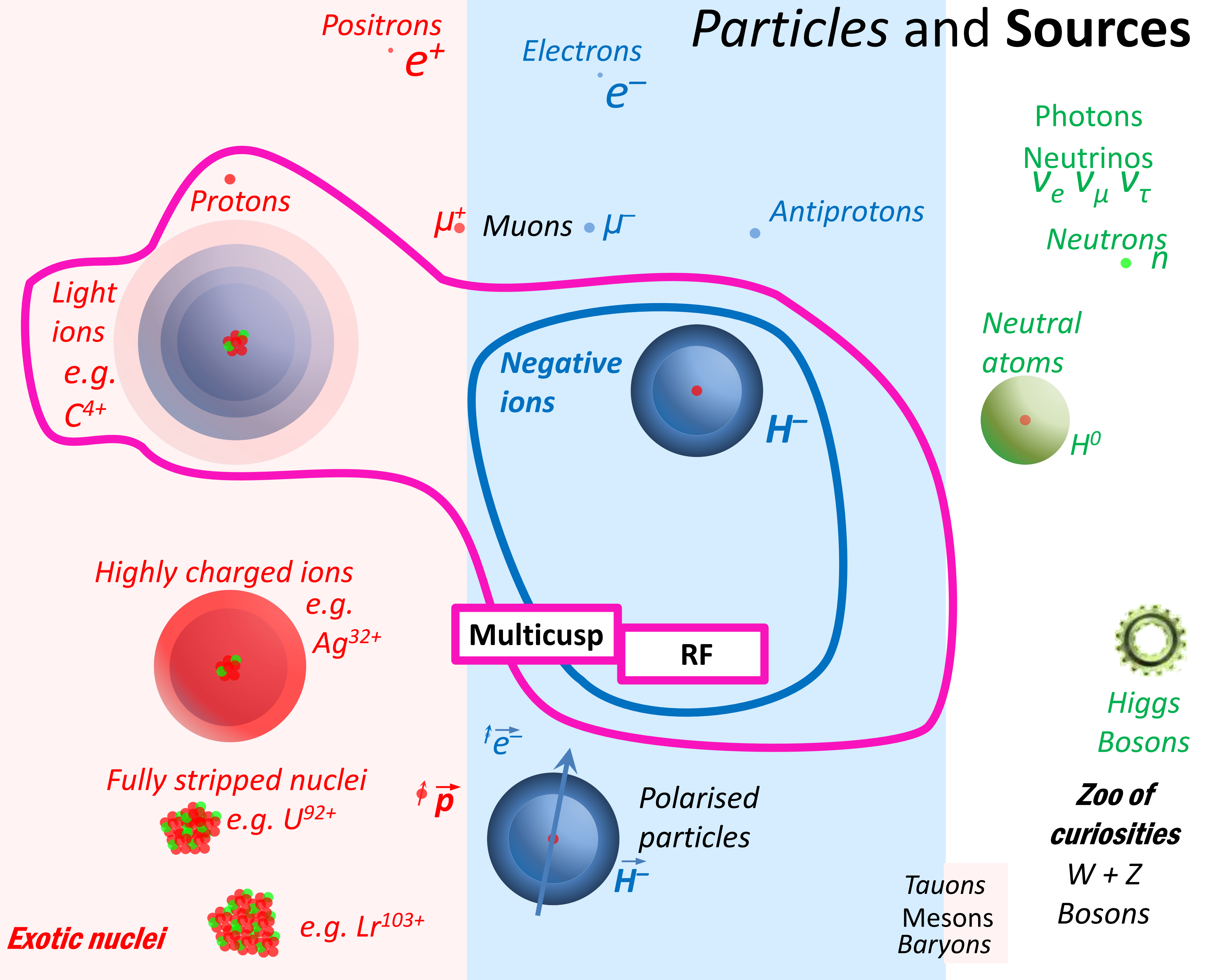
60 mA H^- 1 ms, 60 Hz

Ceasiated External RF Solenoid Coil Multicusp Volume Source

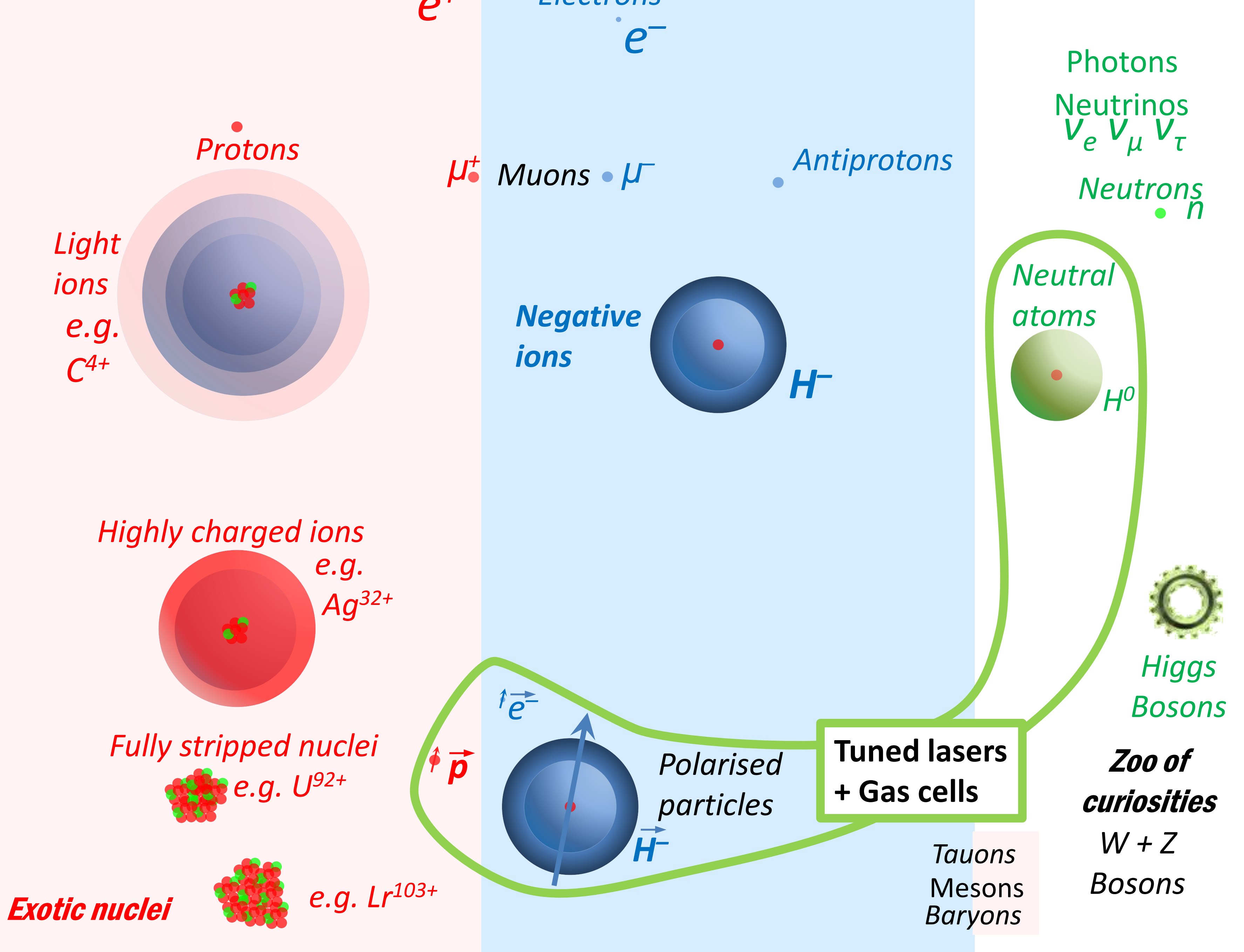


50 mA H^-
500 μs, 3 Hz

Particles and **Sources**

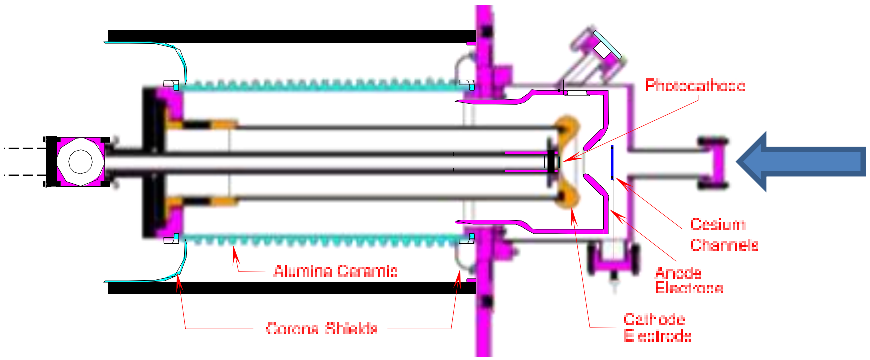


Particles and **Sources**

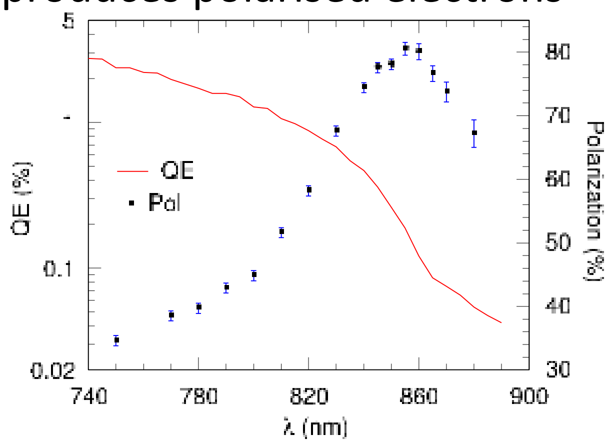


Polarised Electrons

Strained GaAs photocathode

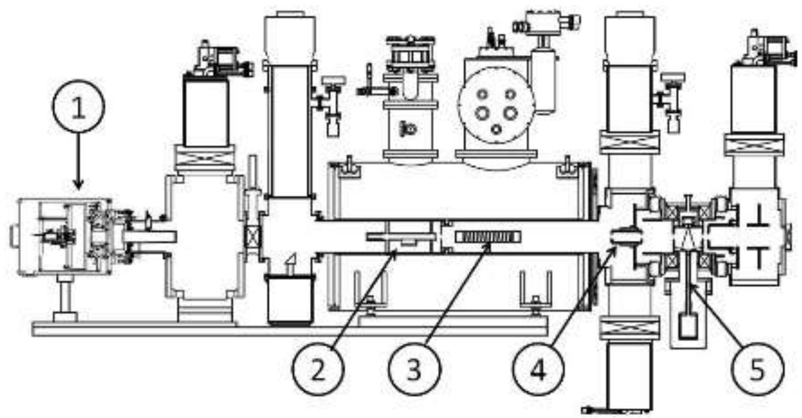


Circularly polarized laser light produces polarised electrons



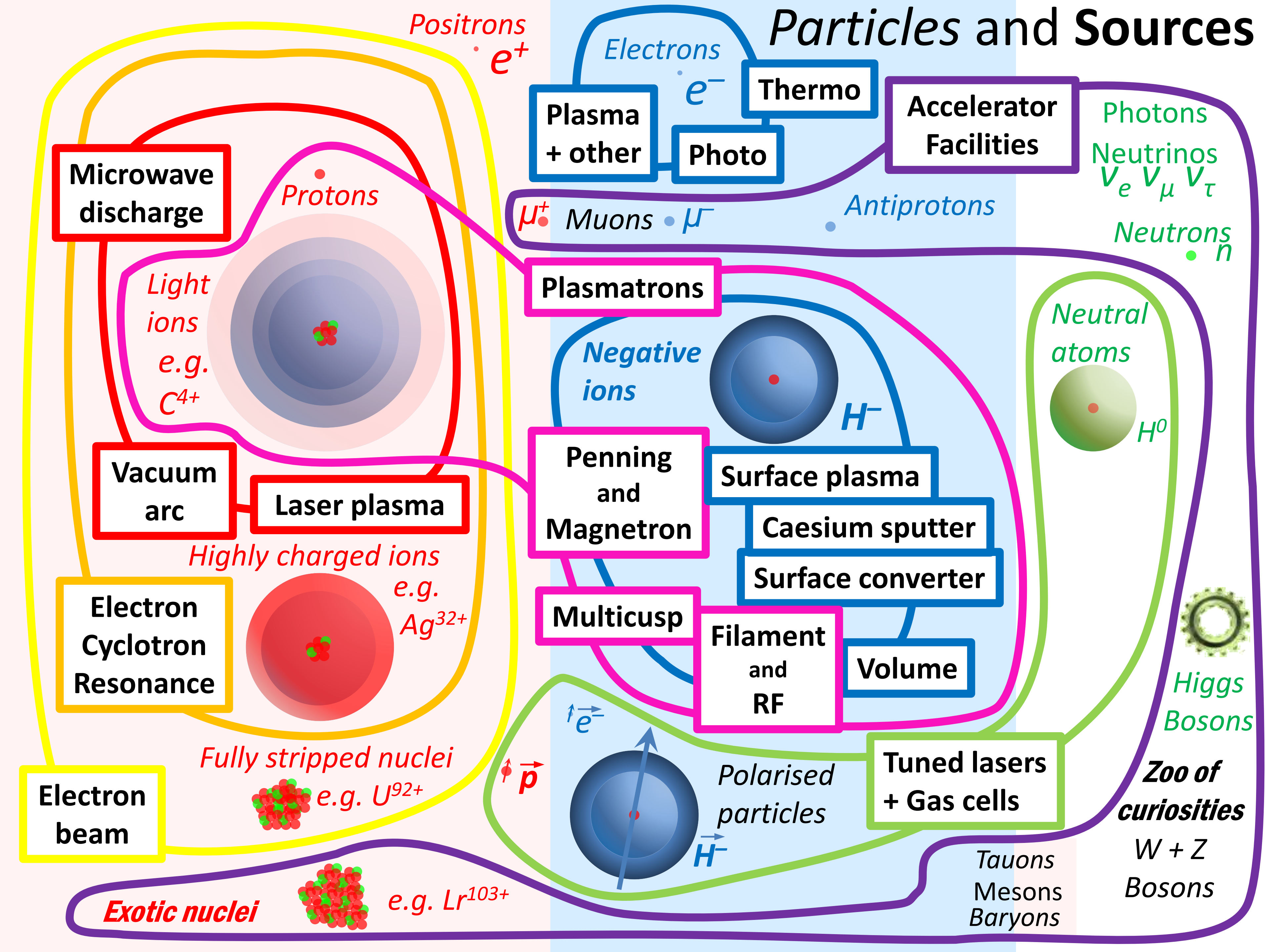
100 μA polarised e⁻

Polarised H⁻



1. High current proton source and H neutraliser cell
2. He ioniser cell
3. Laser pumped Rb-vapour cell
4. Sona-transition
5. Na jet ioniser cell

1.6 mA 400 μs polarised H⁻


Particles and Sources
Positrons
e+
Electrons
e−
Plasma + other
Thermo
Photo
Accelerator Facilities
Photons
Neutrinos
νe νμ ντ
μ+
Muons
μ−
Antiprotons
Neutrons
n
Microwave discharge
Protons
Light ions e.g. C4+
Plasmatrons
Negative ions
H−
Neutral atoms
H0
Vacuum arc
Laser plasma
Penning and Magnetron
Surface plasma
Caesium sputter
Surface converter
Highly charged ions
e.g. Ag32+
Electron Cyclotron Resonance
Multicusp
Filament and RF
Volume
Higgs Bosons
e−
p
Polarised particles
H−
Tuned lasers + Gas cells
Fully stripped nuclei
e.g. U92+
Electron beam
Zoo of curiosities
W + Z Bosons
Tauons
Mesons
Baryons
Exotic nuclei
e.g. Lr103+

Which Source?

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

Reliability


24
open
7


WE
NEVER
CLOSE

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

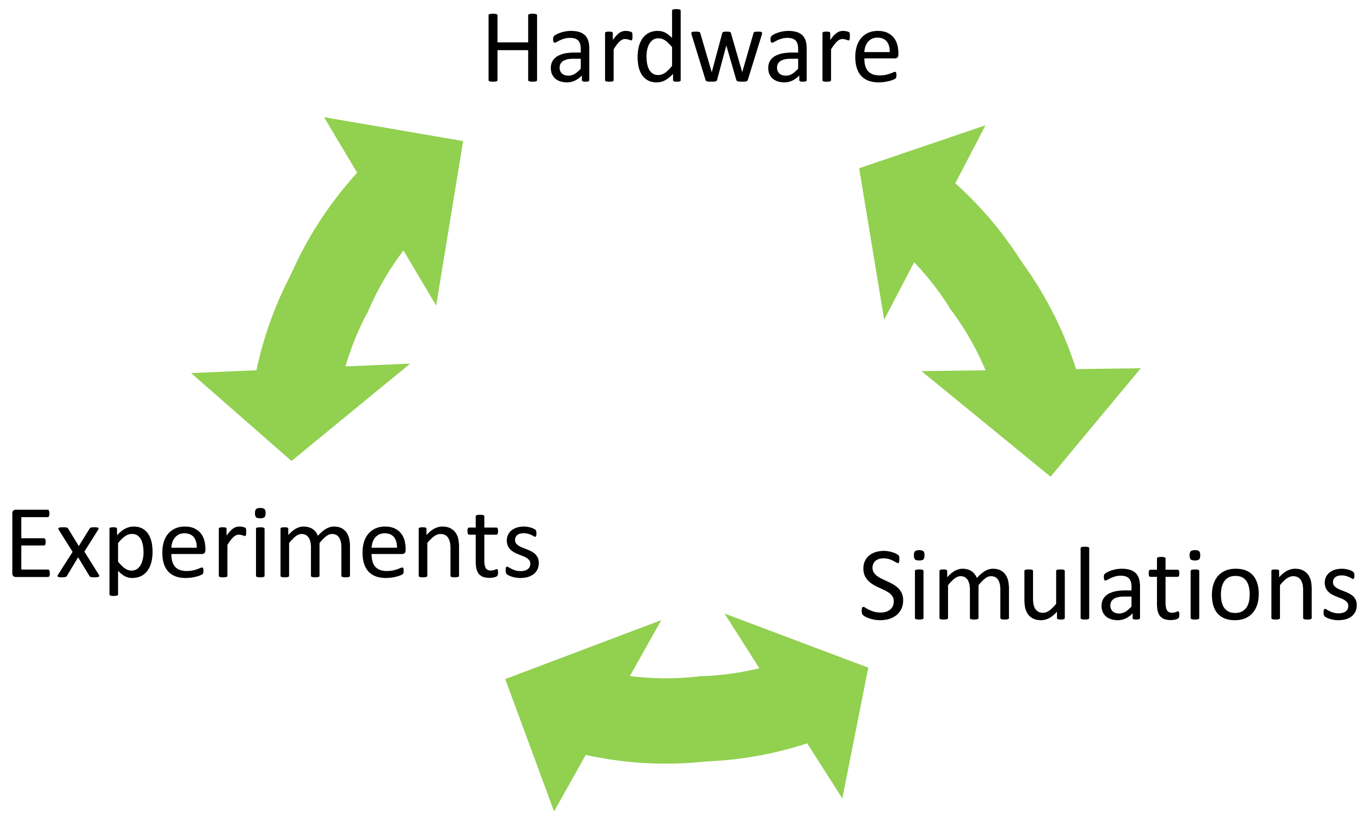
Development strategy

- Simulations
- Test stands
- Diagnostics

Diagnostics for Developing Sources

- **Beam current** e.g. toroids, faraday cups.
- **Emittance** e.g. slit-grid, pepperpot, slit-slit, Alison electric sweep scanner.
- **Profile** e.g. scintillator, wire scanner, laser wire scanner.
- **Energy spread** e.g. retarding potential energy analyser.
- **Species analyses** e.g. dipole sector magnet, Wein filter
- **Plasma diagnostics** e.g. optical, Langmuir probes

The Development Cycle



Summary

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

Thank you for listening