Ion sources and highly charged ions

Timothy Bartesch
Overview

1. Basics
2. Ion Sources
3. Applications
4. Summary
Quintessential Ion source

- 3 basic parts
- difference - plasma source and ion source
- extractor - a word of historical origin
Characteristics of an ion source are determined by the plasma and the extractor.

**ion beam current**
- det. plasma density, plasma electron temperature,
- extractor voltage, extractor geometry

**beam emittance**
- det. plasma density distribution, plasma ion temperature,
- extractor geometry

**beam composition**
- composition of the plasma
What is plasma?

- fourth state of matter (particle energie)
  → solid → liquid → gaseous → plasma
- consists of electrons, ions and neutrals
- plasma density --- multiple charged ions → plasma electron density
- laboratory plasma \(10^8 - 10^{16}\) 1/ cm³
  room temperature gas \(~3.3\times10^{12}\) 1/ cm³
- plasma temperature \(1\text{eV} = 11600\text{K}\)
  diff. temperatures for electrons, ions, neutrals and magnetic fields likely
Extraction System

Child-Langmuir law

\[ j_{cl} = \frac{4}{9} \varepsilon_0 \sqrt{\frac{2eQ}{m}} \frac{1}{d^2} U_{N_0} \]

- emission area planar
- ions zero initial longitudinal energy

\[ I_{cl} = \frac{4}{9} \pi r^2 \varepsilon_0 \sqrt{\frac{2eQ}{m}} \frac{1}{d^2} U_{N_0} \]

- cylindrically-symmetric extraction system

(extracted ion beam current limited by space-charge forces – not emission)
Extraction System

same extraction voltage for different plasma densities $N_1 < N_2 < N_3$

- distance $d^*$ adjusts so the electric field strength at the meniscus is zero
- emitting area changes (concave $\rightarrow$ convex) $\Rightarrow$ extracted current changes
- case II most important for many applications
Energy of the beam is independent of the extractor voltage $\Rightarrow V_{ps} = V_{extr}$

$E = eQ (V_{extr} - V_{ch})$ (ions $Q^+$)

backflow suppression

space charge compensation
Elemental ion source:

- $V_{\text{extr}}$ determines ion energy
- plasma source electronics must be biased at the extraction voltage
- suppressor voltage might be at 10% of the extr. voltage
- 3rd electrode at the same potential as the space into which the ion beam is injected
Different kinds of ion sources

- *Electron Bombardement Ion Sources*
- *Radio-Frequency Driven Ion Sources*
- Microwave Ion Sources
- ECR Ion Sources
- Laser Ion Sources
- Vacuum Arc Ion Sources
- Negative Ion Sources
- *Ion Sources for Heavy Ion Fusion*
RF Ion Source

- 1940: using rf voltage to create a plasma
- can operate with any type of background gas (f.e. oxygen which can easily poison tungsten filament cathodes [wolfram heizdraht kathoden])
- useful for long-life operation and clean plasma production
- used by the semiconductor industry and as H⁻ ion sources in many particle accelerator systems
working principle

- electrons oscillate plasma
- external RF coil
- four (not independent) external variables which affect the resulting ion beam
  - gas pressure
  - rf field
  - external magnetic field
  - extraction voltage

inductively coupled RF source

(Thonemann type)
Typical operating parameters

- $10^{-3}$ Torr $\sim 10^{-6}$ atm
- rf power 350W
- oscillator frequency 13MHz
- extraction voltage 3kV
- magnetic field 4mT
- estimated ion density $10^{11}$ 1/cm³
Bernas Ion Source

- economically viable → fully automated ion implanter
  → ion source has to have repeatable characteristics (lab sources normally don’t)

- examples of economic viable ion sources are Bernas and Freeman type sources extensively used for ion implantation (doping wavers in the process of semiconductor manufacture)

- developed by Bernas 1958
- first used in the early 1970s by Gamma Industries – fully accepted for commercial implantation after modification and used by Nova Associates in 1982
• additional electrode (reflector) 
oszillation $\rightarrow$ more efficient ionisation

• directly heated tungsten filament 
(helix instead of hairpin)

• lifetime limited by sputtering 
(especially of the filament)

• filament has a strong magnetic field 
which affects the plasma 
(and is hard to shape correctly)

$\rightarrow$ indirectly heated cathode as improvement (see next slide)
indirectly heated cathode

emitting surface thick enough for long lifetime

more reproducible

Replacement of one source with another is possible while still achieving almost identical performance

slit ~40mm X ~3.5mm
EBIT (electron beam ion trap)

- produces, traps and excites very highly charged ions
- ions - observed or extracted
- in 1994 bare Uranium (U^{+92}) at LLNL (Super-EBIT)
- highly charged ions at rest

- high current density electron beam (up to 5000 A/cm²)
- electron beam starts with a diameter of ~1mm and is then compressed to 100 micrometers by a 3T axial magnetic field provided by a pair of superconduction helmholz coils
EBIT (electron beam ion trap)

- ions are trapped radially and axially
- electrons are stripped of until $E_n > E_{beam}$
- electron – ion interactions produce x-rays
- cooling via new low Z-gas ions
- trapping times of several hours have been observed
Applications

• highly charged ions
  – tumor therapy
  – possible observation of bound-state beta decay
• ion sources
  – sputtering (mass spectroscopy / thin-film deposition)
  – ion implementation
  – fusion
    • giant ion sources for neutral beams (tokamak)
    • ion sources for heavy ion fusion
Fusion

- **magnetic confinement**
doughnut shaped reactors
fuel – very hot plasma
very-high-energy neutral beams

- **inertial confinement**
ion beams or lasers as “drivers“ to ignite a D-T fusion target
present mainline research is to use high power laser beams
Heavy Ion Fusion (inertial confinement fusion concept)
requirements for the driver

- 5mm diameter target requires ~3-7MJ beam energy/ pulse length 10ns

- for heavy ions with atomic mass 200 – kin energy <10GeV + beam charge 1mC needed (lighter ions: less kin. energy but more current (or charge))

- total current therefore ~100kA → high current device
  - Europeans use storage rings
  - In the USA induction linacs are used
HIF induction linacs

- Ion source
- ESQ
- Acceleration with magnetic focusing
- Target focusing

- ~1A/beam
- ~12A/beam
- ~600A/beam
- ~6kA/beam
- ~10^{-5}s
- ~4 * 10^{-6}s
- ~100ns
- ~10ns
4. Summary

- basic ion source working principle
- discussion of two present ion sources
- a source for highly stripped ions
- application: heavy ion fusion
References

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