Particle Sources

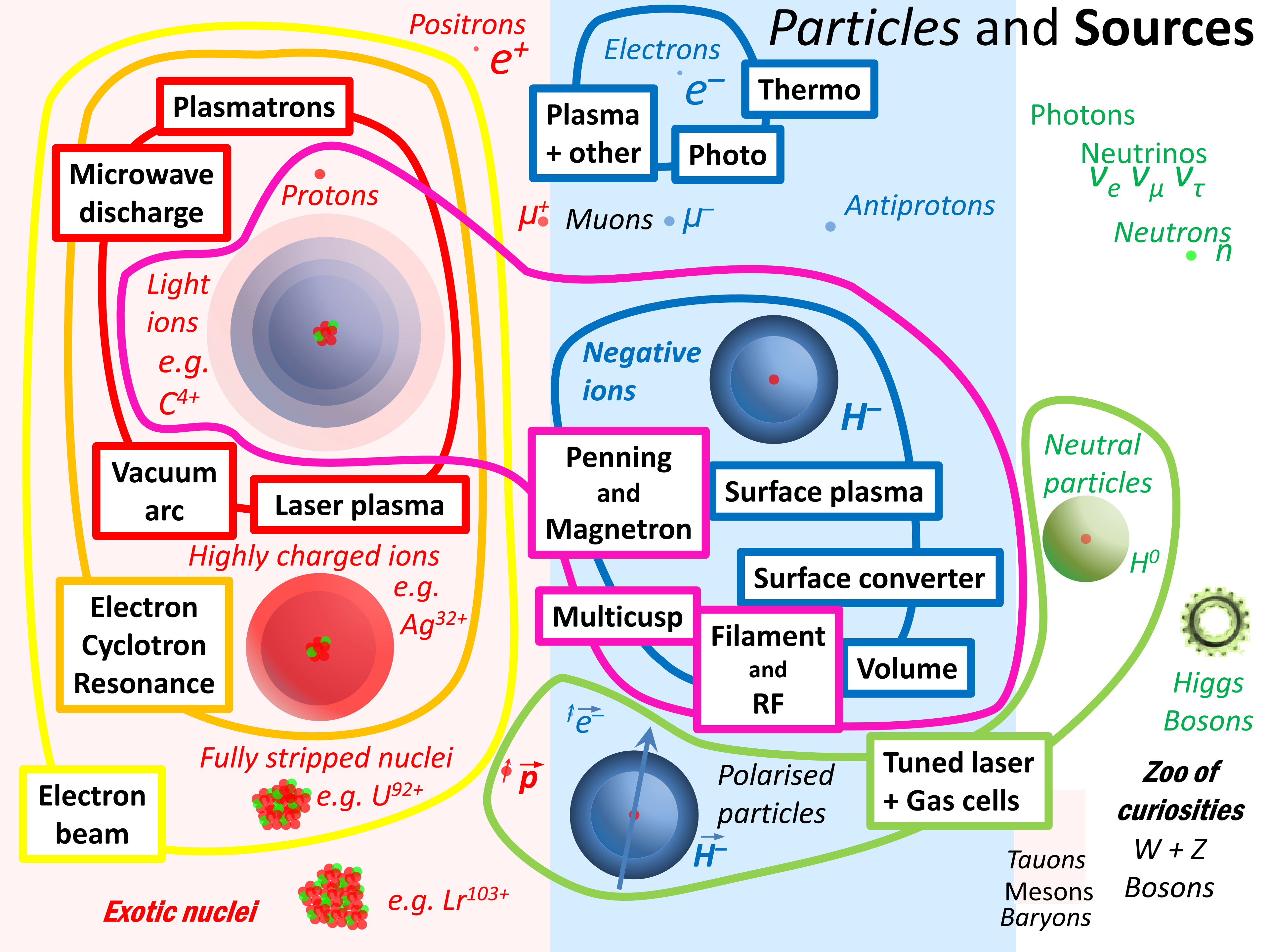
Dan Faircloth

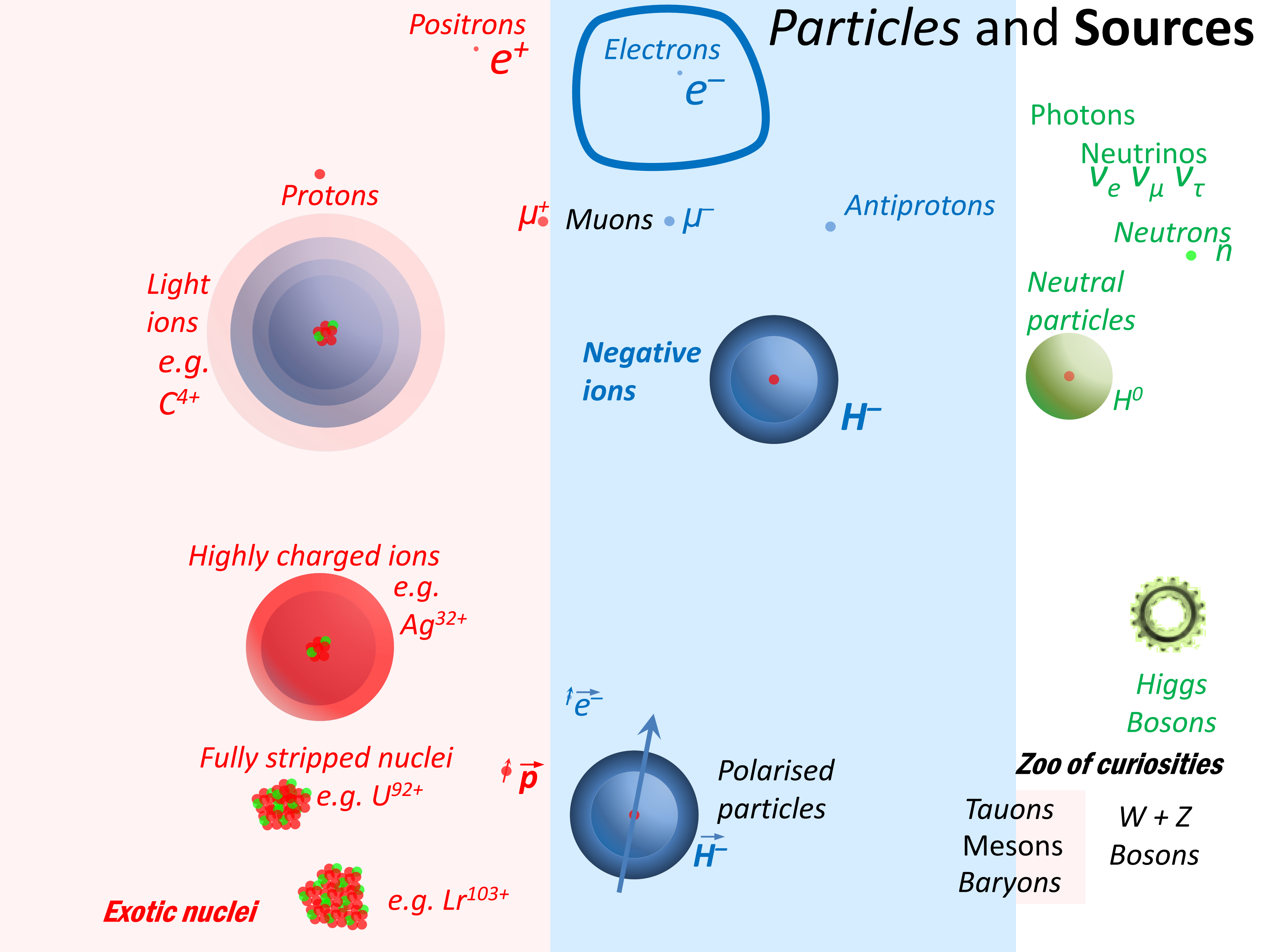
Rutherford Appleton Laboratory

CERN Accelerator School

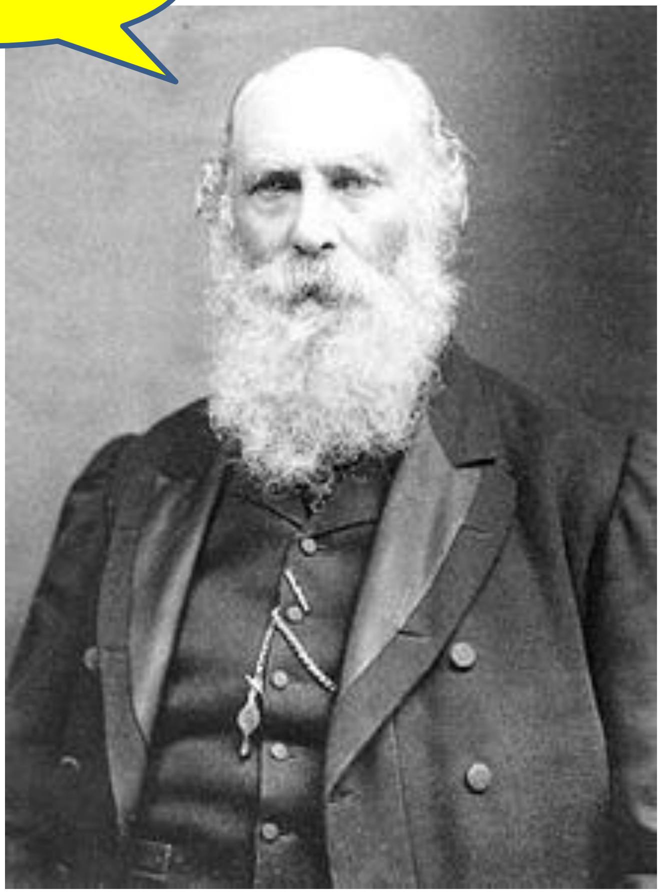
27 September 2018

Particles and **Sources**




Particles and Sources
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+}
Neutral particles
Negative ions
H^-
H^0
Highly charged ions
e.g. Ag^{32+}
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+}

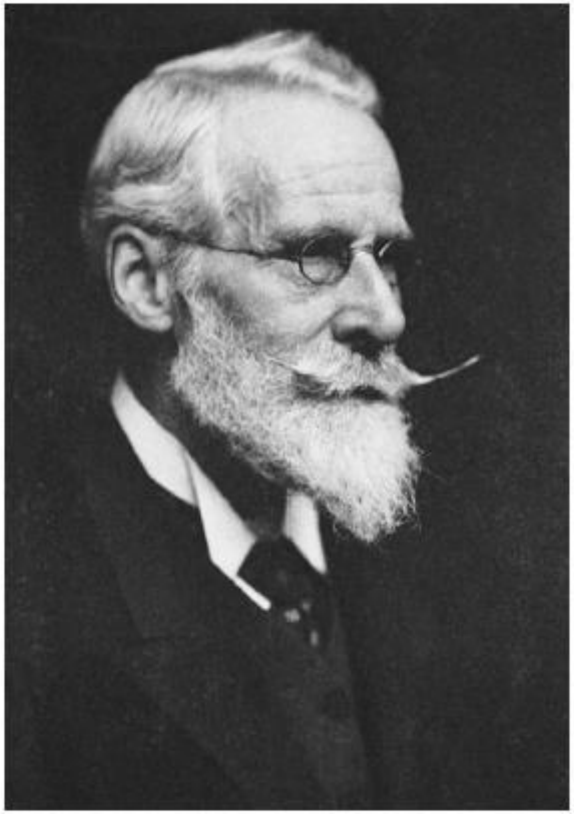
The Electron!

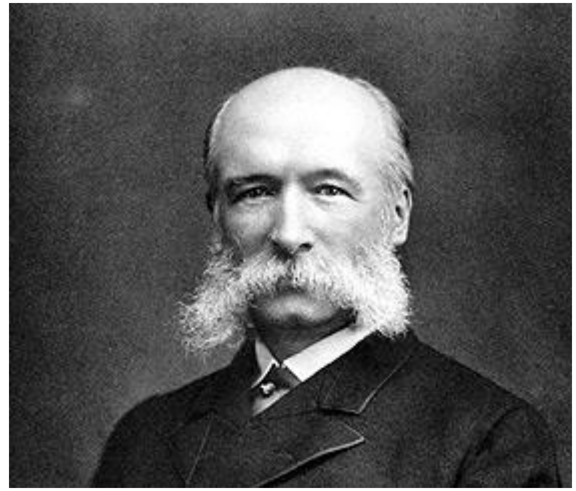


George Johnstone Stoney
1894

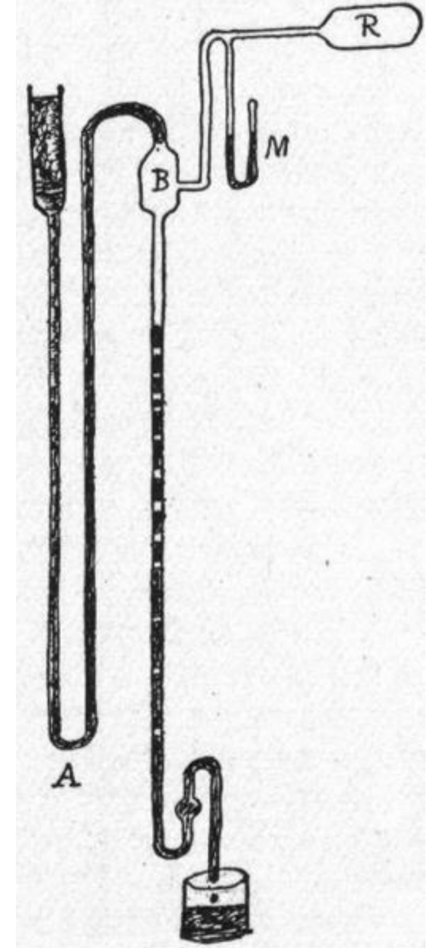
J. J. Thomson
1897

Early 1870's

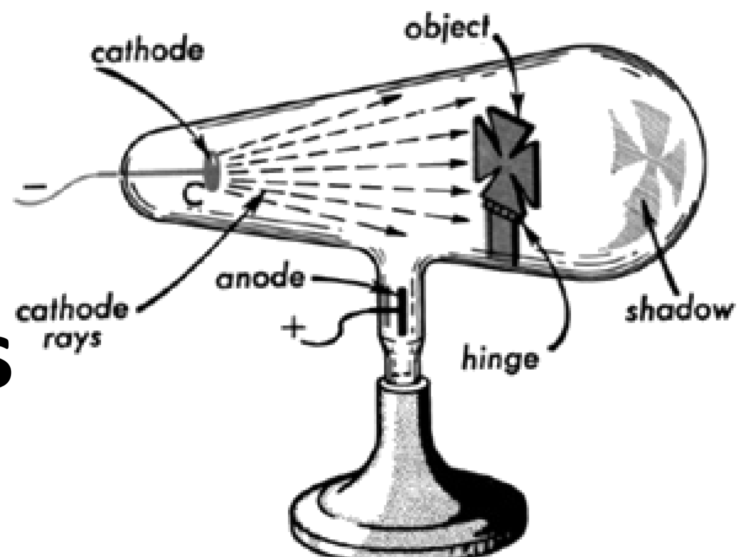




Hermann Sprengel

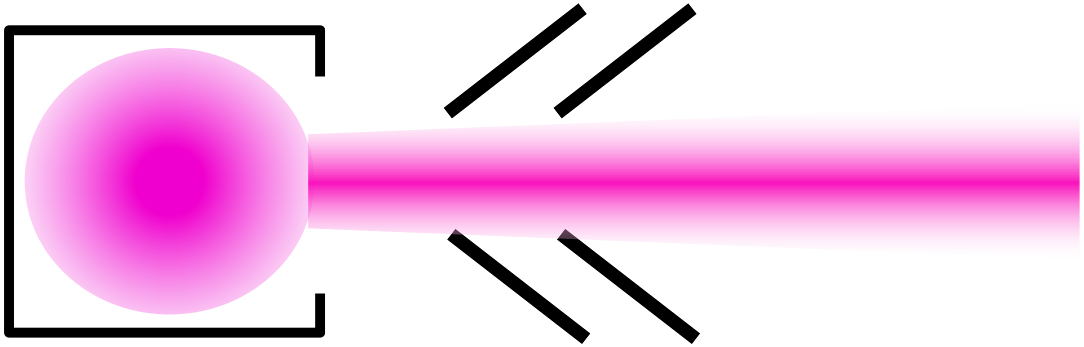


Improved mercury pump 10^{-5} mBar



William Crookes

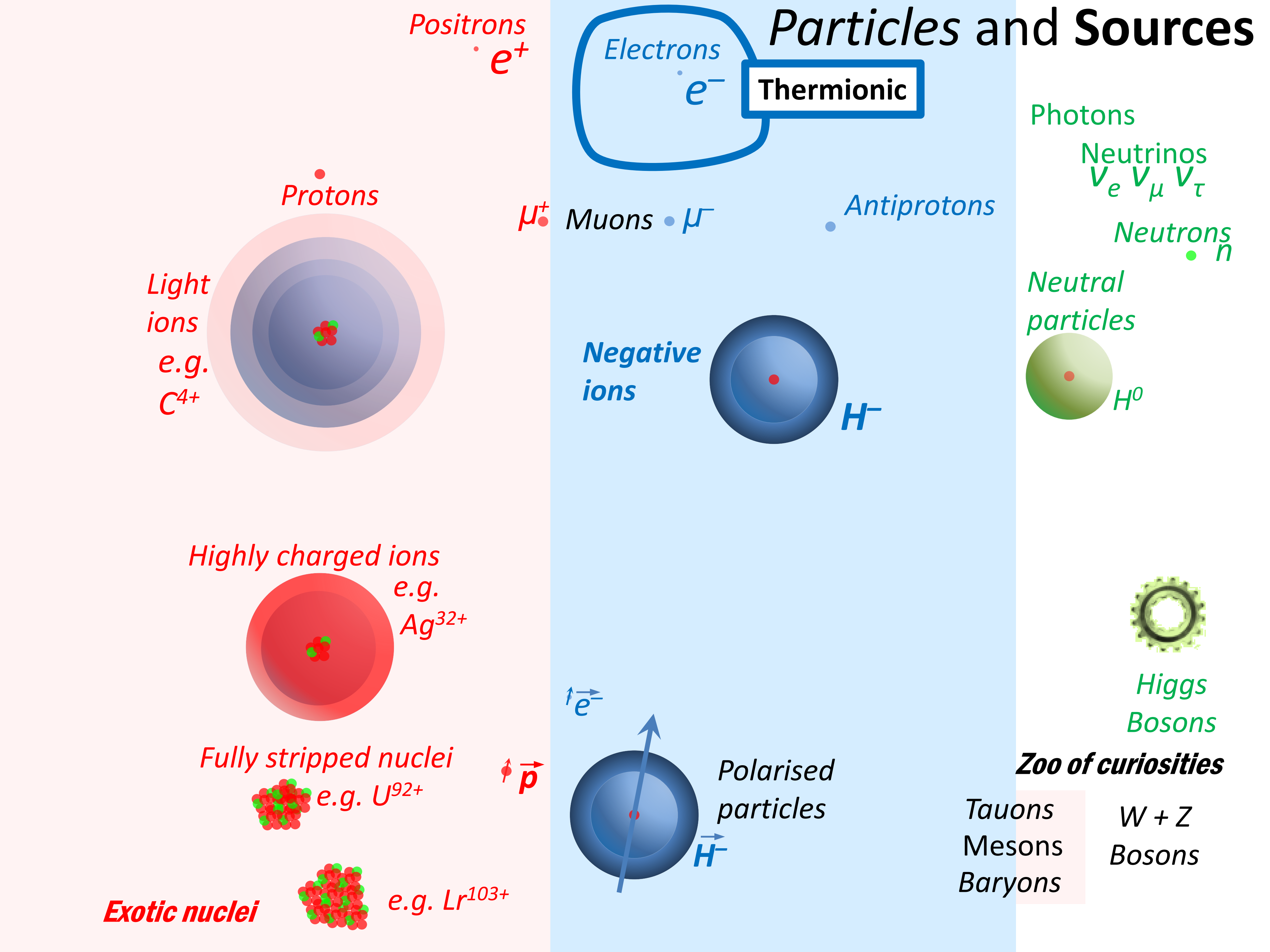
Particle sources/guns generally consist of:



Something to make the particles

+

An extraction system to shape and accelerate a beam



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e+
Electrons
e−
Thermionic
Photons
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νe νμ ντ
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p
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Polarised particles
H−
Zoo of curiosities
Tauons
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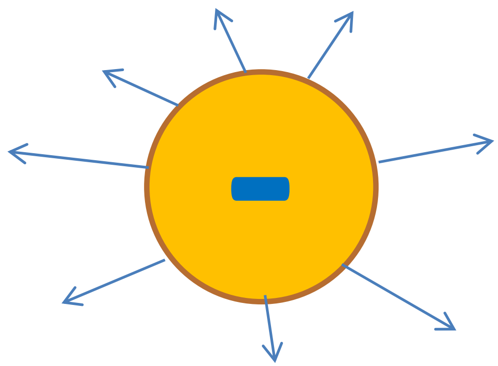
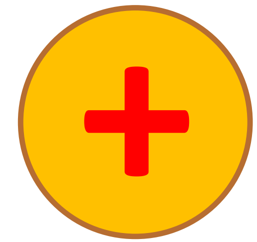
Baryons
W + Z Bosons
Exotic nuclei
e.g. Lr103+

Fredrick Guthrie

British scientific writer and professor



A red hot metal ball looses negative charge...

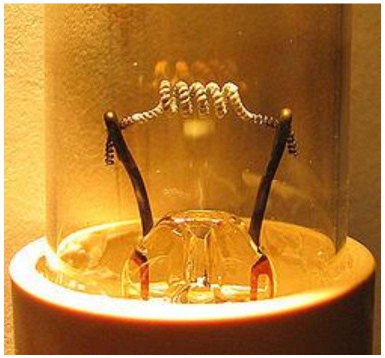


...whereas a positively charged one keeps its charge

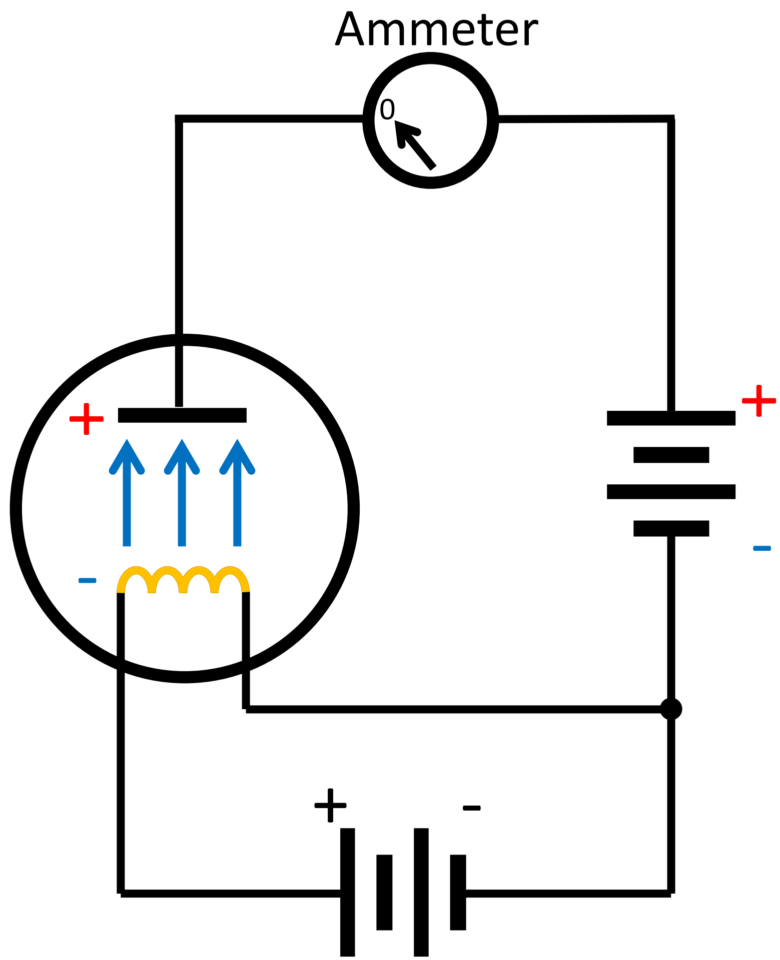
Elements of Heat in 1868

First experimental observation of thermionic emission

Thermionic Emission



1880 Thomas Edison



The “Edison effect”

Thermionic Emission

Corpuscles

J. J. Thomson
1897

1901 Owen Richardson

Cambridge University

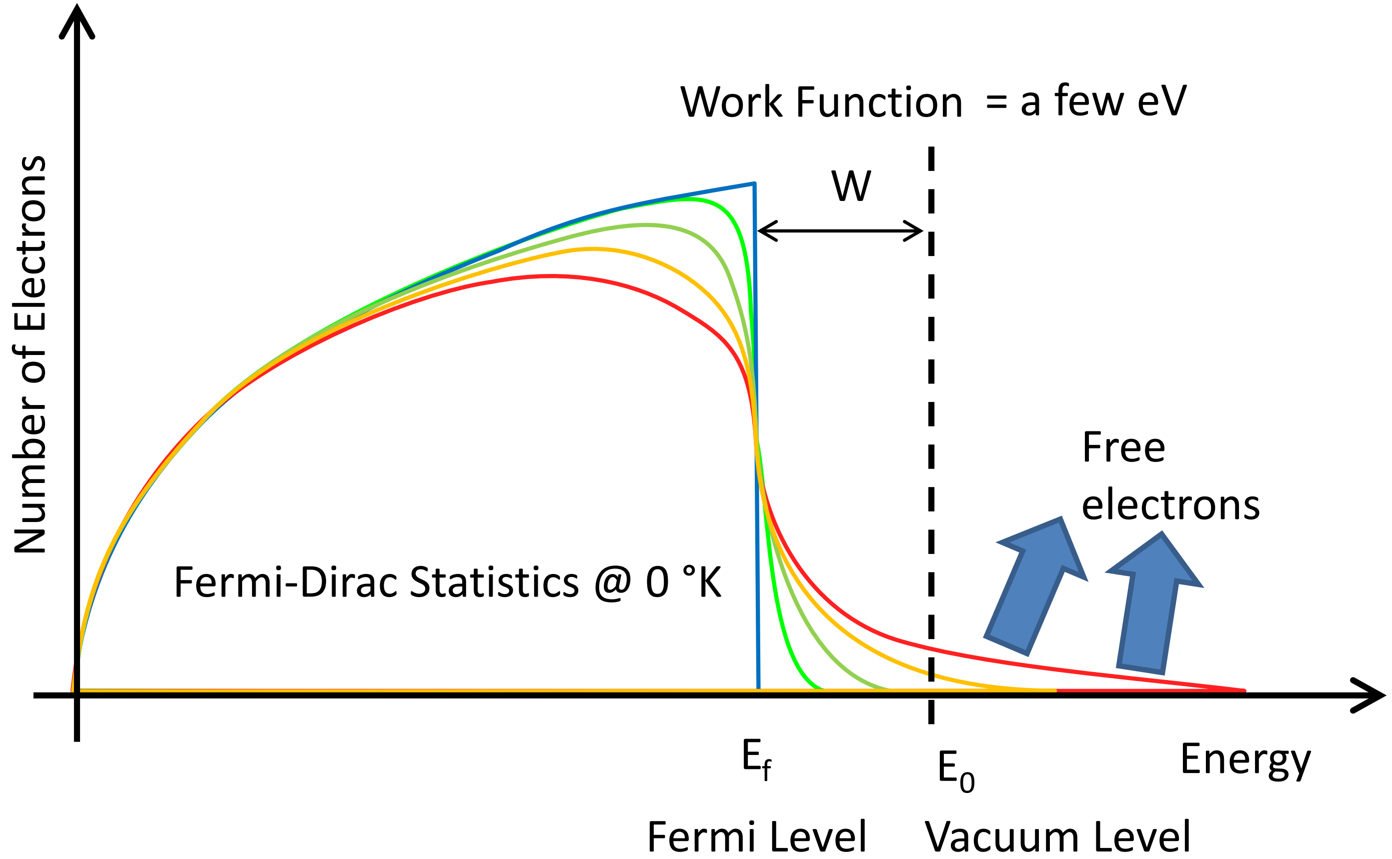
$$J = A_G T^2 e^{\frac{-W}{kT}}$$

Richardson's Law

Same form as the Arrhenius equation

Current increases exponentially with temperature

Thermionic Emission



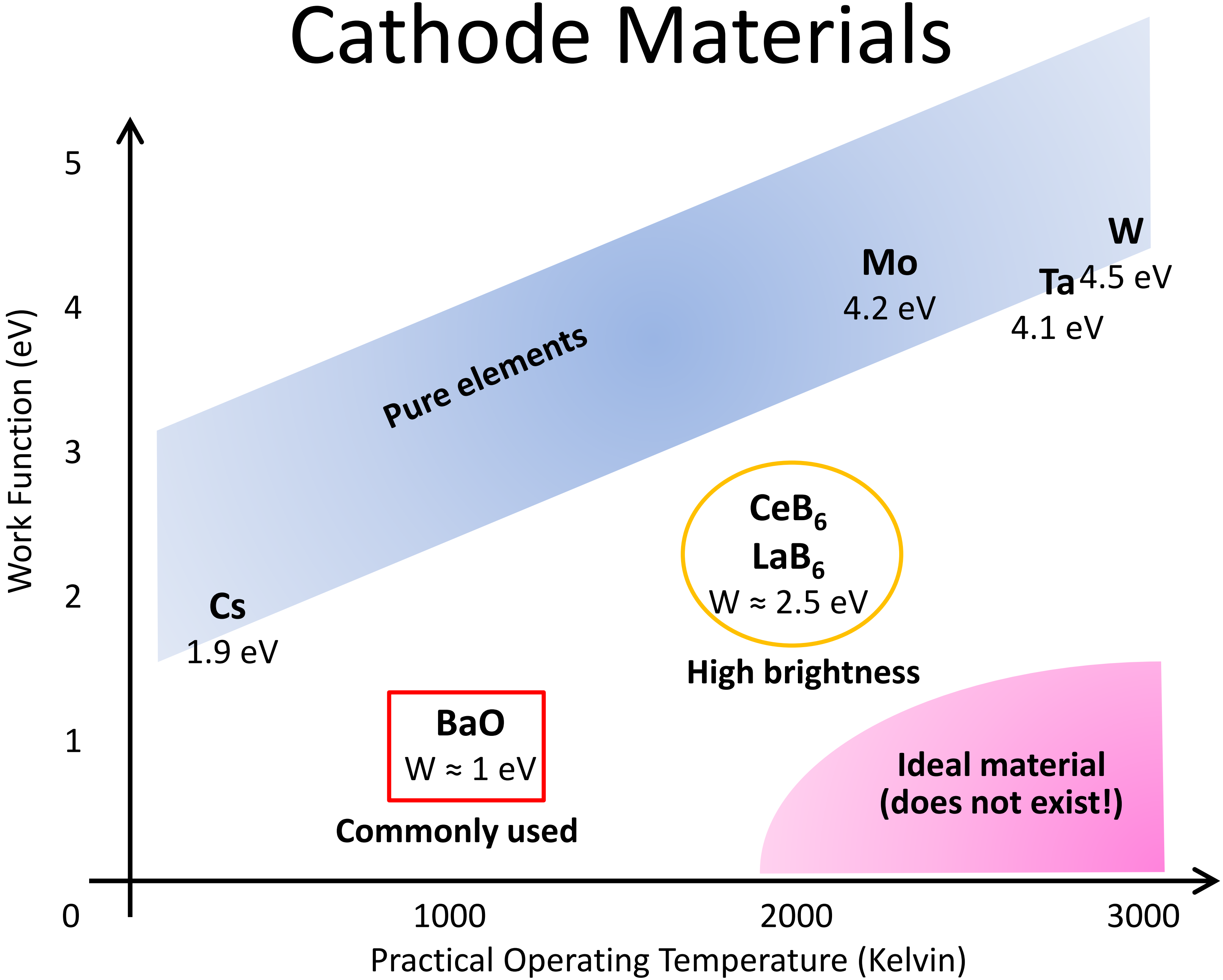
$$J = A_G T^2 e^{\frac{-W}{kT}}$$

For a good electron emitter you need:

Lowest possible work function

Highest possible temperature

Cathode Materials

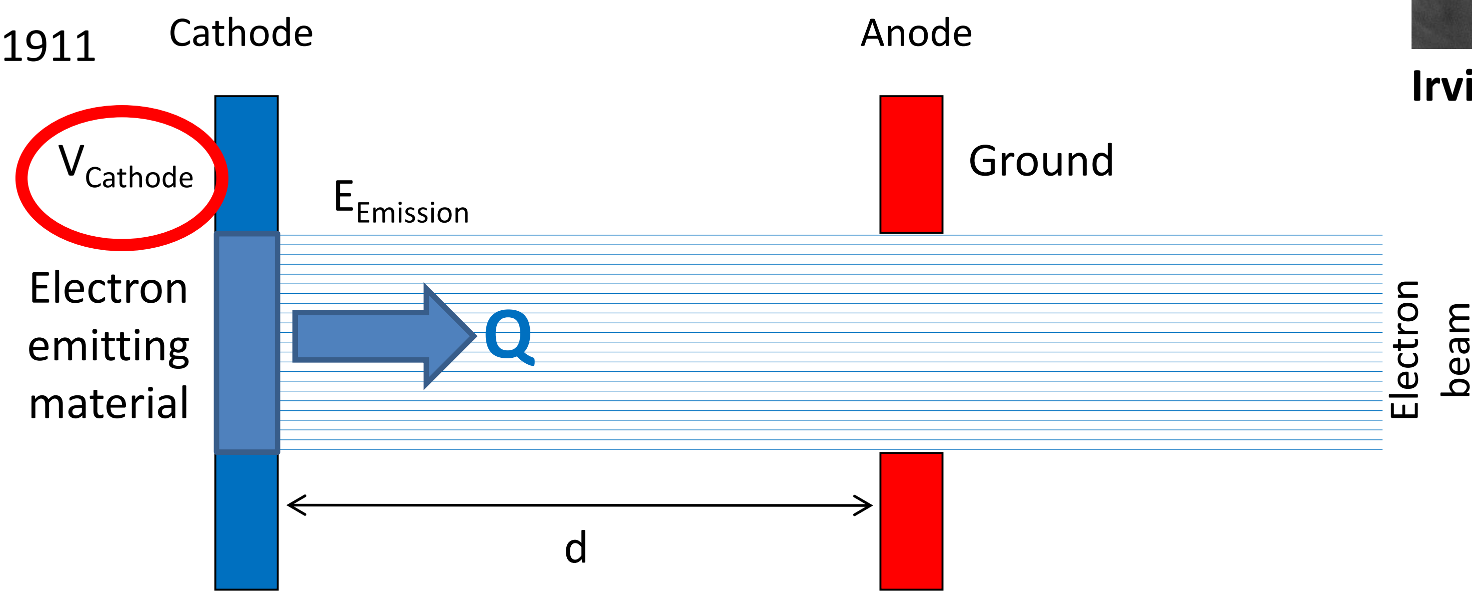


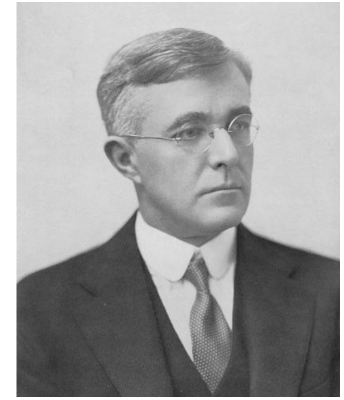
Child-Langmuir Law

(Space charge limited extraction)

C.D Child

1911





Irving Langmuir

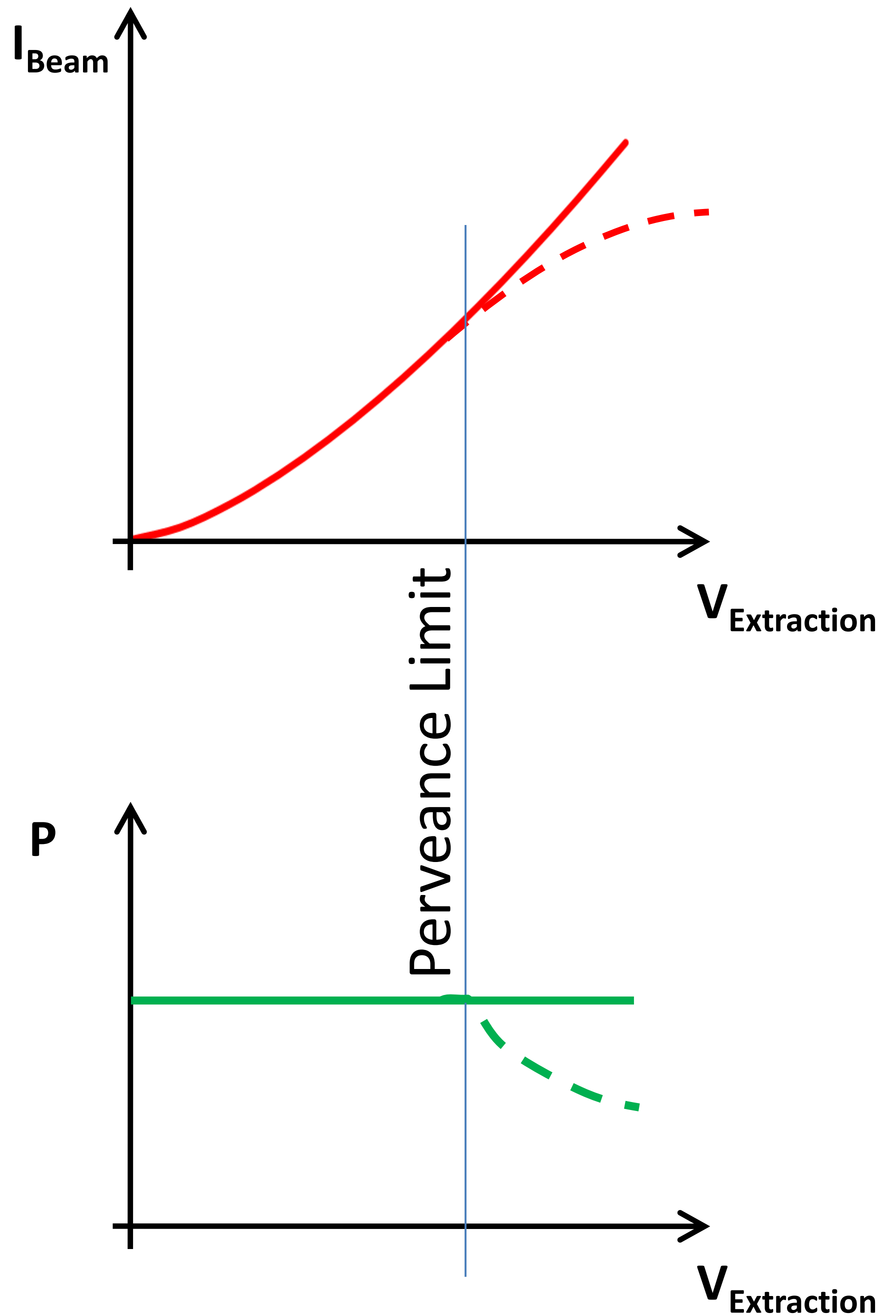
1913

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

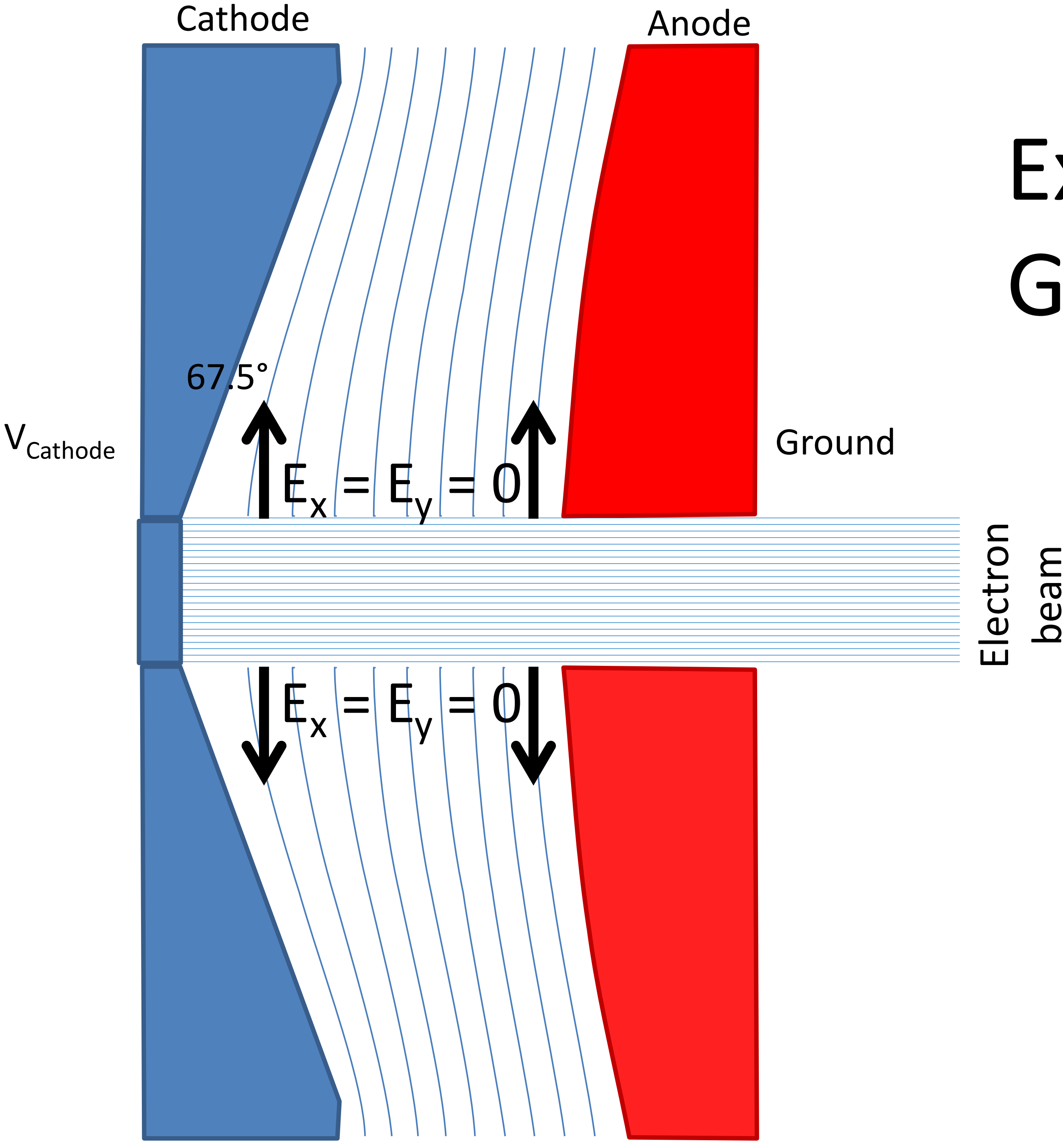
$$I \propto V^{\frac{3}{2}}$$

Perveance

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

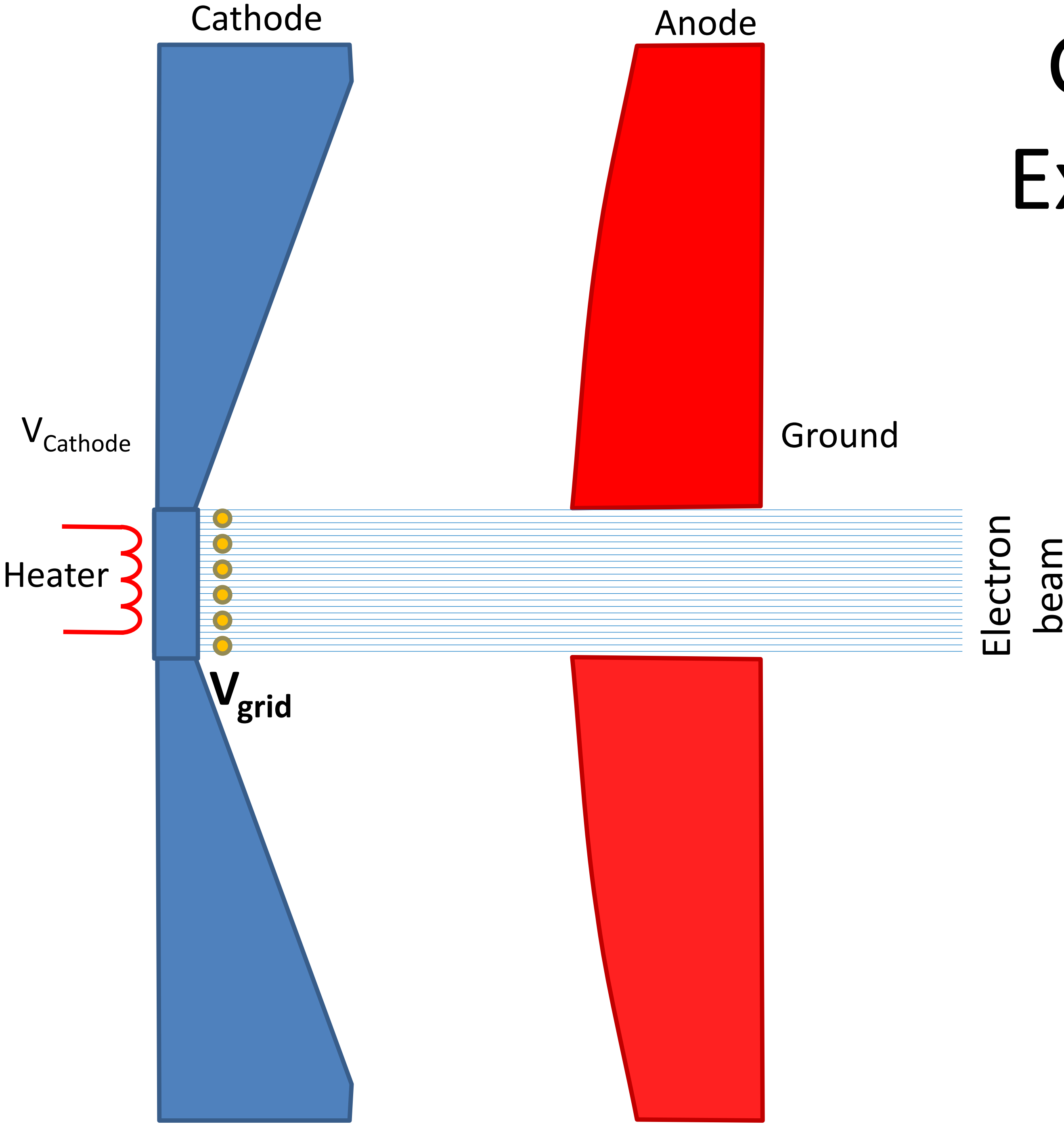


Pierce Extraction Geometry



Gridded Extraction

(A triode amplifier)



CPI Communications & Power Industries

Eimac

YU 171

Thermionic dispenser cathode with integrated heater and grid

Sinter of W and BaO

$1 cm^2$
12 W heater

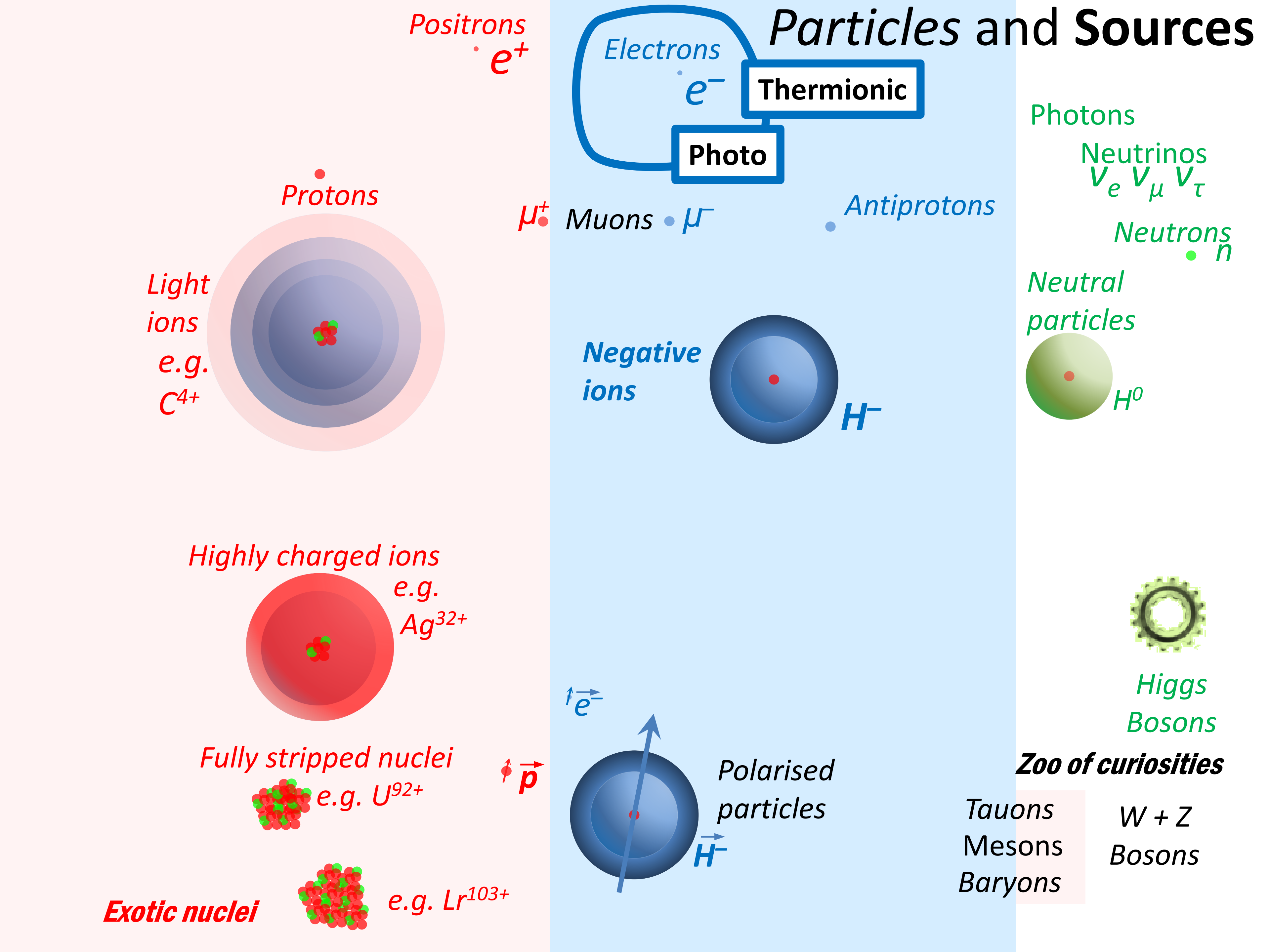
diamond

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



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C4+
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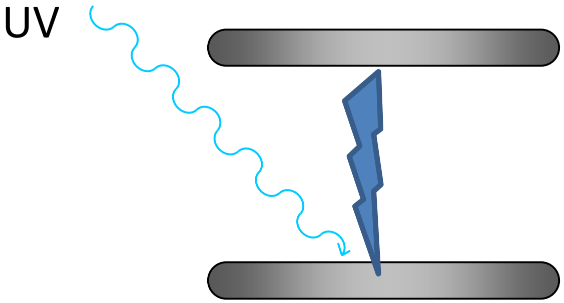
H0
Highly charged ions
e.g.
Ag32+
Higgs
Bosons
Polarised
particles
Fully stripped nuclei
e.g. U92+
p
Zoo of curiosities
Tauons
Mesons
Baryons
W + Z
Bosons
Exotic nuclei
e.g. Lr103+

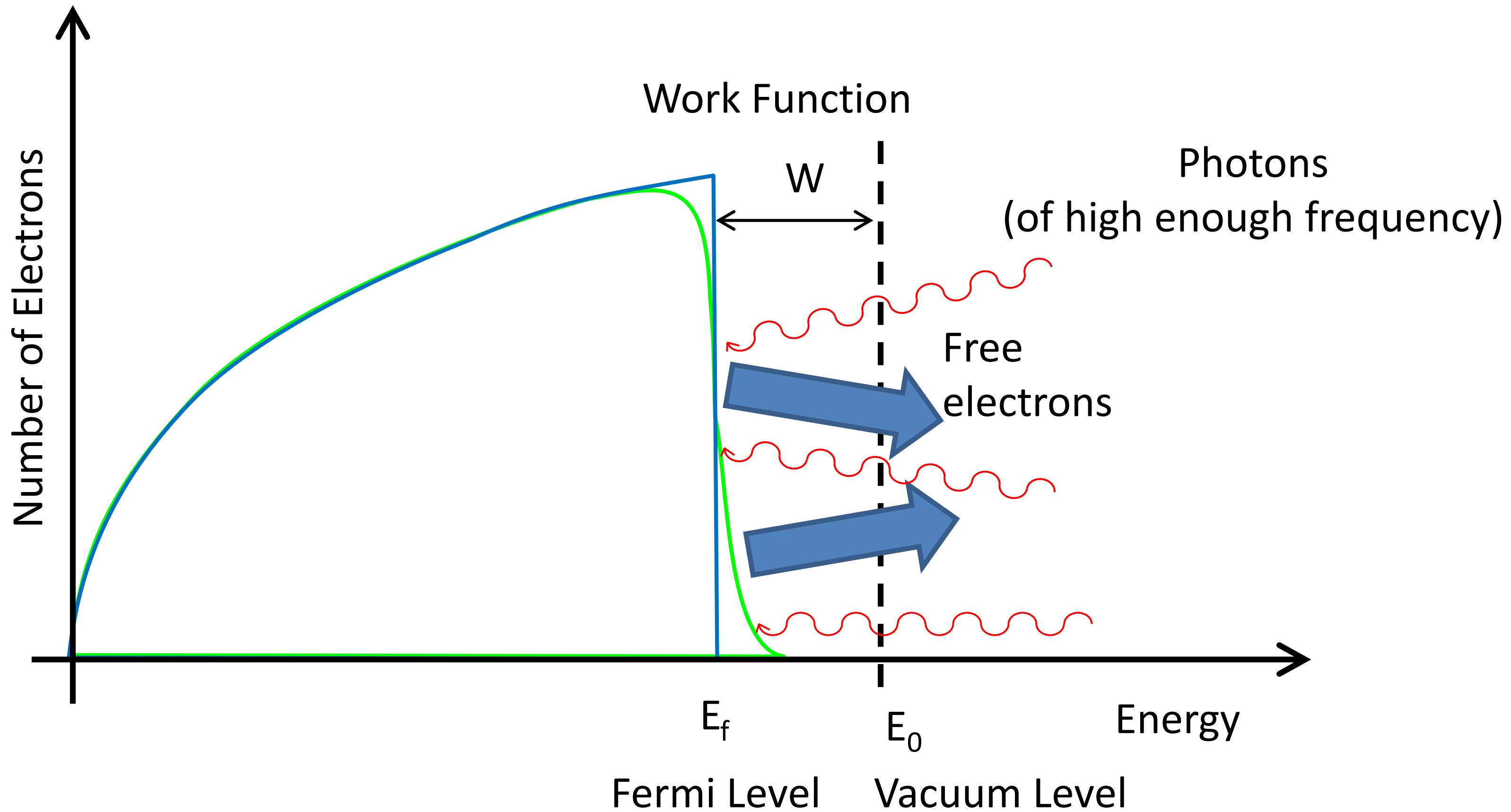
Photo Emission

First observed by Heinrich Hertz in 1887



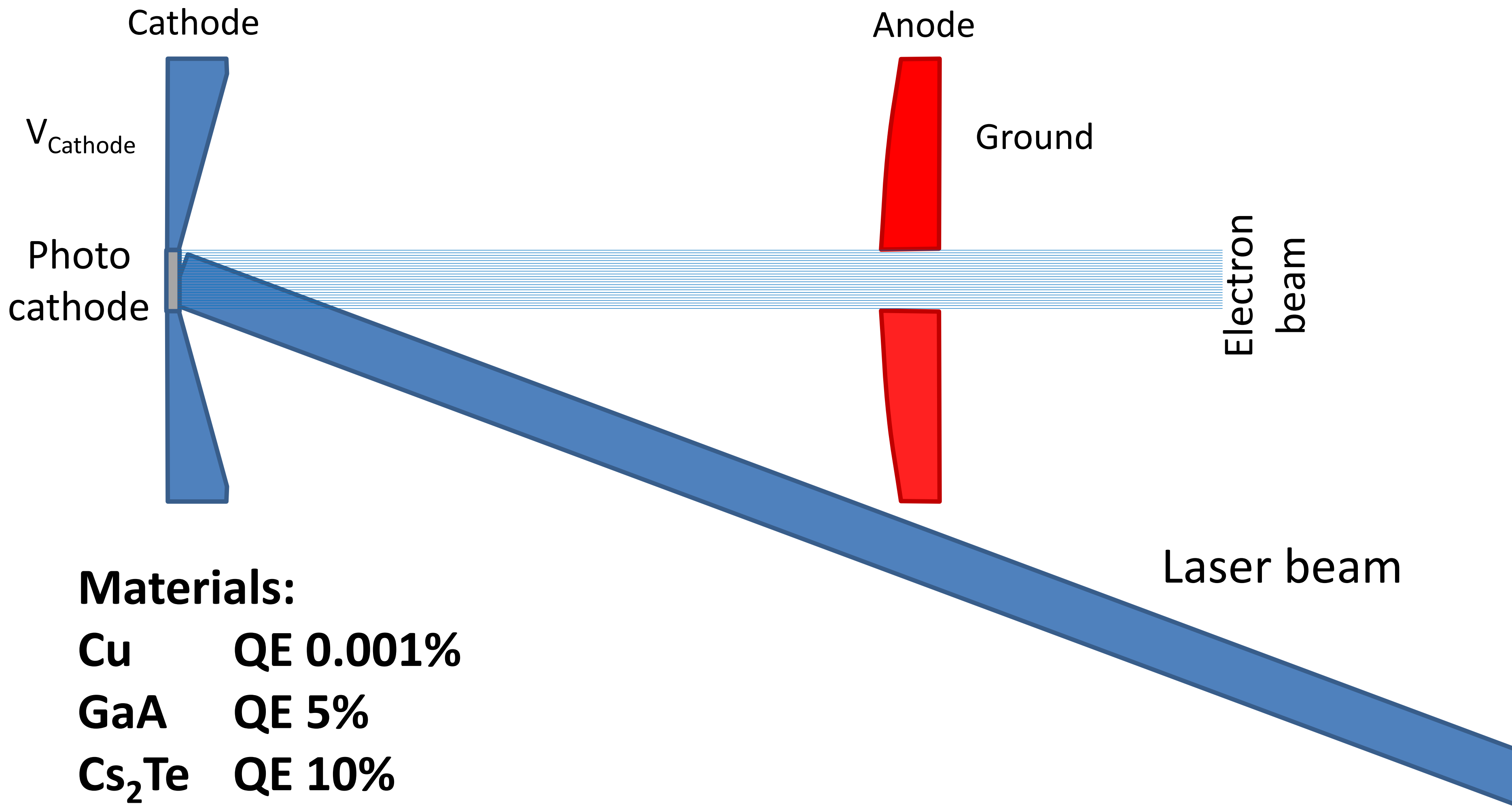
Theoretical explanation by Einstein in 1905

Photo electric emission



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

Photo Emission Gun



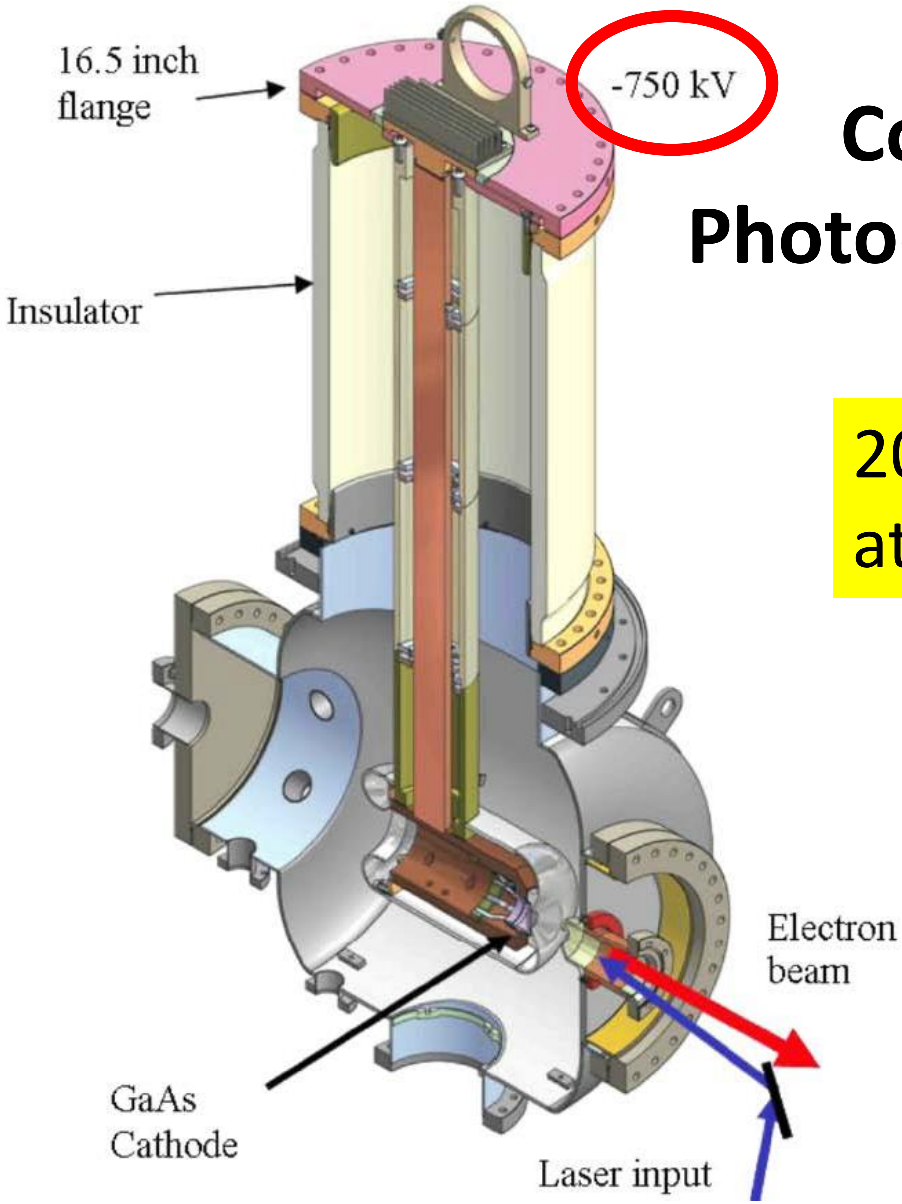
Materials:

Cu **QE 0.001%**

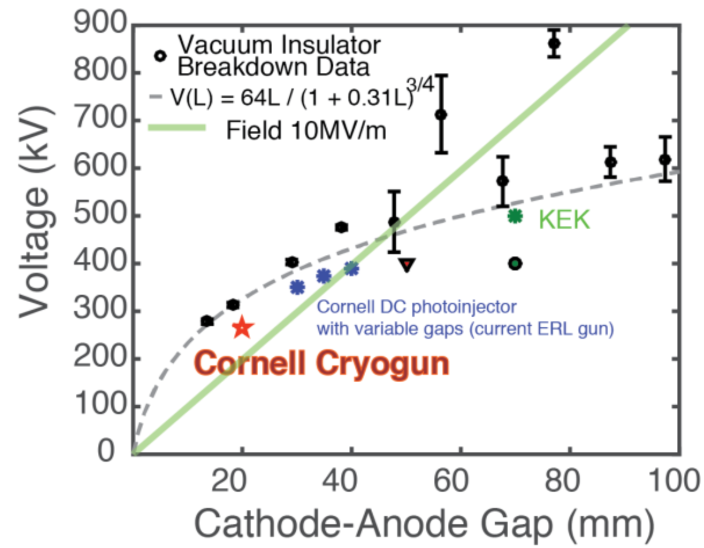
GaA **QE 5%**

Cs_2Te **QE 10%**

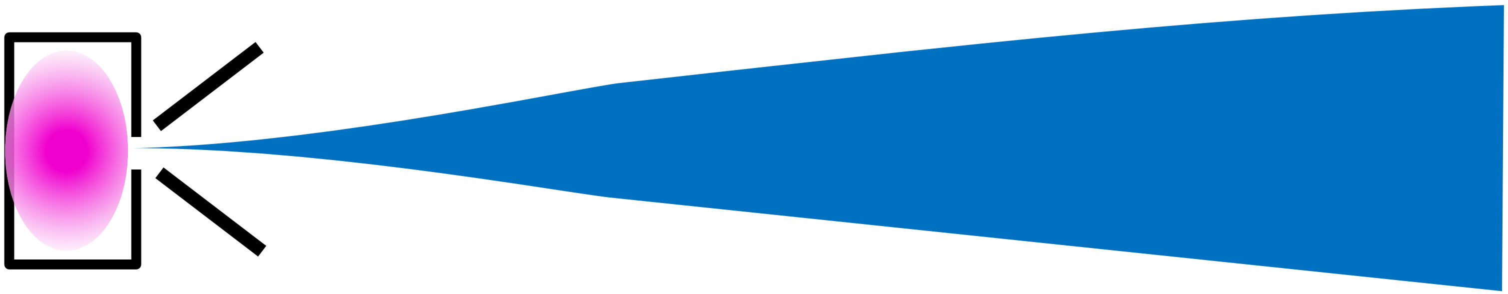
Cornell DC Photoemission gun

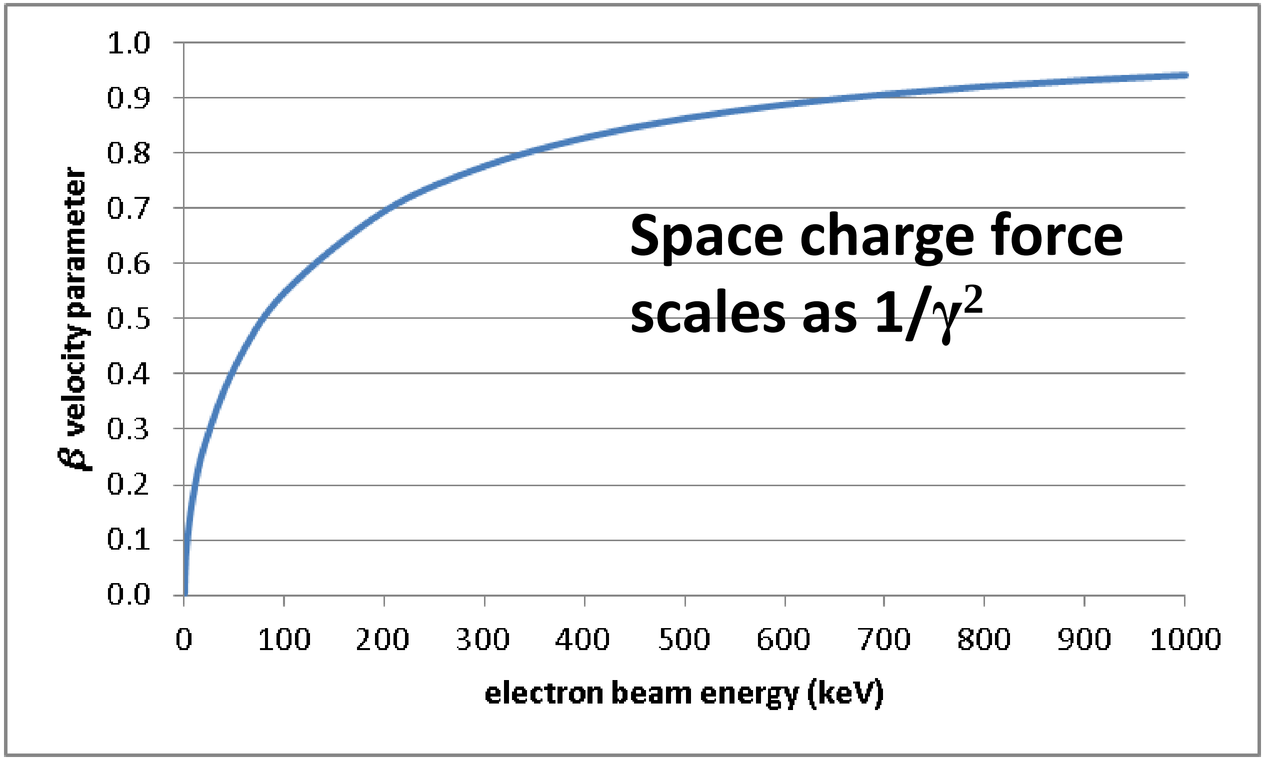


20 mA average current at 250kV



Space Charge





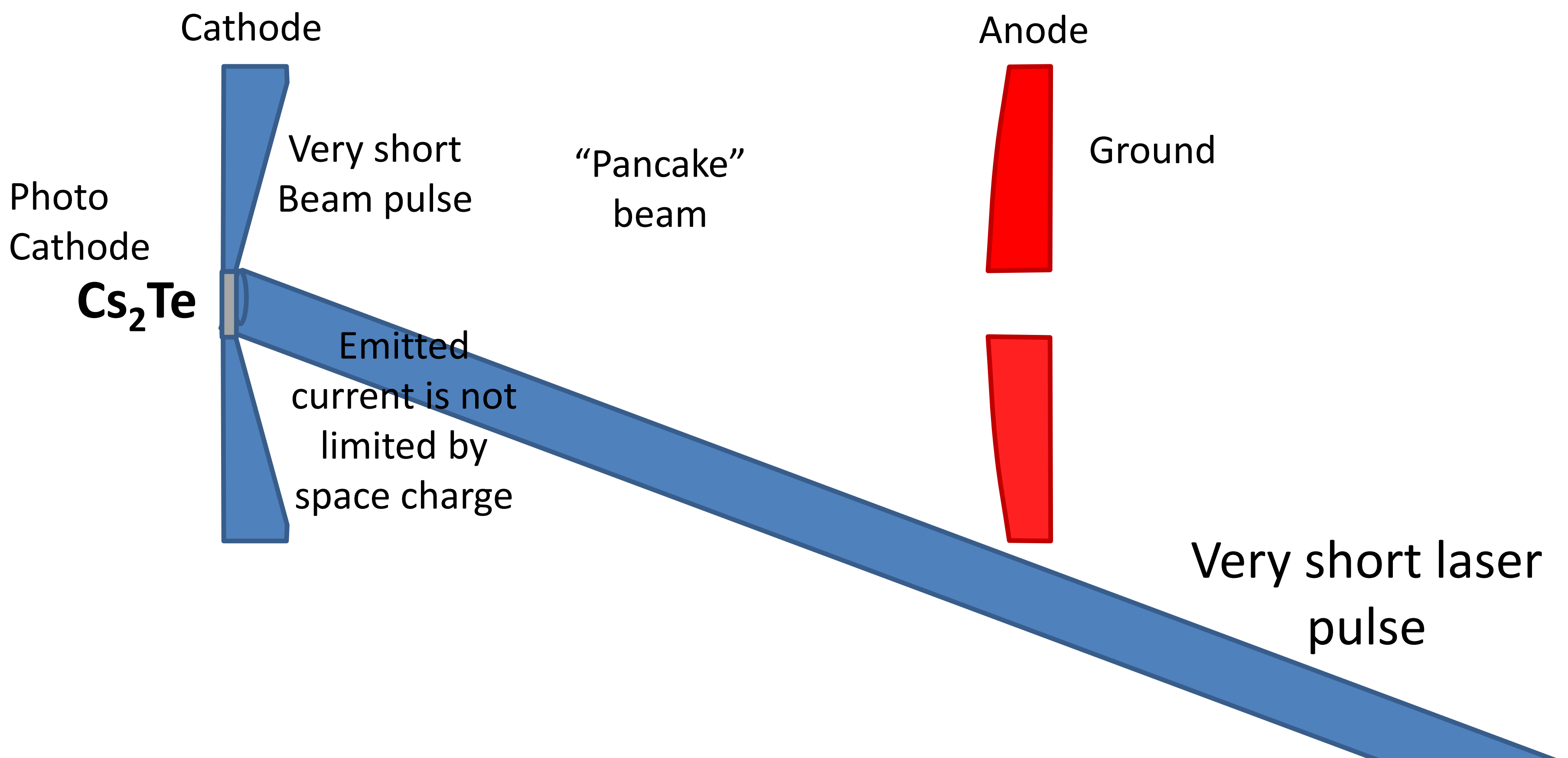
Space charge force scales as $1/\gamma^2$

At 500 keV electron $\gamma = 2$

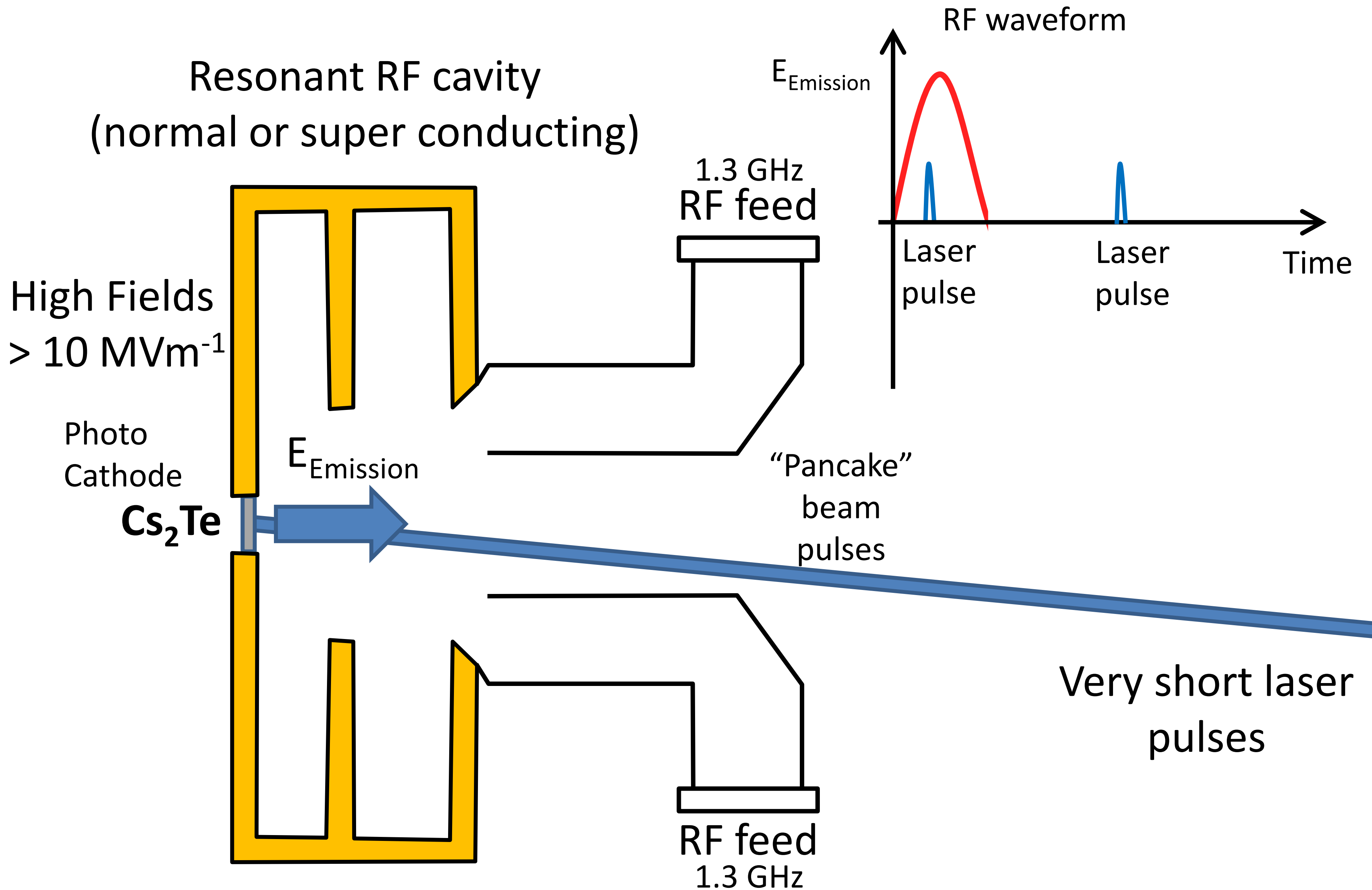
(940 MeV proton $\gamma = 2$)

Another reason to use lasers is…

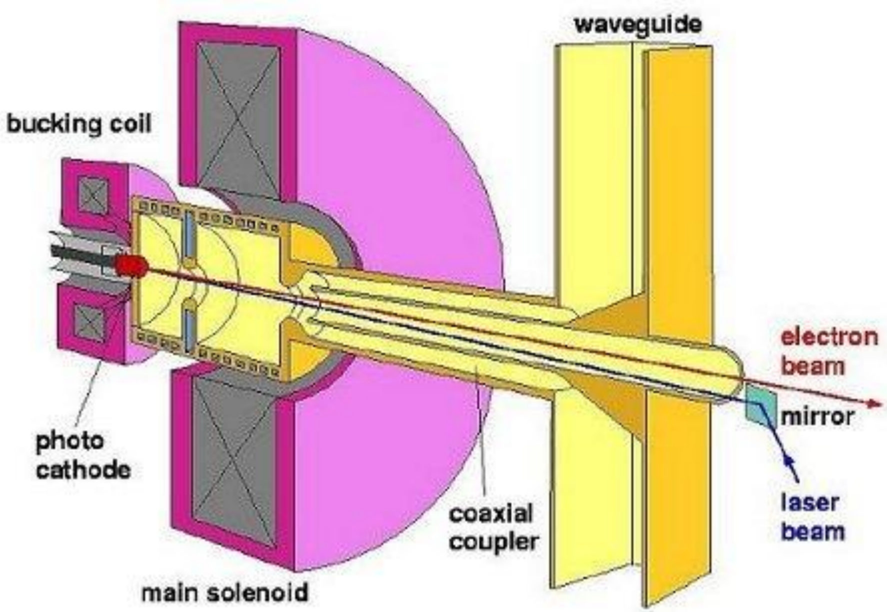
Lasers are so fast they can easily beat Child-Langmuir (to be fair, so can gridded extraction)



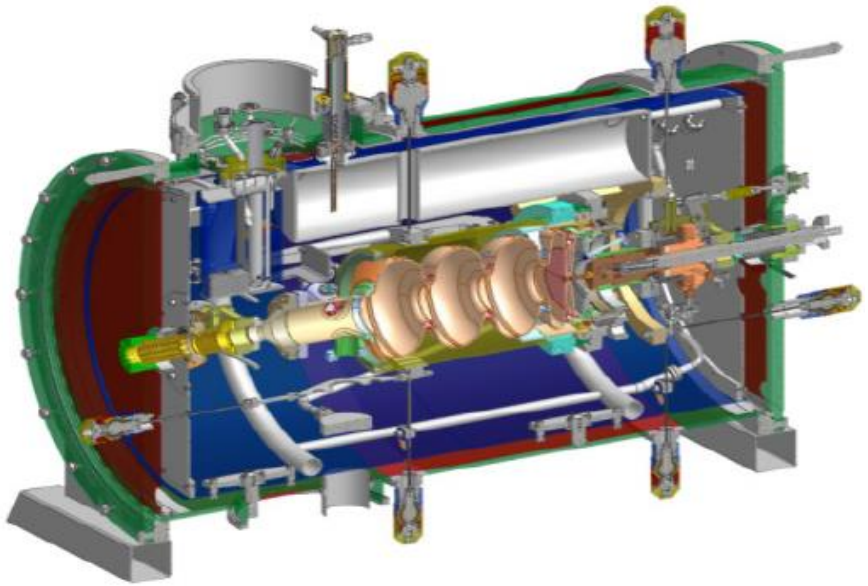
RF Photemission Source



Normally conducting



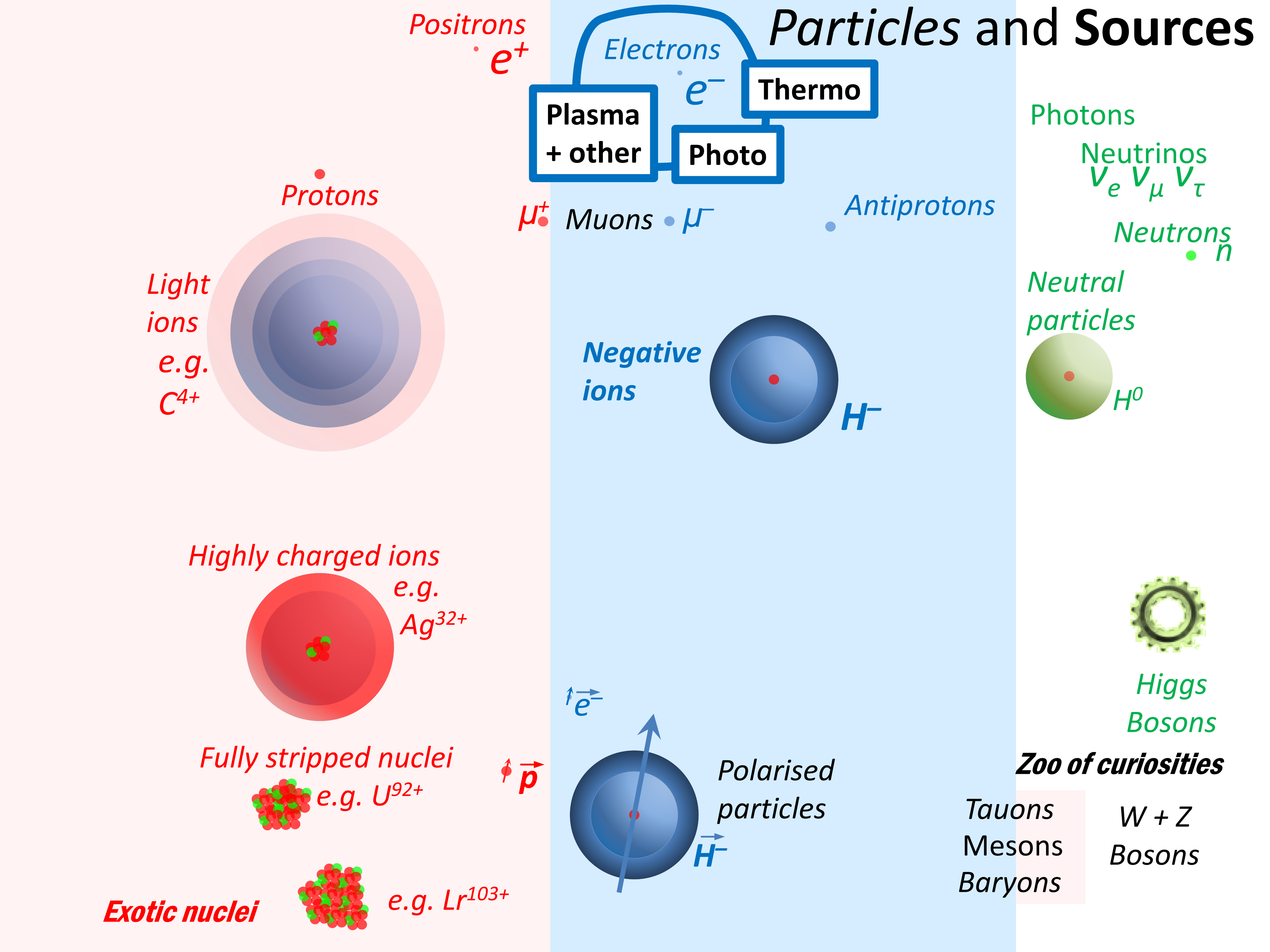
Super conducting



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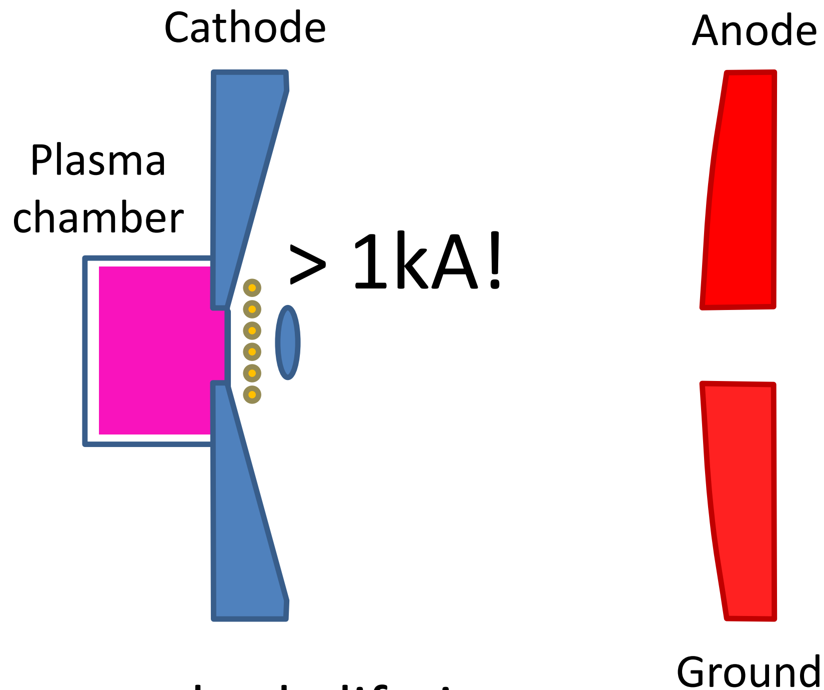
Neutral particles
H0
Highly charged ions
e.g. Ag32+
Higgs Bosons
Fully stripped nuclei
e.g. U92+
p
e−
Polarised particles
H−
Zoo of curiosities
Tauons
Mesons
Baryons
W + Z Bosons
Exotic nuclei
e.g. Lr103+

Plasma Cathode

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



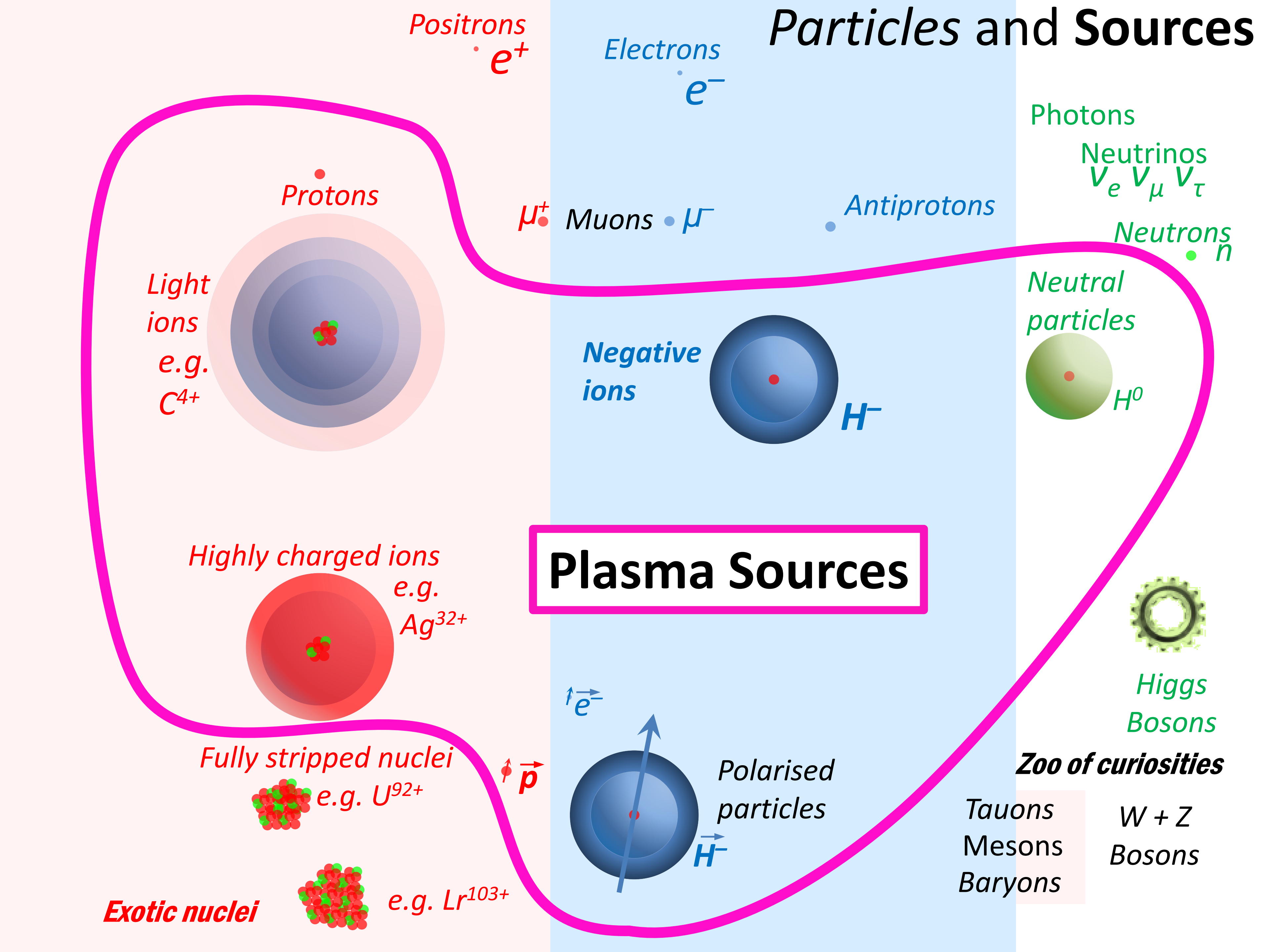
Long cathode lifetimes

Other electron sources:

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

Rarely used in accelerators:

Field emission from needle arrays
Diamond amplifiers
Etc...



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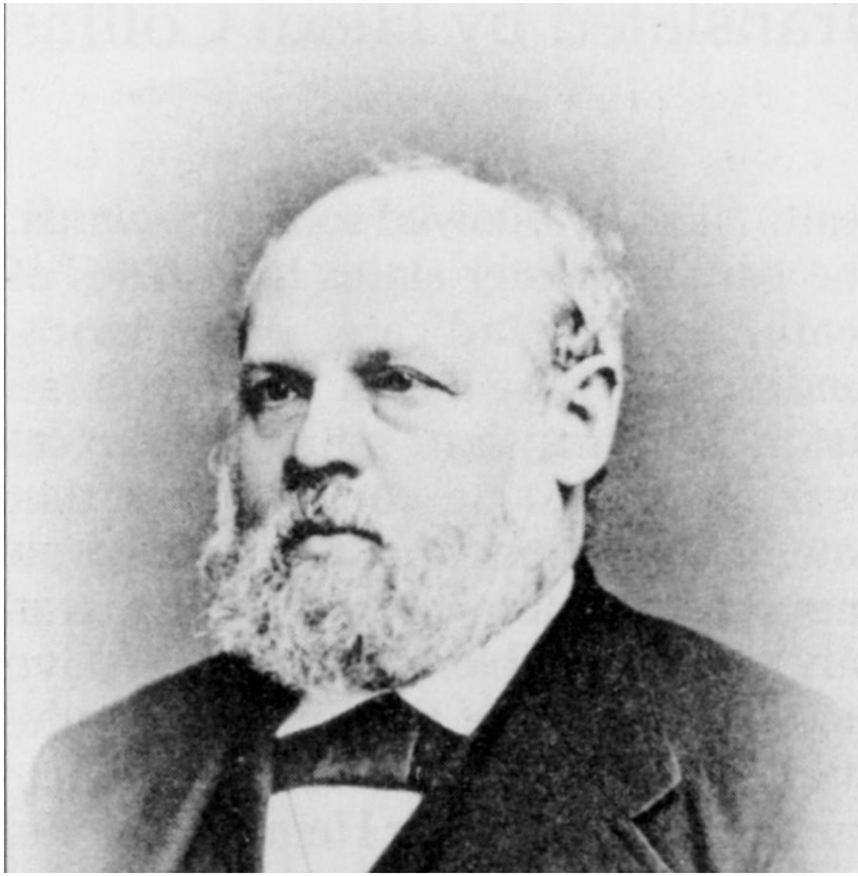
Plasma Pioneers



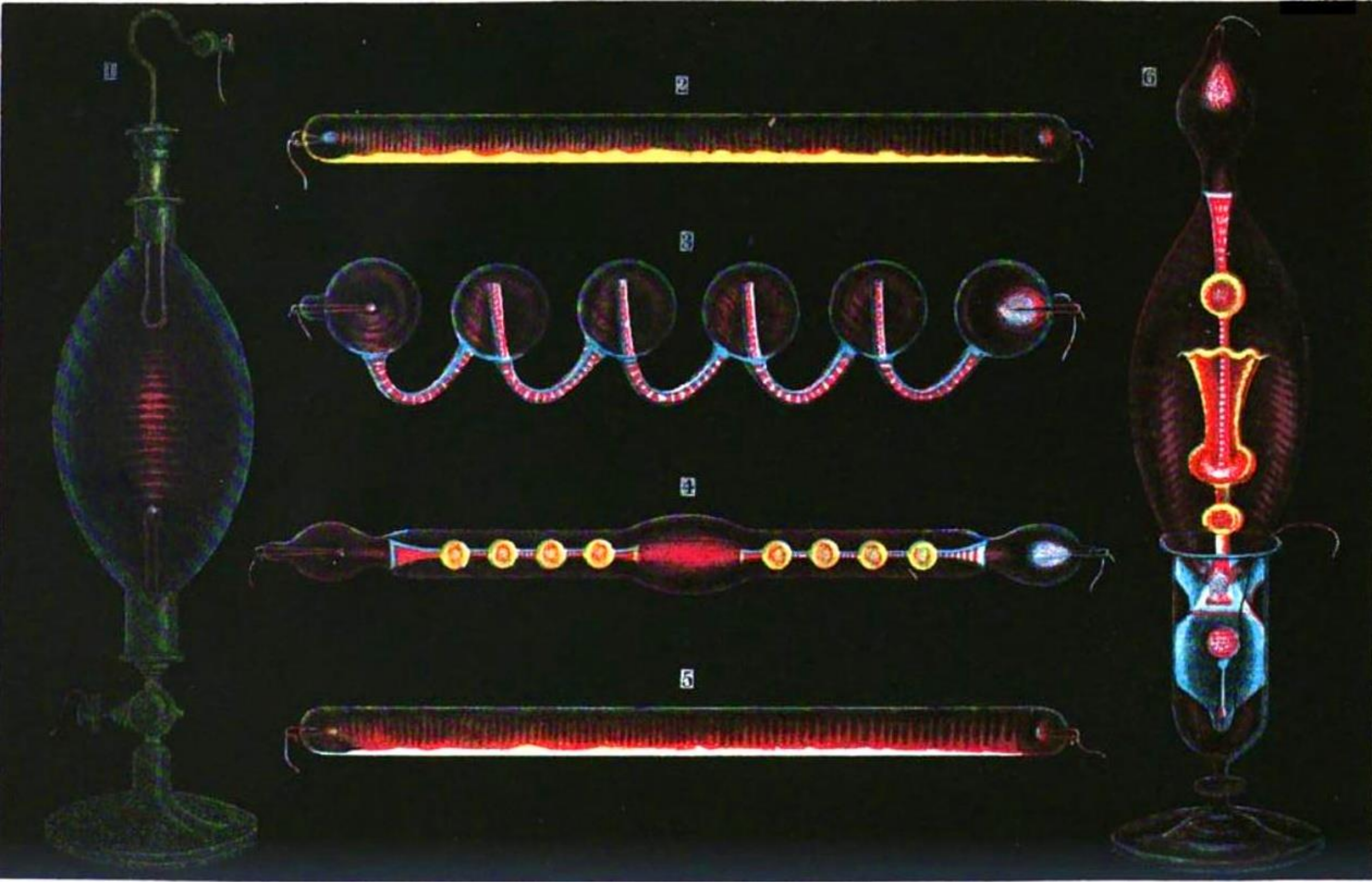
Heinrich Geißler

Julius Plücker

Mid 1850’s University of Bonn

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

magnetism could move the glow discharge



Drawing of Geissler tubes from 1860’s French physics book

Basic Plasma Properties

Density, *n (per cm³)*

n_e = density of electrons

n_i = density of ions

n_n = density of neutrals

Charge State, *q*

H^{+} → $q = +1$

Pb^{3+} → $q = +3$

H^{-} → $q = -1$

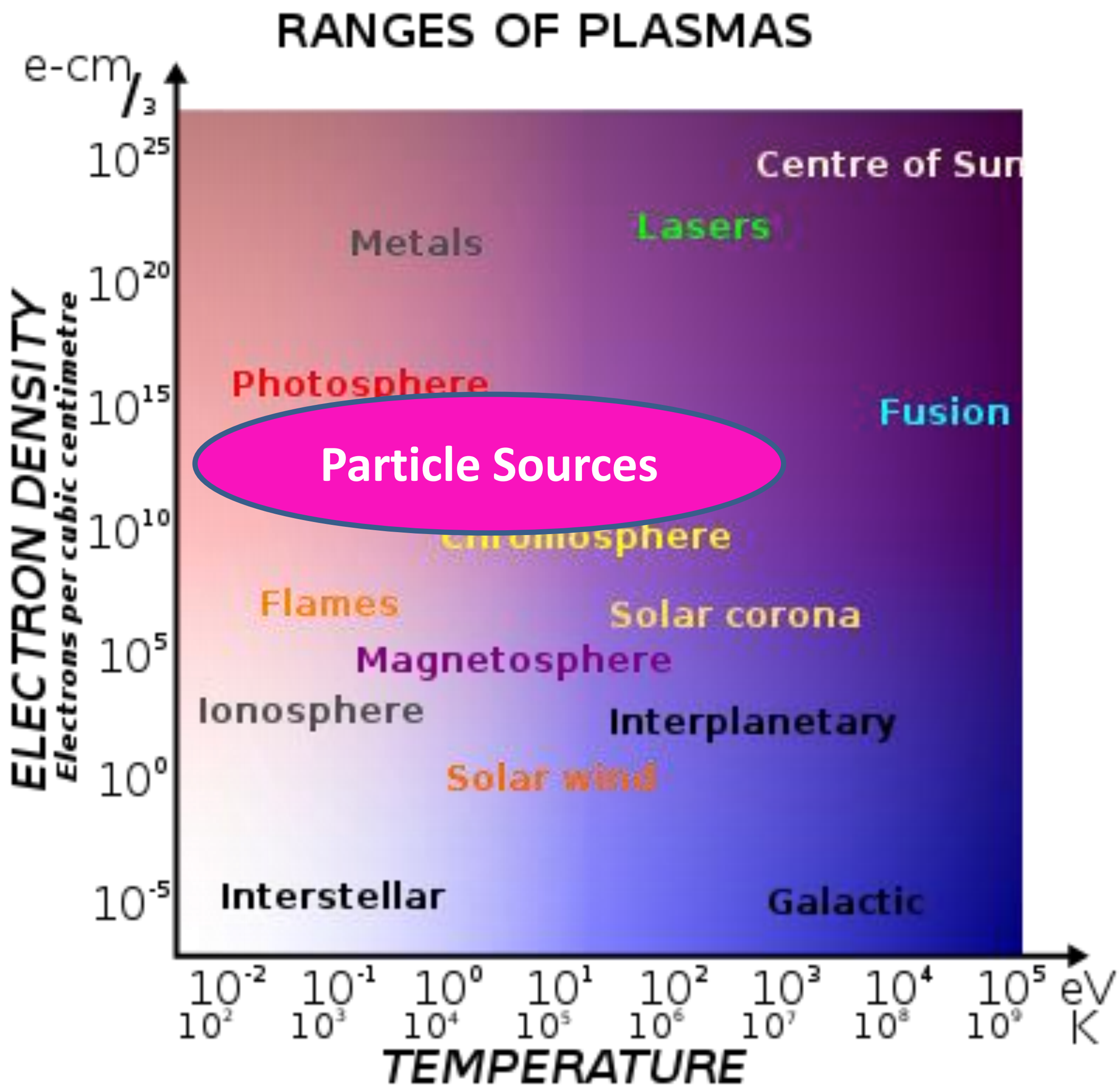
Temperature, *T* (eV)

T_e = temperature of electrons

T_i = temperature of ions

T_n = temperature of neutrals

11600°K = 1 eV

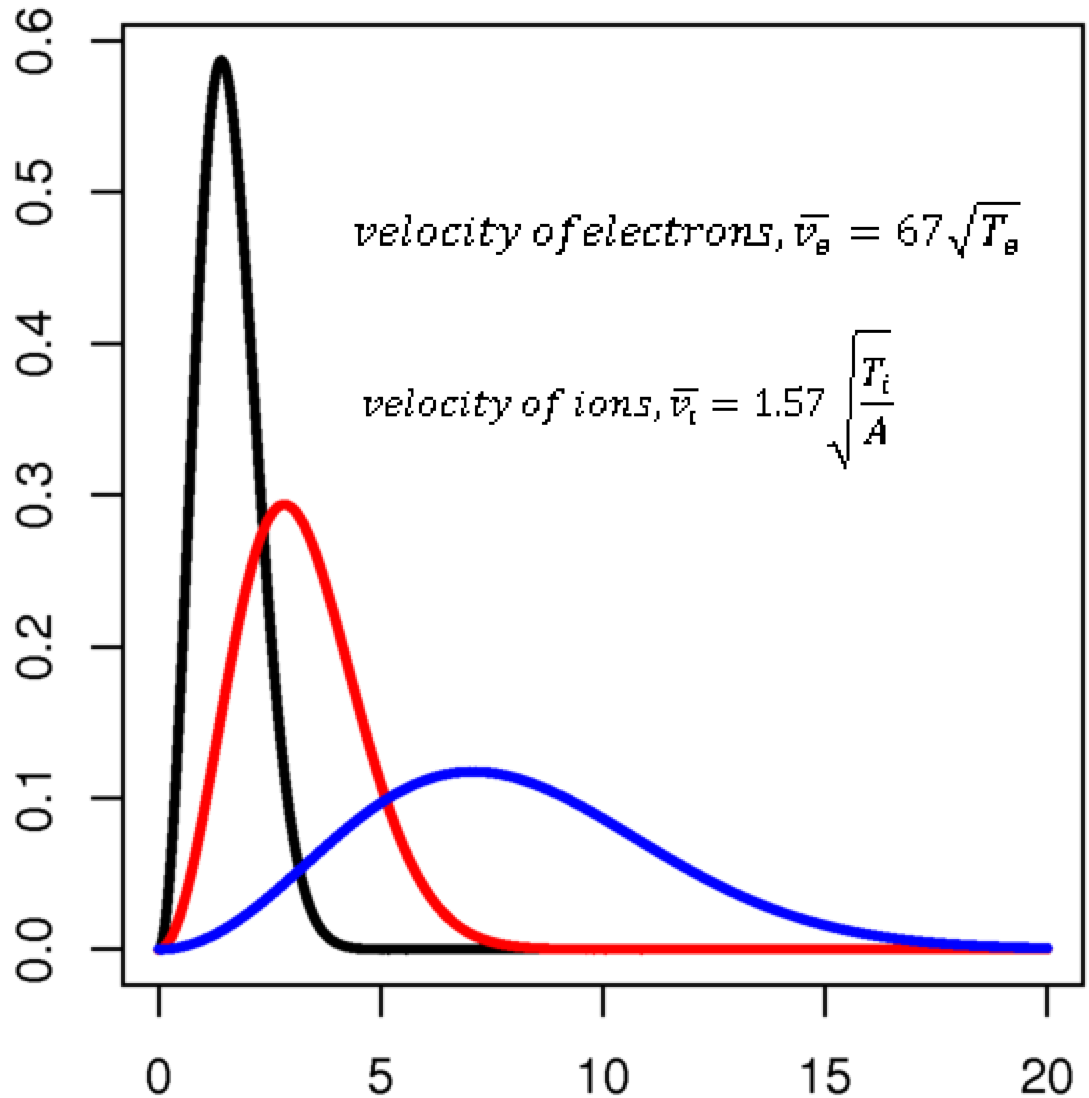

RANGES OF PLASMAS
e-cm/3
ELECTRON DENSITY
Electrons per cubic centimetre
10^25
10^20
10^15
10^10
10^5
10^0
10^-5
Centre of Sun
Lasers
Metals
Photosphere
Fusion
Particle Sources
Flames
Solar corona
Magnetosphere
Ionosphere
Interplanetary
Solar wind
Interstellar
Galactic
10^-2 10^-1 10^0 10^1 10^2 10^3 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

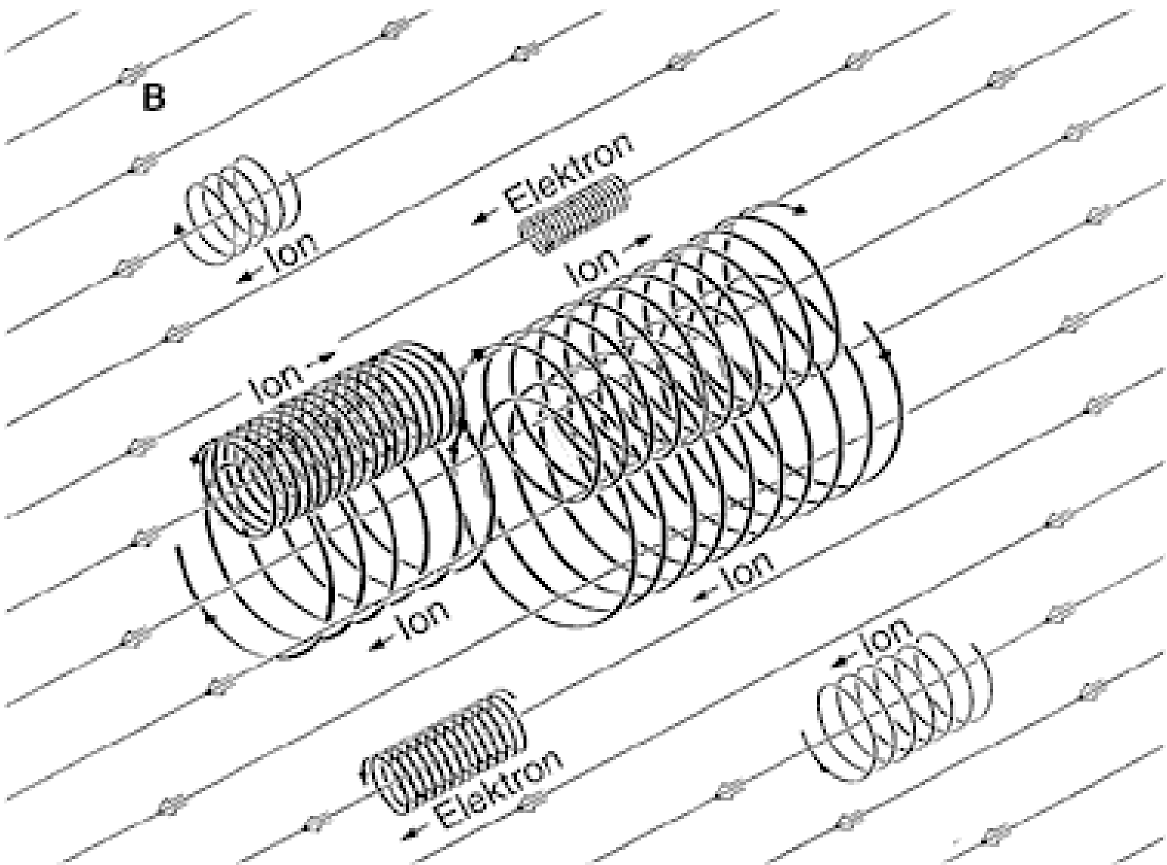
If thermalised velocity distributions should follow Maxwell Boltzmann statistics

However, in magnetic fields:

$$v_x \neq v_y \neq v_z$$

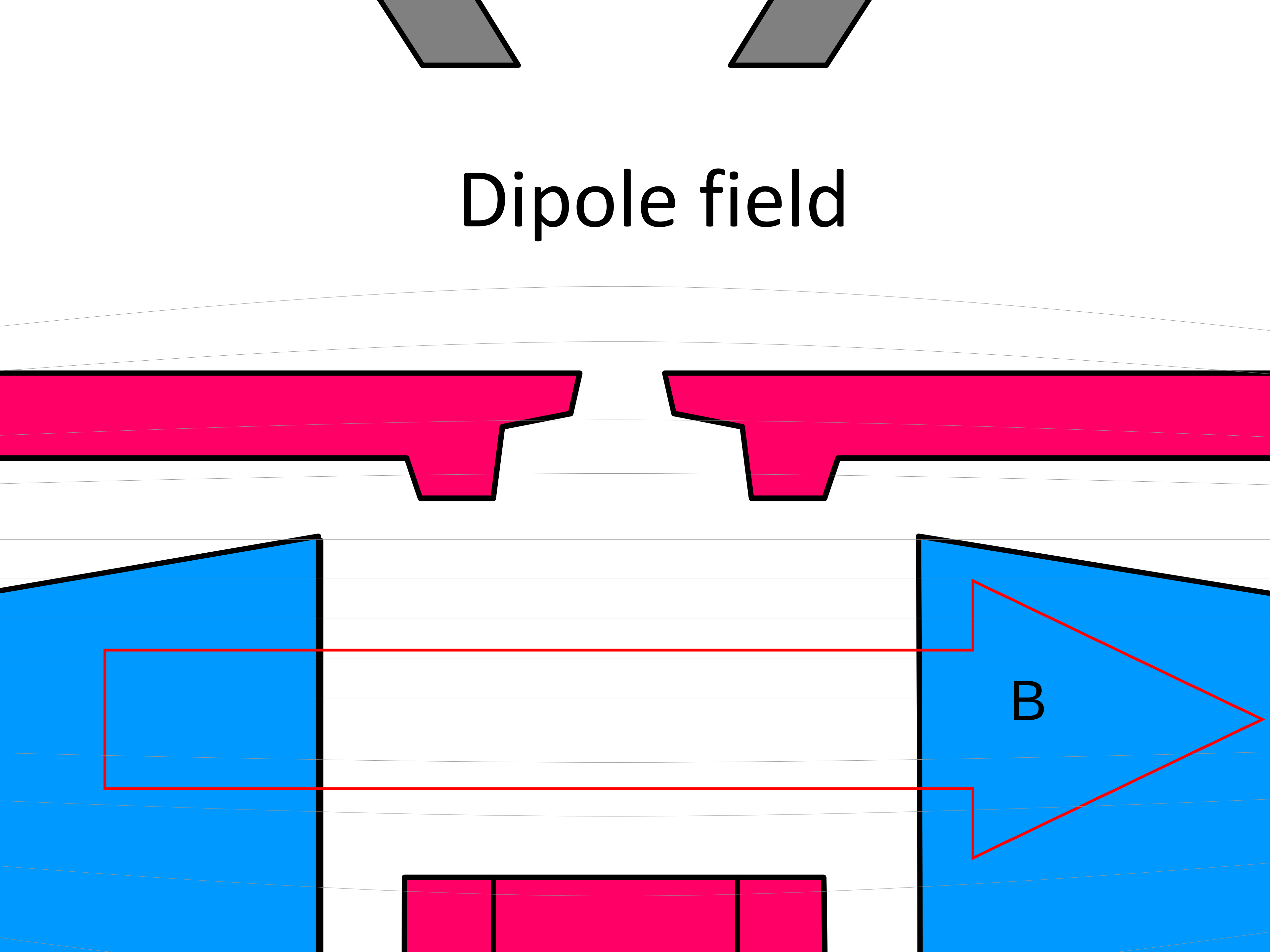


Magnetic Confinement

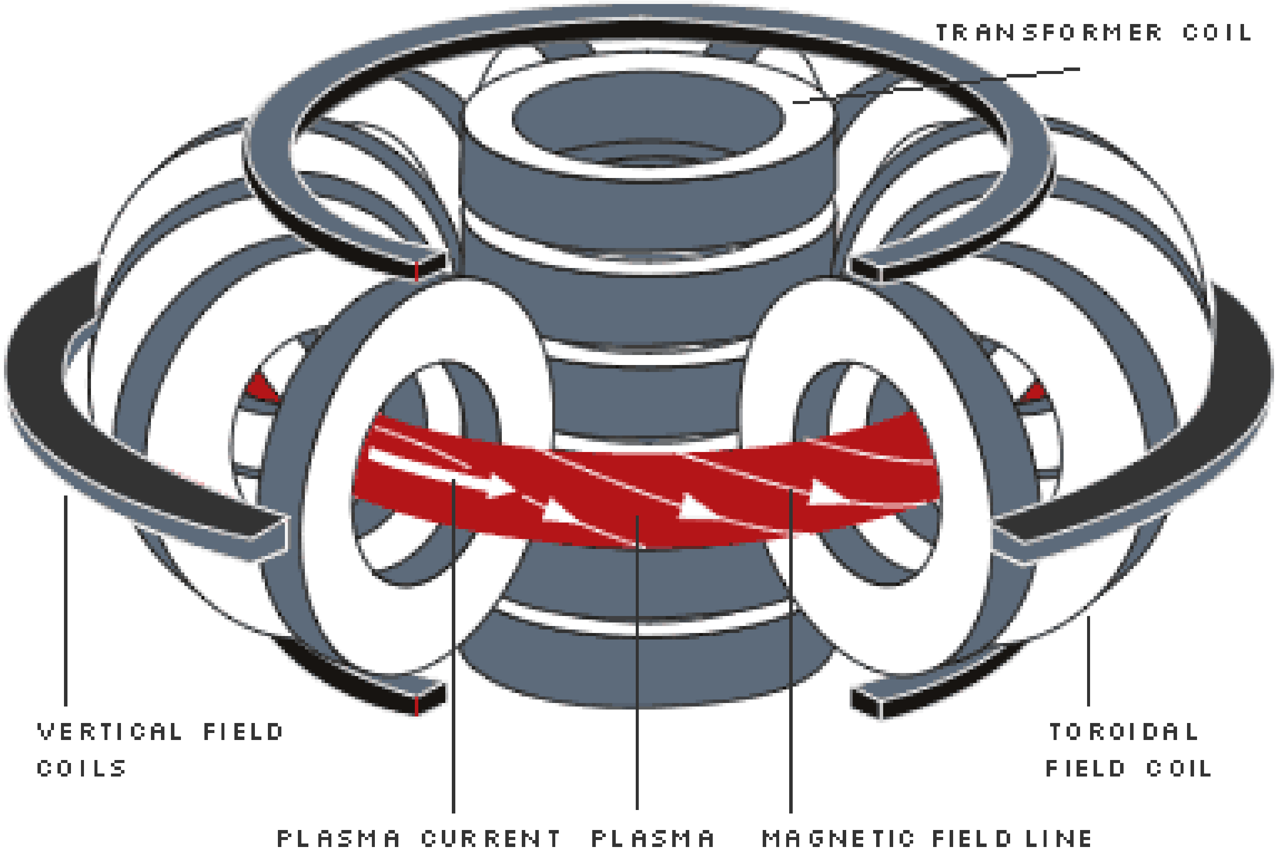


Particles spiral along magnetic field lines

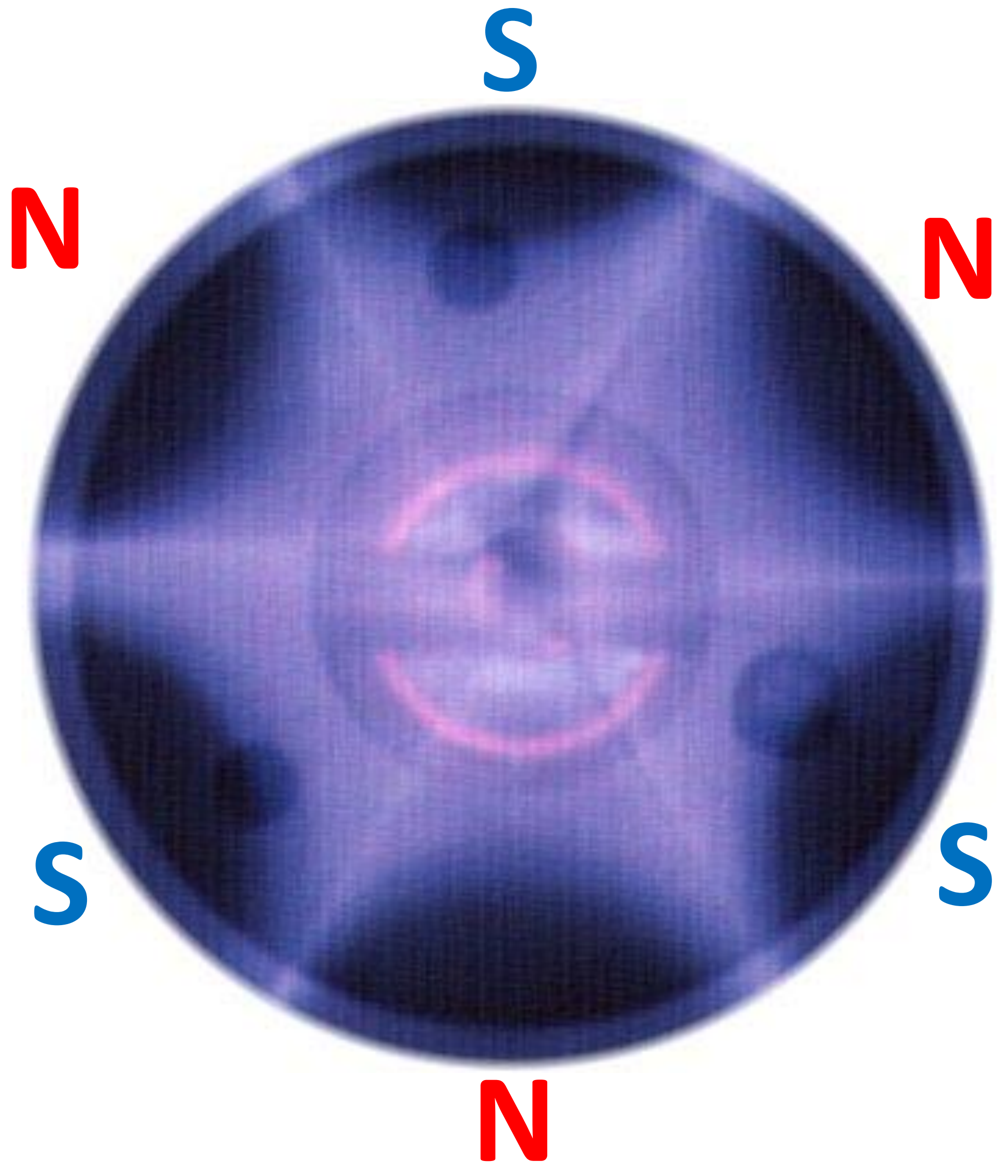
Dipole field



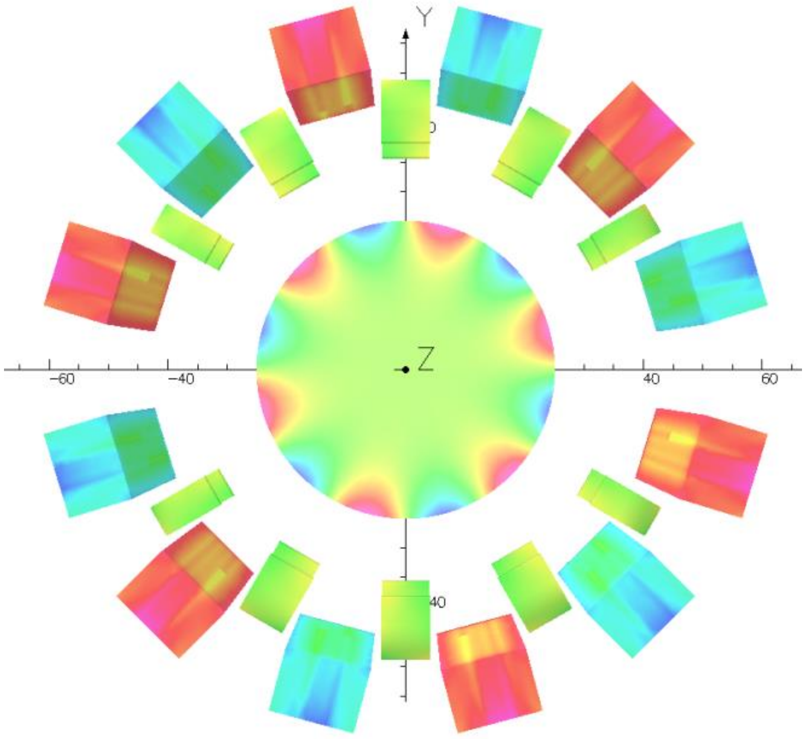
Solenoid field

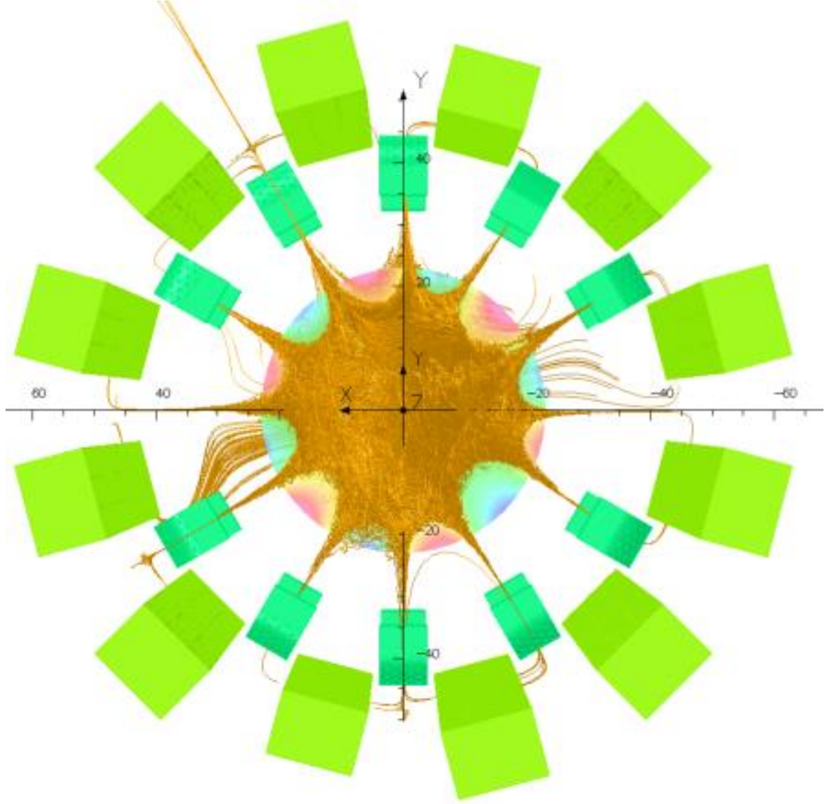


Hexapole

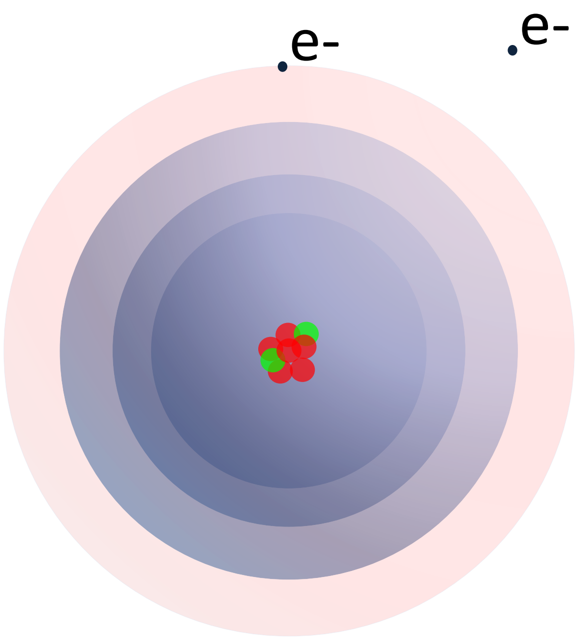


Multicusp Confinement



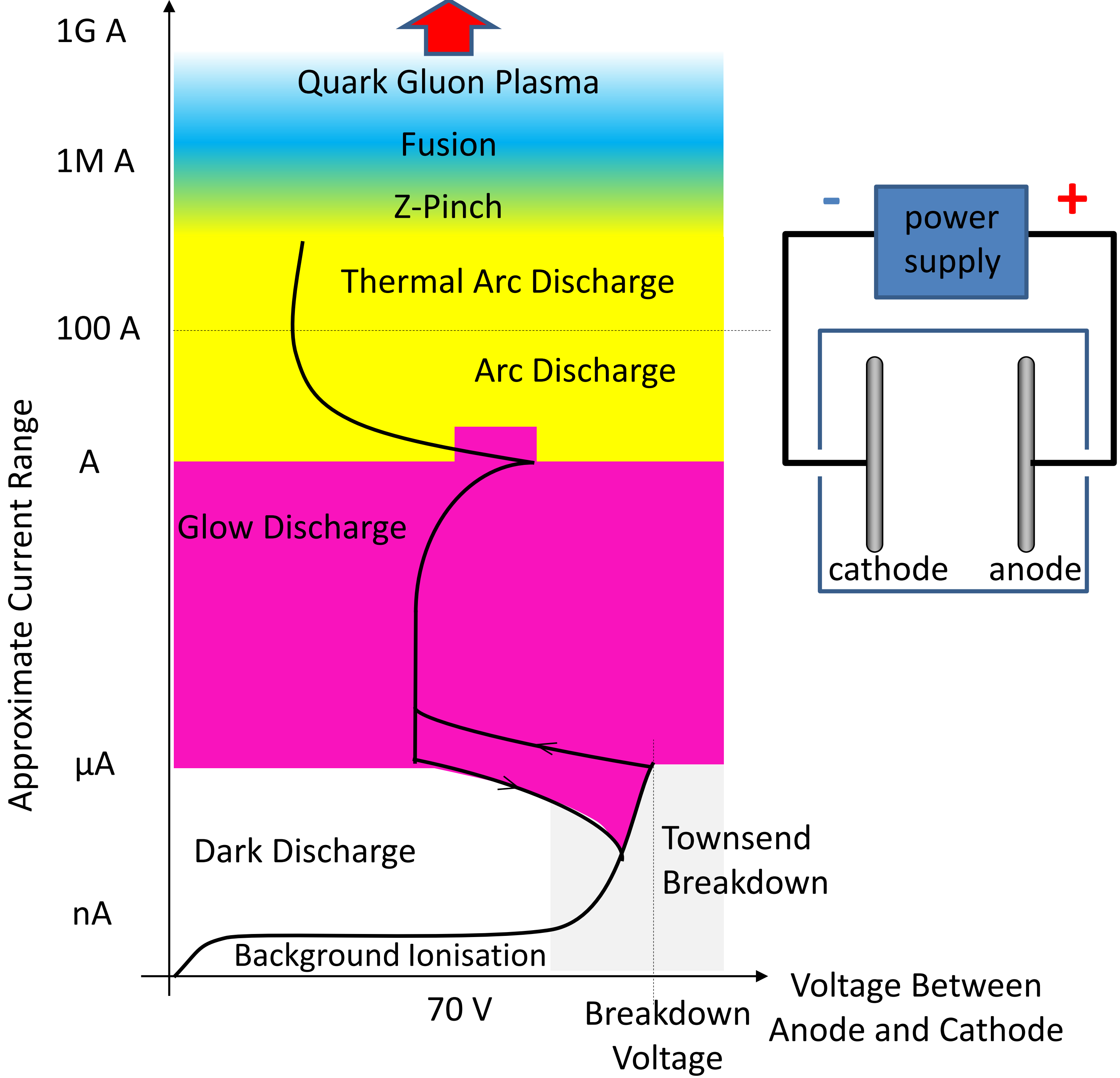


Ionisation



Positive Ion

Most sources rely on electron impact ionisation


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
Background Ionisation
Townsend
Breakdown
70 V
Breakdown
Voltage
Voltage Between
Anode and Cathode
-
power
supply
+
cathode
anode

Percentage Ionisation

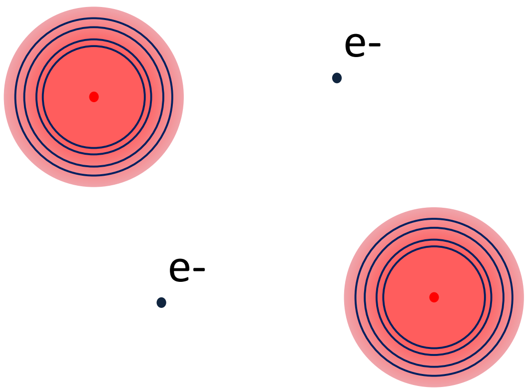
$$\frac{n_i}{n_i + n_n}$$

$> 10\ \% \rightarrow$ Highly ionised
$< 1\ \% \rightarrow$ Weakly ionised

Quasi Neutrality

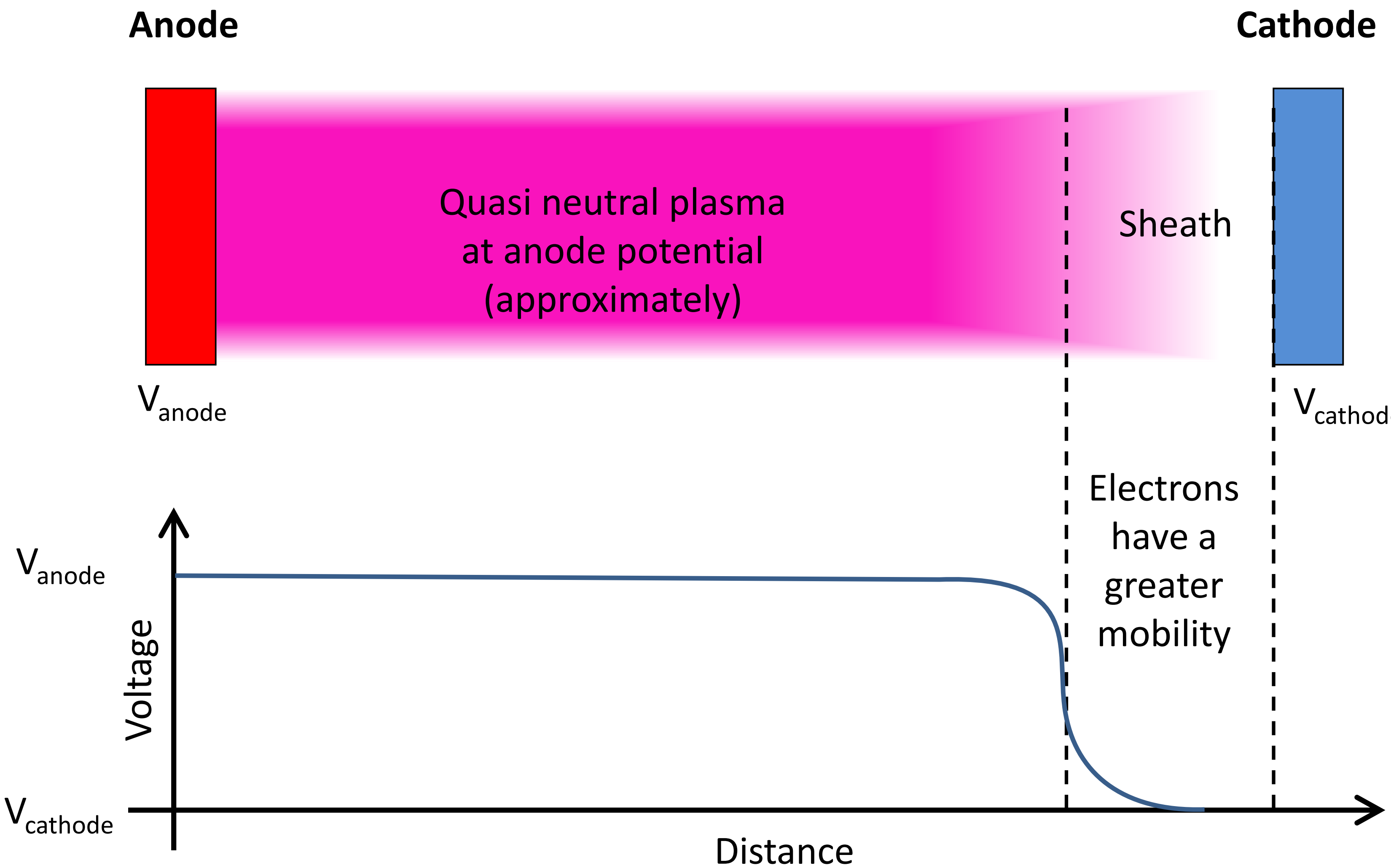
$$\sum q_i \, n_i = n_e$$

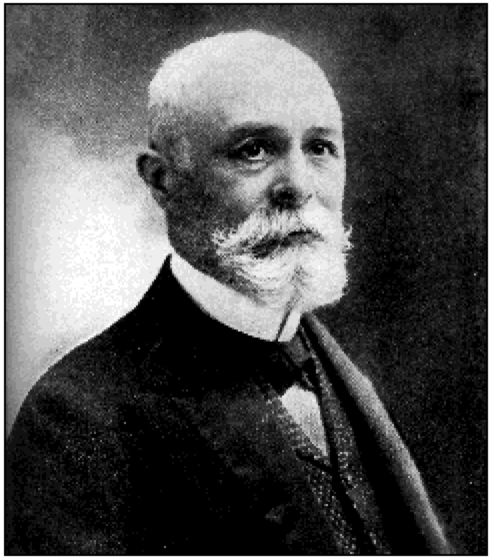
Debye Length



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

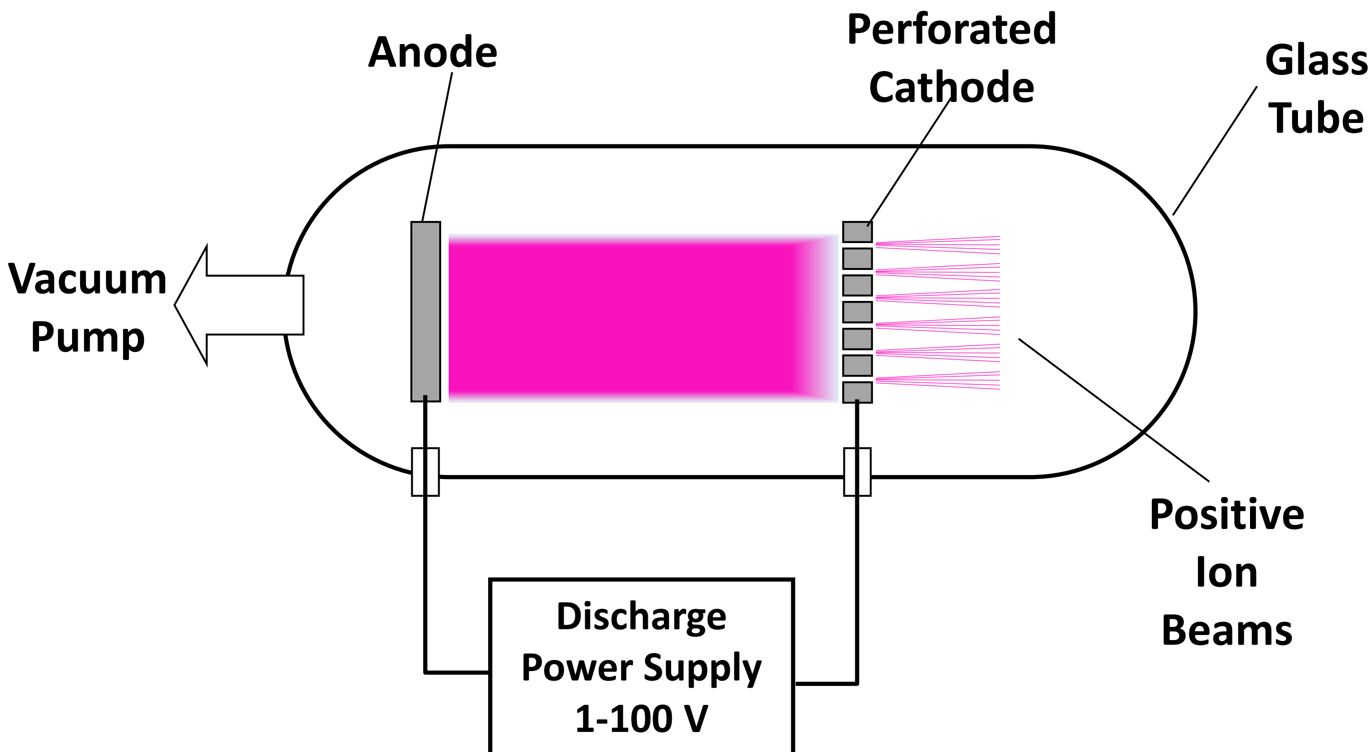
Cathode Sheath



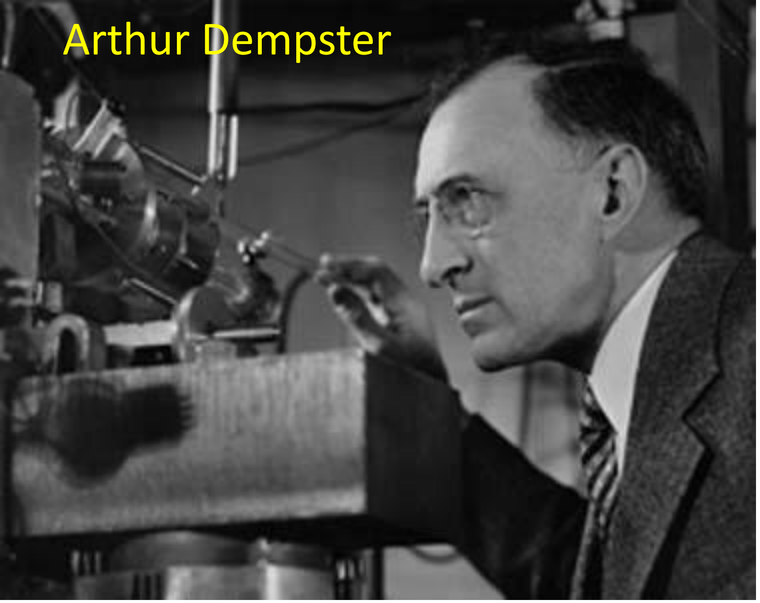


Canal Ray Source

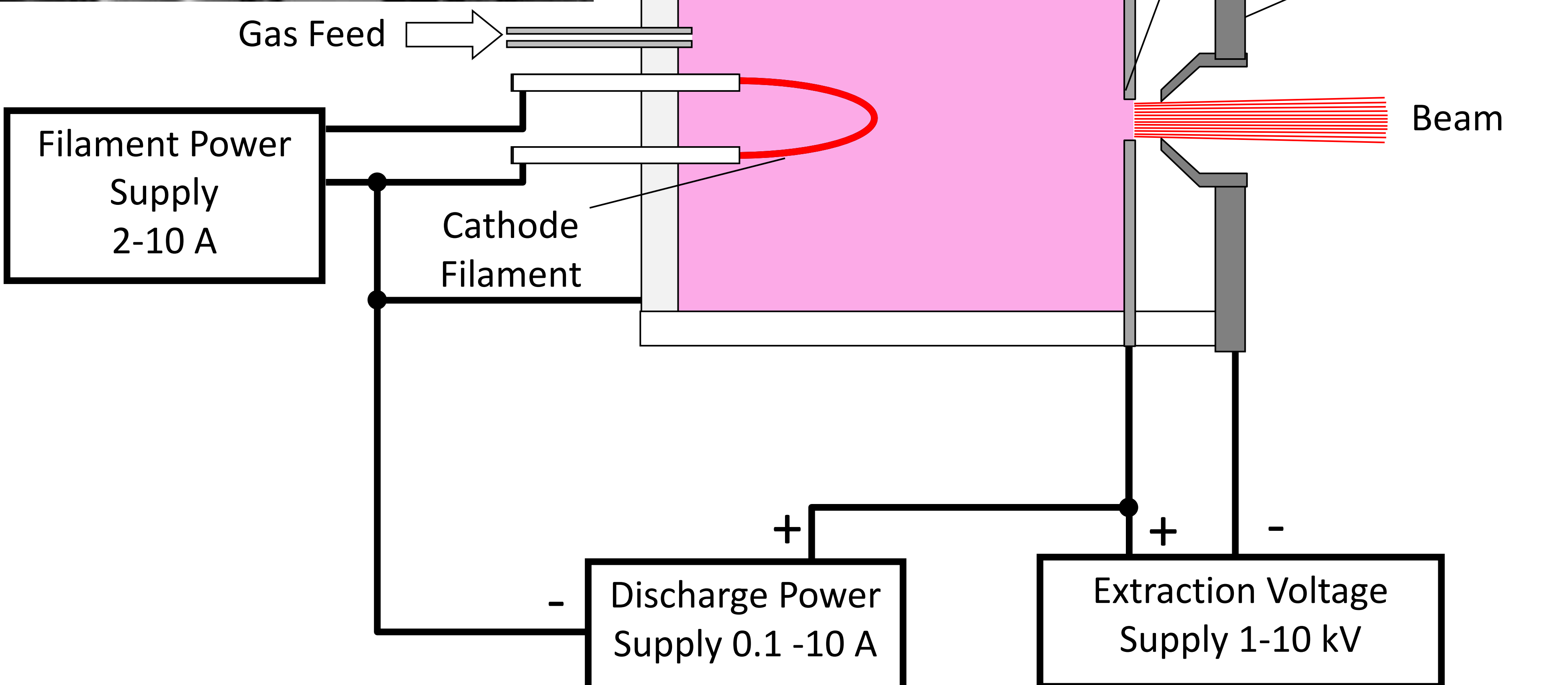
In 1886 Eugen Goldstein discovered canal rays

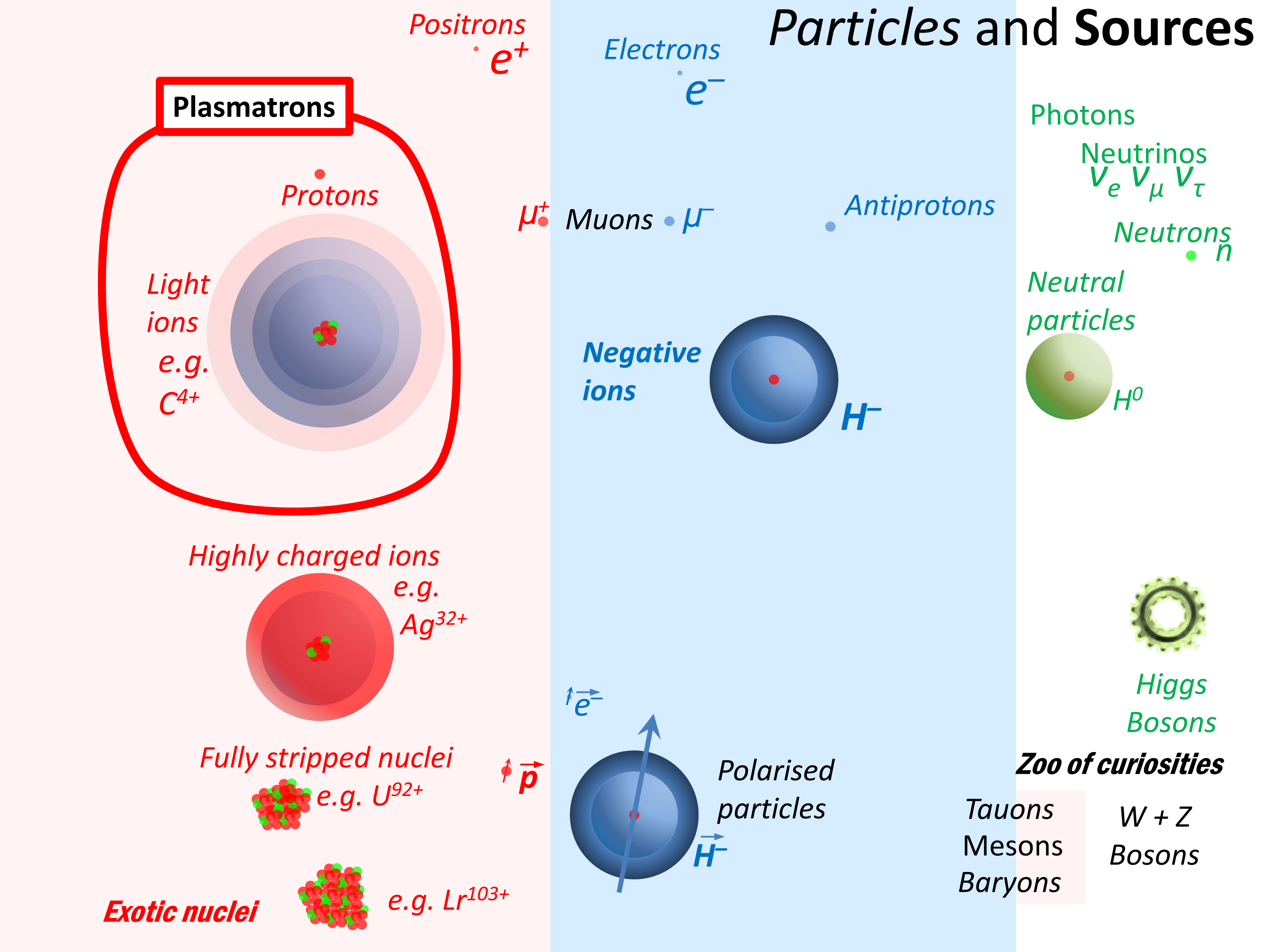


Electron Bombardment Source (1916)

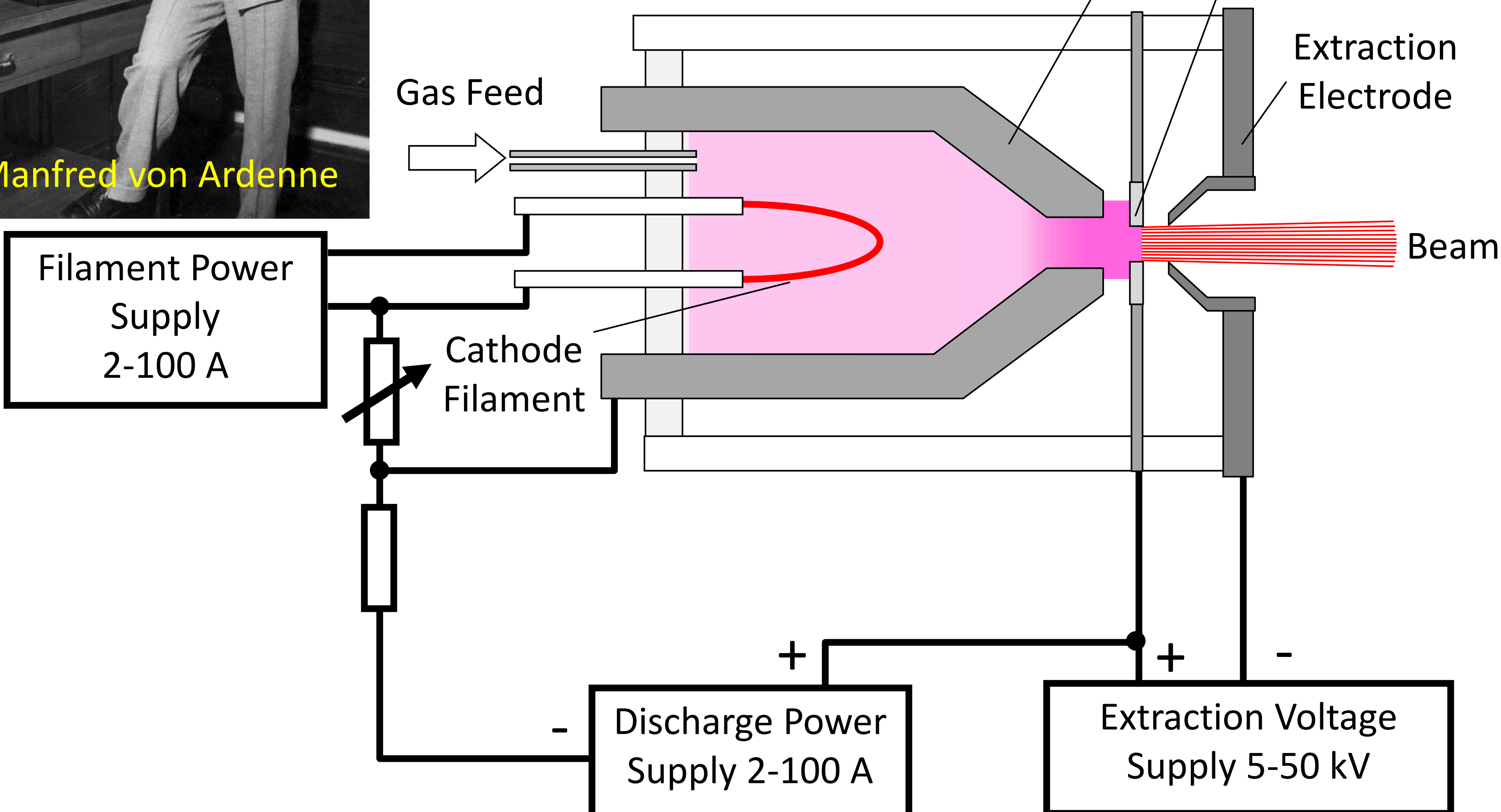


Early mass spectrometry

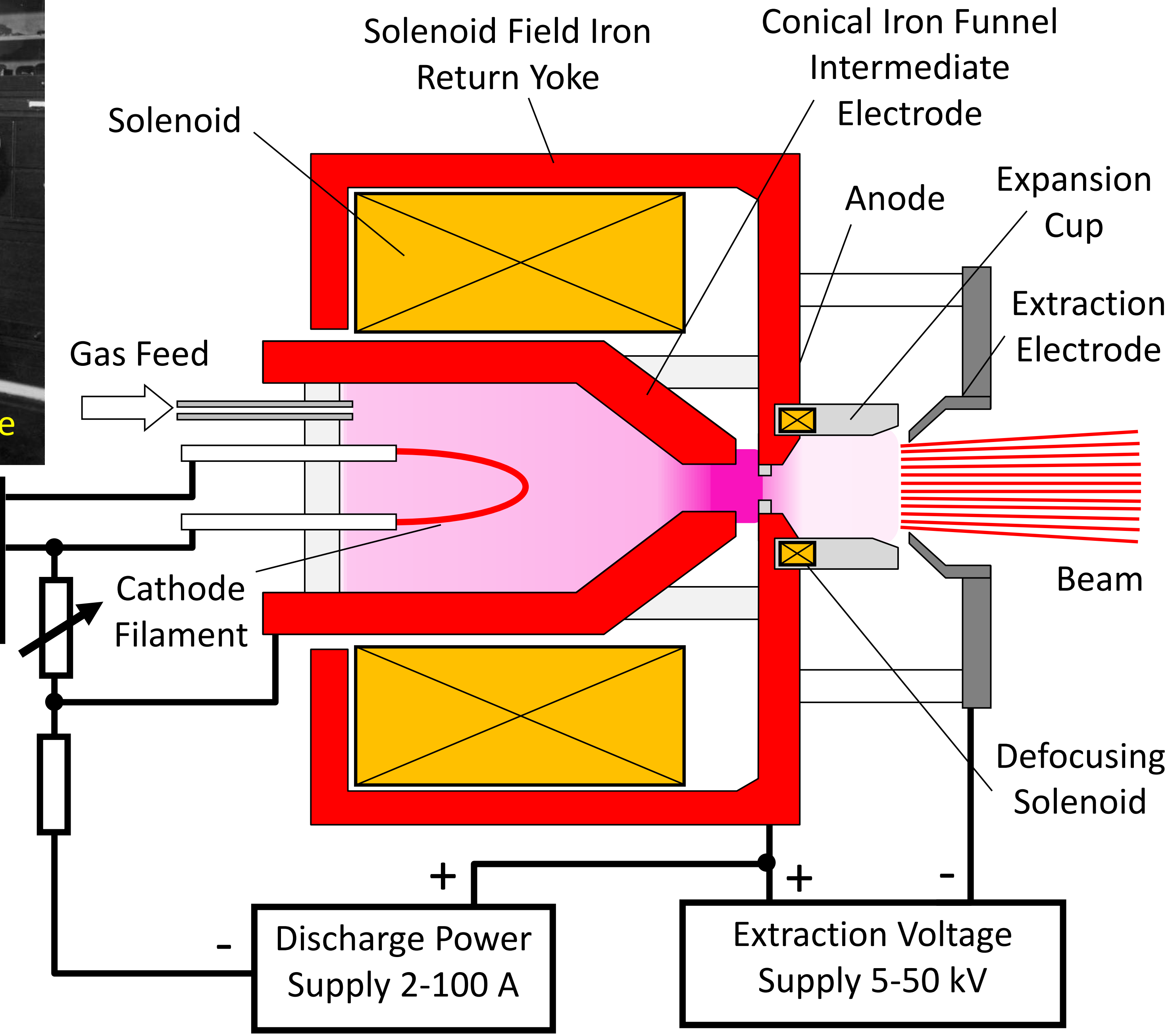



Particles and Sources
Positrons
e^+
Electrons
e^-
Plasmatrons
Protons
Light ions e.g. C^{4+}
μ^+
Muons μ^-
Antiprotons
Photons
Neutrinos
ν_e ν_μ ν_τ
Neutrons
n
Neutral particles
H^0
Negative ions
H^-
Highly charged ions
e.g. Ag^{32+}
Fully stripped nuclei
e.g. U^{92+}
$\vec{p}$
$\vec{e}^-$
Polarised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

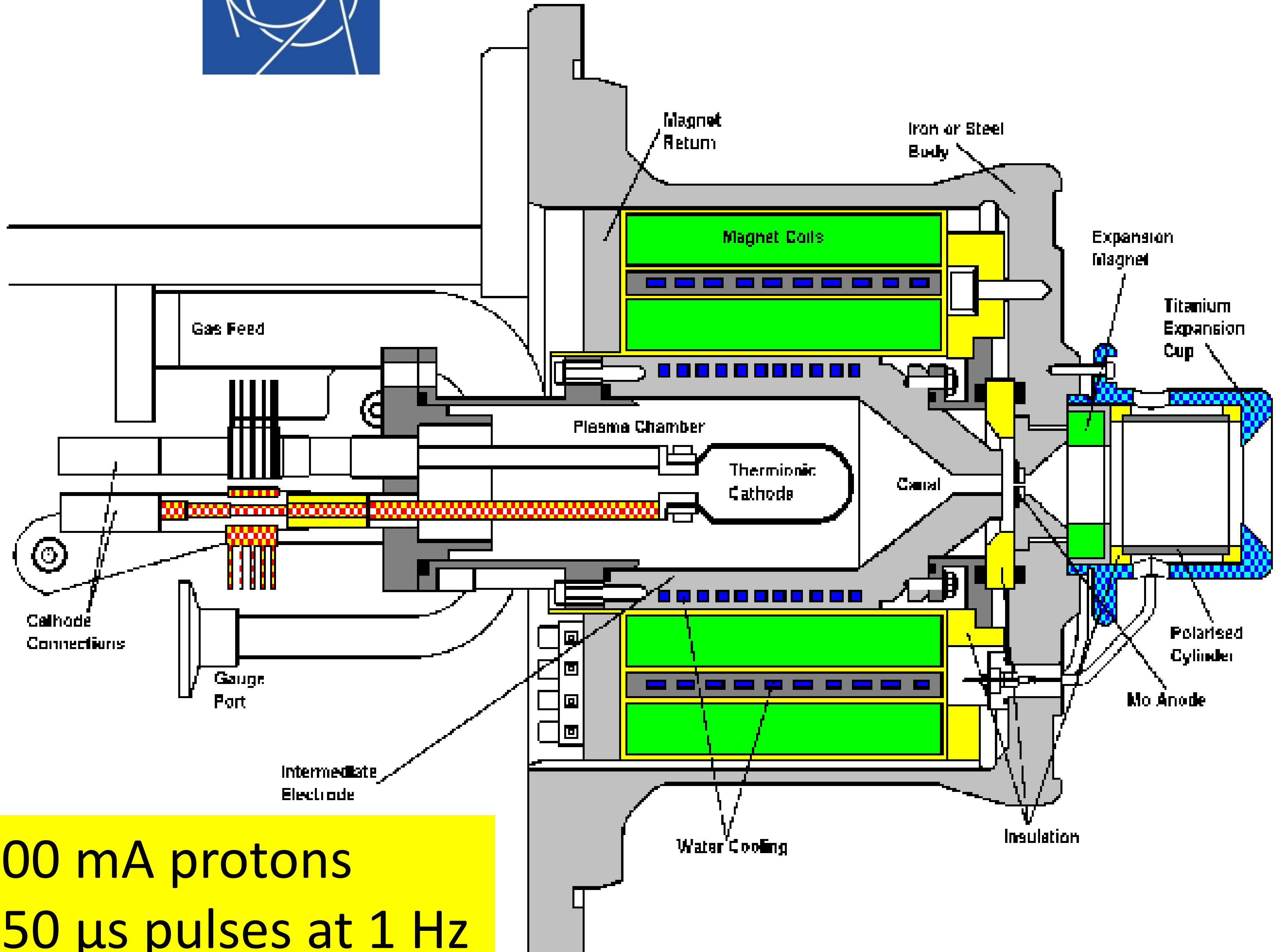
Plasmatron (late 1940s)



Duoplasmatron (1956)

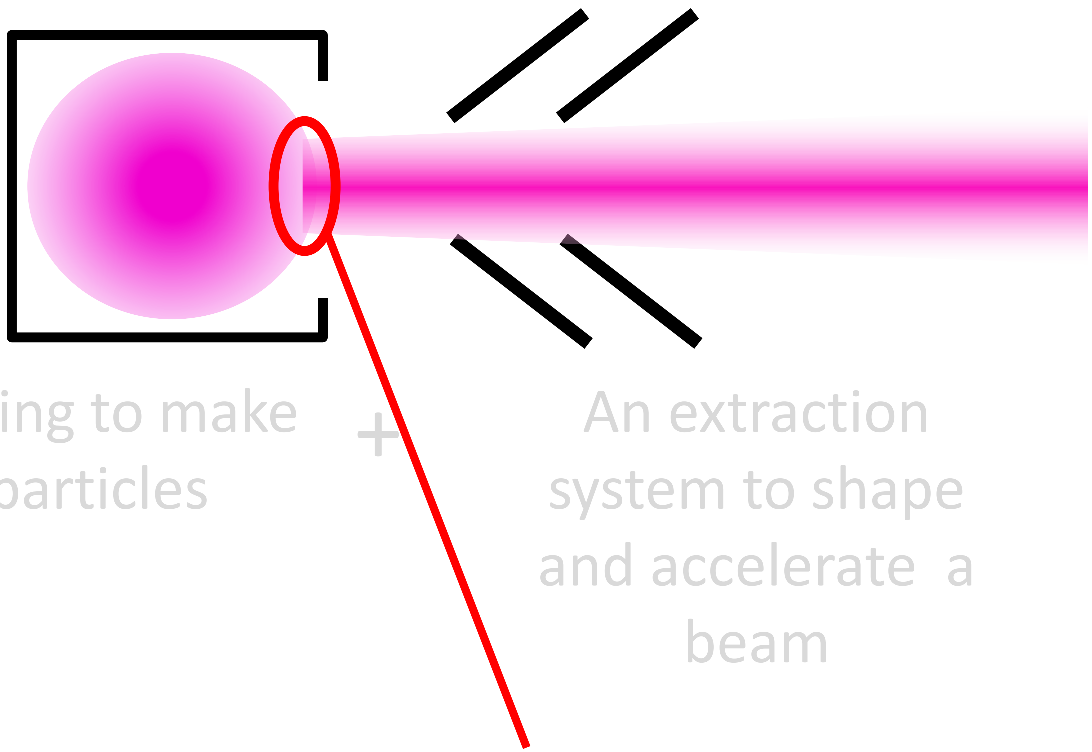


Duoplasmatron



300 mA protons
150 µs pulses at 1 Hz

Particle sources/guns generally consist of:



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

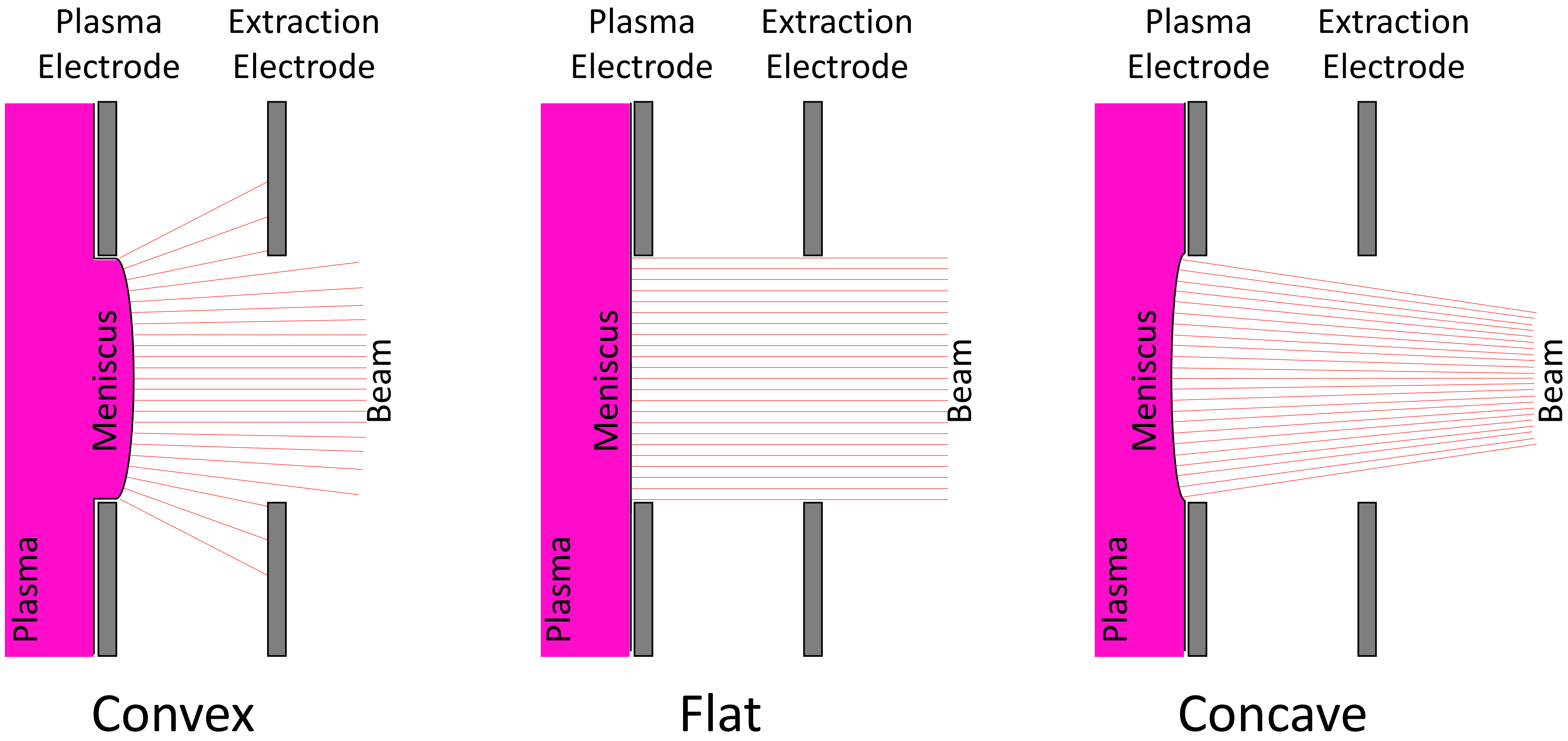
Plasma Mencius

…is not actually a surface

because of Debye length, it has a thickness,

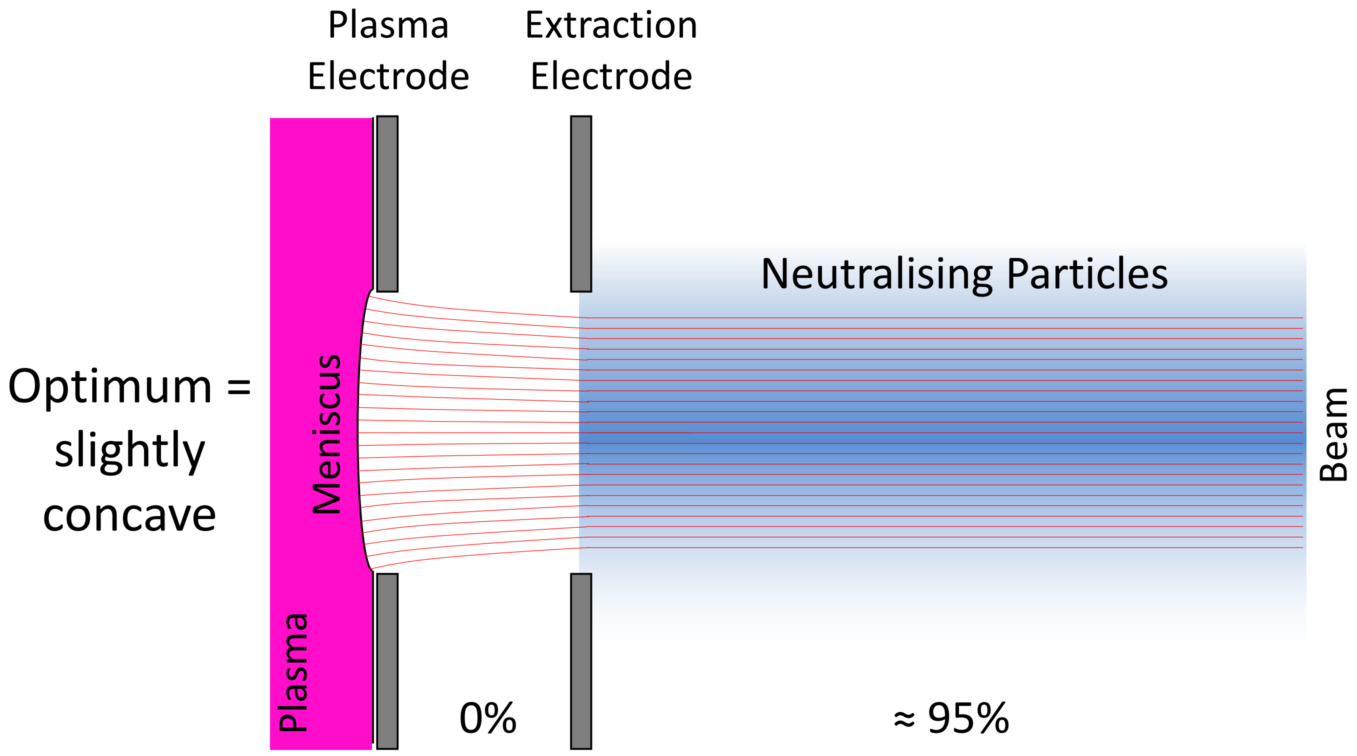
but it is a useful concept when considering the optics of extraction…

Plasma Mencius



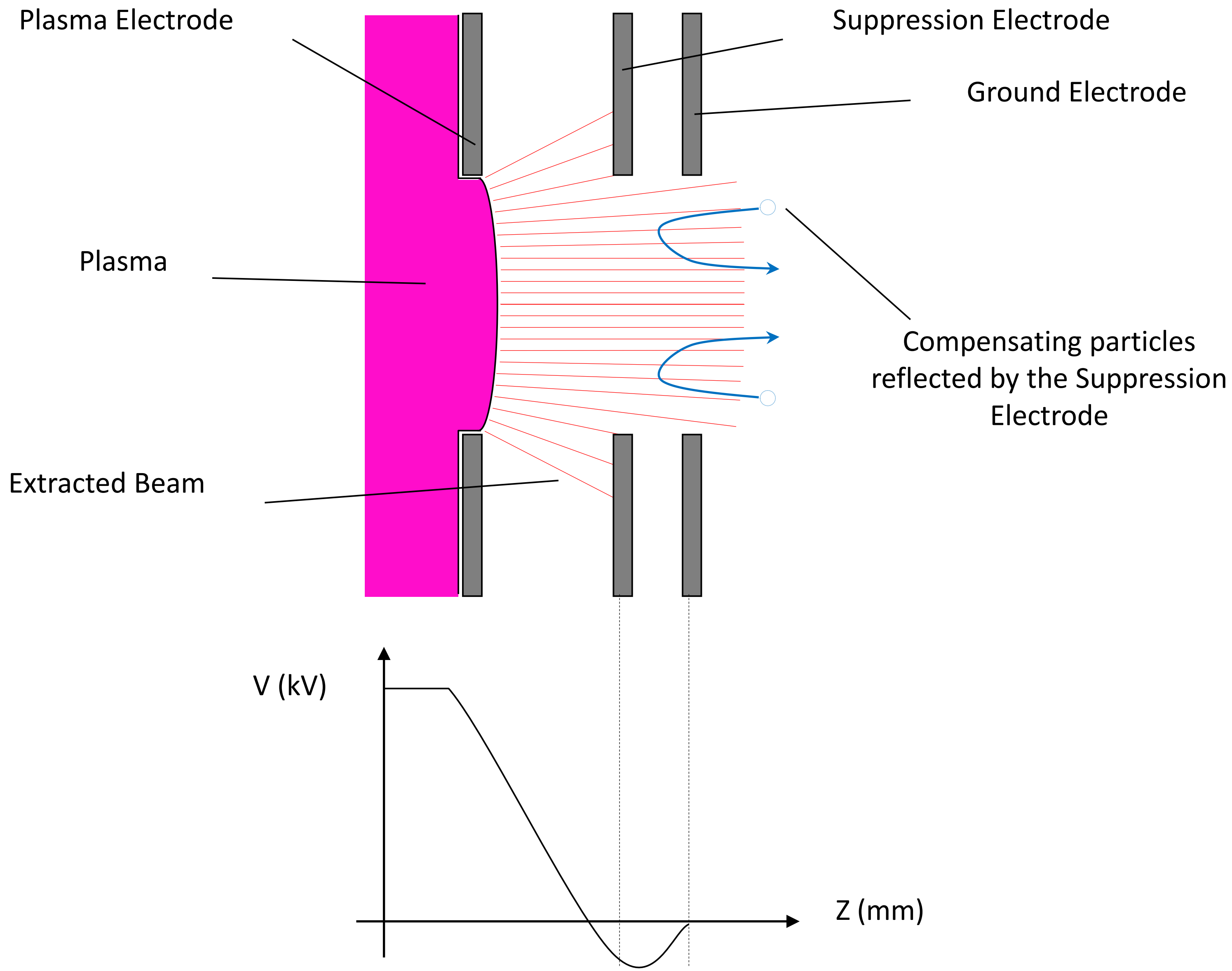
Not including space charge effects

Space Charge



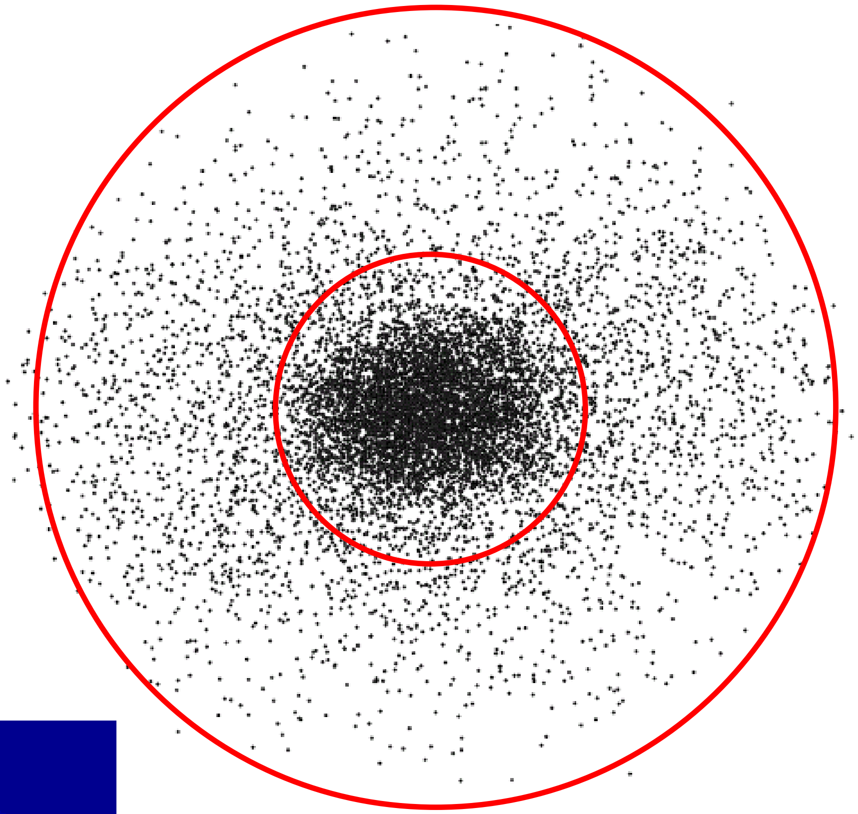
Percentage compensation

Suppressor Electrode

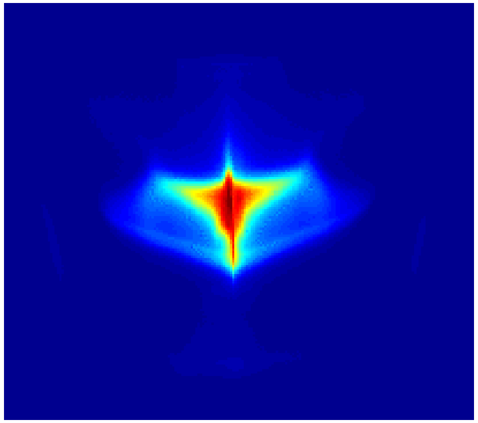


Emittance of Real Beams

Halo Effect
- Plasma boundary
- Fringe fields



How big is this beam?



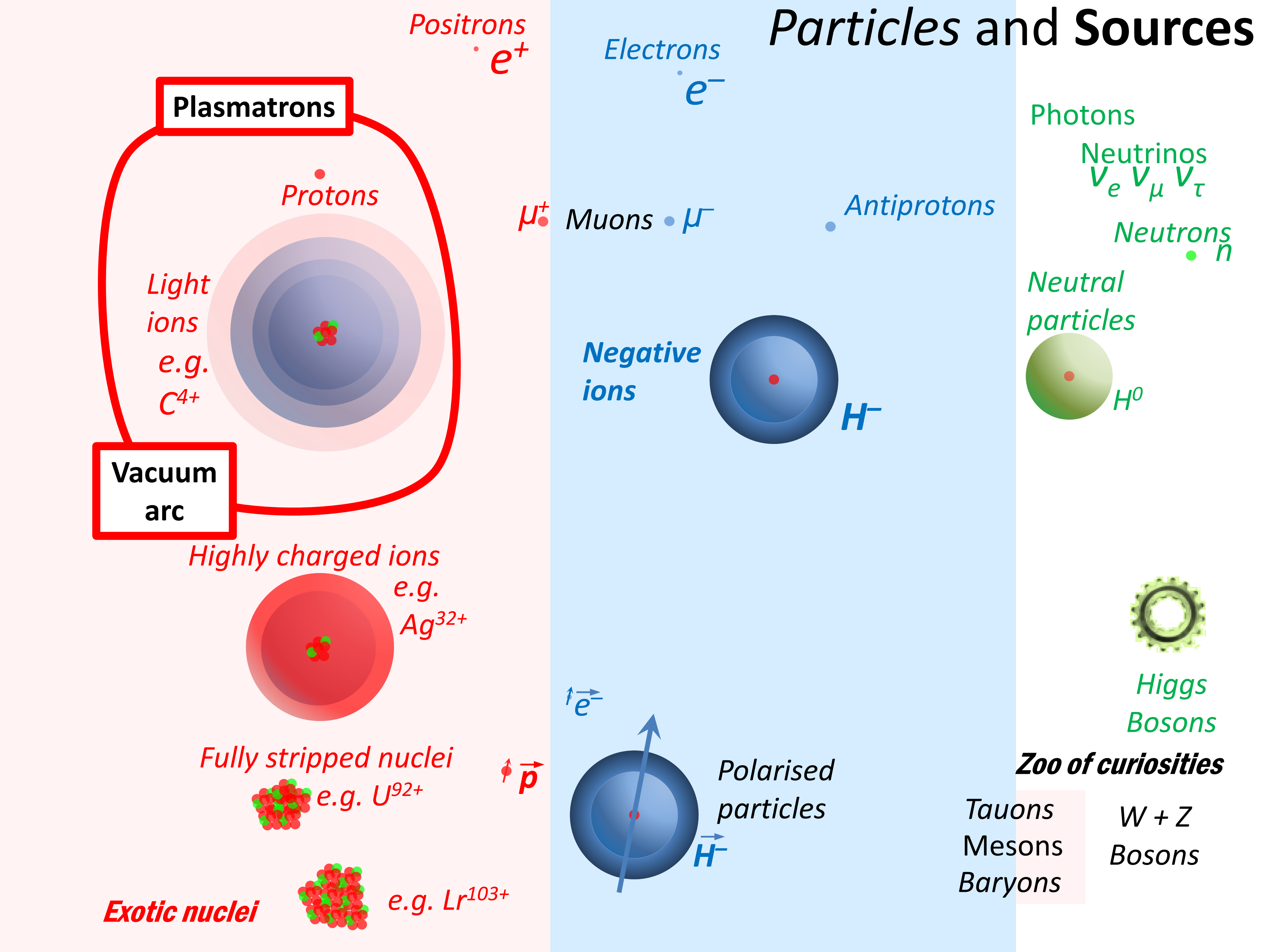
95% emittance

rms emittance

Brightness

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

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



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H0
Vacuum arc
Highly charged ions
e.g. Ag32+
Higgs Bosons
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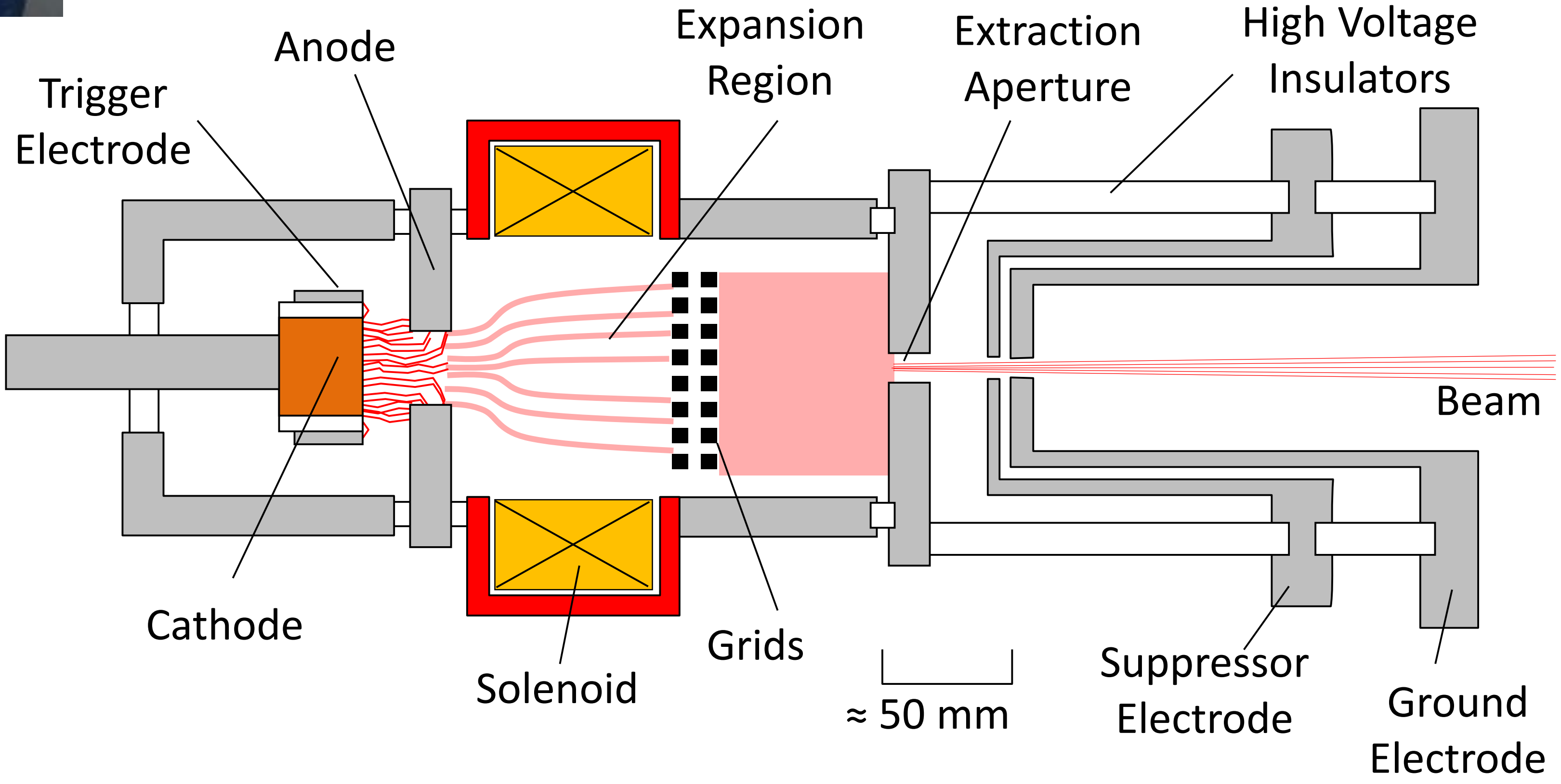
Fully stripped nuclei
e.g. U92+
p
Polarised particles
H−
Zoo of curiosities
Tauons
Mesons
Baryons
W + Z Bosons
Exotic nuclei
e.g. Lr103+

Vacuum Arc Ion Sources

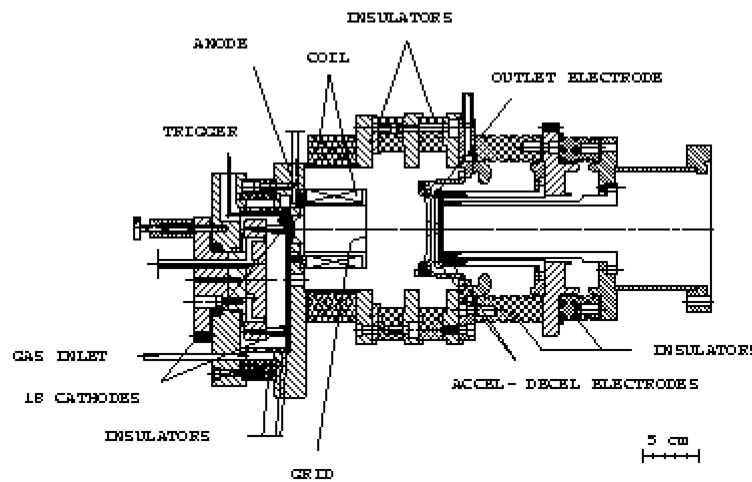
1980s - Ian Brown at Lawrence Berkley Lab (and others)



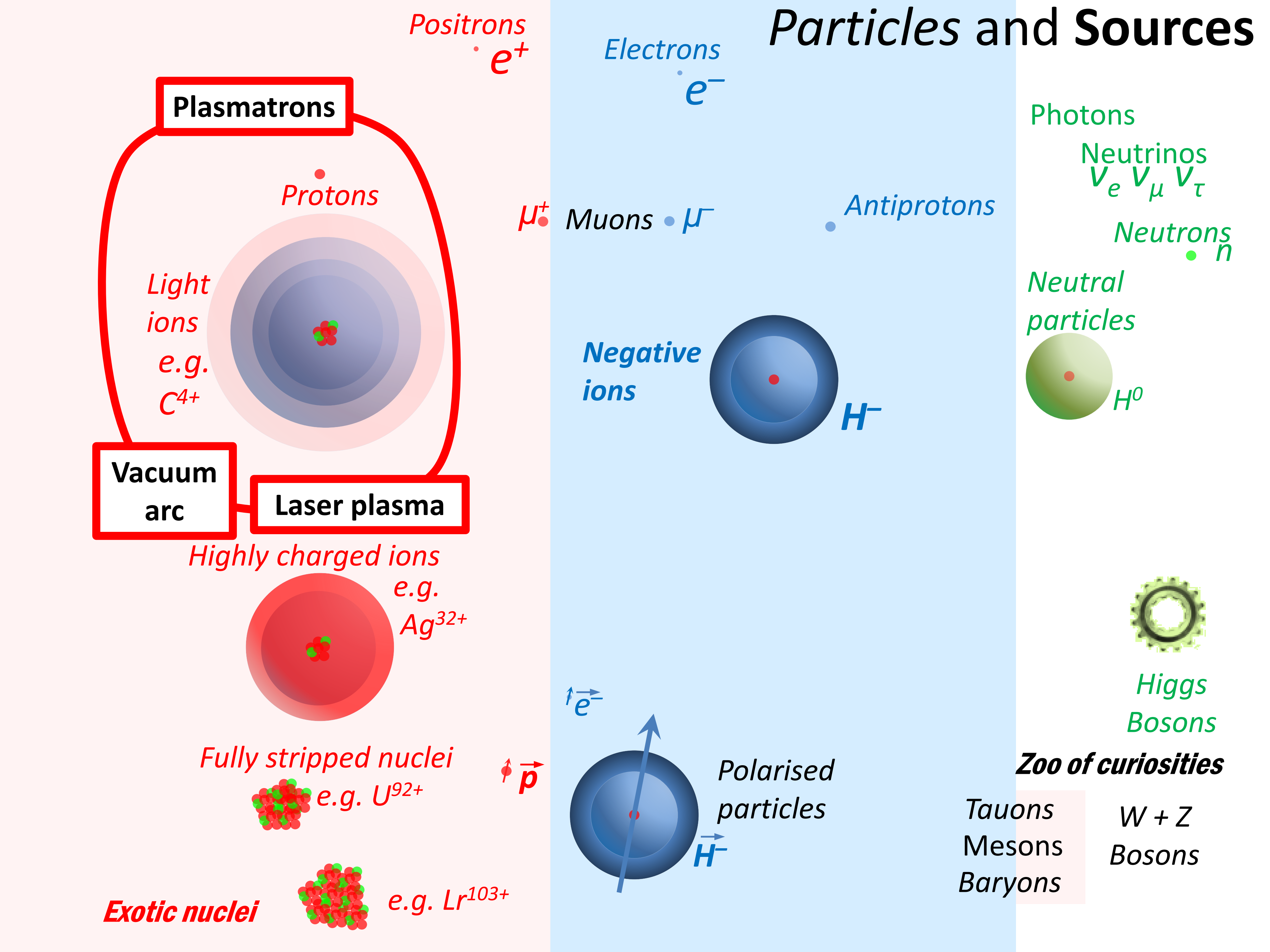
BERKELEY LAB

MEtal Vapor Vacuum Arc (MEVVA)

GSI MEVVA



15 mA of U^{4+} ions



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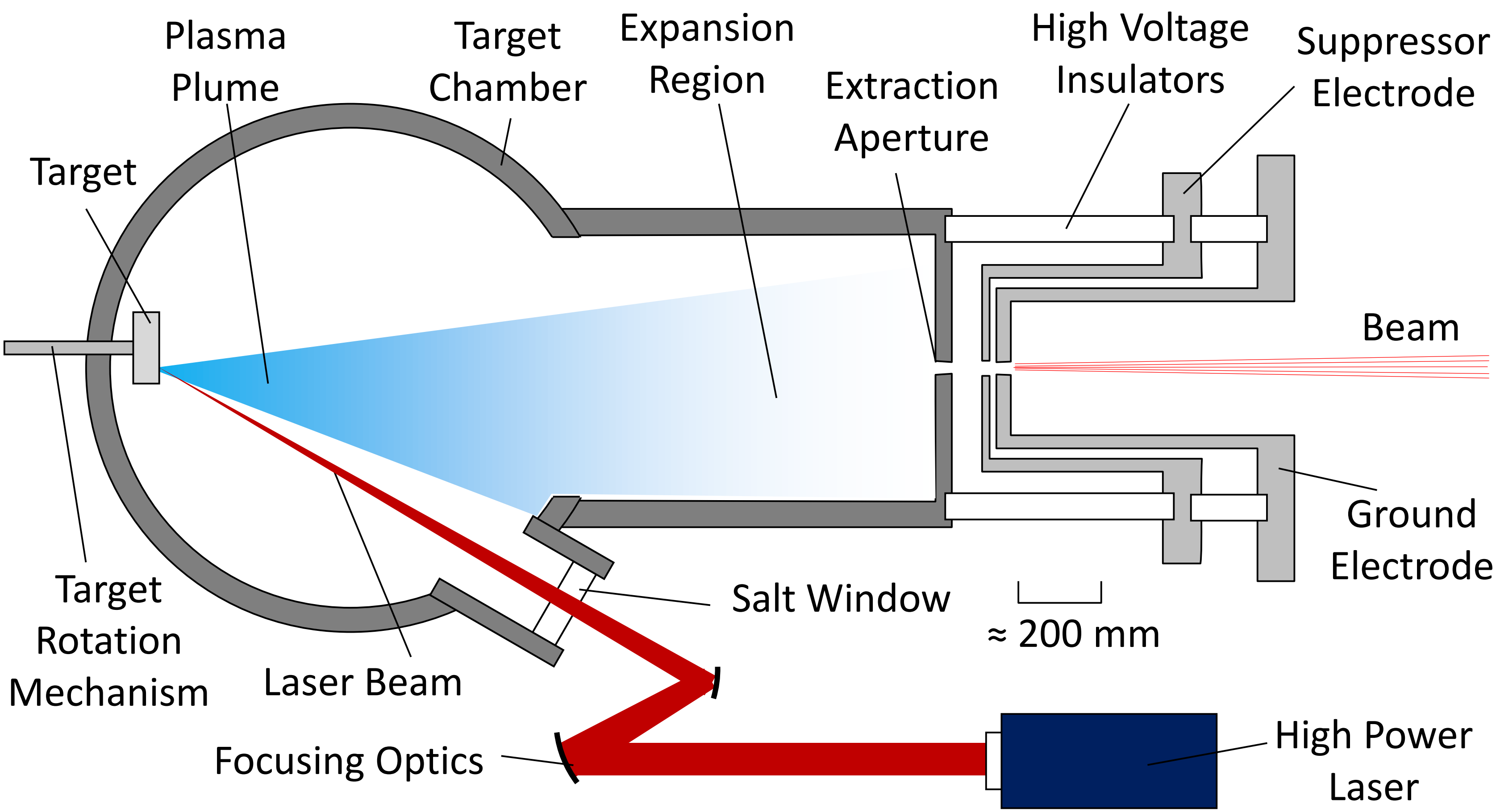
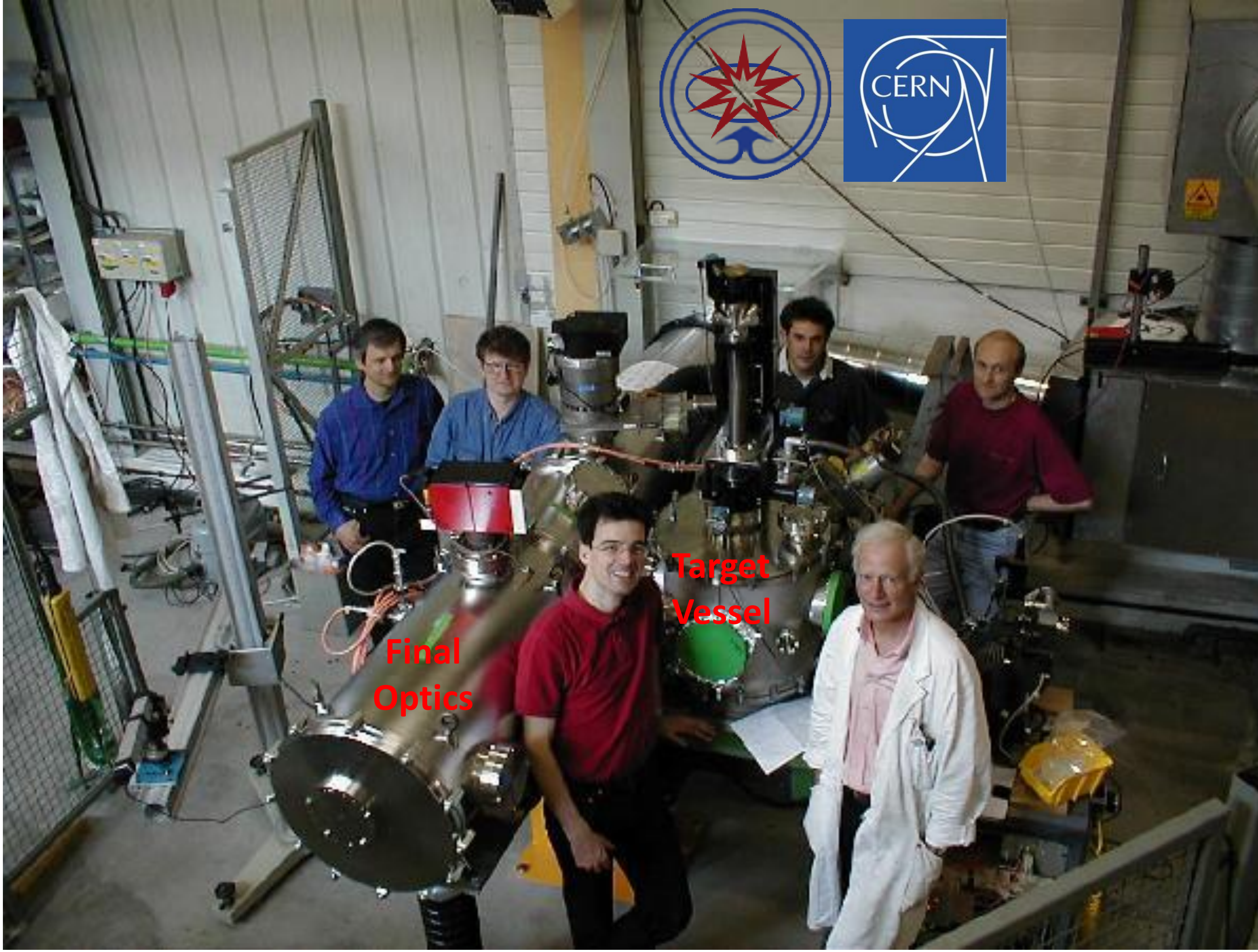
e.g. Lr^{103+}

Laser Plasma Ion Sources



1 -100 Joules per pulse!



ITEP Laser source at CERN

ITEP Laser source at CERN

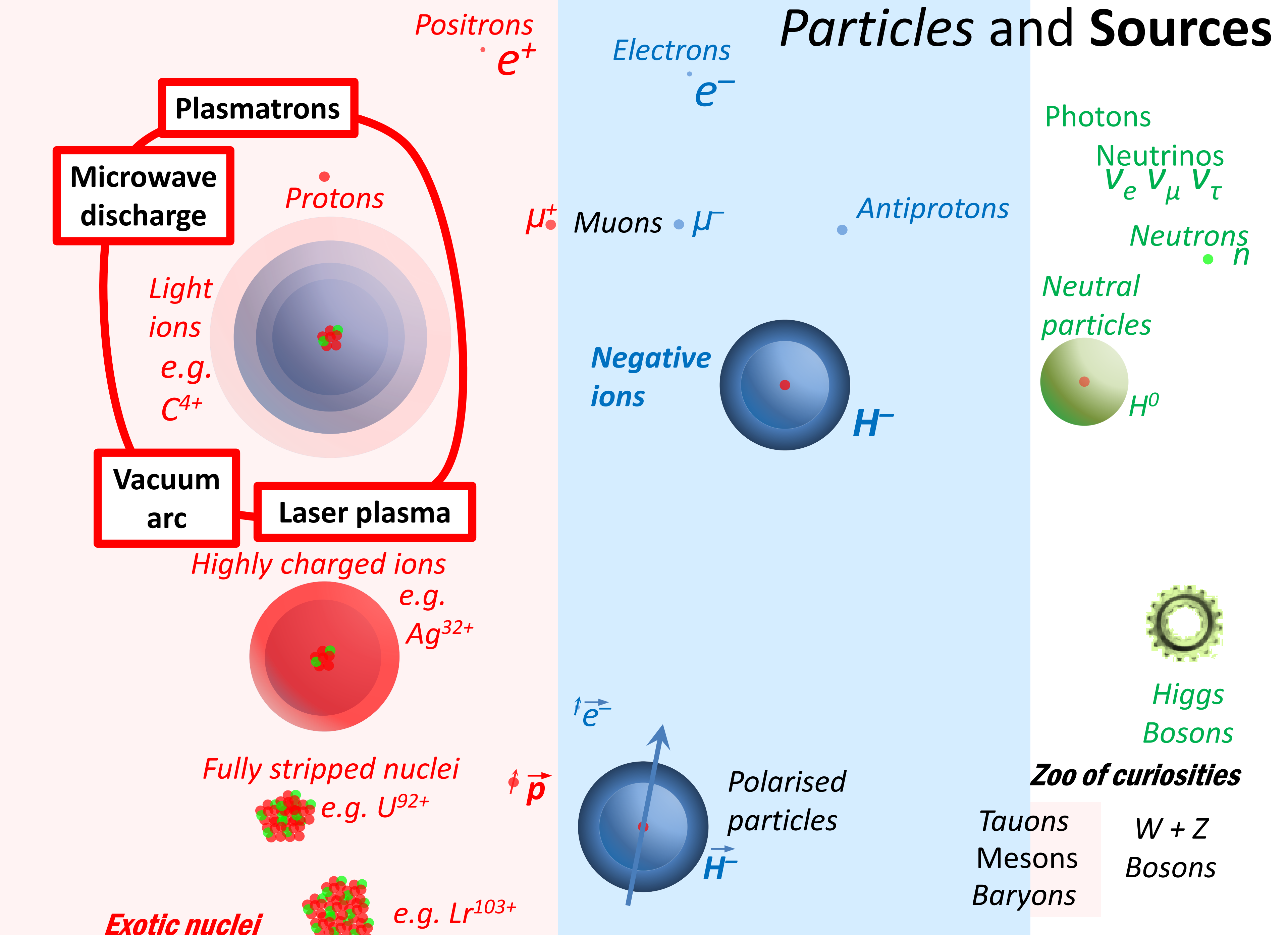
TWAC at ITEP Moscow

7 mA, 10 μs pulses of C^{4+}

BNL and RIKEN

Masahiro Okamura has demonstrated
Direct Plasma Injection into an RFQ

Particles and **Sources**



Dan Faircloth CAS 2012

Microwave Ion Sources

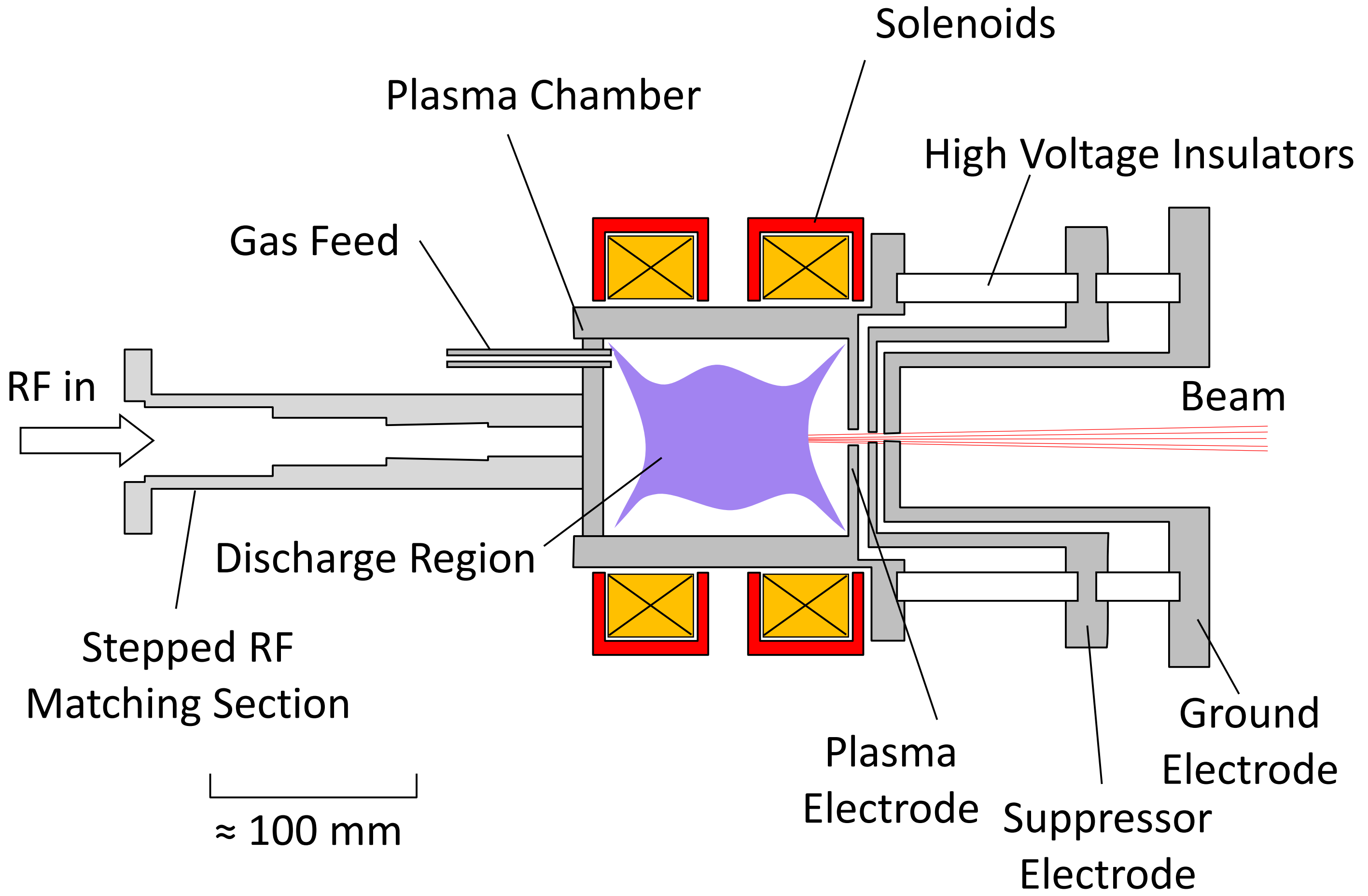
Off resonance

= Microwave discharge ion sources

On resonance

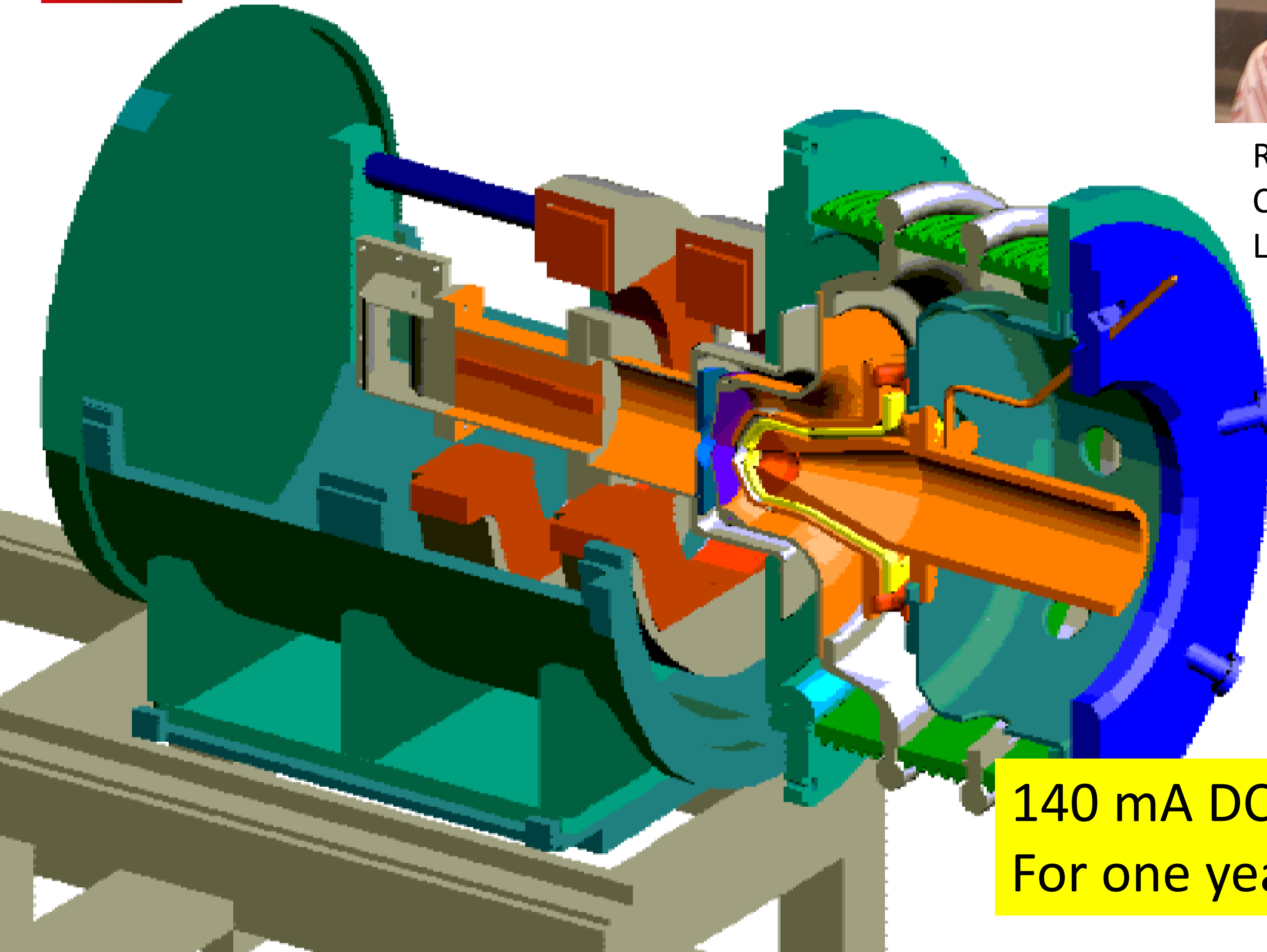
= Electron Cyclotron Resonance (ECR) sources

Microwave Discharge Ion Source



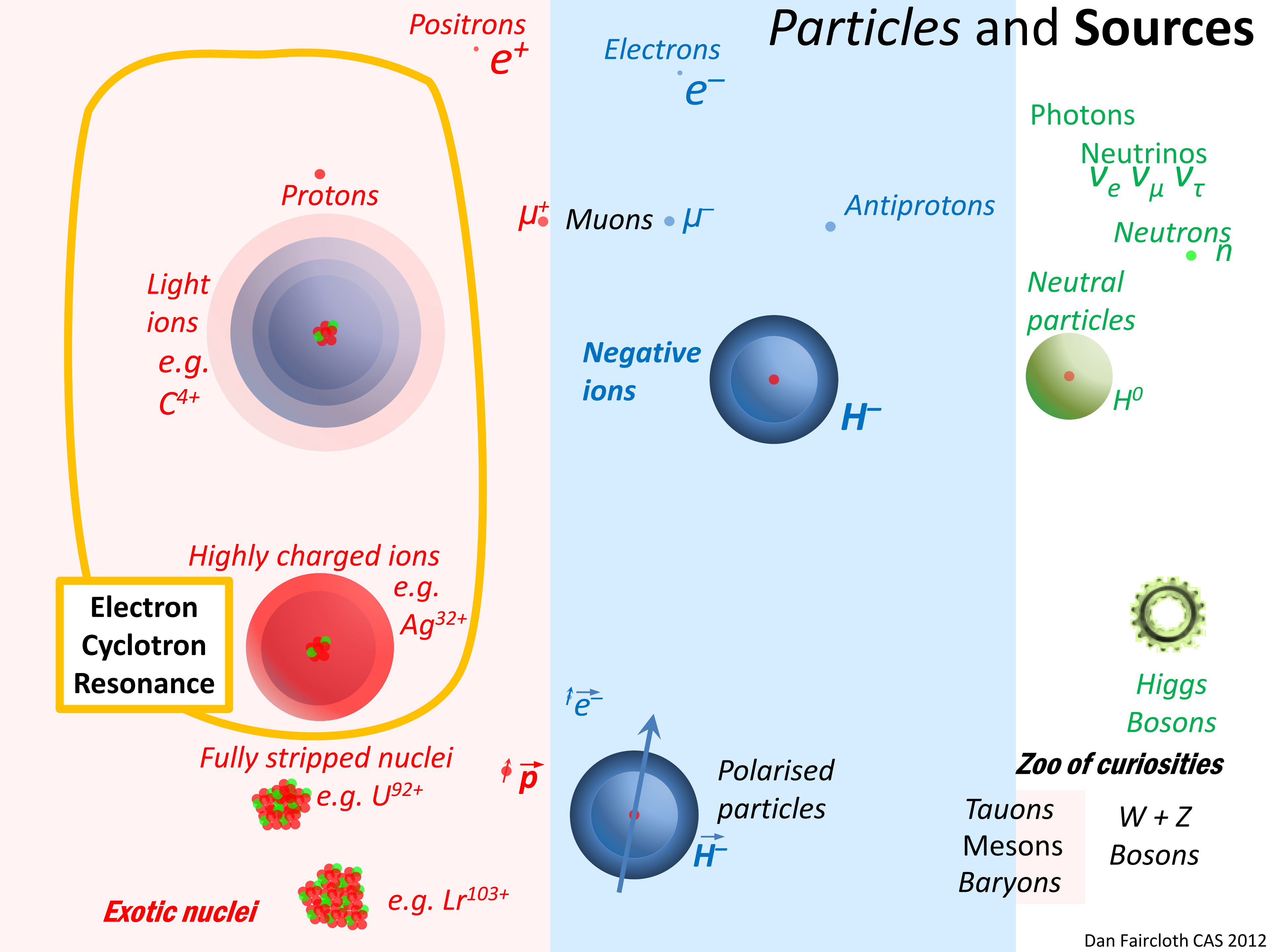
2.45 GHz commonly used

SILHI Microwave Source



Rafael Gobin
CEA Saclay
Late 1990s

140 mA DC protons
For one year!



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Fully stripped nuclei
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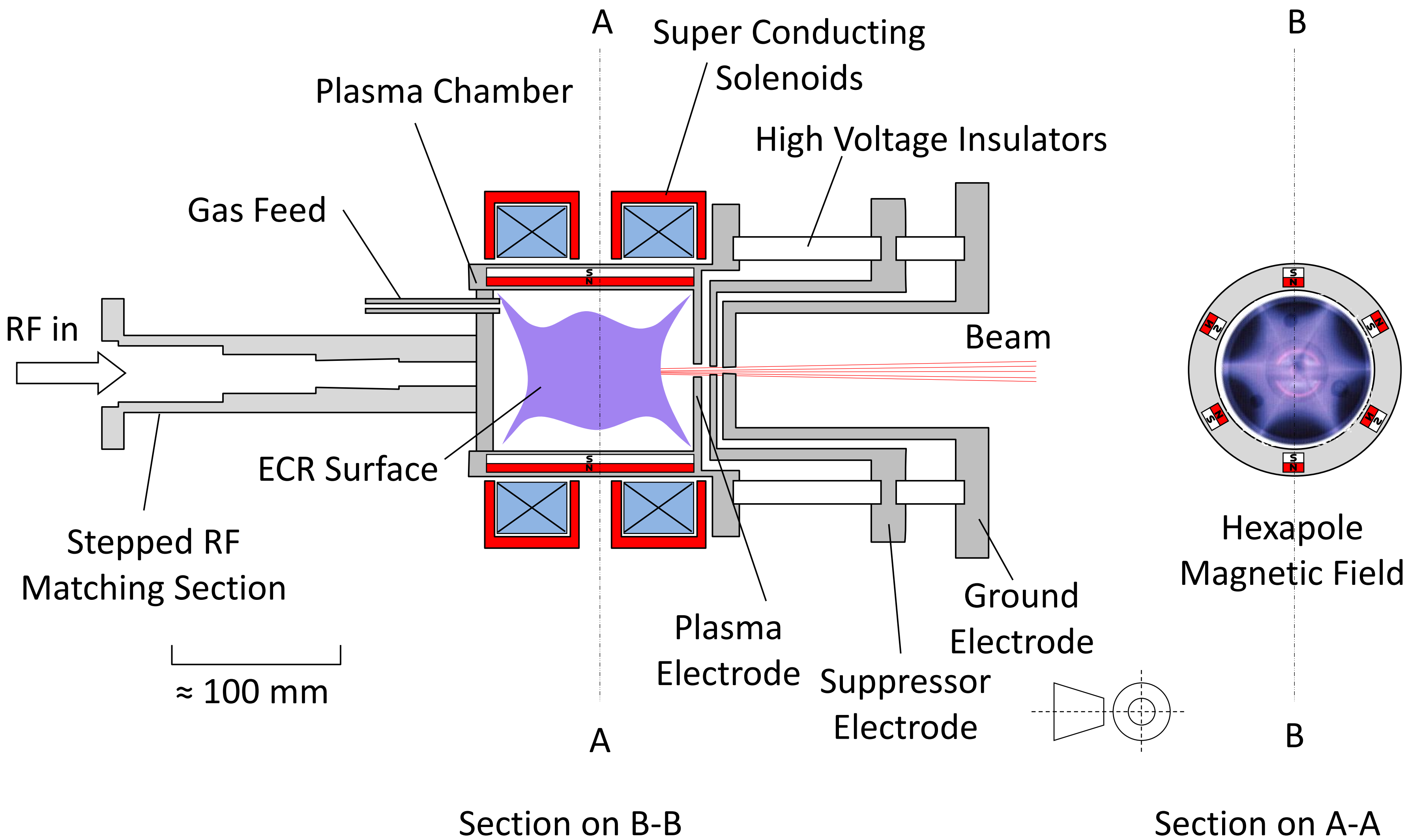
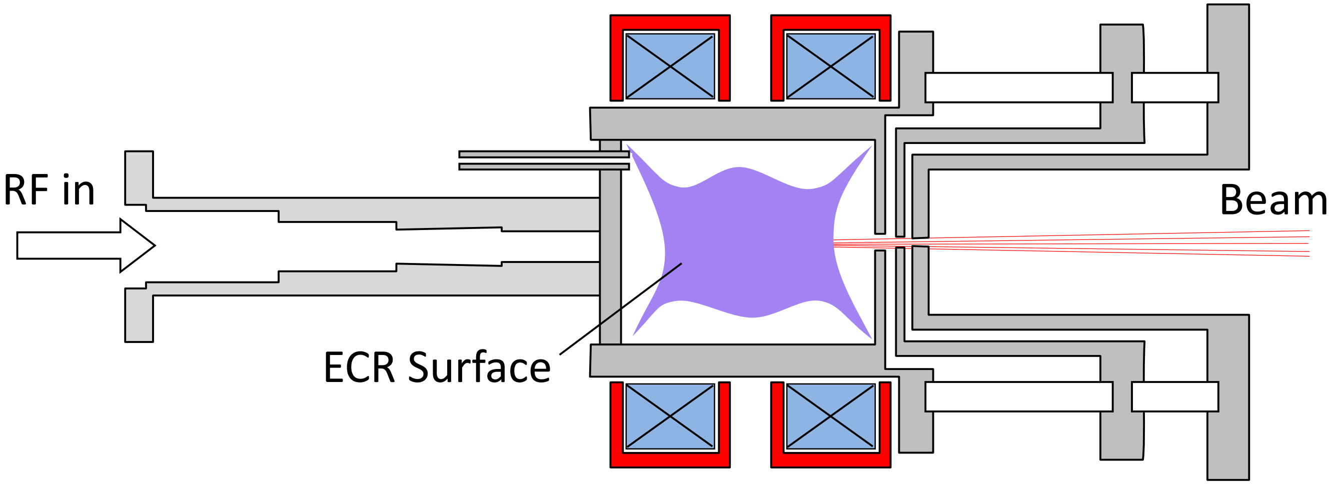
Polarised particles
Zoo of curiosities
Tauons
Mesons
Baryons
W + Z Bosons
H−
Exotic nuclei
e.g. Lr103+
Dan Faircloth CAS 2012

ECR Ion Source



ECR Surface



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

Higher frequency = higher charge states

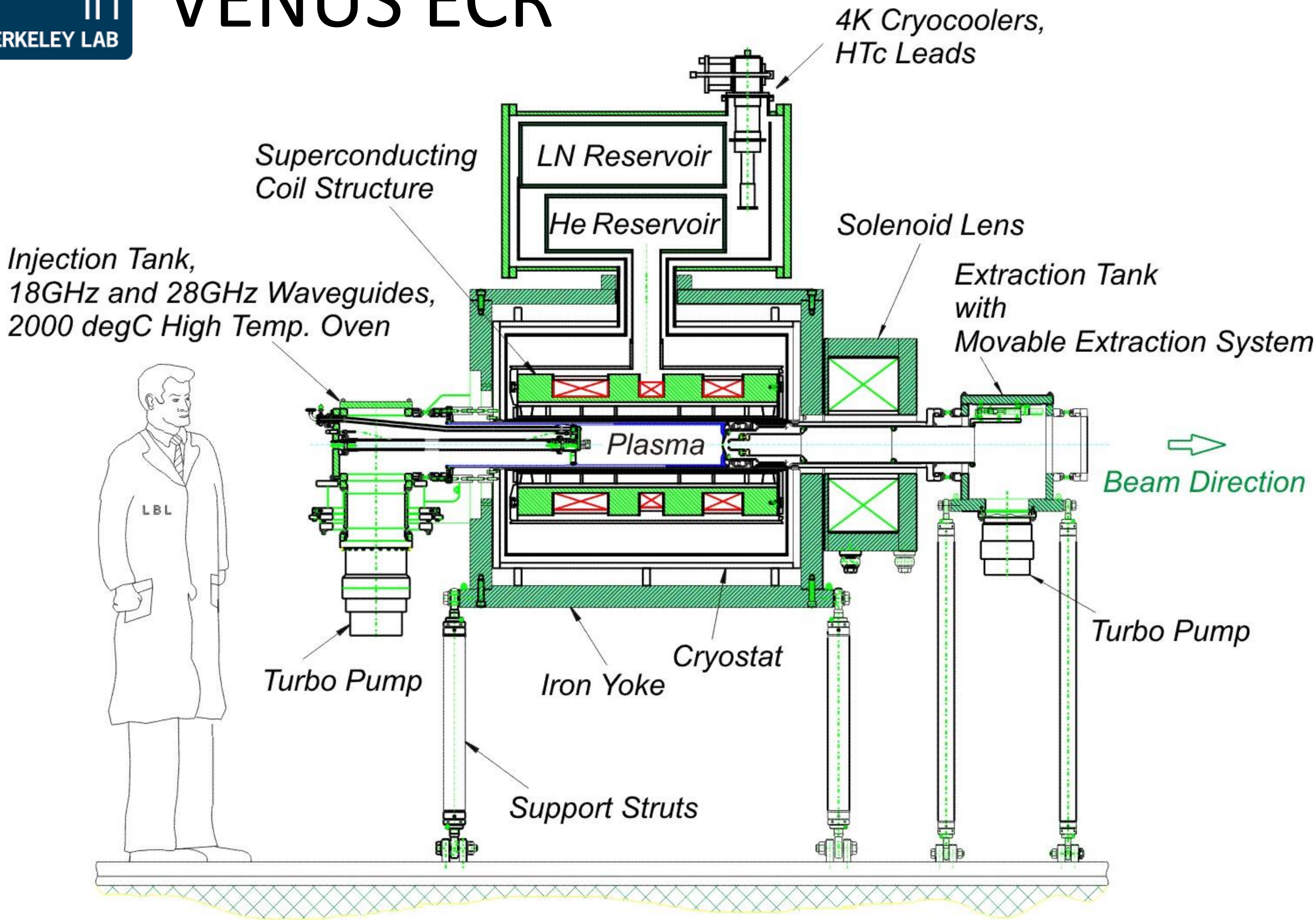
28 GHz superconducting VENUS ECR

Daniela Leitner
LBNL
Late 2000s

BERKELEY LAB

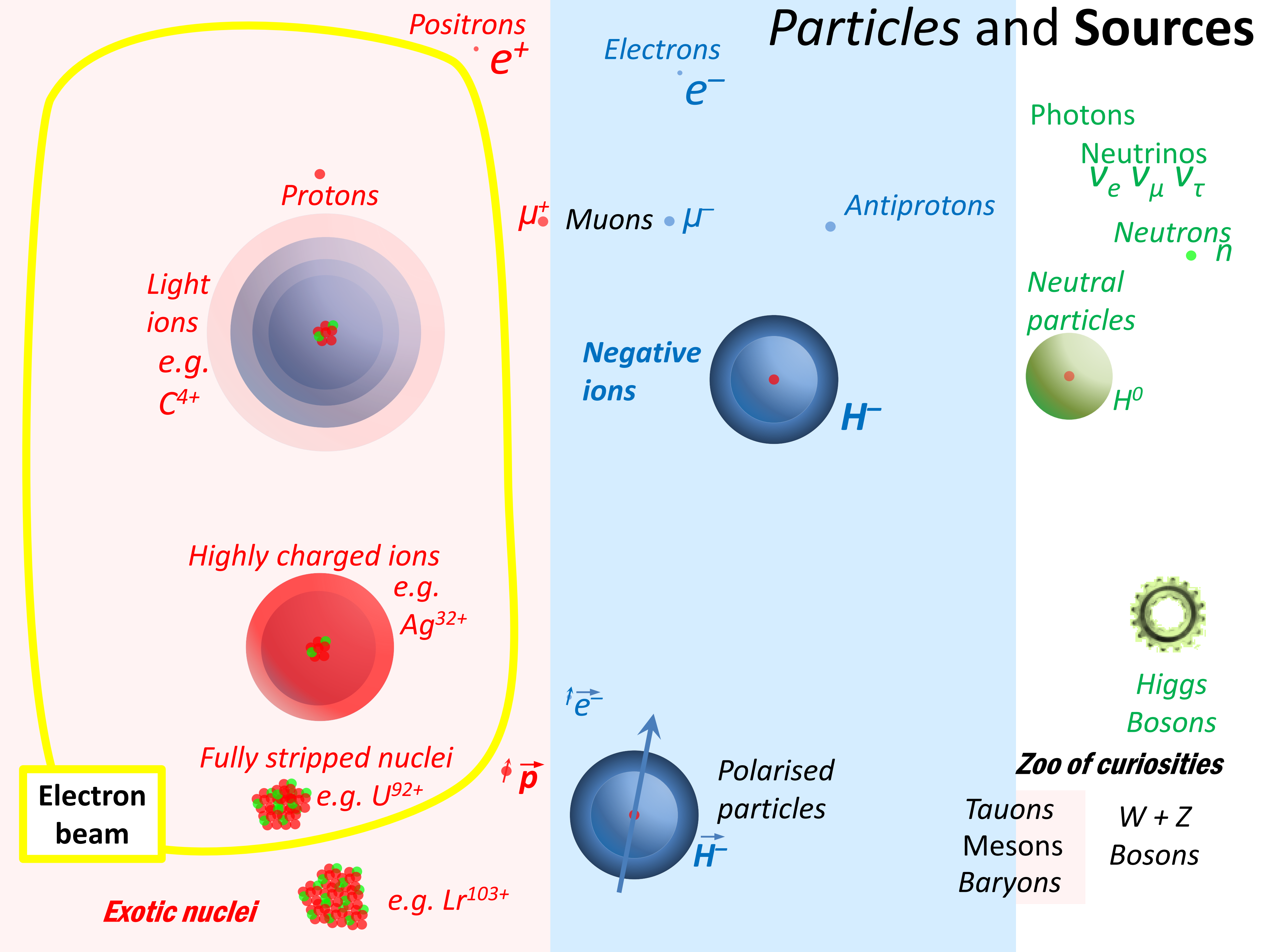
200 eμA U^{34+} ions
4.9 eμA U^{47+} ions

VENUS ECR

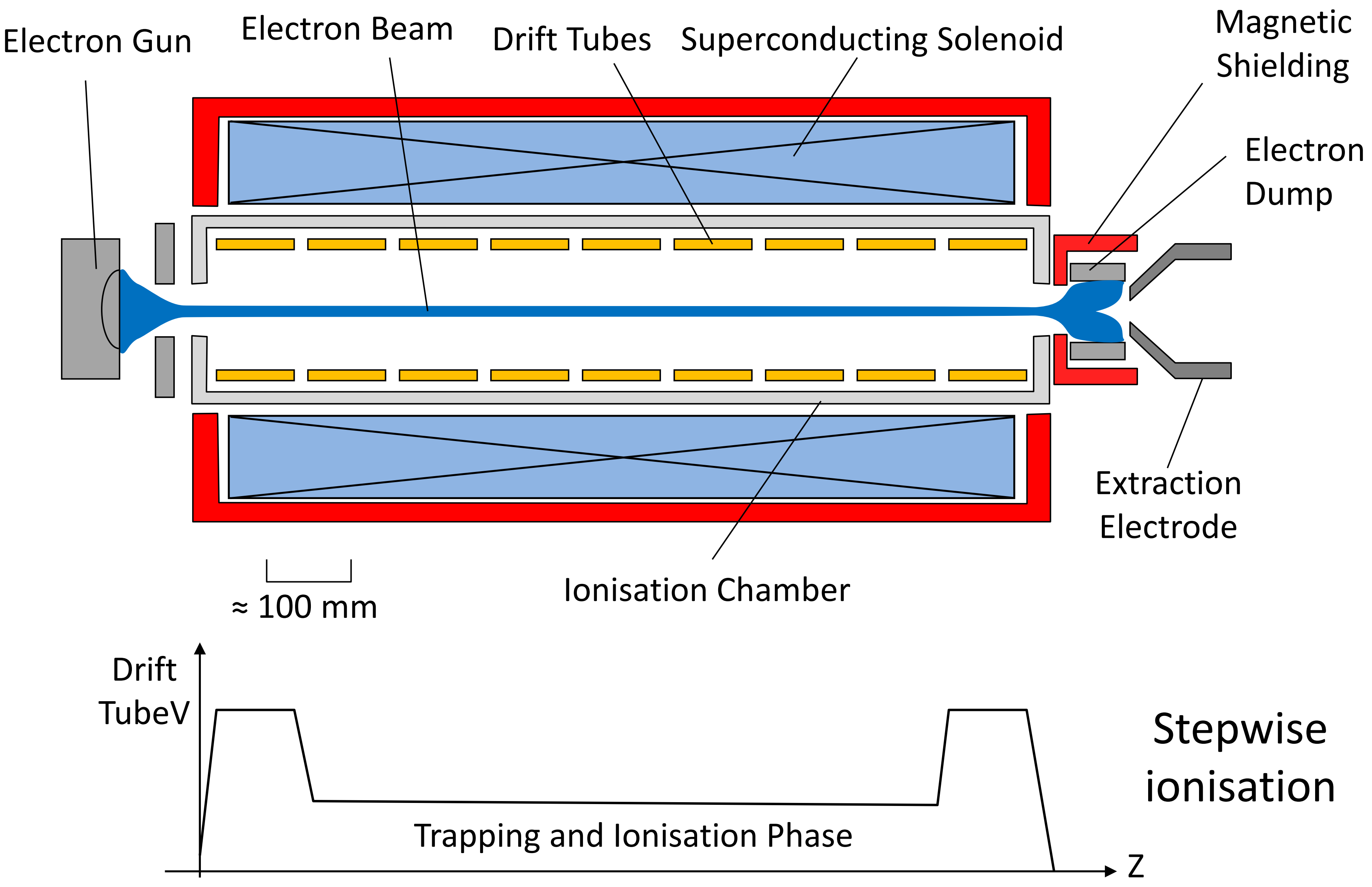


4K Cryocoolers,
HTc Leads
Superconducting
Coil Structure
LN Reservoir
He Reservoir
Solenoid Lens
Injection Tank,
18GHz and 28GHz Waveguides,
2000 degC High Temp. Oven
Extraction Tank
with
Movable Extraction System
LBL
Plasma
Beam Direction
Turbo Pump
Cryostat
Iron Yoke
Turbo Pump
Support Struts

Particles and Sources

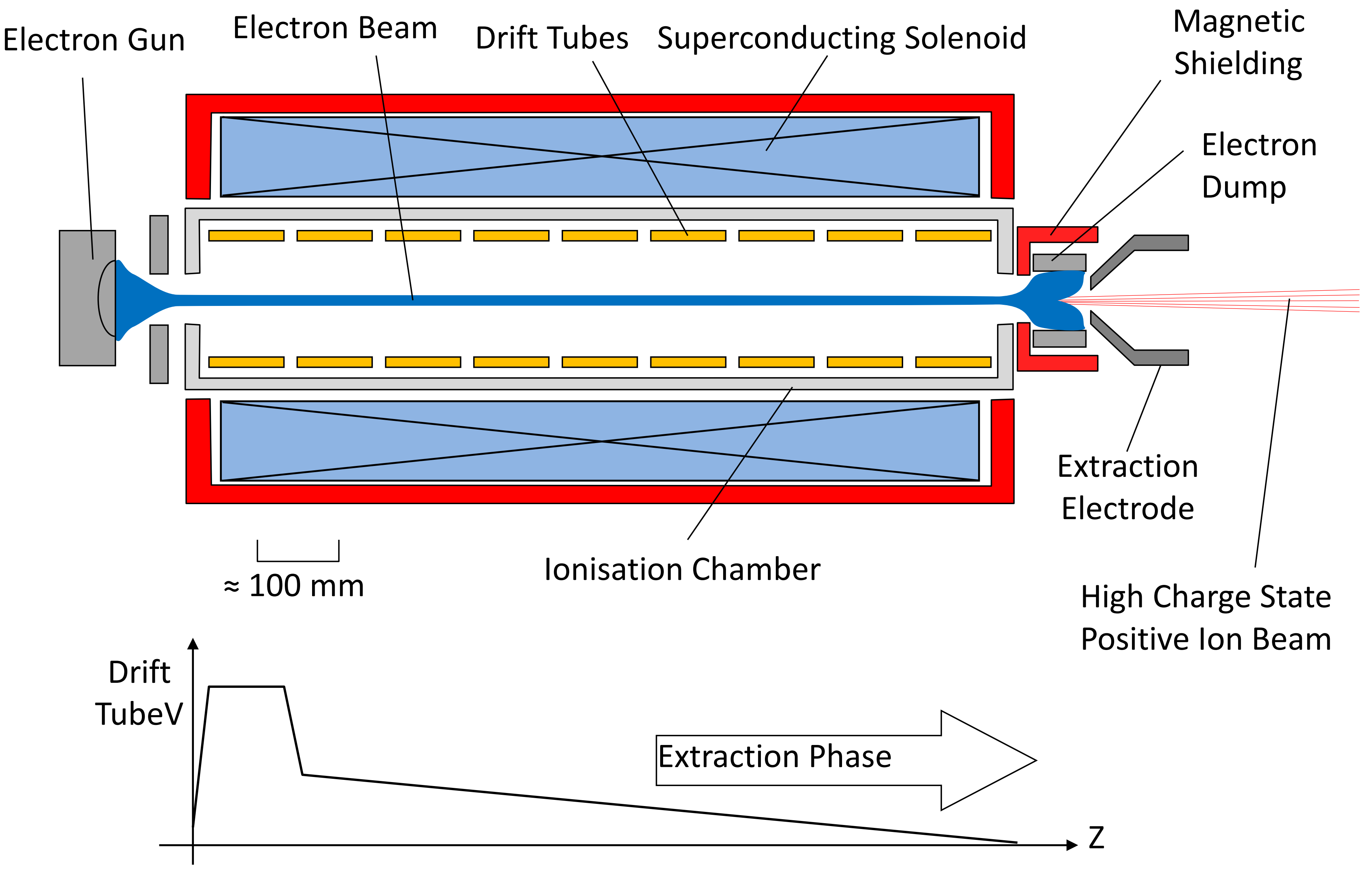


Electron Beam Ion Sources

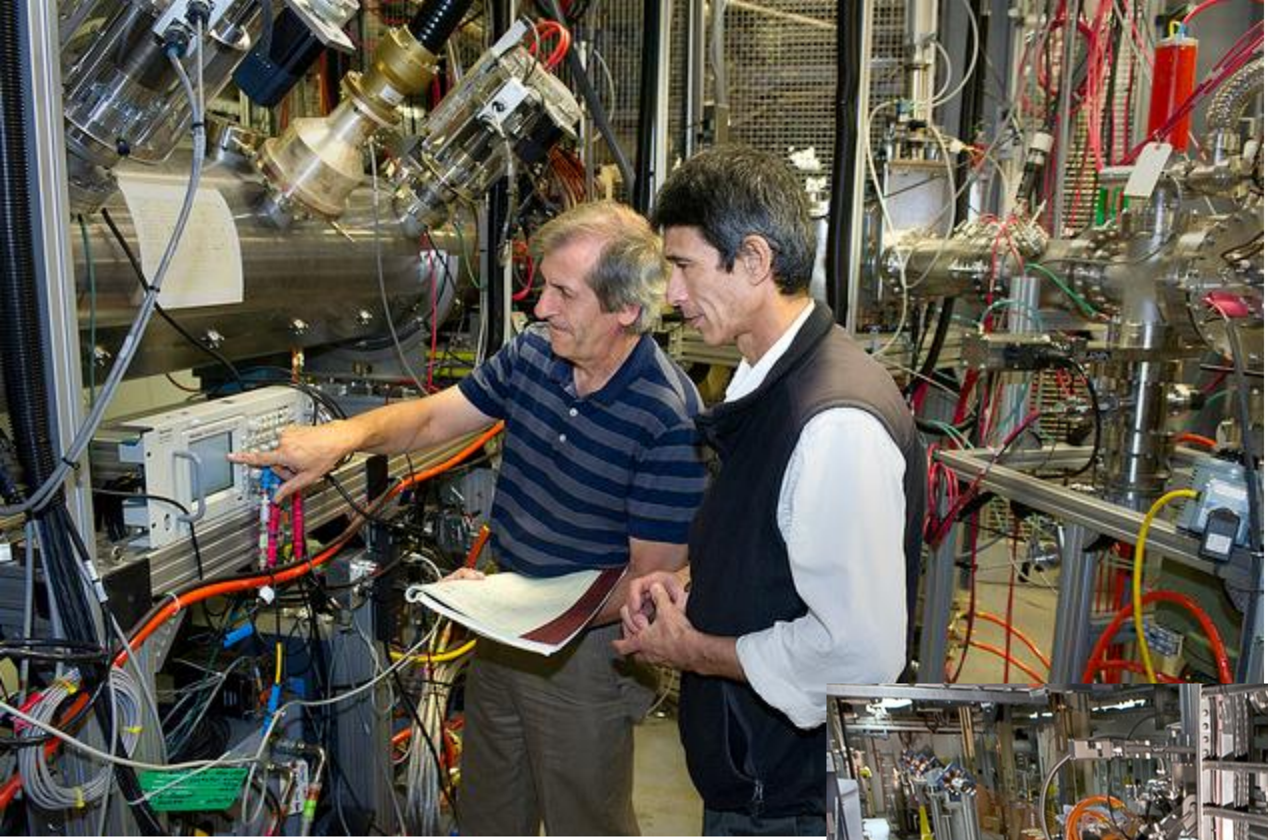


Stepwise ionisation

Electron Beam Ion Sources



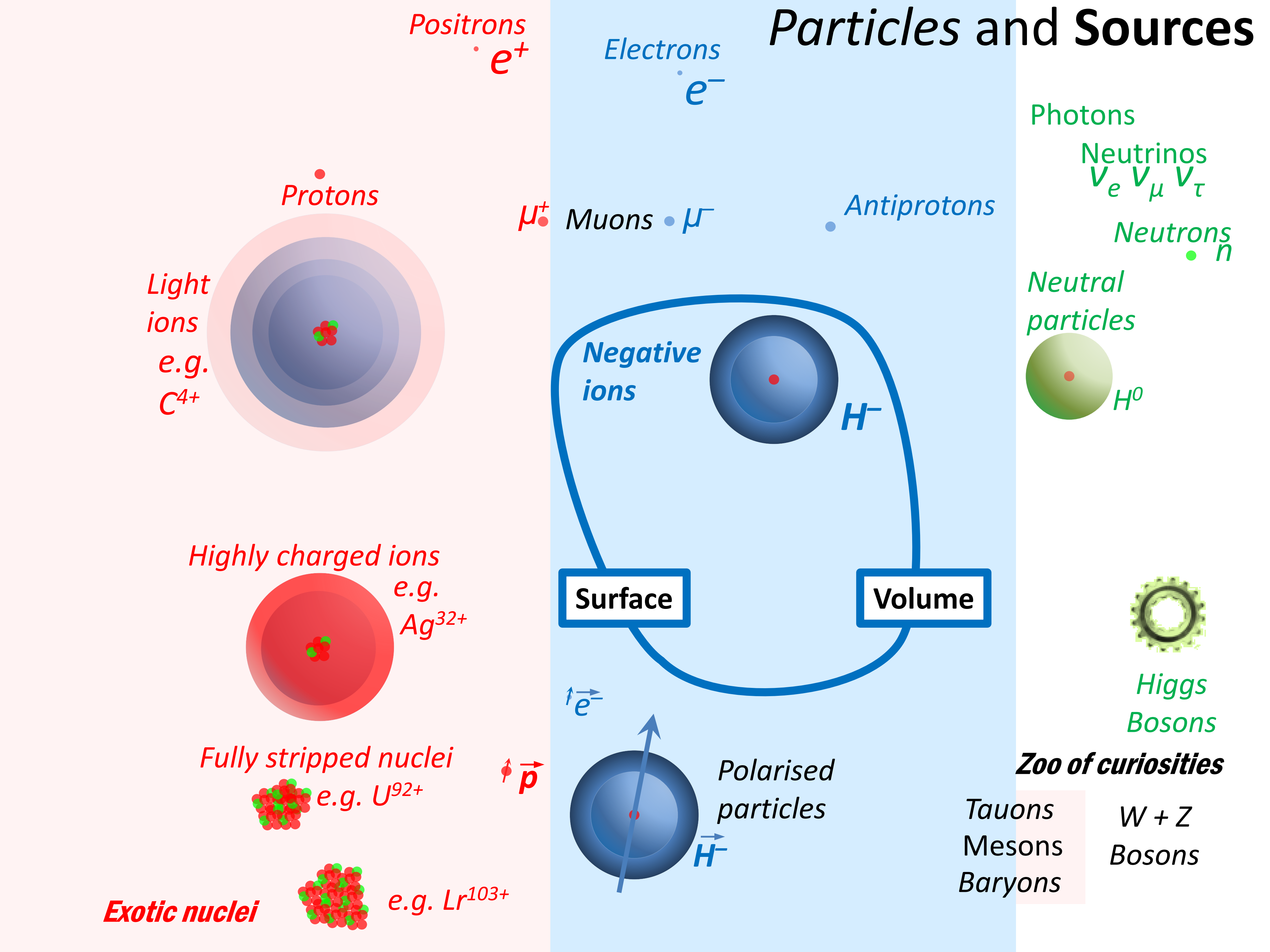
BROOKHAVEN
NATIONAL LABORATORY



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

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 much larger cross sections than H^0

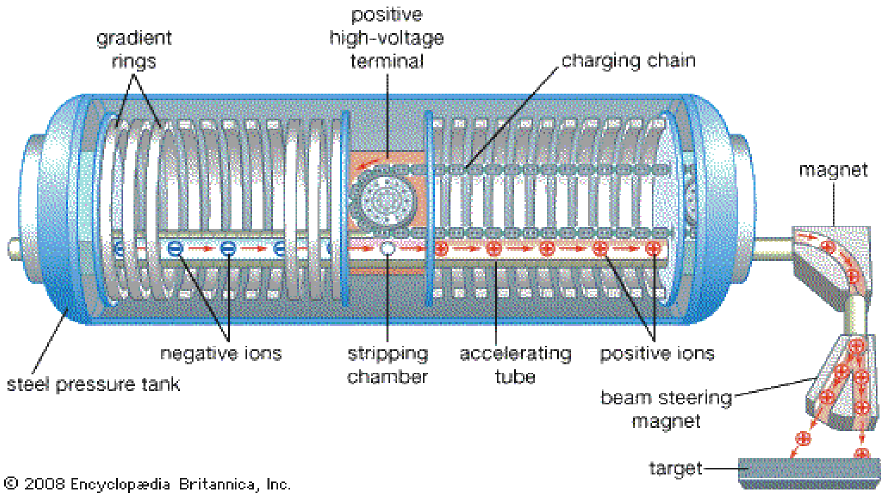
Up to 30 times for e^- collisions

Up to 100 times for H^+ collisions

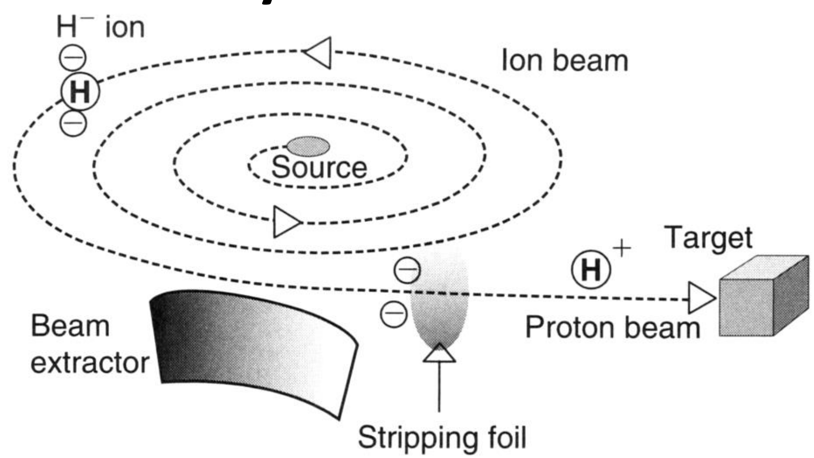
H^- are very fragile!

Applications

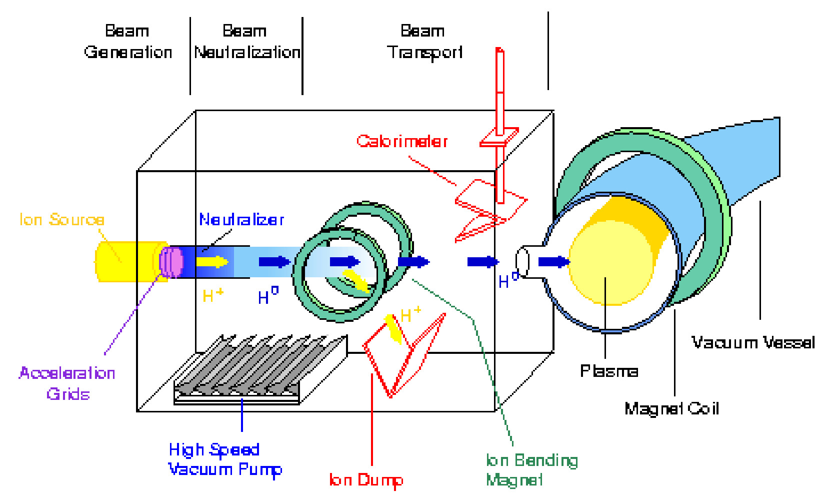
Tandem accelerators



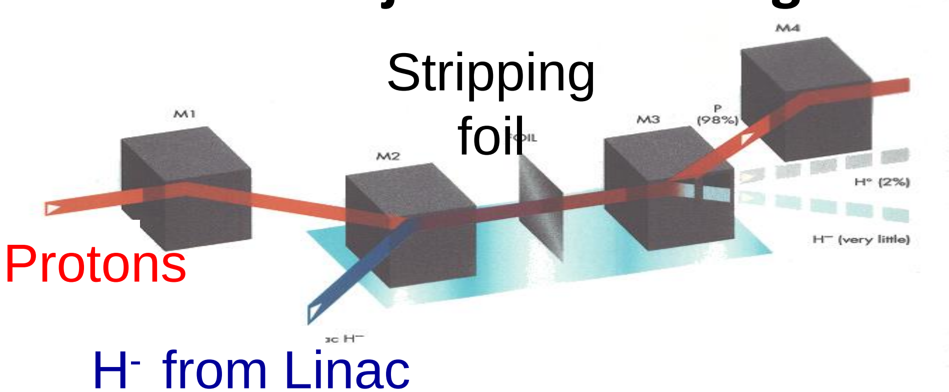
Cyclotron extraction



Neutral Beams



Multi-turn injection into rings

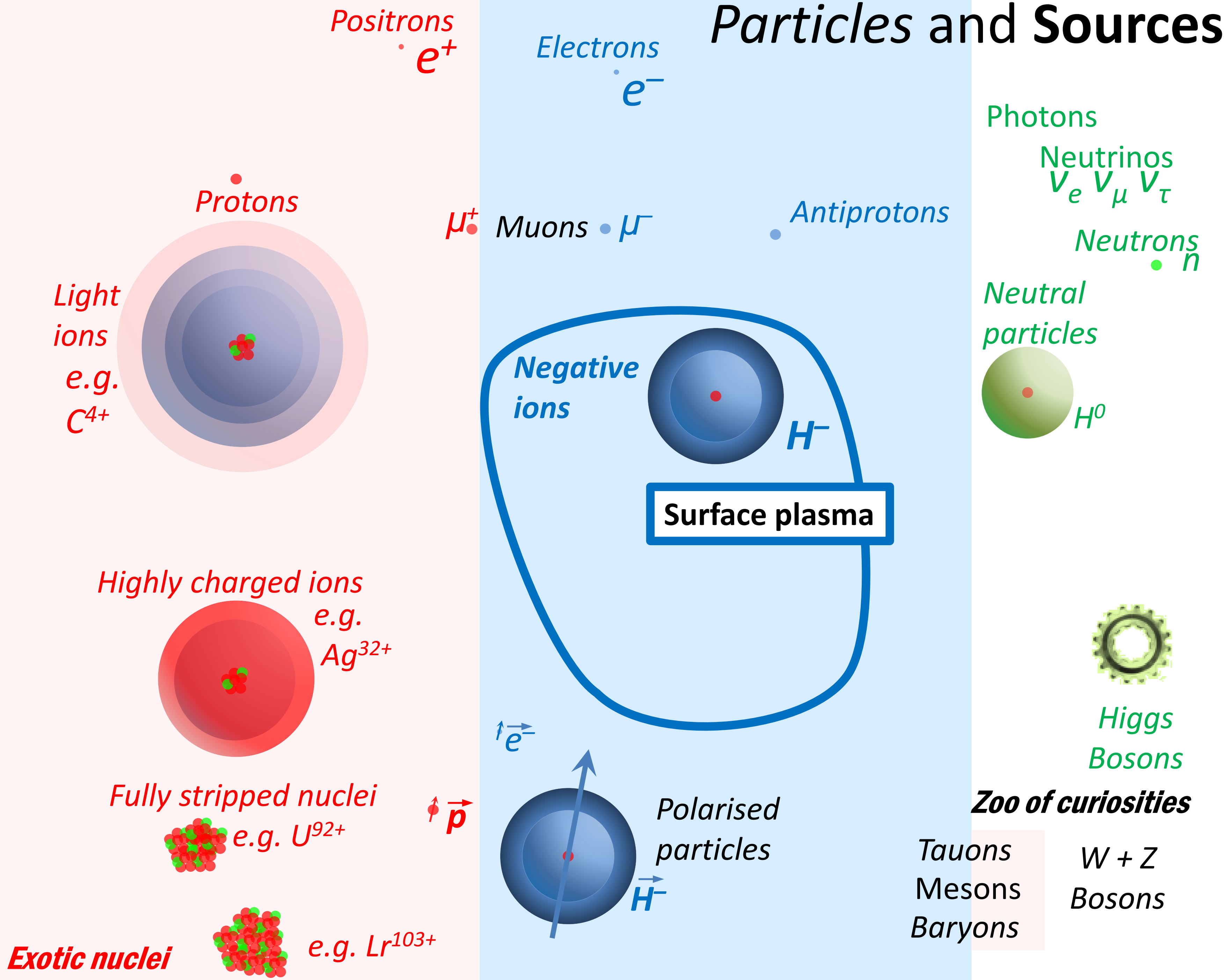


Early attempts at producing negative ion beams:

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

2. Extraction from existing ion sources
   - mostly electrons extracted

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)

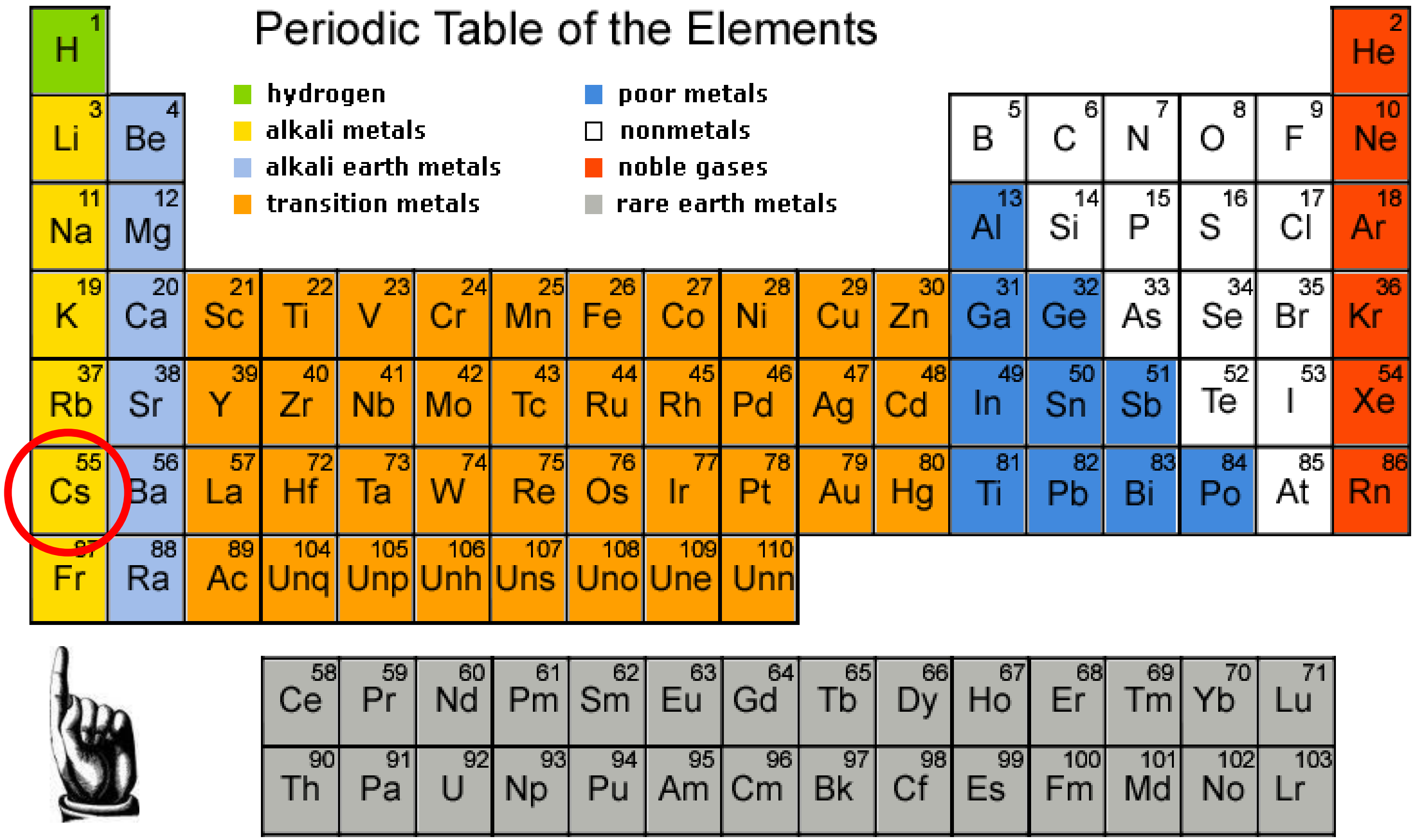
Gennady Dimov

Yuri Belchenko

Vadim Dudnikov

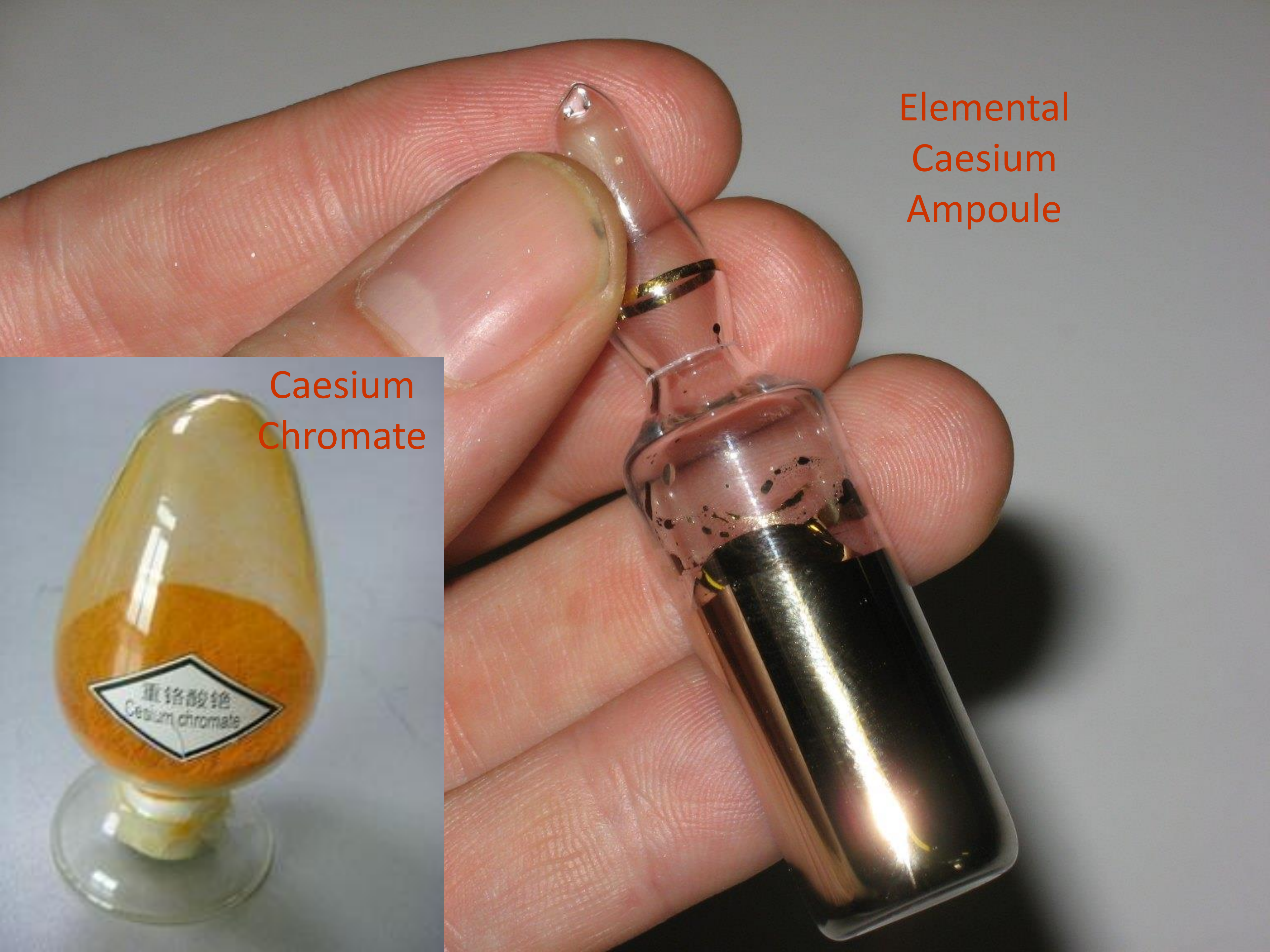
Caesium! – The magic elixir

More reactive

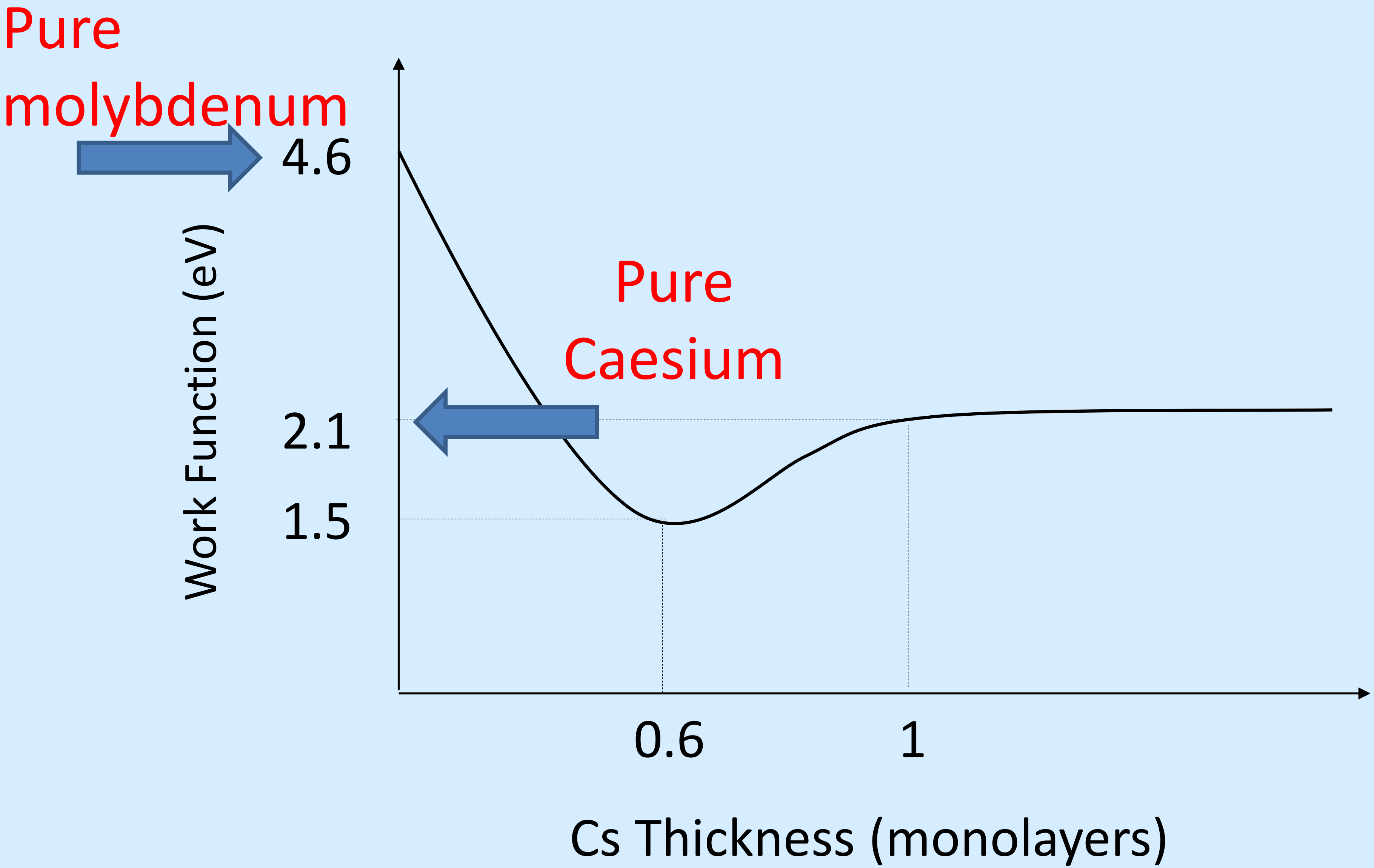


1 electron in the outer orbital

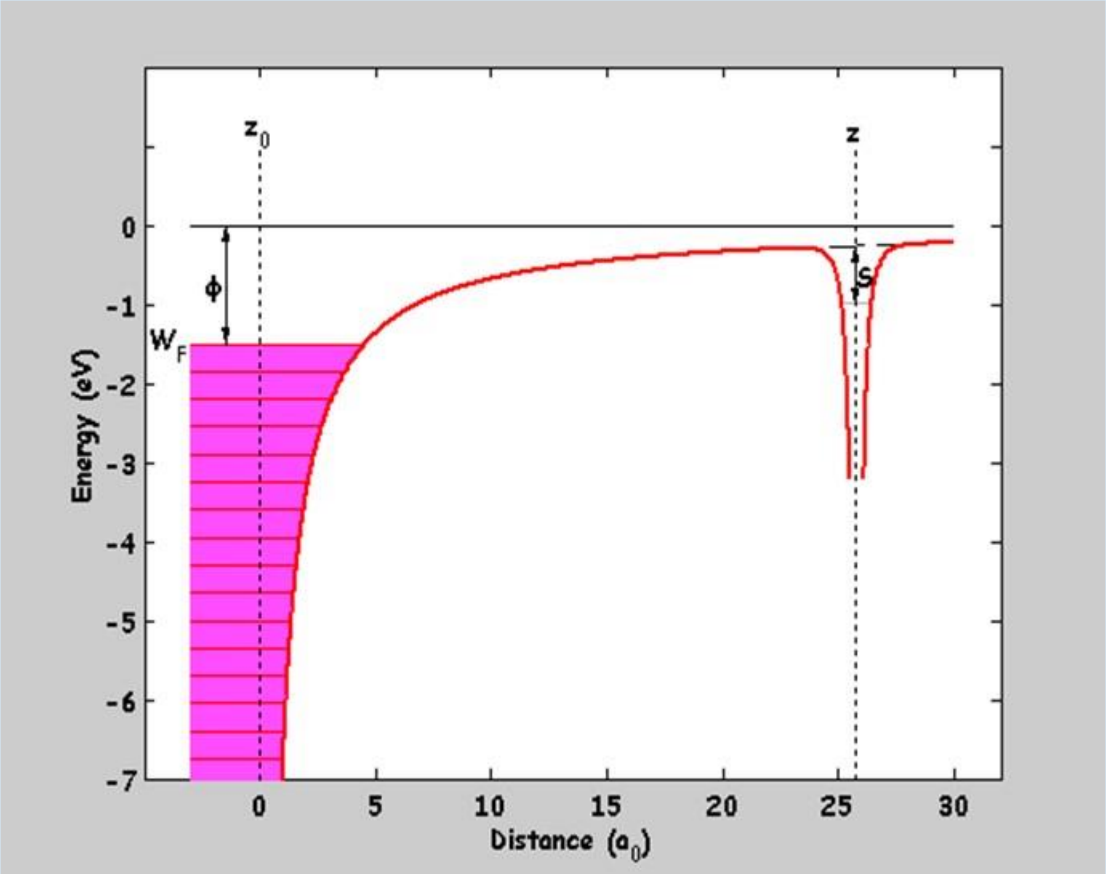
An amazing donor of electrons
= great for making negative ions

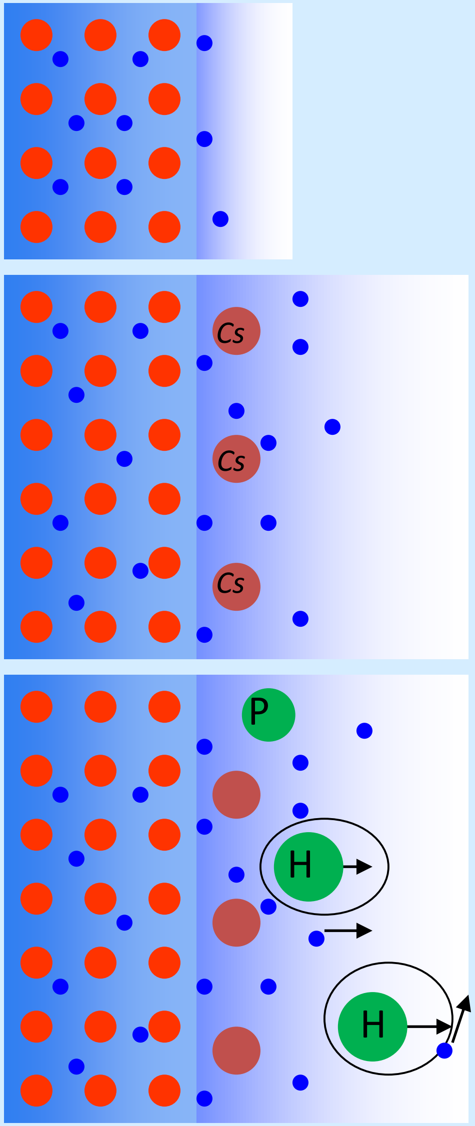

Elemental
Caesium
Ampoule
Caesium
Chromate
Cesium chromate

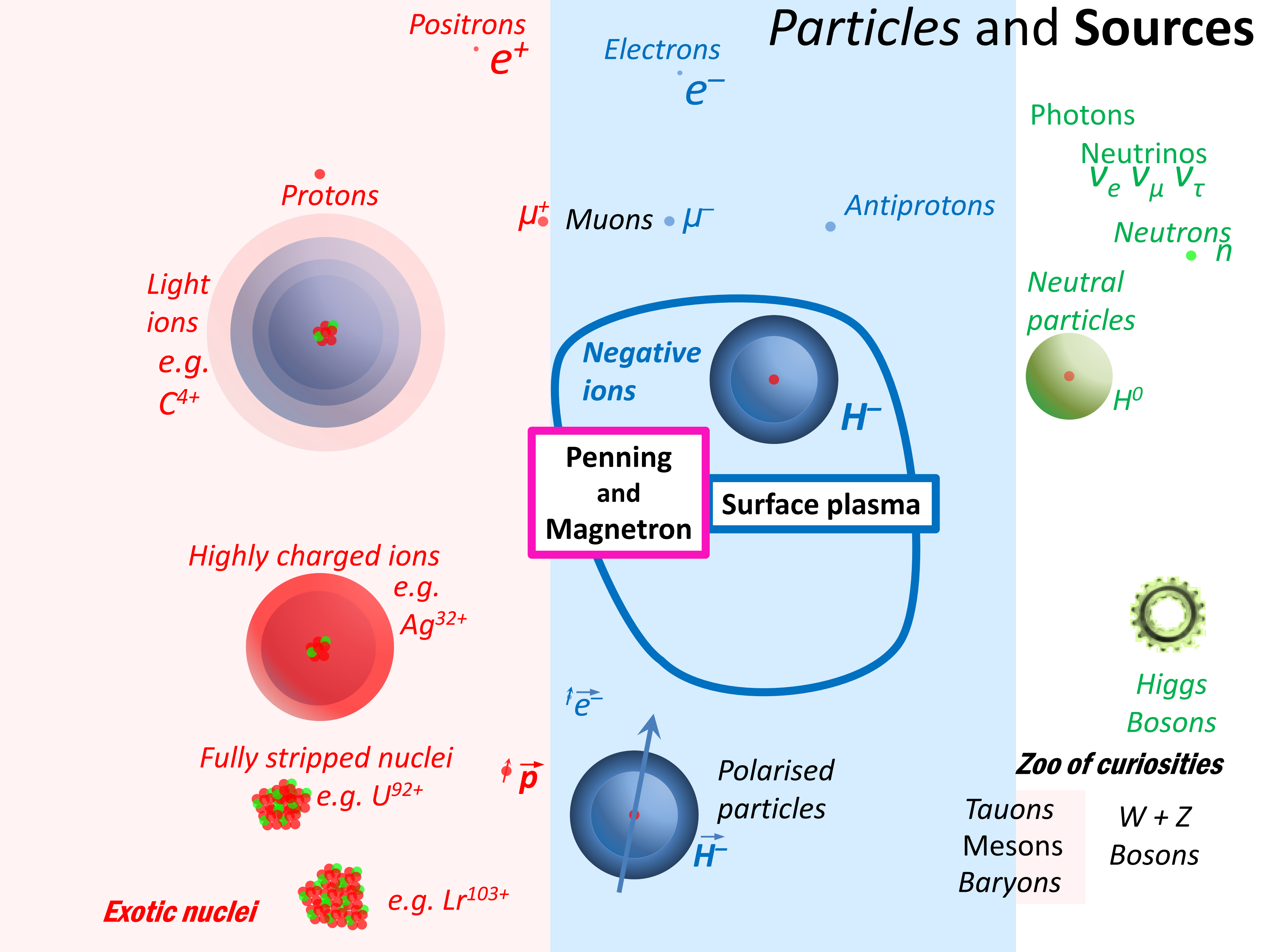
Caesium coverage and work function



Fermilevels



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Exotic nuclei
e.g. Lr103+

Early 1970s Budker Institute of Nuclear Physics Novosibirsk

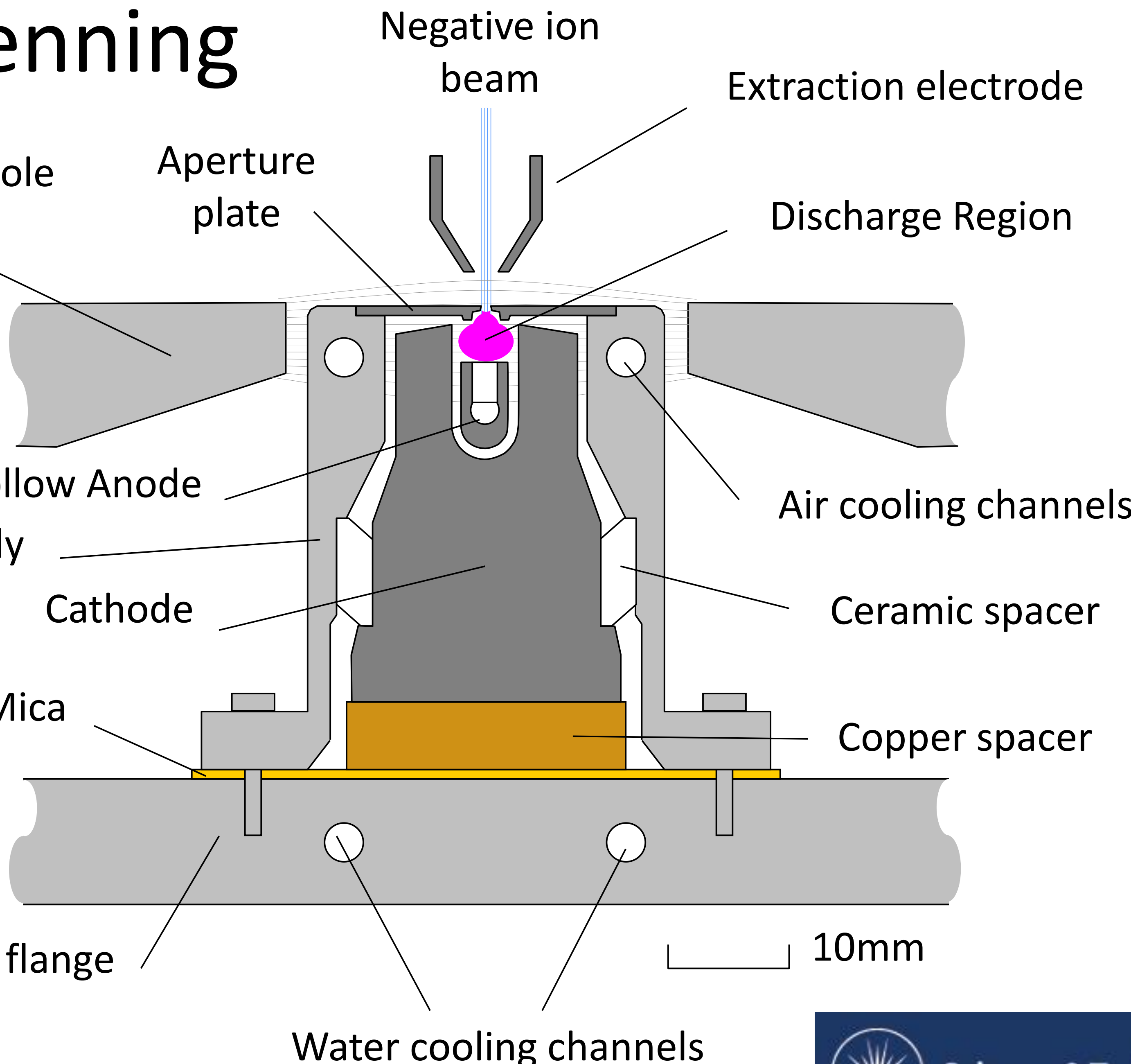
Vadim Dudnikov

Penning SPS

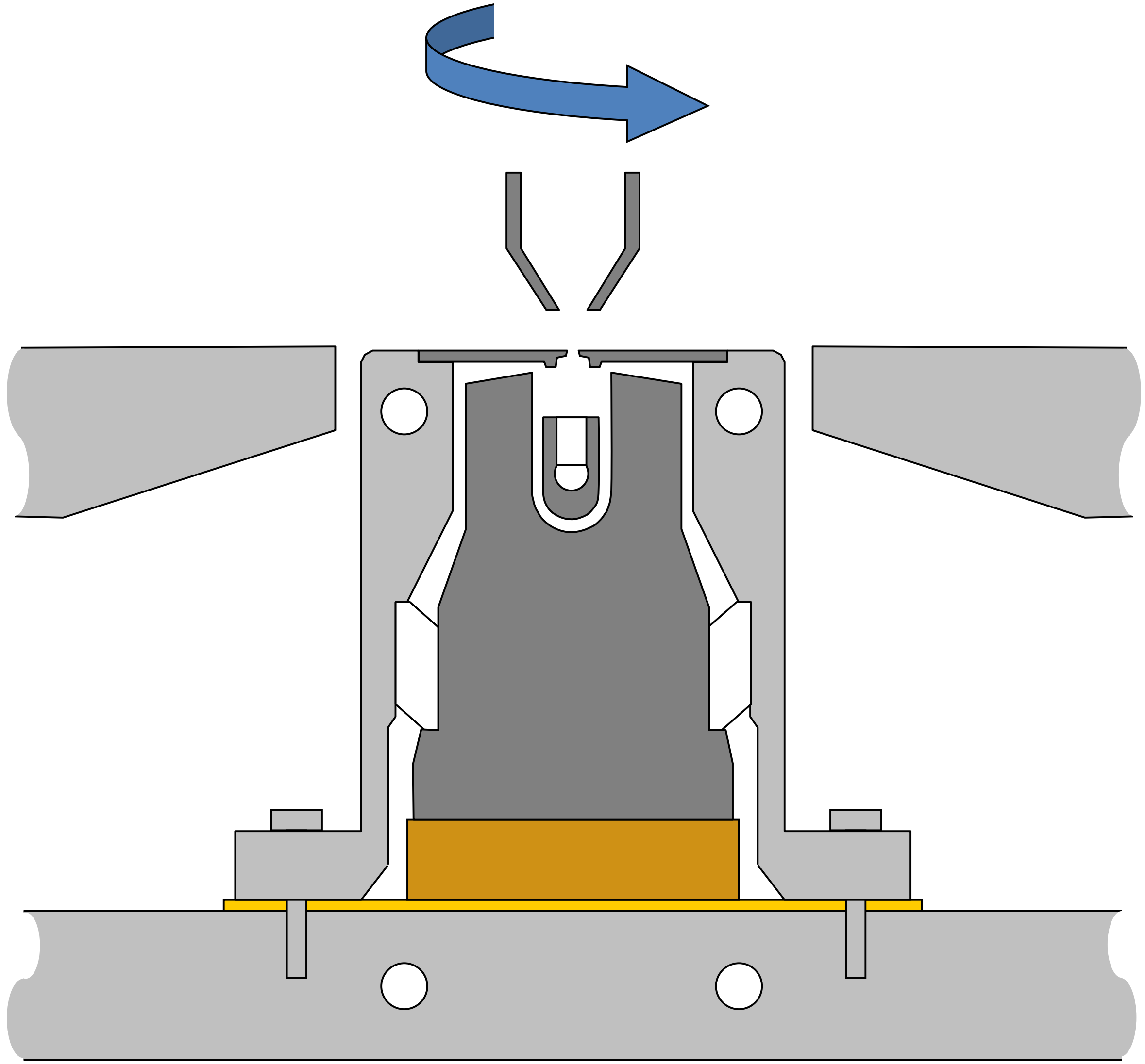
Very high current density > 1 Acm^{-2}

Low noise

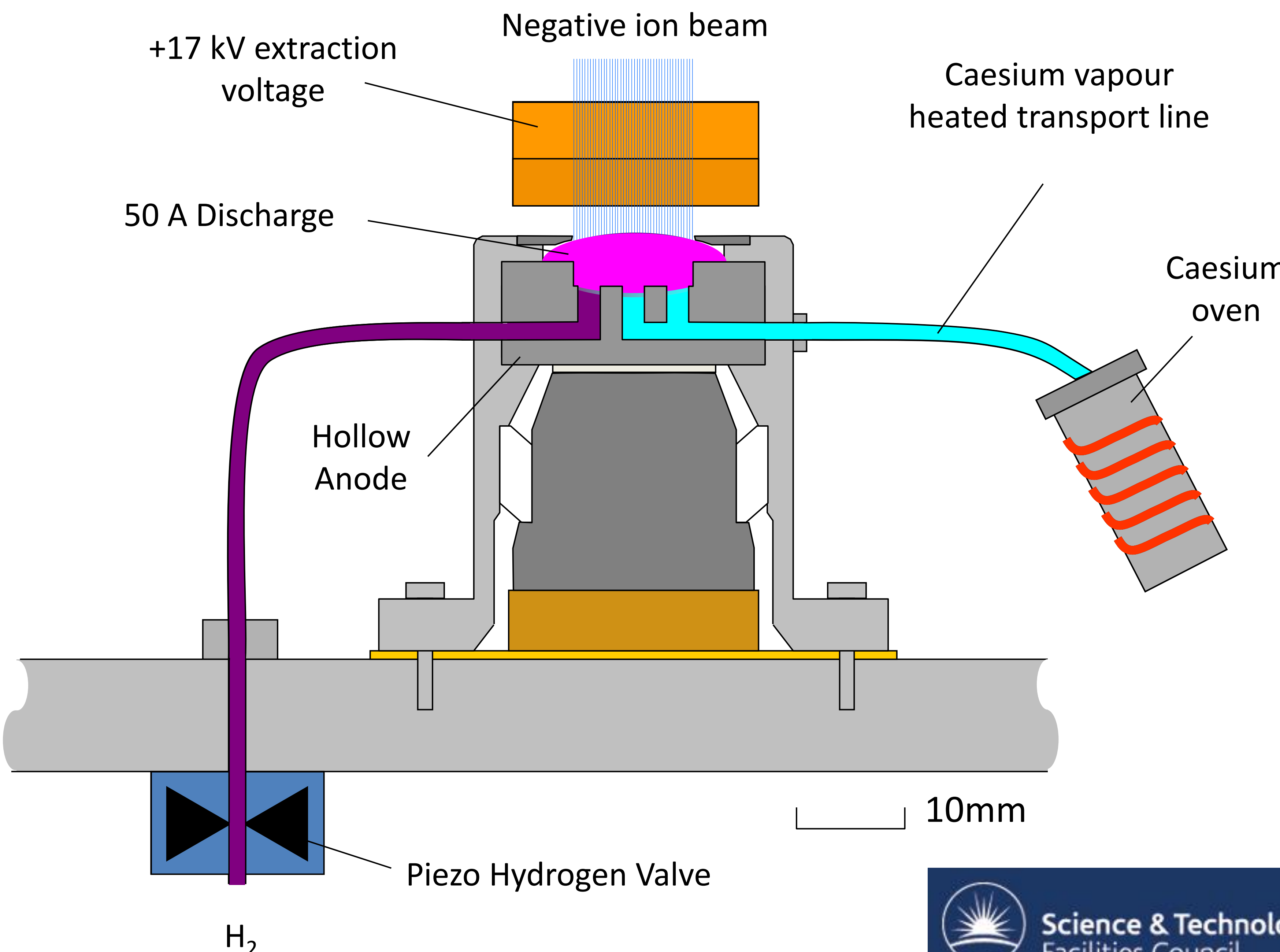
ISIS Penning



Science & Technology Facilities Council



Science & Technology
Facilities Council



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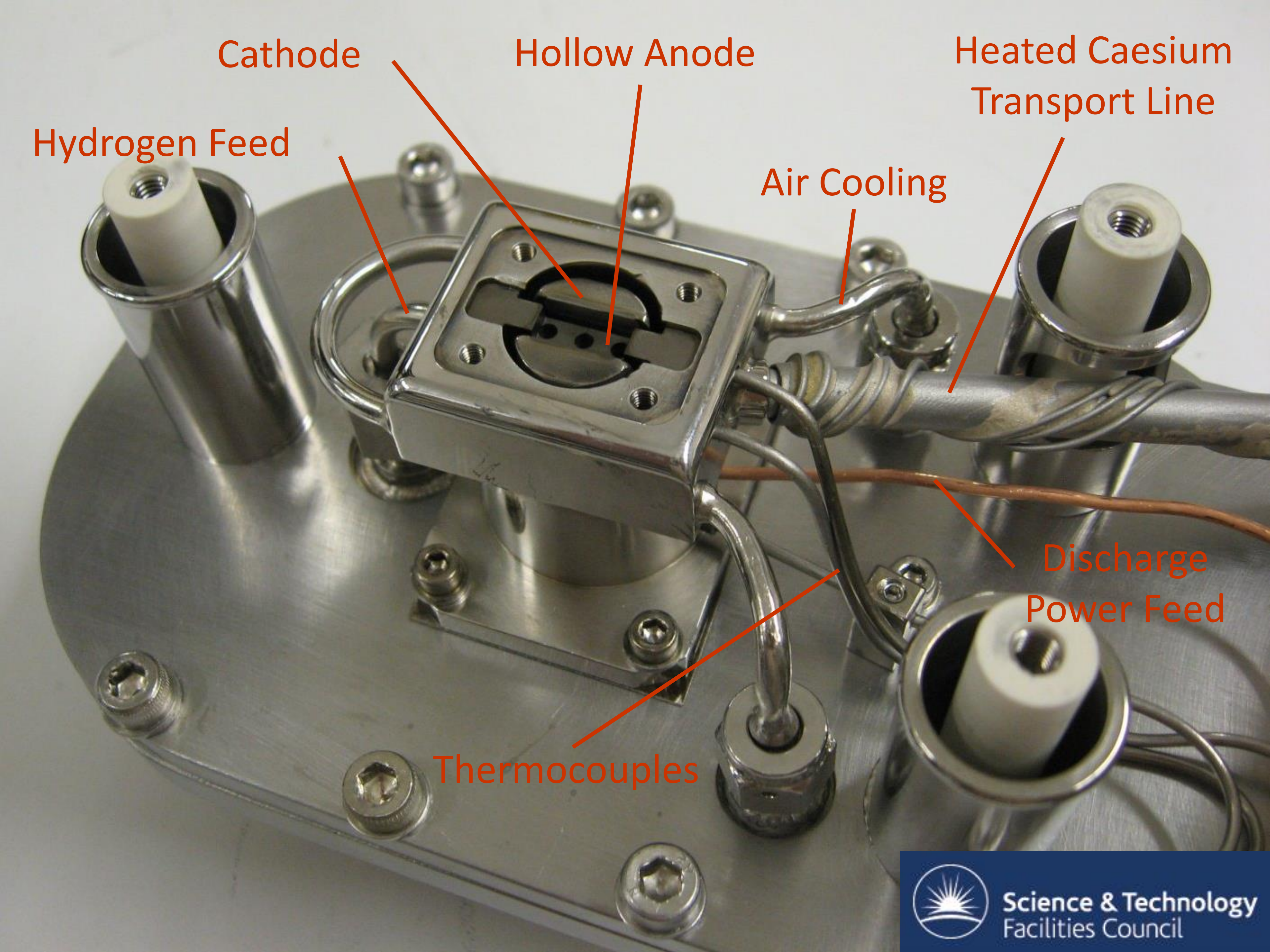

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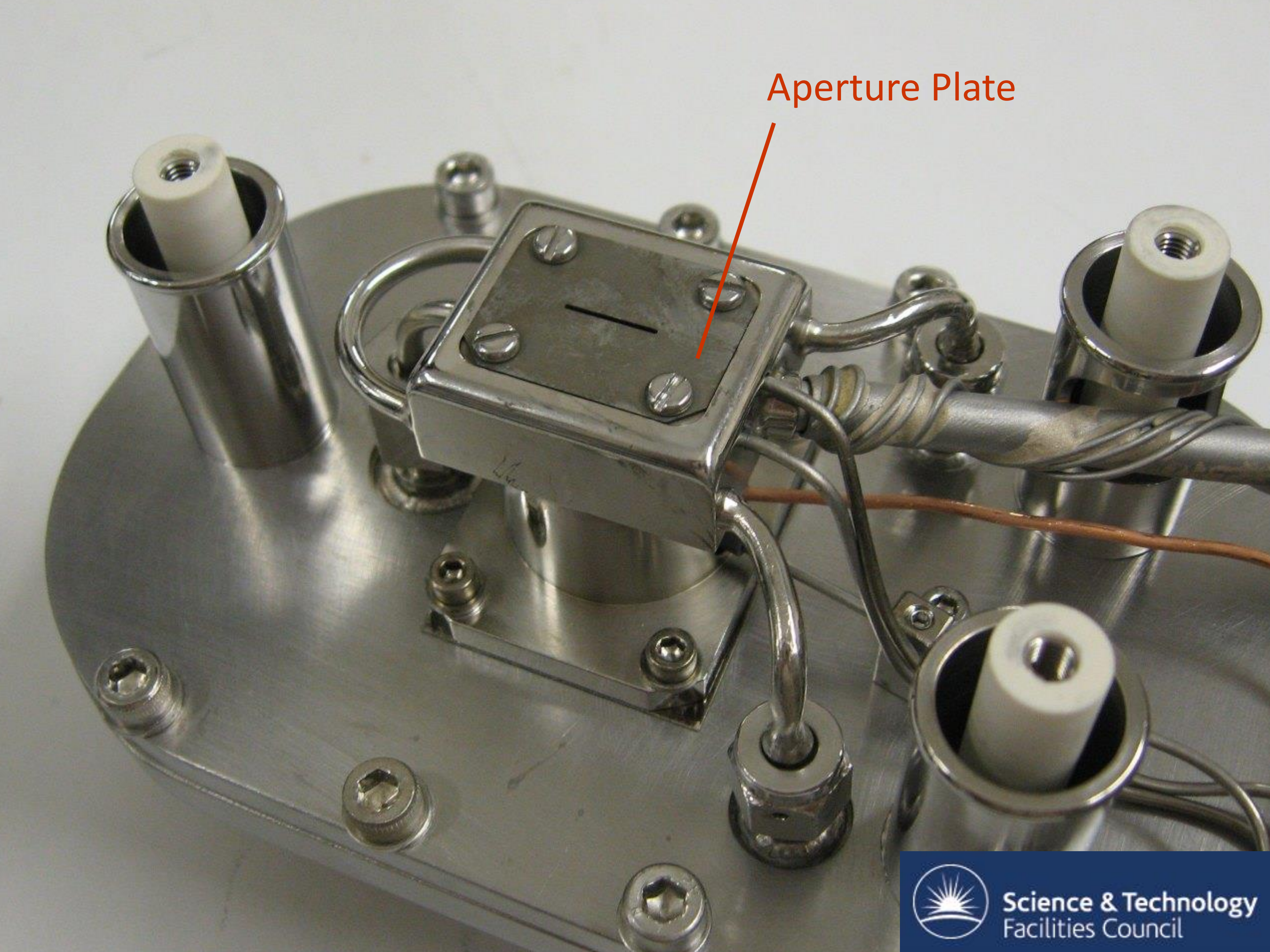

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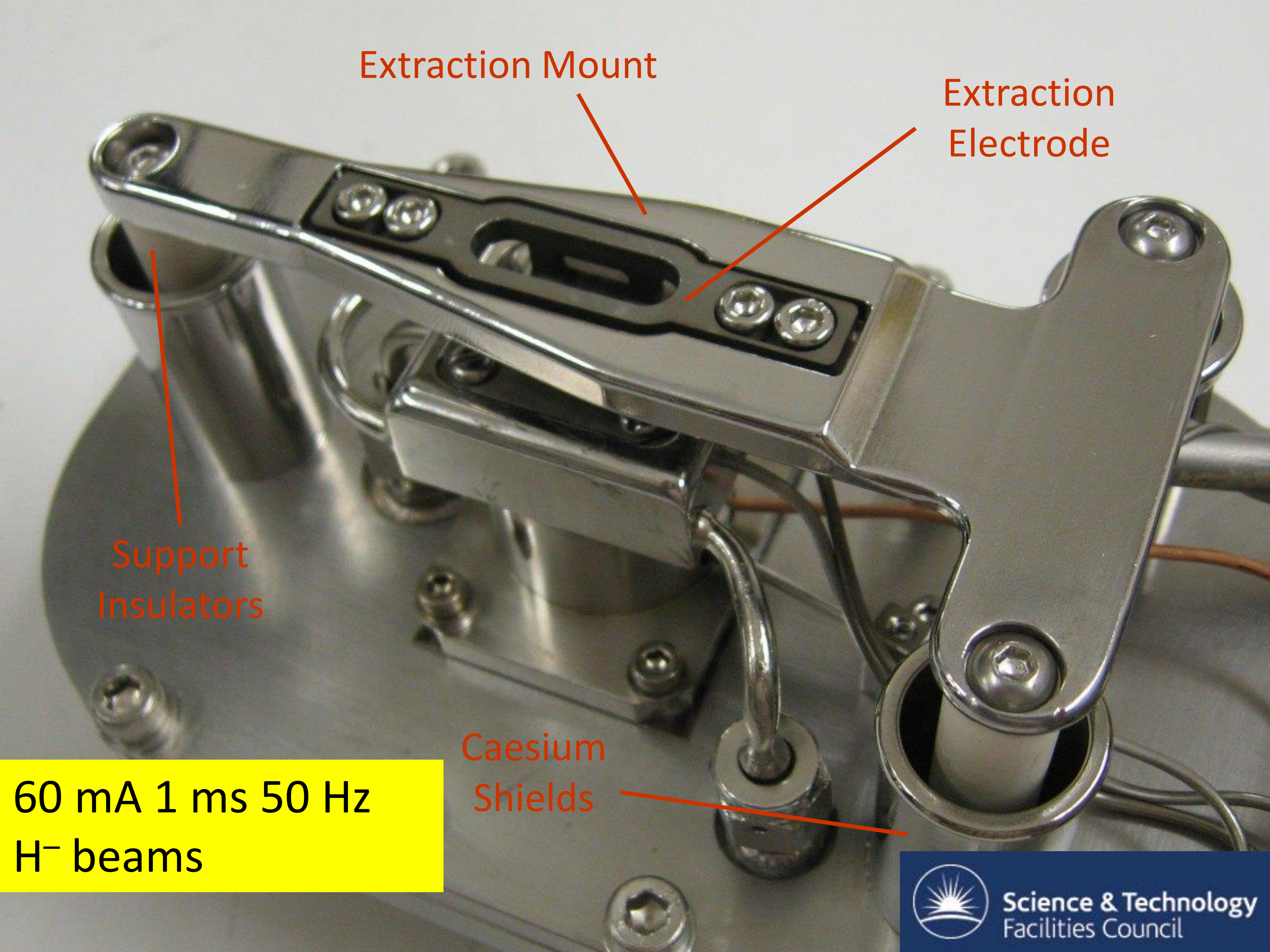


60 mA 1 ms 50 Hz
H^- beams

Early 1970s Budker Institute of Nuclear Physics Novosibirsk

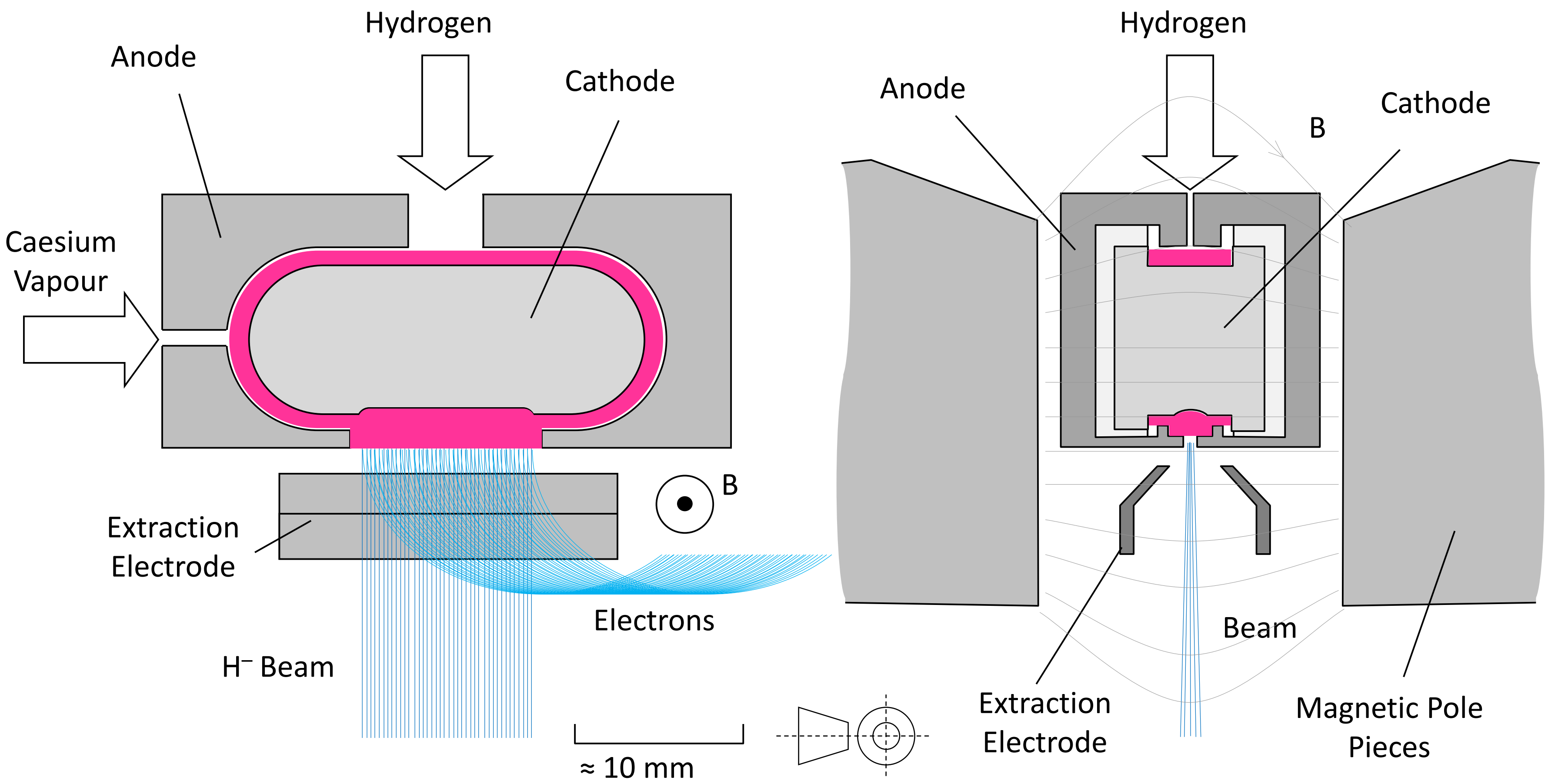
Magnetron SPS

Gennady Dimov

Yuri Belchenko

Vadim Dudnikov

Magnetron SPS



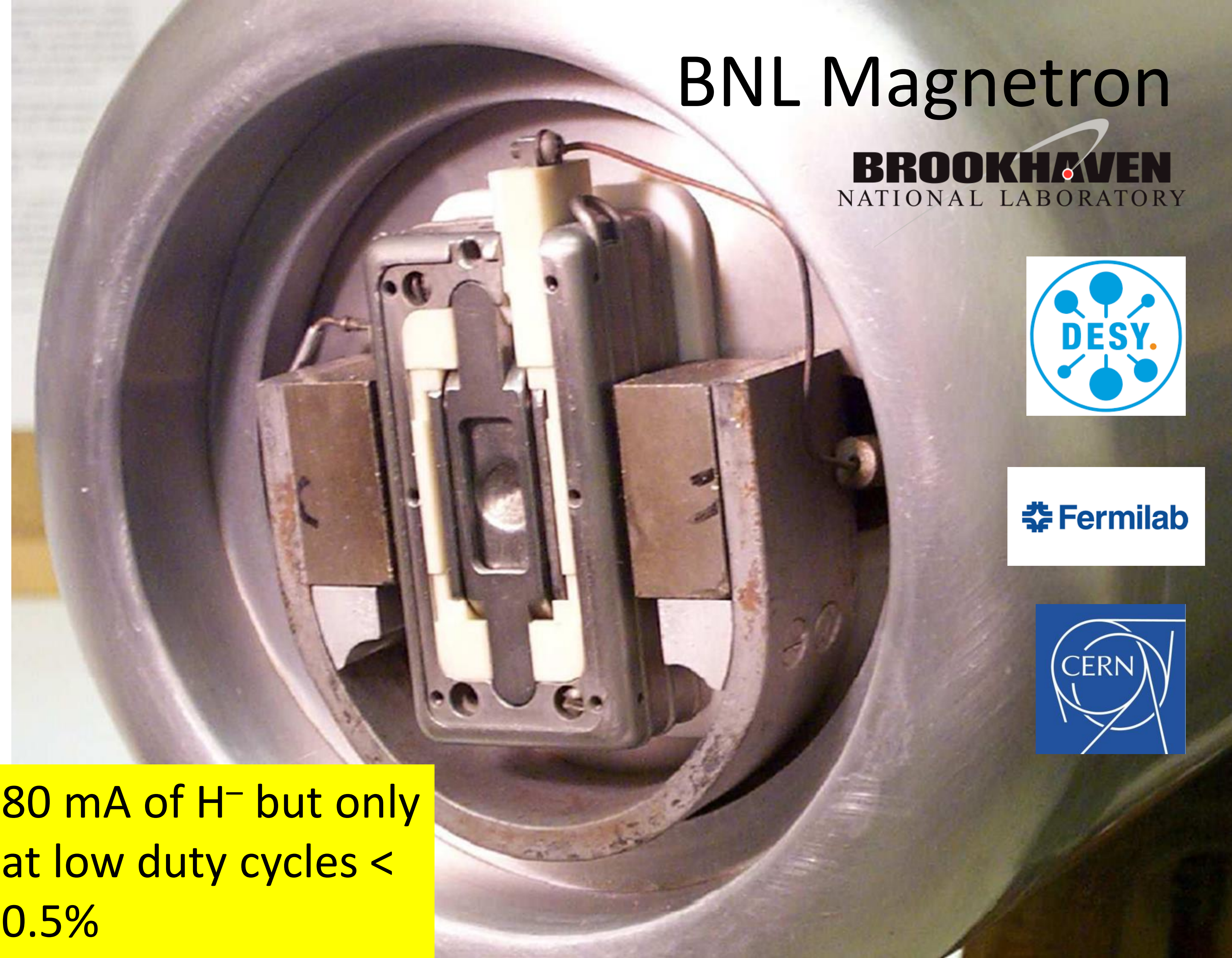
BNL Magnetron

BROOKHAVEN NATIONAL LABORATORY

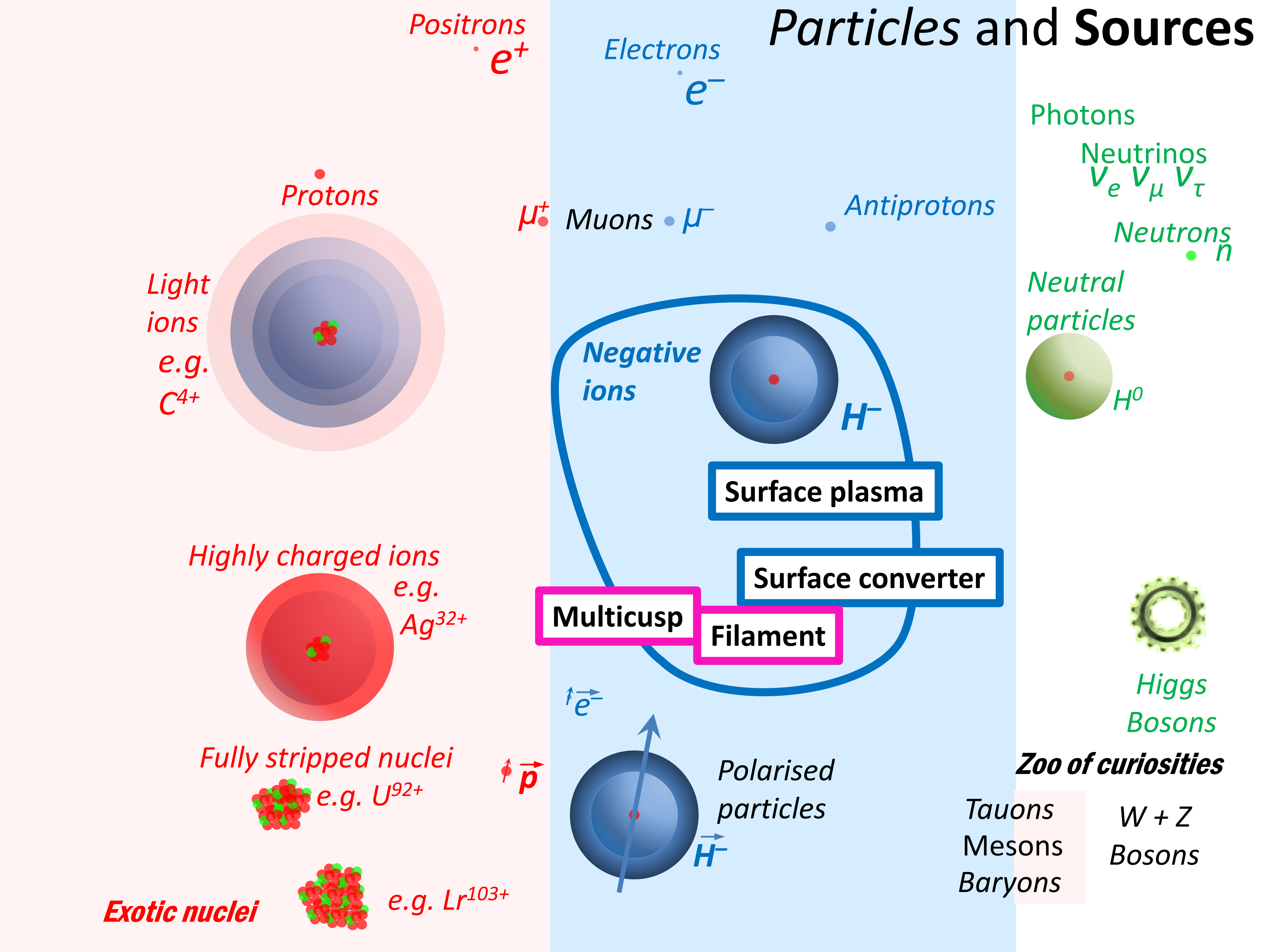
DESY.

Fermilab

CERN



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



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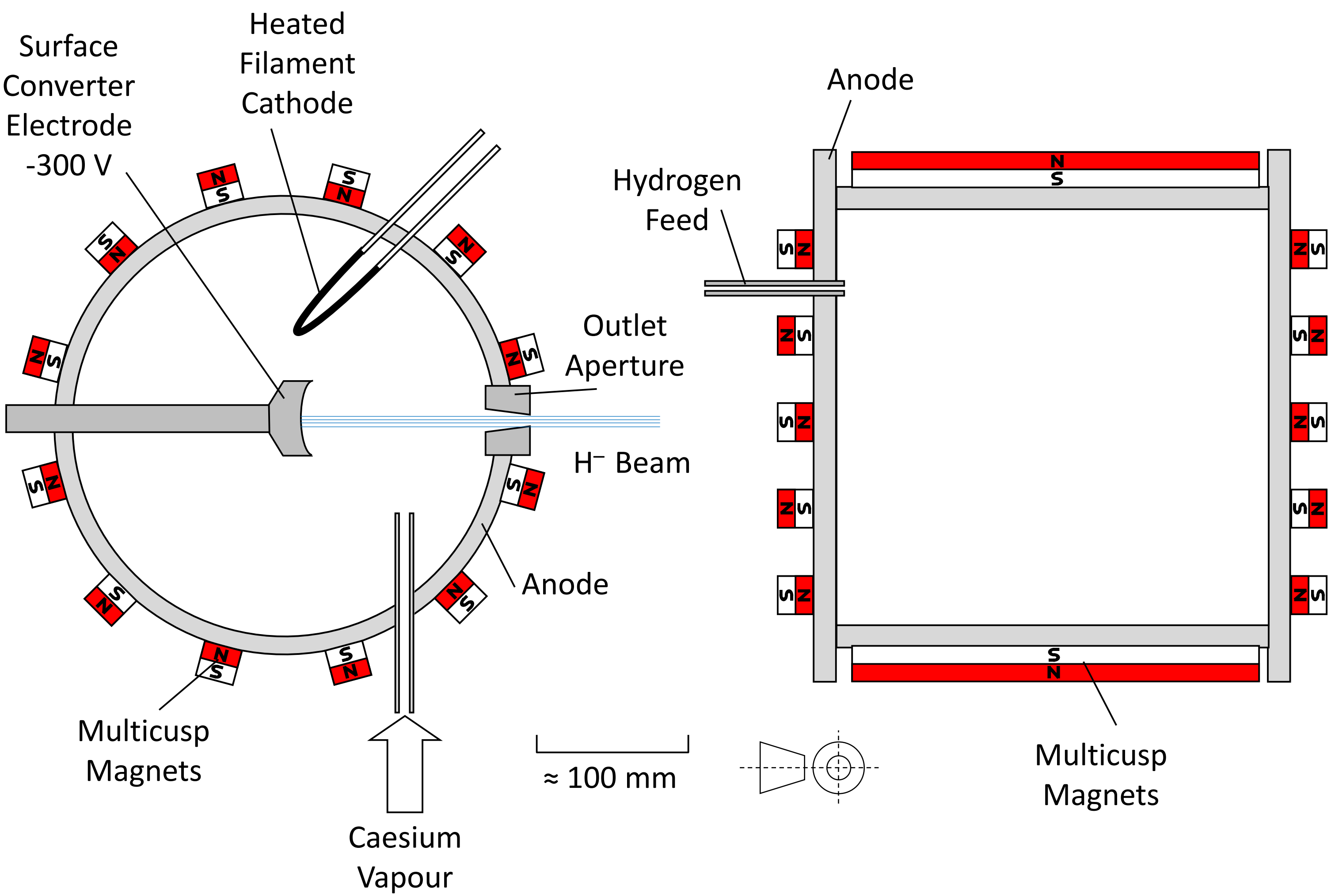
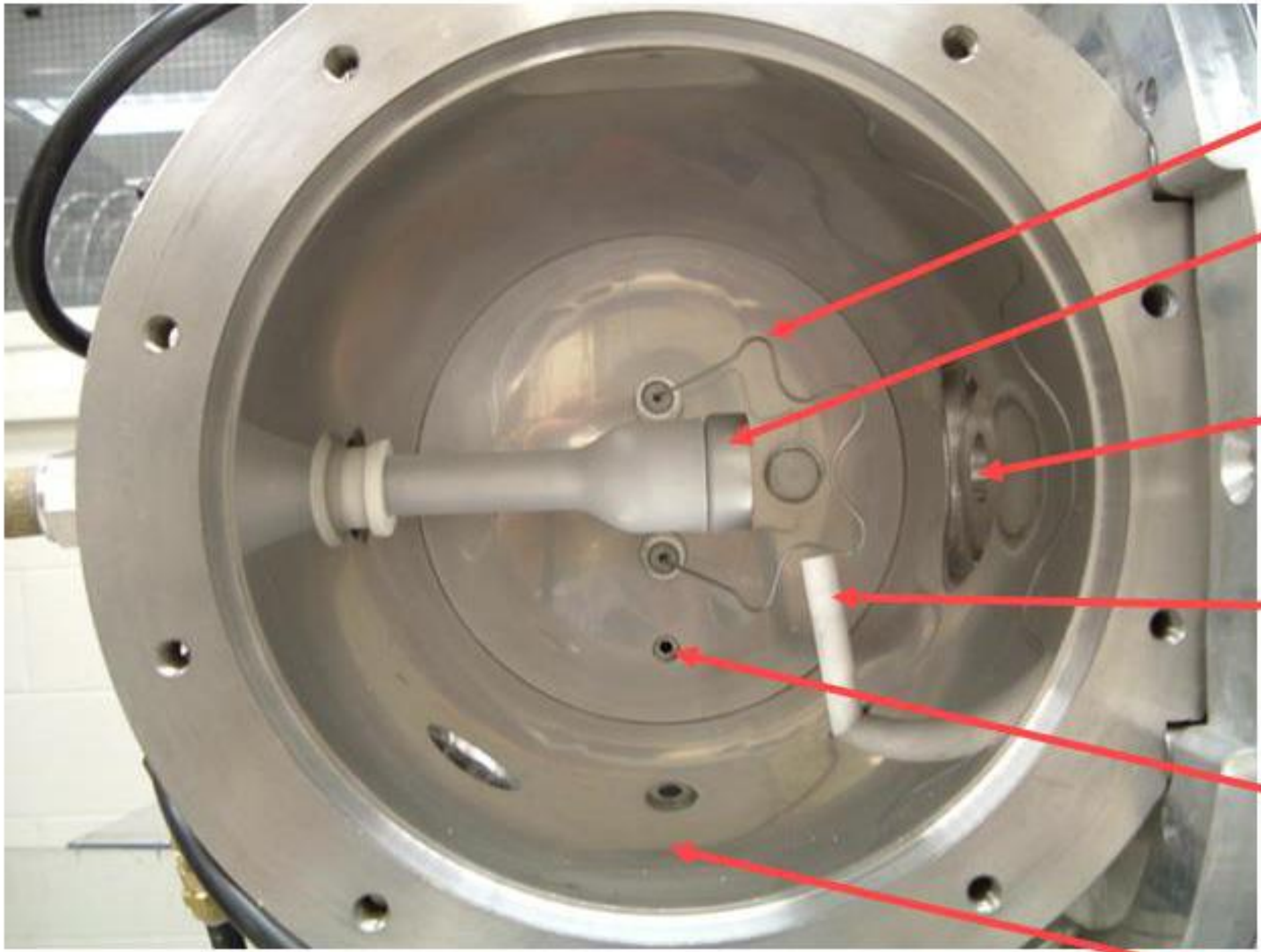
e.g. Lr103+

Filament cathode multicusp surface converter source

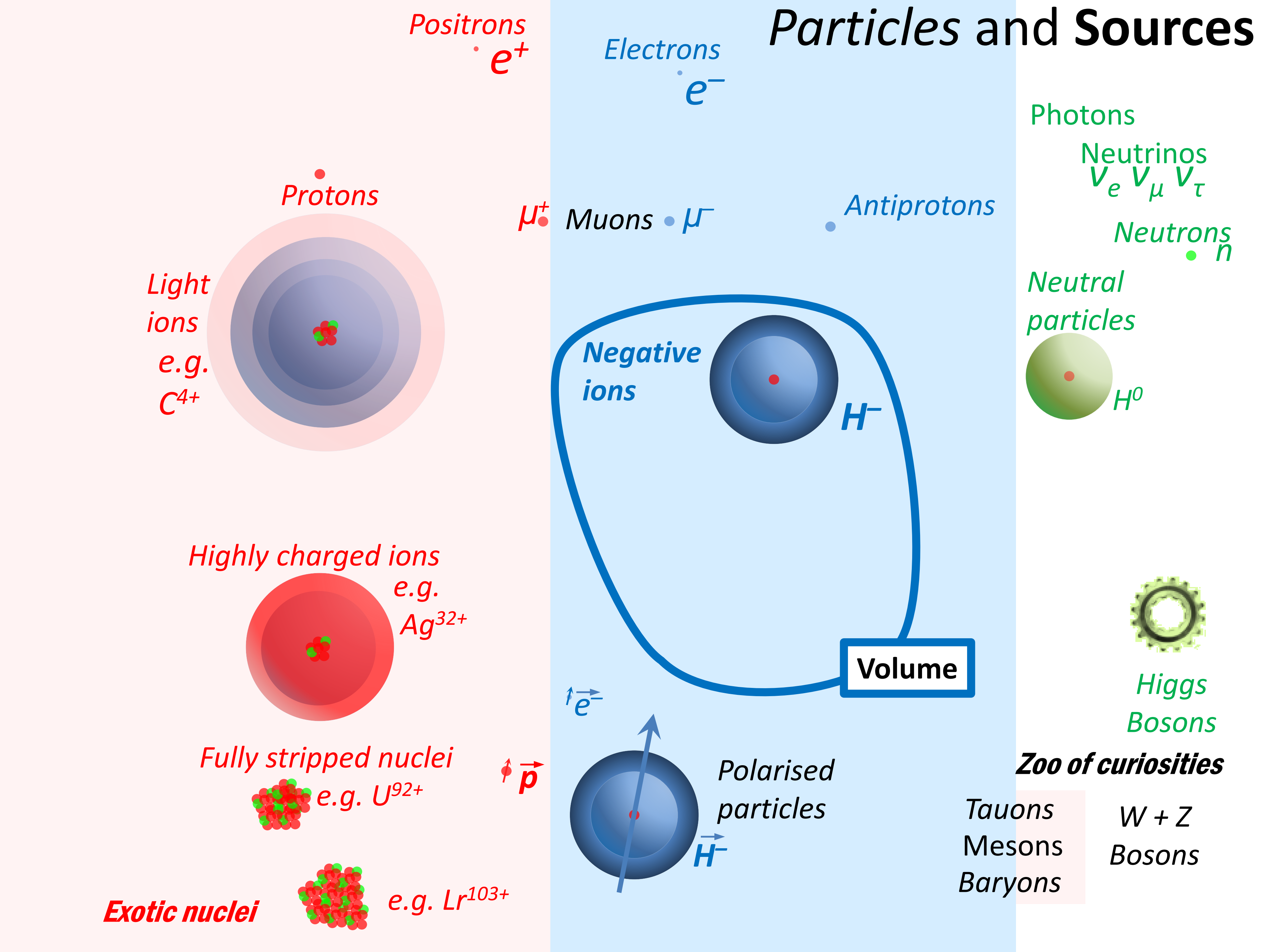


LANSE Surface Converter Source



18 mA 1 ms 120 Hz H^- beam

Los Alamos NATIONAL LABORATORY



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

Volume Production

Marthe Bacal
Ecole Polytechnique
mid 1970's

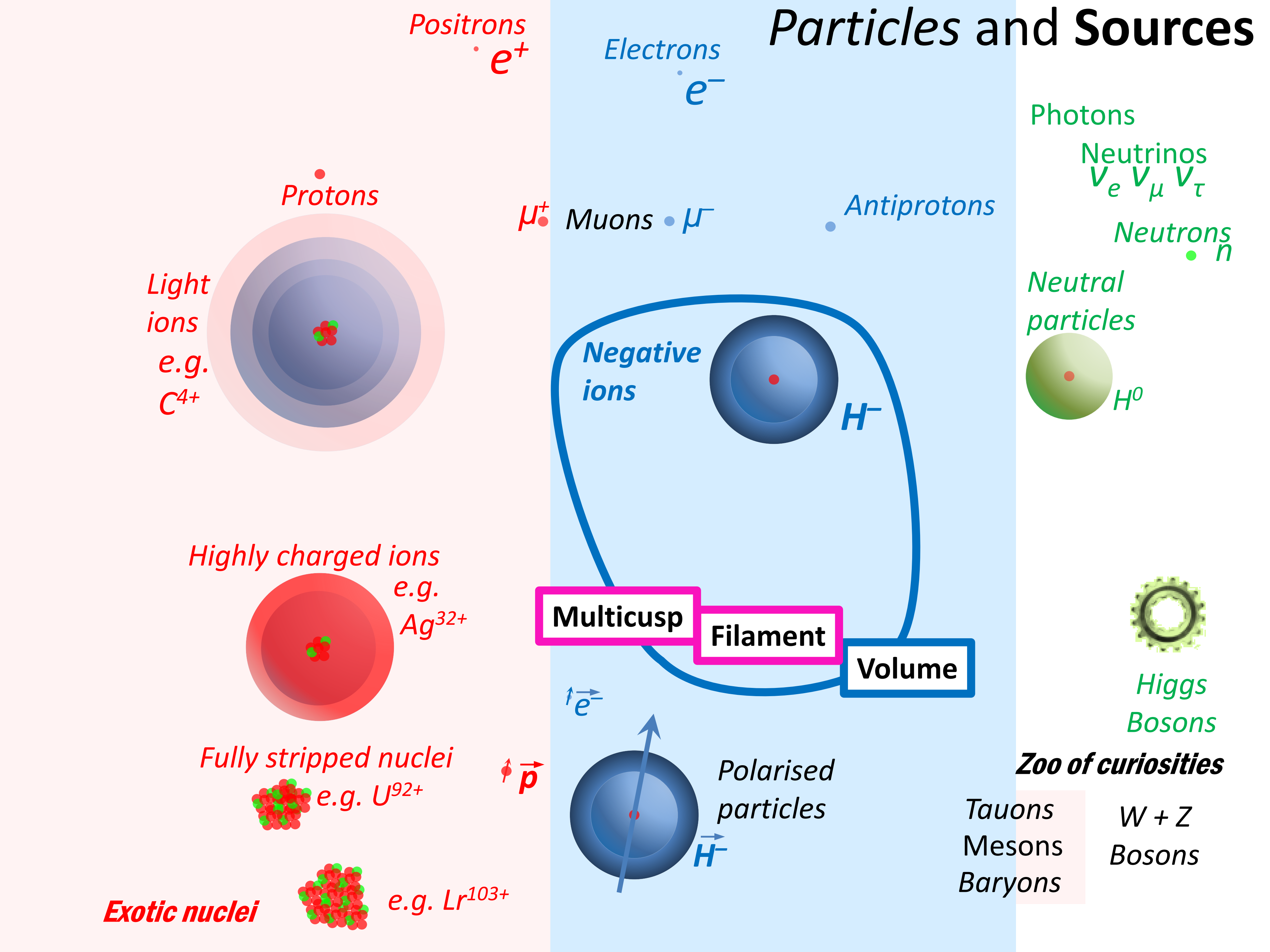
ÉCOLE POLYTECHNIQUE ParisTech

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

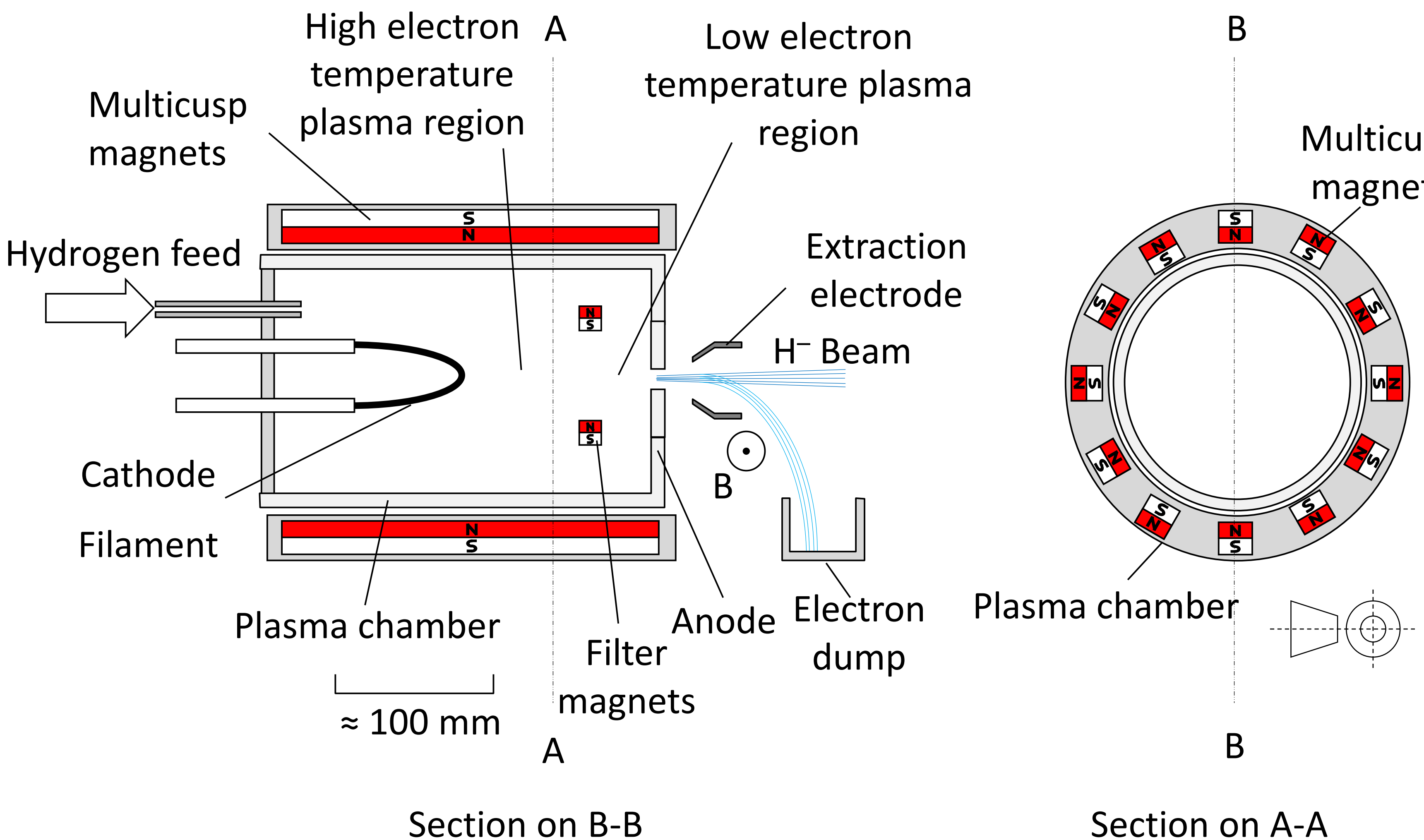
Dissociative attachment
of low energy electrons
to rovibrationally excited
H_2 molecules

Sources developed by
Ehlers + Leung at LBNL

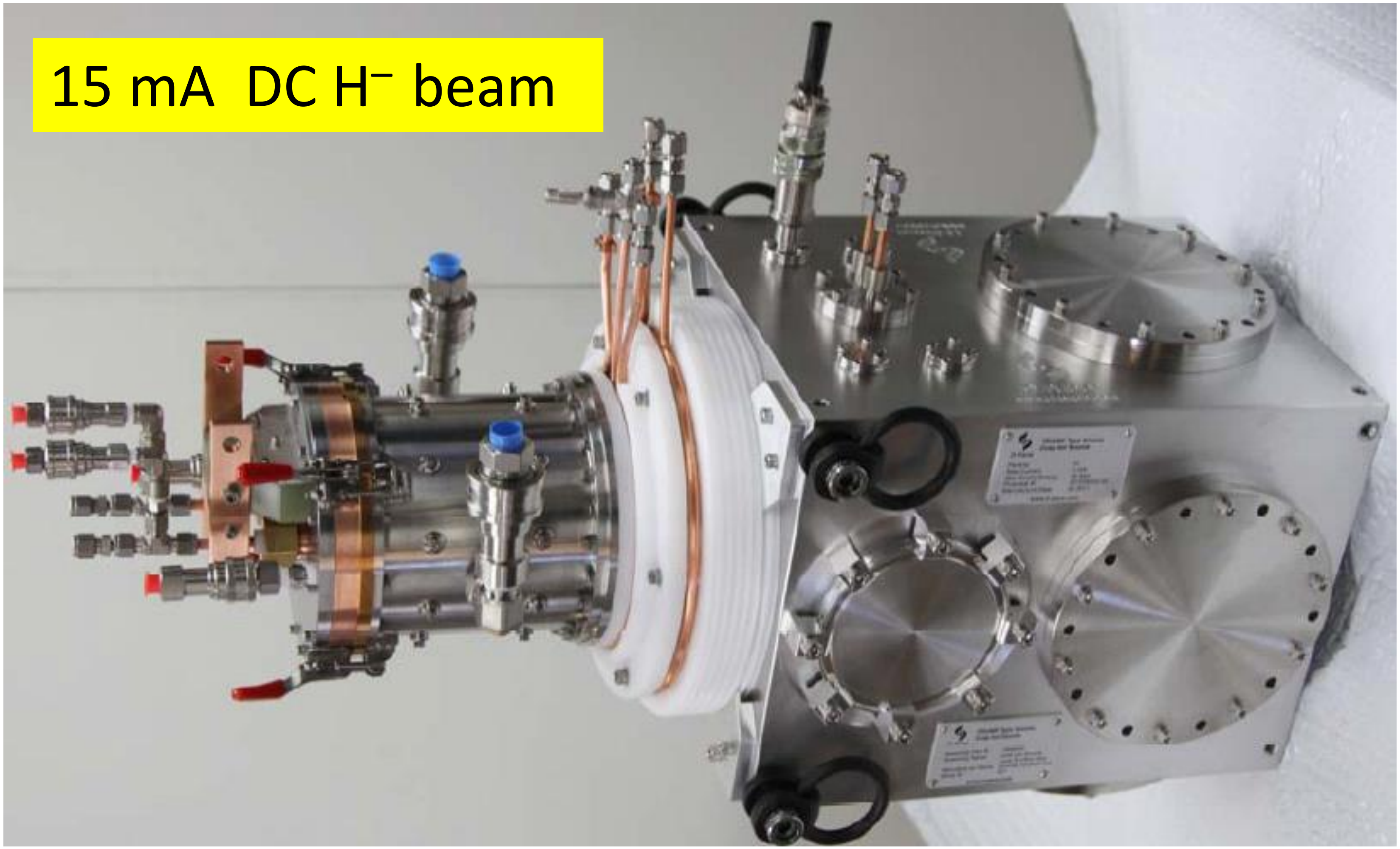
BERKELEY LAB


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
Highly charged ions
e.g.
Ag^{32+}
Multicusp
Filament
Volume
$\vec{e}^-$
Higgs
Bosons
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+}

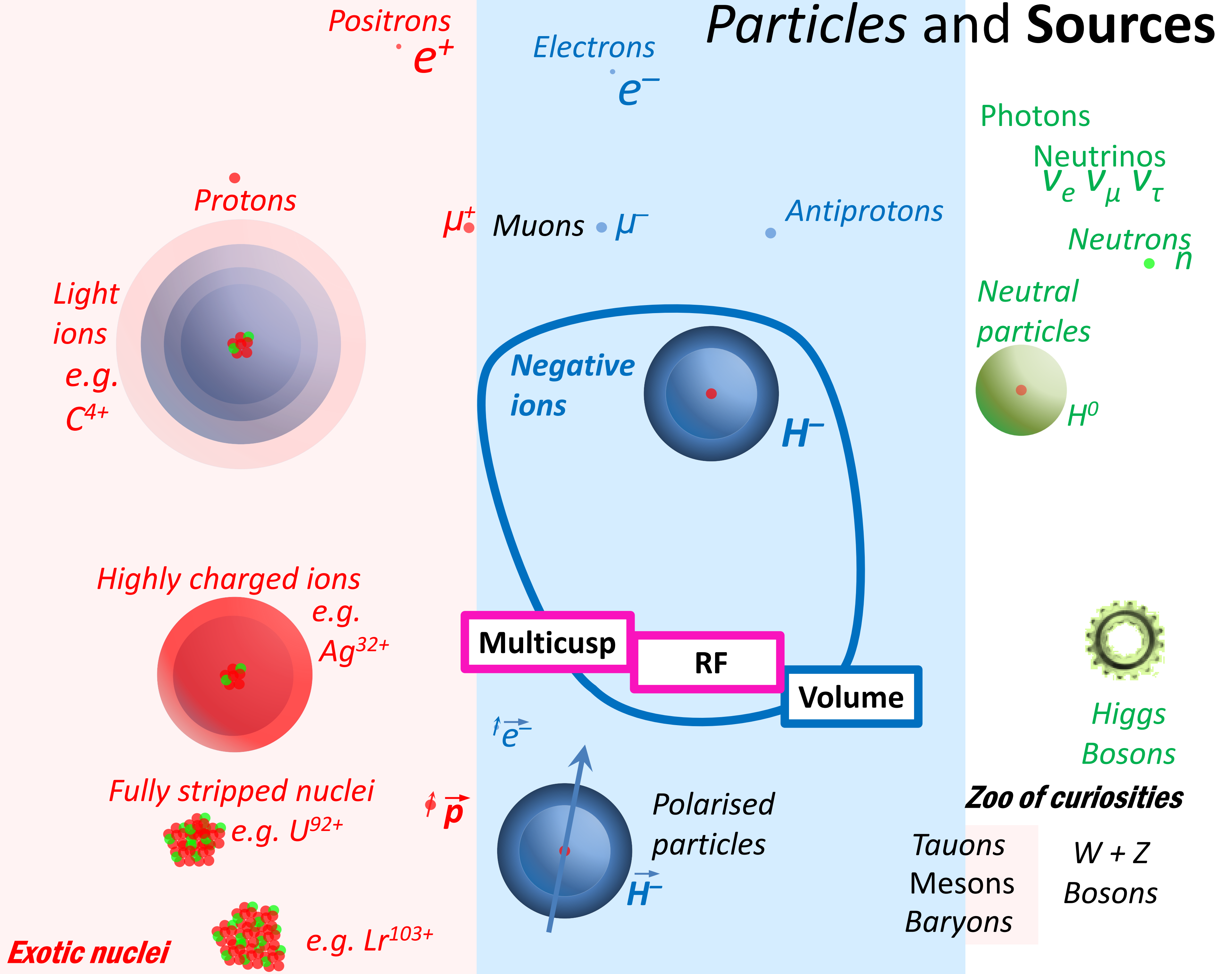
Multicusp Filament Volume Source

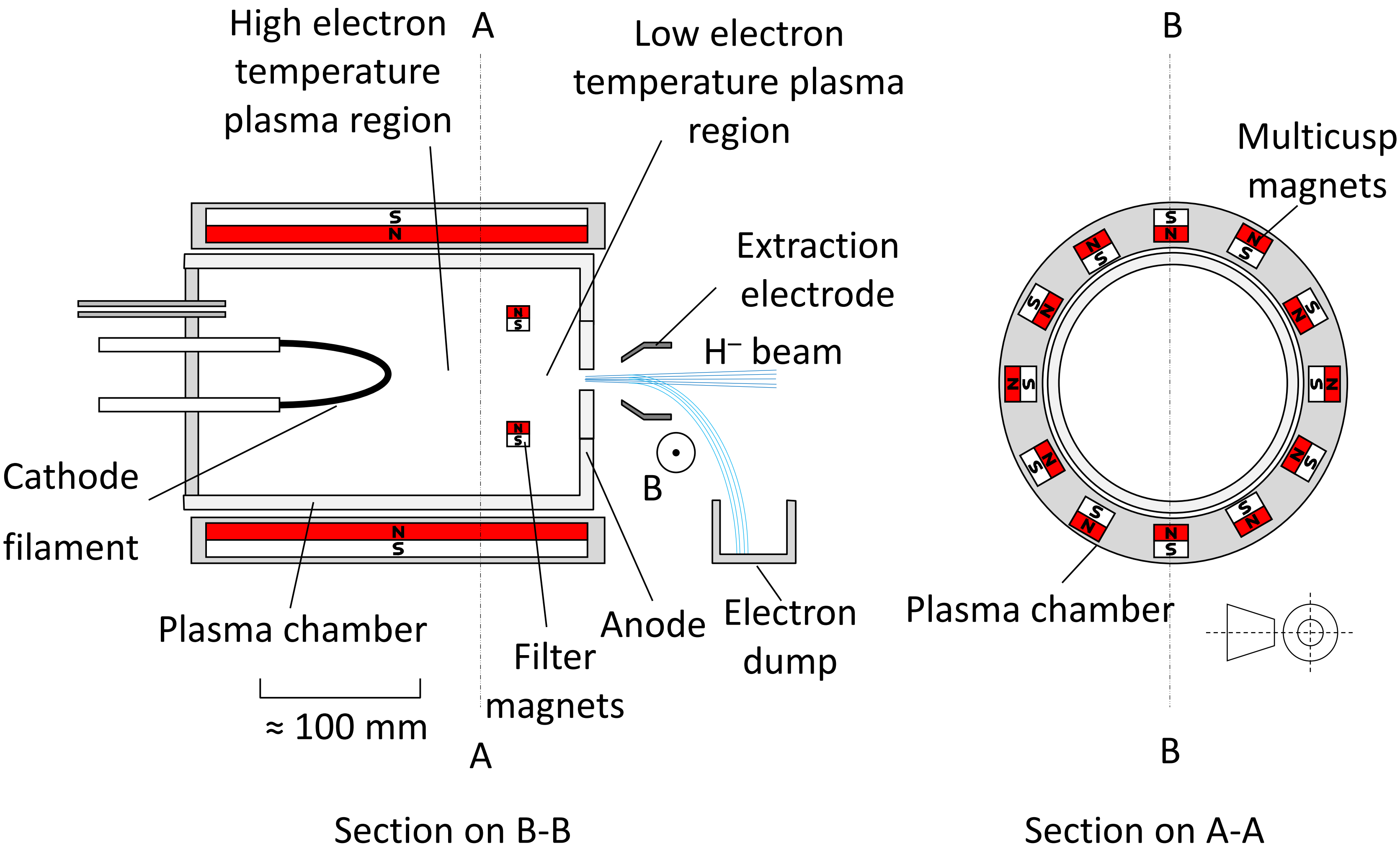


D-Pace Filament Volume Source

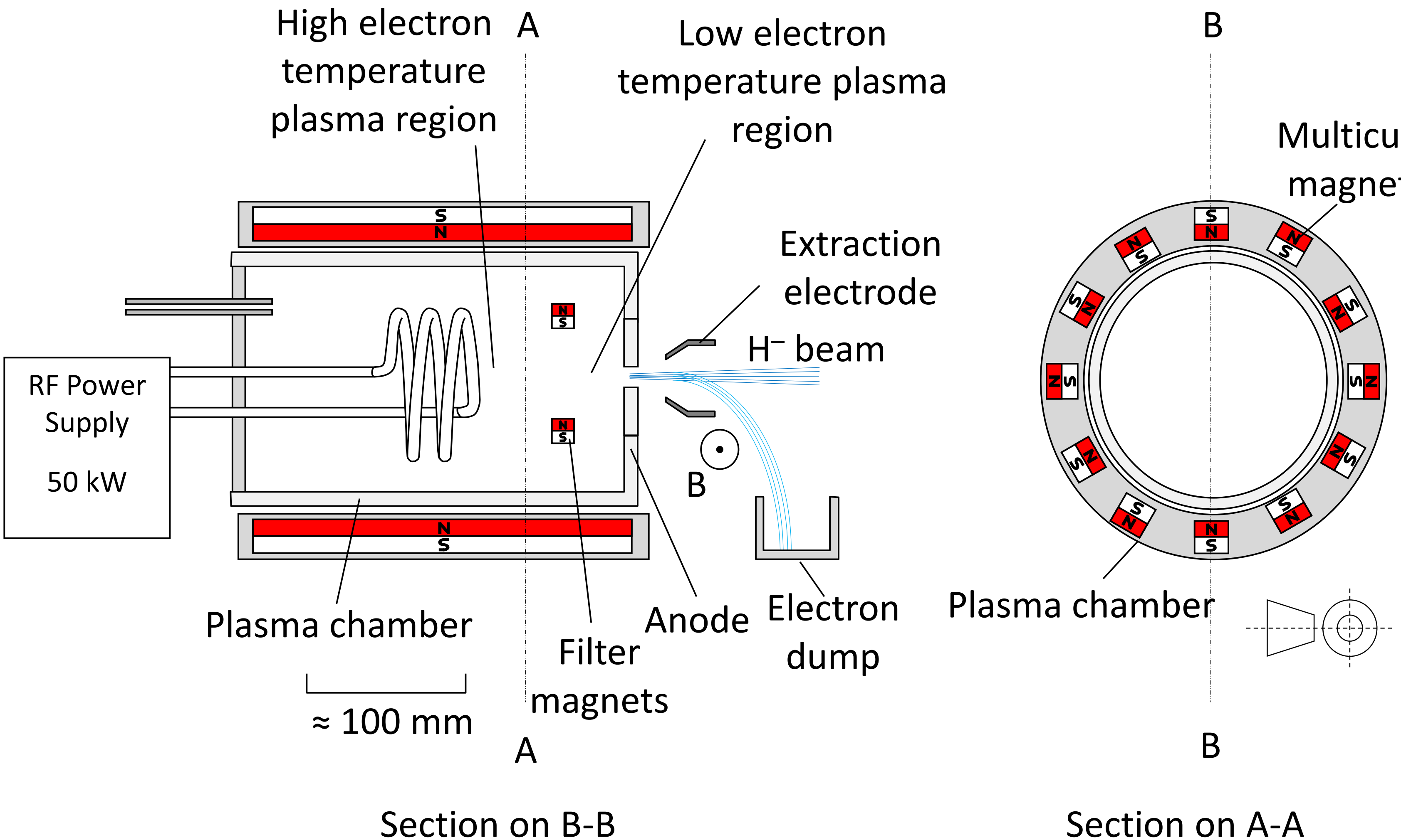


Particles and **Sources**

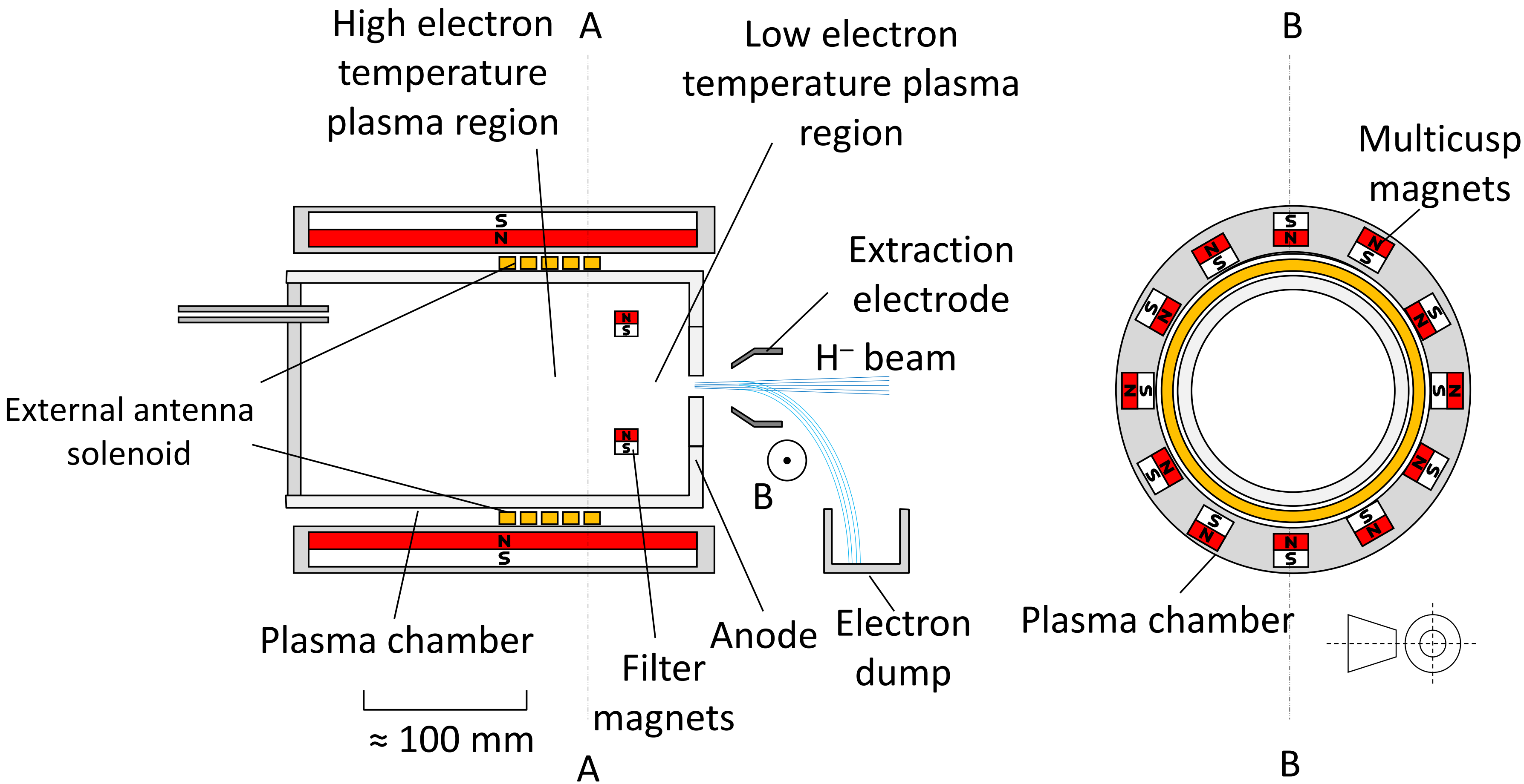



High electron temperature plasma region
A
Low electron temperature plasma region
B
Multicusp magnets
Extraction electrode
H⁻ beam
S
N
N
S
Cathode filament
B
Plasma chamber
Filter magnets
Anode
Electron dump
Plasma chamber
≈ 100 mm
A
B
Section on B-B
Section on A-A

Internal RF Solenoid Antenna Volume Source



External RF Solenoid Antenna Volume Source

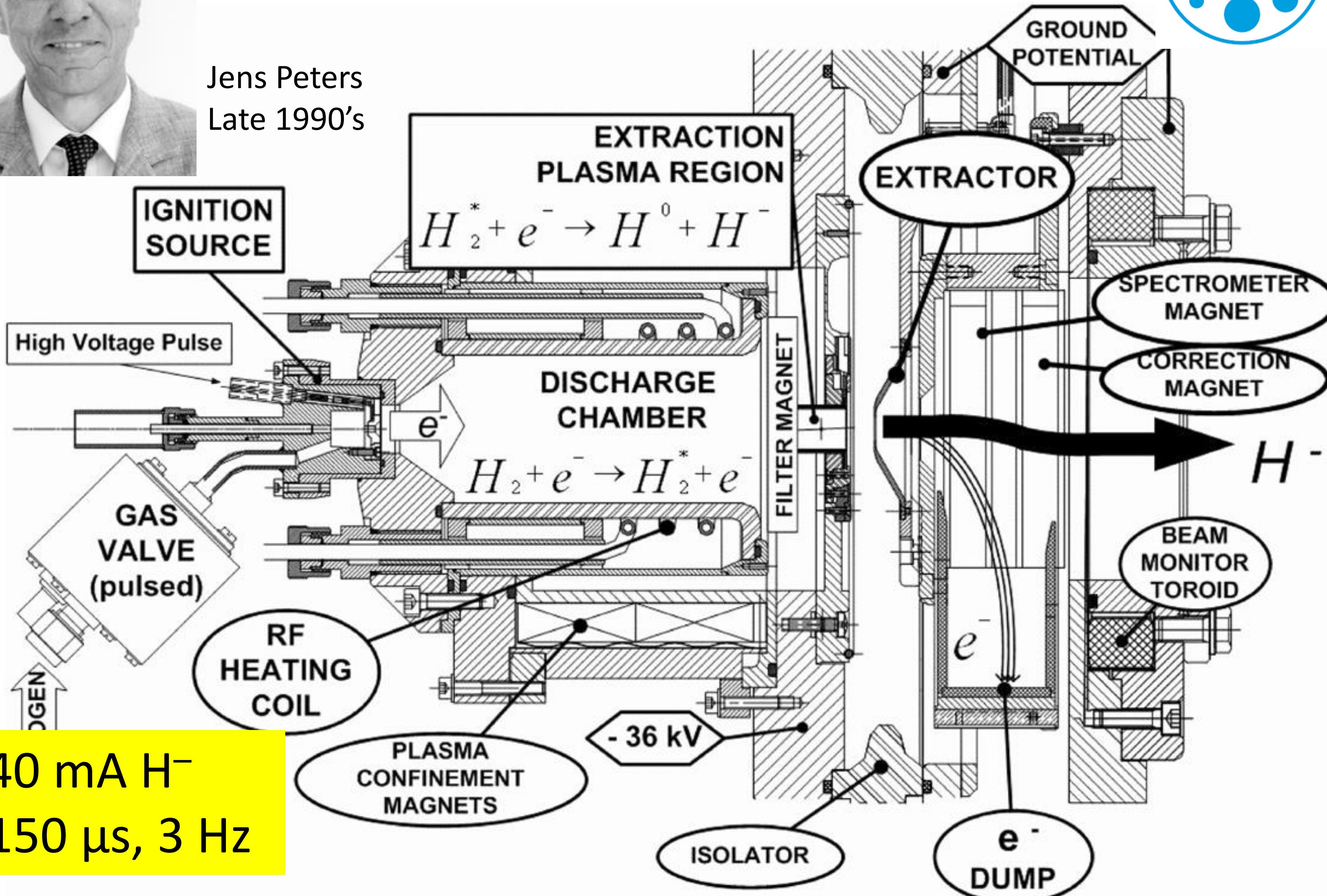


Section on B-B

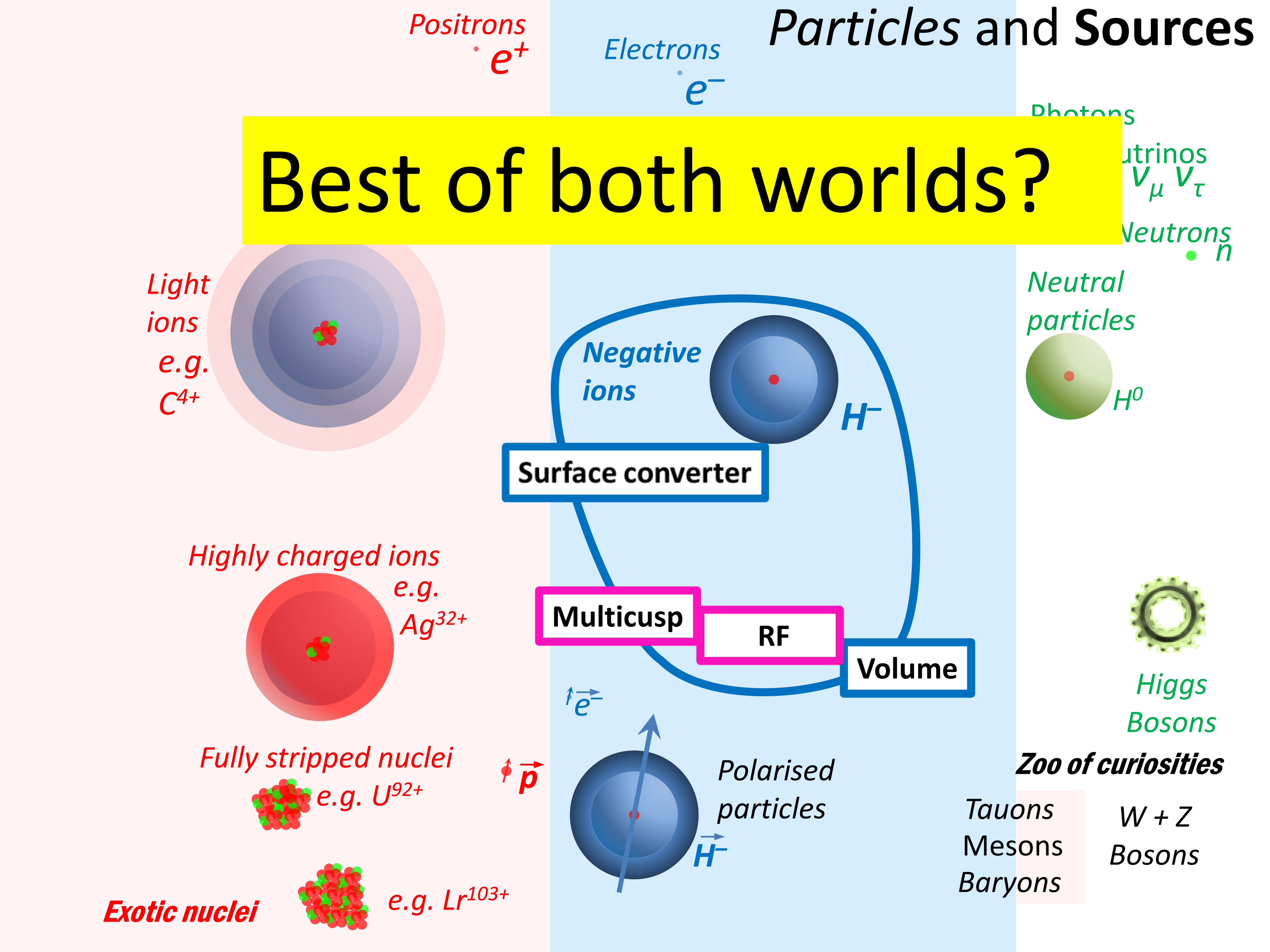
Section on A-A

HERA Source

Jens Peters
Late 1990’s



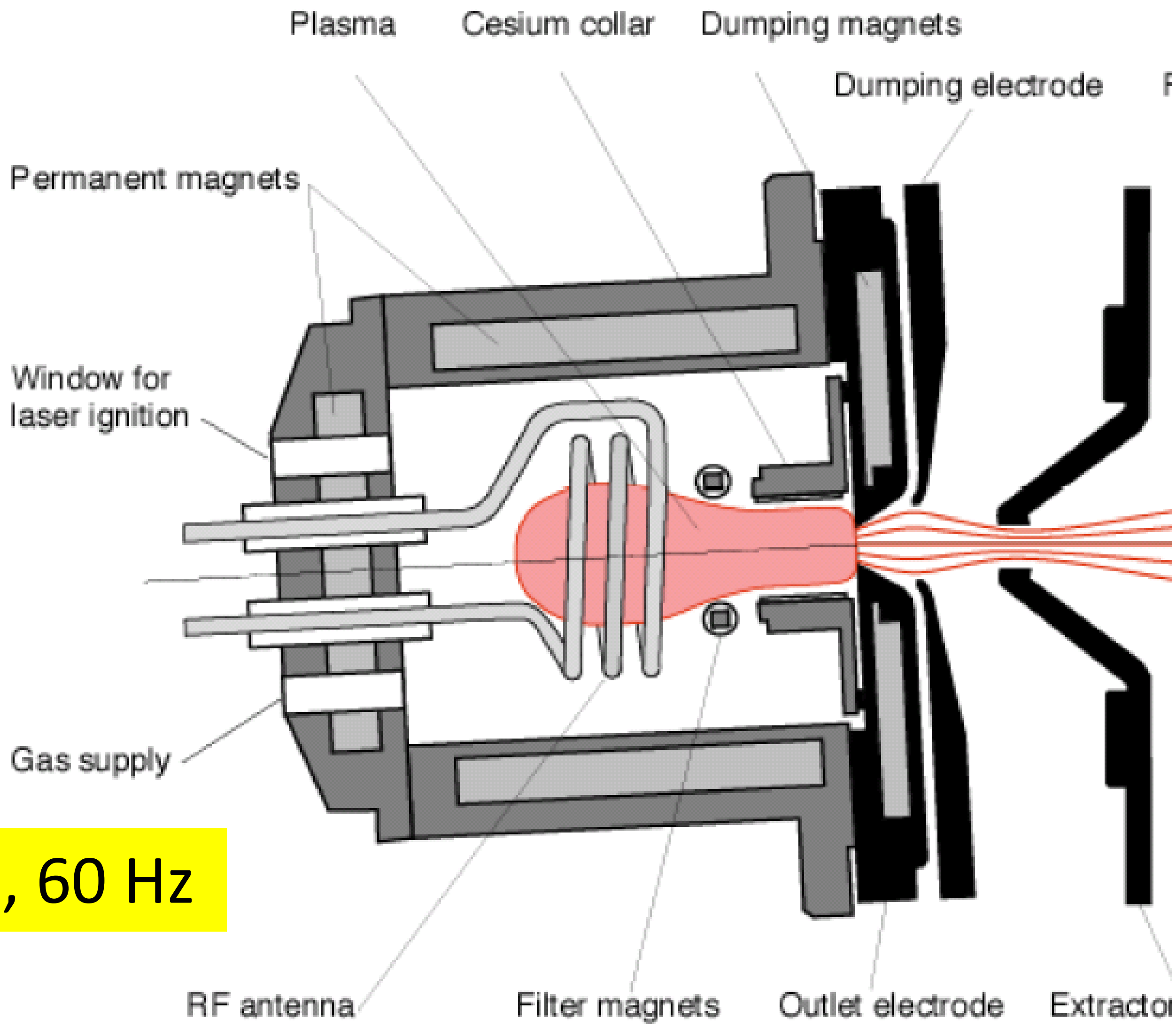
40 mA H^-
150 µs, 3 Hz



Particles and Sources
Best of both worlds?
Positrons
e+
Electrons
e−
ν_μ ν_τ
n
Light ions e.g. C4+
Negative ions
H−
Neutral particles
H0
Surface converter
Multicusp
RF
Volume
Highly charged ions e.g. Ag32+
Fully stripped nuclei e.g. U92+
p
e−
Polarised particles
H−
Higgs Bosons
Zoo of curiosities
Tauons
Mesons
Baryons
W + Z Bosons
Exotic nuclei
e.g. Lr103+

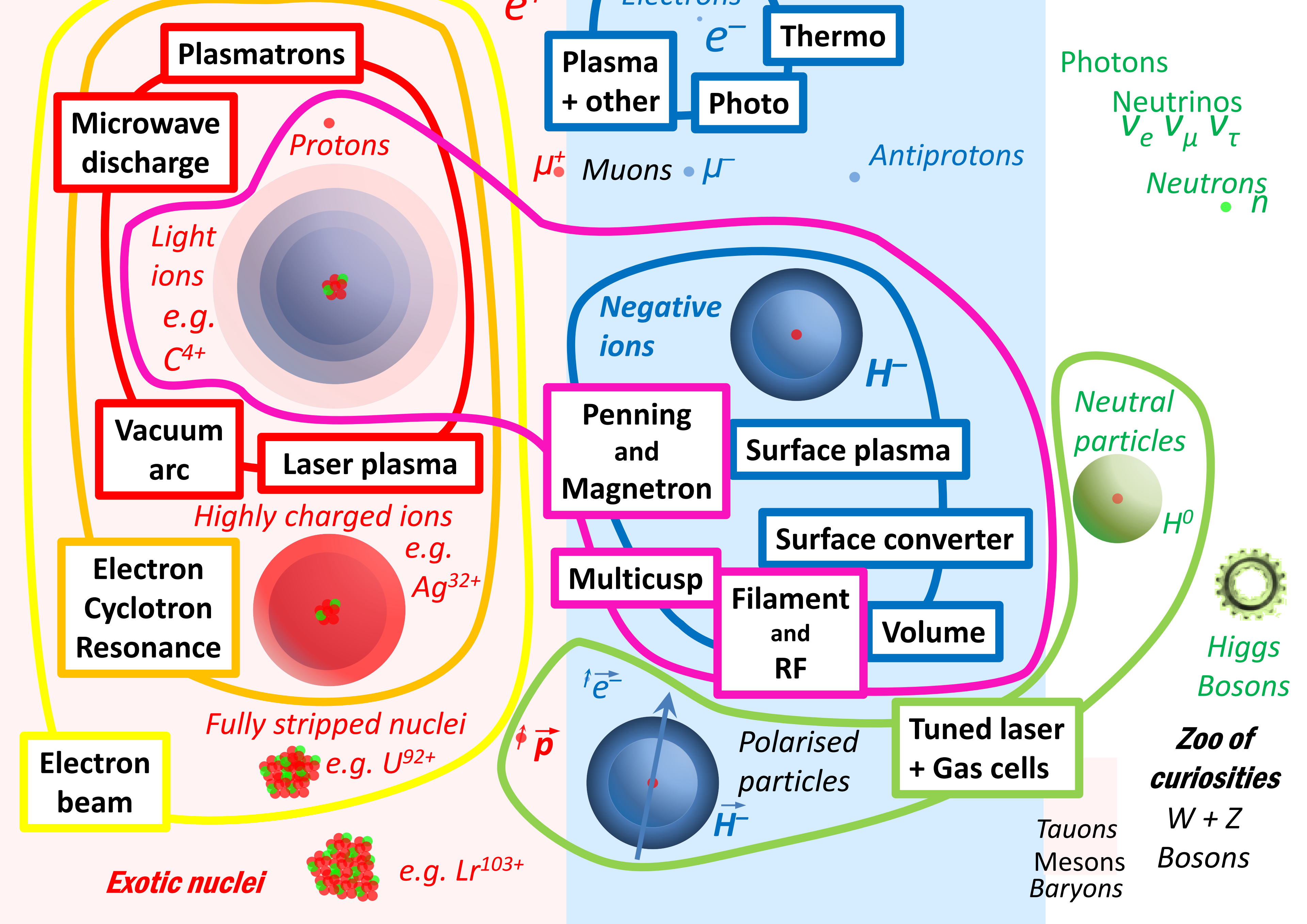
SNS ion source

CERN have developed a ceasiated external antenna source for LINAC4



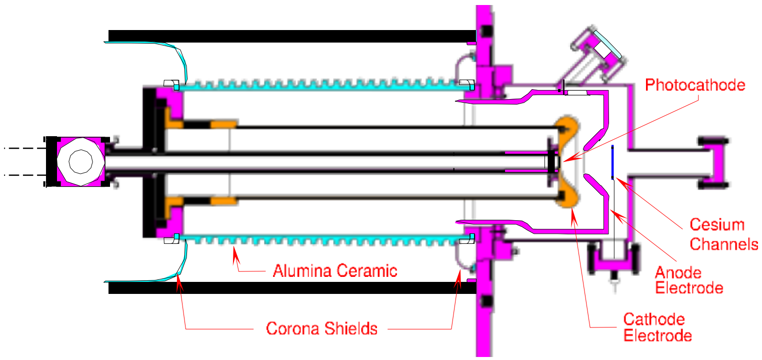
60 mA H^- 1 ms, 60 Hz

Particles and **Sources**

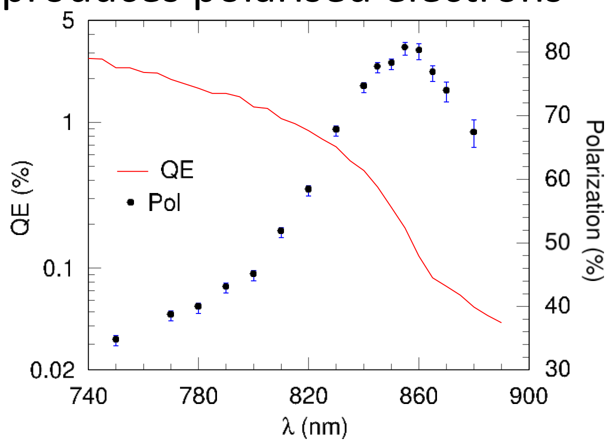


Polarised Electrons

Strained GaAs photocathode

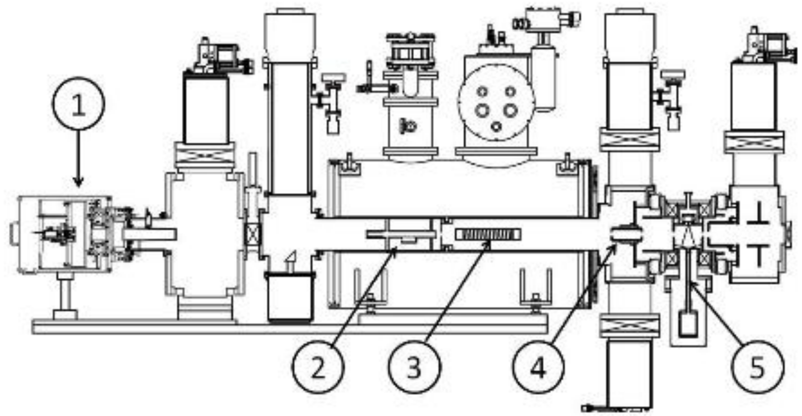


Circularly polarized laser light produces polarised electrons



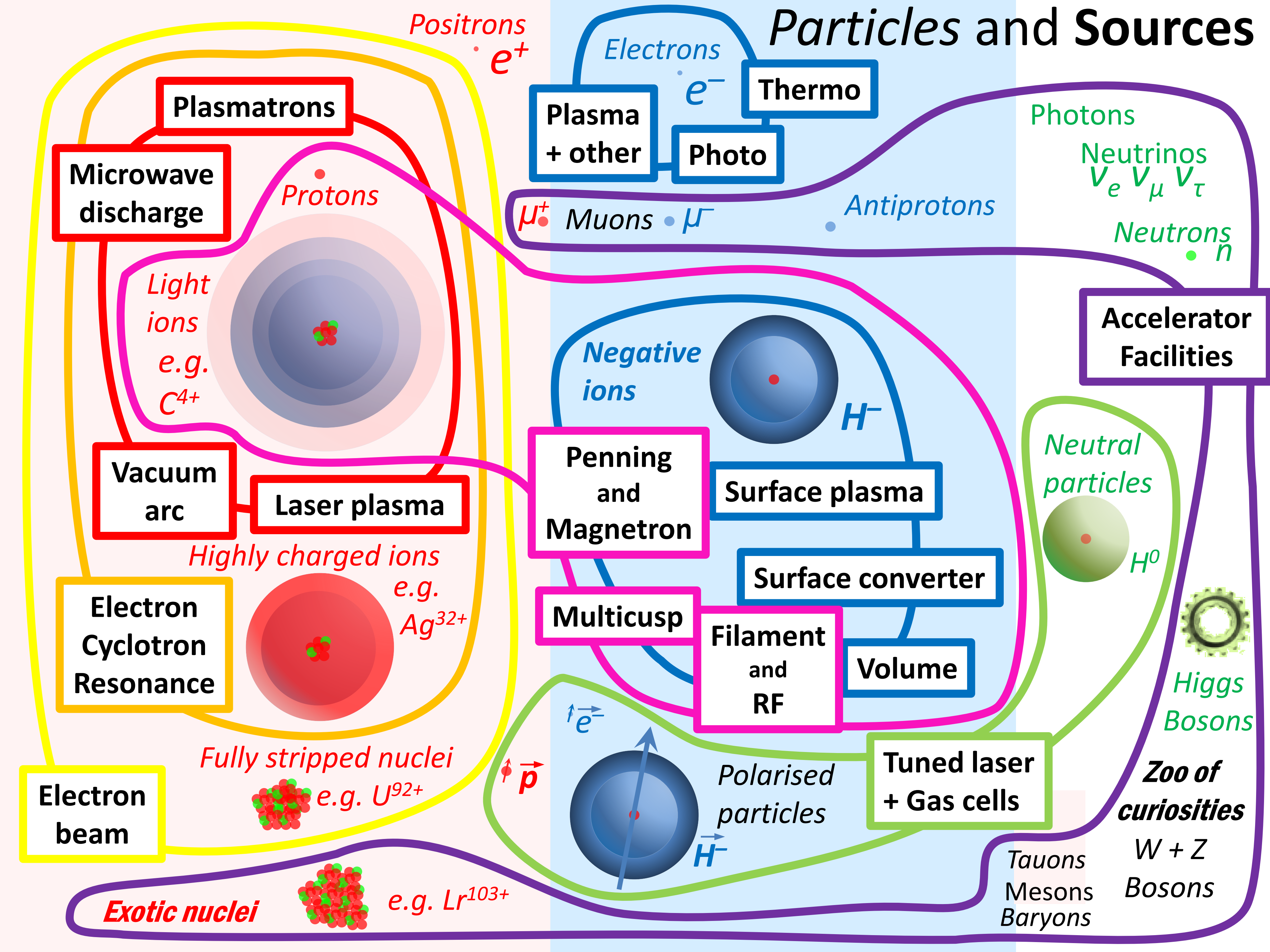
100 μA polarised e⁻

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

Which Source?

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

Reliability – is critical!

- 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

hydrogen

human error

vacuum systems

compressed air supplies

temperature controllers

high voltage power supplies

control systems

mains power

laser systems

personnel interlocks

material purity

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
Questions?