It contains several observations from 2019 on the behavior of the source.

Attempt to find reasons for the observed instability.
From Source to Ring

Wish list:
- ~100 uA; ~1 us; ~square pulses
  - Only 650 ns-long pulses injectable by kicker
- Good Stability/Repeatability
  - order ~1% for intensity and beam shape
  - order ~0.1% better for energy
- Transverse optics matched to ring

Only DC Power Supplies control via PLC in Faraday Cage
Beam observations
Typical acquisition begin 2019

- Rough calibration for BPMs
- Poor signal quality for Pearson

Considered area

- “Fast” spikes (max)
- BPM saturation @~250 uA (Wrong calibration!)
- “Slow” baseline (min)

100 uA calibration pulse injected in Pearson

18 us beam
Going further ahead in the line, with better Pearson, applying some scaling factors to fit Pearson calibration loop (we were overestimating intensity in BPMs by about factor 2.7)

Arc 31V, 6.1A
Gas 1.1 sccm
Filament 50A

Note: time of flight of signals adjusted by hand

Everything calibrated wrt to this pulse injected in the Pearson
Typical acquisition end of 2019 - zoom

- BPMs saturate around 100 uA (assuming full transport from source)
- Pearson bandwidth ~ 3 MHz
- LPU has very high bandwidth, (but also higher low-frequency cut-off, so it induces a droop)

Arc 31V, 6.1A
Gas 1.1 sccm
Filament 50A
Scan over some parameters

- Basic parameters: $2650 \text{ V}_{\text{puller}}$; 6% filament; $70 \text{ V}_{\text{arc}}$

---

**Gas: 0.8 sccm**

![Graph](image1)

**Gas: 1.7 sccm**

![Graph](image2)
And a better beam

- Going further ahead in the line, with better Pearson, applying some scaling factors to fit Pearson calibration loop (we were overestimating intensity in BPMs by about factor 2.7)

Seems like going up further in filament current is not helping to get more ions. To be checked!
1. Calibration factor of LPU to crosscheck intensity measurement

2. BPMs calibration factor: why 2.7 times error wrt “standard” formula?

3. Measure $I_{beam}(I_{fil})$ and $I_{beam}(Q_{sccm})$
   - How high can we go?
   - Check beam size (emittance) while going up.
Looking more in detail at the source
Title: Source control

- Control via PLC of main DC voltages
- Filament automatically regulated to keep Arc current stable (?)

**Flow controller**
- 0.80 scm
- 0.82 scm

**Filament**
- 6 V, 44.7 A
- Mode: ARC, 6.0%

**Arc**
- 70 V, 1.5 A
- 70 V

**Puller positive**
- 2560 V, 0.0 mA

**Puller negative**
- 250 V
- 225 V, 0.0 mA

**Potential**
- 0.000 kV
- 55 kV, 232 uA

**Quadrupole 1**
- On/Off

**Quadrupole 2**
- On/Off

**400Hz Converter**
- Status: On/Off

**Diagram**
- Puller [V] vs. t
- Orientation: N, S
- Soft Iron
- Permanent magnets hidden here
- Decapole magnets
- Plasma chamber

*Note: The orientation of the Soft Iron is uncertain.*
Source cabling

from Ana Megía-Macías - [link]
**Source operation point**
(with respect to source user manual graphs)

<table>
<thead>
<tr>
<th>Beam Current</th>
</tr>
</thead>
<tbody>
<tr>
<td><a href="#">Graph 1</a></td>
</tr>
<tr>
<td><strong>ELENA source</strong></td>
</tr>
<tr>
<td>I_{arc} = 1-2 A</td>
</tr>
<tr>
<td>U_{arc} = 70 V</td>
</tr>
<tr>
<td>Q = 0.006-0.018 Torr*l/s</td>
</tr>
</tbody>
</table>
Settings used in the past by Ralf

- Note that arc and filament currents are much higher here (IPAC2015)!
- (but probably due to a different filament length/diameter)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>100 $\mu$A H$^-$</th>
<th>150 $\mu$A p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc Current</td>
<td>[A] 3.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Arc Voltage</td>
<td>[A] 75</td>
<td>75</td>
</tr>
<tr>
<td>Extraction Voltage</td>
<td>[kV] -3.0</td>
<td>+2.9</td>
</tr>
<tr>
<td>Suppression Voltage</td>
<td>[kV] +.2</td>
<td>-0.2</td>
</tr>
<tr>
<td>Filament Current</td>
<td>[A] 76.0</td>
<td>73.4</td>
</tr>
<tr>
<td>Gas Flow</td>
<td>[sccm] 0.90</td>
<td>0.60</td>
</tr>
</tbody>
</table>

**TWISS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>[µm rad]</th>
<th>[m/µrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{RMS,norm}$</td>
<td>0.26</td>
<td>0.37</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>-0.11</td>
<td>-0.14</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.37</td>
<td>0.27</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>2.76</td>
<td>3.74</td>
</tr>
</tbody>
</table>
General behavior of source parameters

- Arc current depends (exponentially?!) on the filament current (for a given gas flow)
- Arc current (for a given Arc voltage and Filament current) does not depend on gas pressure (until the plasma stops)
- Filament voltage only depends on filament current, independently of the plasma

Flow=0.7sccm

Should we expect (?):

$$I_{arc} \approx I_{fil}e^{-\text{const} / \sqrt{I_{fil}}}$$

Look more in detail! But it doesn’t seems so

Note: from experience this behavior seems to saturate. To be checked!

From this behavior it looks like we are dominated by thermionic emission, but this point then?!
Vacuum considerations
Vacuum measurements

Typical operation:
• 3e-6 mbar for 0.8 sccm
• (2e-6 with vacuum valve toward ELENA open)

Static vacuum pressure as function of injected H₂
Estimated pressure in the source

\[ C_{or, mol, H_2}[l/s] = 43.8 \cdot A \quad @20\text{deg for H}_2 \]

\[ A := \text{cross section} \ [\text{cm}^2] \]

\[ P_c \cdot S = Q = C_{or}(P_s - P_c) \]

\[ P_c \left( \frac{S}{C_{or}} + 1 \right) = P_s = \frac{2200}{5.5} + 1) P_c = 400 P_c \]

\[ 1 \text{[sccm]} = 0.016 \text{[mbar} \cdot \text{l/s]} \]

---

**Estimate of gas density:**

\[ n_{H_2} = N_A \frac{P_s}{RT} \]

\[ n_{H_2} = 2.47 \times 10^{22} [\text{m}^{-3} \cdot \text{mbar}^{-1}] \cdot P_s \text{[mbar]} \]

\[ P_s = 1.2 \times 10^{-3} \text{[mbar]}; \quad n_{H_2} = 3 \times 10^{19} [\text{m}^{-3}] \]

---

**2200 l/s pump (DN250)**

- **0.8 sccm H\textsubscript{2} injected**
  - (1.3e-2 mbar l/s)

- **Meas. 3e-6 mbar**
  - (2e-6 if opening valve)

**Crosscheck of expected vacuum pressure**:

\[ P_c = \frac{Q}{S} = \frac{1.3 \times 10^{-2}}{2200} = 6 \times 10^{-6} \text{[mbar]} \]

we are wrong only of factor 2 somewhere

**Crosscheck of expected vacuum pressure**: $V_s = 5^2 \pi 17.5 \text{ cm}^3 = 1.37 \text{ [L]}$
Frequency of the instability
Long pulses (390 us) - different gas P

2650 $V_{\text{puller}}$; 6% filament (7 V$_{\text{fil}}$, 45.8 A$_{\text{fil}}$); 30 V$_{\text{arc}}$ (1.5 A$_{\text{arc}}$); 0.8 sccm

2650 $V_{\text{puller}}$; 6% filament (7 V$_{\text{fil}}$, 45.8 A$_{\text{fil}}$); 30 V$_{\text{arc}}$ (1.5 A$_{\text{arc}}$); 1.6 sccm
Long pulses (390 us) – different $V_{\text{arc}}$

2650 $V_{\text{puller}}$; 6% filament ($7V_{\text{fil}}$, 46.6 $A_{\text{fil}}$); 20 $V_{\text{arc}}$ (1.5 $A_{\text{arc}}$); 1.6 sccm

2650 $V_{\text{puller}}$; 6% filament ($7V_{\text{fil}}$, 45.8 $A_{\text{fil}}$); 30 $V_{\text{arc}}$ (1.5 $A_{\text{arc}}$); 1.6 sccm
Long pulses (390 us)

2650 $V_{\text{puller}}$; 6% filament (7$V_{\text{fil}}$, 45.8 $A_{\text{fil}}$); 30 $V_{\text{arc}}$ (1.5 $A_{\text{arc}}$); 0.8 sccm

FFT of several shots, and mean over all FFTs:
Mean FFT over 3 configurations

No specific frequency pops out, maybe tendency to move peak to higher frequencies for higher gas pressures?! Could it be compatible with plasma frequency?

• (Tried to looked at other data with shorter pulses, fewer shots, different conditions… difficult to conclude anything: to be repeated with longer pulses, scanning over arc voltage.)

Did the “average peak” frequency change? Factor 2?
If $f_e = 1$ MHz, then plasma electron density of the order of $1e10$ [m$^{-3}$].

- Is this plausible? It seems way too small!

If we double the gas injection, we should double the plasma density.

- If so, we should expect $\sqrt{2}$ higher plasma frequency.

The same applies for the "ion" density. In our case we talk about protons, i.e.:

$$f_i = f_e \sqrt{\frac{m_e}{m_i}} \approx f_e \sqrt{\frac{0.511}{938}} \approx 0.023 \times f_e \approx 0.21\sqrt{n_i}$$

- for $f_i = 1$ MHz we should then expect a plasma proton density of $2e13$ [m$^{-3}$].

All values way too far from estimated gas density in the source: $3e19$ [m$^{-3}$]
1. The “simplest” plasma dynamics seems to be excluded.
   1. Still interesting to make a frequency analysis scanning over arc voltage.
2. Measure proton beam!
   □ Maybe we are seeing un-stable H- production
   □ p-production more stable?
3. Measure e- beam stability on puller
Is the filament warm enough?
Thermoionic Emission Estimate

\[ j = AT^2e^{-\frac{e\Phi W}{k_B T}} \]

where:

\[ \Phi_W = 4.52 \text{[V]} \text{(Tungsten)} \]
\[ = 2.63 \text{[V]} \text{(Thoriated Tungsten)} \]
\[ k_B = 8.617 \times 10^{-5} \text{[eV/K]} \]
\[ A \approx 6 \times 10^5 \text{[Am}^{-2}\text{K}^{-2}] \text{(Tungsten)} \]
\[ \approx 3 \times 10^4 \text{[Am}^{-2}\text{K}^{-2}] \text{(Thoriated Tungsten)} \]

- Assuming 8 cm long Tungsten filament, 1 mm diameter
  - => surface = 8e-2 * 3.14 = 0.25 m²

- Assuming 2000 K; I = 2.44 A!
  - ?! We don’t see this current if we don’t inject gas.
  - Assuming 1800 K; I = 0.1 A => this would be compatible with obs.

Can it still be that the filament current is too low?
Re-check temperature estimate! (starting from next slide)
The hypothesis is that we operate with a too low filament current and that uneven ion sputtering on the cathode (in time and space) creates discharge spikes. Calculations show that the filament temperature is 2200 K over a ~8 cm length (total filament length ~13 cm), which would yield approximately 500 mA emitted electron current. The total discharge current, made up of electrons leaving and positive ions drifting towards the cathode, is similar (1-2 A). Thus, it’s difficult to explain the temporal instability of the extracted ions with an uneven ion sputtering phenomenon.

According to the manual:
A. The filament current should be >45 A (for a filament with a larger diameter than presently installed)
B. “There is also a lesser contribution to the arc current from the positive ions reaching the filament.”
Arc current > 0 only with gas: are we running the source in “glow discharge mode”?

We need ~30 V to “start” the plasma, then down to ~20 V to stop it. Does our control allow to explore this region?

Note: here, with “arc control” $I_{\text{arc}}$ is stabilized by very small variation of $I_{\text{filament}}$.

Fig. 3: The current voltage characteristics of a typical electrical discharge

From *Ion sources for high-power hadron accelerators* by D. C. Faircloth - [link](#)
1. Repeat measurement with no gas injected.
   1. Can we confirm thermionic emission behavior?
   2. Are we in between thermionic emission and glow discharge regime?
2. What is Ralf normally seeing in his sources?
   1. WARNING! With bad vacuum (i.e. after intervention), we saw high $I_{\text{arc}}$ with no injected $\text{H}_2$ gas, but maybe because of rest gas being ionized.
On H- production
**H⁻ production mechanism**

- **Production H⁻ production via:**
  \[ H₂^*(ν ≥ 5) + e^- → H^- + H \]
  - Vibrationally-excited H₂ in state 5 or above.
  - \( e^- < 1\text{eV} \) (H⁻ binding energy = 0.75 eV)

- **Excitation of H₂ molecule:**
  \[ H₂(ν = 0) + e_{fast}^- → H₂^*(ν ≥ 5) + e + hν \]
  - It requires \( e_{fast}^- > 20 \text{eV} \)

- **H⁻ “destroyed” by two main processes:**
  \[ H^- + H^+ → 2H \quad \text{H}^- + H → H₂^* + e^- \]

Indeed, if \( V_{arc} < 20 \text{ V} \), \( I_{arc} \) drops and we indeed don’t see any(?) H⁻. Is it really 20 eV? Not 10 eV?
Separation of plasma in regions with different electron energies

- Mainly via e\(^{-}\) diffusion, controlled by the presence of magnetic field perpendicular to H- extraction axis
  - Field expected to be around 260 Gauss
    - (see Magnetic_Filter_Configuration_2001.pdf)
- Without magnetic field, diffusion governed by:
  
  \[ D_e = \frac{k_B T_e}{m_e \nu_c} \]
  
  where

  \[ \nu_c = n_e K T_e^{-3/2} \]
  
  collision frequency.

  \[ K \]
  
  constant describing collision process (no estimate, yet).
- It gets “modified” by magnetic field B via:

  \[ D_\perp = \frac{\nu_c^2}{\nu_c^2 + \Omega_{ce}^2} D_e \]
  
  where:

  \[ \Omega_{ce} = \frac{eB}{m_e} \]
  
  is gyrofrequency (729/0.4 MHz e\(^{-}/p\)).

  \[ r_g = \frac{\nu_\perp}{\Omega_{ce}} \]
  
  is gyroradius (\(~1/40\) mm e\(^{-}/p\)).
- Too high electron density (n\(_e\)) or too low magnetic field (B) spoils this fundamental separation.
1. Looks like the H$_2$ ionization/excitation is driven both by thermionic discharge and gas discharge.

2. Should be looking in expected collision frequency to estimate actual separation between plasmas.

3. Proton gyrofrequency is close to our 1 MHz observed instability. Does it mean something?
Voltages/Currents during plasma ignition
Measuring discharge ignition

2650 $V_{\text{puller}}$; (FILAMENT mode) 6 $V_{\text{fil}}$, 45.1 $A_{\text{fil}}$; 40 $V_{\text{arc}}$ (1.2 $A_{\text{arc}}$); 0.8 sccm

- $I_{\text{arc}}$ measured with Pearson 150 (0.5 V/A) on arc PC output (in Faraday Cage)
- $V_{\text{arc}}$ measured on PC output on high impedance scope

600 mV => 1.2 A: OK?!
Fall time of Arc voltage (without plasma)

Without plasma, switching off Arc PC from 40 V

- $I_{\text{arc}}$ measured with Pearson 150 (0.5 V/A) on arc PC output
- $V_{\text{arc}}$ measured on PC output on high impedance, 100 kOhm resistance (see picture) – To be repeated with smaller $R$

$\tau = RC$

$= 1.44 \times t_{1/2}$

$C = \frac{1.44 \times t_{1/2}}{R}$

$\approx \frac{15[\text{s}]}{100[\text{kOhm}]} = 150\mu\text{F}$

Lower limit, could be much higher!
Fall time of Arc voltage (with plasma)

Without plasma, switching off Arc PC from $V_{arc} = 40 \text{ V}$, $I_{arc} = 1.2 \text{ A}$

- $I_{arc}$ measured with Pearson 150 (0.5 V/A) on arc PC output
- $V_{arc}$ measured on PC output on high impedance scope (without external loading resistance)

Does not fit value from un-loaded case?!

$$R = \frac{V}{I} \approx \frac{40}{1.2} \approx 33[\text{Ohm}]$$

$$C = \frac{1.44 \times t_{1/2}}{R} \approx \frac{1.44 \times 100[\text{ms}]}{33[\text{Ohm}]} = 4363[\mu \text{F}]$$

Plasma goes off
Regulation of Arc PC (unloaded)

Starting Arc from 0 to 40 V, without filament (i.e. no plasma)
Restart and Regulation

Stop/Start plasma, going down to 20 V and then back up to 30 V on Arc PC

- $I_{\text{arc}}$ measured with Pearson 150 (0.5 V/A) on arc PC output
- $V_{\text{arc}}$ measured on PC output on high impedance scope

Stopping plasma

Re-staring plasma

~720 mA: OK?!

1120 mA: OK?!
Filament voltage stability during ignition

Without/with plasma, starting arc PC from 0V to 40 V

- $I_{\text{arc}}$ measured with Pearson 150 on arc PC output
- $V_{\text{fil}}$ measured on filament PC output on high impedance scope (without external loading resistance)

Ripple <1 kHz, also audible near Faraday cage. But no other perturbation seen.

1.2 A: OK?!
1. **Repeat measurements close to the source.**

1. We are looking for another signal in the source showing the instability we observe on the beam!

2. Looking near the PCs we could be masked by C of cables + PC and by several inductances around cables…
Try measuring instability on Arc current
The goal is to see if there is a correlation between the spikes in the extracted current and noise on the arc current supply. That could be an indication of an erratic arc current mainly being caused by secondary emission from the anode and not electron emission from the cathode.

Install a Pearson 110 around the cables either at the source or in the HV cage.

Note that both inside the HV cage and at the source these cables are surrounded by many ferrite rings, installed by Ralf Gebel. Removed during the measurement.
Measure instabilities of arc current

Pearson 110 current transformer placed around arc return cable 10 cm from the exit of the plasma chamber. The source was operated with 38 A filament current and 1 A arc current.

The first peaks in the damped oscillation corresponds to $170 \text{ mV} \times 0.1 \text{ A/V} = 17 \text{ mA}$, which is still significantly lower than the average 1 A arc current. The noise is related to the switching of the puller electrode in time.

! No erratic noise corresponding to the signal seen on the extracted current !
Other parameters
4 mA extractable H- current

- analytic formula for a planar diode
- plasma electrode diameter 4.2 mm, distance plasma electrode to puller 5 mm, extraction voltage 3000 V, ignoring electrons)

Significantly higher than 100 uA being extracted!

Ralf Gebel from Julich writes ‘9 mm and 6 mm plasma electrode versions should be available too, if you need more beam current. 6 mm is fine for 300 uA. 9 mm if you need a milliamp
Logbook of other measurements/results
Scan over parameters (old)
Scan over some parameters

- Basic parameters: 0.8 sccm; 2650 V\textsubscript{puller}; 6% filament; 70 V\textsubscript{arc}
- Looking at 10us window for min, mean, max and integrated charges over several shots

BPM saturation @~250 uA.

+ should scale everything by ~1/2.5, i.e. max=100 uA
Scan over some parameters

- Basic parameters: \(0.8 \text{sccm}; 2650 \, V_{\text{puller}}; 6\% \text{ filament}; 70 \, V_{\text{arc}}\)
- Some representative single shots acquisitions

BPM saturation @\(~250 \, \text{uA}.\)
+should scale everything by \(~1/2.5, \text{i.e. max}=100 \, \text{uA}\)
Seeing the instability elsewhere
Possible beam observations

Possible to make ~100 uA beams @source

Poor pointing stability after some time, sometimes

Shot-to-shot, Intra-pulse, Intensity Instability in ELENA

Pick-ups in ELENA:
Sum signals

20us

Differential pumping (3x Turbo + 1x NEG)
Electrostatic Quadrupoles
Vertical Corrector
Magnetic Septum
Kicker
Quadrupole + BPMs
Pick-ups in ELENA:
Sum signals

20us

Pearson Transformer

Fast Vacuum Valve

ELENA Dipole
Looking at other signals

Frist BPM in Ring (modified head amplifier)

BPM after LPU (not modified)

LPU in ELENA Ring
Looking at other signals

Using one plate of Ion Switch as Faraday Cup
Looking at other signals

Using the orbit corrector in LNS line as BPM (with charge amplifier used in ELENA ring BPMs)

Difficult measurement, as amplifiers saturates quickly if there are losses on the electrodes.

Sum or Delta: quickly saturated

Sum or Delta: “well” behaving
Vacuum: installation of new Pearson
Pumping down speed after Pearson 110 removal
Vacuum measurements 2/2

Pumping down speed after new Pearson 5753 installation
Note ~1 day time scale
Puller current

WRONG! CALBE IS SHIELDED…

Without Arc/Filament, puller @ +250 V/-2650 V;

- Current measured with Pearson 150 on **puller switch** output (peak ~200 mA)
- Current measured with Pearson 150 on **arc PC negative** output (peak ~15 mA)

- Signals very stable and reproducible. Amplitude decreases with puller voltage.

**Overview**

**Zoom at start of pulse**
- It seems like oscillation on puller is easily dumped with some ferrite (doing two turns around ferrite with puller switch unit output cable).
  - But it induces also a “longer” perturbation on Arc current signal (real or electromagnetic noise?!
    Note that puller cable goes through one of the Arc/Filament hollow cables…)
- NOTE: measurement maybe taken with Arc/Filament ON. To be re-checked.
Some tests on source parameters
4 Dec 2019
Logbook of CHARGING UP Effects
Well known issue in 2018, it “disappeared” in 2019 when running the source in pulsed mode. It came back at end of 2019 when running in DC mode.

Example of 16/12/2020 (elogbook)

- Beam lost ⇒ Changed H₂ cartridge ⇒ beam came back “slowly” by itself in the center of BTV, but afterwards it moved again.
- Trying to vent the source ⇒ the beam seemed to be stable, at least for a few hours.
- Trying to mess-up with source steering, closing/opening valves.
  - Several attempts in ~30 minutes, but beam came back all the time the same.

Measured “current” on first LNS quad electrodes

Beam spot NOT moving on BTV

Venting the source

Restart Beam

Tests with source valves/steering/puller

18th Feb. 2020 - ELENA Source Status and Plans
28/06/2018 (elogbook)

- Beam was reported to be moving around…
- Many other similar acquisition in 2018. In some, it was evident that when beam was suddenly lost, those signals where very much different.