Particle Sources - The most important part of the whole machine

Dan Faircloth
Ion Source Section Leader
Rutherford Appleton Laboratory
Positively Charged Particles

- Protons
- Light ions e.g. $C^{4+}$
- Highly charged ions e.g. $Ag^{32+}$
- Fully stripped nuclei e.g. $U^{92+}$
- Exotic nuclei e.g. $Lr^{103+}$

Negatively Charged Particles

- Electrons $e^-$
- Muons $\mu^-$
- Antiprotons
- Negative ions
- Polarised particles

Neutral Particles

- Neutrons $\bar{n}$
- Higgs Bosons
- Tauons Mesons Baryons
- W + Z Bosons

Zoo of curiosities

- Neutrinos $\nu_e \, \nu_\mu \, \nu_\tau$
- Photons
- Light ions e.g. $C^{4+}$
- Highly charged ions e.g. $Ag^{32+}$
- Fully stripped nuclei e.g. $U^{92+}$
- Exotic nuclei e.g. $Lr^{103+}$
**Particles and Sources**

- **Positrons** $e^+$
- **Electrons** $e^-$
- **Thermo**
- **Photo**
- **Negative ions**
  - $\mu^+$ Muons
  - $\mu^-$ Antimuons
- **Neutral particles**
  - $H^0$
- **Antiprotons**
- **Highly charged ions**
  - $C^{4+}$
  - $Ag^{32+}$
- **Fully stripped nuclei**
  - $U^{92+}$
  - $Lr^{103+}$
- **Vacuum arc**
- **Microwave discharge**
- **Laser plasma**
- **Microwave discharge**
- **Electron Cyclotron Resonance**
- **Plasmatrons**
- **Penning and Magnetron**
- **Surface plasma**
- **Surface converter**
- **Multicusp**
- **Filament and RF**

**Zoo of curiosities**

- **Thermo Photo Plasmas**
- **Other Penning and Magnetron**
- **Magnetron**

**Baryons**

- **Higgs Bosons** $W + Z$

**Mesons**

- **Electron Cyclotron Resonance**
- **Volume**

**Photons**

- **Neutrinos** $\nu_e \, \nu_\mu \, \nu_\tau$
- **Neutral particles** $\bar{n}$
- **Positrons** $e^+ + other$
Particles and Sources

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

Electrons

George Johnstone Stoney
1894

Corpuscles

J. J. Thomson
1897
Early 1870’s

William Crookes

Hermann Sprengel

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

Inferiority complex...
Because they’re so small!

Ion Sources
Particle sources/guns consist of:

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

- Positrons: $e^+$
- Electrons: $e^-$
- Neutrinos: $\nu_e, \nu_\mu, \nu_\tau$
- Neutrons: $n$
- Protons: $p$
- Antiprotons: $\bar{p}$
- Muons: $\mu^+$, $\mu^-$
- Antimuons: $\bar{\mu}^+$, $\bar{\mu}^-$
- Photons: $\gamma$
- Polarised particles: $\vec{e}^+$, $\vec{e}^-$
- Antitauons: $\bar{\tau}^-$
- Higgs Bosons
- Mesons
- Baryons
- zoo of curiosities

- 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: $H^0$
- Thermionic
Fredrick Guthrie
British scientific writer and professor

Elements of Heat in 1868

First experimental observation of thermionic emission
Thermionic Emission

1880 Thomas Edison

The “Edison effect”
Thermionic Emission

1880 Thomas Edison

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

For a good electron emitter you need:

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

- Lowest possible work function
- Highest possible temperature

Number of Electrons

Energy

Fermi-Level

Vacuum-Level

Work Function = a few eV

Fermi-Dirac Statistics @ 0 °K

Free electrons
Cathode Materials

Work Function (eV) vs. Practical Operating Temperature (Kelvin)

- **Cs**: 1.9 eV, Commonly used
- **BaO**: 1 eV, Commonly used
- **CeB$_6$**: W $\approx$ 2.5 eV, High brightness
- **LaB$_6$**: W $\approx$ 2.5 eV, High brightness
- **Mo**: 4.2 eV
- **Ta**: 4.5 eV
- **W**: 4.1 eV

Ideal material (does not exist!)
Child-Langmuir Law

(Space charge limited extraction)

C.D Child 1911

Irving Langmuir 1913

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

**Perveance**

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

(A triode amplifier)
Thermionic dispenser cathode with integrated heater and grid

Sinter of W and BaO

1 cm²
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
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%
- Cs₂Te  QE 10%
Cornell DC Photoemission gun

20mA average current at 250kV
Space Charge
Space charge force scales as $1/\gamma^2$.

At 500 keV electron $\gamma = 2$

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

Cathode
Cs$_2$Te
Photo Cathode

Very short Beam pulse

“Pancake” beam

Emitted current is not limited by space charge

Anode

Ground

Very short laser pulse
RF Photemission Source

Resonant RF cavity
(normal or super conducting)

High Fields
> 10 MVm⁻¹

Photo Cathode

Cs₂Te

RF waveform

Laser pulse

1.3 GHz RF feed

1.3 GHz

“Pancake” beam pulses

RF feed

Very short laser pulses
High brightness low emittance guns for FEL

- Normally conducting
  - 20 ps, 1 nC pulses (50 A pulse)
- Super conducting
  - 15 ps, 1 nC pulses (67 A pulse)
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

- Electrons $e^-$
- Positrons $e^+$
- Muons $\mu^-$
- Antiprotons
- Protons
- Neutrons $n$
- Neutrinos $\nu_e, \nu_\mu, \nu_\tau$
- Antineutrinos $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$
- Photons
- Higgs Bosons
- Exotic nuclei e.g. $^{32+}\text{Ag}$, $^{92+}\text{U}$, $^{103+}\text{Lr}$
- Polarised particles
- Fully stripped nuclei e.g. $^{4+}\text{C}$
- Light ions e.g. $^{4+}\text{C}$
- Highly charged ions e.g. $^{32+}\text{Ag}$
- Neutral particles $H^0$
- Negative ions
- Positrons $e^+$
- Antiprotons
- Neutral particles $n$
- Tauons
- Mesons
- Zoo of curiosities
- W + Z Bosons

Plasma Sources
Ionisation

Most sources rely on electron impact ionisation
Most sources rely on electron impact ionisation
Most sources rely on electron impact ionisation
Electrical Discharges

Approximate Current Range

Log I

- 100 A
- A
- μA
- nA

Voltage Between Anode and Cathode

Dark Discharge

70 V

Background Ionisation
Arc Discharge
Glow Discharge
Breakdown
Voltage

Approximate Current Range

1G A
1M A
100 A
A
µA
nA

Quark Gluon Plasma
Fusion
Z-Pinch
Thermal Arc Discharge
Arc Discharge
Glow Discharge
Dark Discharge
Townsend Breakdown
Background Ionisation

70 V
Breakdown Voltage
Voltage Between Anode and Cathode
Basic Plasma Properties

**Density, $n$ (per cm$^3$)**

- $n_e = \text{density of electrons}$
- $n_i = \text{density of ions}$
- $n_n = \text{density of neutrals}$

**Charge State, $q$**

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

**Temperature, $T$ (eV)**

- $T_e = \text{temperature of electrons}$
- $T_i = \text{temperature of ions}$
- $T_n = \text{temperature of neutrals}$

$11600^\circ K = 1 \text{ eV}$
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
Solenoid field
Dipole field
Hexapole
Multicusp Confinement
Collisions

Concept of mean free path does not work in a plasma

The average time it takes for a particle to be deflected by 90°

Charged particle trajectories are constantly affected by their neighbours electric fields

Relaxation time = 90° deflection time
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

\[ \lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e q_e^2}} \]
Plasma Sheath

Electrons have a greater mobility
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
In 1886 Eugen Goldstein discovered canal rays.
Electron Bombardment Source (1916)

- Discharge Power Supply 0.1 - 10 A
- Electron Bombardment Source (1916)
- Filament Power Supply 2-10 A
- Early mass spectrometry
- Beam
- Extraction Electrode
- Anode
- Extraction Voltage Supply 1-10 kV
- Cathode
- Filament
- Gas Feed

Arthur Dempster
**Particles and Sources**

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

**Plasmatrons**

- **Light ions** e.g. $C^{4+}$
- **Fully stripped nuclei** e.g. $U^{92+}$
- **Highly charged ions** e.g. $Ag^{32+}$
- **Exotic nuclei** e.g. $Lr^{103+}$

**Particles**

- **Protons** $p$
- **Antiprotons** $\bar{p}$
- **Negative ions** $H^-$
- **Neutral particles** $H^0$

**Sources**

- **Neutral particles**
- **Exotic nuclei**
- **Negative ions**
Plasmatron (late 1940s)

- Filament Power Supply 2-100 A
- Gas Feed
- Cathode
- Conical Intermediate Electrode
- Anode
- Extraction Electrode
- Extraction Voltage Supply 5-50 kV
- Beam
- Discharge Power Supply 2-100 A

Manfred von Ardenne
Duoplasmatron (1956)

- **Filament Power Supply**: 2-100 A
- **Cathode Filament**
- **Gas Feed**
- **Solenoid Field Iron**
- **Return Yoke**
- **Anode**
- **Cone Iron Funnel**
- **Intermediate Electrode**
- **Expansion Cup**
- **Extraction Electrode**
- **Defocusing Solenoid**
- **Beam**
- **Discharge Power Supply**: 2-100 A
- **Extraction Voltage Supply**: 5-50 kV
300 mA protons
150 μs pulses at 1 Hz
Particle sources/guns consist of:

- Something to make the particles
- An extraction system to create and accelerate a beam

The emission surface is critical to the quality of the beam
Plasma Mencius

Convex

Flat

Concave

Not including space charge effects
Space Charge

Optimum = slightly concave

Percentage compensation

≈ 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

\[ B = \frac{I}{\varepsilon_x \varepsilon_y} \]

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

- Protons ($p$)
- Electrons ($e^-$)
- Muons ($\mu^+$)
- Antiprotons ($\bar{p}$)
- Neutrons ($n$)
- Positrons ($e^+$)
- Neutrinos ($\nu_e$, $\nu_\mu$, $\nu_\tau$)
- Photons
- Higgs Bosons
- Higgs Bosons ($W + Z$)
- Tauons
- Mesons
- Baryons

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

Highly charged ions e.g. $C^{4+}$, $Ag^{32+}$

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

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

Microwave
Microwave Ion Sources

Off resonance
= Microwave discharge ion sources

On resonance
= Electron Cyclotron Resonance (ECR) sources
**Particles and Sources**

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

**Microwave discharge**

**Plasmatrons**
Microwave Discharge Ion Source

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

RF in $\approx 100$ mm

2.45 GHz commonly used
SILHI Microwave Source

Rafael Gobin
CEA Saclay
Late 1990s

140 mA DC protons
For one year!
Sophisticated Extraction System
Particles and Sources

- Positrons: $e^+$
- Electrons: $e^-$
- Muons: $\mu^+$, $\mu^-$
- Antiprotons
- Neutrinos: $\nu_e$, $\nu_\mu$, $\nu_\tau$
- Photons
- Neutrons: $n$
- Protons
- Antiprotons
- Neutral particles: $H^0$
- Fully stripped nuclei: e.g. Ag$^{32+}$, U$^{92+}$
- Light ions: e.g. C$^{4+}$
- Highly charged ions
- Vacuum arc
- Microwave discharge
- Plasmatrons
- Exotic nuclei: e.g. Lr$^{103+}$

Zoo of curiosities

- Polarised particles
- Baryons
- Mesons
- Tauons
- Higgs Bosons
- W + Z Bosons

Dan Faircloth CAS 2012
Vacuum Arc Ion Sources

1980s - Ian Brown and others
Lawrence Berkley Lab
MEVVA

GSI MEVVA

15 mA of $U^{4+}$ ions
**Particles and Sources**

- **Positrons** $e^+$
- **Electrons** $e^-$
- **Muons** $\mu^+$, $\mu^-$
- **Antiprotons** $\bar{p}$
- **Protons** $p$
- **Neutrons** $n$
- **Electrons** $e^-$
- **Neutrons** $\bar{n}$
- **Muons** $\mu^+$, $\mu^-$
- **Antiprotons** $\bar{p}$
- **Protons** $p$
- **Neutrons** $n$
- **Electrons** $e^-$
- **Neutrons** $\bar{n}$
- **Protons** $p$
- **Neutrons** $n$
- **Neutral particles** $H^0$
- **Photons** $\gamma$
- **Neutrinos** $\nu_e$, $\nu_\mu$, $\nu_\tau$
- **Zoo of curiosities**

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

**Exotic nuclei**

**Sources**
- Plasmatrons
- Microwave discharge
- Vacuum arc
- Laser plasma
Laser Plasma Ion Sources

Target Chamber

Laser Plasma Ion Sources

Expansion Region

Extraction Aperture

High Voltage Insulators

Suppressor Electrode

Ground Electrode

Beam

≈ 200 mm

Salt Window

Target Rotation Mechanism

Laser Beam

Focusing Optics

High Power Laser

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

Very Recently

Masahiro Okamura, BNL and RIKEN demonstrated Direct Plasma Injection into an RFQ

7 mA, 10 μs pulses of C⁴⁺
Light ions e.g. $\text{C}^{4+}$

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

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

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

Electron Cyclotron Resonance

Positrons $e^+$

Electrons $e^-$

Muons $\mu^-$

Antiprotons

Neutral particles $\text{H}^0$

Polarised particles

Electrons $\bar{\nu}_e$

Neutrons $\nu_e$

Negative ions

Protons

Higgs Bosons

Mesons

Baryons

Zoo of curiosities

W + Z Bosons

Dan Faircloth CAS 2012
ECR Surface

\[ \omega_{ECR} = 2\pi f_{ECR} = \frac{eB}{m} \]
28 GHz superconducting VENUS ECR

Daniela Leitner
LBNL
Late 2000s

200 eμA U^{34+} ions
4.9 eμA U^{47+} ions
Particles and Sources

- Positrons $\cdot e^+$
- Electrons $\cdot e^-$
- Muons $\cdot \mu^+$
- Antiprotons
- Neutrinos $\nu_e, \nu_\mu, \nu_\tau$
- Neutrons $\cdot n$
- Higgs Bosons
- Photons
- Neutral particles $\cdot H^0$
- Exotic nuclei
  - e.g. $Ag^{32+}$
  - e.g. $U^{92+}$
- Highly charged ions
  - e.g. $C^{4+}$
- Fully stripped nuclei
  - e.g. $U^{92+}$
- Light ions
  - e.g. $C^{4+}$
- Electron beam
- Polarised particles
- Muons $\cdot \mu^-$
- Negative ions
- Protons $\cdot \pi^+$
- Positrons $\cdot e^+$
- Neutral particles $\cdot H^0$
- Electron $\cdot e^-$
- Neutrons $\cdot n$
- Exotic nuclei
  - e.g. $Lr^{103+}$
- Tauons
- Mesons
- Baryons
- W + Z Bosons

Dan Faircloth CAS 2012
Electron Beam Ion Sources

- Electron Gun
- Electron Beam
- Drift Tubes
- Superconducting Solenoid
- Magnetic Shielding
- Electron Dump
- Extraction Electrode
- Ionisation Chamber
- ≈ 100 mm
- Drift Tube $V$
- Trapping and Ionisation Phase
- Stepwise ionisation
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 $e^-$
- Muons $\mu^+$
- Antiprotons
- Protons
- Neutrons $n$
- Protons
- Antiprotons
- Muons $\mu^-$
- Neutrons $n$
- Photons
- Neutrinos $V_e$, $V_\mu$, $V_\tau$

- Light ions e.g. $C^{4+}$
- Exotic nuclei e.g. $U^{92+}$
- Fully stripped nuclei e.g. $U^{92+}$
- High charged ions e.g. $Ag^{32+}$
- Exotic nuclei e.g. $Lr^{103+}$
- Polarised particles
- Higgs Bosons
- Tauons
- Mesons
- Baryons
- Zoo of curiosities
- $W + Z$ Bosons

Dan Faircloth CAS 2012
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 a much larger cross section than H0
  30 times for e− collisions
  100 times for H+ collisions

H− are very fragile!
Applications

Tandem accelerators
- gradient rings
- positive high-voltage terminal
- charging chain
- magnet
- steel pressure tank
- stripping chamber
- accelerating tube
- positive ions
- beam steering magnet
- target

Cyclotron extraction
- H⁻ ion
- Source
- Ion beam
- Beam extractor
- Stripping foil
- Proton beam

Neutral Beams
- Beam Generation
- Beam Neutralization
- Beam Transport
- Calorimeter
- Ion Source
- Neutralizer
- Acceleration Grids
- High Speed Vacuum Pump
- Ion Dump
- Plasma
- Magnet Coil

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
Off Axis Duoplasmatron Extraction

Displacement

1960’s George Lawrence
Los Alamos
Off Axis Duoplasmatron Extraction

![Graph showing electron and H⁻ current as a function of displacement (mm). The graph has two curves: one for electron current (dashed line) and one for H⁻ current (solid line). The x-axis represents displacement in mm, and the y-axis represents current in mA for electron current and μA for H⁻ current.]
Negative Ion Extraction

Electrons will also be extracted
Up to 1000 times the $\text{H}^-$ current!
Use a magnetic field
Dump must be properly designed

Best sources:
only 0.5 times $\text{H}^-$ current
Particles and Sources

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

Dan Faircloth CAS 2012
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
5 g Caesium Ampoule
Fermi levels
Control caesium oven temperature to vary caesium vapour pressure to control caesium coverage.
Light ions
  e.g. C^{4+}

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

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

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

Protons

Muons
  \( \mu^- \)

Antiprotons

Electrons
  \( e^- \)

Positrons
  \( e^+ \)

Polarised particles

Neutral particles
  \( H^0 \)

Higgs Bosons

Zoo of curiosities

Mesons

Tauons

W + Z Bosons

Surface plasma

Penning and Magnetron

Dan Faircloth CAS 2012
Magnetron Source

- Anode
- Cathode
- Hydrogen
- Caesium Vapour
- Extraction Electrode
- $H^- \text{ Beam}$
- Electrons
- $\approx 10 \text{ mm}$
- Magnetic Pole Pieces
80 mA of H\textsuperscript{−} but only at low duty cycles < 0.5%
Penning SPS Ion Sources

• Invented by Dudnikov in the 1970’s
• Very high current density > 1 A cm$^{-2}$
• Low noise
• Does not work without cesium
Negative Ion Beam

Piezo Hydrogen Valve

Caesium Oven

Caesium Vapour

Heated Transport Line

Hollow Anode

50 A Discharge

Source Runs at 50 Hz Rep Rate

10mm

$H_2$

+17 kV Extraction Voltage

Piezo Hydrogen Valve

50 Hz Rep Rate
Aperture Plate
Electrode Support Insulators Caesium Shields

Extraction Mount

Extraction Electrode

Support Insulators

Caesium Shields

ISIS Ion Source

60 mA 2 ms 50 Hz H⁻ beams
Light ions e.g. \( \text{C}^{4+} \)

Fully stripped nuclei e.g. \( \text{U}^{92+} \)

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

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

Positrons \( e^+ \)

Electrons \( e^- \)

Muons \( \mu^+ \)

Antiprotons

Neutral particles \( \text{H}^0 \)

Photons

Neutrinos \( V_e, V_\mu, V_\tau \)

Neutral particles \( \bar{n} \)

Protons

Muons \( \mu^- \)

Antiprotons

Polarised particles

Zoo of curiosities

W + Z Bosons

Baryons

Polarised

Surface plasma

Surface converter

Multicusp

Filament
Filament Cathode Multicusp Surface Converter Source

Surface Converter Electrode
-300 V

Heated Filament Cathode

Hydrogen Feed

Outlet Aperture

H⁻ Beam

Anode

Caesium Vapour

Multicusp Magnets

≈ 100 mm
LANL with multiple filaments:
1 A of H⁻
Particles and Sources

- Protons $\cdot p$
- Electrons $\cdot e^-$
- Muons $\cdot \mu^-$
- Antiprotons
- Positive 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. $Lr^{103+}$
- Neutrons $\cdot n$
- Neutral particles
- Photons
- Neutrinos $\nu_e \nu_\mu \nu_\tau$
- Higgs Bosons
- Zoo of curiosities
- Tauons
- Mesons
- Baryons
- Polarised particles
- $W + Z$ Bosons
- Dan Faircloth CAS 2012

Volume
Volume Production

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

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

Developed by Ehlers + Leung at LBNL

Marthe Bacal
Ecole Polytechnique
mid 1970’s
Multicusp Filament Volume Source

Many Variations: e.g. JPARC use a LaB$_6$ cathode

Multicusp magnets
Hydrogen feed
Cathode
Filament
Plasma chamber

≈ 100 mm

Multicusp magnets

High electron temperature plasma region
Low electron temperature plasma region

Electron dump
Extraction electrode

H⁻ Beam

Section on A-A

Section on B-B
D-Pace 15 mA DC H⁻ Multicusp Volume Source
**Particles and Sources**

- **Protons** \(p\)
- **Electrons** \(e^-\)
- **Positrons** \(e^+\)
- **Muons** \(\mu^-\)
- **Antiprotons**
- **Neutrons** \(n\)
- **Neutrinos** \(\nu\)
- **Photons**
- **Mesons**
- **Baryons**
- **Higgs Bosons**
- **W + Z Bosons**

**Highly charged ions**
- e.g. \(Ag^{32+}\)
- e.g. \(U^{92+}\)
- e.g. \(Lr^{103+}\)

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

**Fully stripped nuclei**
- e.g. \(U^{92+}\)

**Exotic nuclei**

**Zoo of curiosities**

**Multicusp**

**RF**

**Volume**
Internal RF Solenoid Antenna Volume Source

- **RF Power Supply**: 50 kW
- **Plasma chamber**: ≈ 100 mm
- **High electron temperature plasma region**
- **Low electron temperature plasma region**
- **Extraction electrode**
- **H^- beam**
- **Filter magnets**
- **Anode**
- **Electron dump**
- **Multicusp magnets**
- **Section on A-A**
- **Section on B-B**
SNS ion source

38 mA H⁻¹ ms, 60 Hz
External RF Antenna Multicusp Source

- Multicusp magnets
- External antenna solenoid
- Filter magnets
- Extraction electrode
- H⁻ Beam
- Electron dump
- Ceramic plasma chamber
- Extraction electrode
- Filter magnets
- External Antenna solenoid
- Multicusp magnets
- Ignition anode
- Pulsed hydrogen
- Ignition element
- Ceramic plasma chamber

≈ 100 mm

Section on B-B

Section on A-A
DESY Source

Jens Peters
Late 1990's

40 mA H⁻
150 μs, 3 Hz
Which Source?

- Type of particle
- Current, duty cycle, emittance
- Lifetime
- Expertise available
- Money available
- Space available
Reliability – is King!

- 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

low voltage power supplies  
cooling water  
compressed air supplies  
control systems

human error  
hydrogen  
vacuum systems

temperature controllers  
high voltage power supplies  
material purity

mains power  
personnel interlocks  
laser systems
Developing Sources

Driven by demand for

– Increases in current, duty cycle and lifetime
– Improvements in beam quality

Development strategy

• Simulations
• Test stands
• Diagnostics
The Development Cycle

- Hardware
- Experiments
- Simulations
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