Ion sources

• Types of ion sources

• Sources of negative ions
• Discharge sources
• Laser ion sources
• Field emission ion sources

• Sources of highly charged ions: ECR, EBIS, EBIT
Negative ion sources

- Cs vapor from an oven fills an enclosed volume between the cooled cathode and the heated ionizing surface; some vapor condenses on the cathode surface.
- Cesium atoms are ionized by the hot surface.
- Cs ions are accelerated towards the cathode, sputtering it.

Some materials will preferentially sputter negative ions; others, neutral or positive particles which pick up electrons as they pass through the condensed Cs layer / vapor, producing negative ions.
Plasma ion source

- Can produce both positive and negative ions and large emission currents (up to mA), but mostly singly charged ions.

Electrons start discharge.
The ion current depends on the plasma density. Constricting the discharge with a magnetic field increases:

- the plasma density,
- the potential difference across the restriction
- the energy of the ionizing electrons.

Plasma escapes through a small aperture in the anode and expands. Ions are extracted afterwards.
Radiofrequency, electrodeless discharge source

- no contamination due to electrode material
- higher stability
Inductively coupled plasma (ICP)

Applications
• optical emission spectroscopy (ICP-OES): Emission lines are observed and analyzed
• mass spectroscopy (ICP-MS): the masses of the ions produced are measured
Laser ion sources

CERN - High Current Laser Ion Source

CO₂ Amplifier
100 J, 1Hz, 15ns

CO₂ Oscillator
150 mJ, 3Hz

Target

Expanding plasma

Extraction system
120 kV

LEBT
Graded Electrostatic Lenses

Double aperture
simulating the RFQ acceptance

Emittance
Current
Charge State Distribution
Current Emittance
Measurements
Principle of ablation laser ion sources

10 ns
20 mJ

Laser
Linse

Plasma

Plasma burst
Plasma expansion and thinning
charge separation
ion extraction and guiding
Field emission: Fowler-Nordheim law

§ 2. The Potential Barrier at the Surface

The Fowler-Nordheim law for the emitted current density $J$ in amp cm$^{-2}$ can be written in the form (Sommerfeld and Bethe 1933)

$$J = 1.55 \times 10^{-6} \frac{E^2}{\phi} \exp \left[ -6.85 \times 10^7 \phi^{3/2} f(y) \frac{v}{E} \right]$$

in which $E$ is the electric field in $\text{V cm}^{-1}$, $\phi$ is the work function of the emitter in $\text{eV}$ and $f(y)$ is a function dependent on the image law, originally calculated by Nordheim (1928) and recently corrected by Burgess, Kroemer and Houston (1953). Equation (1) has been established on the assumptions that it is legitimate.
Formation of the Taylor cone

Electrostatic forces deform the liquid surface and produce an „atomically“ sharp tip (Taylor cone).

Simulation of time evolution of the tip shape
Electrospray molecular sources

- Liquid flows through a needle at high voltage relative to a nearby surface.
- The electric field at the tip causes the liquid to be “fissioned” into fine electrically charged droplets.
- Ionization results from desorption of ions from them.
- Ions from delicate organic molecules can be prepared.
Sources of highly charged ions

Motivation: Atomic physics in very strong fields

Methods of ionization

Sources of highly charged ions:
• Electron cyclotron resonance ions sources (ECRIS)
• Electron beam ion sources (EBIS)
• Electron beam ion traps (EBIT)
Physics of highly charged ions

- Relativistic effects grow with $Z^4$,
- Quantum electrodynamics (QED) also scales with $Z^4$

Series expansion in non-perturbative QED: coupling constant $Z \alpha \approx 1$

Many virtual photons, each interaction $Z \times$ stronger than in H

- Highly charged ions reduce the many-electron contributions while scaling up QED and relativistic effects.
- Few-particle QED is still nearly unexplored
- Nuclear size effects strongly influence electronic structure
Physics of highly charged ions

Highly charged ions are strongly affected by relativistic and QED effects.

Schrödinger:
- \( E_n = R_y \cdot Z^2/n^2 \)
  - \( n=1 \):
    - \( s_{1/2}, p_{1/2} \)
    - \( 115 \text{ keV} \)
  - \( n=2 \):
    - \( s_{1/2}, p_{1/2}, p_{3/2} \)
  - \( n=3 \):
    - \( s_{1/2} \)

Dirac:
- + relativity
- \( p_{3/2} \)
- \( s_{1/2}, p_{1/2} \)

QED:
- + radiation field
- \( p_{3/2} \)
- \( s_{1/2}, p_{1/2} \)

Lamb shift:
- \( 132.3 \text{ keV} \)
- \( 131.8 \text{ keV} \)
- \( 1s \text{ Lamb shift} \)

for \( U^{92+} \): 464 eV

Highly charged ions are strongly affected by relativistic and QED effects.
Ionization potential rises from 10 eV to 130000 eV
Production by sequential electron impact ionization

As the ion charge state goes up:

- growing ionization potential: $10 \text{ eV} \rightarrow 130000 \text{ eV}$
- diminishing cross section: $10^{-16} \text{ cm}^2 \rightarrow 10^{-24} \text{ cm}^2$

beam electron with energy $E_k$
Electron confinement: multicusp sources

- The plasma ionization degree depends on the balance between electron production and losses to the walls.
- To keep the electrons in the plasma, a strong multipole magnetic field surrounds the plasma volume.
- The increased path length due to the magnetic field increases the ionization probability.
- Improved ionization efficiency at lower pressure by reducing recombinati
Electron cyclotron resonance ion source

- Electrons rotate in a magnetic field $B$ with frequency 
  $\omega = e \times B / m$
and are heated by microwaves at that frequency.
- Longitudinal confinement by magnetic field configuration.
- Radial confinement by magnetic multipoles.
- High electron temperature: multi-charged ion production at densities $> 10^{12}$ electrons/cm³.
- Used on cyclotrons and synchrotrons for the production of HCl beams.
Electron cyclotron resonance ion source (ECRIS)

- multiply to highly charged ions (Ar$^{18+}$, Xe$^{40+}$..)
- currents up to 1 mA for O$^{6+}$
- but rapidly falling currents for higher charge states
• Hot plasma - configured with six cusps - is shaped by the sextupole magnets surrounding the plasma chamber.
• Solenoid magnets form the ends of the magnetic bottle, confining the plasma to the central region of the chamber.
Electron beam ion source (EBIS)

• An intense electron beam interacts with ions trapped in an electrostatic well.
• Ions are confined radially by the space charge in the electron beam and axially by positive electrodes.
• The ions can be investigated within the trap or expelled by lowering the potential of one end electrode.
Space charge potential: a line charge

Poisson’s equation in cylindrical coordinates

\[ \nabla^2 V_{sp} = -\frac{\rho}{\varepsilon_0} \quad \text{and} \quad \nabla^2 = \frac{1}{r} \frac{\partial}{\partial r} r \frac{\partial}{\partial r} \]

Resulting potential with boundary conditions

\[ V_{sp}(r \leq r_e) = \frac{I_e}{4\pi \varepsilon_0 v_e} \left[ \left( \frac{r}{r_e} \right)^2 + \ln \left( \frac{r_e}{r_{dt}} \right)^2 - 1 \right] \]

\[ V_{sp}(r \geq r_e) = \frac{I_e}{2\pi \varepsilon_0 v_e} \ln \left( \frac{r}{r_{dt}} \right). \]
Space charge potential of an electron beam

$E_{\text{beam}} = 2162 \text{ eV}$

$I_{\text{beam}} = 40 \text{ mA}$

space charge potential

electron density

center drift tube radius
Space charge potential of an electron beam

Space charge potential (V) vs. Distance from axis (μm)

- $E_{\text{beam}} = 2162$ eV
- $I_{\text{beam}} = 40$ mA

**Parameters:**
- Electron beam radius
- Electron density
- Center drift tube radius
Electron Beam Ion Source (EBIS)

- Positive ions
- High charge states up to $U^{90+}$
- Small extracted currents
The electron beam ion trap (EBIT)

• As electrons collide with the ions in the beam, they strip off electrons until the energy required to remove the next electron is higher than the beam energy.

• The original LLNL EBIT (1986) used an electron beam energy of about 30 keV to make neon-like uranium ($U^{82+}$).

• SuperEBIT achieved an electron beam energy of 200 keV, enough to make bare uranium ($U^{92+}$).
Production of HCl with an electron beam ion trap

- **Radially:**
  - Electron beam
  - Space charge
  - Total trap potential $U_{\text{trap}} \approx 200 \text{ V}$
  - $(U_{\text{trap}} \times \text{ion charge}) \approx 10000 \text{ eV}$
  - Ion current density $15000 \text{ A/cm}^2$
  - Electron density $n_e \approx 10^{13} \text{ e}/\text{cm}^3$

- **Axially:**
  - Electrod assembly
  - Axial potential
  - Collector
  
  - Current $I = 450 \text{ mA}$
  - Energy $E = 5 \text{ keV}$

**Note:**
- The diagram illustrates the setup with labeled components and associated data points.
Section through the HD-EBIT I (1999)

The original Livermore EBIT (1986)
Photoionization

**direct PI**

\[ E = h\nu \]

\[ E_{\text{kin}} + E_{\text{binding}} \]

\[ \gamma \]

**resonant PI**

\[ E = h\nu \]

\[ E_{\text{res}} \]

interference → Fano profiles

doubly excited → autoionizing
Photoionization

- Indirect Ionization (Resonances)
- Ionization Threshold (Ionization Potential)
- Direct Ionization (Background)
- Interference

Photoionization Cross Section vs. Photon Energy
Merged ion-photon beam apparatus: ion beam and photon beam overlap and interact

Schlachter et al., LBNL
Photoionization of ions

Photoionization of ions

Kjeldsen et al., Aarhus
Measured and calculated cross sections for PI of $C^{2+}$ ions. Solid curve: $R$-matrix results assuming 60% of ground state (gs) ions, 30% in the $^3P_0$ and 5% each in the $^3P_1$ and $^3P_2$ metastable (ms) states in the primary beam.

X-ray spectra of quasars indicate the presence of highly charged C, N, O, Ne and Fe ions

Around black holes or neutron stars, X rays generated by infalling matter photoionize the surroundings: Photoabsorption lines appear.

Iron K-shell radiation is the last spectral signature of baryonic matter before crossing the event horizon.
Photoabsorption lines due to warm-hot intergalactic medium

Blazar H2356-309: Line-of-sight crosses the Sculptor Wall, a large-scale superstructure of galaxies at z ~ 0.03

Date: 11 May 2010, Satellite: XMM-Newton; artist's impression of WHIM in the Sculptor Wall
Photoion extraction and charge analysis

After interaction with photons, ions and photoions are extracted, mass selected and detected.
Fe$^{14+}$ photoionization

(a) Absolute cross section
(b) Experiment
(c) RMBPT

2p-3d
HULLAC
MCDF
Experiment

2s-3p
2p-4d
2p-5d
2s-4p
Comparison with theory for Fe$^{14+}$

- Doppler shift depends on prediction
- Hypothetical two-phase outflows in NGC 3783
- Results confirm RMBPT calculations: no two-phase outflows

Magenta dots: our data
Red curve: HULLAC
Black curve: RMBPT

Fe XV: $\approx 40$ mÅ
Doppler shift corrected based on experiment

Precise measurements of HCl X-ray absorption line positions and cross sections are possible with EBITs
Accelerators

• Acceleration schemes for ions
• Electrostatic accelerators
• RF accelerators
Van de Graaff principle

- Purely electrostatic acceleration
- Ion source is installed at high voltage terminal
- Potential is caused by charging up the terminal with a mechanical charge transport chain
Tandem van de Graaff accelerator (1930)

- Tank with insulating gas ($\text{SF}_6$)
- Negative ions $C^-$
- Stripping
- Positive ions $C^6^+$

Potential:
- 0 Volt
- 10 MV
- 0 Volt

Energy:
- 20 keV
- 10.02 MeV
- 70.02 MeV

AAMOP 2011-2012 2011-11-02
Van de Graaff accelerator

MPI-K: 12 MV tandem accelerator

Tank (5.3 bar SF₆)

Terminal inside the tank

van de Graaff principle

High voltage terminal

Charge

Ground

Negative ion source

Tank (5.3 bar SF₆)

Rubber conveyor belt or metal/insulator chain (Pelletron)
The cyclotron

In 1930 the New York Times announced that a "new apparatus to hurl particles at a speed of 37,000 miles per second in an effort to obtain a long-sought goal — the breaking up of the atom — was described here today by Professor Ernest O. Lawrence of the University of California."

One of the original Lawrence cyclotrons
The synchrotron

- Ring with bending magnets and RF cavity synchronously accelerate particle bunches
- Magnetic focusing by quadrupoles and by radial field gradients in the bending magnets
HF linear accelerator structures

- Deliver bunched beams
- Use powerful RF generators
- High voltage generated by resonantly driven drift tubes

Wideröe (1928)
Heavy ion linear accelerators at the GSI Darmstadt
Radio-frequency quadrupoles as accelerators

- RFQs do not use drift tubes but resonant waveguides at $f \approx 100-500 \text{ MHz}$

- Oscillating electric field and shape of electrodes induces an longitudinal accelerating component in $z$ direction

\[ a = \text{minimum distance from axis} \]
\[ ma = \text{maximum distance from axis} \]
\[ m = \text{modulation factor} \]
To produce higher charge states in accelerators, ions in low charge states pass through a very thin foil where electrons are stripped.

Example:
- ion source produces a beam of $20 \text{ keV} \; \text{Ne}^{2+}$
- accelerated to: $20 \text{ MeV} \; \text{Ne}^{2+}$
- after passing stripper: $20 \text{ MeV} \; \text{Ne}^{10+}$
Electron cooling in storage rings

• Ions interact $10^6$ times per second with a collinear beam of cold electrons at nearly the same speed.
• The transversal components of the ion motion are cooled.

• Momentum spread $\Delta p/p : 10^{-4} – 10^{-5}$
• Beam diameter : 2 mm