Particle Sources

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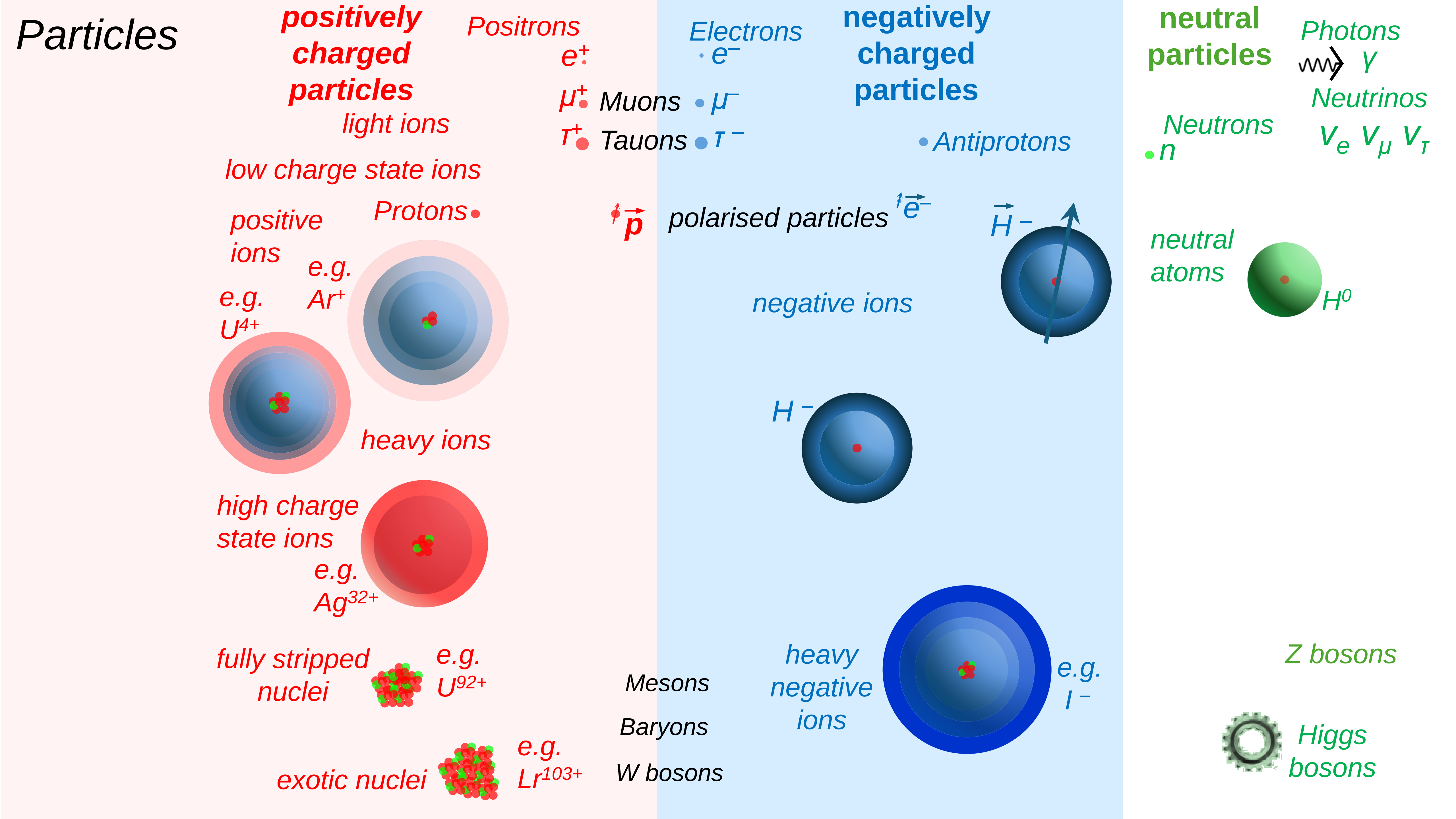
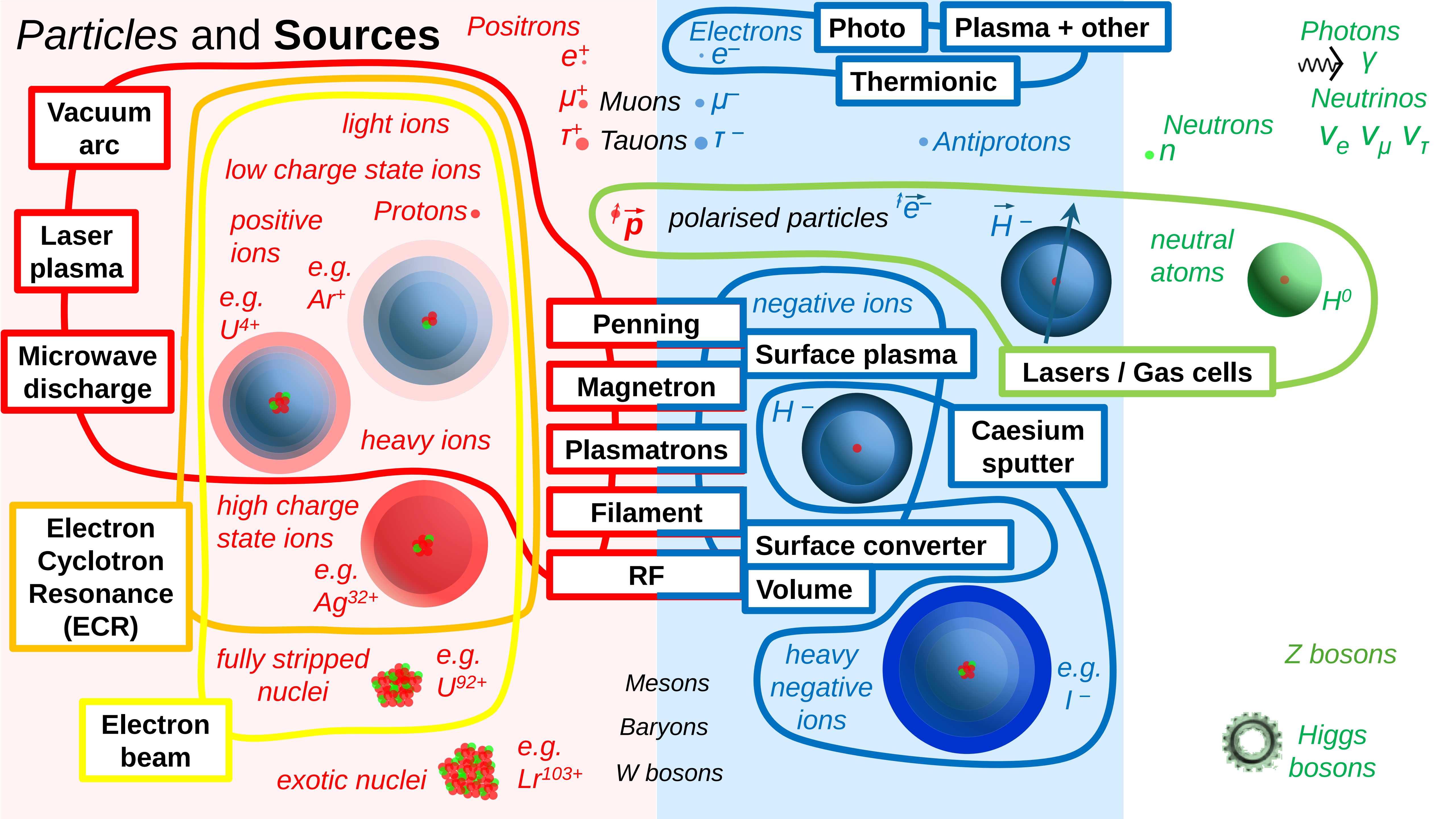
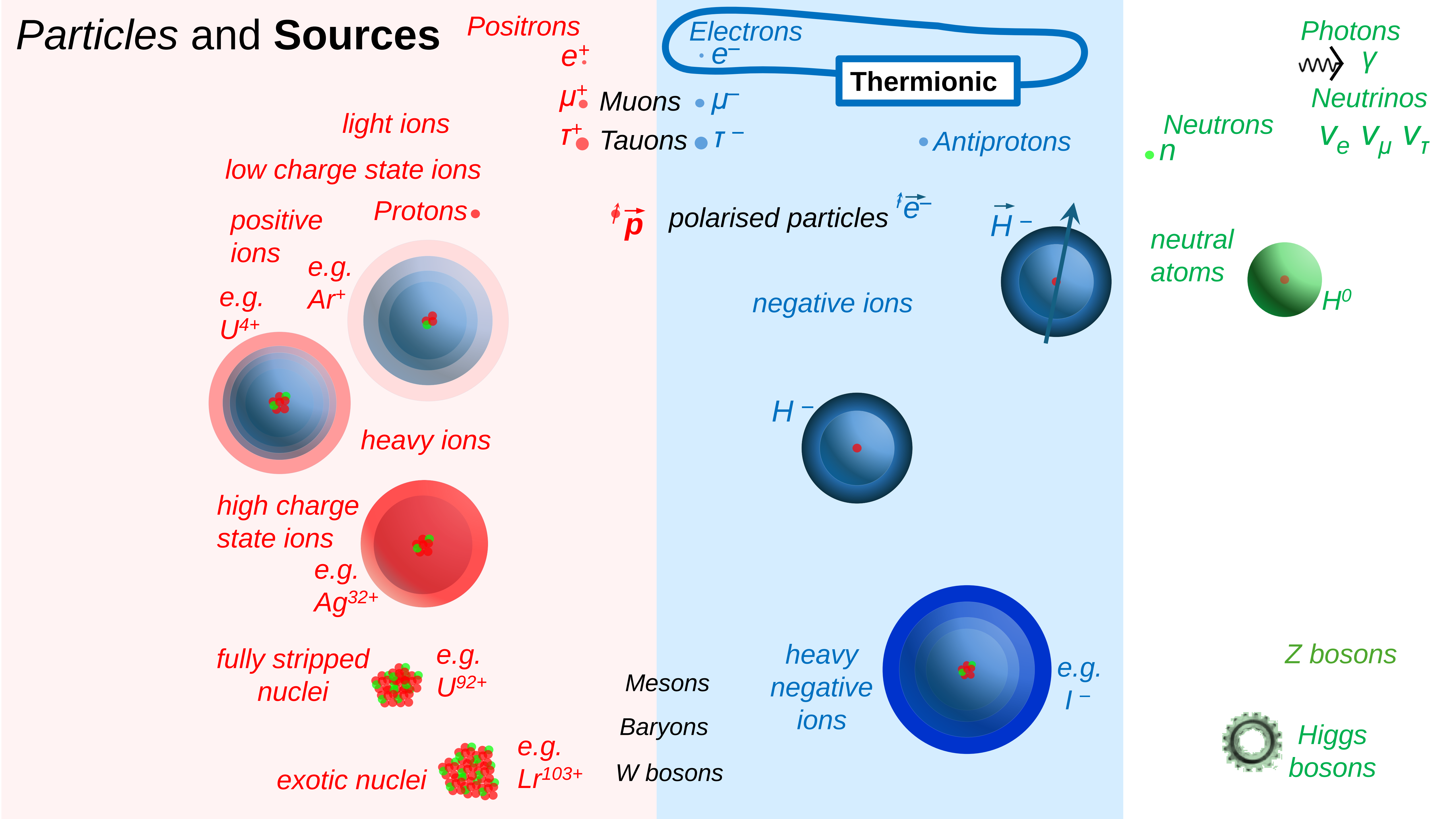
CERN Accelerator School, Introduction to Accelerator Physics
Santa Susanna, Spain
Tuesday 24th September 2024


Particles
positively charged particles
Positrons
e+
μ+
Muons
μ−
τ+
Tauons
τ −
Electrons
e−
negatively charged particles
neutral particles
Photons
γ
Neutrinos
νe νμ ντ
Neutrons
n
light ions
low charge state ions
Antiprotons
Protons
p
polarised particles
e−
H −
positive ions
e.g. Ar+
e.g. U4+
negative ions
neutral atoms
H0
heavy ions
H −
high charge state ions
e.g. Ag32+
fully stripped nuclei
e.g. U92+
Mesons
Baryons
W bosons
heavy negative ions
e.g. I −
Z bosons
Higgs bosons
exotic nuclei
e.g. Lr103+



Particles and Sources
Positrons
e+
μ+ Muons μ−
τ+ Tauons τ −
Electrons
e−
Photo
Plasma + other
Thermionic
Antiprotons
Photons
γ
Neutrinos
νe νμ ντ
Neutrons
n
Vacuum arc
Laser plasma
Microwave discharge
Electron Cyclotron Resonance (ECR)
Electron beam
light ions
low charge state ions
positive ions
Protons
e.g. Ar+
e.g. U4+
heavy ions
high charge state ions
e.g. Ag32+
fully stripped nuclei
e.g. U92+
exotic nuclei
e.g. Lr103+
Mesons
Baryons
W bosons
p
polarised particles
e−
H −
neutral atoms
H0
Penning
Magnetron
Plasmatrons
Filament
RF
negative ions
Surface plasma
Lasers / Gas cells
Caesium sputter
Surface converter
Volume
heavy negative ions
e.g. I −
Z bosons
Higgs bosons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W bosons
Photons
γ
Neutrinos
νe νμ ντ
Neutrons
n
neutral atoms
H0
Z bosons
Higgs bosons

Thermionic emission

1901 Owen Richardson

Cambridge University

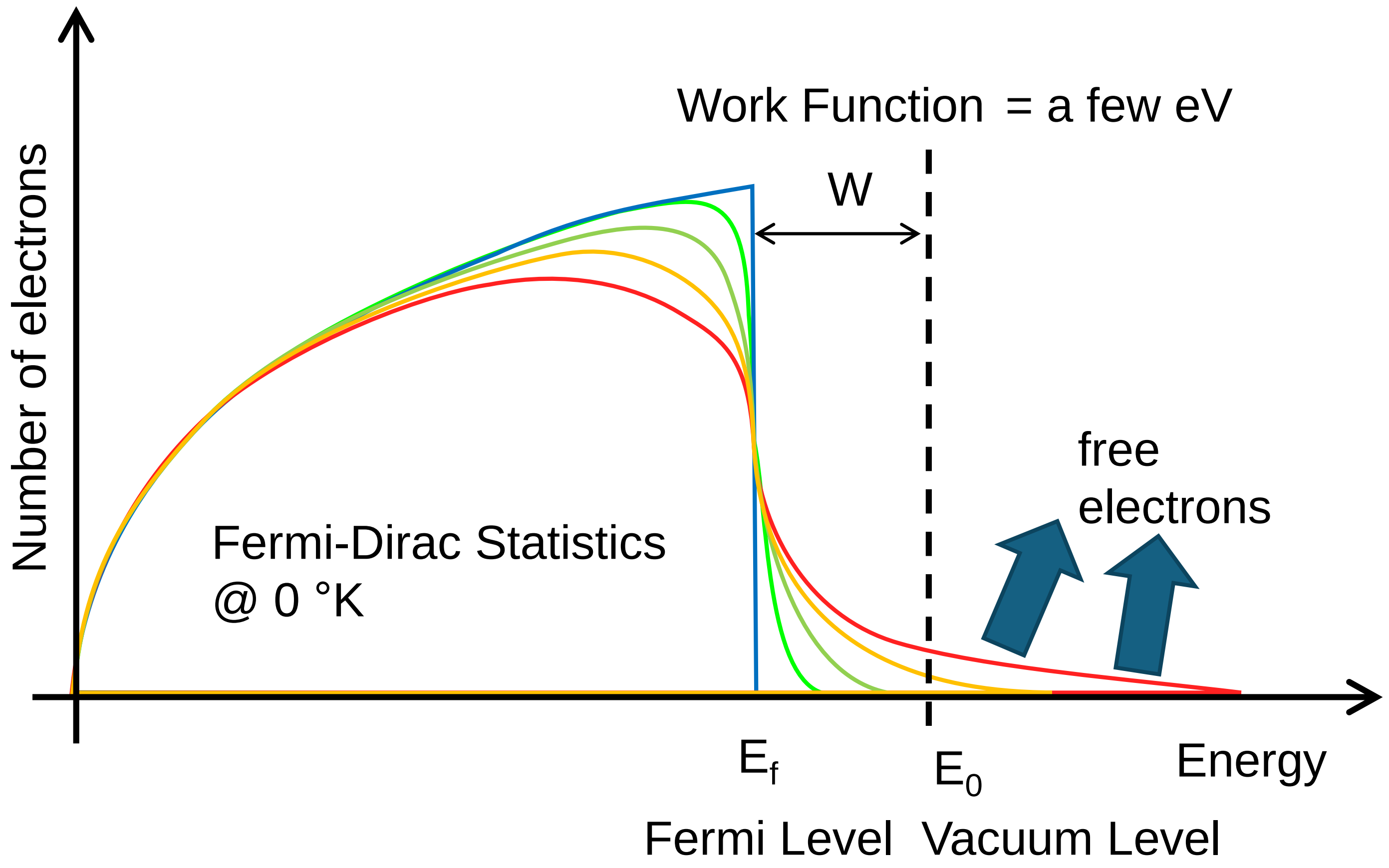
$$J = A_G T^2 e^{\frac{-W}{kT}}$$

Richardson's Law

Same form as the Arrhenius equation

Current rapidly increases with temperature

Thermionic emission



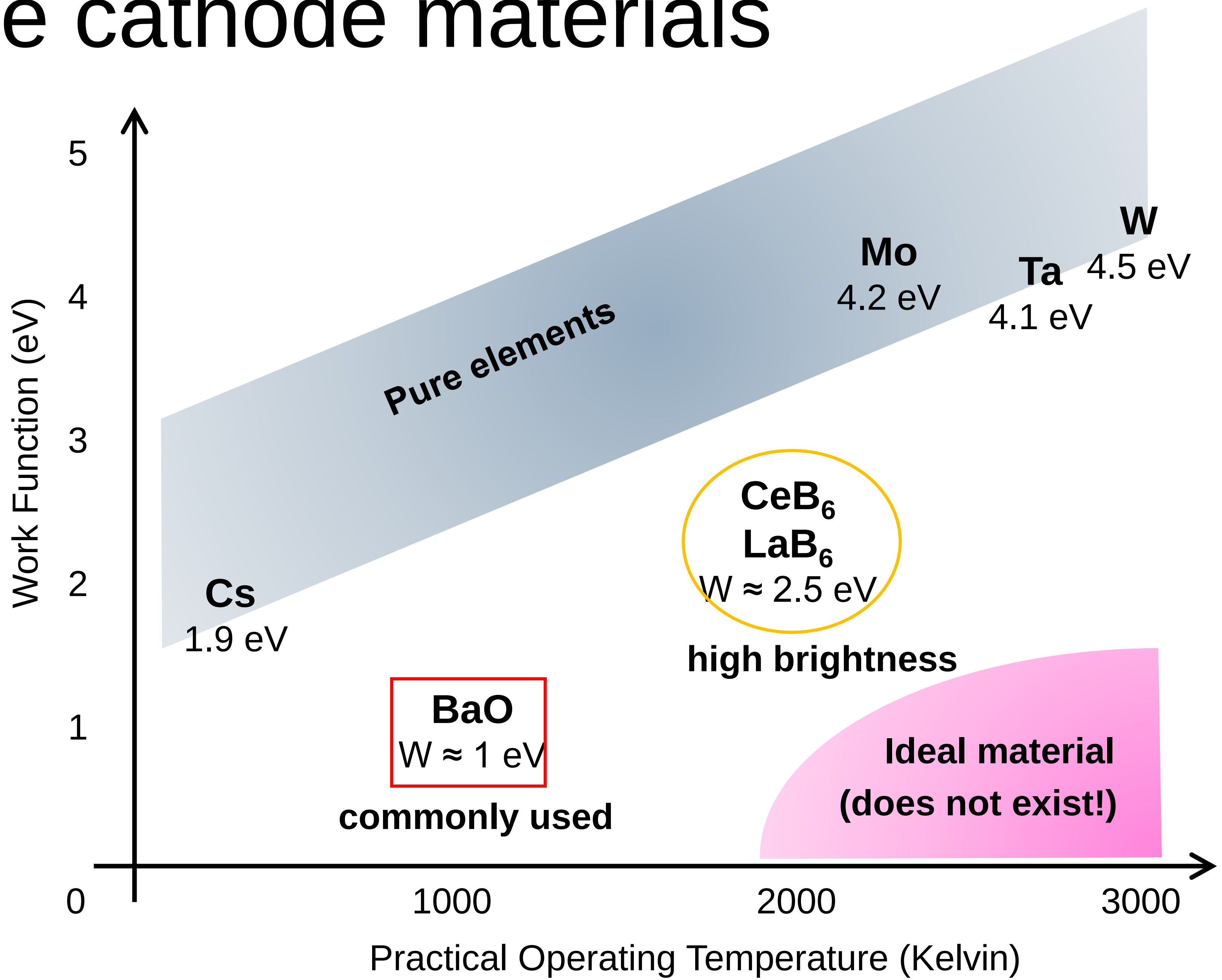
$$J = A_G T^2 e^{\frac{-W}{kT}}$$

For a good electron emitter you need:

Lowest possible work function

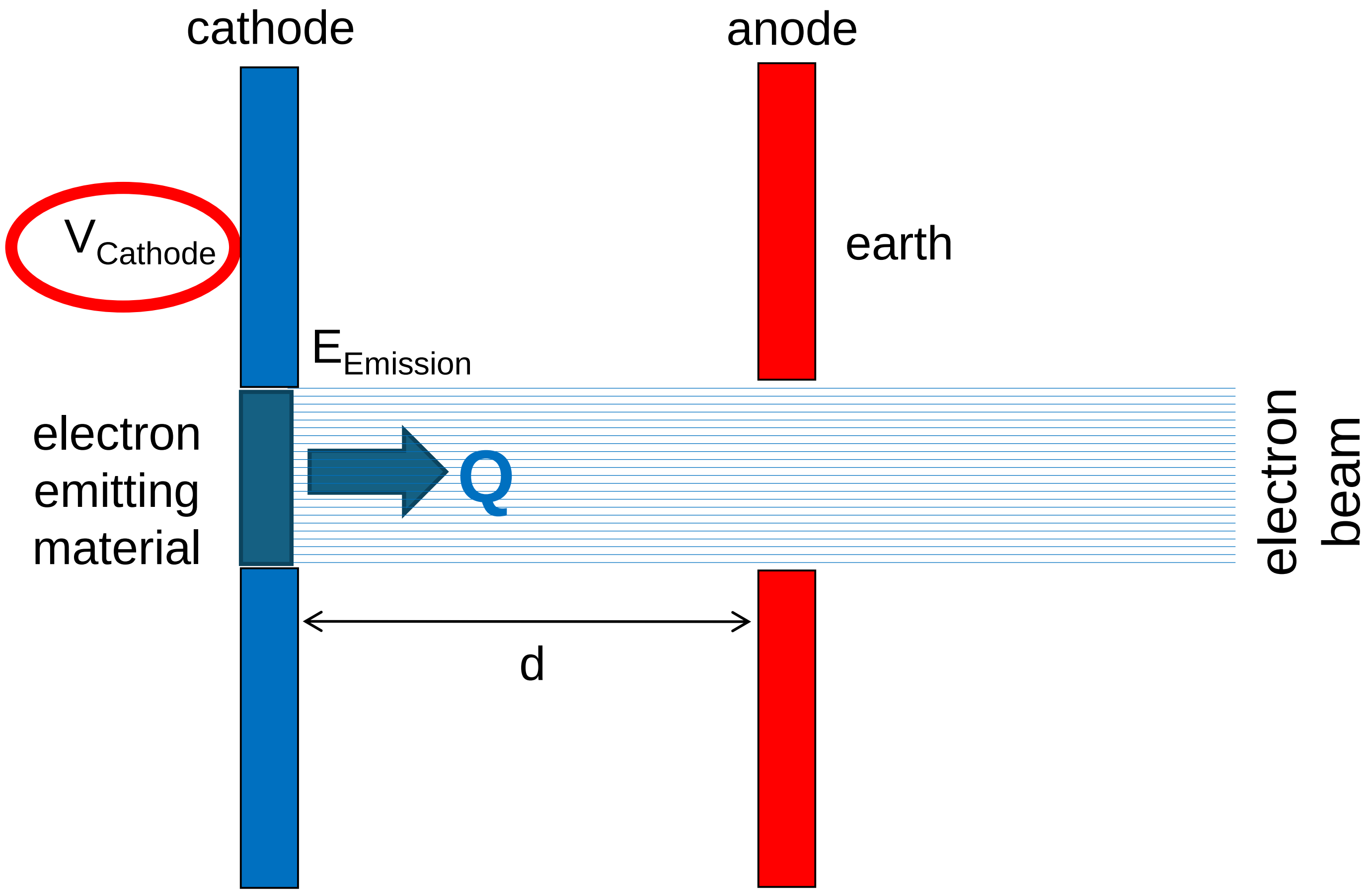
Highest possible temperature

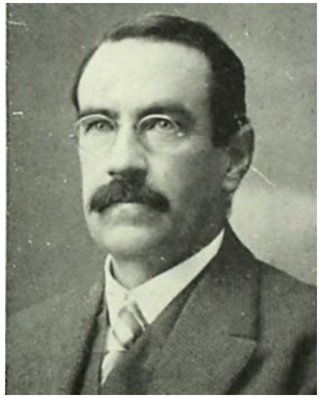
Suitable cathode materials



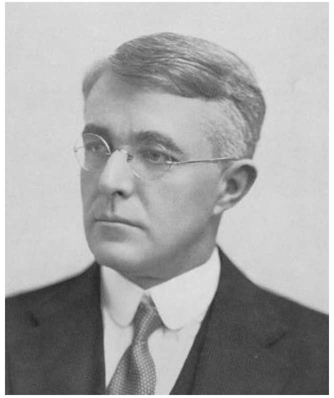
Child-Langmuir Law

(Space charge limited extraction)





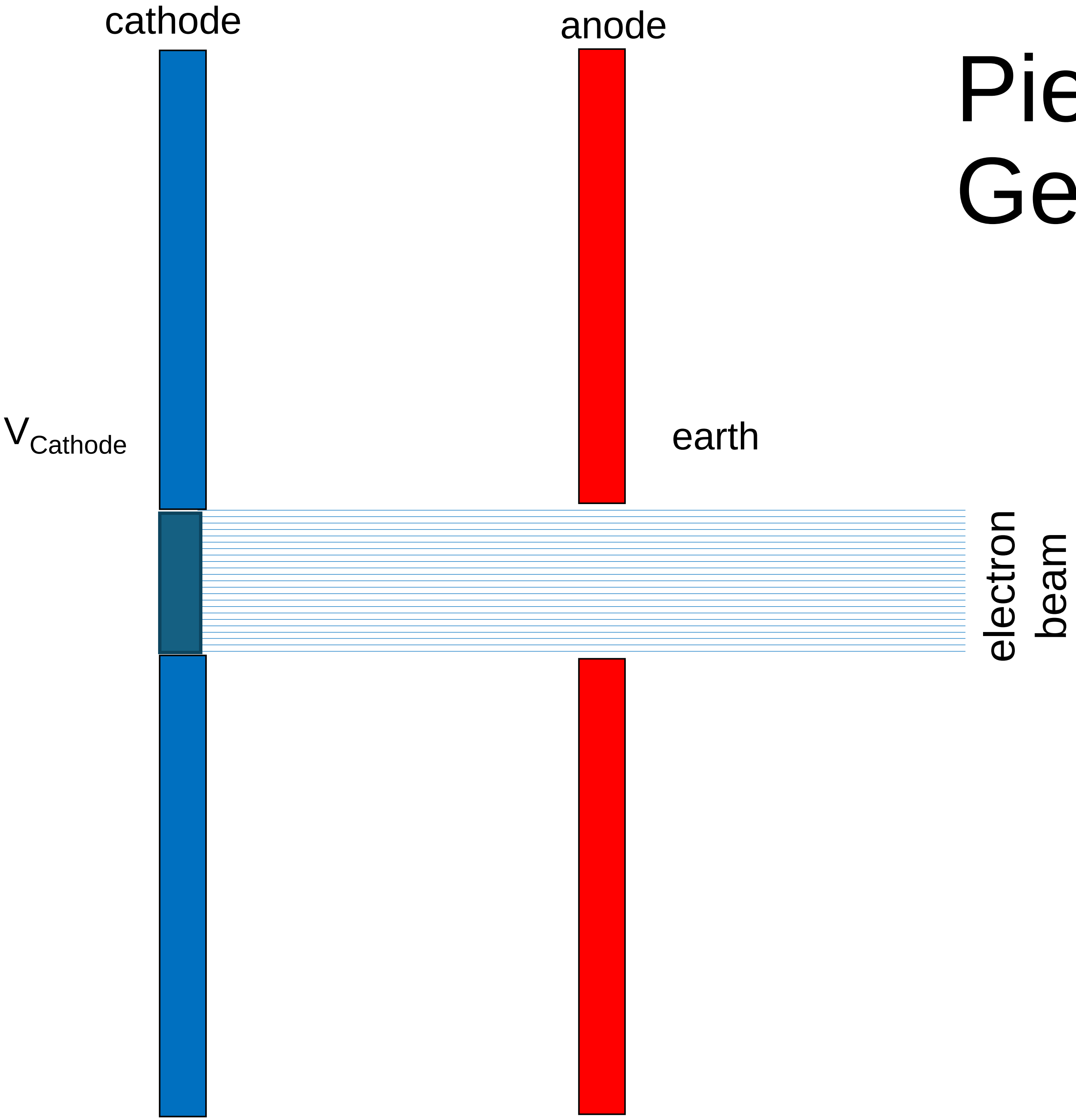
C.D Child
1911



I Langmuir
1913

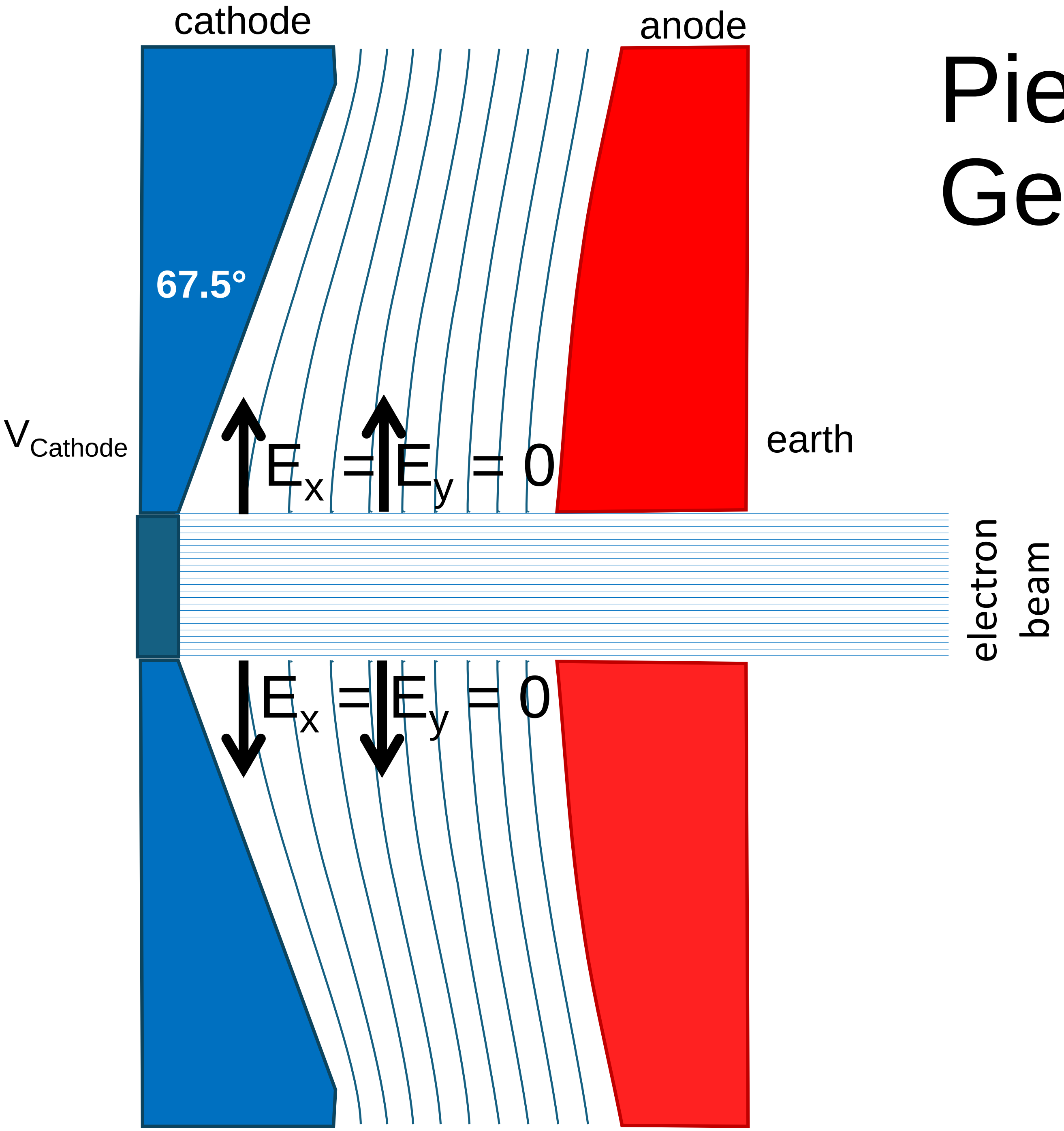
$$j = \frac{\frac{4}{9}\varepsilon_0 \sqrt{\frac{2e}{m_e}} V^{\frac{3}{2}}}{d^2}$$

Pierce Extraction Geometry



J R Pierce

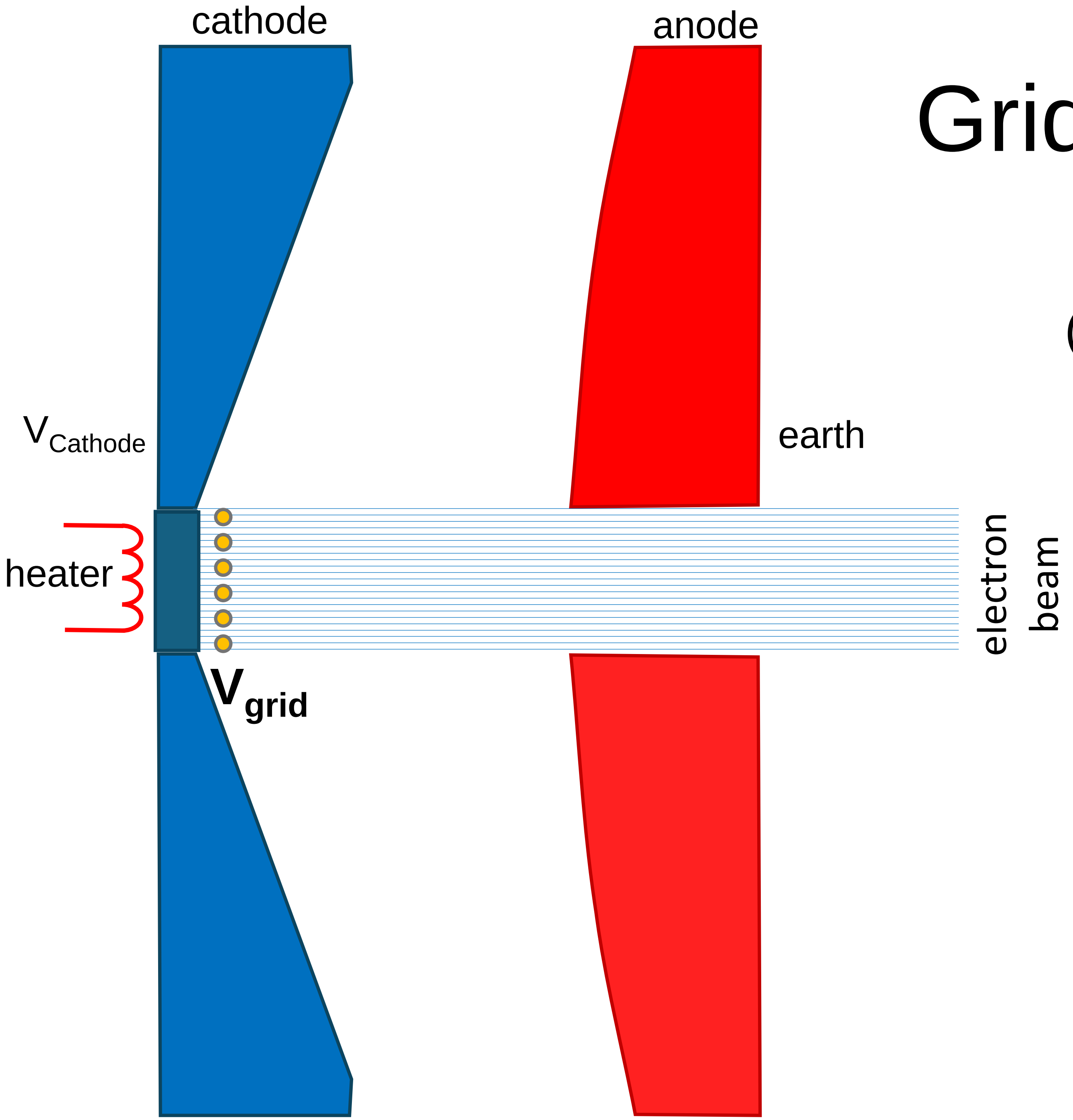
Pierce Extraction Geometry



J R Pierce

Gridded Extraction

(A triode amplifier)



90 kV triode gun with Pierce geometry

diamond

PAUL SCHERRER INSTITUT
PSI
Swiss Light Source

Communications & Power Industries

YU 171

Thermionic dispenser cathode
with integrated heater and grid

Sinter of W and BaO

$1cm^2$
12 W heater

1000 ns, 3 nC long pulses
or
1 ns, 1.5 nC short pulses

Lifetime =
several thousand
hours

Particles and **Sources**

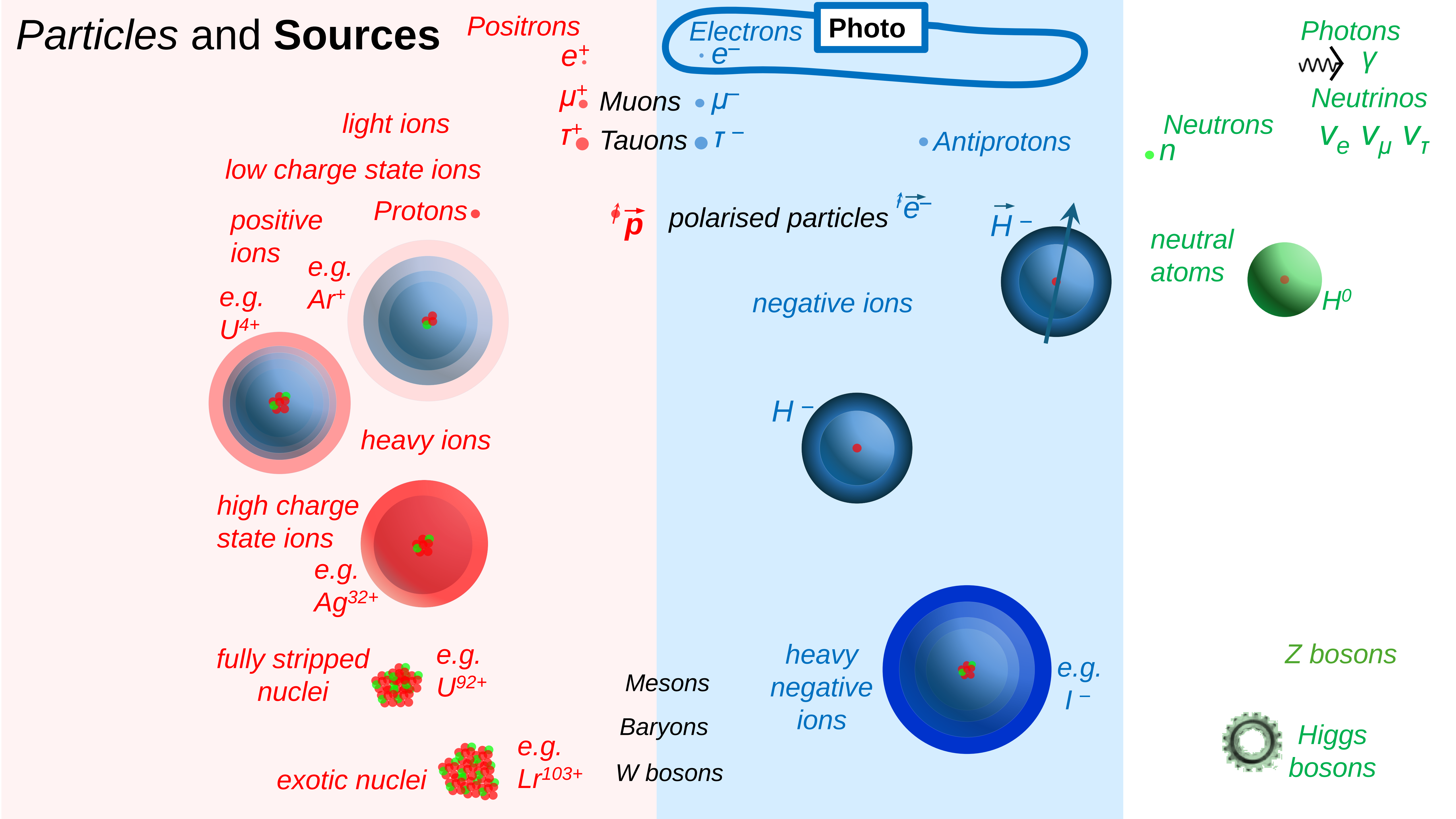
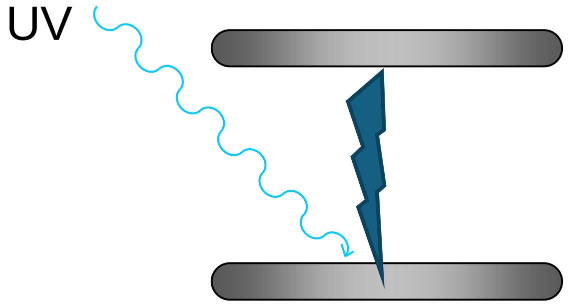


Photo emission

first observed by Heinrich Hertz in 1887



theoretical explanation
by Einstein in 1905

Photo electric emission

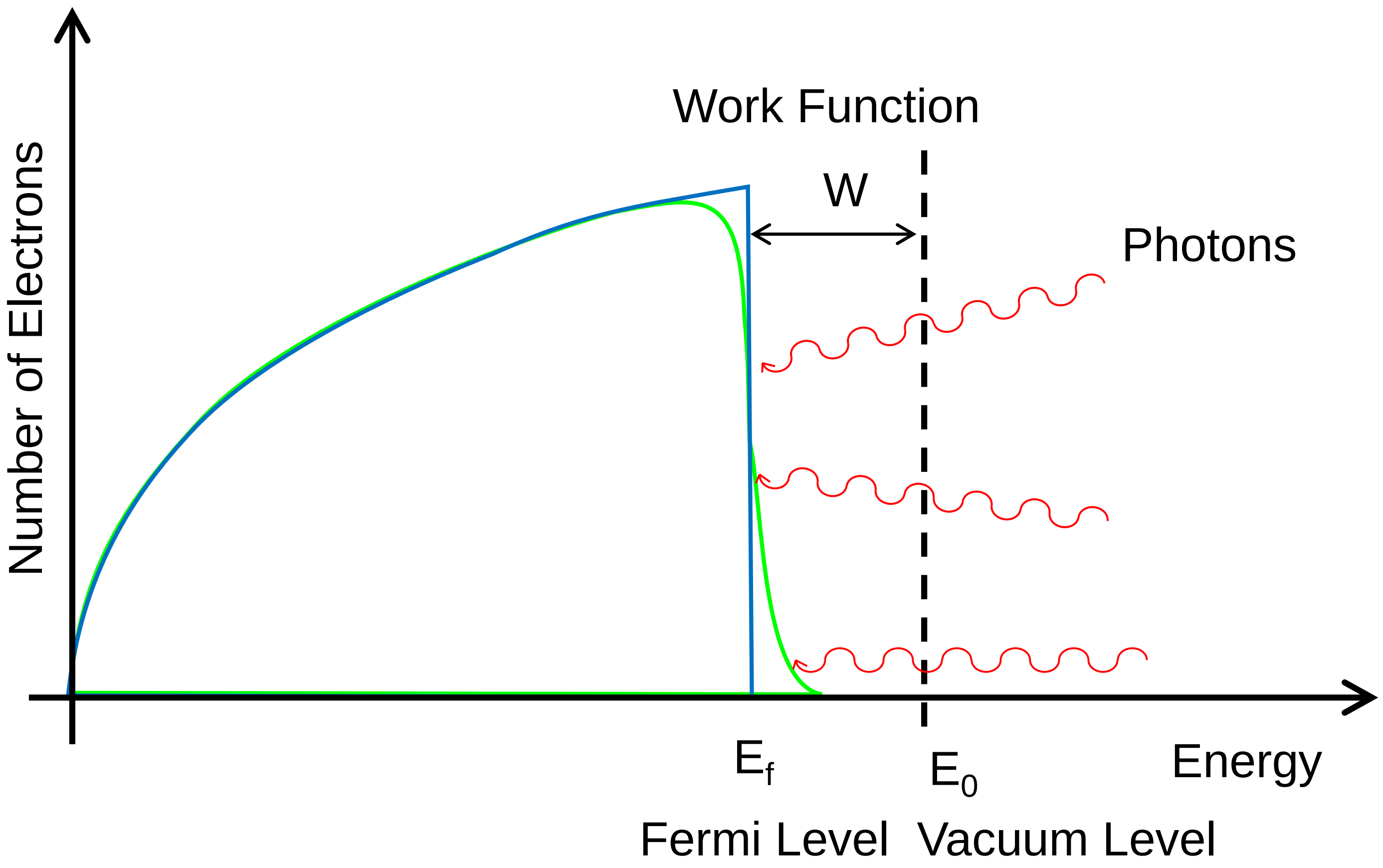
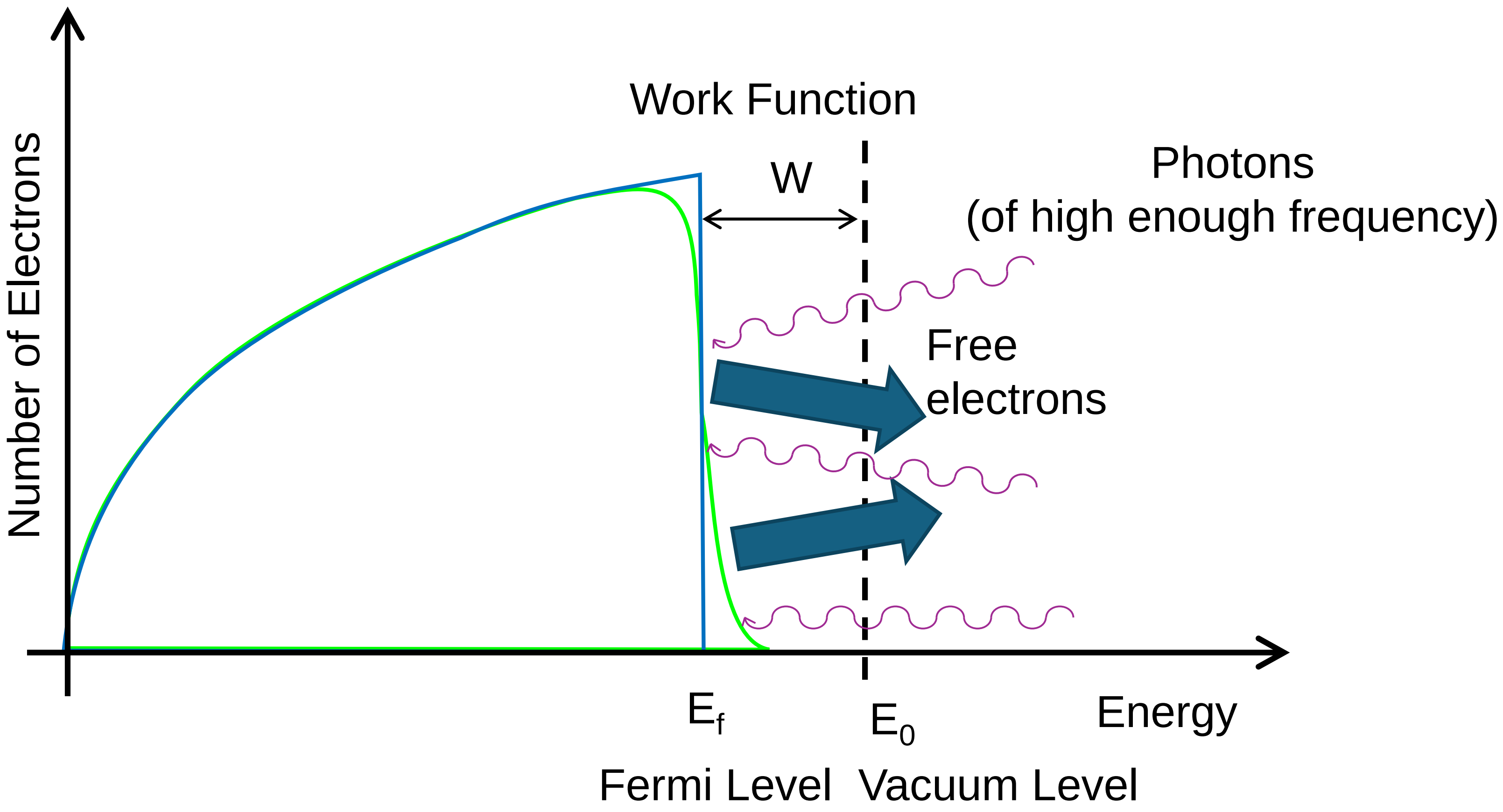
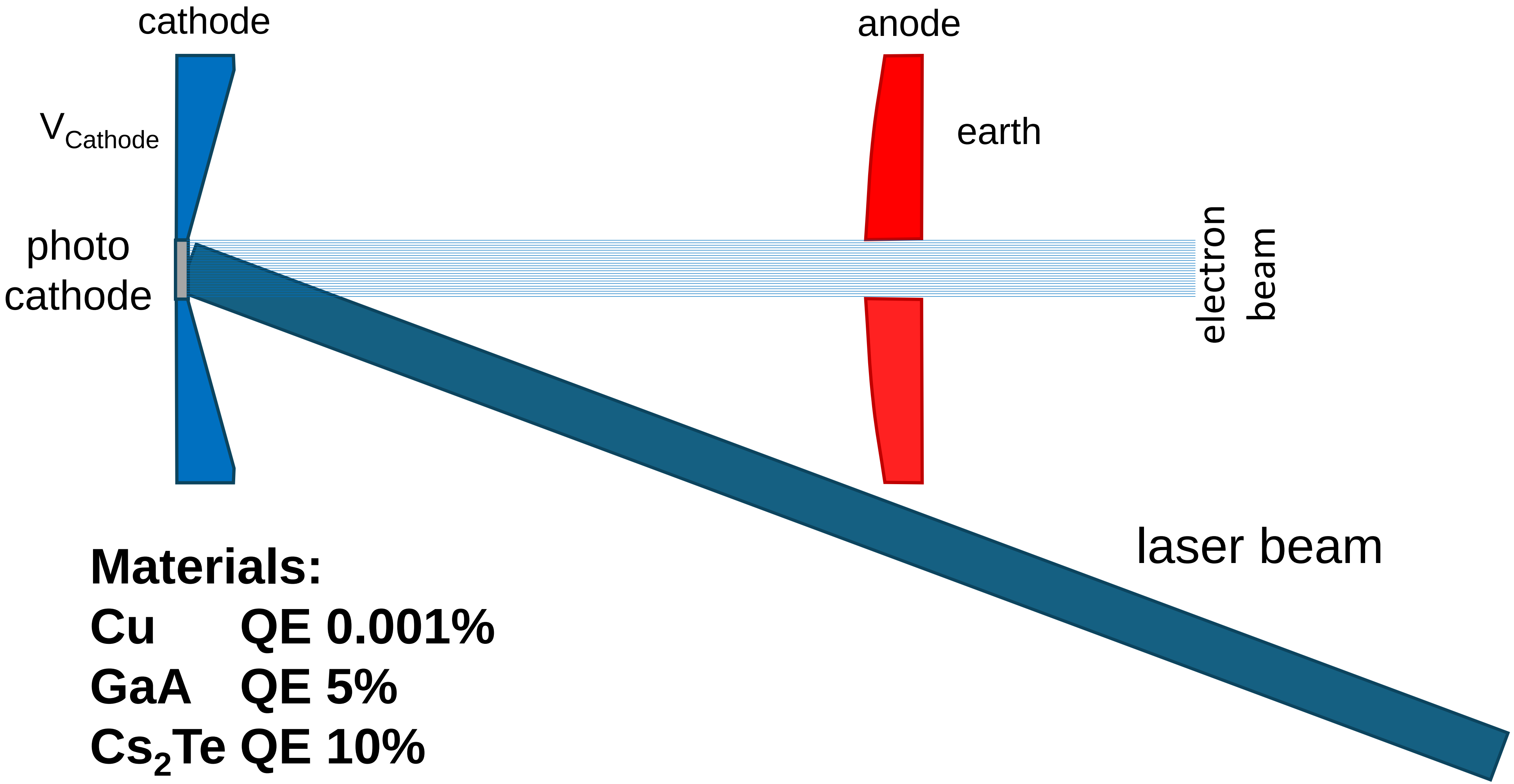


Photo electric emission

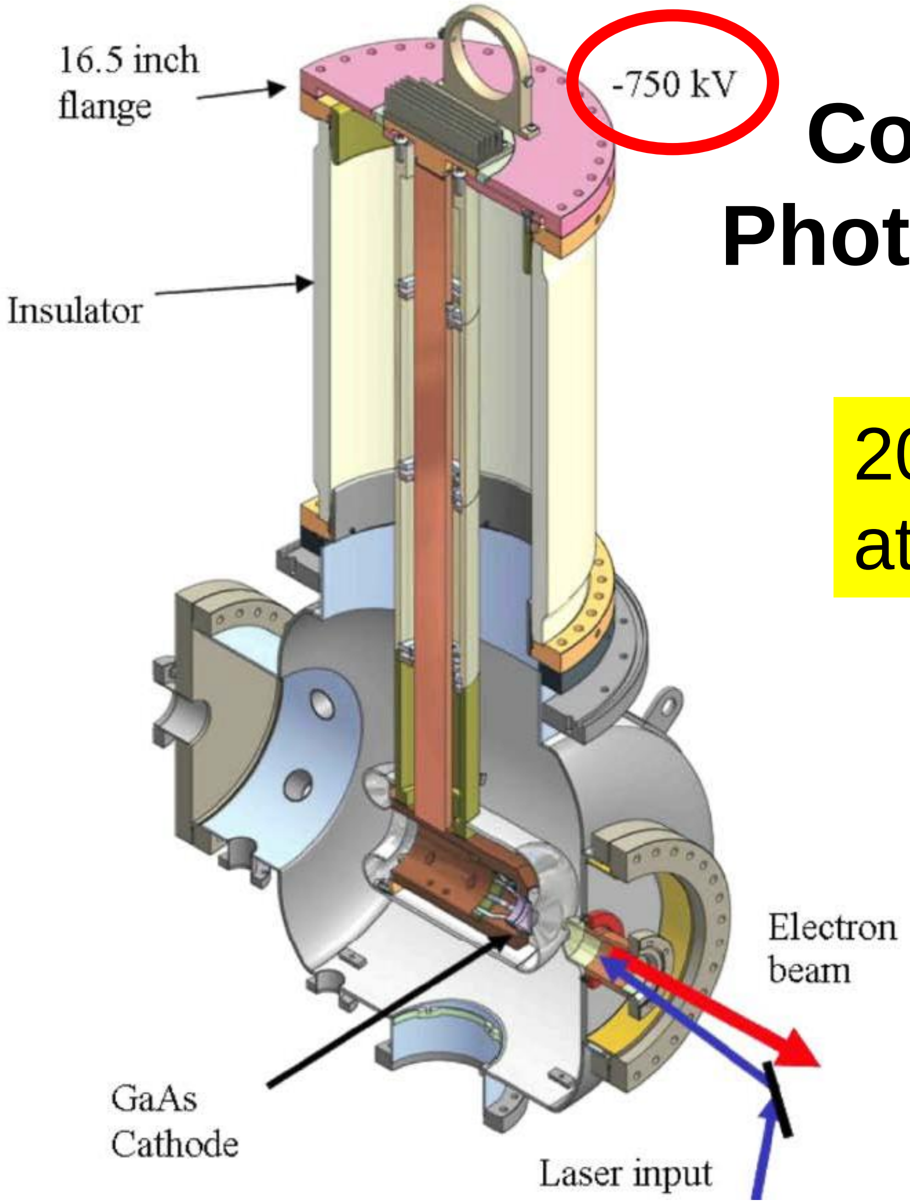


$$\text{Quantum Efficiency (QE)} = \frac{\text{Number of electrons produced}}{\text{Number of incident photons}}$$

Photo Emission Gun

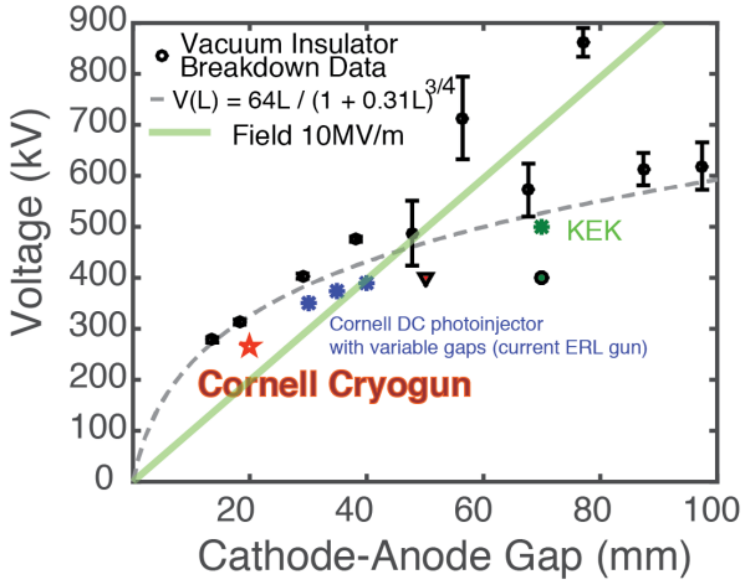


Materials:
Cu QE 0.001%
GaA QE 5%
Cs_2Te QE 10%

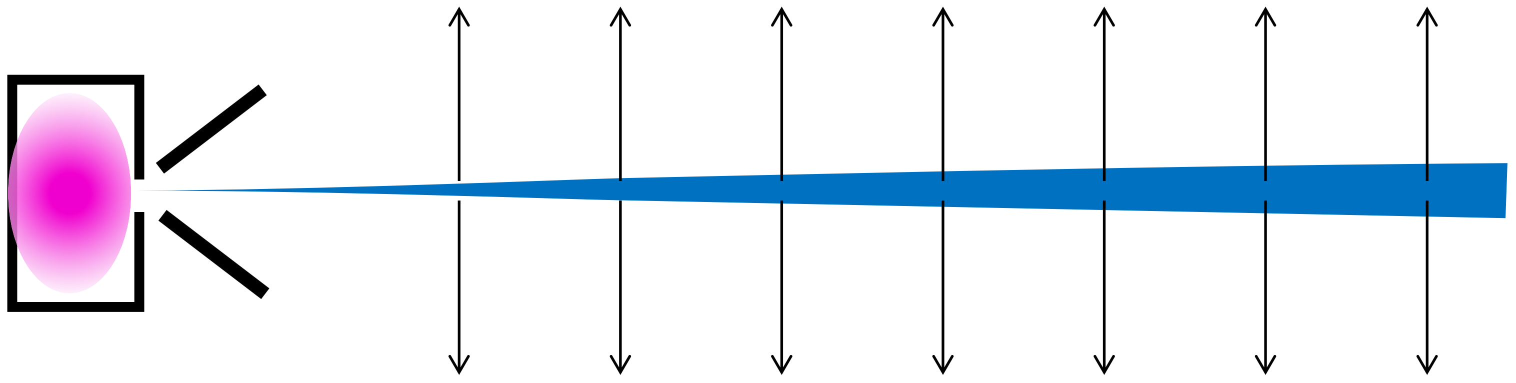


Cornell DC Photoemission gun

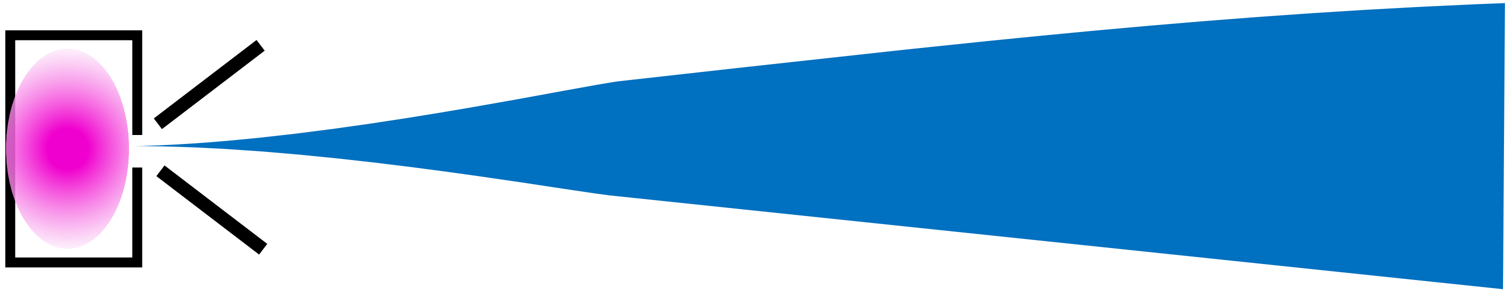
20 mA average current
at 250kV

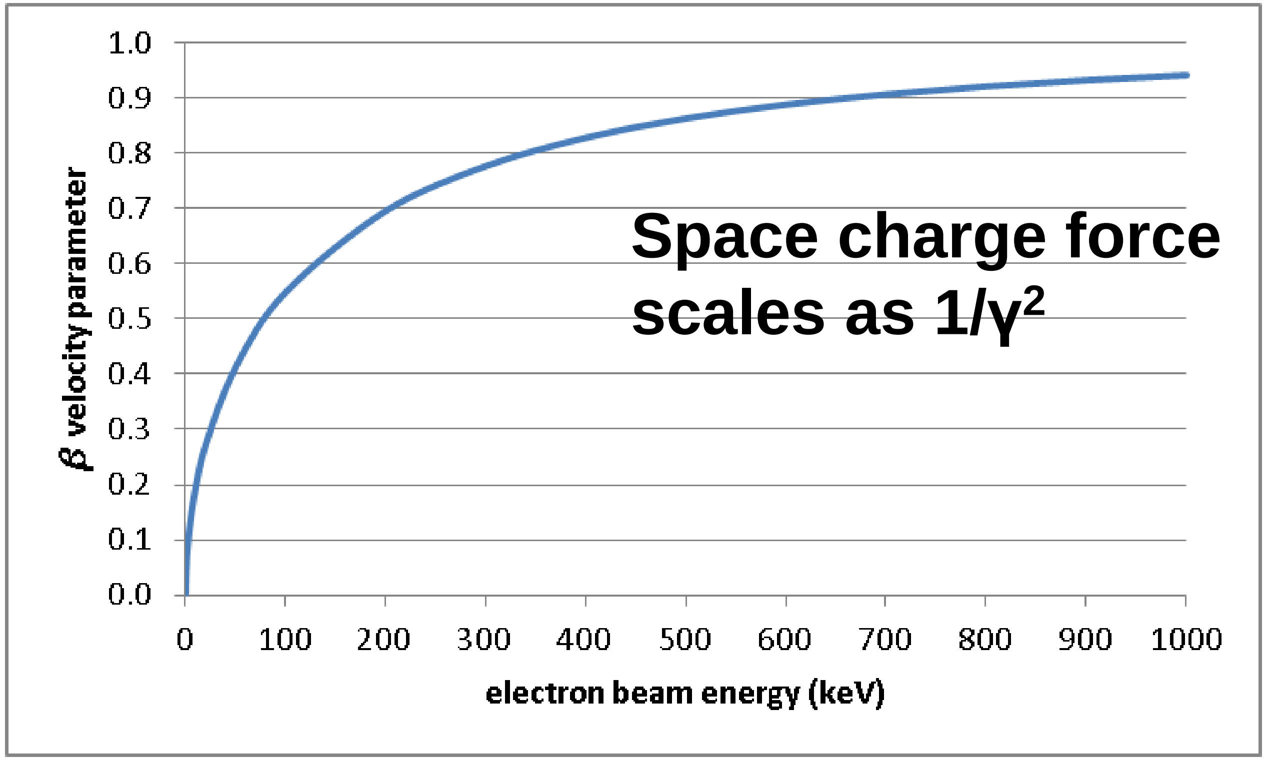


Space Charge



Space Charge





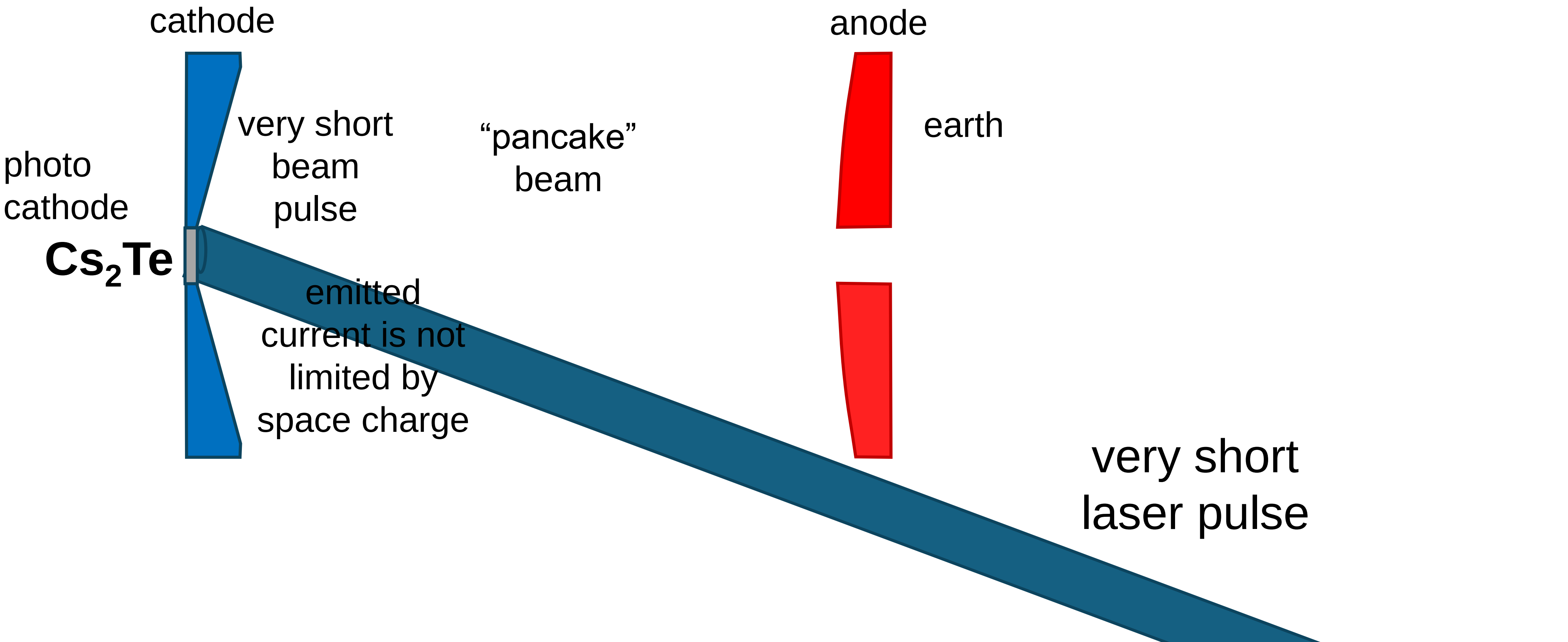
@ 500 keV electron γ = 2

(940 MeV proton γ = 2)

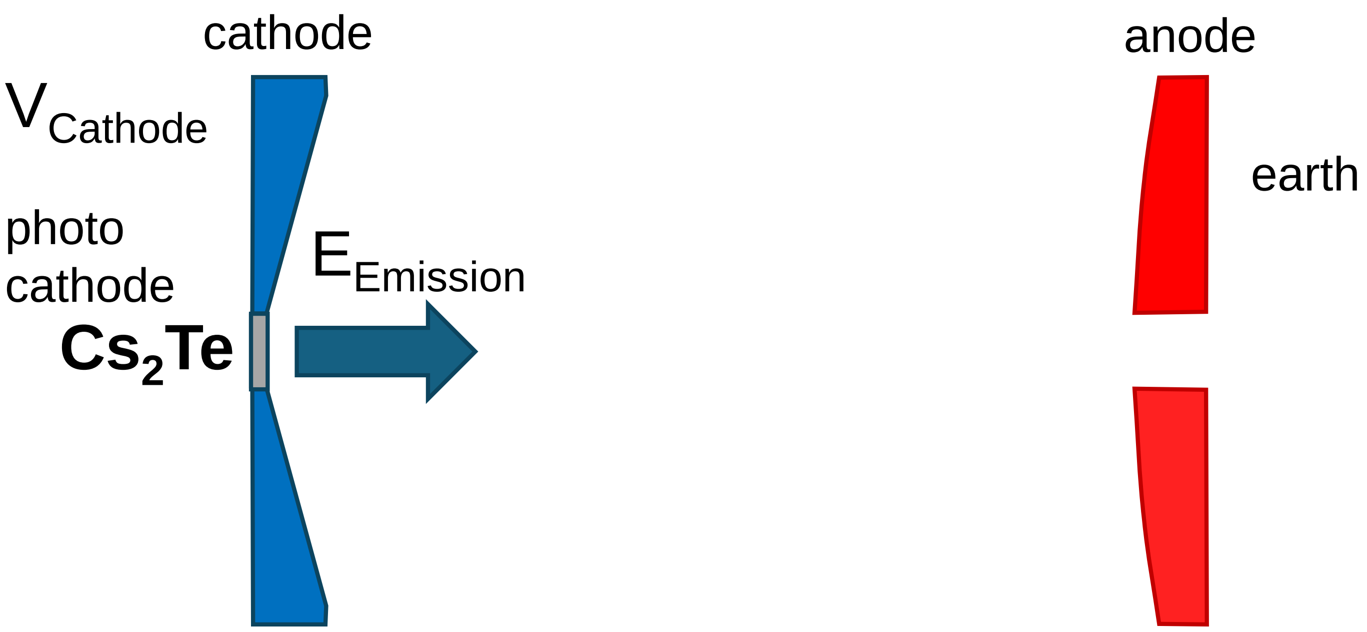
Another reason to use lasers is…

Lasers are so fast they can easily beat Child-Langmuir

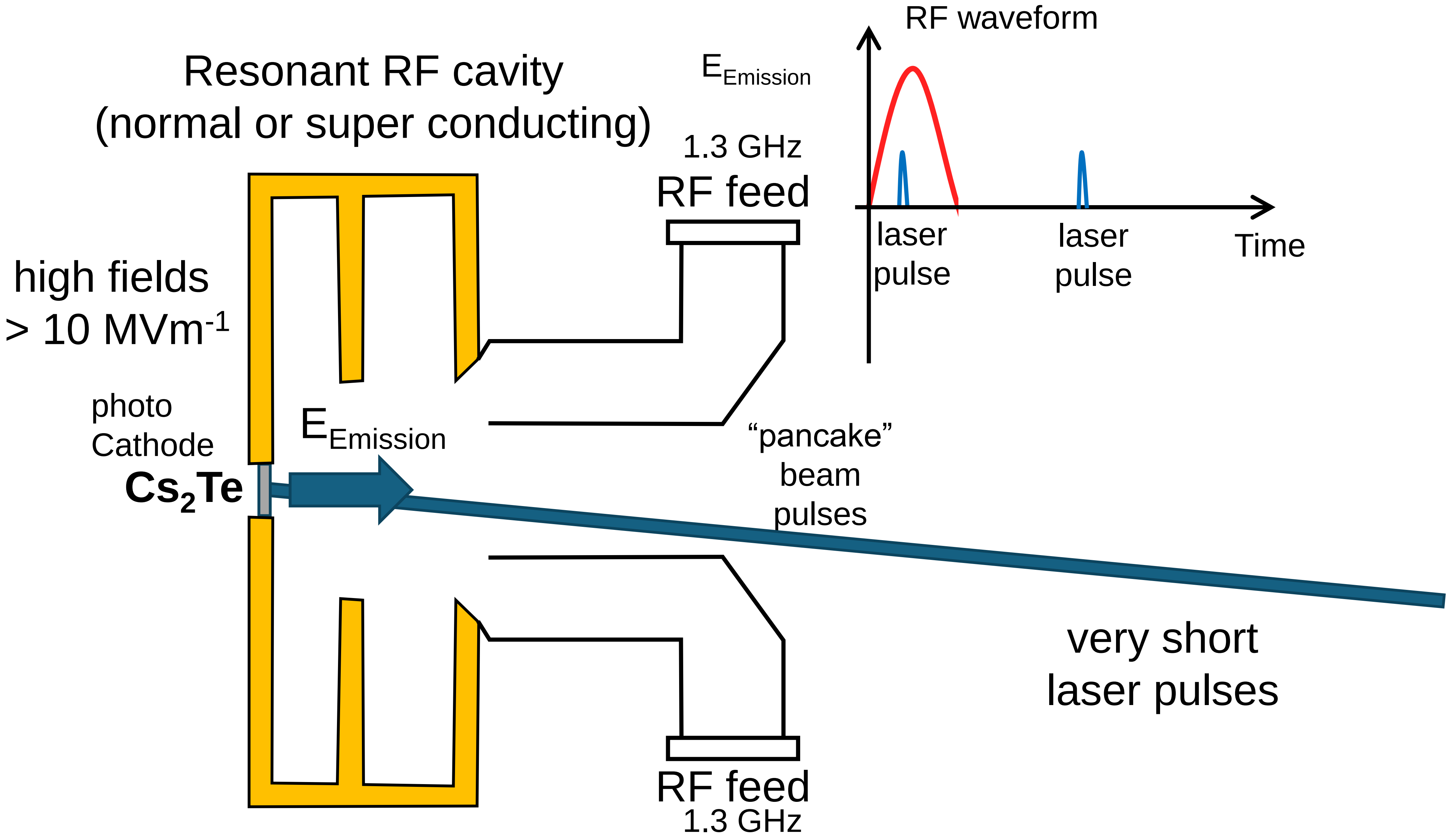
(actually so can gridded extraction)



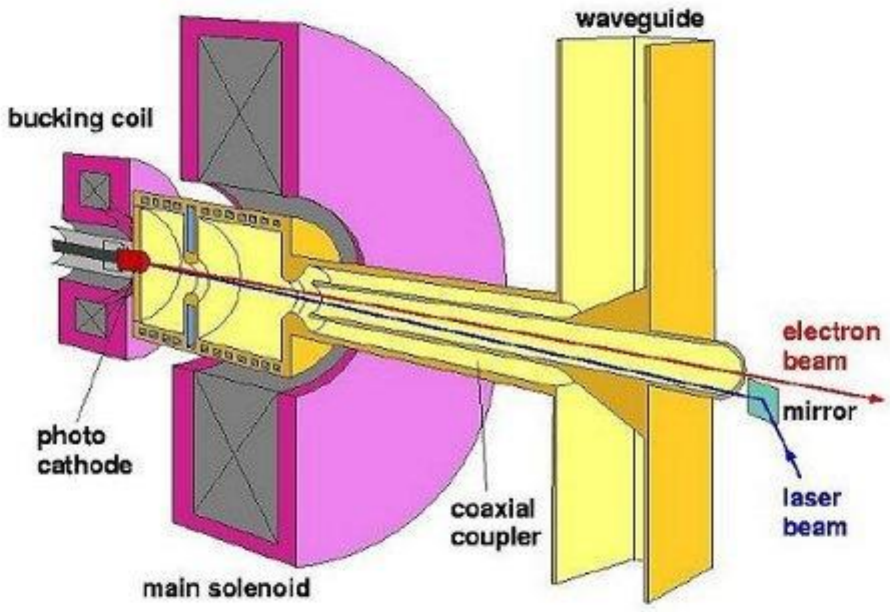
RF Photoemission Source



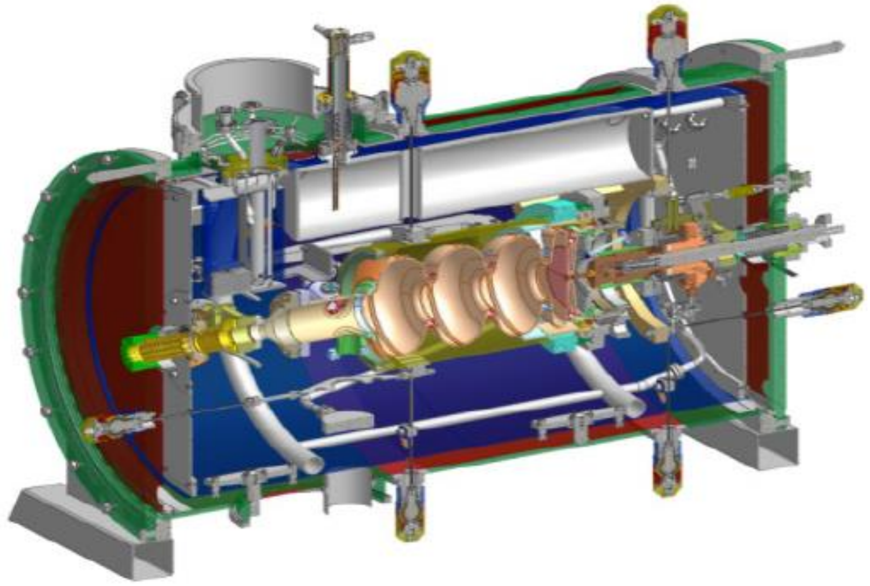
RF Photoemission Source



Normally conducting



Super conducting

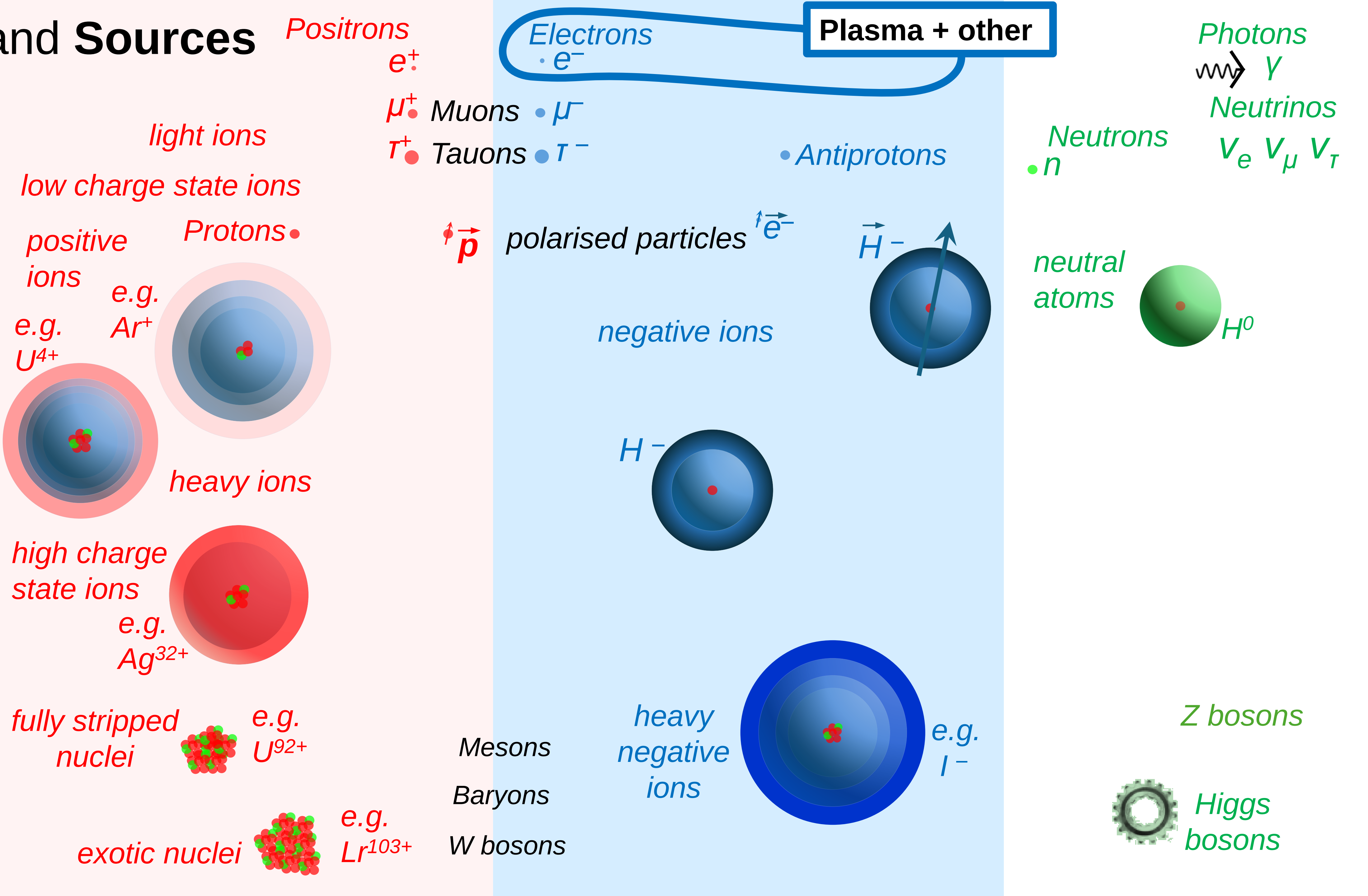


20 ps, 1 nC pulses
(50 A pulse)

15 ps, 1 nC pulses
(67 A pulse)

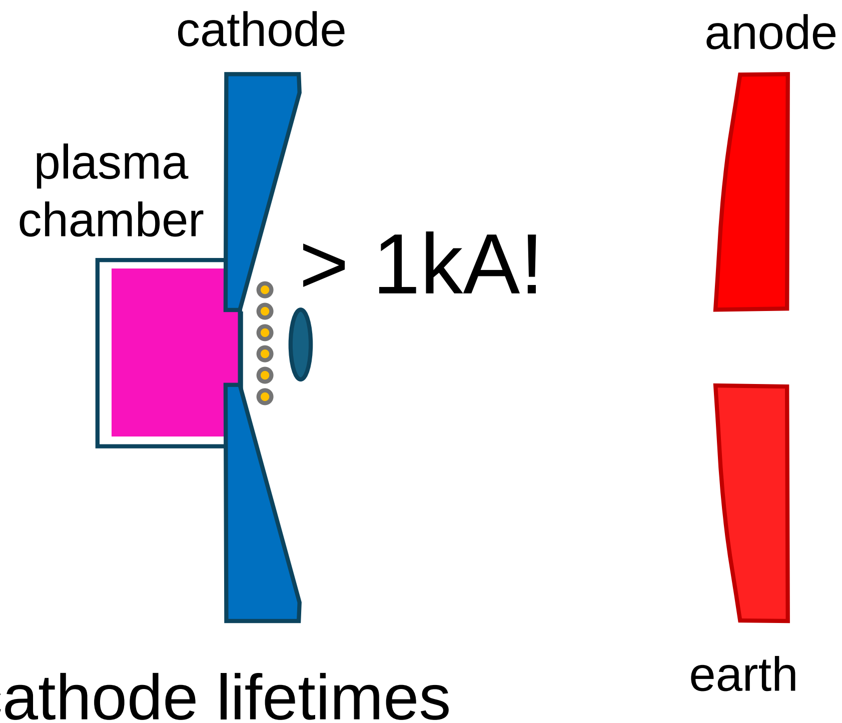
High brightness low emittance guns for FEL

Particles and **Sources**



Plasma Cathode

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



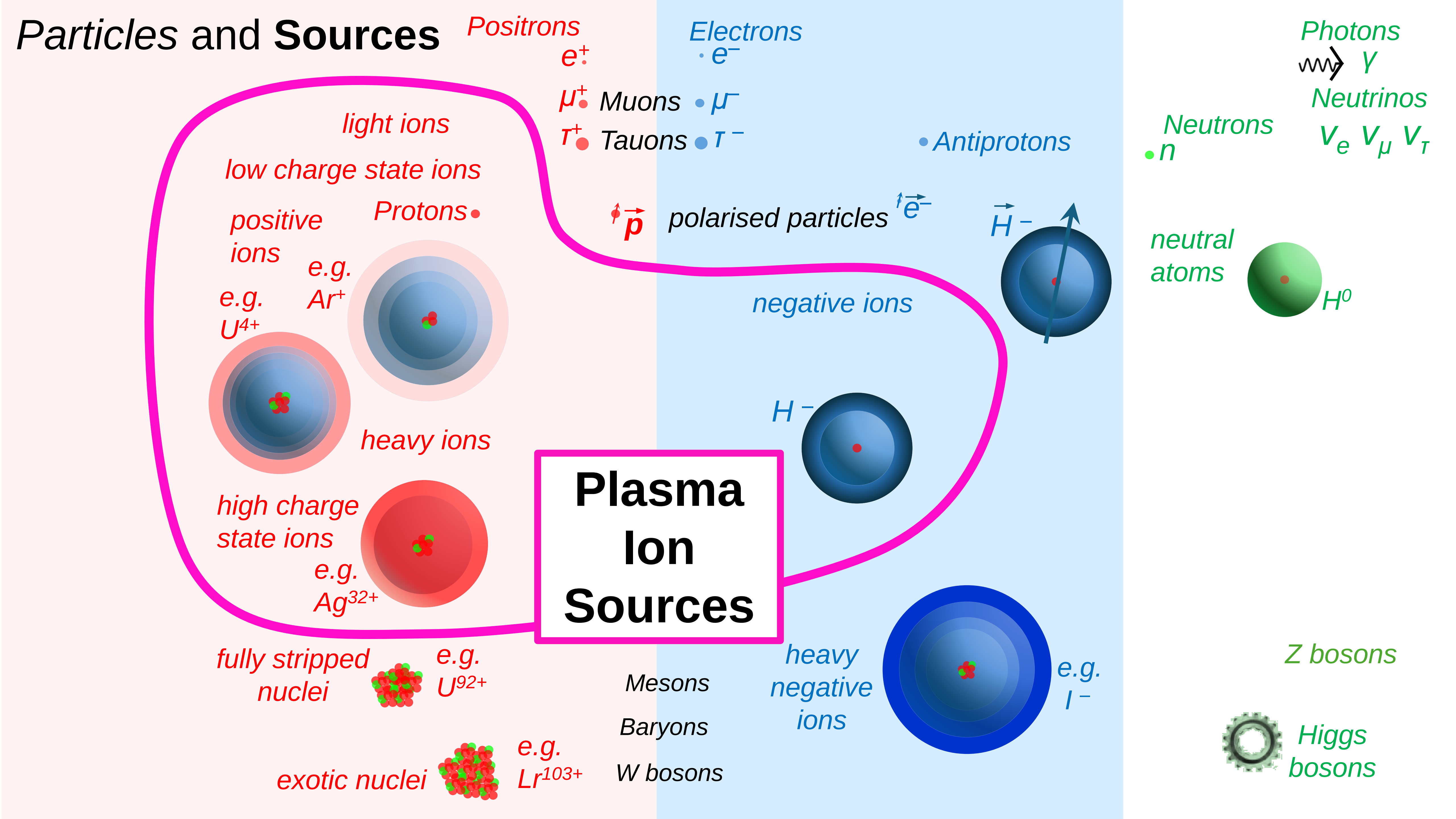
long cathode lifetimes

Other electron sources:

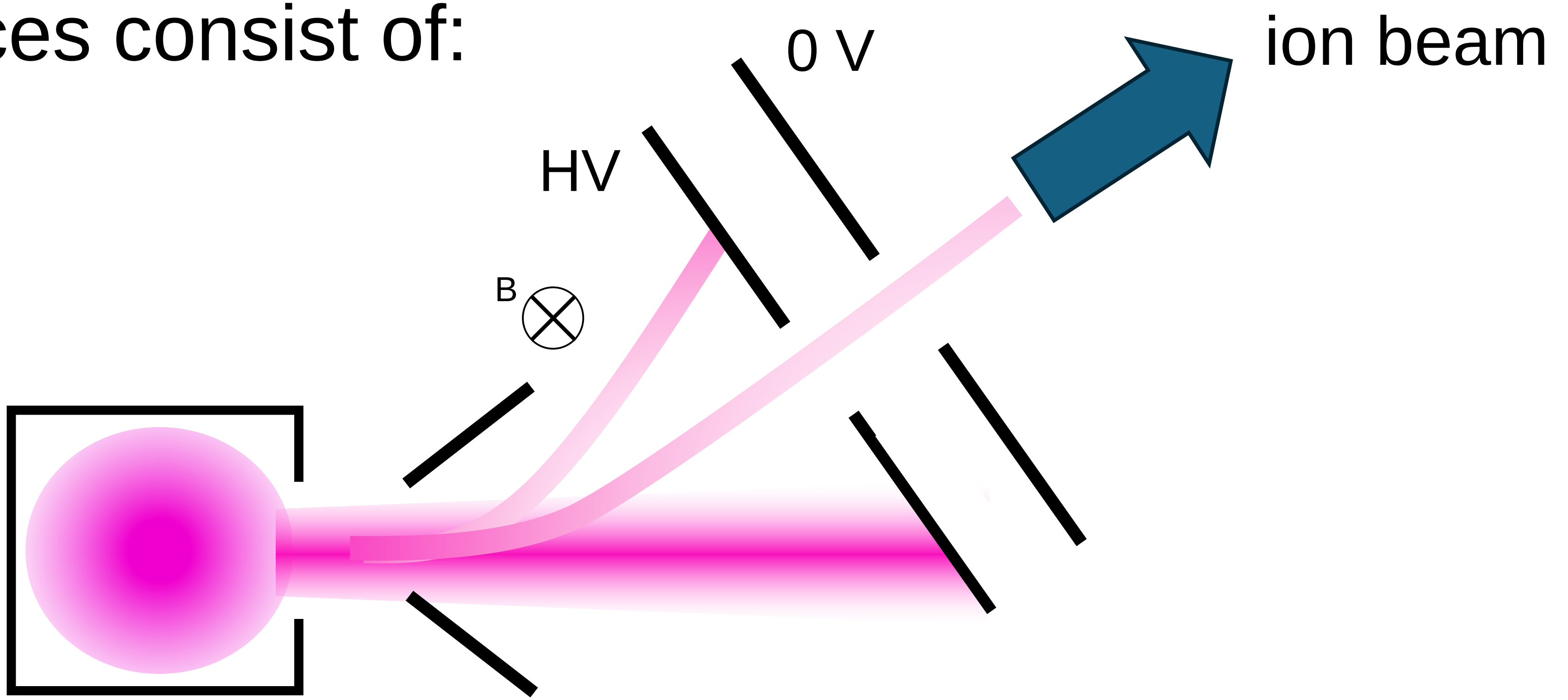
Combinations of those already mentioned e.g. photo-thermionic

Field emission from needle arrays
Diamond amplifiers
etc...

Particles and **Sources**



Plasma ion sources consist of:

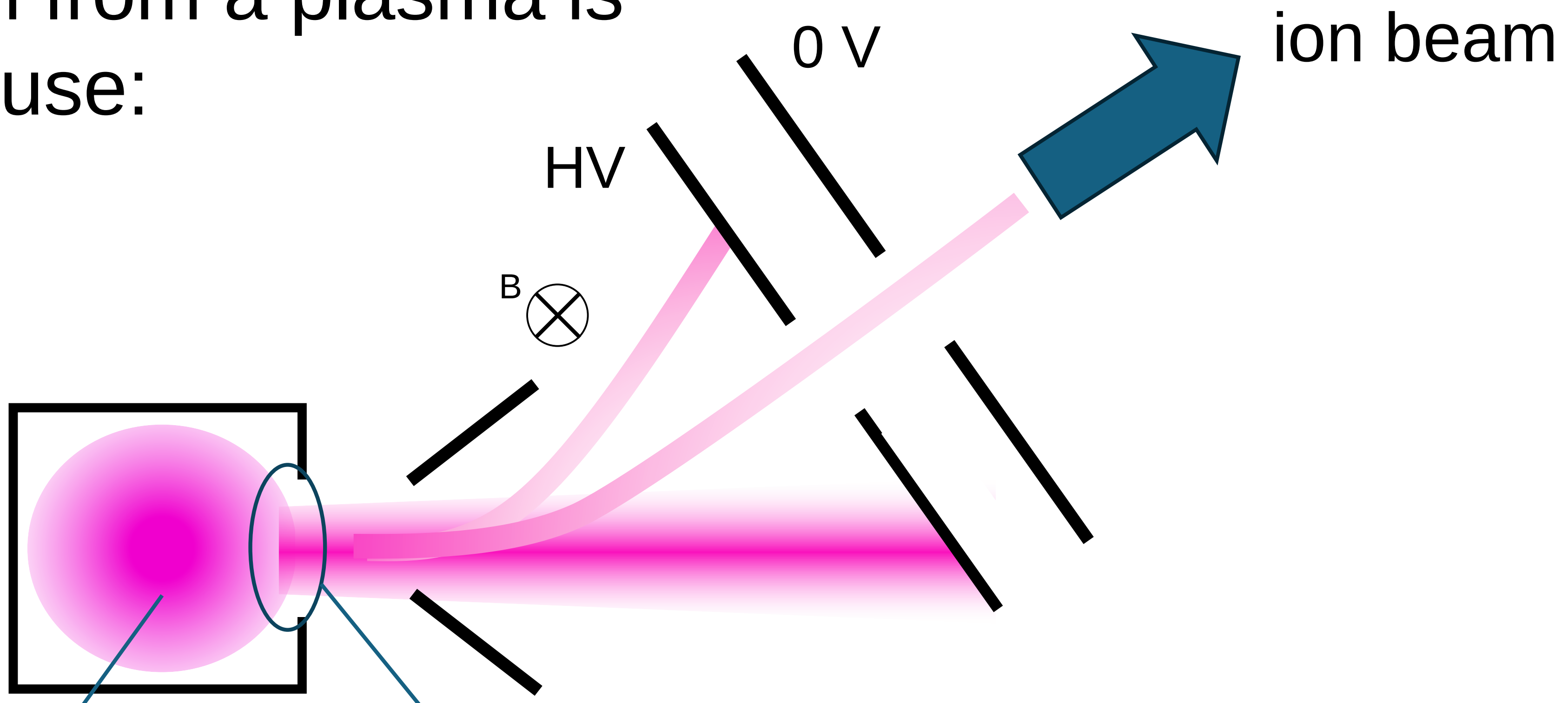


plasma generator + extraction system

(to make ionised particles)

(to select the correct particle species
to accelerate and shape the beam)

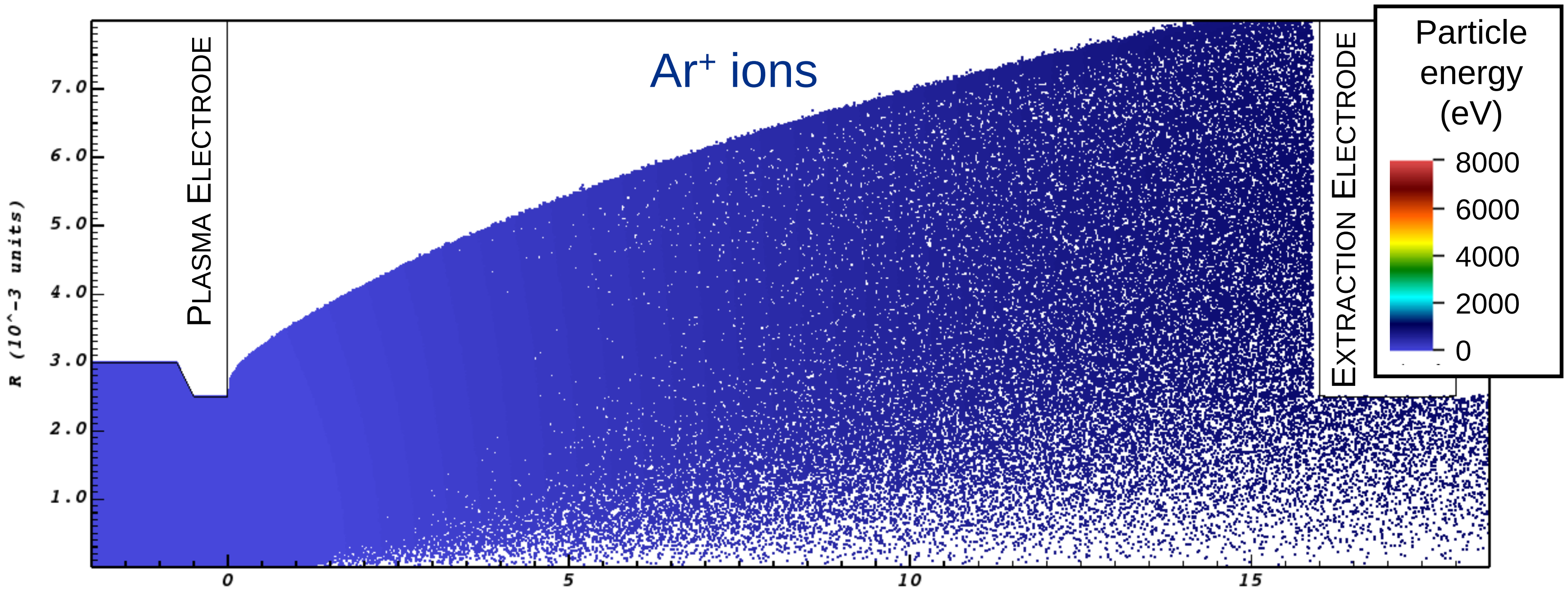
Extracting a beam from a plasma is complicated because:

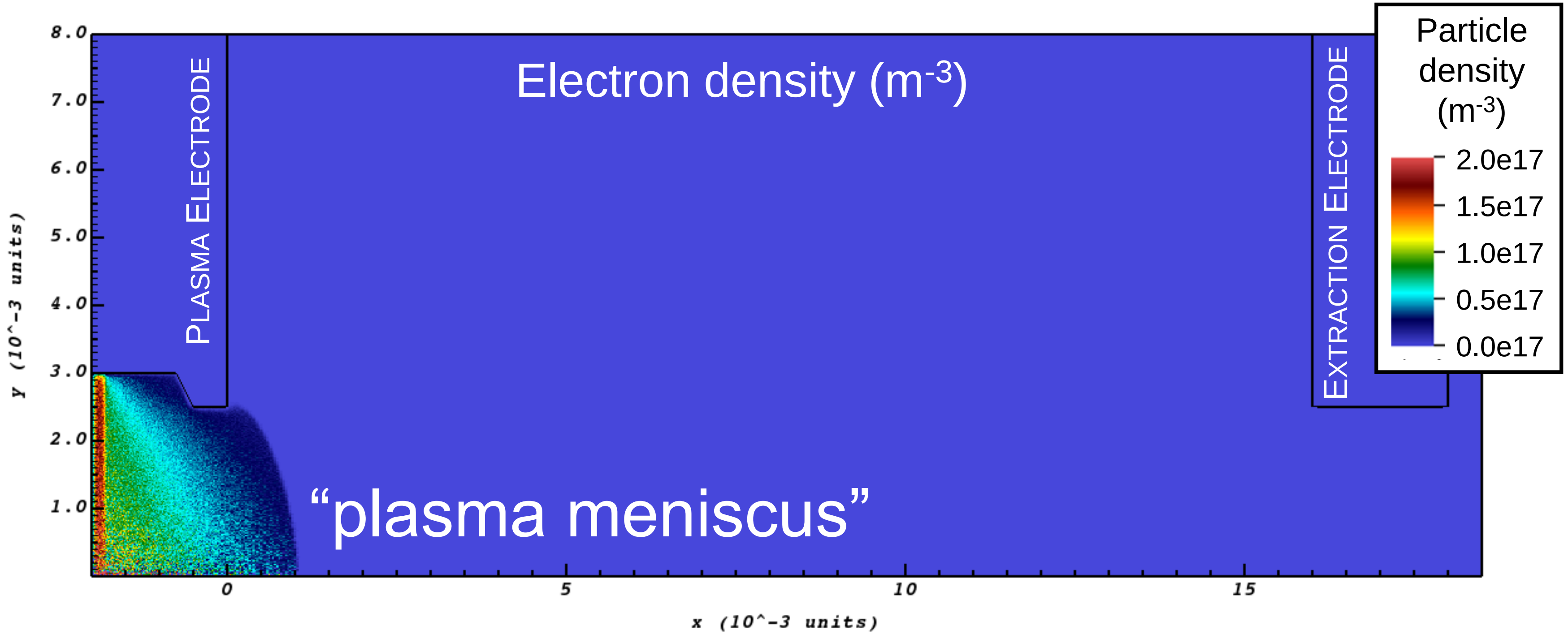


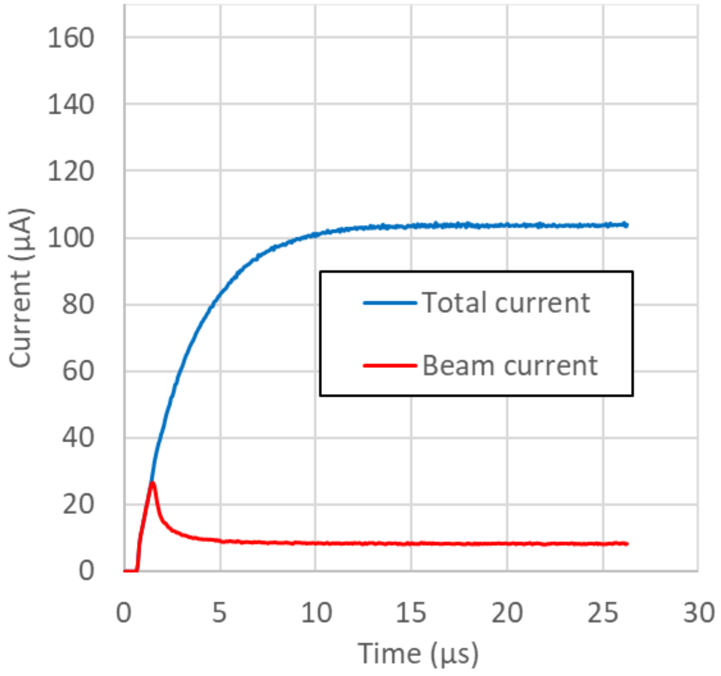
1. Plasmas contain different particle species

2. The emission surface is a dynamic equilibrium

1 kV Extraction Voltage

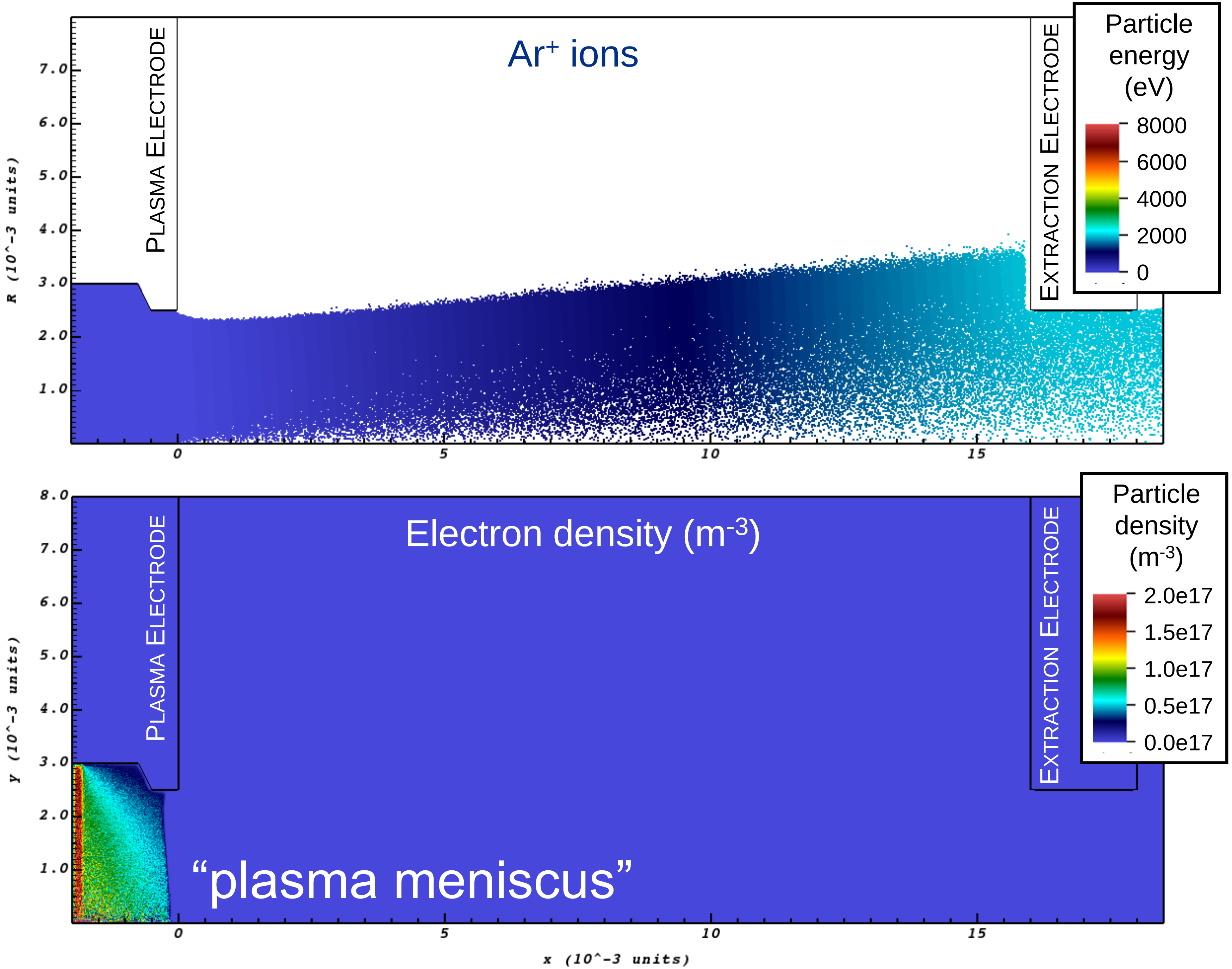


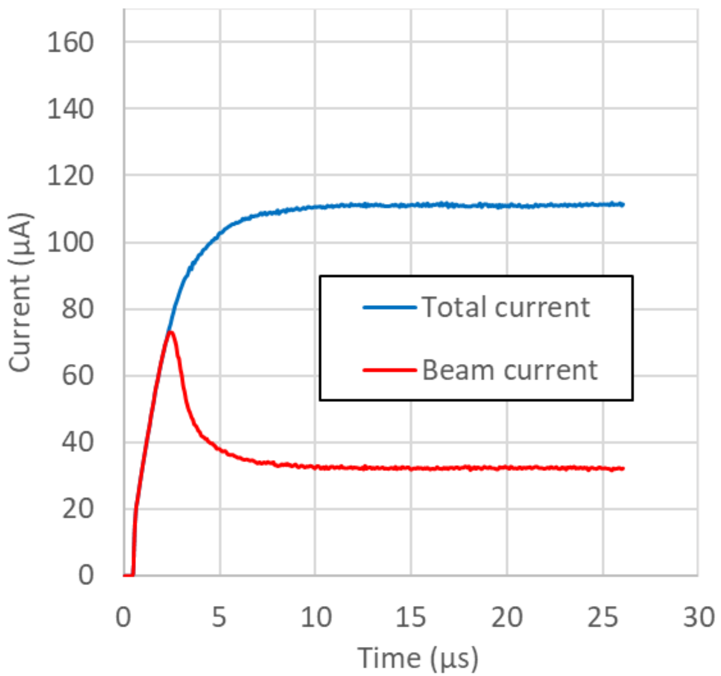




The plasma density balances the applied extraction field to form a "meniscus"

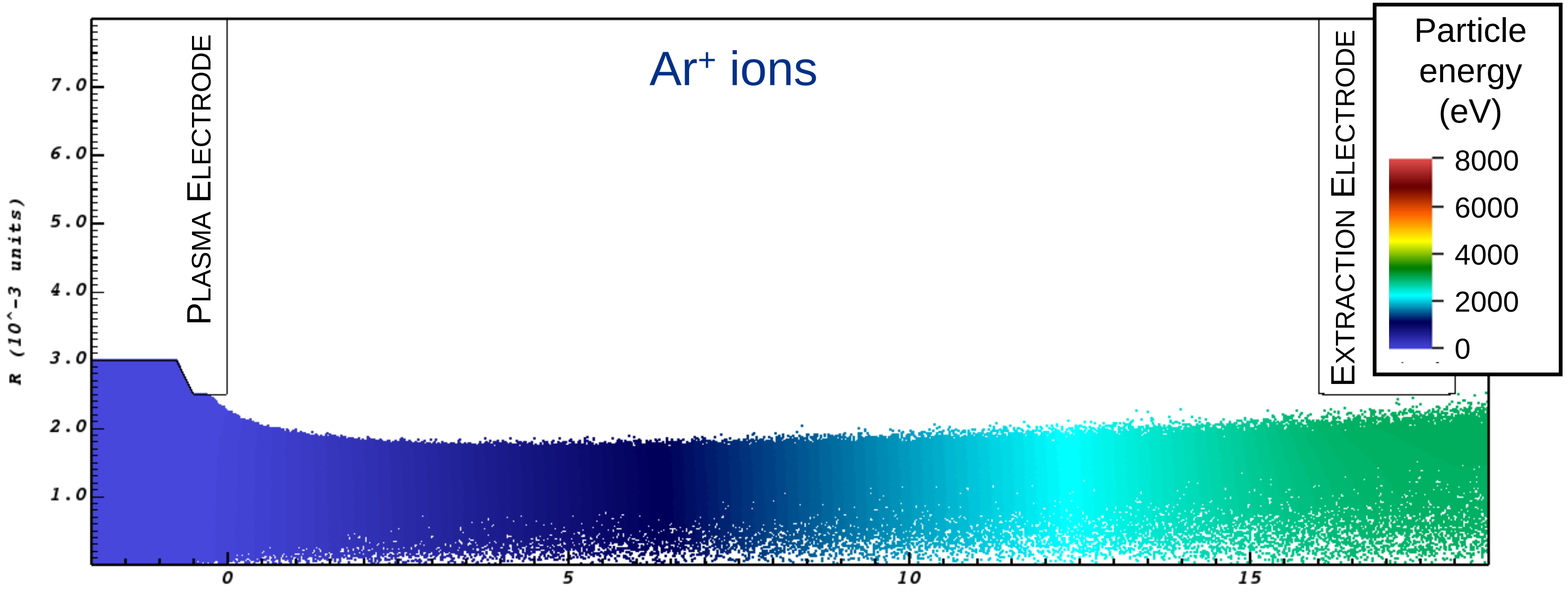
2 kV Extraction Voltage

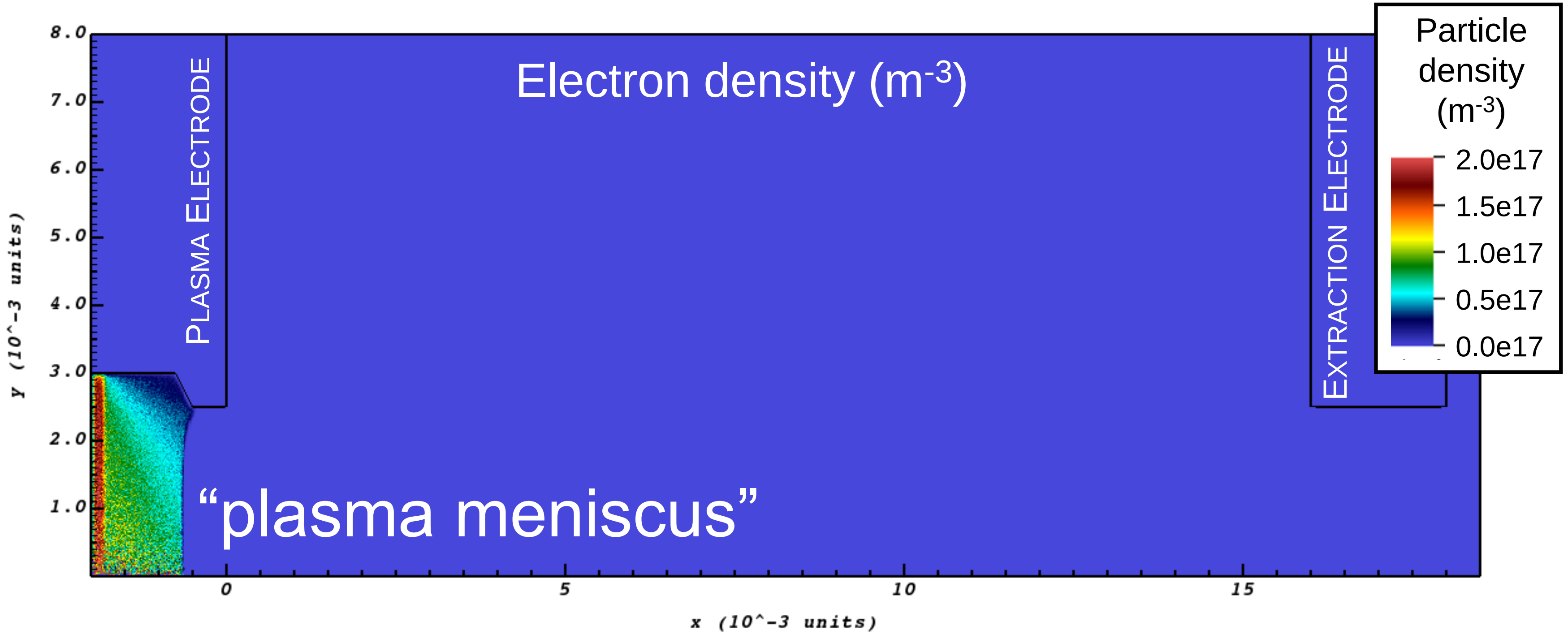


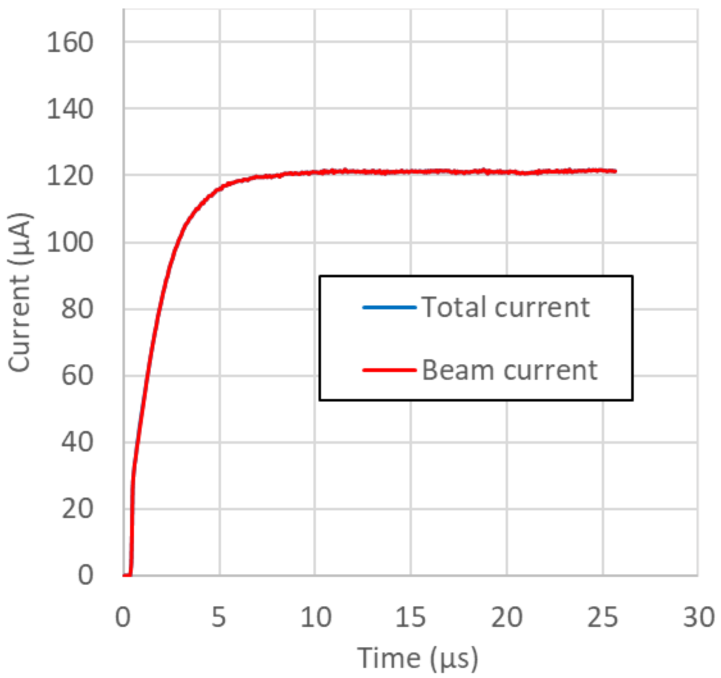


The "meniscus" is pushed back as the extraction voltage is increased

3 kV Extraction Voltage

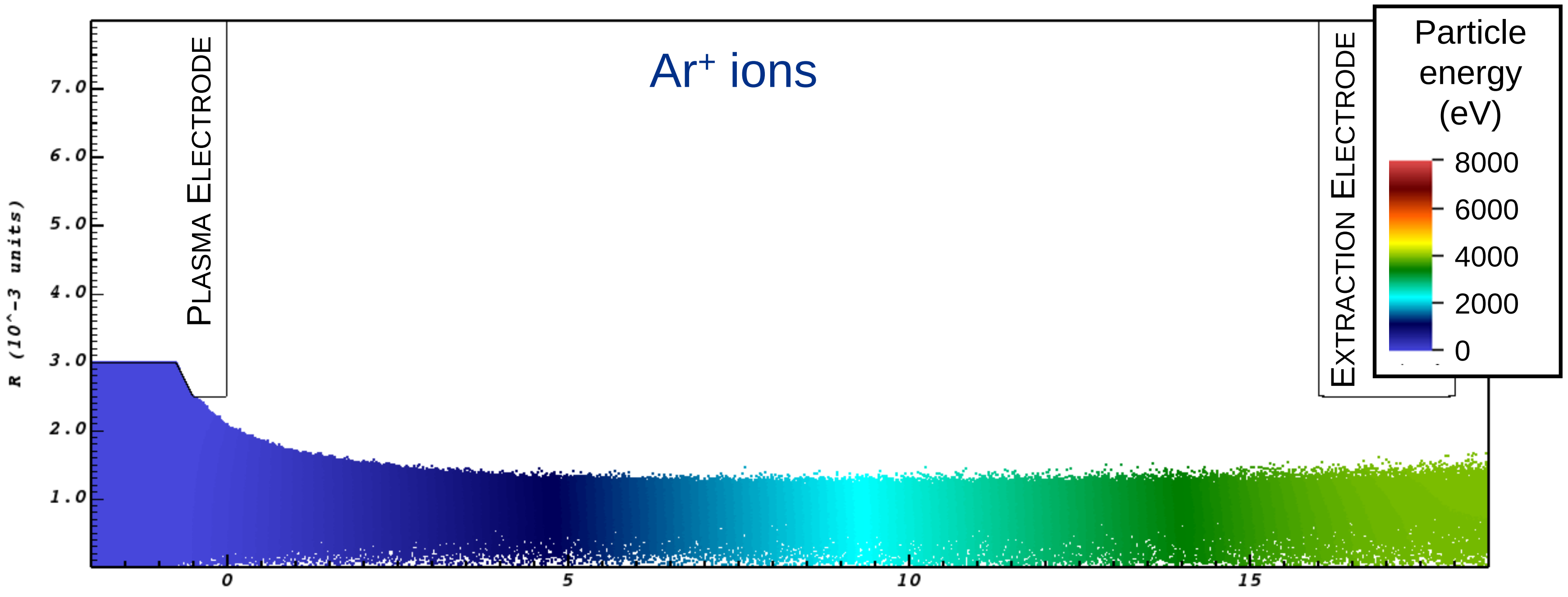


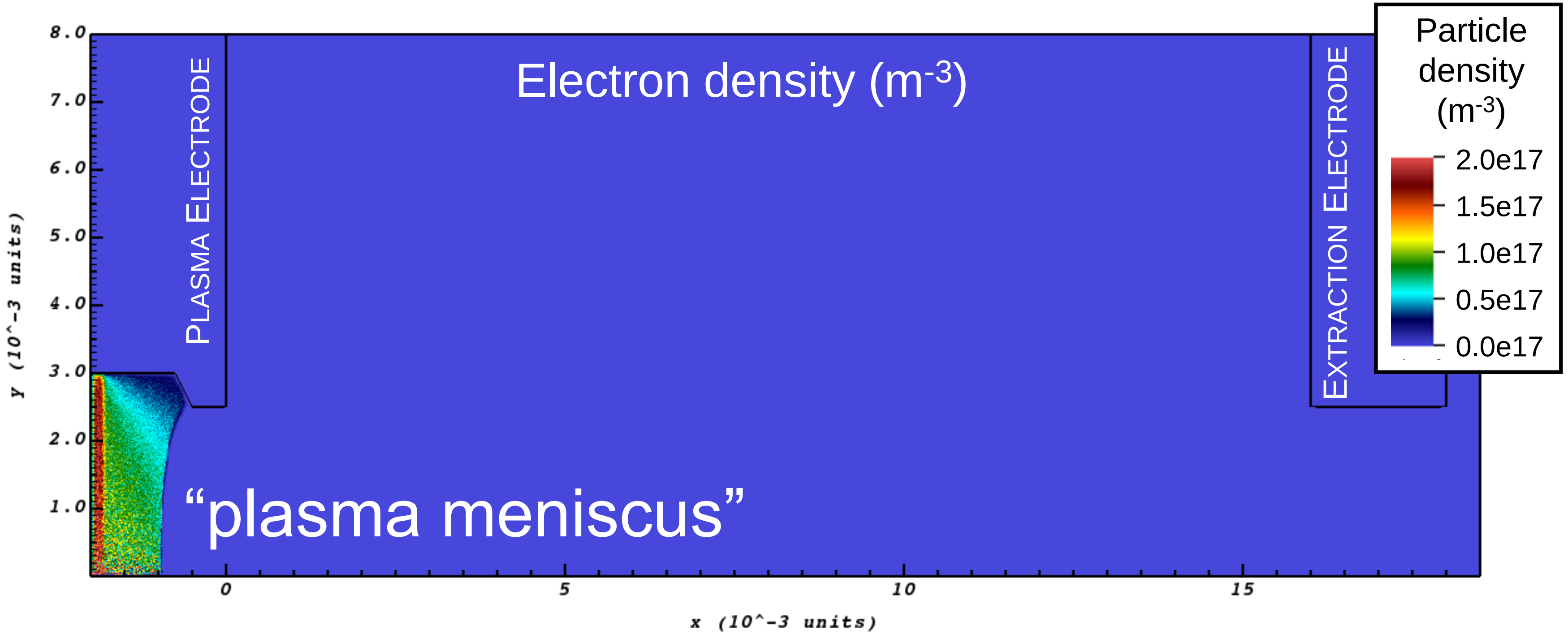


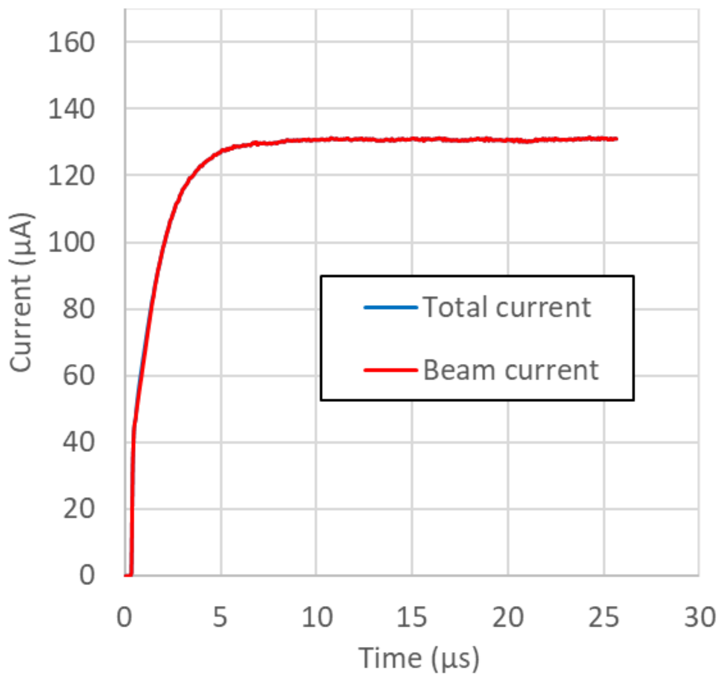


The "meniscus" is pushed back as the extraction voltage is increased

4 kV Extraction Voltage

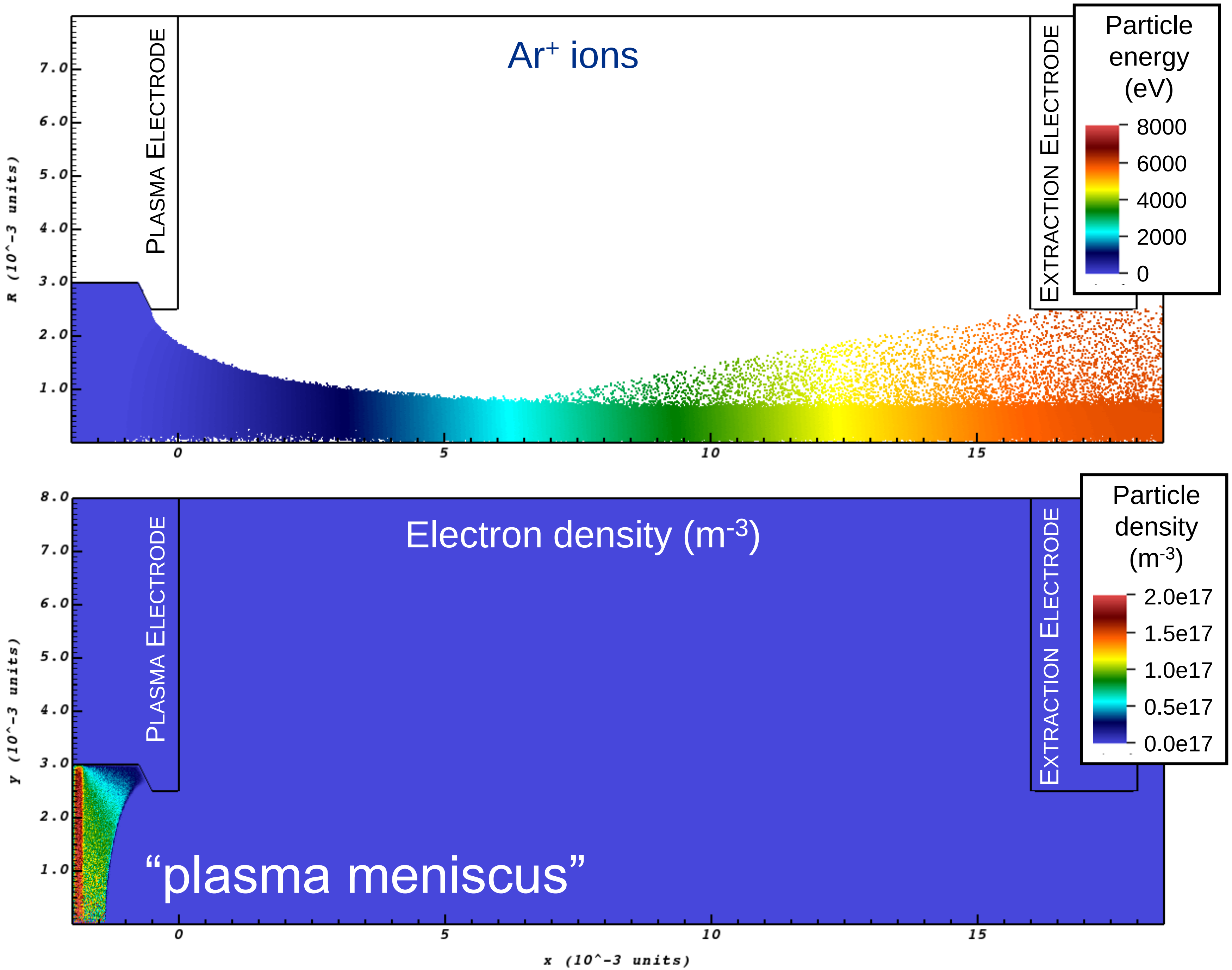


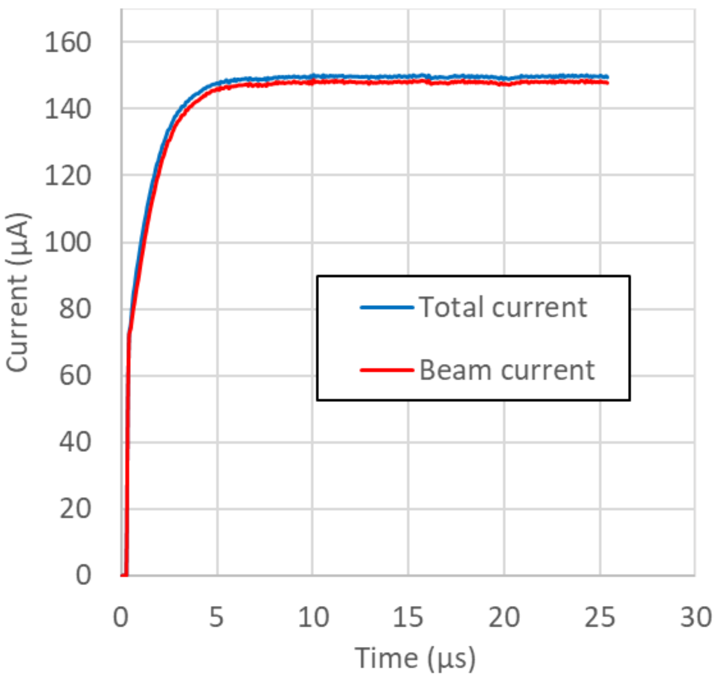




causing the beam to change shape as the extraction voltage changes

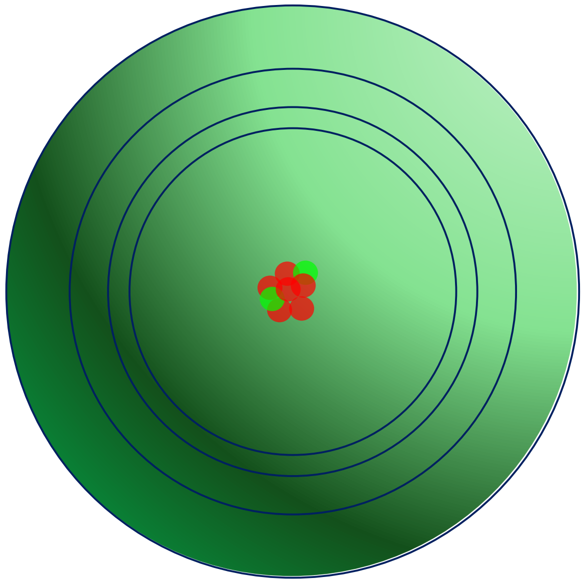
6 kV Extraction Voltage





causing the beam to change shape as the extraction voltage changes

Plasma generation - Ionisation

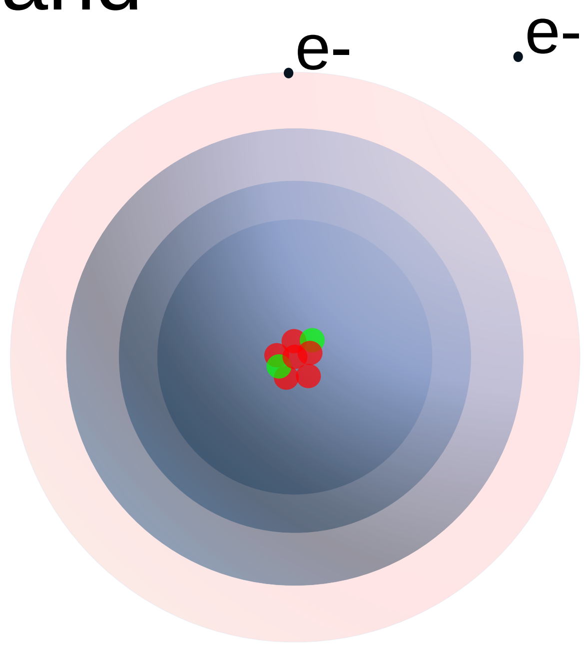


neutral atom

Most sources rely on electron impact ionisation

Plasma generation - Ionisation

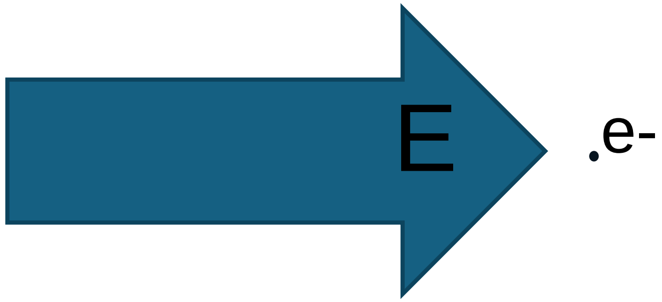
Electrons also drive many other key **excitation** and **disassociation** plasma processes

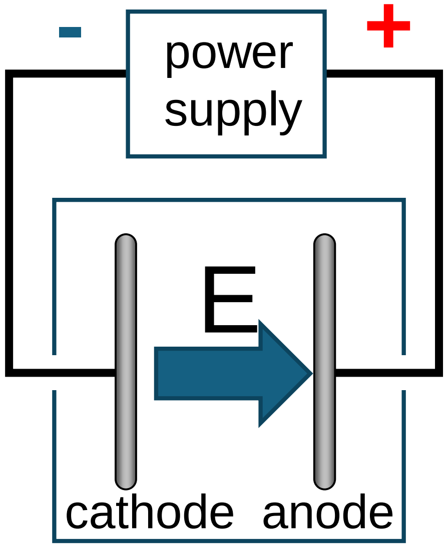


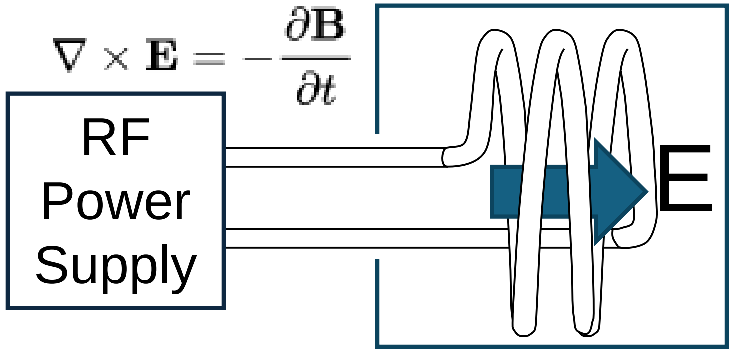
positive ion

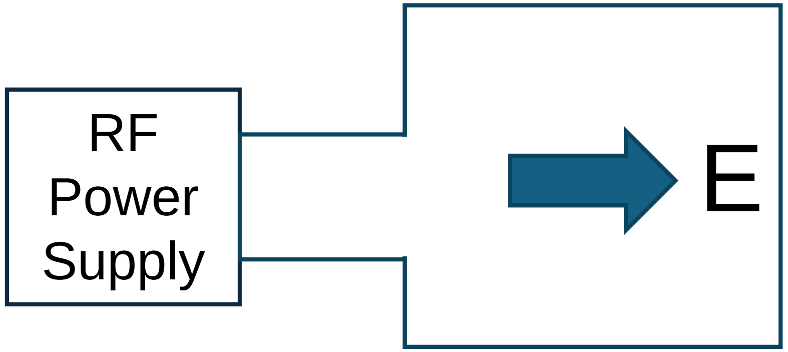
Most sources rely on electron impact ionisation

Accelerating electrons









(a) Capacitively Coupled Plasma (CCP)

Voltage applied to electrodes creates electric field

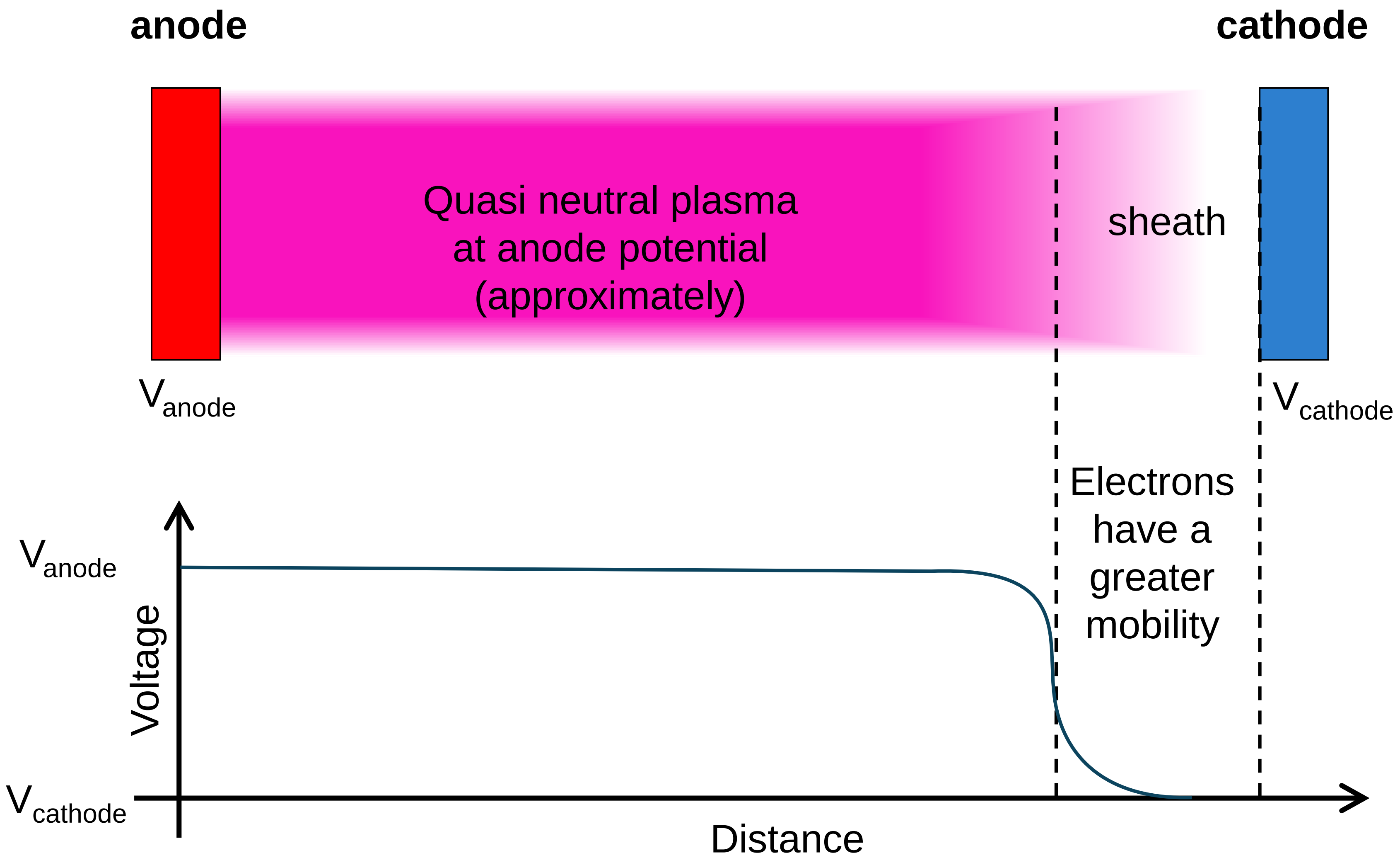
(b) Inductively Coupled Plasma (ICP)

Time varying current in a coil creates a magnetic field the induces a time varying electric field

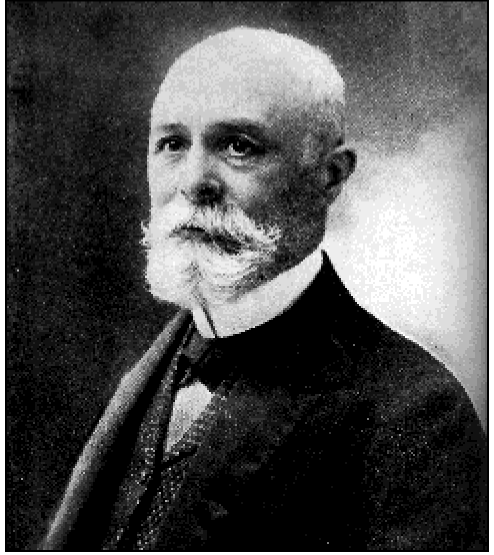
(c) RF Cavity
(waveguide or coax coupled)

The electric field component of an electromagnetic wave in a cavity

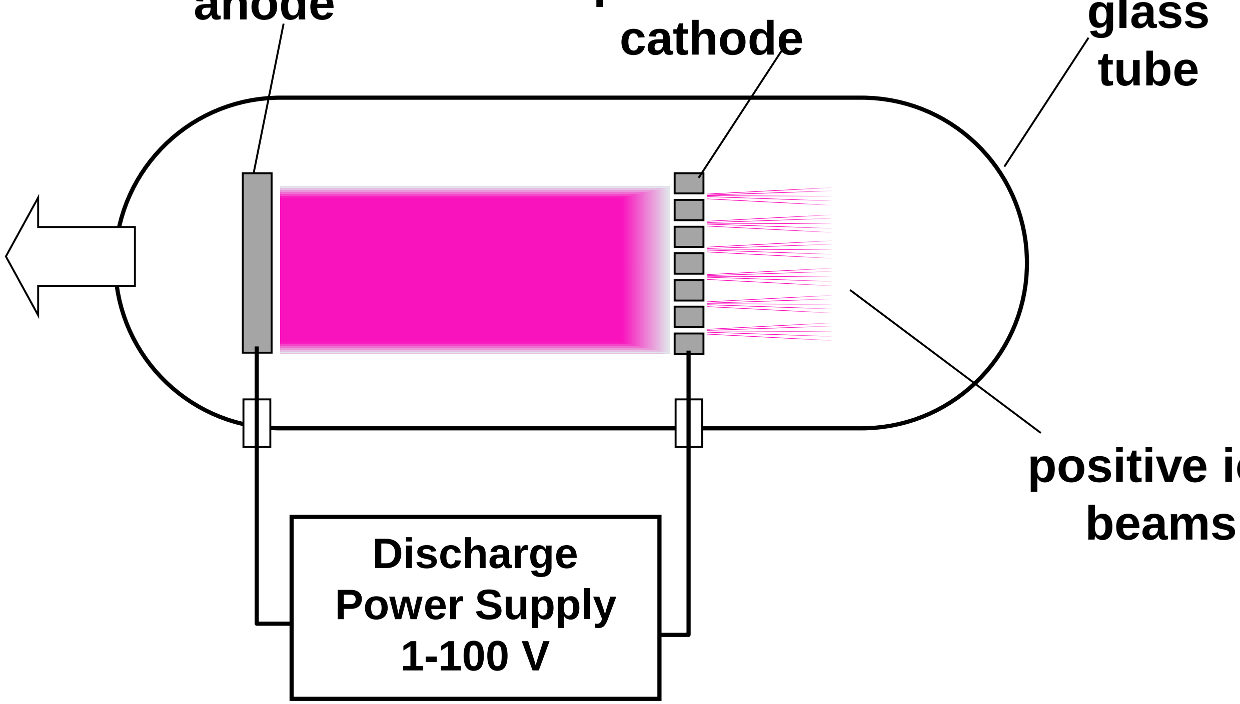
Fast, light, electrons - sheath phenomena



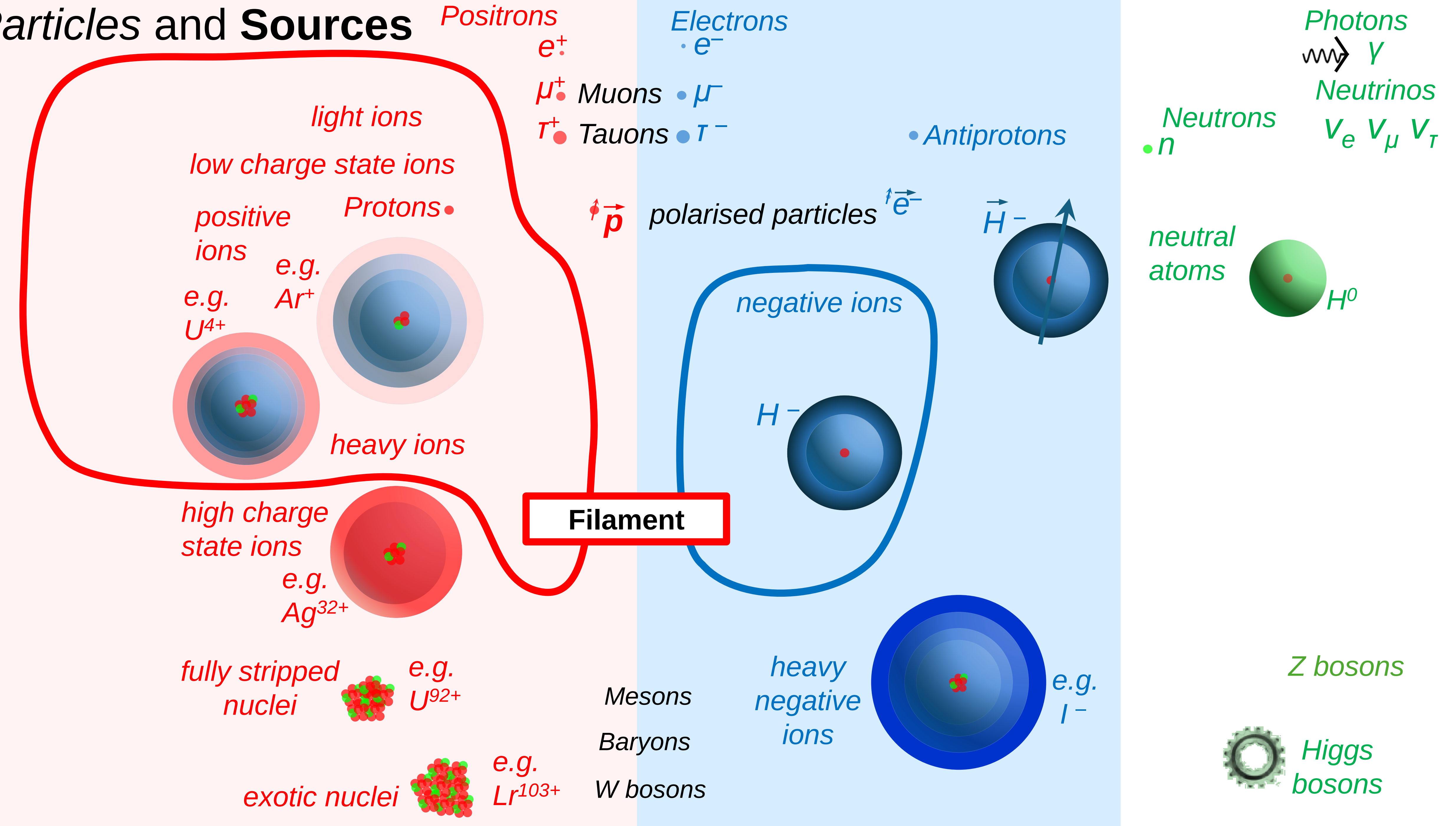
Canal Ray Source



In 1886 Eugen Goldstein discovered canal rays



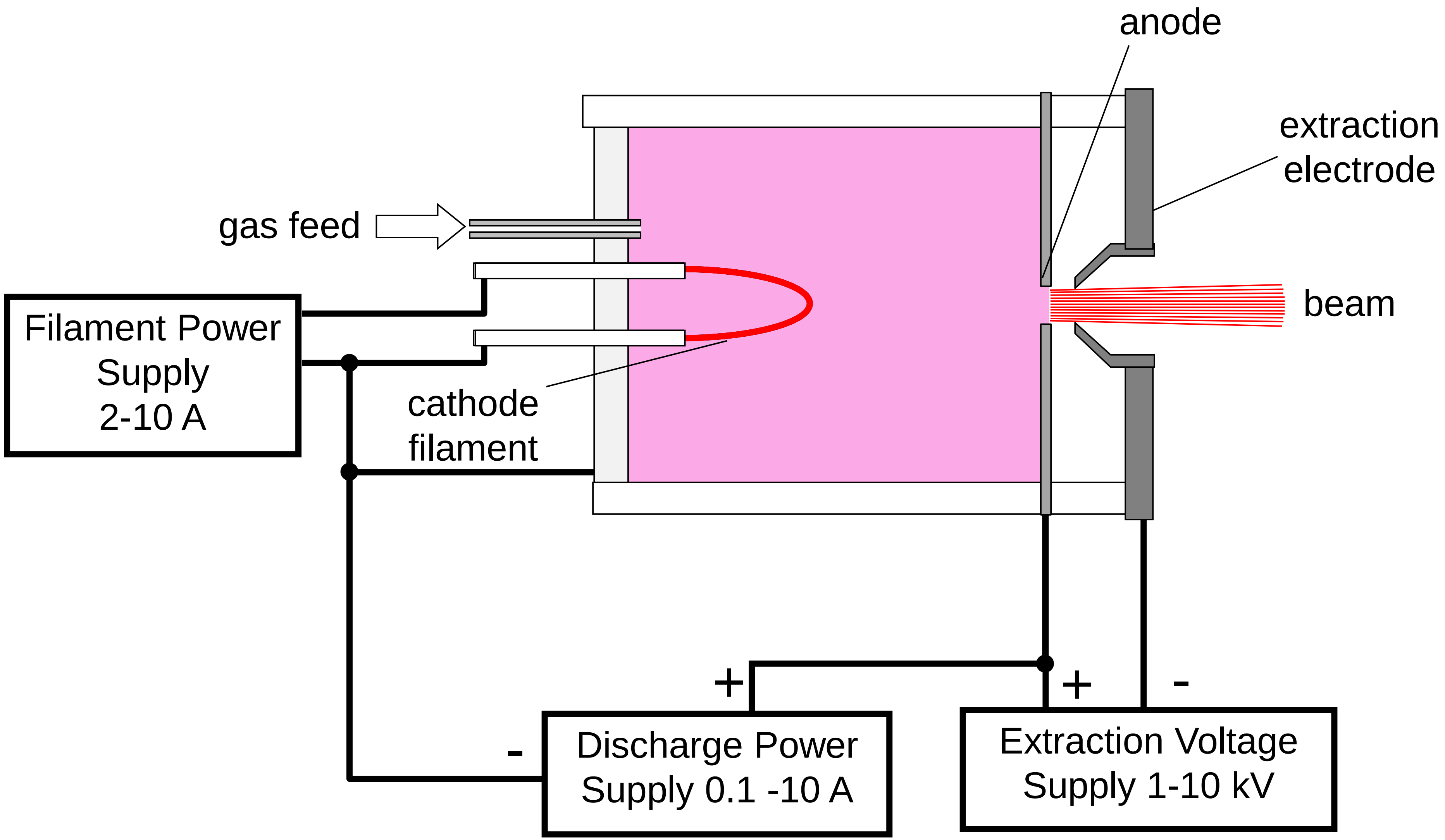
Particles and **Sources**

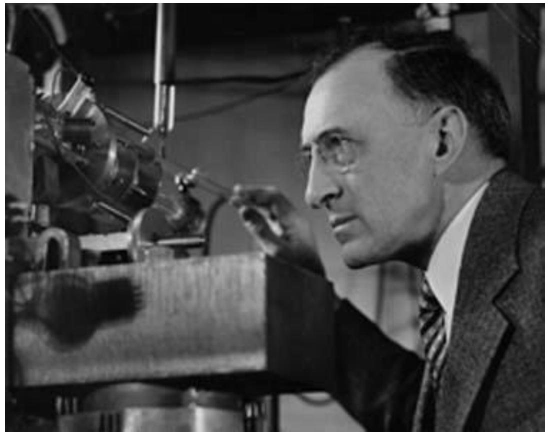


Heated Cathode Filament Source

Electron Bombardment Source

“the first true ion source”

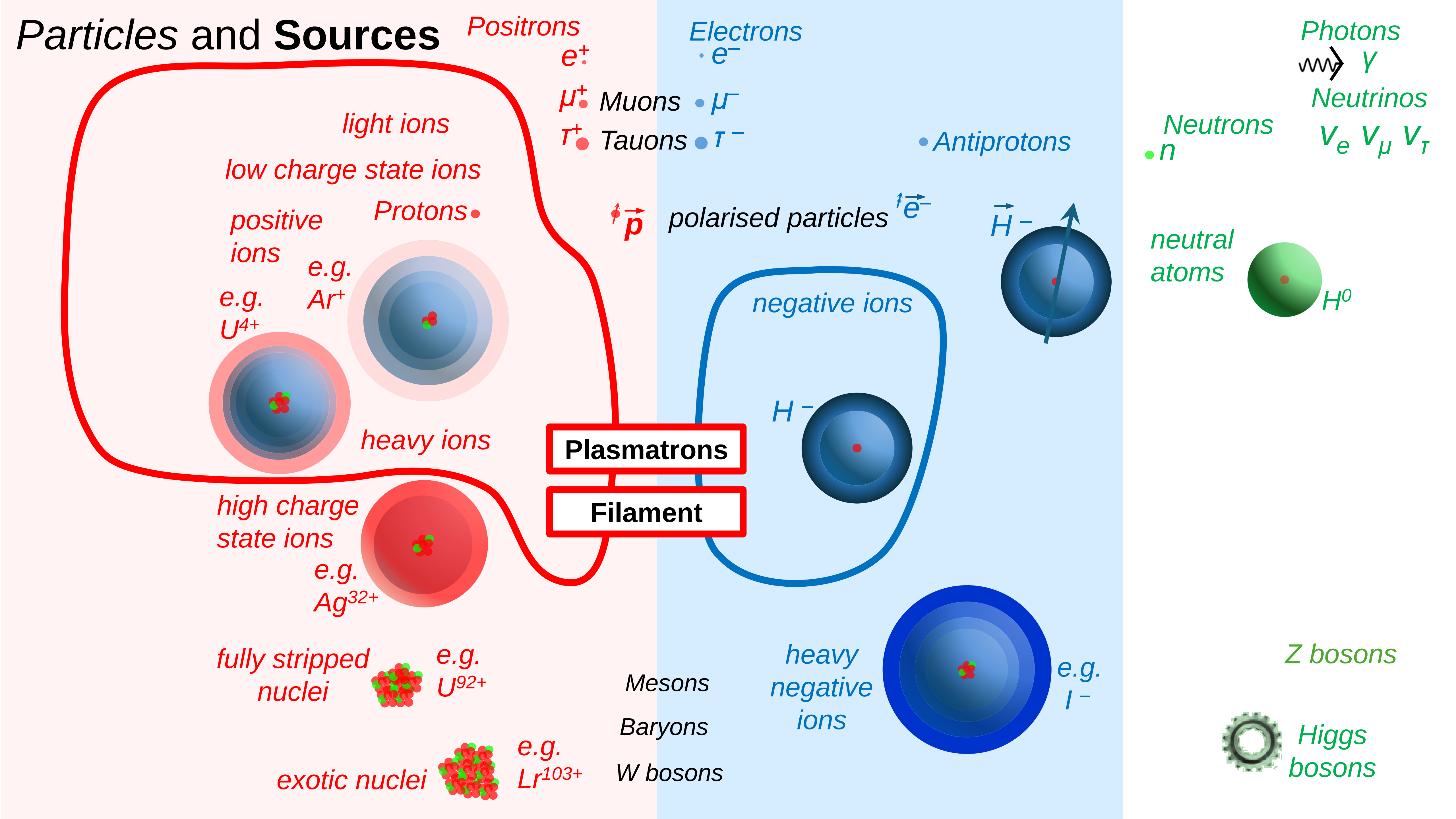




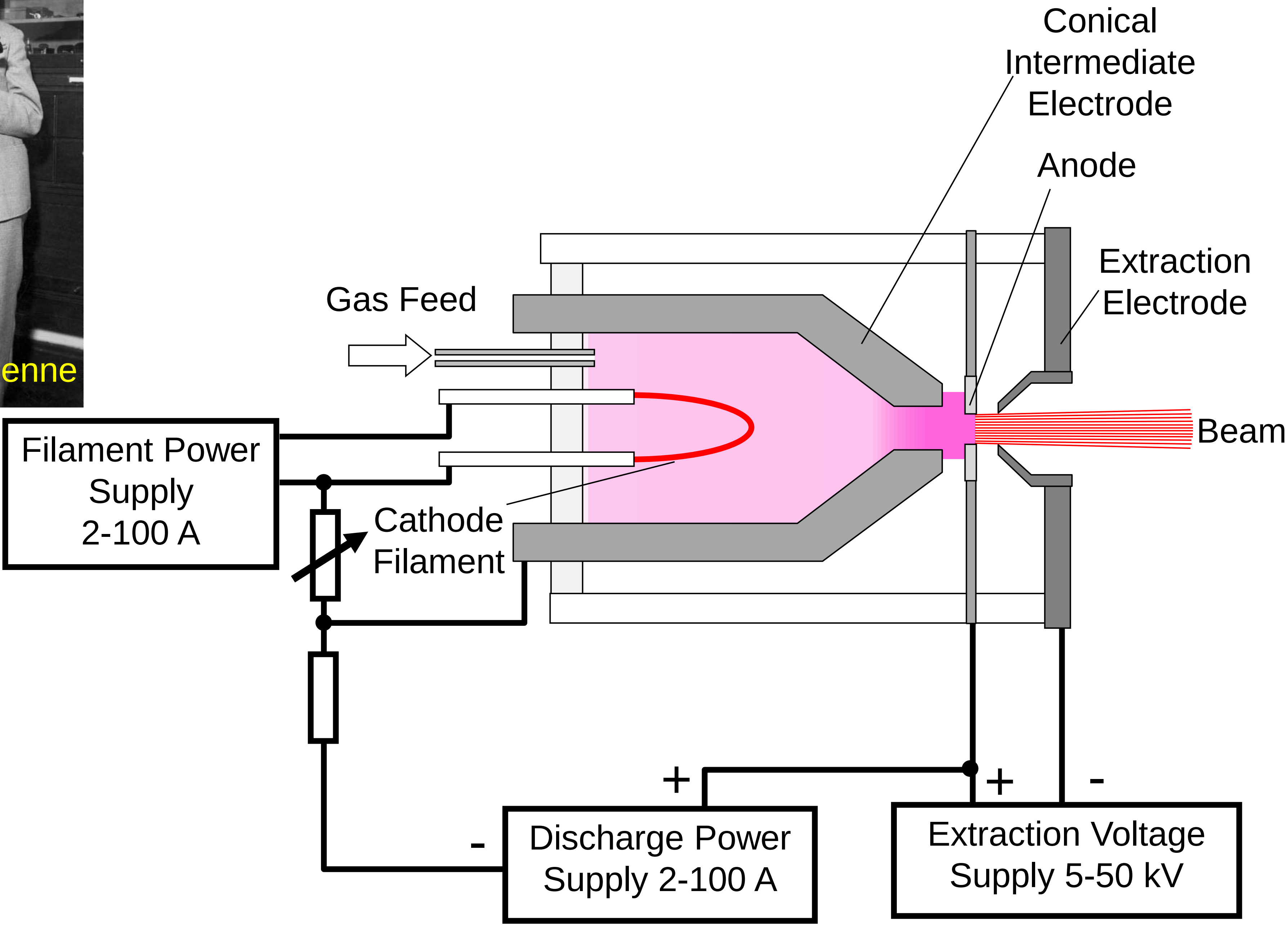
Arthur Dempster 1916

developed for early mass spectrometry

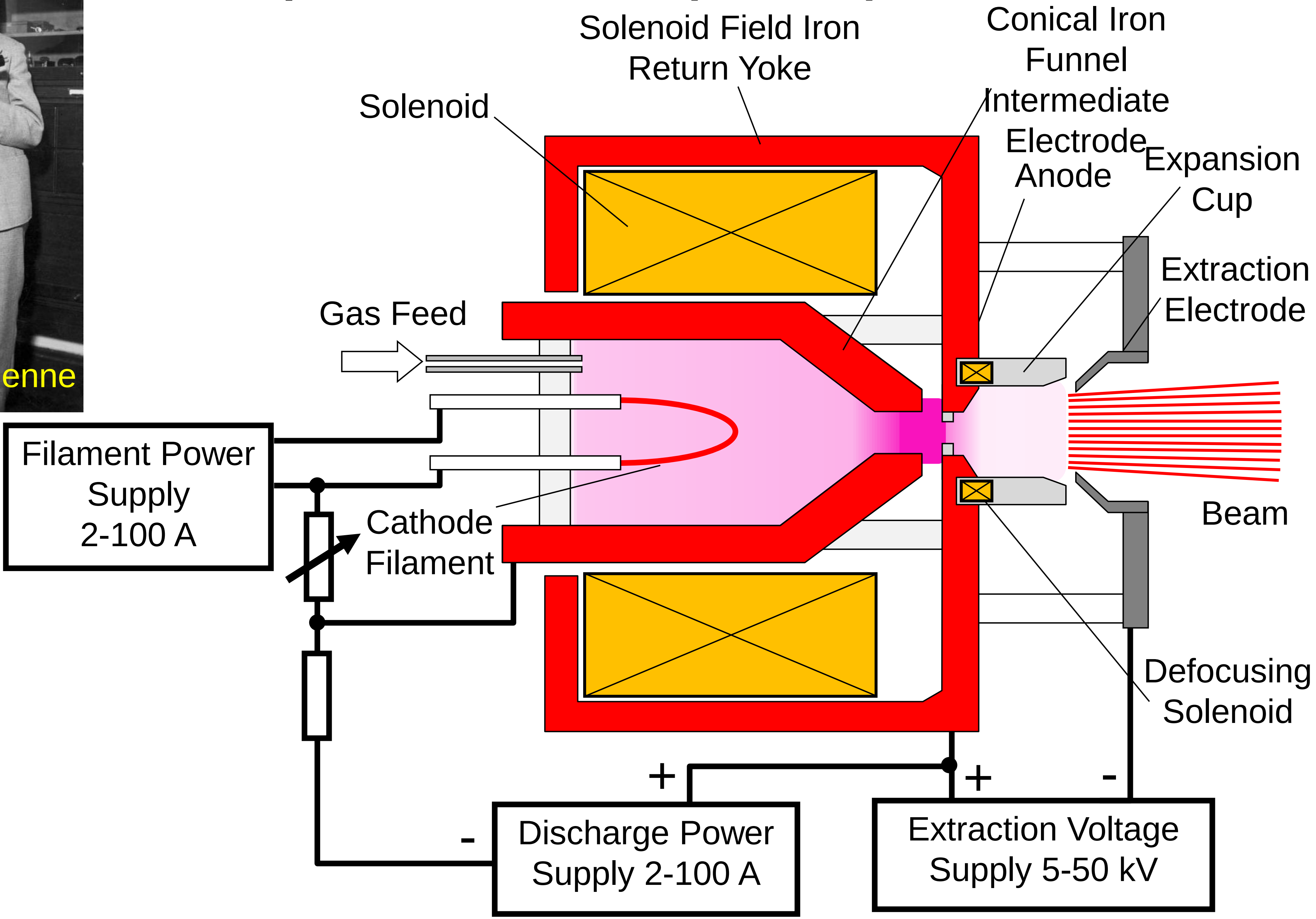
Particles and Sources



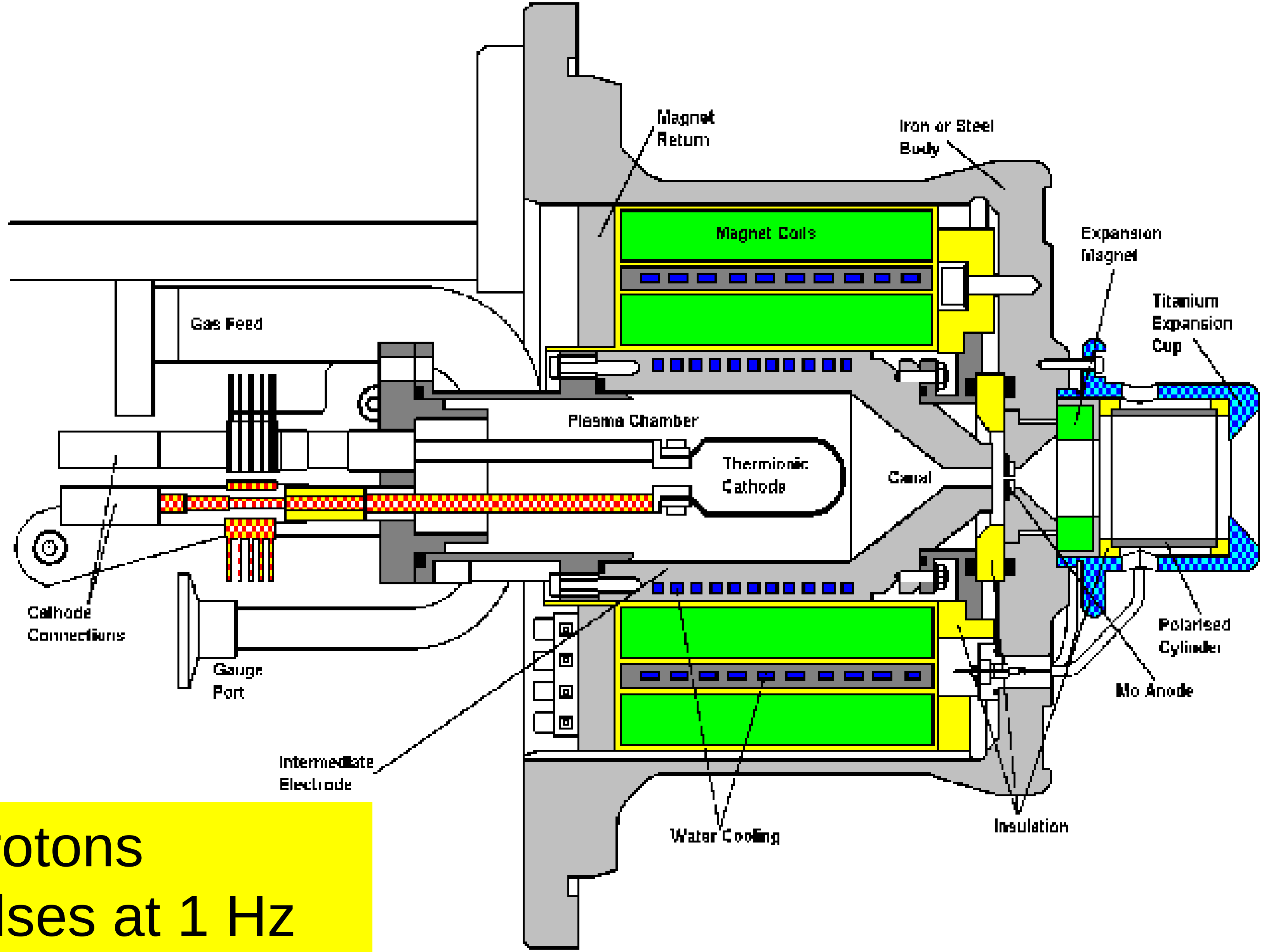
Plasmatron (late 1940s)



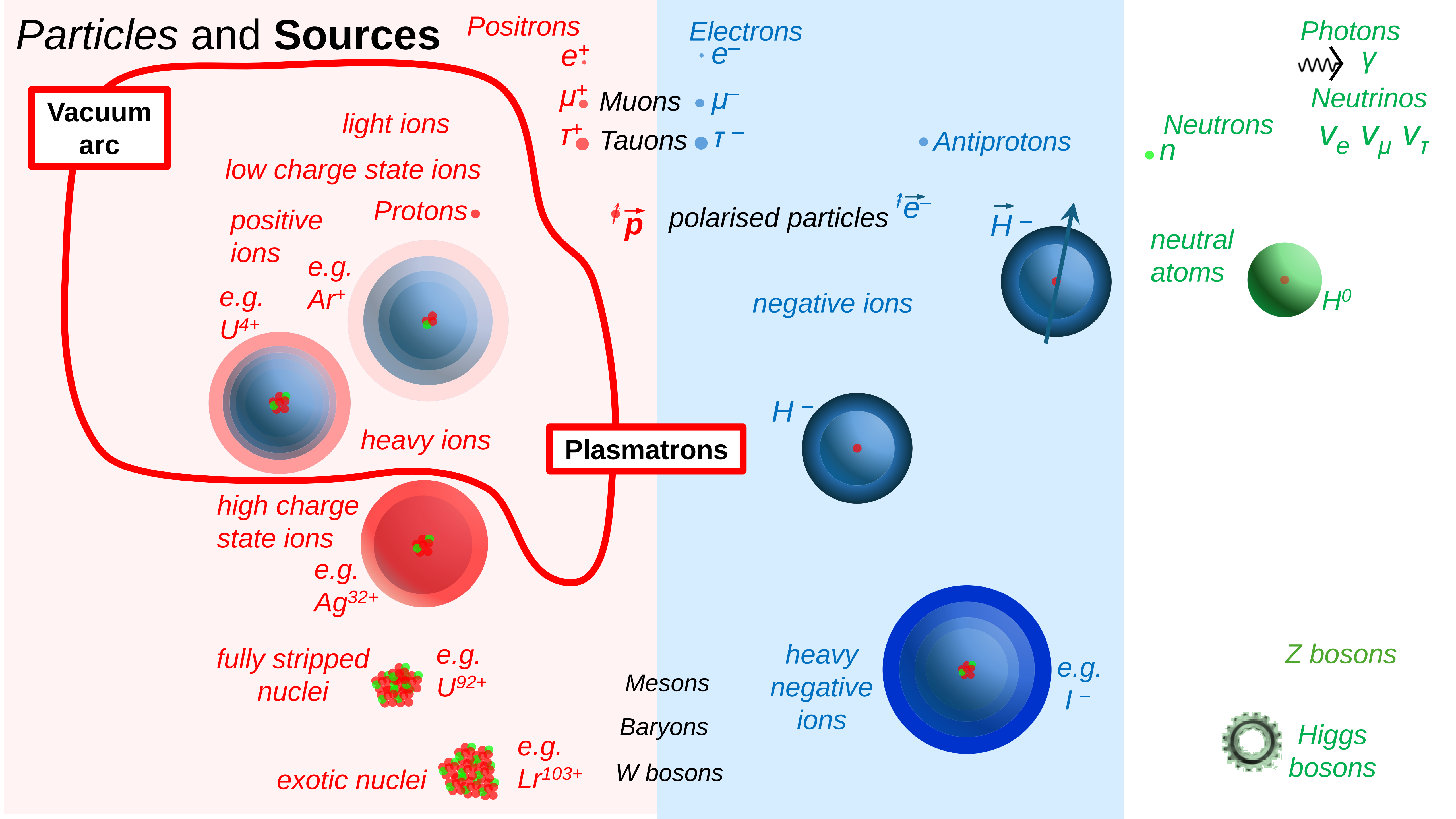
Duoplasmatron (1956)



Duoplasmatron



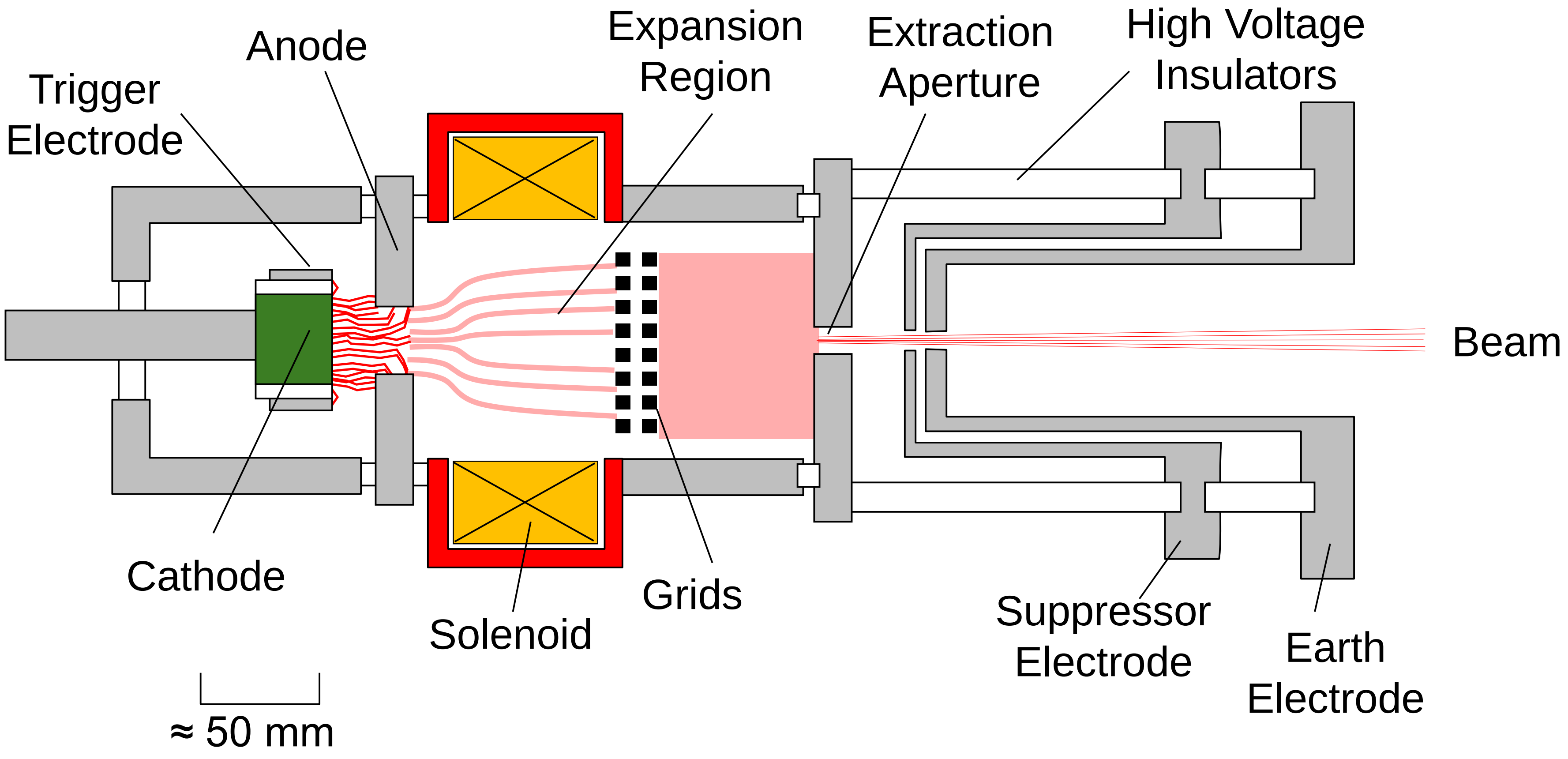
300 mA protons
150 μs pulses at 1 Hz



Particles and Sources
Positrons
e+
μ+
Muons
μ−
τ+
Tauons
τ −
Electrons
e−
Antiprotons
Photons
γ
Neutrinos
νe νμ ντ
Neutrons
n
Vacuum arc
light ions
low charge state ions
positive ions
Protons
e.g. Ar+
e.g. U4+
heavy ions
p
polarised particles
e
H −
neutral atoms
H0
negative ions
Plasmatrons
H −
high charge state ions
e.g. Ag32+
fully stripped nuclei
e.g. U92+
exotic nuclei
e.g. Lr103+
Mesons
Baryons
W bosons
heavy negative ions
e.g. I −
Z bosons
Higgs bosons

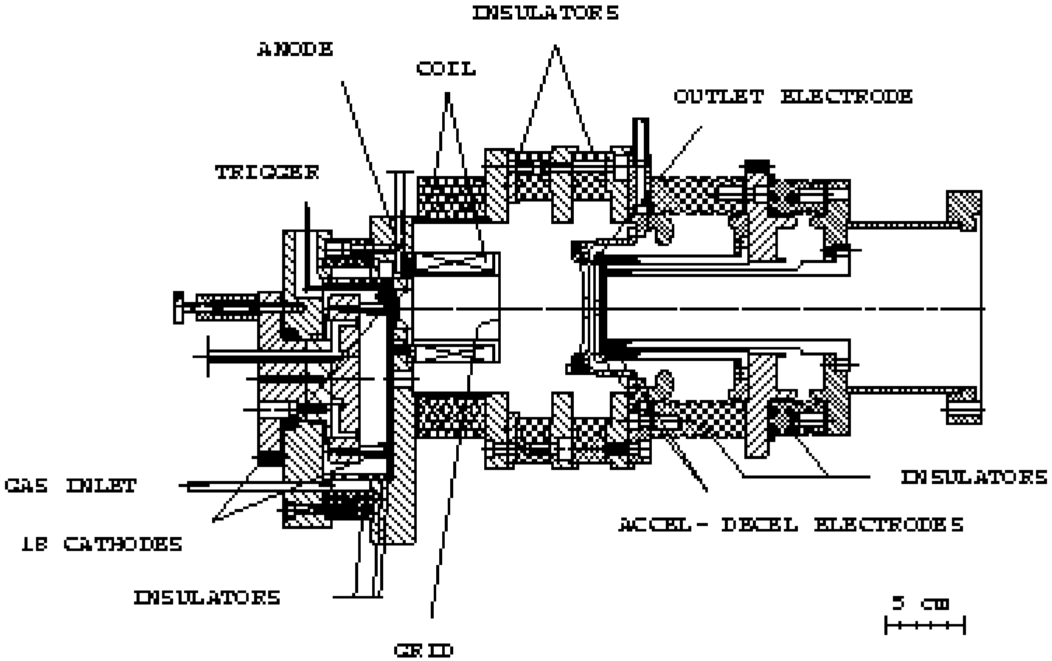
Vacuum Arc Ion Sources

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

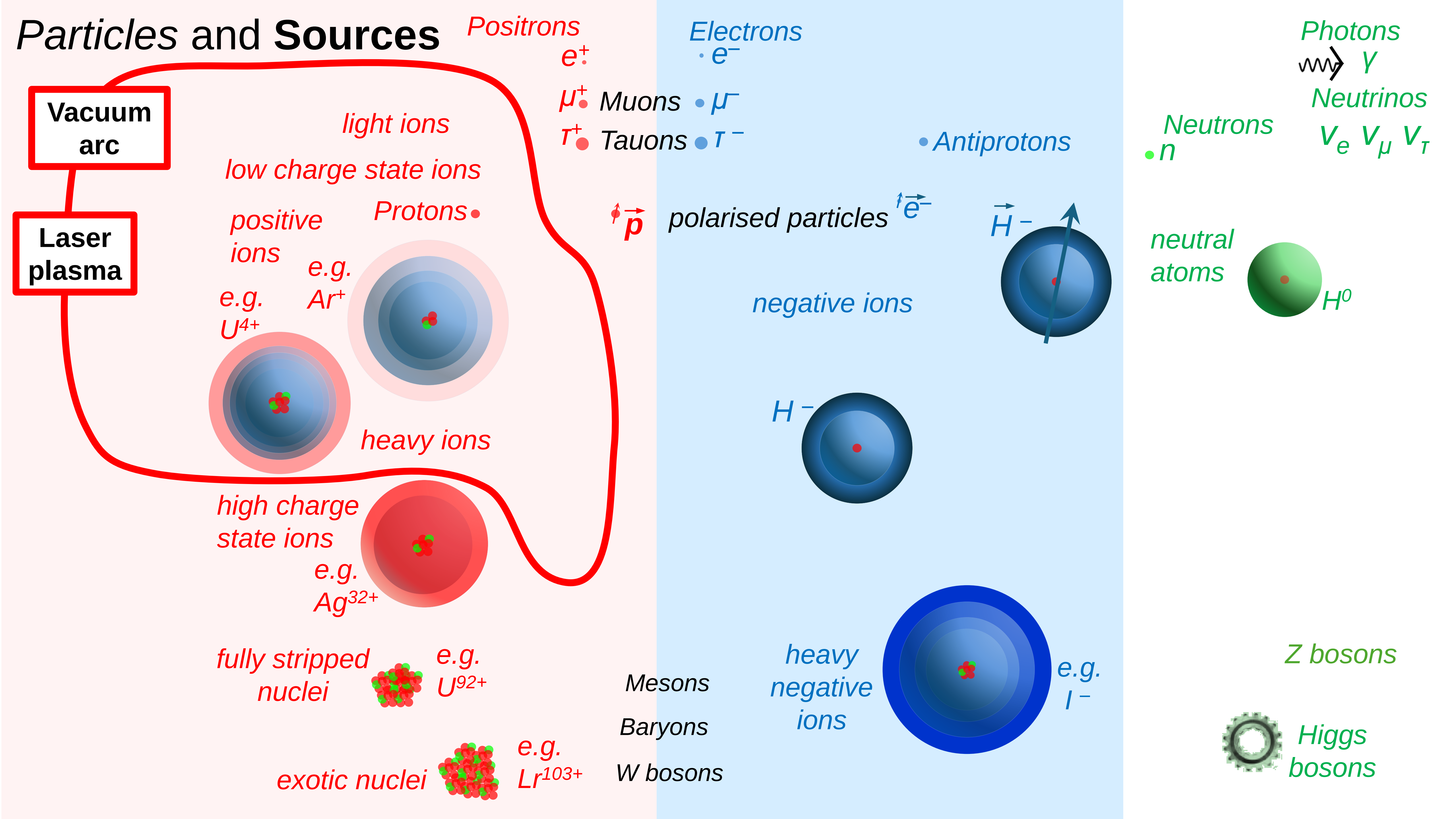


MEtal Vapor Vacuum Arc (MEVVA)

MEVVA



15 mA of U^{4+} ions


Particles and Sources
Positrons
e+
μ+
τ+
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Tauons
Electrons
e−
μ−
τ −
Antiprotons
Photons
γ
Neutrinos
νe νμ ντ
Neutrons
n
Vacuum arc
Laser plasma
light ions
low charge state ions
positive ions
Protons
e.g. Ar+
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fully stripped nuclei
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p
polarised particles
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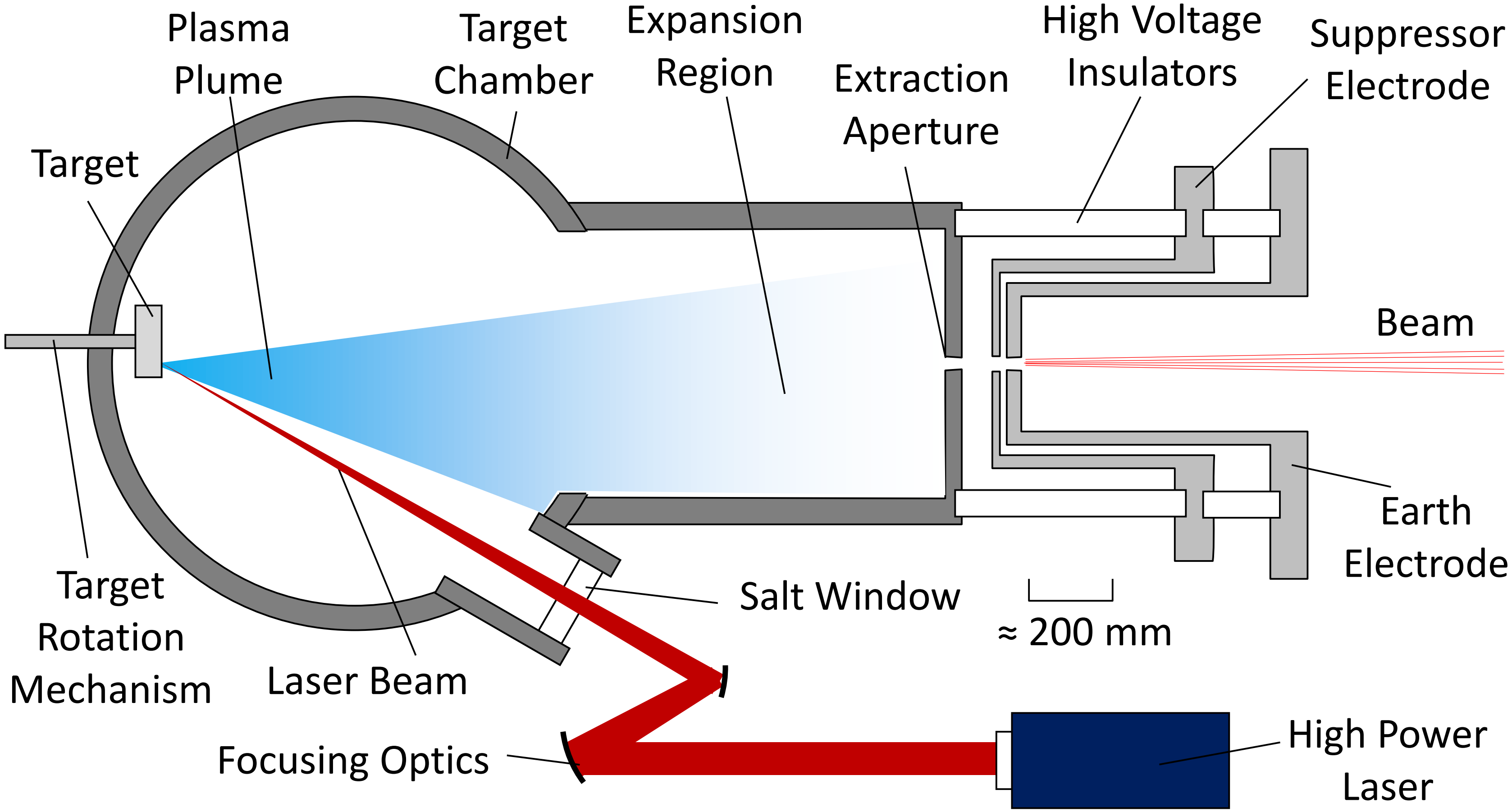
H −
negative ions
neutral atoms
H0
H −
Mesons
Baryons
W bosons
heavy negative ions
e.g. I −
Z bosons
Higgs bosons

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+}

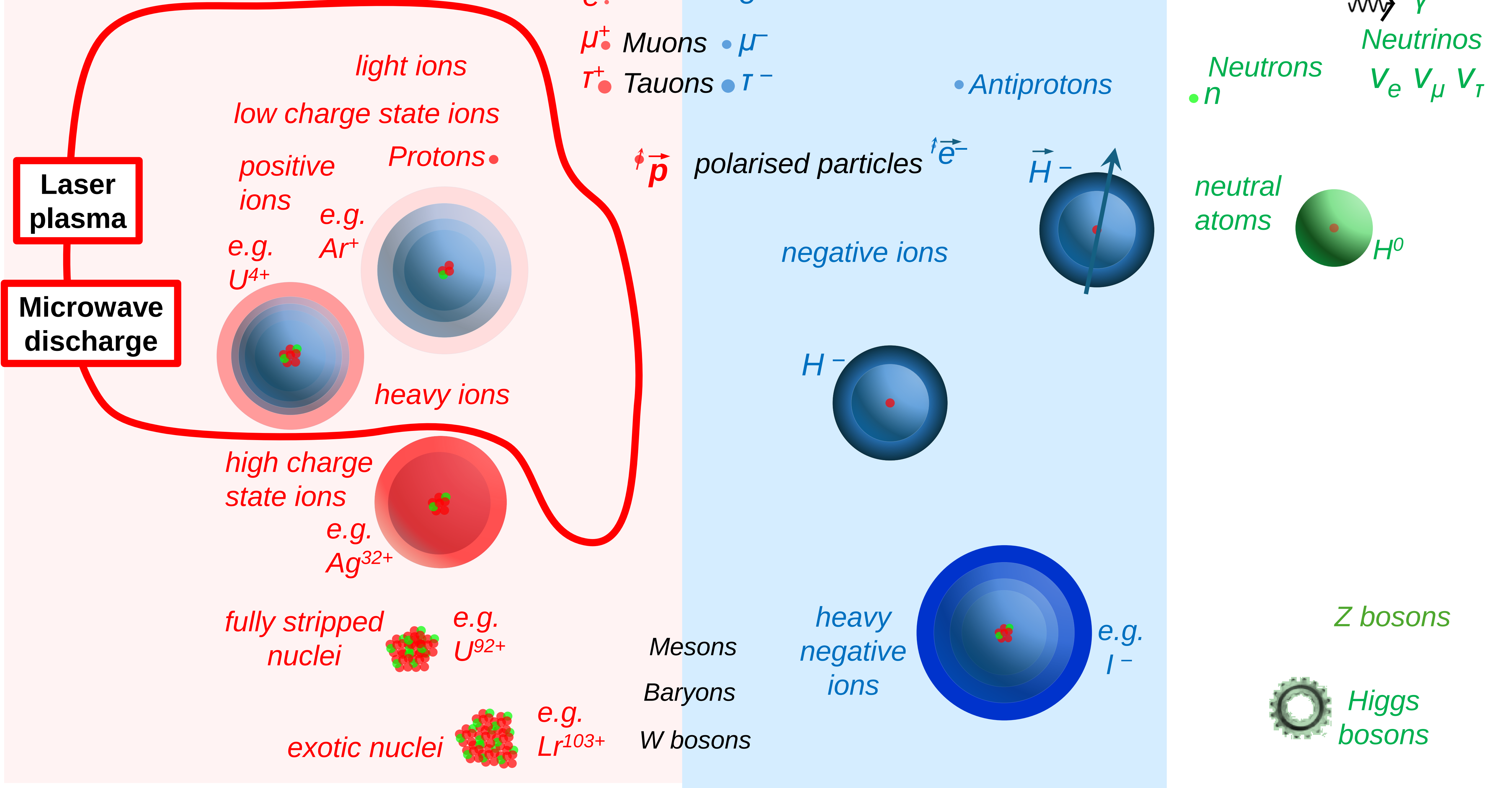
BNL and RIKEN

BROOKHAVEN NATIONAL LABORATORY

RIKEN

Masahiro Okamura has demonstrated
Direct Plasma Injection into an RFQ

Particles and **Sources**

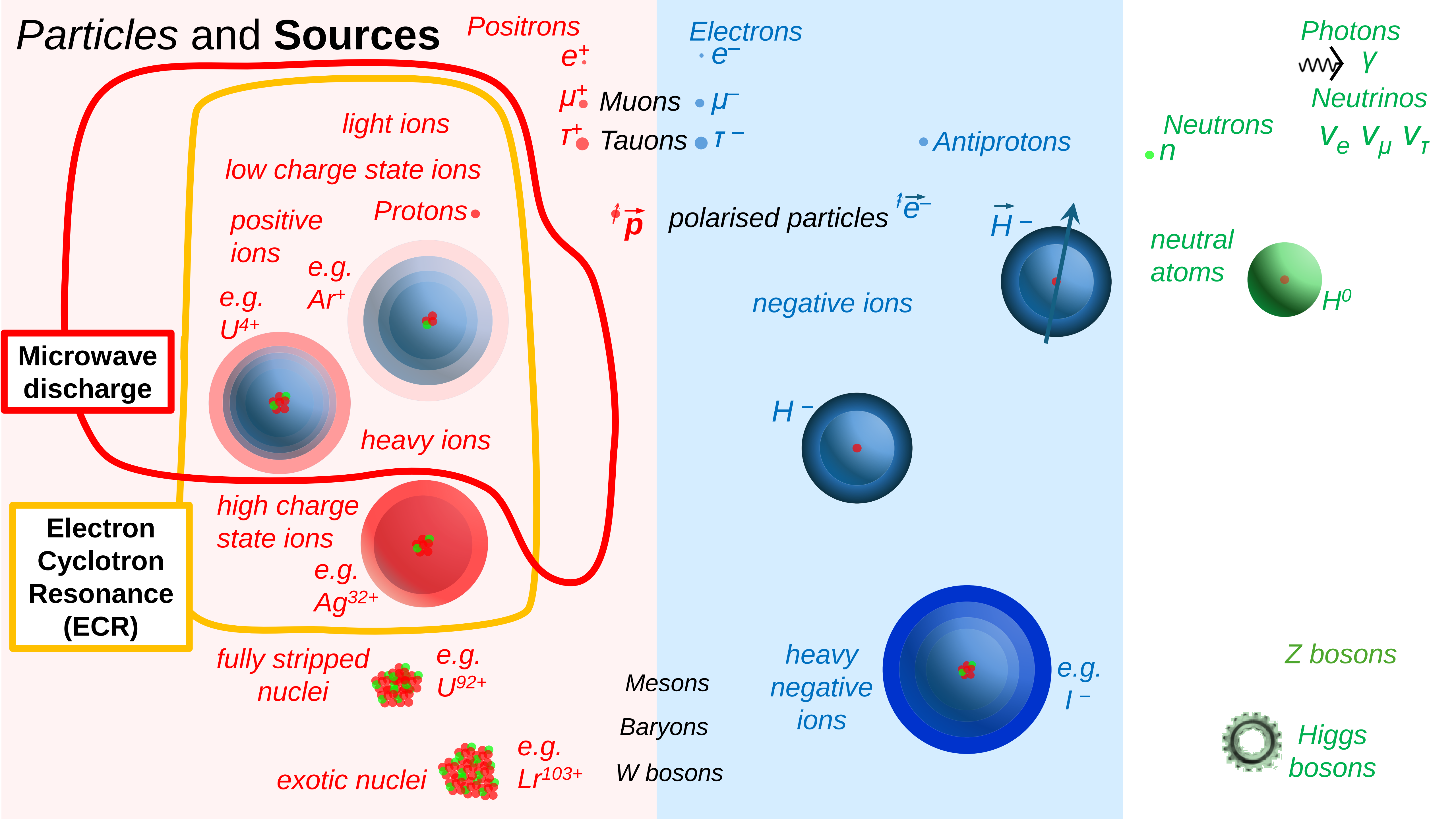


Microwave Ion Sources

There are two types of **microwave driven** ion source:

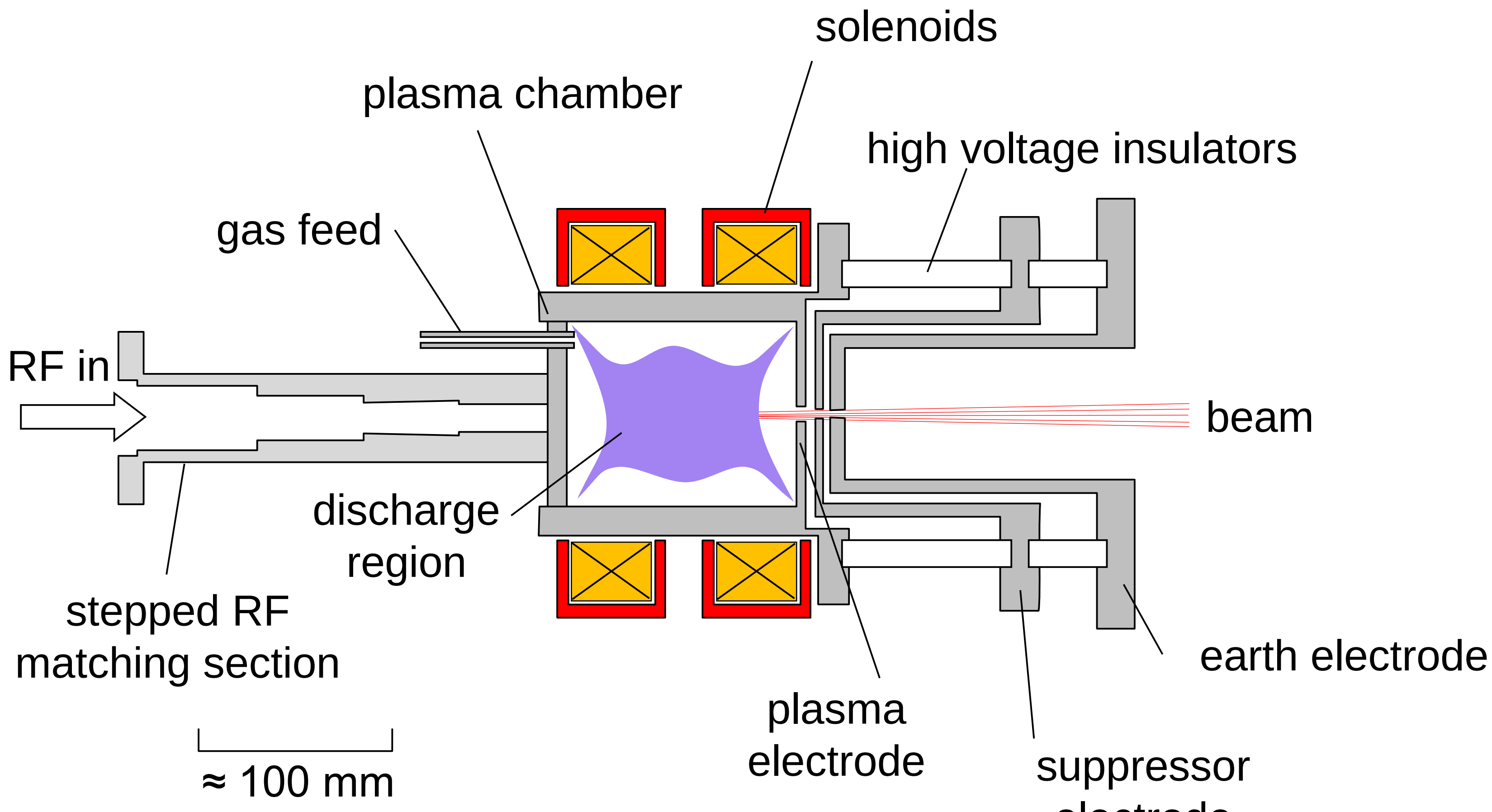
1. High pressure microwave discharge sources

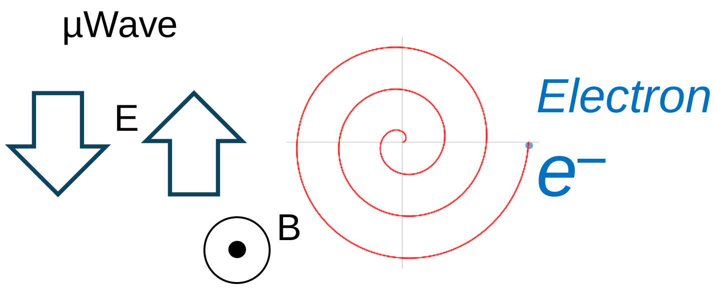
2. Electron Cyclotron Resonance (ECR) sources



Particles and Sources
Positrons
e^+
μ^+
Muons
μ^-
τ^+
Tauons
τ^-
Electrons
e^-
Photons
γ
Neutrinos
ν_e ν_μ ν_τ
Neutrons
n
Antiprotons
light ions
low charge state ions
Protons
positive ions
e.g. Ar^+
e.g. U^{4+}
heavy ions
$\vec{p}$
polarised particles
$\vec{e}^-$
$\vec{H}^-$
negative ions
neutral atoms
H^0
Microwave discharge
H^-
high charge state ions
e.g. Ag^{32+}
Electron Cyclotron Resonance (ECR)
fully stripped nuclei
e.g. U^{92+}
Mesons
Baryons
W bosons
heavy negative ions
e.g. I^-
Z bosons
Higgs bosons
exotic nuclei
e.g. Lr^{103+}

Microwave Discharge Ion Source



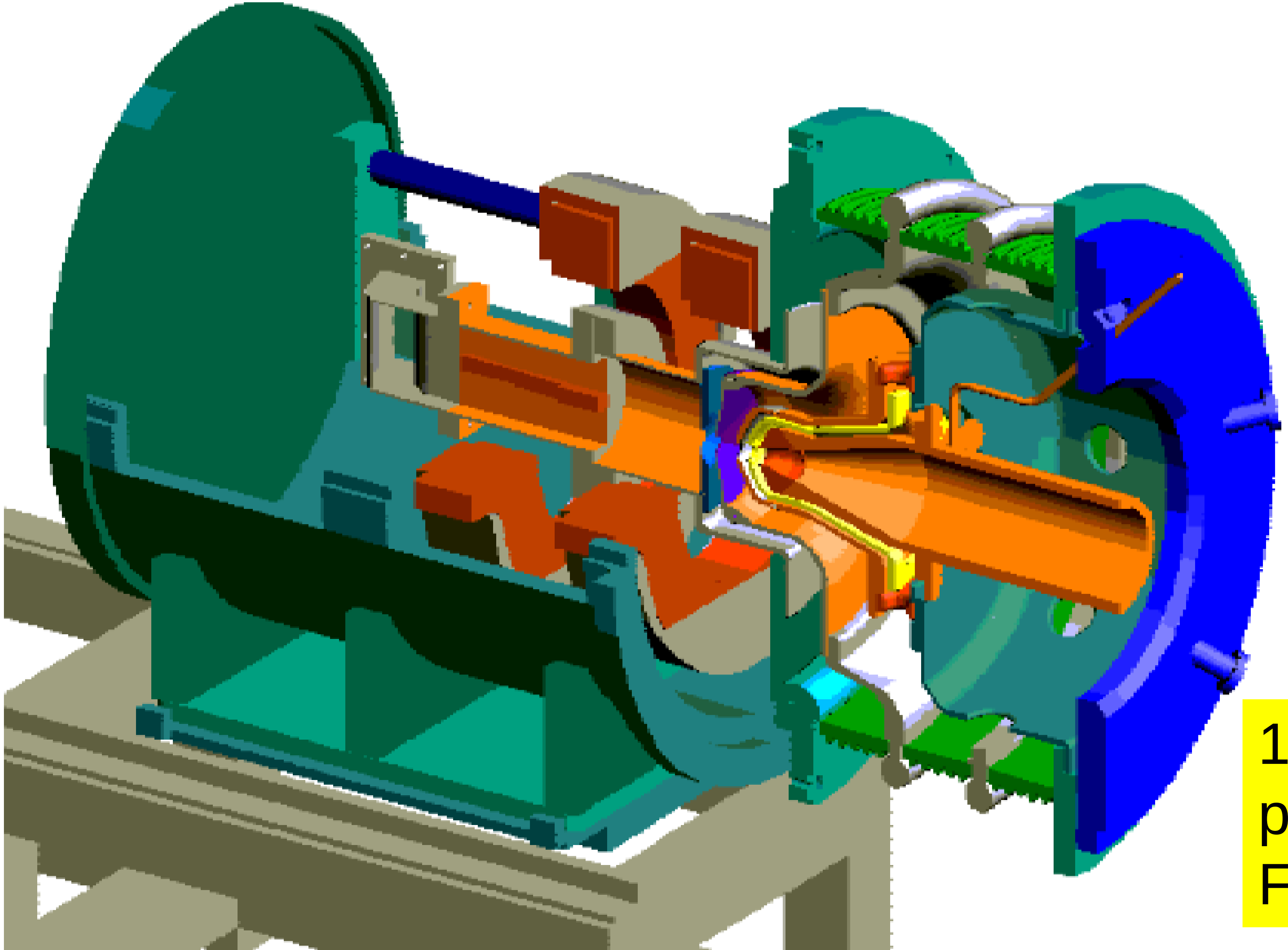


2.45 GHz
commonly used

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

87.5 mT

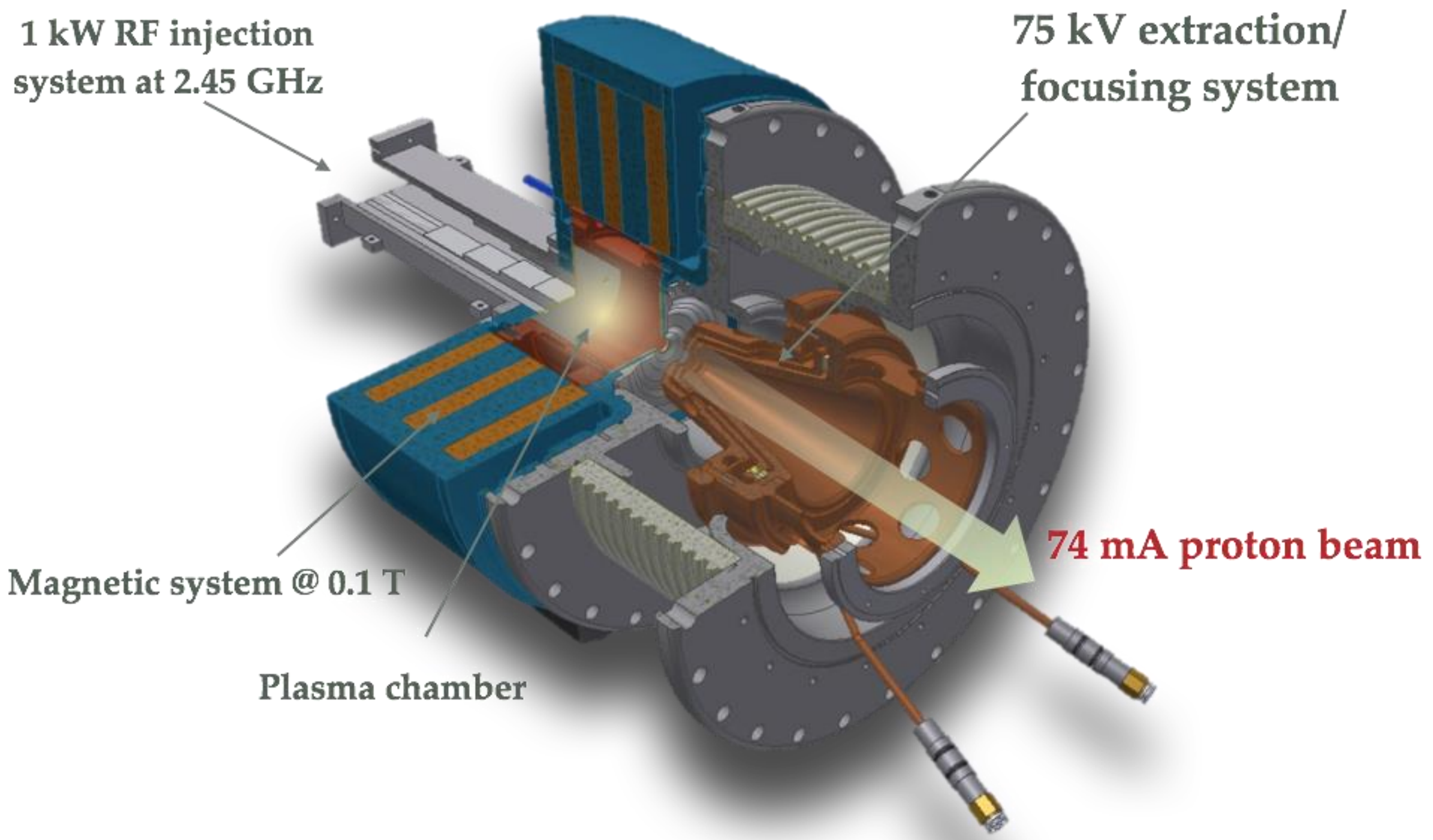
SILHI Microwave Source



Rafael Gobin
CEA Saclay
Late 1990s

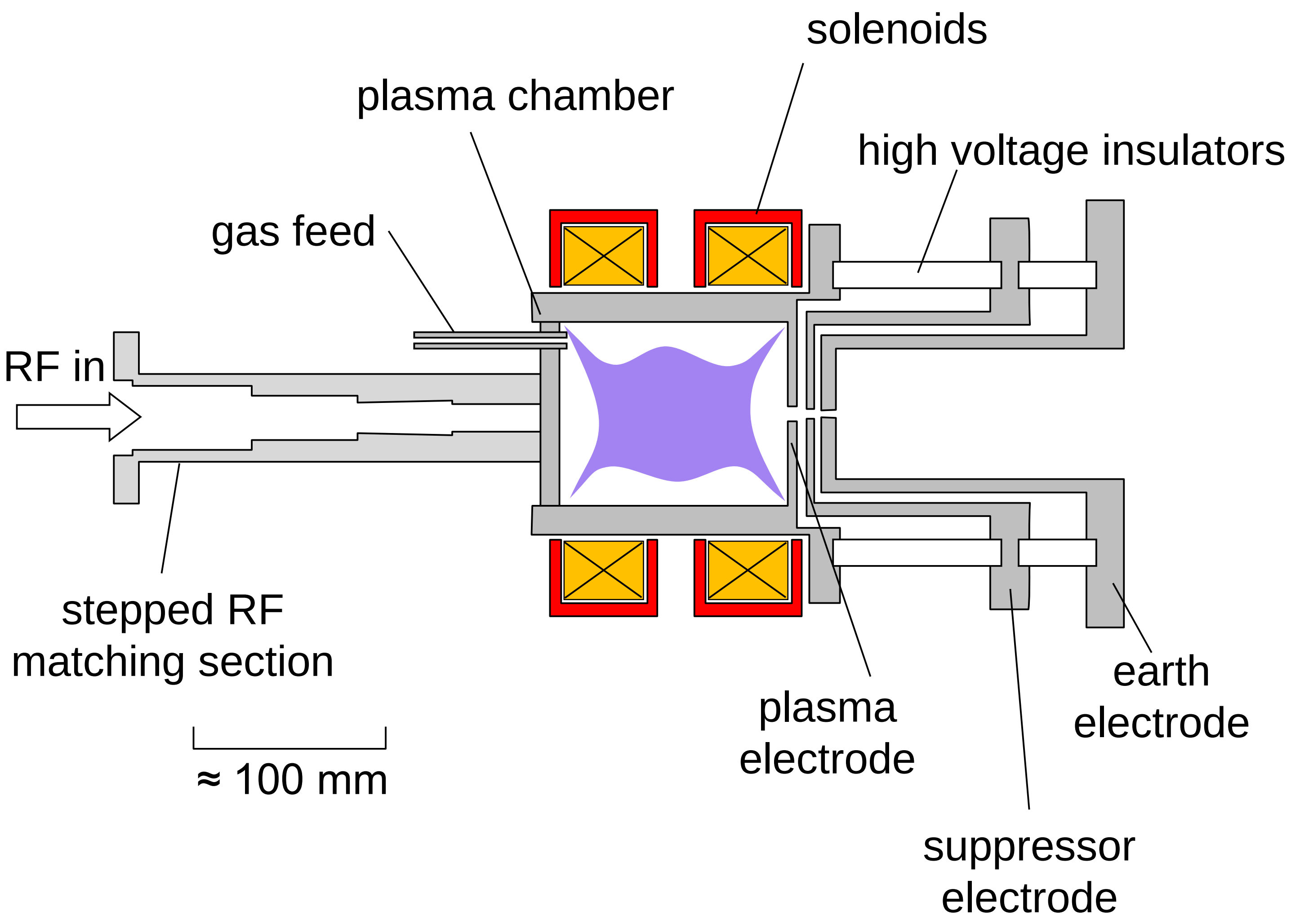
140 mA DC
protons
For one year!

ESS Source

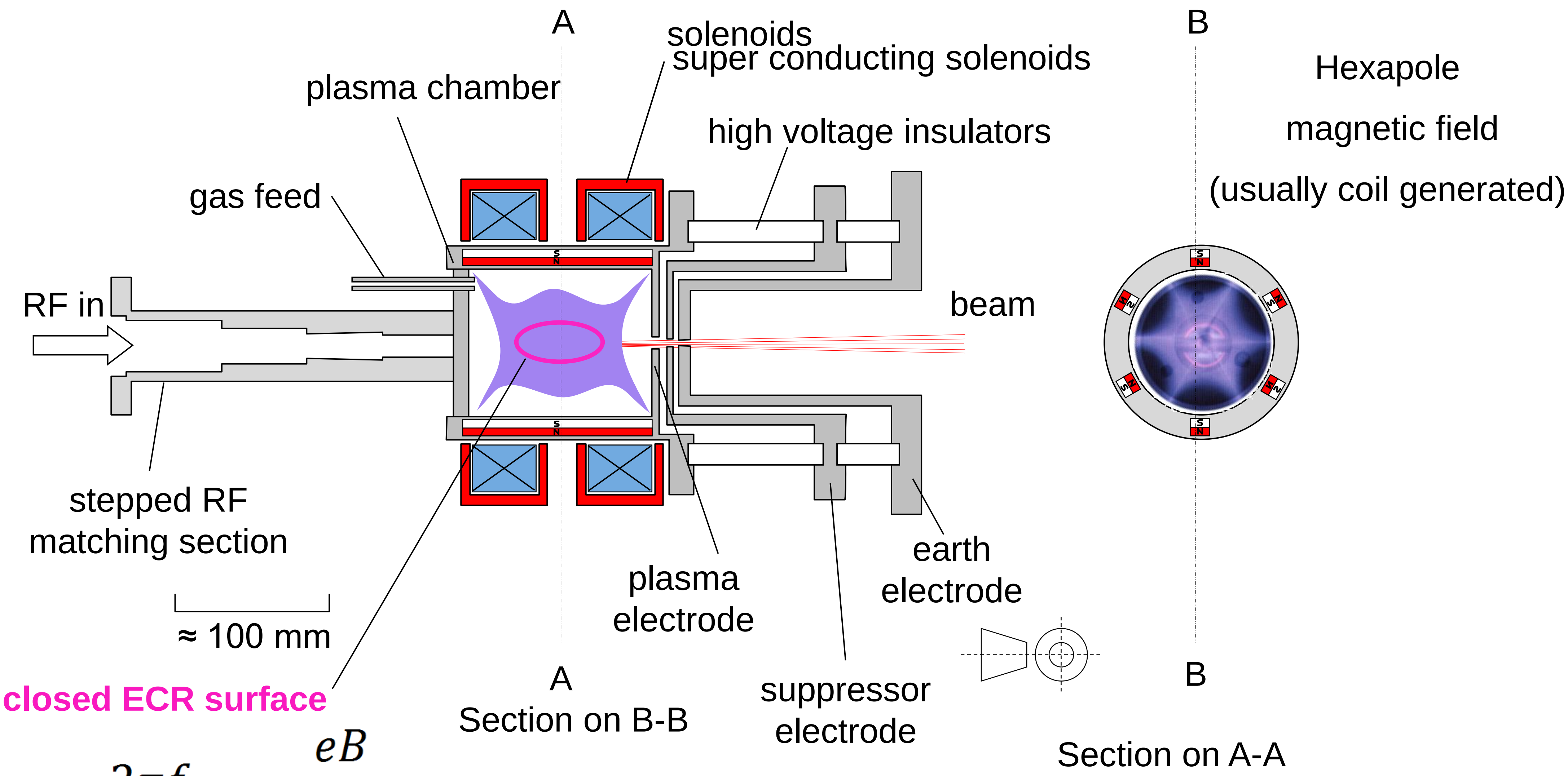


SILHI source via INFN

Microwave Discharge Ion Source



ECR Ion Source



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

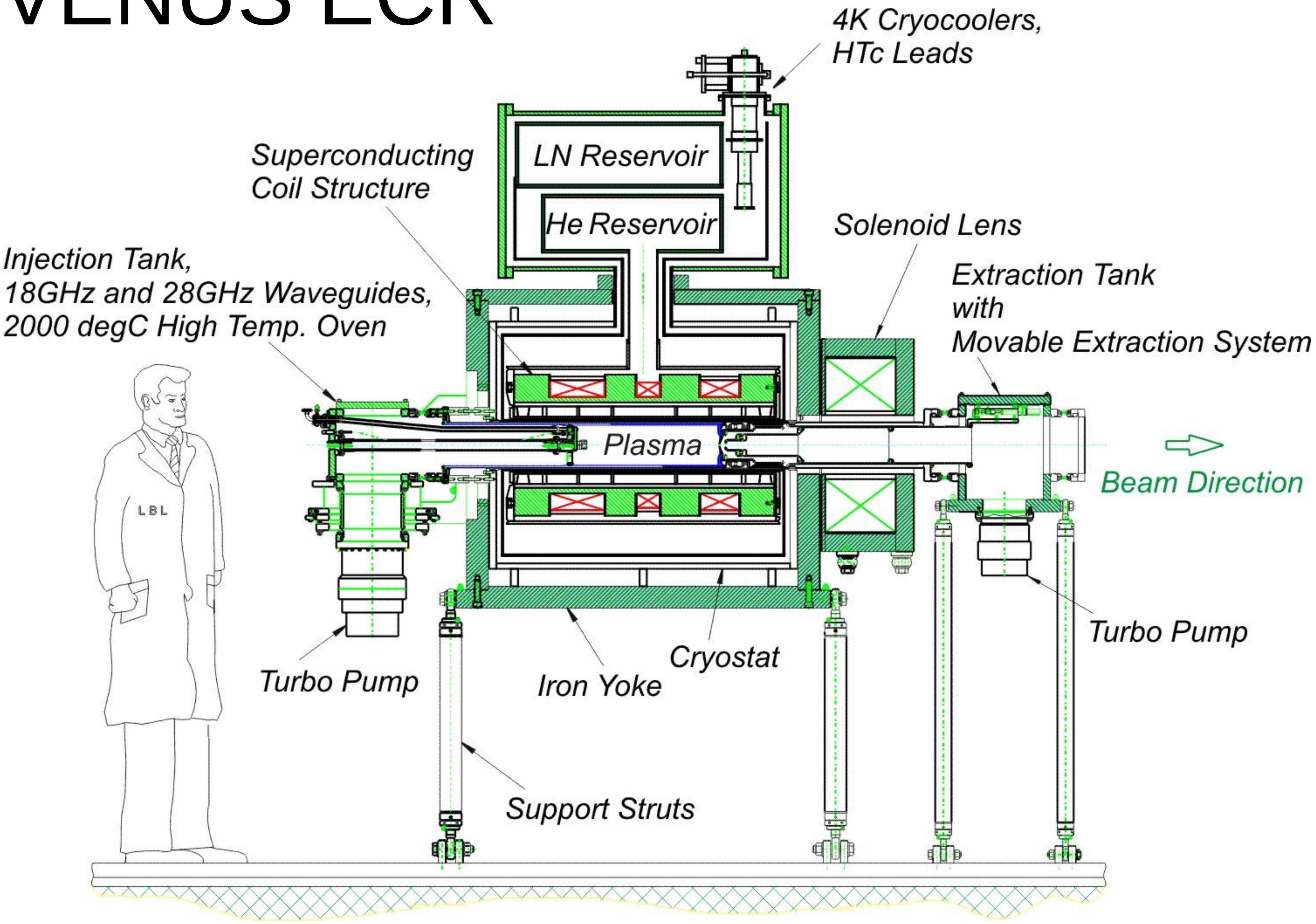
28 GHz superconducting VENUS ECR

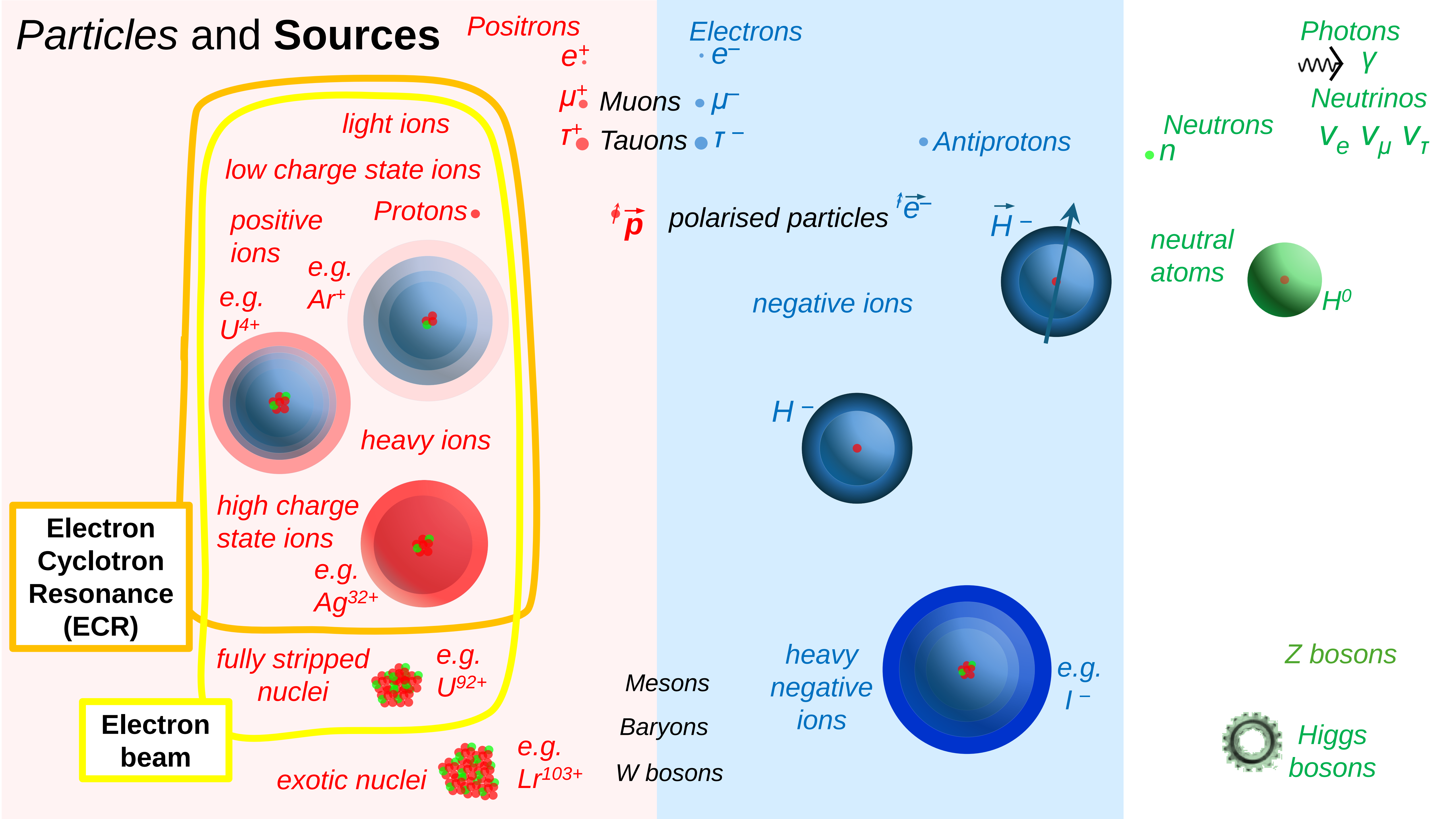
Daniela Leitner
LBNL
Late 2000s

Higher frequency = higher charge states

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

VENUS ECR


4K Cryocoolers,
HTc Leads
LN Reservoir
He Reservoir
Superconducting
Coil Structure
Solenoid Lens
Injection Tank,
18GHz and 28GHz Waveguides,
2000 degC High Temp. Oven
Extraction Tank
with
Movable Extraction System
Plasma
Beam Direction
LBL
Turbo Pump
Cryostat
Iron Yoke
Turbo Pump
Support Struts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e+
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e−
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Electron Cyclotron Resonance (ECR)
Electron beam
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polarised particles
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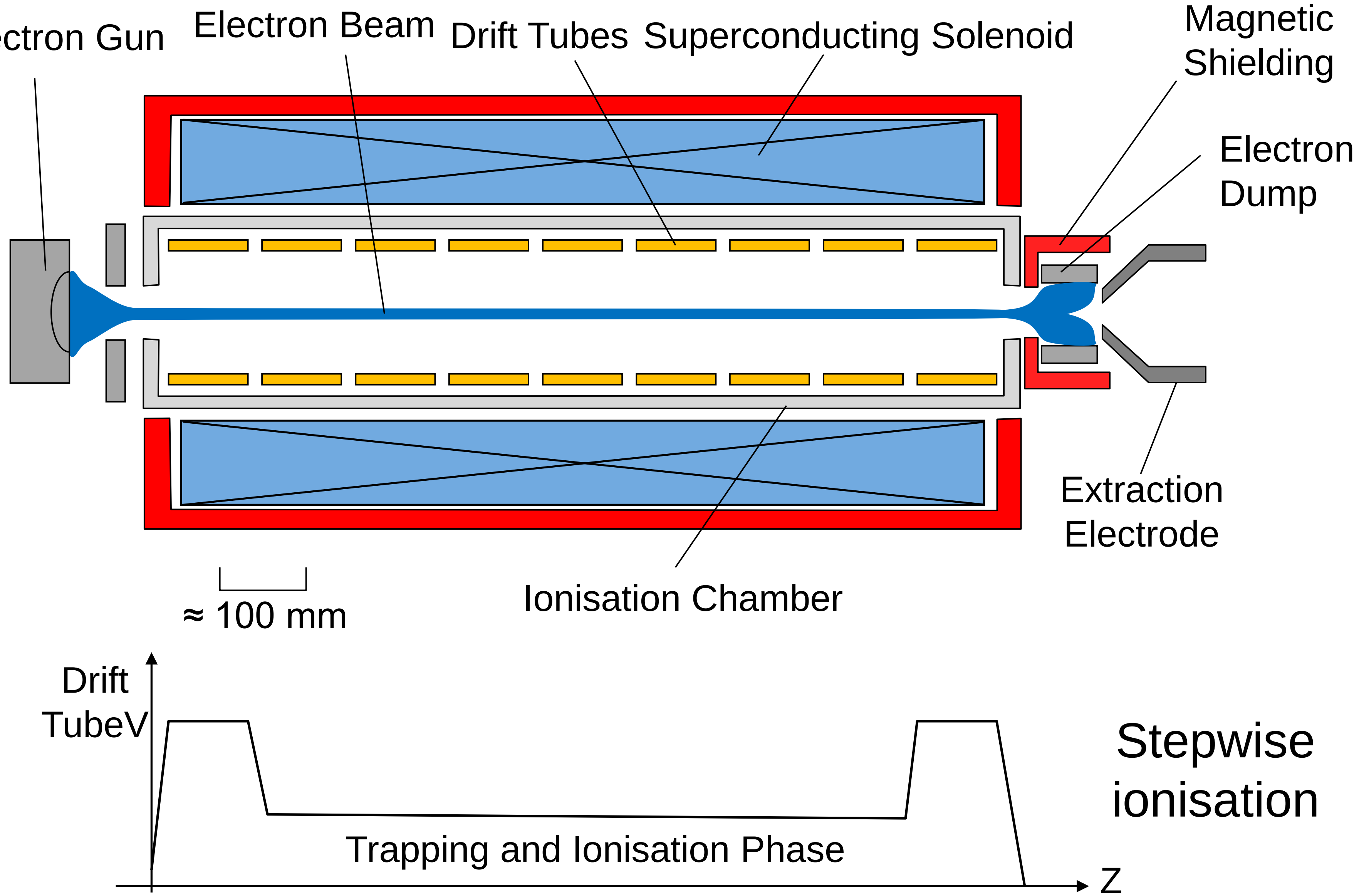
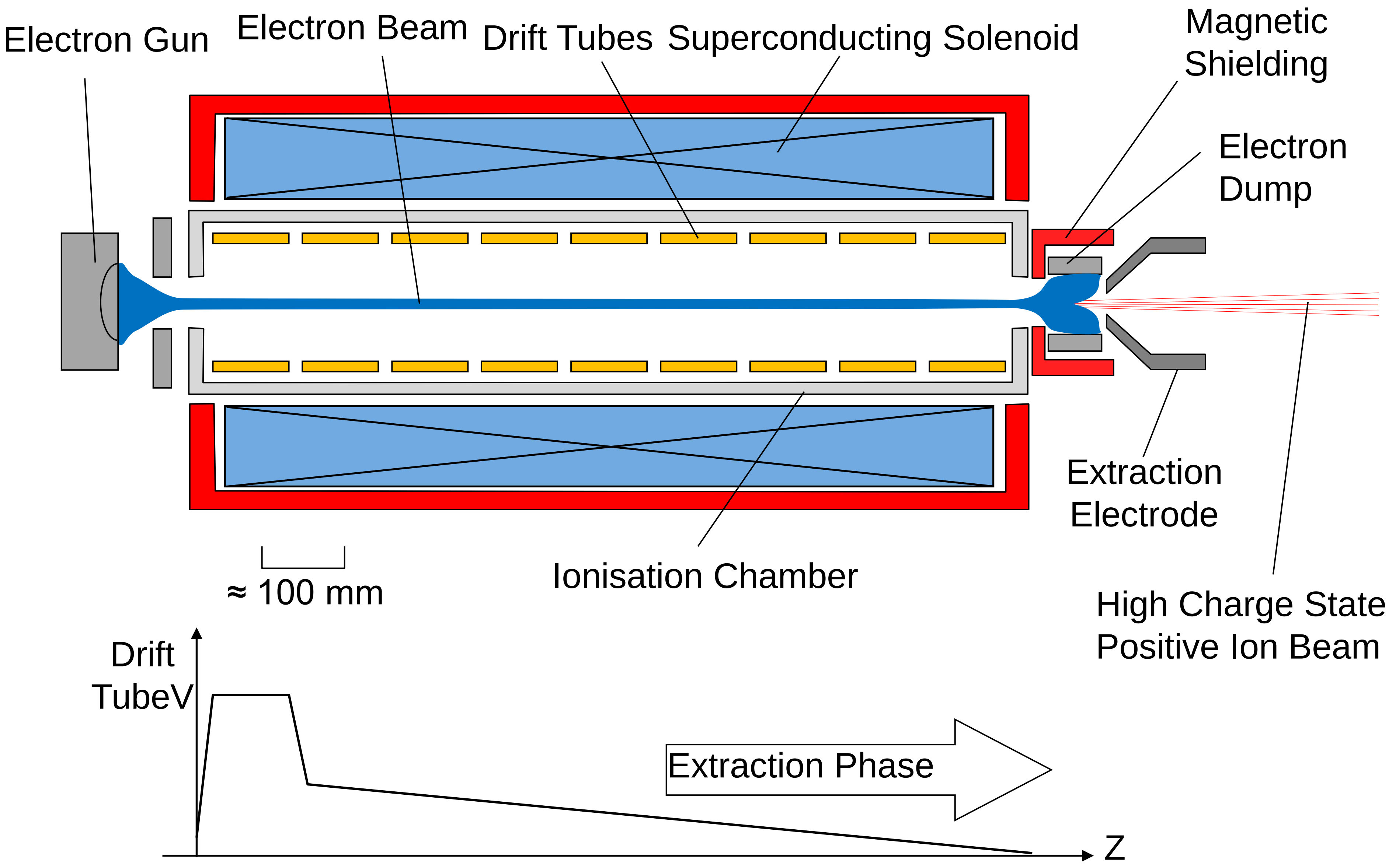
H −
negative ions
neutral atoms
H0
H −
Mesons
Baryons
W bosons
heavy negative ions
e.g. I −
Z bosons
Higgs bosons

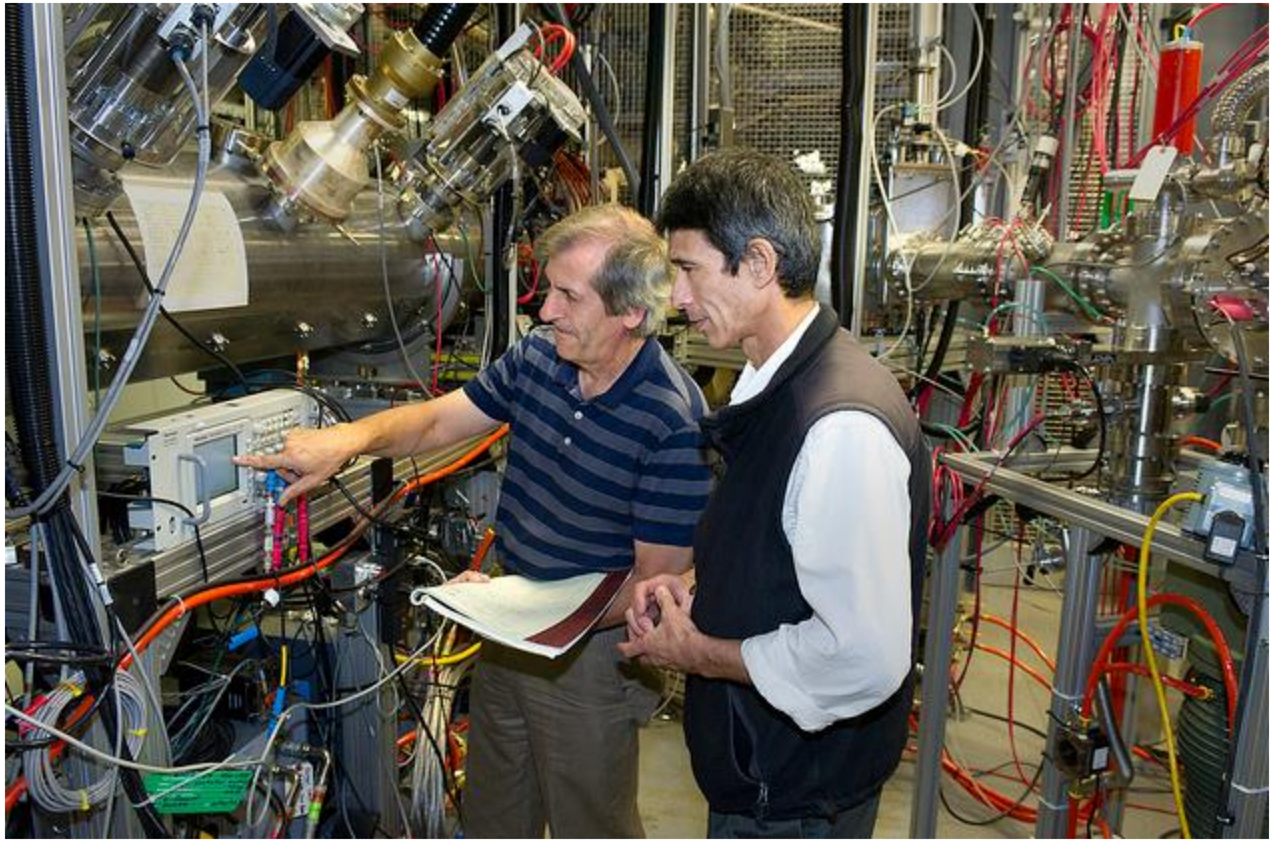
Electron Beam Ion Sources



Stepwise ionisation

Electron Beam Ion Sources



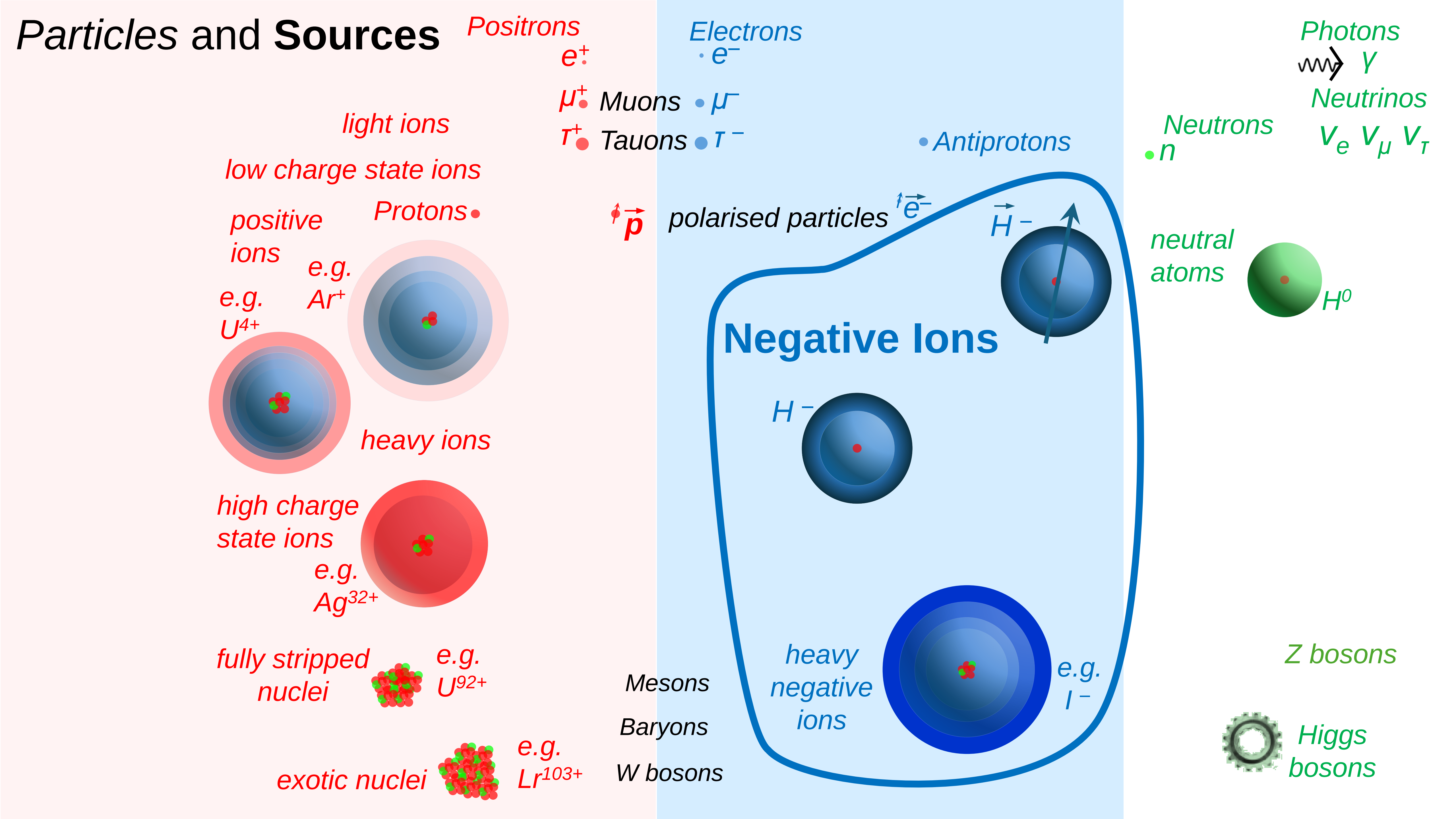


BROOKHAVEN NATIONAL LABORATORY

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+
μ+ Muons μ−
τ+ Tauons τ −
Electrons
e−
Photons
γ
Neutrinos
νe νμ ντ
Neutrons
n
Antiprotons
light ions
low charge state ions
positive ions
Protons
p
polarised particles
e
H −
Negative Ions
neutral atoms
H0
e.g. Ar+
e.g. U4+
heavy ions
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high charge state ions
e.g. Ag32+
fully stripped nuclei
e.g. U92+
Mesons
Baryons
W bosons
heavy negative ions
e.g. I −
Z bosons
Higgs bosons
exotic nuclei
e.g. Lr103+

Negative Ion Sources

Knocking 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

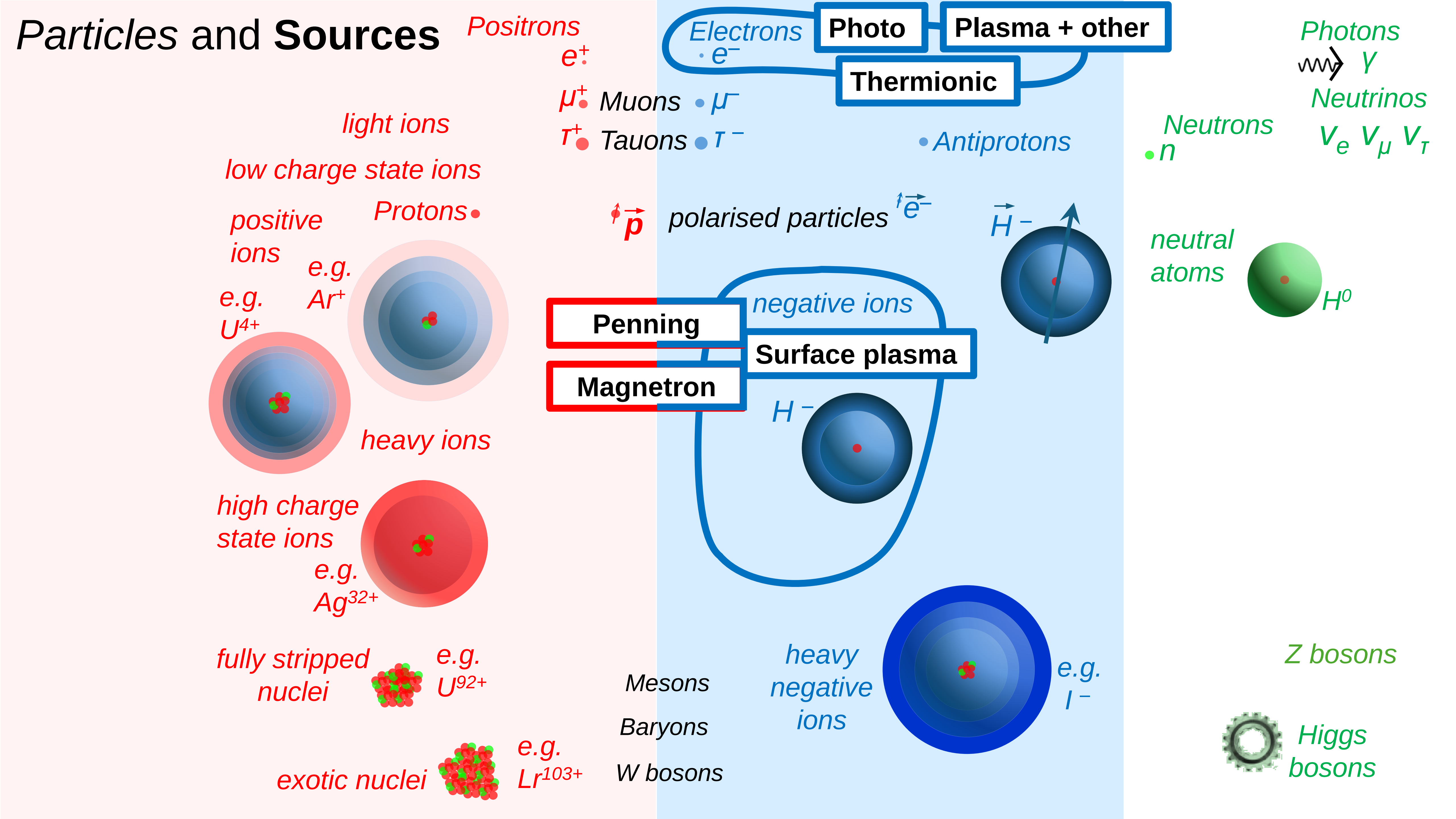
Up to 100 times for H^+ collisions

H^- are very fragile!

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
Positrons
e+
μ+ Muons μ−
τ+ Tauons τ −
Electrons
e−
Photo
Plasma + other
Thermionic
Photons
γ
Neutrinos
νe νμ ντ
Neutrons
n
Antiprotons
light ions
low charge state ions
positive ions
Protons
p
polarised particles
e−
H −
e.g. Ar+
e.g. U4+
neutral atoms
H0
Penning
Magnetron
negative ions
Surface plasma
H −
heavy ions
high charge state ions
e.g. Ag32+
fully stripped nuclei
e.g. U92+
exotic nuclei
e.g. Lr103+
Mesons
Baryons
W bosons
heavy negative ions
e.g. I −
Z bosons
Higgs bosons

Early 1970s Budker Institute of Nuclear Physics Novosibirsk

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

Surface Plasma Sources (SPS)

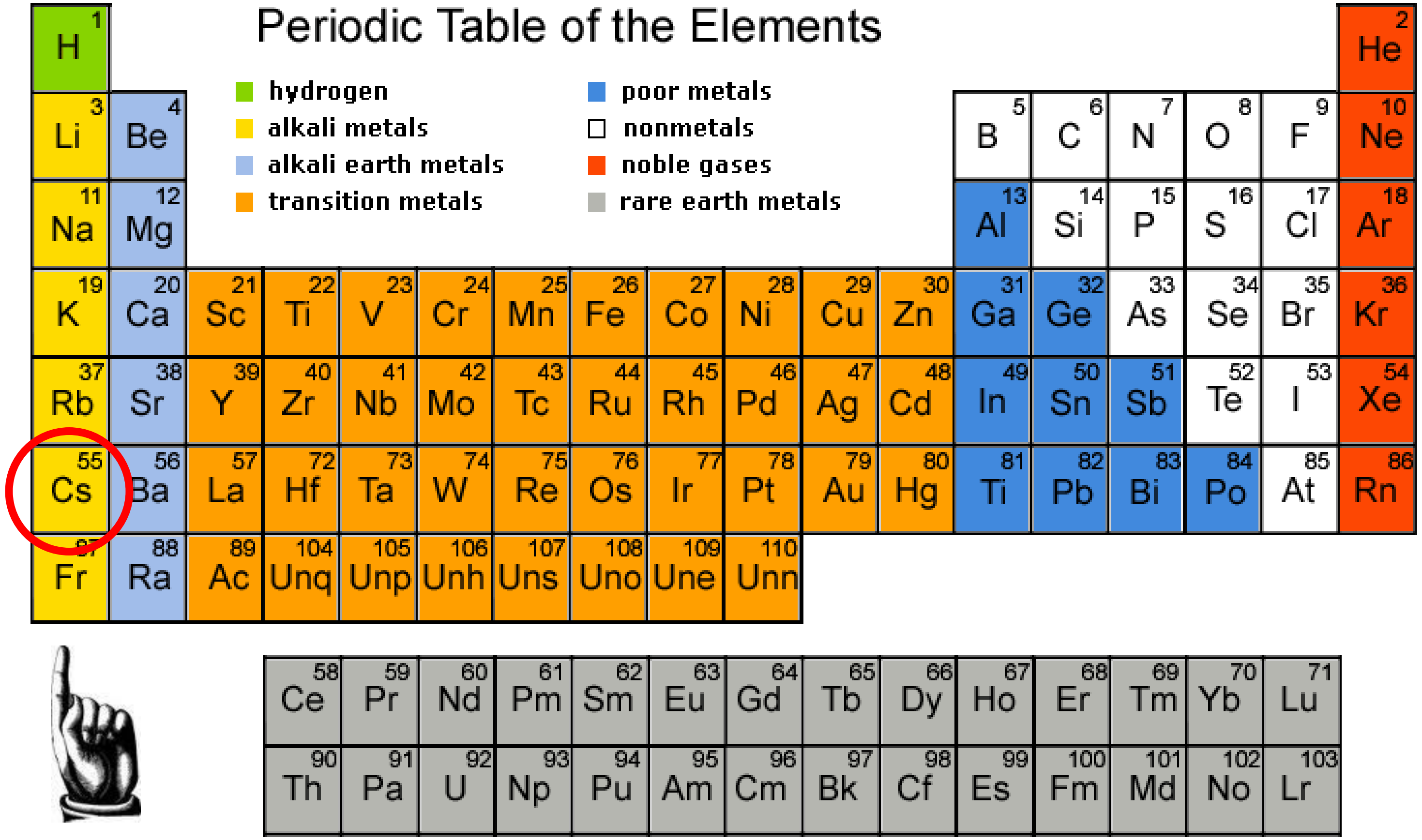
Gennady Dimov

Yuri Belchenko

Vadim Dudnikov

Caesium – The magic elixir of negative ion sources!

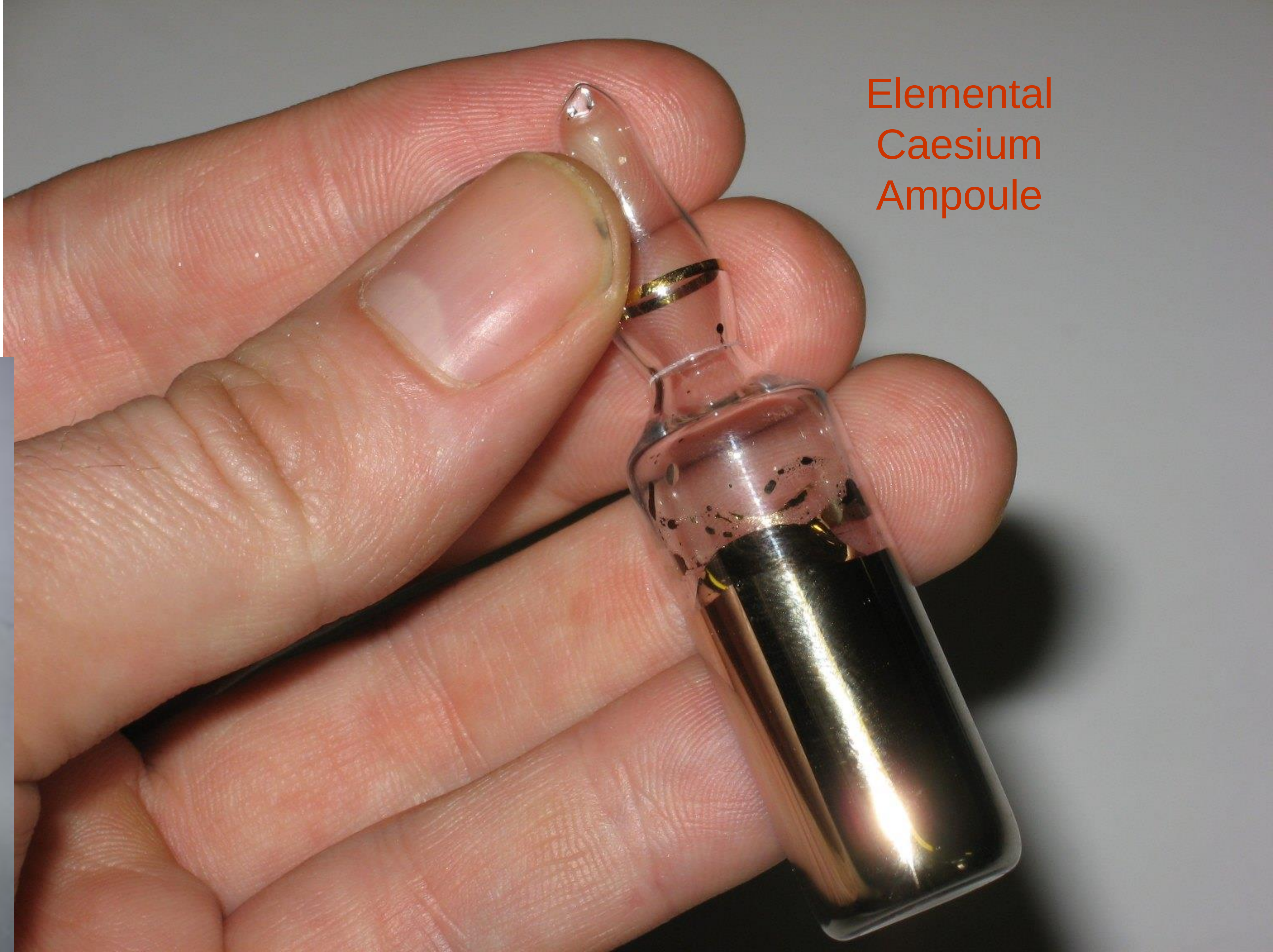
More reactive



1 electron in the outer orbital

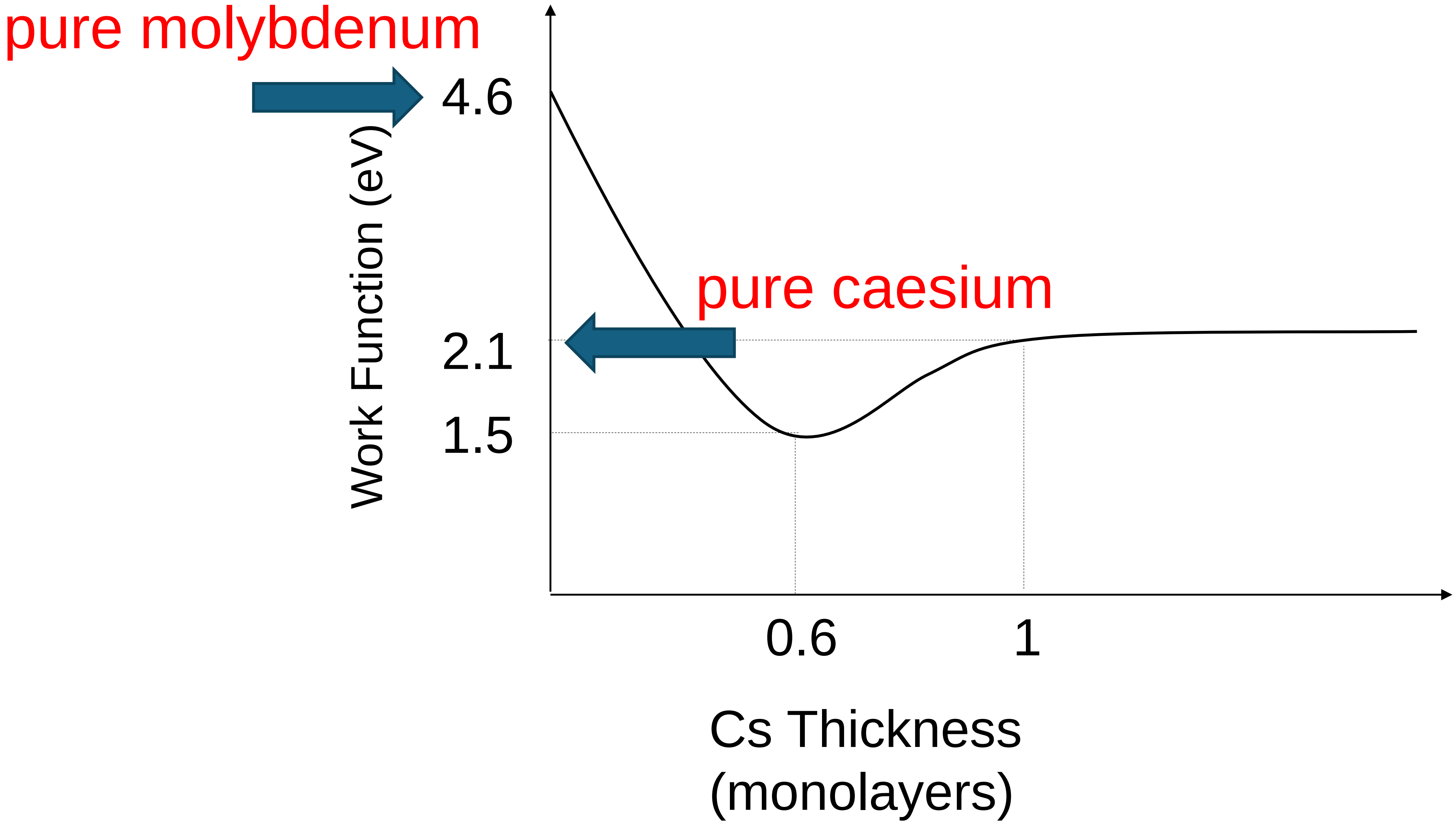
An amazing donor of electrons
= great for making negative ions

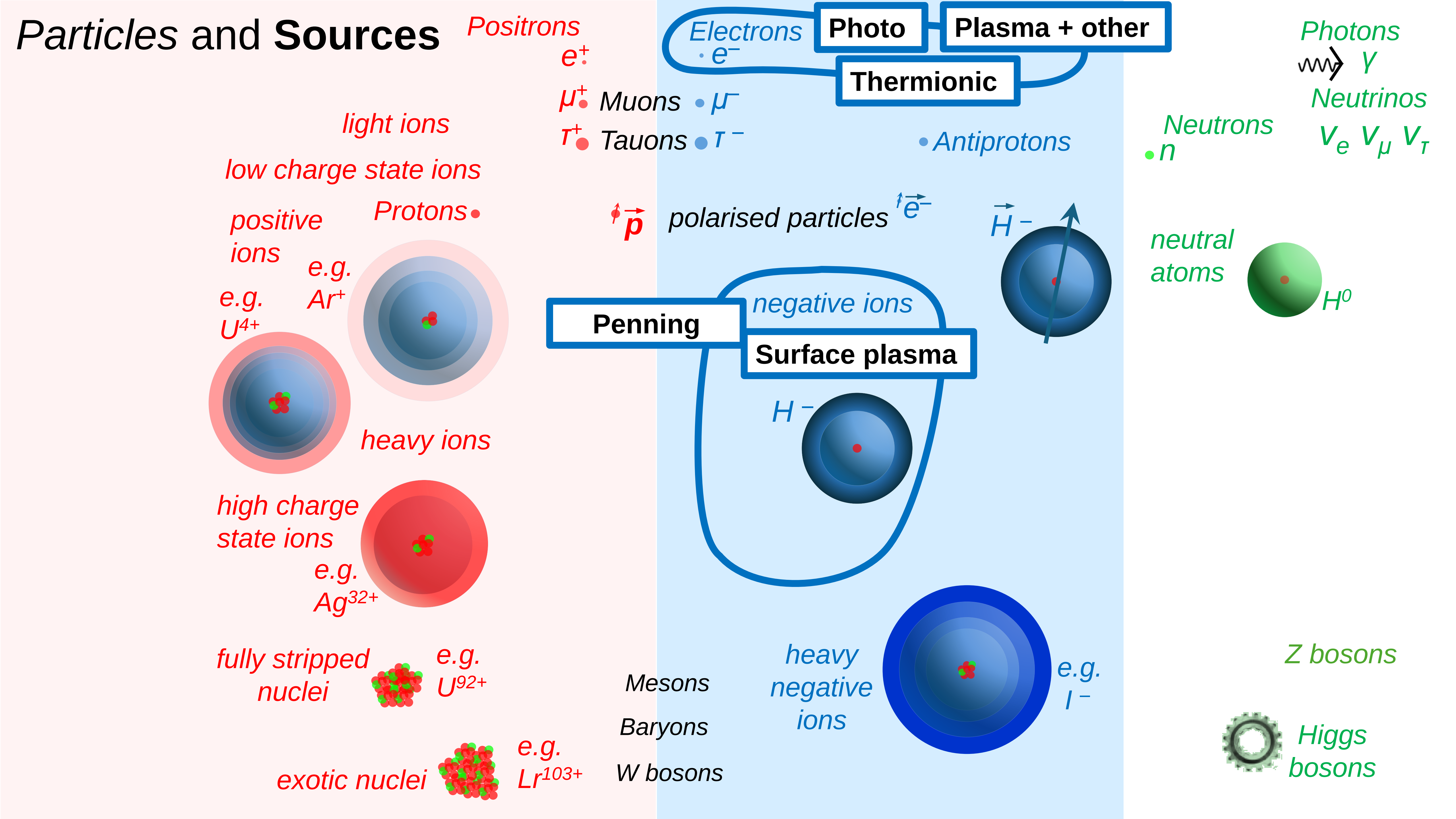
Caesium
Chromate



Elemental
Caesium
Ampoule

Caesium coverage and work function





Particles and Sources
Positrons
e^+
μ^+ Muons μ^-
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light ions
low charge state ions
positive ions
Protons
e.g. Ar^+
e.g. U^{4+}
heavy ions
high charge state ions
e.g. Ag^{32+}
fully stripped nuclei
e.g. U^{92+}
exotic nuclei
e.g. Lr^{103+}
Electrons
e^-
Photo
Plasma + other
Thermionic
Antiprotons
$\vec{p}$ polarised particles $\vec{e}^-$
$\vec{H}^-$
Penning
negative ions
Surface plasma
H^-
Mesons
Baryons
W bosons
heavy negative ions
e.g. I^-
Photons
γ
Neutrinos
ν_e ν_μ ν_τ
Neutrons
n
neutral atoms
H^0
Z bosons
Higgs bosons

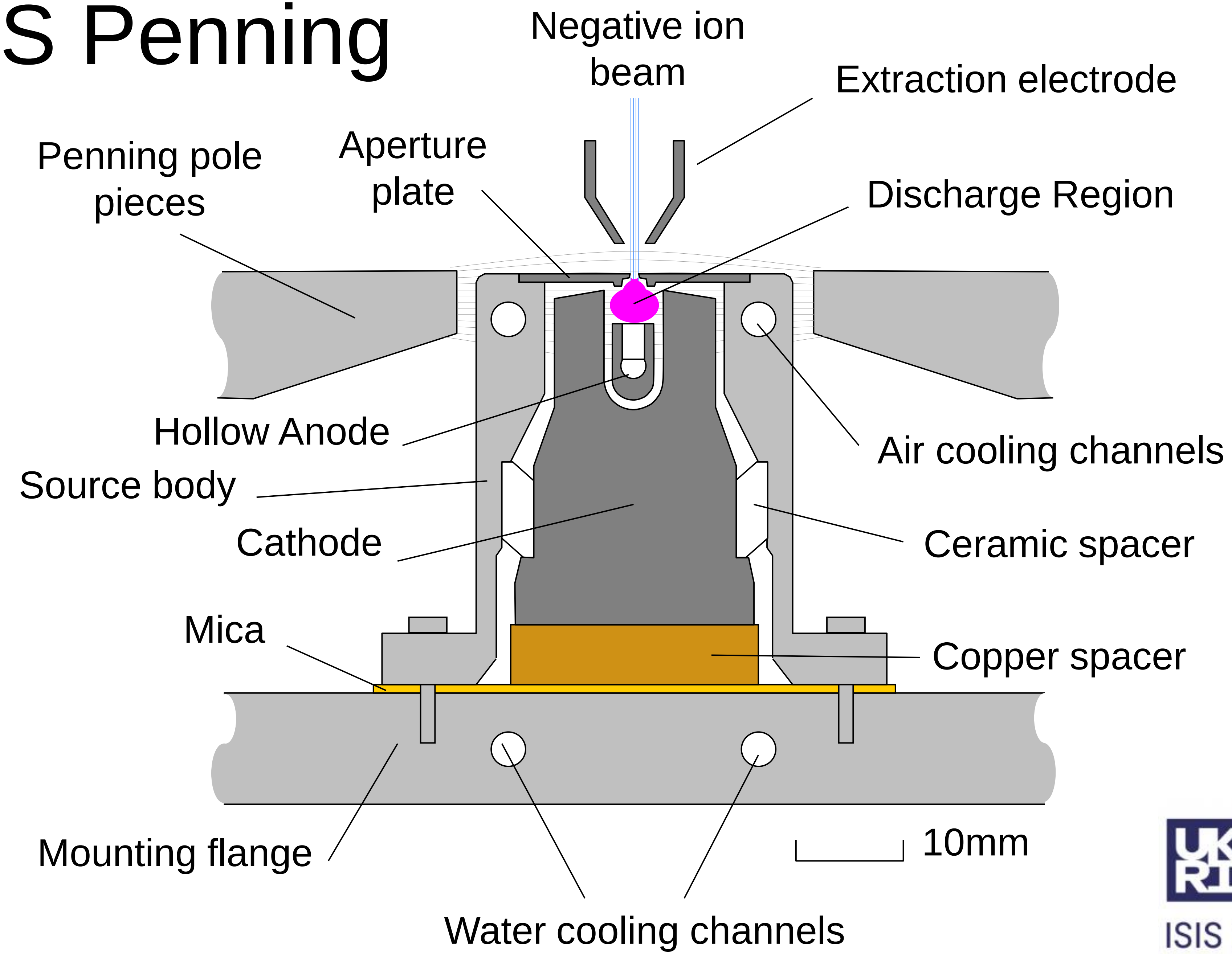
Early 1970s Budker Institute of Nuclear Physics Novosibirsk

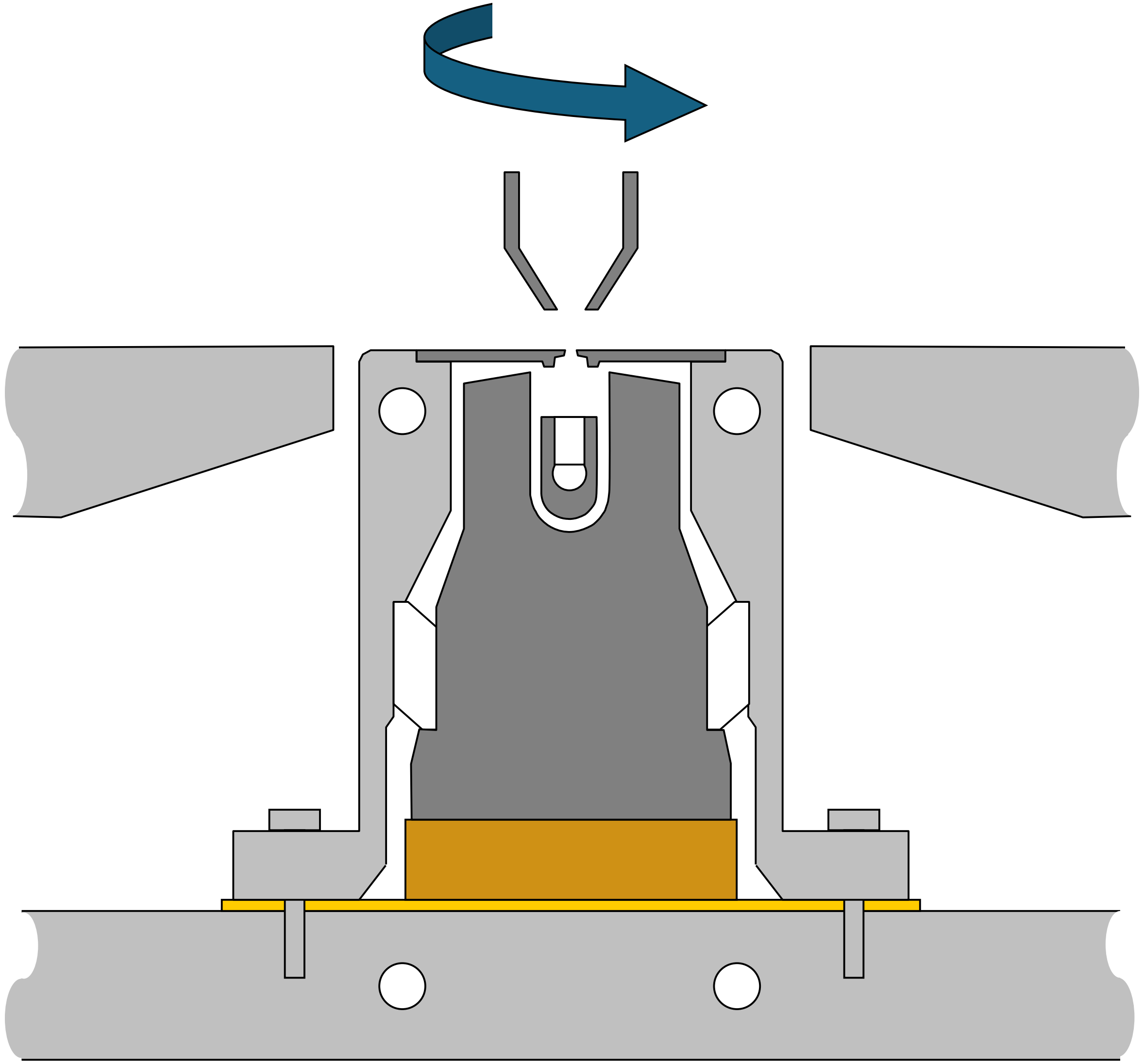
Penning SPS

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

Vadim Dudnikov

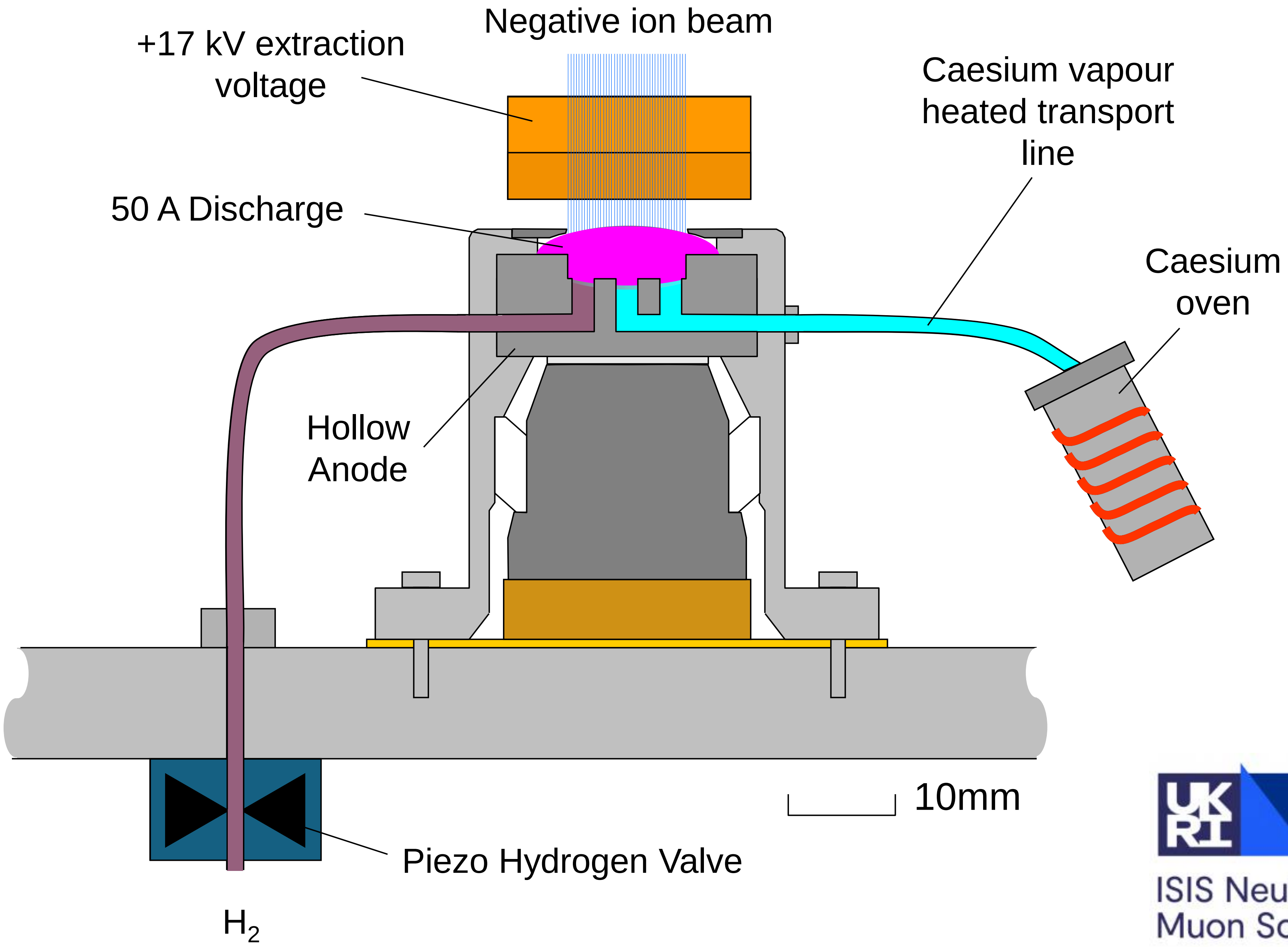
ISIS Penning





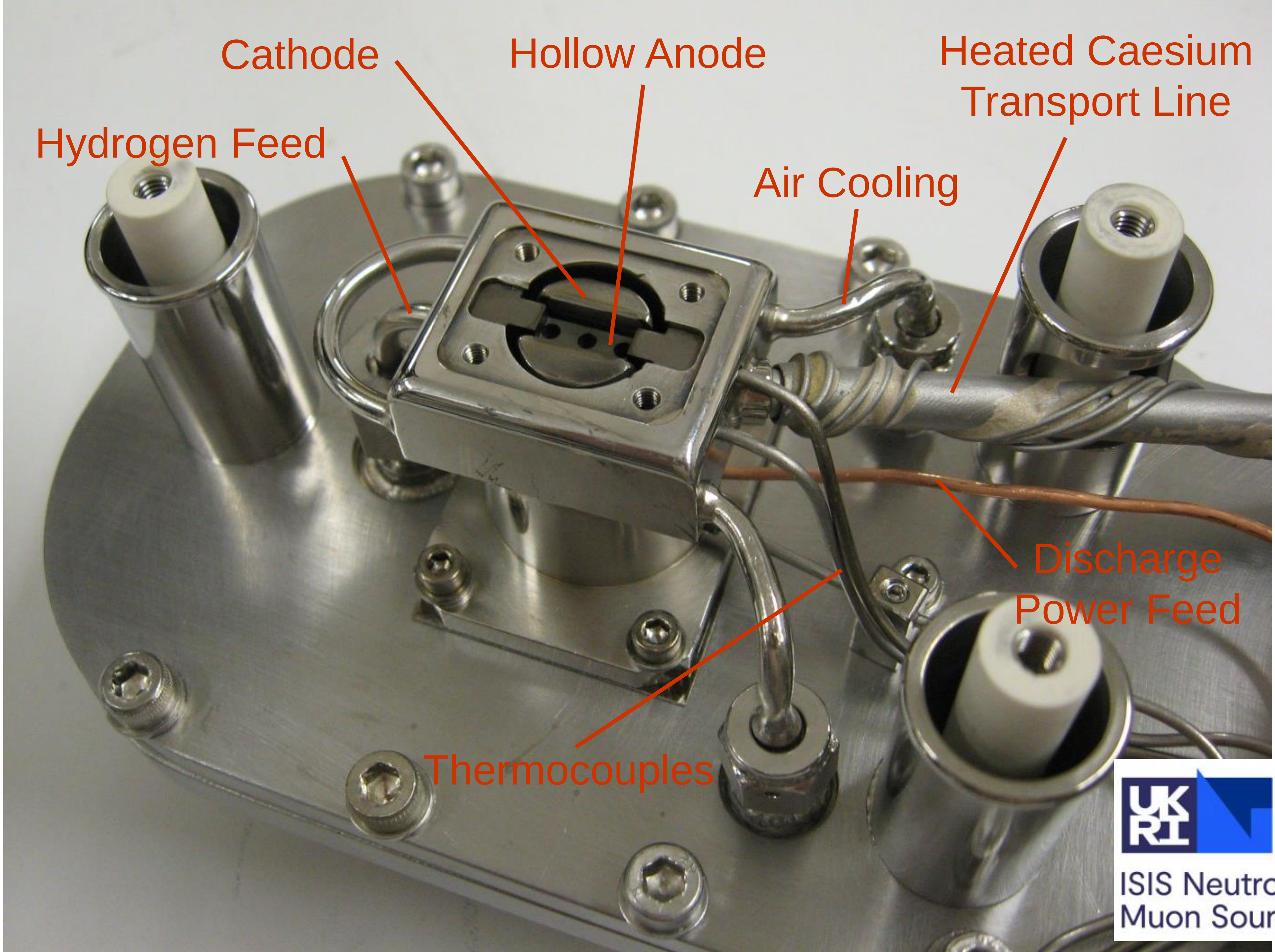
Science and Technology Facilities Council

ISIS Neutron and Muon Source

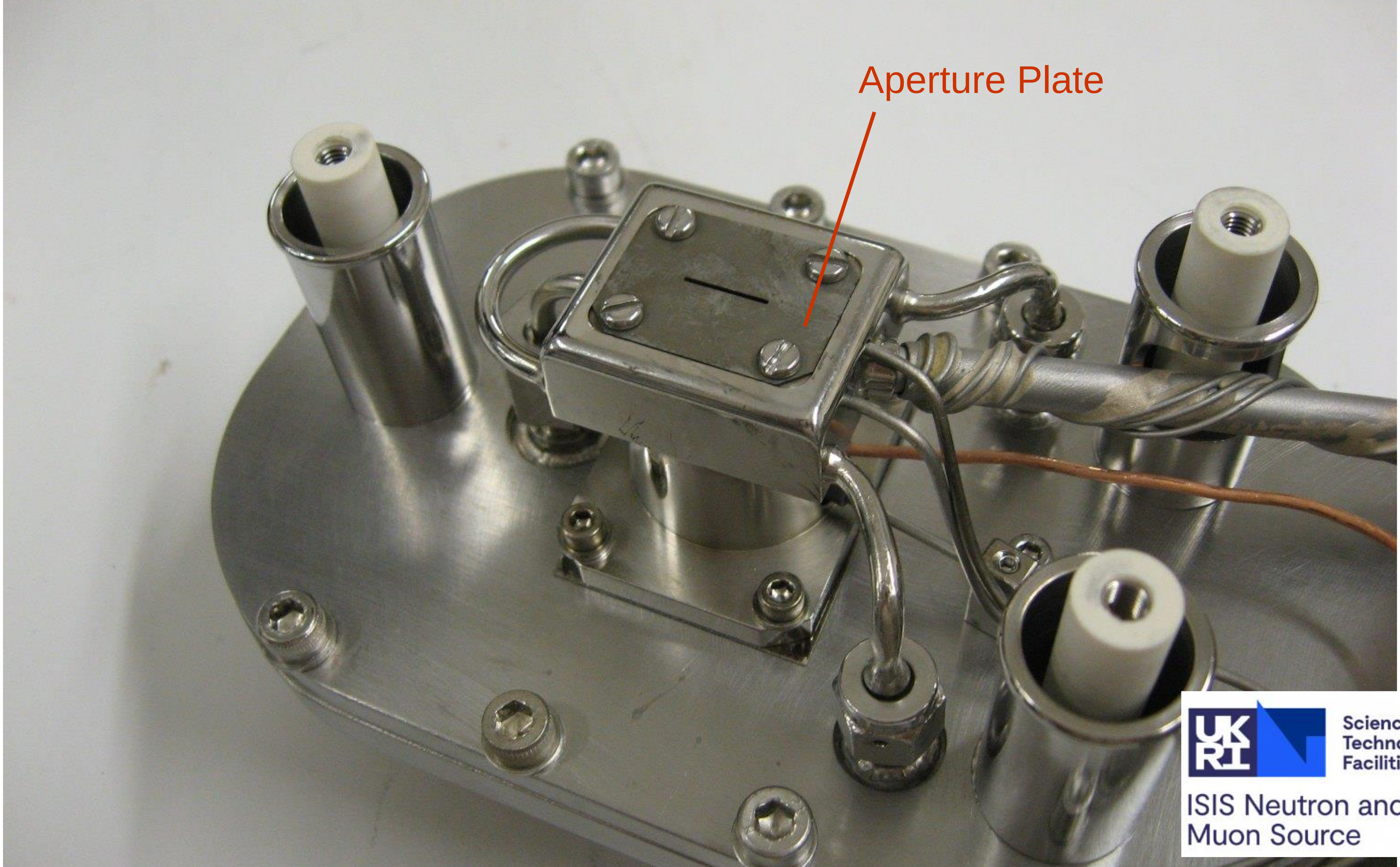


Science and Technology Facilities Council

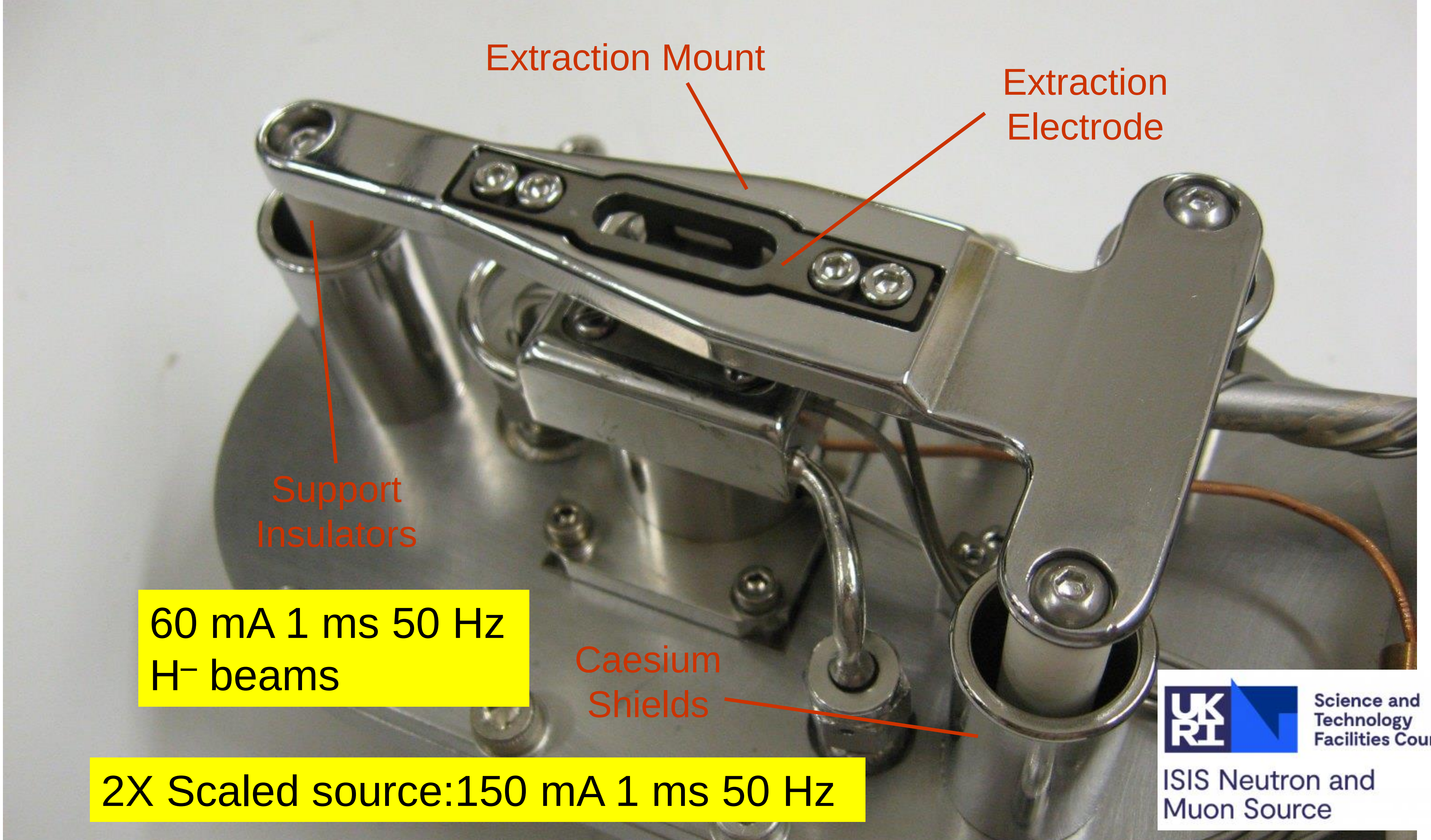
ISIS Neutron and Muon Source



Science and Technology Facilities Council
ISIS Neutron and Muon Source



Science and Technology Facilities Council
ISIS Neutron and Muon Source

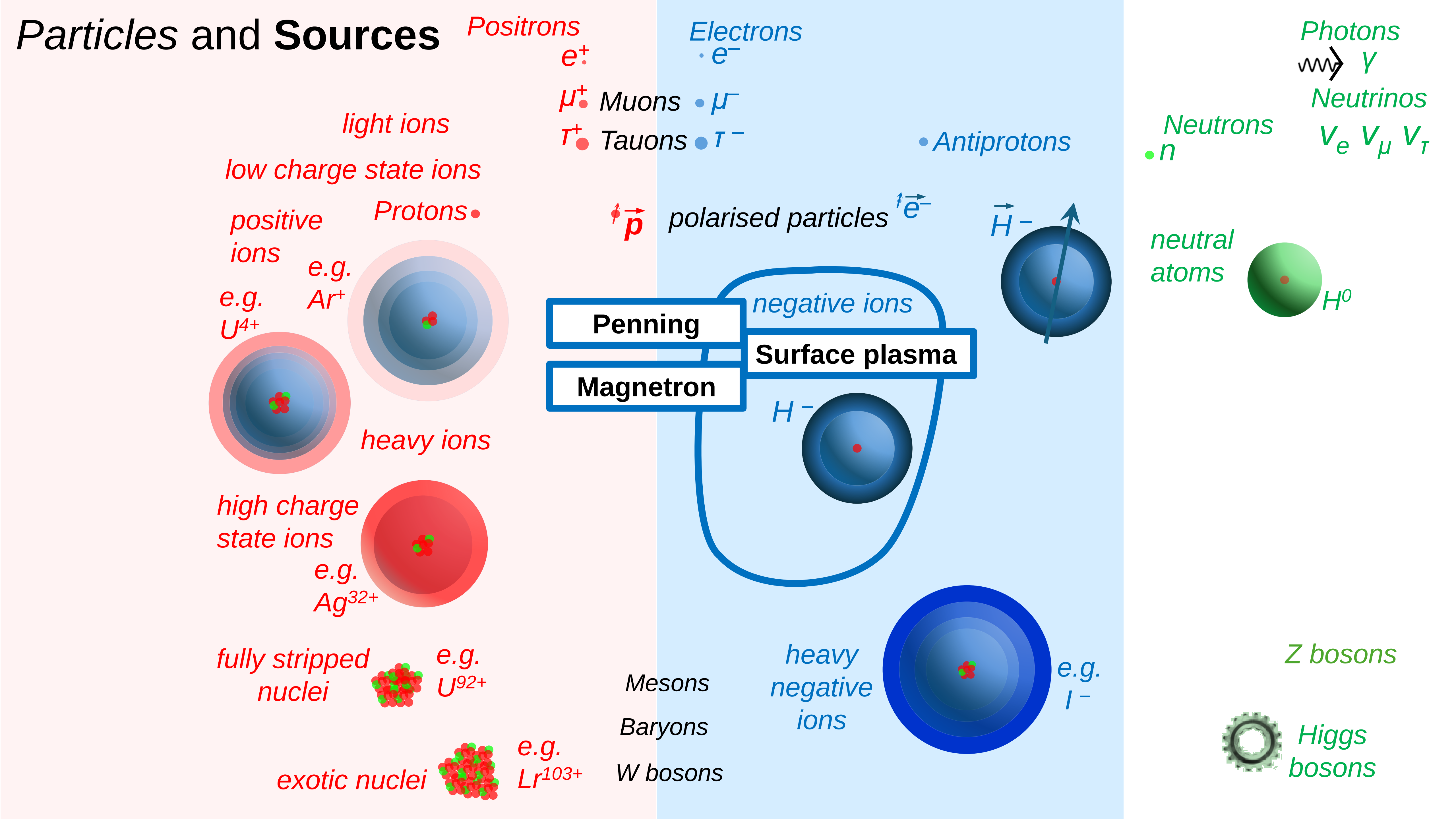


60 mA 1 ms 50 Hz
H^- beams

2X Scaled source:150 mA 1 ms 50 Hz

UKRI Science and Technology Facilities Council
ISIS Neutron and Muon Source

Particles and **Sources**



Early 1970s Budker Institute of Nuclear Physics Novosibirsk

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

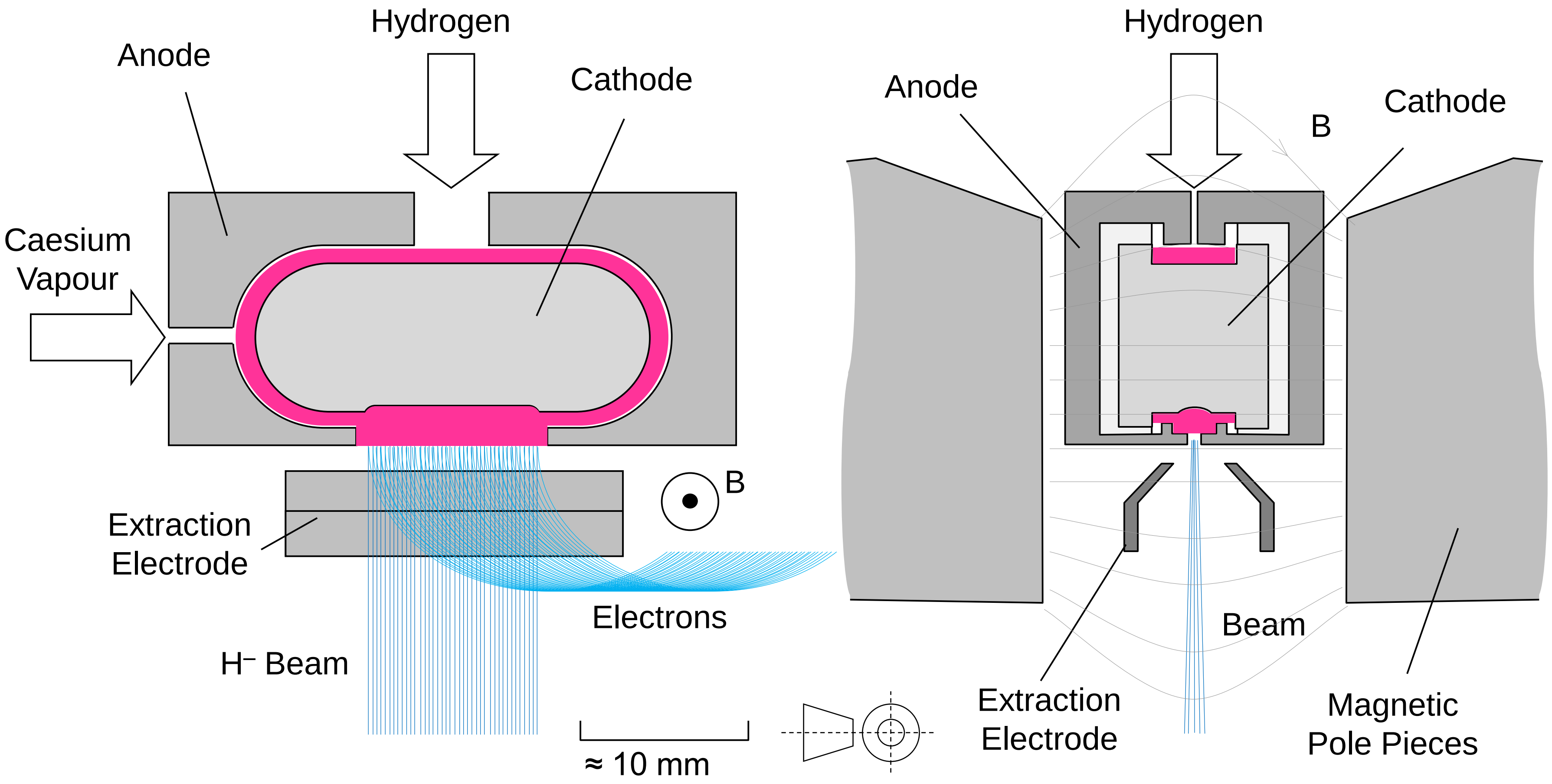
Magnetron (SPS)

Gennady Dimov

Yuri Belchenko

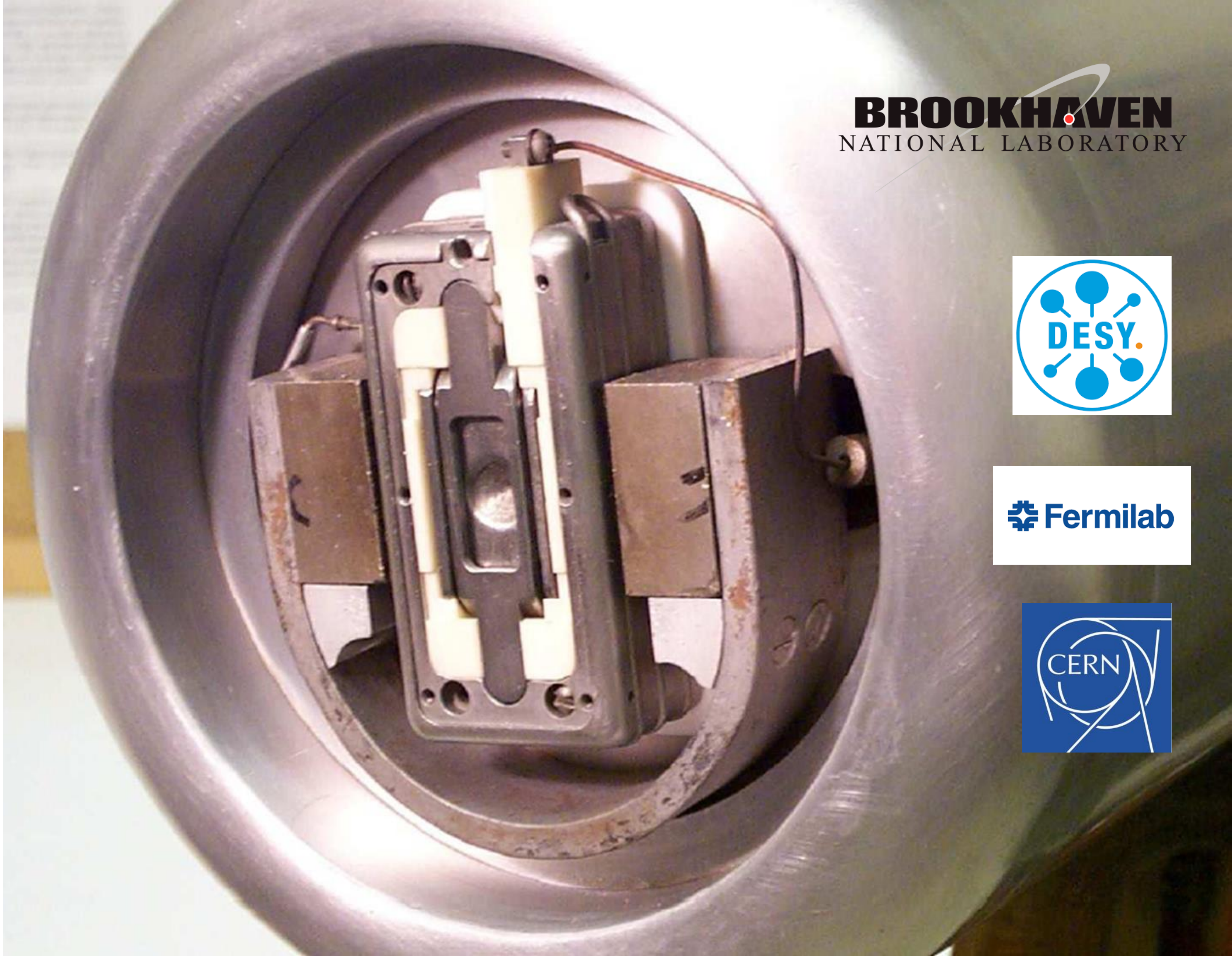
Vadim Dudnikov

Magnetron SPS

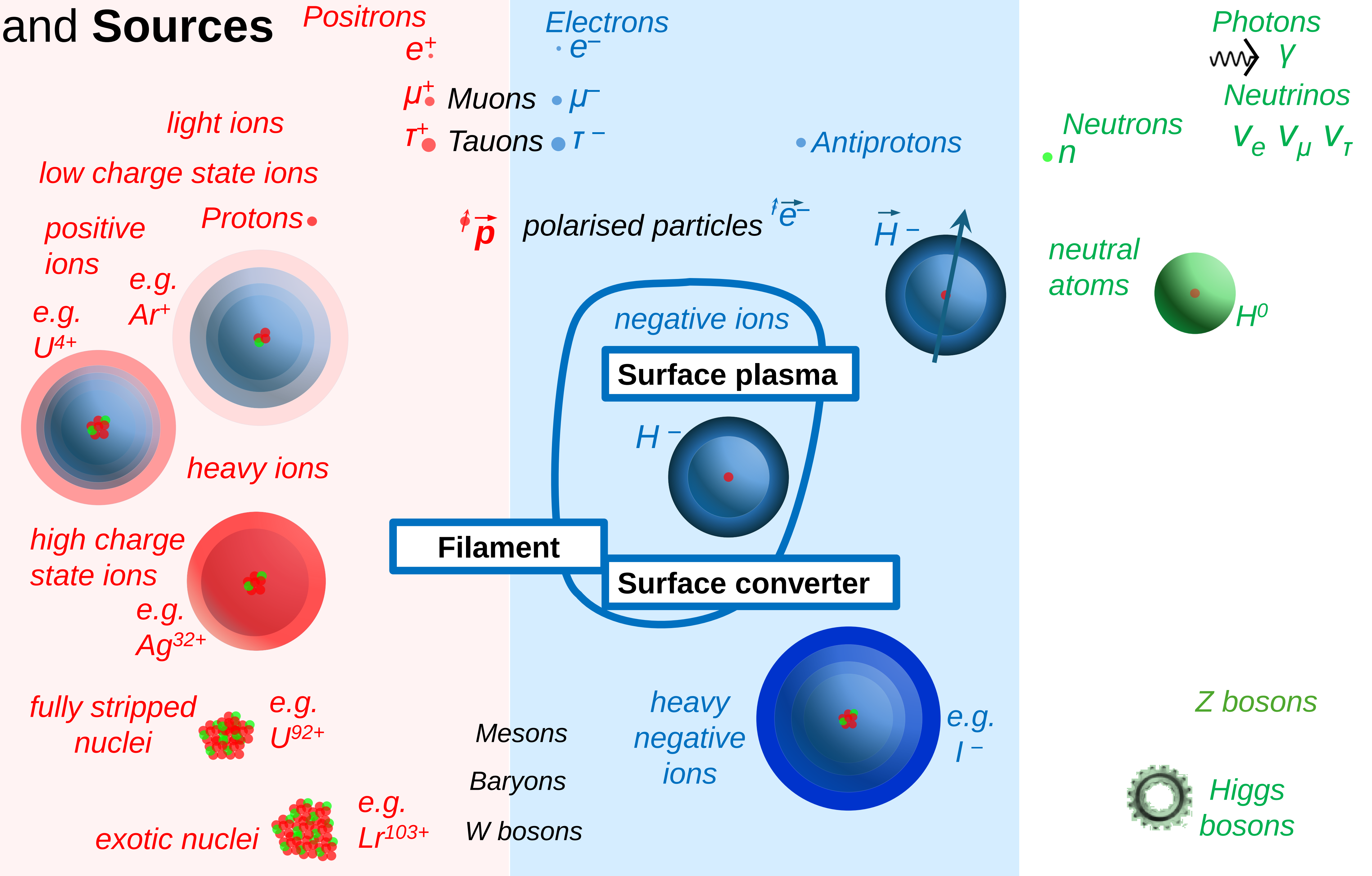


BNL Magnetron

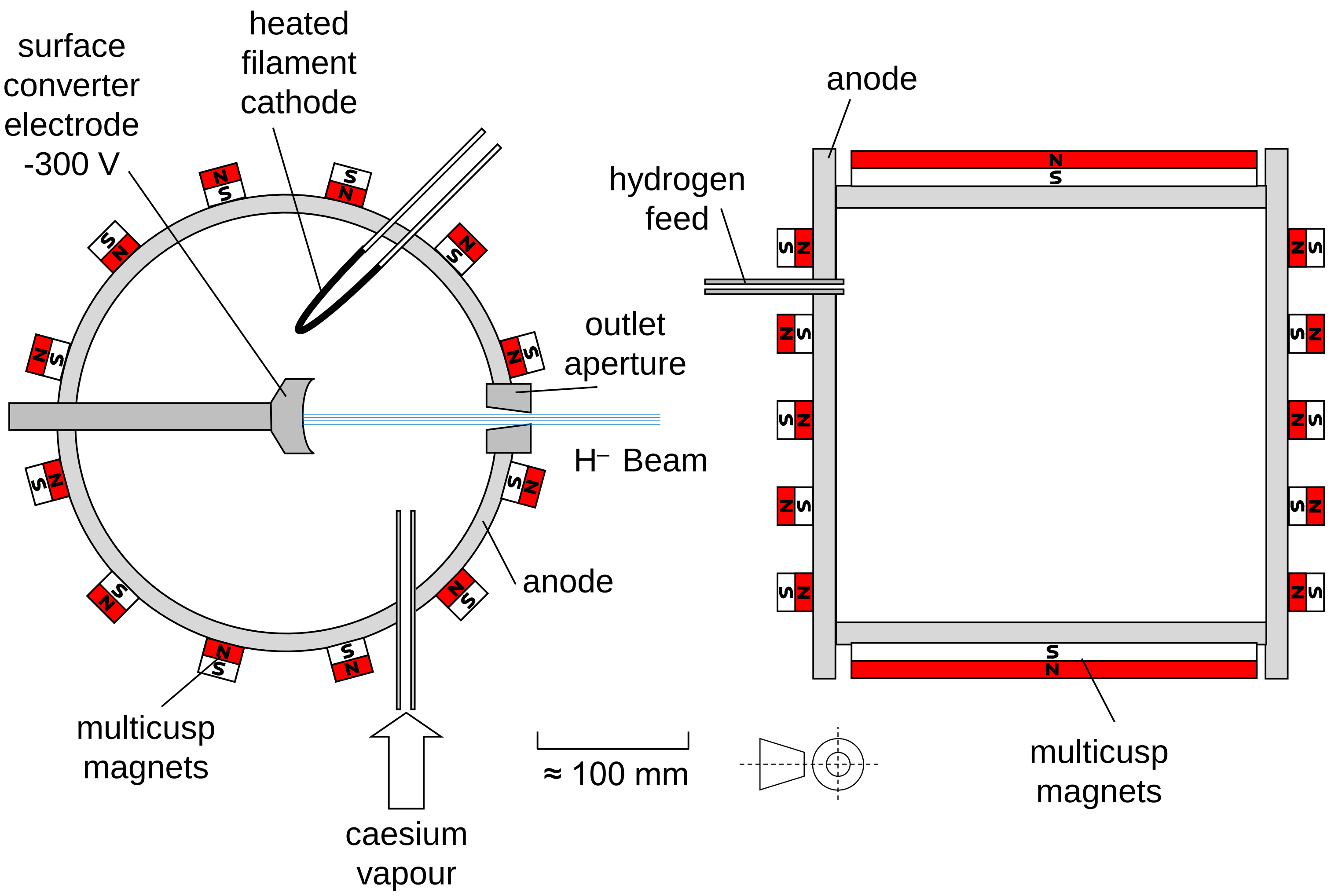
80 mA of H^- but only at low duty cycles < 0.5%



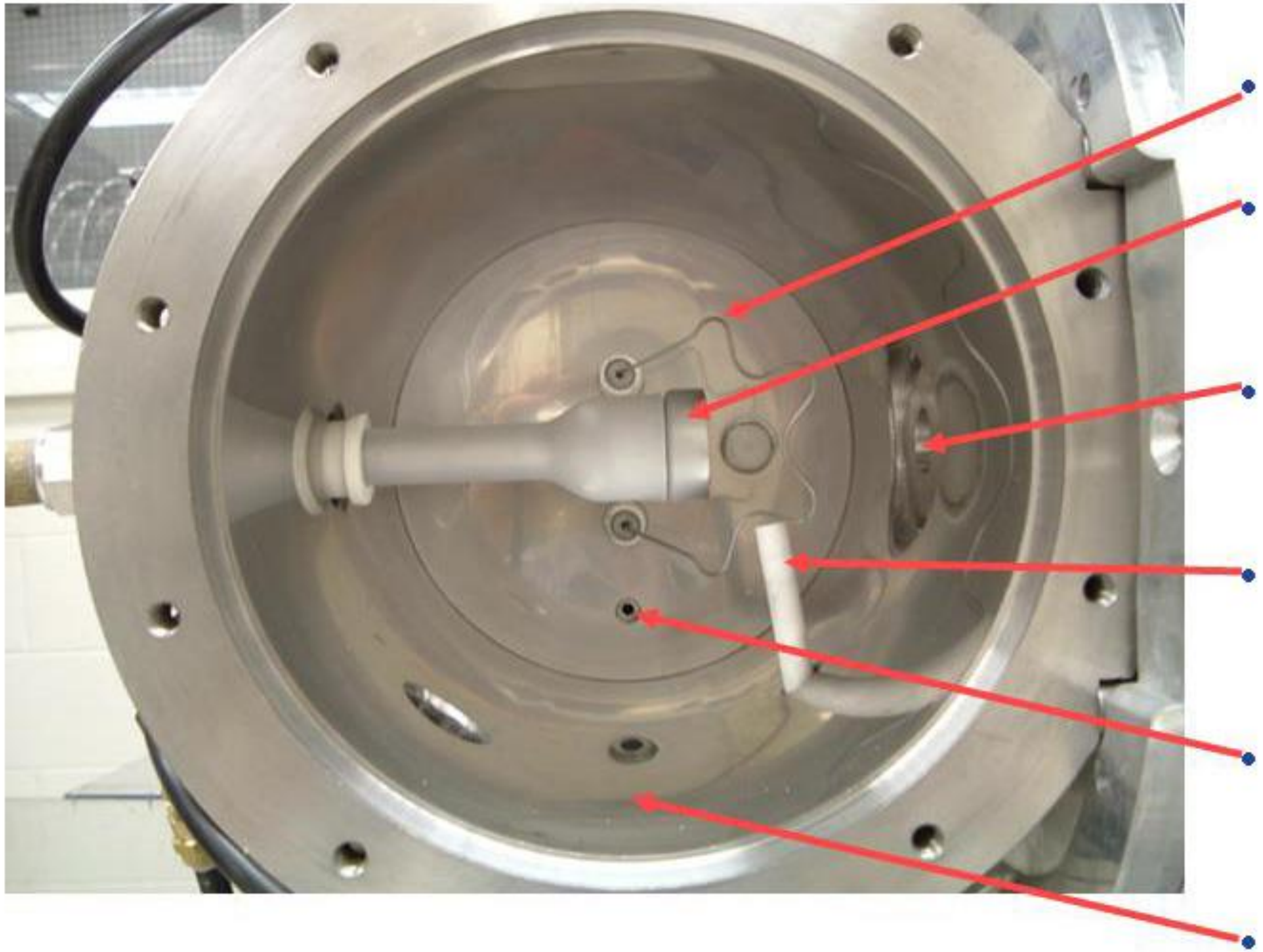
Particles and **Sources**



Filament cathode surface converter source

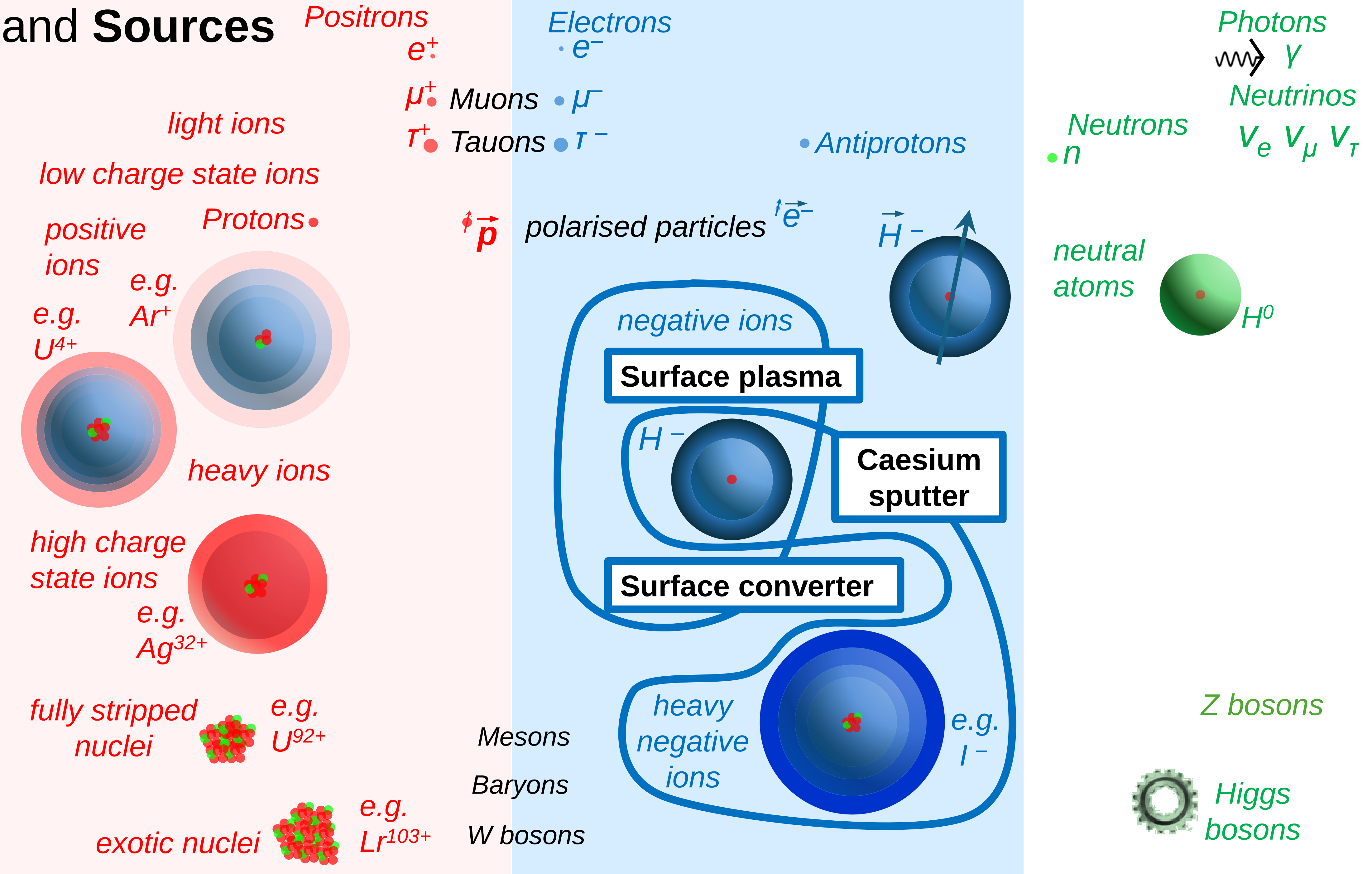


LANSE Surface Converter Source



18 mA 1 ms 120 Hz H^- beam

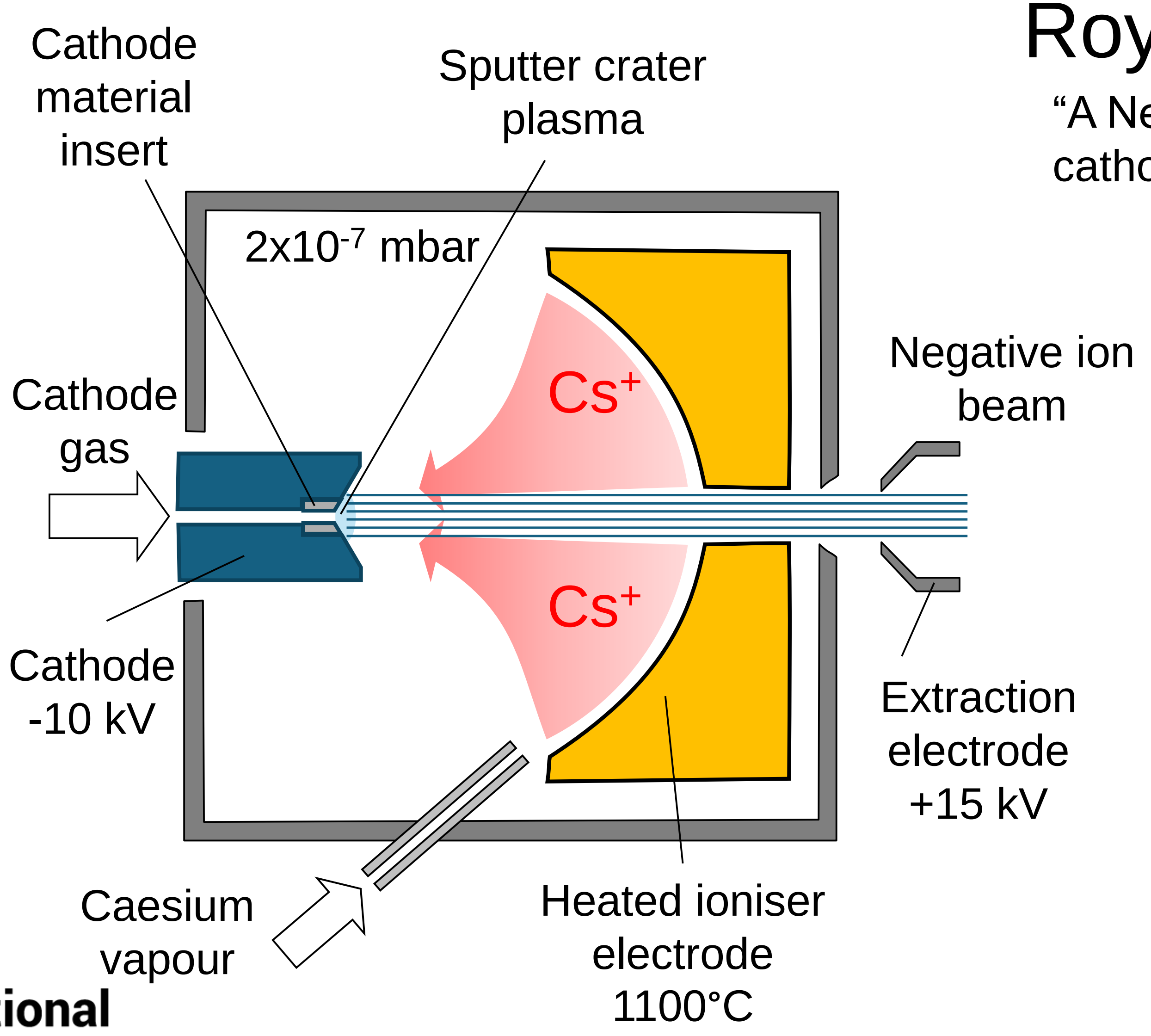
Particles and **Sources**



SNICS (Source of Negative Ions by Caesium Sputtering)

Roy Middelton et. al.

"A Negative-Ion Cookbook"
cathode material and gas recipes



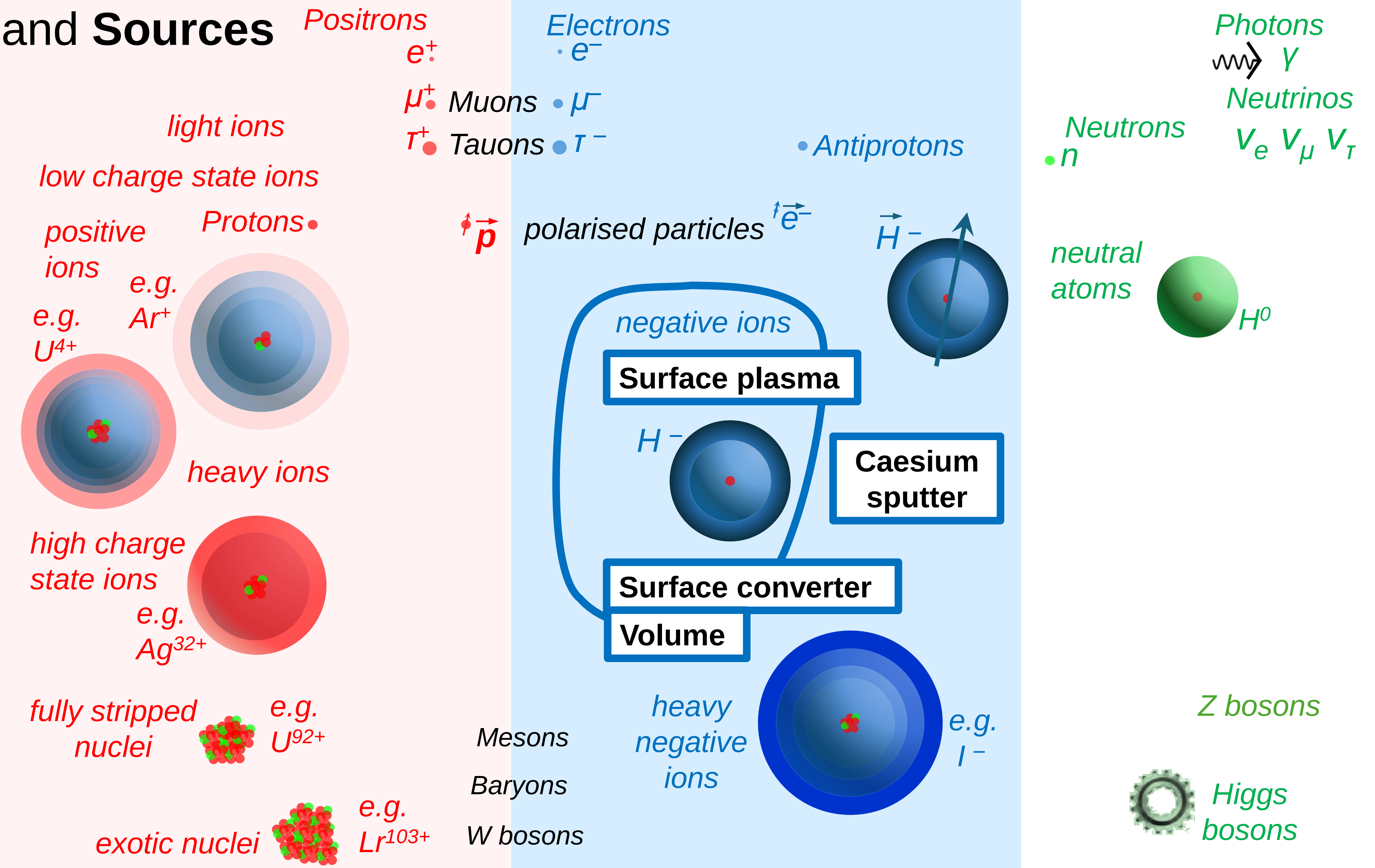
Negative ion currents (in μA)

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	CaH_3^- 0.8	Y^- 0.66	ErO^- 10
B_2^- 73	TiH^- 10	Zr^- 9.4	TmO^- 1.0
C^- 260	VH^- 25	Nb^- 7	YbO^- 1.0
C_2^- 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
MgH_2^- 1.5	ZnO^- 12	Sb^- 16	Au^- 150
Al^- 7	GaO^- 7	Te^- 20	PbO^- 1
Al_2^- 50	Ge^- 60	I^- 220	Bi^- 3.5

National Electrostatics Corp.

Produces a large range of different negative ions

Particles and **Sources**



Marthe Bacal
Ecole Polytechnique
mid 1970's

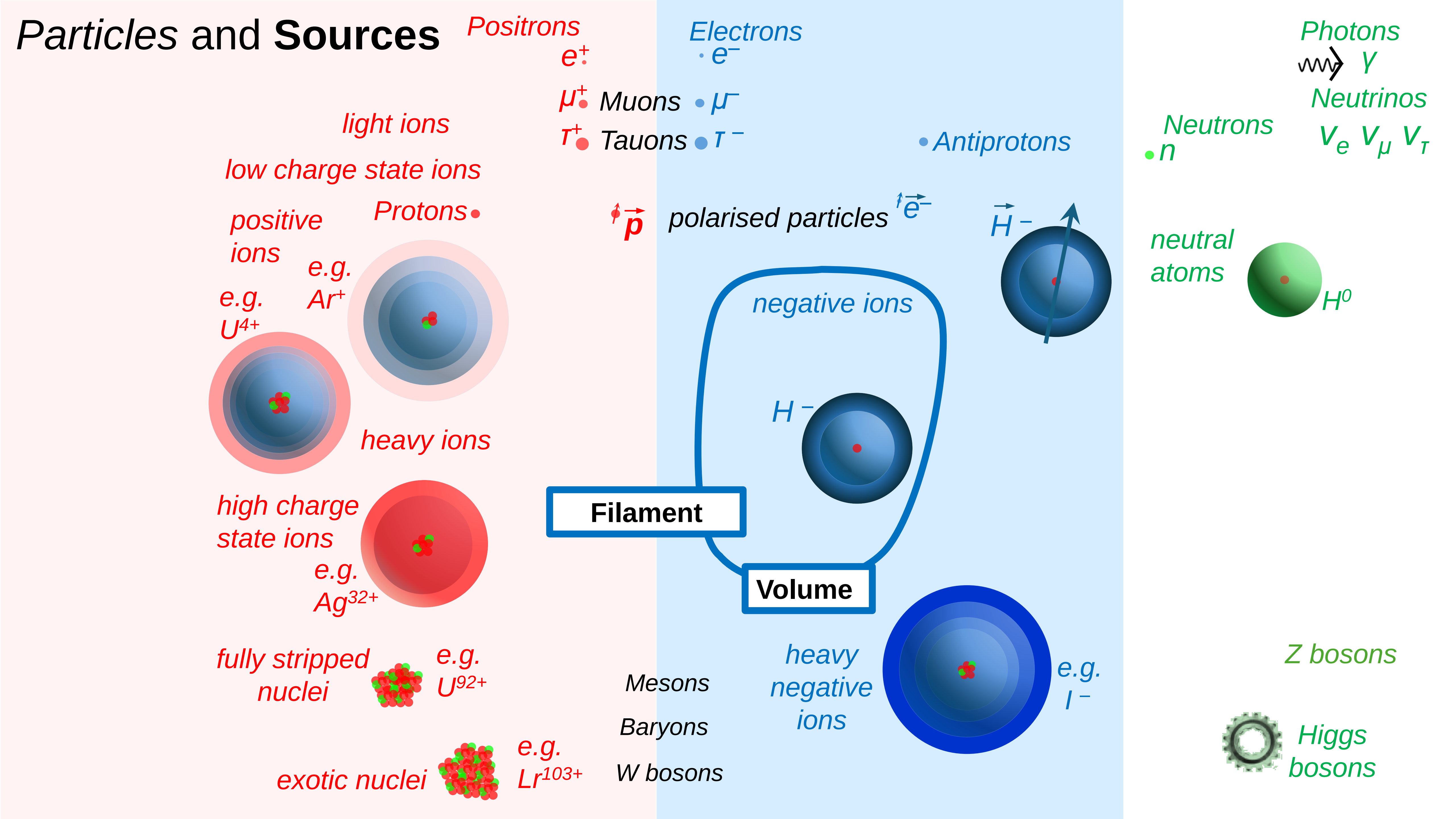
Volume Production

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

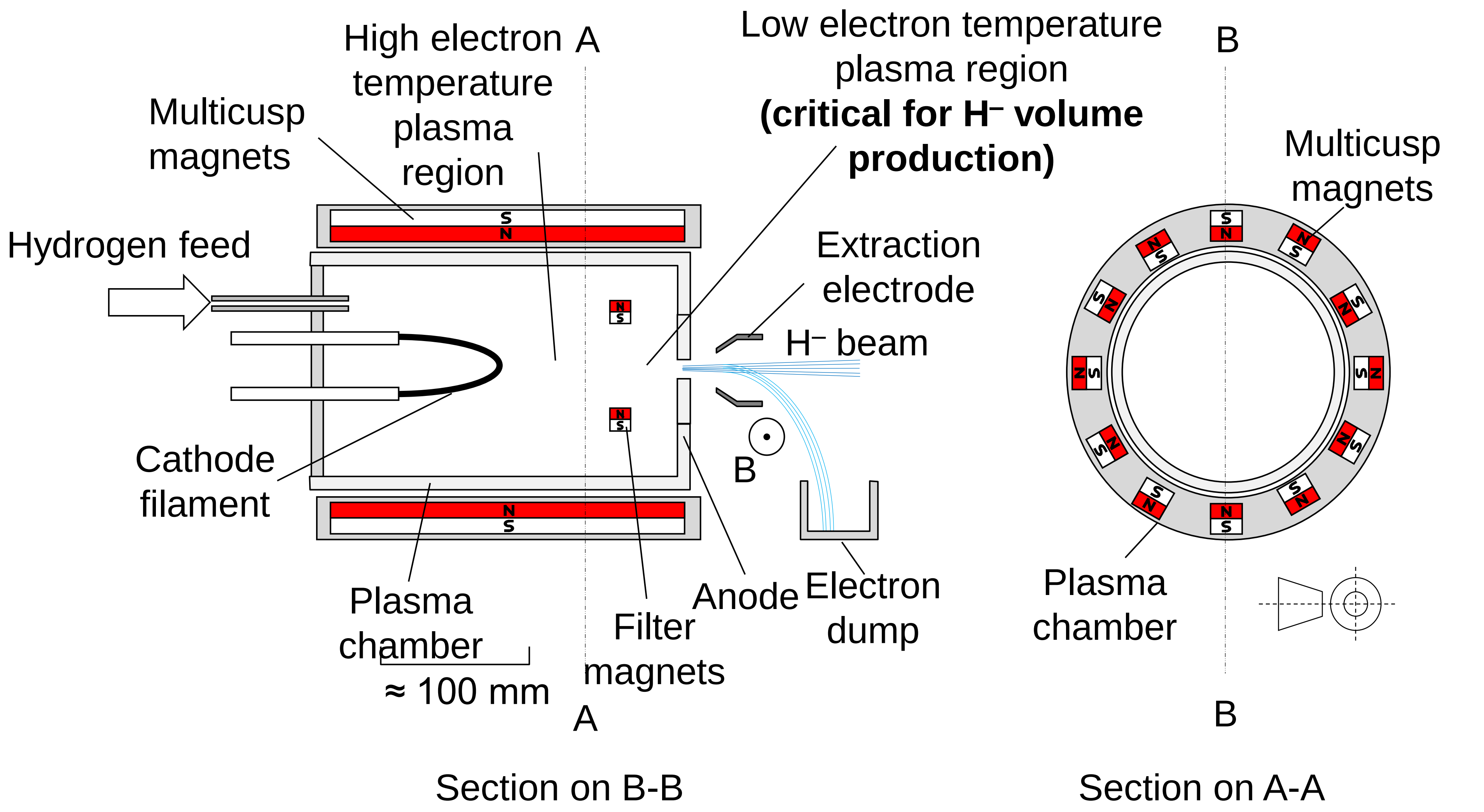
Dissociative attachment of **low energy** electrons to rovibrationally excited H_2 molecules

Sources developed by
Ehlers + Leung at LBNL

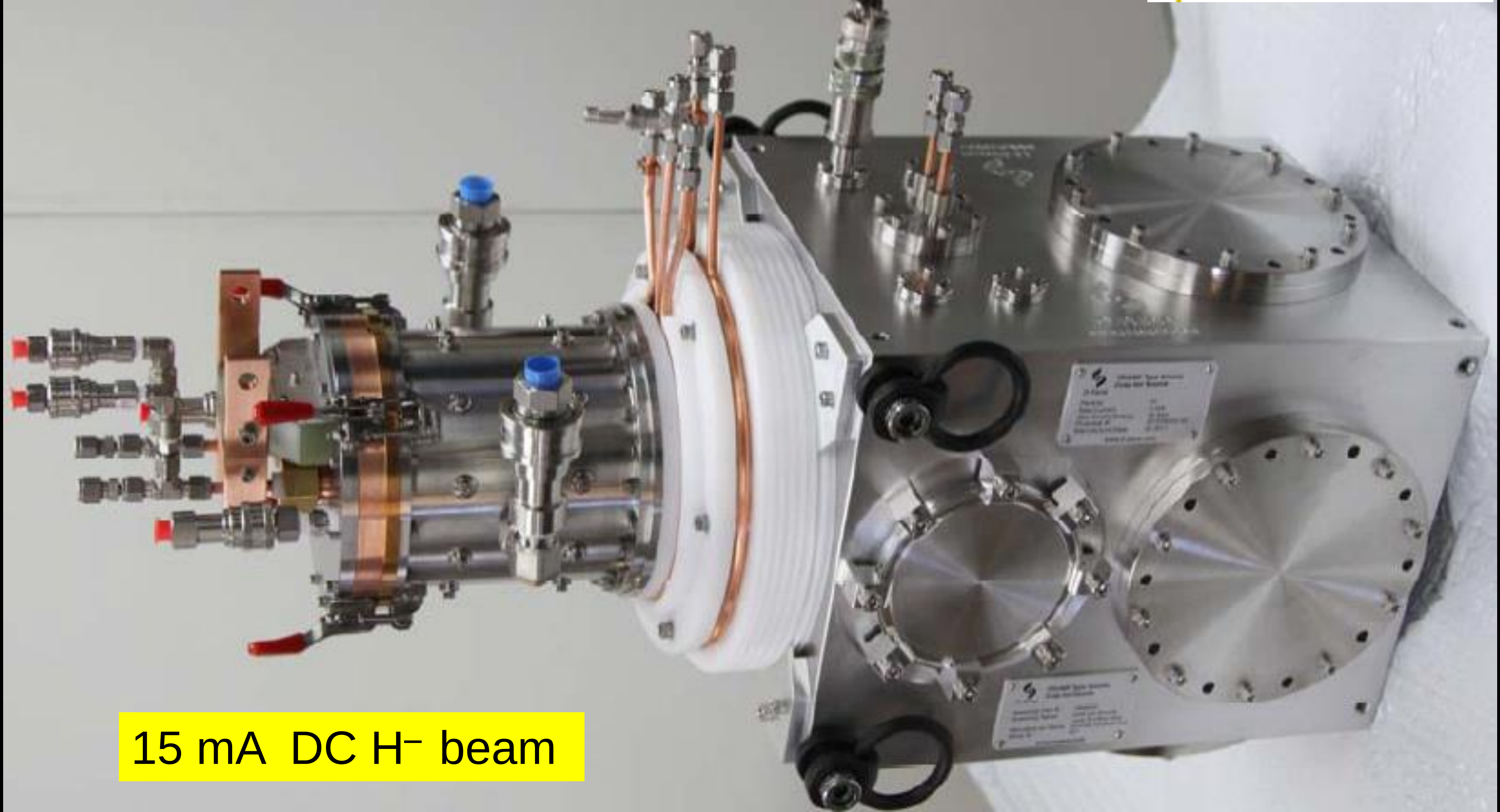
Particles and **Sources**



Multicusp Filament Volume Source

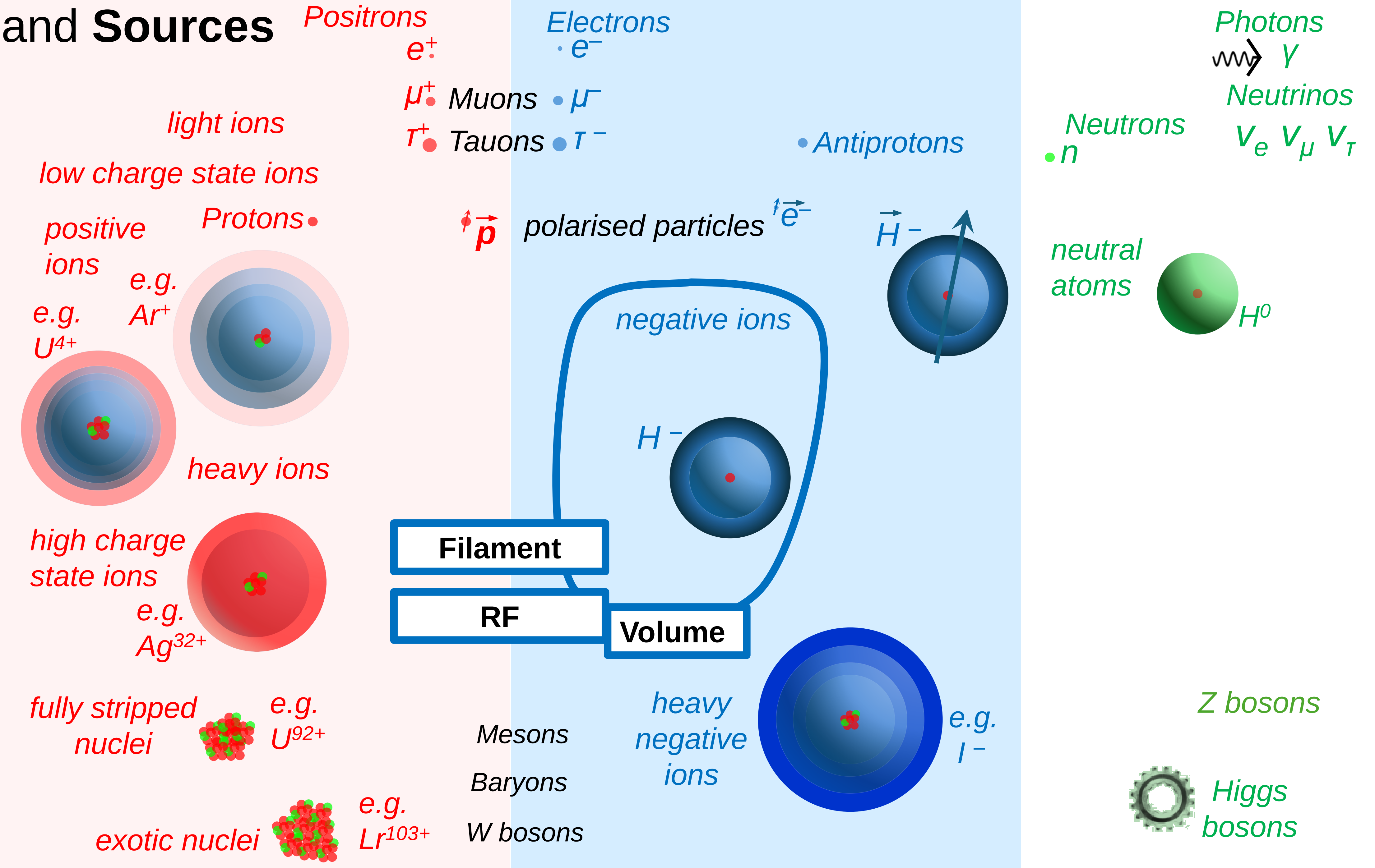


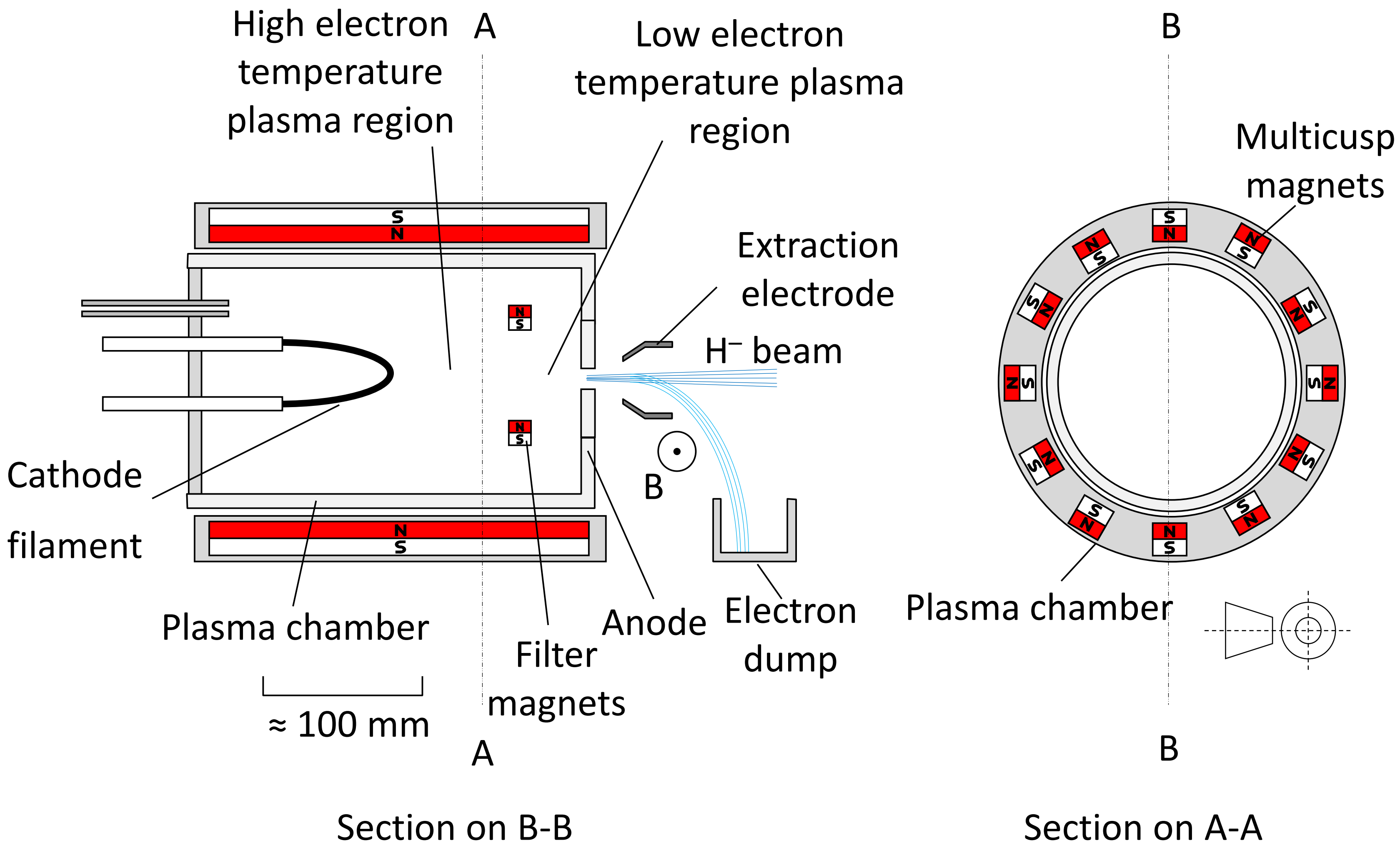
Filament Volume Source



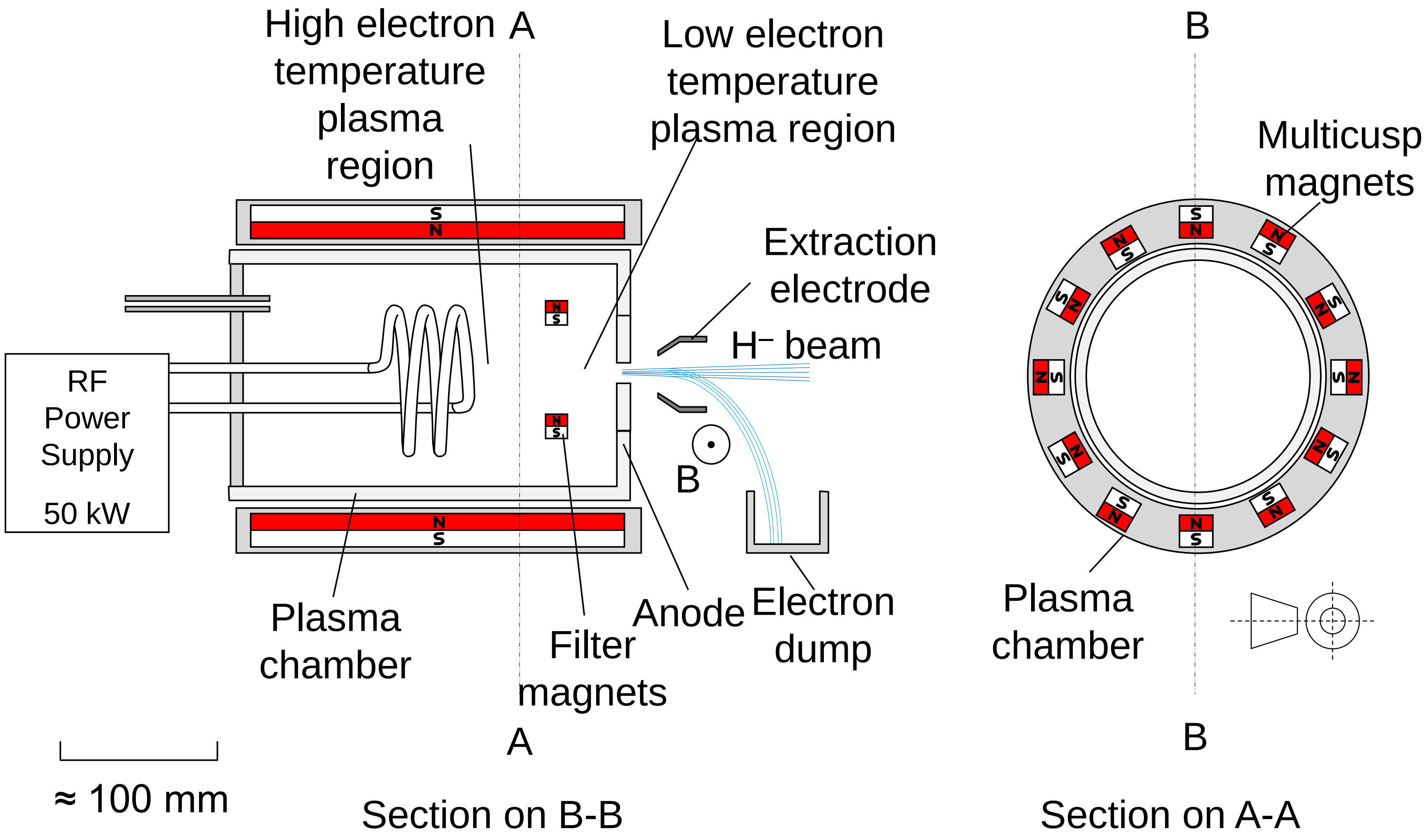
15 mA DC H^- beam

Particles and **Sources**

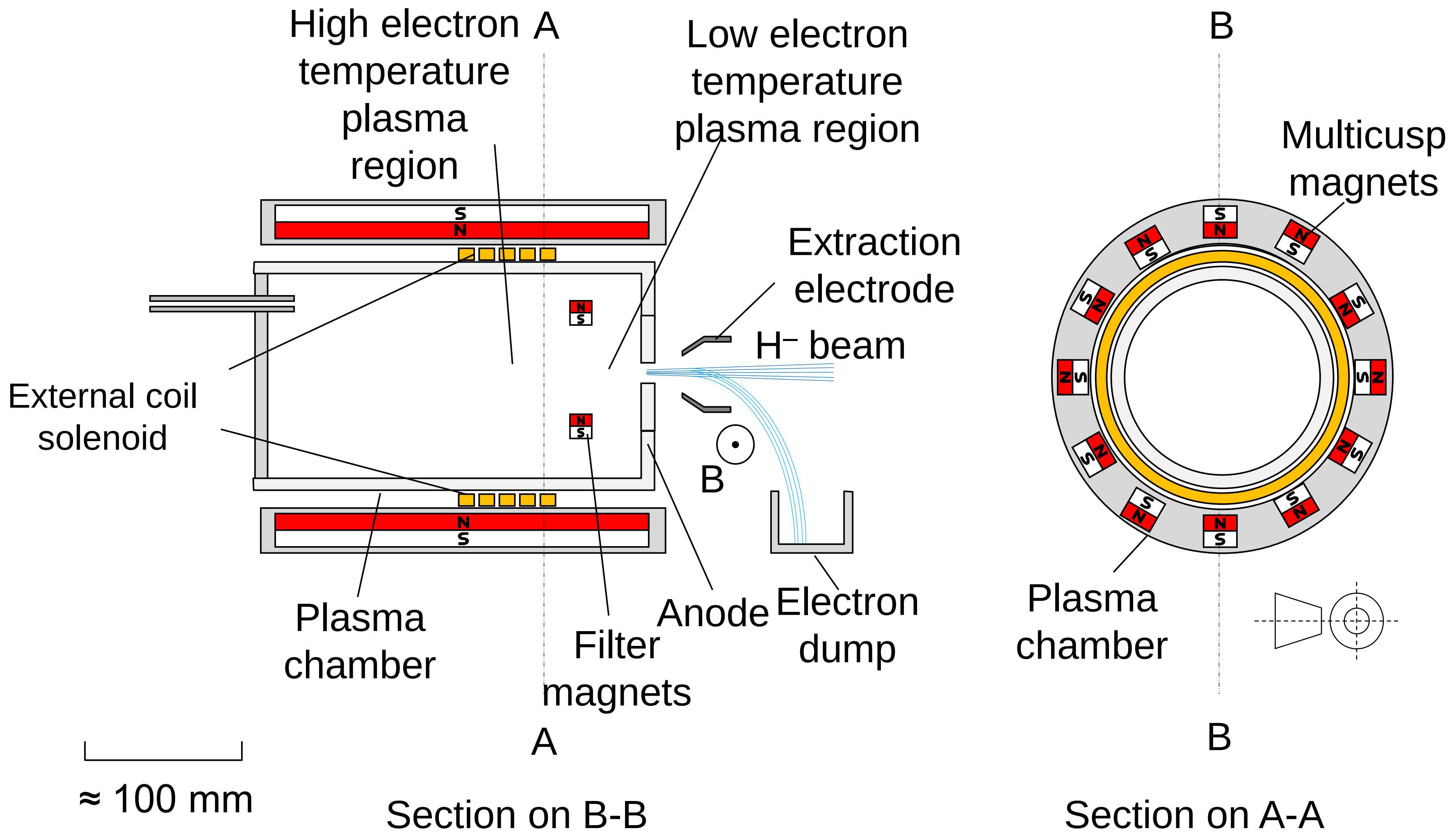



High electron temperature plasma region
A
Low electron temperature plasma region
B
Multicusp magnets
Extraction electrode
H⁻ beam
Cathode filament
B
Plasma chamber
Filter magnets
Anode
Electron dump
Plasma chamber
≈ 100 mm
A
B
S
N
Section on B-B
Section on A-A

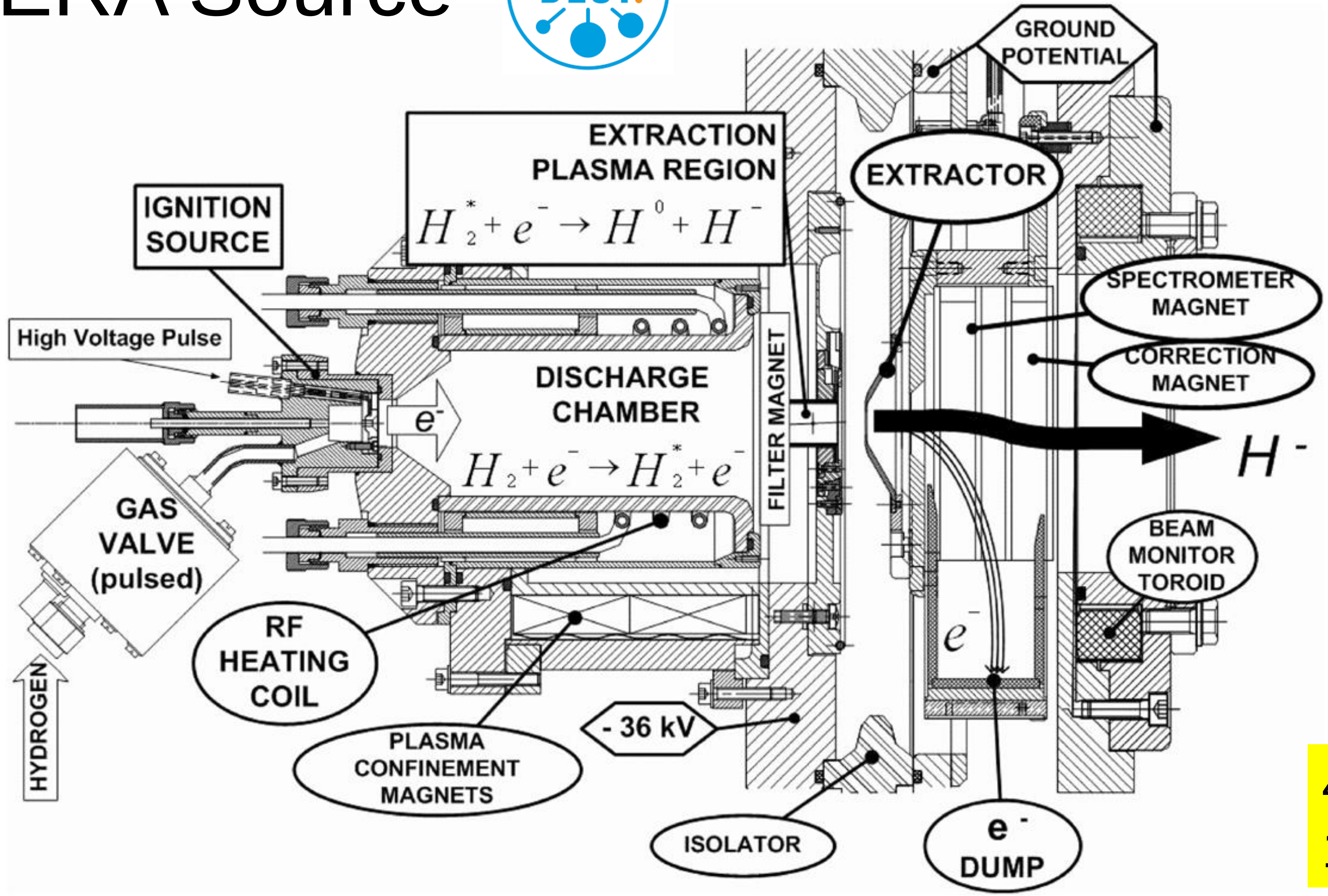
Internal RF Solenoid Coil Volume Source



External RF Solenoid Coil Volume Source



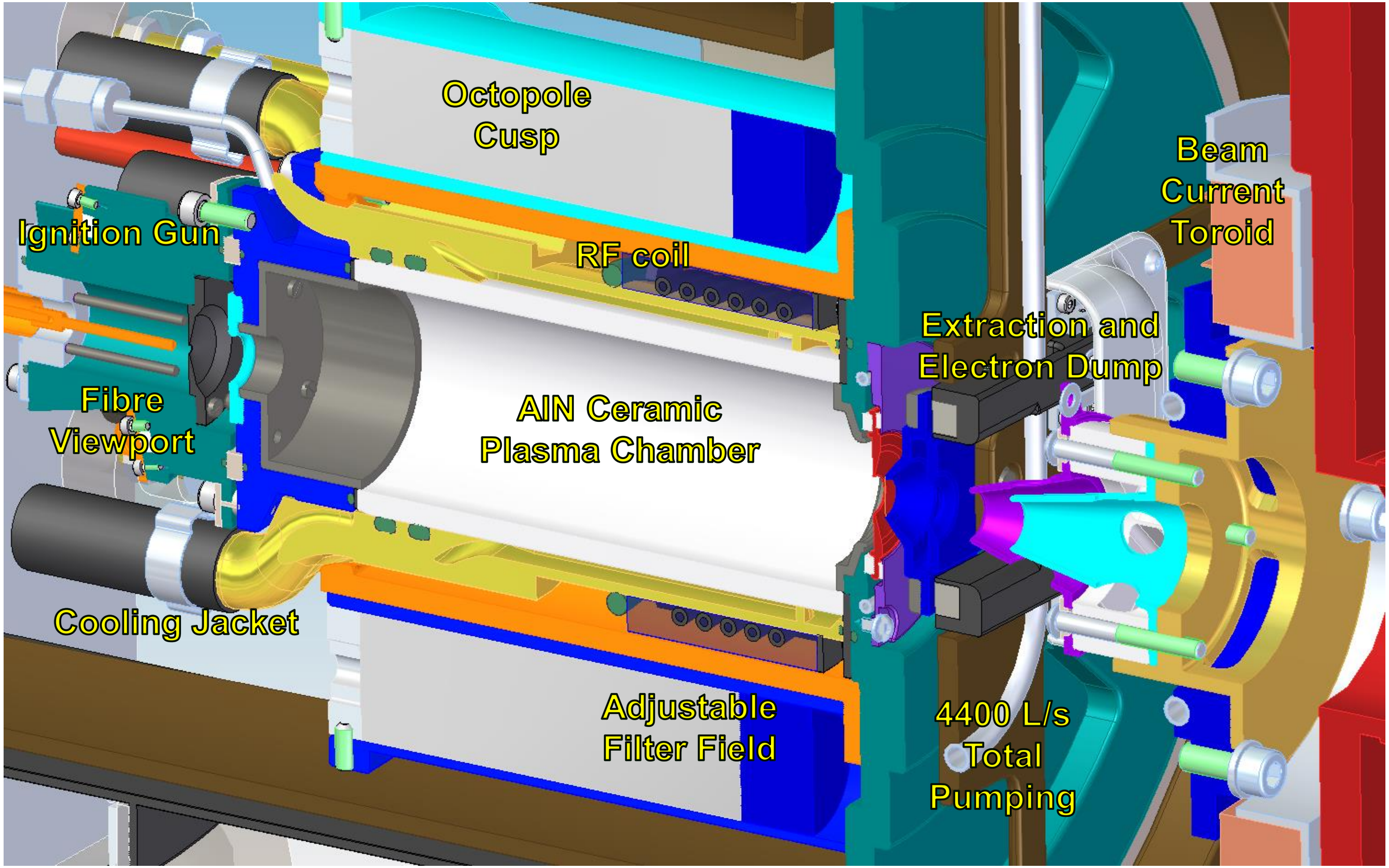
HERA Source



Jens Peters
Late 1990’s

40 mA H^-
150 μs, 3 Hz

ISIS RF H⁻ Ion Source (currently in commissioning)



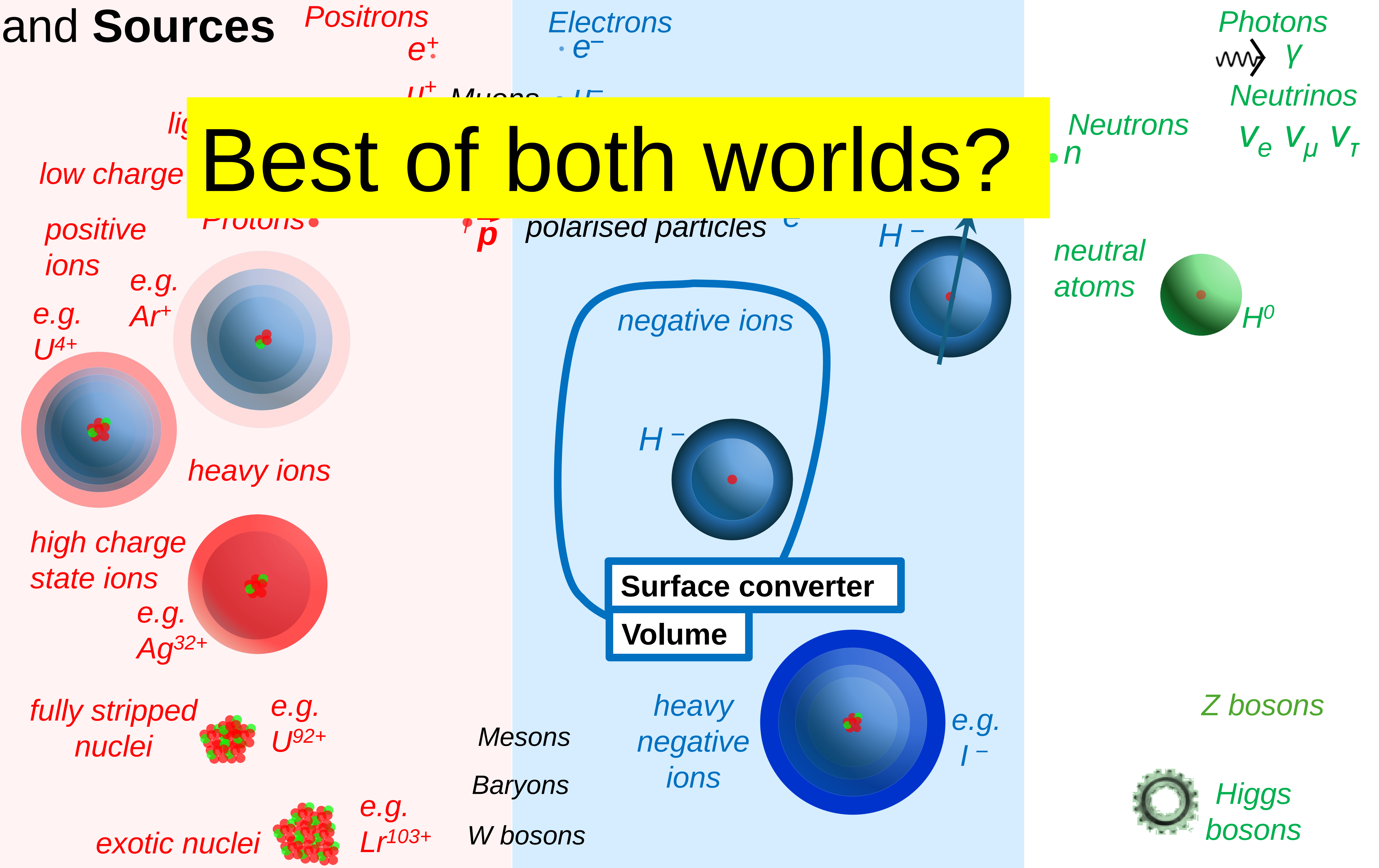
30 mA H^-
250 µs, 50 Hz

Science and Technology Facilities Council

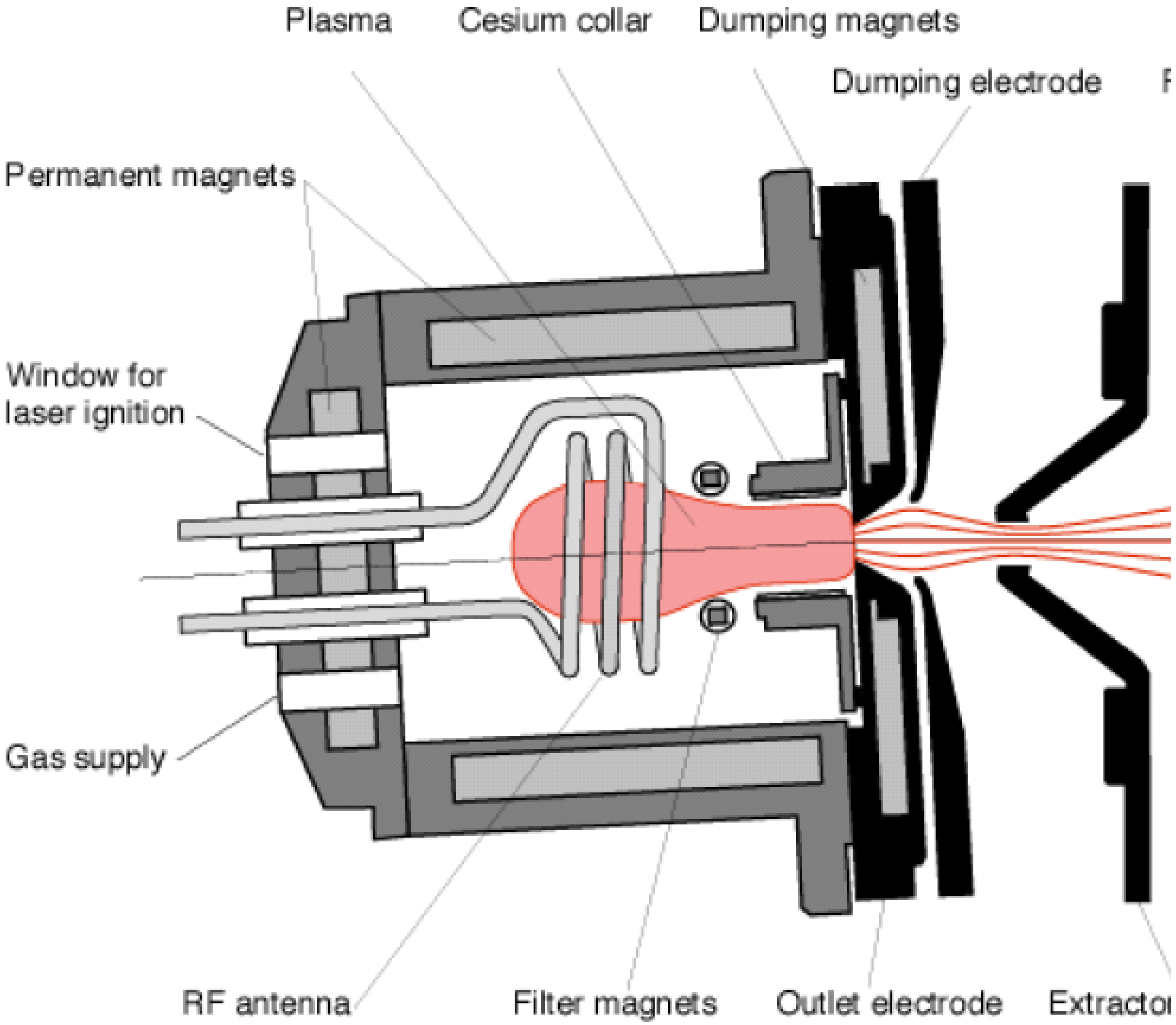
ISIS Neutron and Muon Source

Particles and **Sources**

Best of both worlds?



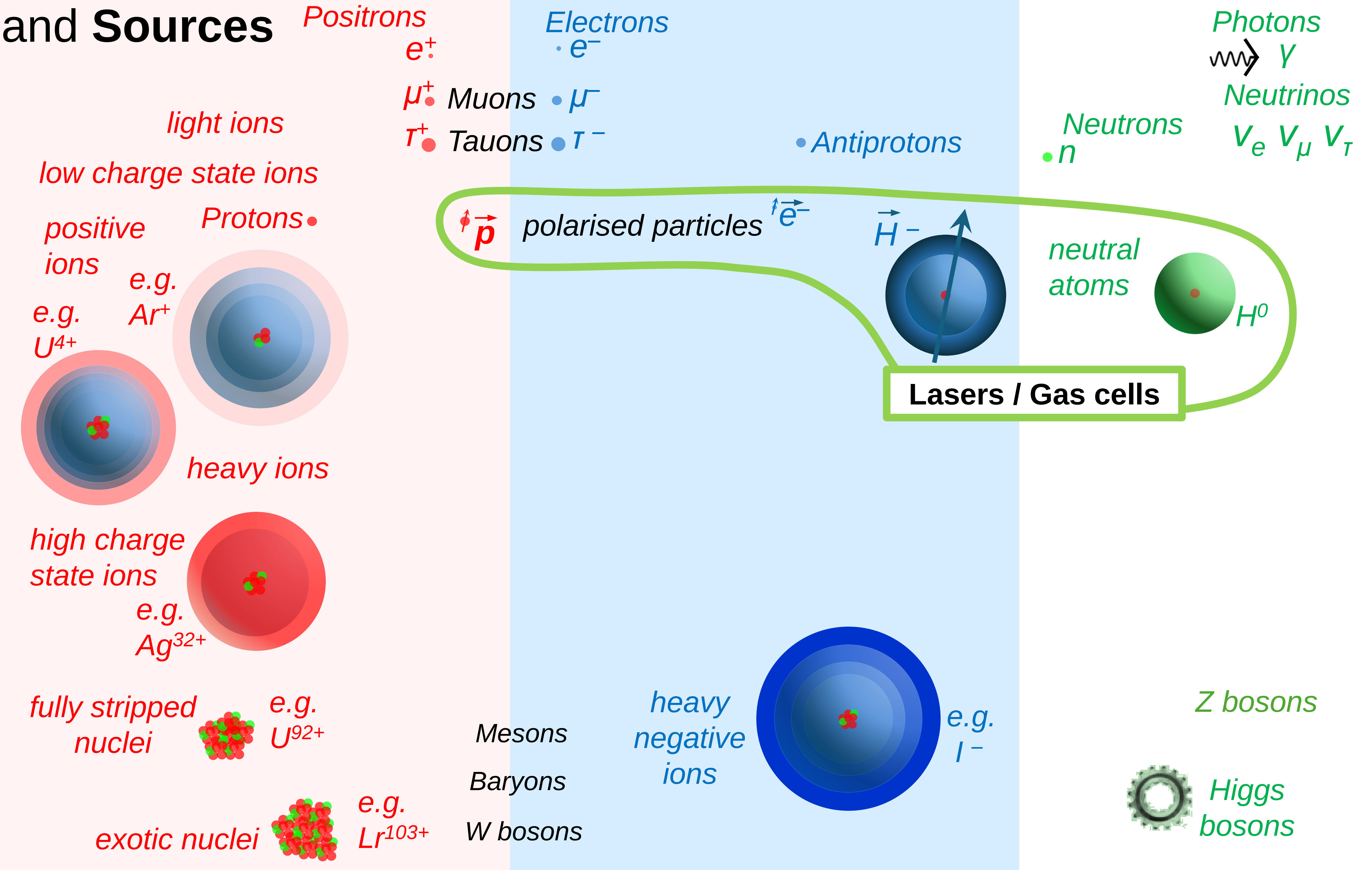
SNS ion source



60 mA H^- 1 ms, 60 Hz

CERN have developed a ceasiated external coil source for LINAC4

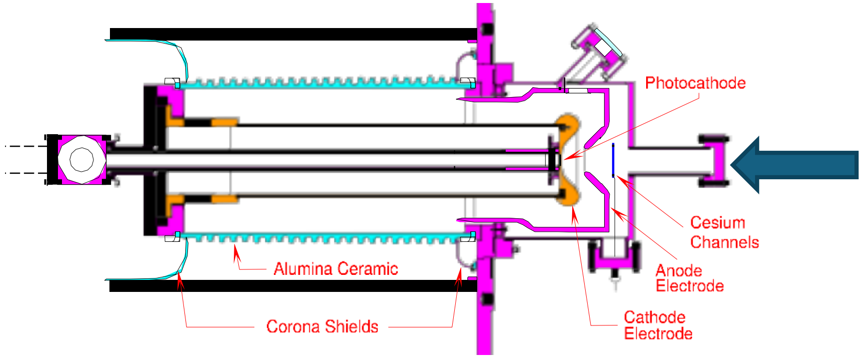
Particles and **Sources**



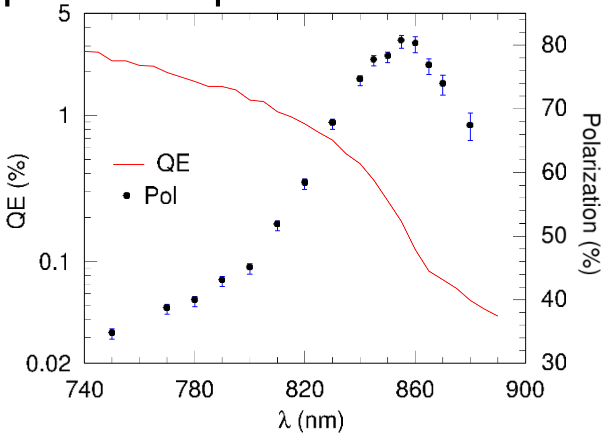
Polarised Electrons

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Strained GaAs photocathode



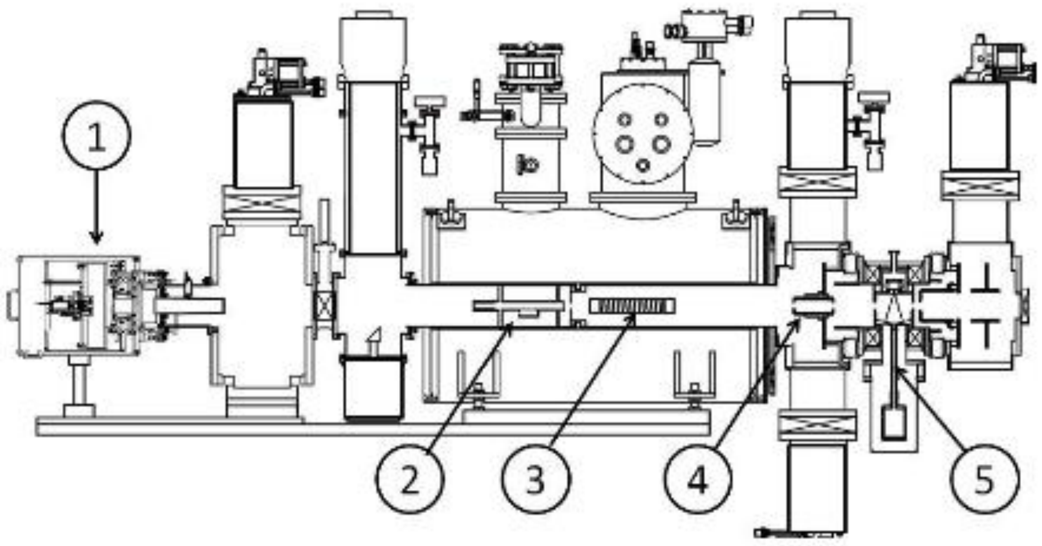
Circularly polarized laser light produces polarised electrons



100 µA polarised e⁻

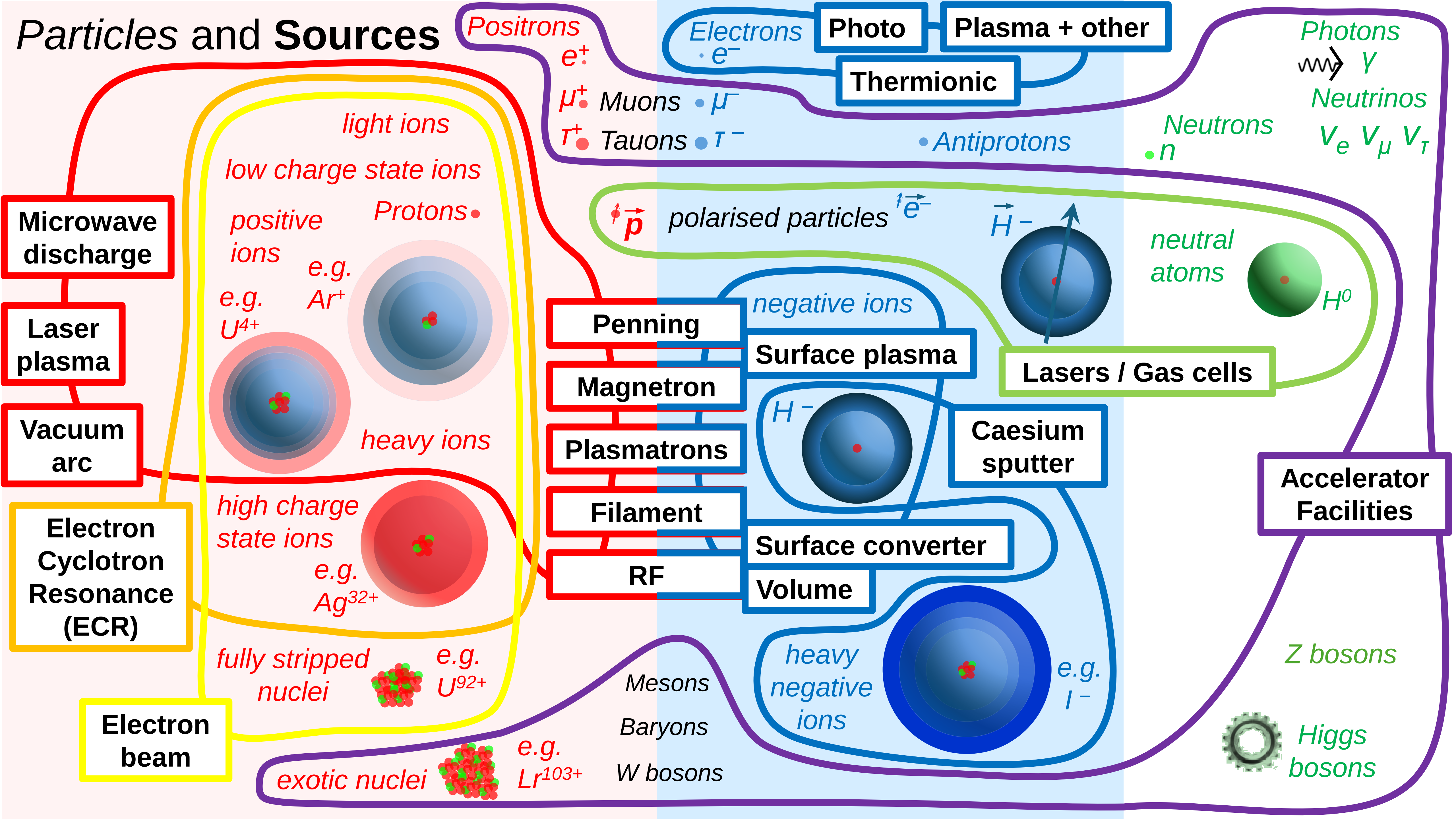
Polarised H⁻

BROOKHAVEN
NATIONAL LABORATORY



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+
μ+ Muons μ−
τ+ Tauons τ−
Electrons
e−
Photo
Plasma + other
Thermionic
Antiprotons
Photons
γ
Neutrinos
νe νμ ντ
Neutrons
n
light ions
low charge state ions
positive ions
Protons
e.g. Ar+
e.g. U4+
heavy ions
high charge state ions
e.g. Ag32+
fully stripped nuclei
e.g. U92+
exotic nuclei
e.g. Lr103+
Mesons
Baryons
W bosons
Microwave discharge
Laser plasma
Vacuum arc
Electron Cyclotron Resonance (ECR)
Electron beam
p
polarised particles
e−
H −
neutral atoms
H0
Lasers / Gas cells
Penning
Magnetron
Plasmatrons
Filament
RF
negative ions
Surface plasma
Caesium sputter
Surface converter
Volume
H −
heavy negative ions
e.g. I −
Accelerator Facilities
Z bosons
Higgs bosons

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

human error

hydrogen

vacuum systems

temperature controllers

high voltage power supplies

compressed air supplies

control systems

mains power

laser systems

material purity

personnel interlocks

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?