35 years of $\text{H}^-$ ions at Fermilab
Outline:

• How we got here
• Where we are
• Where we are headed
Figure: V. Dudnikov
Metals have an abundance of loosely bound electrons, for molybdenum it takes 4.6eV to removed an electron.

Cesium has a work function of 2.1eV, but can lower the surface work function of molybdenum to 1.6eV with a 0.6 monolayer.

Since the work function exceeds the electron affinity of hydrogen atoms, a majority of hydrogen particles leave the surface as neutrals. However a few will pick up an excess electron when leaving the surface.

Some of these H- ions will make their way through the plasma to the anode and be extracted.
Magnetron sources

**Plasma parameters**

- $n_{H_2} \sim 10^{16}$ cm$^{-3}$
- $n_e \sim 10^{13}$-$10^{14}$ cm$^{-3}$
- $T_e \sim 1$ eV / 15 eV

- In gas discharge plasma positive hydrogen and cesium ions are formed
- These ions are accelerated toward the cathode
- Some of the ions that strike the surface have enough energy to "bounce" off the surface, and some small number of those leave the surface as H- ions.
Prototype magnetron H- ion source bought by FNAL for $40k from Brookhaven in the late 70’s

- This source was designed for fusion research
- Low current DC source
- Large gas volume (important later on)
- Used Cs pellets to enhance H-production
BNL source was installed in bell jar and tested at 15Hz

Interesting side note early tests were done using cesium chromate and titanium powder to make cesium tablets that were inserted into the cathode.
Chuck Schmidt chose the new source volume based on source pressure.

The fill time of the BNL source was 8.3ms and it did not reach high enough pressure for plasma to form at 15Hz repeat.
Original source drawings done on CW Schmidt’s kitchen table in 1976

Clever design by Chuck Schmidt reduced internal volume by a factor of 10!
Chuck’s source that was used in the Cockcroft-Walton accelerators:

Compact size
- Chuck Schmidt’s original design.
- Based on the BNL source
- Appropriate for pulsed operation.
The original magnetron used a flat cathode which will become very important later on!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc current</td>
<td>180A</td>
</tr>
<tr>
<td>Arc Voltage</td>
<td>130V</td>
</tr>
<tr>
<td>Beam current</td>
<td>50mA</td>
</tr>
<tr>
<td>Power efficiency</td>
<td>2mA/kW</td>
</tr>
<tr>
<td>Source lifetime</td>
<td>3 months</td>
</tr>
</tbody>
</table>
The source was mounted pointing down with a 90deg bend magnet.

There was a cold box that trapped Cs before it entered the accelerating column.

Co-extracted electrons swept away by the bend magnet
Cockcroft–Walton continued

- 750keV accelerating column
- 100kV between each electrode

Dome contains ion source electronics and vacuum pumping
The 1st H- ions accelerated down Linac

Like all good accelerator experiments, it took less than 1 shift to prove that it works!
The original cathode was used for years. Then it was decided to groove the cathode on one side to help focus the beam at the anode extraction slit. This was a huge improvement. Later, the cathodes were grooved all the way around thinking that it would reduce “noise” in the extracted beam current which was thought to be the result of too low of a plasma volume.
Average power now: 156V x 35A x15 (1/s) x 60(μs) = 4.9W

Arc current went from 180A to 35A with cathode focusing!

This is where things remained until the installation of the new ion source and RFQ......
Where we are now...
The ion source is based on a design by Jim Alessi of BNL
Different extraction scheme

Cockcroft-Walton

• DC accelerating voltage
• Extractor pulsed

New source with RFQ

• Source pulsed to -35kV
• Extractor at ground
• Higher voltage across extraction gap ($I \propto V^{3/2}$)
BNL Style Source

Magnetron Source

Figures: Jim Alessi BNL

Spherical focusing dimple cathode!
BNL style source, huge improvement!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc current</td>
<td>15A</td>
</tr>
<tr>
<td>Arc Voltage</td>
<td>150V</td>
</tr>
<tr>
<td>Beam current</td>
<td>100mA</td>
</tr>
<tr>
<td>Power efficiency</td>
<td>67mA/kW</td>
</tr>
<tr>
<td>Source lifetime</td>
<td>9 months!</td>
</tr>
</tbody>
</table>

Increase in power efficiency comes from:
- Spherical dimpled cathode
- 35kV extraction
New FNAL magnetron

- 10 inch source cube
- Technicians involved with design
- Round aperture
New FNAL source design

- extraction gap .090in
- anode cover plate
- extraction cone
- gas valve
- ceramic extractor standoffs
- Cs tube
- cathode connections
- ~11in
Some studies done on new magnetron

Pervance, able to achieve 1A/cm² @35kV

- **Figure: M. Stockli**

- **anode**

- **extractor**

- **Figure: M. Stockli**
LEBT emittance with nominal RFQ settings

Vertical 0.25 $\pi$ mm mrad normalized $1\sigma$

Horizontal 0.15 $\pi$ mm mrad normalized $1\sigma$
## Evolution of magnetron cathodes

<table>
<thead>
<tr>
<th>Cathode Type</th>
<th>Arc Voltage (V)</th>
<th>Arc Current (A)</th>
<th>Beam Current (mA)</th>
<th>Power Efficiency (mA/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Cathode</td>
<td>130</td>
<td>180</td>
<td>50</td>
<td>2.0</td>
</tr>
<tr>
<td>Asymmetric Grooved</td>
<td>150</td>
<td>50</td>
<td>50</td>
<td>6.7</td>
</tr>
<tr>
<td>Symmetric Grooved</td>
<td>150</td>
<td>50</td>
<td>50</td>
<td>6.7</td>
</tr>
<tr>
<td>Dimpled Cathode</td>
<td>150</td>
<td>18</td>
<td>90</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Note: BNL ≈ 67 mA/kW
Extractor sparking, one of our greatest challenges!

There have been 6 main issues that have lead to high spark rates:
1. Materials used
2. Magnetic Field
3. Source pressure
4. Extraction gap pressure
5. Cs control
6. Source electronics
Materials

Materials play a big role, once the damage is done there is nothing left to do other than pull the source and fix it.

- Original extractor cone tip made out of molybdenum
- Energy of spark would cause damage that would lead to the need to pull the source and fix
- BNL uses tungsten for cone tips. They sent us one to try out. Big improvement in eliminating the damage from sparking

- Original inner anode cover plate made out of titanium
- Severe case of erosion increased the aperture from 0.125in to 0.25in!
- Once again BNL ("ahead of the curve") sent us a molybdenum cover plate which has clearly solved the erosion problem
Magnetic field

- Magnetic field plays a big role in both confinement and sweeping away co-extracted electrons.
- Magnetrons prefer 1kG in the plasma region for proper confinement.
- Original magnets were marginal to start with and ended up too low (~700G) when warmed up.
- Redesigned the magnets and yoke with the help of Jim Volk.

Original design: 4 SmCo disks

Final design: 2 SmCo rectangular magnets with higher field, thicker yoke
For all simulations:
- Extractor cone = 0V
- Cathode = -35.2kV

Simulation by CY Tan
If source pressure is too high, one possibility is that the path length for the fragile $H^-$ ions is so long that the probability is high that some number of them will lose their electron on the way to the extraction aperture, leaving an excess of electrons to be extracted. Leading to sparking.
Another possibility is low average cube pressure. When the pressure is too low in the extraction gap and we are operating in a different regime of the Paschen curve.
Cesium Control

If the cesium layer is too thick/thin:
- Work function increases
- H⁻ production decreases
- Number of free electrons increases
Examples of excess cesium in the source

Lots of Cs deposits on extractor plate (dark rings)

Outline of inner anode cover plate
Source electronics

HRM in the HV rack hangs up during heavy sparking. During resets the HRM is off for a few seconds which means that the arc is not on during that time. This allows the cathode and source body to cool off since the only heating is from the arc power:

\[(150\text{V})(15\text{A})(15\text{Hz})(230\mu\text{s}) = 7.8\text{W average power}\]
What we are working on:

- Solid State extractor pulsers
- New gas valves
- 2 stage extraction
- Removing HRM from HV rack
- Current regulated arc modulator
- Better Cs boiler (no glass, heat tape)
- Tungsten dimpled cathode
Current extractor pulser
- Vacuum tube based
- 150μs rise time
- Tube lifetime 3 months
- Long arc PW needed (230μs)
- Source duty factor 0.3%

DTI Solid State Switches
- 9.6μs rise time
- 50kV, 50A switches
- Source duty factor 0.12% a decrease of 40%!
- Should allow even longer lifetimes
Gas Valves

The current gas valves are Veco PV-10 piezoelectric valves. They are fast and reliable for the most part and have been in use since day one.

Piezo disk

Viton wafer provides seal

Comparison of gas valve removed from H- and the one installed

Calibration is done by adjusting the tension on the retainer

End up with a hysteresis curve like these. The valves start to open around 20V and are fully open by 100V
Gas Valves

However, these valves have a terrible temperature dependence!

- Even a change as small as 1°C changes the arc current by about 1.5 A, and a change in source pressure of $1 \times 10^{-6}$ Torr!
- This is a big change that can lead to sparking and big changes in beam current!

Veco PV-10 data sheet

- 10% / 5 degC
Gas Valves

We are currently testing a solenoid type valve that should have no temperature dependence.
2 stage extraction scheme

- We only 27kV across extraction gap
- Less voltage should reduce sparking
- No need to pulse HV rack (it would set at 35kV DC)
- Currently testing on test stand

-35kV – (-27kV) – (-8kV) = 0
HRM removal

- Plan to remove HRM and install it in a ground controls rack.
- Communication via fiber transceivers will be installed.
- Will be a big help in reducing the affect of sparking.
- Will reduce overall spark rate due to asynchronous rebooting of HRM.

Thanks to Mike Kucera for pursuing this option!
We use 5g ampules of Cs.
Sometimes Cs gets trapped in the broken glass.

Need to get rid of heat tape and go to heater like BNL.

Cs on W H- production peak is broader.
All of this is cool, but the coolest thing about working on sources is: You don’t have to commit a crime to be on the cover of the Chicago Tribune!
Thanks for your attention!