Development of cold cathode ion source

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Outline

• Introduction
• Vacuum
• Gas discharge
• Ion beam
• Experimental set up
• Results
• Summary
Introduction
What is ion source

- Ion source is a device that makes ion beam
- Components:
  plasma source, ion extraction system, beam transport

The Physics and Technology of Ion Sources, Ian G. Brown, ISBN 3-527-40410-4
applications

• Ion implantation
• Neutron generator
• Accelerators
• Mass spectrometers
• Ion engines
• Focused Ion Beam (FIB) Microscopy
Ion implantation

• Electronic devices and materials
• Change optical, electrical and etc. of surface properties

Neutron generator

• Non destructive testing
• BNCT (boron neutron cancer therapy)

http://www.qsl.net/k/k0ff/7Manalgs/Neutron%20Reflection/Compact%20accelerator%20neutron%20generators%20-%20The%20Industrial%20Physicist.htm
Mass spectrometers

http://www.esrl.noaa.gov/gmd/outreach/isotopes/mass_spec.html
Ion engine

Focused Ion Beam (FIB) Microscopy

http://www.si.edu/mci/EarlyPhotography/fib.html
Different kind of ion sources

• Based on their electric power source, magnetic field, temperature of cathode, other characteristic of ion source component
• Ion beam diameter, extraction of ion beam, One or more holes or grid
• Hot cathode, cold cathode, radio frequency and ...
Penning ion source

- Advantages:
  Simple, long-life cathodes, compact, produced different ion beams from different gases, low voltage power supply

http://article.sapub.org/image/10.5923.j.instrument.20120105.02_029.gif
Vacuum
What is Vacuum

- Pressure lower than atmospheric pressure or number density of particles lower than atmospheric number density of particles
  1. low vacuum - atmospheric pressure to 1 mbar
  2. medium vacuum - 1 mbar to $10^{-3}$ mbar
  3. high vacuum - $10^{-3}$ mbar to $10^{-8}$ mbar
  4. ultra-high vacuum - $10^{-8}$ mbar to $10^{-12}$ mbar
  5. extreme high vacuum - less than $10^{-12}$ mbar

1 millibar = 100 pascals = 0.000986923267 atmosphere = 0.750061683 torr
Vacuum Generation

- We used two pumps
  - Rotary vane pumps

Fundamentals of Vacuum Technology Walter Umrath, 1998
Vacuum Generation

- And (Oil) Diffusion pumps

Fundamentals of Vacuum Technology
Walter Umrath, 1998
Vacuum measurement

• Direct and indirect measurement
• Direct or absolute vacuum gauges: pressure as the force which acts on an area
• Indirect pressure measurement: pressure is determined as a function of a pressure dependent (density dependent) property (thermal conductivity, ionization probability, electrical conductivity) of the gas
Pirani vacuum gauge

![Diagram of Pirani vacuum gauge]

- **I.** Thermal dissipation due to radiation and conduction in the metallic ends
- **II.** Thermal dissipation due to radiation and convection
- **III.** Thermal dissipation due to the gas, pressure-dependent

Fundamentals of Vacuum Technology Walter Umrath, 1998

[http://bama.ua.edu/~surfspec/vacbasics.htm](http://bama.ua.edu/~surfspec/vacbasics.htm)
Vacuum

\[ Q = C(P_1 - P_2) \]

\[ C = C_1 + C_2 + \ldots \]

\[ \frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots \]
Vacuum

\[ C_0 = \sqrt{\frac{RT}{2\pi M}} A \]

- Pipe

\[ C_{\text{pipe}} = \alpha C_0 \]

\[ \alpha = \frac{1}{1 + \frac{3L}{4D}} \]
Gas discharge
Causes of gas discharge

- Impact of high energy electrons with particles
- Impact of ions with particles
- Photo ionization
- Contact or surface ionization
- Secondary electrons
Gas discharge in constant electric field

• Paschen's law and Townsend theory of ionization

\[ V_b = \frac{B' pd}{\ln(A' pd) - \ln M_d} = f(pd) \]

Townsend theory of ionization

• Each electron produces $\alpha$ electron-ion pairs per length unit
• $N$ electrons after $dx$ length propagation produced $dN$ electron-ion pairs with

$$dN = N(x) \alpha dx$$

• current multiplication factor $\eta$

$$\eta = \frac{N_a}{N_0} = \frac{i_a}{i_0} = e^{\alpha d}$$
Townsend theory of ionization

- Townsend’s first coefficient

\[ \alpha = nAe \left( -\frac{B}{E} \right) \]

- Each ion produces \( \gamma_j \) secondary electrons

\[ \gamma_j (e^{\alpha d} - 1) = k \]

- \( ke^{\alpha d} \) electrons reach the anode
Townsend theory of ionization

- \( k \gamma_j (e^{\alpha d} - 1) = k^2 \) electrons are produced
- In n’t level \( n_e \) electrons are produced
  \[
  n_e = e^{\alpha d} (1 + k + k^2 + ...) = e^{\alpha d} \frac{1 - k^n}{1 - k}
  \]
- If \( k < 1 \)
  \[
  \lim_{n \to \infty} \frac{1 - k^n}{1 - k} = \frac{1}{1 - k}
  \]
- current multiplication factor \( \eta \)
  \[
  \eta = \frac{e^{\alpha d}}{1 - \gamma_j (e^{\alpha d} - 1)}
  \]
Townsend theory of ionization

\[ \alpha d = \frac{p}{E} V_b = A' p d e^{-B' pd / V_b} = \ln(1 + \frac{1}{\gamma}) = M_d \]

\[ A' = \frac{A n}{p}, \quad B' = \frac{B n}{p} \]

• Paschen's law

\[ V_b = \frac{B' pd}{\ln(A' pd) - \ln M_d} = f(pd) \]
Paschen's curve

Ion Beam
Production and acceleration of beam

- Ion beam produced via extractor
- Ion beam transport, accelerate and focused or converge via electrostatic lenses
- Mass and charged selection aperture: two different electric and magnetic fields produced parallel and opposite electric and magnetic forces that cause selection one kind of ion beam
Ion beam properties

- Beam current, beam energy, energy spectrum, beam emittance:

$$\varepsilon_{\text{rms}} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

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Simulation

• SIMION Ion and Electron Optics Simulator
• Computational Fluid Dynamics (CFD)
• COMSOL Multiphysics + MATLAB

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Experimental set up
Penning ion source
Cathode, anode and anti cathode of penning ion source
Penning trap

L. Bartha, "Positive ion source"
Electric potential of penning source simulated with COMSOL
Electric potential of penning source simulated with COMSOL
Magnetic field coil

- Space limitations
- Wire limit \( d = \sqrt{\frac{I}{2}} \)
- Magnetic field does not depend on wire diameter

\[
\begin{align*}
l &= kd \\
h &= md \\
N &= mk \\
d &= a\sqrt{i}
\end{align*}
\]

\[
\begin{align*}
h &= md = \frac{N}{k} d = \frac{N}{l} d^2 = \frac{N}{l} a^2 i
\end{align*}
\]
Magnetic field coil

\[ B = \mu_0 n I \]

\[ n = \frac{N}{l} \]

\[ h = \frac{N}{l} \frac{a^2 B_{\text{max}}}{\mu_0 n} = \frac{a^2 B_{\text{max}}}{\mu_0} \]

\[ B_{\text{max}} = \frac{\mu_0 h}{a^2} \]
simulation of magnetic field with COMSOL

\[ i = 3A \]
Calibration of magnetic field
Circuits of plasma and ion extraction

- Diode bridge


- Simulation with PSpice (Personal Simulated Program with Integrated Circuit Emphasis)
acceleration

• Cockroft-Walton generator

Results
Plasma current dependence to voltage

\[ I = 700 \times 10^{-2} \text{ mbar} \]

\[ R_{pl} = 500 \text{ k}\Omega \]

\[ B = 700 \text{ gauss} \]

\[ \Delta I = 0.001 \text{ mA} \]
Dependence of discharge current to magnetic field in different voltages

\[ P = 1.7 \times 10^{-2} \text{ mbar} \quad R_{\text{pl}} = 500 \text{ k}\Omega \quad \Delta I = 0.001 \text{ mA} \]
Dependence of breakdown voltage to magnetic field

\[ P = 1.7 \times 10^{-2} \text{ mbar} \quad R_{pl} = 500 \text{ k}\Omega \]
Production of oxygen ion beam

\[ P = 4 \times 10^{-2} \text{ mbar} \quad B = 425 \text{ gauss} \quad V_{pl} = 1500 \text{ V} \]
\[ D = 1.5 \text{ mm} \quad R_{pl} = 500 \text{ k}\Omega \quad i_{pl} = 1 \text{ mA} \]
\[ h = 1.5 \text{ mm} \quad R_{ext} = 280 \text{ k}\Omega \quad \Delta I_{ext} = 20 \text{ nA} \]
Production of oxygen ion beam

\[ P = 4 \times 10^{-2} \text{ mbar} \quad B = 498 \text{ gauss} \quad V_{pl} = 2000 \text{ V} \]
\[ D = 2 \text{ mm} \quad R_{pl} = 500 \text{ k}\Omega \quad i_{pl} = 1 \text{ mA} \]
\[ h = 2 \text{ mm} \quad R_{ext} = 40 \text{ k}\Omega \quad \Delta I_{ext} = 25 \text{ nA} \]
Production of argon ion beam

\[ P = 4 \times 10^{-2} \text{ mbar} \quad B = 560 \text{ gauss} \quad V_{pl} = 3000 \text{ V} \]

\[ D = 2 \text{ mm} \quad R_{pl} = 500 \text{ k}\Omega \quad i_{pl} = 1 \text{ mA} \]

\[ h = 2 \text{ mm} \quad R_{ext} = 48.3 \text{ k}\Omega \quad \Delta I_{ext} = 20 \text{ nA} \]
Other works

- Measurement of ion beam properties
- Production of helium and nitrogen beam
- Mass and charged selection aperture
- Production 100 KeV ion beam
Summary
Summary

• Ion source, components, applications
• Vacuum and gas discharge
• Ion beam
• Penning ion source
• Results
Thanks for your attention