AN OVERVIEW OF LINAC ION SOURCES

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Scope Limitations for this Presentation

- **Sources for high-duty-factor rf Linacs**
  - 5% - cw

- **Tutorial character**
  - Taking the ‘Sourcery’ out of Ion Sources

- **No attempt at encyclopedic format**
  - Fundamentals
  - Major lines of development
  - Key operational parameters
  - General and type-specific limitations and problems

- **Peak sample results included**

- **Not included**
  - Penning (PIG)
  - Duoplasmatrons
  - Duopigatrons
  - Beam formation issues in detail
  - LEBTs
Contents

- **Introduction** *(already given)*
- **Particle feeding methods**
- **Plasma generation**
  - Filament driven
  - Rf driven
- **Multicusp sources**
  - Filament driven
  - Rf driven
- **ECR Ion Sources**
  - ECRIS for Highly charged Ions
  - ECRIS as Charge Breeders
  - ECRIS for High-current Beams
Particle Feeding Methods (1)
Materials in pure, gaseous form

- **Needle valve**
- **Regulated valve**
  - May need fast-pulsed valve to reduce average pressure in LEBT
Particle Feeding Methods (2)
Non-gaseous elements

- **Gaseous compounds**
  - e. g., C from CO₂

- **Liquid compounds with sufficient vapor pressure**
  - e. g., B from BF₃
  - Many compounds contain an **aggressive component**
    - Erosion of source parts, especially hot filaments
    - Increased **sparking** rate in extraction system

- **Oven**
  - Need to limit re-condensation material fed into source
    - **Oven should be coldest of internal source parts**
    - Dual heating systems
  - Might benefit from auxiliary gas to stabilize discharge
Particle Feeding Methods (3)

CHORDIS with oven

R. Keller & F. Nöhmayer, GSI Darmstadt
Particle Feeding Methods (4)
Cathode sputtering

- **Technique well suited for high-melting materials**
  - Dedicated sputtering electrode
  - Biasing existing electrode
    - Made from, or coated with, material of interest
  - Needs auxiliary gas to release desired particles from electrode
    - Self-sputtering does occur but is not a stable process
  - **Sputtering current regulates share** of desired species in plasma
    - Maximum 10-20%
  - Need to limit re-condensation of sputtered material
    - Similar solution as with oven
Plasma Generation (1)
Creating and maintaining a discharge (NOT: arc)

- **Sustained by dc power and thermionic cathodes (filaments)**
  - Continuous (dc)
  - Pulsed

- **Sustained by rf power**
  - Continuous (cw)
  - Pulsed (modulated)

- **Choice of discharge voltage and current values influences plasma composition**
  - Total beam current
  - Singly or multiply charged ions

- **Cathode filaments**
  - Tungsten, tungsten/rhenium or tantalum wire
    - Lifetime limitations
    - Resistance-increase data for diagnostics
  - Earth-alkaline oxide paste on nickel or platinum mesh
    - Used for hydrogen feeding gas (low sputtering rate)
Plasma Generation (2)
Filament lifetime assessment for dc discharges, R. Keller et al., NIBS Conf. 2008

‘Creep’ phenomenon for material under stress
Data can be used to predict time of failure
-> Adjust filament heating power
Approach supported by analytical/computational model
Model shows exponential growth and catastrophic failure
0.05-mm ‘nick’ reduces lifetime by factor of 2

Typical resistance-increase plot – heating power was varied twice
Rf Sustained Discharges (1)

Fundamentals

- Typical frequencies 1-13.56 MHz
- No fast-eroding components such as filaments
- Need impedance matcher
  - Amplifier typically 50 Ohm
  - Plasma about 1 Ohm
- Ignition poses a problem
  - Cw operation mode: Raise gas pressure for ignition
  - Pulsed operation mode: several options
    - Add low-power cw amplifier
      - Decouple power flow
      - Protect cw amplifier from reflected power as plasma impedance changes
    - Add spark-gap chamber or ‘plasma gun’ combined with pulsed gas valve
Rf Sustained Discharges (2)
‘High’ pressure discharge chamber added to facilitate ignition

\[ \text{Rf Heating Coil behind Ceramic Cylinder} \]

\[ \text{MULTICUSP Plasma Confinement Magnets} \]

\[ H_2 + e^{-} \rightarrow H^0 + e^- \]

\[ H^- \rightarrow H_2^+ + e^- \]
Rf Sustained Discharges (3)
Antenna options

- Antenna needs to be insulated from plasma
  - Avoid arcing, meltdown

- Internal antenna
  - Porcelain coated
    - Single- or multi-layer
  - Incompatibility of thermal expansion coefficients leads to cracks
    - Water/vacuum accident waiting to happen

- External antenna
  - Major part of discharge chamber made from Al₂O₃ or, better AlN
  - Needs to be engineered for desired duty factor
    - Heat transfer
    - Maximum temperature gradient
    - May have to be protected from discharge heat load by Faraday shield
Rf Sustained Discharges (4)
Ion source with external antenna

SNS H⁺ Ion Source

1 ms/60 Hz pulsed operation

100 mA beam current from 7-mm aperture

R. F. Welton et al., SNS-ORNL Oak Ridge
Multicusp (’Bucket’) Sources (1)
Fundamentals

- **Stable plasma confinement achieved by minimum-B configuration**
  - Magnetic fields increase with increasing distance from discharge center
  - Increases ionization probability for electrons
    - Significantly reduces plasma-loss area
  - Facilitates space-charge compensation of extracted beam (no oscillations)
  - Realized by lining discharge chamber with permanent magnets
    - High-current sources (8 – 20 magnets around)
  - Permanent-magnet or electro-magnet sextupoles
    - ECR sources
  - Higher number of magnets enlarges ‘field-free’ cross-sectional area
    - Uniform plasma density allows use of wide multi-aperture extraction systems
Multicusp Sources (2)
Heavy ions

Conservative formula for single aperture, single ion species, single charge state:

\[ I \text{ [mA]} = 0.5 \ A^{-1/2} \ U^{3/2} \ [kV^{3/2}] \]

Multicusp Sources (3)
H\(^+\)/D\(^+\) generation fundamentals

- Need to be optimized for atomic ion (H\(^+\)/D\(^+\)) production
- Molecular ions compete for share in plasma
- Cannot simply push discharge voltage to optimum value as with multi-charged (heavy) ions
- Need to excite vibrational states of H\(_2\)/D\(_2\) molecules
  - Requires low-energy electrons
- Install hot liner or BN liner
  - Creates ‘pre-dissociation’
- Install magnetic dipole filter across discharge chamber
  - Keeps energetic electrons from penetrating across filter field into secondary chamber
  - Low-energy electrons pushed through by elastic collisions, ExB drift
- Alternative: ECR source (see below)
Multicusp Sources (4)
H⁻/D⁻ generation fundamentals

- **Volume- and surface production**, see *M. Bacal, Nucl. Fusion (2006)*

- **Volume production issues similar to (H⁺/D⁺) ion production**
  - Install magnetic dipole filter across discharge chamber
    - Keeps energetic electrons from penetrating across filter field into secondary chamber
    - Low-energy electrons pushed through by elastic collisions, E×B drift
  - Need to excite ro-vibrational states of H₂/D₂ molecules
    - Requires even lower low-energy electrons

- **Even 10-eV electrons and neutrals can destroy H⁻/D⁻**
  - Provide short paths to outlet aperture
  - Less-than-proportional scaling of beam current vs. aperture area

- **Surface production relies on resonant-tunneling charge-exchange of H⁺/D⁻ from surface with low work function**
  - Cesiated Mo etc.
  - Barium
Multicusp Sources (5)
H⁻/D⁻ generation by volume production

Multicusp source with magnetic dipole filter
(J. Peters, ICIS Conf. 2007)

Peak result

40 mA of H⁻ over 3 ms
Cesium-free
Multicusp Sources (6)
H⁻/D⁻ Generation by surface production

LANSCE H⁻ Ion Source with cesiated, biased converter

0.8 ms-60/120 Hz operation

Up to 25 mA beam current from 9.8-mm aperture

300-eV beam energy inside source

R. L. York, R. R. Stevens et al., LANL Los Alamos
Electron Cyclotron-Resonance Sources (1)
Fundamentals, see R. Geller, ECRIS Workshop (1987)

- Filament-free
  - Very long times-between-services even at cw conditions

- Microwave driven in 2.45-28 GHz frequency range

- Longitudinal magnetic mirror field

- Resonance condition \( B_{\text{res}} [T] = 0.0354 f [\text{GHz}] \)

- Highly charged ions
  - Low gas pressure \(< 10^{-6} \text{ Torr}\)
  - High density
  - High magnetic field for plasma confinement
  - Low magnetic field better for extracting more beam current
  - Transverse confinement by sextupole
  - Cut-off electron density \( n_e [\text{cm}^{-3}] \leq 1.25 \times 10^{10} f^2 [\text{GHz}^2] \)

- High-current beams
  - Higher gas pressure \( \sim 10^{-3} \text{ Torr} \)
  - Overdense wave penetration mode
Electron Cyclotron-Resonance Sources (2)
VENUS ECR Source for highly charged ions

Solenoid field 3.4 T peak
1 T resonance at 28 GHz

Sextupole field 2.1 T at chamber wall

Peak results [ electr. μ A ]

\[
\begin{align*}
16^6O^{6+} & \quad 2850 \\
16^7O^{7+} & \quad 85 \\
129^28Xe^{28+} & \quad 222 \\
129^38Xe^{38+} & \quad 7 \\
238^34U^{34+} & \quad 202 \\
238^35U^{35+} & \quad 175 \\
238^47U^{47+} & \quad 5 \\
238^50U^{50+} & \quad 1.9
\end{align*}
\]

D. Leitner et al., LBNL Berkeley
Electron Cyclotron-Resonance Sources (3)
Issues and trends with ECR Sources for highly charged ions

- **Hollow-beam formation often noted**
  - Poor transport properties

- **X-ray generation becomes increasingly severe issue as plasma density, frequency and microwave power increase**
  - Requires external radiation shielding
  - Jeopardizes internal equipment (superconducting coils)

- **Ion production appears to depend on resonance volume**
  - Surface area of ‘resonance cigar’ times electron Larmor radius
  - Two-frequency microwave power
  - Broadband amplifier with Traveling-Wave Tube

- **Small frequency adjustments beneficial** - [L. Celona et al., ECRIS Conf. (2008)]
  - Improves microwave mode selection
  - Increased power efficiency, about 30%
  - Improved beam profile
    - Hollow triangle -> solid ‘star’
Electron Cyclotron-Resonance Sources (4)
Charge Breeders

- Serving Secondary Beam Facilities
  - FAIR, RIA/FRIB

- Collects radioactive ions from primary target

- Ionizes captured ions to higher charge states
  - Improve efficiency of secondary accelerator

- Main aspects
  - Modular design minimizes radioactive waste upon turnover
  - Beam-current output depends on primary accelerator and target
  - Particle efficiency critical

Peak result from ANL Argonne, see G. Savard et al., ECRIS Conf. 2008

$^{133}\text{Cs}^{20+}$ at 3%
$^{85}\text{Rb}^{15+}$ at 3.6% particle efficiency
Electron Cyclotron-Resonance Sources (5)
High-current ECR Sources

- **Penetration of microwaves into overdense plasma**
  
  
  - Utilized by microwave driven proton source
    - 2.45 GHz frequency
    - About 1 kW cw power
    - 0.0875 T ECR resonance field
      - Solenoids or permanent magnets used
      - Beam optics similar to ‘field-free’ extraction systems
    - No transverse plasma-confinement configuration

Peak result from LEDA project, Los Alamos

*120 mA transportable dc beam with 90% proton share from 8.6-mm outlet aperture*

*See J. D. Sherman et al., ICIS Conf. (2001)*
Recent Ion Source Information
Meetings and Journals

- **International Conference on Ion Sources**

- **International Workshop on ECR Ion Sources**
  - Latest workshop held 2 weeks ago in Chicago

- **International Conference on Negative Ions, Beams and Sources**
  - Meeting formerly called Int. Symp. on Production and Neutralization of Negative Ions and Beams

- **Physical Review Special Topics - Accelerators and Beams**
- **IEEE Transactions on Plasma Science**
- **Applied Physics Letters**