Particle Sources

Dan Faircloth
Rutherford Appleton Laboratory
**Particles and Sources**

- **Positrons**: $e^+$
- **Electrons**: $e^-$
- **Muons**: $\mu^+$, $\mu^-$
- **Antiprotons**: $\bar{p}$
- **Neutrons**: $n$
- **Protons**: $p$
- **Electrons**: $e^-$
- **Neutrons**: $n$
- **Neutral particles**: $H^0$
- **Light ions**: e.g. $C^{4+}$
- **Highly charged ions**: e.g. $Ag^{32+}$
- **Fully stripped nuclei**: e.g. $U^{92+}$
- **Exotic nuclei**: e.g. $Lr^{103+}$
- **Negative ions**: $e^-$
- **Positive ions**: $e^+$
- **Antiprotons**: $\bar{p}$
- **Mesons**
- **Baryons**
- **Zoo of curiosities**
- **Photons**
- **Higgs Bosons**
- **Zoo of curiosities**
- **Neutrinos**: $\nu_e$, $\nu_\mu$, $\nu_\tau$
- **Bosons**: $W$, $Z$
- **Mesons**
- **Baryons**
- **Zoo of curiosities**
- **W + Z Bosons**
- **Higgs Bosons**
The Electron!

Electrons

George Johnstone Stoney
1894

Corpuscles

J. J. Thomson
1897
Early 1870’s

Hermann Sprengel

Improved mercury pump
$10^{-5}$ mBar

William Crookes
Particle sources/guns generally consist of:

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

- Positrons \( e^+ \)
- Electrons \( e^- \)
- Muons \( \mu^- \)
- Antiprotons
- Neutrinos \( \nu_e, \nu_\mu, \nu_\tau \)
- Photons
- Neutrons \( n \)
- Neutral particles
- Higgs Bosons
- Zoo of curiosities
- Tauons
- Mesons
- Baryons
- W + Z Bosons

- Light ions e.g. \( C^{4+} \)
- Highly charged ions e.g. \( Ag^{32+} \)
- Fully stripped nuclei e.g. \( U^{92+} \)
- Exotic nuclei e.g. \( Lr^{103+} \)
- Protons
- \( \mu^+ \)
- \( H^0 \)
- \( He^+ \)
- \( H^- \)
- Polarised particles
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

The “Edison effect”

1880 Thomas Edison
Thermionic Emission

Richardson’s Law

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

Same form as the Arrhenius equation

Current increases exponentially with temperature

J. J. Thomson
1897

Corpuscles

Cambridge University

1901 Owen Richardson

1901 Owen Richardson
Thermionic Emission

\[ J = A_G T^2 e^{-W/kT} \]

For a good electron emitter you need:

- Lowest possible work function
- Highest possible temperature

Work Function = a few eV

Number of Electrons

Energy

Fermi Level

Vacuum Level

Fermi-Dirac Statistics @ 0 °K

Free electrons
Cathode Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Work Function (eV)</th>
<th>Practical Operating Temperature (Kelvin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs</td>
<td>1.9 eV</td>
<td>Commonly used</td>
</tr>
<tr>
<td>BaO</td>
<td>W ≈ 1 eV</td>
<td>Ideal material (does not exist!)</td>
</tr>
<tr>
<td>CeB₆</td>
<td>W ≈ 2.5 eV</td>
<td>High brightness</td>
</tr>
<tr>
<td>LaB₆</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td>4.2 eV</td>
<td></td>
</tr>
<tr>
<td>Ta</td>
<td>4.5 eV</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>4.1 eV</td>
<td></td>
</tr>
</tbody>
</table>
Child-Langmuir Law

(Space charge limited extraction)

\[ j = \frac{4}{9} \varepsilon_0 \sqrt{\frac{2e}{m_e}} \frac{V^3}{d^2} \]
\[ I \propto \sqrt[3]{V^2} \]

**Perveance**

\[ P = \frac{I}{\sqrt[3]{V^2}} \]
Pierce Extraction
Geometry

$E_x = E_y = 0$

Ground

$\text{Cathode}$

$\text{Anode}$

$V_{\text{Cathode}}$

$67.5^\circ$

$E_x = E_y = 0$

$\text{Electron beam}$
Gridded Extraction

(A triode amplifier)
YU 171

Thermionic dispenser cathode with integrated heater and grid

Sinter of W and BaO

1 cm$^2$

12 W heater

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

Swiss Light Source
**Particles and Sources**

- **Positrons** $e^+$
- **Electrons** $e^-$
- **Thermionic**
- **Photo**
- **Muons** $\mu^+$, $\mu^-$
- **Antiprotons**
- **Neutrinos** $\nu_e$, $\nu_\mu$, $\nu_\tau$
- **Photons**
- **Neutrons** $n$
- **Neutral particles** $H^0$
- **Higgs Bosons**
- **Zoo of curiosities**
  - **Mesons**
  - **Baryons** $p$, $\bar{p}$
  - **Polarised particles**
  - **Tauons**
  - **W + Z Bosons**

**Exotic nuclei**
- e.g. $U^{92+}$
- e.g. $Lr^{103+}$

**Fully stripped nuclei**
- e.g. $C^{4+}$

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

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

**Negative ions**
- e.g. $H^-$

**Neutral particles**
- $H^0$
Photo Emission

First observed by Heinrich Hertz in 1887

Theoretical explanation by Einstein in 1905
Photo electric emission

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$_2$Te QE 10%
Cornell DC Photoemission gun

20 mA average current at 250kV

-750 kV

Diagram showing a photoemission gun with labels for 16.5 inch flange, Insulator, GaAs Cathode, Laser input, and Electron beam. Graph showing voltage vs. cathode-anode gap with data points and a trend line labeled "Cornell Cryogun."
Space charge force scales as $1/\gamma^2$.

At 500 keV electron $\gamma = 2$

(940 MeV proton $\gamma = 2$)
Another reason to use lasers is...
Lasers are so fast they can easily beat Child-Langmuir (to be fair, so can gridded extraction)

- Very short laser pulse
- Emitted current is not limited by space charge
- "Pancake" beam
RF Photemission Source

Resonant RF cavity
(normal or super conducting)

High Fields
> 10 MVm⁻¹

Photo Cathode
Cs₂Te

RF waveform

E_{Emission}

1.3 GHz
RF feed

“Pancake” beam pulses

Very short laser pulses

Laser pulse

Laser pulse

Time
Normally conducting

20 ps, 1 nC pulses (50 A pulse)

High brightness low emittance guns for FEL

Super conducting

15 ps, 1 nC pulses (67 A pulse)
Particles and Sources

- Protons
- Neutrons $n$
- Electrons $e^-$
- Muons $\mu^+$, $\mu^-$
- Antiprotons
- Positrons $e^+$
- Photon
- Higgs Bosons
- High charged ions e.g. Ag$^{32+}$
- Fully stripped nuclei e.g. U$^{92+}$
- Exotic nuclei e.g. Lr$^{103+}$
- Neutral particles $H^0$
- Tauons
- Mesons
- Baryons
- Polarised particles
- Zoon of curiosities

Thermo

Photo

Electrons $e^-$
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

Rarely used in accelerators:
Field emission from needle arrays
Diamond amplifiers
Etc...

Long cathode lifetimes
Particles and Sources

- Positrons $e^+$
- Electrons $e^-$
- Muons $\mu^-$
- Antiprotons
- Neutrinos $\nu_e$, $\nu_\mu$, $\nu_\tau$
- Photons
- Neutrons $n$
- Neutral particles $H^0$
- Higgs Bosons
- Protoons
- Muons $\mu^+$
- Antiprotons
- Exotic nuclei e.g. $Ag^{32+}$, $U^{92+}$, $Lr^{103+}$
- Light ions e.g. $C^{4+}$
- Neutral particles $H^0$
- Fully stripped nuclei e.g. $U^{92+}$
- Polarised particles
- Plasma Sources
- Tauons Mesons Baryons $W + Z$ Bosons
- Zoo of curiosities
- Mesons
- Tauons
- Baryons

Zoo of curiosities

- Polarised particles
- Plasma Sources
Plasma Pioneers

Heinrich Geißler

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

Mid 1850’s University of Bonn

Julius Plücker

magnetism could move the glow discharge
Drawing of Geissler tubes from 1860’s French physics book
Basic Plasma Properties

Density, \( n \) (per cm\(^3\))

- \( n_e \) = density of electrons
- \( n_i \) = density of ions
- \( n_n \) = density of neutrals

Charge State, \( q \)

- \( H^+ \rightarrow q = +1 \)
- \( Pb^{3+} \rightarrow q = +3 \)
- \( H^- \rightarrow q = -1 \)

Temperature, \( T \) (eV)

- \( T_e \) = temperature of electrons
- \( T_i \) = temperature of ions
- \( T_n \) = temperature of neutrals

11600°K = 1 eV
Particle Sources

RANGES OF PLASMAS

- Centre of Sun
- Metals
- Lasers
- Fusion
- Photosphere
- Chromosphere
- Flames
- Solar corona
- Magnetosphere
- Ionosphere
- Interplanetary
- Solar wind
- Interstellar
- Galactic
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
Multicusp Confinement
Most sources rely on electron impact ionisation
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

\[ \lambda_D = \sqrt{\frac{\varepsilon_0 kT_e}{n_e q_e^2}} \]
Cathode Sheath

Electrons have a greater mobility at anode potential (approximately)

Quasi neutral plasma at anode potential (approximately)

Electrons have a greater mobility

Voltage

Distance
In 1886 Eugen Goldstein discovered canal rays.
Electron Bombardment Source (1916)

Arthur Dempster

Early mass spectrometry

- Filament Power Supply: 2-10 A
- Extraction Voltage Supply: 1-10 kV
- Discharge Power Supply: 0.1-10 A
- Gas Feed
- Cathode Filament
- Anode
- Extraction Electrode
- Beam
Particles and Sources

- Positrons: $e^+$
- Electrons: $e^-$
- Neutrinos: $\nu_e, \nu_\mu, \nu_\tau$
- Photons
- Neutrons: $n$
- Antiprotons
- Protons
- Muons: $\mu^+$, $\mu^-$
- Antimuons: $\bar{\mu}$
- Antineutrons: $\bar{n}$
- Higgs Bosons
- Tauons: $\tau^+$, $\tau^-$, $\bar{\tau}$
- W and Z Bosons
- Mesons
- Baryons: $p$, $\bar{p}$
- Polarised particles
- Neutrino oscillations
- Zoo of curiosities

- Exotic nuclei: e.g. $\text{Lr}^{103+}$
- Fully stripped nuclei: e.g. $\text{U}^{92+}$
- Light ions: e.g. $\text{C}^{4+}$
- Highly charged ions: e.g. $\text{Ag}^{32+}$
- Neutral particles: $H^0$
Plasmatron (late 1940s)

Manfred von Ardenne

Filament Power Supply 2-100 A

Gas Feed

Cathode Filament

Discharge Power Supply 2-100 A

Conical Intermediate Electrode

Anode

Extraction Voltage Supply 5-50 kV

Beam

Extraction Electrode
Duoplasmatron (1956)

- **Filament Power Supply**: 2-100 A
- **Gas Feed**
- **Cathode**
- **Solenoid Field Iron Return Yoke**
- **Conical Iron Funnel Intermediate Electrode**
- **Expansion Cup**
- **Extraction Electrode**
- **Beam**
- **Defocusing Solenoid**

- **Discharge Power Supply**: 2-100 A
- **Extraction Voltage Supply**: 5-50 kV

- **Manfred von Ardenne**
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

Not including space charge effects
Space Charge

- Plasma Electrode
- Extraction Electrode
- Neutralising Particles
- Meniscus
- Percentage compensation

Optimum = slightly concave

0% - 95%
Suppressor Electrode

Plasma Electrode

Suppression Electrode

Ground Electrode

Plasma

Extracted Beam

Compensating particles reflected by the Suppression Electrode

$V$ (kV)

$Z$ (mm)
Emittance of Real Beams

Halo Effect
- Plasma boundary
- Fringe fields

How big is this beam?

95% emittance
rms emittance
Brightness

$$B = \frac{I}{\epsilon_x \epsilon_y}$$

Be careful- Some definitions include factors of 2, 8 and $\pi$
Are the emittances normalised?
Particles and Sources

- Protons $\cdot p$
- Positrons $\cdot e^+$
- Electrons $\cdot e^-$
- Muons $\cdot \mu^+$
- Muons $\cdot \mu^-$
- Antiprotons $\cdot \bar{p}$
- Neutrinos $\nu_e$ $\nu_\mu$ $\nu_\tau$
- Neutrons $\cdot n$
- Photons
- Neutral particles $\cdot H^0$
- Higgs Bosons
- Tauons
- Mesons
- Baryons

Zoo of curiosities

- Plasmatrons
- Vacuum arc
- Light ions e.g. $C^{4+}$
- Fully stripped nuclei e.g. $U^{92+}$
- Exotic nuclei e.g. $Lr^{103+}$
- Polarised particles

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

Neutral particles

W + Z Bosons
Vacuum Arc Ion Sources

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

- Positrons $e^+$
- Electrons $e^-$
- Muons $\mu^+$, $\mu^-$
- Antiprotons
- Neutrinos $\nu_e$, $\nu_\mu$, $\nu_\tau$
- Neutrons $\bar{n}$
- Photons
- Higgs Bosons
- Higgs Bosons
- Neutral particles $H^0$
- Plasmatrons
- Laser plasma
- Vacuum arc
- Protons
- Light ions e.g. $C^{4+}$
- Fully stripped nuclei e.g. $Ag^{32+}$
- Negative ions
- Exotic nuclei e.g. $Lr^{103+}$
- Polarised particles
- Other particles
- Tauons, Mesons, Baryons
- W + Z Bosons
- Zoo of curiosities
Laser Plasma Ion Sources

- Target Chamber
- Expansion Region
- Extraction Aperture
- High Voltage Insulators
- Suppressor Electrode
- Ground Electrode
- Salt Window
- ≈ 200 mm

1 -100 Joules per pulse!
ITEP Laser source at CERN
TWAC at ITEP Moscow

7 mA, 10 μs pulses of C⁴⁺

Masahiro Okamura has demonstrated Direct Plasma Injection into an RFQ
**Particles and Sources**

- **Positrons** \( e^+ \)
- **Electrons** \( e^- \)
- **Muons** \( \mu^- \)
- **Antiprotons** \( \bar{p} \)
- **Protons** \( H^- \)
- **Negative ions**

**Sources**

- **Microwave discharge**
- **Vacuum arc**
- **Laser plasma**
- **Plasmatrons**

**Fully stripped nuclei**
- \( U^{92+} \)
- \( Ag^{32+} \)
- \( Lr^{103+} \)

**Light ions**
- \( C^{4+} \)

**Highly charged ions**
- Polarised particles

**Neutral particles**
- \( H^0 \)
- \( H^- \)

**Zoo of curiosities**

- **Mesons**
- **Baryons**
- **W + Z Bosons**
- **Higgs Bosons**
- **Neutrinos** \( \nu_e \), \( \nu_\mu \), \( \nu_\tau \)

**Exotic nuclei**
- Dan Faircloth CAS 2012
Microwave Ion Sources

Off resonance

= Microwave discharge ion sources

On resonance

= Electron Cyclotron Resonance (ECR) sources
Microwave Discharge Ion Source

- Stepped RF Matching Section
- Plasma Chamber
- Solenoids
- High Voltage Insulators
- Gas Feed
- Discharge Region
- Plasma Electrode
- Suppressor Electrode
- Ground Electrode

RF in ≈ 100 mm

2.45 GHz commonly used
SILHI Microwave Source

140 mA DC protons
For one year!
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

200 $\mu$A $^{34+}$ ions
4.9 $\mu$A $^{47+}$ ions
**Particles and Sources**

- **Positrons** $e^+$
- **Electrons** $e^-$
- **Muons** $\mu^+$, $\mu^-$
- **Antiprotons** $\bar{p}$
- **Protons** $p$
- **Neutrons** $n$
- **Exotic nuclei**
- **Electron beam**
- **Positron beam** $e^+$
- **Light ions** e.g. $C^{4+}$
- **Fully stripped nuclei** e.g. $U^{92+}$
- **Highly charged ions** e.g. $Ag^{32+}$
- **Negative ions**
- **Positive ions**
- **Neutral particles** $H^0$
- **Polarised particles**
- **Zoo of curiosities**
- **Higgs Bosons**
- **Baryons** $p$, $\bar{p}$
- **Mesons**
- **Bosons** $W$, $Z$
- **Electron** $e^-$
- **Positron** $e^+$
- **Neutrinos** $\nu_e$, $\nu_\mu$, $\nu_\tau$
- **Zoo of curiosities**
- **W + Z Bosons**
- **Electron beam**
- **Exotic nuclei** e.g. $Lr^{103+}$
Electron Beam Ion Sources

- Electron Gun
- Electron Beam
- Drift Tubes
- Superconducting Solenoid
- Magnetic Shielding
- Electron Dump
- Extraction Electrode
- Ionisation Chamber
- ≈ 100 mm
- Stepwise ionisation

Diagram details:
- Drift Tube
- TubeV
- Trapping and Ionisation Phase
- Z
Electron Beam Ion Sources

- Electron Gun
- Electron Beam
- Drift Tubes
- Superconducting Solenoid
- Magnetic Shielding
- Electron Dump
- Extraction Electrode
- Ionisation Chamber
- ≈ 100 mm
- High Charge State Positive Ion Beam

Drift TubeV

Extraction Phase
1.7 emA, 10 µs, 5 Hz
Ag^{32+} ions

Fully stripped nuclei can be obtained in EBIT mode
Particles and Sources

- **Positrons** $\cdot e^+$
- **Electrons** $\cdot e^-$
- **Antiprotons**
- **Muons** $\cdot \mu^+$
- **Neutral particles** $H^0$
- **Neutrinos** $V_e\ V_\mu\ V_\tau$
- **Neutral particles** $\cdot n$
- **Photons**
- **Zoo of curiosities**
  - Higgs Bosons
  - Mesons
  - Tauons
  - W + Z Bosons

**Types of Particles**

- **Light ions** e.g. $C^{4+}$
- **Highly charged ions** e.g. $Ag^{32+}$
- **Fully stripped nuclei** e.g. $U^{92+}$
- **Exotic nuclei** e.g. $Lr^{103+}$
- **Negative ions** $H^-$
- **Polarised particles** $\vec{e}^-$
- **Surface**
- **Volume**
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
$H^-\text{has much larger cross sections than } H^0$
  Up to 30 times for $e^-\text{collisions}$
  Up to 100 times for $H^+\text{collisions}$

$H^-$ are very fragile!
Applications

Tandem accelerators

Cyclotron extraction

Neutral Beams

Multi-turn injection into rings

Stripping foil

Protons

H⁻ from Linac
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 \( e^- \)
- Muons \( \mu^- \)
- Antiprotons
- Protons
- Neutrons \( \bar{n} \)
- Photons
- Higgs Bosons
- Neutrinos \( \nu_e, \nu_\mu, \nu_\tau \)
- Surface plasma
- Negative ions
- Light ions e.g. \( C^{4+} \)
- Highly charged ions e.g. \( Ag^{32+} \)
- Fully stripped nuclei e.g. \( U^{92+} \)
- Exotic nuclei e.g. \( Lr^{103+} \)
- Polarised particles
- Neutral particles \( H^0 \)
- Exotic nuclei
- Tauons
- Mesons
- Baryons
- W + Z Bosons
- Zoo of curiosities
Early 1970s Budker Institute of Nuclear Physics
Novosibirsk
Production of H\textsuperscript{–} ions by surface ionisation with the addition of cesium

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
Caesium coverage and work function

Pure molybdenum

Work Function (eV)

Pure Caesium

Cs Thickness (monolayers)
Fermi levels
Particles and Sources

- Positrons ($e^+$)
- Electrons ($e^-$)
- Neutrinos ($\nu$)
- Photons
- Protons
- Antiprotons
- Muons ($\mu^+$, $\mu^-$)
- Mesons
- Tauons
- Polarised particles
- Baryons
- W + Z Bosons
- Higgs Bosons

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$^{103+}$

Neutral particles e.g. H$^0$

Surface plasma

Penning and Magnetron

Zoo of curiosities
Penning SPS

Very high current density > 1 A/cm²
Low noise
Piezo Hydrogen Valve

H$_2$

Hollow Anode

50 A Discharge

+17 kV extraction voltage

Negative ion beam

Caesium vapour heated transport line

Caesium oven

10mm
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

- Anode
- Cathode
- Hydrogen
- Caesium Vapour
- Extraction Electrode
- H⁻ Beam
- Electrons
- Magnetic Pole Pieces
- Beam
- Extraction Electrode
- ≈ 10 mm
80 mA of H\(^-\) but only at low duty cycles < 0.5%
Particles and Sources

- Positrons: $e^+$
- Electrons: $e^-$
- Muons: $\mu^+$, $\mu^-$
- Antiprotons
- Neutrinos: $\nu_e$, $\nu_\mu$, $\nu_\tau$
- Photons
- Neutrons: $n$
- Protons: $p$
- Antiprotons: $\bar{p}$

Highly charged ions:
- e.g. C$^{4+}$
- e.g. Ag$^{32+}$
- e.g. U$^{92+}$
- e.g. Lr$^{103+}$

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

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

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

Surface plasma

Surface converter

Multicusp

Filament

Polarised particles

Zoo of curiosities

W + Z Bosons

Baryons

Mesons

Higgs Bosons

Neutral particles

Neutral particles: $H^0$

Electrons

Negative ions

Neutral particles

Positive ions

Surfuntion converter

Surface plasma
Filament cathode multicusp surface converter source

- Surface Converter Electrode
- Heated Filament Cathode
- Multicusp Magnets
- Caesium Vapour
- Hydrogen Feed
- Outlet Aperture
- Anode
- Multicusp Magnets
- H⁻ Beam

Scales: ≈ 100 mm
LANSE Surface Converter Source

18 mA 1 ms 120 Hz H⁻ beam
**Particles and Sources**

- **Positrons** $e^+$
- **Electrons** $e^-$
- **Muons** $\mu^+$, $\mu^-$
- **Antiprotons**
- **Protons**
- **Neutral particles** $H^0$
- **Polarised particles**
- **Light ions** e.g. $C^{4+}$
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- **Fully stripped nuclei** e.g. $U^{92+}$
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- **Zoo of curiosities**
  - **Mesons**
  - **Baryons** $p$, $\bar{p}$
  - **W + Z Bosons**
  - **Higgs Bosons**
  - **Neutrinos** $\nu_e$, $\nu_\mu$, $\nu_\tau$
  - **Photons**

**Volume**
Volume Production

\[ \text{H}_2^* + e (\leq 1 \text{ eV}) \rightarrow \text{H}^- + \text{H}^0 \]

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**

- **Positrons** \(e^+\)
- **Electrons** \(e^-\)
- **Muons** \(\mu^-\)
- **Antiprotons**
- **Light ions** e.g. \(C^{4+}\)
- **Highly charged ions** e.g. \(Ag^{32+}\)
- **Fully stripped nuclei** e.g. \(U^{92+}\)
- **Exotic nuclei** e.g. \(Lr^{103+}\)
- **Polarised particles**

**Neutral particles**
- **Protons** \(H^+\)
- **Antiprotons**
- **Neutral particles** \(H^0\)
- **Electrons** \(e^-\)
- **Neutrons** \(n\)
- **Positrons** \(e^+\)
- **Muons** \(\mu^-\)

**Polarised particles**
- **Photons**
- **Neutral particles**
- **Higgs Bosons**
- **Zoo of curiosities**
- **W + Z Bosons**
- **Baryons**
- **Mesons**
- **Tauons**

**Volume**
- **Multicusp**
- **Filament**
Multicusp Filament Volume Source

Hydrogen feed

Cathode

Filament

Plasma chamber

≈ 100 mm

Multicusp magnets

Multicusp magnetics

High electron temperature plasma region

Low electron temperature plasma region

Extraction electrode

H⁻ Beam

Anode

Electron dump

Filter magnets

Section on B-B

Section on A-A
D-Pace Filament Volume Source

15 mA DC H⁻ beam
Particles and Sources

- Positrons $e^+$
- Electrons $e^-$
- Muons $\mu^+$
- Antiprotons
- Neutrinos $\nu_e, \nu_\mu, \nu_\tau$
- Photons
- Neutrons $n$
- Higgs Bosons $W^+, Z$
- Exotic nuclei e.g. $^{92+}U$
- Fully stripped nuclei e.g. $^{32+}Ag$
- Light ions e.g. $^4+C$
- Highly charged ions e.g. $^{103+}Lr$
- Neutral particles $H^0$
- Multicusp
- RF
- Volume
- Polarised particles
- Zoo of curiosities
- Tauons
- Mesons
- Baryons
- Bosons $W^+, Z$
- W + Z Bosons
Plasma chamber
Cathode
filament
Plasma chamber
≈ 100 mm
Section on A-A
Section on B-B
High electron temperature plasma region
Low electron temperature plasma region
Multicusp magnets
Filter magnets
Extraction electrode
H⁻ beam
Electrode
Anode
Electron dump
Internal RF Solenoid Antenna
Volume Source

High electron temperature plasma region

Low electron temperature plasma region

Extraction electrode

H⁻ beam

Filter magnets

Anode

Electron dump

Plasma chamber

≈ 100 mm

RF Power Supply
50 kW

Section on B-B

Multicusp magnets

Plasma chamber

Section on A-A
External RF Solenoid Antenna Volume Source

High electron temperature plasma region

Low electron temperature plasma region

Extraction electrode

H⁻ beam

Electron dump

Filter magnets

Anode

Plasma chamber

≈ 100 mm

External antenna solenoid

Plasma chamber

Section on B-B

Section on A-A

Multicusp magnets
HERA Source

Jens Peters
Late 1990’s

40 mA H^−
150 μs, 3 Hz
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+}
- Positrons \( e^+ \)
- Electrons \( e^- \)
- Neutrinos \( \nu_\mu, \nu_\tau, \nu_\tau \)
- Neutral particles \( H^0 \)
- Protons \( p \)
- Antiprotons \( \bar{p} \)
- Neutrons \( n \)
- Photons \( \gamma \)
- Positrons \( e^- \)
- Muons \( \mu^- \)
- Polarised particles
- Surface converter
- Multicusp
- RF
- Volume
- Higgs Bosons
- Zoo of curiosities
- W + Z Bosons

Baryons
Mesons
Tauons
CERN have developed a cesiated external antenna source for LINAC4

SNS ion source

60 mA H⁻¹ ms, 60 Hz
Particles and Sources

- Electrons $e^-$
- Positrons $e^+$
- Protons $p^-
- Neutrons $n^+
- Antiprotons $\bar{p}$
- Neutrinos $\nu_e, \nu_\mu, \nu_\tau$
- Antineutrinos $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$
- Higgs Bosons
- Z Bosons
- W Bosons
- Baryons
- Pions
- Mesons
- Tauons
- Photons
- Polarised particles
- Surface plasma
- Surface converter
- Penning and Magnetron
- Multicusp
- Filament and RF
- Volume
- Plasma $e^-$
- Photo
- Thermo
- Vacuum arc
- Electron Cyclotron Resonance
- Laser plasma
- Microwave discharge
- Plasmatrons
- Electron beam
- Fully stripped nuclei e.g. $U^{92+}$, $C^{4+}$, $Ag^{32+}$
- Light ions e.g. $C^{4+}$
- Rare nuclei e.g. $Lr^{103+}$
- Microwave discharge
- Tuned laser + Gas cells
- Zoo of curiosities
Polarised Electrons

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

100 μA polarised e⁻

1.6 mA 400 μs polarised H⁻
Light ions e.g. $\text{C}^{4+}$

Fully stripped nuclei

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

Vacuum arc

Laser plasma

Electron Cyclotron Resonance

Electron beam

Positrons $e^+$

Particles and Sources

Electrons $e^-$

Thermo

Plasma + other

Muons $\mu^+$ $\mu^-$

Antiprotons

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

Photons

Neutrons $\bar{n}$

Accelerator Facilities

Neutral particles

Higgs Bosons

Zoo of curiosities W + Z Bosons

Baryons

Thermo Photo

Penning and Magnetron

Surface plasma

Surface converter

Volume

Polarised particles

Tuned laser + Gas cells

Laser plasma

Laser Plasma

Microwave discharge

Microwave discharge

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

Exotic nuclei
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
Reliability also depends on:

Everything Else!

cryogenic systems
timing systems
machine interlocks
communication systems
high voltage power supplies
vacuum systems
low voltage power supplies
cooling water
compressed air supplies
temperature controllers
machine interlocks
timing systems
high voltage power supplies
control systems
mains power
personnel interlocks
human error
hydrogen
vacuum systems
compressed air supplies
control systems
cooling water
laser systems
material purity
Summary

• Particle sources are a huge interesting subject
• A perfect mixture of engineering and physics
• We have only scratched the surface
Thank you for listening
Questions?