Particle Sources

Dan Faircloth

Rutherford Appleton Laboratory

CERN Accelerator School, Introduction to Accelerator Physics
Vysoke-Tatry, Slovakia
Saturday 14th September 2019

Particles

Positrons e^+

Electrons e^-

Photons

Neutrinos ν_e ν_μ ν_τ

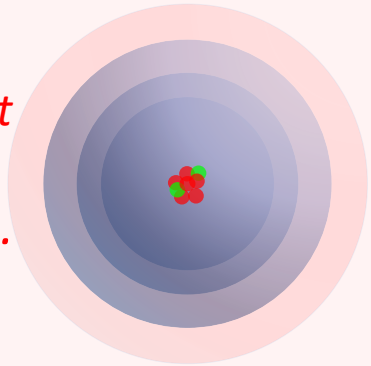
Protons

μ^+ Muons μ^-

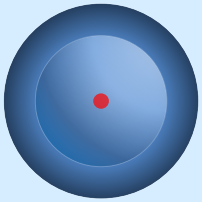
Antiprotons

Neutrons n

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



Negative ions



H^-

Neutral atoms

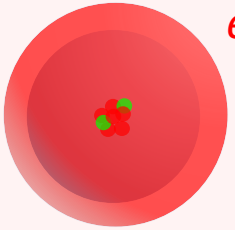
H^0

Positively Charged Particles

Negatively Charged Particles

Neutral Particles

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



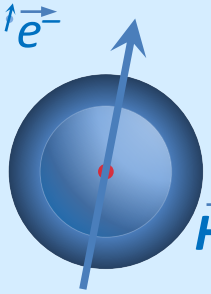
Higgs Bosons

Fully stripped nuclei

e.g. U^{92+}

$\vec{p}$

$\vec{e}^-$



Polarised particles

$\vec{H}^-$

Zoo of curiosities

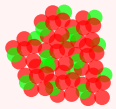
$W + Z$ Bosons

Tauons

Mesons

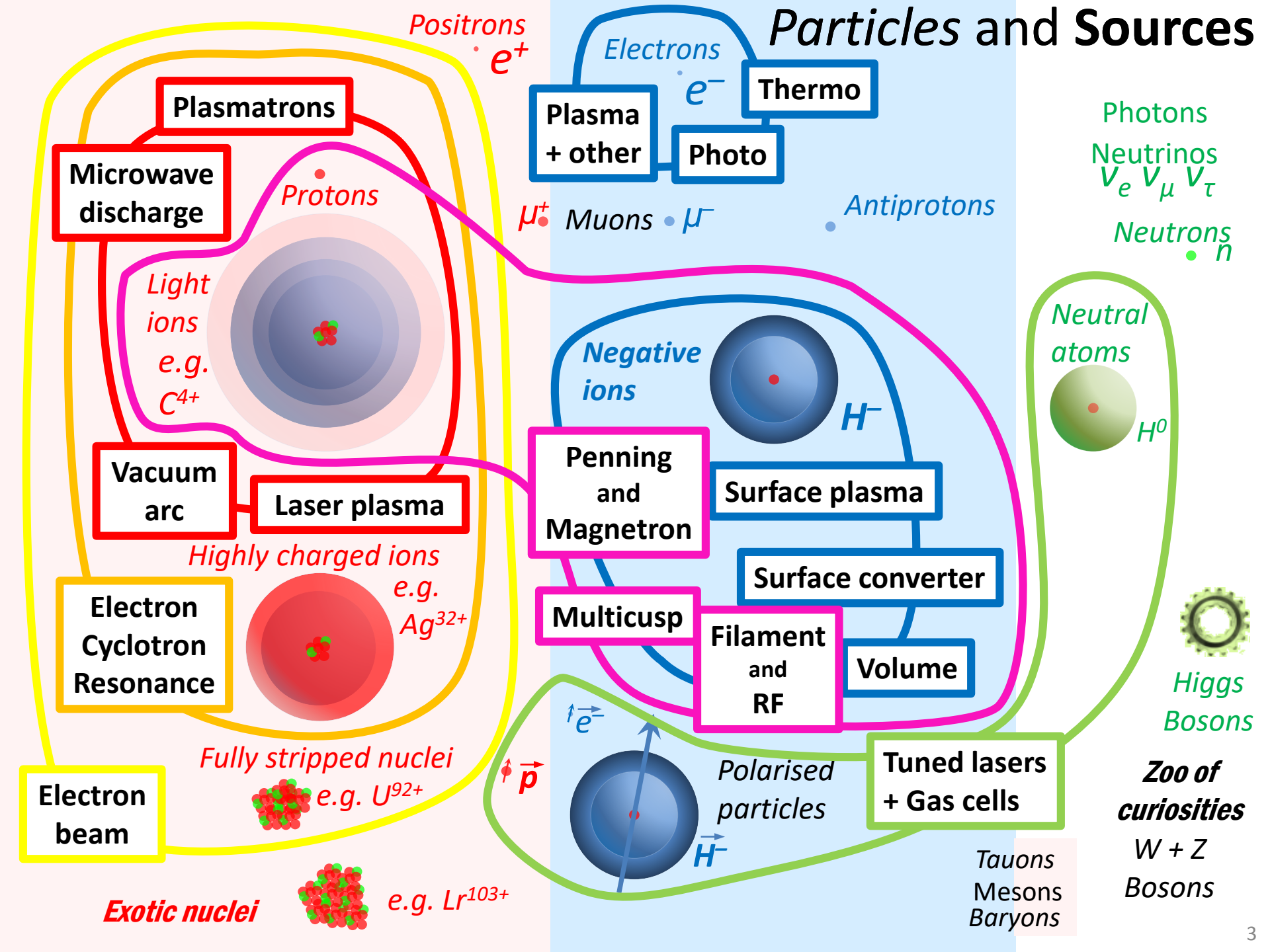
Baryons

Exotic nuclei



e.g. Lr^{103+}

Particles and **Sources**



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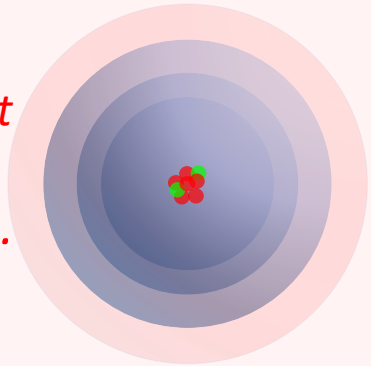
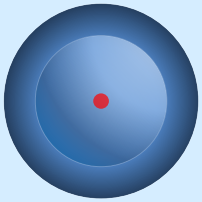


Negative ions



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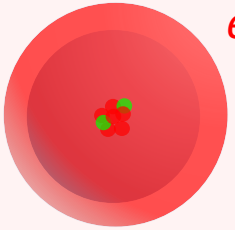
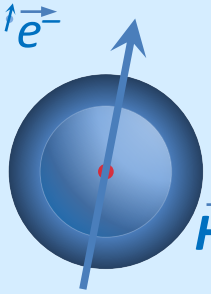


Higgs Bosons

$\vec{e}$



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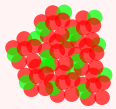
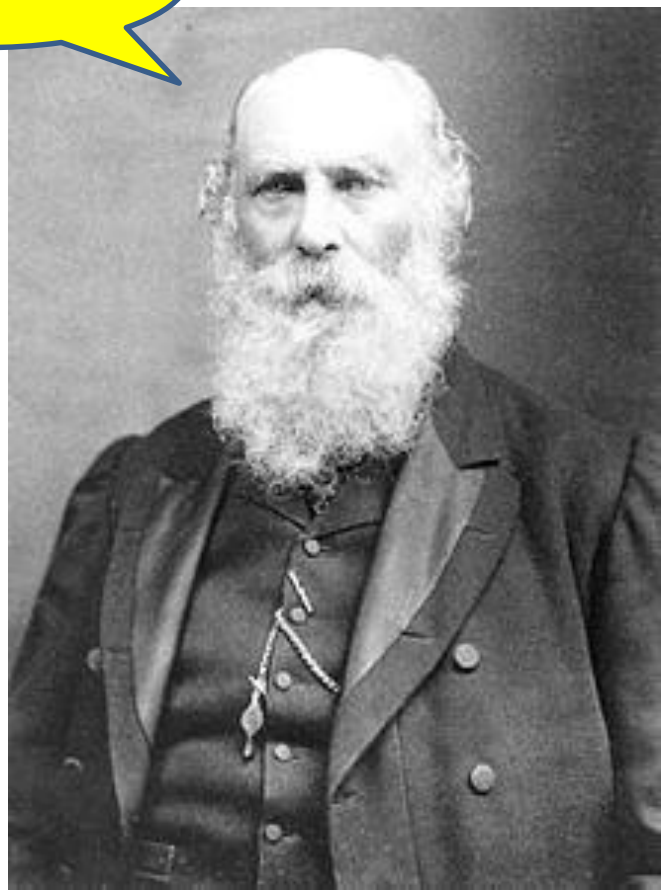


e.g. Lr^{103+}

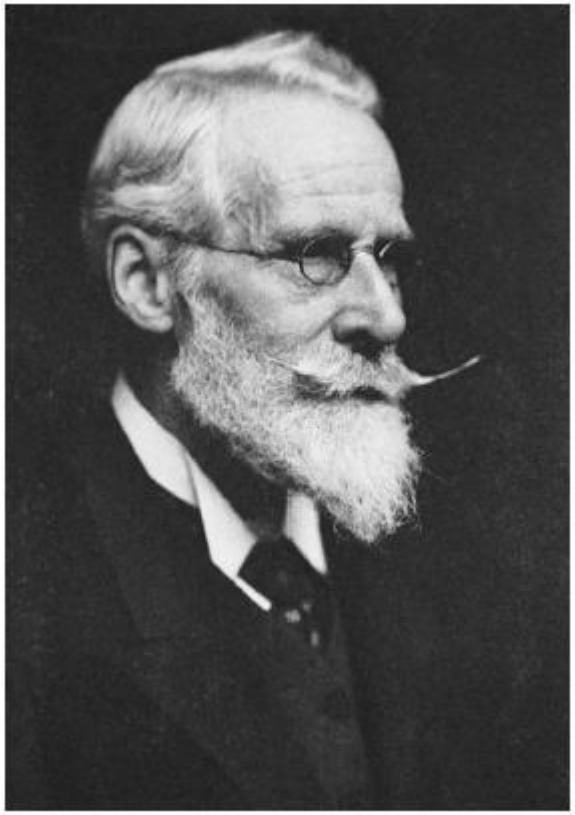
The Electron!



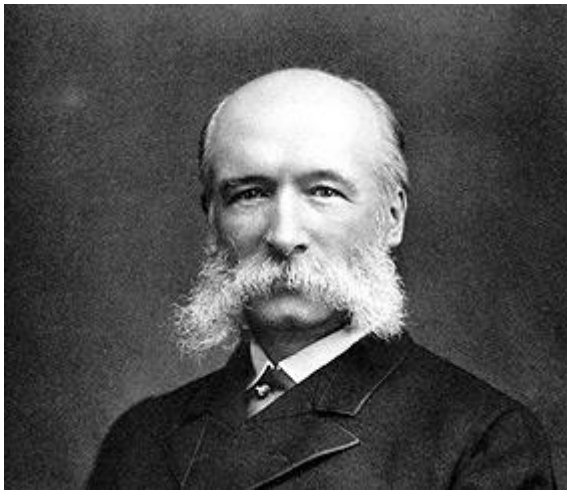
George Johnstone Stoney
1894

J. J. Thomson
1897

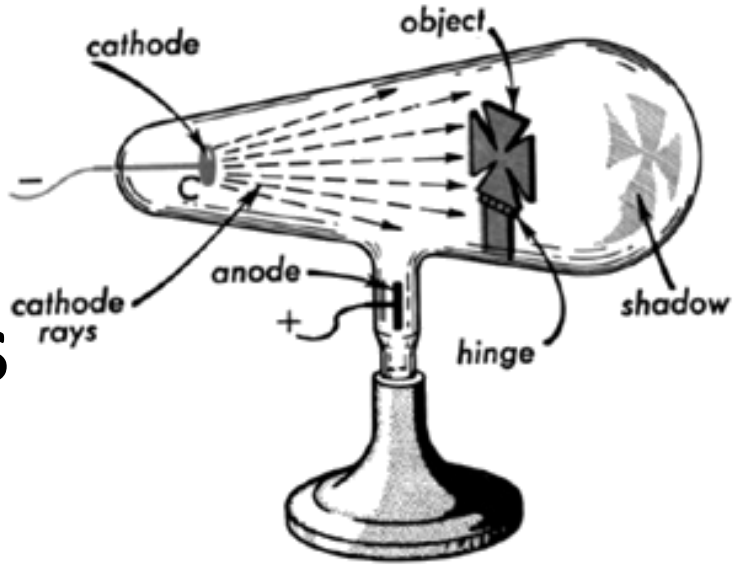
Early 1870's

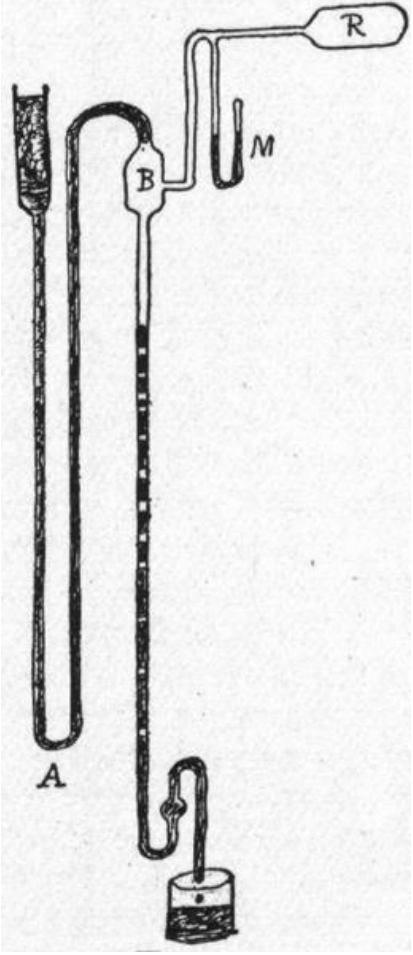


William Crookes



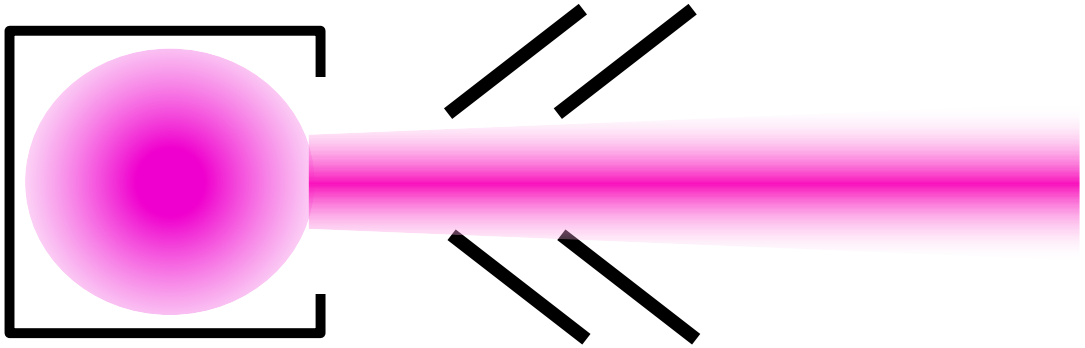
Hermann Sprengel





Improved mercury pump 10^{-5} mBar

Particle sources/guns generally consist of:



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

Particles and **Sources**

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Electrons e^- **Thermionic**

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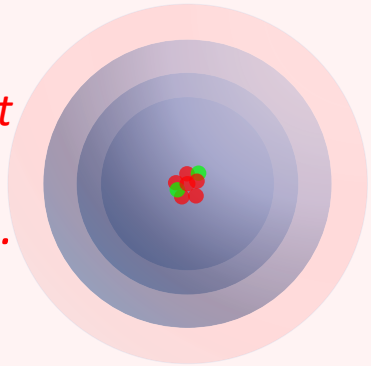
μ^+ Muons μ^-

Antiprotons

Neutrons $\bar{n}$

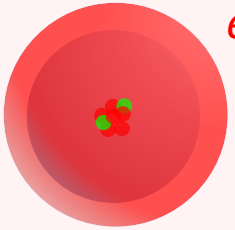
Neutral particles

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



Negative ions

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



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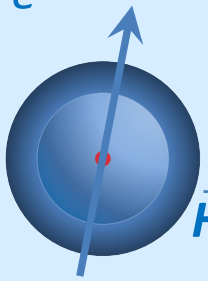

Polarised particles

Zoo of curiosities

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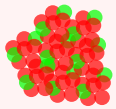
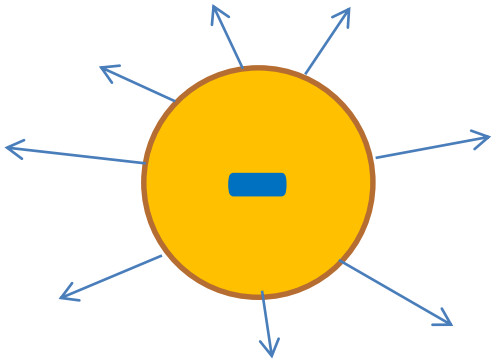
Exotic nuclei



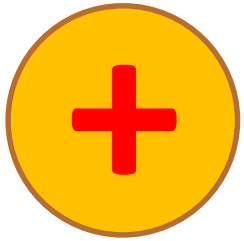
e.g. Lr^{103+}

Fredrick Guthrie

British scientific writer and professor



A red hot metal ball looses negative charge...

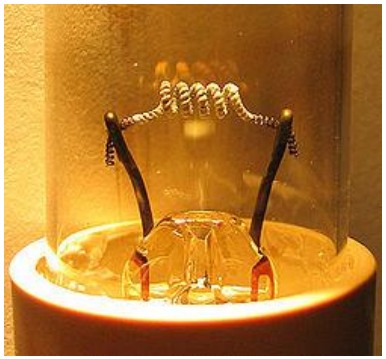


...whereas a positively charged one keeps its charge

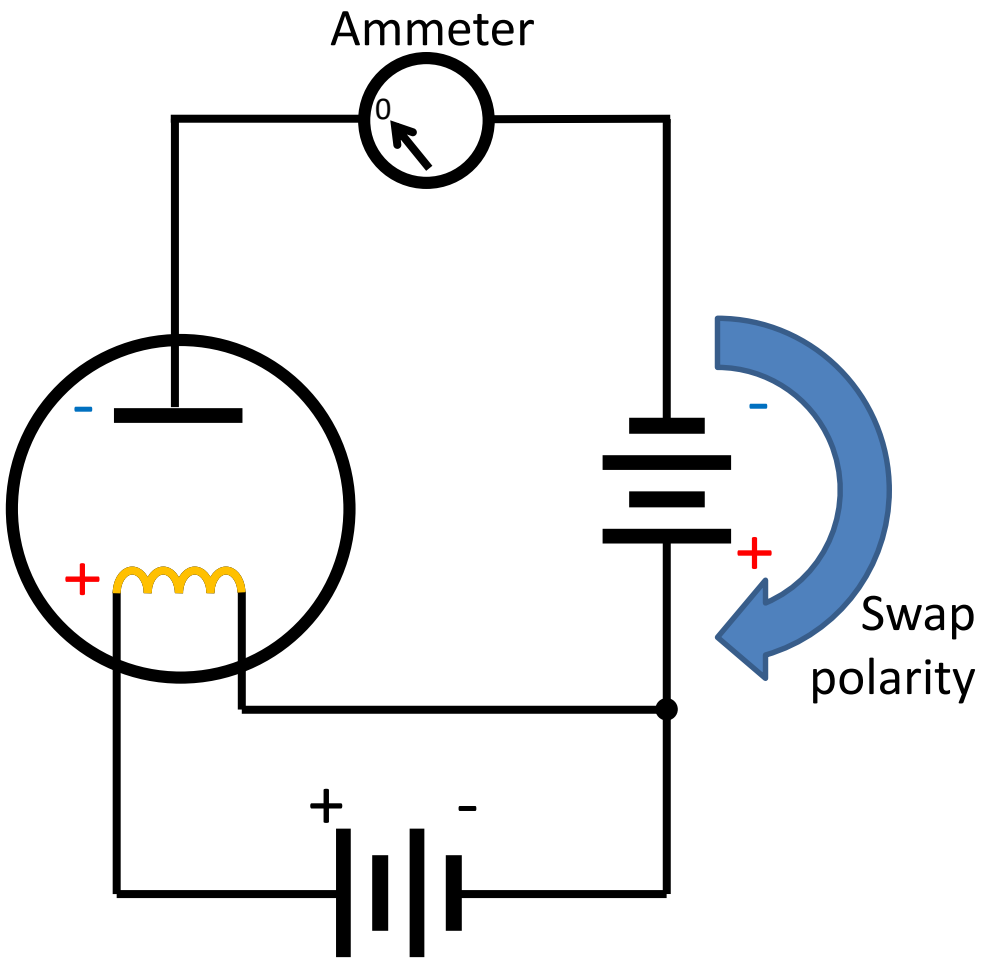
Elements of Heat in 1868

First experimental observation of thermionic emission

Thermionic Emission

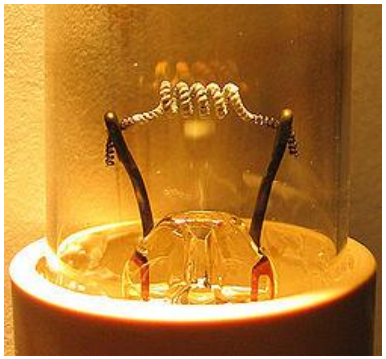


1880 Thomas Edison



The “Edison effect”

Thermionic Emission



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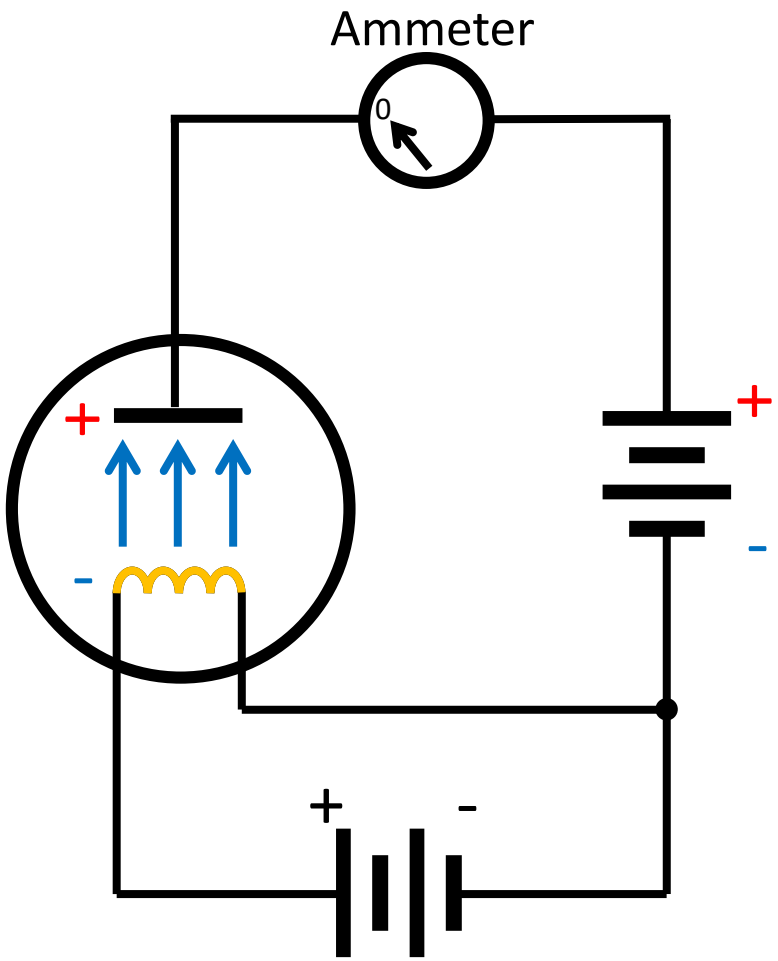


The “Edison effect”

Thermionic Emission

Corpuscles

J. J. Thomson
1897

Cambridge University

1901 Owen Richardson

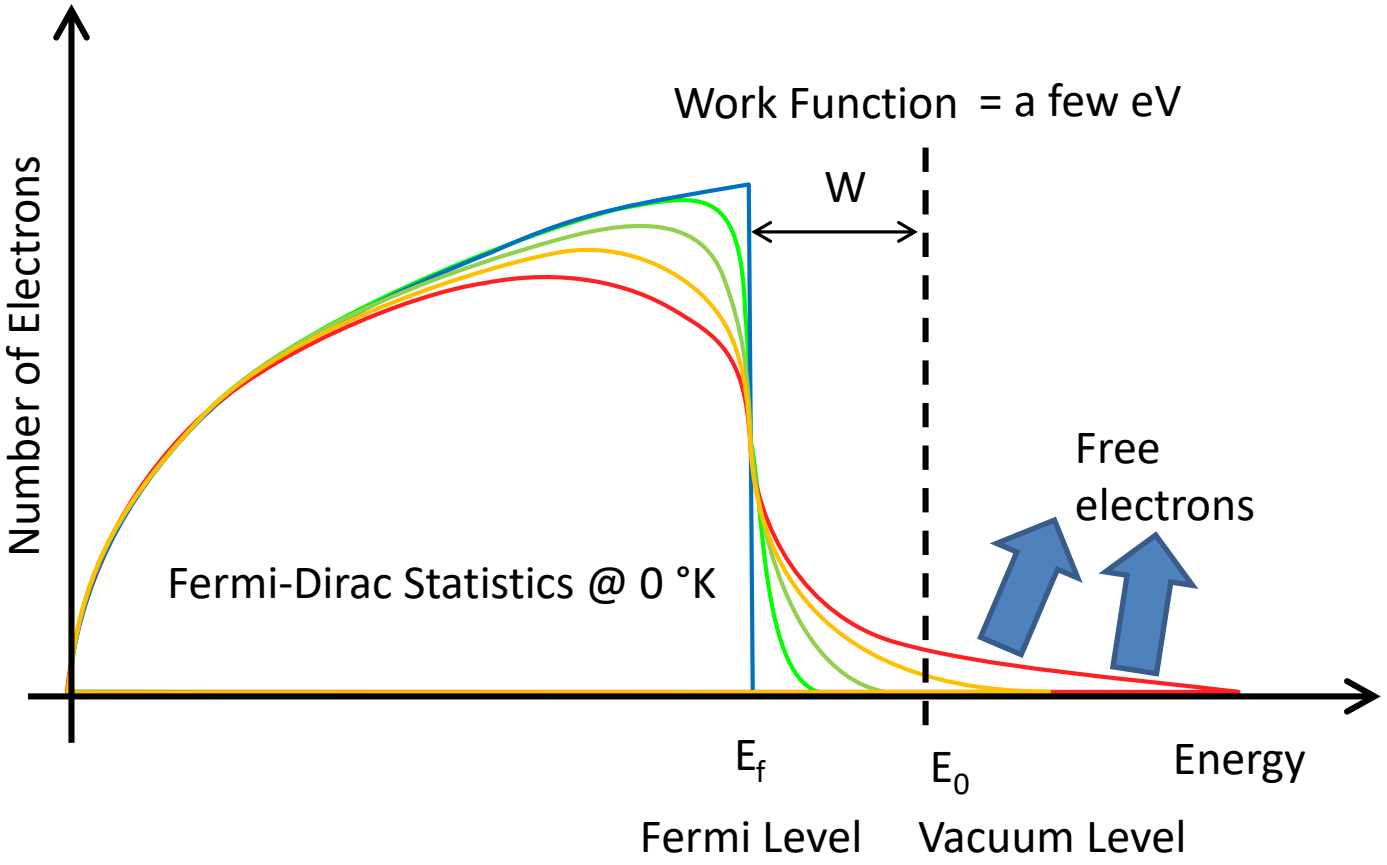
$$J = A_G T^2 e^{\frac{-W}{kT}}$$

Richardson's Law

Same form as the Arrhenius equation

Current increases exponentially with temperature

Thermionic Emission



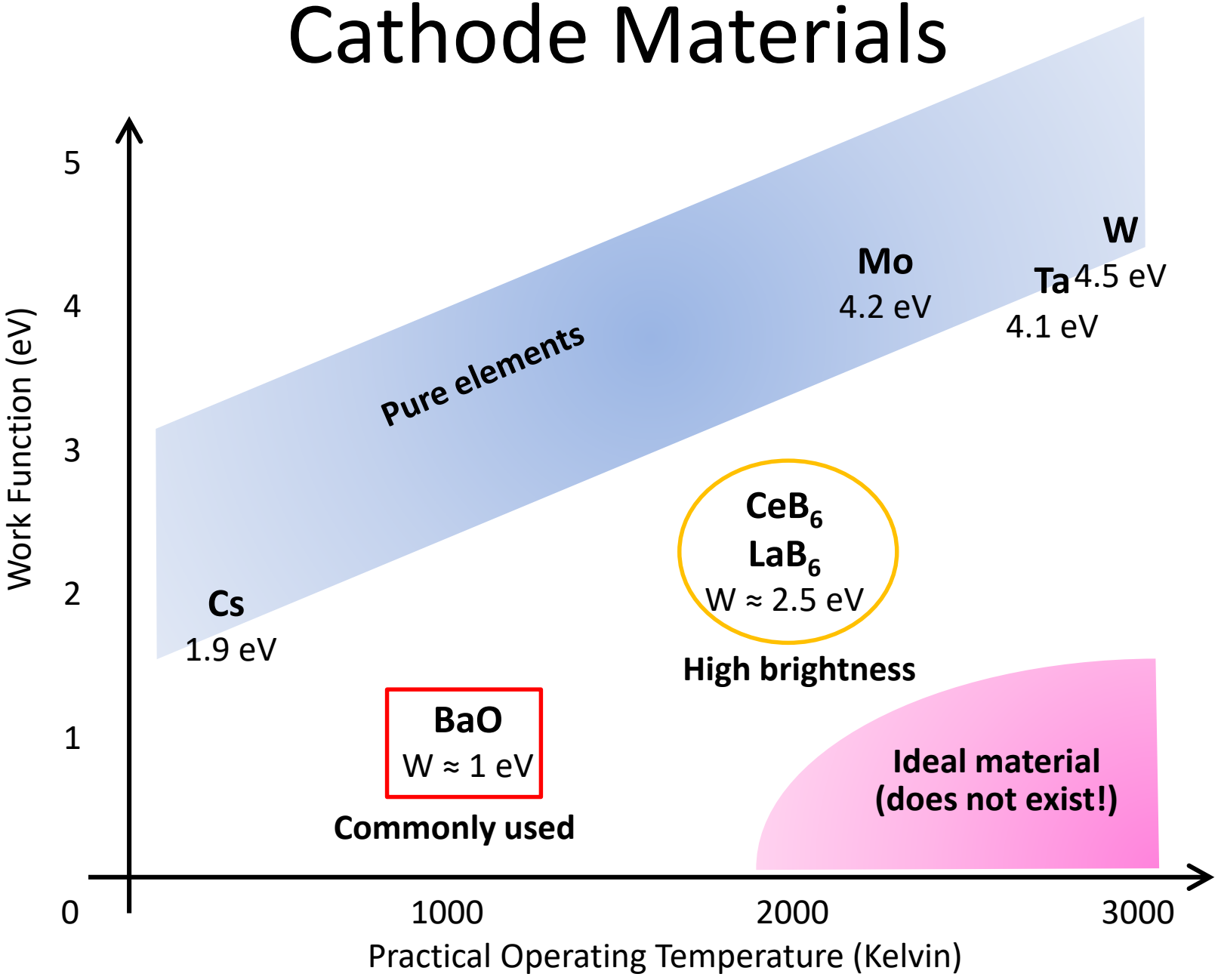
$$J = A_G T^2 e^{\frac{-W}{kT}}$$

For a good electron emitter you need:

Lowest possible work function

Highest possible temperature

Cathode Materials

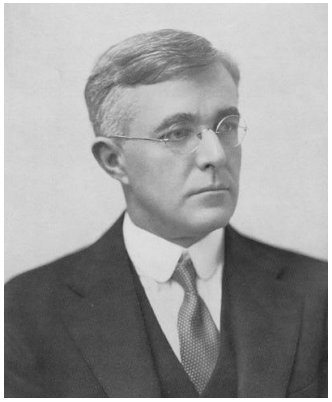


Child-Langmuir Law

(Space charge limited extraction)

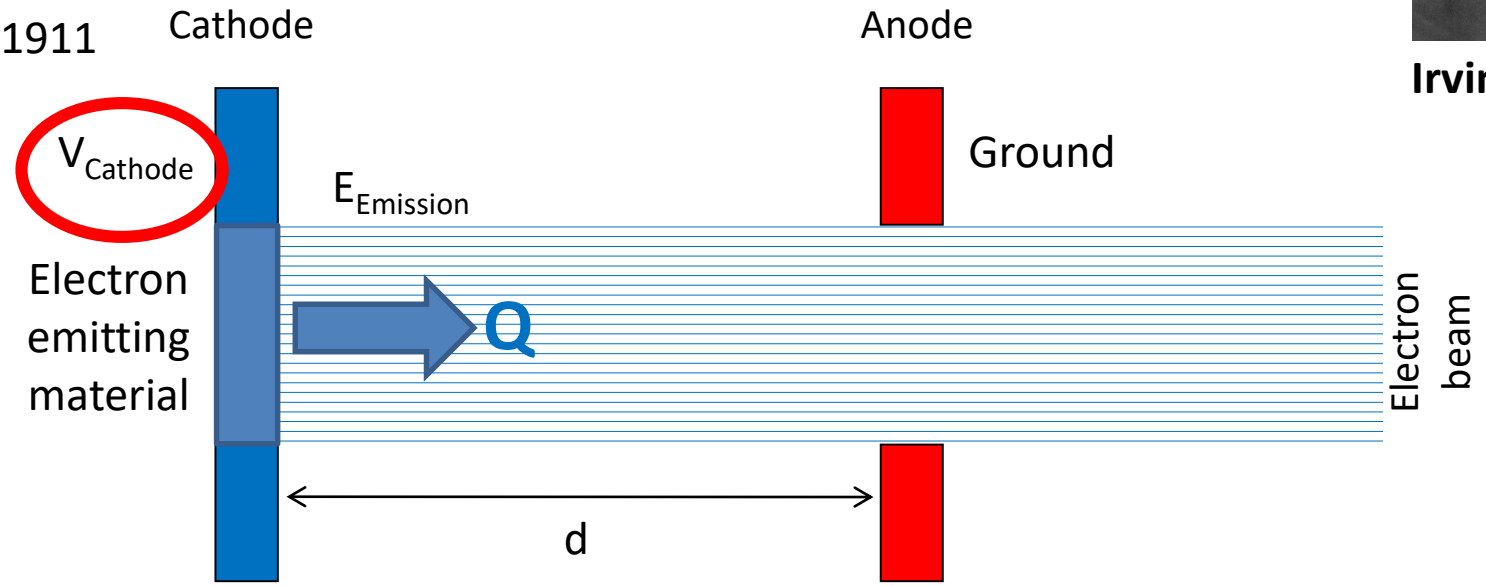
C.D Child

1911



Irving Langmuir

1913

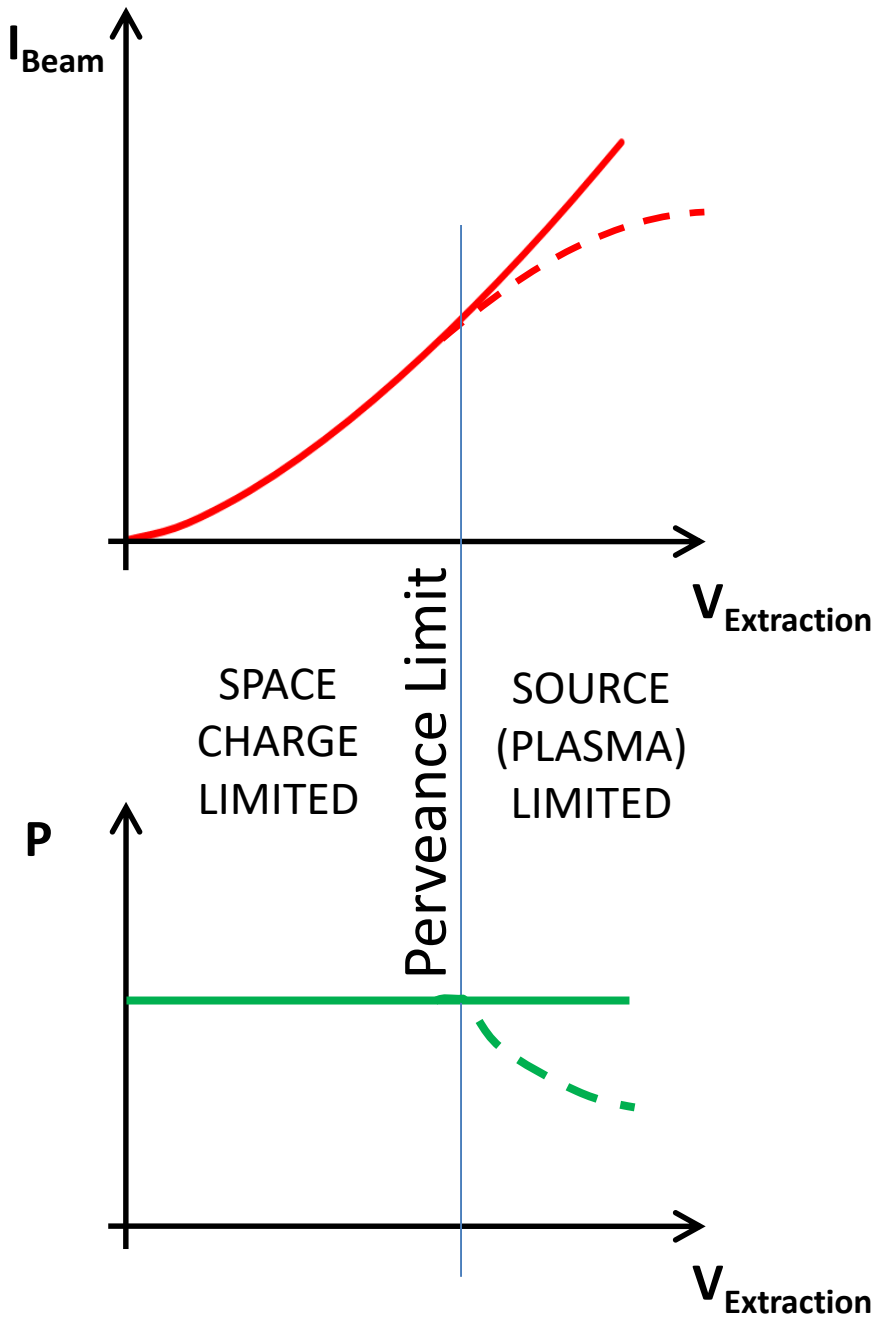


$$j = \frac{\frac{4}{9}\varepsilon_0\sqrt{\frac{2e}{m_e}}V^{\frac{3}{2}}}{d^2}$$

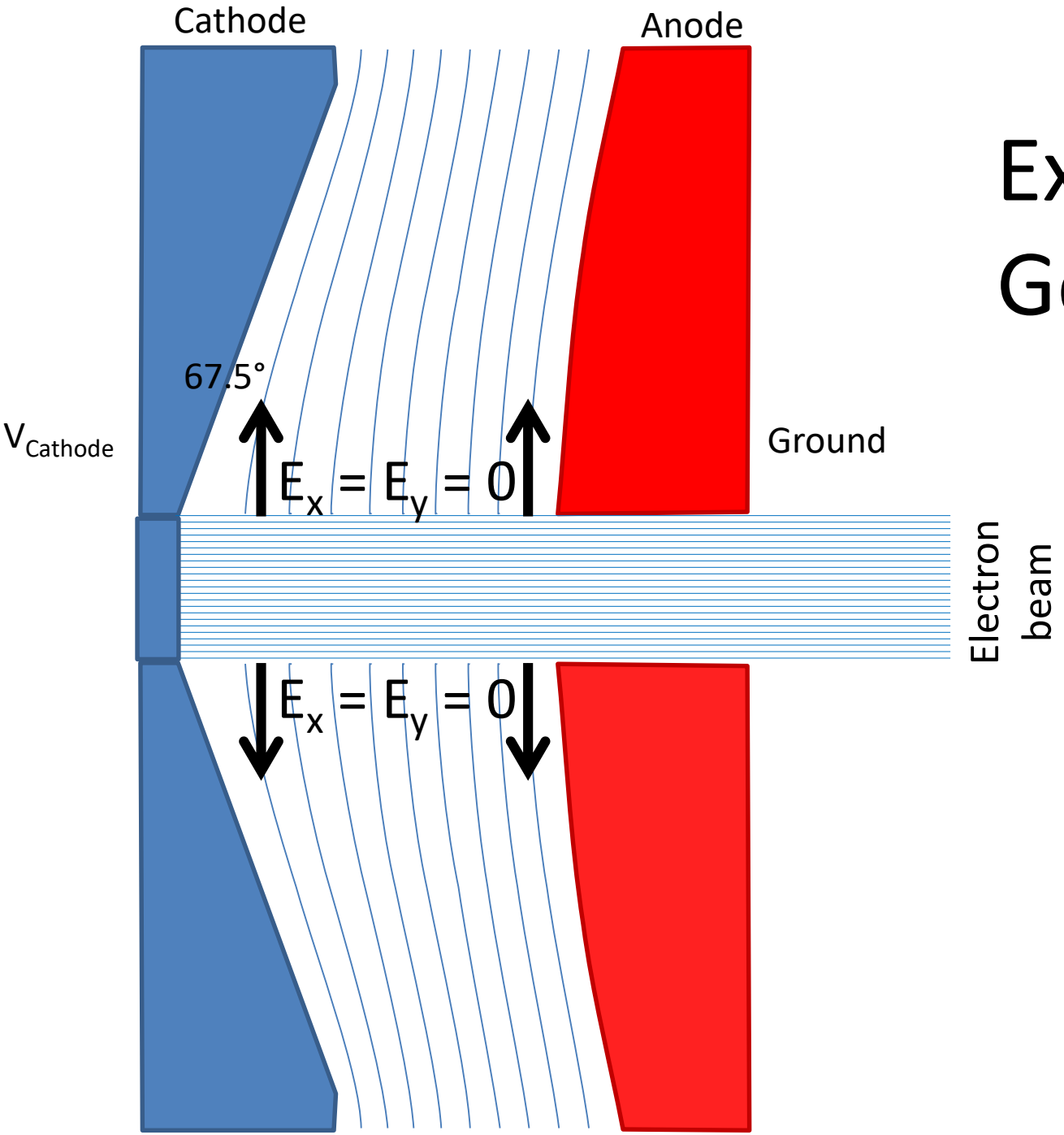
$$I \propto V^{\frac{3}{2}}$$

Perveance

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

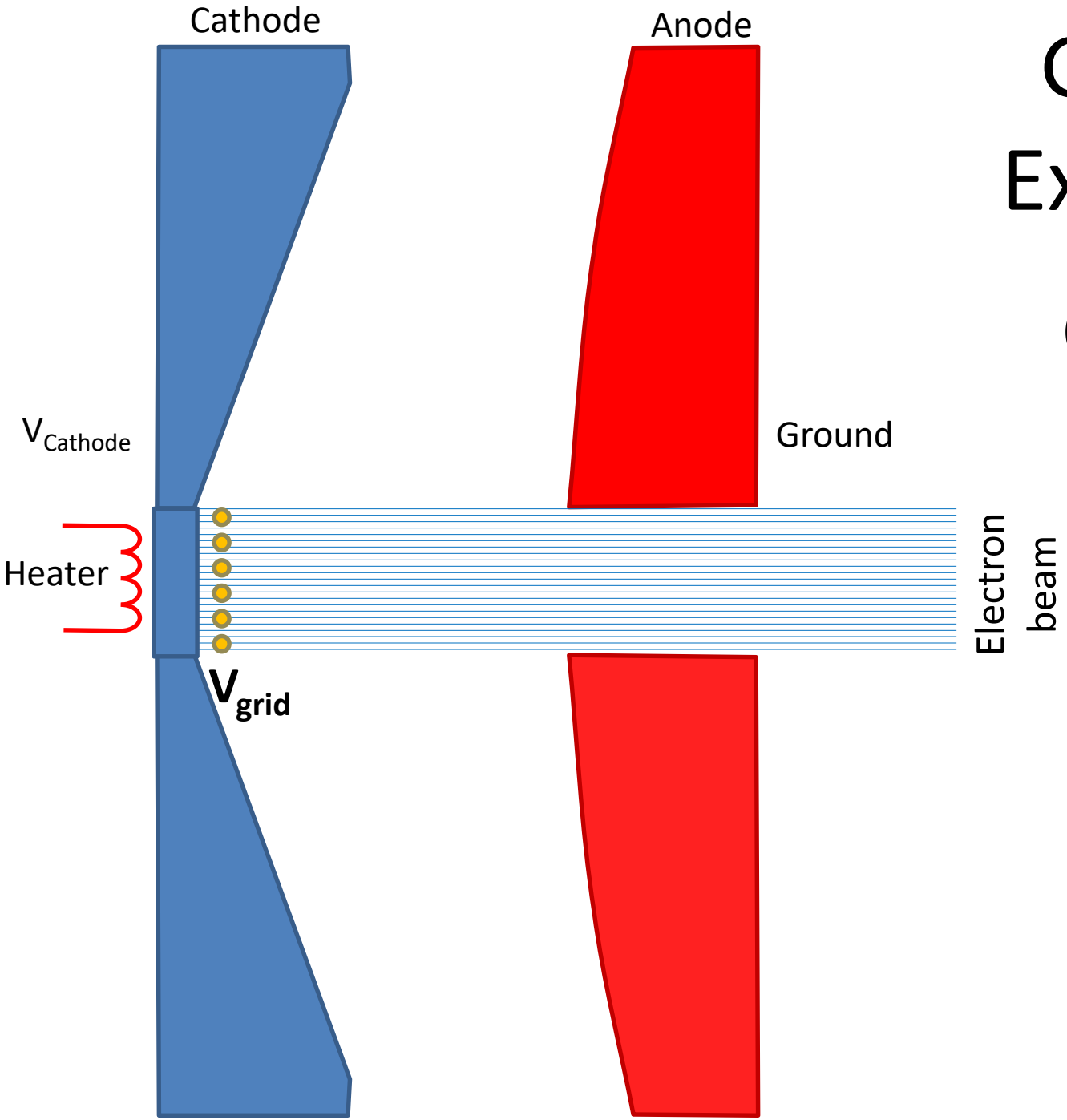


Pierce Extraction Geometry



Gridded Extraction

(A triode amplifier)



Communications & Power Industries

Eimac®

YU 171

Thermionic dispenser cathode with integrated heater and grid

Sinter of W and BaO

1cm^2
12 W heater

diamond

PAUL SCHERRER INSTITUT

PSI

Swiss Light Source

90 kV triode gun with Pierce geometry

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

Lifetime =
several thousand hours

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Photo

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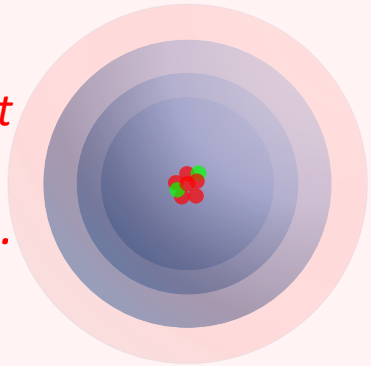

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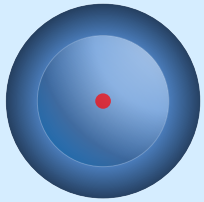

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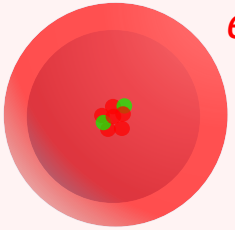

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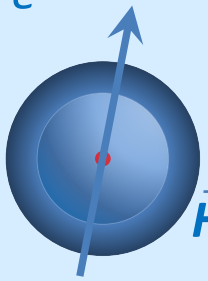

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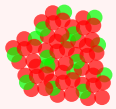
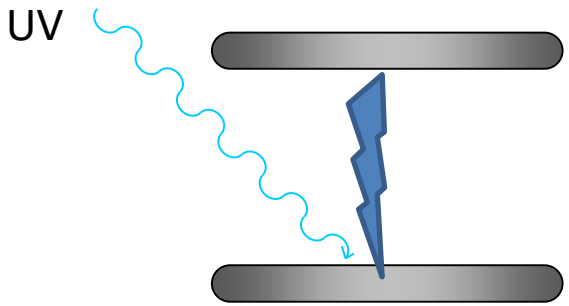


e.g. Lr^{103+}

Photo Emission

First observed by Heinrich Hertz in 1887



Theoretical explanation by Einstein in 1905

Photo electric emission

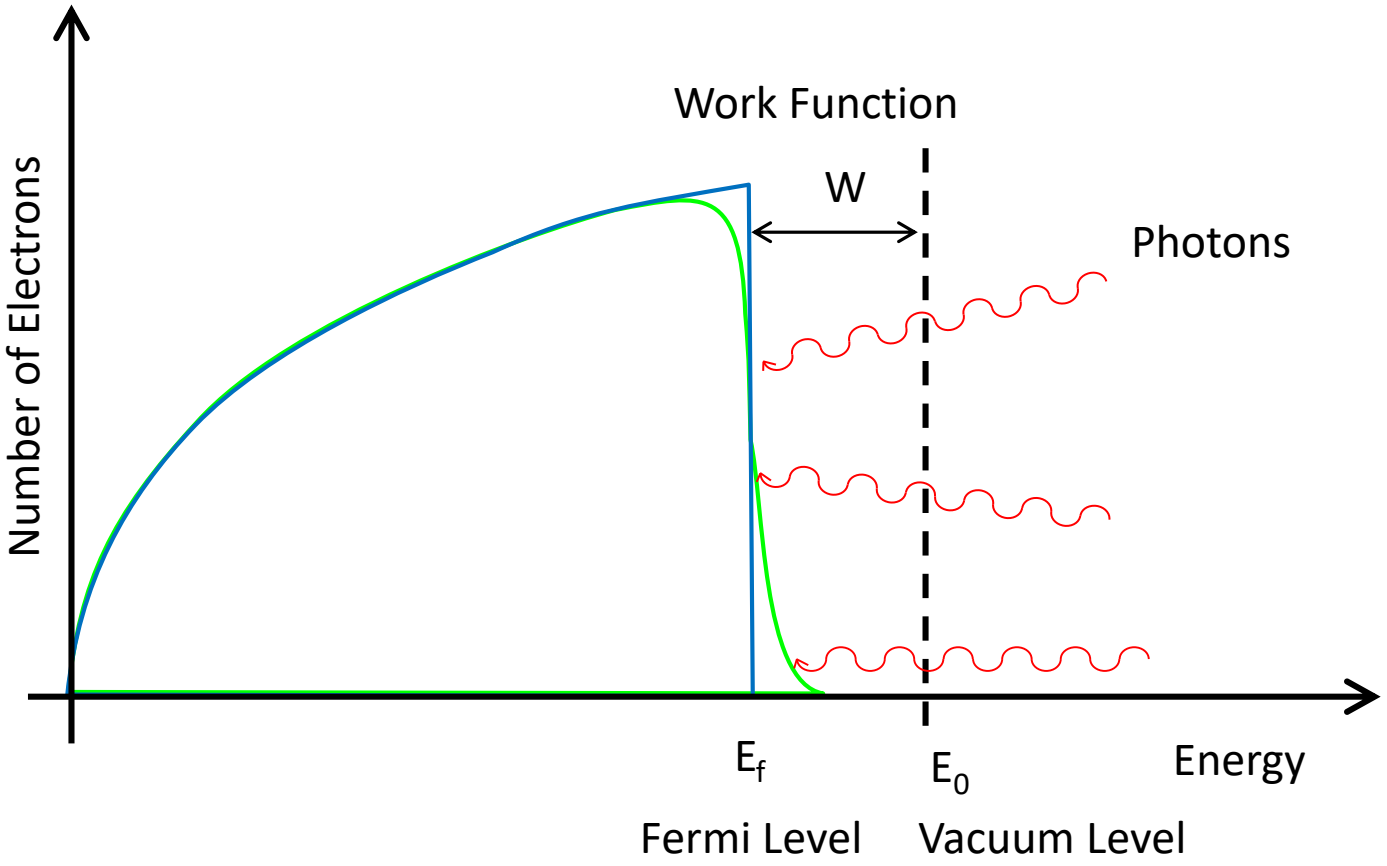
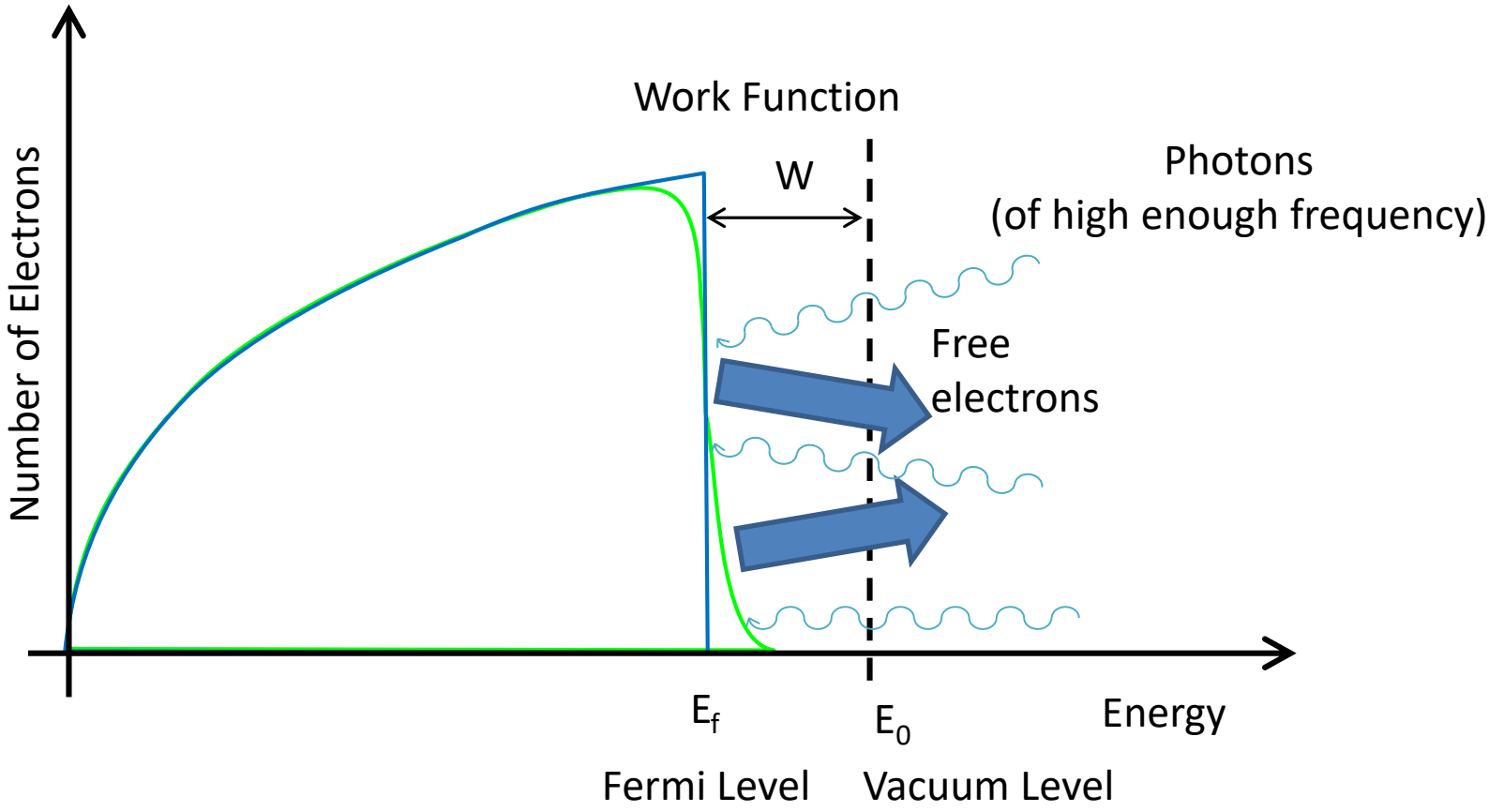
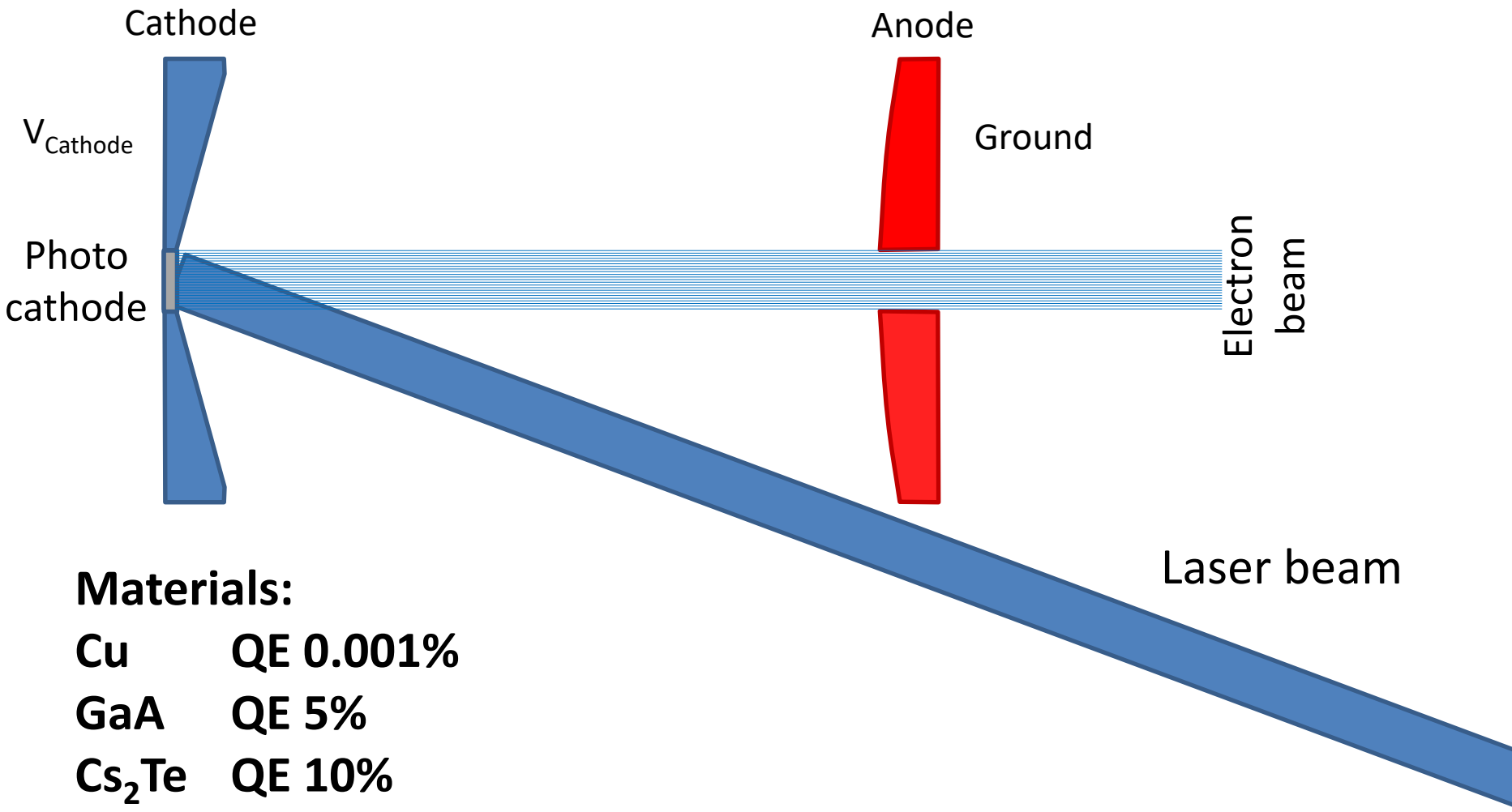


Photo electric emission



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

Photo Emission Gun



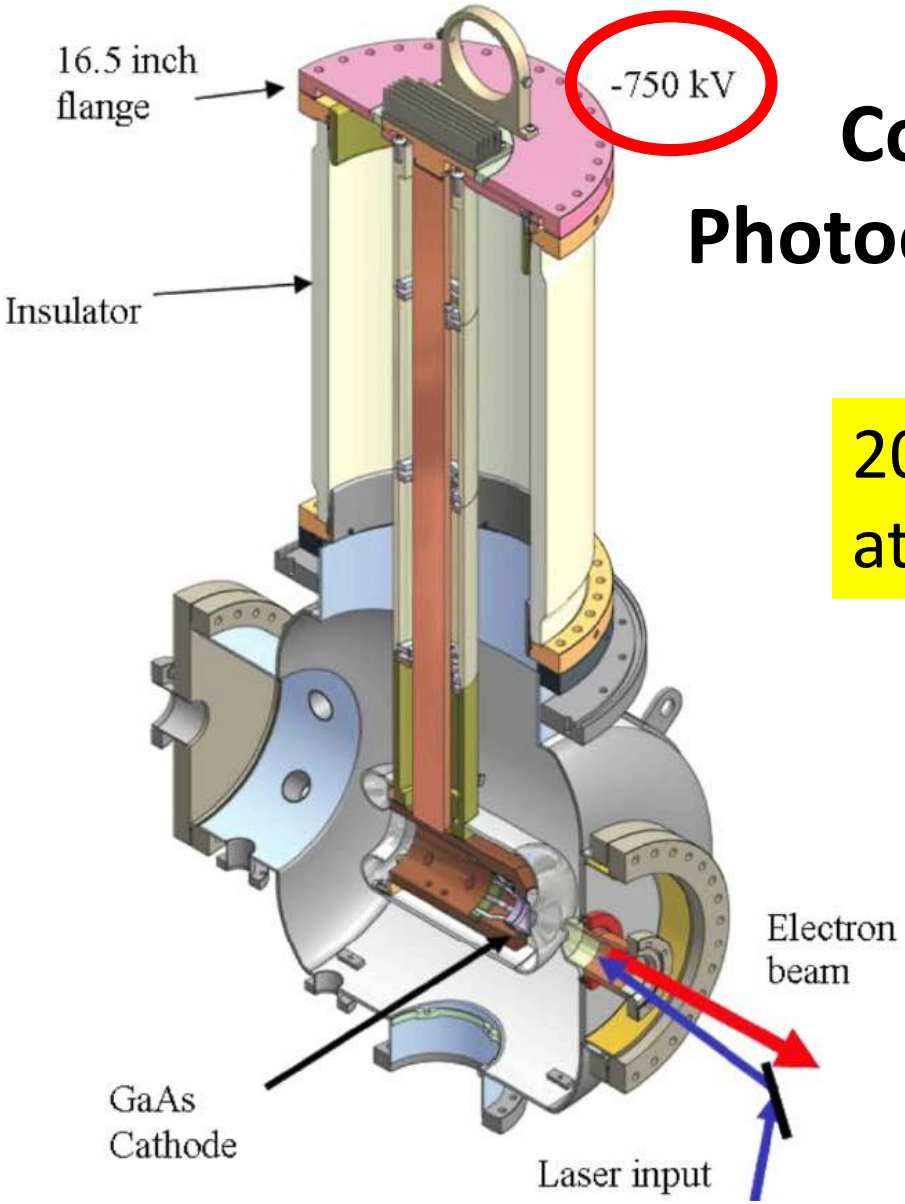
Materials:

Cu QE 0.001%

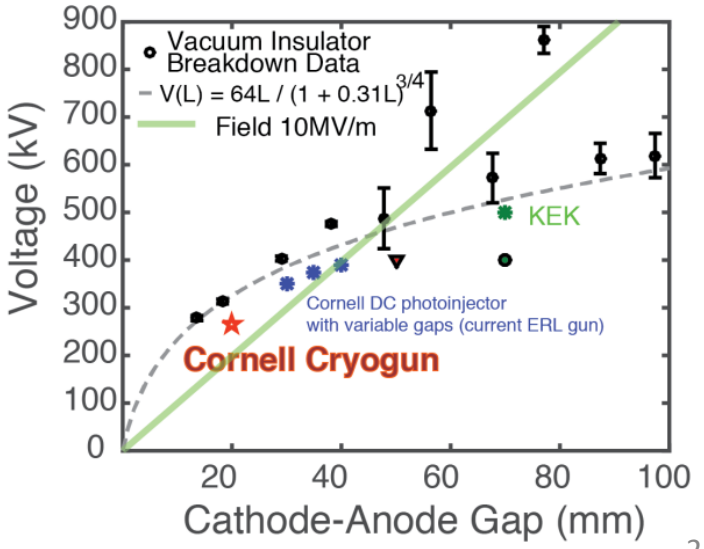
GaA QE 5%

Cs_2Te QE 10%

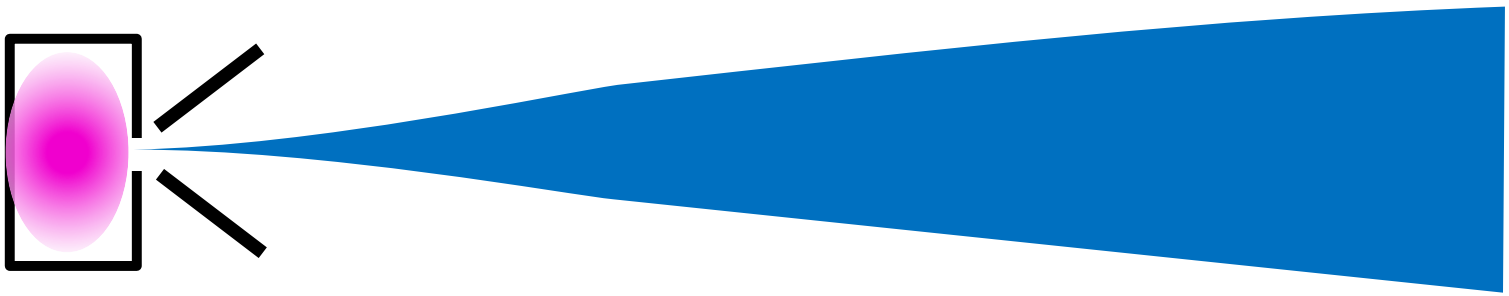
Cornell DC Photoemission gun

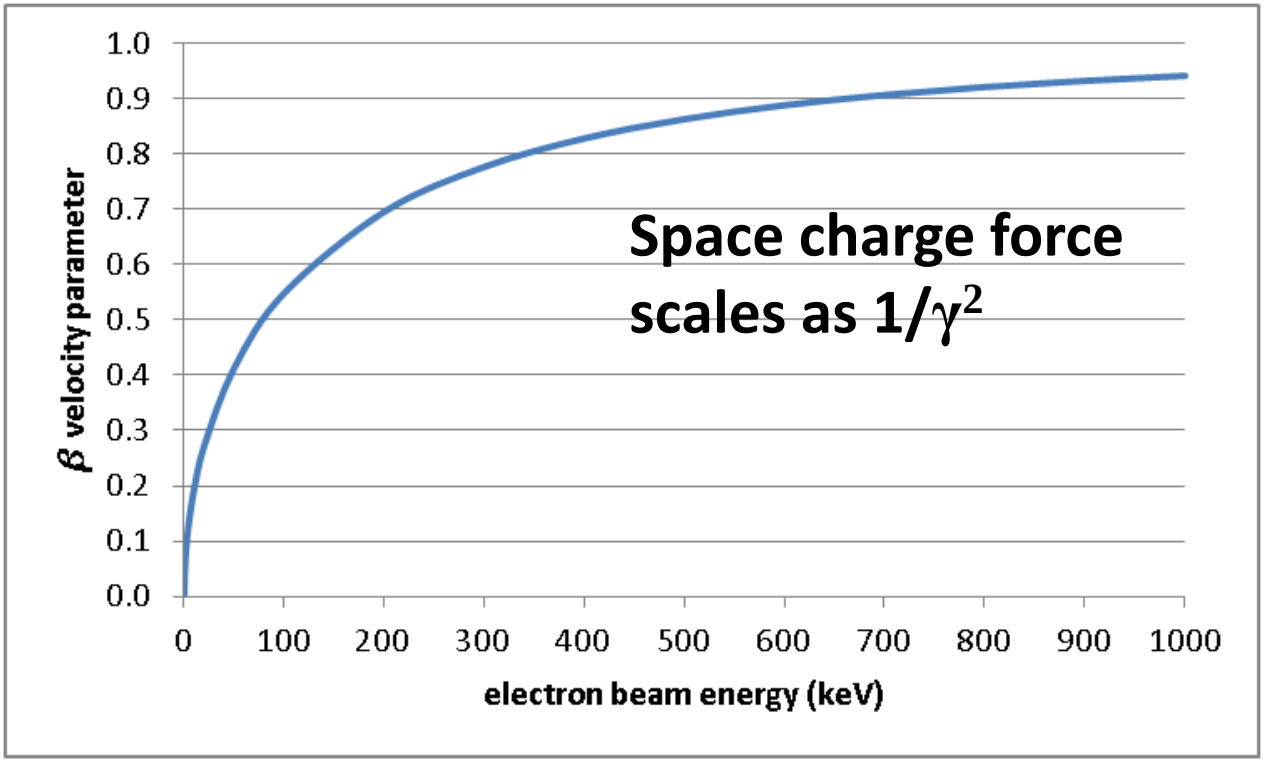


20 mA average current at 250kV



Space Charge



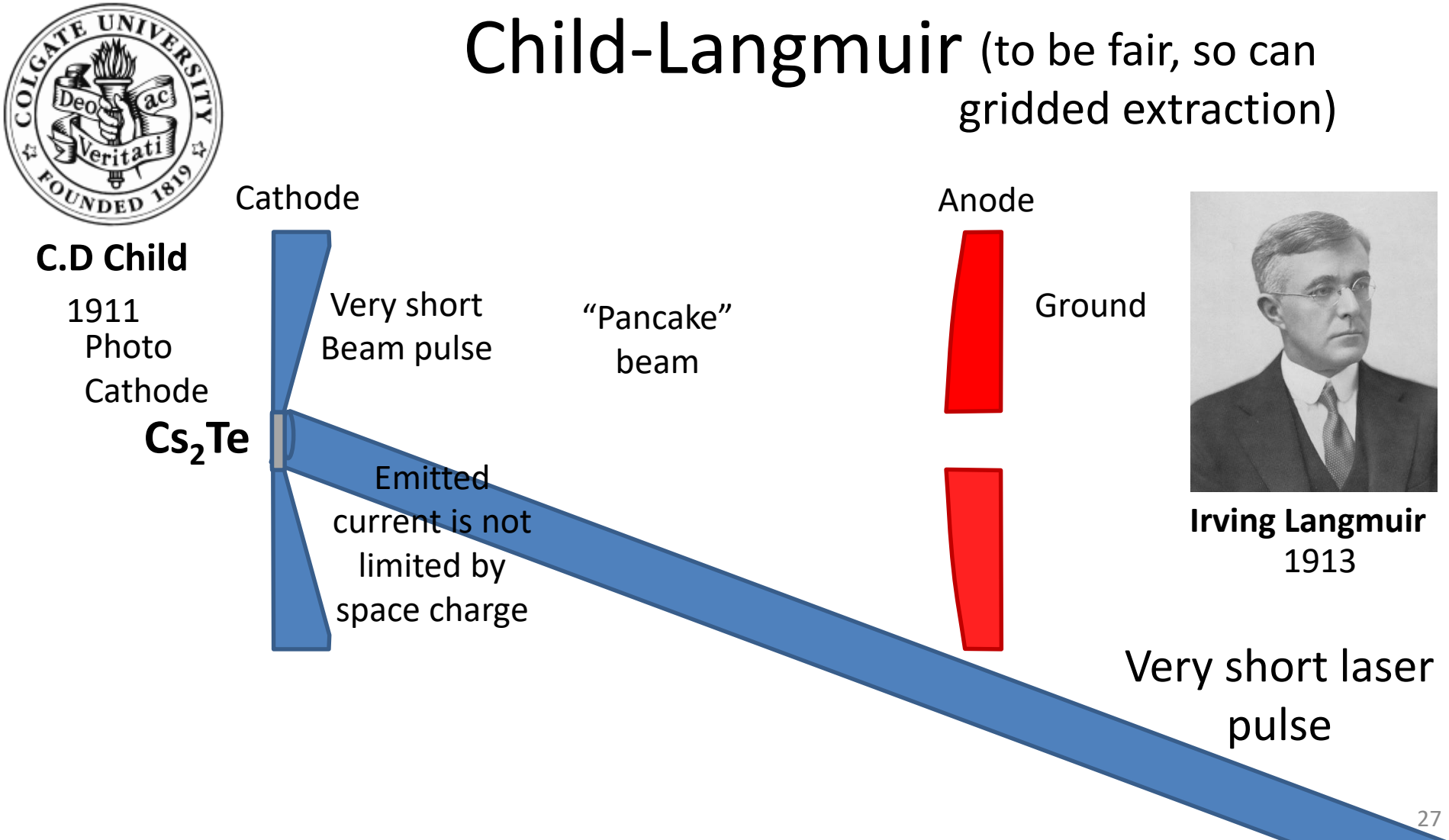


At 500 keV electron $\gamma = 2$

(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)



C.D Child

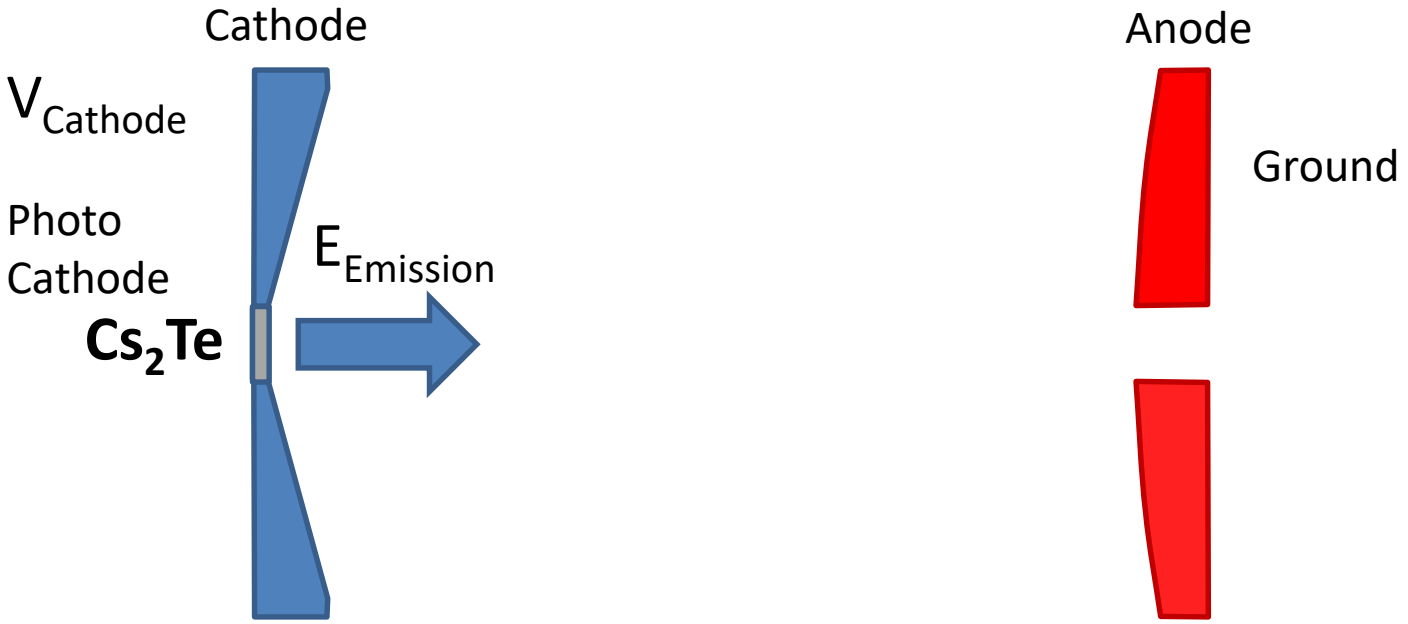
1911

Photo Cathode

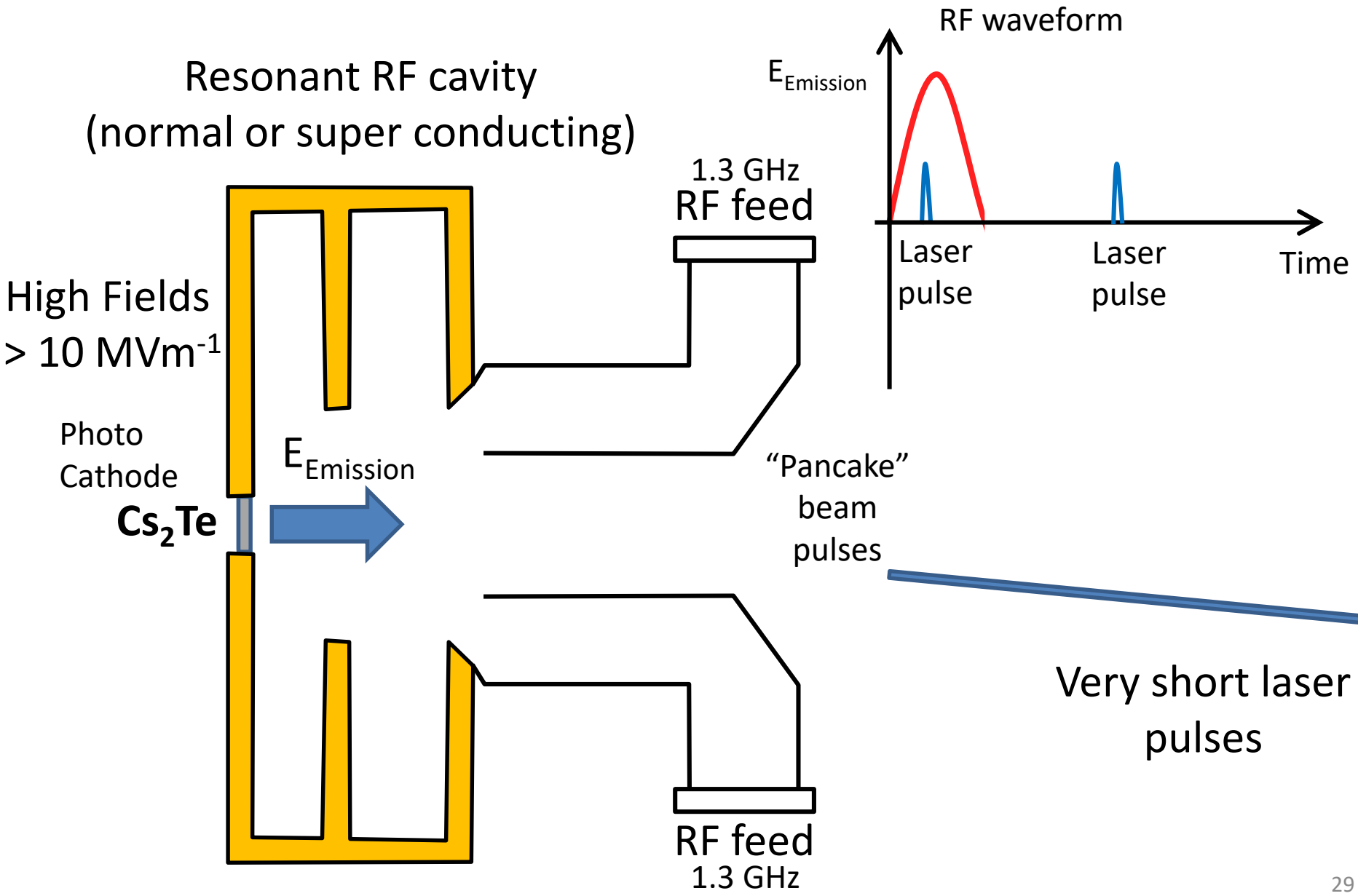
Cs_2Te

Irving Langmuir
1913

RF Photemission Source



RF Photemission Source



PITZ Photo Injector Test Facility Zeuthen

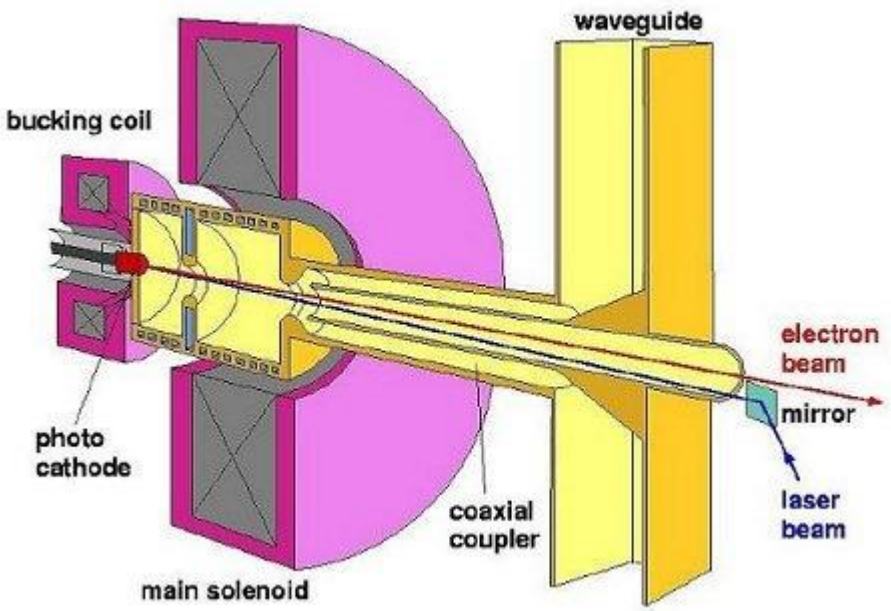
HELMHOLTZ GEMEINSCHAFT

DESY

HZDR

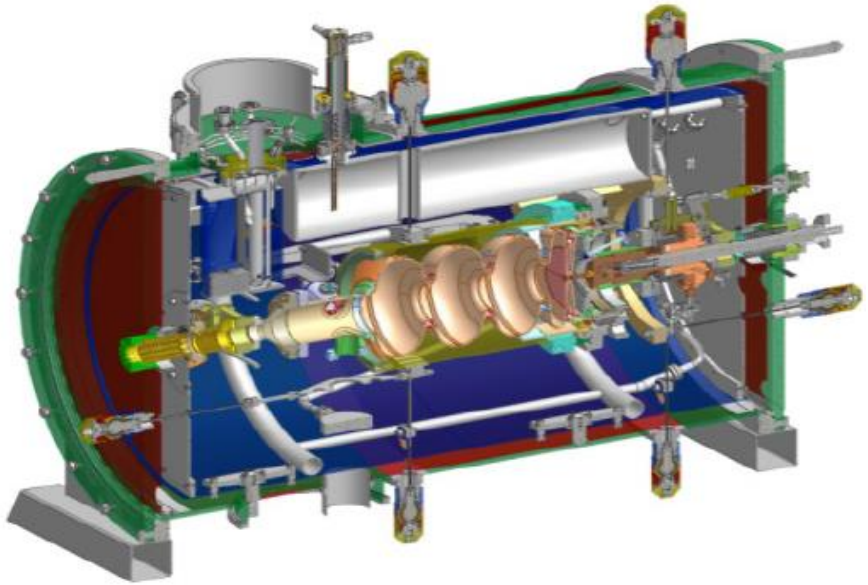
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Normally conducting



20 ps, 1 nC pulses
(50 A pulse)

Super conducting



15 ps, 1 nC pulses
(67 A pulse)

High brightness low emittance guns for FEL

Particles and **Sources**

Positrons e^+

Electrons e^-

Thermo

Plasma + other

Photo

Photons

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

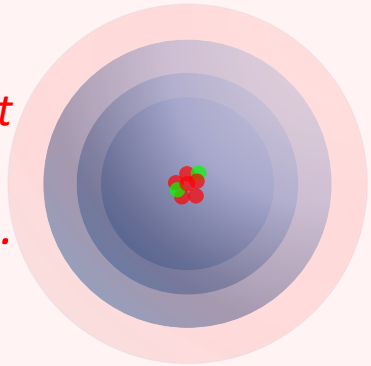
Protons

μ^+ Muons μ^-

Antiprotons

Neutrons n

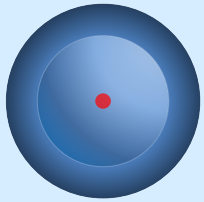
Light ions e.g. C^{4+}



Neutral particles

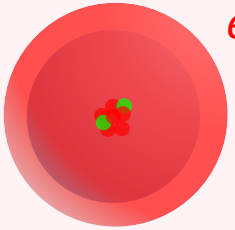
H^0

Negative ions



H^-

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



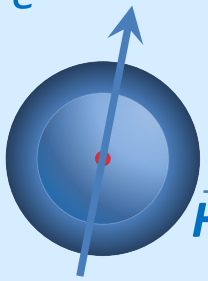
Higgs Bosons

$\uparrow\vec{e}^-$

Fully stripped nuclei

e.g. U^{92+}

$\uparrow\vec{p}$



Polarised particles

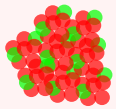
$\vec{H}^-$

Zoo of curiosities

Tauons
Mesons
Baryons

$W + Z$ Bosons

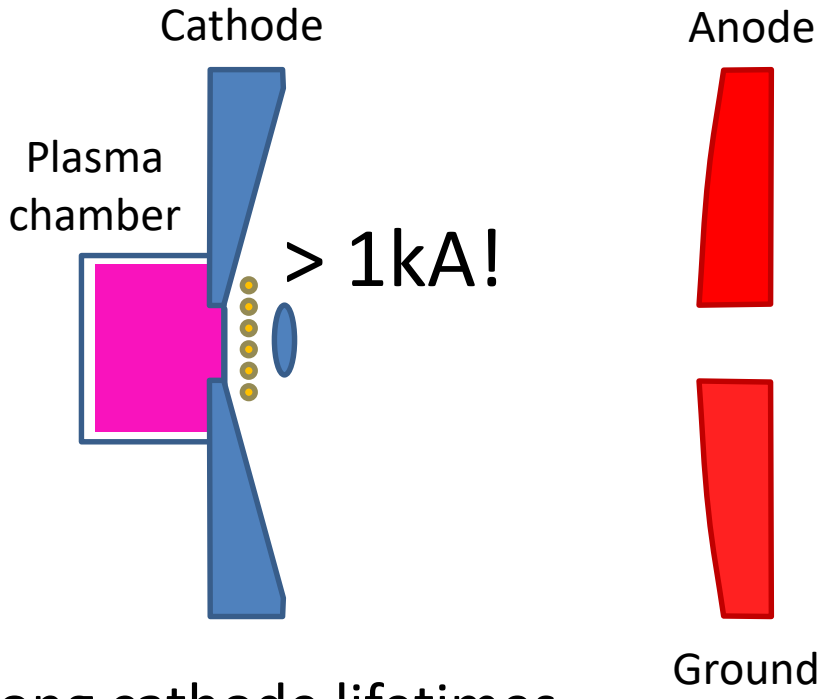
Exotic nuclei



e.g. Lr^{103+}

Plasma Cathode

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



Long cathode lifetimes

Other electron sources:

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

Rarely used in accelerators:

Field emission from needle arrays
Diamond amplifiers
Etc...

Particles and **Sources**

Positrons e^+

Electrons e^-

Photons

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

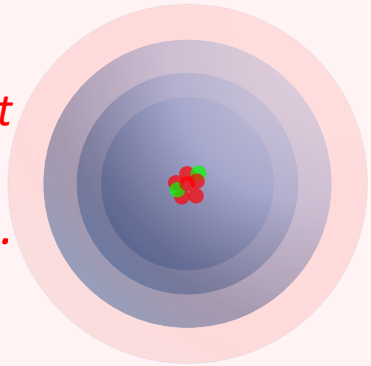
Protons

μ^+ Muons μ^-

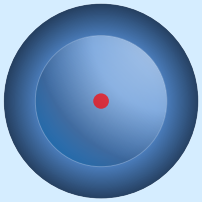
Antiprotons

Neutrons n

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



Negative ions



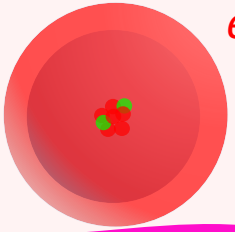
H^-

Neutral particles

H^0

Plasma Sources

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

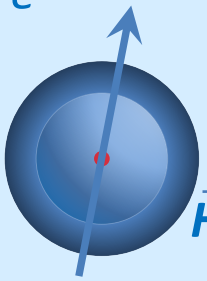


Higgs Bosons

$\uparrow\vec{e}^-$

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

$\uparrow\vec{p}$



Polarised particles

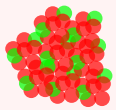
$\vec{H}^-$

Zoo of curiosities

Tauons
Mesons
Baryons

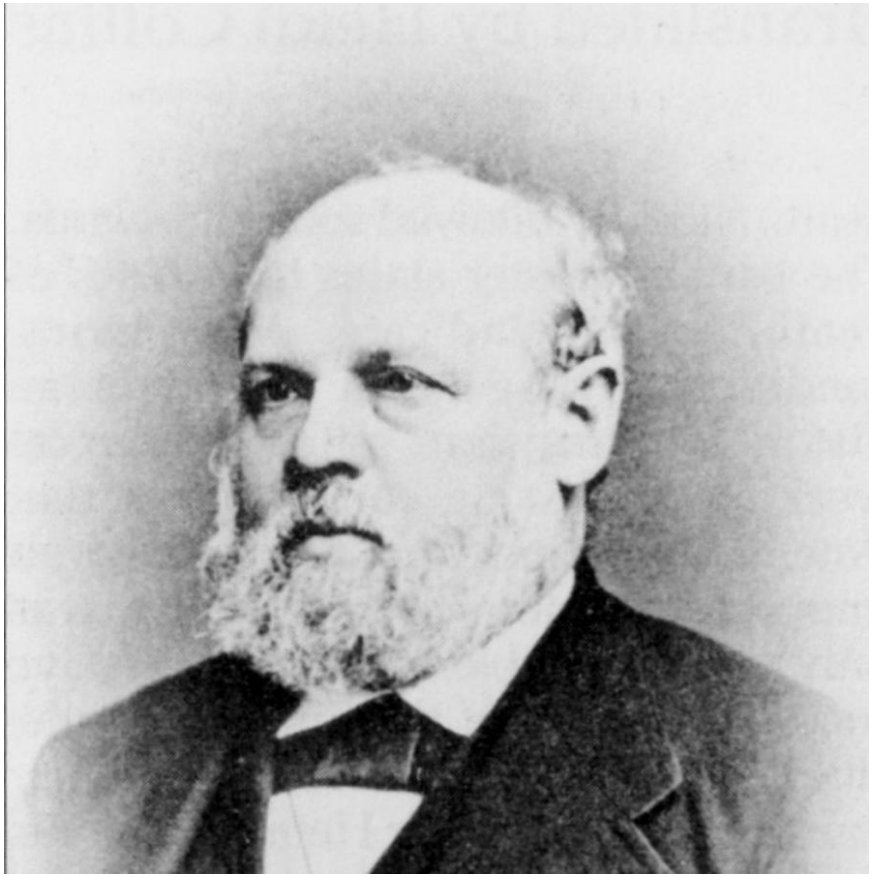
$W + Z$ Bosons

Exotic nuclei



e.g. Lr^{103+}

Plasma Pioneers



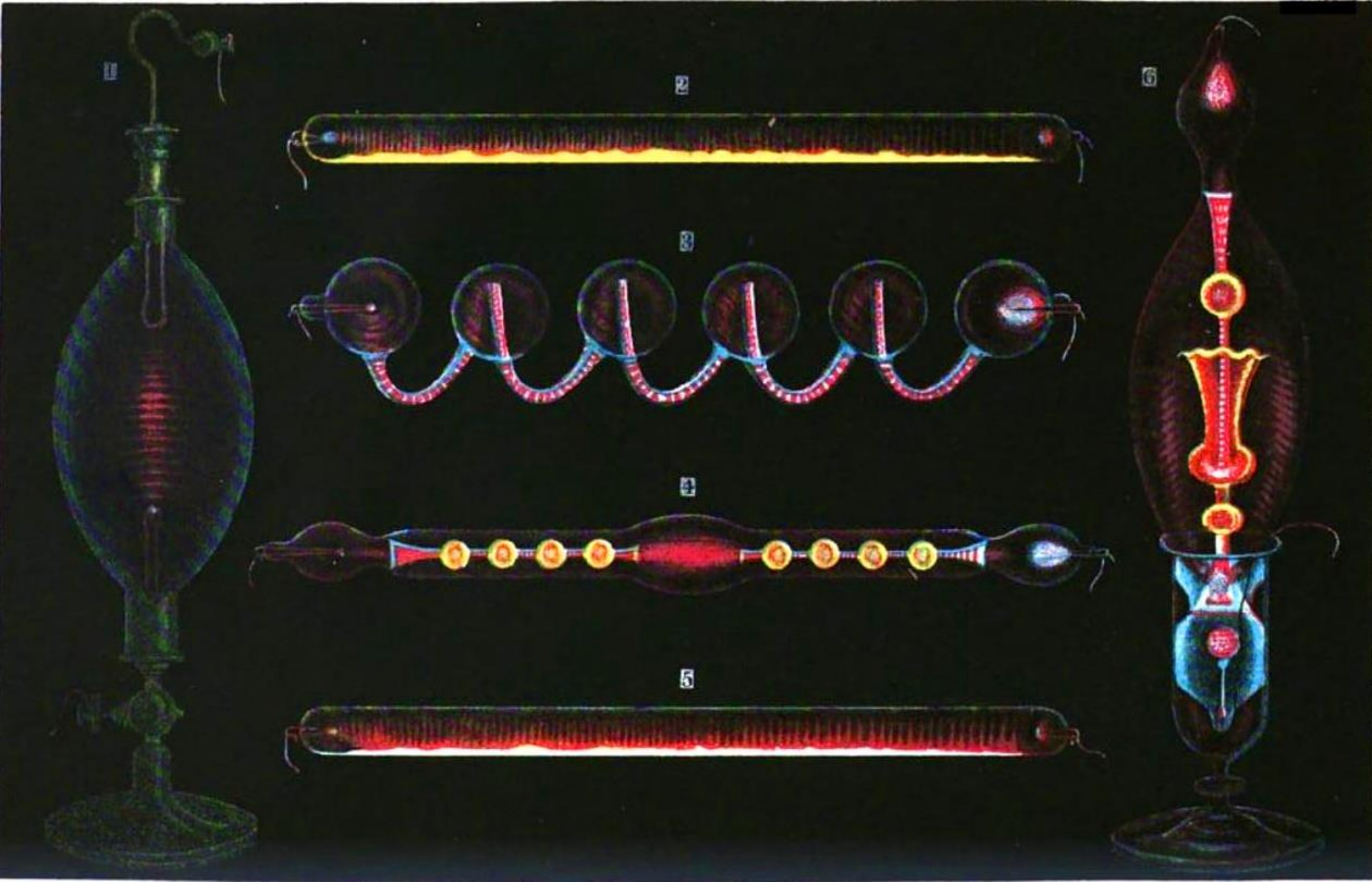
Heinrich Geißler

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 or m³)*

n_e = density of electrons

n_i = density of ions

n_n = density of neutrals

Charge State, *q*

$H^+ \rightarrow q = +1$

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

$H^- \rightarrow q = -1$

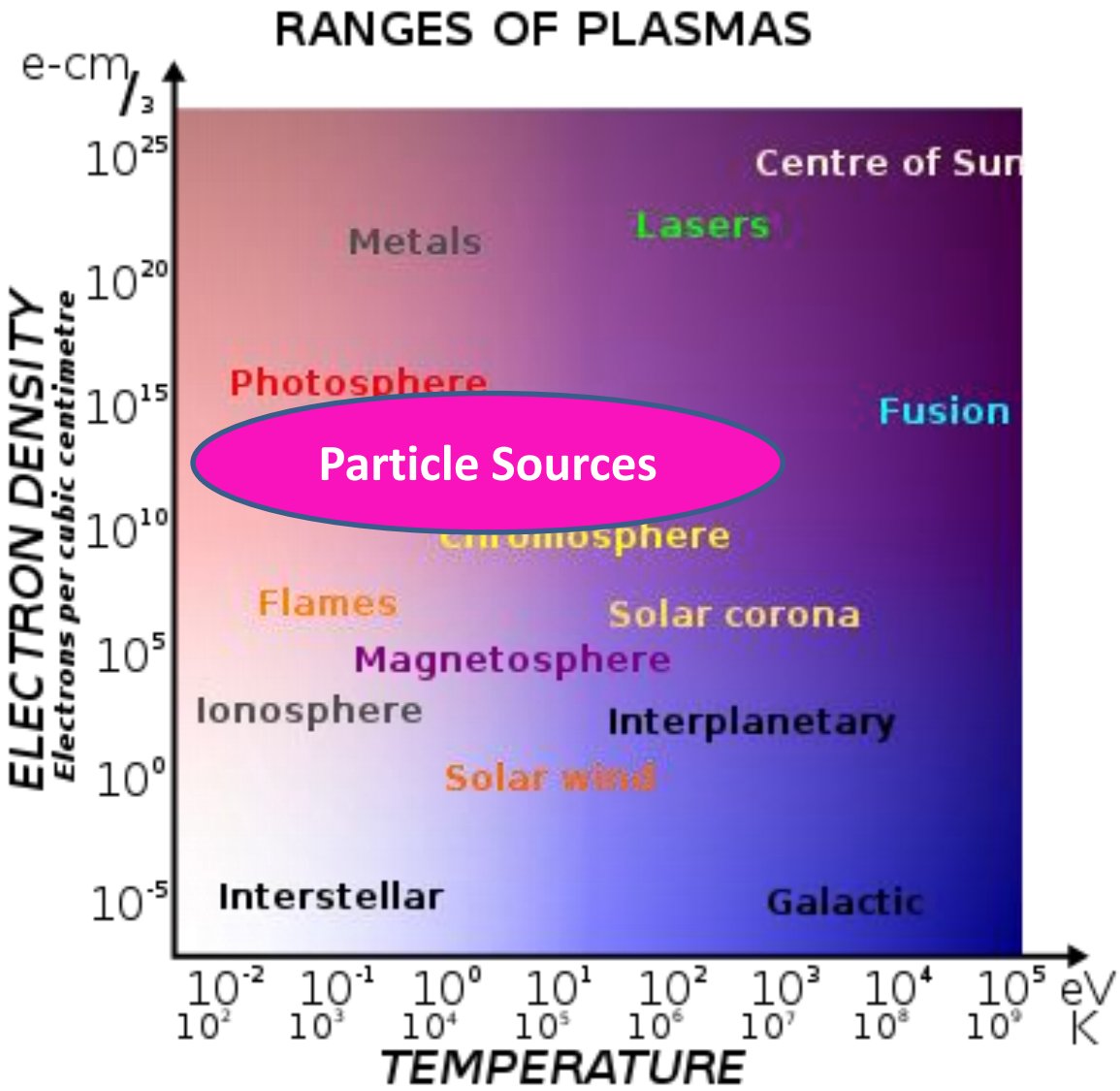
11600°K = 1 eV

Temperature, *T* (eV)

T_e = temperature of electrons

T_i = temperature of ions

T_n = temperature of neutrals

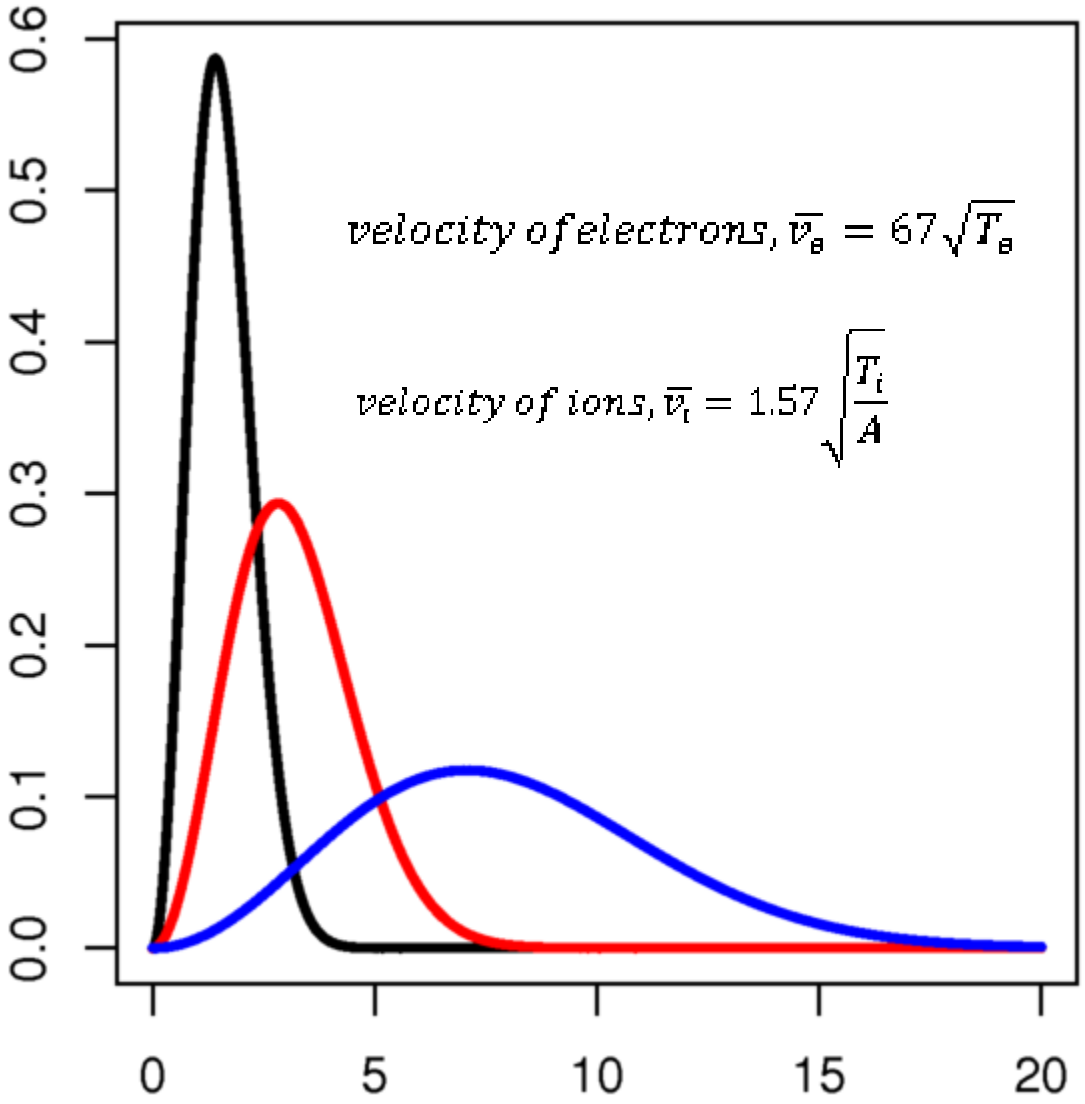

RANGES OF PLASMAS
e-cm/3
ELECTRON DENSITY
Electrons per cubic centimetre
10^25
10^20
10^15
10^10
10^5
10^0
10^-5
Centre of Sun
Lasers
Metals
Photosphere
Fusion
Particle Sources
Chromosphere
Flames
Solar corona
Magnetosphere
Ionosphere
Interplanetary
Solar wind
Interstellar
Galactic
10^-2 10^-1 10^0 10^1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

Temperature Distribution

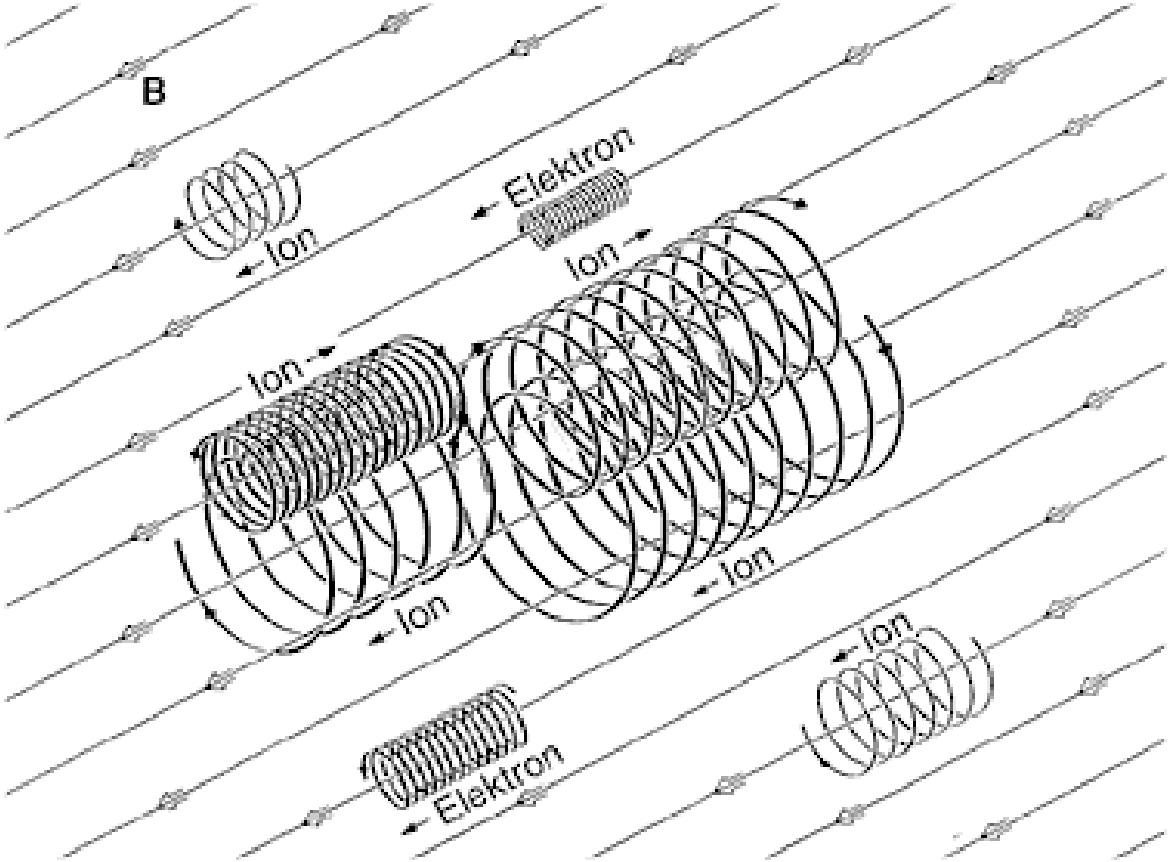
If thermalised velocity distributions should follow Maxwell Boltzmann statistics

However, in magnetic fields:

$$v_x \neq v_y \neq v_z$$

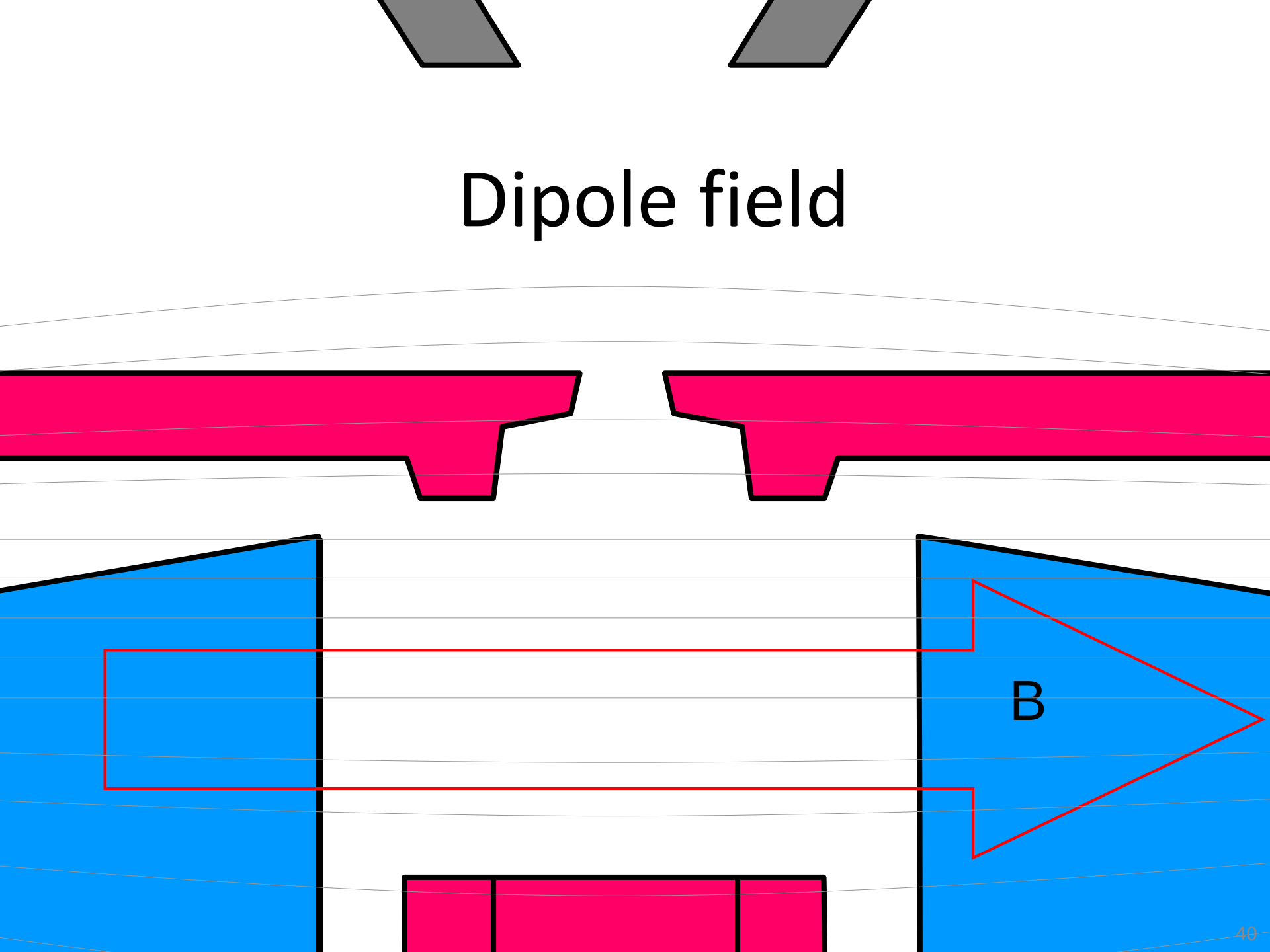


Magnetic Confinement

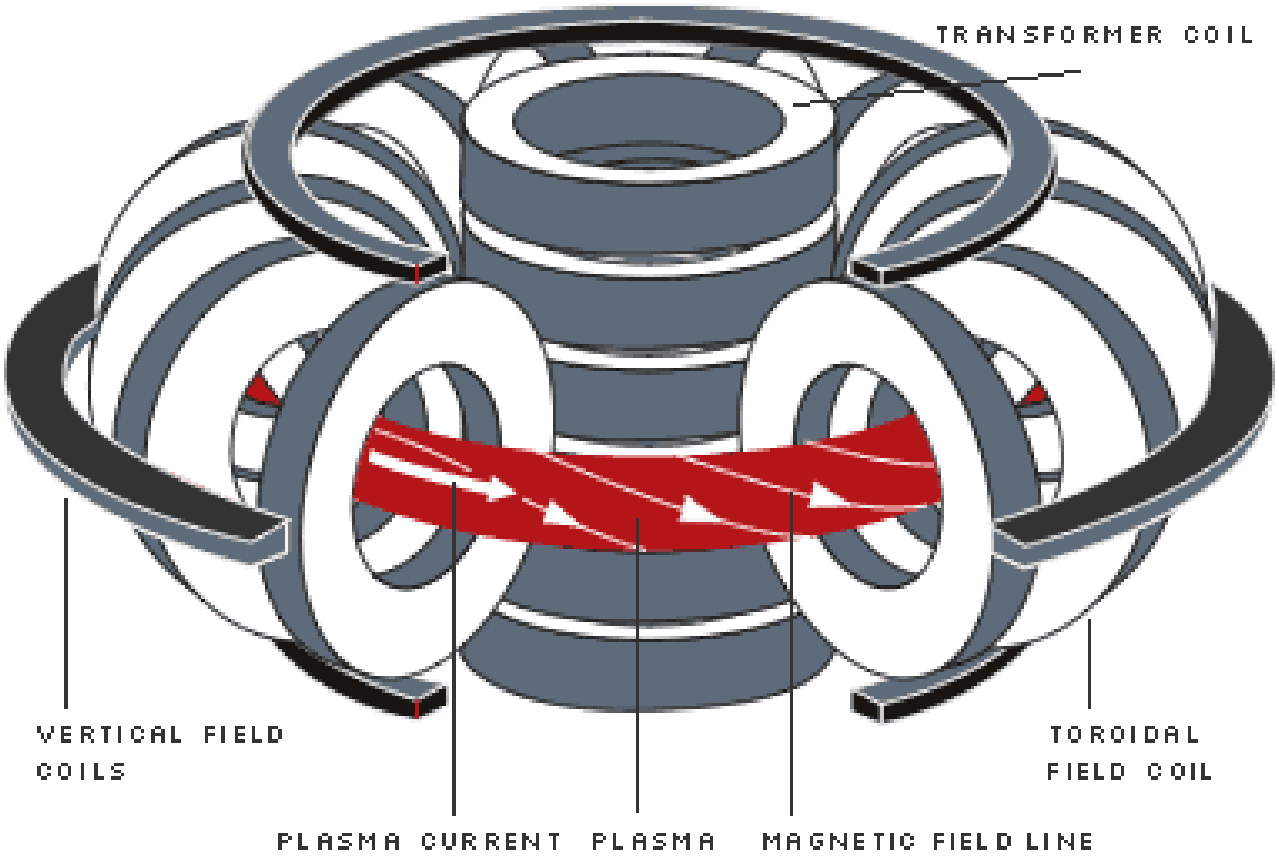


Particles spiral along magnetic field lines

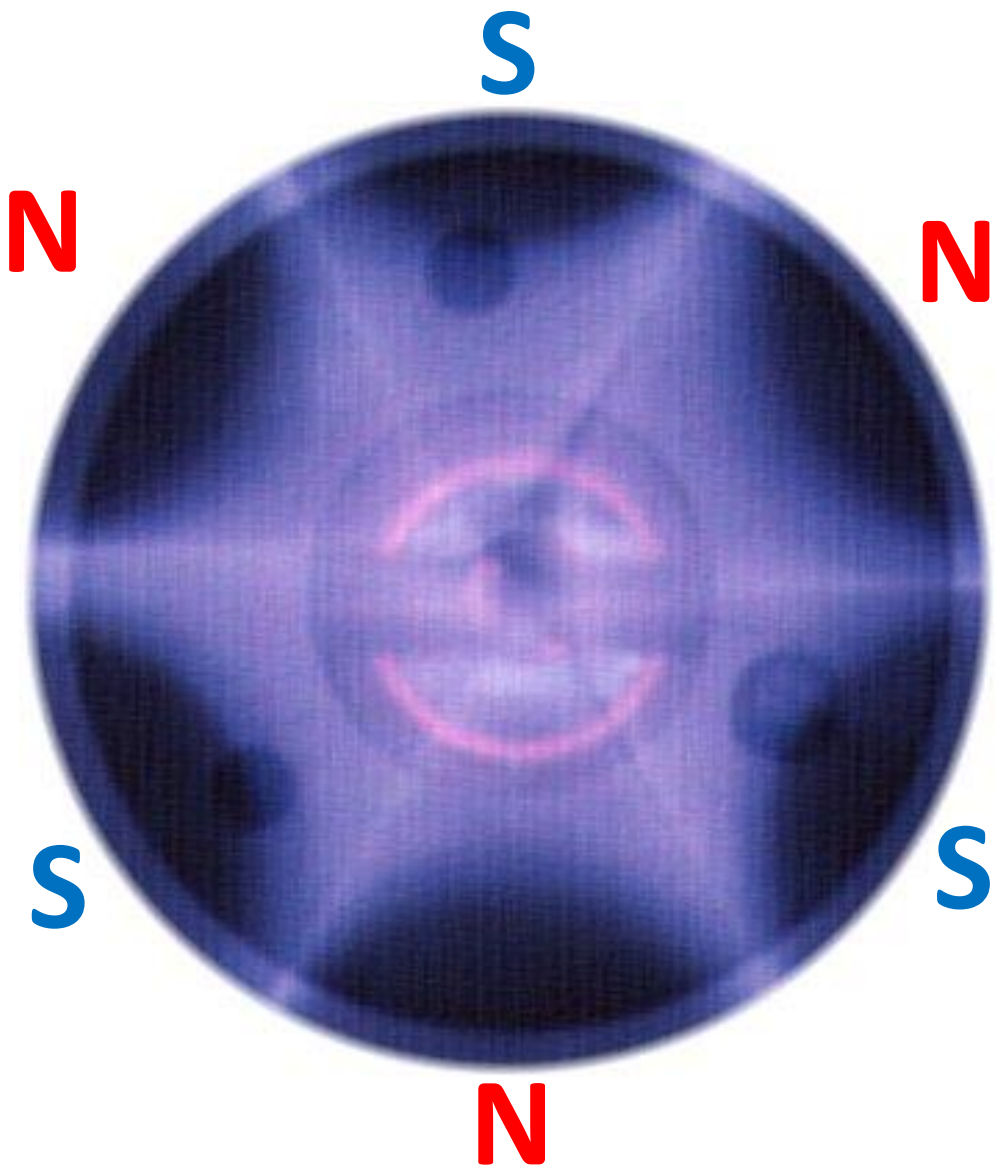
Dipole field



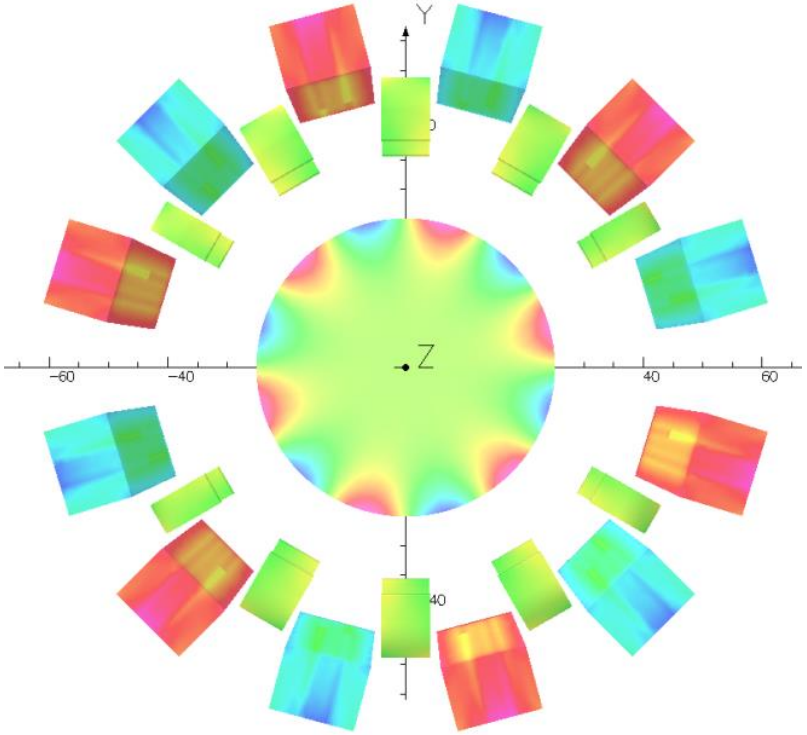
Solenoid field

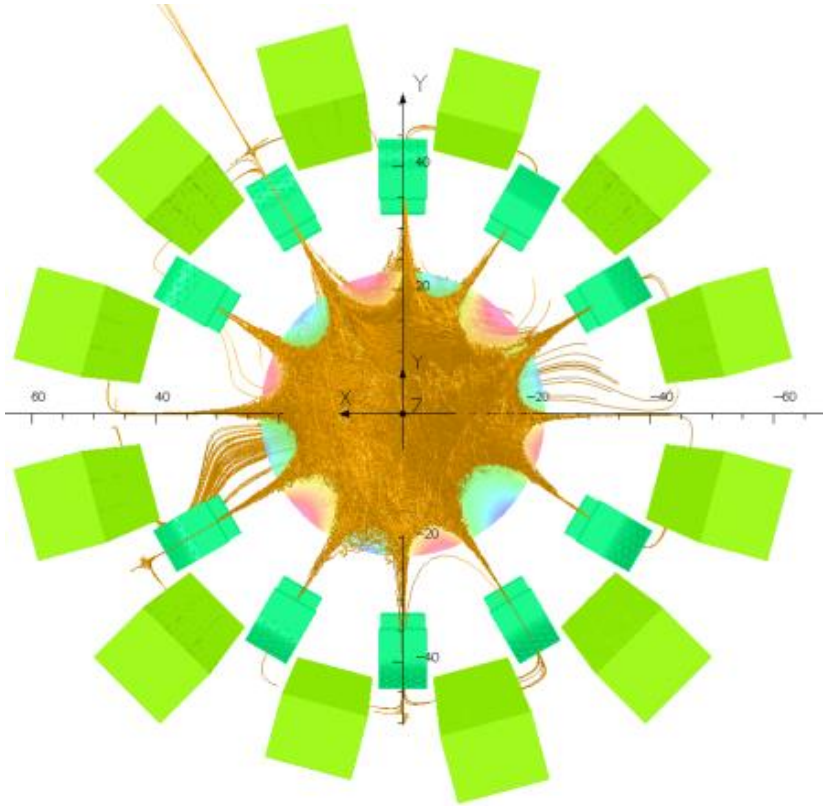


Hexapole

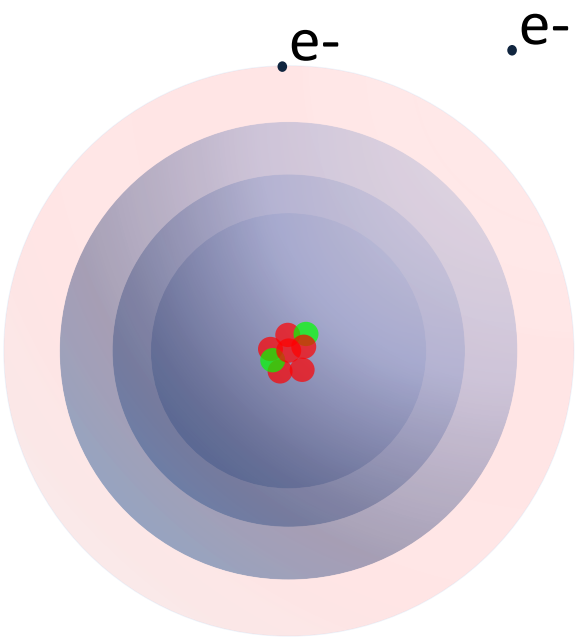


Multicusp Confinement



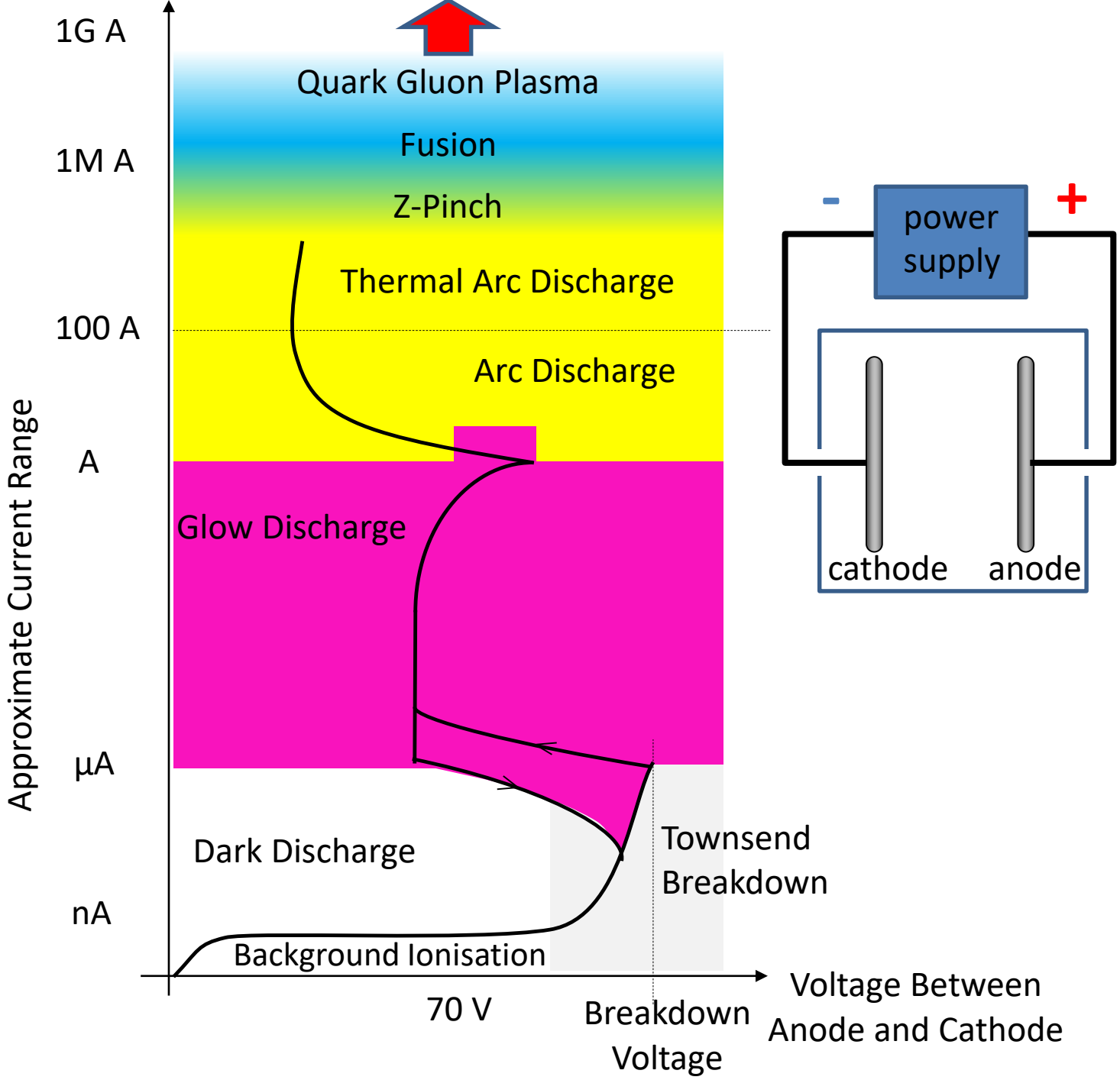


Ionisation



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

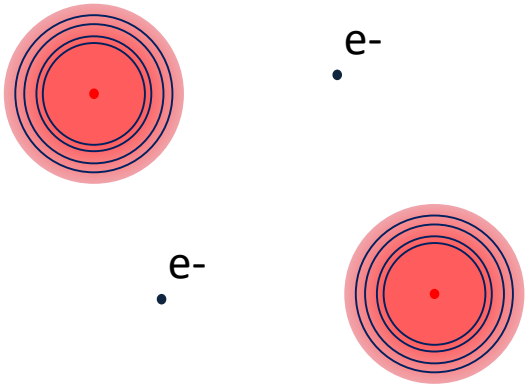
$$\frac{n_i}{n_i + n_n}$$

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

Quasi Neutrality

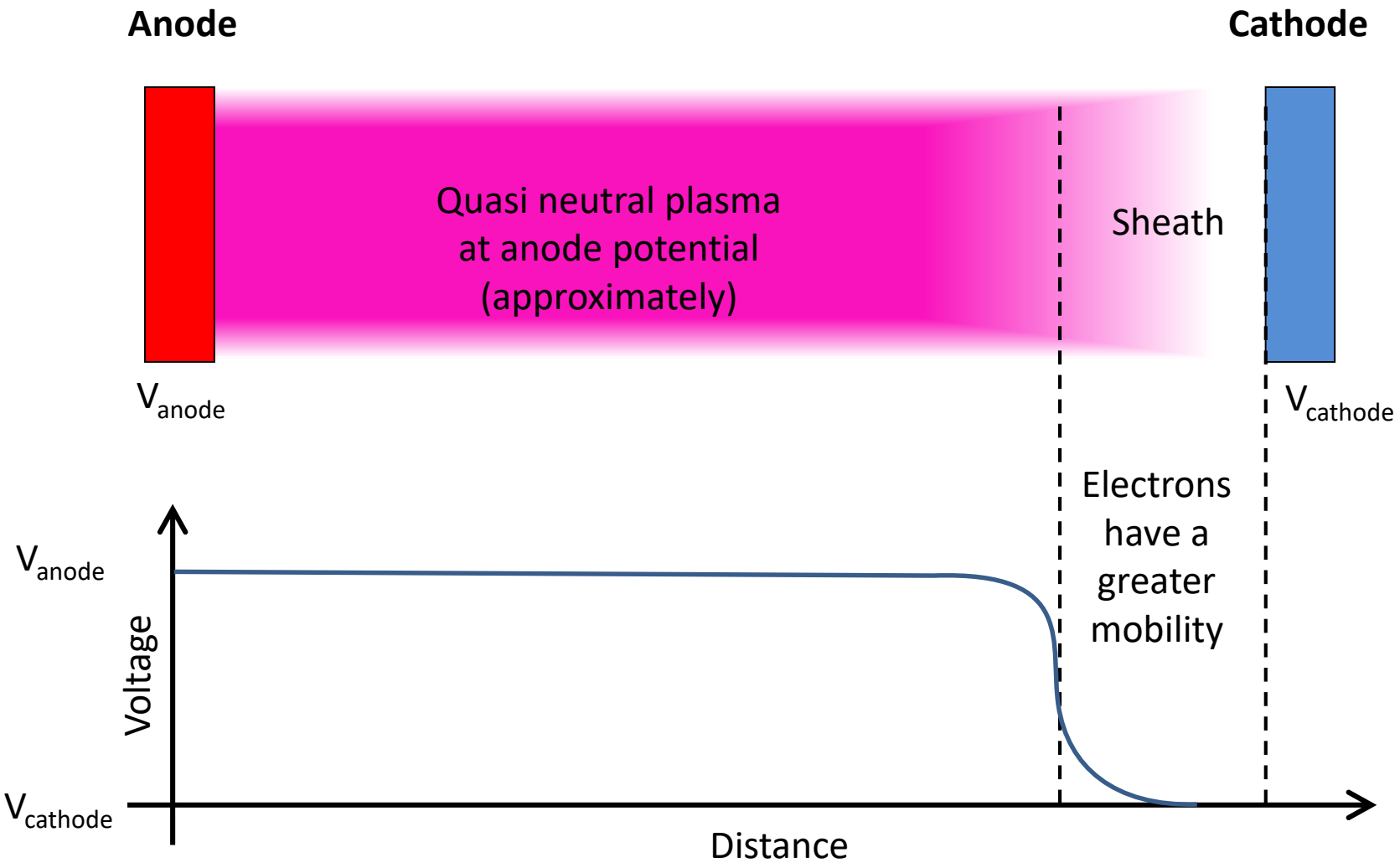
$$\sum q_i n_i = n_e$$

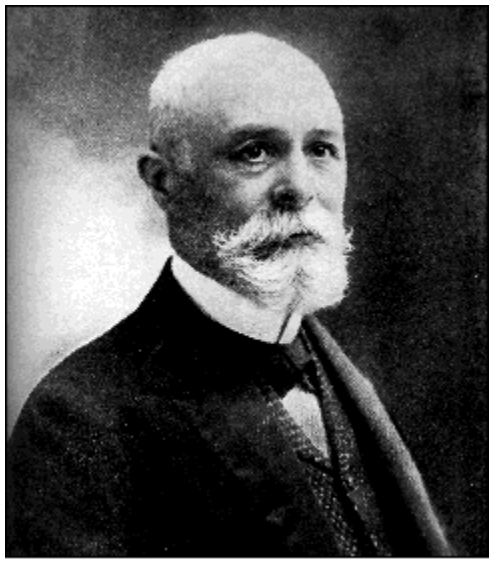
Debye Length



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

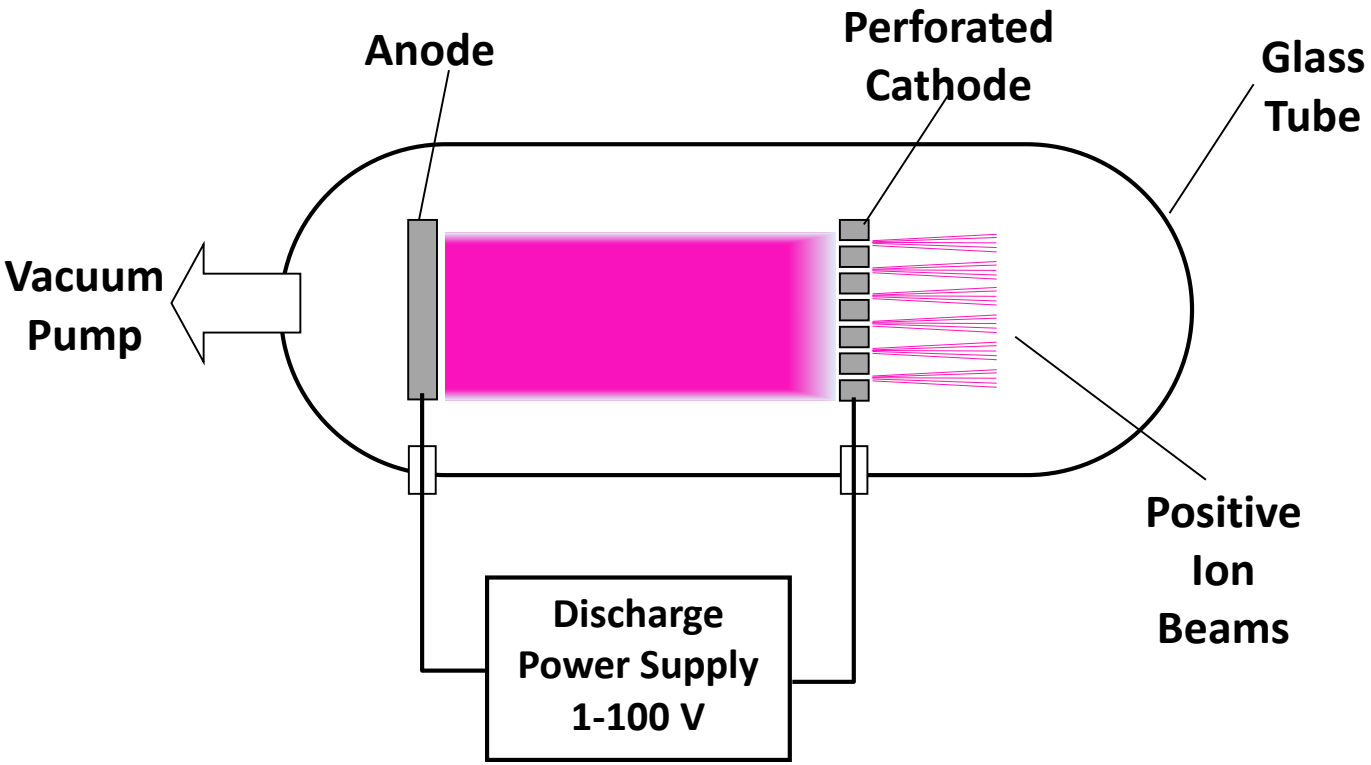
Cathode Sheath





Canal Ray Source

In 1886 Eugen Goldstein discovered canal rays



Electron Bombardment Source (1916)

Early mass spectrometry

Particles and **Sources**

Positrons e^+

Electrons e^-

Photons

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

Plasmatrons

Protons

μ^+ Muons μ^-

Antiprotons

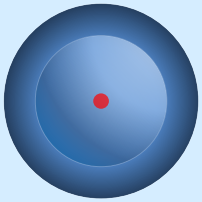
Neutrons n

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

Neutral particles

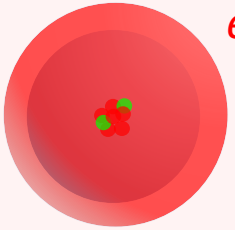
H^0

Negative ions



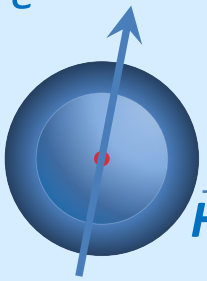
H^-

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



Higgs Bosons

$\uparrow\vec{e}^-$



Polarised particles

$\vec{H}^-$

Zoo of curiosities

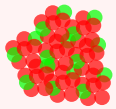
Fully stripped nuclei e.g. U^{92+}

$\uparrow\vec{p}$

Tauons
Mesons
Baryons

$W + Z$ Bosons

Exotic nuclei

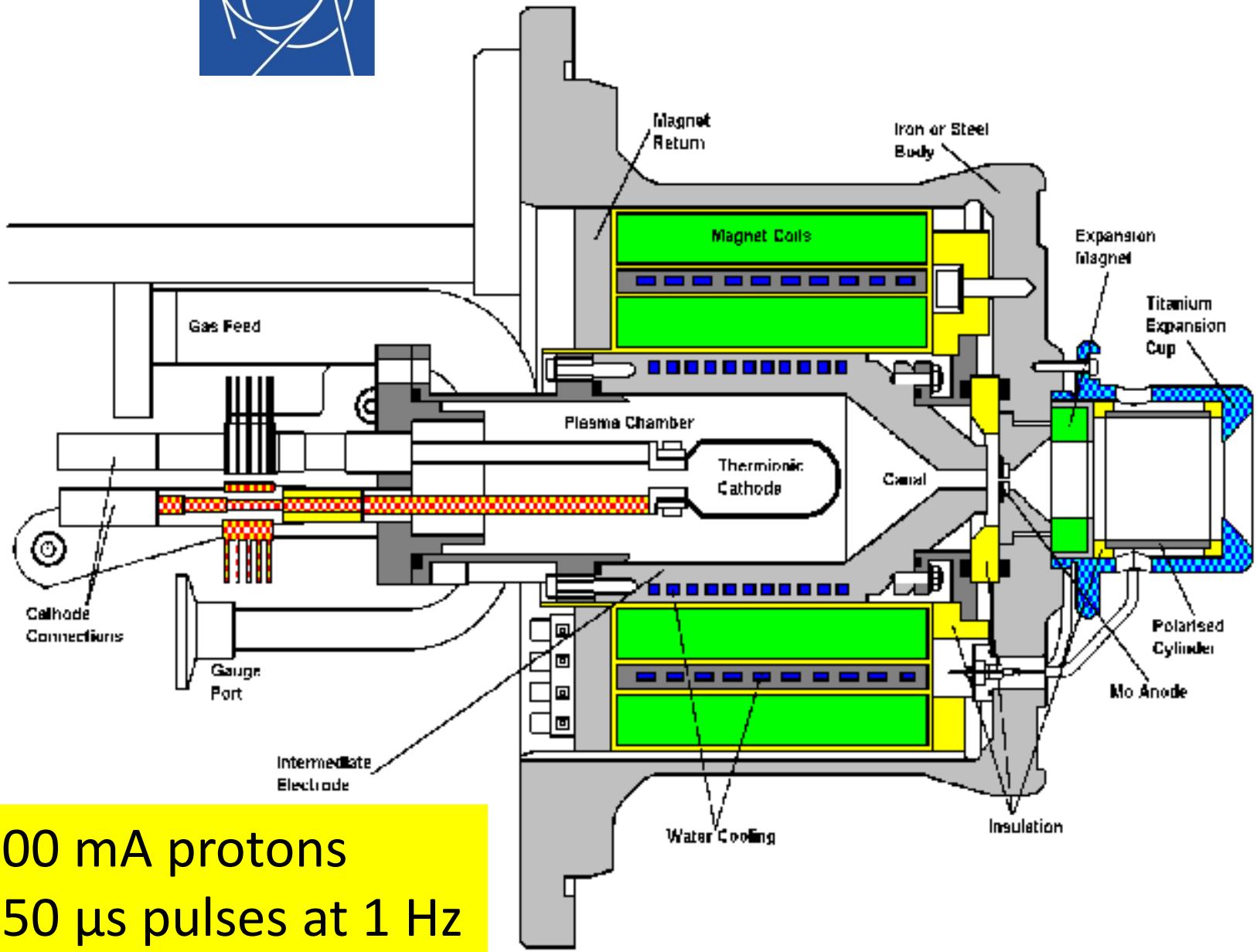


e.g. Lr^{103+}

Plasmatron (late 1940s)

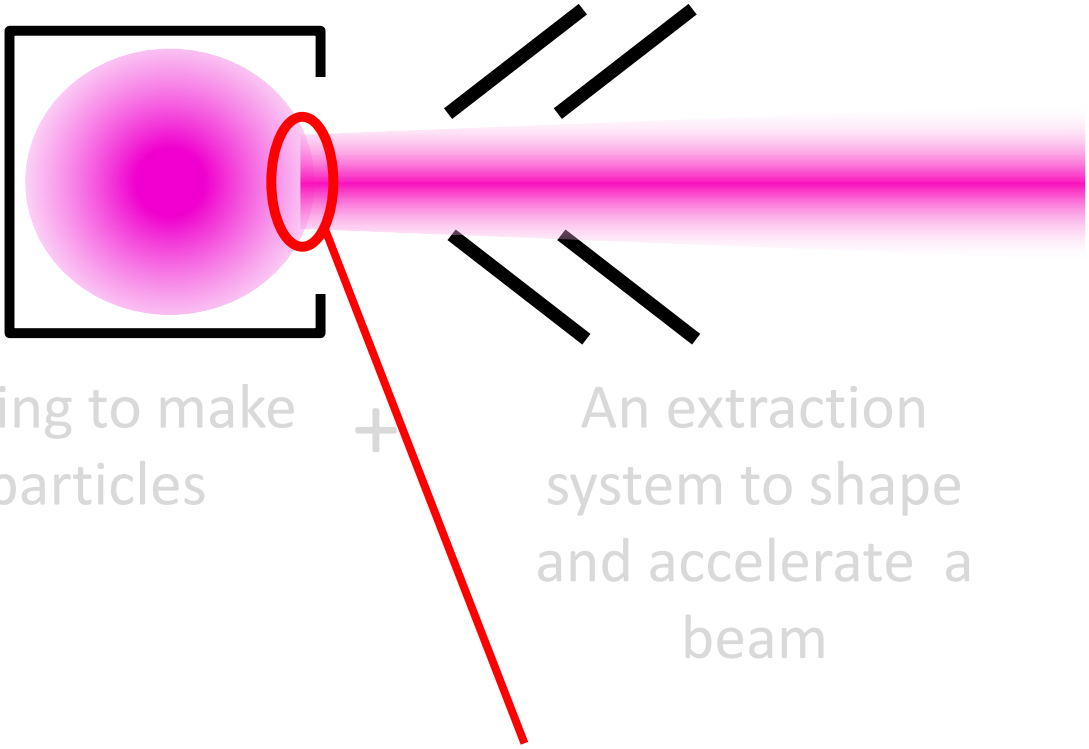
Duoplasmatron (1956)

Duoplasmatron



300 mA protons
150 µs pulses at 1 Hz

Particle sources/guns generally consist of:



Something to make the particles

+

An extraction system to shape and accelerate a beam

The emission “surface” is critical to the quality of the beam

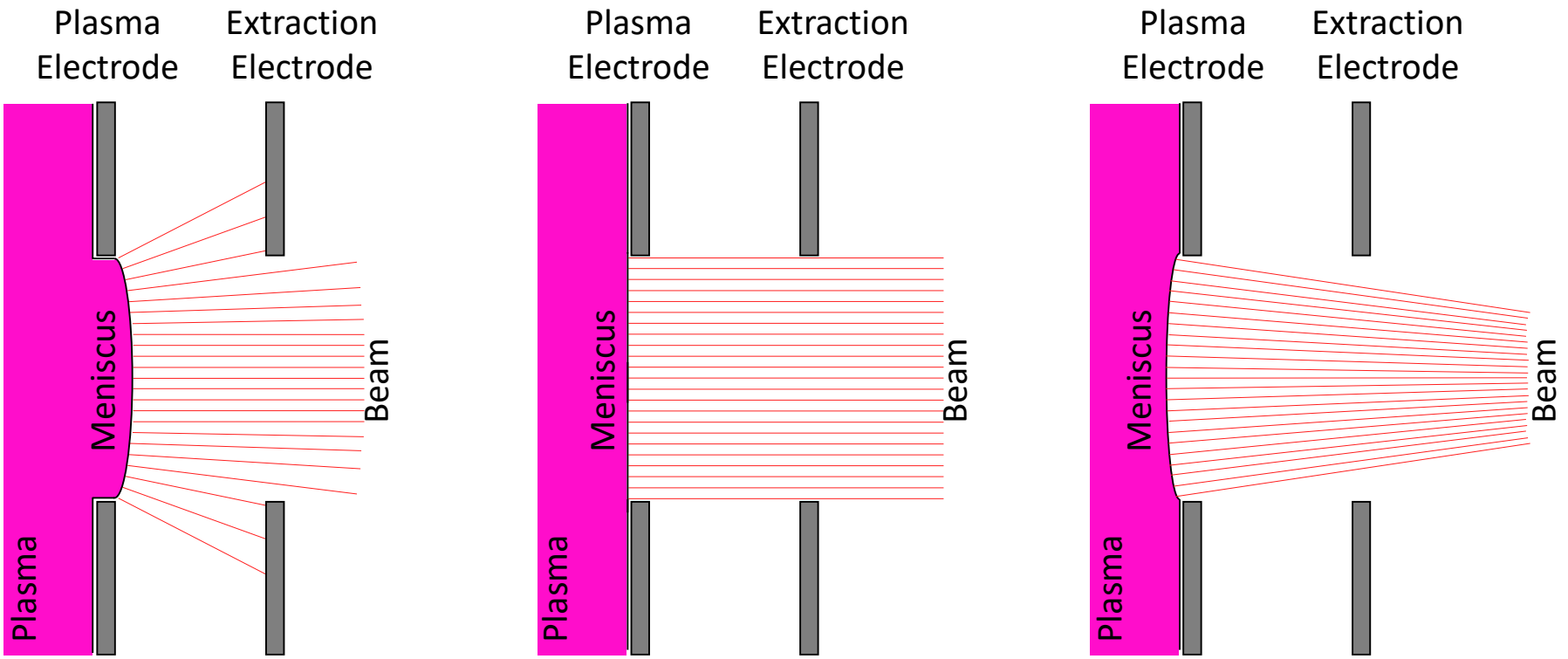
Plasma Mencius

…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…

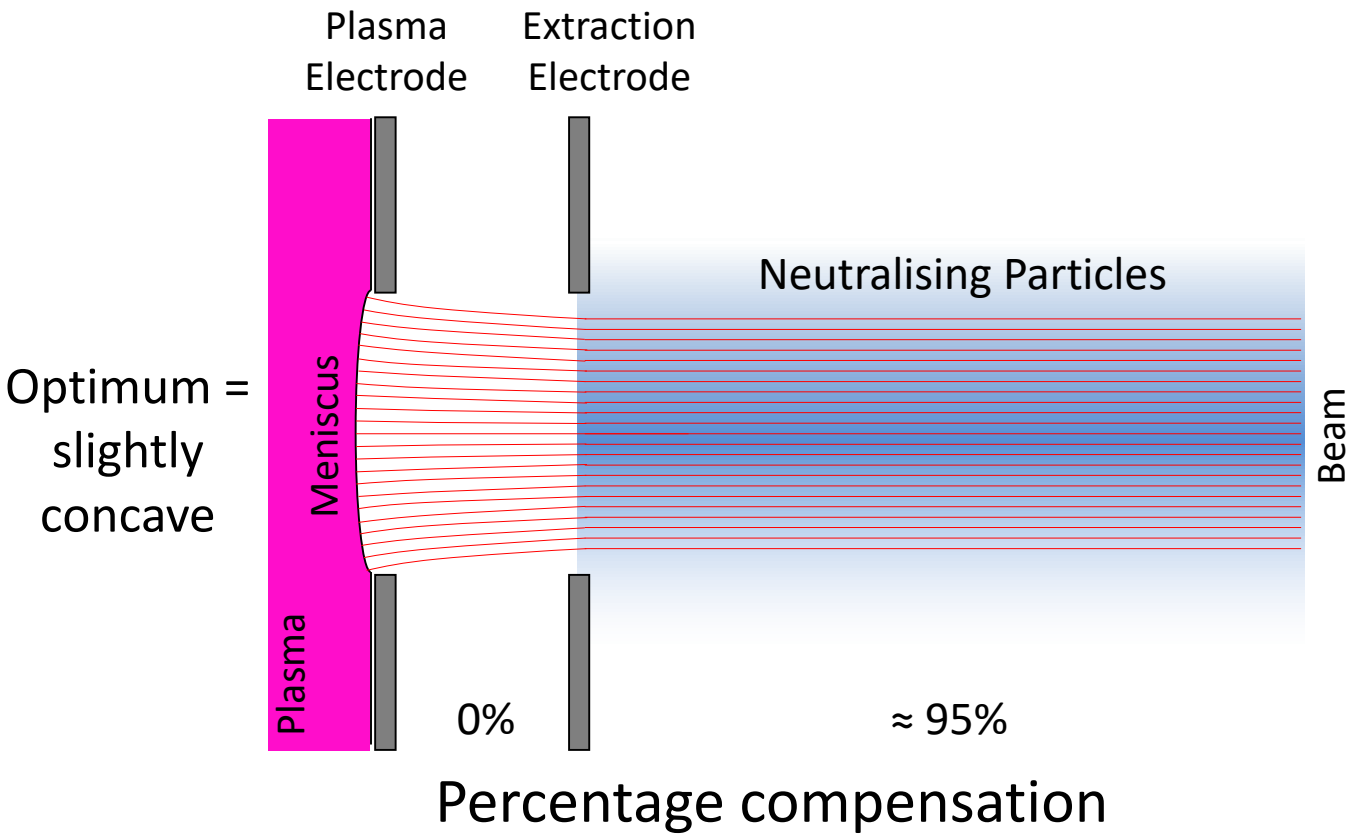
Plasma Mencius



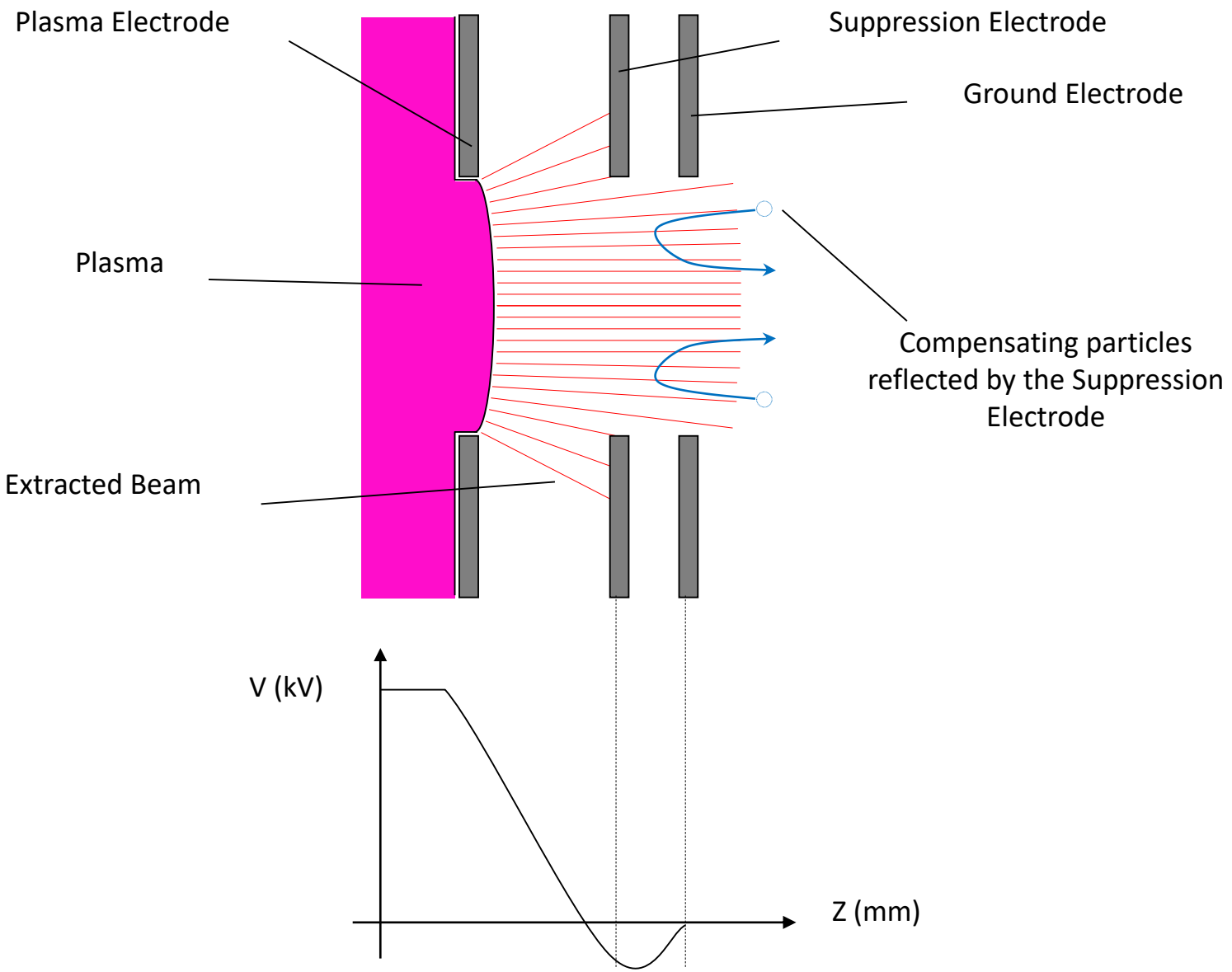
Convex Flat Concave

Not including space charge effects

Space Charge



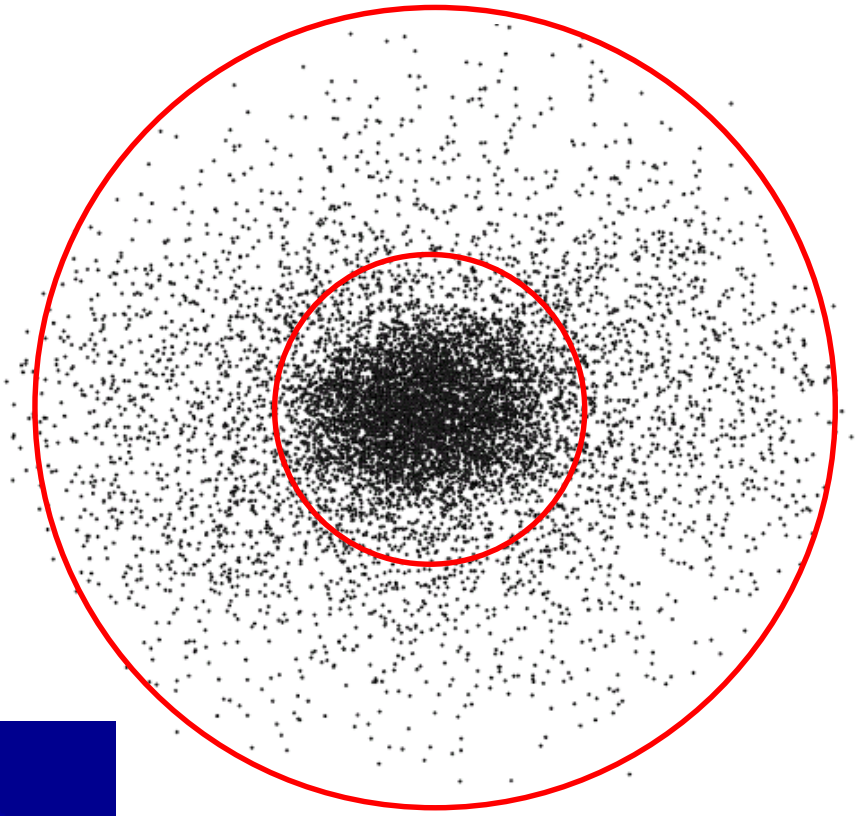
Suppressor Electrode



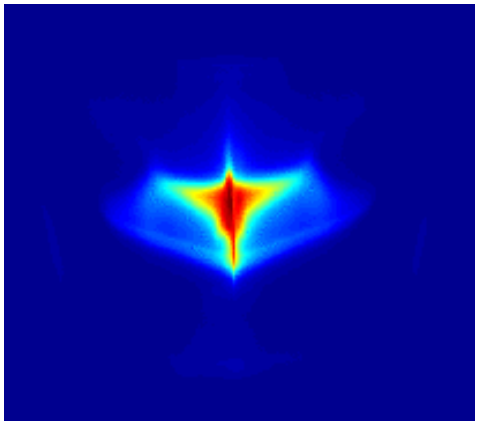
Emittance of Real Beams

Halo Effect

- Plasma boundary
- Fringe fields



How big is this beam?



95% emittance

rms emittance

Brightness

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

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

Particles and **Sources**

Positrons e^+

Electrons e^-

Photons

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

Plasmatrons

Protons

μ^+ Muons μ^-

Antiprotons

Neutrons n

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

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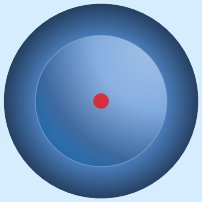
H^0

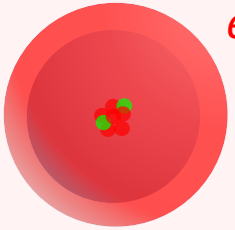
Negative ions



H^-

Vacuum arc

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

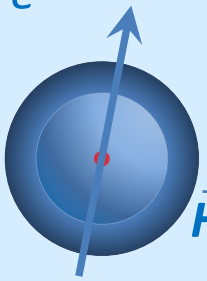


Higgs Bosons

$\vec{e}^-$

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

$\vec{p}$



Polarised particles

$\vec{H}^-$

Zoo of curiosities

Tauons
Mesons
Baryons

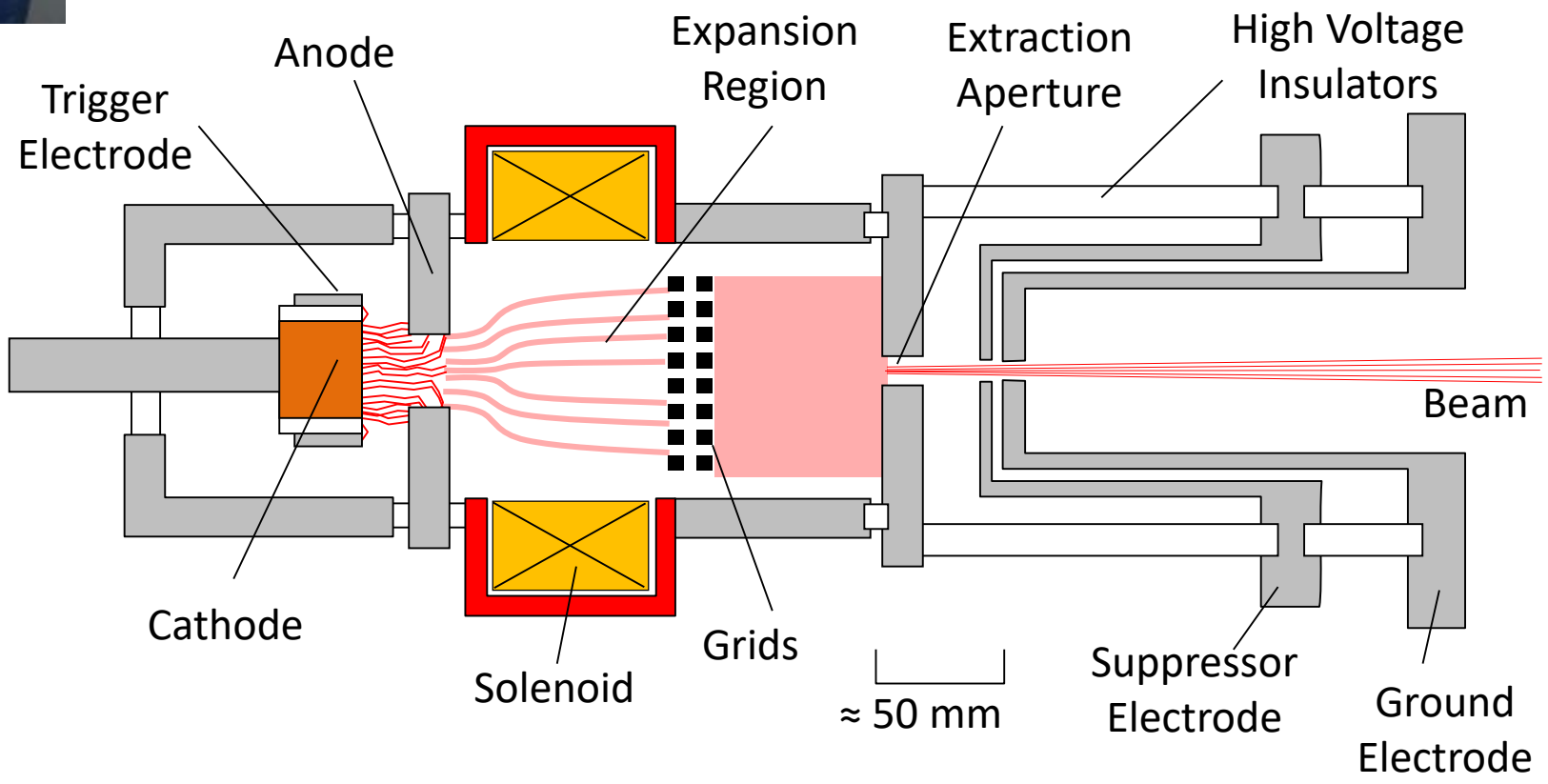
$W + Z$ Bosons

Exotic nuclei

e.g. Lr^{103+}

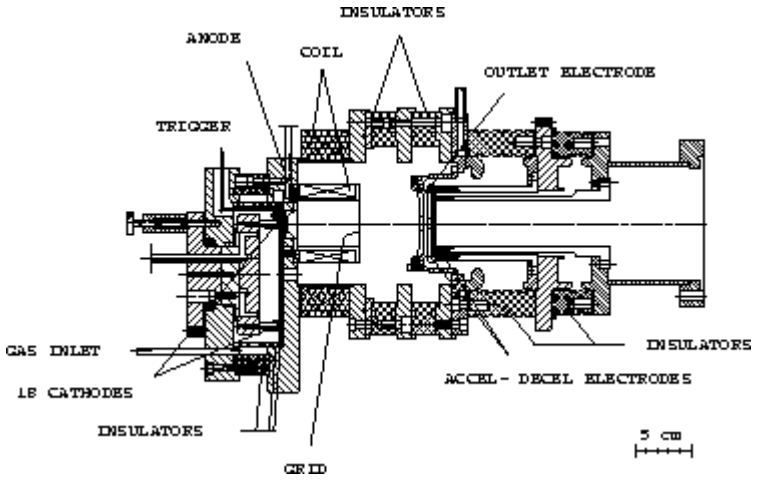
Vacuum Arc Ion Sources

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



MEtal Vapor Vacuum Arc (MEVVA)

GSI MEVVA



15 mA of U^{4+} ions

Particles and **Sources**

Positrons e^+

Electrons e^-

Photons

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

Plasmatrons

Protons

μ^+ Muons μ^-

Antiprotons

Neutrons n

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

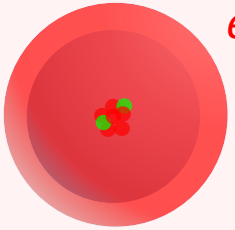
Neutral particles

Negative ions

Vacuum arc

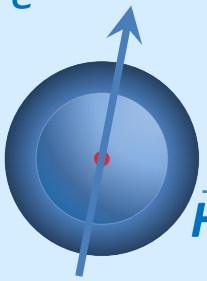
Laser plasma

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



Higgs Bosons

$\uparrow\vec{e}^-$



Polarised particles

Zoo of curiosities

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

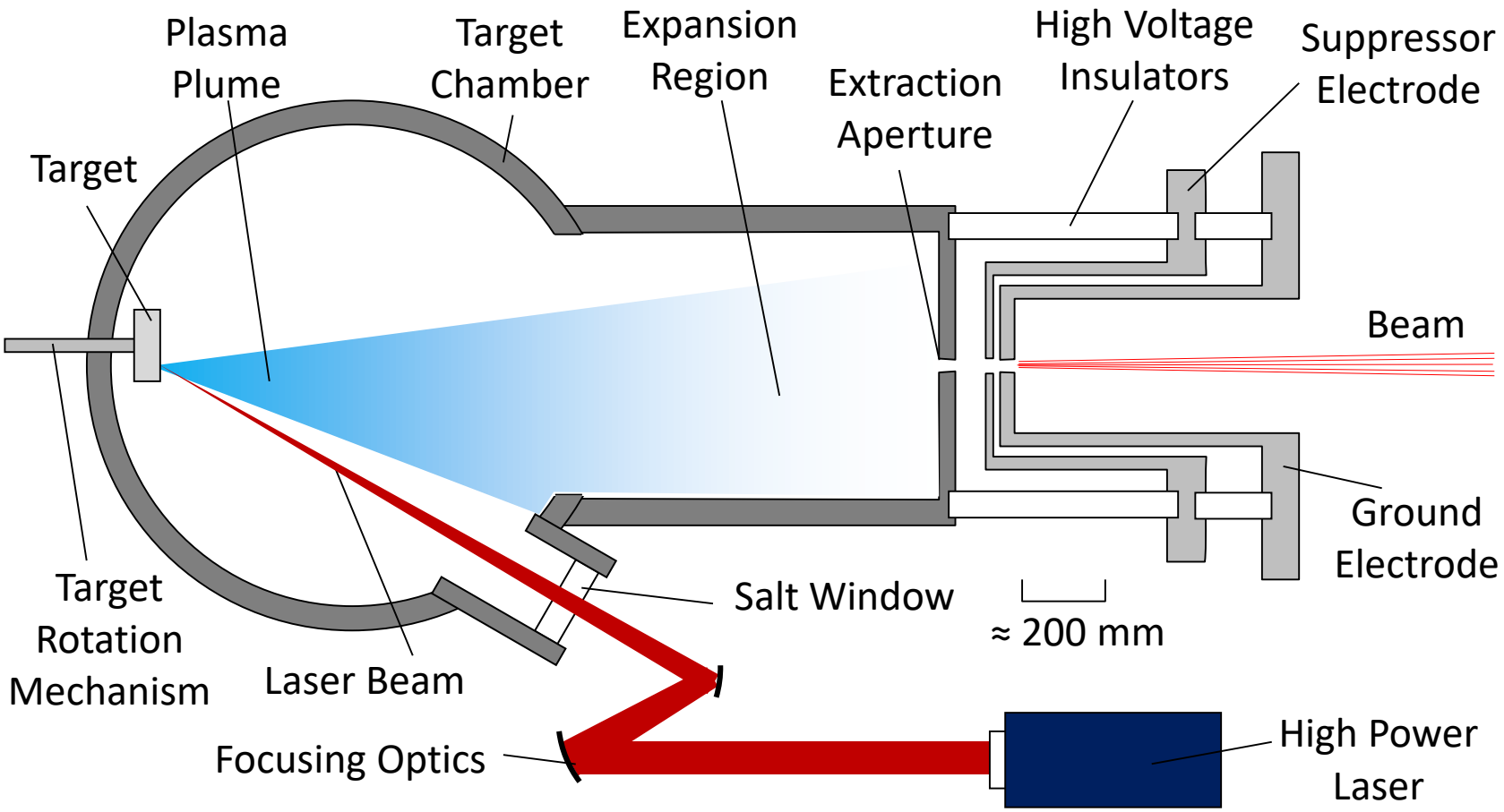
$\uparrow\vec{p}$

Tauons
Mesons
Baryons

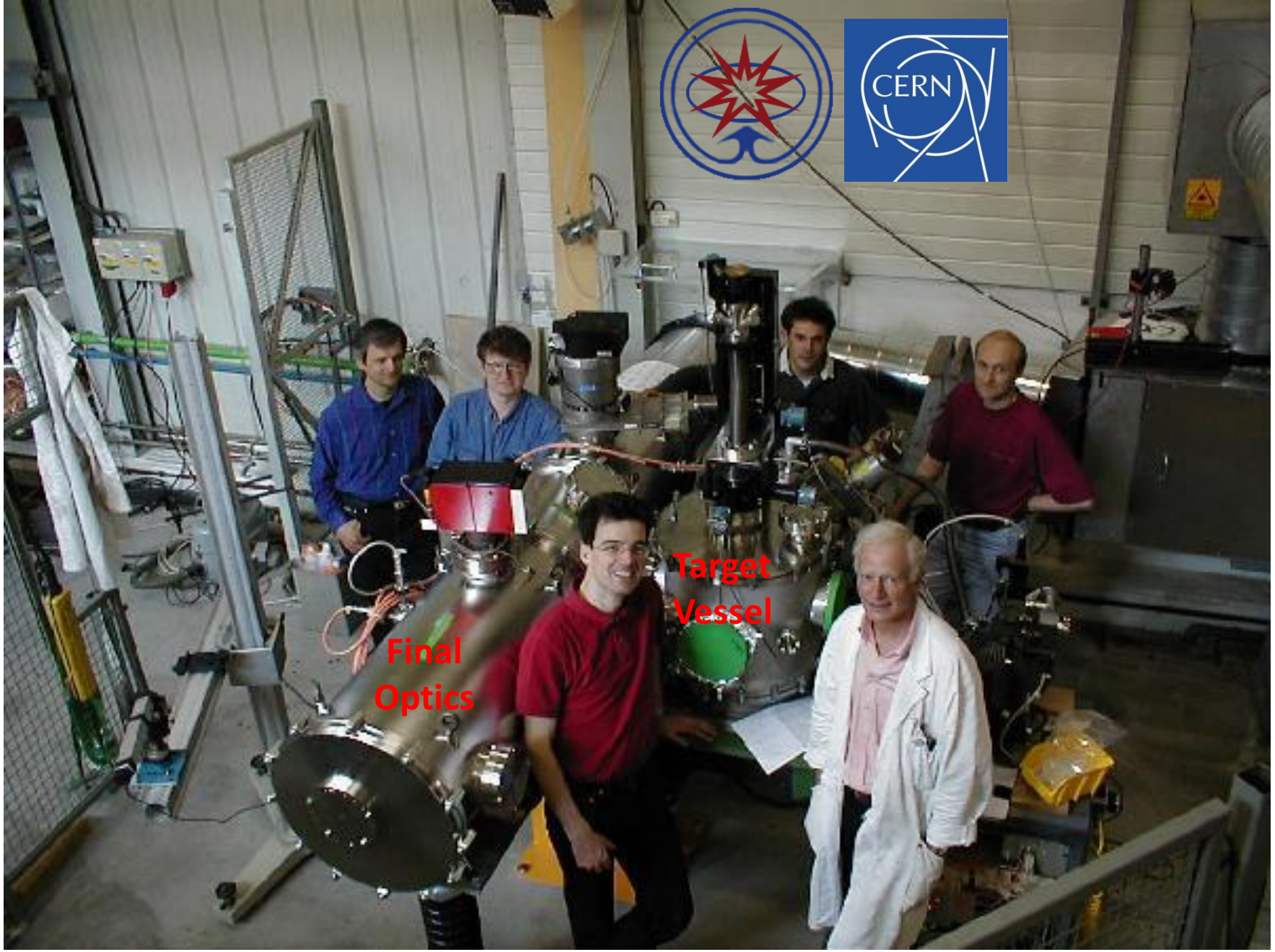
$W + Z$ Bosons

Exotic nuclei 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**

Positrons e^+

Electrons e^-

Photons

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

Plasmatrons

Microwave discharge

Protons

μ^+ Muons μ^-

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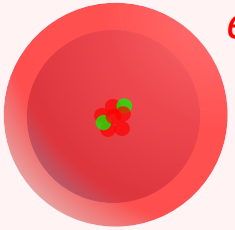
Highly charged ions e.g. Ag^{32+}



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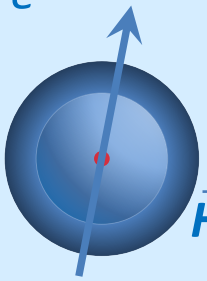

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$\vec{H}^-$

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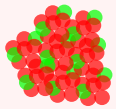
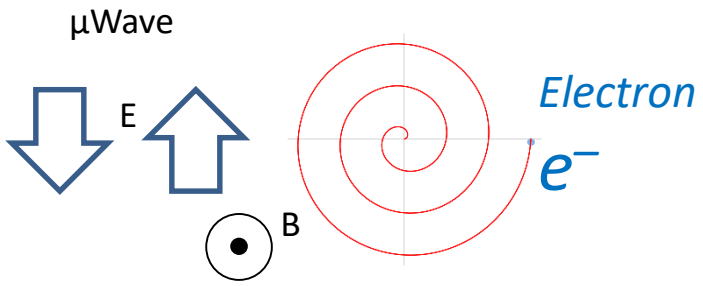


Microwave Ion Sources

Off resonance (or high pressure)

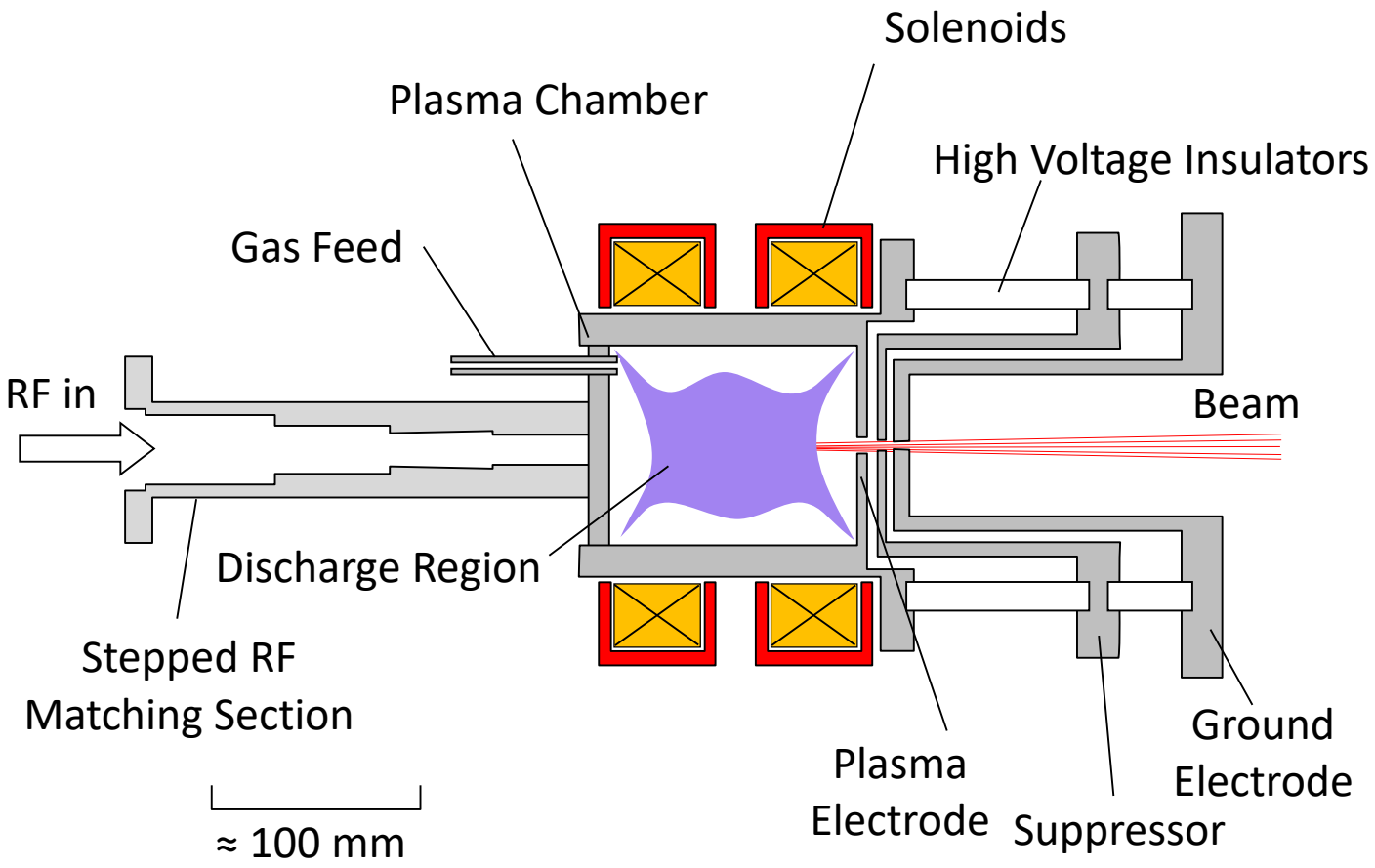
= Microwave discharge ion sources



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!

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+}

Electron Cyclotron Resonance

Higgs Bosons

$\uparrow\vec{e}^-$

$\uparrow\vec{p}$

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

Polarised particles $\vec{H}^-$

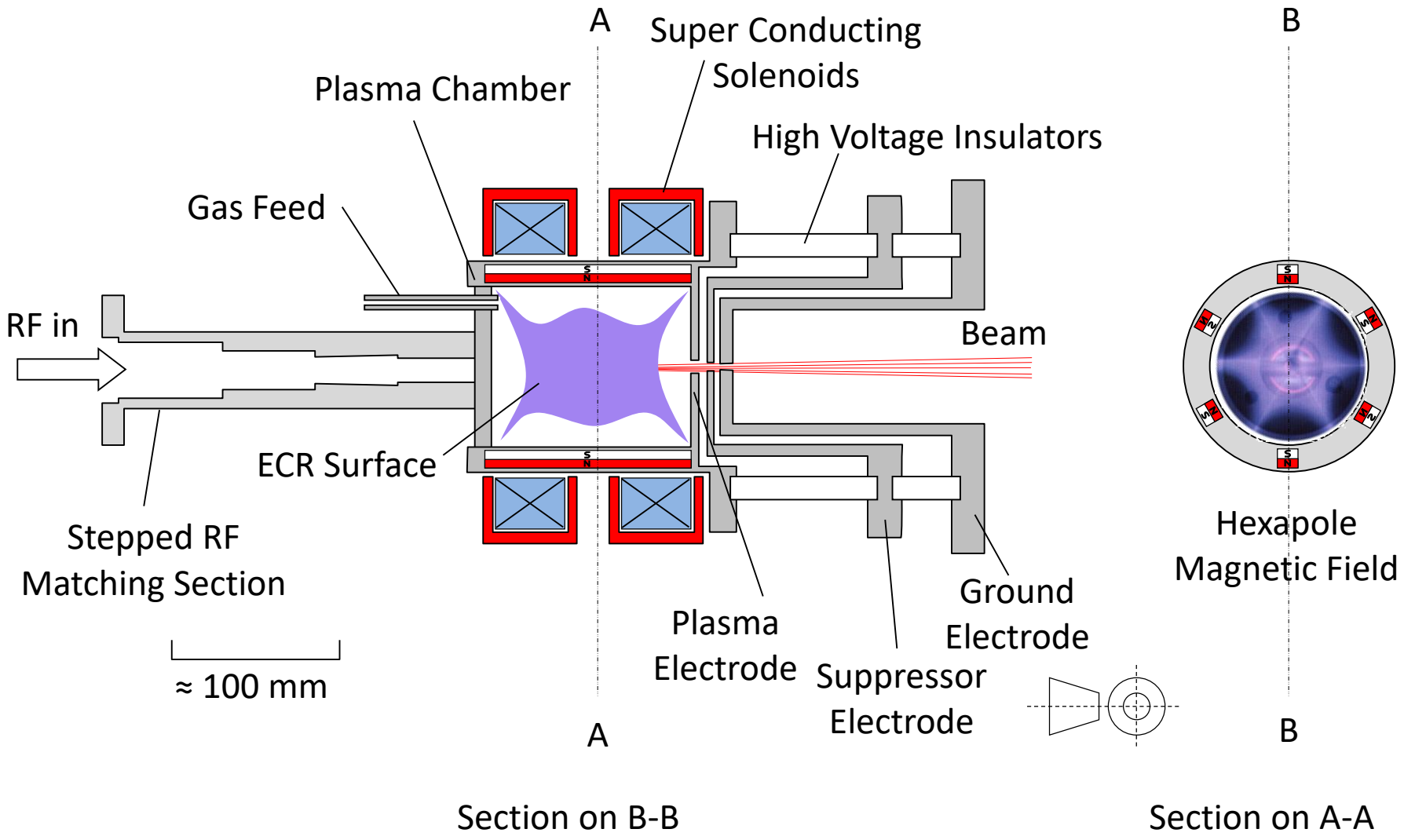
Zoo of curiosities

Tauons
Mesons
Baryons

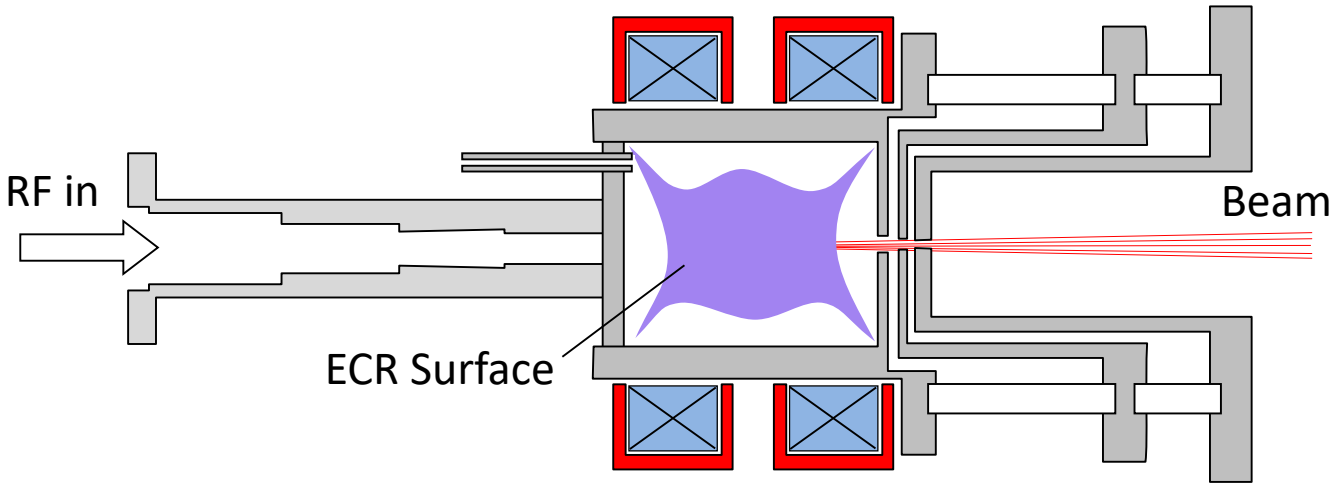
$W + Z$ Bosons

Exotic nuclei e.g. Lr^{103+}

ECR Ion Source



ECR Surface



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

Higher frequency = higher charge states

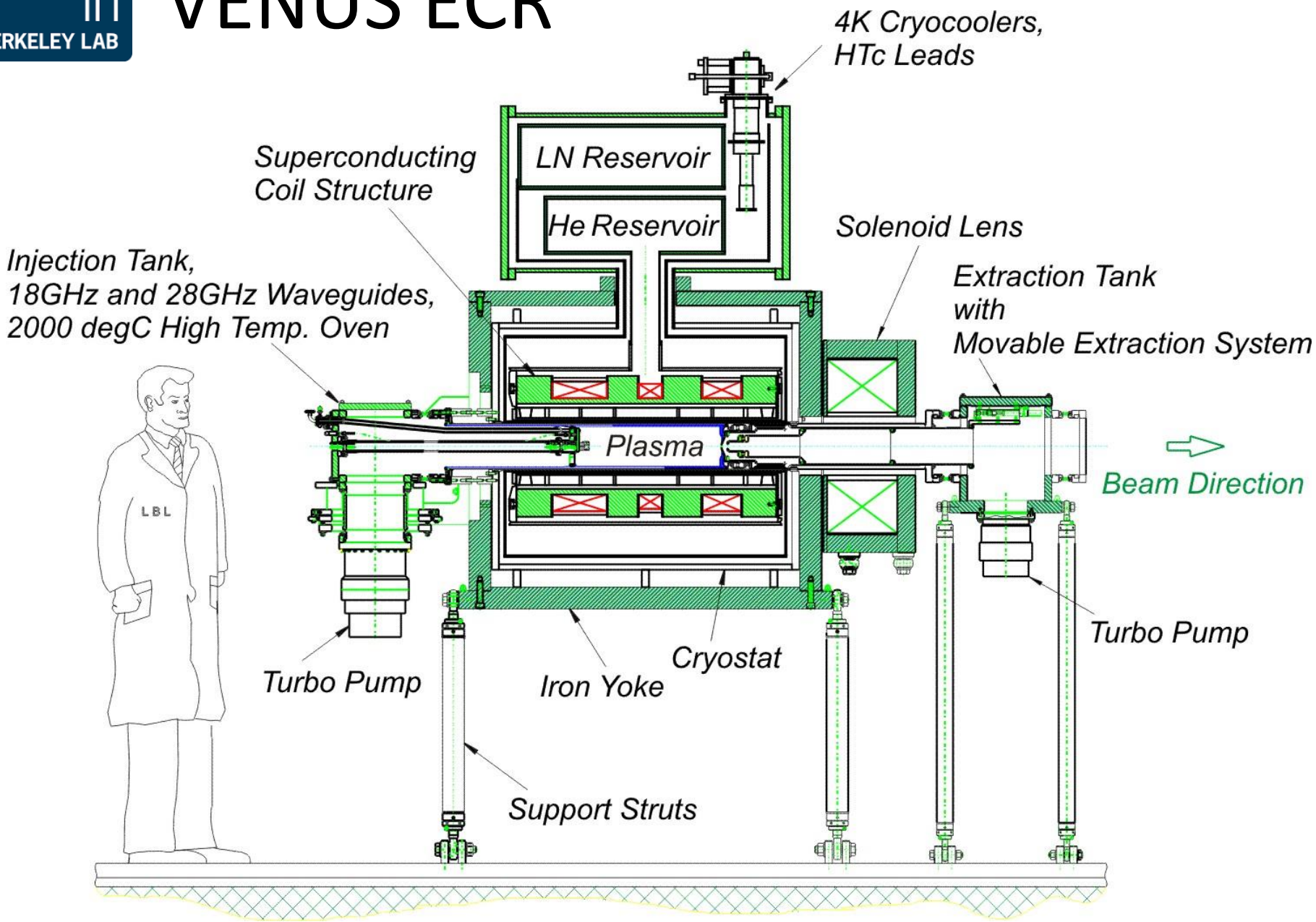
28 GHz superconducting VENUS ECR

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

Particles and **Sources**

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Electrons e^-

Photons

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Neutrons n

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

Negative ions H^-

Neutral particles H^0

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

$\uparrow\vec{e}^-$

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$\uparrow\vec{p}$

Polarised particles $\vec{H}^-$

Zoo of curiosities

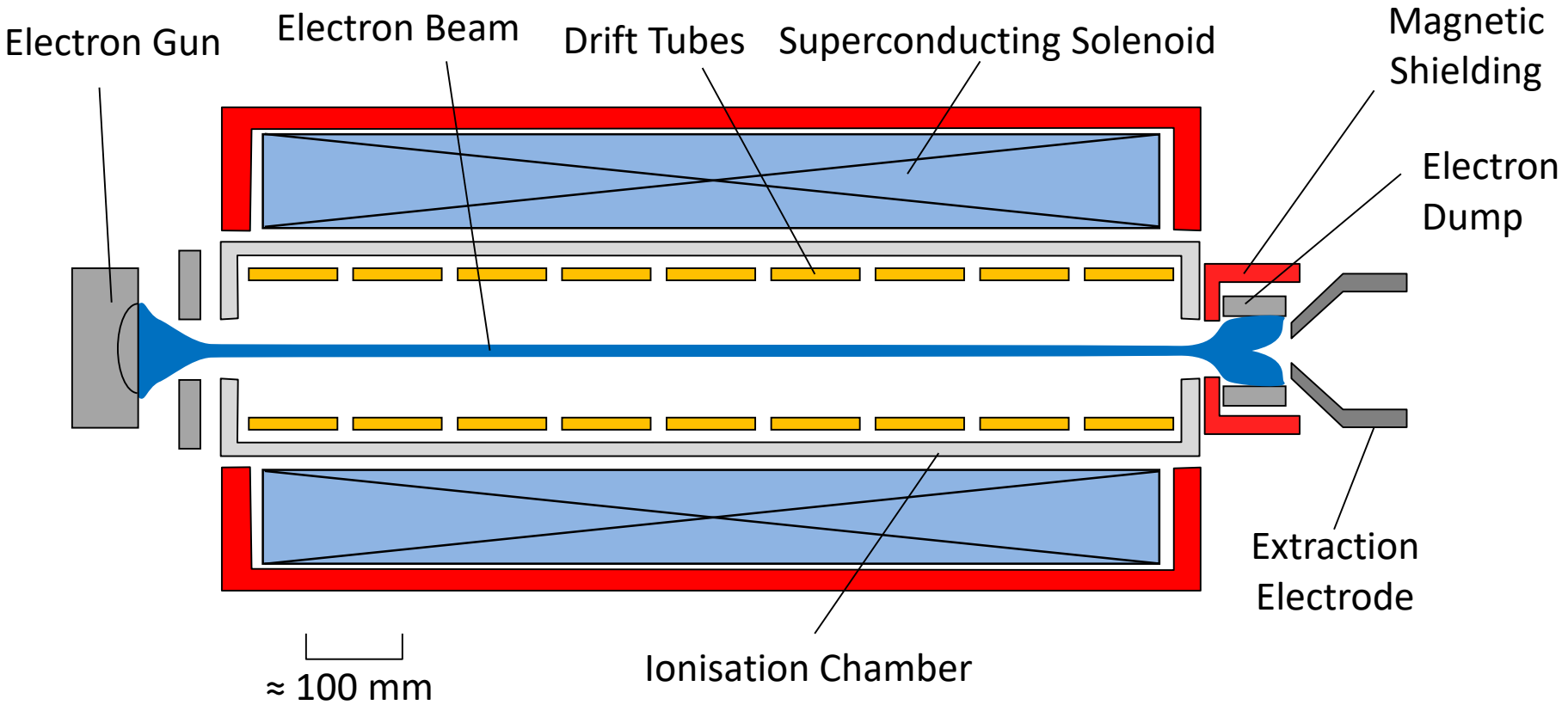
Tauons
Mesons
Baryons

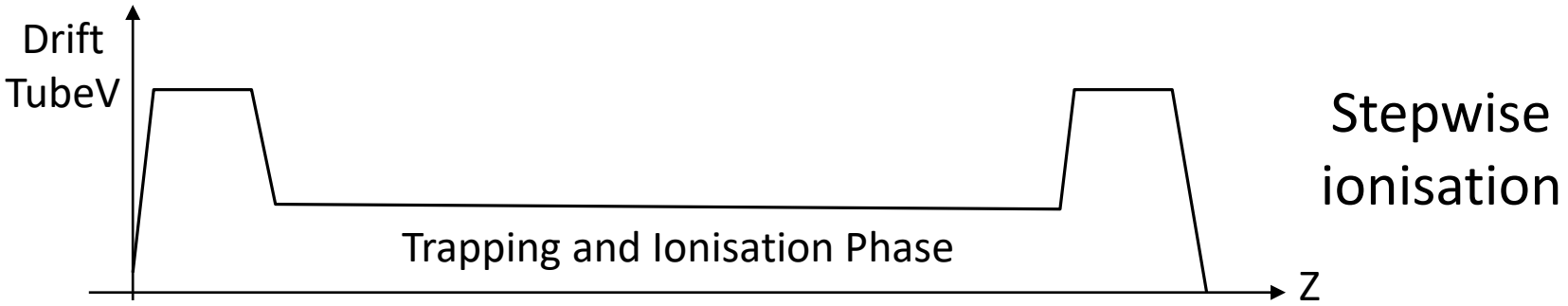
$W + Z$ Bosons

Electron beam

Exotic nuclei e.g. Lr^{103+}

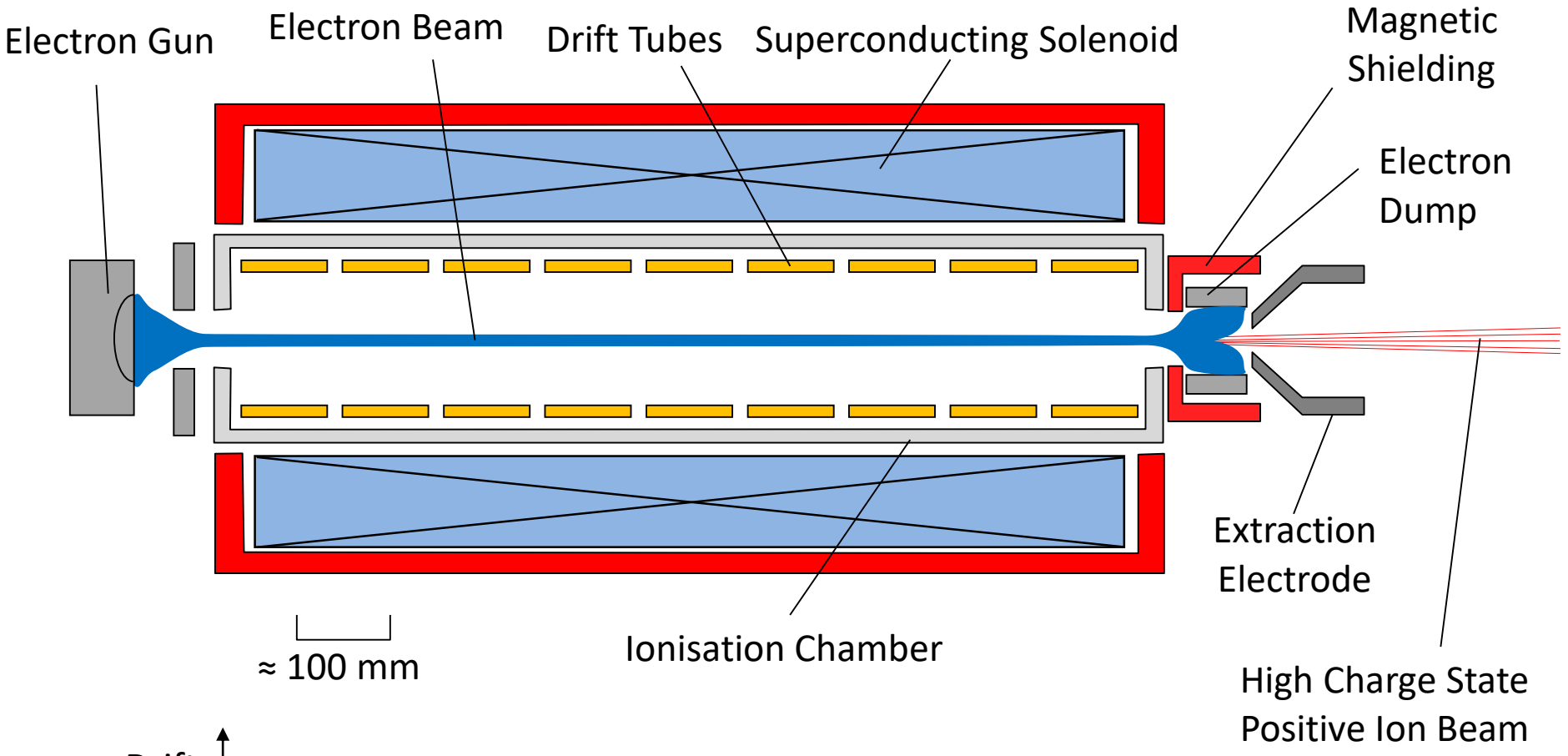
Electron Beam Ion Sources

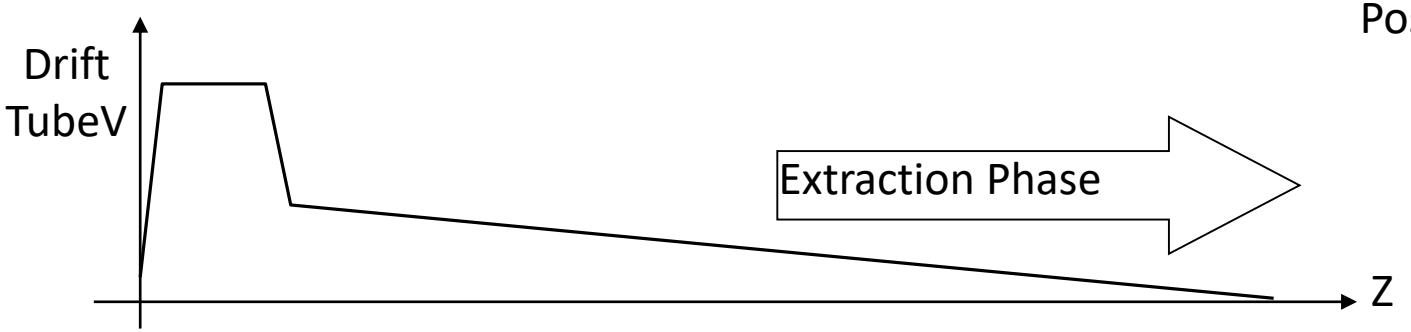


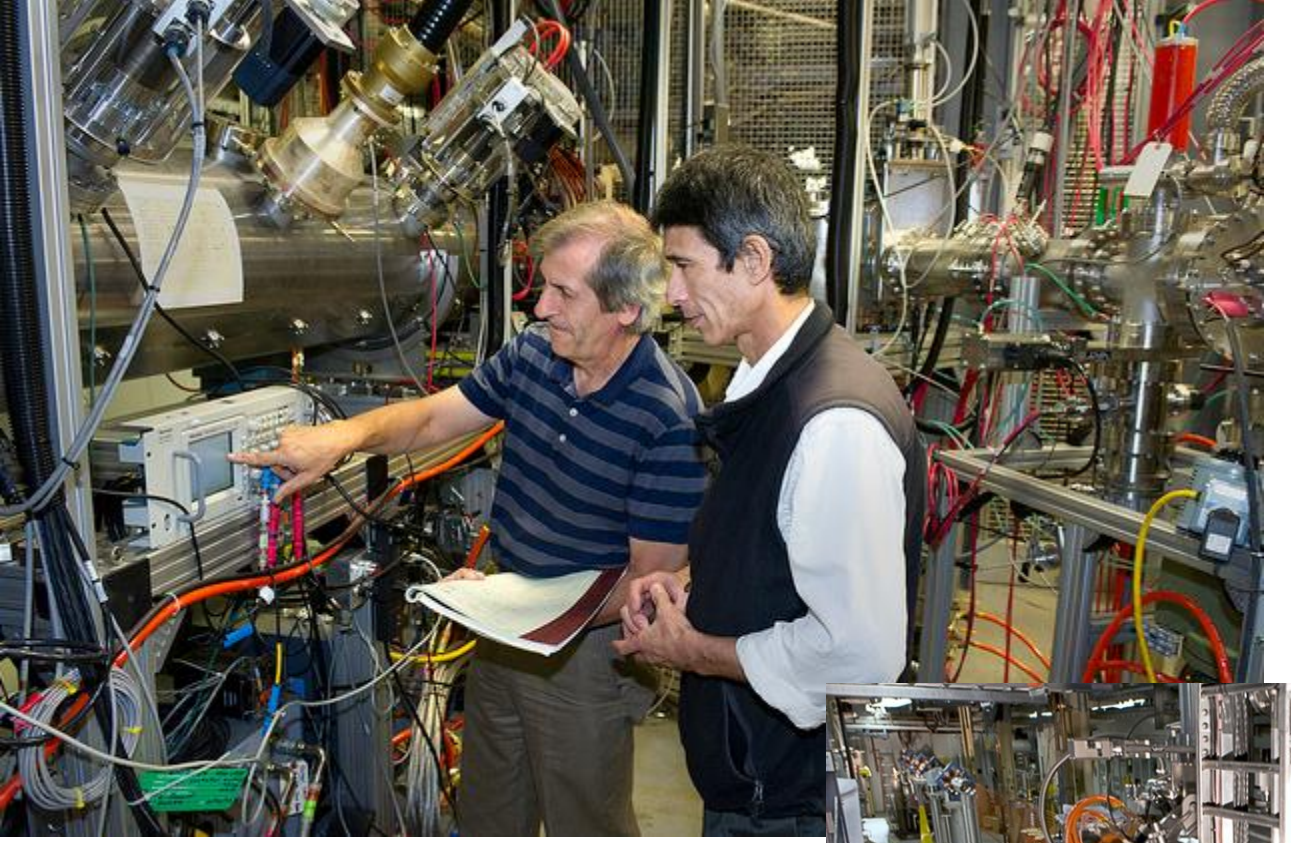


Stepwise ionisation

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

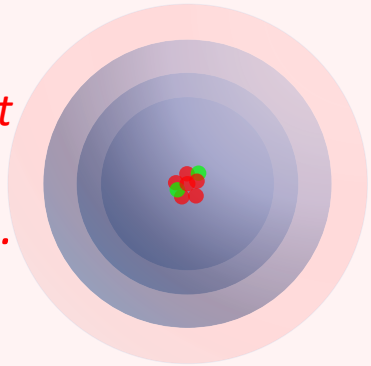
Protons

μ^+ Muons μ^-

Antiprotons

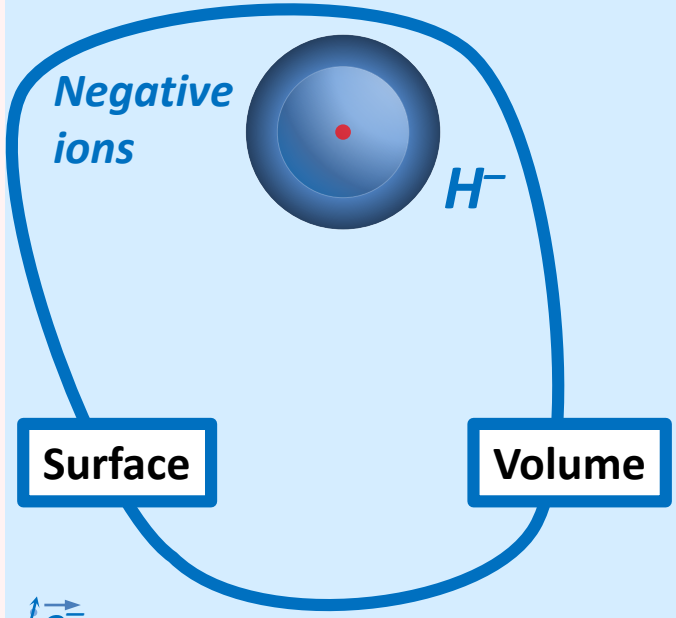
Neutrons n

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

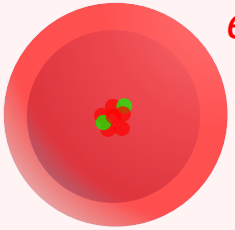


Neutral particles

H^0



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



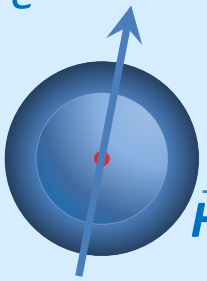
Higgs Bosons

$\uparrow\vec{e^-}$

Fully stripped nuclei

e.g. U^{92+}

$\uparrow\vec{p}$



Polarised particles

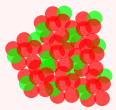
$\vec{H^-}$

Zoo of curiosities

Tauons
Mesons
Baryons

$W + Z$ Bosons

Exotic nuclei



e.g. Lr^{103+}

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

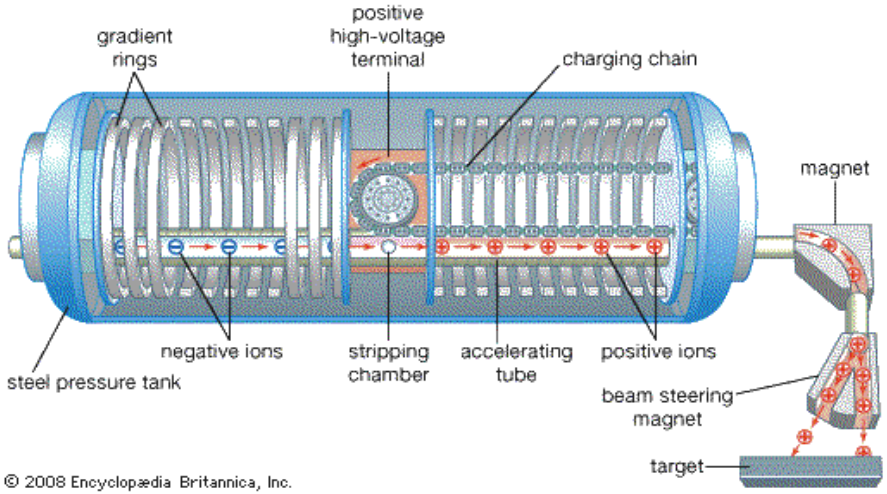
H^- has much larger cross sections than H^0

- Up to 30 times for e^- collisions
- Up to 100 times for H^+ collisions

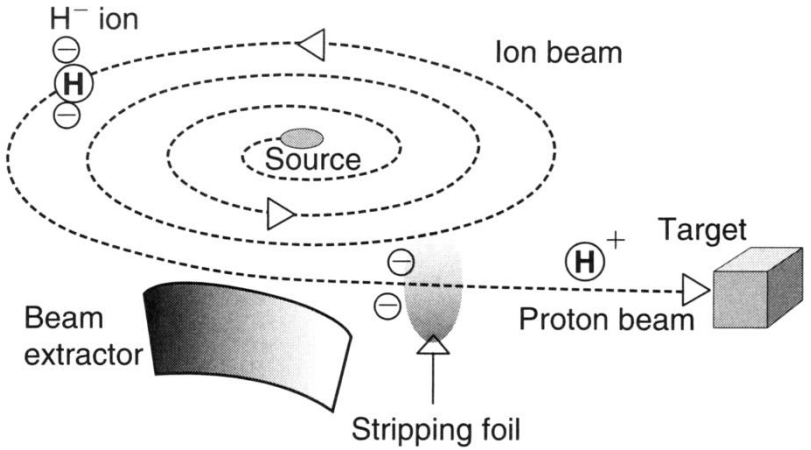
H^- are very fragile!

Applications

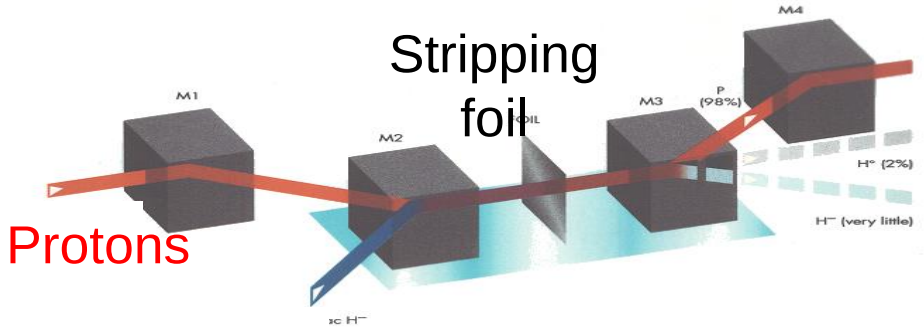
Tandem accelerators



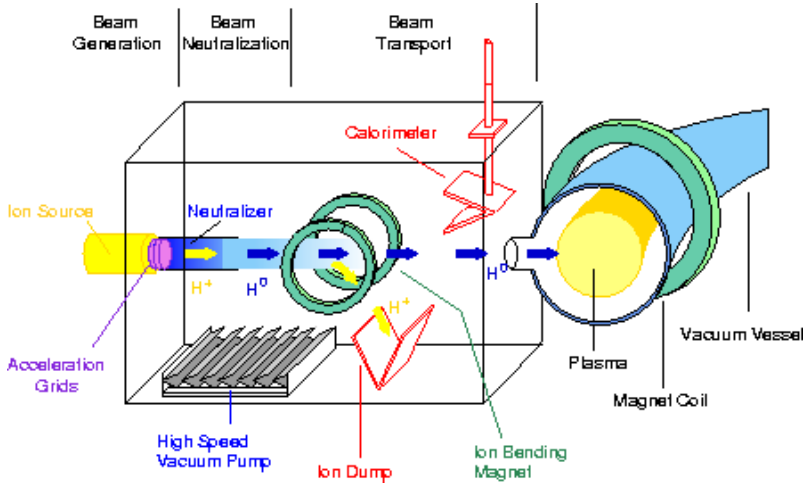
Cyclotron extraction



Multi-turn injection into rings



Neutral Beams



Early attempts at producing negative ion beams:

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

2. Extraction from existing ion sources
    - mostly electrons extracted

Particles and **Sources**

Positrons e^+

Electrons e^-

Photons

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

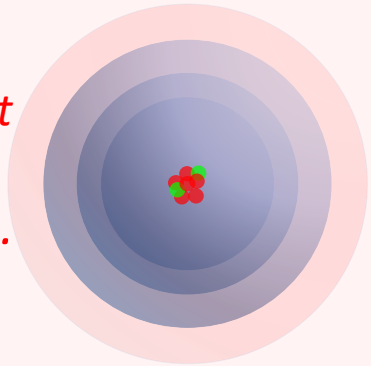
Protons

μ^+ Muons μ^-

Antiprotons

Neutrons n

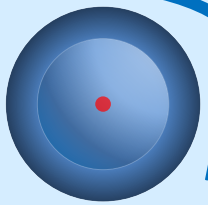
Light ions e.g. C^{4+}



Neutral particles

H^0

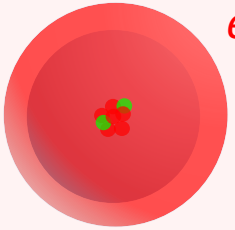
Negative ions



H^-

Surface plasma

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



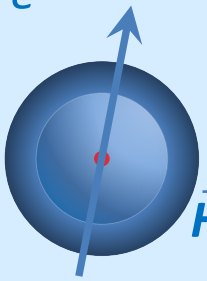
Higgs Bosons

$\uparrow\vec{e}^-$

Fully stripped nuclei

e.g. U^{92+}

$\uparrow\vec{p}$



Polarised particles

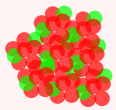
$\vec{H}^-$

Zoo of curiosities

Tauons
Mesons
Baryons

$W + Z$ Bosons

Exotic nuclei



e.g. Lr^{103+}

Early 1970s Budker Institute of Nuclear Physics

Novosibirsk

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

Surface Plasma Sources (SPS)

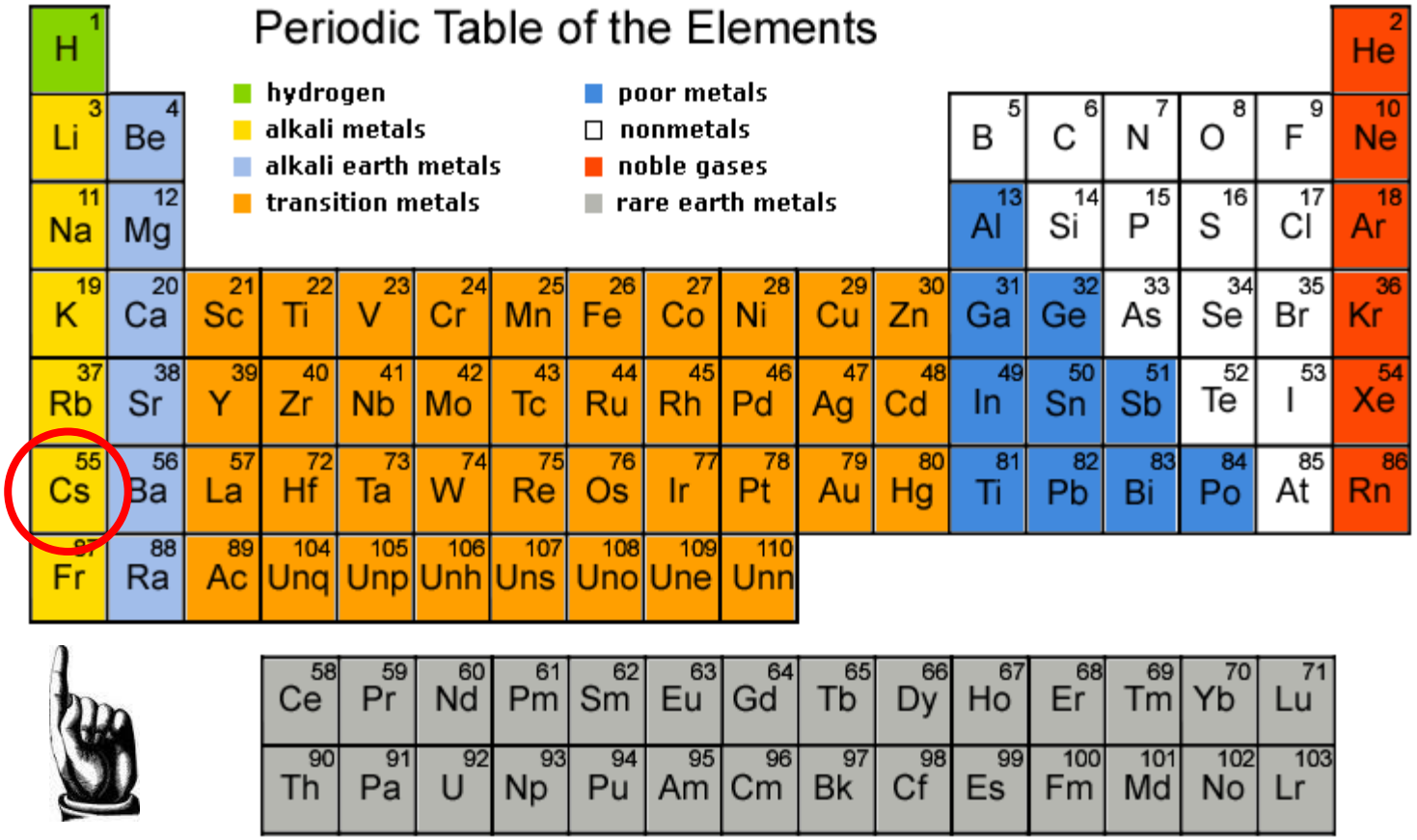
Gennady Dimov

Yuri Belchenko

Vadim Dudnikov

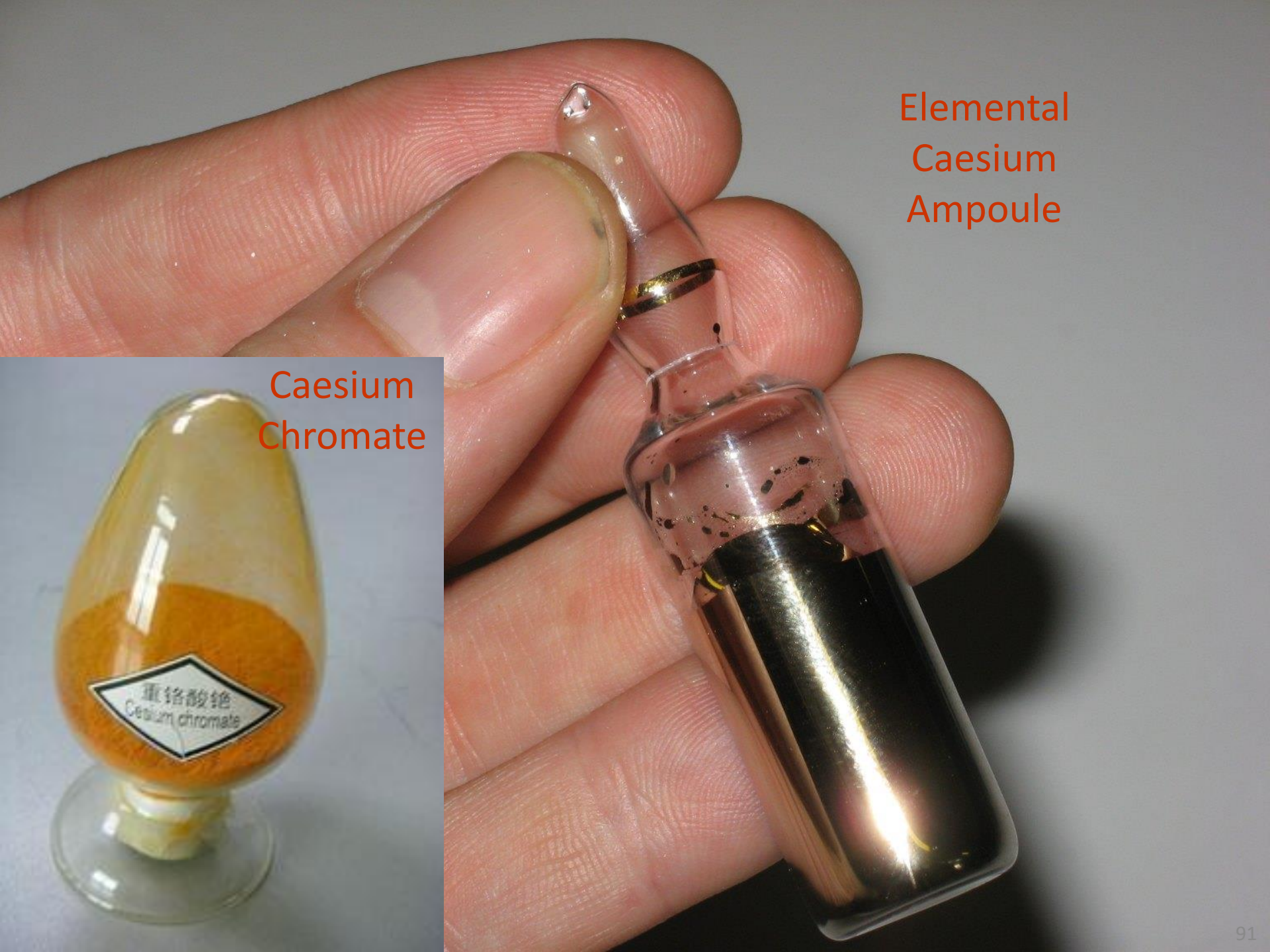
Caesium! – The magic elixir

More reactive

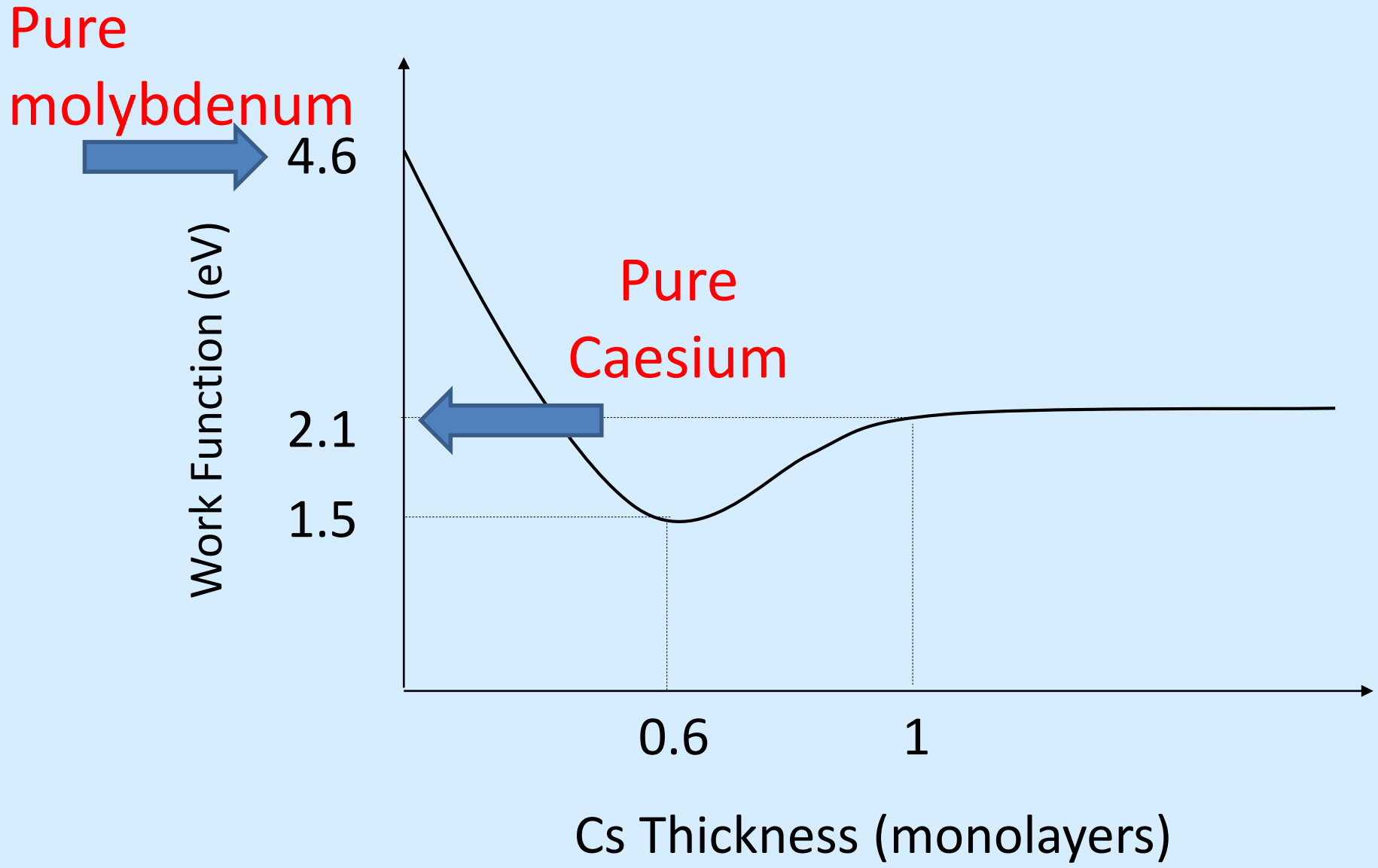


1 electron in the outer orbital

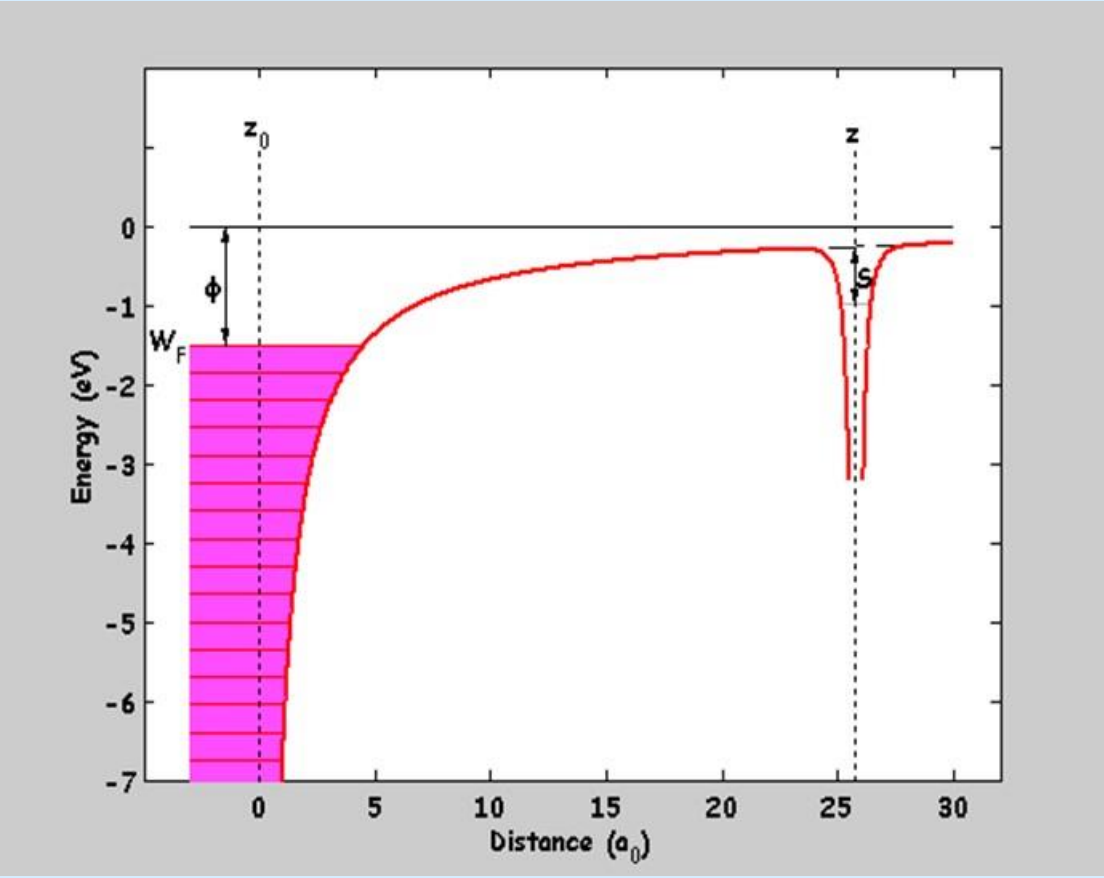
An amazing donor of electrons
= great for making negative ions

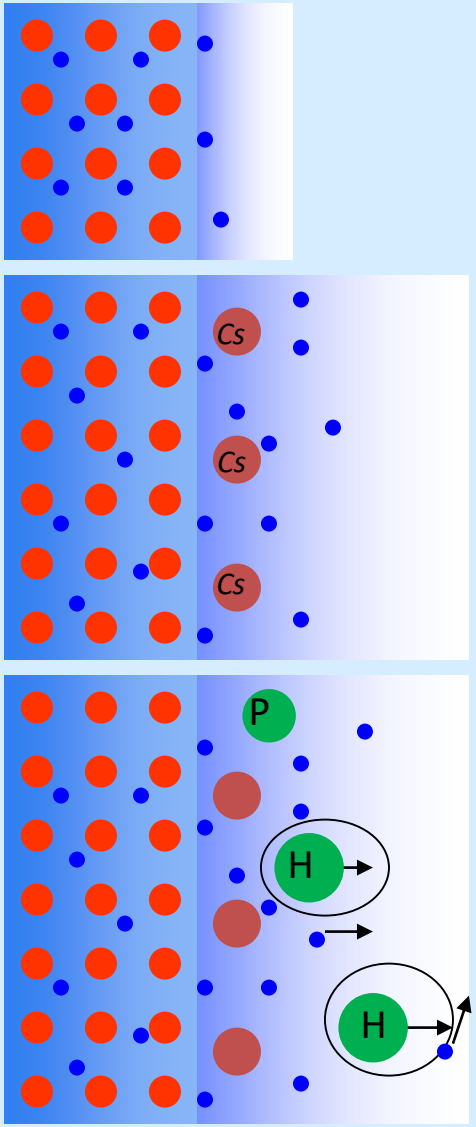

Elemental
Caesium
Ampoule
Caesium
Chromate
重铬酸铯
Cesium chromate

Caesium coverage and work function



Fermilevels





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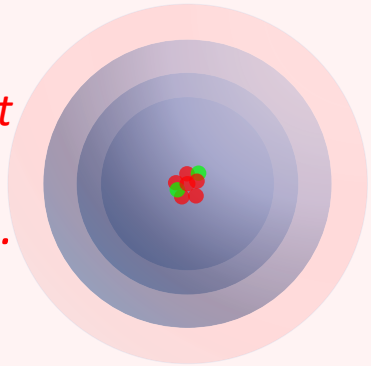
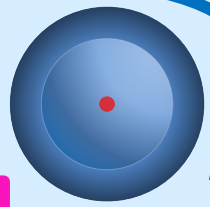


Neutral particles

H^0

Negative ions

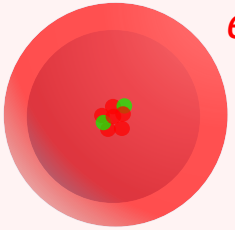


H^-

Penning and Magnetron

Surface plasma

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



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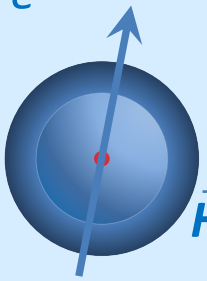
e.g. U^{92+}

$\uparrow\vec{p}$



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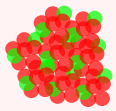


e.g. Lr^{103+}

Early 1970s Budker Institute of Nuclear Physics Novosibirsk

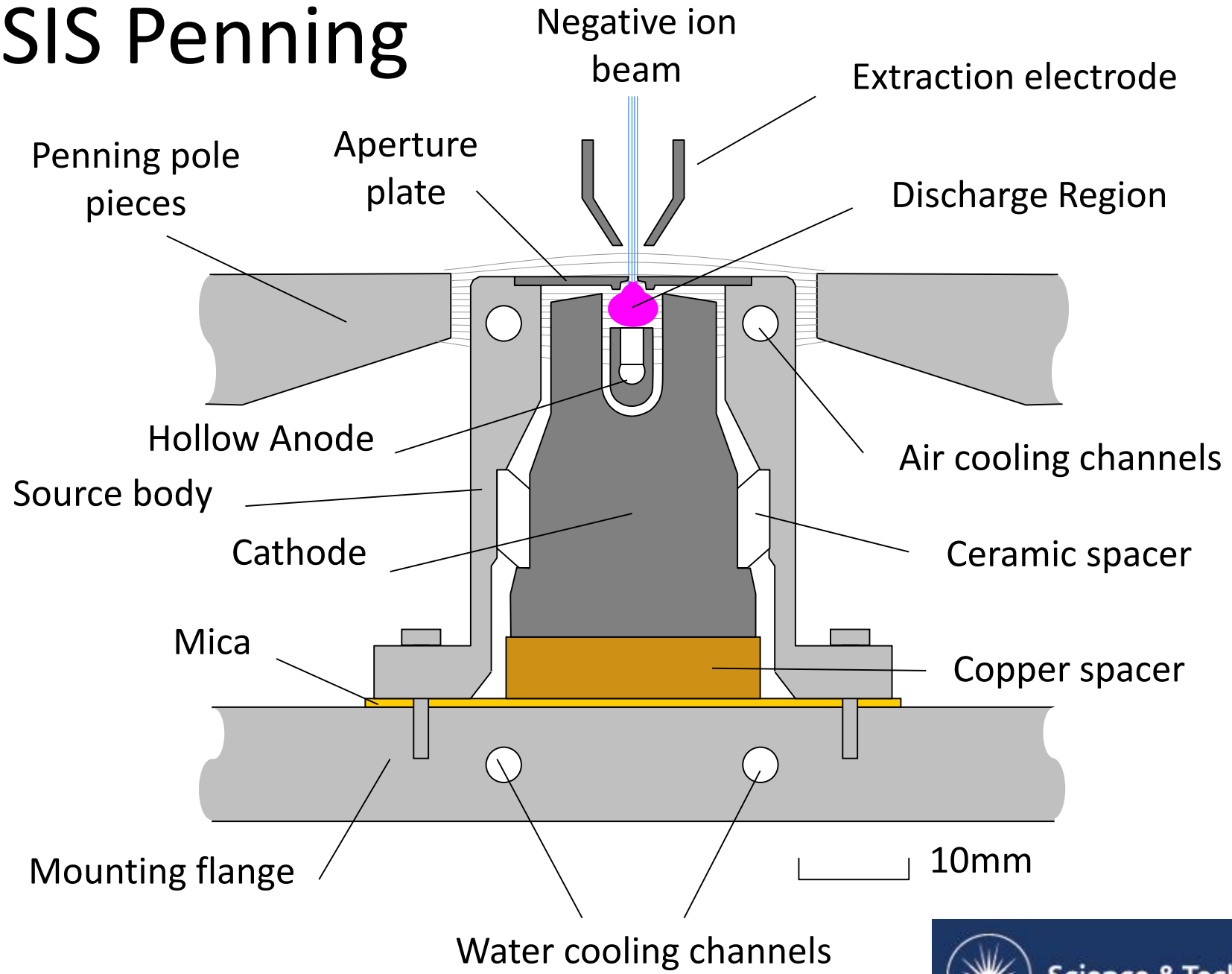
Vadim Dudnikov

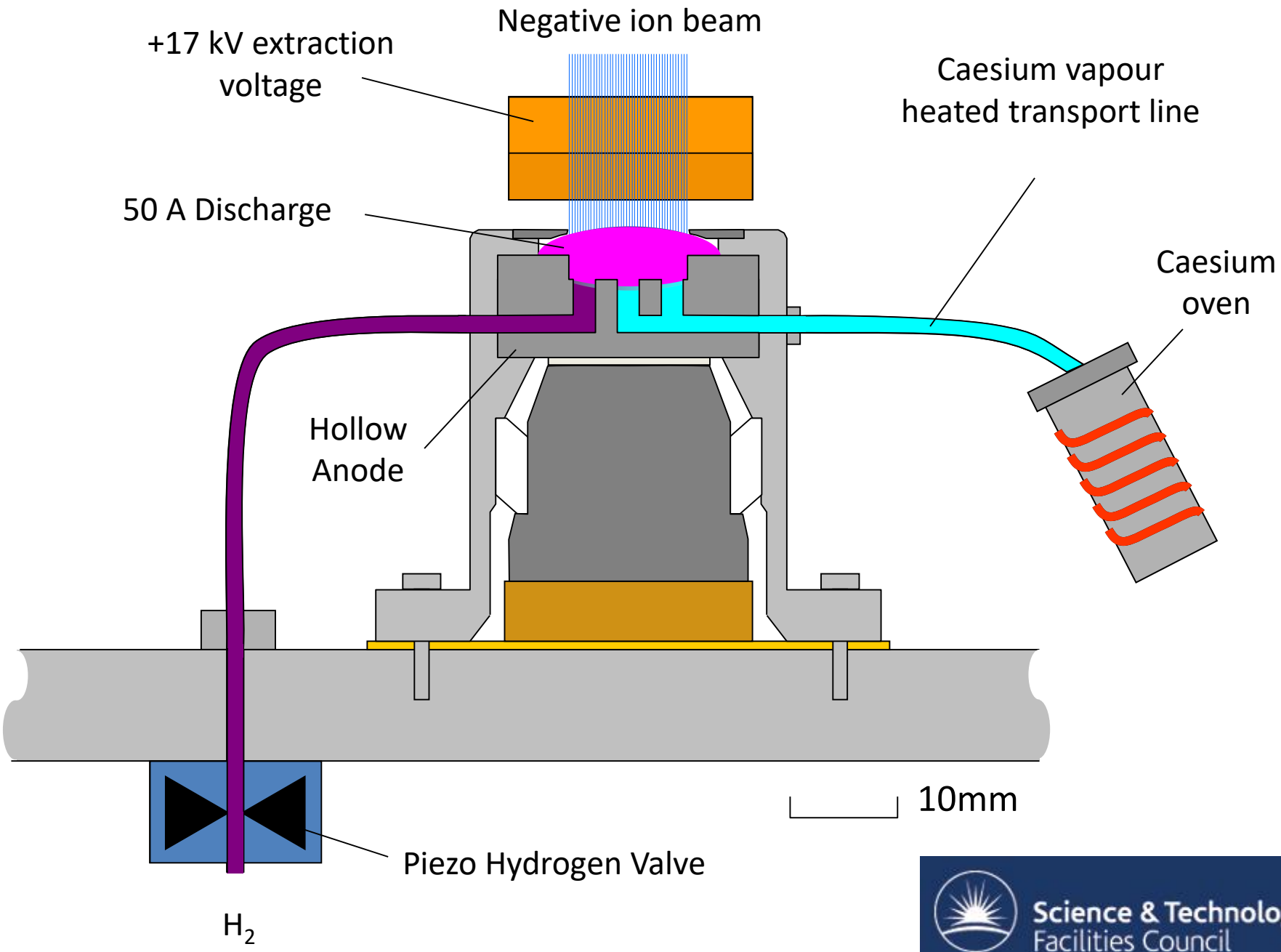
Penning SPS

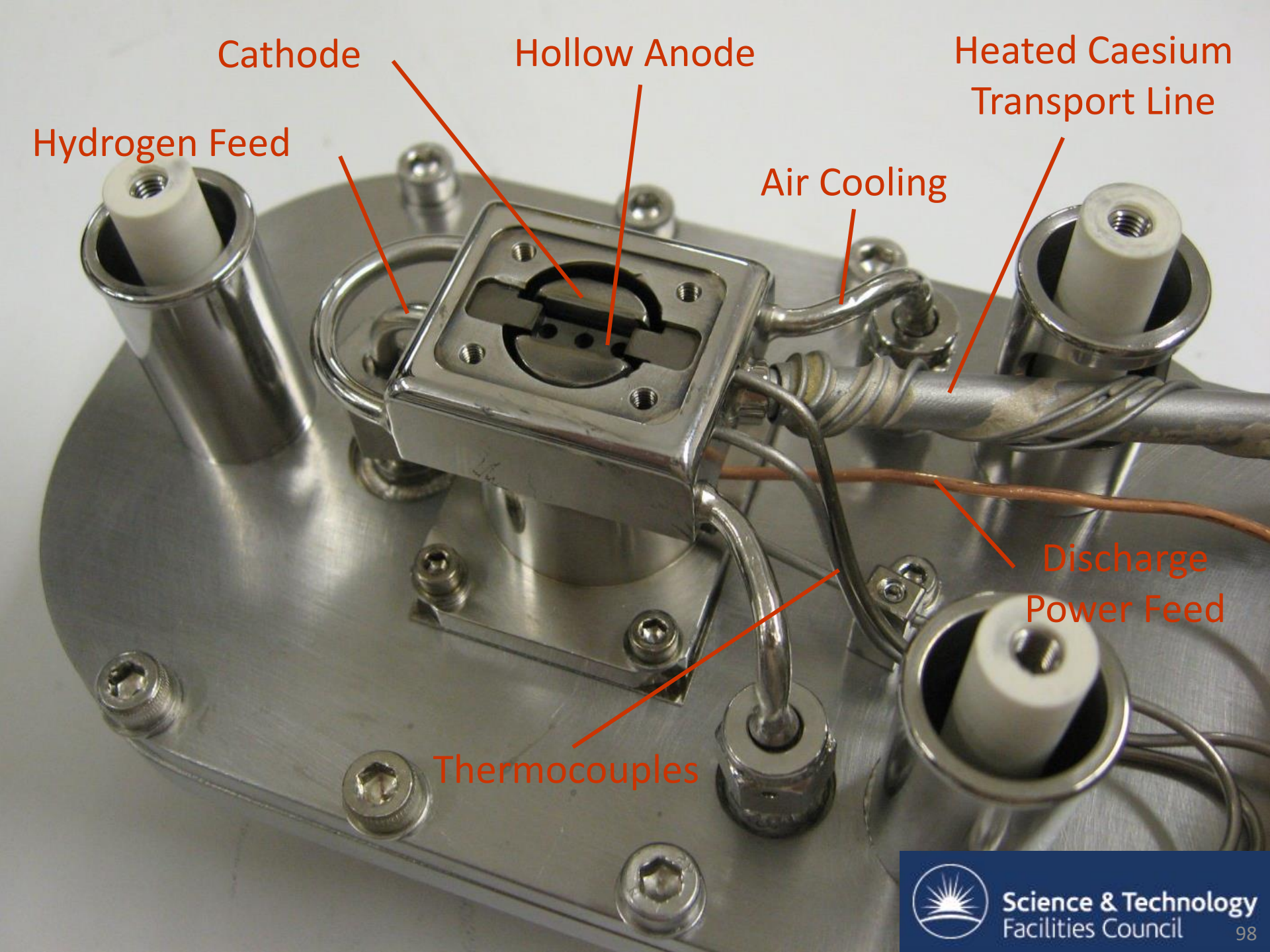
Very high current density > 1 Acm^{-2}

Low noise

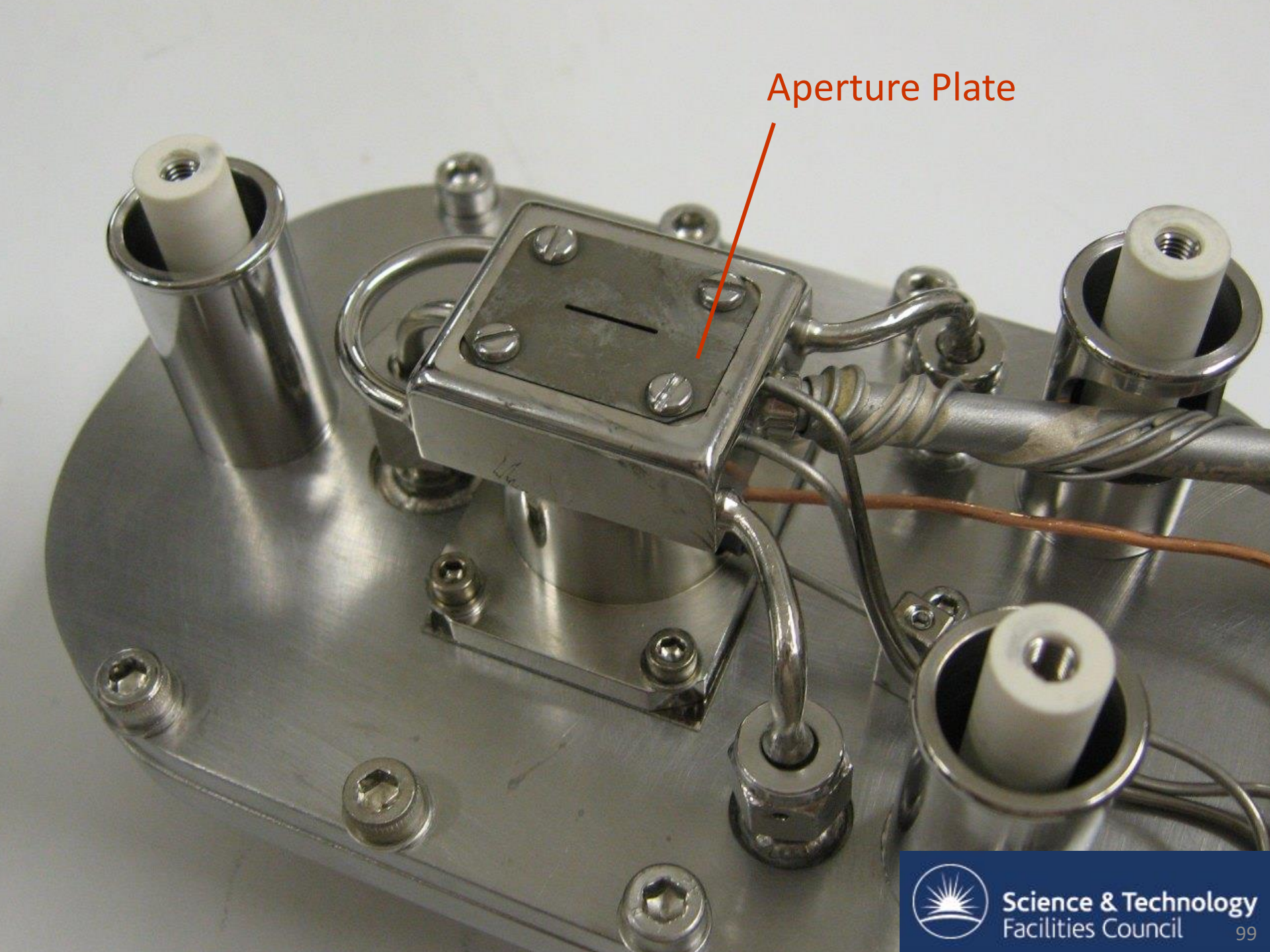
ISIS Penning

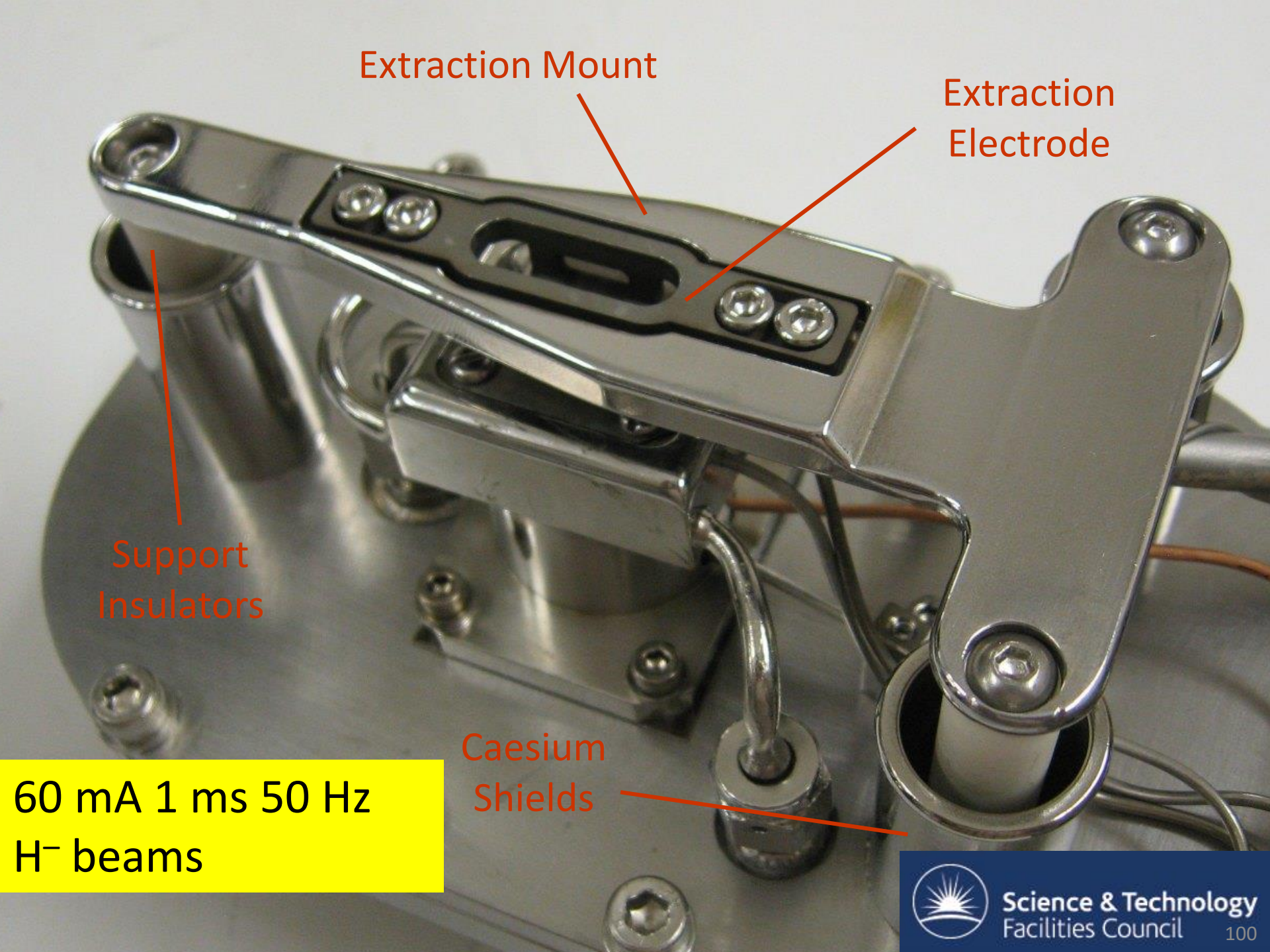



Negative ion beam
+17 kV extraction voltage
Caesium vapour heated transport line
50 A Discharge
Caesium oven
Hollow Anode
10mm
Piezo Hydrogen Valve
H_2



Science & Technology Facilities Council


Aperture Plate


Extraction Mount
Extraction Electrode
Support Insulators
Caesium Shields
60 mA 1 ms 50 Hz
H⁻ beams

Early 1970s Budker Institute of Nuclear Physics Novosibirsk

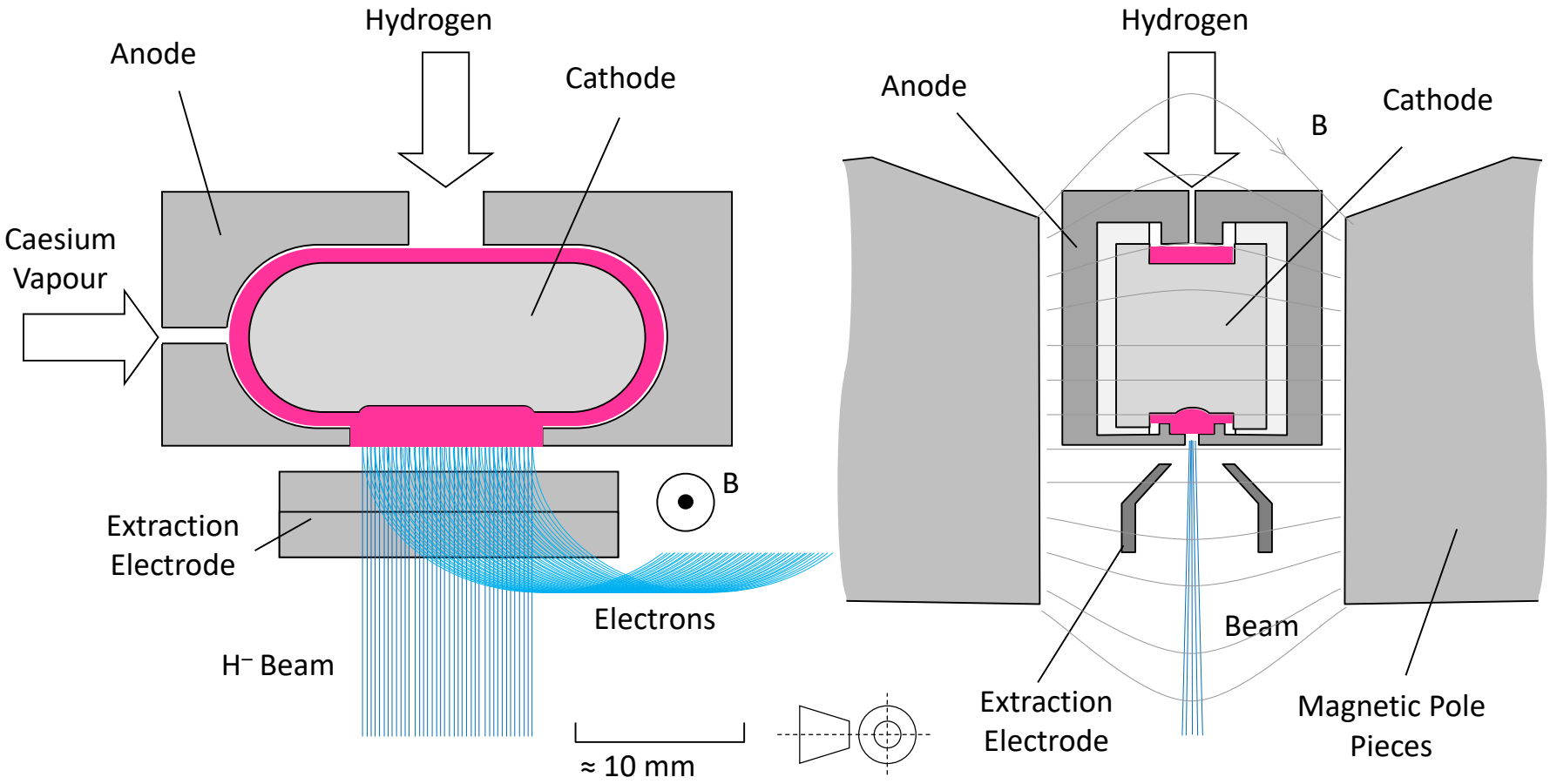
Magnetron SPS

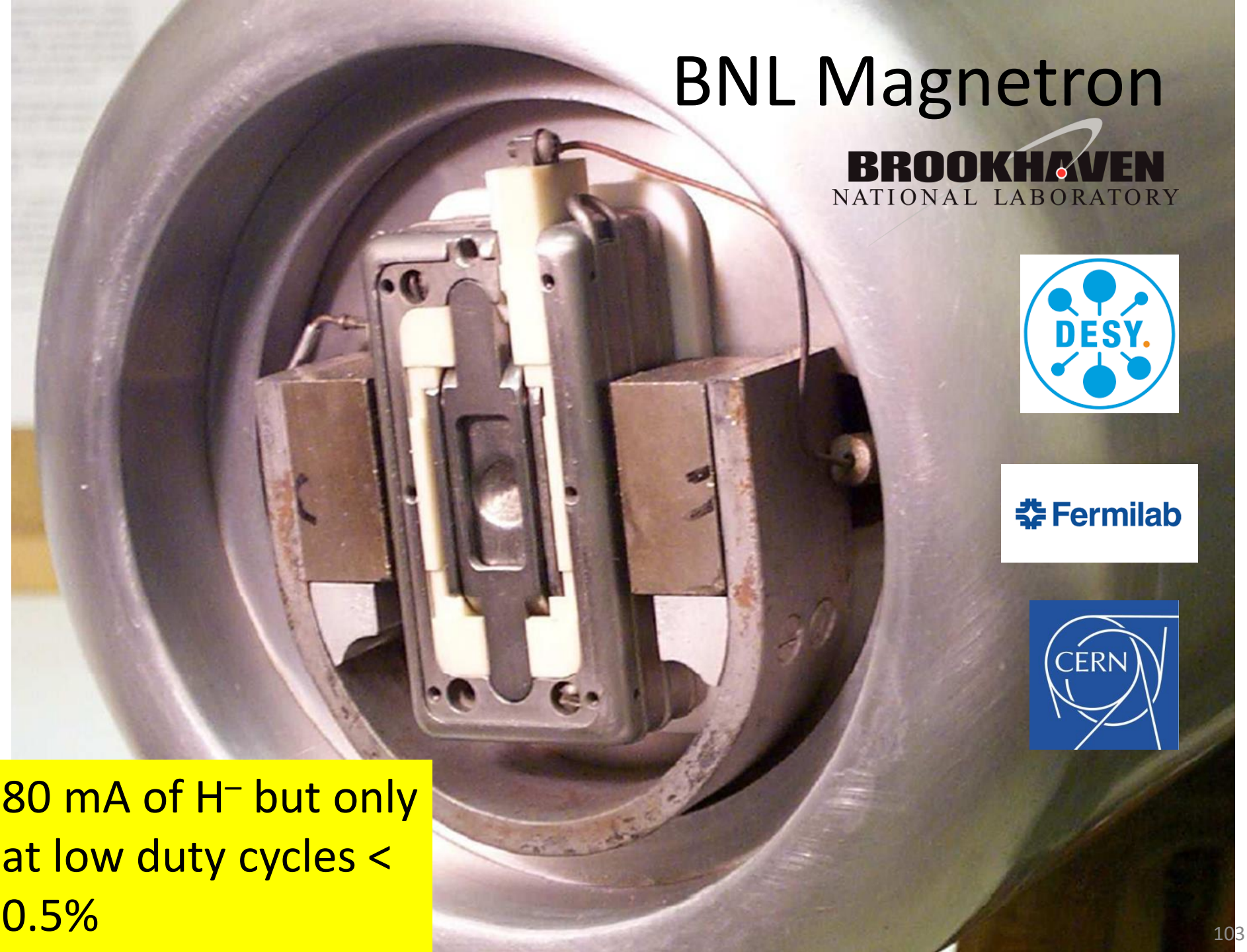
Gennady Dimov

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%

Particles and **Sources**

Positrons e^+

Electrons e^-

Photons

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

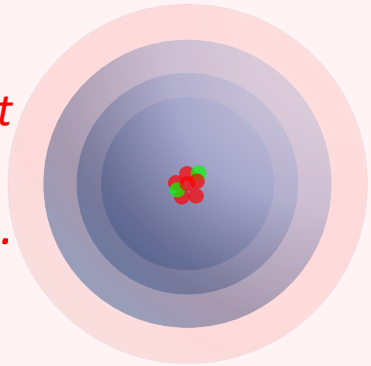
Protons

μ^+ Muons μ^-

Antiprotons

Neutrons n

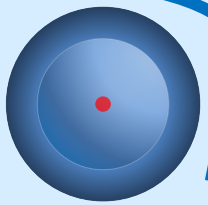
Light ions e.g. C^{4+}



Neutral particles

H^0

Negative ions



H^-

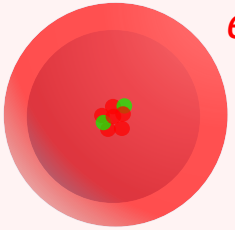
Surface plasma

Surface converter

Multicusp

Filament

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



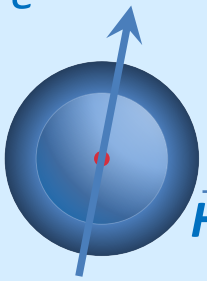
Higgs Bosons

$\vec{e}$

Fully stripped nuclei

e.g. U^{92+}

$\vec{p}$



Polarised particles

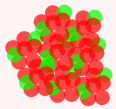
$\vec{H}^-$

Zoo of curiosities

Tauons
Mesons
Baryons

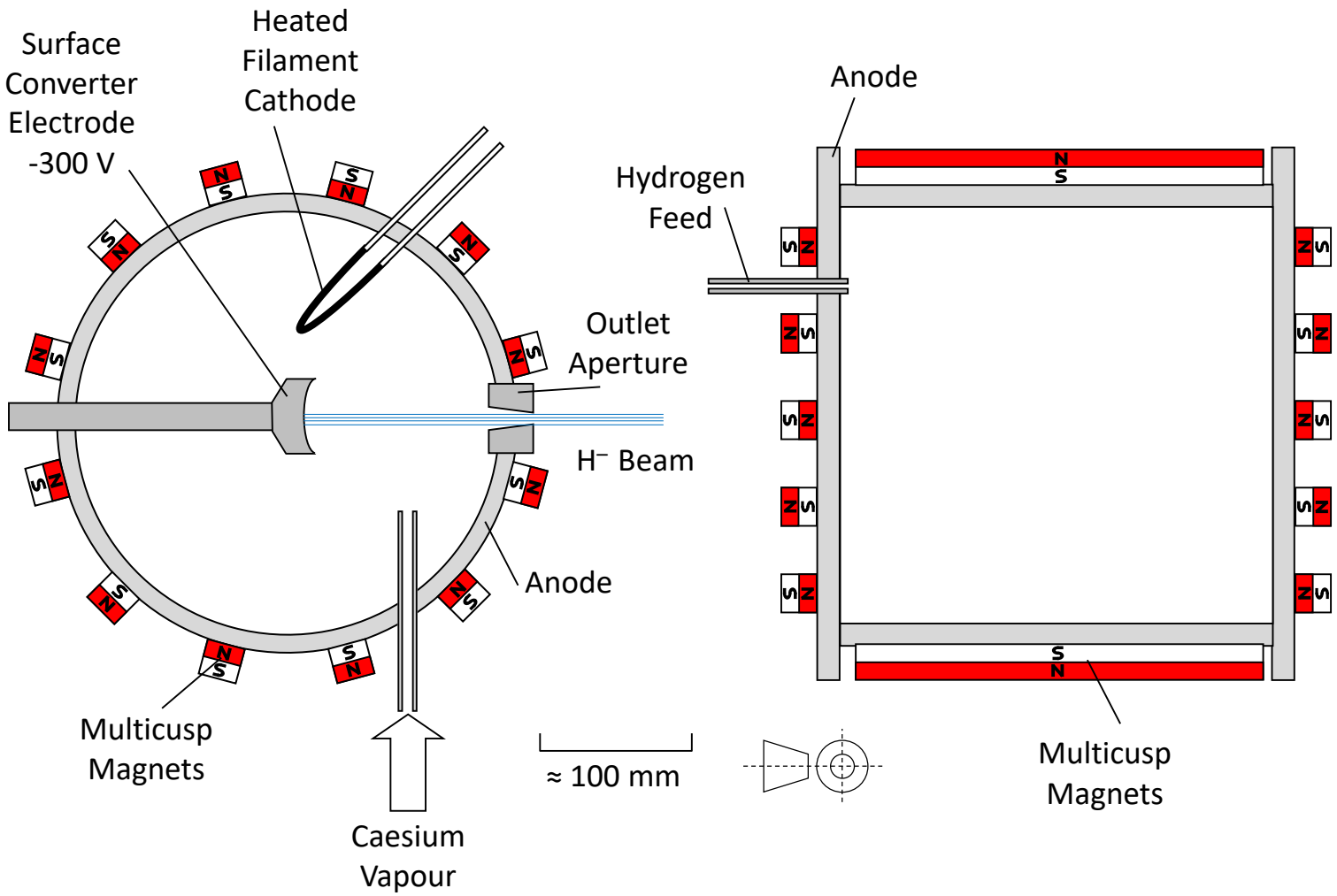
$W + Z$ Bosons

Exotic nuclei

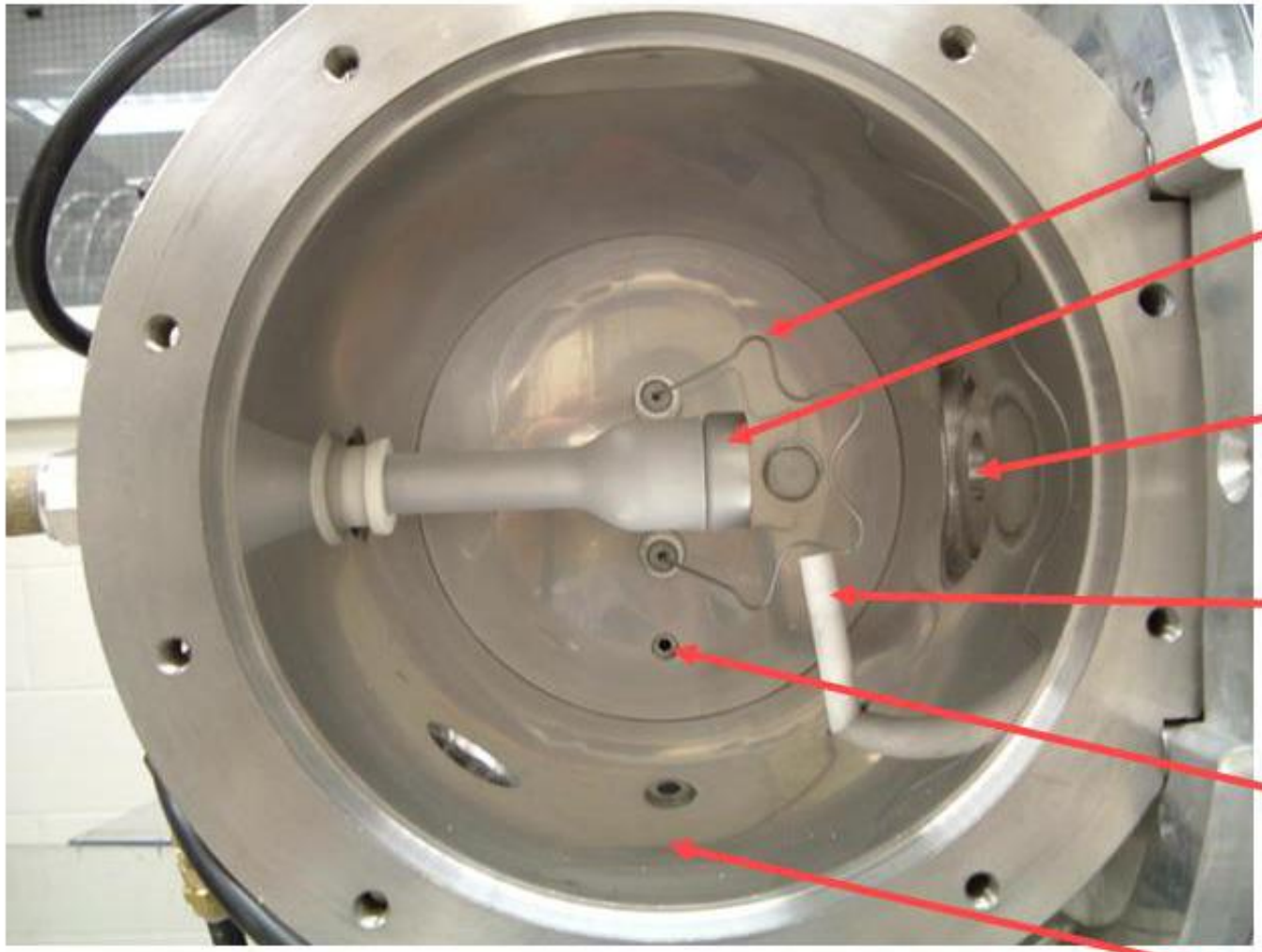


e.g. Lr^{103+}

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

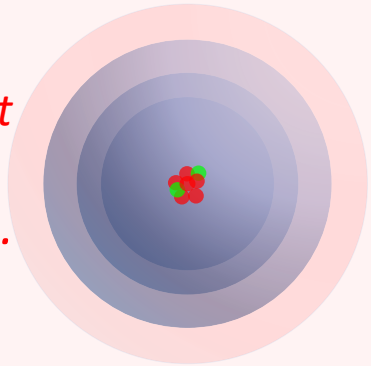
Protons

μ^+ Muons μ^-

Antiprotons

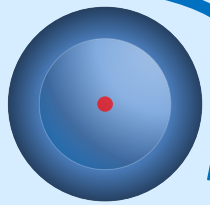
Neutrons n

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



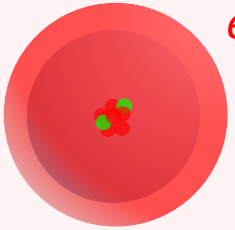
Neutral particles

Negative ions



Volume

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

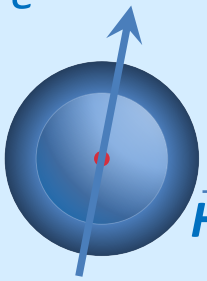


Higgs Bosons

$\vec{e}^-$

Fully stripped nuclei

$\vec{p}$



Polarised particles

$\vec{H}^-$

Zoo of curiosities

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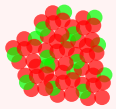
Baryons

$W + Z$ Bosons

Exotic nuclei



Marthe Bacal
Ecole Polytechnique
mid 1970's

ÉCOLE POLYTECHNIQUE ParisTech

Volume Production

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

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

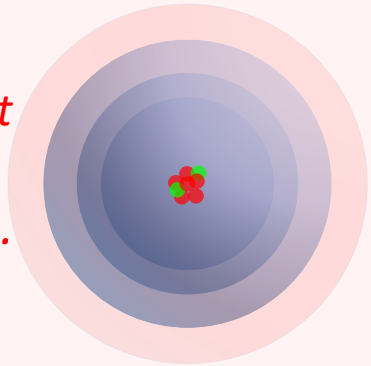
Protons

μ^+ Muons μ^-

Antiprotons

Neutrons n

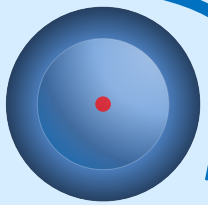
Light ions e.g. C^{4+}



Neutral particles

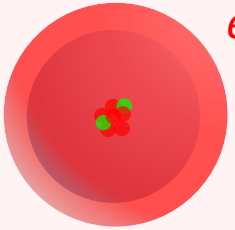
H^0

Negative ions



H^-

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



Multicusp

Filament

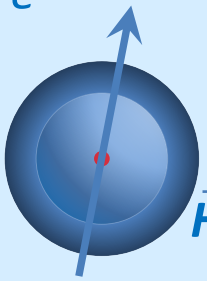
Volume

Higgs Bosons

$\uparrow\vec{e^-}$

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

$\uparrow\vec{p}$



Polarised particles

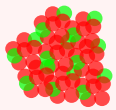
$\vec{H^-}$

Zoo of curiosities

Tauons
Mesons
Baryons

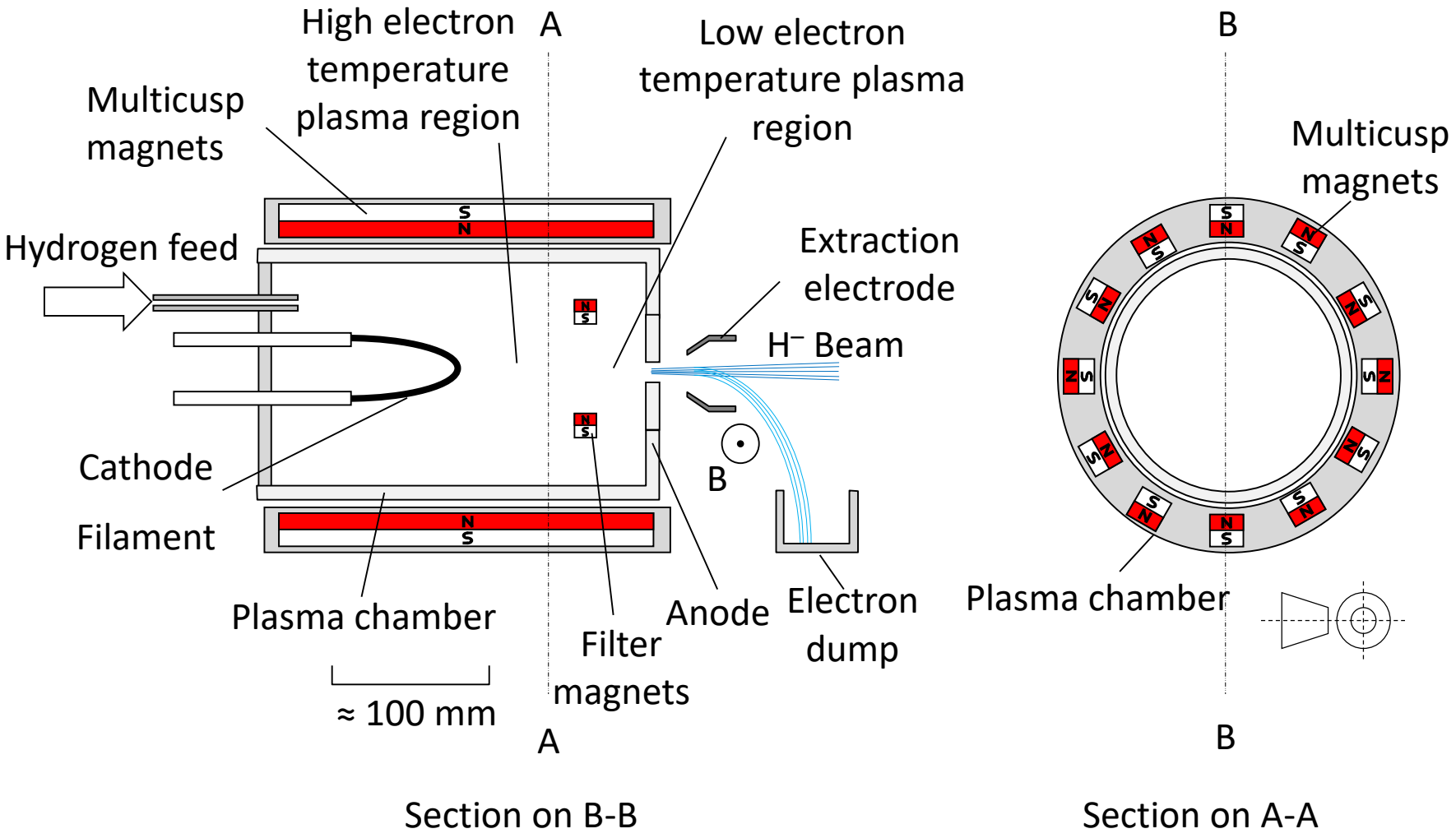
$W + Z$ Bosons

Exotic nuclei

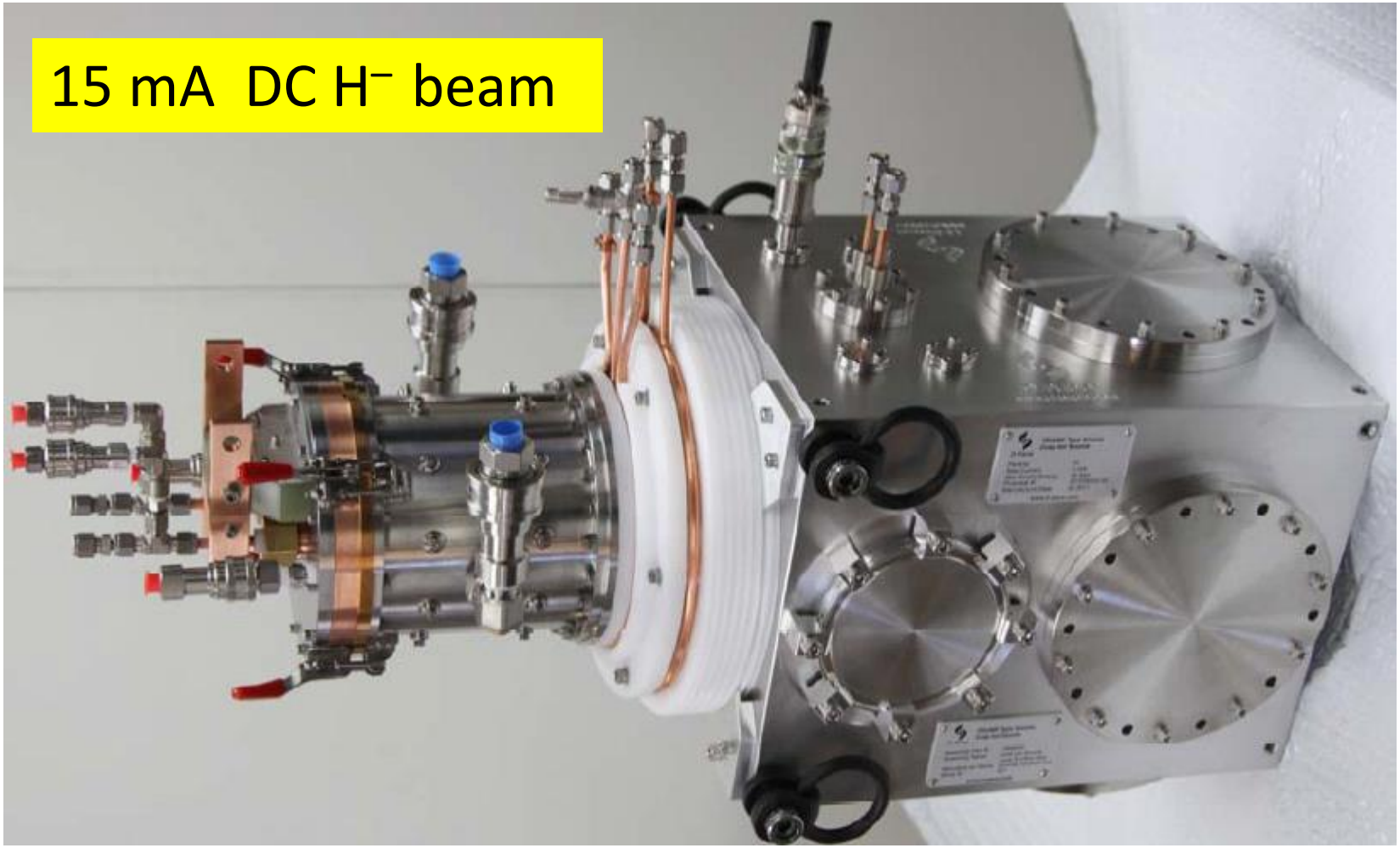


e.g. Lr^{103+}

Multicusp Filament Volume Source



D-Pace Filament Volume Source



Particles and **Sources**

Positrons e^+

Electrons e^-

Photons

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

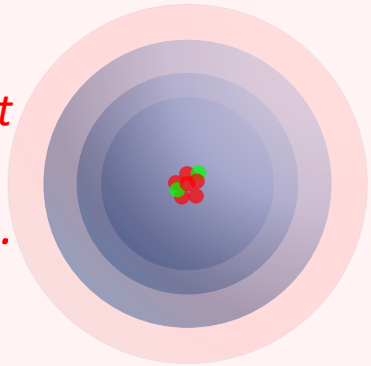
Protons

μ^+ Muons μ^-

Antiprotons

Neutrons n

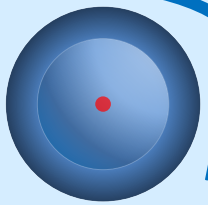
Light ions e.g. C^{4+}



Neutral particles

H^0

Negative ions



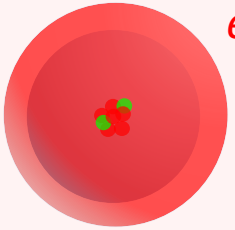
H^-

Multicusp

RF

Volume

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



Higgs Bosons

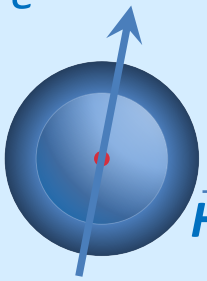
Zoo of curiosities

$\vec{e}^-$

Fully stripped nuclei

e.g. U^{92+}

$\vec{p}$



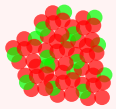
Polarised particles

$\vec{H}^-$

Tauons
Mesons
Baryons

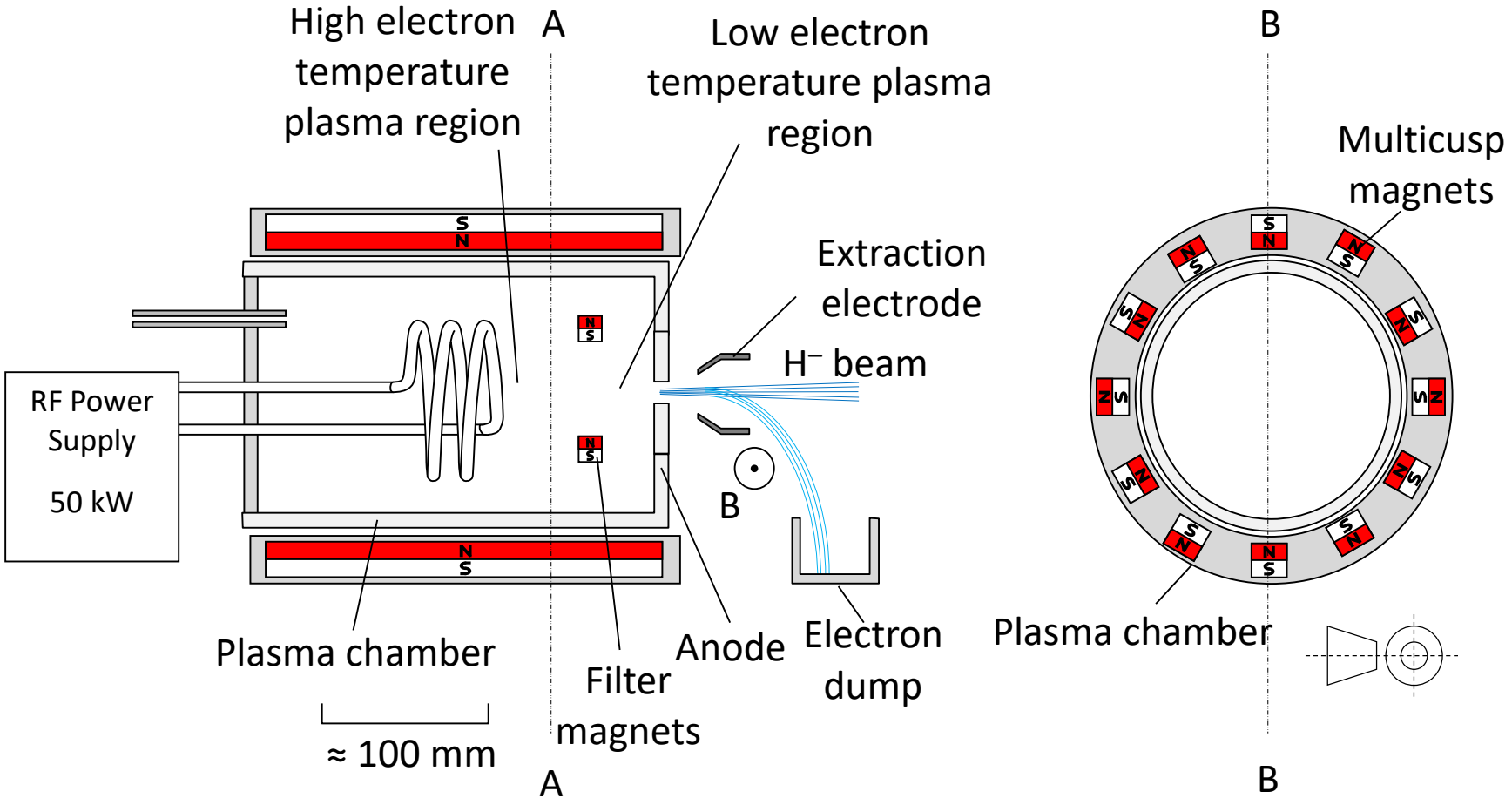
$W + Z$ Bosons

Exotic nuclei

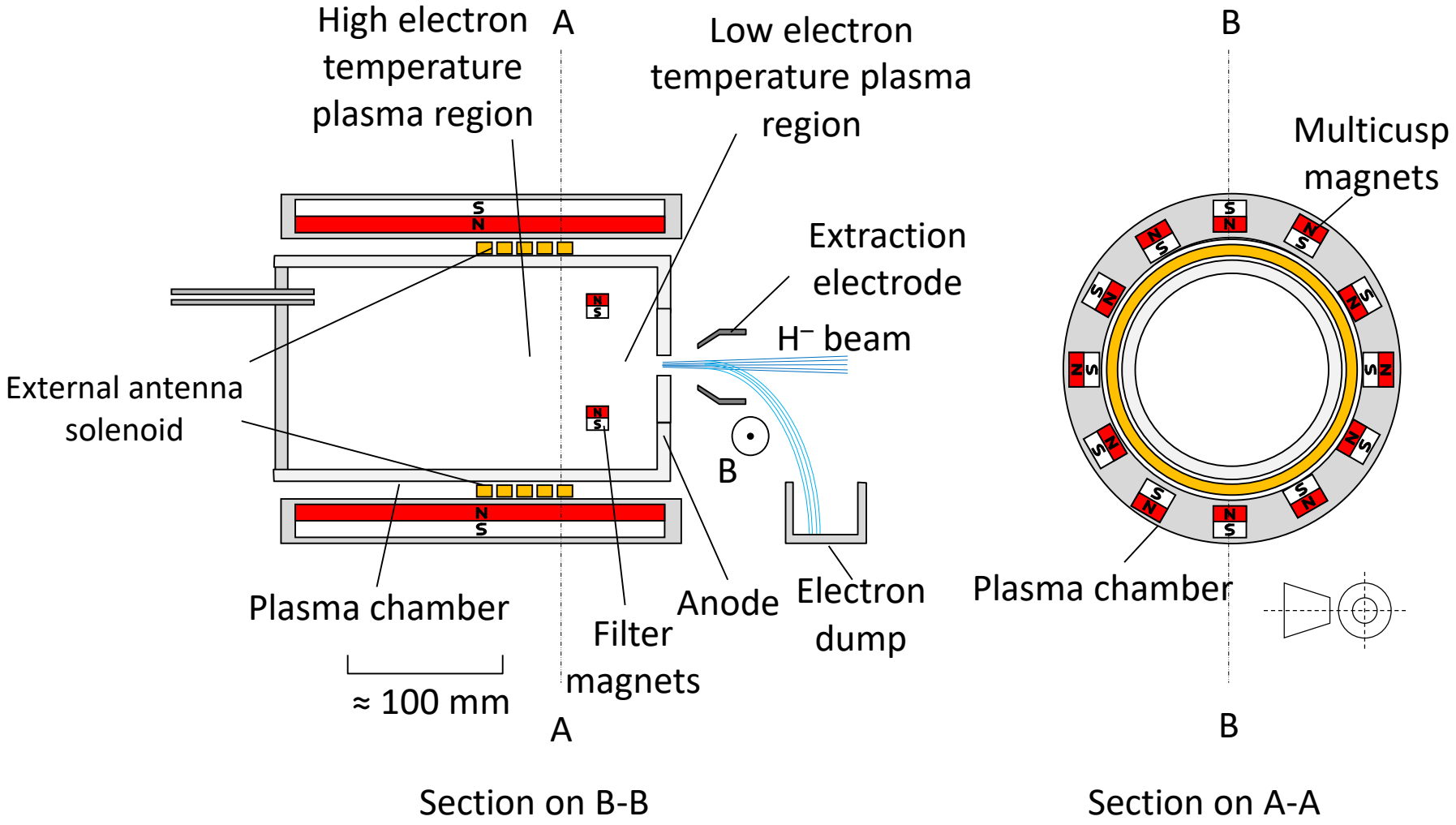


e.g. Lr^{103+}

Internal RF Solenoid Antenna Volume Source

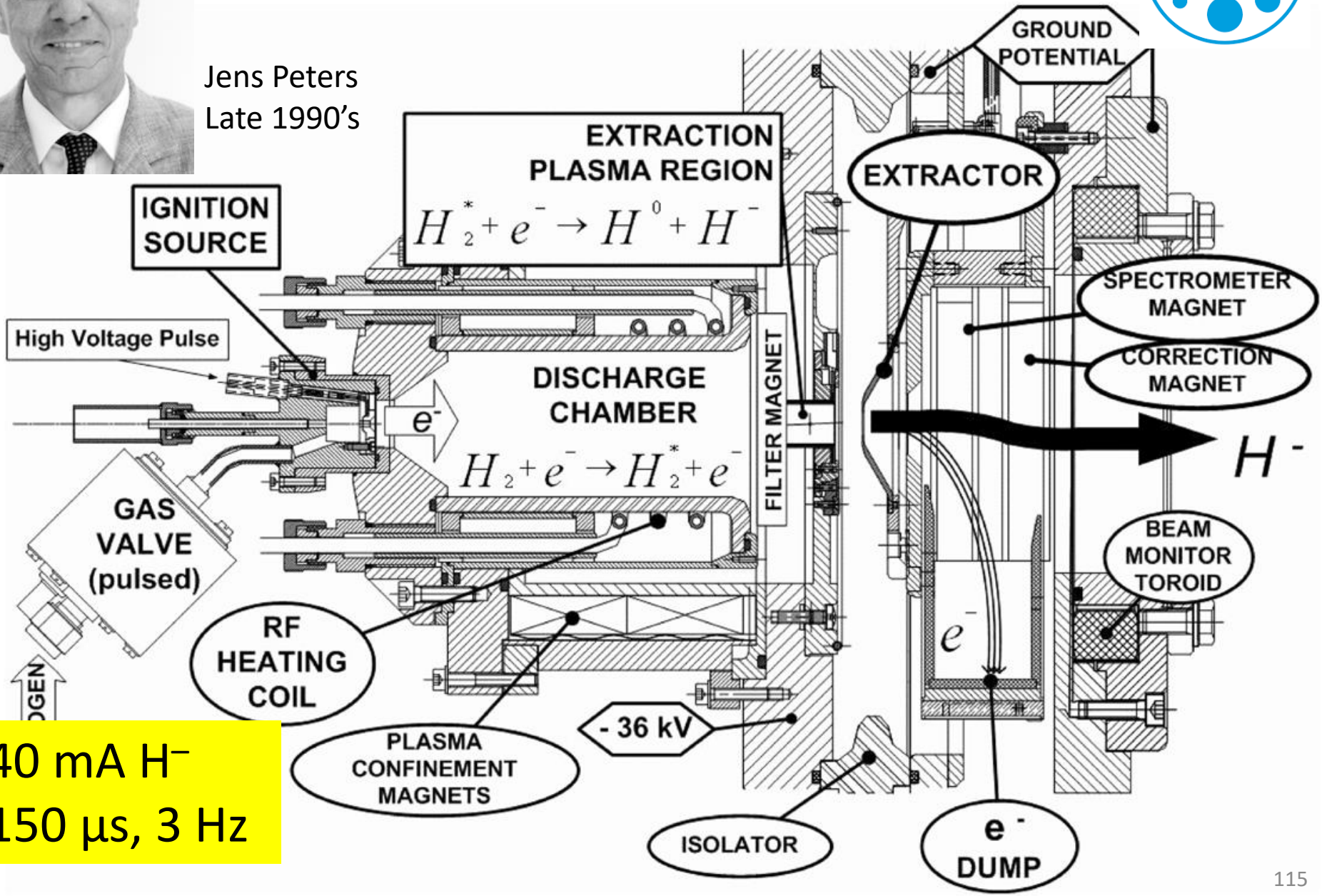


External RF Solenoid Antenna Volume Source



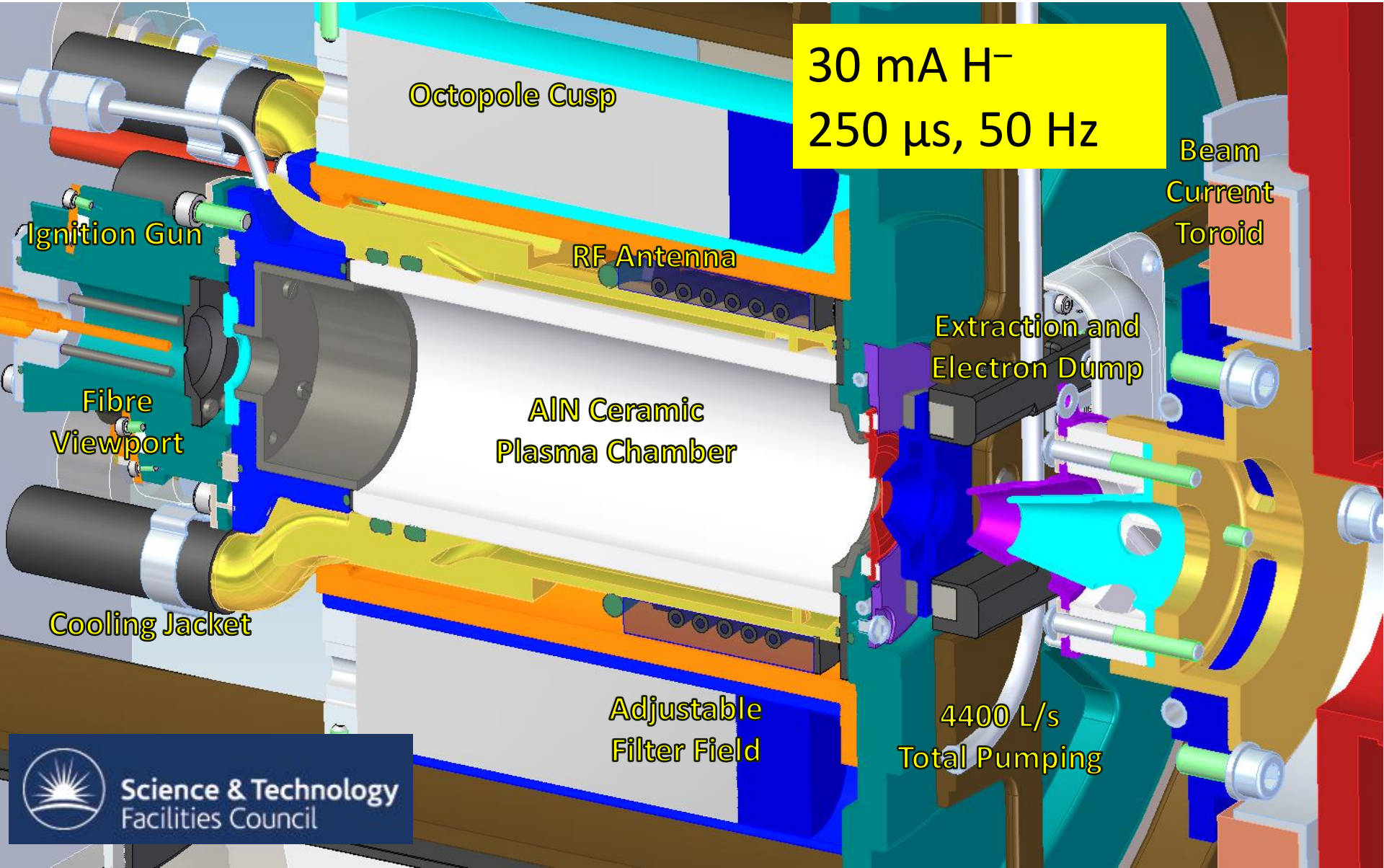
HERA Source

Jens Peters
Late 1990's



40 mA H^-
150 µs, 3 Hz

ISIS RF H^- Ion Source (under construction)



Particles and **Sources**

Positrons e^+

Electrons e^-

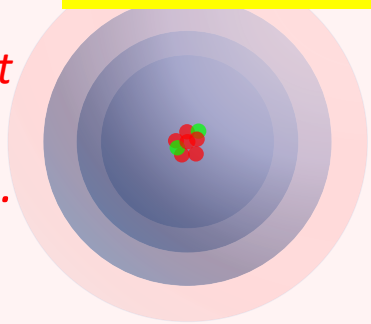
Photons

Neutrinos ν_μ ν_τ

Neutrons n

Best of both worlds?

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



Negative ions H^-

Surface converter

Multicusp

RF

Volume

Neutral particles H^0

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

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

$\vec{e}^-$

$\vec{p}$

Polarised particles $\vec{H}^-$

Exotic nuclei e.g. Lr^{103+}

Higgs Bosons

Zoo of curiosities

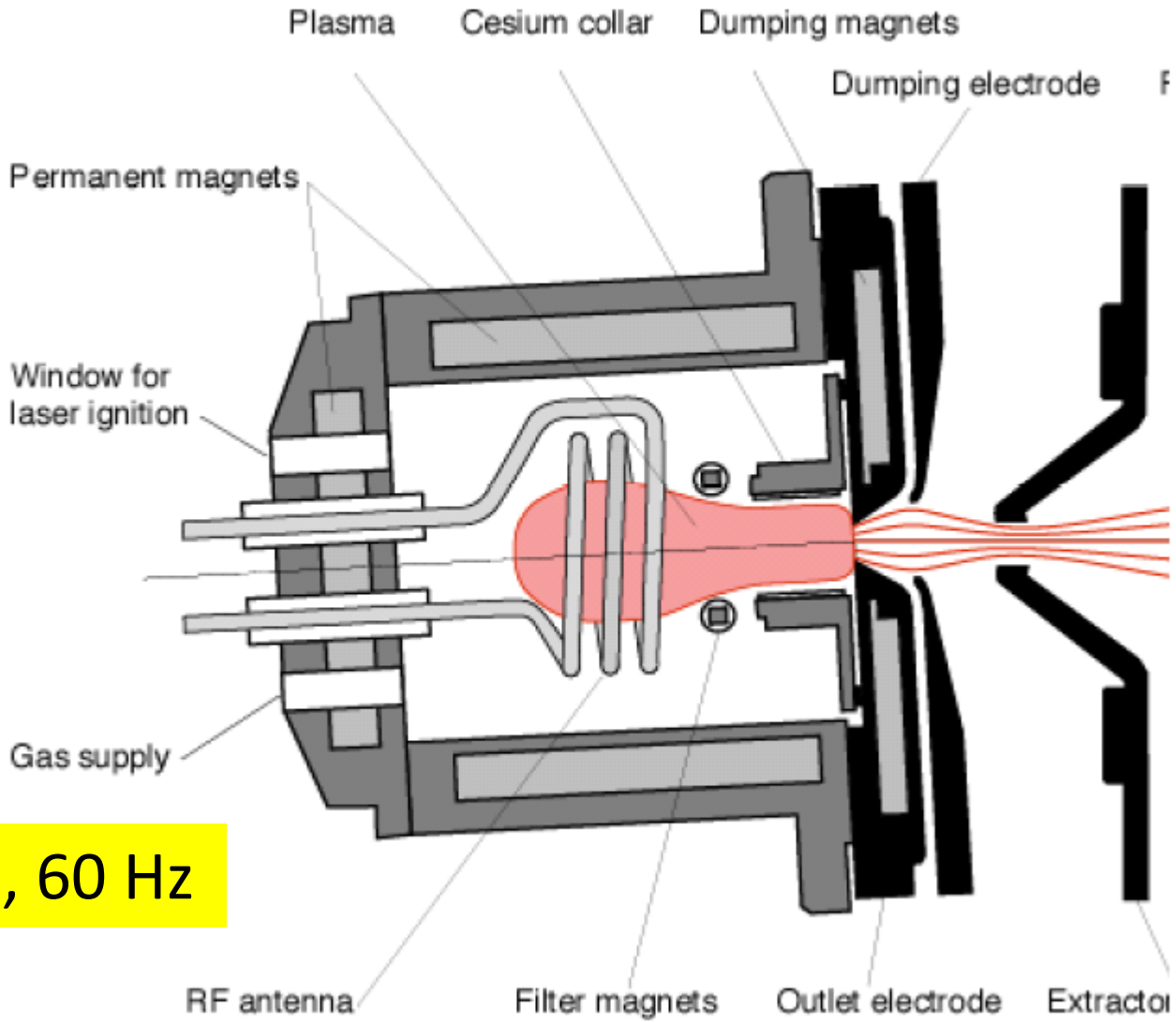
Tauons
Mesons
Baryons

$W + Z$ Bosons

CERN have developed a ceasiated external antenna source for LINAC4

SNS ion source

OAK RIDGE National Laboratory



60 mA H^- 1 ms, 60 Hz

Particles and **Sources**

Positrons e^+

Electrons e^-

Photons

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

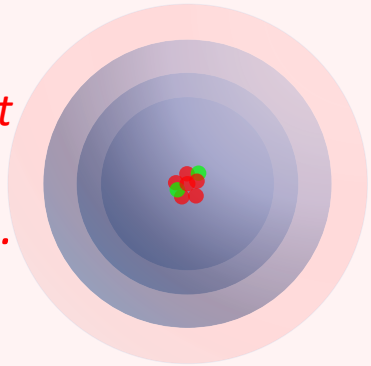
Protons

μ^+ Muons μ^-

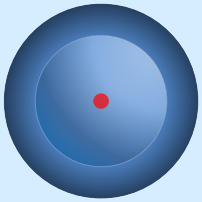
Antiprotons

Neutrons n

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

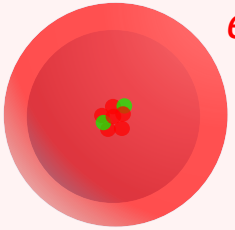


Negative ions H^-



Neutral atoms H^0

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



Higgs Bosons

$\uparrow\vec{e}^-$

$\uparrow\vec{p}$

Polarised particles

$\vec{H}^-$

Tuned lasers + Gas cells

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

Zoo of curiosities

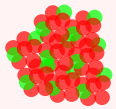
W + Z Bosons

Tauons

Mesons

Baryons

Exotic nuclei

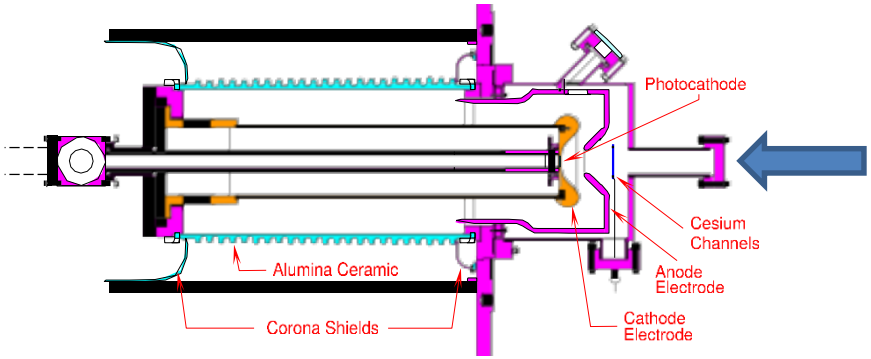


e.g. Lr^{103+}

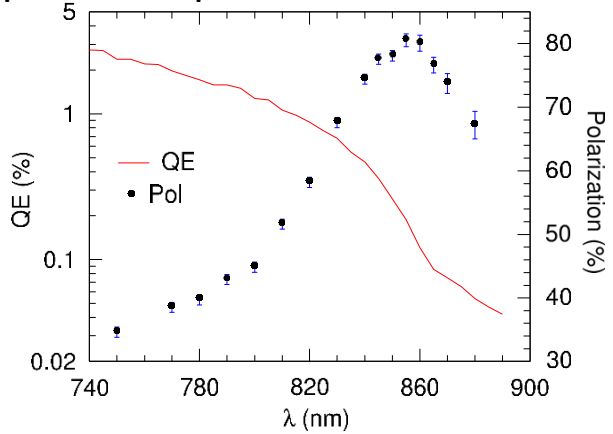
Polarised Electrons

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Strained GaAs photocathode



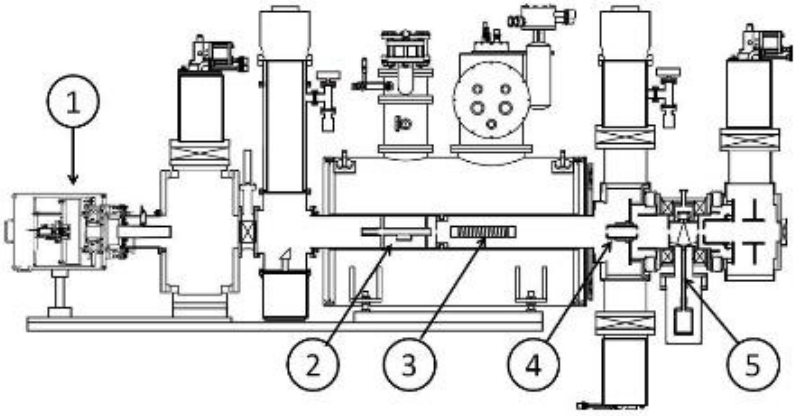
Circularly polarized laser light produces polarised electrons



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^+

Electrons e^-

Plasmatrons

Microwave discharge

Plasma + other

Thermo

Photo

Accelerator Facilities

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

Vacuum arc

Laser plasma

Penning and Magnetron

Surface plasma

Surface converter

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

Electron Cyclotron Resonance

Multicusp

Filament and RF

Volume

Higgs Bosons

$\uparrow\vec{e}^-$

$\uparrow\vec{p}$

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+}

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

compressed air supplies

temperature controllers

high voltage power supplies

control systems

mains power

personnel interlocks

material purity

laser systems

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?