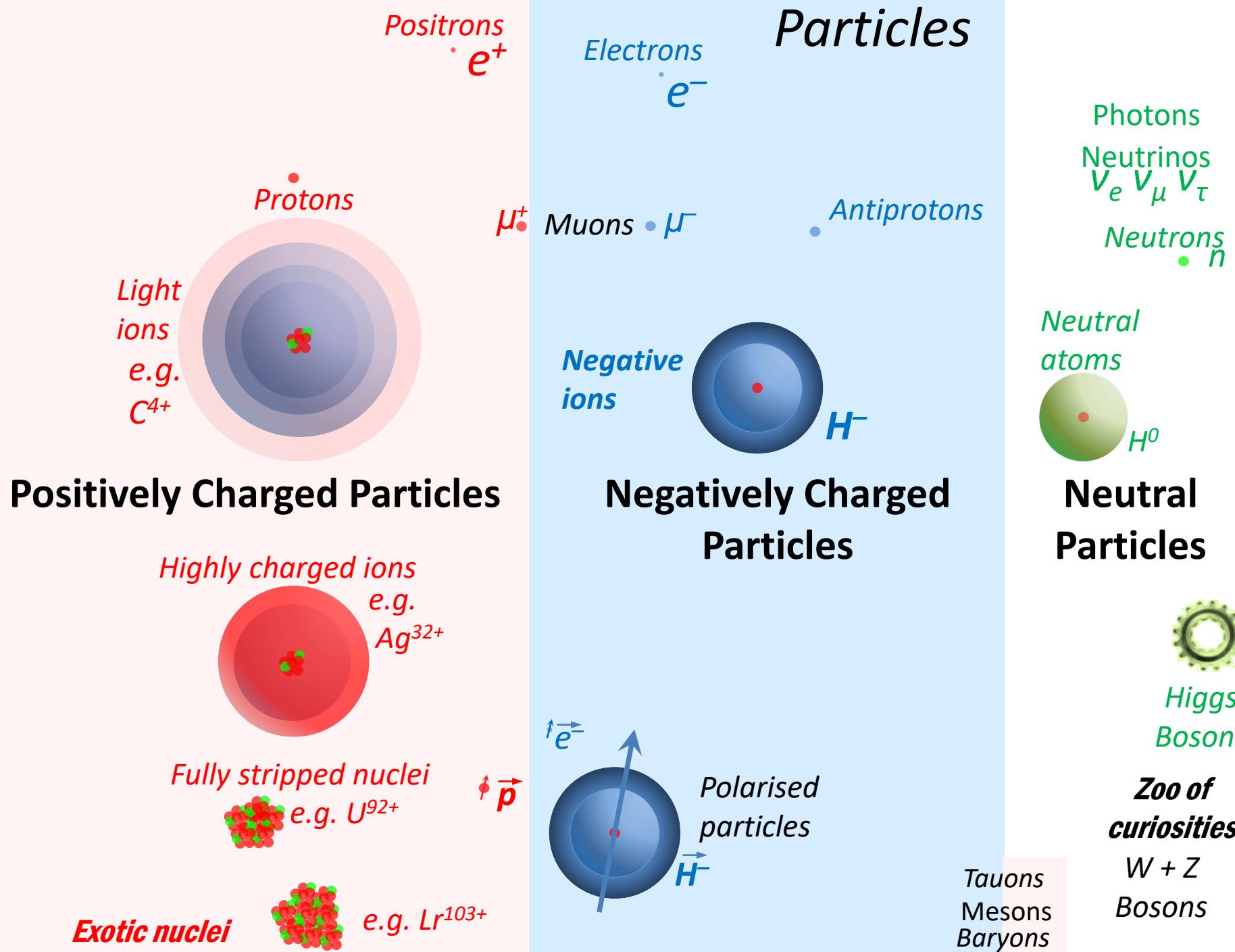


# Particle Sources

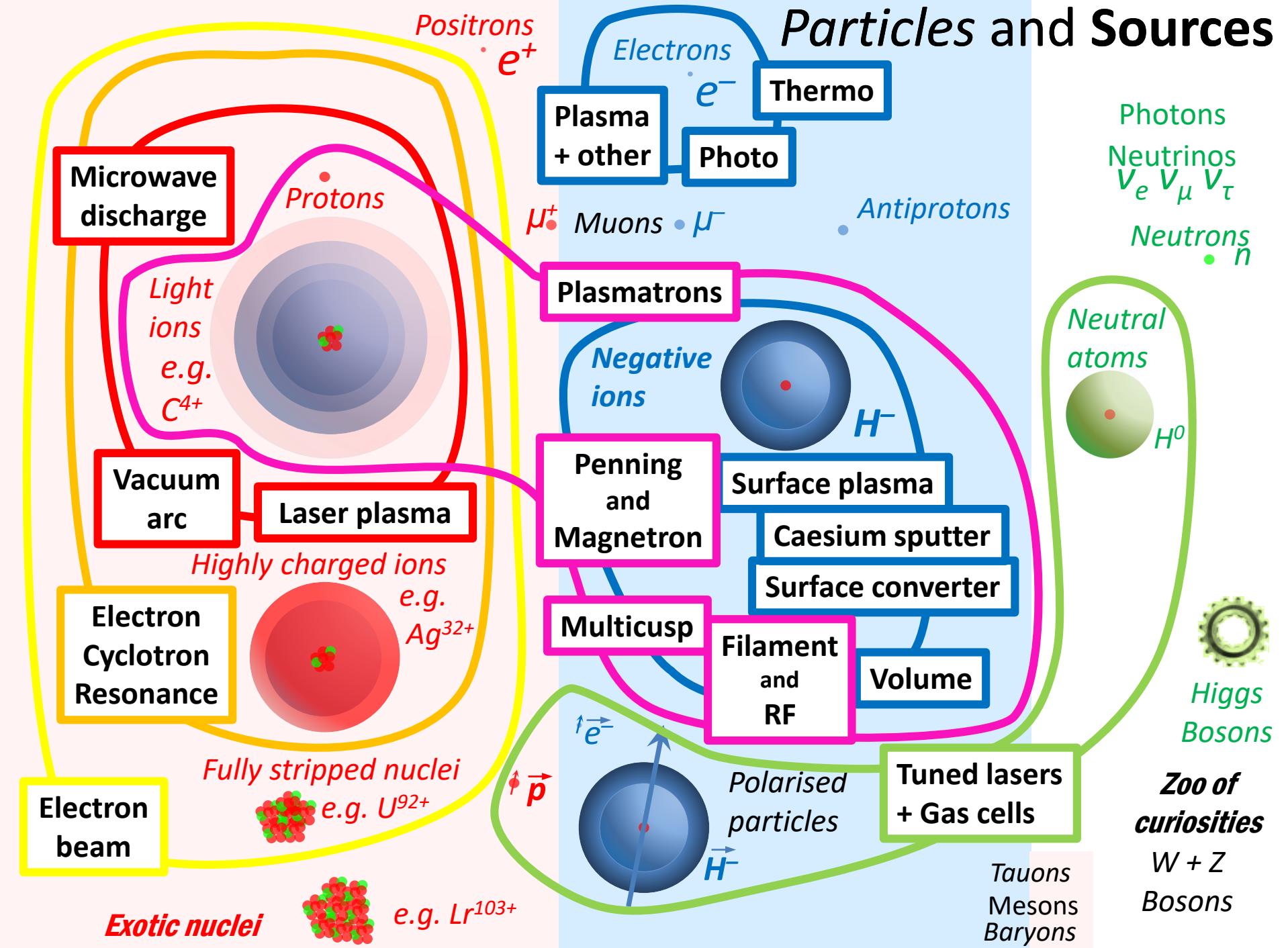
Dan Faircloth

ISIS Low Energy Beams Group Leader  
Rutherford Appleton Laboratory  
STFC-UKRI

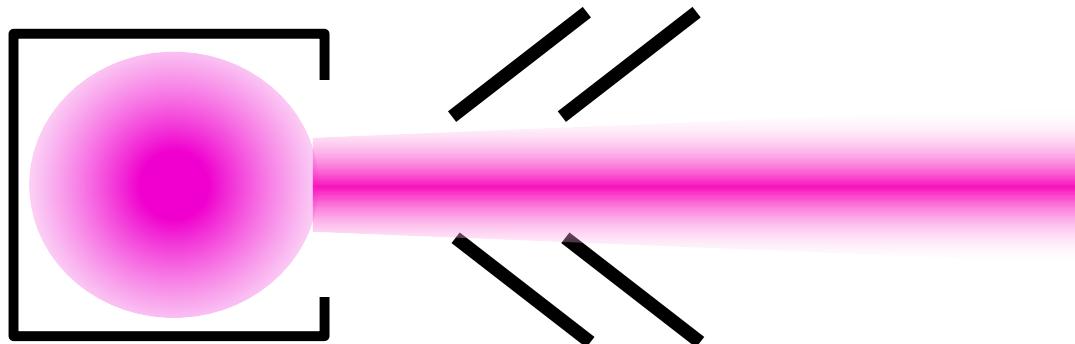
CERN Accelerator School, Introduction to Accelerator Physics  
Kaunas, Lithuania,  
Friday 23<sup>rd</sup> September 2022



# Particles and Sources



Particle sources/guns generally consist of:

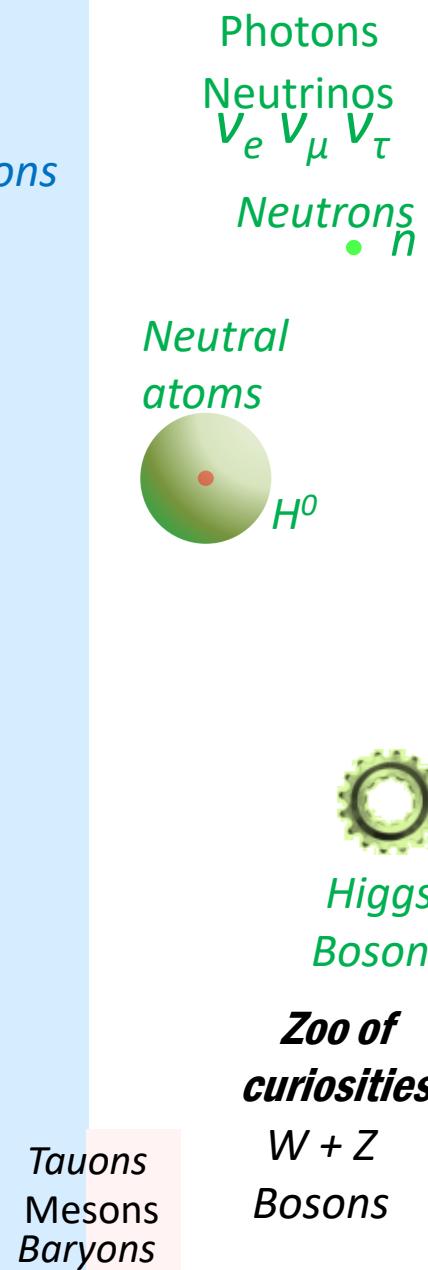
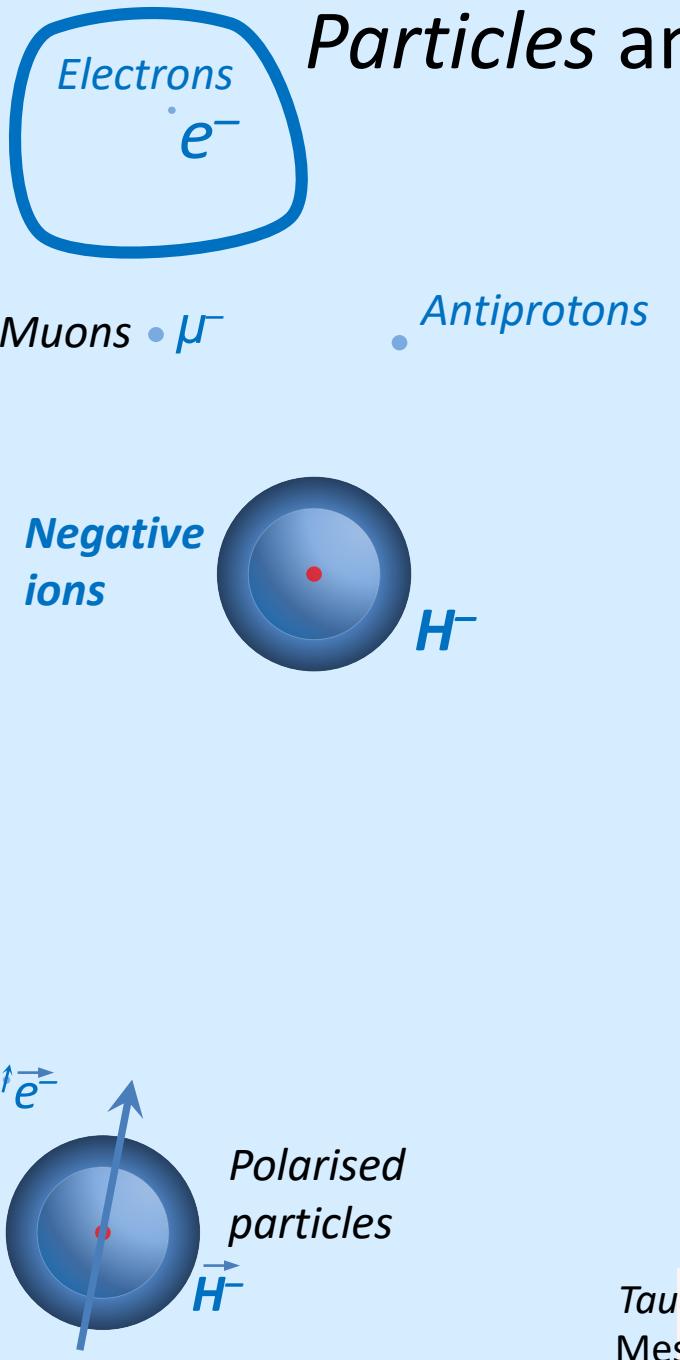
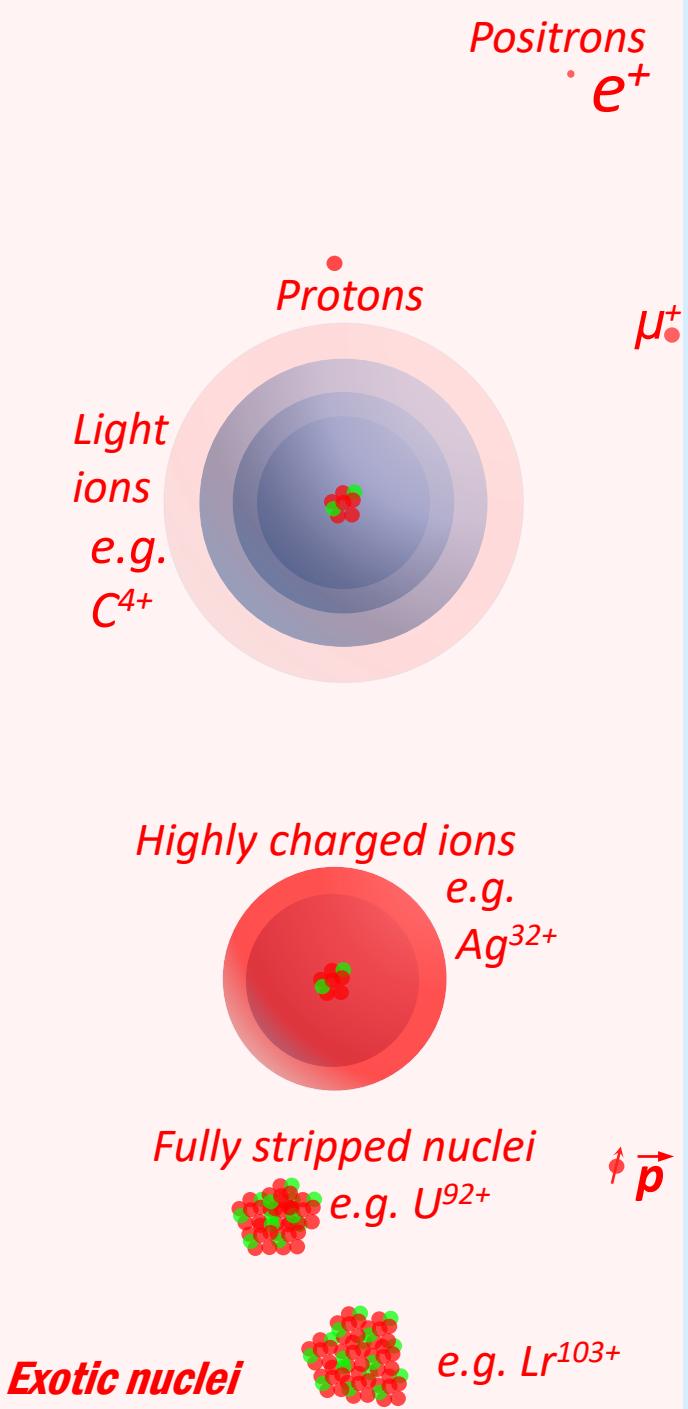


Something to make  
the particles

+

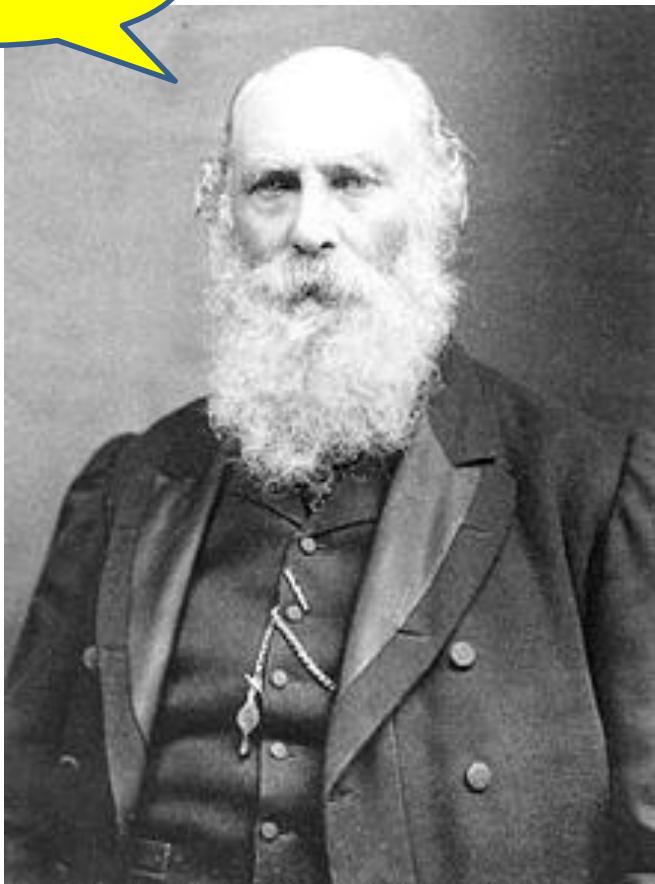
An extraction  
system to shape  
and accelerate a  
beam

# Particles and Sources



# The Electron!

**Electrons**



**George Johnstone Stoney**

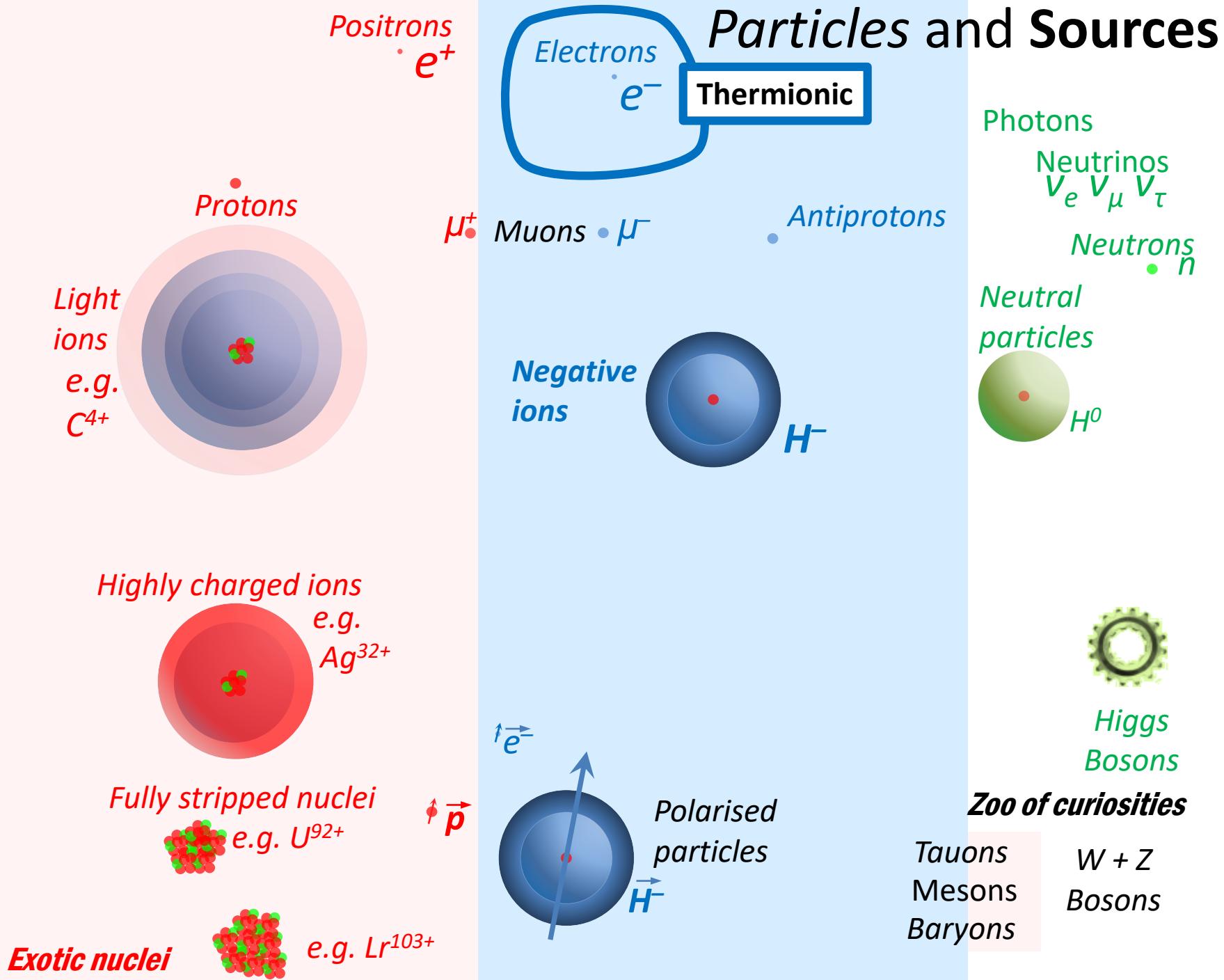
1894

**Corpuscles**



**J. J. Thomson**

1897



# Thermionic Emission



Corpuscles



J. J. Thomson  
1897

Cambridge University

1901 Owen Richardson

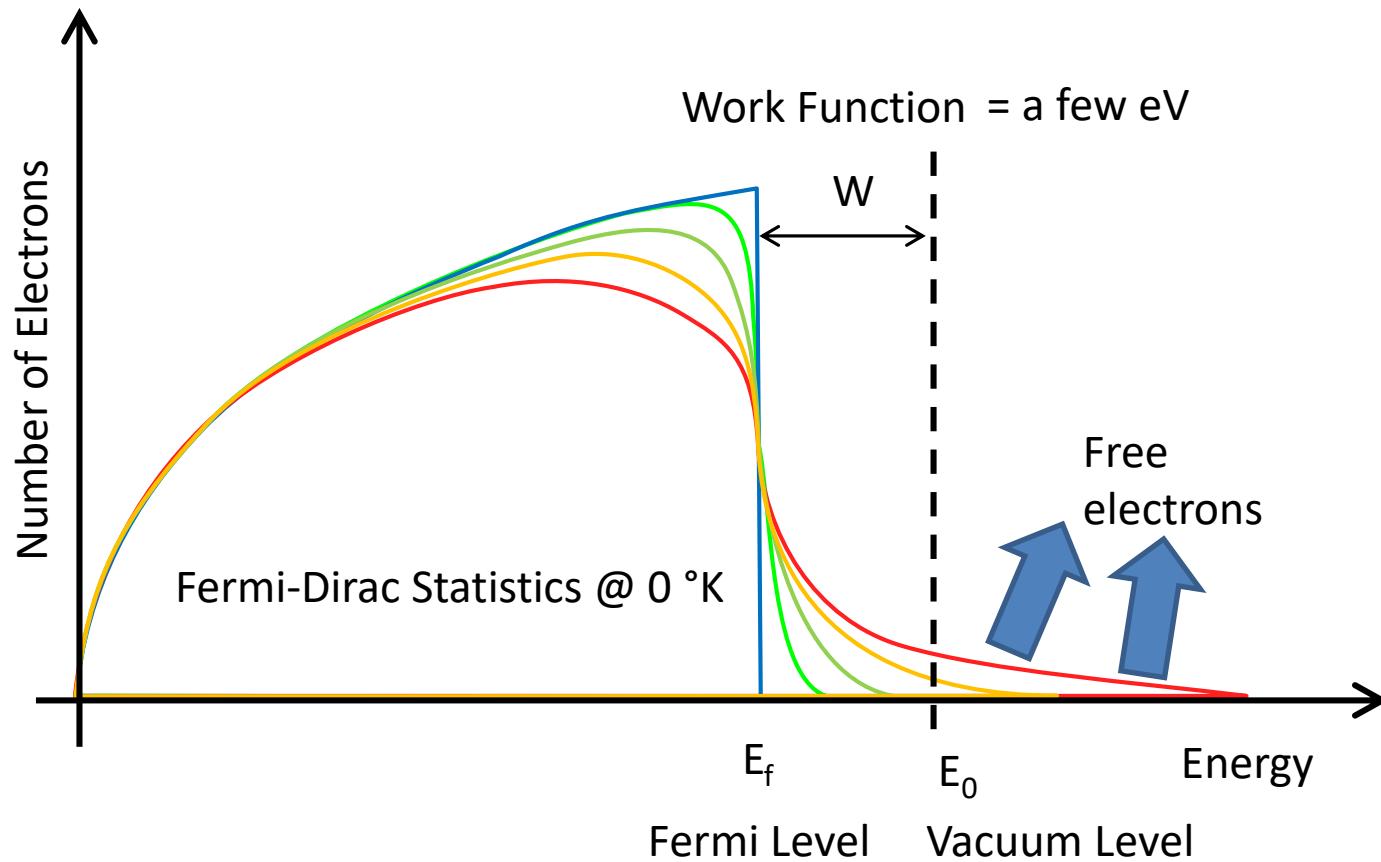
$$J = A_G T^2 e^{\frac{-W}{kT}}$$

Richardson's Law

Same form as the  
Arrhenius equation

Current rapidly  
increases with  
temperature

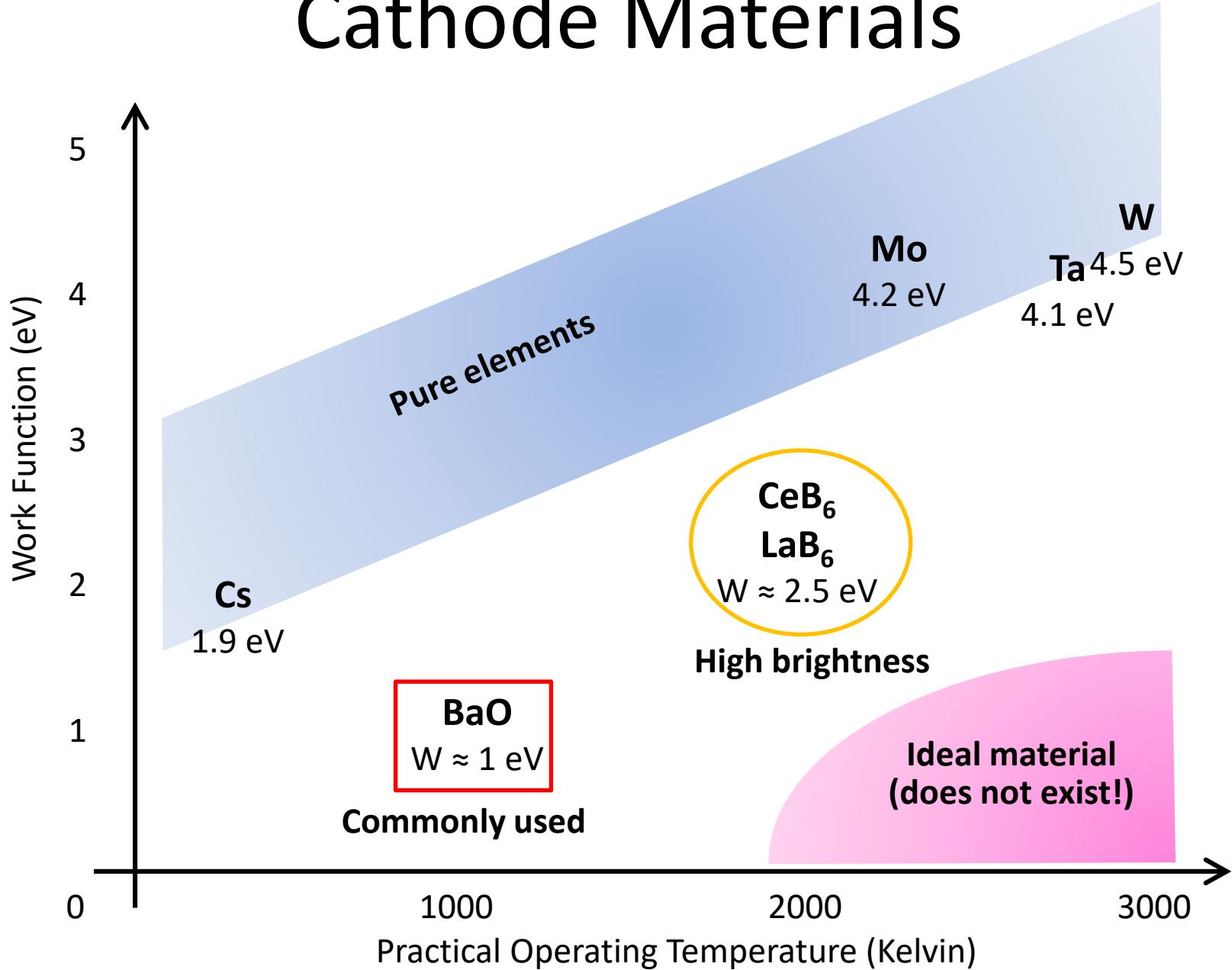
# Thermionic Emission



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

For a good electron emitter you need:  
Lowest possible work function  
Highest possible temperature

# Cathode Materials





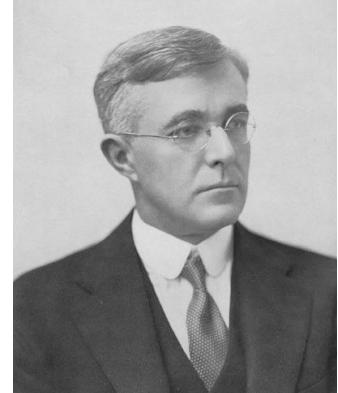
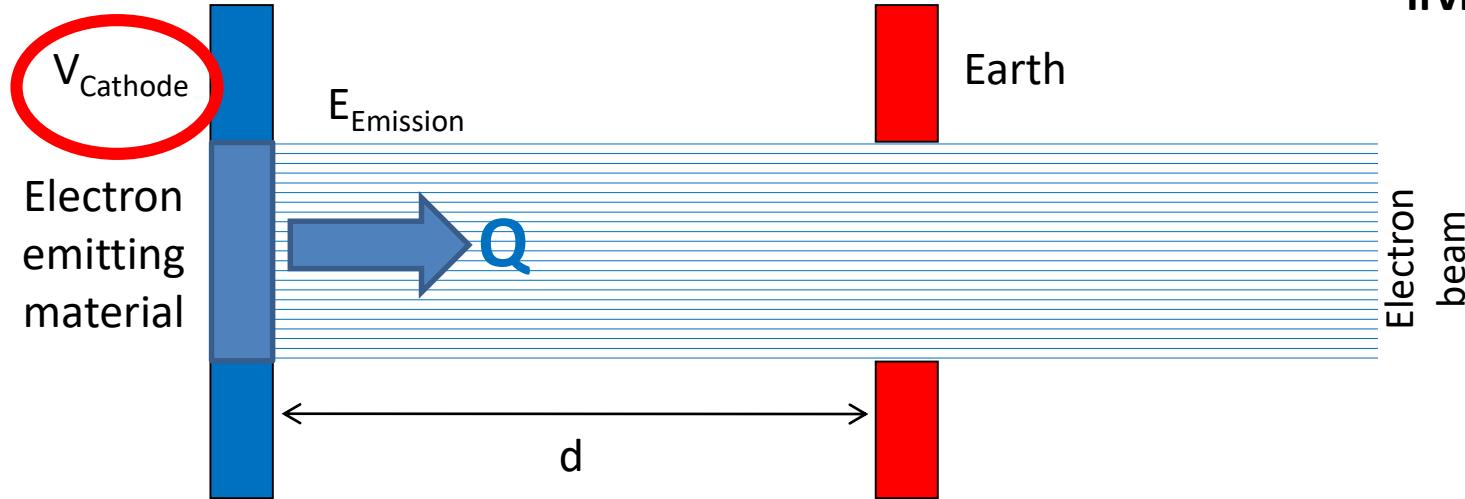
# Child-Langmuir Law

(Space charge limited extraction)

C.D Child

1911

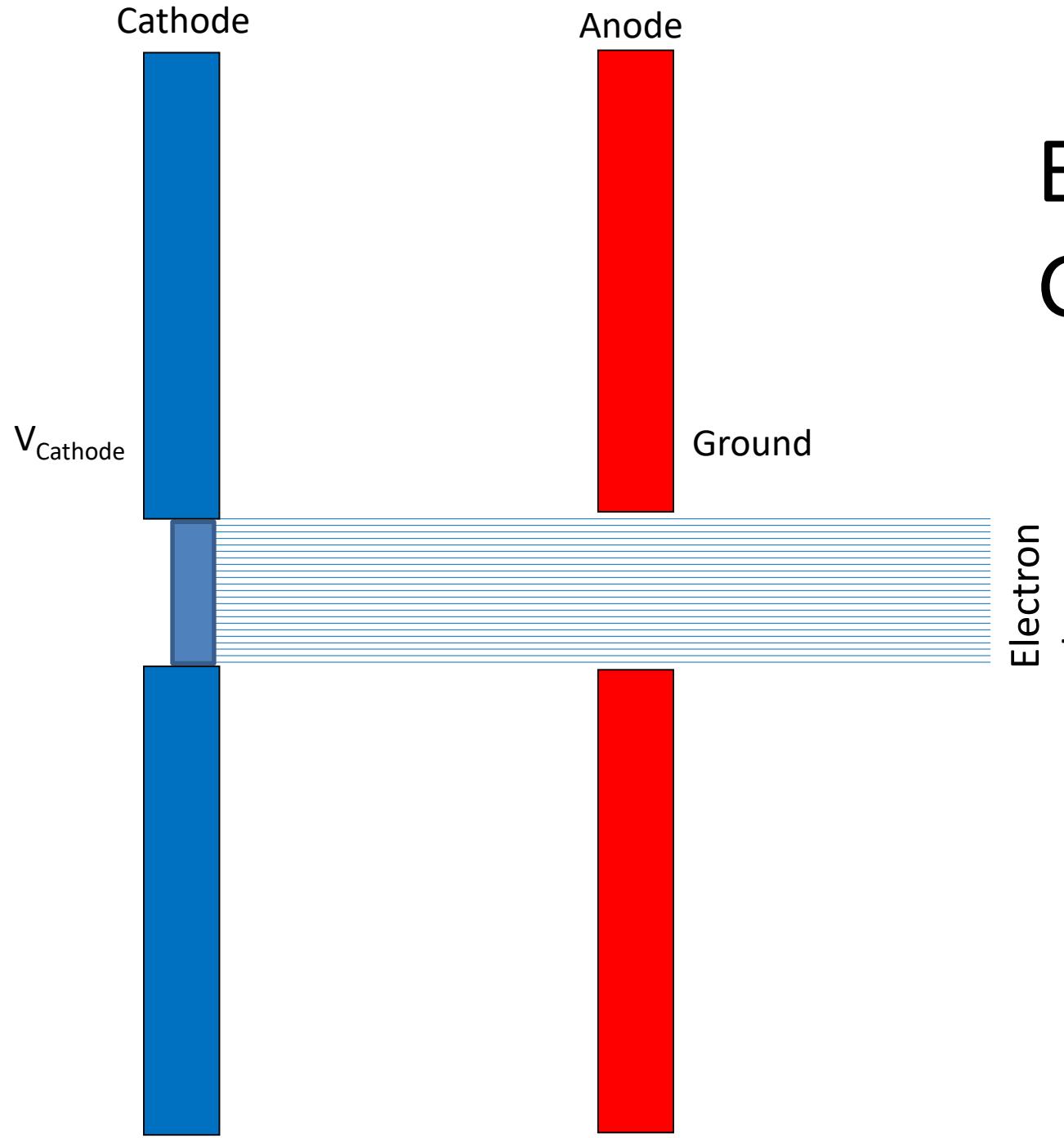
Cathode



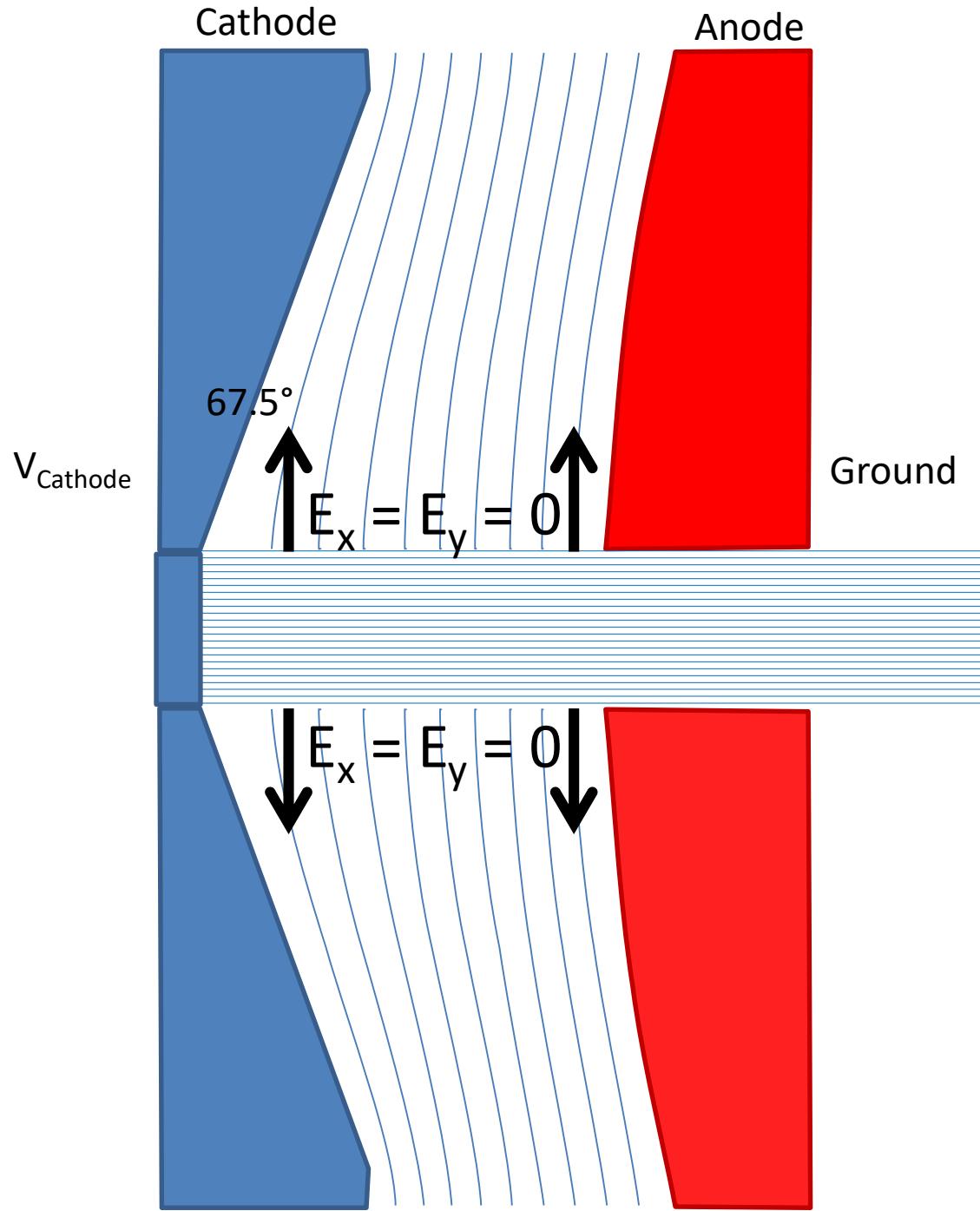
Irving Langmuir  
1913

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

# Pierce Extraction Geometry

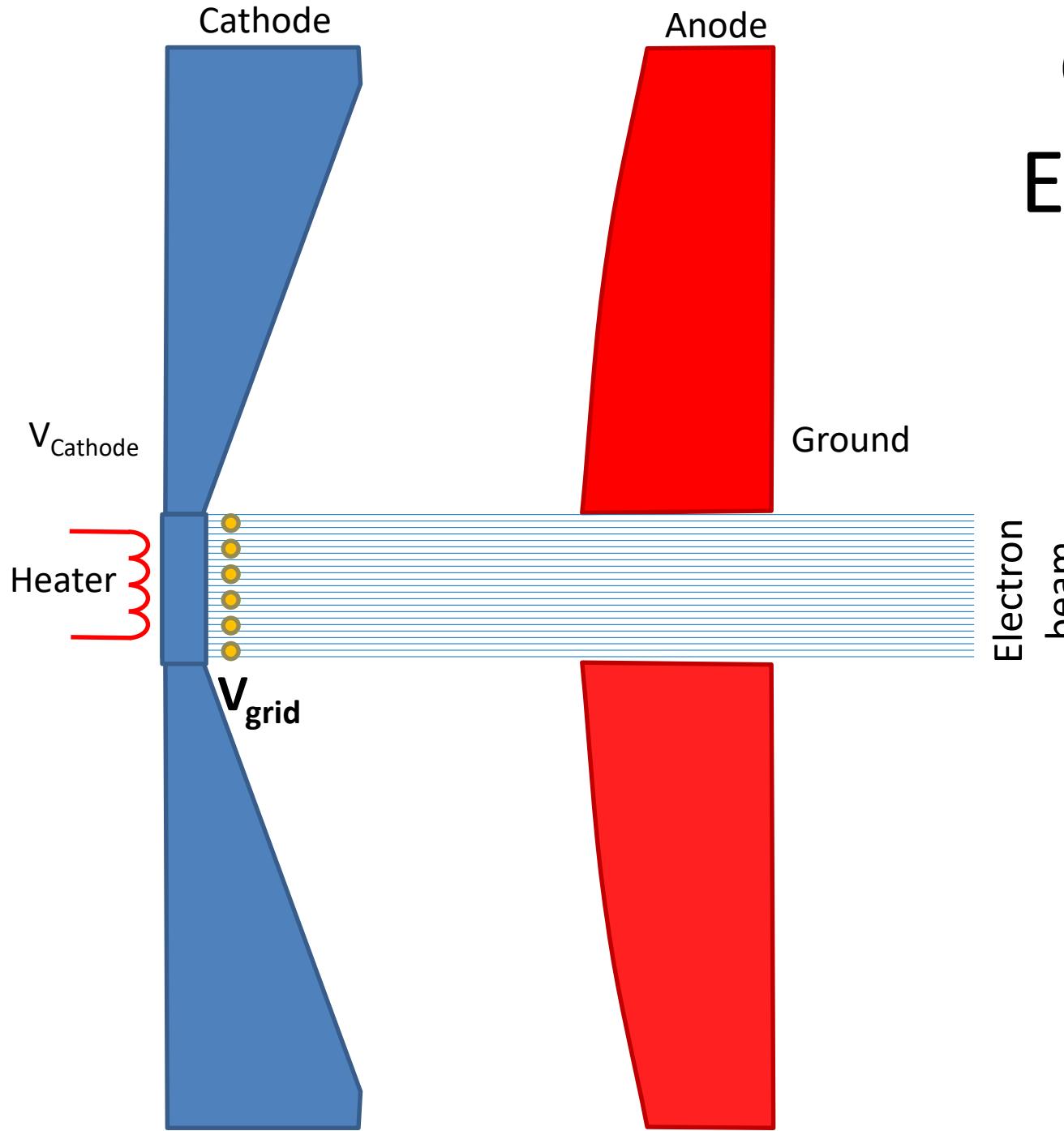


# Pierce Extraction Geometry



# Gridded Extraction

(A triode amplifier)





**YU 171**

*Thermionic dispenser cathode  
with integrated heater and grid*



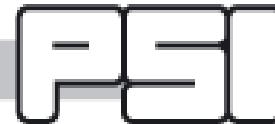
Sinter of W and BaO

1cm<sup>2</sup>

12 W heater



PAUL SCHERRER INSTITUT



Swiss Light Source

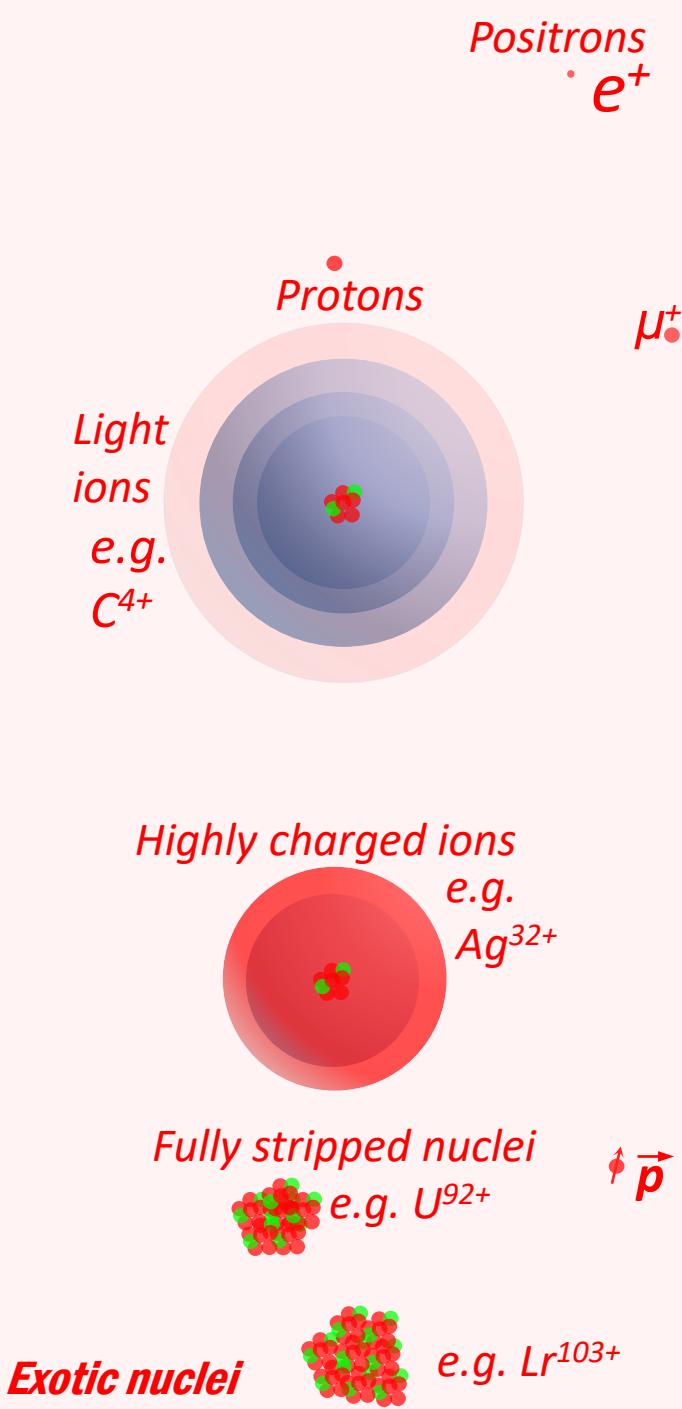
90 kV triode gun with Pierce geometry

1000 ns, 3 nC long pulses  
or

1 ns, 1.5 nC short pulses

Lifetime =  
several thousand hours

# Particles and Sources



Photons  
Neutrinos  
 $\nu_e \nu_\mu \nu_\tau$   
Neutrons  
 $n$

Neutral particles  
 $H^0$



Higgs  
Bosons

## Zoo of curiosities

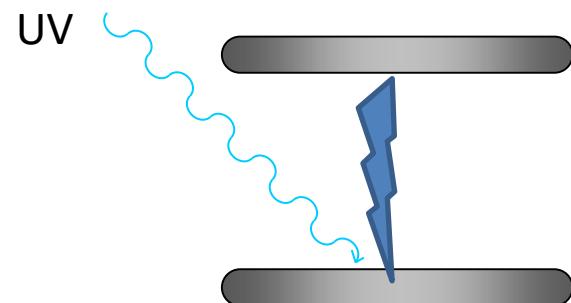
Tauons  
Mesons  
Baryons

$W + Z$   
Bosons

# Photo Emission



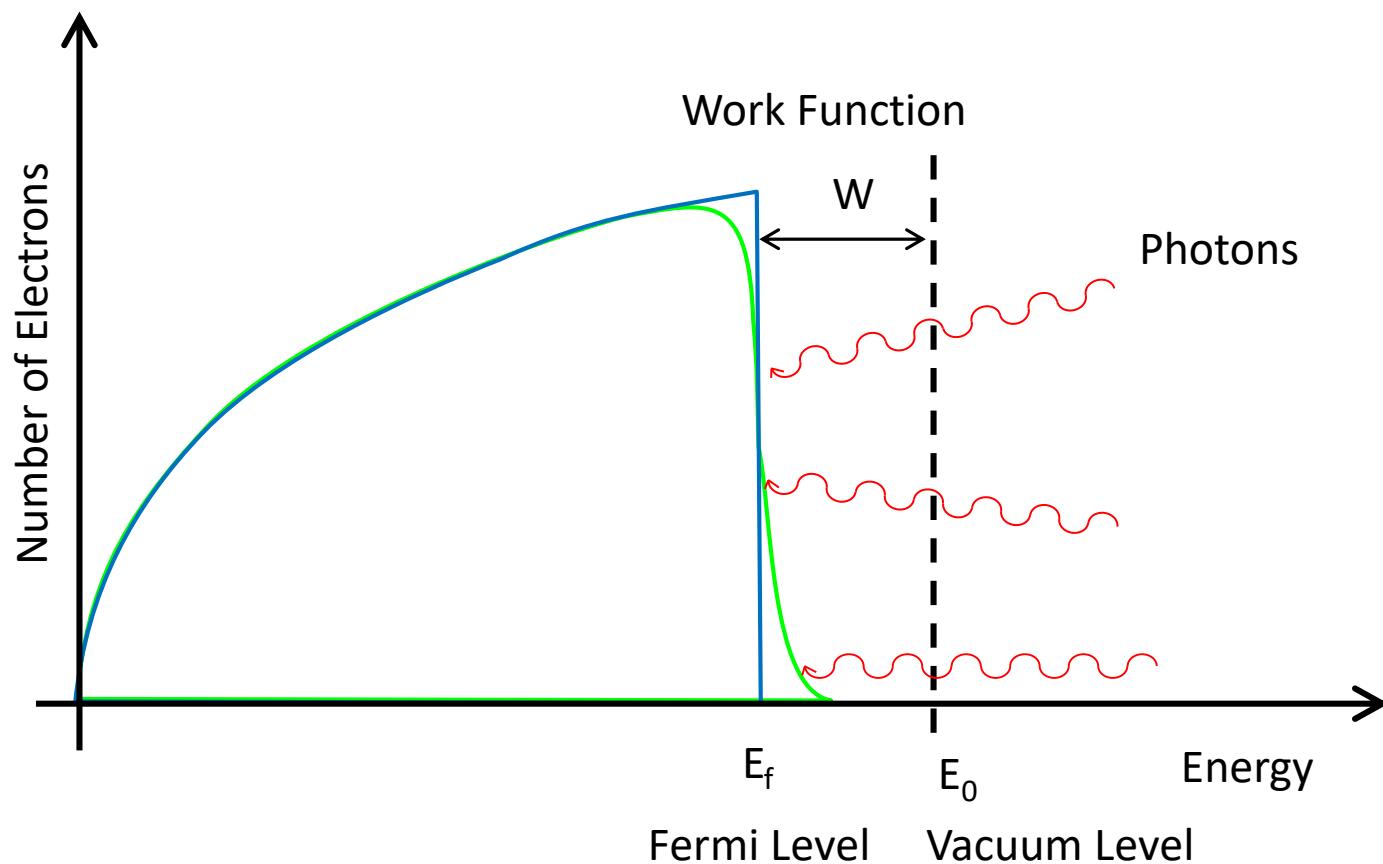
First observed by Heinrich Hertz in 1887



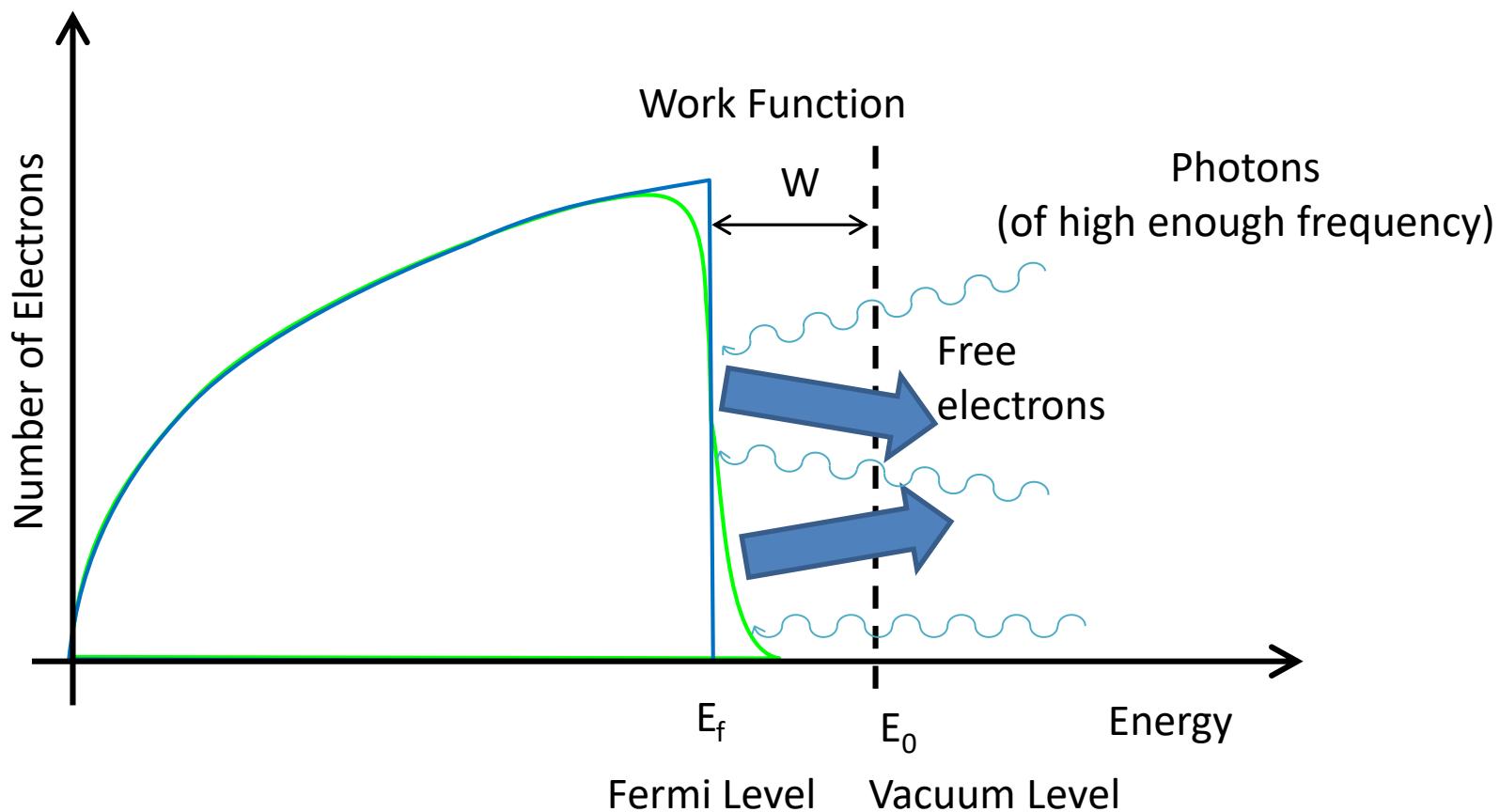
Theoretical explanation by  
Einstein in 1905



# Photo electric emission

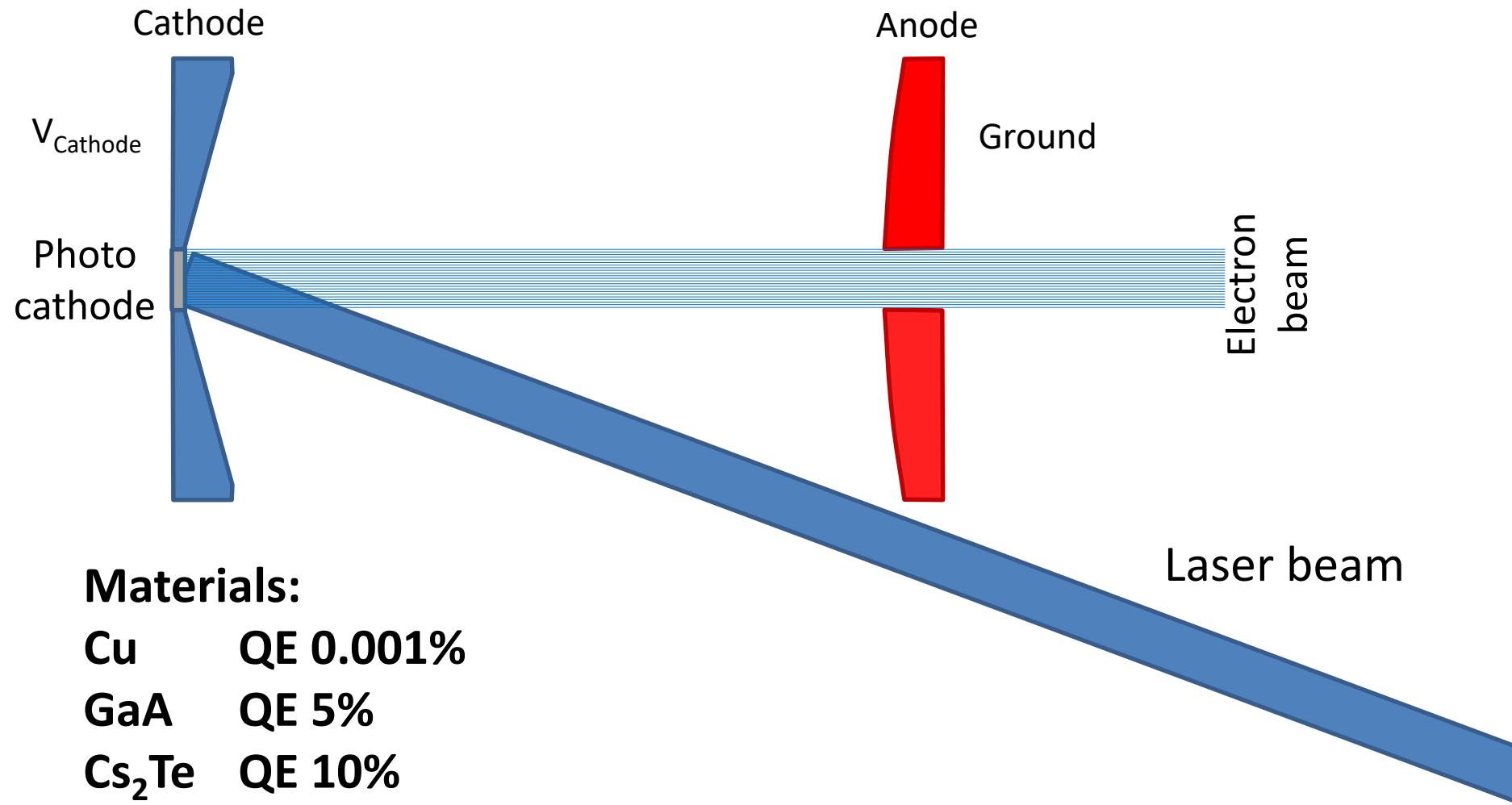


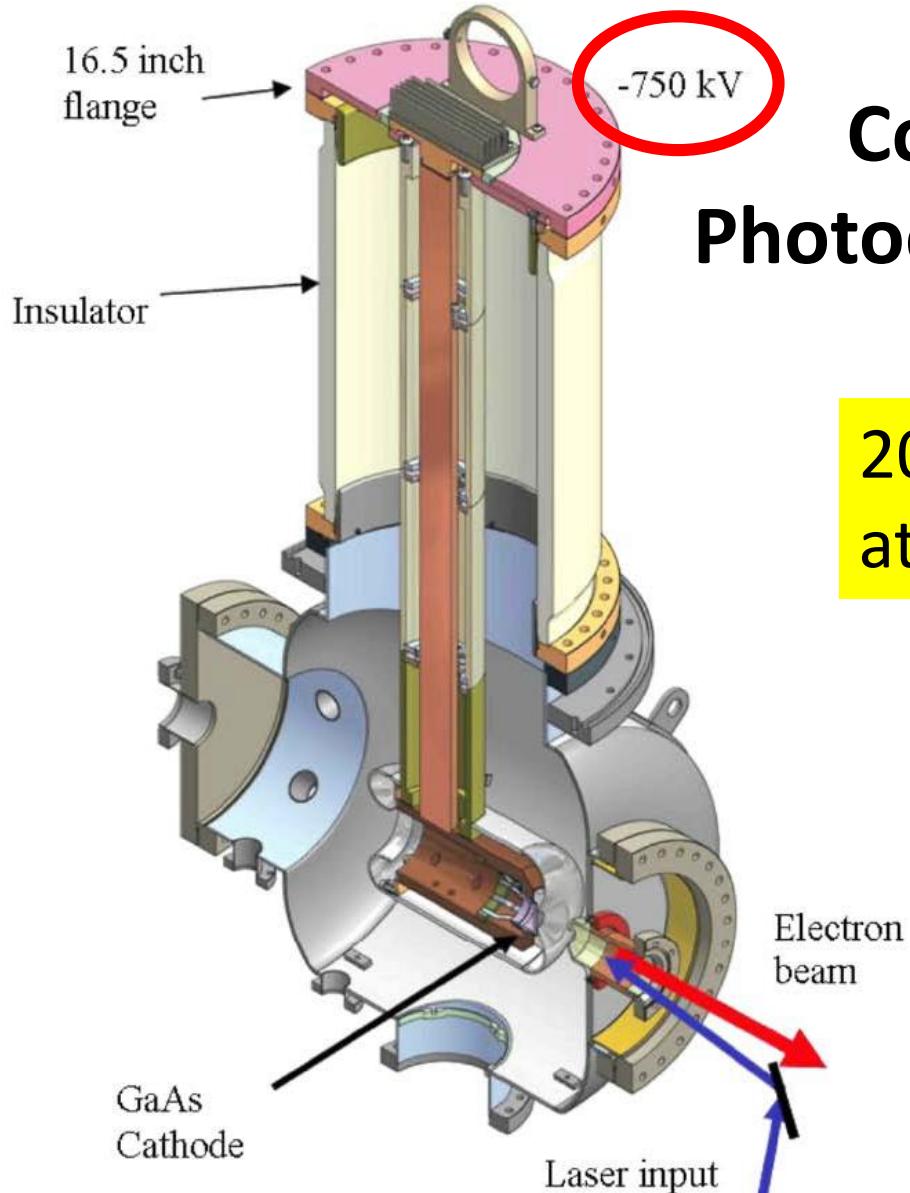
# Photo electric emission



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

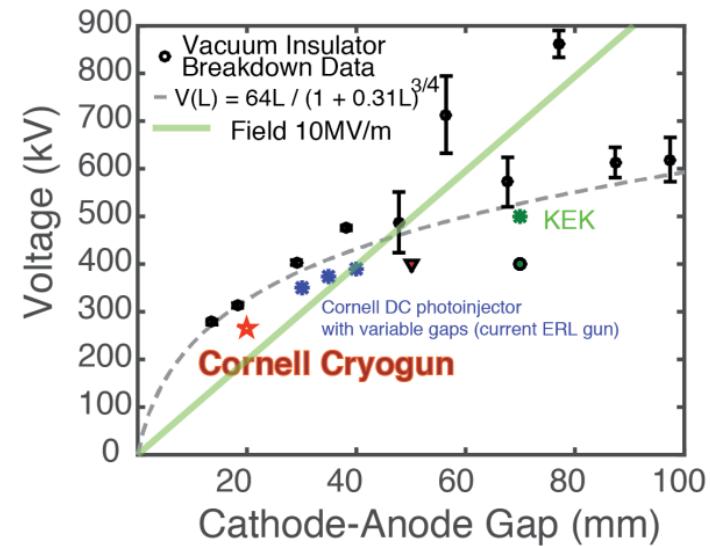
# Photo Emission Gun



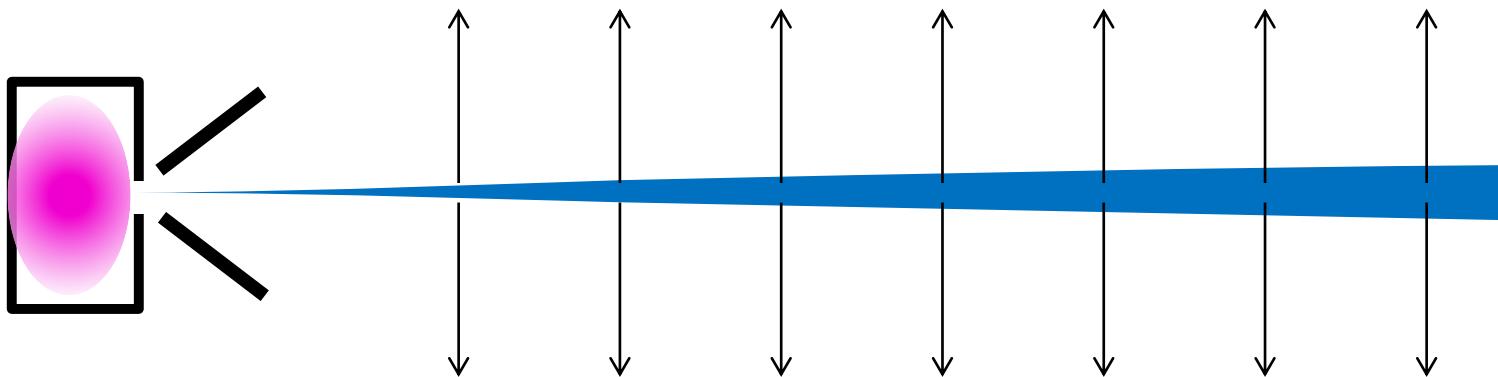


# Cornell DC Photoemission gun

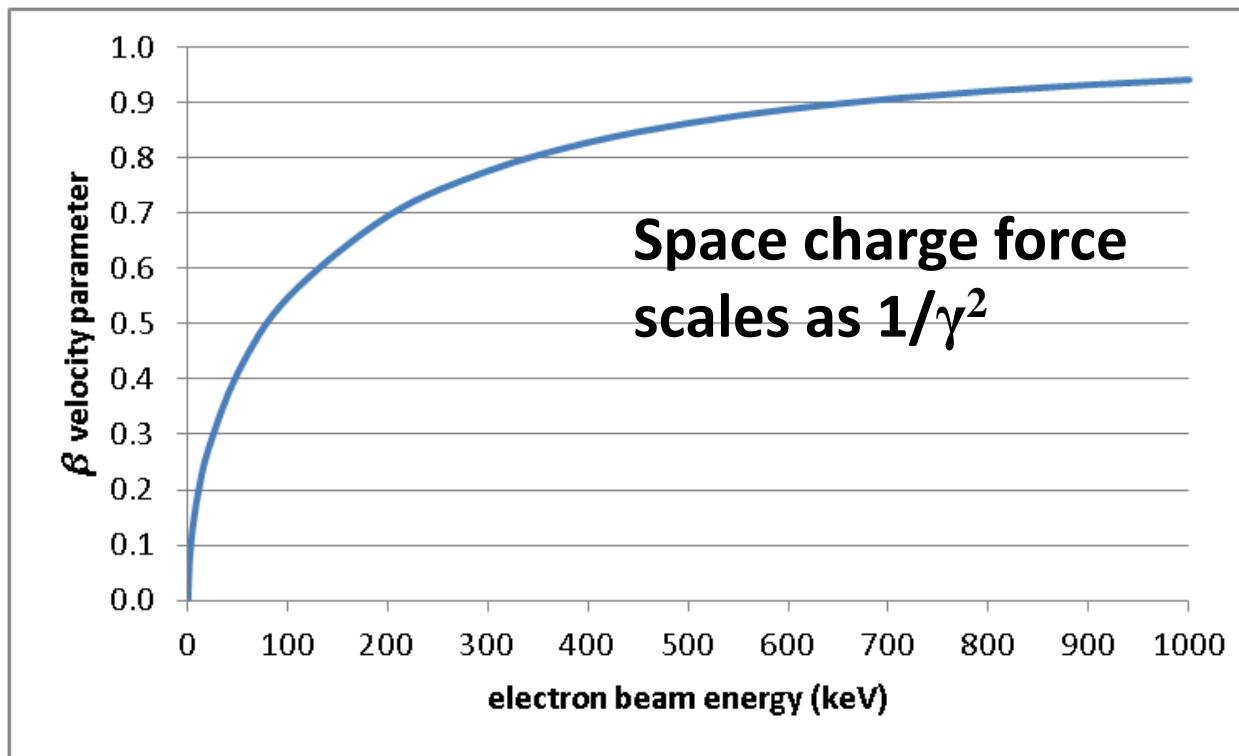
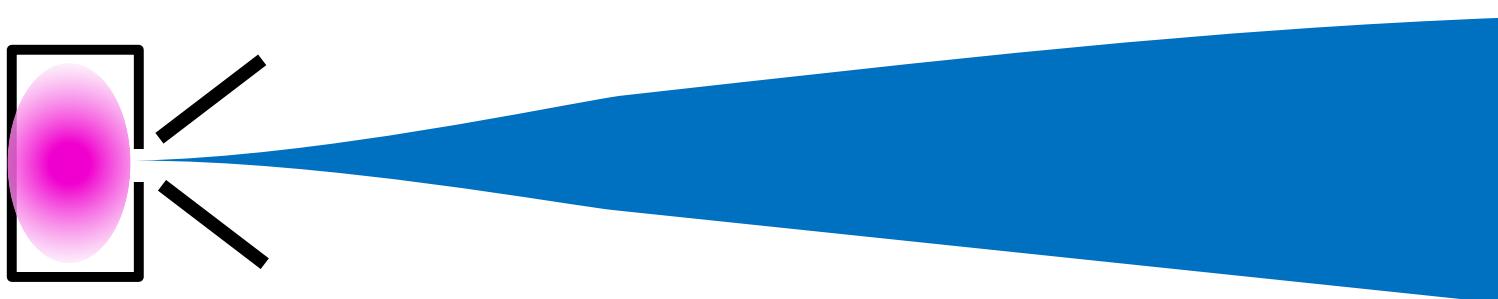
20 mA average current  
at 250kV



# Space Charge



# Space Charge

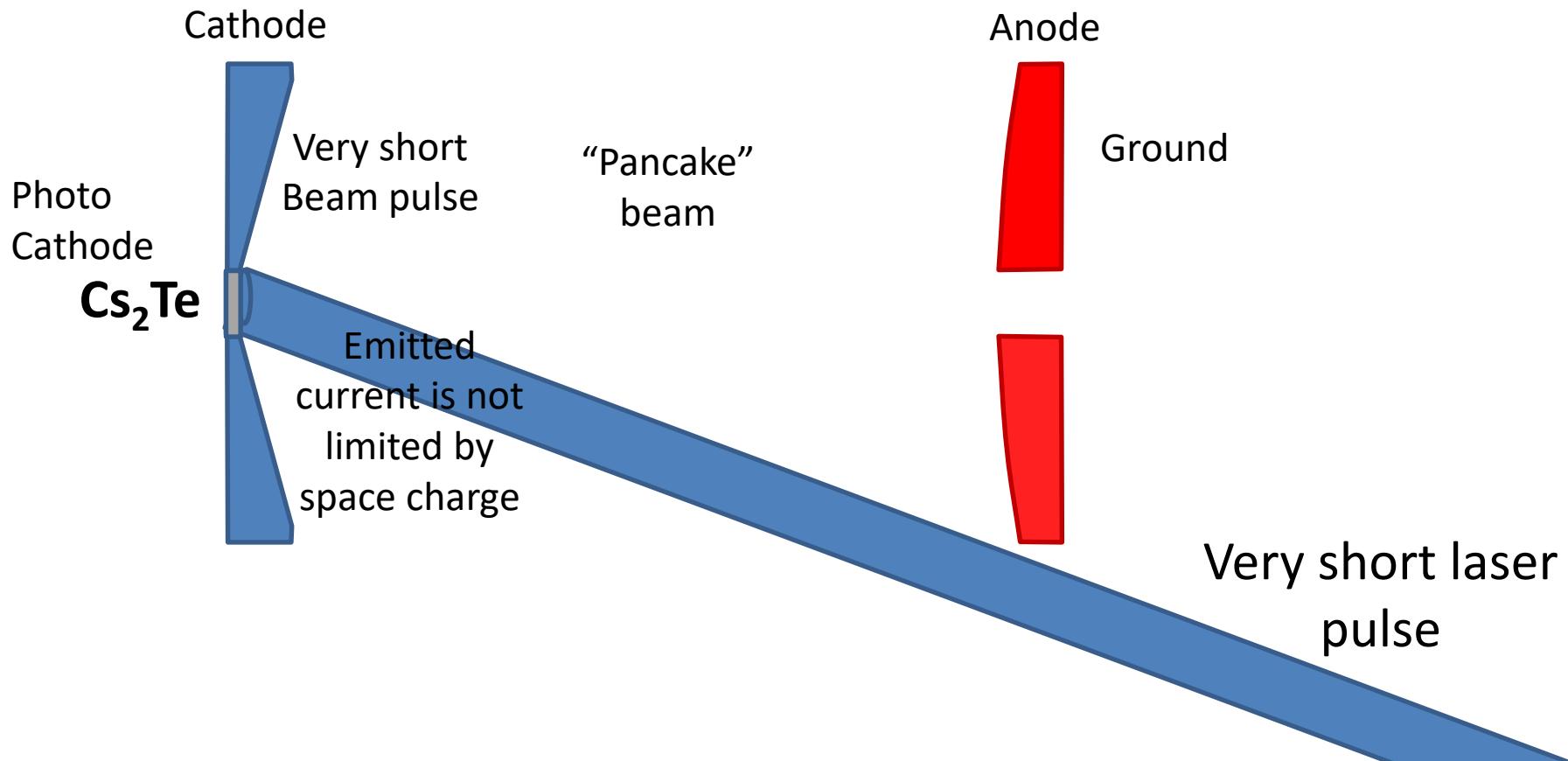


At 500 keV  
electron  $\gamma = 2$

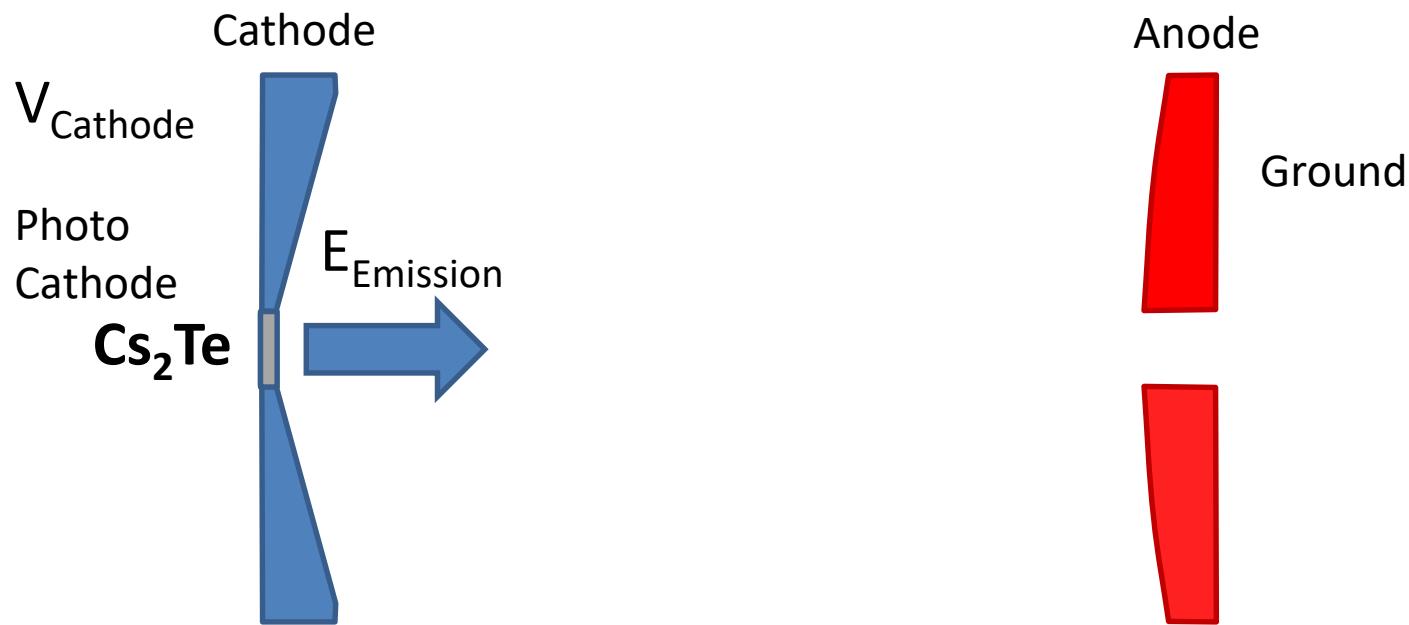
(940 MeV  
proton  $\gamma = 2$ )

# Another reason to use lasers is...

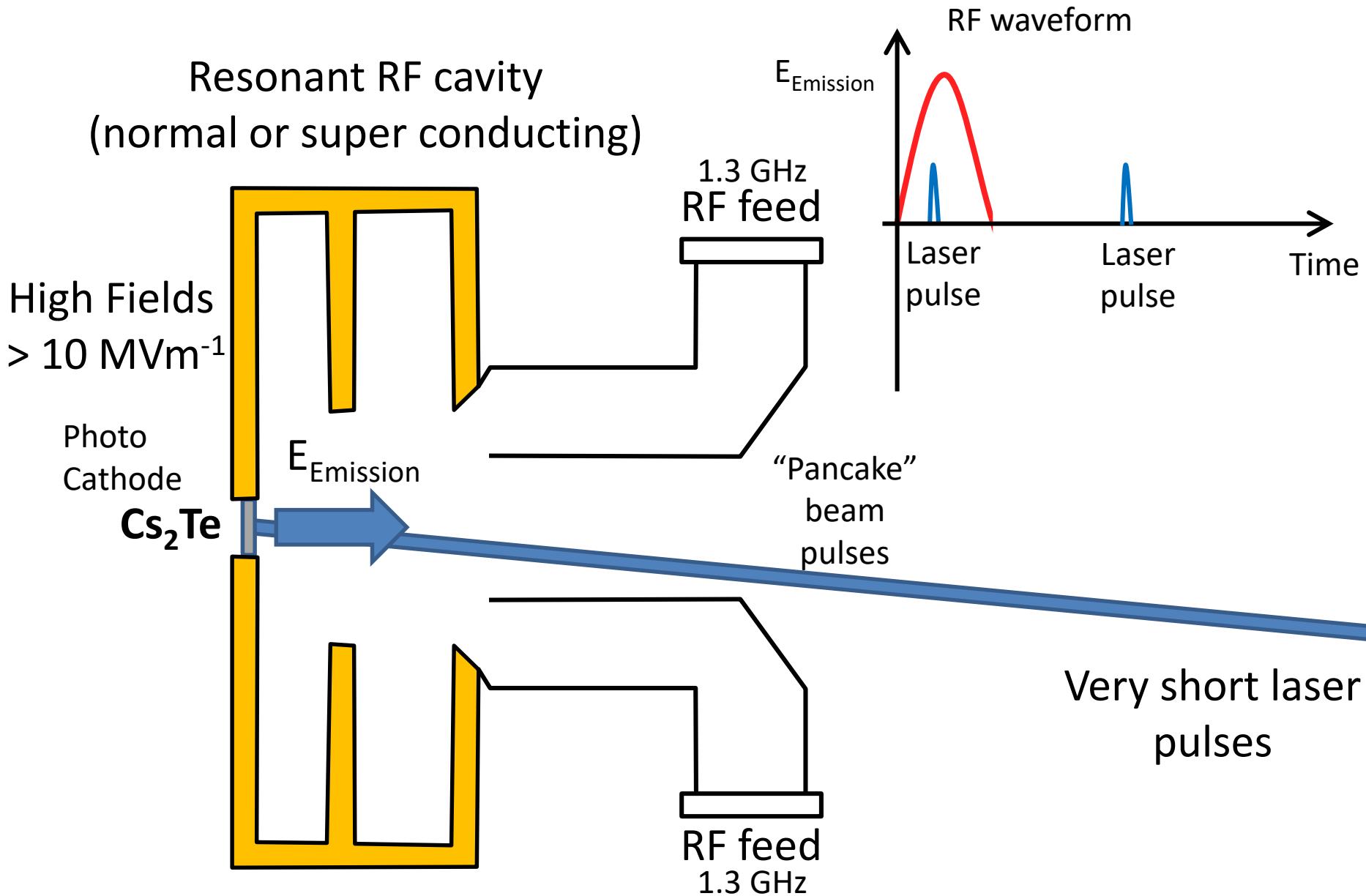
Lasers are so fast they can easily beat  
Child-Langmuir (so can gridded  
extraction)



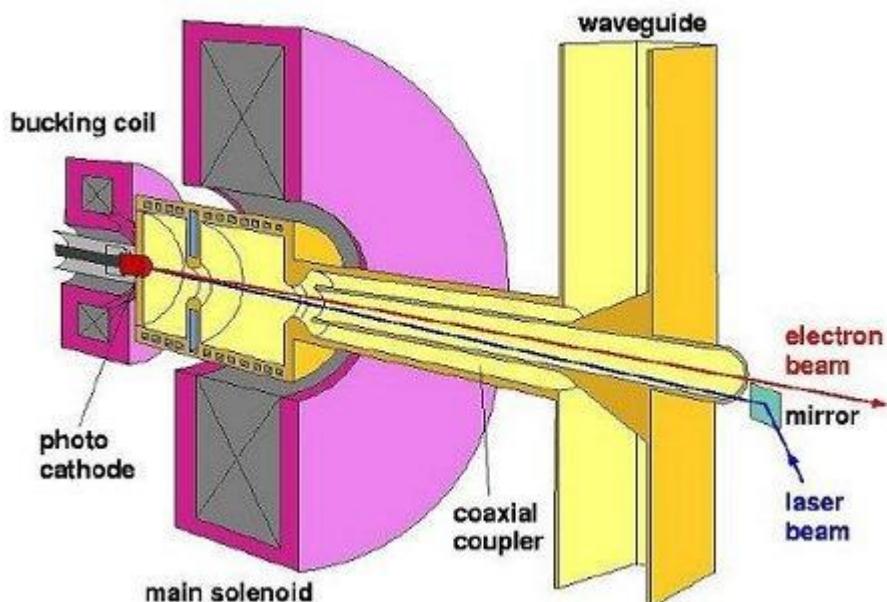
# RF Photoemission Source



# RF Photoemission Source

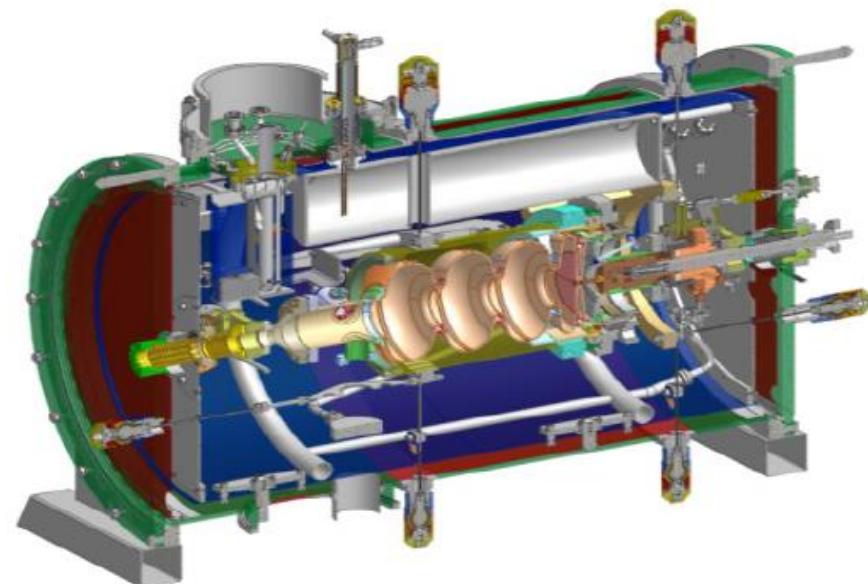


## Normally conducting



20 ps, 1 nC pulses  
(50 A pulse)

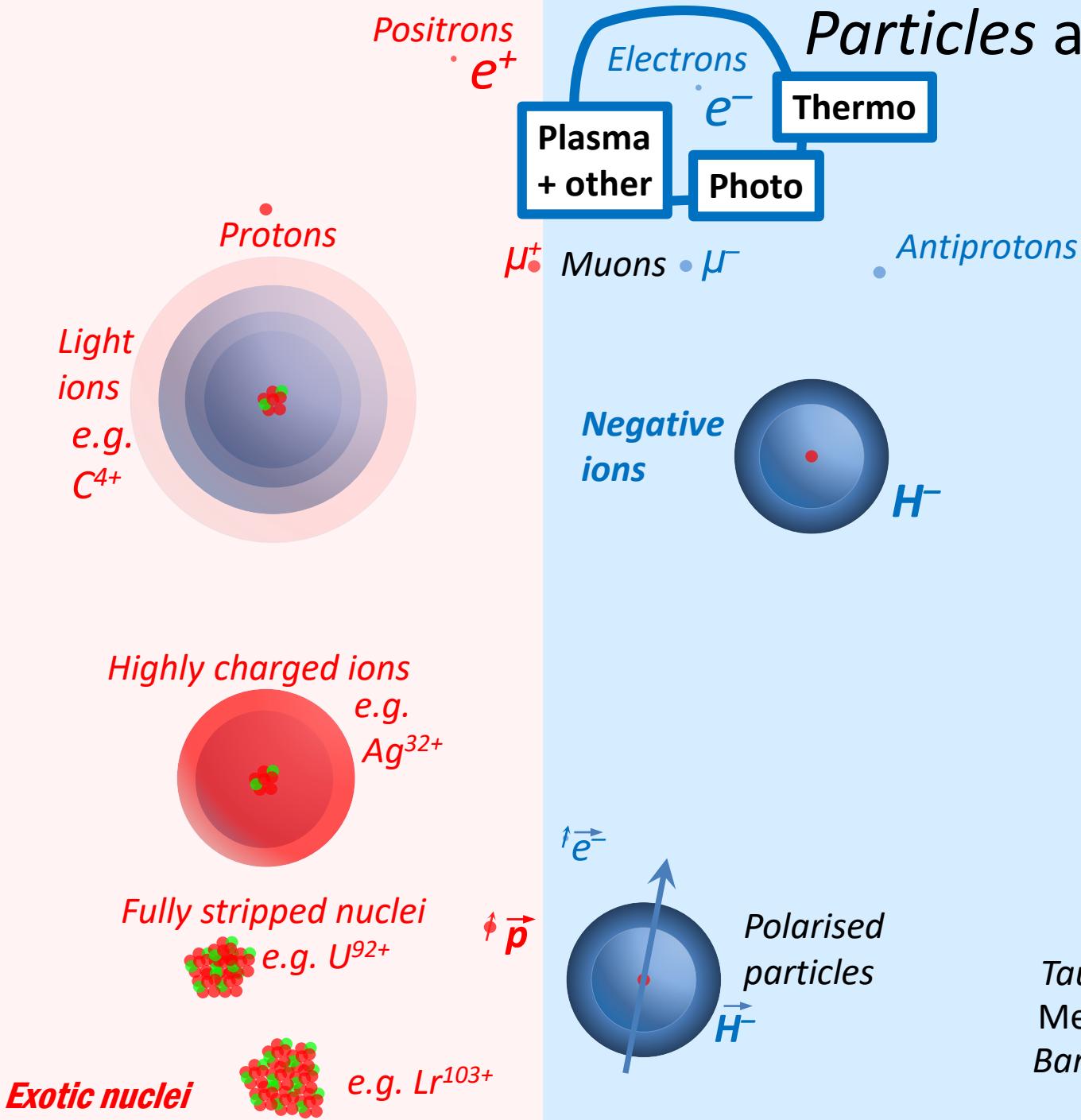
## Super conducting



15 ps, 1 nC pulses  
(67 A pulse)

High brightness low emittance guns for FEL

# Particles and Sources



**Photons**

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

**Neutrons**  $n$

**Neutral particles**

$H^0$



**Higgs  
Bosons**

## Zoo of curiosities

Tauons

Mesons

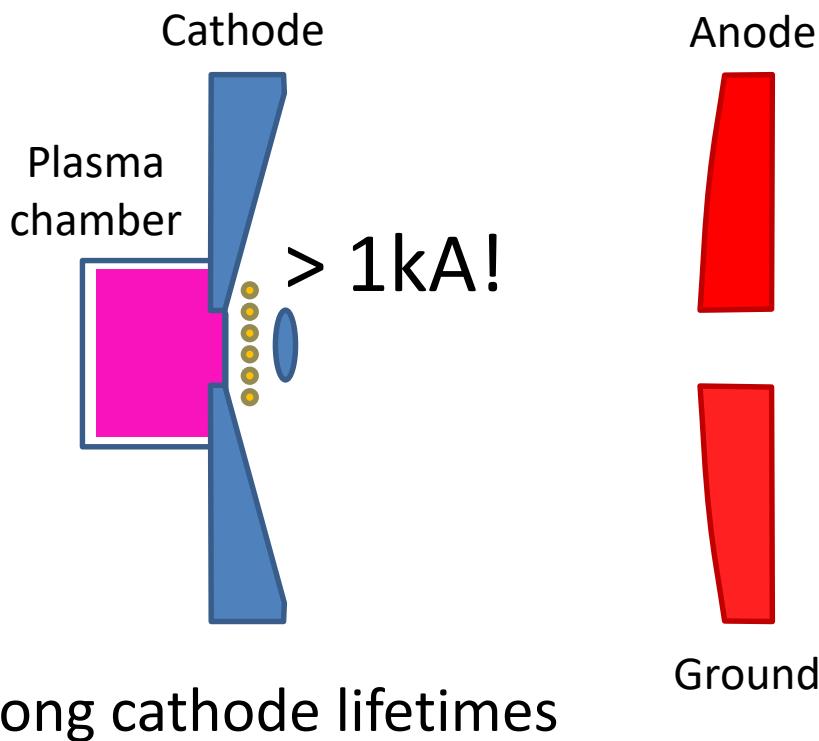
Baryons

$W + Z$

Bosons

# Plasma Cathode

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

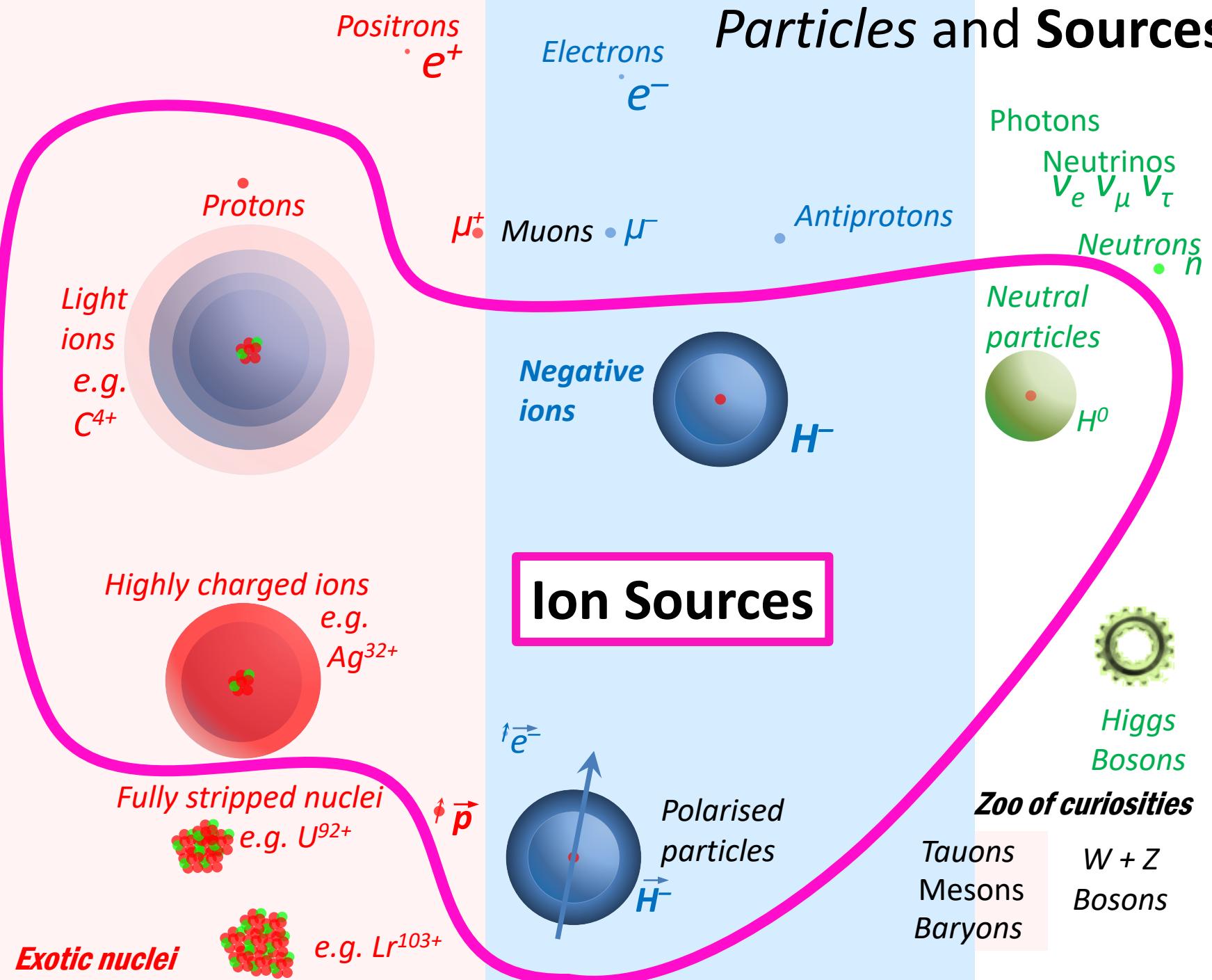


Other electron sources:

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

Field emission from needle arrays  
Diamond amplifiers  
Etc...

# Particles and Sources



# Basic Plasma Properties

## Density, $n$ (per $\text{cm}^3$ or $\text{m}^3$ )

$n_e$  = density of electrons

$n_i$  = density of ions

$n_n$  = density of neutrals

## Charge State, $q$

$\text{H}^+$  →  $q = +1$

$\text{Pb}^{3+}$  →  $q = +3$

$\text{H}^-$  →  $q = -1$

## Temperature, $T$ (eV)

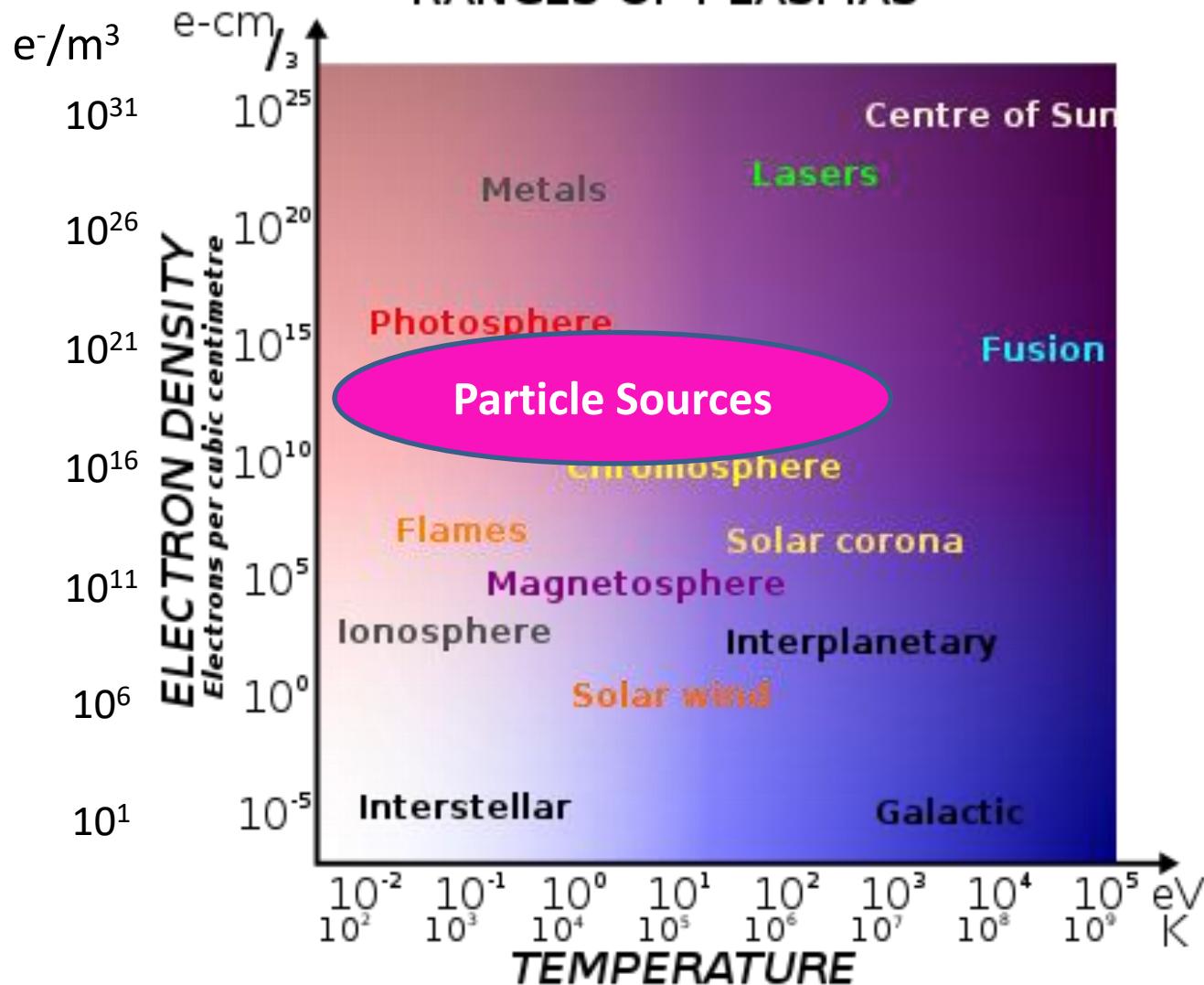
$T_e$  = temperature of electrons

$T_i$  = temperature of ions

$T_n$  = temperature of neutrals

$11600^\circ\text{K} = 1 \text{ eV}$

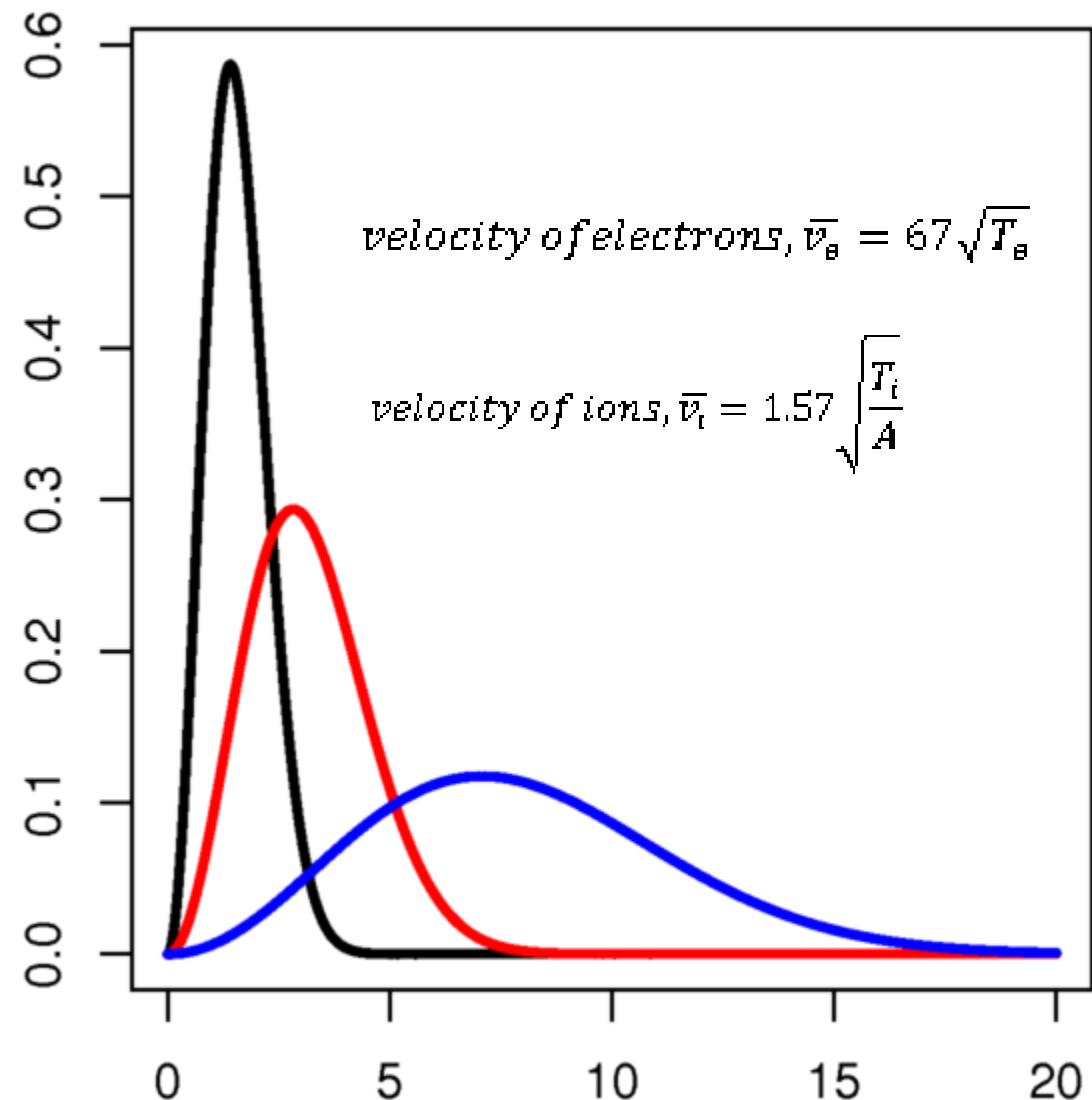
## RANGES OF PLASMAS



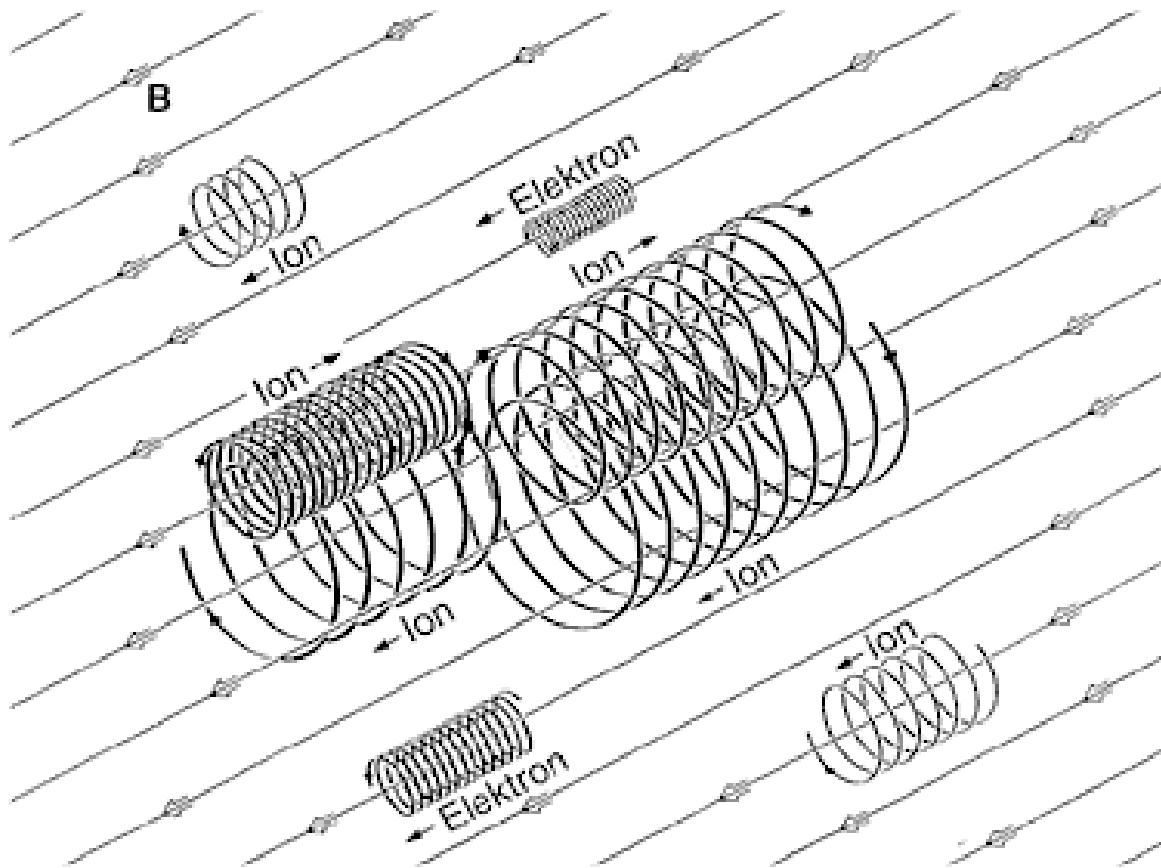
# Temperature Distribution

If thermalised  
velocity  
distributions  
should follow  
Maxwell Boltzmann  
statistics

However, in  
magnetic fields:  
 $v_x \neq v_y \neq v_z$

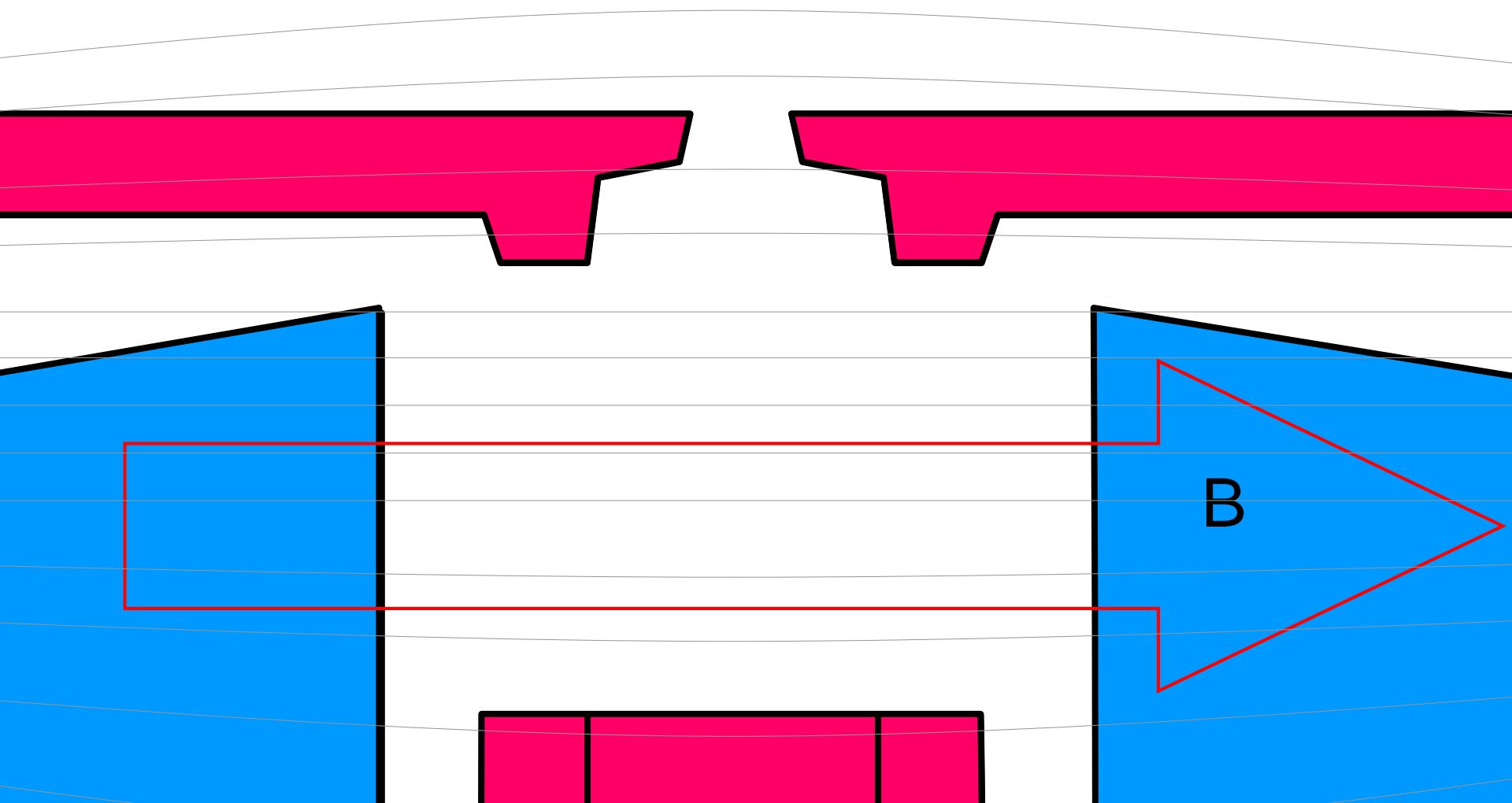


# Magnetic Confinement

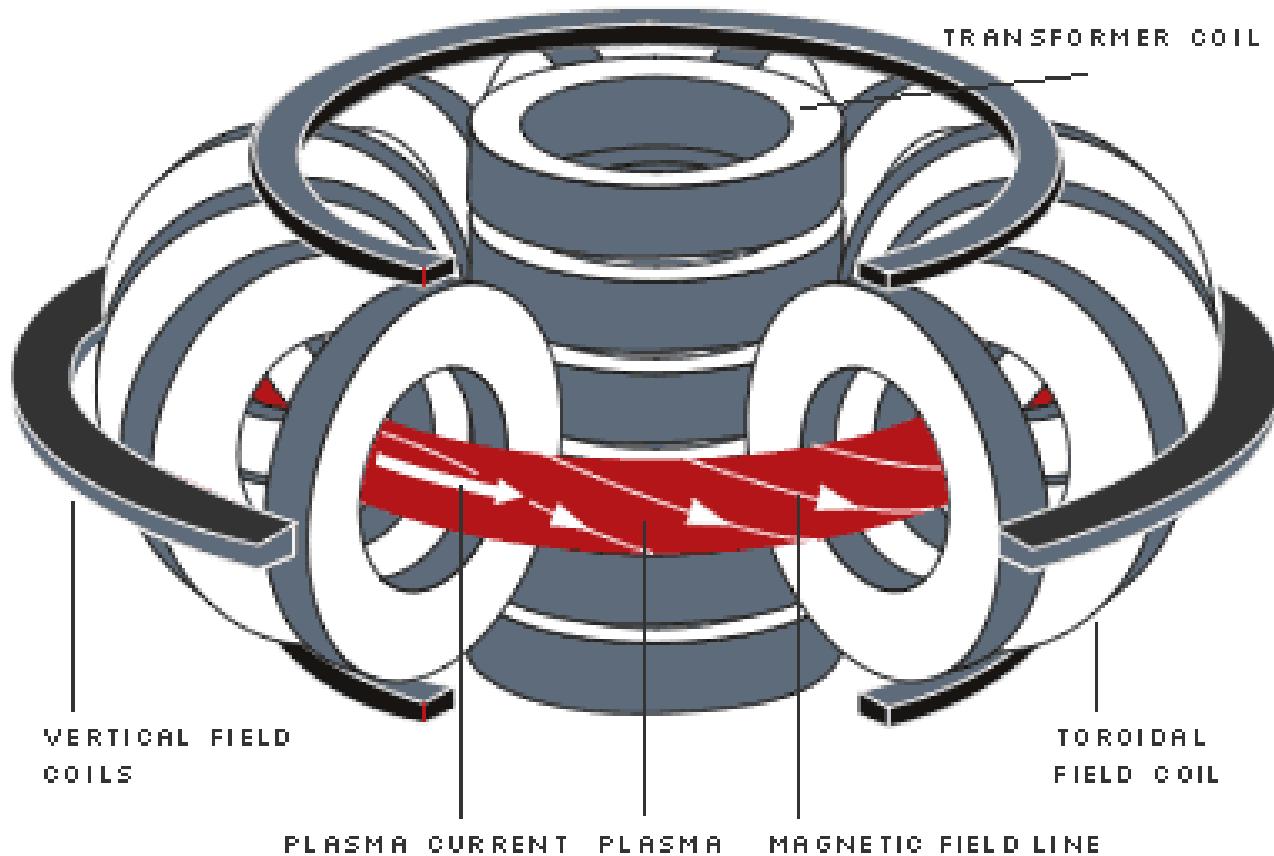


Particles spiral along magnetic field lines

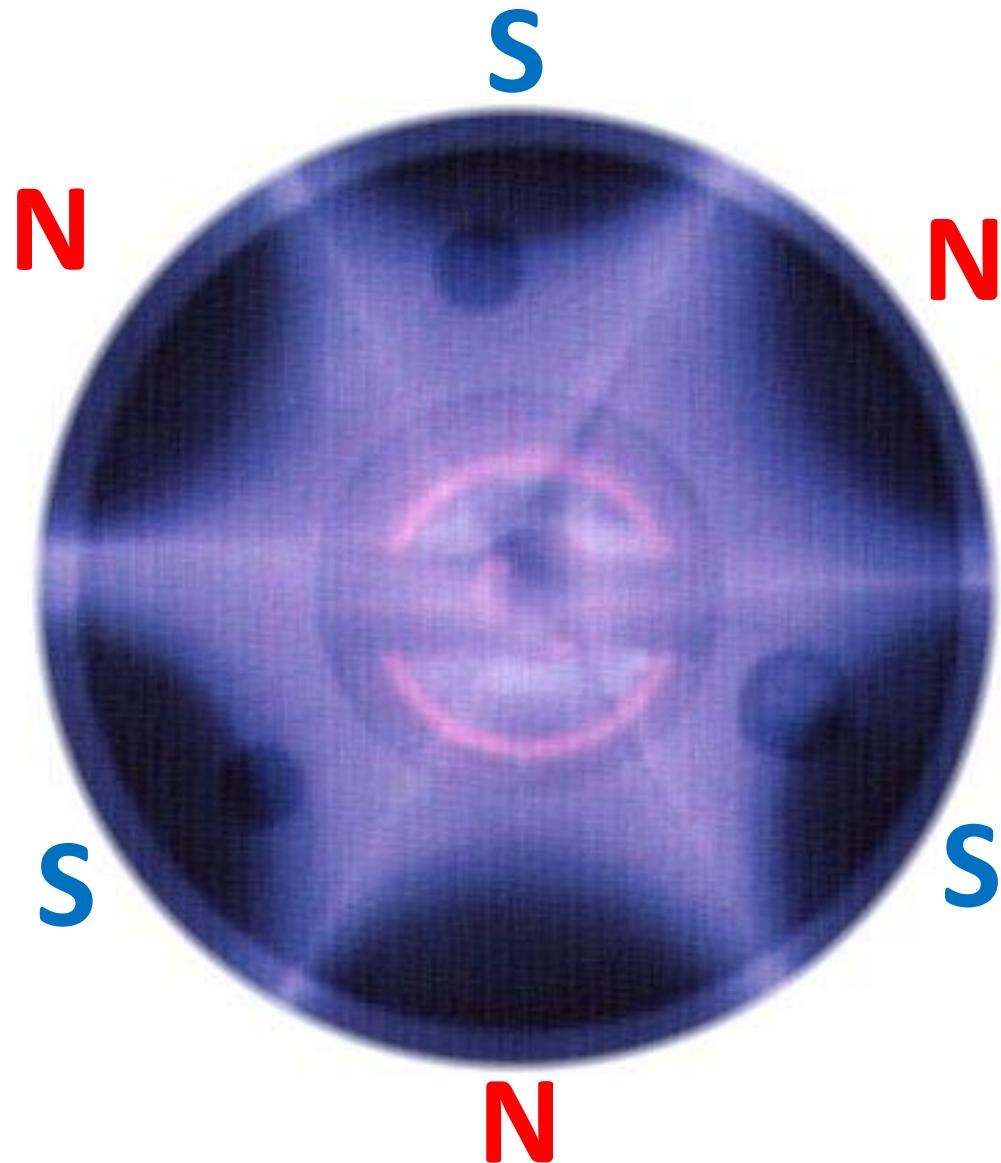
# Dipole field



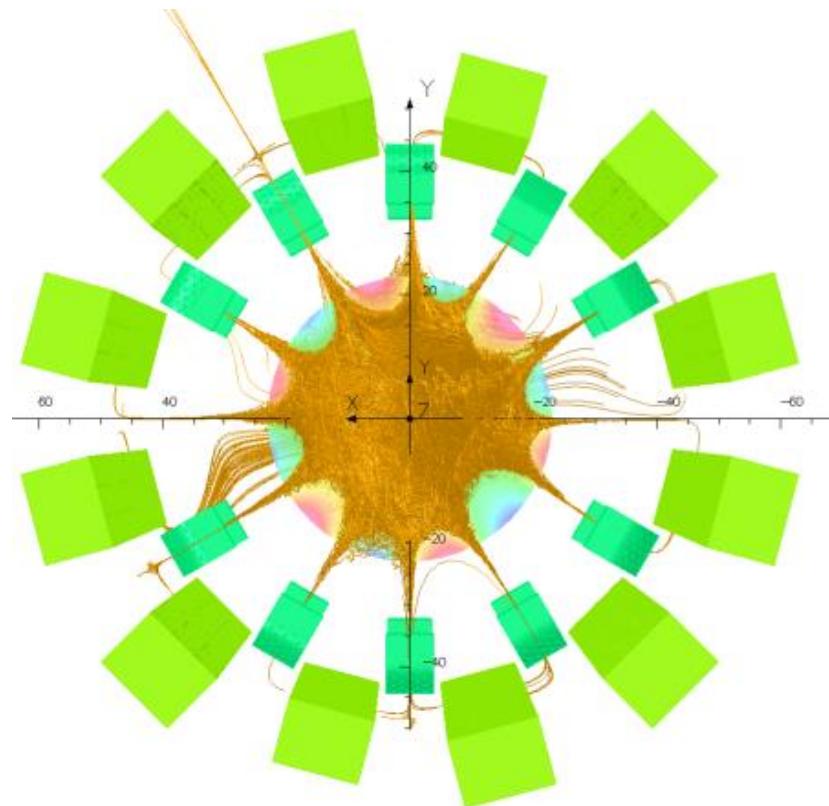
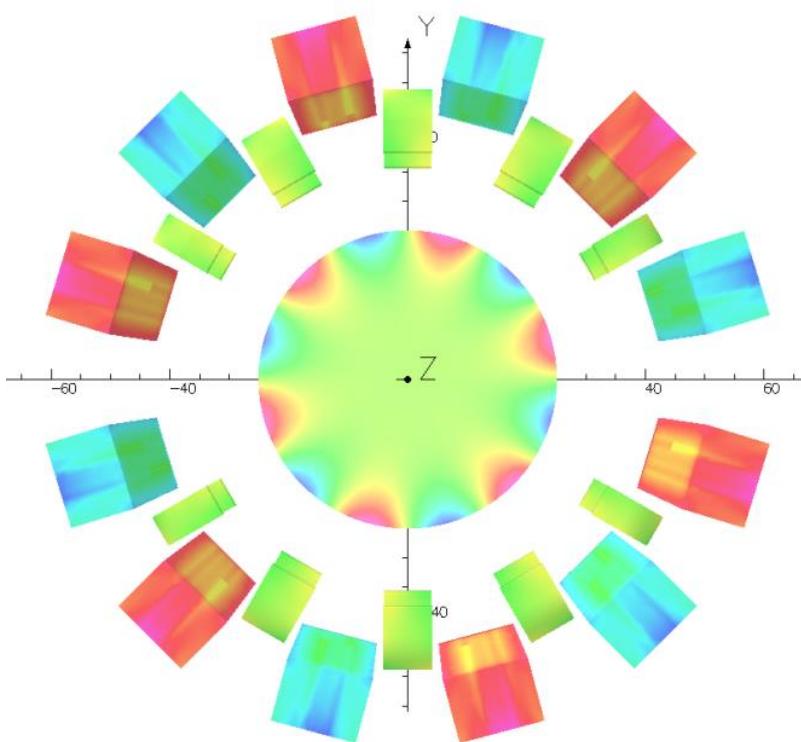
# Solenoid field



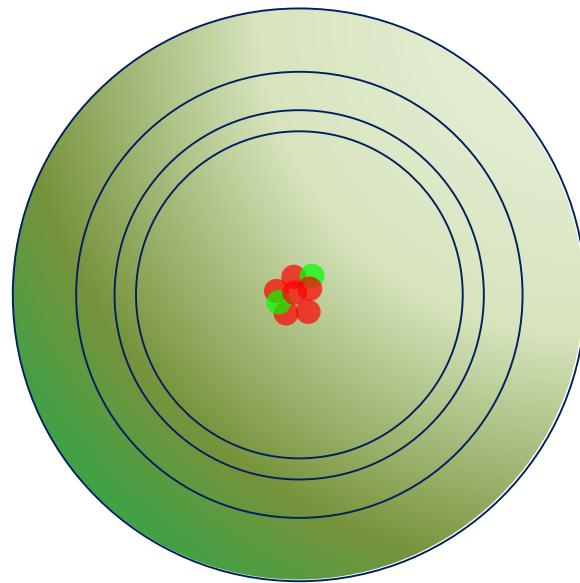
# Hexapole



# Multicusp Confinement



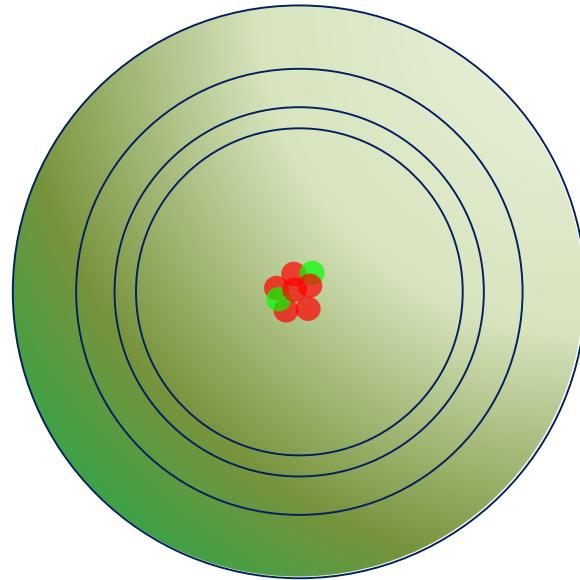
# Ionisation



Neutral Atom

Most sources rely on electron impact ionisation

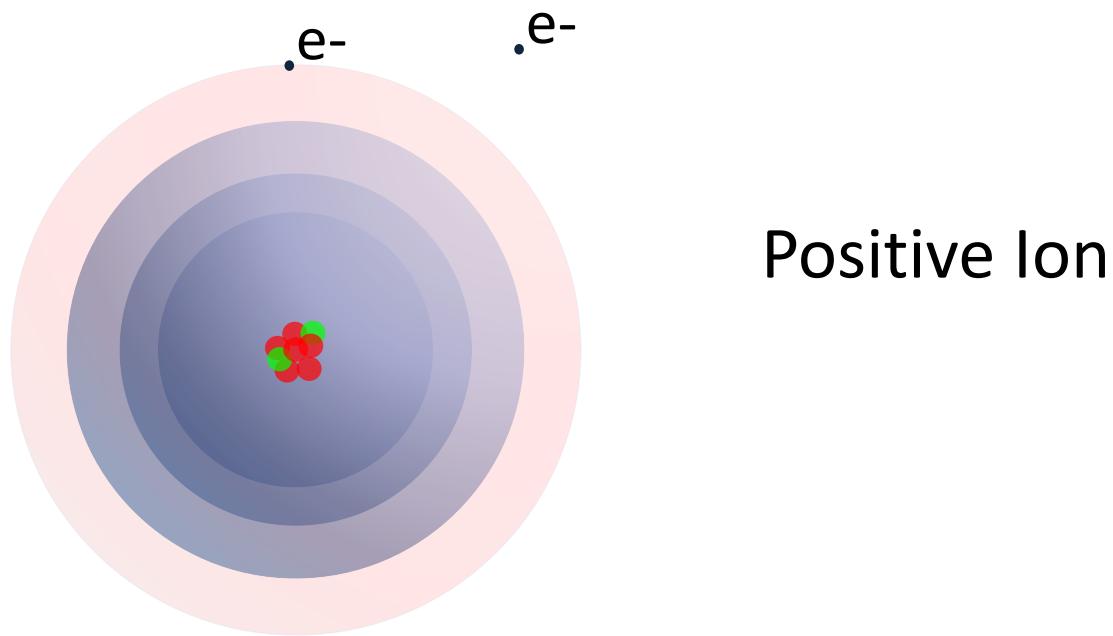
# Ionisation



Neutral Atom

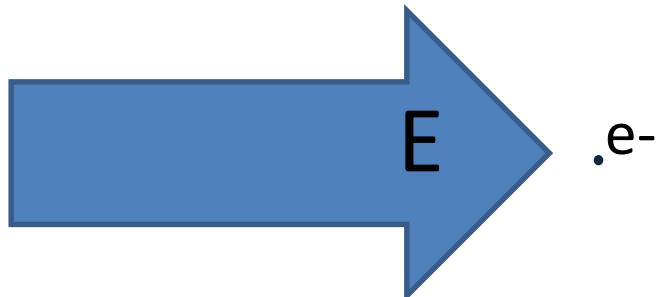
Most sources rely on electron impact ionisation

# Ionisation

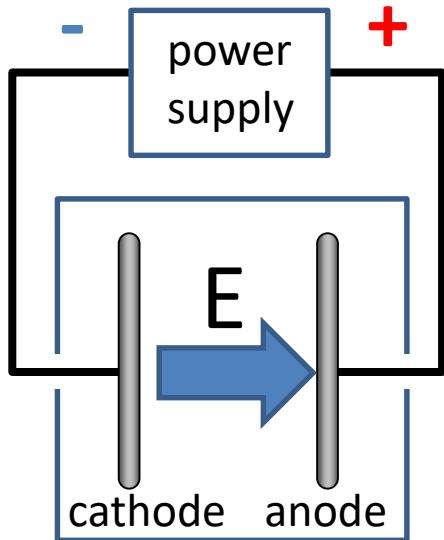


Most sources rely on electron impact ionisation

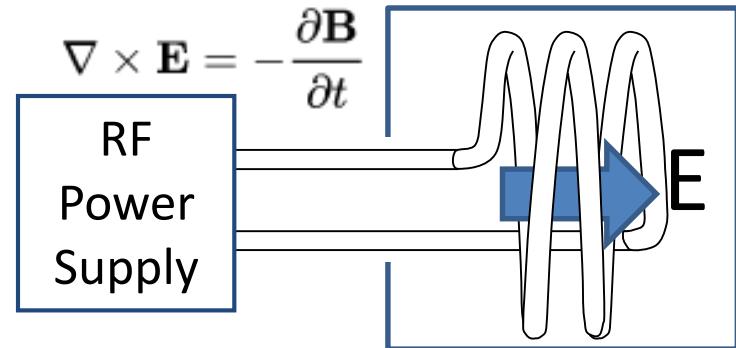
# Accelerating electrons



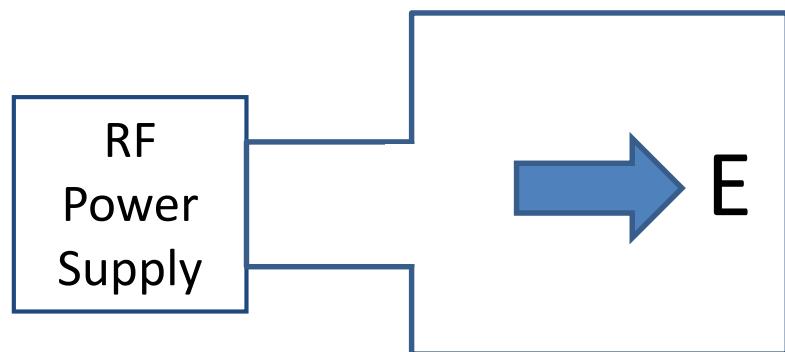
(a) Capacitively Coupled Plasma (CCP) = Voltage applied to electrodes creates electric field



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



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



# Percentage Ionisation

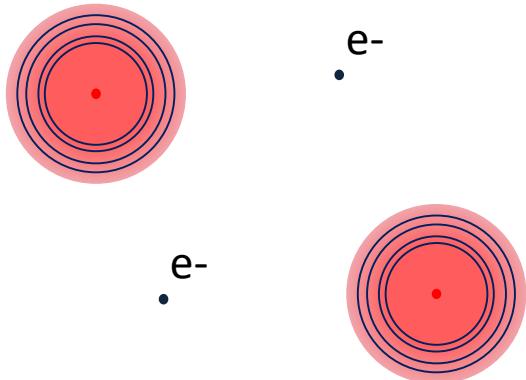
$$\frac{n_i}{n_i + n_n}$$

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

# Quasi Neutrality

$$\sum q_i n_i = n_e$$

# Debye Length



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

# Cathode Sheath

Anode



$V_{\text{anode}}$

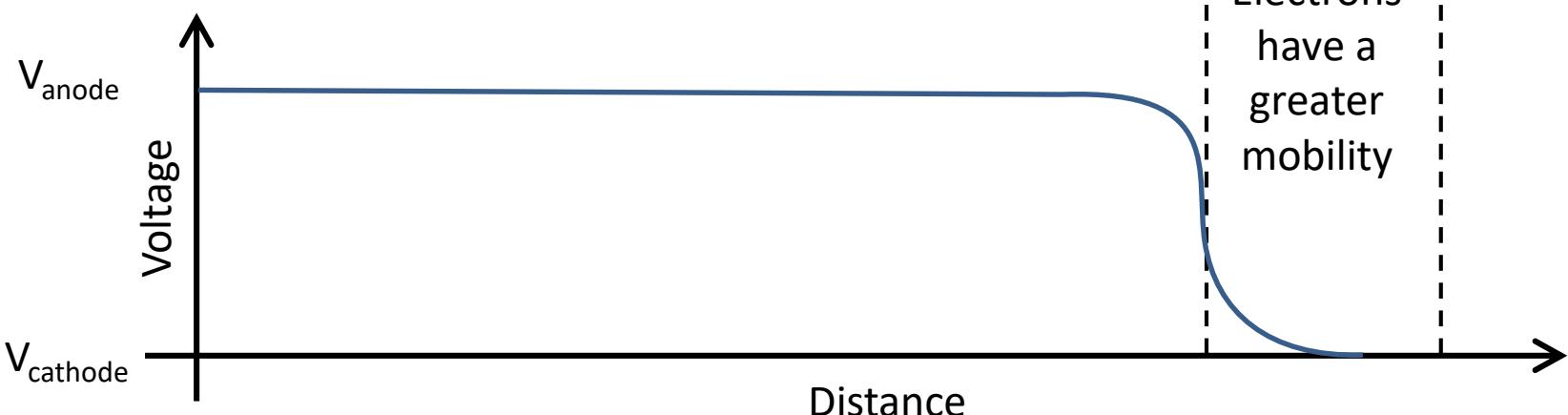
Quasi neutral plasma  
at anode potential  
(approximately)

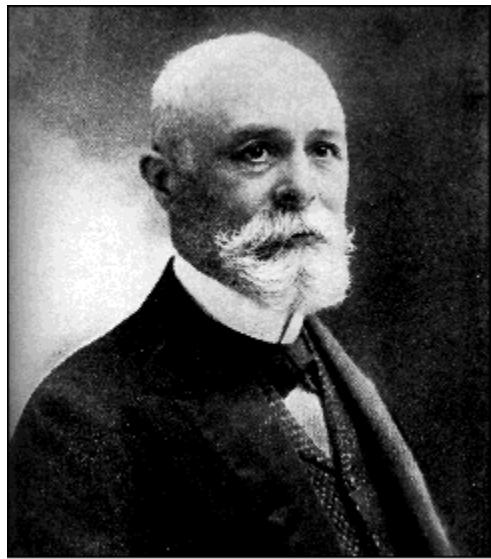
Cathode



$V_{\text{cathode}}$

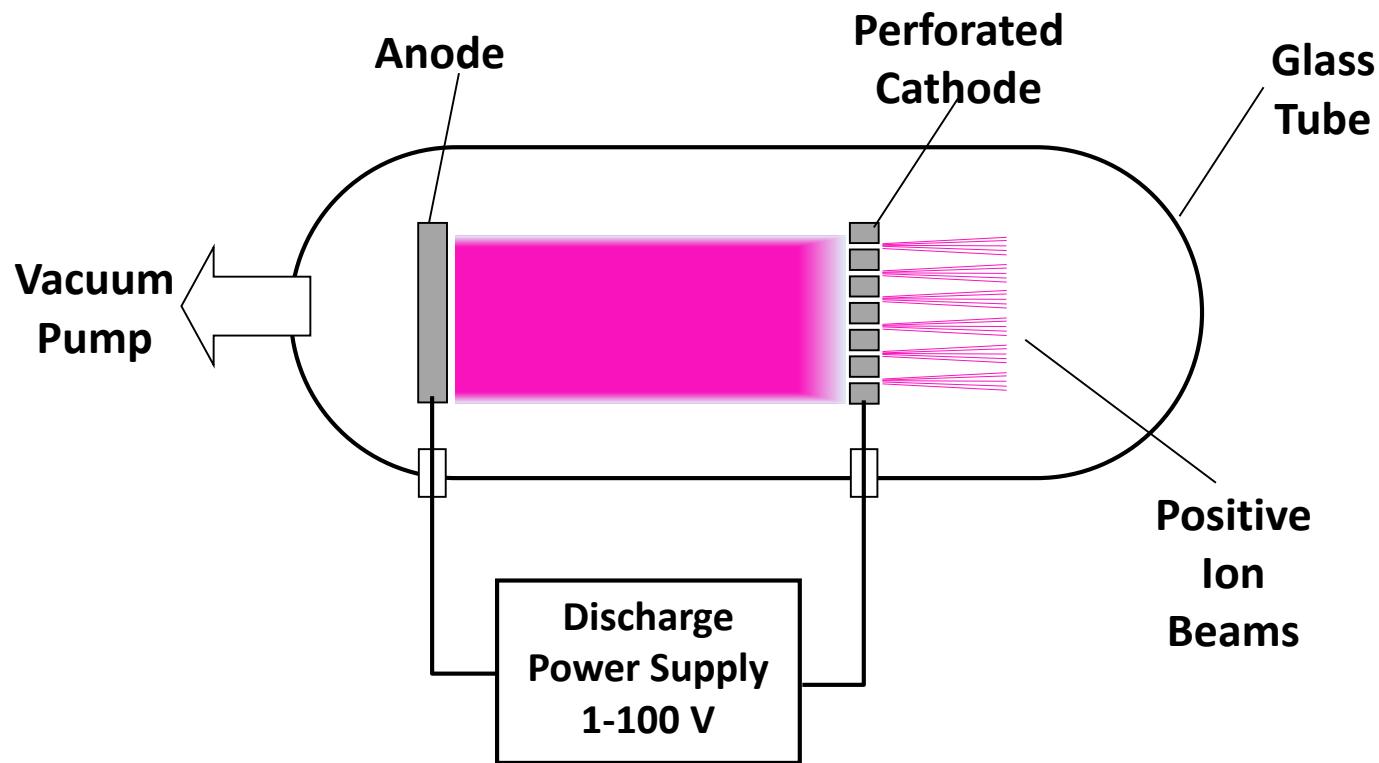
Sheath



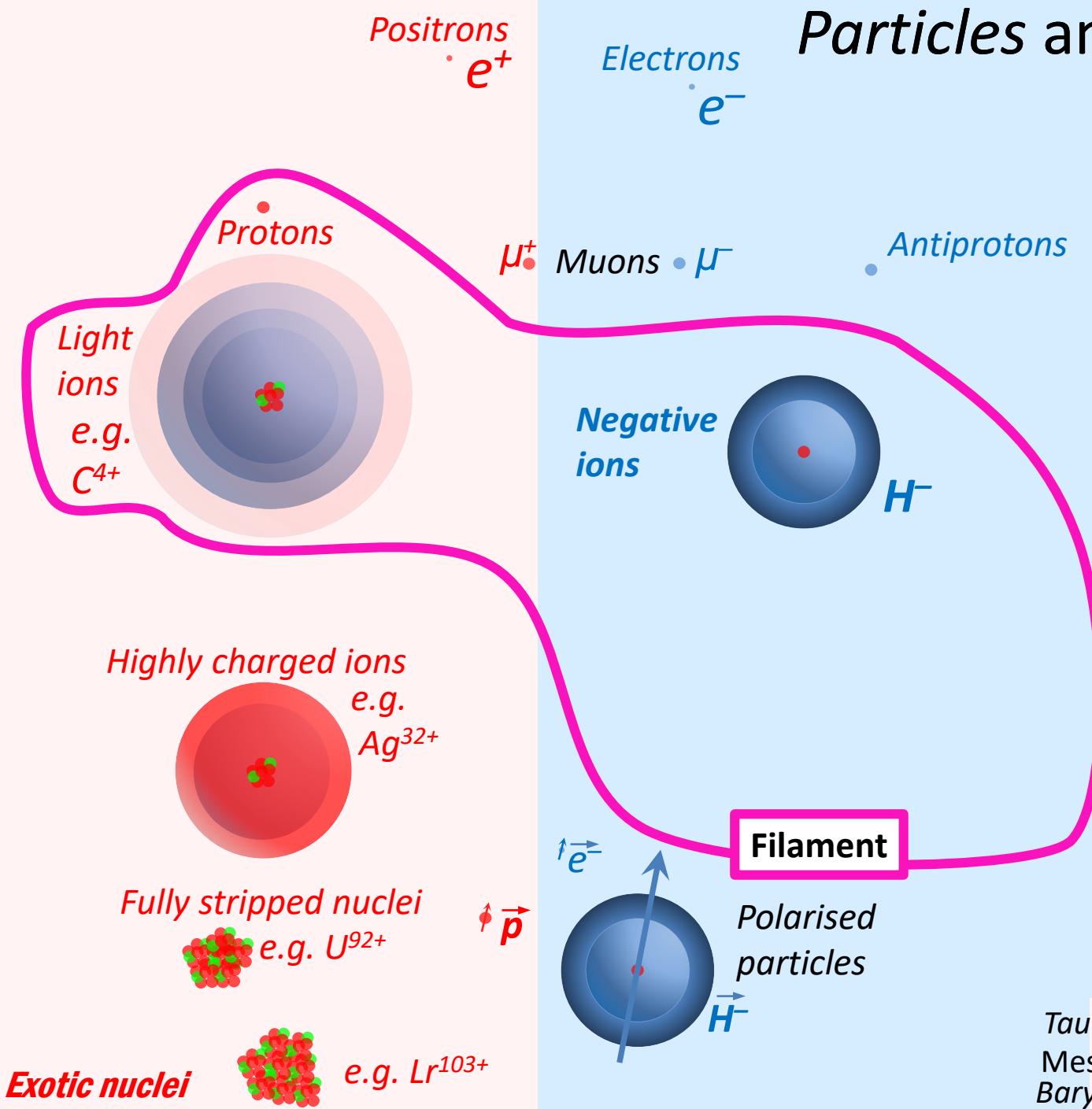


# Canal Ray Source

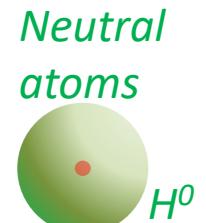
In 1886 Eugen Goldstein discovered canal rays



# Particles and Sources



Photons  
Neutrinos  
 $\nu_e \nu_\mu \nu_\tau$   
Neutrons  
 $n$

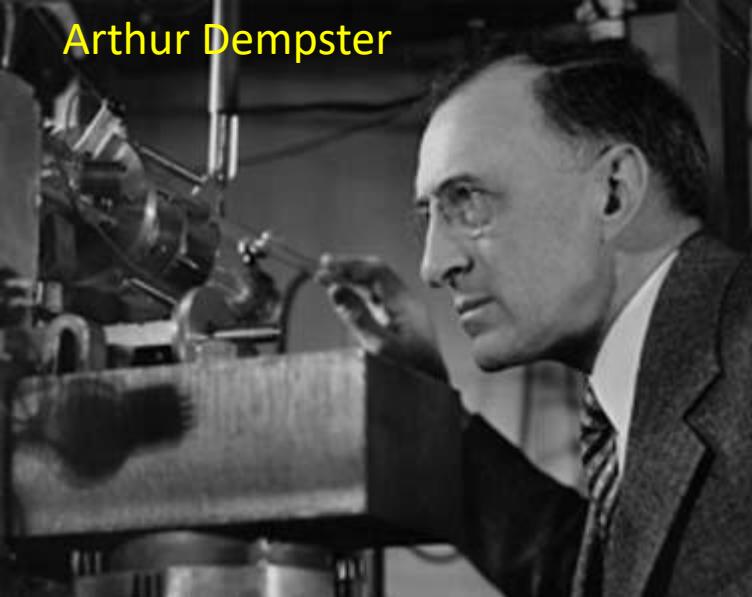


Higgs  
Bosons

Zoo of  
curiosities  
 $W + Z$   
Bosons

Tauons  
Mesons  
Baryons

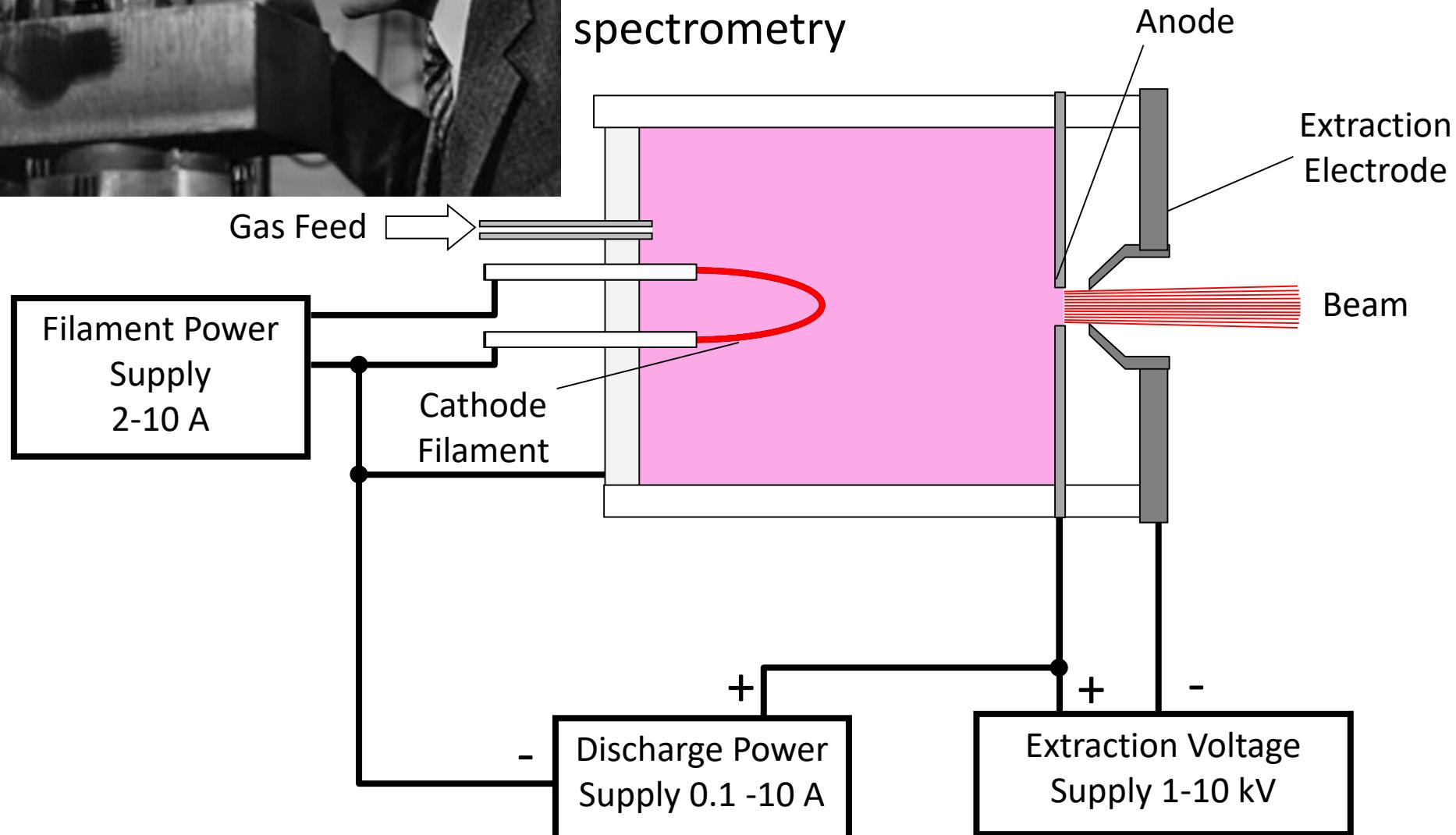
Arthur Dempster



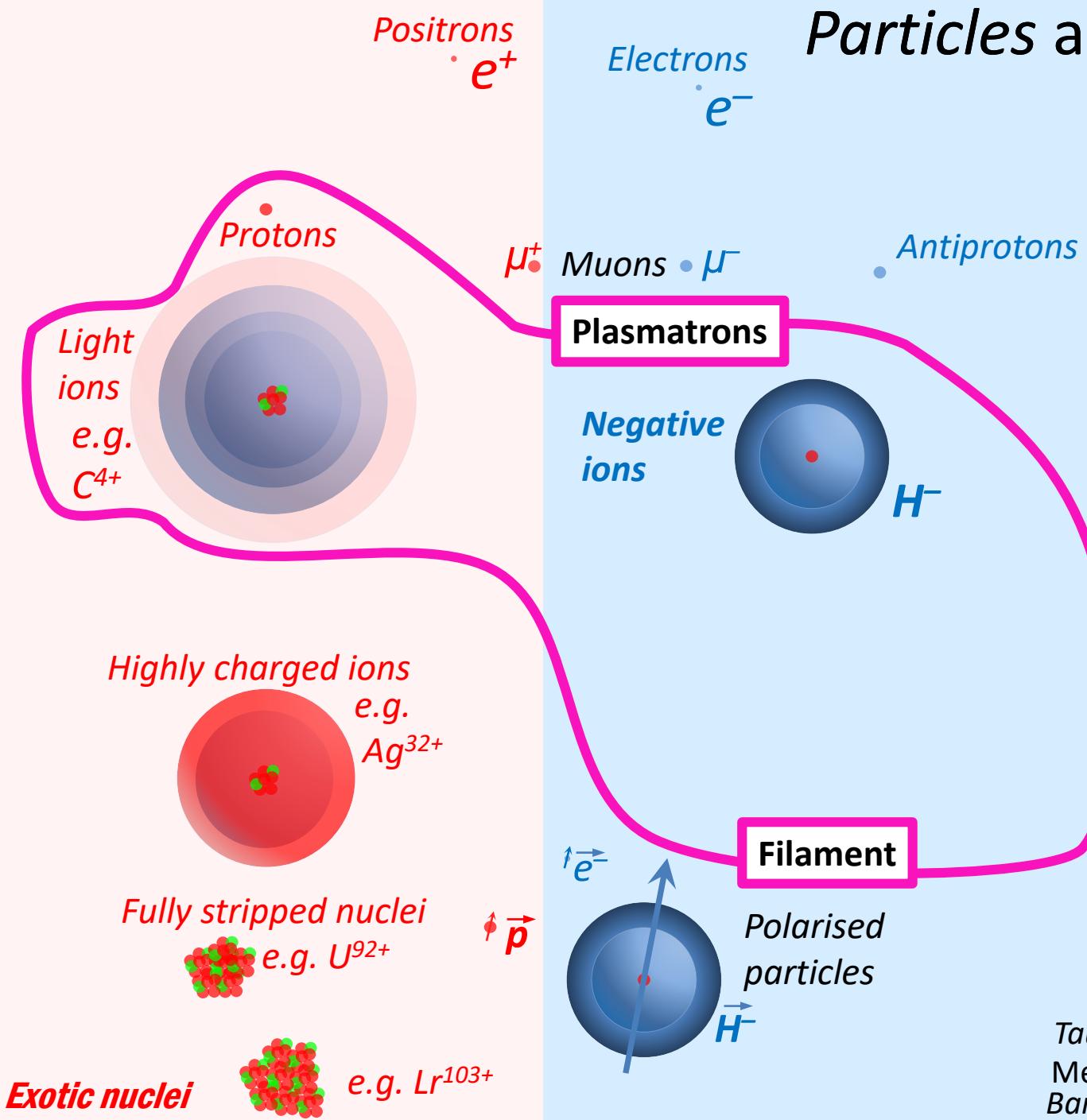
# Electron Bombardment Source (1916)

## The First True Ion Source (A Filament Source)

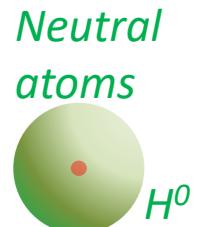
Early mass  
spectrometry



# Particles and Sources



Photons  
Neutrinos  
 $\nu_e \nu_\mu \nu_\tau$   
Neutrons  
 $n$

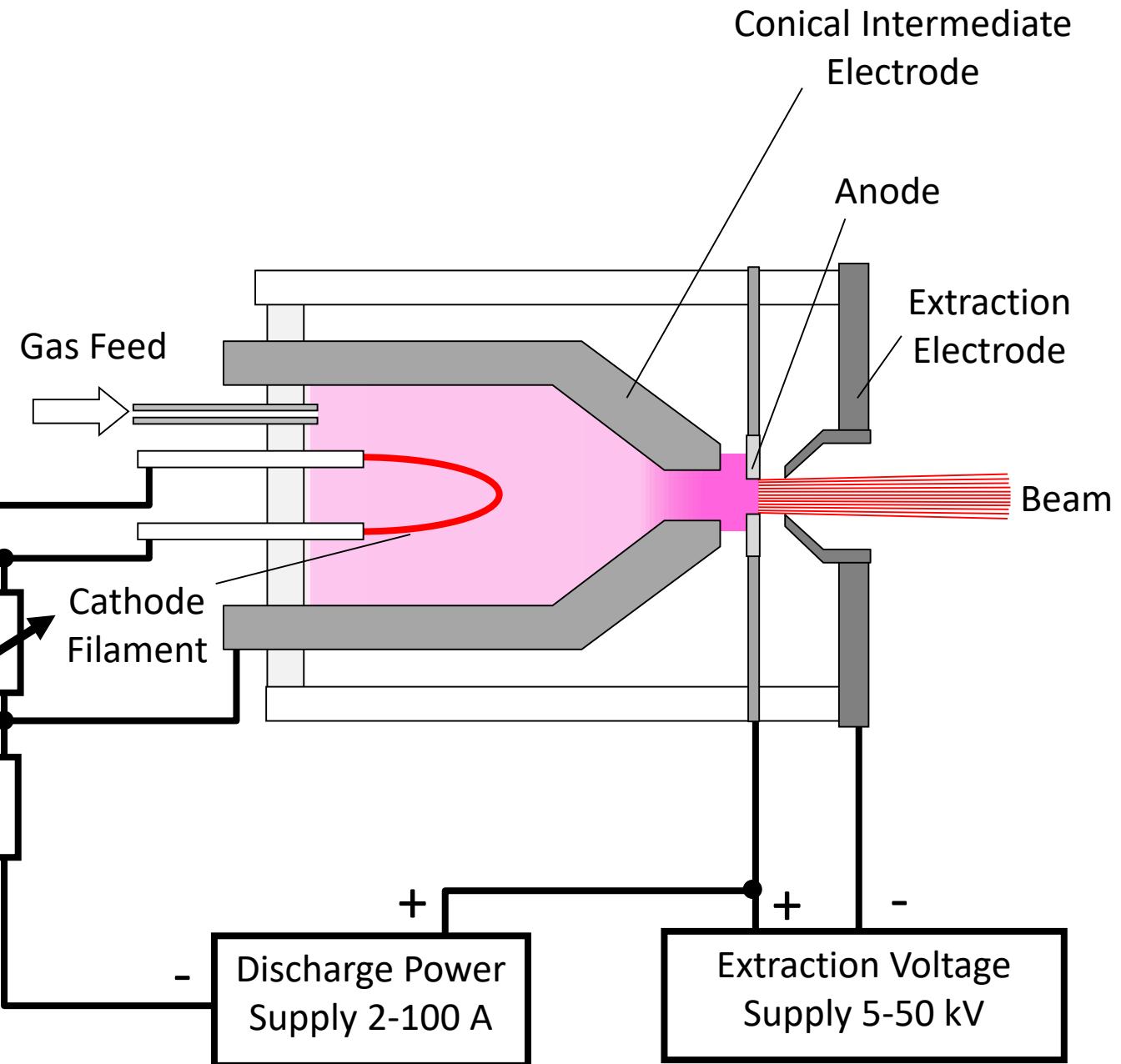


Zoo of curiosities

$W + Z$   
Bosons

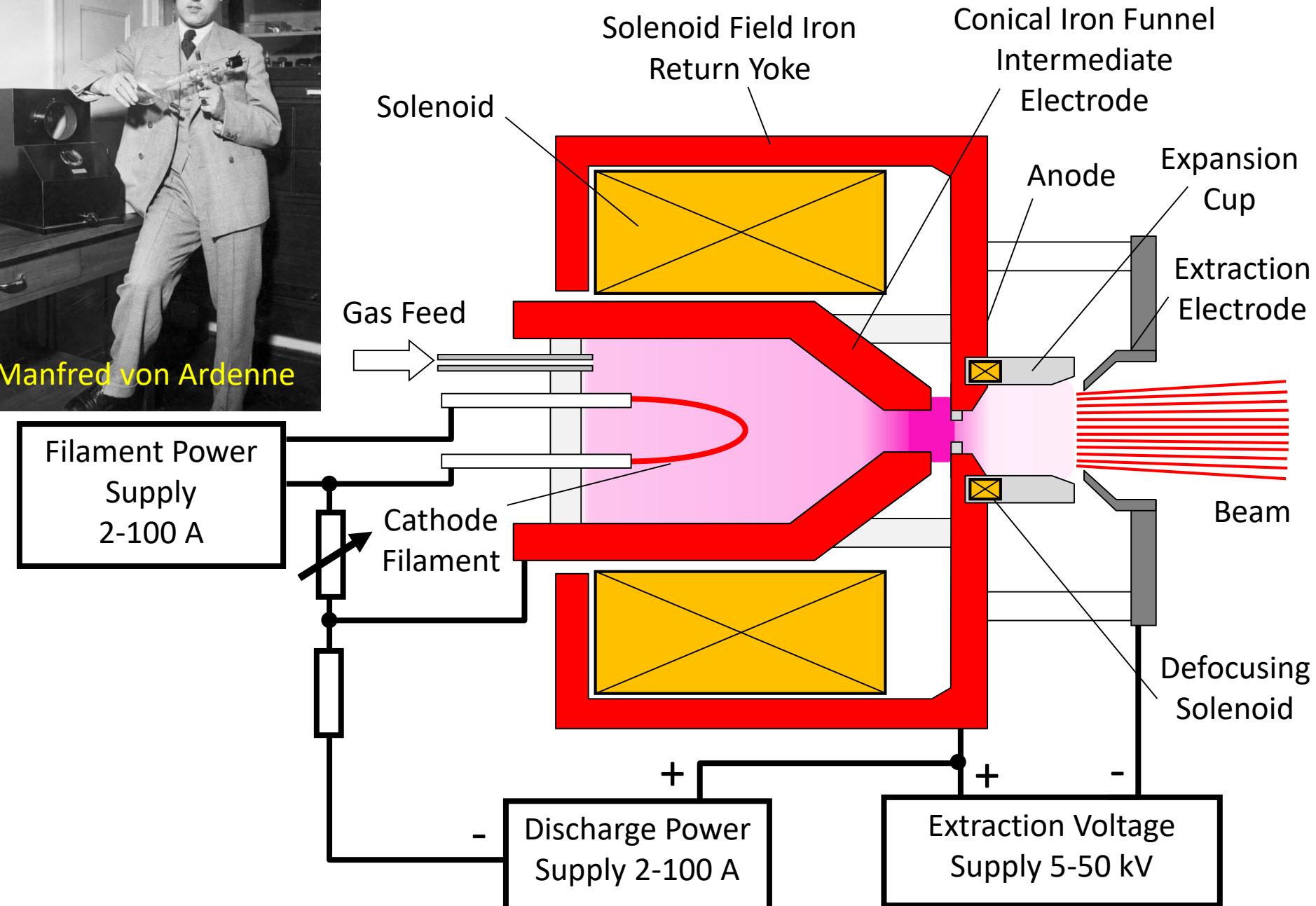
Tauons  
Mesons  
Baryons

# Plasmatron (late 1940s)



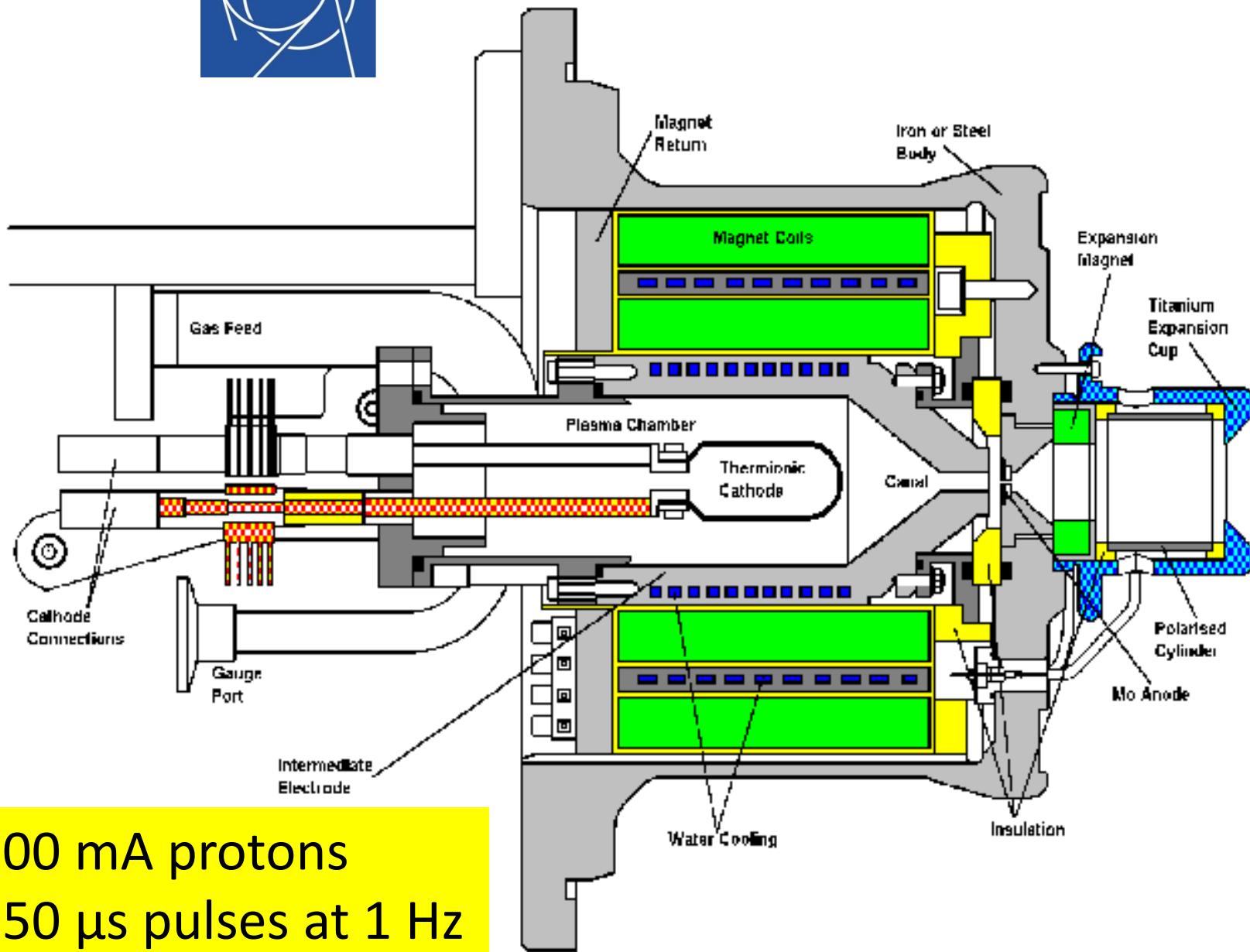


# Duoplasmatron (1956)



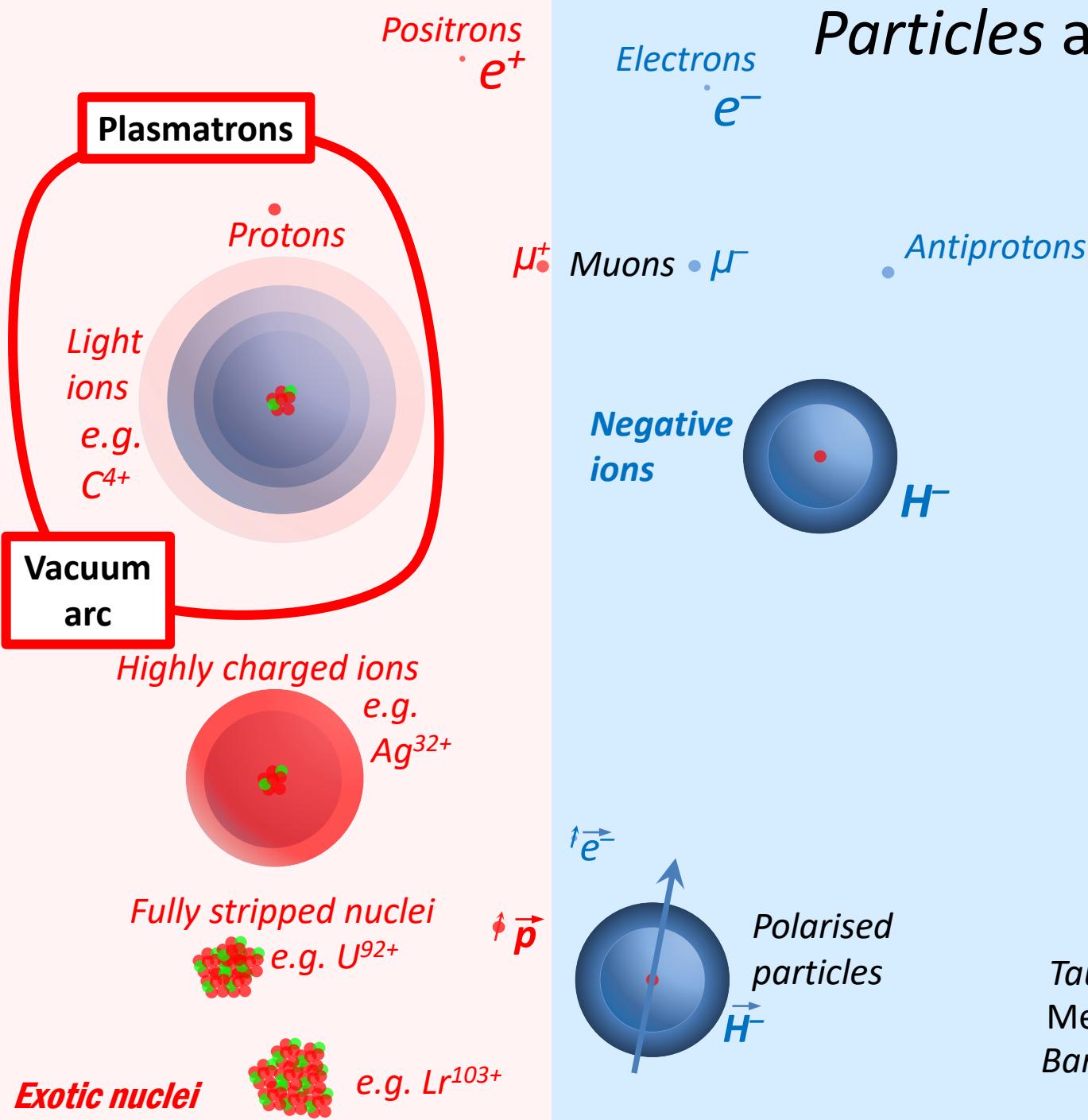


# Duoplasmatron



300 mA protons  
150  $\mu$ s pulses at 1 Hz

# Particles and Sources



Photons  
Neutrinos  $\nu_e \nu_\mu \nu_\tau$   
Neutrons  $n$

Neutral particles  
 $H^0$



Higgs Bosons

## Zoo of curiosities

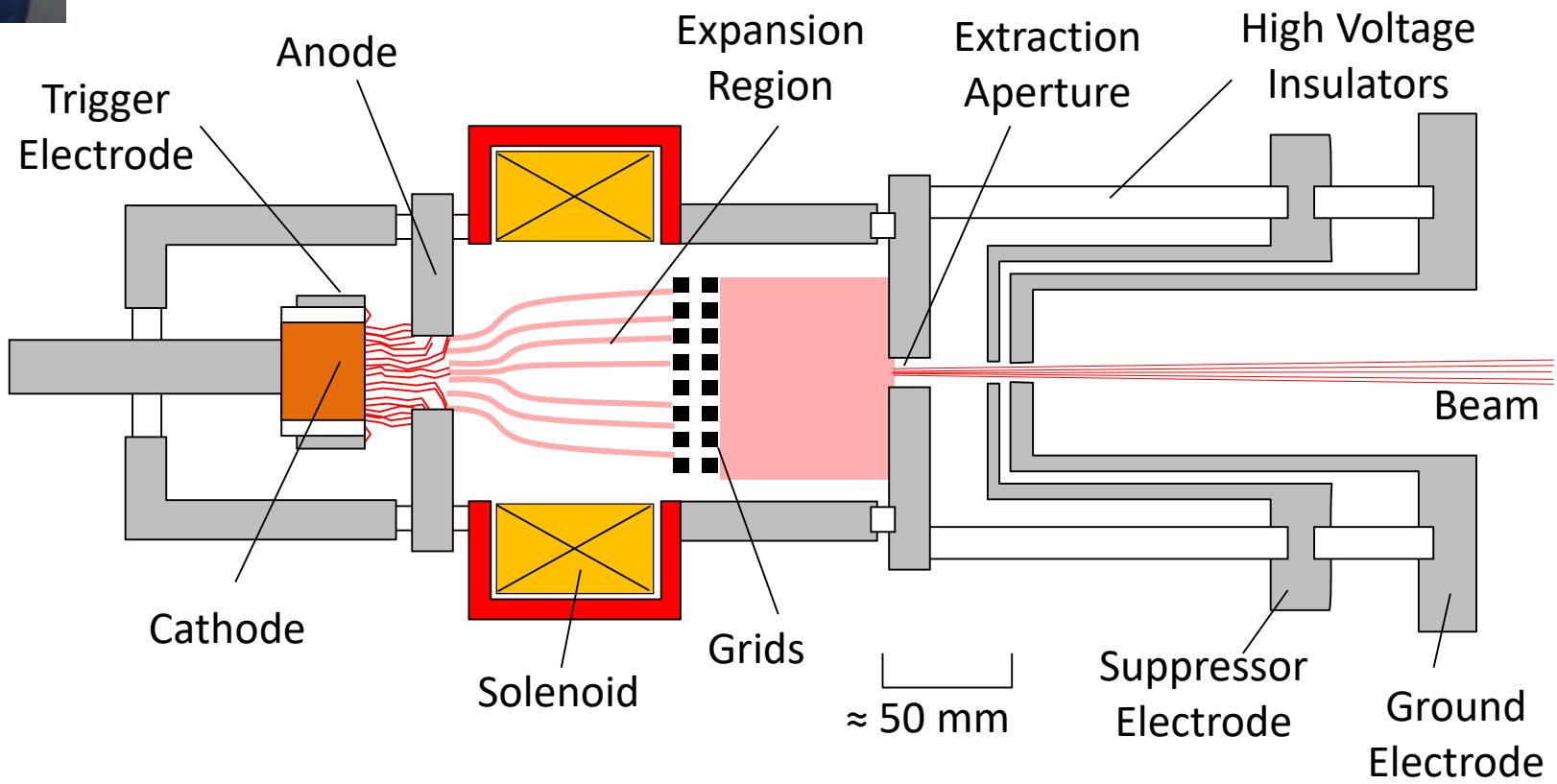
Tauons  
Mesons  
Baryons

$W + Z$   
Bosons



# Vacuum Arc Ion Sources

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

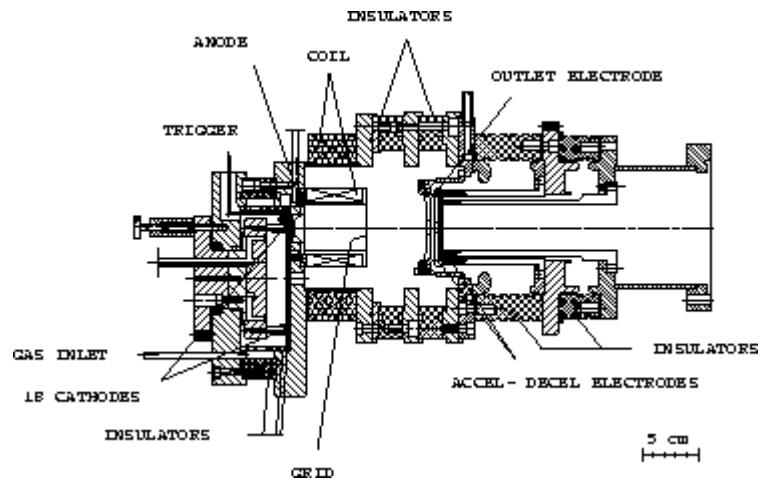




# MEtal Vapor Vacuum Arc (MEVVA)

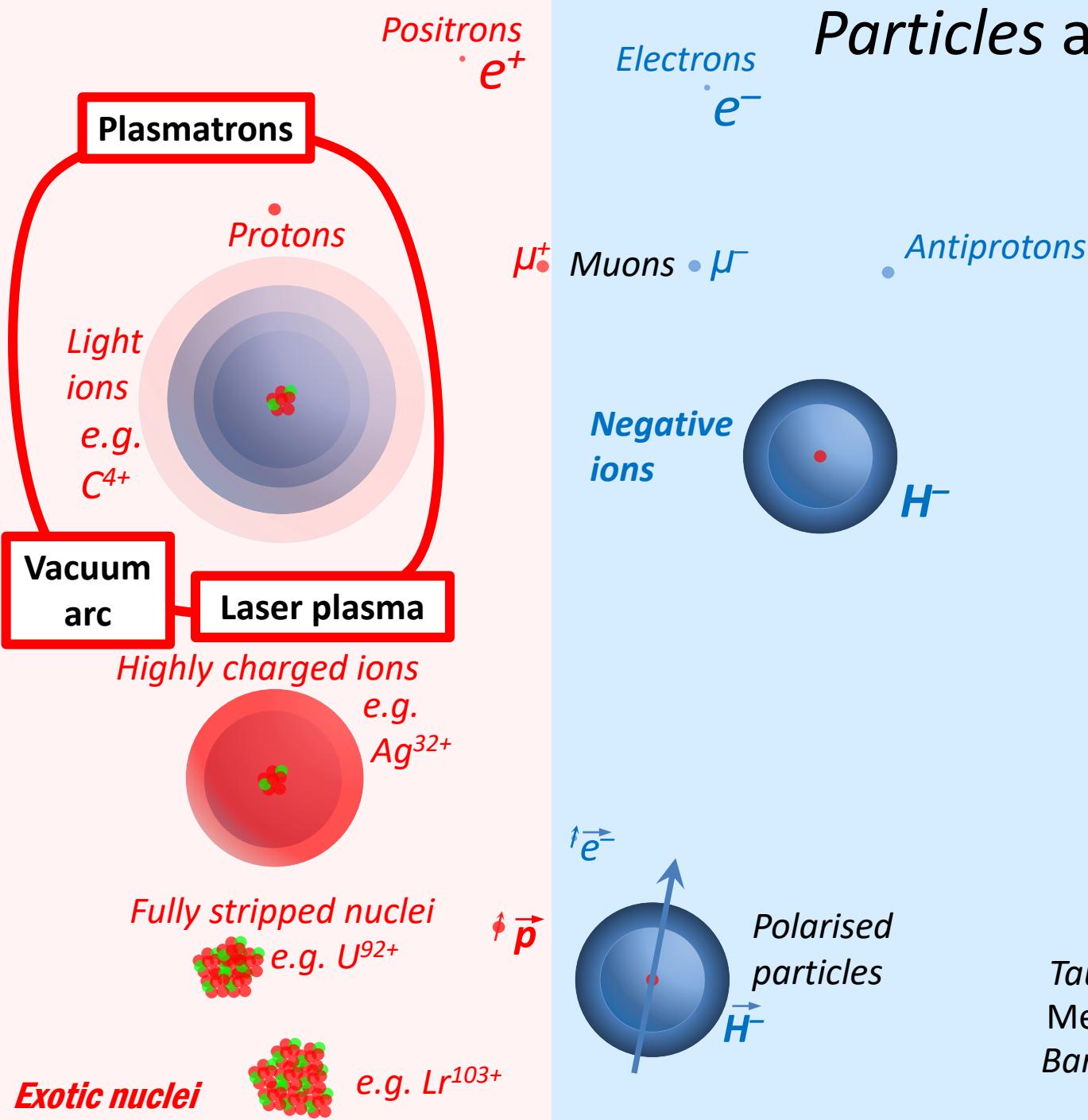


**G SI** MEVVA



15 mA of U<sup>4+</sup> ions

# Particles and Sources



Photons  
Neutrinos  $\nu_e \nu_\mu \nu_\tau$   
Neutrons  $n$

Neutral particles  
 $H^0$



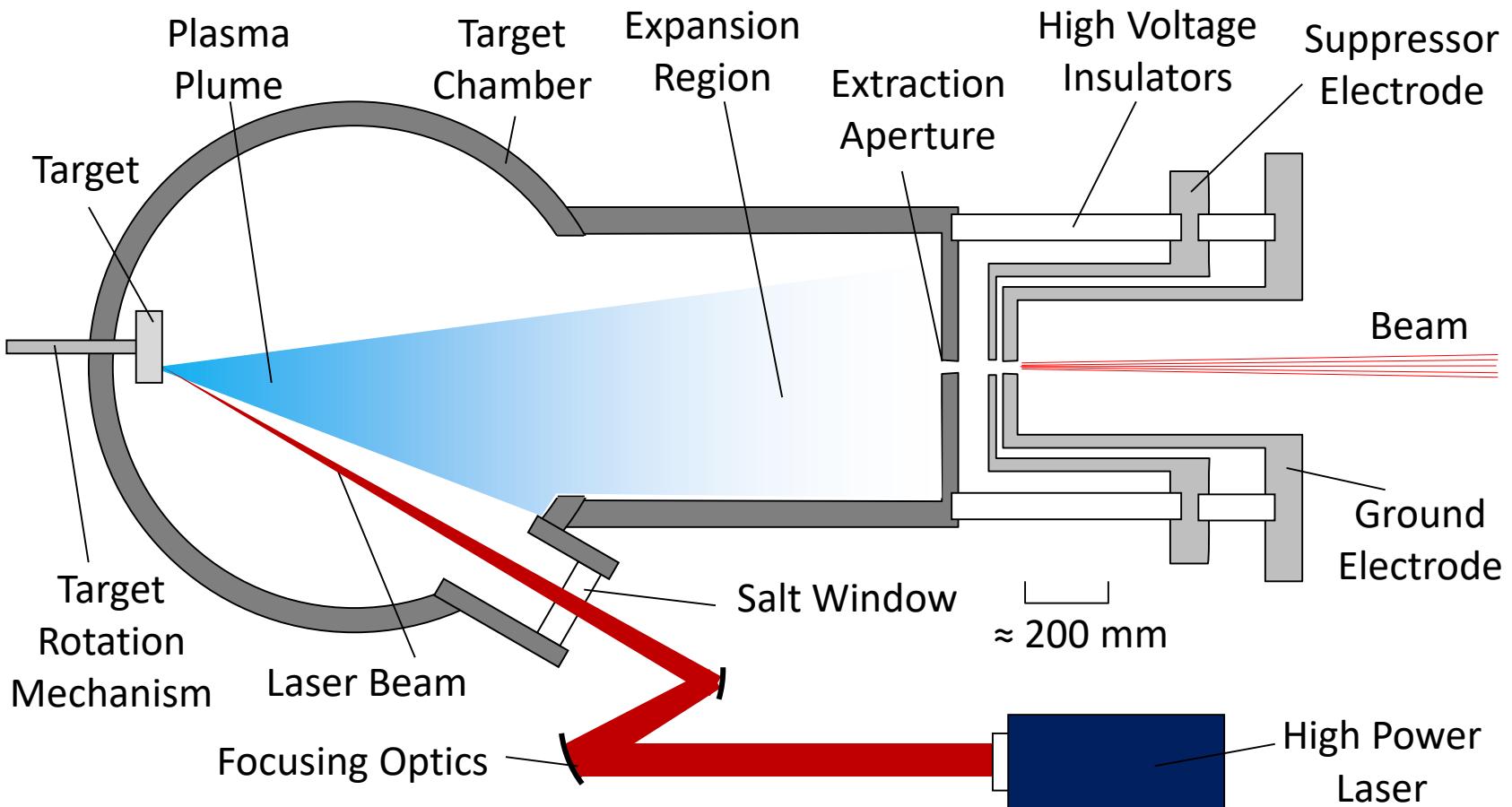
Higgs Bosons

## Zoo of curiosities

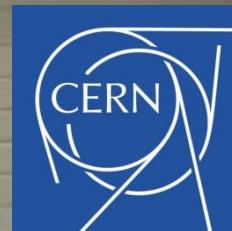
Tauons  
Mesons  
Baryons

$W + Z$   
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  $\mu$ s pulses of C<sup>4+</sup>

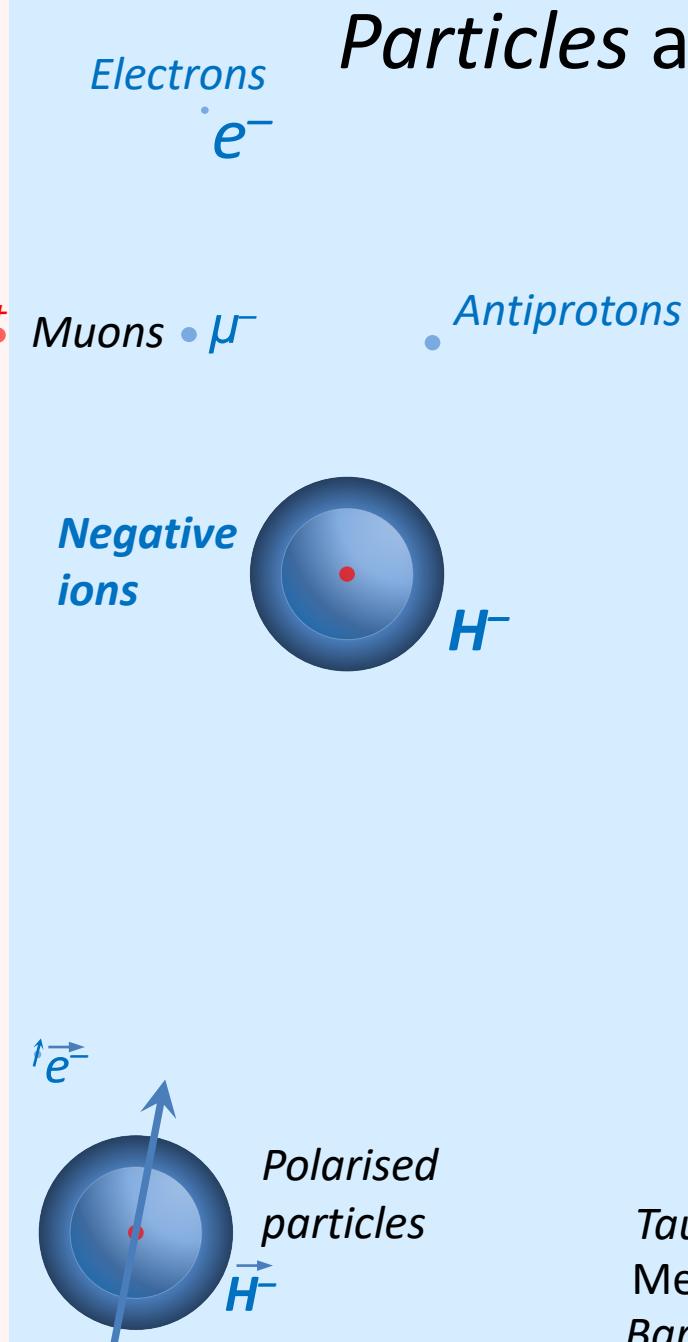
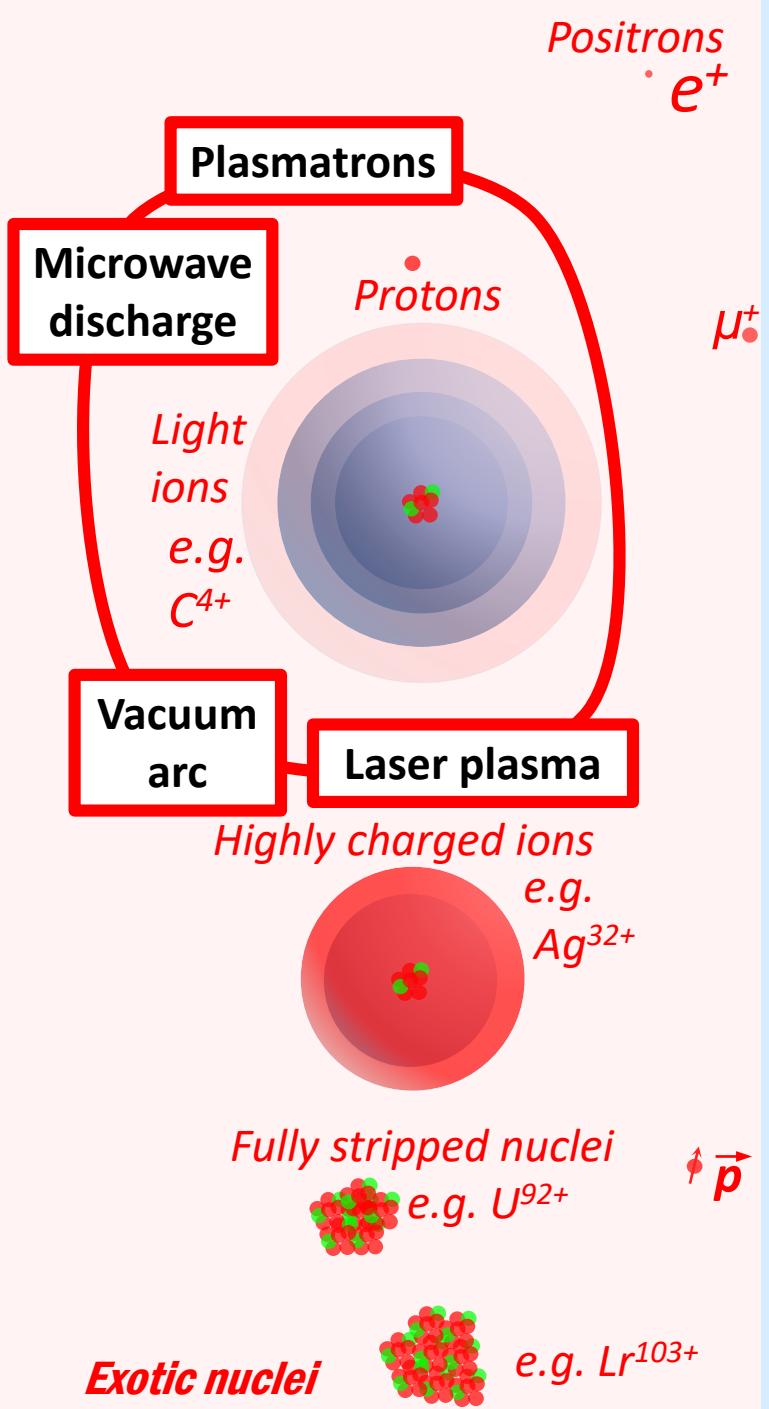


BNL and RIKEN



Masahiro Okamura has demonstrated  
Direct Plasma Injection into an RFQ

# Particles and Sources



Photons  
Neutrinos  
 $\nu_e \nu_\mu \nu_\tau$   
Neutrons  
 $n$

Neutral particles  
 $H^0$



Higgs  
Bosons

## Zoo of curiosities

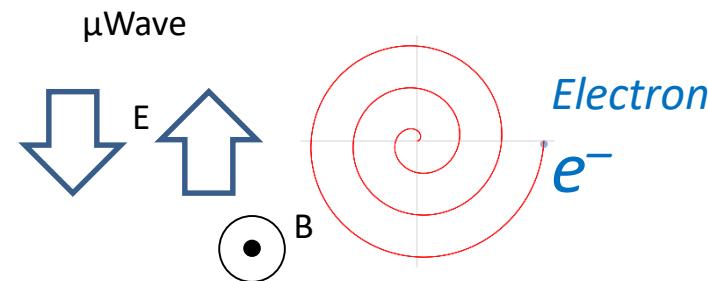
Tauons  
Mesons  
Baryons

$W + Z$   
Bosons

# Microwave Ion Sources

Off resonance (or high pressure)

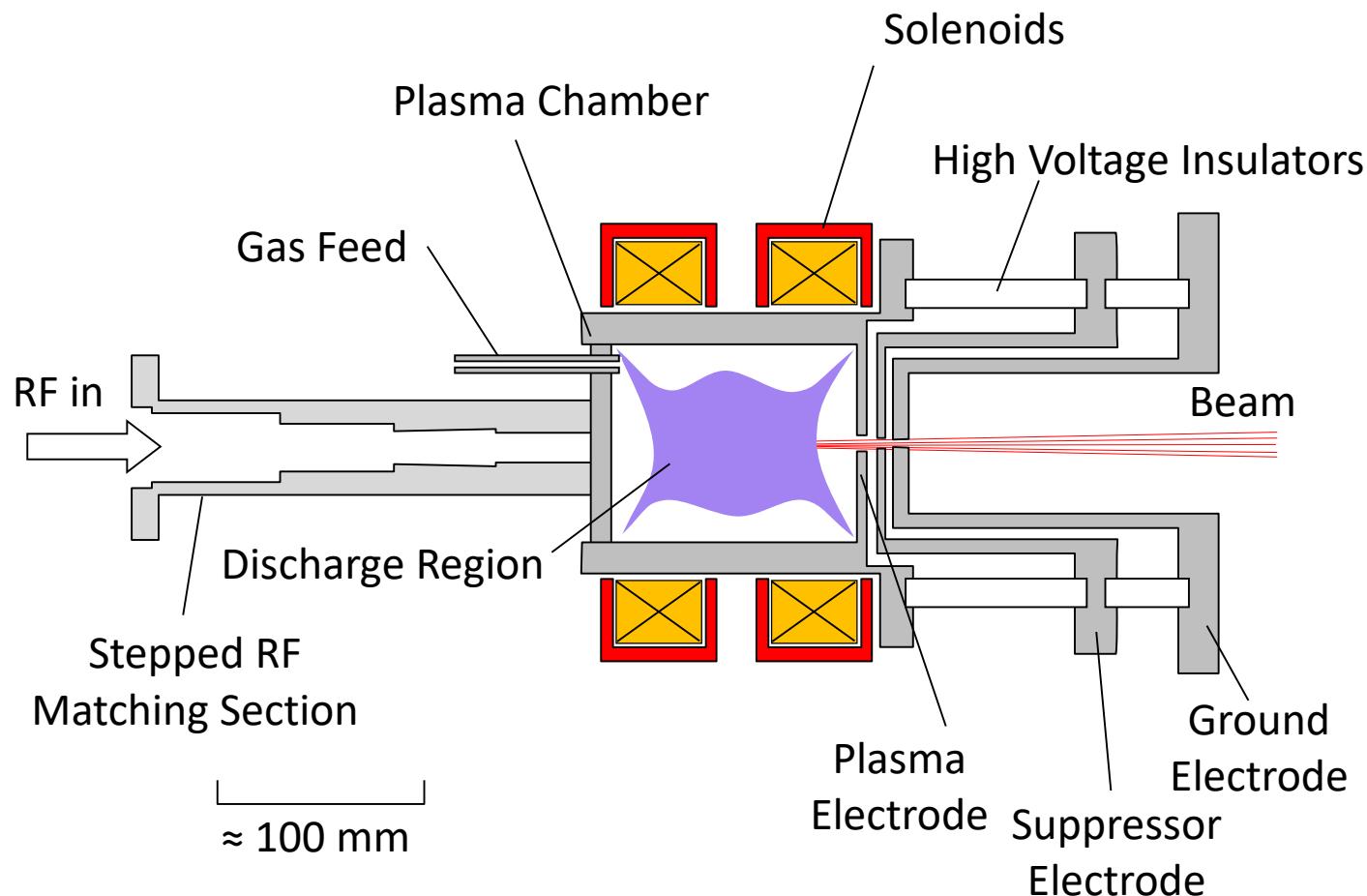
= Microwave discharge ion sources



On resonance

= Electron Cyclotron Resonance (ECR) sources

# Microwave Discharge Ion Source

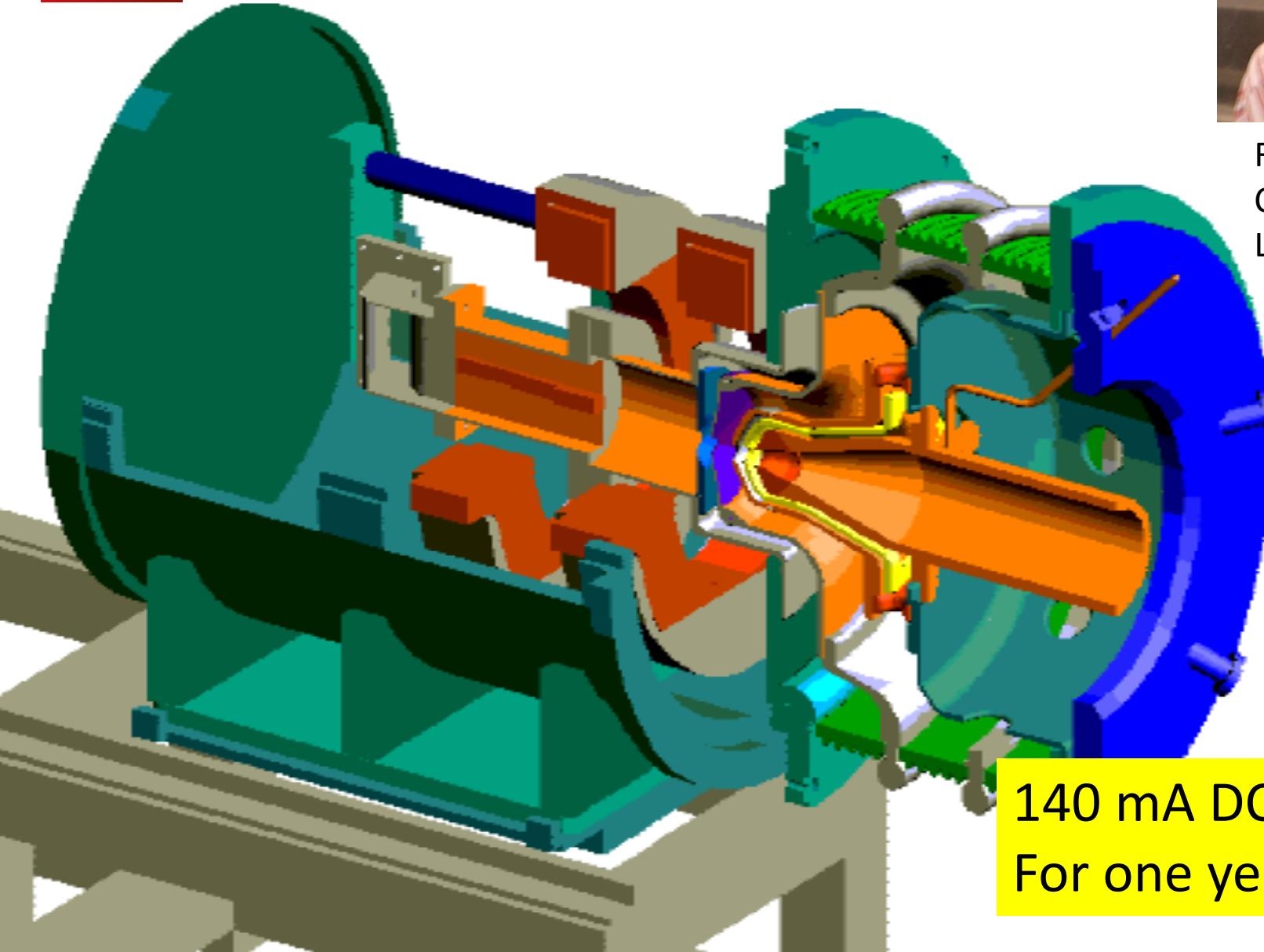


2.45 GHz  
commonly  
used

# SILHI Microwave Source

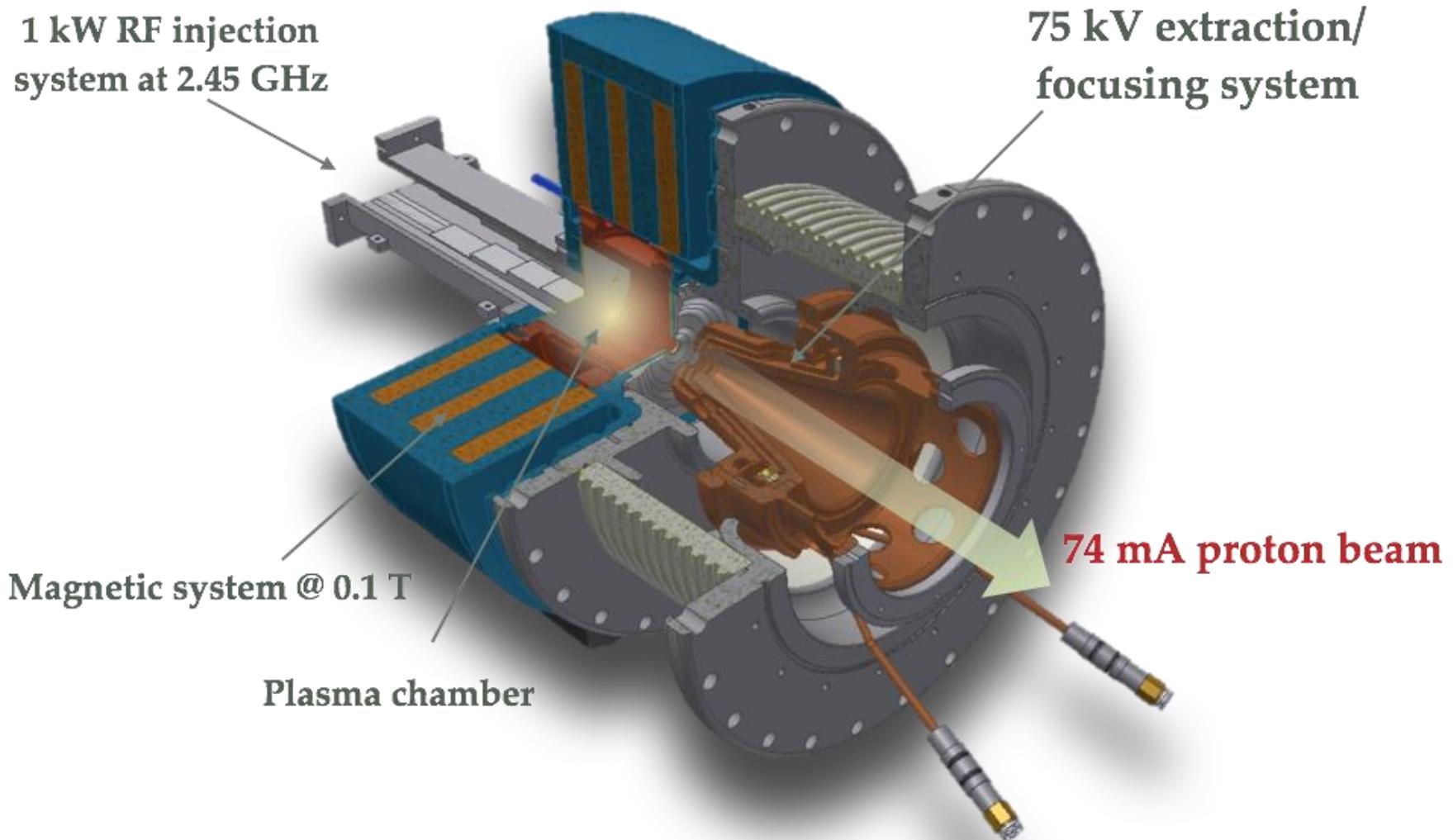


Rafael Gobin  
CEA Saclay  
Late 1990s



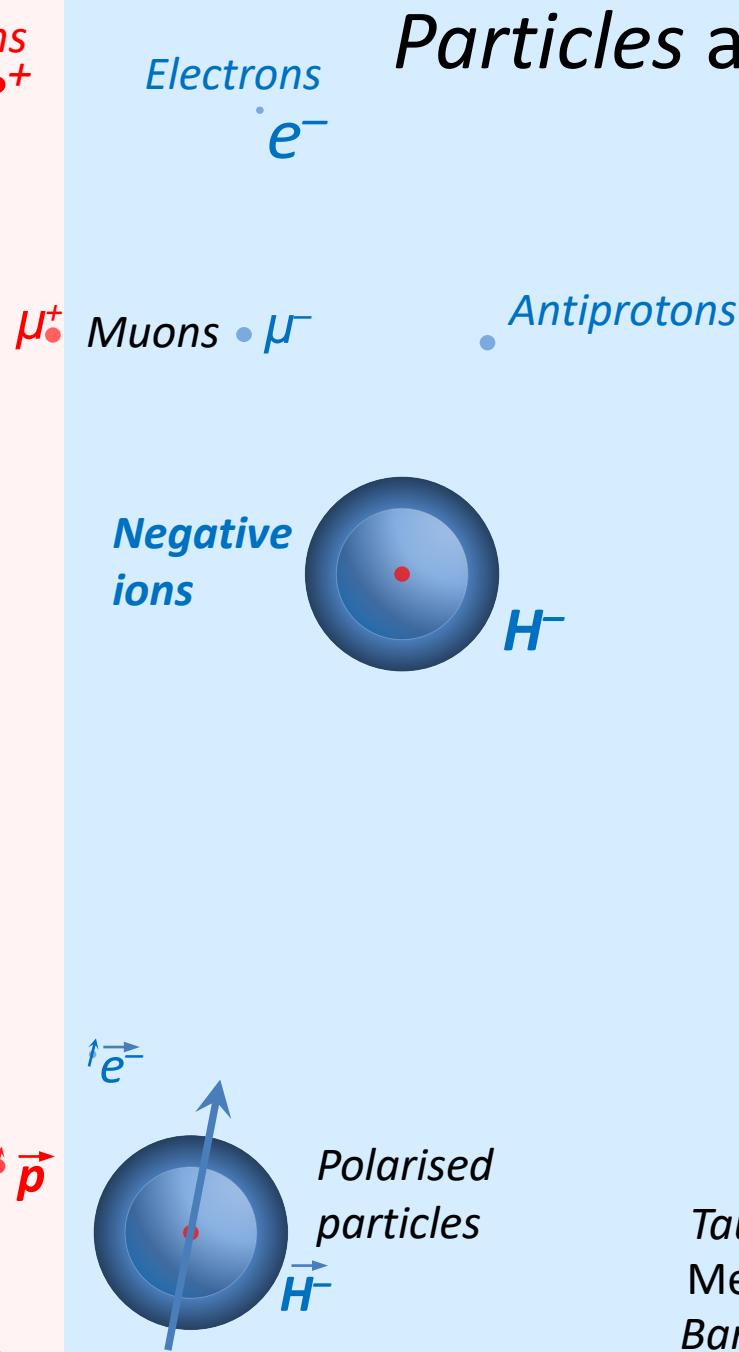
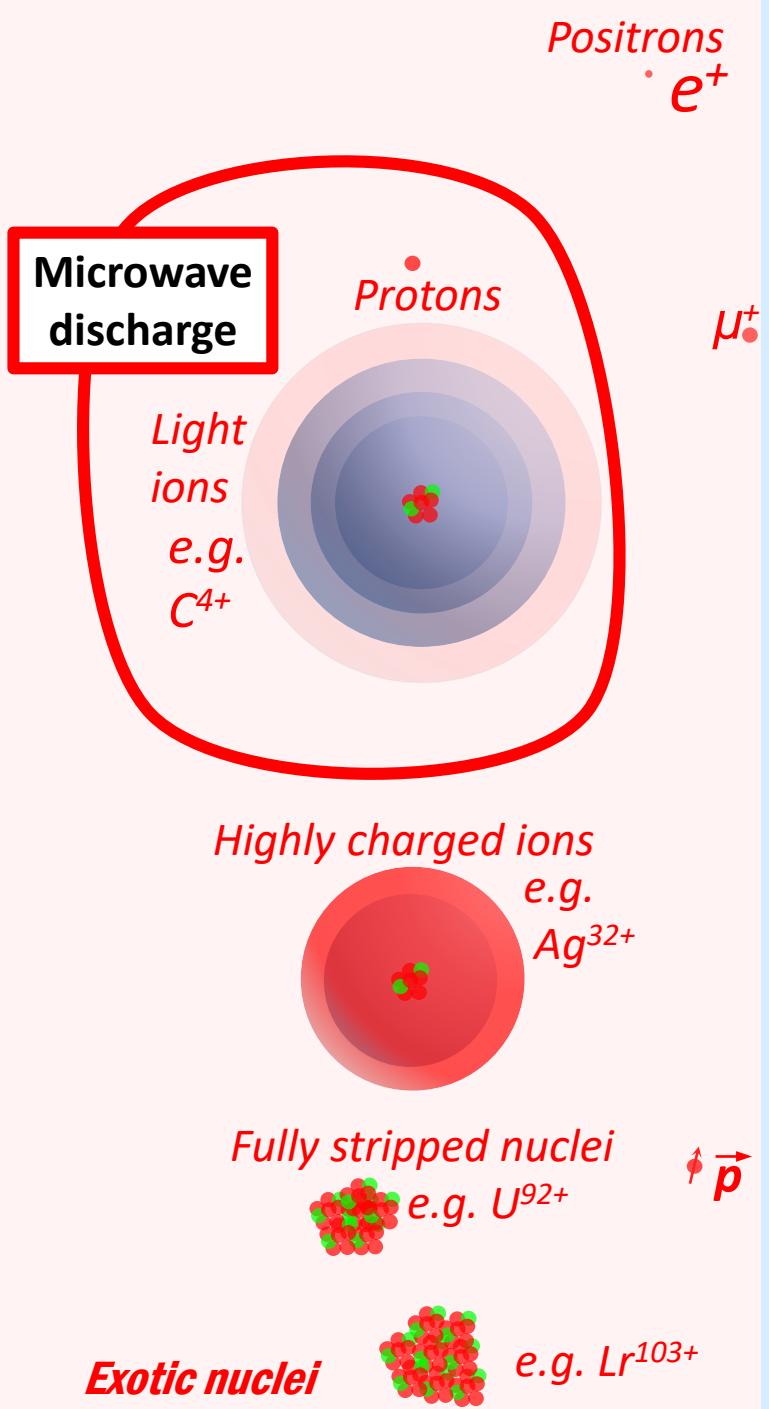
140 mA DC protons  
For one year!

# ESS Source



SILHI source via INFN

# Particles and Sources



Photons  
Neutrinos  
 $\nu_e \nu_\mu \nu_\tau$   
Neutrons

Neutral particles  
 $H^0$



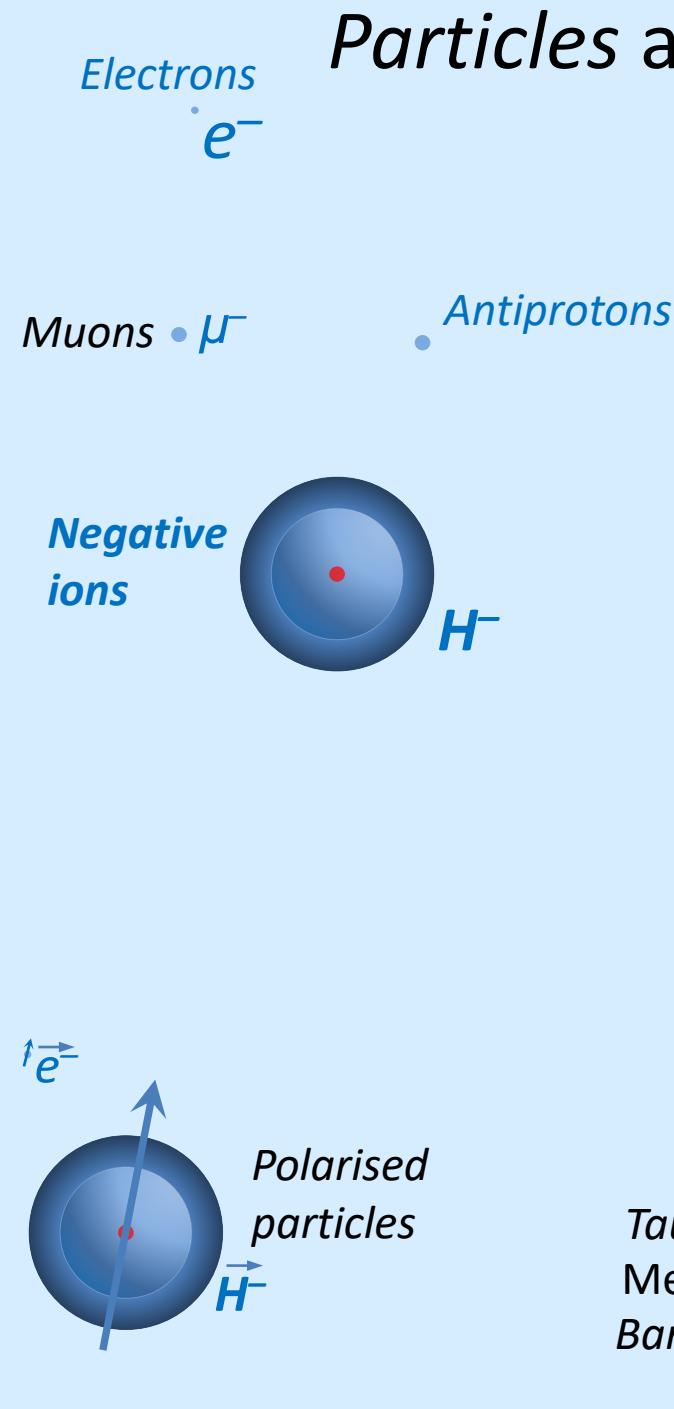
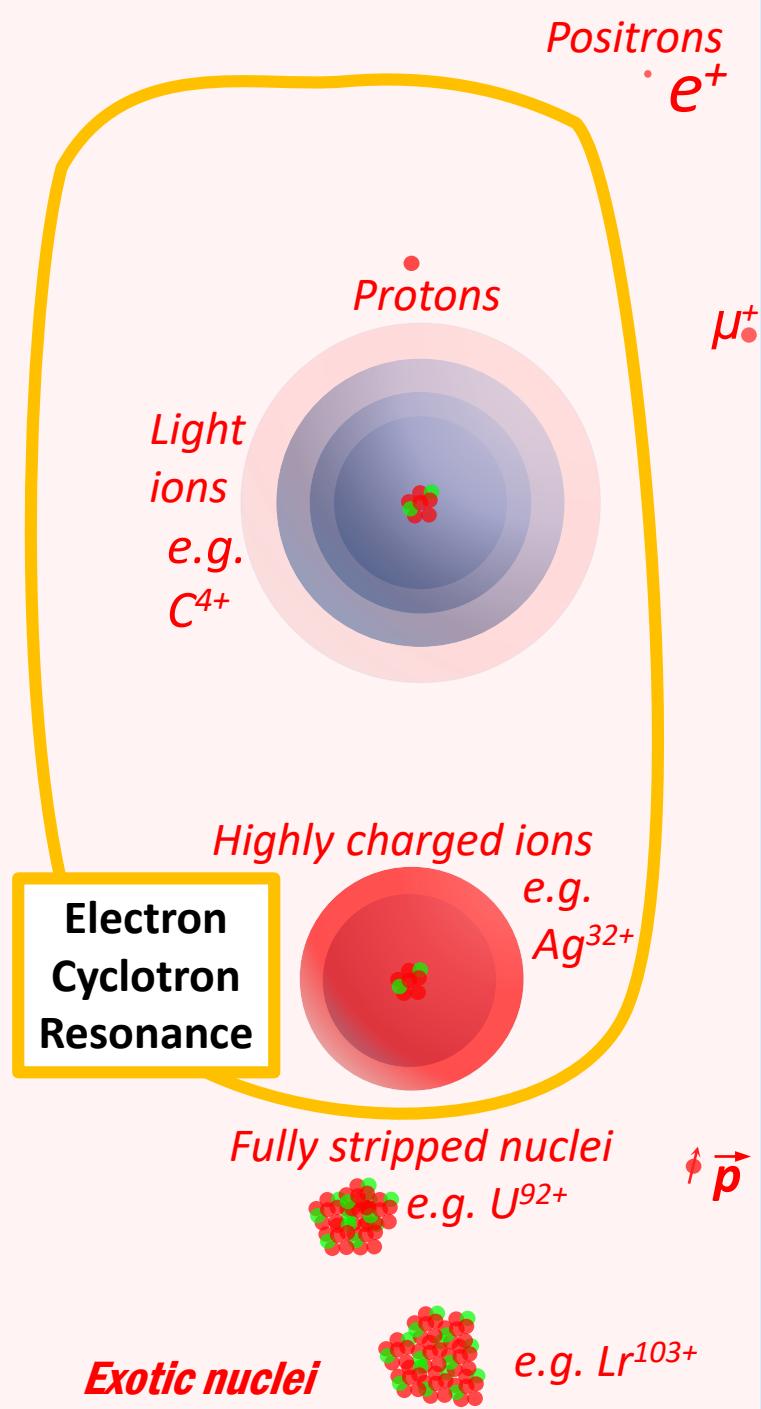
Higgs  
Bosons

## Zoo of curiosities

Tauons  
Mesons  
Baryons

$W + Z$   
Bosons

# Particles and Sources



Photons  
Neutrinos  
 $\nu_e \nu_\mu \nu_\tau$   
Neutrons  
 $n$

Neutral particles  
 $H^0$

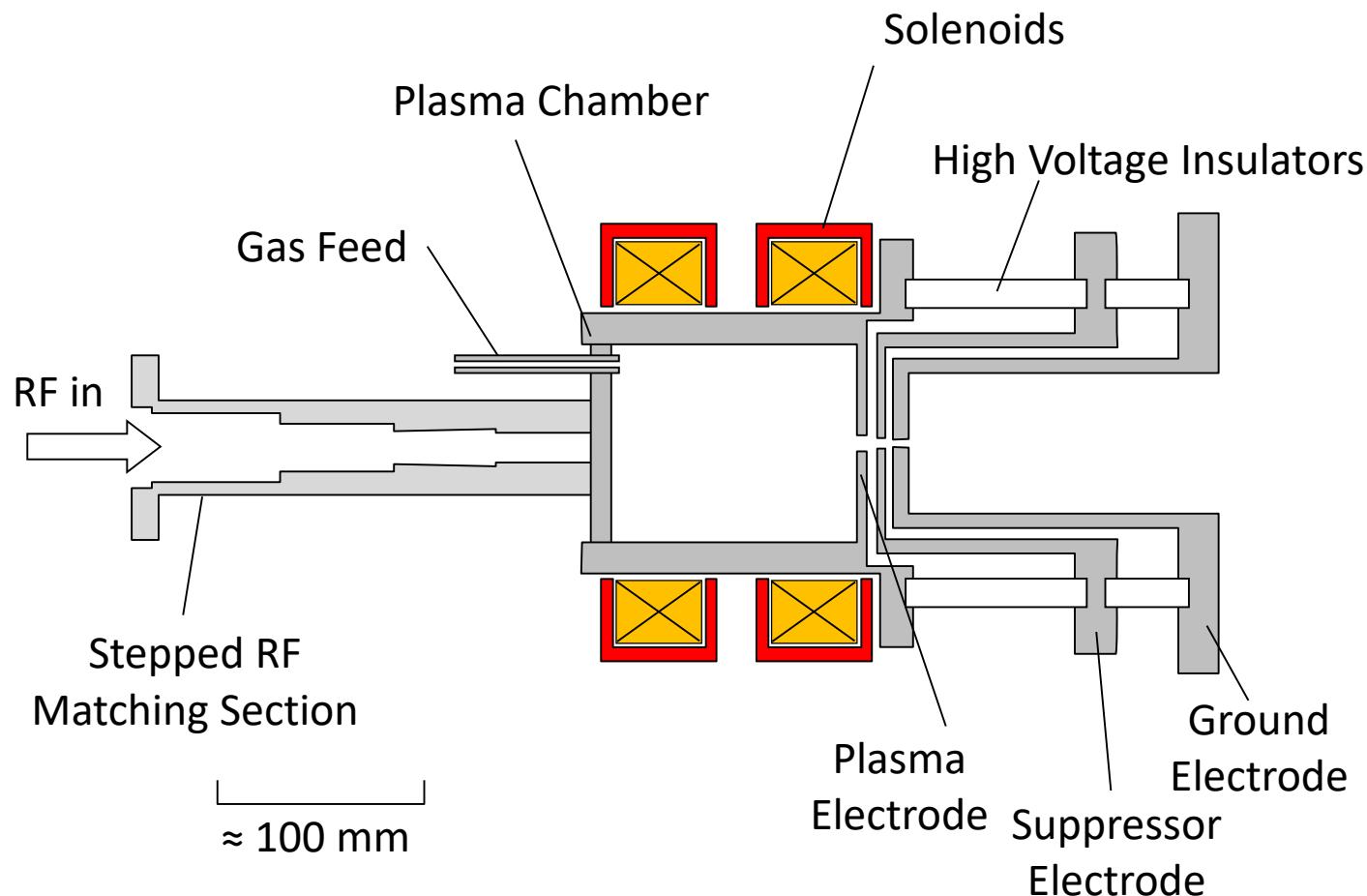


Higgs  
Bosons

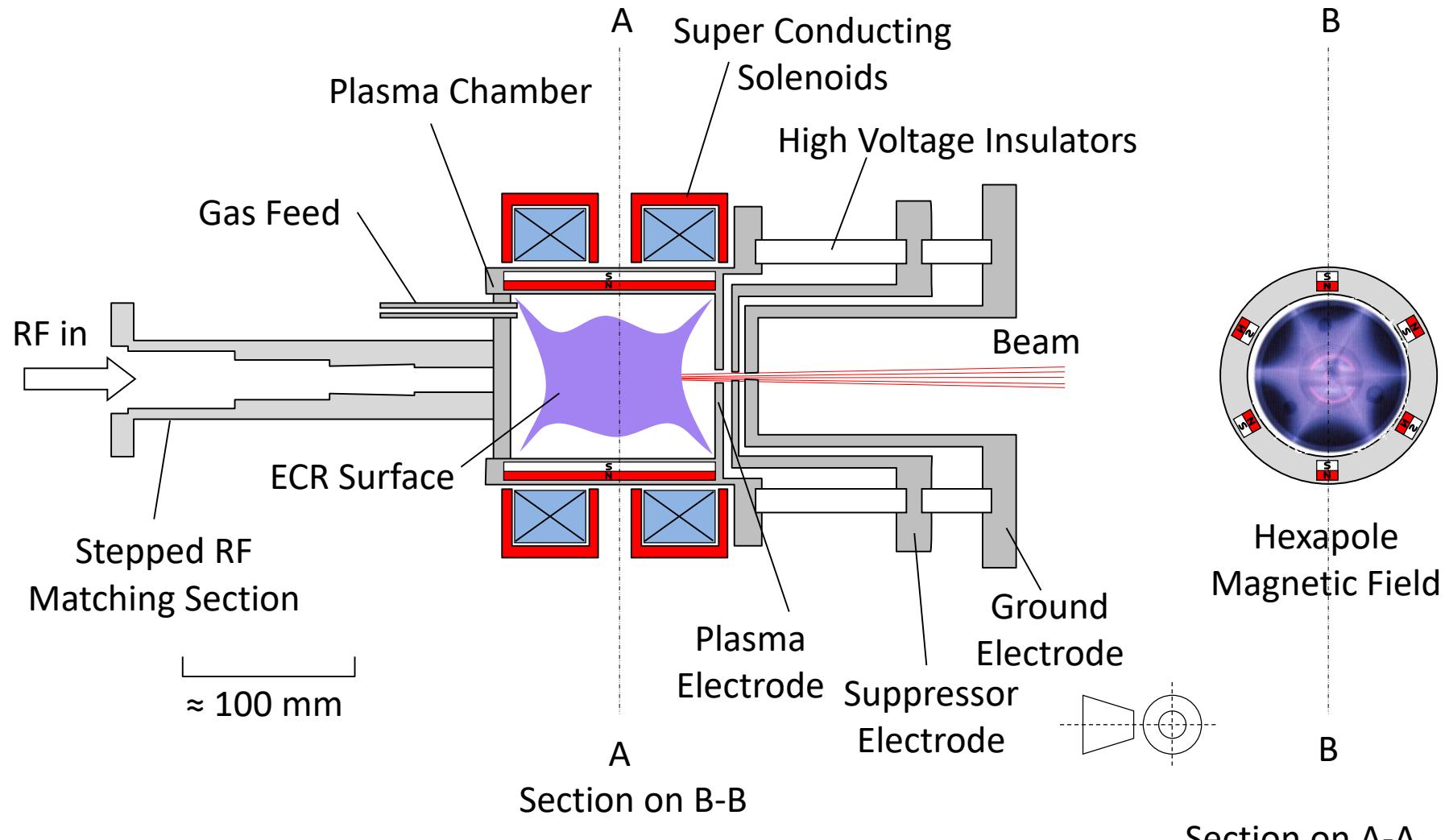
Zoo of curiosities

Tauons	$W + Z$
Mesons	Bosons
Baryons	

# Microwave Discharge Ion Source



# ECR Ion Source



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

Higher frequency = higher charge states

# 28 GHz superconducting VENUS ECR



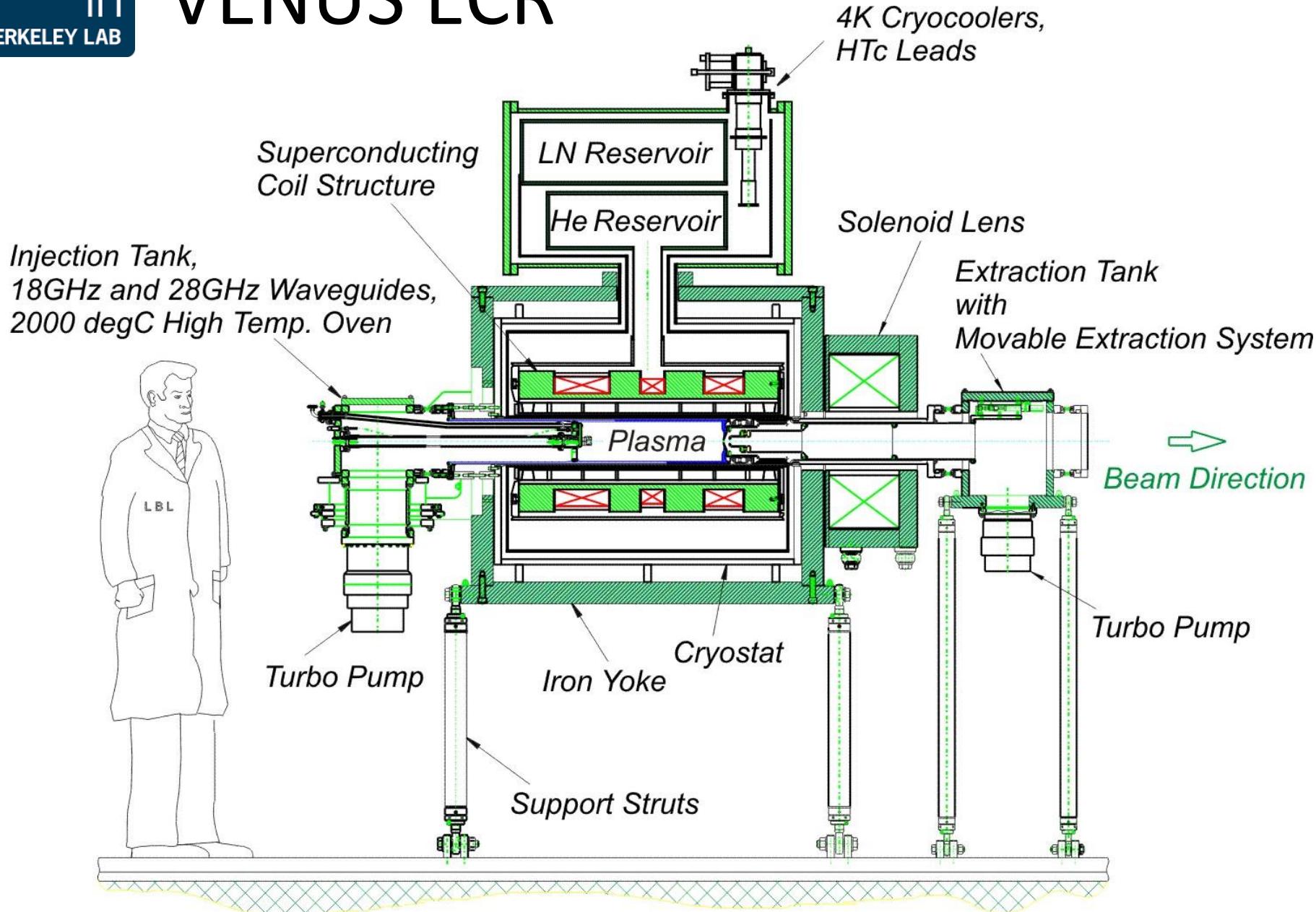
Daniela Leitner  
LBNL  
Late 2000s



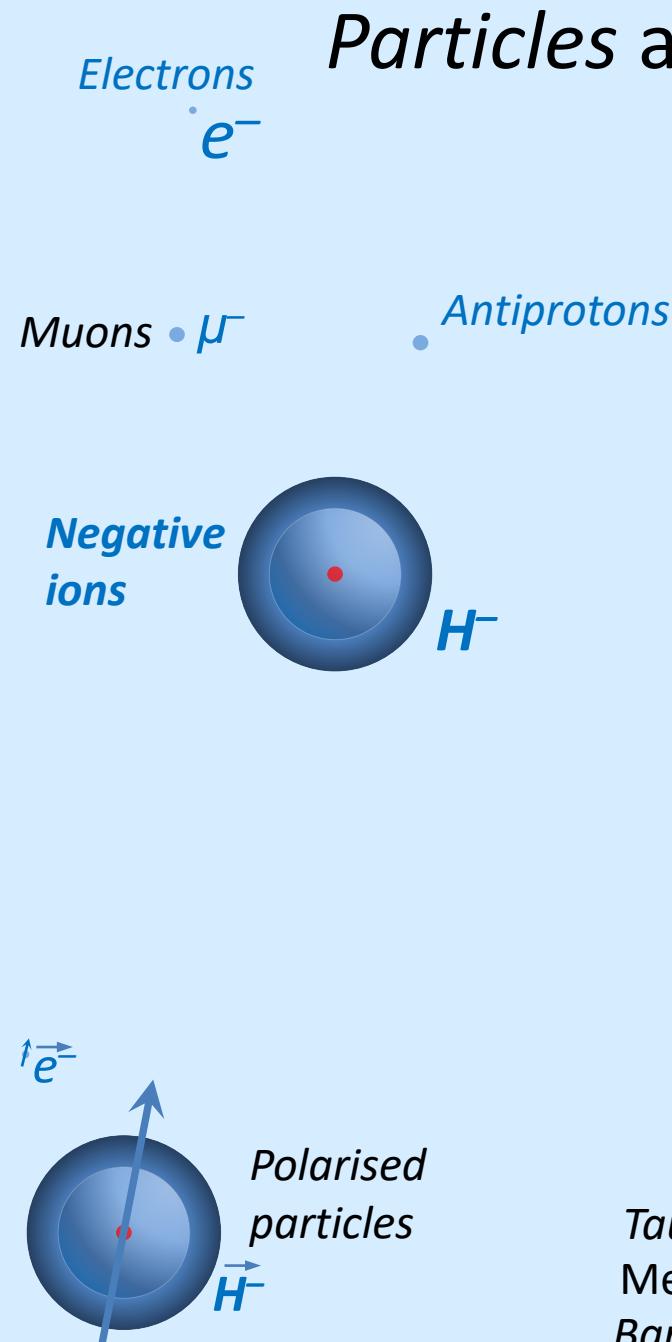
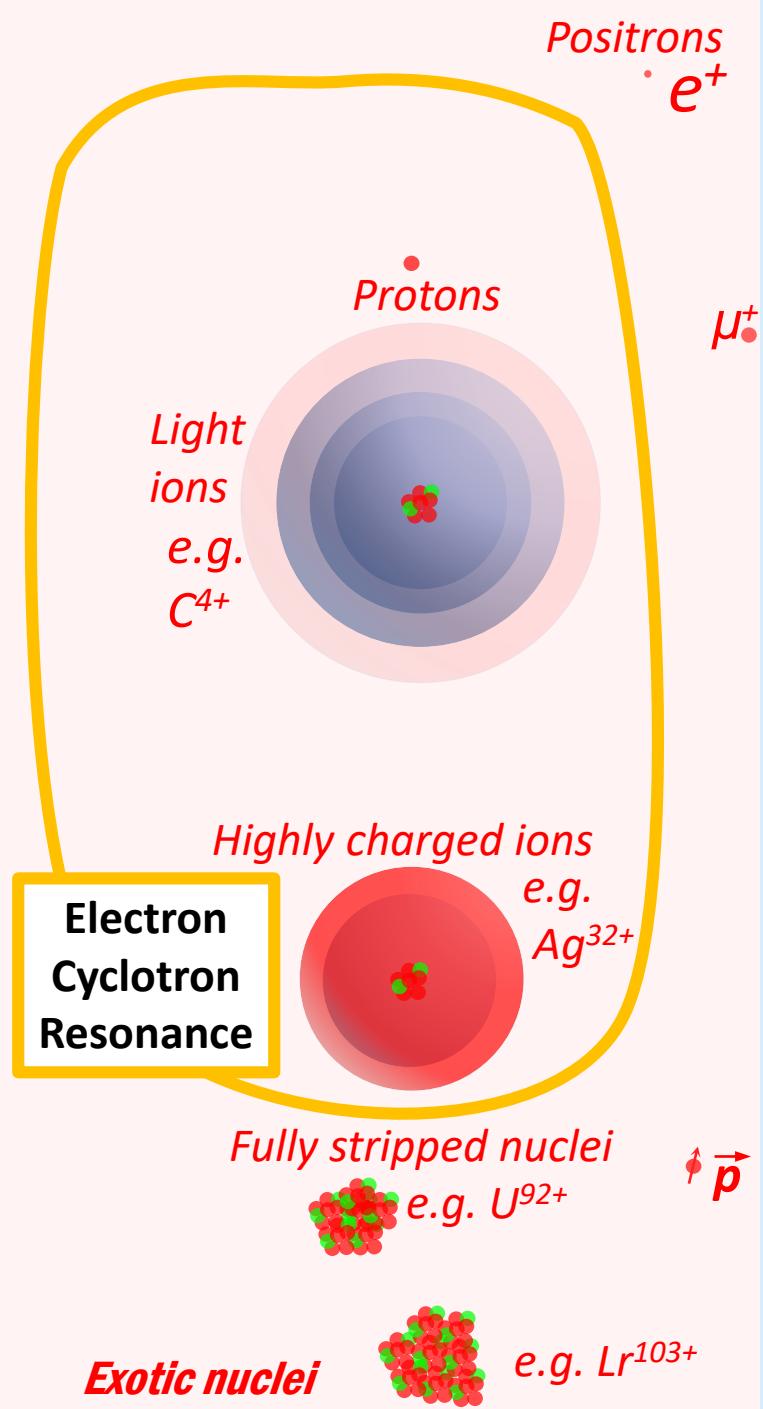
200 e $\mu$ A U<sup>34+</sup> ions  
4.9 e $\mu$ A U<sup>47+</sup> ions



# VENUS ECR



# Particles and Sources



Photons  
Neutrinos  
 $\nu_e \nu_\mu \nu_\tau$   
Neutrons  
 $n$

Neutral particles  
 $H^0$

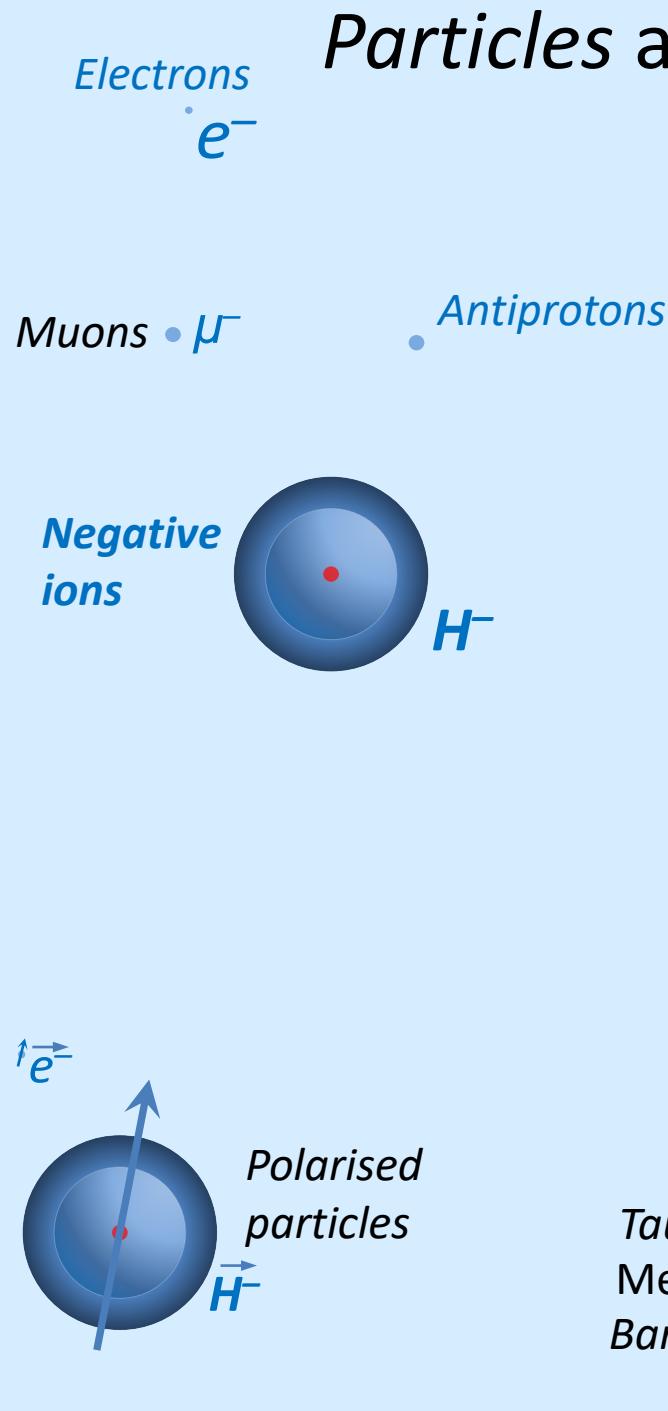
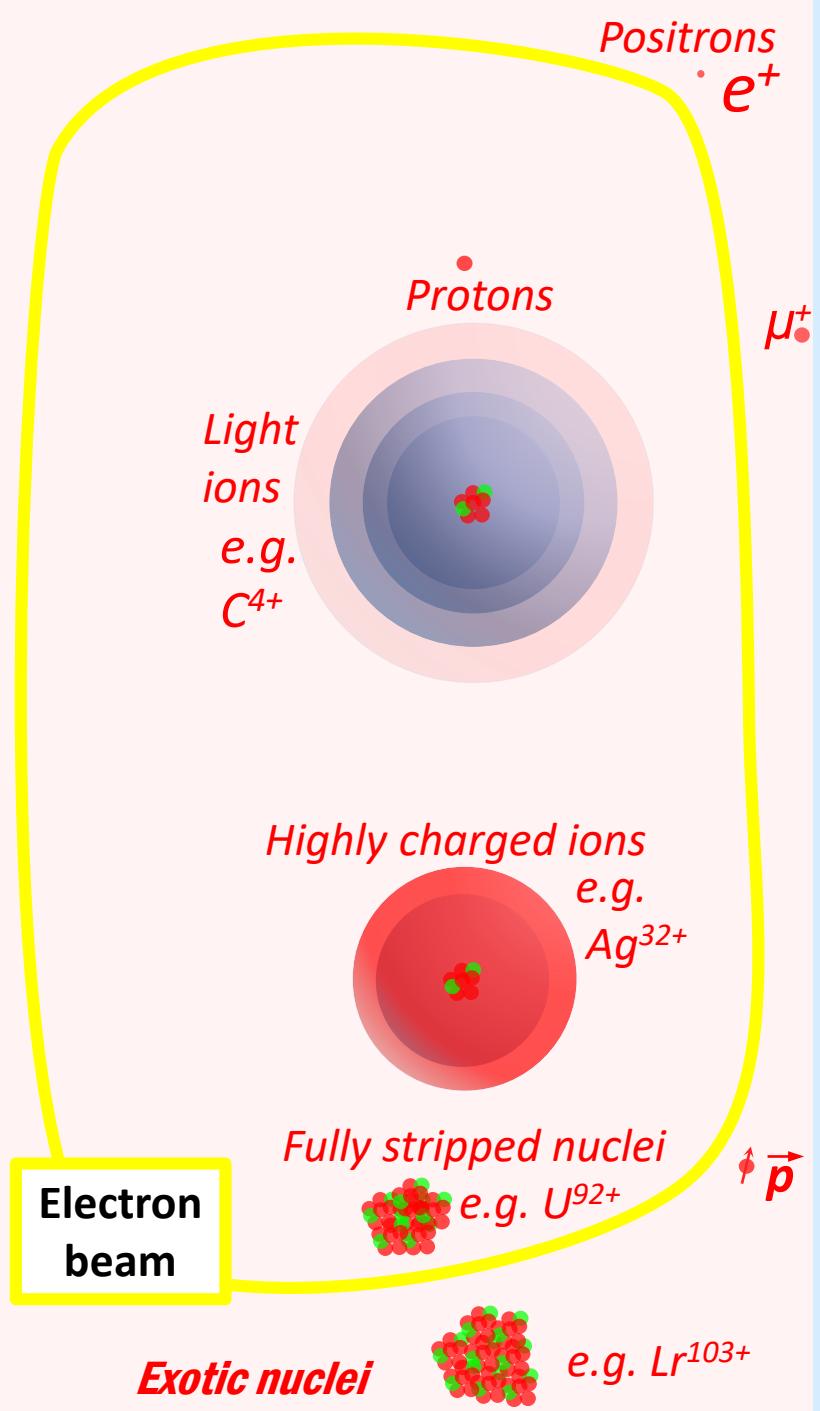


Higgs  
Bosons

Zoo of curiosities  
Tauons  
Mesons  
Baryons

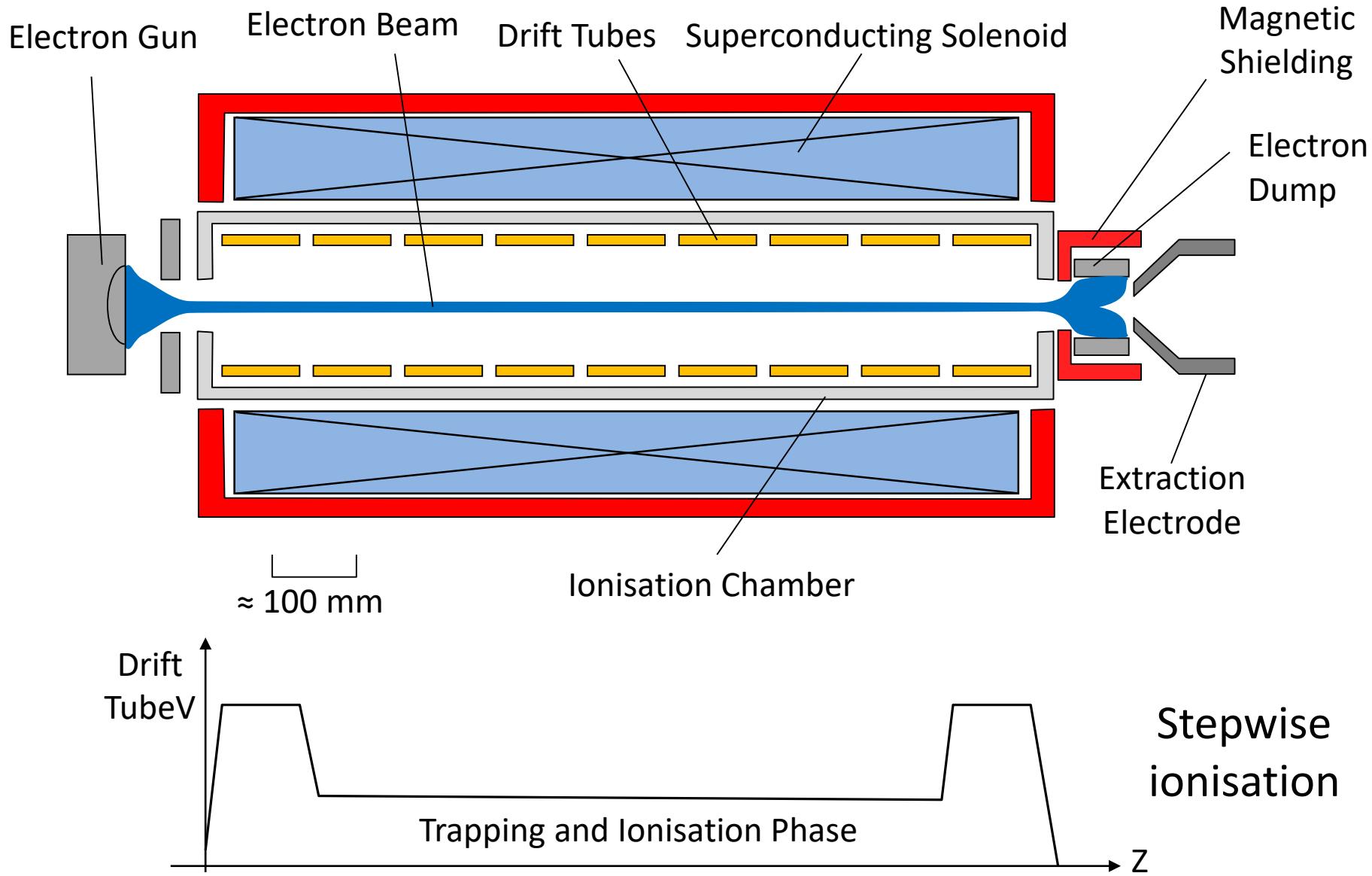
$W + Z$   
Bosons

# Particles and Sources

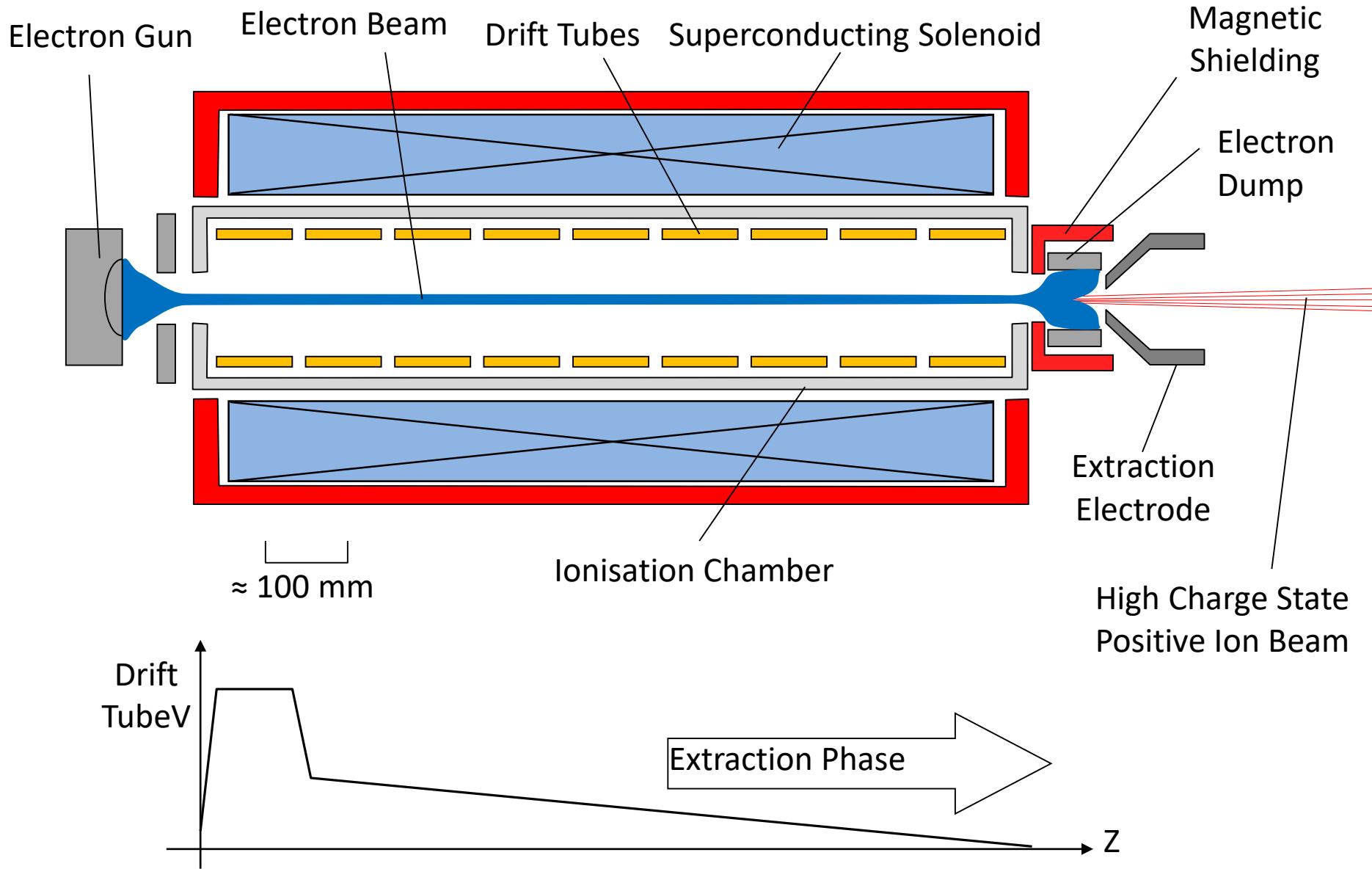


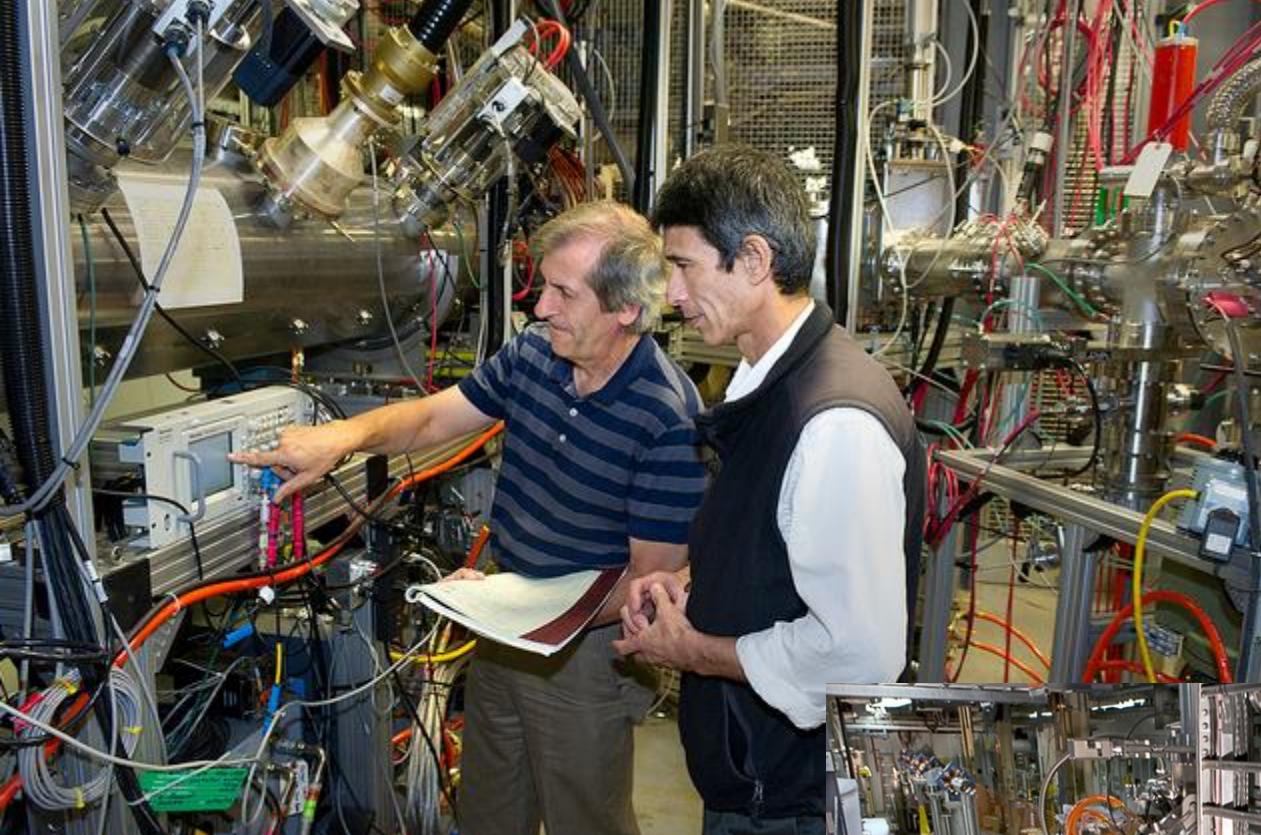
Photons	
Neutrinos	$\nu_e \nu_\mu \nu_\tau$
Neutrons	$n$
Neutral particles	$H^0$
Higgs Bosons	
<b>Zoo of curiosities</b>	
Tauons	
Mesons	
Baryons	
	$W + Z$ Bosons

# Electron Beam Ion Sources



# Electron Beam Ion Sources



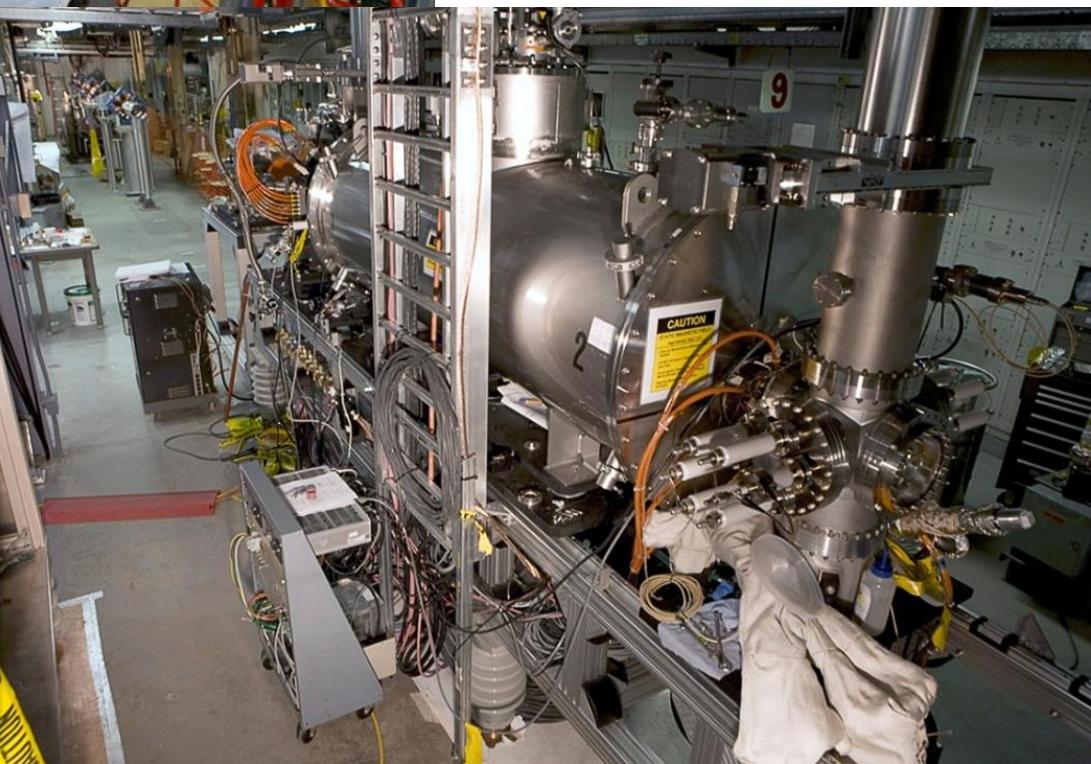


**BROOKHAVEN**  
NATIONAL LABORATORY

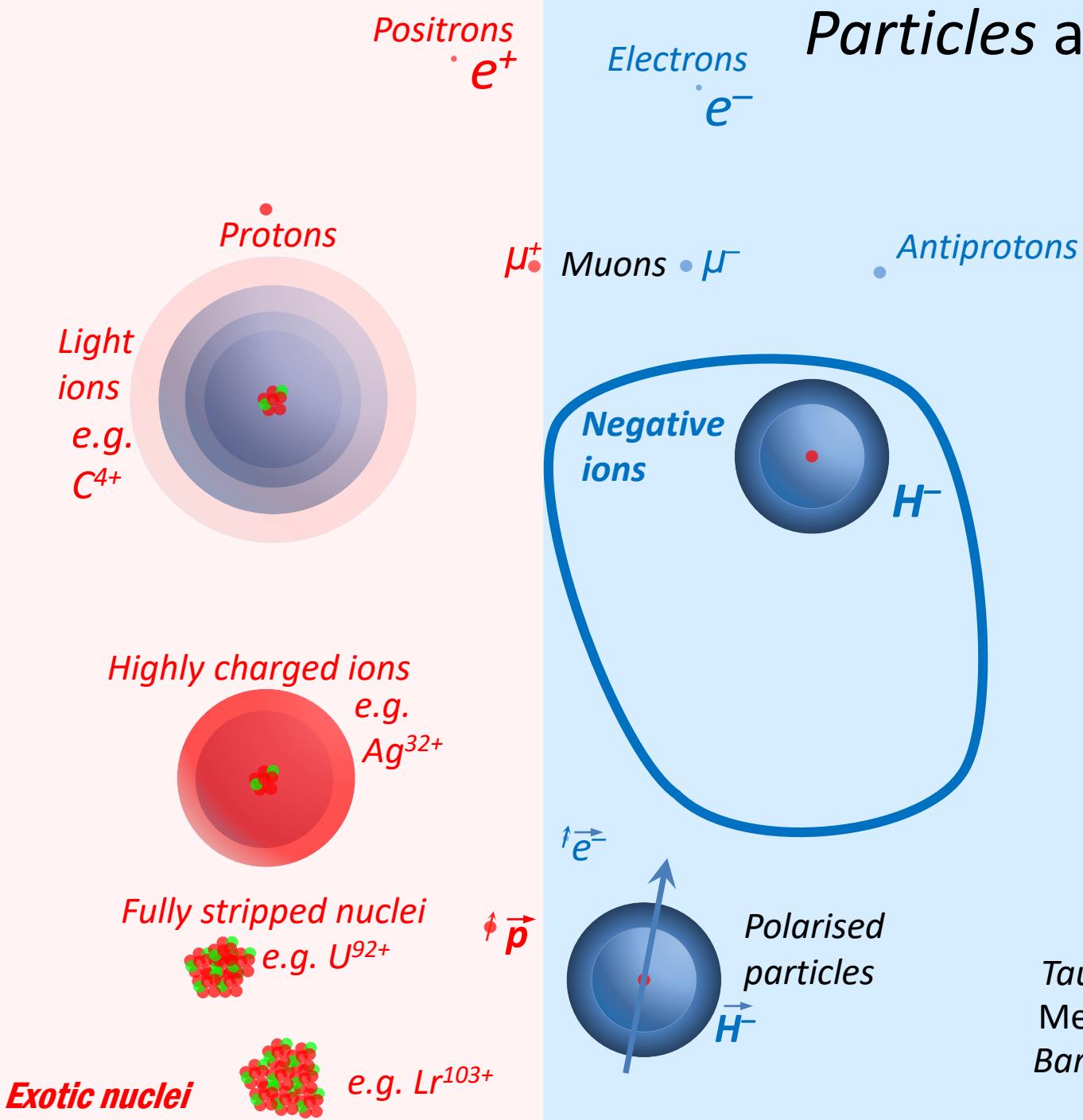
Jim Alessi  
BNL

1.7 emA, 10  $\mu$ s, 5 Hz  
 $\text{Ag}^{32+}$  ions

Fully stripped nuclei can  
be obtained in EBIT mode



# Particles and Sources



Photons  
Neutrinos  $\nu_e \nu_\mu \nu_\tau$   
Neutrons  $n$

Neutral particles  
 $H^0$



Higgs  
Bosons

## Zoo of curiosities

Tauons  
Mesons  
Baryons

$W + Z$   
Bosons

# 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  $H^0$

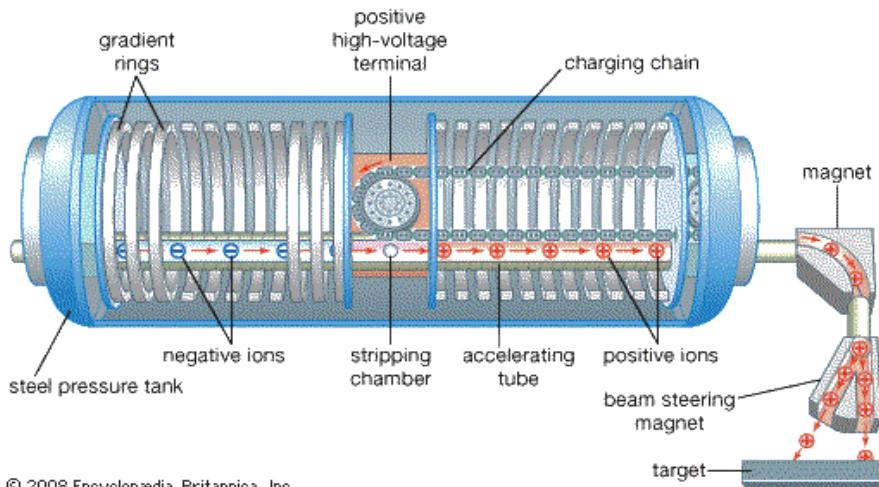
- Up to 30 times for  $e^-$  collisions

- Up to 100 times for  $H^+$  collisions

$H^-$  are very fragile!

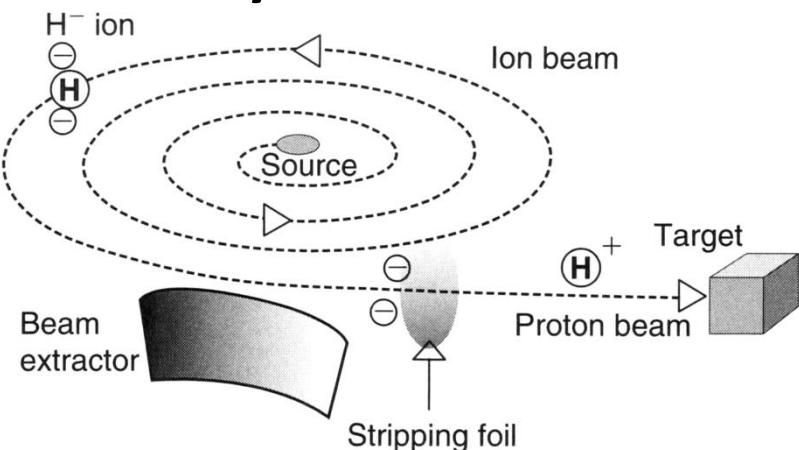
# Applications

## Tandem accelerators

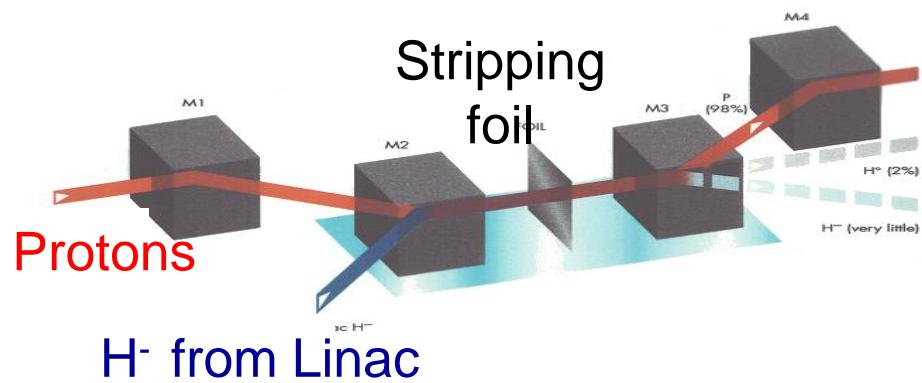


© 2008 Encyclopædia Britannica, Inc.

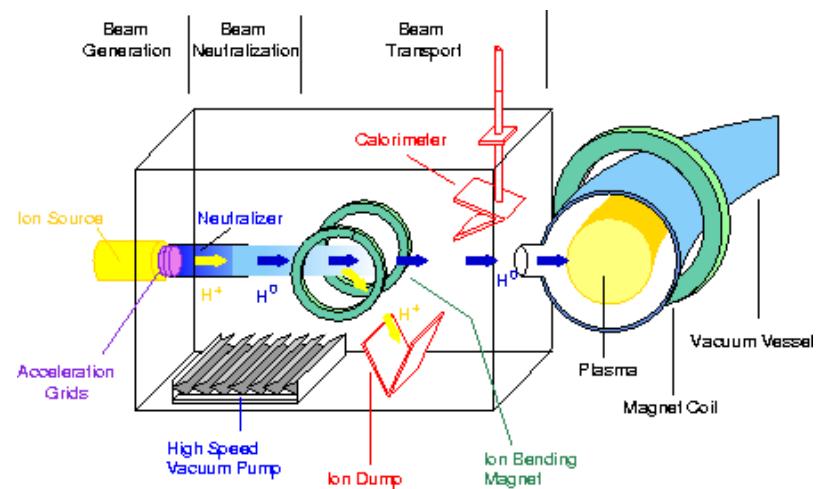
## Cyclotron extraction



## Multi-turn injection into rings



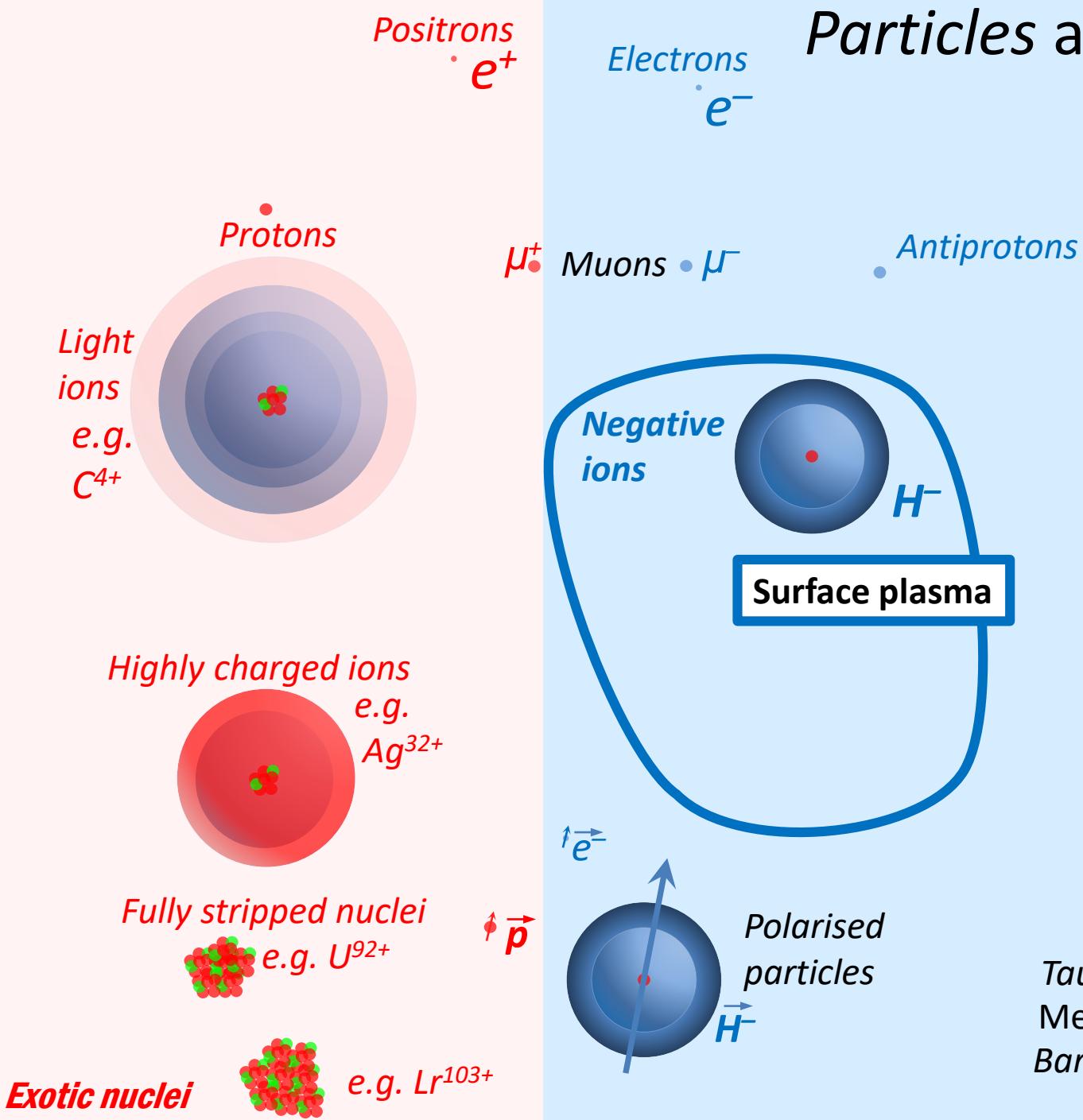
## Neutral Beams



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



Photons  
Neutrinos  $\nu_e \nu_\mu \nu_\tau$   
Neutrons  $n$

Neutral particles  
 $H^0$



Higgs  
Bosons

**Zoo of curiosities**

Tauons	$W + Z$
Mesons	Bosons
Baryons	

# Early 1970s Budker Institute of Nuclear Physics Novosibirsk

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

## Surface Plasma Sources (SPS)



Gennady Dimov



Yuri Belchenko



Vadim Dudnikov

# Caesium – The magic elixir of negative ion sources!



More reactive



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



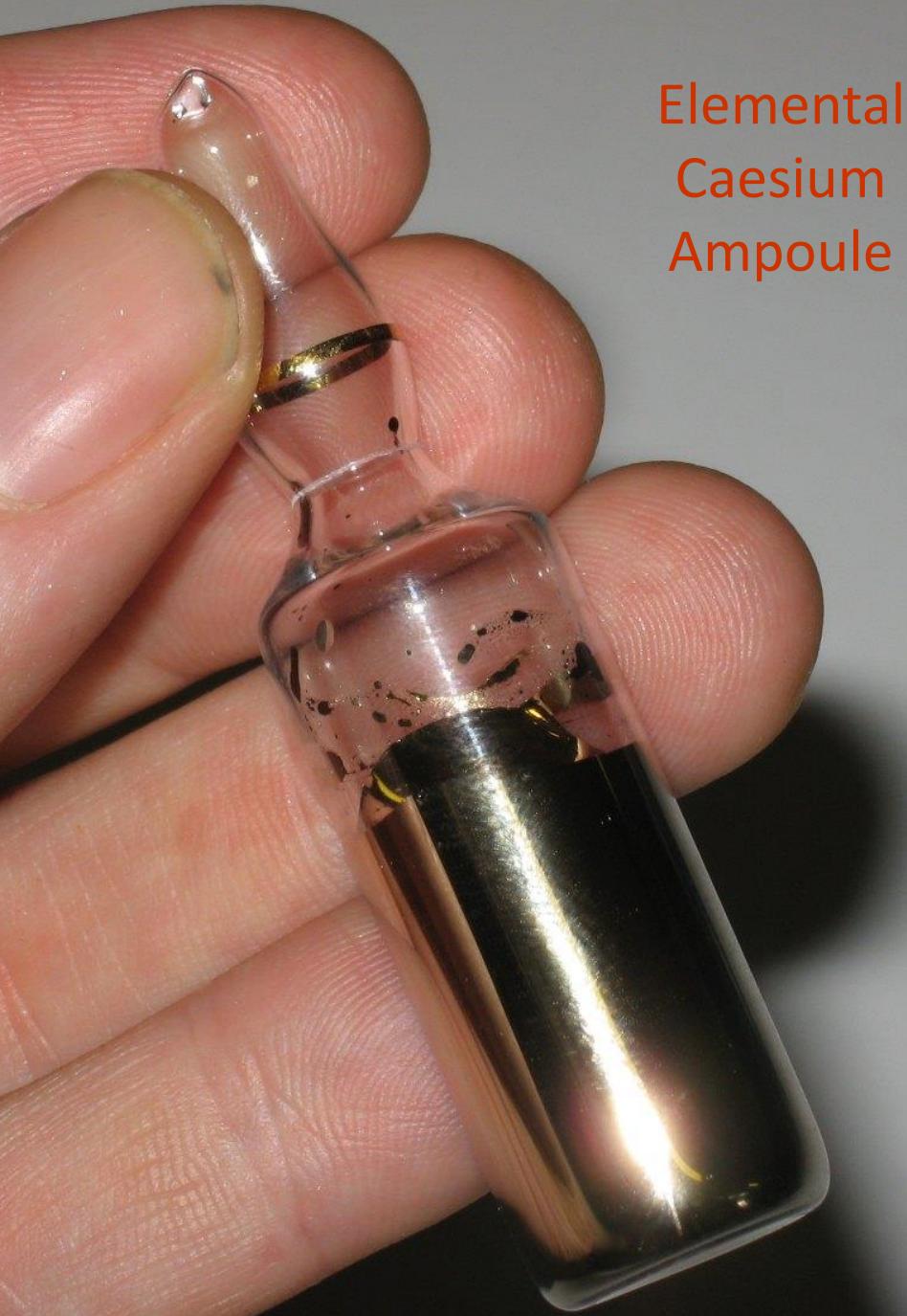
1 electron in  
the outer  
orbital

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

An amazing donor of electrons  
= great for making negative ions



Caesium  
Chromate



Elemental  
Caesium  
Ampoule

# Caesium coverage and work function

Pure

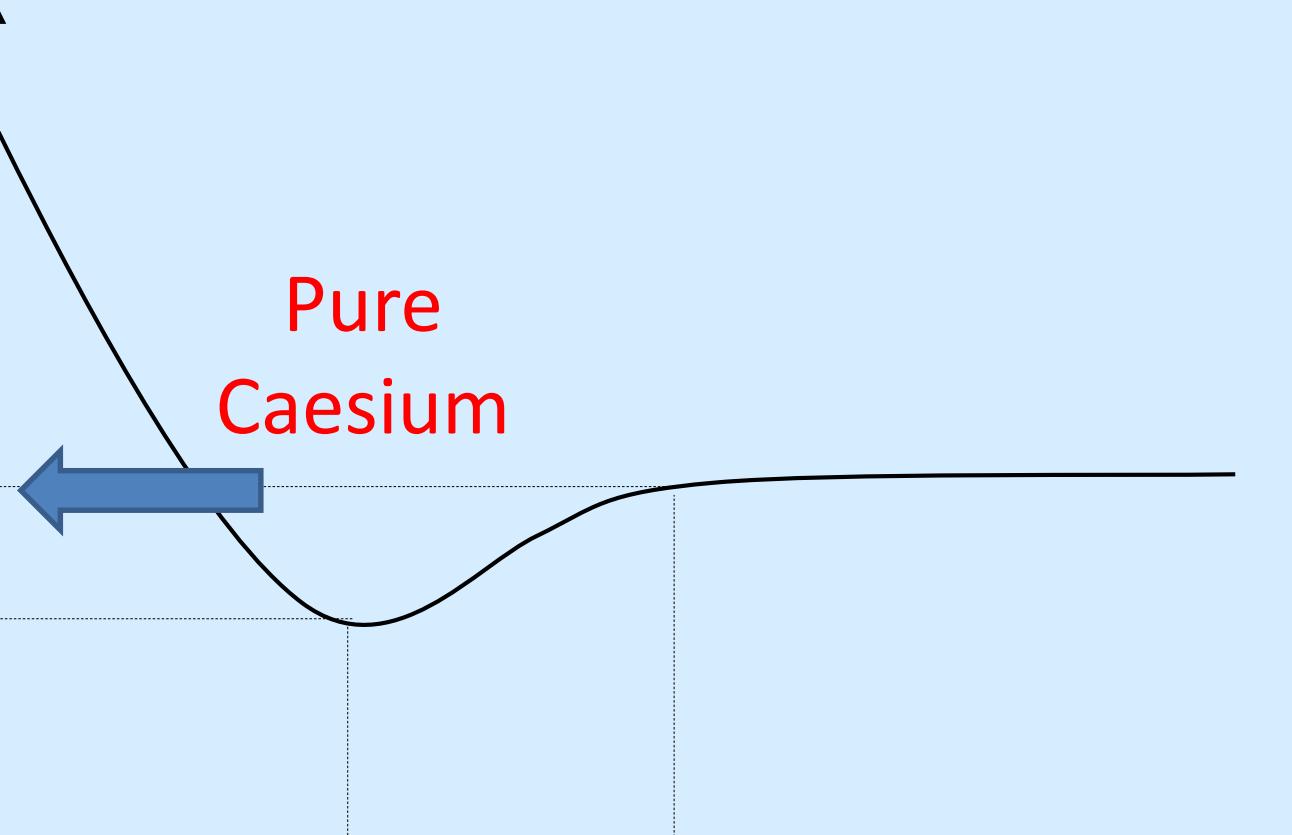
molybdenum



Work Function (eV)

4.6

Pure  
Caesium

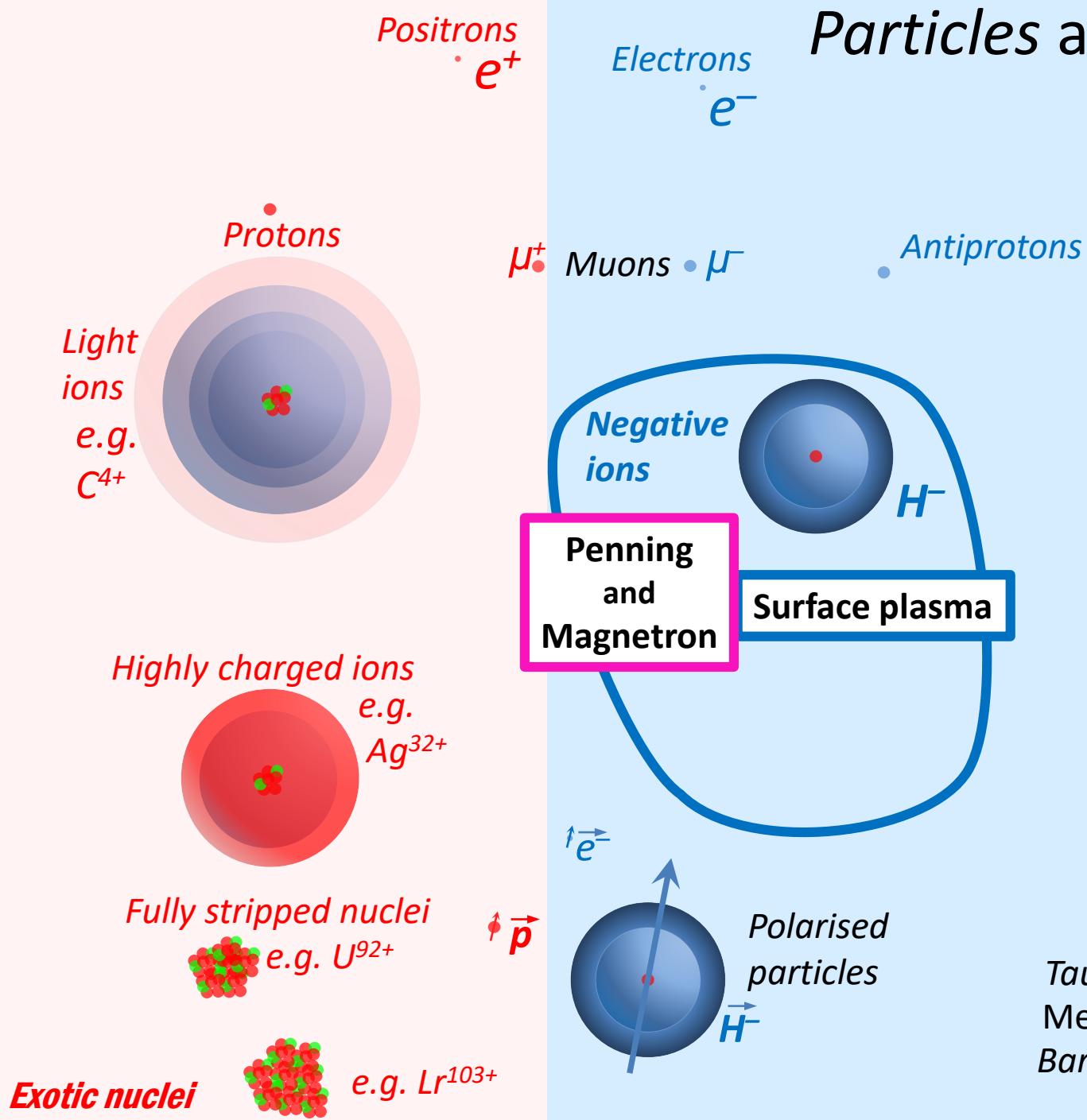


0.6

1

Cs Thickness (monolayers)

# Particles and Sources



Photons  
Neutrinos  
 $\nu_e \nu_\mu \nu_\tau$   
Neutrons  
 $n$

Neutral particles  
 $H^0$



Higgs  
Bosons

## Zoo of curiosities

Tauons  
Mesons  
Baryons

$W + Z$   
Bosons

# Early 1970s Budker Institute of Nuclear Physics Novosibirsk

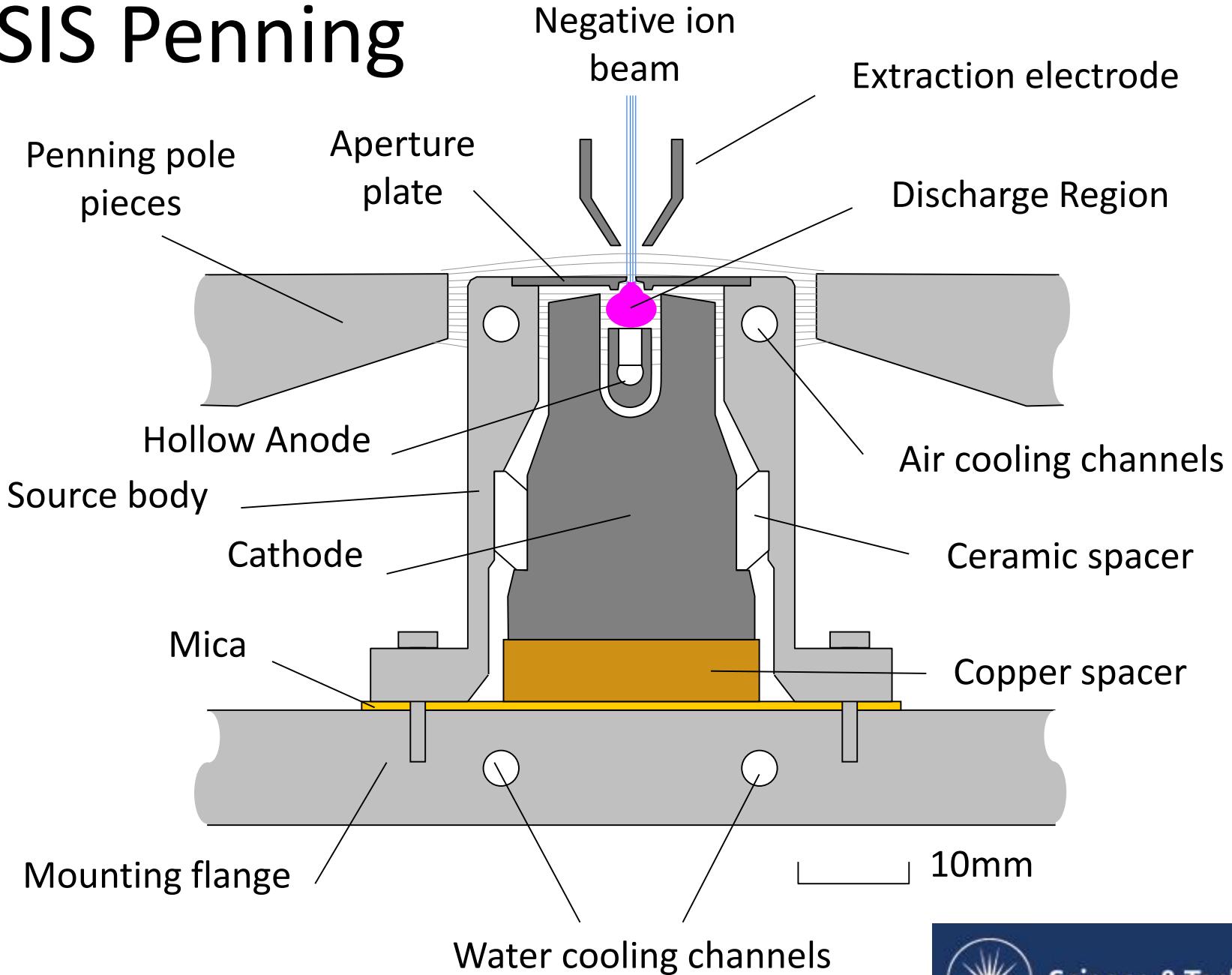


Vadim Dudnikov

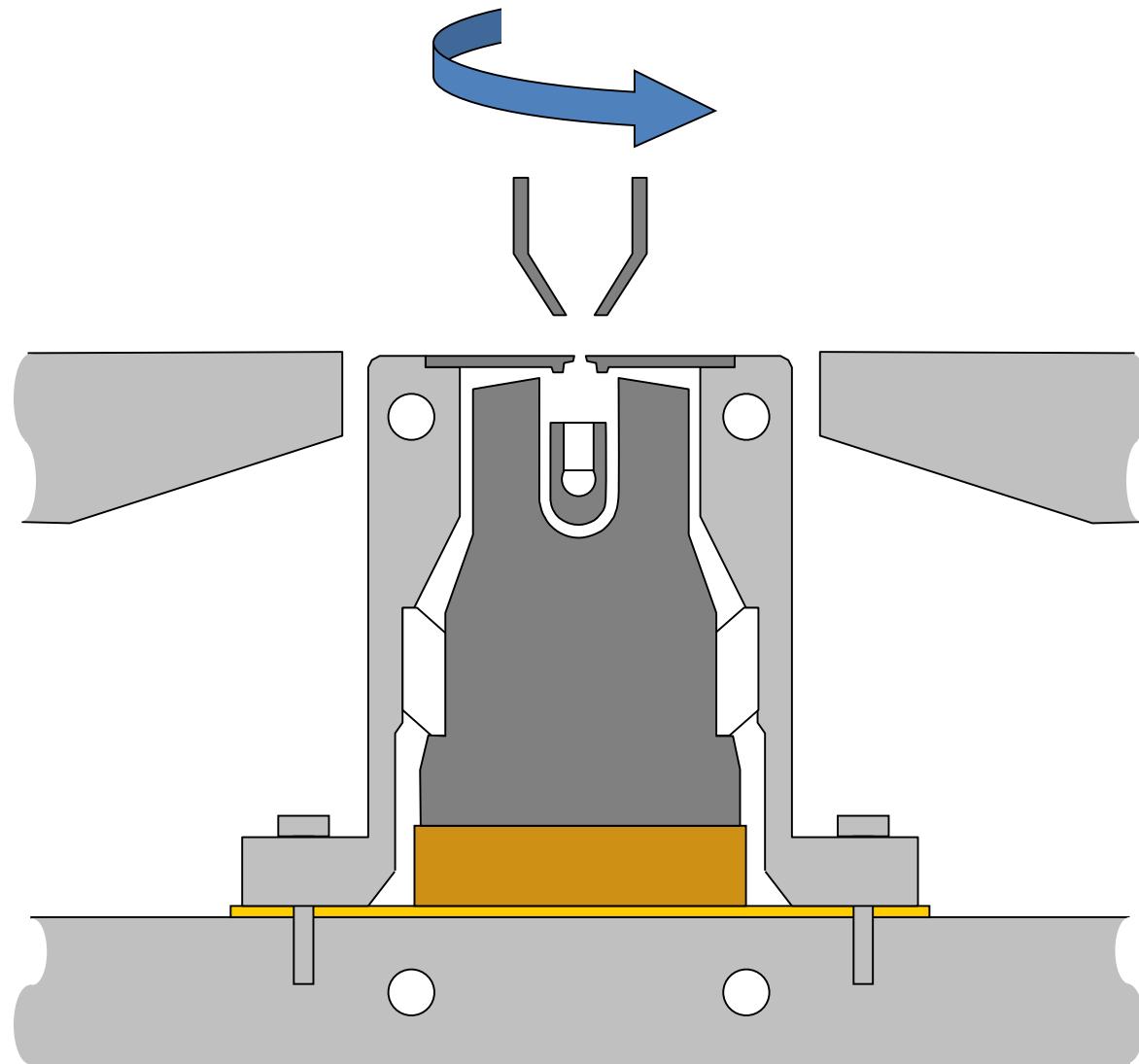
## Penning SPS

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

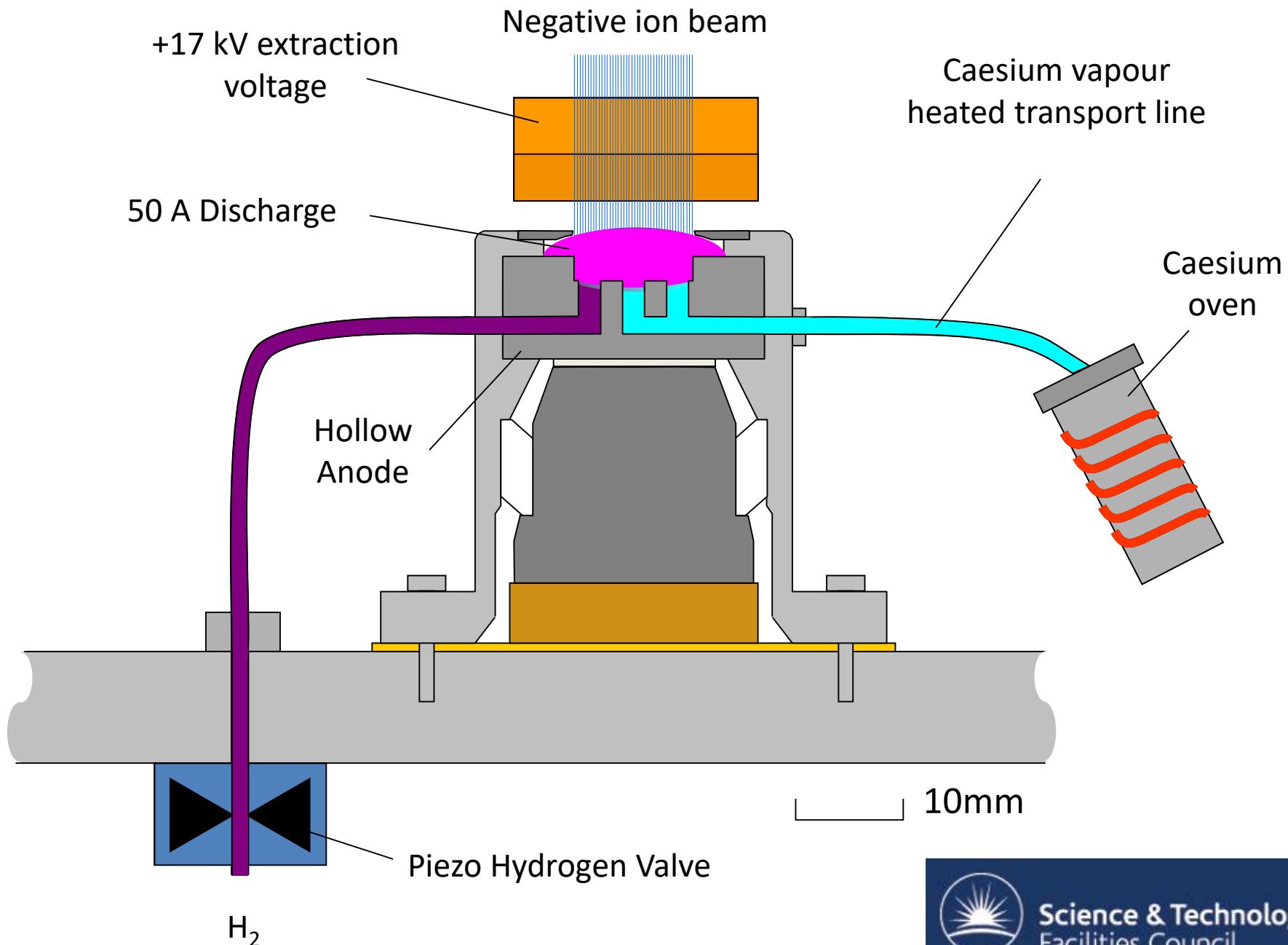
# ISIS Penning



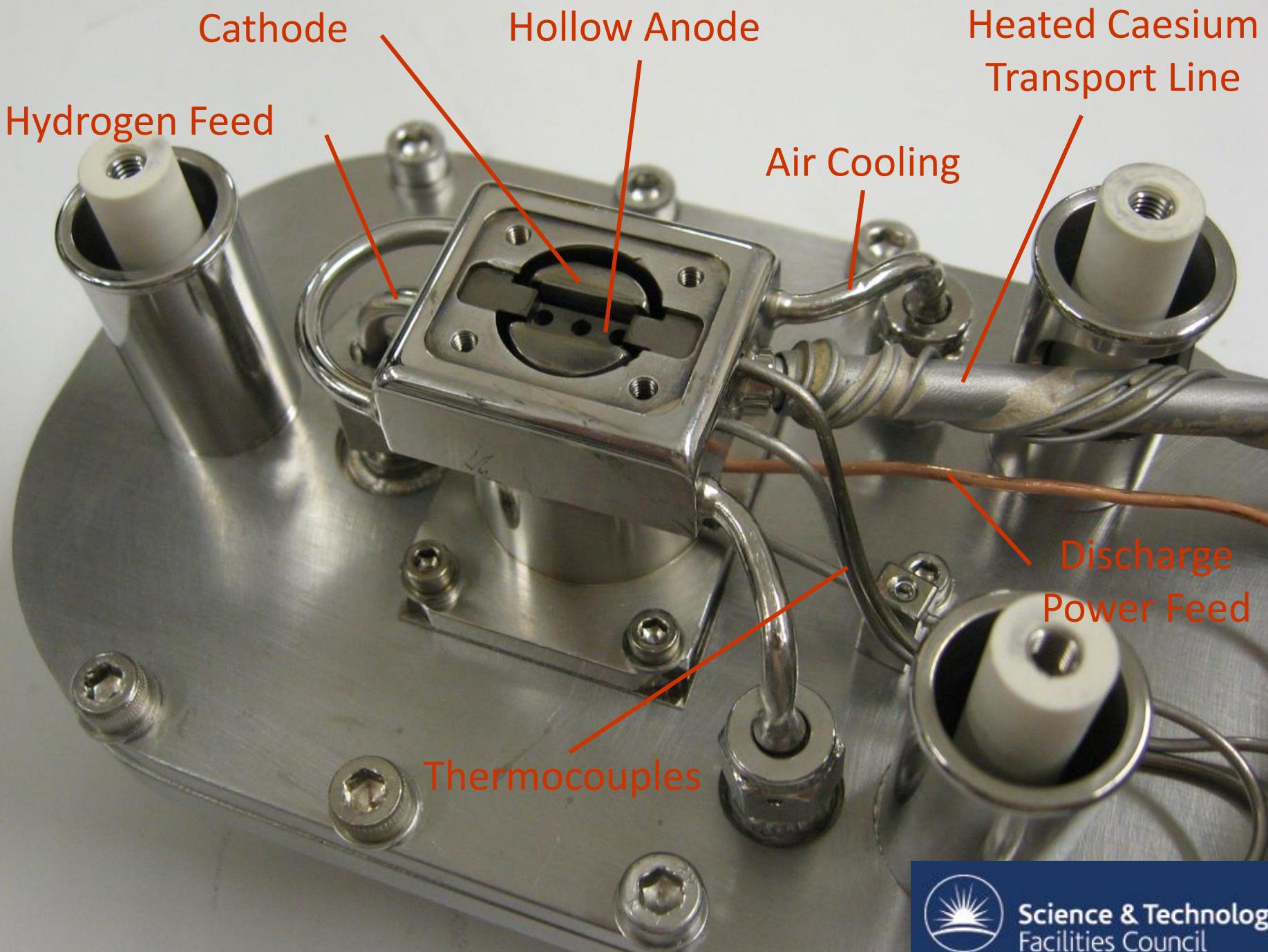
Science & Technology  
Facilities Council



Science & Technology  
Facilities Council

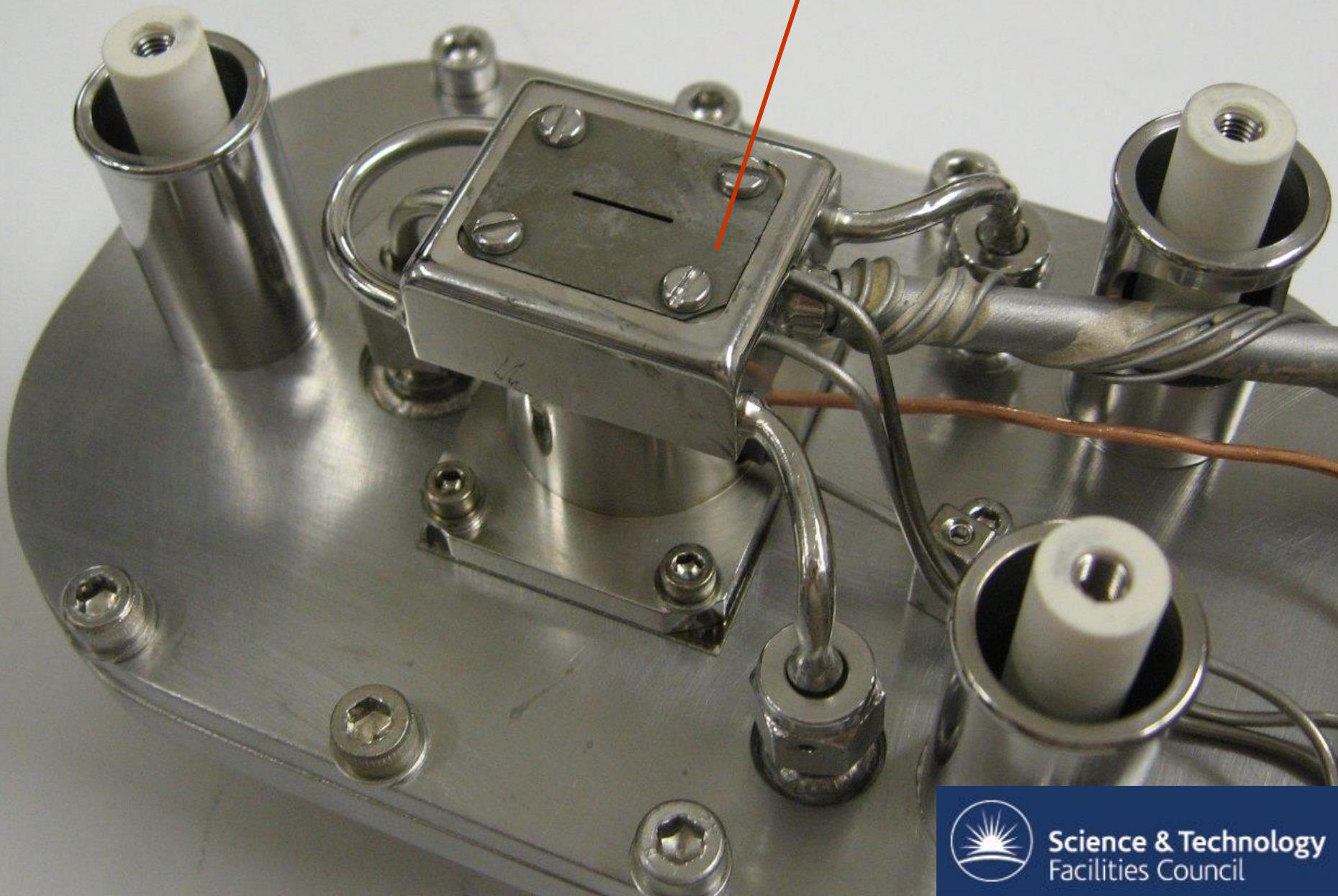


Science & Technology  
Facilities Council

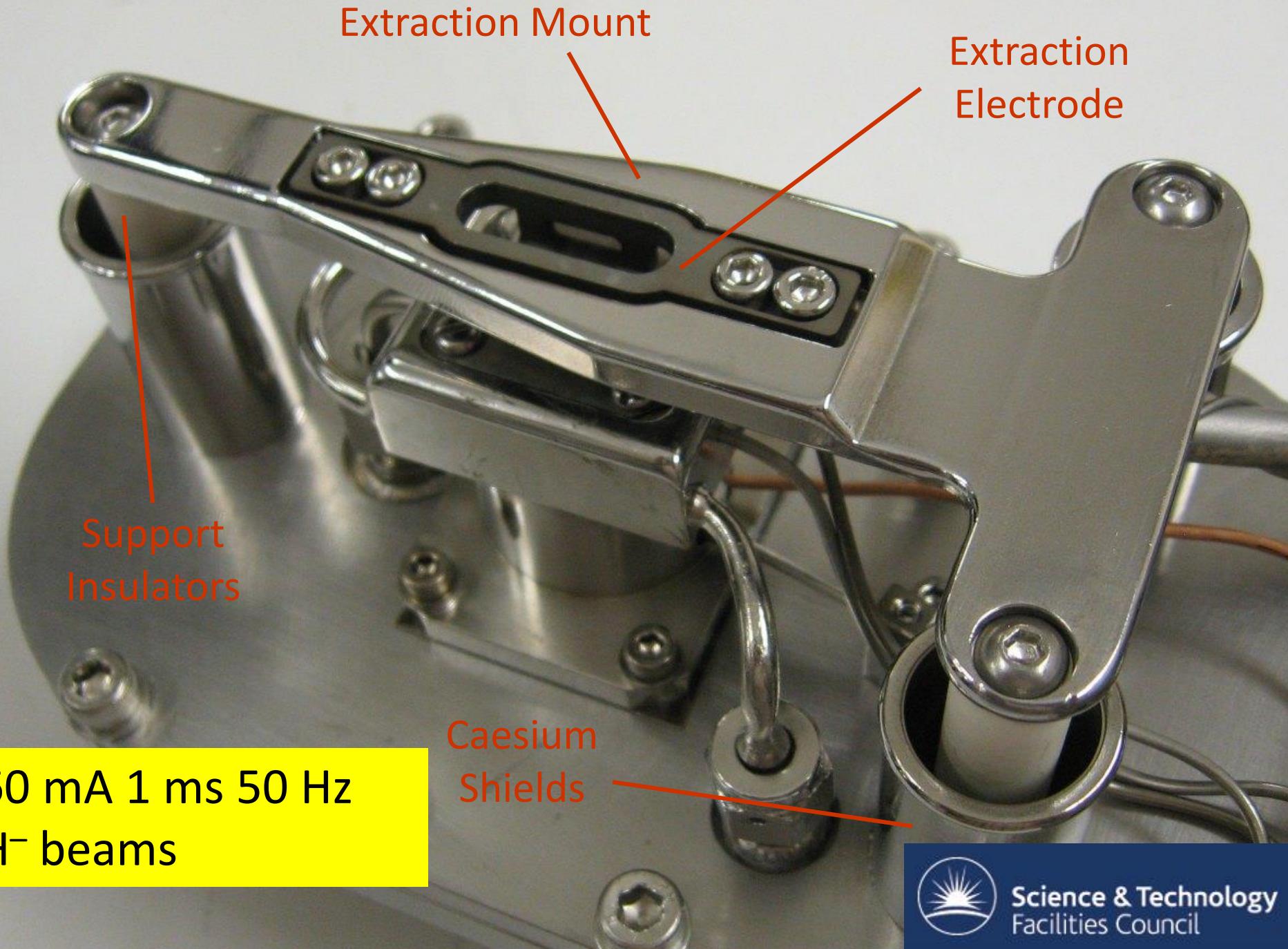


Science & Technology  
Facilities Council

Aperture Plate



Science & Technology  
Facilities Council



Science & Technology  
Facilities Council

# Early 1970s Budker Institute of Nuclear Physics Novosibirsk

## Magnetron SPS



Gennady Dimov

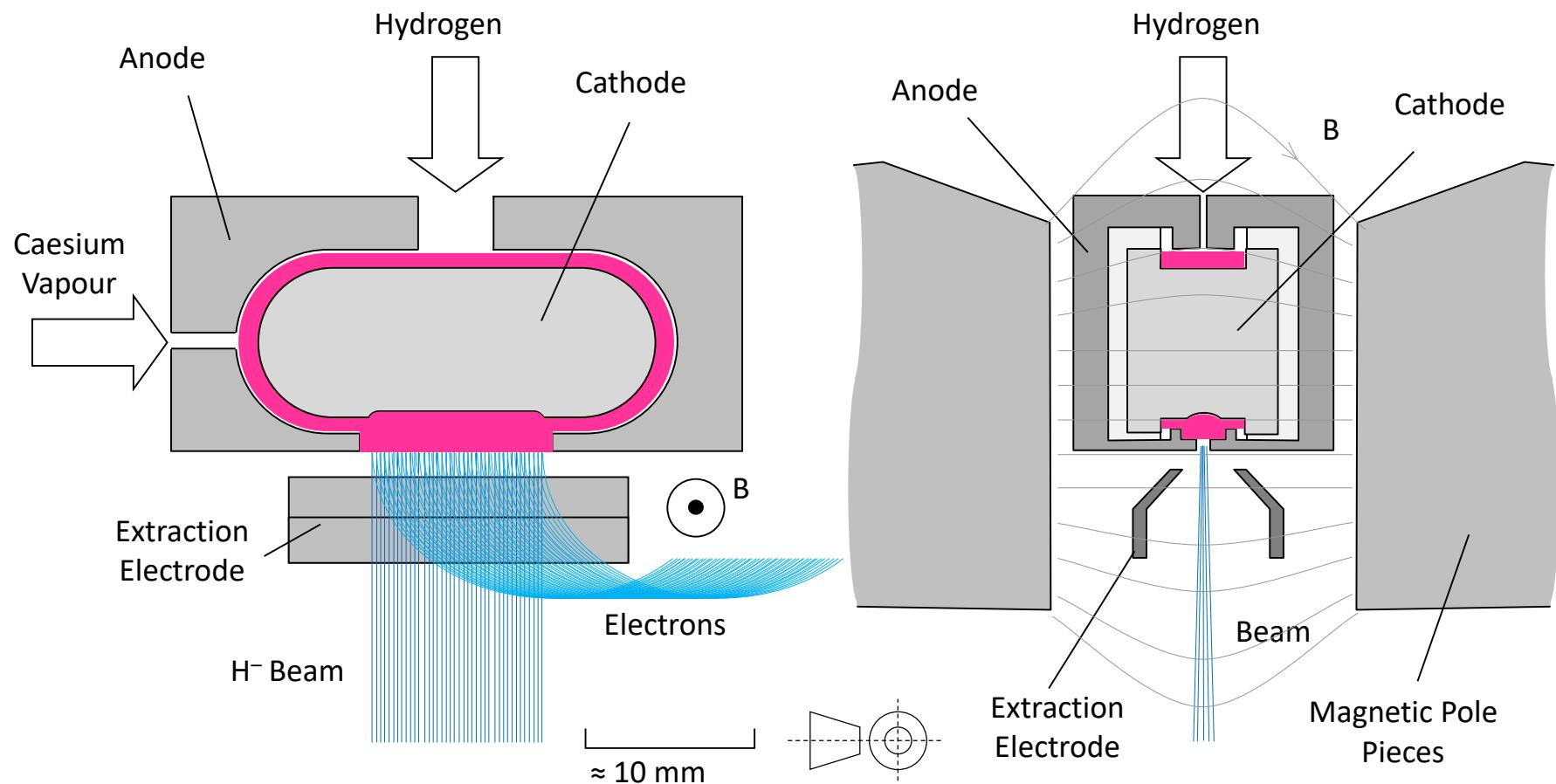


Yuri Belchenko



Vadim Dudnikov

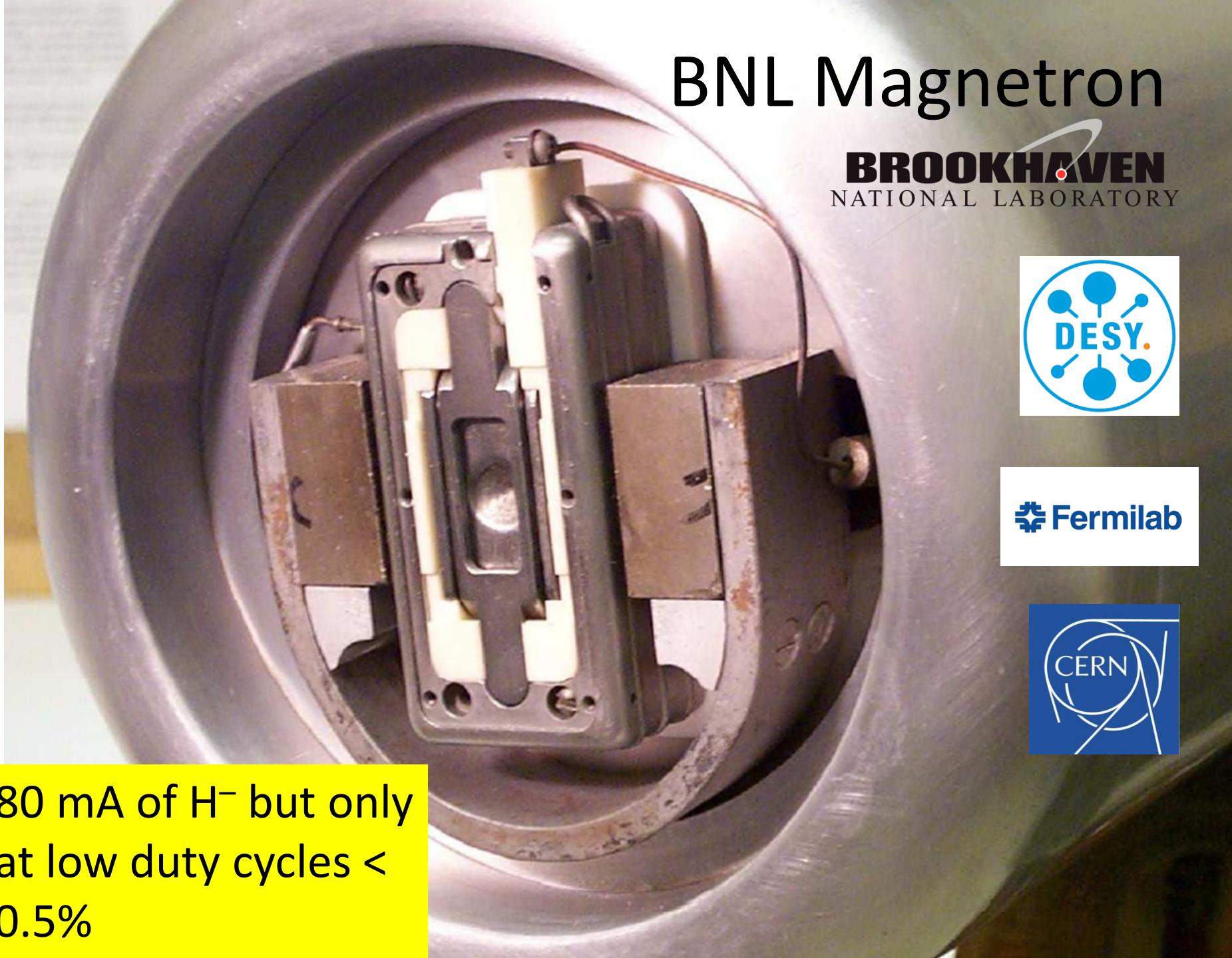
# Magnetron SPS



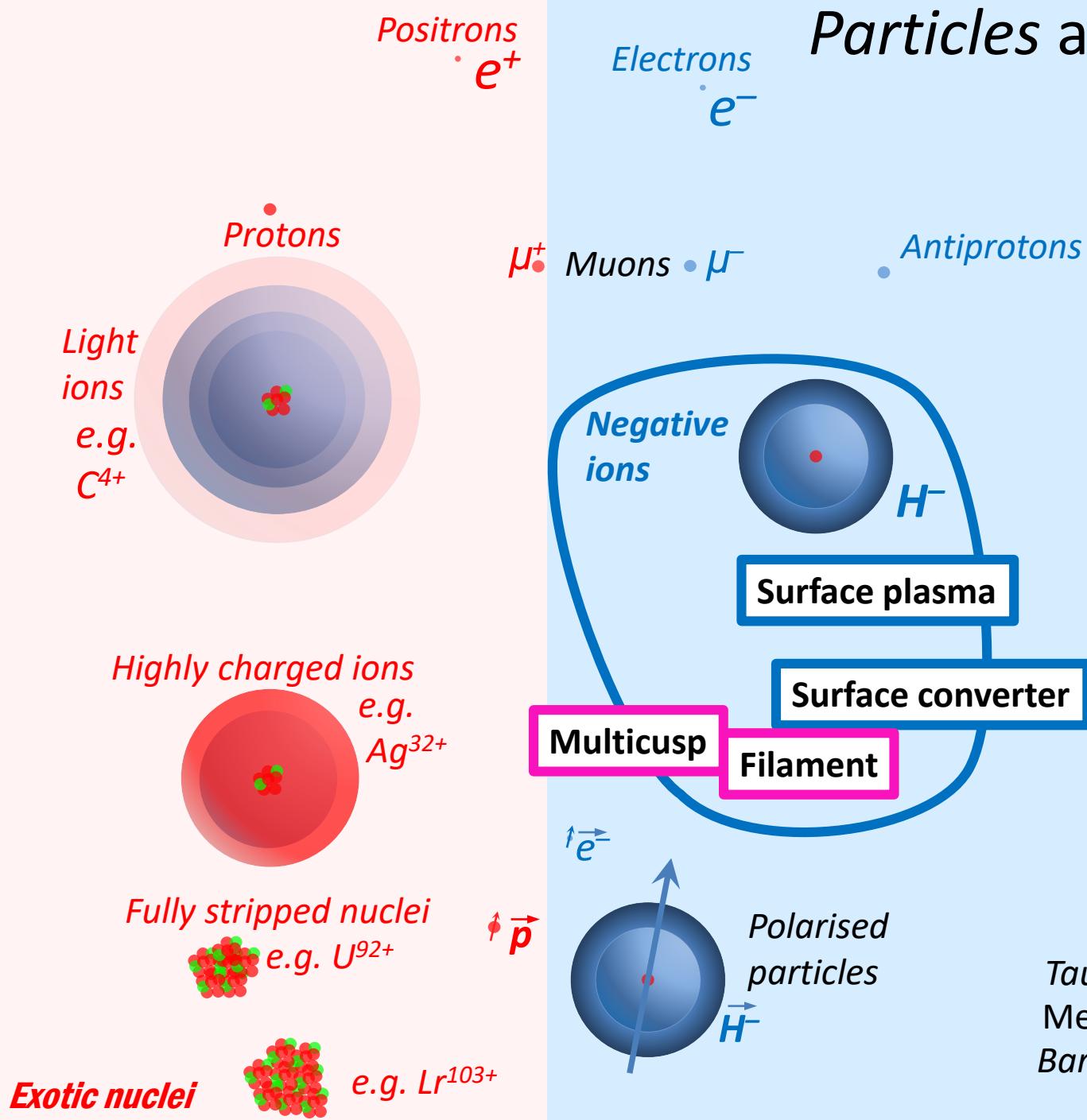
# BNL Magnetron



80 mA of H<sup>-</sup> but only  
at low duty cycles <  
0.5%



# Particles and Sources



Photons

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

Neutrons  $n$

Neutral particles

$H^0$



Higgs  
Bosons

Zoo of curiosities

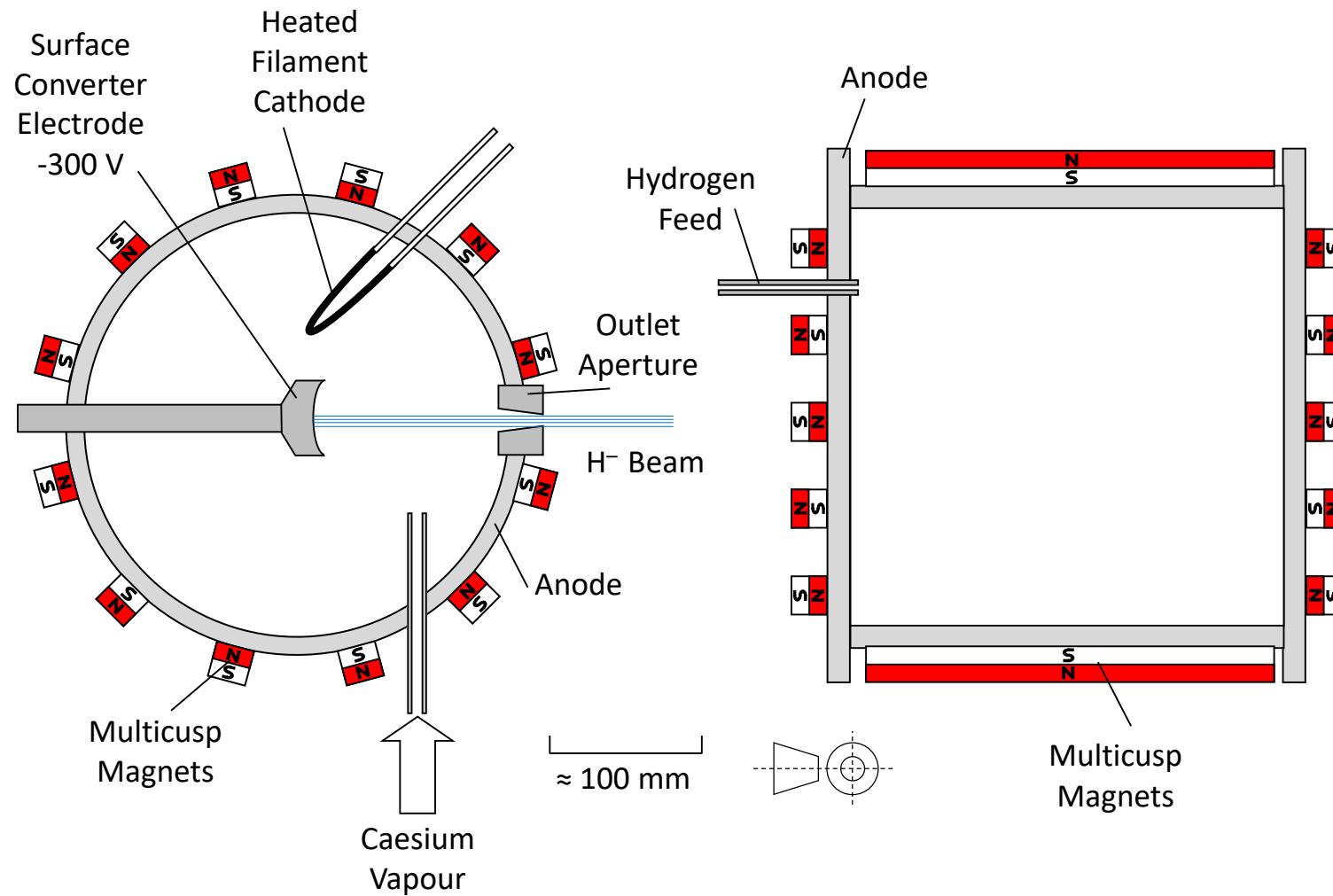
Tauons

Mesons

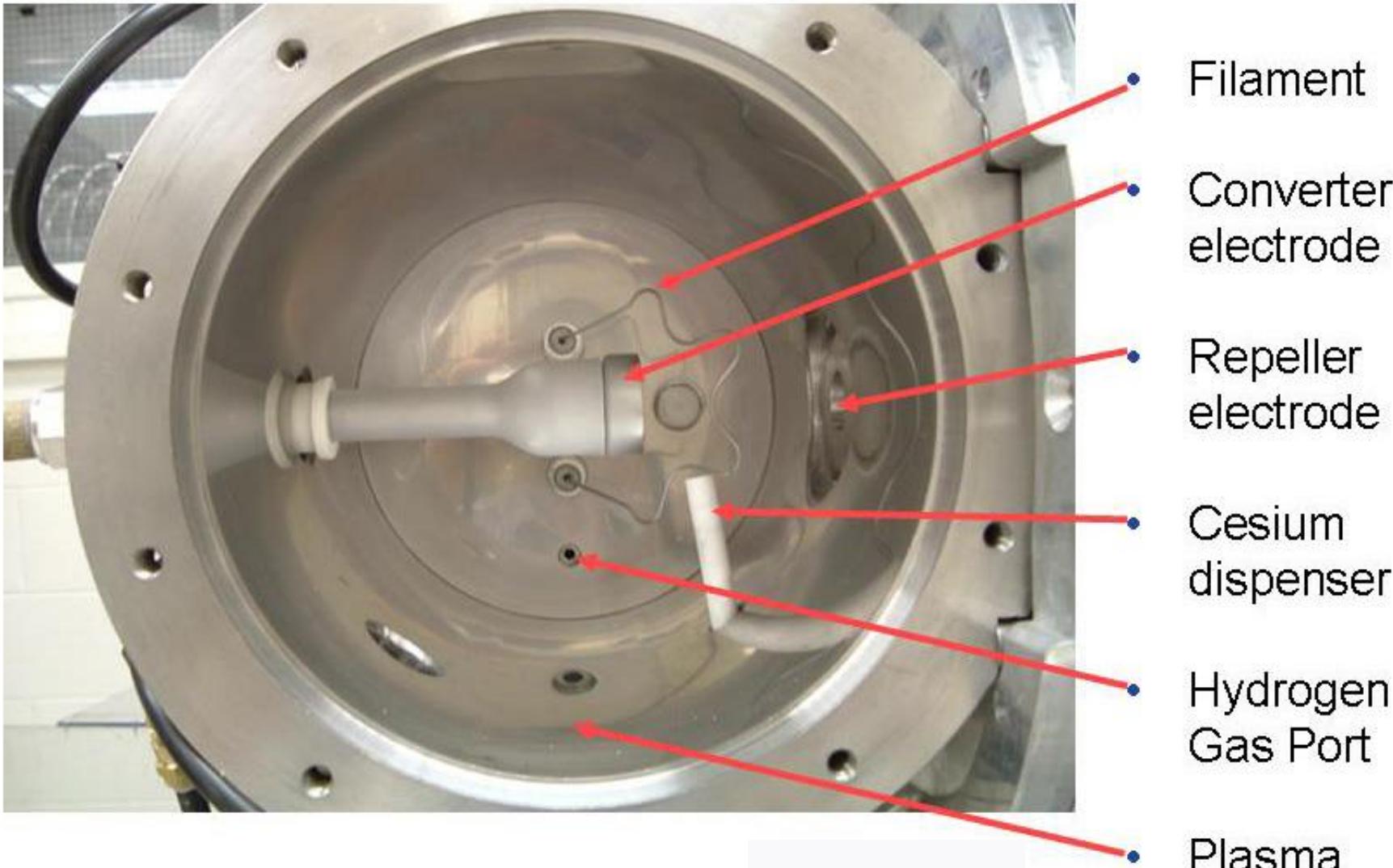
Baryons

$W + Z$   
Bosons

# Filament cathode multicuspl surface converter source

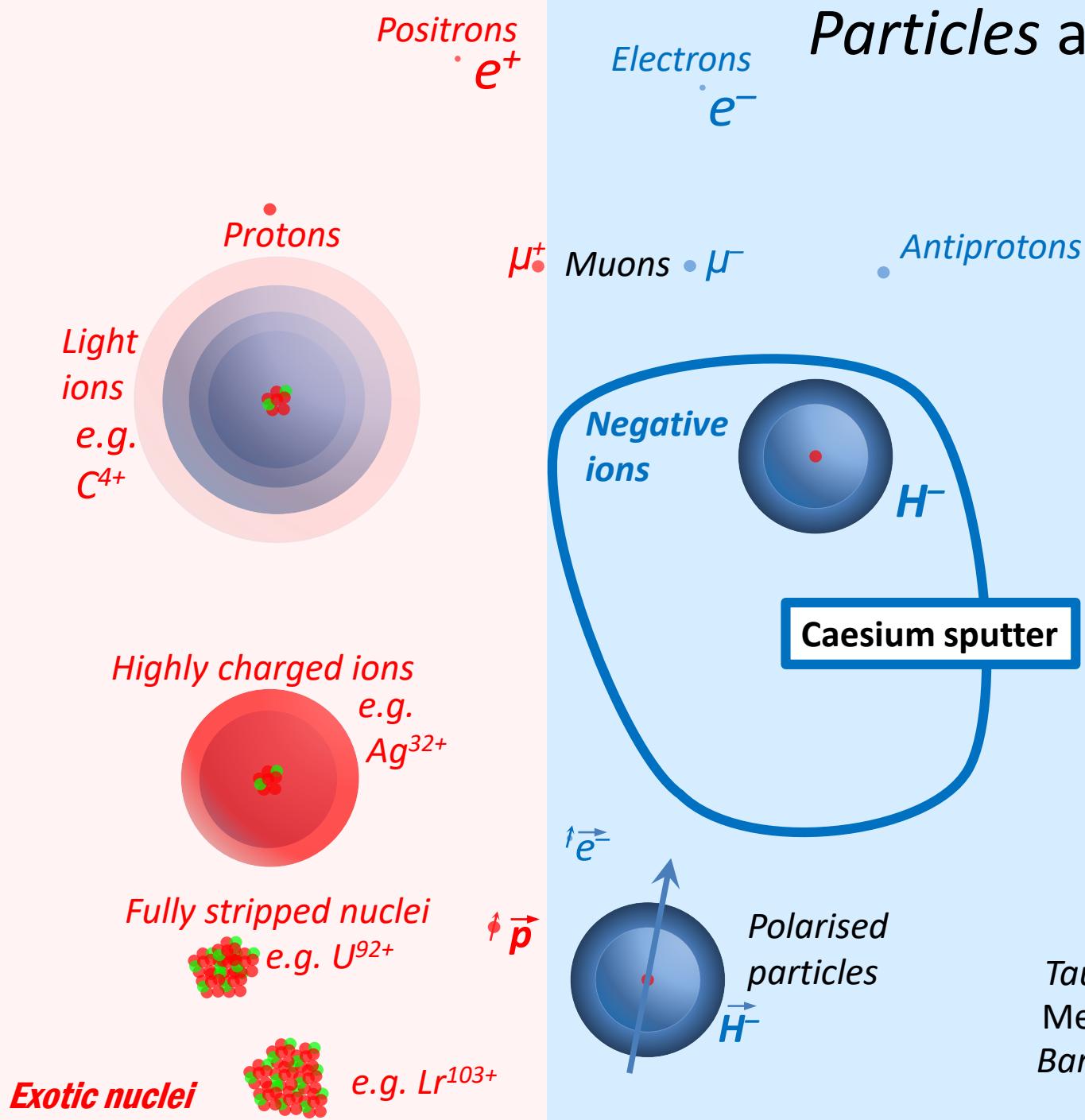


# LANSE Surface Converter Source



18 mA 1 ms 120 Hz H<sup>-</sup> beam

# Particles and Sources



Photons  
Neutrinos  $\nu_e \nu_\mu \nu_\tau$   
Neutrons  $n$

Neutral particles  
 $H^0$



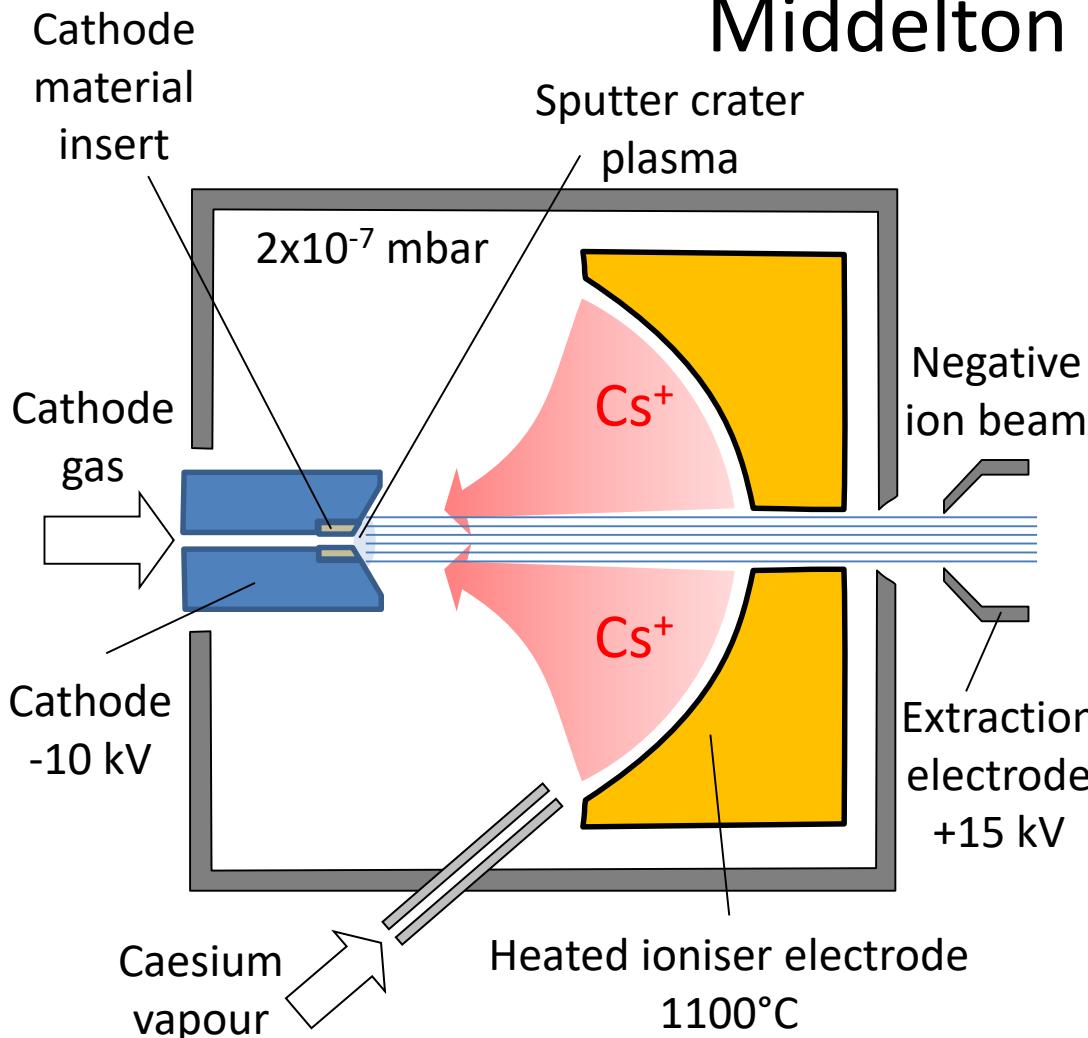
Higgs  
Bosons

Zoo of curiosities  
Tauons  
Mesons  
Baryons

$W + Z$   
Bosons

# SNICS (Source of Negative Ions by Cesium Sputtering)

## Middleton et al



### Currents in $\mu\text{A}$

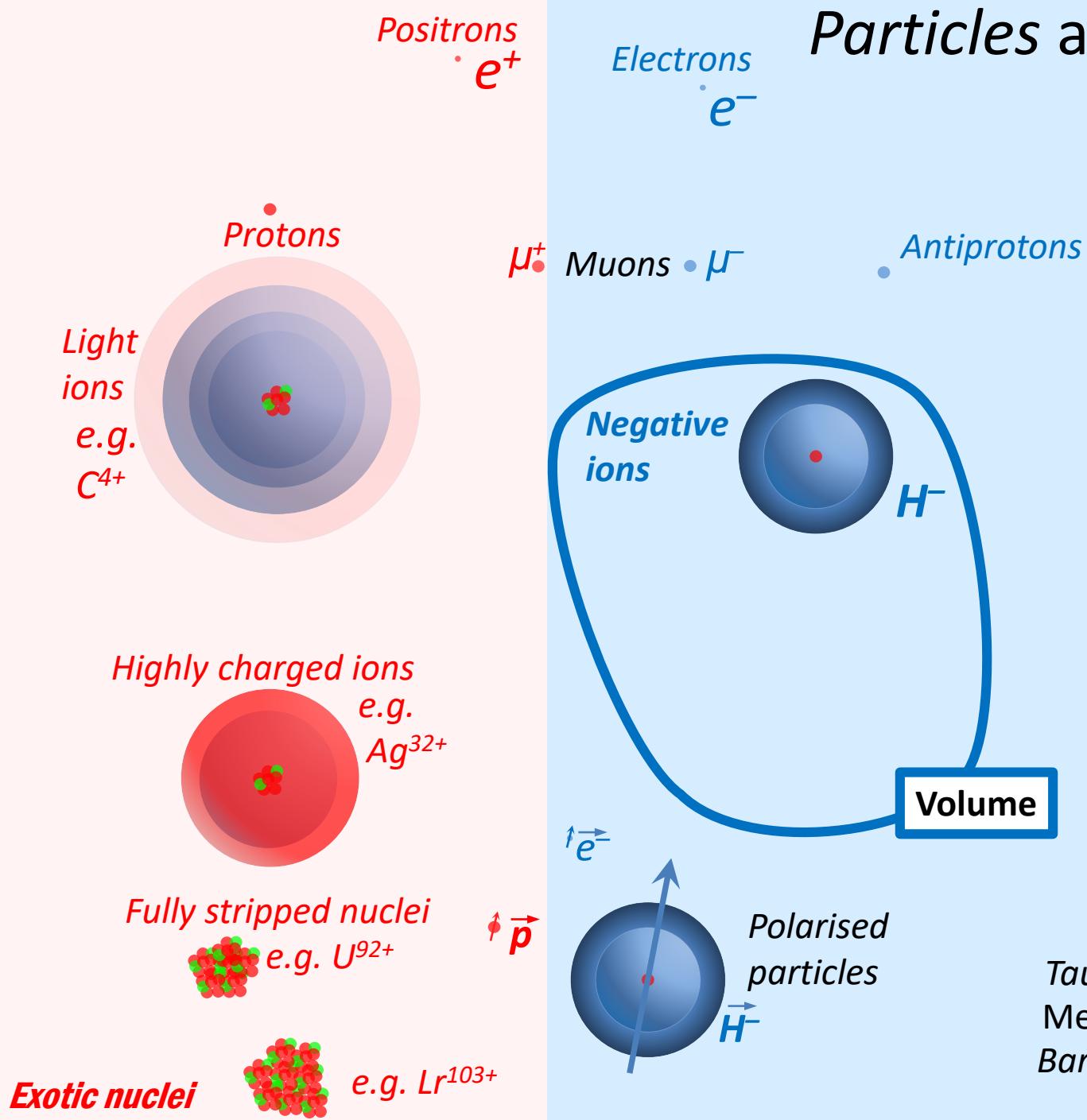
H-130	Si- 430	As- 60	Cs- 1.5
D- 150	P- 125	Se- 10	CeO- 0.2
Li- 4	S- 100	Br- 40	NdO- 0.3
BeO- 10	Cl- 100	Sr- 1.5	EuO- 1.0
B- 60	CaH3- 0.8	Y- 0.66	ErO- 10
B2- 73	TiH- 10	Zr- 9.4	TmO- 1.0
C- 260	VH- 25	Nb- 7	YbO- 1.0
C2- 40	Cr- 5	Mo- 5	Ta- 9.5
CN- 12	MnO- 4	Rh- 5	TaO- 6
CN-(15N) 20	Fe- 20	Ag- 13	W- 2.5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

Produces a large range of different negative ions



**National  
Electrostatics  
Corp.**

# Particles and Sources





# Volume Production



Dissociative attachment  
of low energy electrons  
to rovibrationally excited  
 $\text{H}_2$  molecules

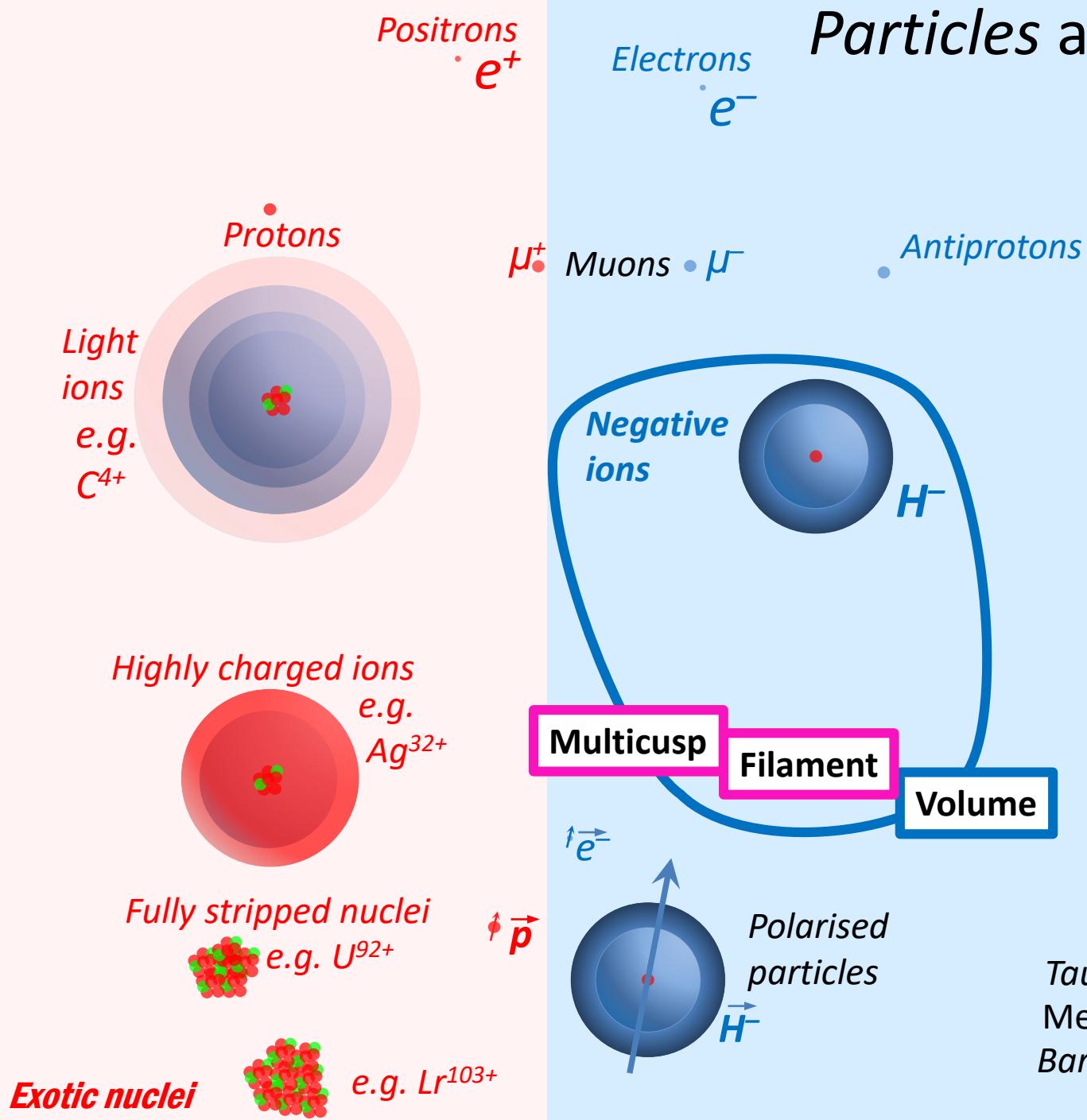
Marthe Bacal  
Ecole Polytechnique  
mid 1970's



Sources developed by  
Ehlers + Leung at LBNL



# Particles and Sources



Photons  
Neutrinos  $\nu_e \nu_\mu \nu_\tau$   
Neutrons  $n$

Neutral particles  
 $H^0$

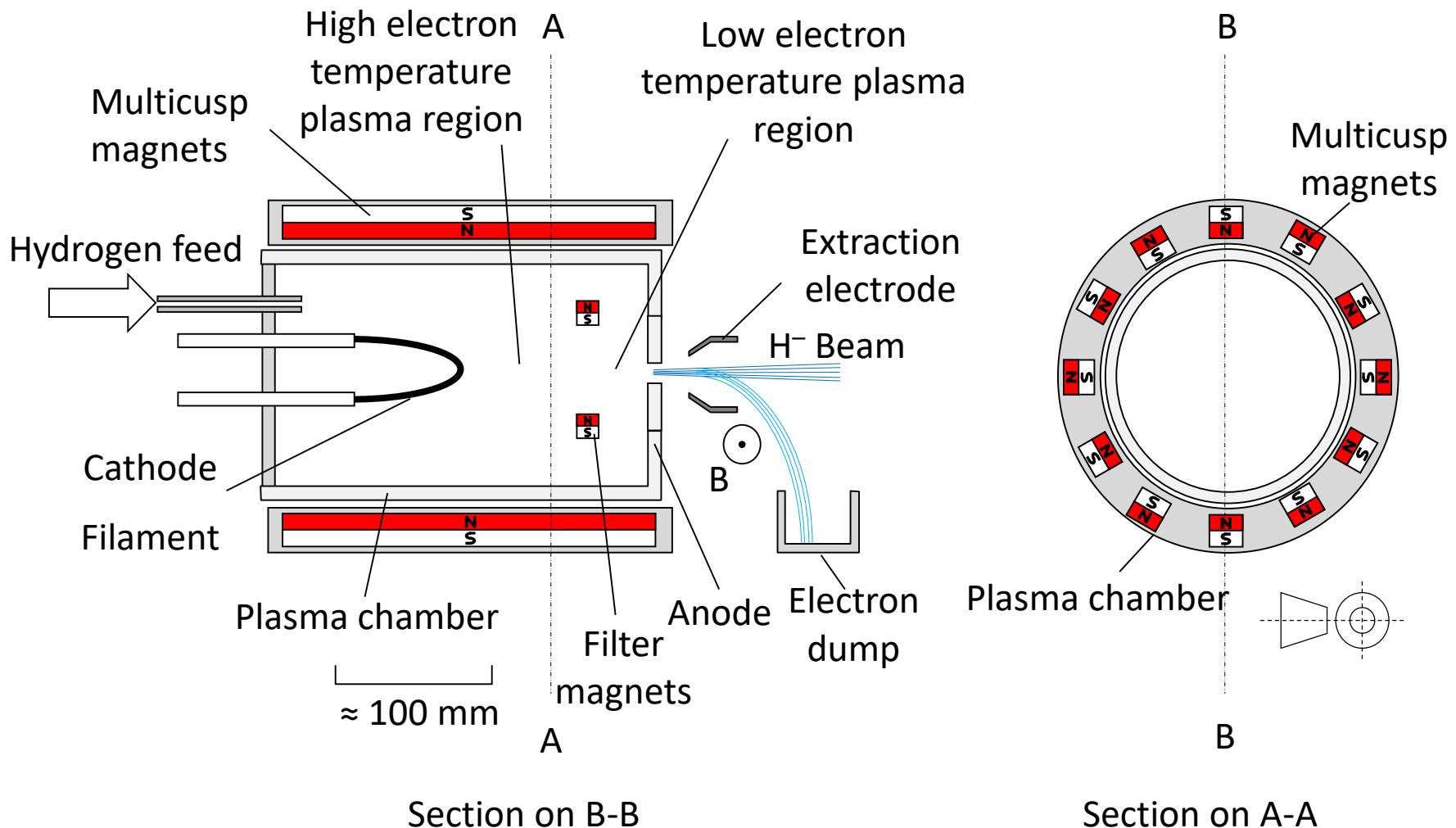


Higgs  
Bosons

Zoo of curiosities  
Tauons  
Mesons  
Baryons

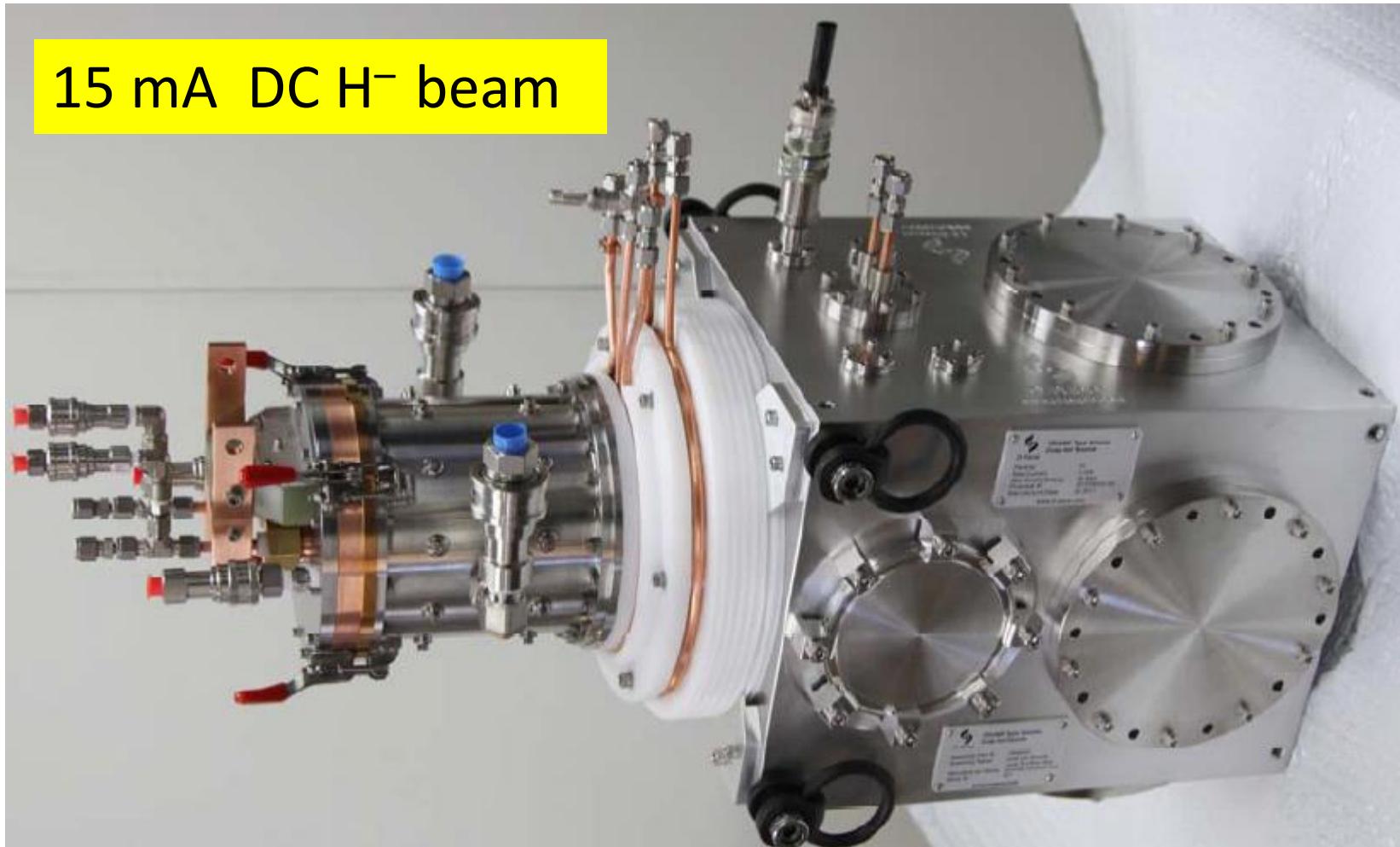
$W + Z$   
Bosons

# Multicusp Filament Volume Source

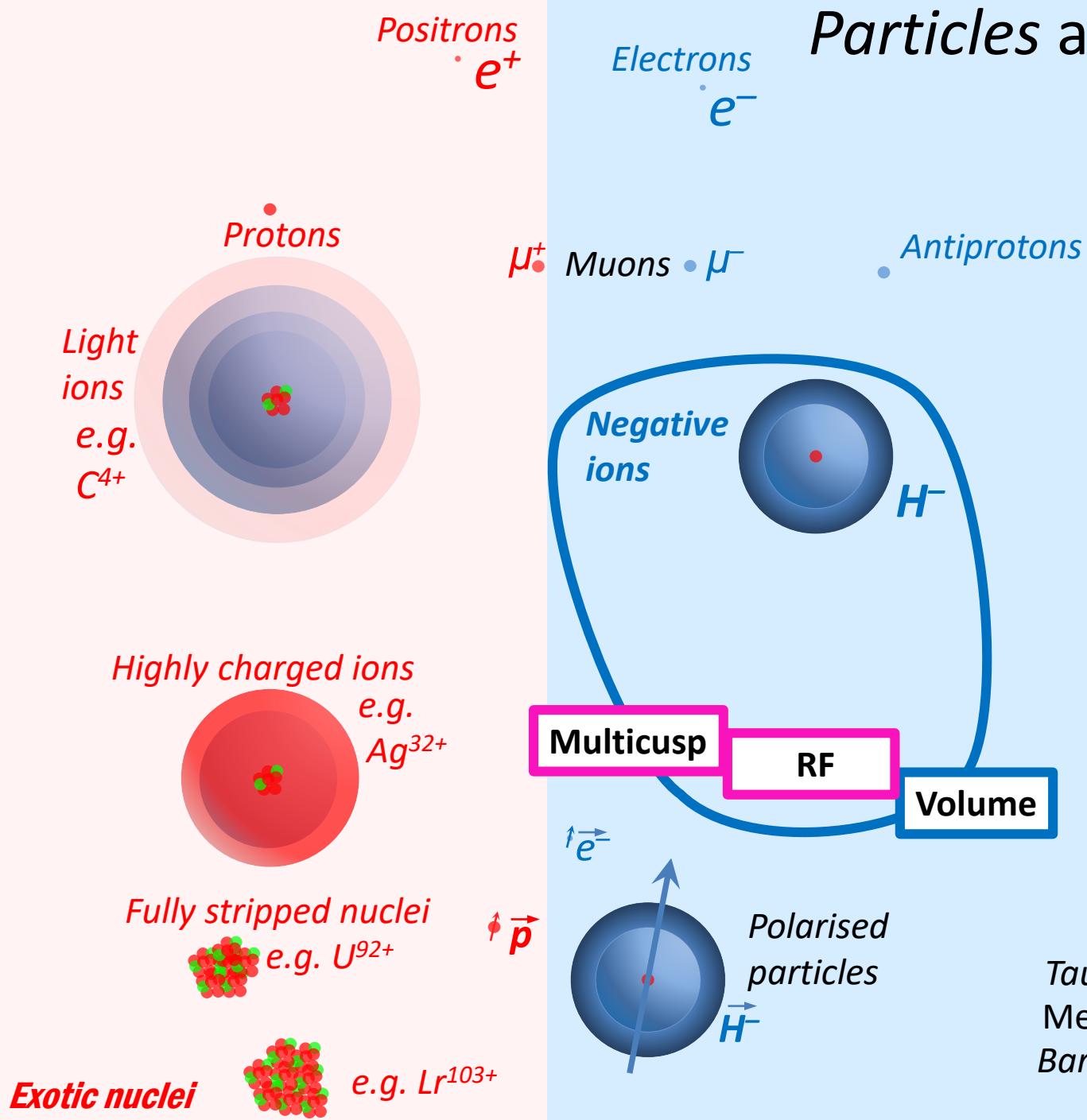


# D-Pace Filament Volume Source

15 mA DC H<sup>-</sup> beam



# Particles and Sources



Photons

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

Neutrons  $n$

Neutral particles

$H^0$



Higgs  
Bosons

## Zoo of curiosities

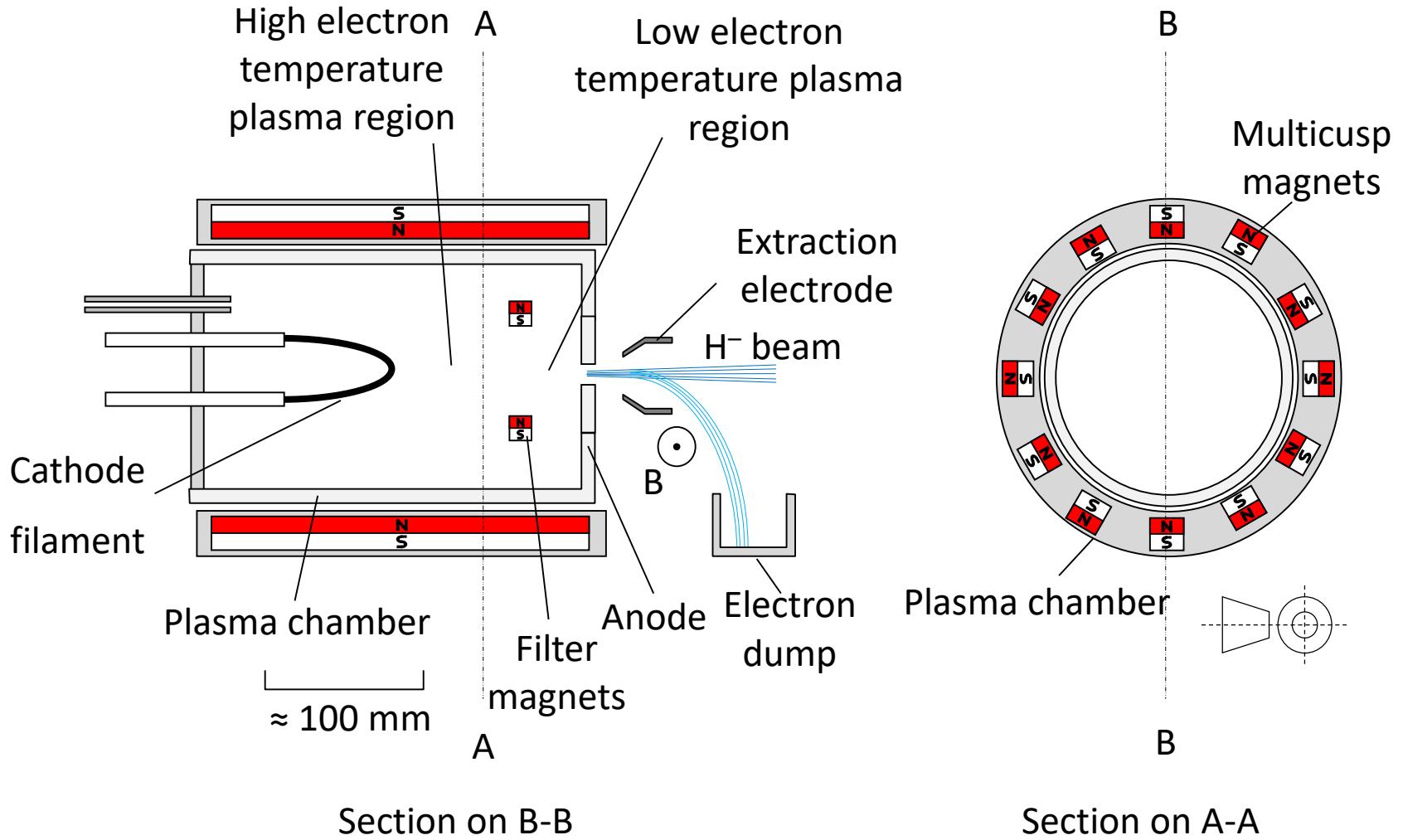
Tauons

Mesons

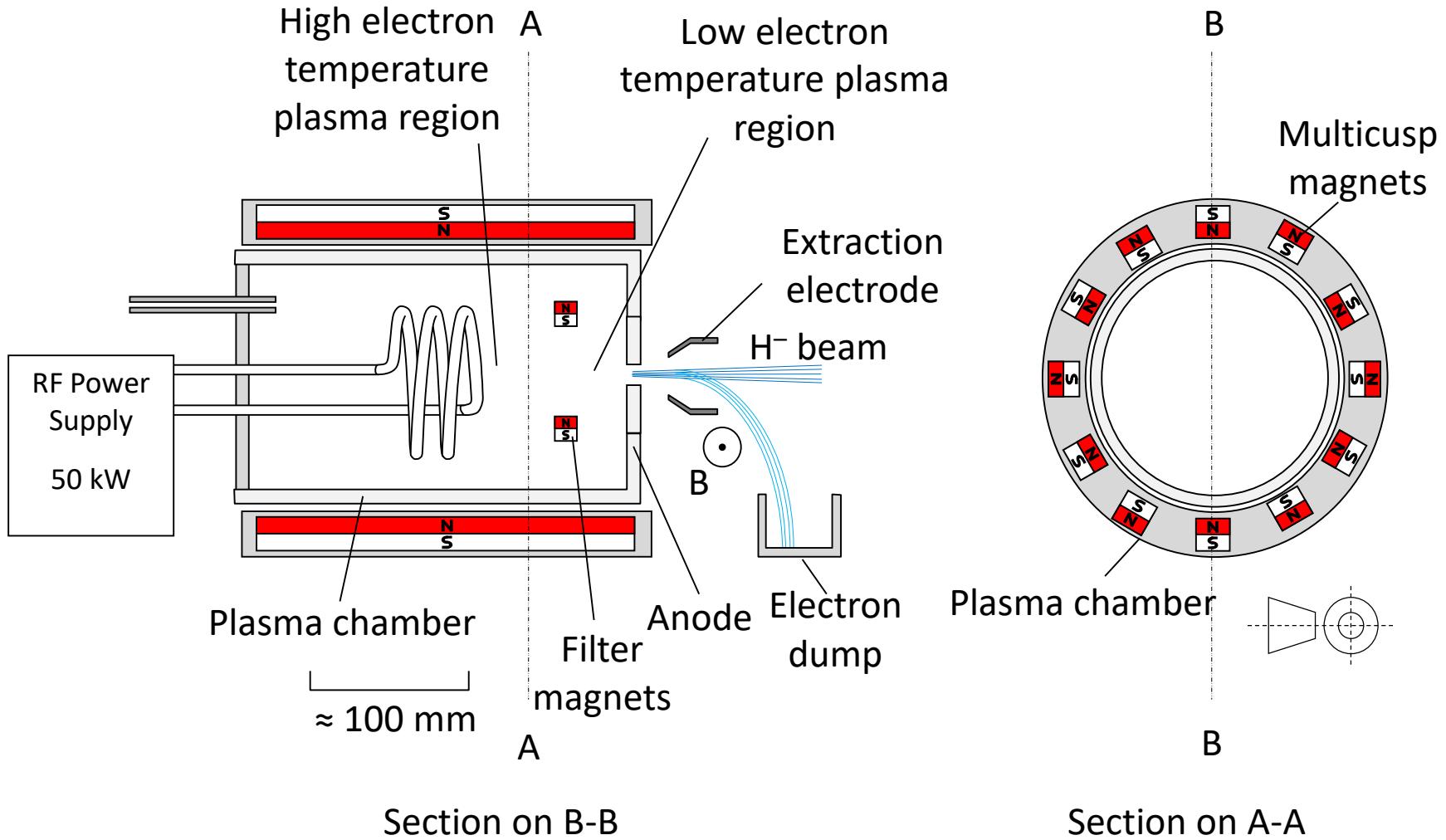
Baryons

$W + Z$

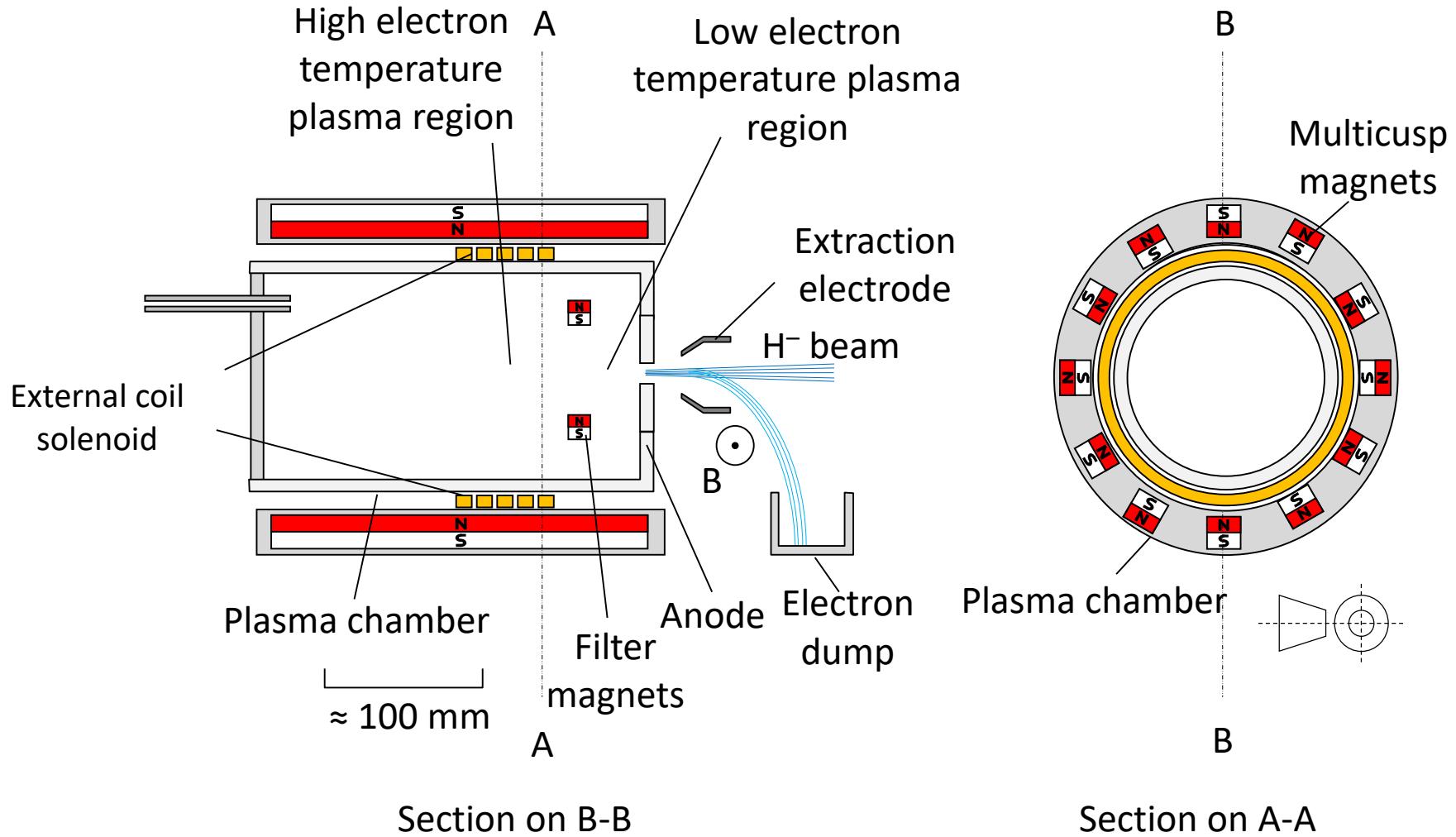
Bosons



# Internal RF Solenoid Coil Volume Source



# External RF Solenoid Coil Volume Source

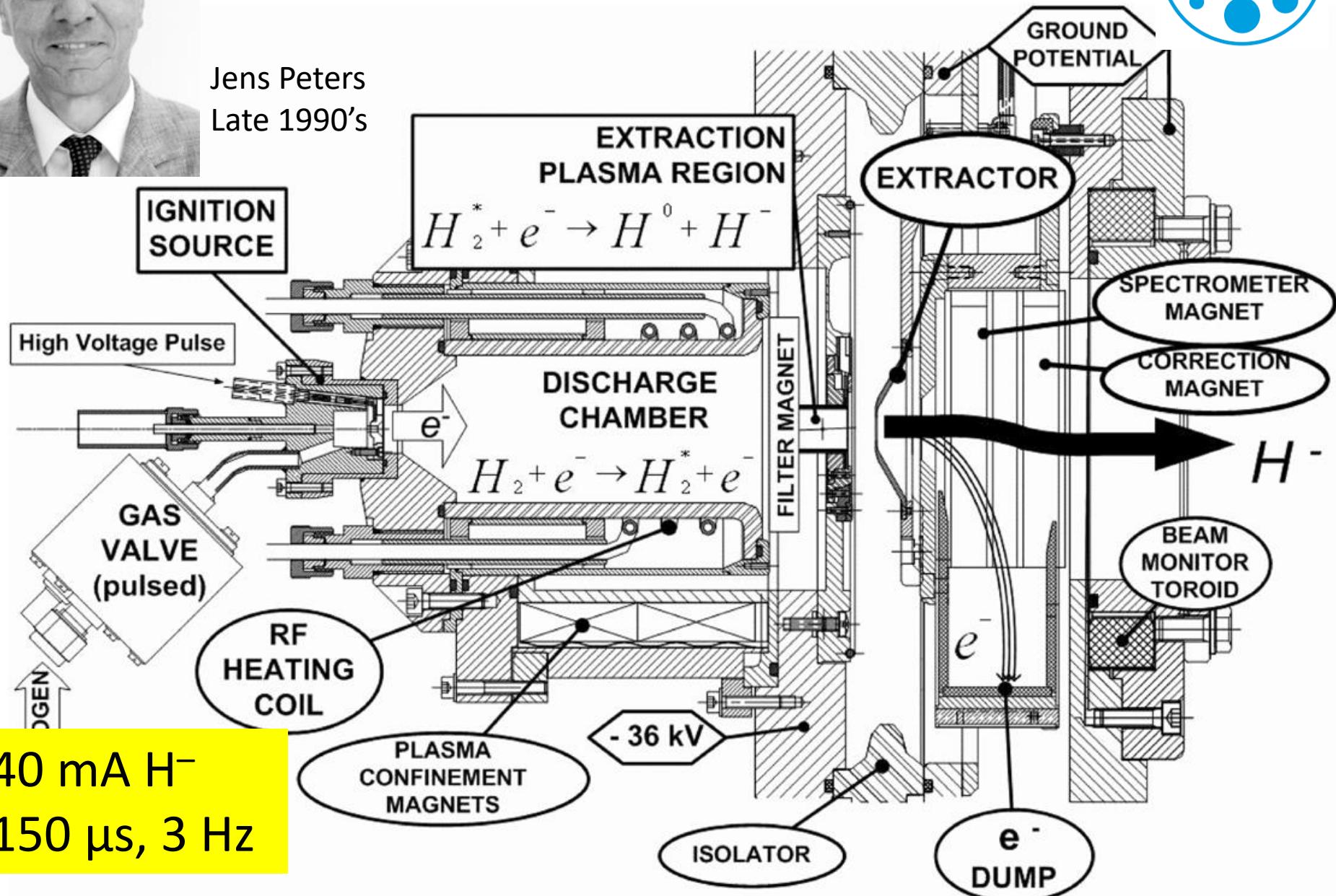




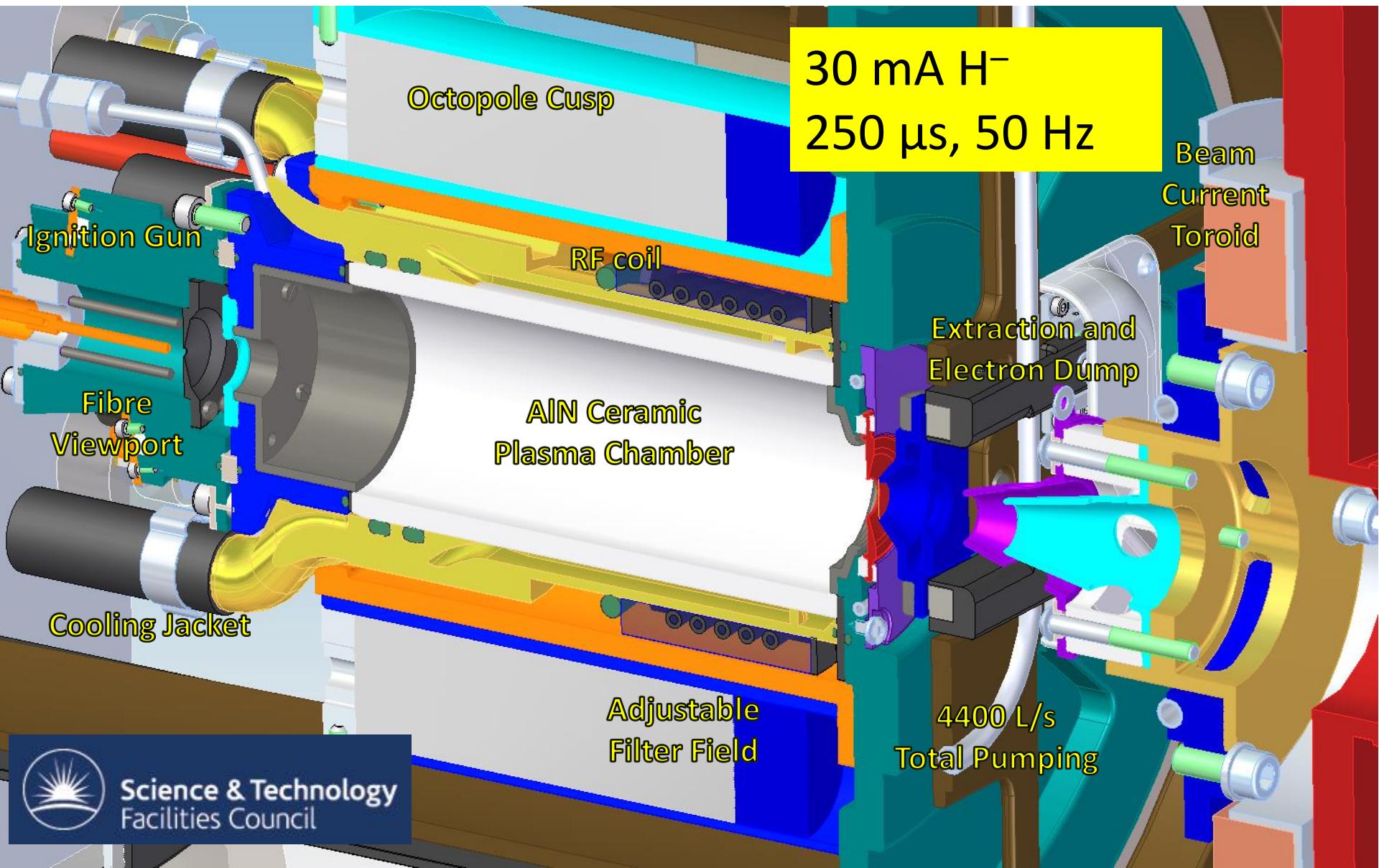
Jens Peters  
Late 1990's



# HERA Source



# ISIS RF H<sup>-</sup> Ion Source (currently in commissioning)



Science & Technology  
Facilities Council

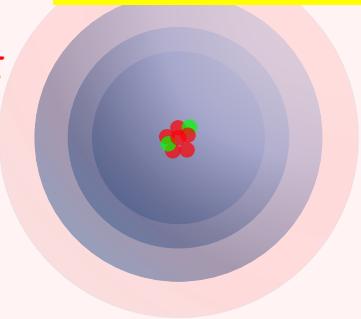
Positrons  
•  $e^+$

Electrons  
•  $e^-$

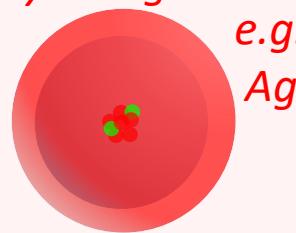
Photons  
Neutrinos  
 $\nu_\mu \nu_\tau$   
Neutrons  
•  $n$

## Best of both worlds?

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



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



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



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

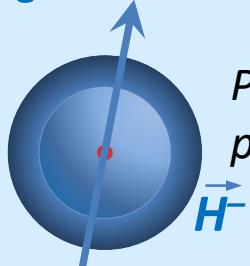
Surface converter

Multicusp

RF

Volume

$\uparrow e^-$



Polarised particles



Higgs  
Bosons

Zoo of curiosities

Tauons  
Mesons  
Baryons

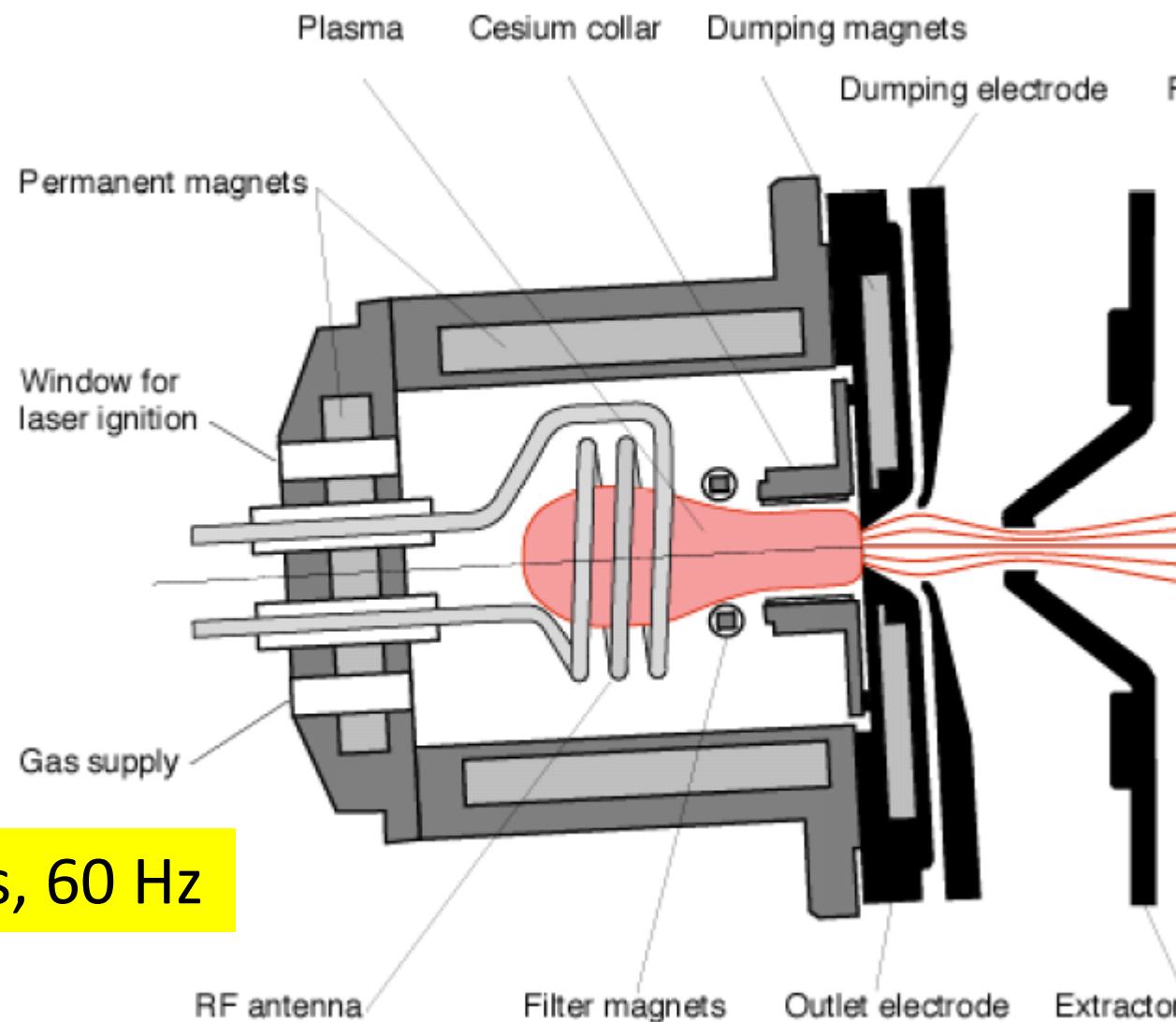
$W + Z$   
Bosons

CERN have developed a cesiated external coil source for LINAC4

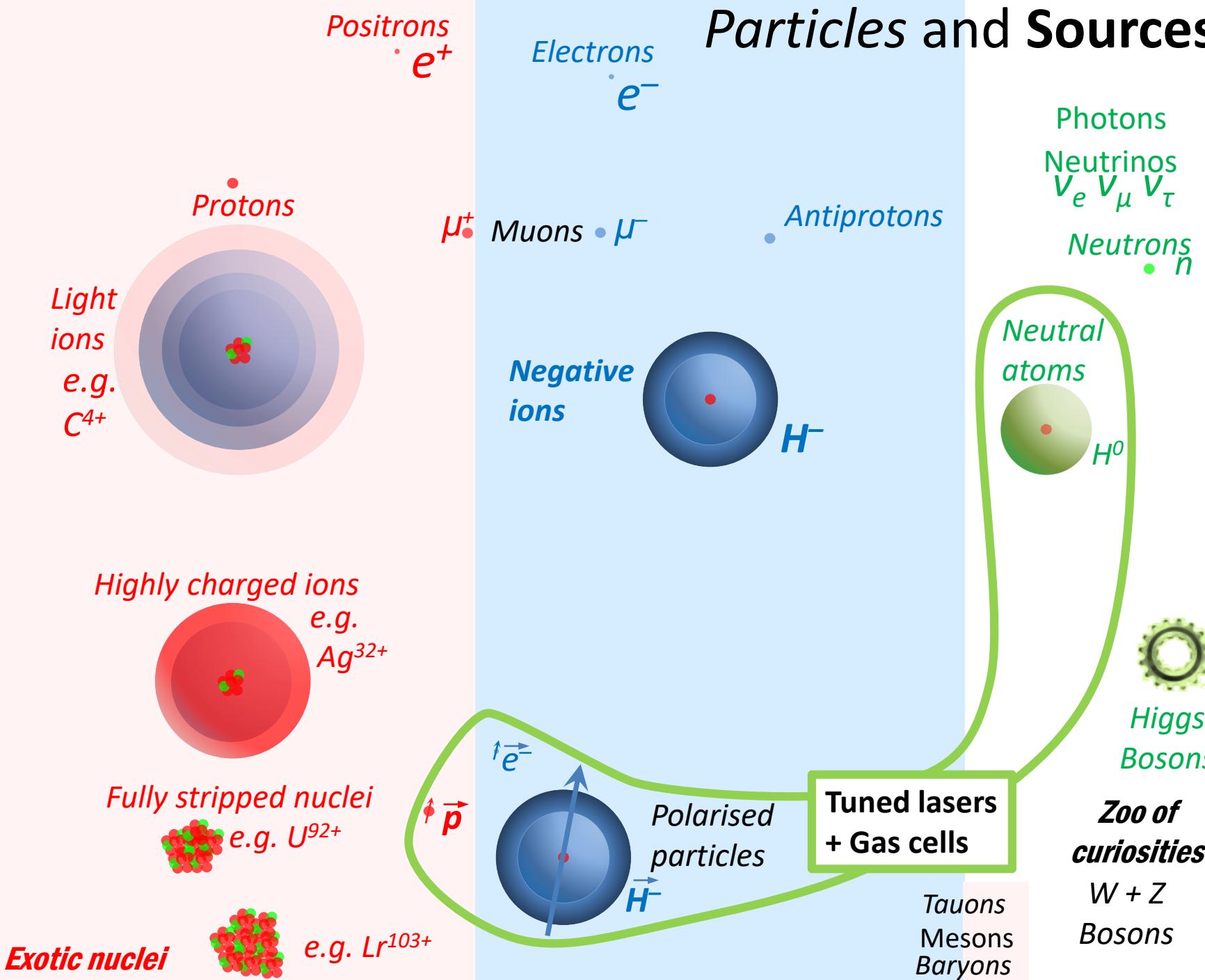


60 mA H<sup>-</sup> 1 ms, 60 Hz

# SNS ion source



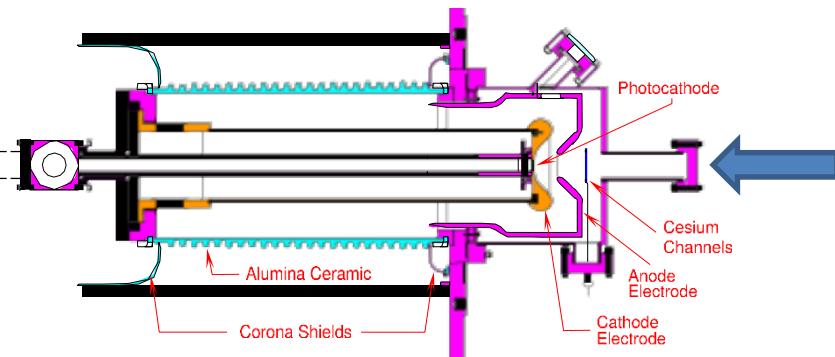
# Particles and Sources



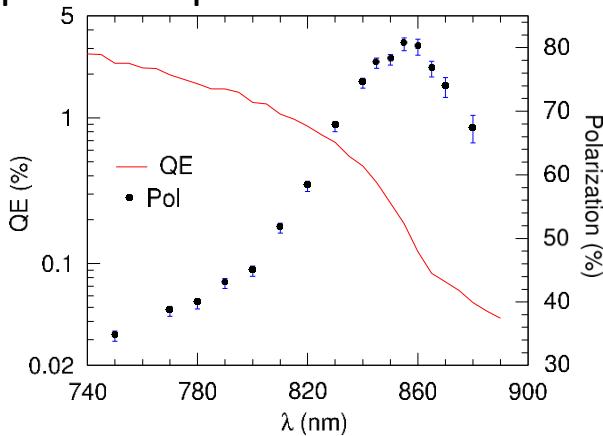
# Polarised Electrons



Strained GaAs photocathode

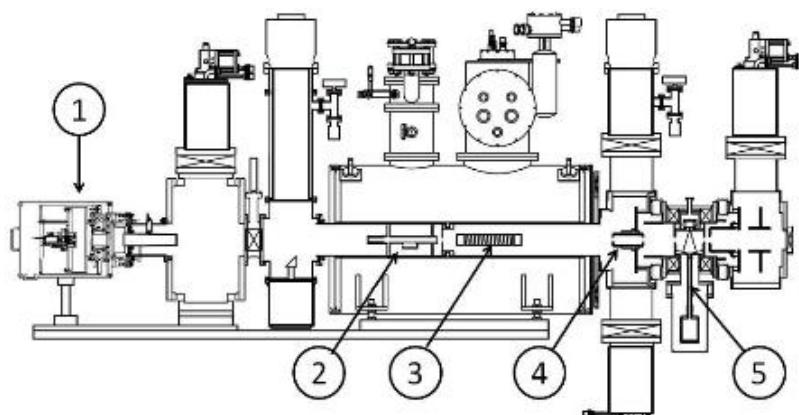


Circularly polarized laser light produces polarised electrons



100  $\mu$ A polarised  $e^-$

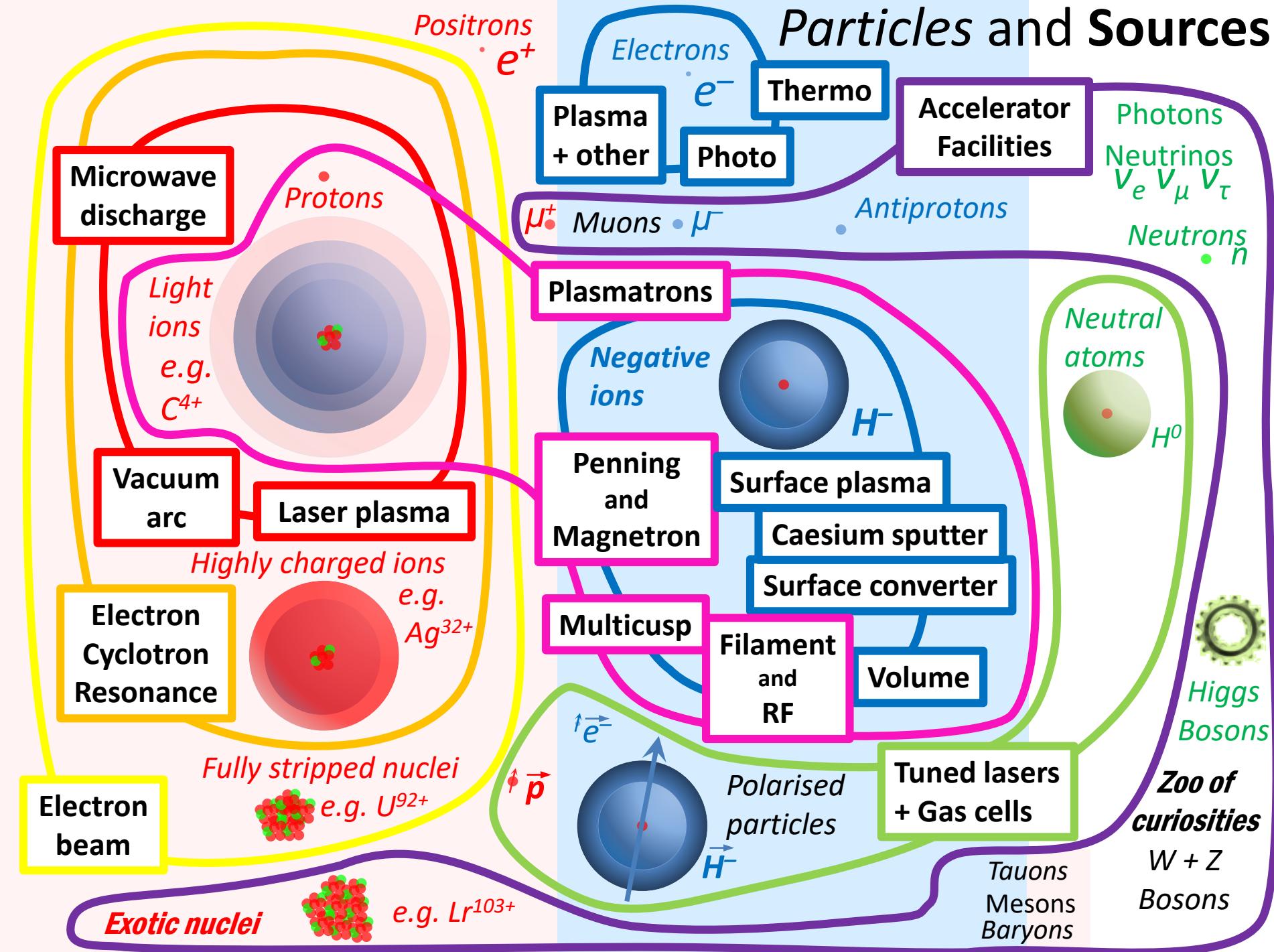
# Polarised H<sup>-</sup>



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  $\mu$ s polarised H<sup>-</sup>

# Particles and Sources



# 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

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?