Negative Ion Beam Extraction

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The Typical Ion Source

Every ion source basically consists of two parts:

1. **Ion production** inside a plasma
2. **Beam extraction** from the plasma
No ‘Typical’ Ion Sources!

‘ELISE’ ITER Demonstration H⁻ Source

ISIS H⁻ Source
Goals of any Extraction System

- High Beam Current
- Operational Flexibility
- Low Beam Emittance
Beam Current: Child-Langmuir Law

Emission current density, \( J \) is:

\[
J = \frac{4}{9} \varepsilon_0 \sqrt{\frac{2qV^{3/2}}{m\,d^2}}
\]

Total extracted current, \( I \) from an area, \( A \) is thus:

\[
I = JA = PV^{3/2}
\]

where:

\[
P = \frac{4}{9} \varepsilon_0 \sqrt{\frac{2q\,A}{m\,d^2}}
\]

- This \( P \) is the **perveance**: depends only on source geometry
- Real measured beam perveance always lower than this
- Assumes infinite, thin, plane electrodes (usually far from true)
- Assumes particles starting with zero velocity (not true from a plasma)
- \( V^{3/2} \) **law** only holds if plasma can actually deliver the current
Emittance

• Quality of beam just as important as quantity
  – Emittance affects machine luminosity and beam-loss
  – Want beam emittance < machine acceptance
• Particles occupy 6-dimensional phase space \((x, P_x, y, P_y, z, P_z)\)
• Practical measurements use position-angle (‘trace’) space
• Emittance scan can tell immediately how a beam is focused
• Also shows up important aberrations (not just pure ellipses)
**Emittance Ellipses and Pitfalls**

What is the best fit ellipse?

Do we use RMS, 4.RMS, 90%, or something else?

Ellipse defined by:
\[ \gamma x^2 + 2\alpha xx' + \beta x'^2 = \epsilon_x \]

where: \( \beta \gamma - \alpha^2 = 1 \)

are the **Twiss parameters**

For real, non-elliptical data sets, calculate 4.RMS emittance statistically:
\[ \epsilon_{4.rms} = 4\sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2} \]

Units usually given in \([\pi \text{ mm mrad}]\), but varies

What units? Watch out for \(\pi\)!
Operational Flexibility

- Accelerator runs in different modes
  - Required beam current
  - Duty factor
  - Chopping fraction

- Emission current density, \( J \) can vary over time
  - Source erosion and aging
  - Caesium and other temperature dynamics
  - Diurnal variation

- Slight changes in spare source characteristics
  - Alignment repeatability
  - Each source needs tuning
  - Steering/focussing sensitive to exact B-field strength

Also: real system won’t be the same as simulated, so need some flexibility in the design

Extraction system must have several tuning knobs

**Triode** extraction or at least an **einzellens** is mandatory to be able to adjust to changing plasma conditions
Extraction Complications

• Plasma-beam interaction
  • Plasma parameters: density, potential, temperature etc
  • Uniformity of current density, quality, intensity
  • Influence of surface-produced negative ions on edges of emission aperture

• Co-extracted electrons
  • Usually higher current than negative ions, high space charge influence
  • Must be removed from beam, how to dump significant power safely
  • Dumping scheme creates asymmetry in extraction system and thus onto beam

• Application-specific requirements
  • Adjustable focussing, steering, chopping, pulsed extraction, large area

• Practical engineering constraints
  • Space left for nuts & bolts, connectors, insulators, diagnostics, pumps, gate valves etc
  • Voltage-holding, required materials, power supplies, budgets, lifetime, maintenance
**Electrodes and Grids**

- Most negative ion sources have triode extraction, consisting of three electrodes
- Naming convention different for accelerator or fusion applications:

<table>
<thead>
<tr>
<th>Application</th>
<th>Electrode #1</th>
<th>Electrode #2</th>
<th>Electrode #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerator</td>
<td>Plasma Electrode</td>
<td>Extraction (or ‘Puller’) Electrode</td>
<td>Ground Electrode</td>
</tr>
<tr>
<td>Fusion</td>
<td>Plasma Grid (PG)</td>
<td>Extraction Grid (EG)</td>
<td>Grounded Grid (GG)</td>
</tr>
<tr>
<td><strong>Function</strong></td>
<td>Biased few volts relative to plasma to suppress co-extracted electrons</td>
<td>Adjustable ~1-10 kV to provide initial acceleration and dump electrons</td>
<td>Fixed, much higher voltage to bring beam to required energy</td>
</tr>
</tbody>
</table>
It All Starts at the ‘Plasma Meniscus’

Particle dynamics at emission aperture *defines* the beam performance throughout entire accelerator: *crucial!*

**Plasma meniscus** is *notional* ‘boundary’ where beam originates

Meniscus sets beam *current, emittance and focussing*. Shape varied by emission current density, extraction voltage and electrode geometry
Particle Tracking to Model the Meniscus

- **Discretise** the problem space on a mesh
- Calculate E-field on the mesh, based on input electrode geometry & voltage
- Calculate (or import) local magnetic fields
- Track particles through the E- and B-fields
- Deposit space charge along **particle tracks**
- Re-calculate electric field based on particle charges
- **Iterate** until converged

**Alternatively:** Particle in Cell (PIC) calculation, where point particles are used (not ‘tracks’). Particles are moved and fields re-calculated in short time steps. Useful if external fields are changing and/or particle **collisions** present.
Suitable Extraction Tracking Codes

- (n)IGUN: Plasma modelling for positive and negative ions. 2D only.
- PBGUNS: Plasma modelling for positive and negative ions. 2D only.
- SIMION: Simple 3D E-field solver and particle tracer. Basic space charge solver and no plasma modelling.
- KOBRA: More advanced 3D E-field solver with positive ion plasma model and PIC capability.
- LORENTZ: State of the art 3D EM solver and particle tracer. Lots of features but no plasma modelling.
- IBSIMU: Plasma modelling for positive and negative ions in 1D, 2D, 2D-axisymmetric & 3D. CAD import. Open source, free, benchmarked.
Space Charge

- 50 mA H⁻ beam
- 5 mm initial radius
- 1000 mm drift distance
- Expands due to its own ‘space charge’
- Space charge forces velocity dependent

**Conclusion:** Need to focus and accelerate low energy beams *hard*
Space Charge Compensation

Space charge increases beam size

Beam ionises residual gas and traps positive ions in beam potential: Space charge compensation.

Takes ~100 µs, depending on vacuum pressure.

Negative ion beams can get over-compensated!
Electron Dumping (‘edump’)

• Removing co-extracted electrons is the bane of H⁻ extraction design!
• Electron current often tens of times higher than H⁻ current
• If dumped at full extraction energy, can be a LOT of power to remove
  • Cooling of extraction system
  • Material choice to avoid sputtering/heat damage
  • Defocus electron beam to reduce surface power density
• Require mass-separation i.e. magnetic deflection
• Turns simple 2D problem into a messy 3D problem
  • Larger mesh, more memory, slower solve time
  • Cannot ignore transverse space charge deflection
  • Secondary particles
  • How to correct for deflected ion beam?
<table>
<thead>
<tr>
<th>Option</th>
<th>Benefit</th>
<th>Drawback</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dump at low energy</td>
<td>• Low deposited power</td>
<td>• Low perveance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Asymmetric beam</td>
</tr>
<tr>
<td>Dump at high energy</td>
<td>• More beam current</td>
<td>• High power dump</td>
</tr>
<tr>
<td></td>
<td>• Better focussing</td>
<td>• Erosion damage</td>
</tr>
<tr>
<td></td>
<td>• Less beam deflection</td>
<td></td>
</tr>
<tr>
<td>Extract at full energy, then reduce energy</td>
<td>• High perveance</td>
<td>• Complicated</td>
</tr>
<tr>
<td>then reduce energy before re-accelerating</td>
<td>• Lower dumped power</td>
<td>• More space required</td>
</tr>
<tr>
<td></td>
<td>• Einzel focussing</td>
<td>• HV sparking</td>
</tr>
<tr>
<td></td>
<td>• Flexible</td>
<td>• Secondary electrons</td>
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Electron Dump Cooling & Material Choice

Rule of thumb: keep dumped electron power density well below 1 kW/mm²
LEBT as Part of Extraction?

• For negative ion sources, we (usually) require:
  • Magnetic filter field
  • Magnetic edump field
  • Strong focussing immediately after extraction
  • Correction of position/angle caused by edump

• Since all these deflection and focussing fields are closely intertwined, we cannot really separate the ion source, extraction and LEBT.

• When reporting beam currents, it’s usually more genuine/honest to state the transported current after the LEBT, rather than just what is extracted.

• For example, the ISIS Penning source easily produces 100 mA, but only 35 mA is transported to the RFQ! (Major project underway to rectify this…)
Extraction Fundamentals

- Strong space charge at low energy
- Design dominated by electron dumping
- Operational flexibility mandatory
- LEBT considered as part of extraction
• Field clamp prevents filter field leaking into extraction
• Decelerate beam before dumping electrons
• Dipole/antidipole eDump B-field
• Dump independent of adjustable puller voltage
• Accelerating einzel lens to control focus
• Combined extraction and electrostatic LEBT
• Dump electrons immediately at low energy
• Low extraction E-field creates convex meniscus
• Accelerate quickly to full 65 keV energy
• Two decelerating einzel lenses to control focus
• Tilted extraction
• Electrostatic xy steerer/chopper before RFQ
• Large emission aperture reduces initial space charge
• eDump field same direction as filter to aid deflection
• Slightly divergent beam for solenoid LEBT injection
• JPARC: beam offset corrected by magnet downstream
• RAL: beam offset corrected by tilted vessel c.f. LEBT
• Multi-aperture source for fusion application
• Three grid structure (eventually MUMAG up to 1 MeV)
• Slightly different edump magnet arrangement
• Electrons dumped onto upstream surface of extract grid
• Require almost parallel beam to avoid losses downstream
Conclusion

• Dealing with electrons is hard
• Necessarily requires 3D model
• Many methods to remove them
• All have engineering compromises
• Many experts at NIBS: get in touch

Good luck!

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