ELENA H-/p source characterization

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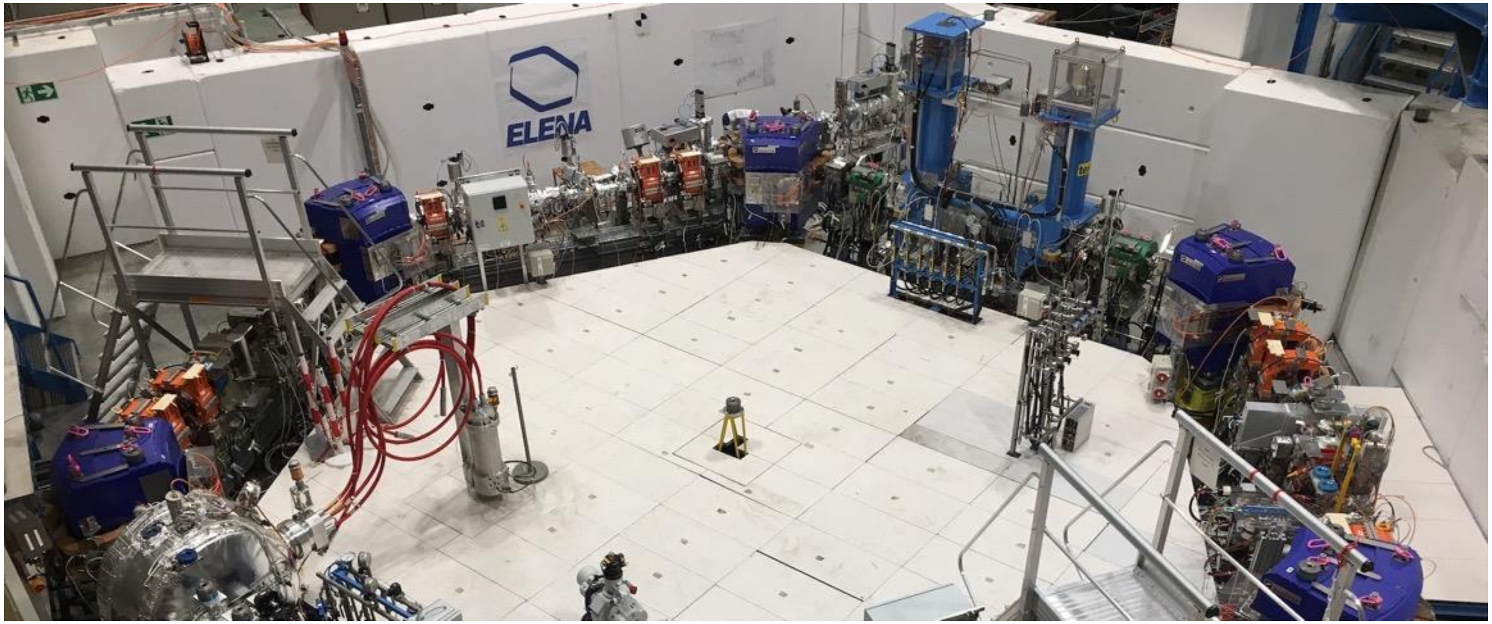
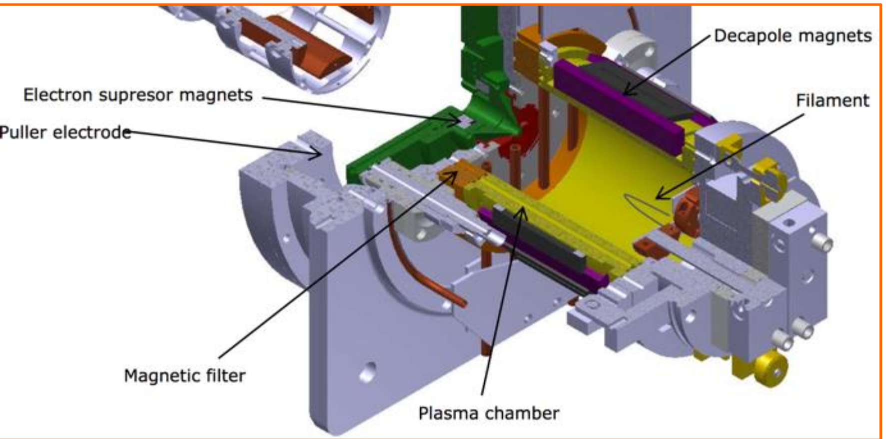
2019/2020



- It contains several observations from 2019 on the behavior of the source.
- Attempt to find reasons for the observed instability.

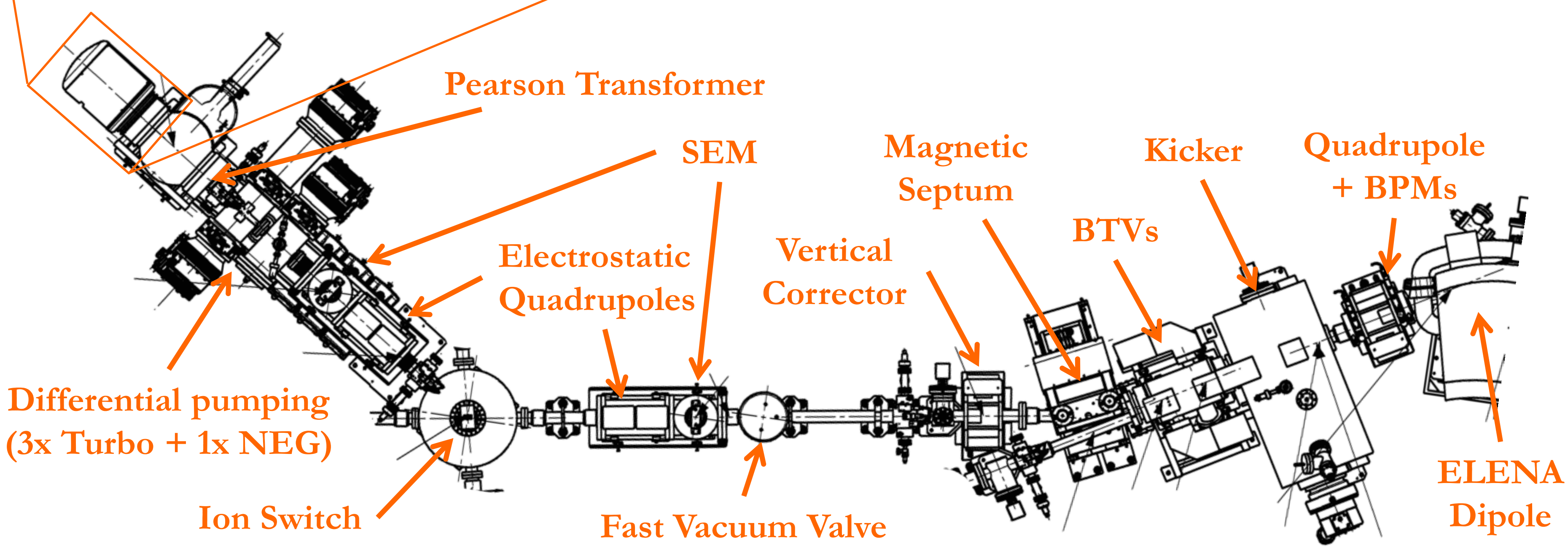
From Source to Ring



Only DC Power Supplies control via PLC in Faraday Cage

Wish list:

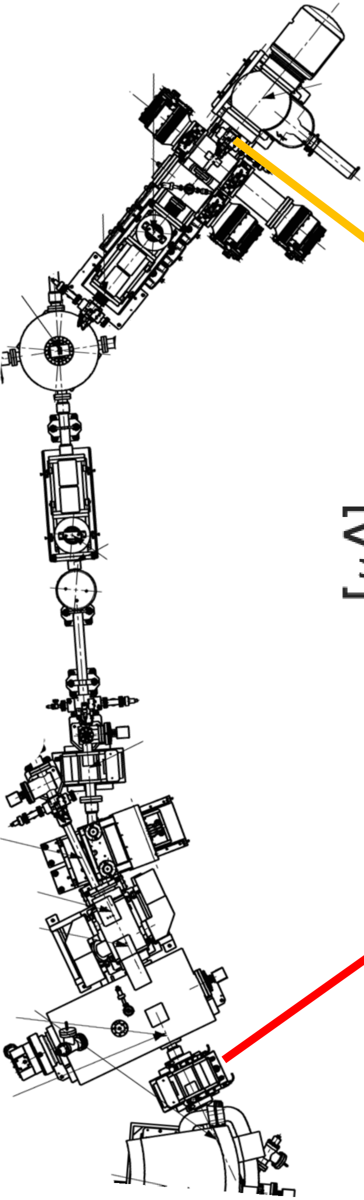
- ~100 uA; ~1 us; ~square pulses
  - Only 650 ns-long pulses injectable by kicker
- Good Stability/Repeatability
  - order ~1% for intensity and beam shape
  - order ~0.1% better for energy
- Transverse optics matched to ring

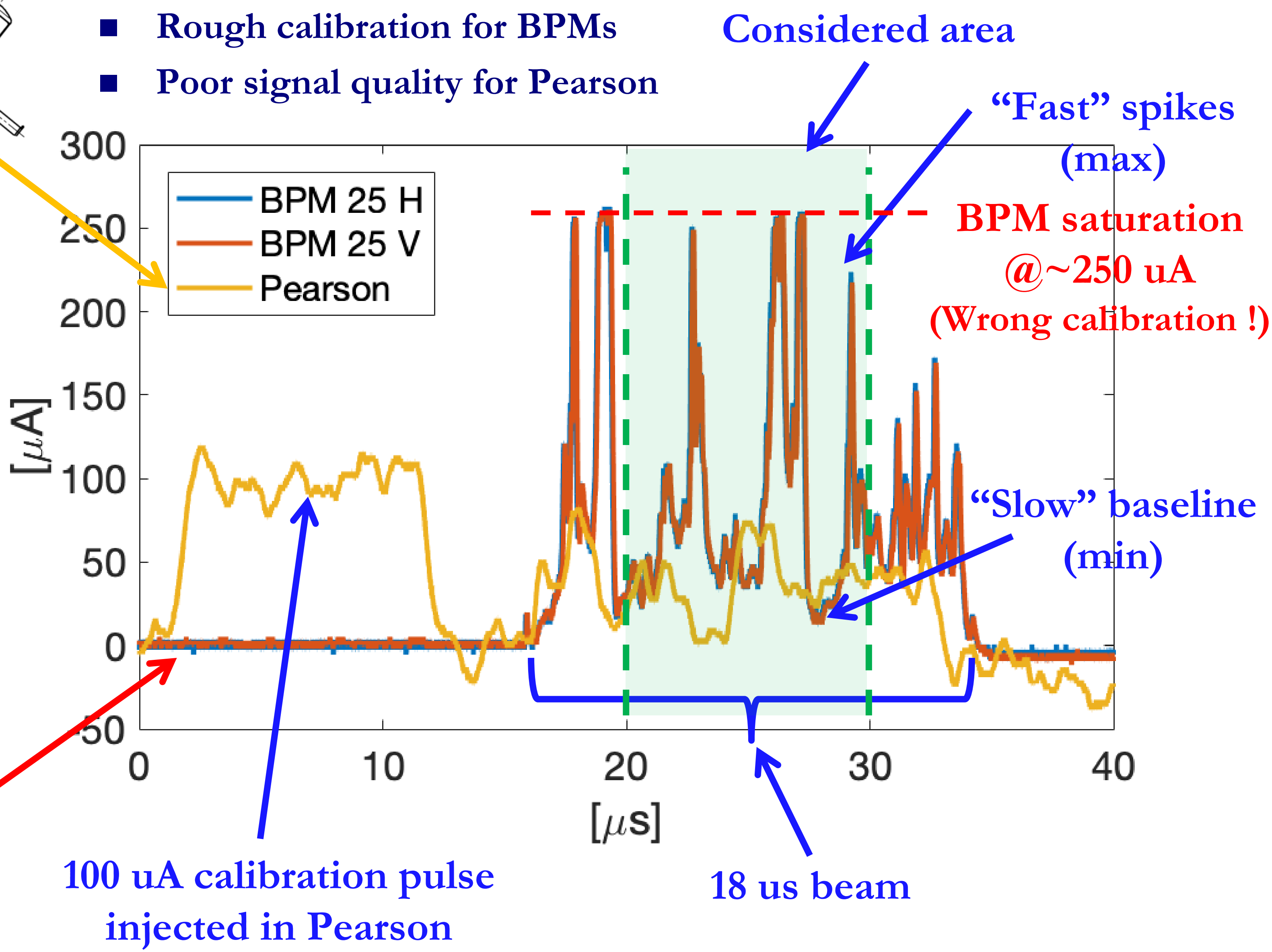


Beam observations

Typical acquisition begin 2019

- Rough calibration for BPMs
- Poor signal quality for Pearson

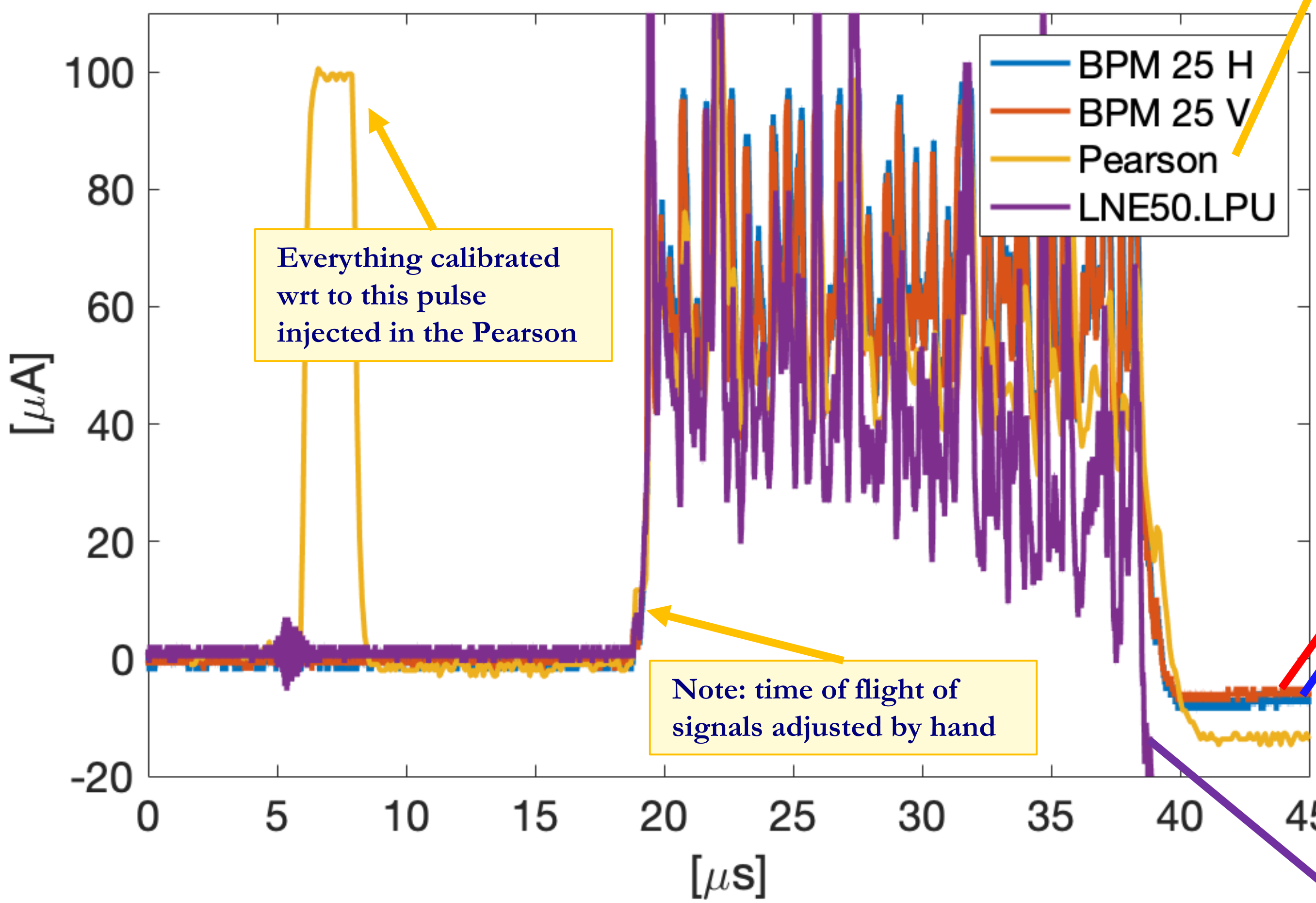


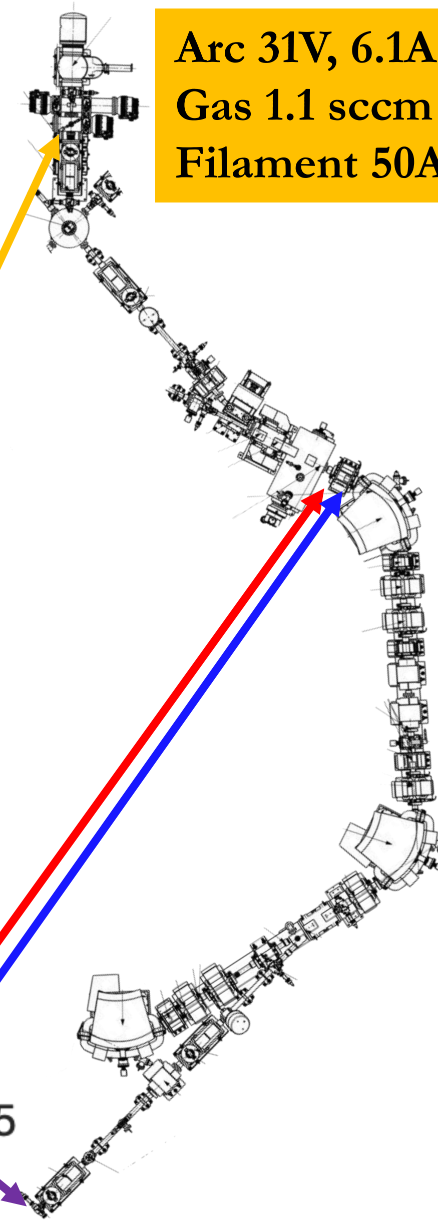


Typical acquisition end of 2019

- 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)

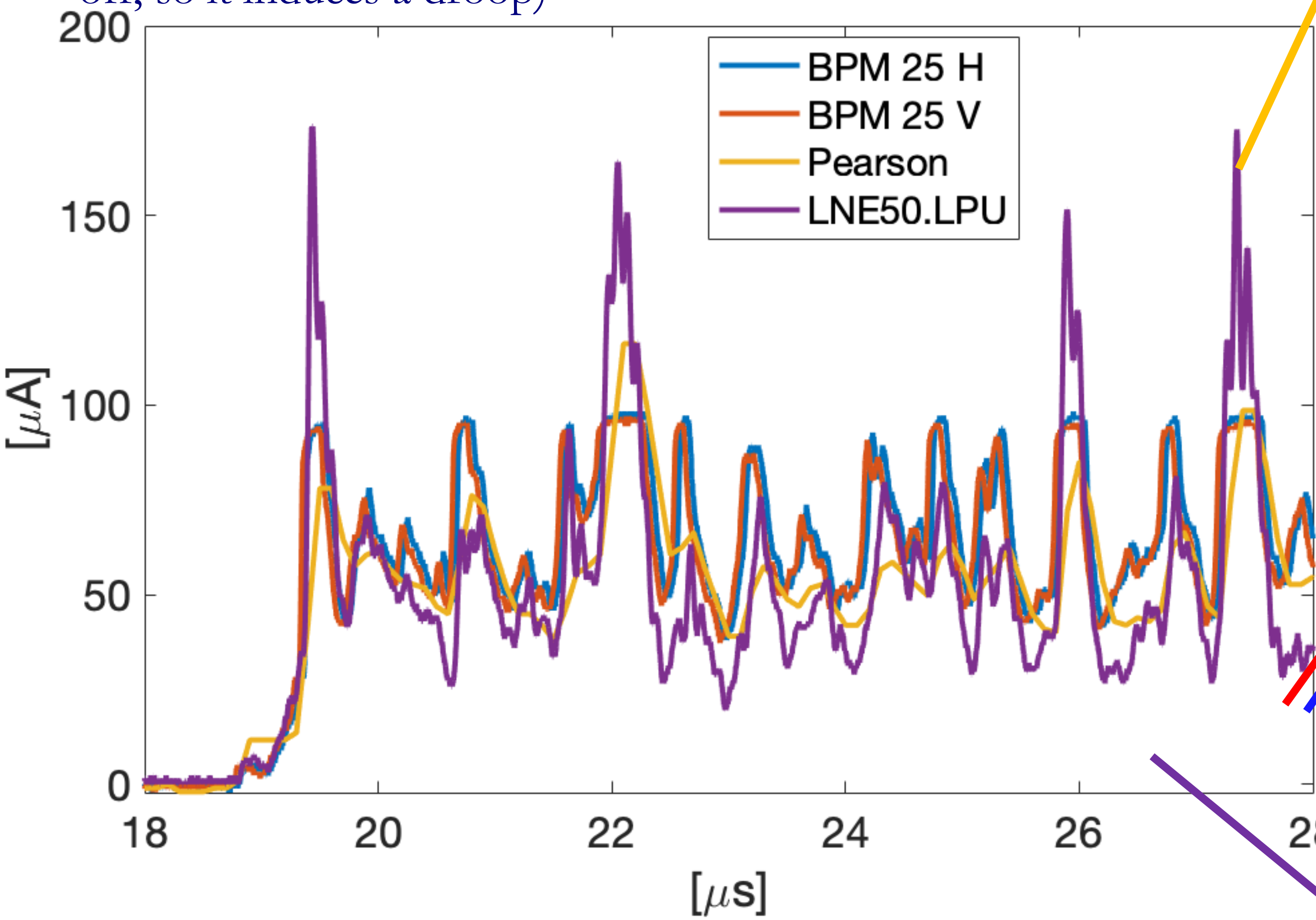
Arc 31V, 6.1A
Gas 1.1 sccm
Filament 50A

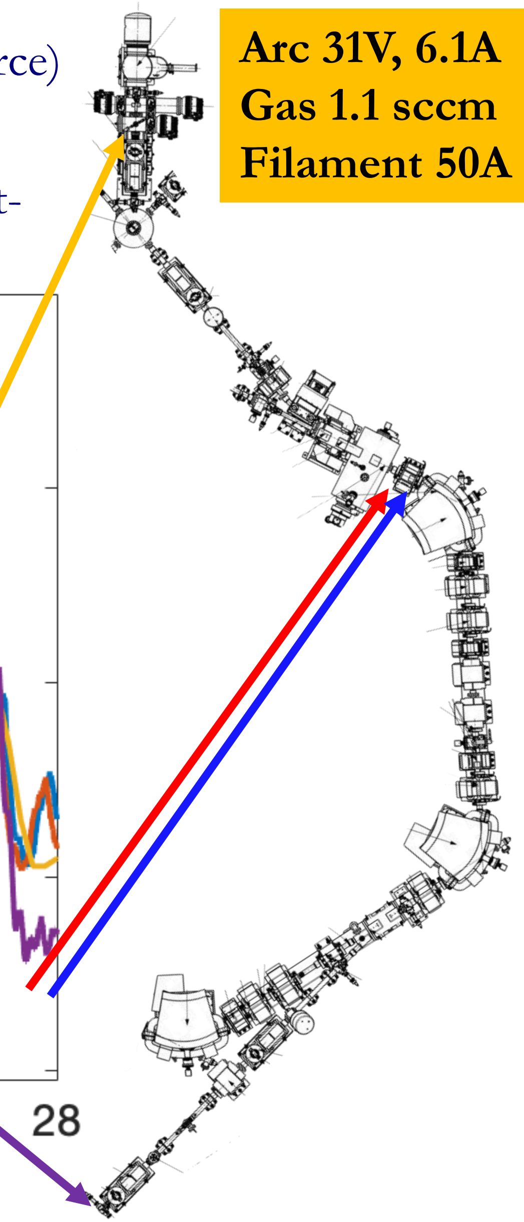




Typical acquisition end of 2019 - zoom

- 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)

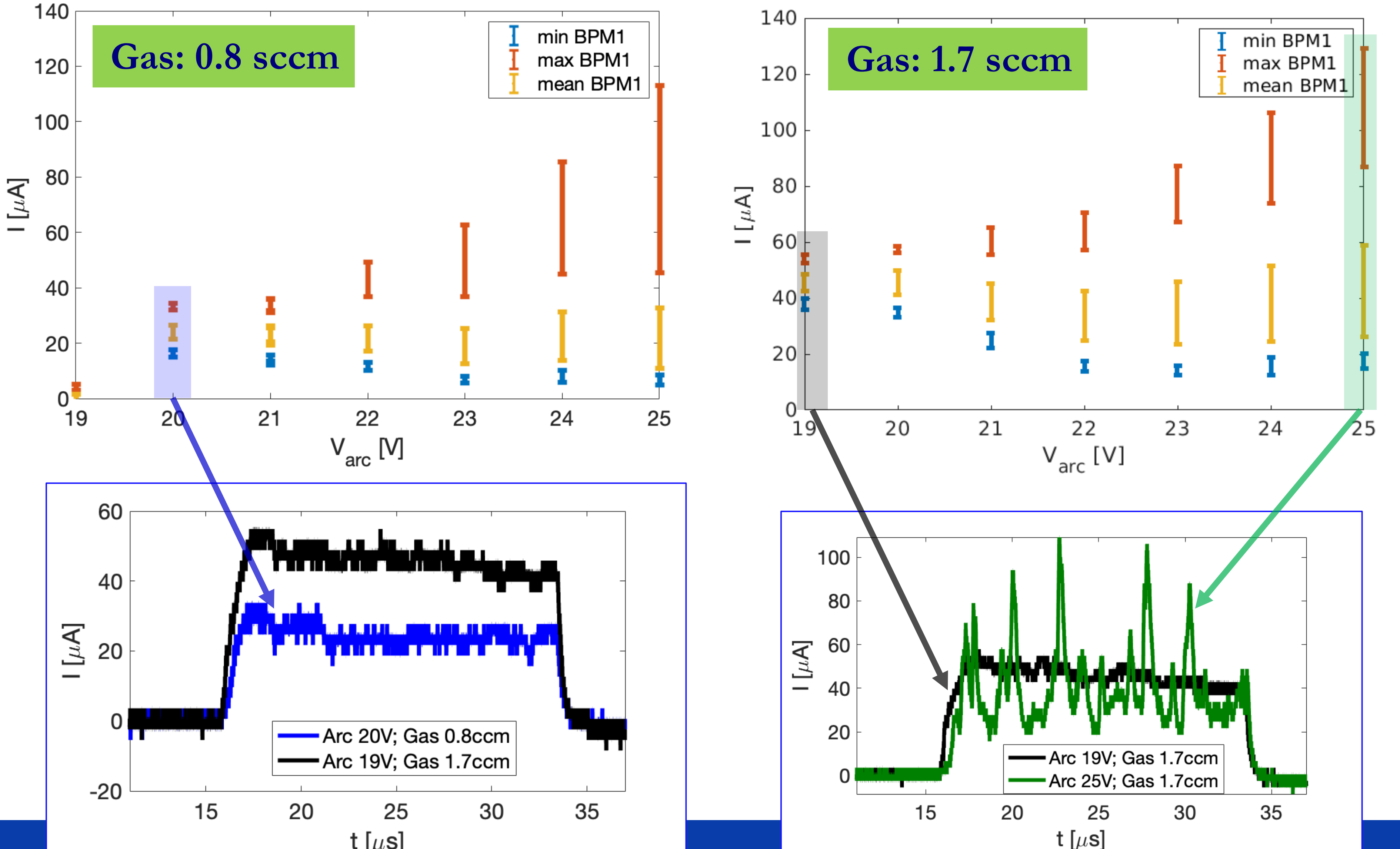




Arc 31V, 6.1A
Gas 1.1 sccm
Filament 50A

Scan over some parameters

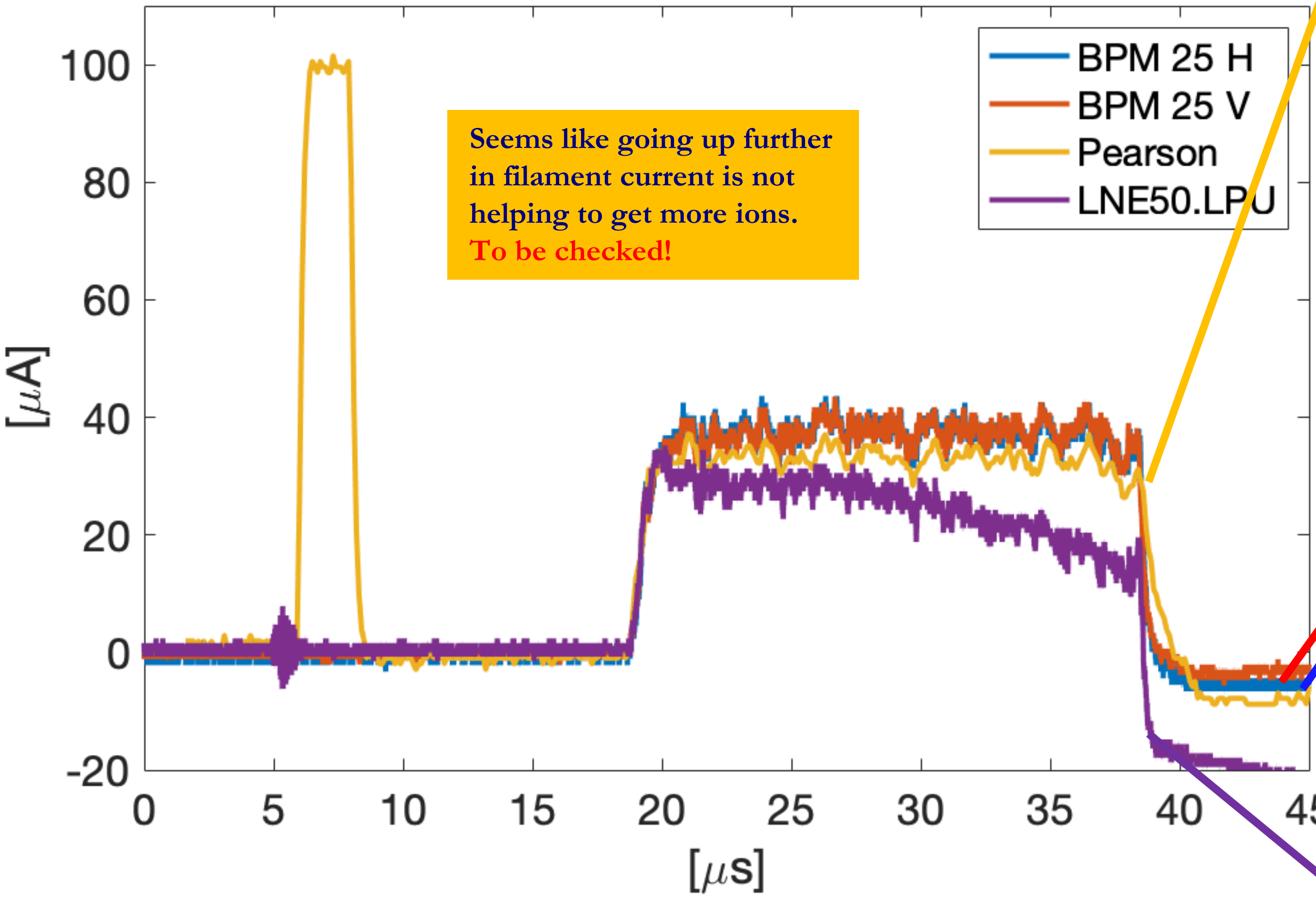
- Basic parameters: 2650 V_{puller}; 6% filament; 70 V_{arc}

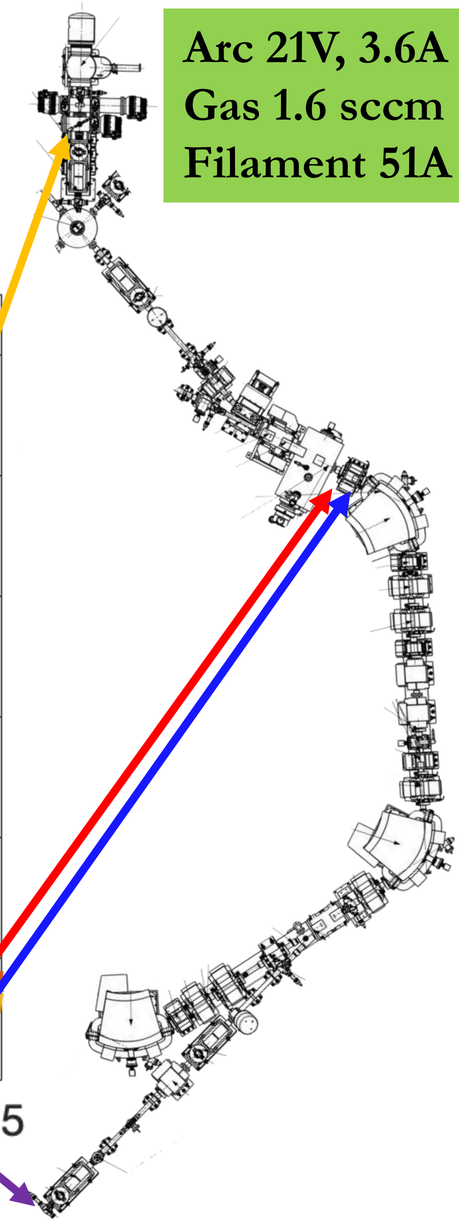


And a better beam

- 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)

Arc 21V, 3.6A
Gas 1.6 sccm
Filament 51A





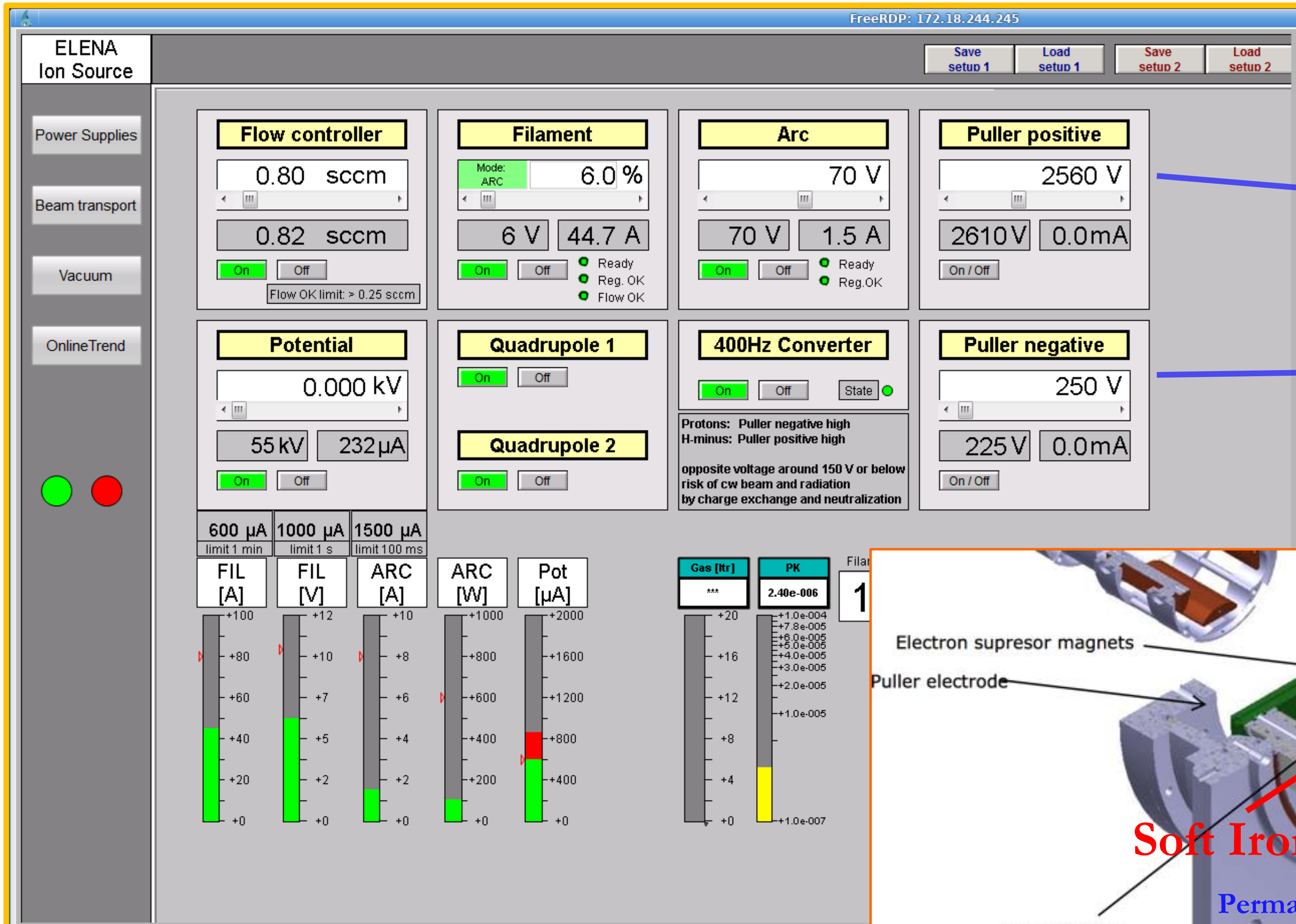
Open questions here (2020)

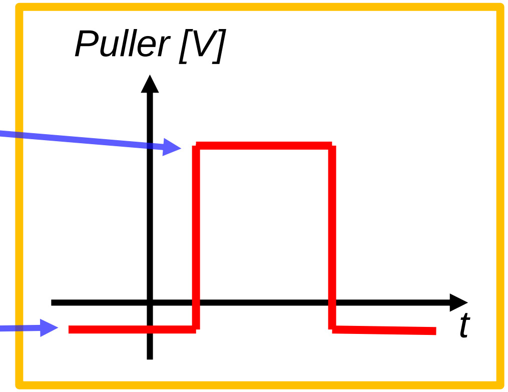
1. **Calibration factor of LPU to crosscheck intensity measurement**
2. **BPMs calibration factor: why 2.7 times error wrt "standard" formula?**
3. **Measure $I_{beam}(I_{fil})$ and $I_{beam}(Q_{sccm})$**
   - ***How high can we go?***
   - ***Check beam size (emittance) while going up.***

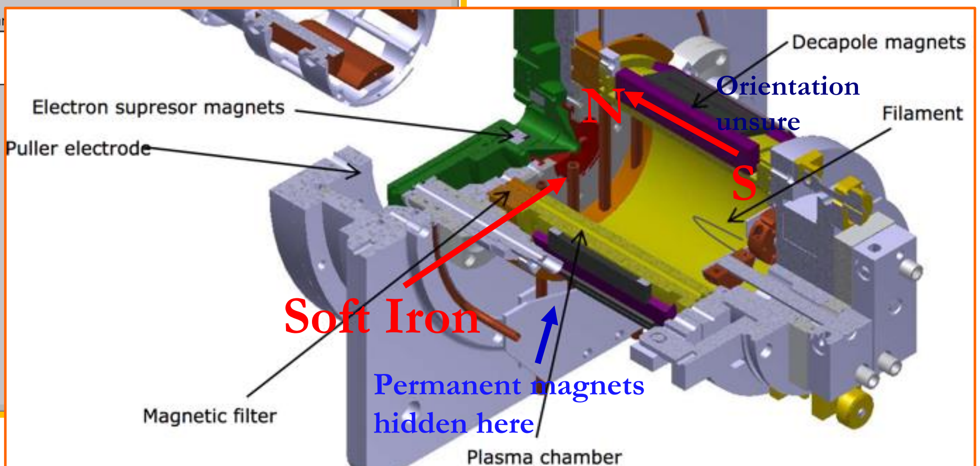
Looking more in detail at the source

Source control

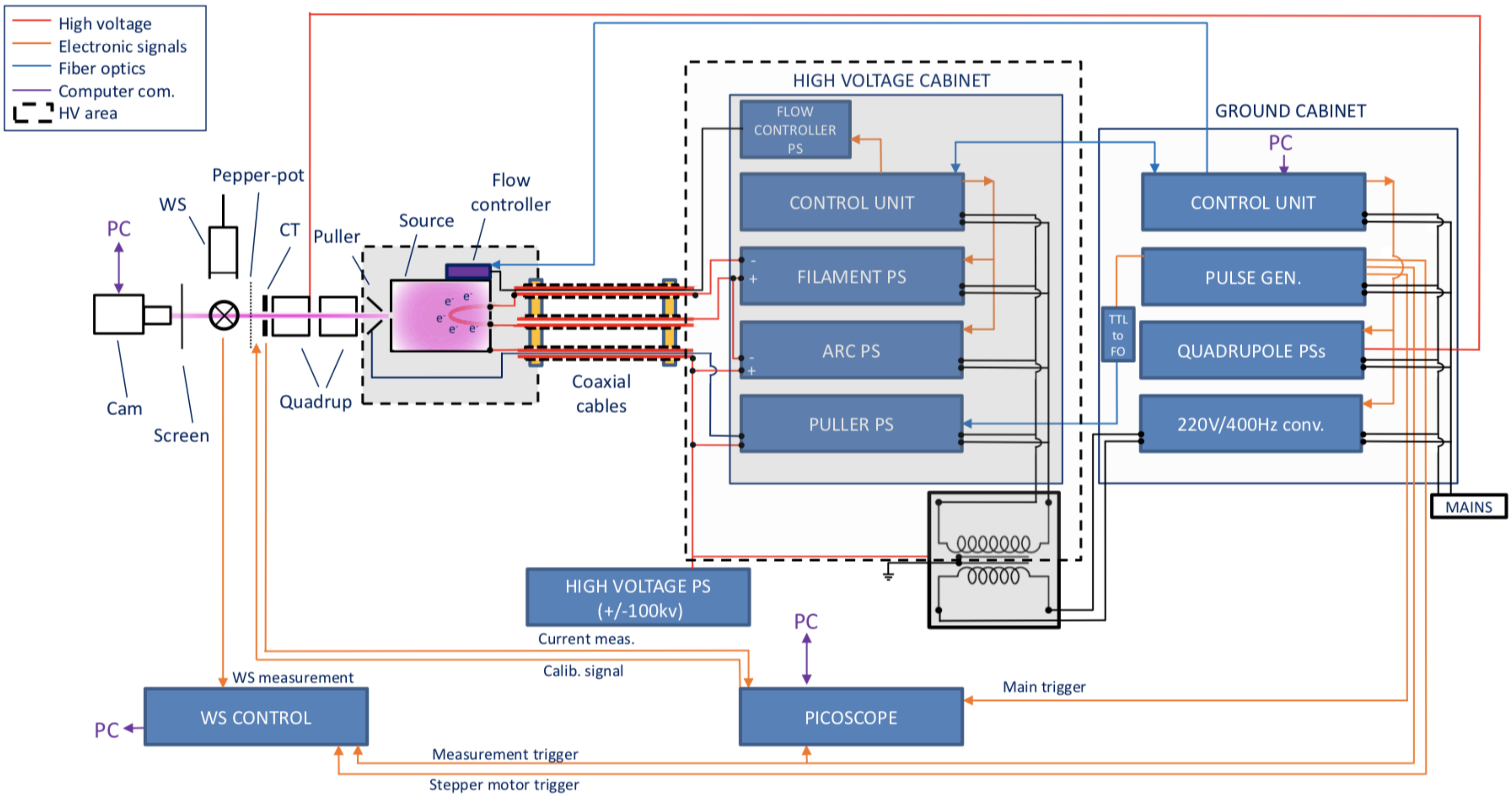
- Control via PLC of main DC voltages
- Filament automatically regulated to keep Arc current stable (?)







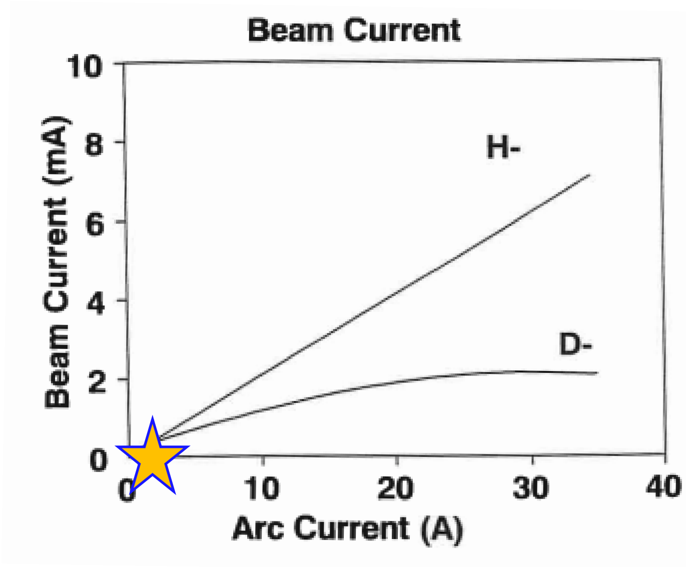
Source cabling



from Ana Megía-Macías - link

Source operation point

(with respect to source user manual graphs)

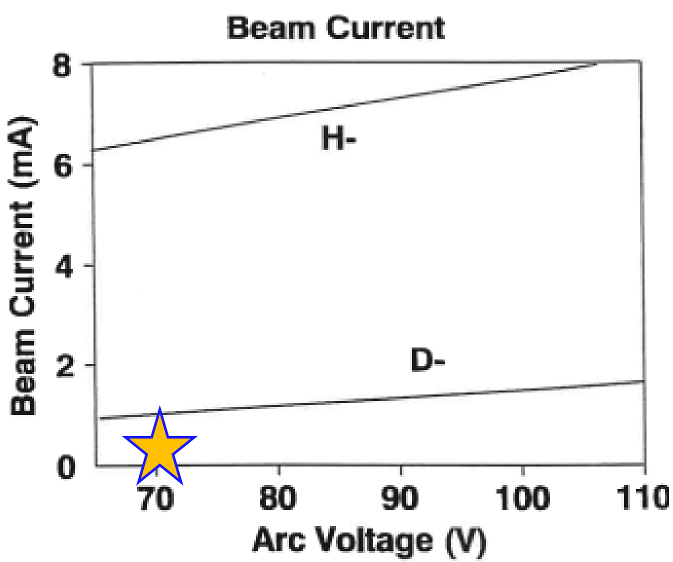


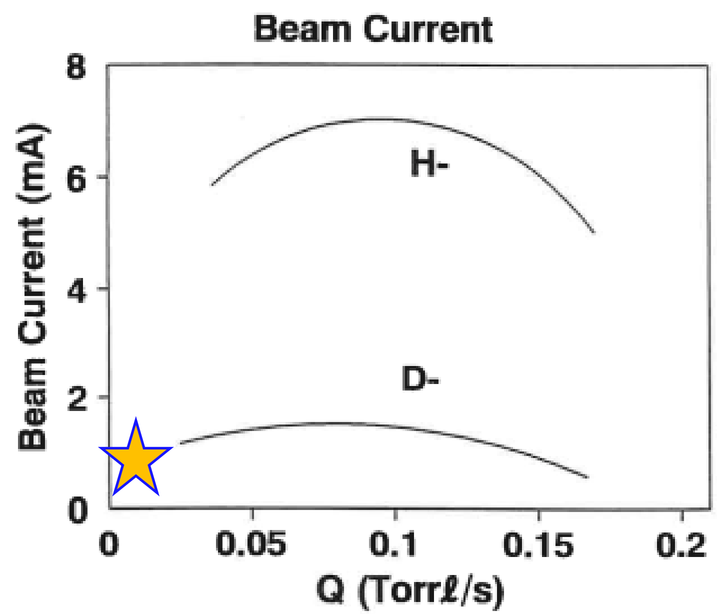
ELENA source

Iarc=1-2 A

Uarc=70 V

Q=0.006-0.018 Torr*l/s





Settings used in the past by Ralf

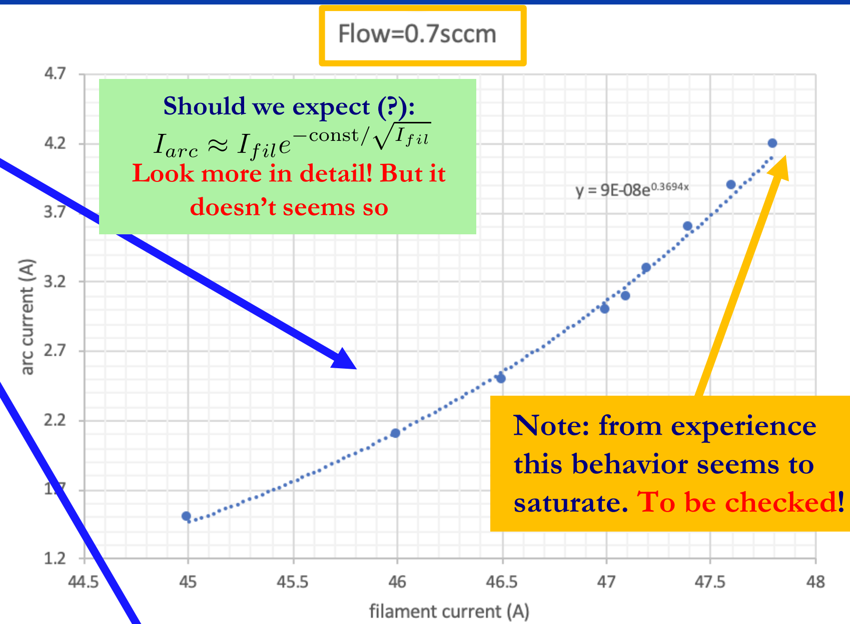
- Note that arc and filament currents are much higher here (IPAC2015)!
  - (but probably due to a different filament length/diameter)

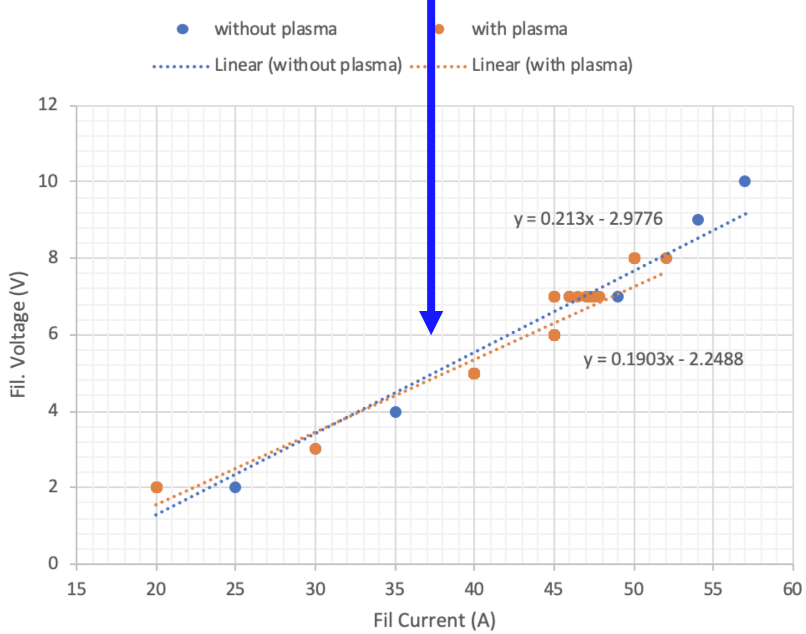
Table 2: Preliminary Results for +/−100 kV Beams

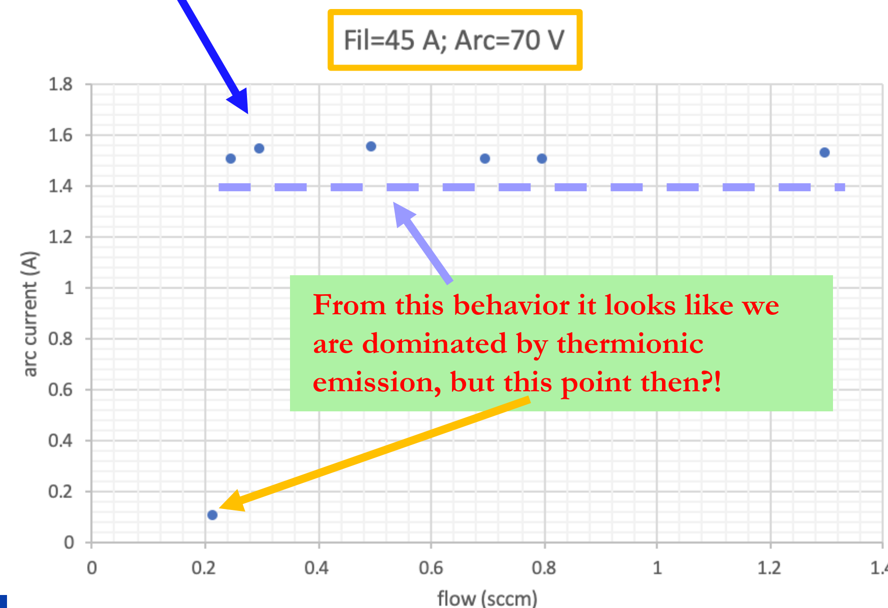
Parameter		100 μA H^-	150 μA p
Arc Current	[A]	$\boxed{3.0}$	1.0
Arc Voltage	[A]	75	75
Extraction Voltage	[kV]	-3.0	+2.9
Suppression Voltage	[kV]	+.2	-0.2
Filament Current	[A]	$\boxed{76.0}$	73.4
Gas Flow	[sccm]	0.90	0.60
TWISS			
$\epsilon_{RMS,norm}$	[μm rad]	0.26	0.37
α		-0.11	-0.14
β	[m/rad]	0.37	0.27
γ	[m/rad]	2.76	3.74

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

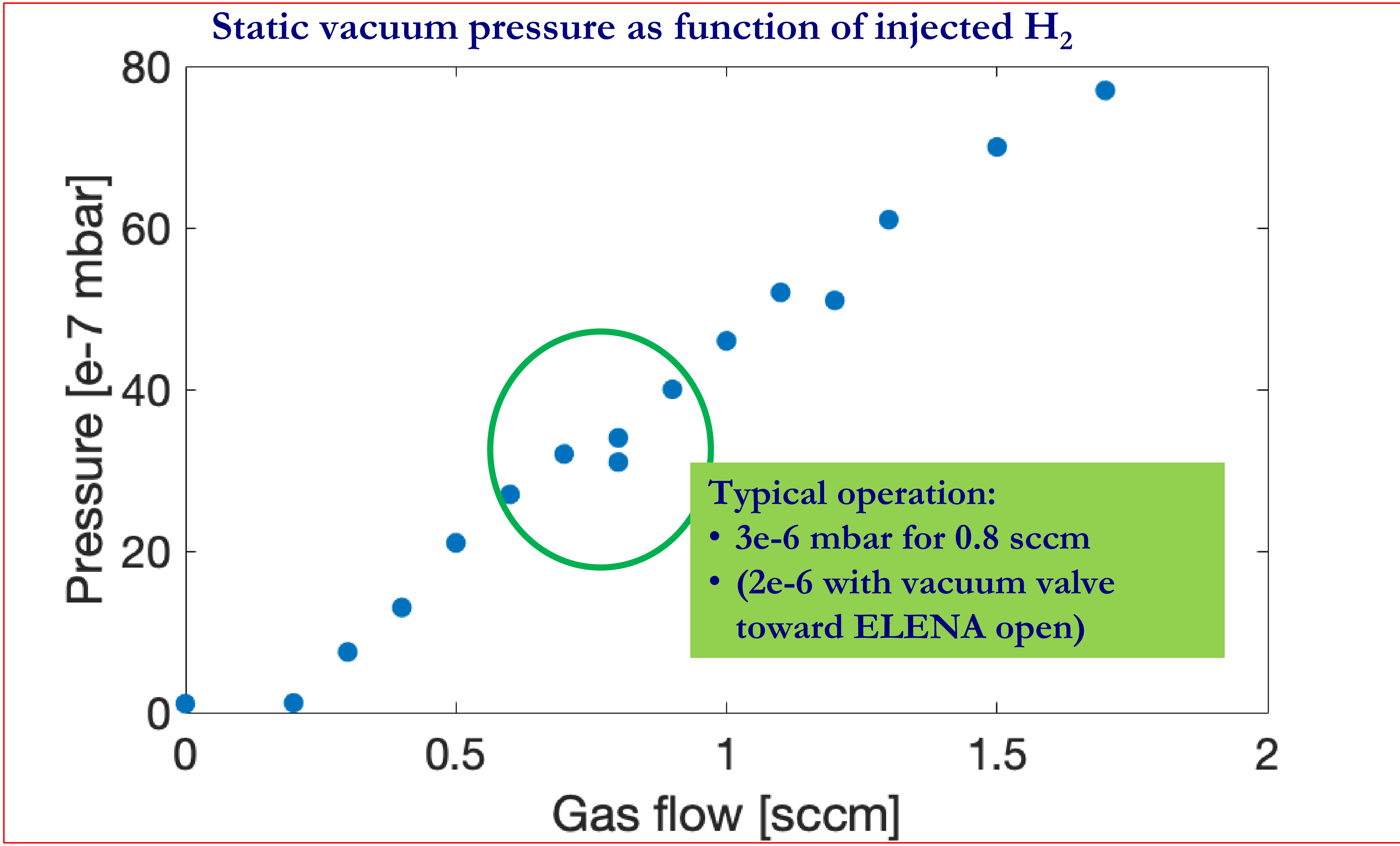






Vacuum considerations

Vacuum measurements



Estimated pressure in the source

$$C_{or,mol,H_2}[\mathrm{l/s}] = 43.8 \cdot A \quad \text{@20deg for } \mathrm{H_2}$$
$$A := \text{cross section } [\mathrm{cm}^2]$$

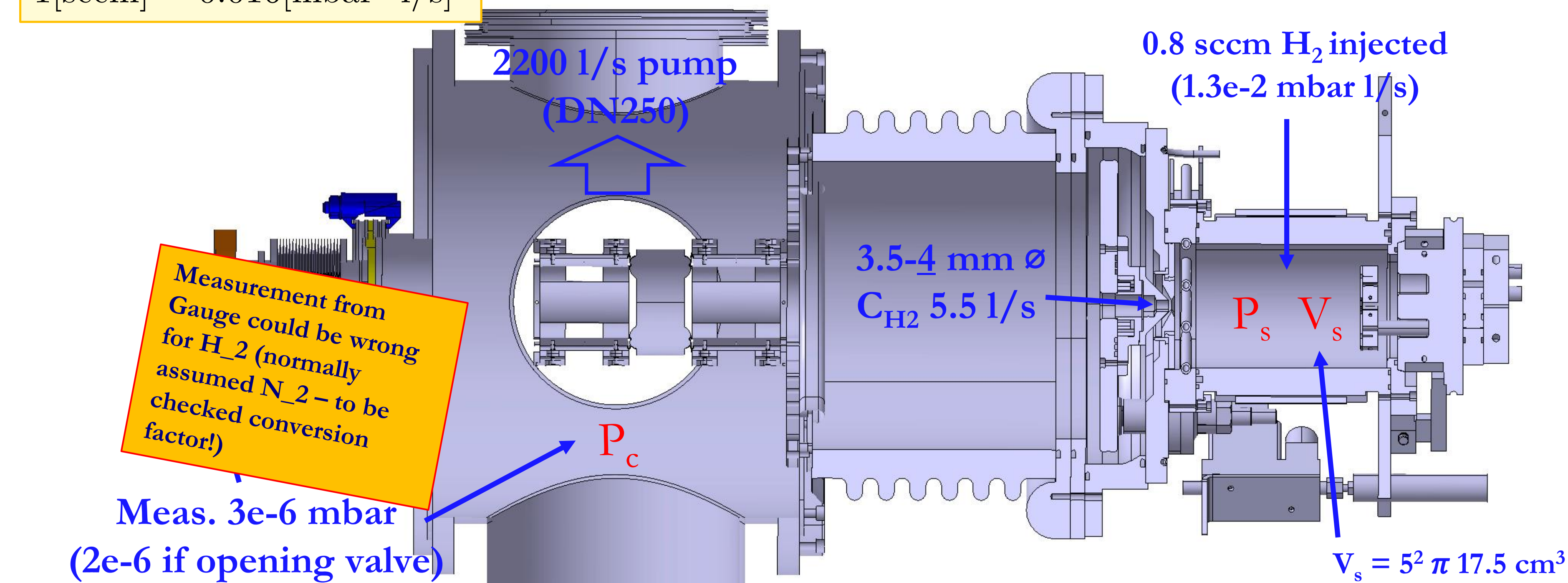
$$P_c \cdot S = Q = C_{or}(P_s - P_c)$$
$$P_c\left(\frac{S}{C_{or}} + 1\right) = P_s = (2200/5.5+1)P_c = 400P_c$$

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

Estimate of gas density:

$$n_{H_2} = N_A \frac{P_s}{RT}$$
$$n_{H_2} = 2.47 \times 10^{22}[\mathrm{m}^{-3} \cdot \mathrm{mbar}^{-1}] \cdot P_s[\mathrm{mbar}]$$

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



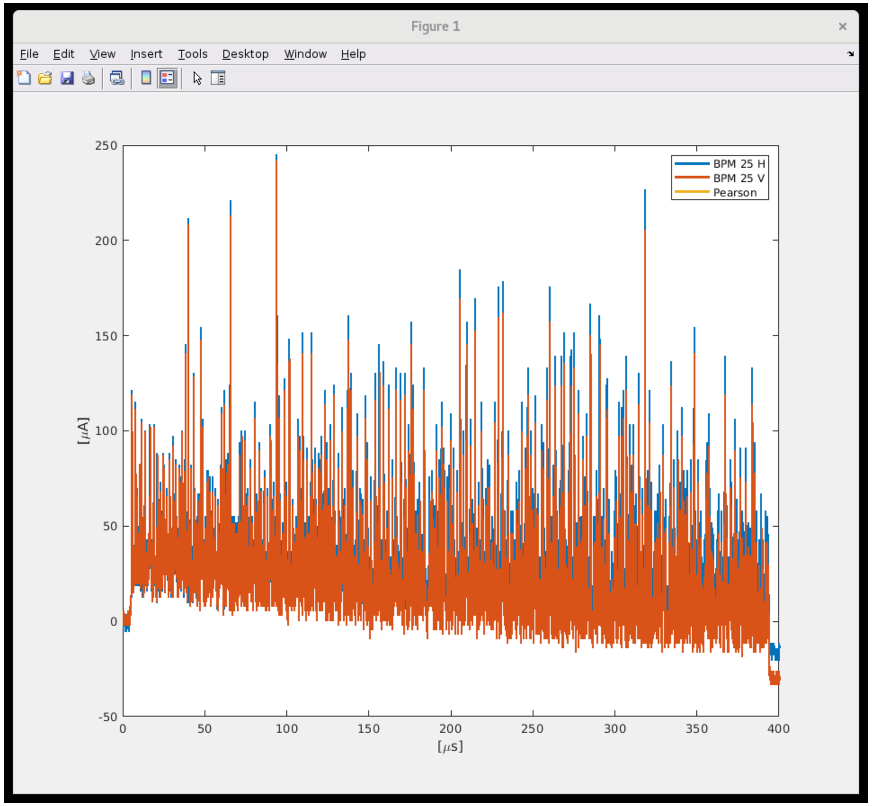
$$P_c = \frac{Q}{S} = \frac{1.3 \times 10^{-2}}{2200} = 6 \times 10^{-6}[\mathrm{mbar}]$$

Crosscheck of expected vacuum pressure : we are wrong only of factor 2 somewhere

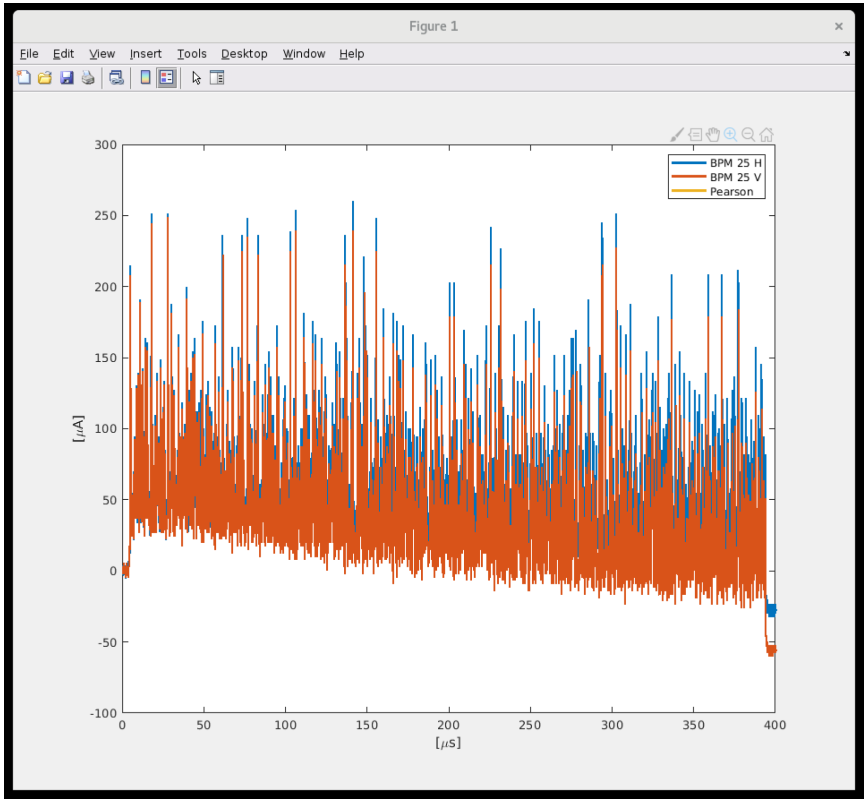
Frequency of the instability

Long pulses (390 us) - different gas P

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

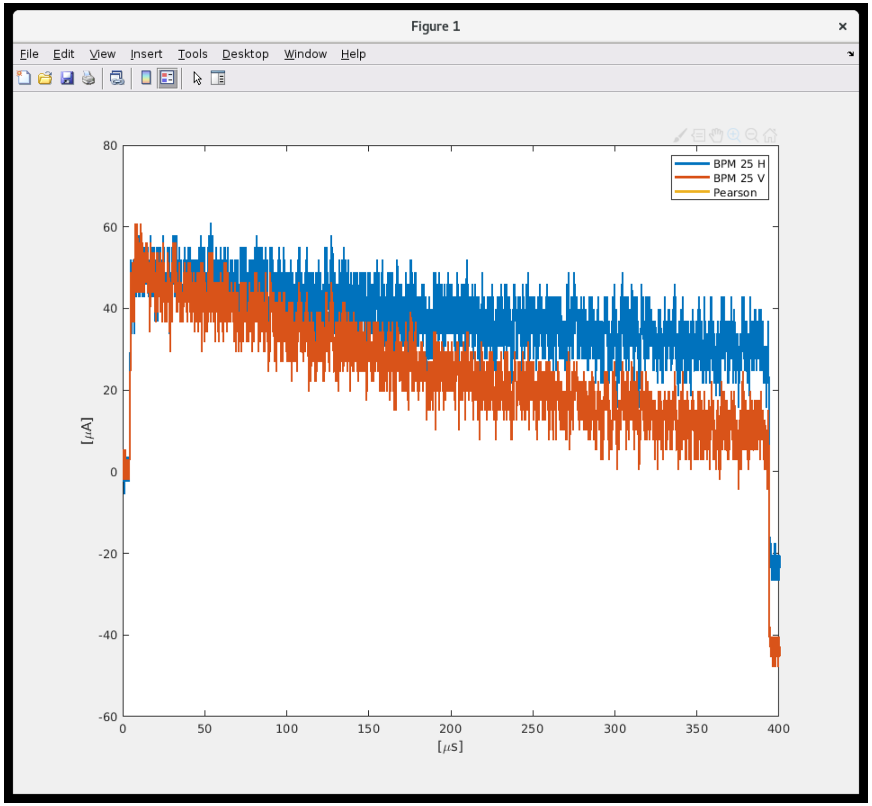


2650 V_{puller}; 6% filament (7V_{fil}, 45.8 A_{fil}); 30 V_{arc} (1.5 A_{arc}); **1.6 sccm**

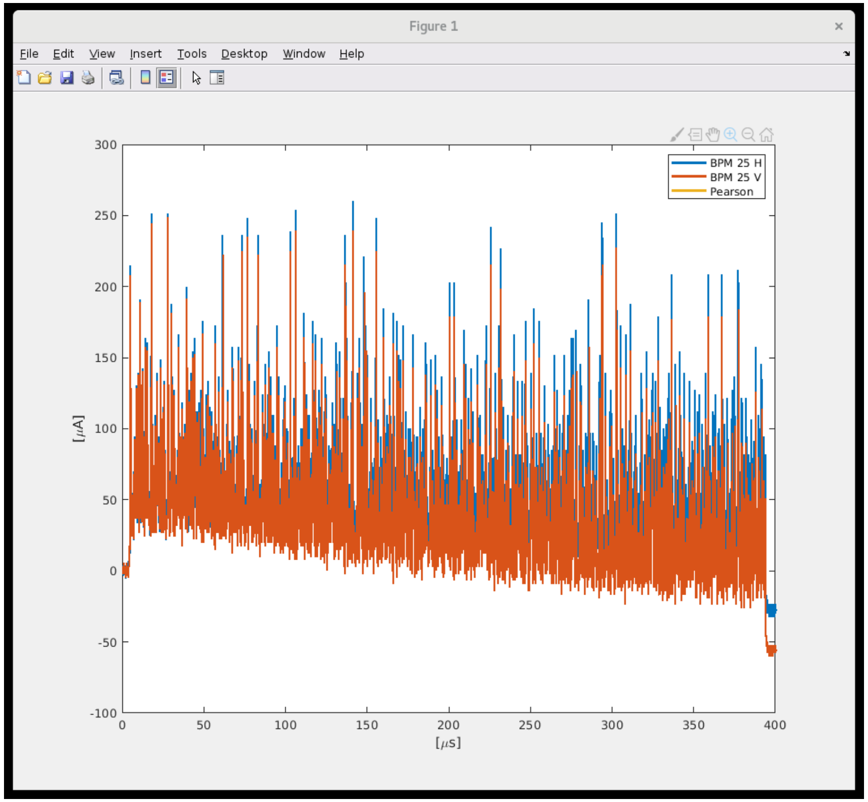


Long pulses (390 us) – different V_{arc}

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

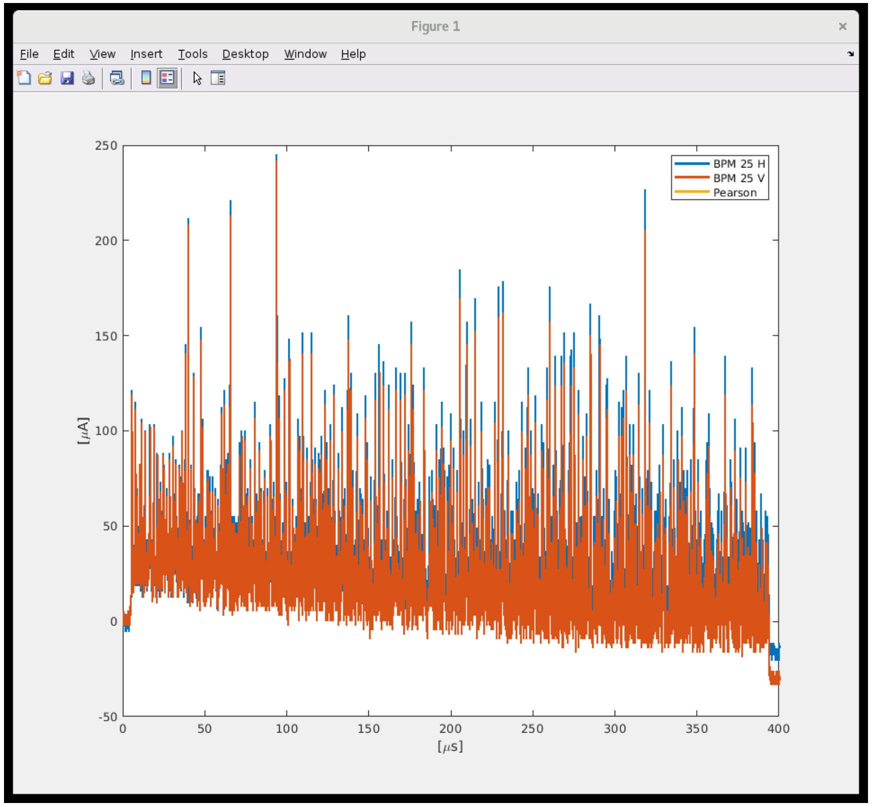


2650 V_{puller}; 6% filament (7V_{fil}, 45.8 A_{fil}); **30 V_{arc}** (1.5 A_{arc}); **1.6 sccm**

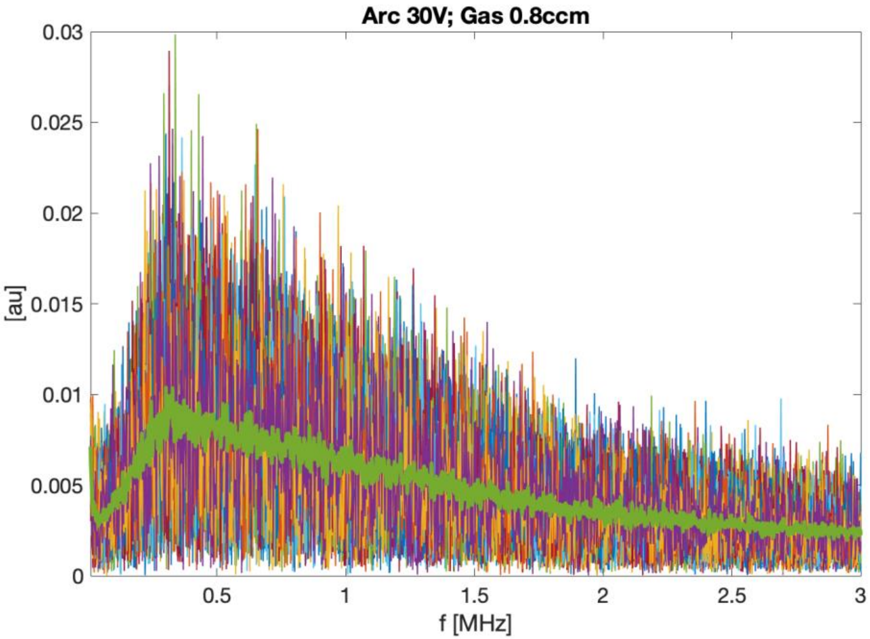


Long pulses (390 us)

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



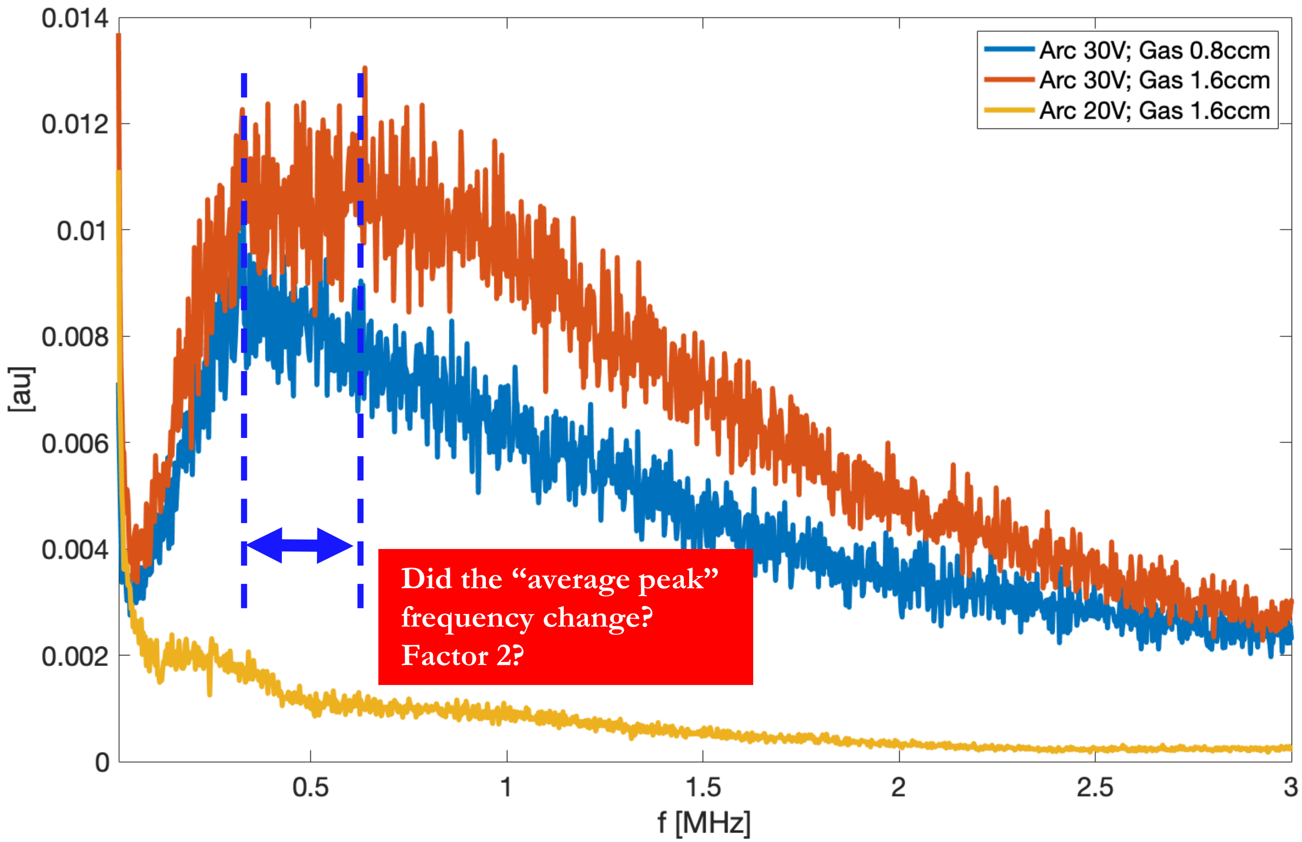
FFT of several shots, and mean over all FFTs:



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.)**



Plasma frequency

$$\omega_p^2 = \frac{n_e e^2}{m_e \epsilon_0} \Rightarrow f = \frac{1}{2\pi}\frac{e}{\sqrt{m_e \epsilon_0}}\sqrt{n_e} = \boxed{8.979\sqrt{n_e}}$$

$$\epsilon_0 = 8.854187817 \cdot 10^{-12}\ [\mathrm{F/m}]$$
$$e = -1.602176634 \cdot 10^{-19}\ [\mathrm{C}]$$
$$m_e = 9.10938188 \cdot 10^{-31}\ [\mathrm{kg}]$$

- 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]

Open questions here (2020)

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

$$j = AT^2 e^{-\frac{e\Phi_W}{k_B T}}$$

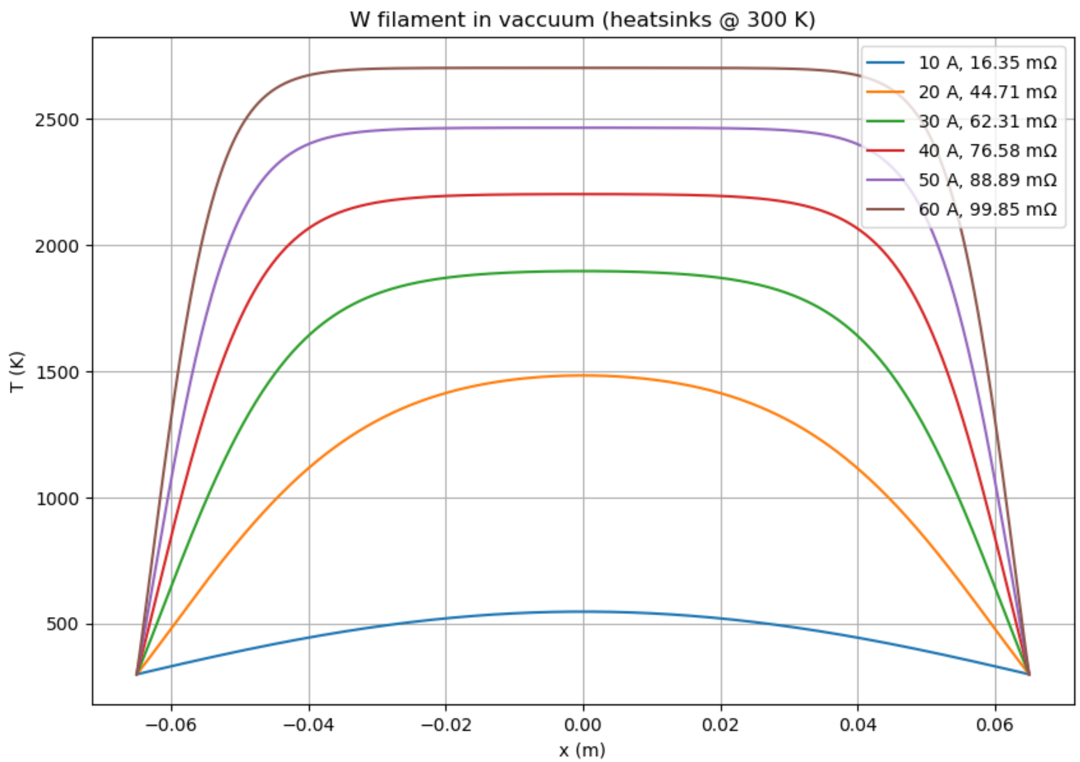
where:

$$\begin{cases} \Phi_W &= 4.52\,[\mathrm{V}](\mathrm{Tungsten}) \\ &= 2.63\,[\mathrm{V}](\mathrm{Thoriated\ Tungsten}) \\ k_B &= 8.617 \times 10^{-5}\,[\mathrm{eV/K}] \\ A &\approx 6 \times 10^5\,[\mathrm{Am^{-2}K^{-2}}](\mathrm{Tungsten}) \\ &\approx 3 \times 10^4\,[\mathrm{Am^{-2}K^{-2}}](\mathrm{Thoriated\ Tungsten}) \end{cases}$$

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

Estimation of filament T



Is this estimate correct? To which precision?

Usually operating with 38-46 A filament current

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 and 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"?

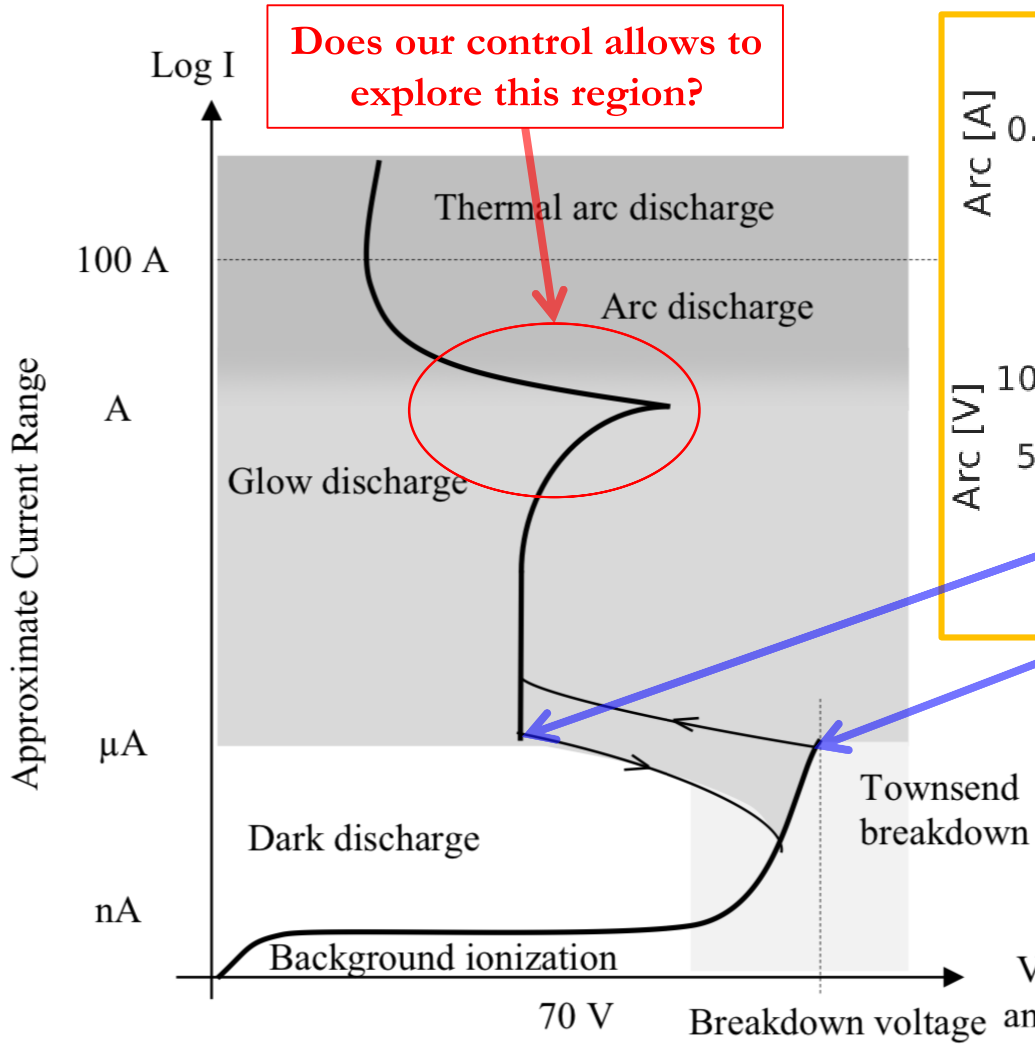
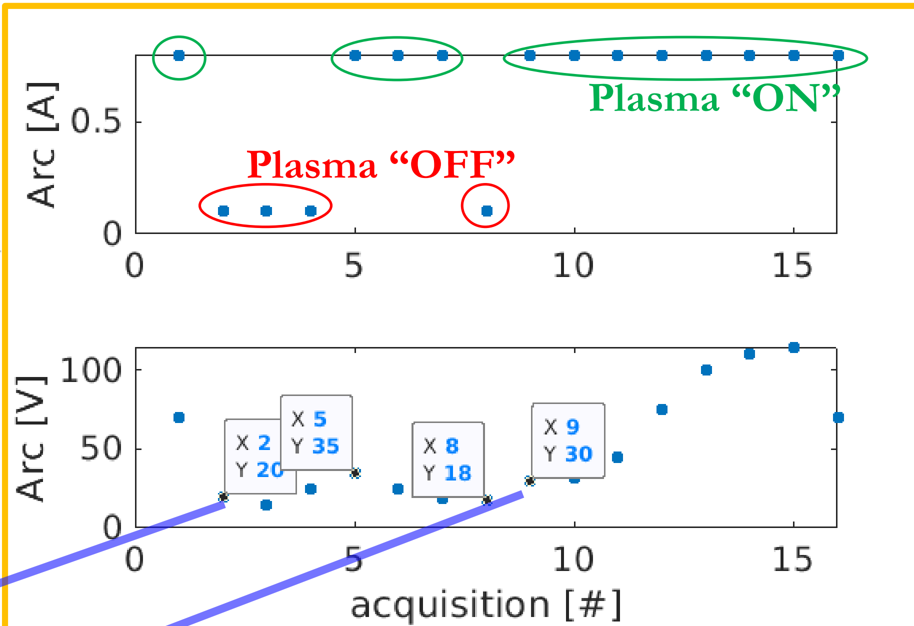


Fig. 3: The current voltage characteristics of a typical electrical discharge



We need ~30 V to "start" the plasma, then down to ~20 V to stop it

Note: here, with "arc control" I_{arc} is stabilized by very small variation of $I_{filament}$!

From ***Ion sources for high-power hadron accelerators*** by *D. C. Faircloth* - link

Open questions here (2020)

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_{arc} with no injected H_2 gas, but maybe because of rest gas being ionized.

On H^- production

H^- production mechanism

- Production H^- production via:

$$H_2^*(\nu \geq 5) + e^- \rightarrow H^- + H$$

  - Vibrationally-excited H_2 in state 5 or above.
  - **e^- < 1eV** (H^- binding energy = 0.75 eV)

- Excitation of H_2 molecule:

$$H_2(\nu = 0) + e^-_{fast} \rightarrow H_2^*(\nu \geq 5) + e + h\nu$$

  - It requires **e^-_{fast} > 20 eV**

Indeed, if V_{arc} < 20 V, I_{arc} drops and we indeed don't see any(?) H^-
Is it really 20 eV? Not 10 eV?

- H^- "destroyed" by two main processes:

$$H^- + H^+ \rightarrow 2H \qquad\qquad H^- + H \rightarrow H_2^* + e^-$$

According to IBA training course EDMS

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:

$$D_e = \frac{k_B T_e}{m_e \nu_c} \quad \text{where} \quad \begin{cases} \nu_c = n_e K T_e^{-3/2} & \text{collision frequency.} \\ K & \text{constant describing collision process (no estimate, yet).} \end{cases}$$

- It gets "modified" by magnetic field B via:

$$D_\perp = \frac{\nu_c^2}{\nu_c^2 + \Omega_{ce}^2} D_e \quad \text{where:} \begin{cases} \Omega_{ce} = \dfrac{eB}{m_e} & \text{is gyrofrequency (729/0.4 MHz e}^-\text{/p).} \\ r_g = \dfrac{v_\perp}{\Omega_{ce}} & \text{is gyroradius (\textasciitilde 1/40 mm e}^-\text{/p).} \end{cases}$$

- **Too high electron density (n_e) or too low magnetic field (B) spoils this fundamental separation.**

Open questions here (2020)

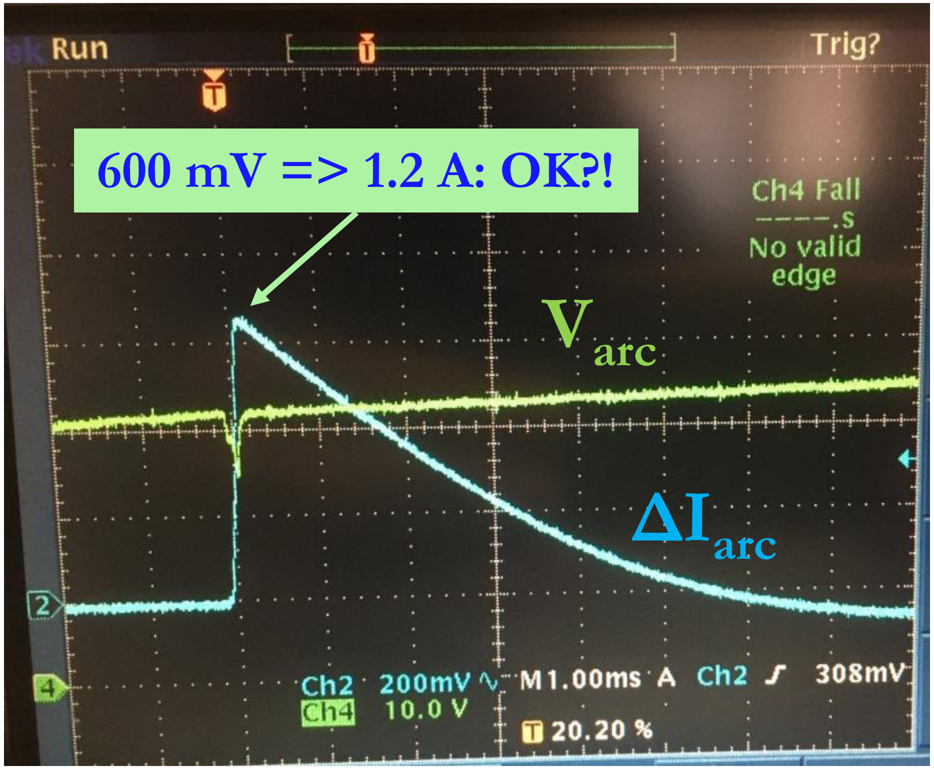
1. Looks like the H_2 ionization/excitation is driven both by thermionic discharge and gas discharge.
2. Should be looking in expected collision frequency to estimate actual separation between plasmas
3. Proton gyrofrequency is close to our 1 MHz observed instability. Does it mean something?

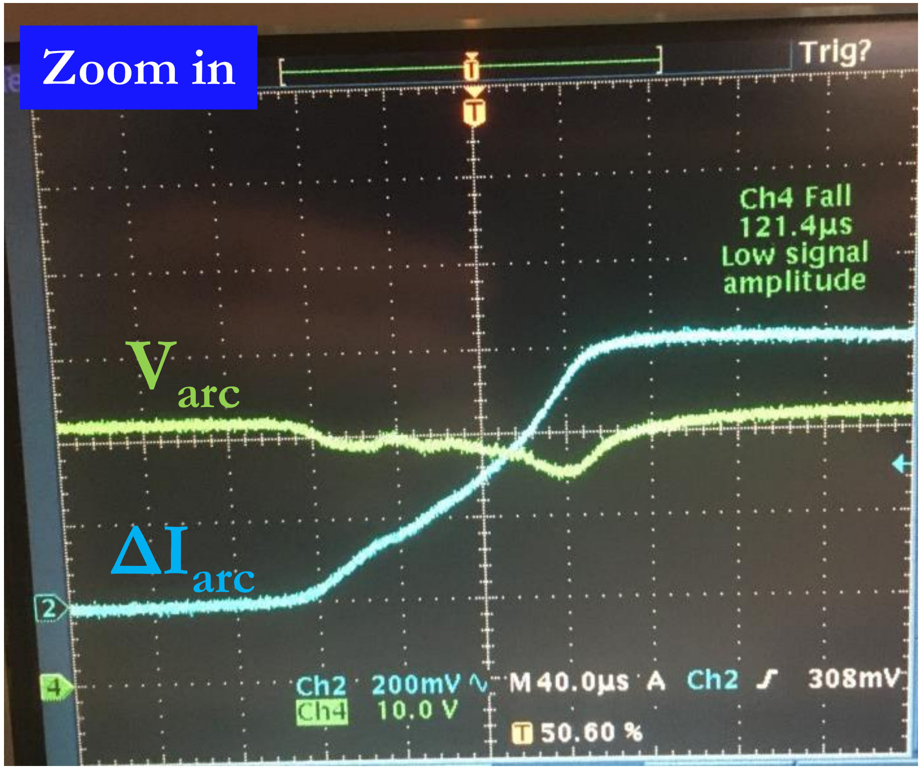
Voltages/Currents during plasma ignition

Measuring discharge ignition

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

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





Fall time of Arc voltage (without plasma)

Without plasma, switching off Arc PC from 40 V

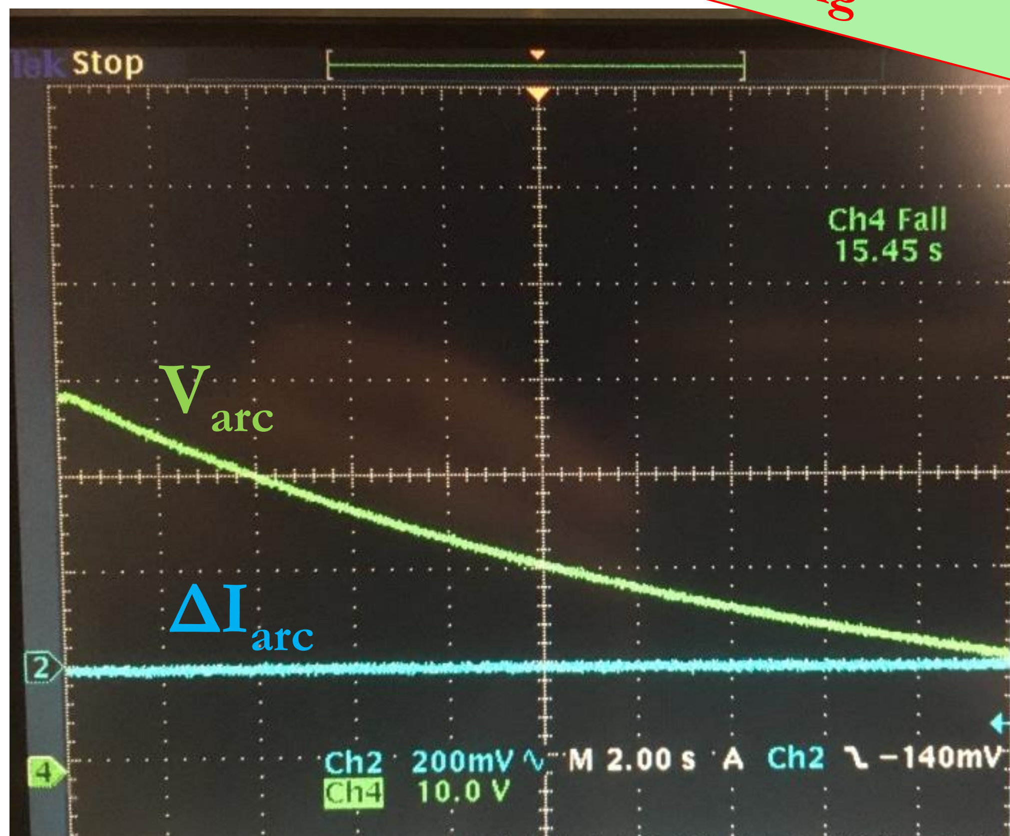
- I_{arc} measured with Pearson 150 (0.5 V/A) on **arc**
- V_{arc} measured on **PC output** on high impedanc
  100 kOhm resistance (see picture) – To be repeated wi

Dodgy measurements!
Probably not interesting/useful and maybe misleading

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

$$C = \frac{1.44 \times t_{1/2}}{R}$$
$$\approx \frac{15[s]}{100[kOhm]} = \boxed{150\mu F}$$

Lower limit, could be much higher!

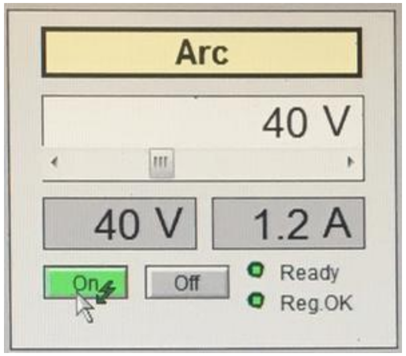


Fall time of Arc voltage (with plasma)

Without plasma, switching off Arc PC **from V_{arc} 40 V** ... **= 1.2 A**

- I_{arc} measured with Pearson 150 (0.5 V/A) on arc ...
- V_{arc} measured on **PC output** on high impedance ... loading resistance)

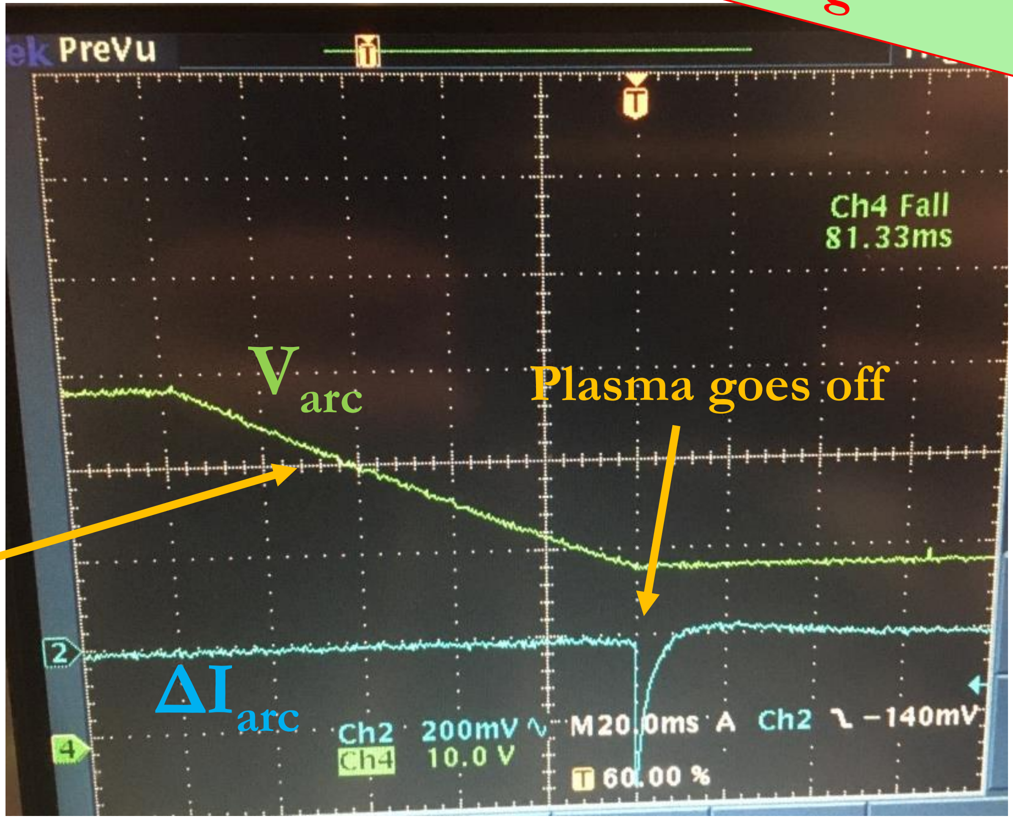
Dodgy measurements! Probably not interesting/useful and maybe misleading



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

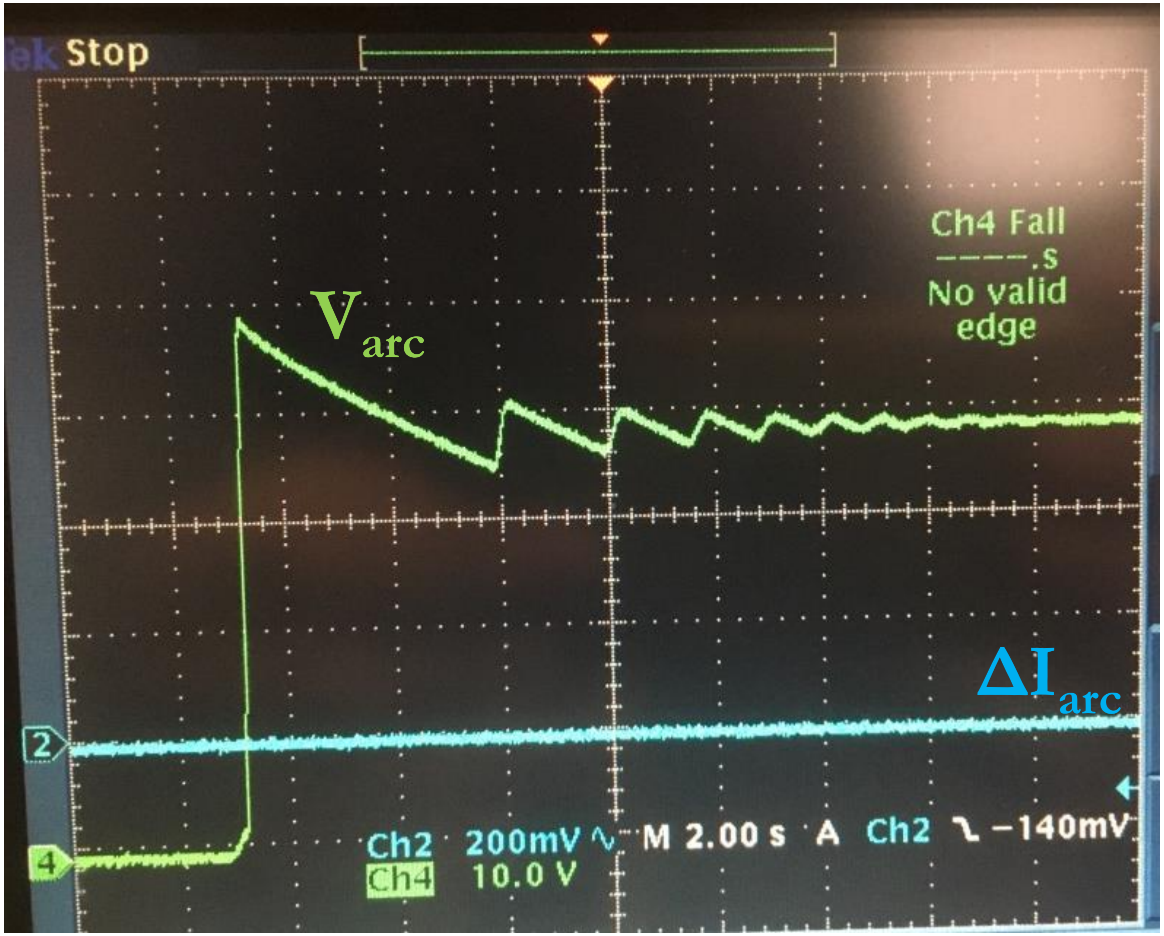
$$C = \frac{1.44 \times t_{1/2}}{R} \approx \frac{1.44 \times 100[ms]}{33[Ohm]} = \boxed{4363\mu F}$$

Does not fit value from un-loaded case?!



Regulation of Arc PC (unloaded)

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

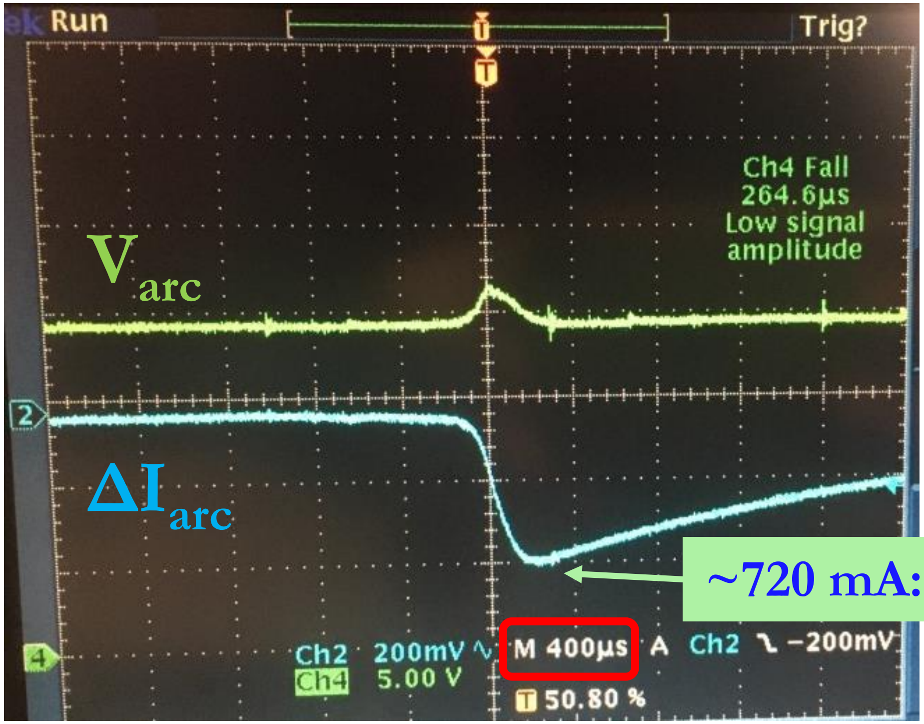


Restart and Regulation

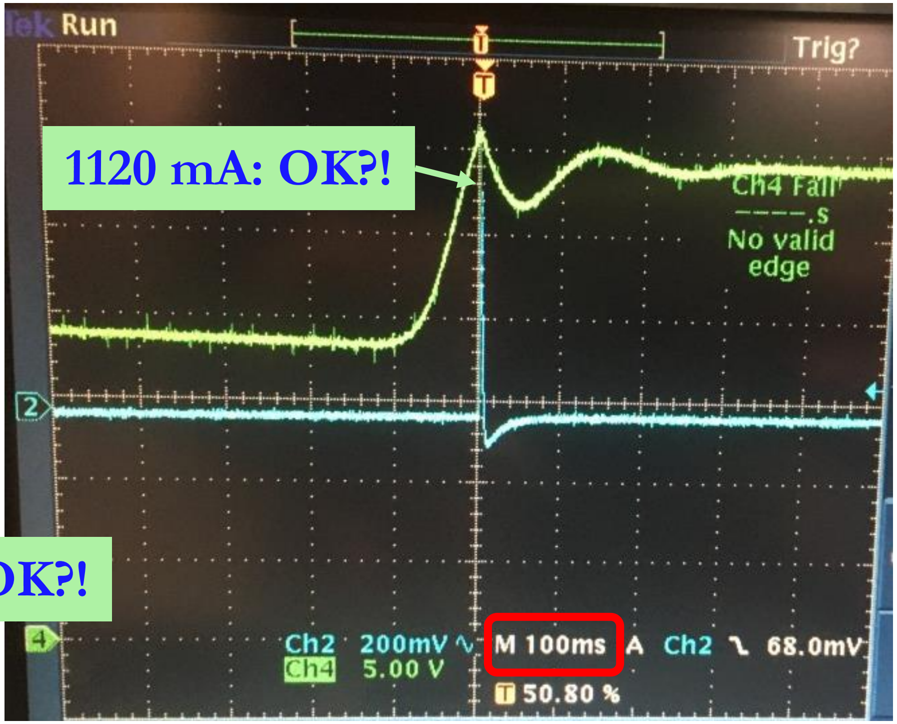
Stop/Start plasma, going down to 20 V and then back up to 30 V on Arc PC

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

Stopping plasma



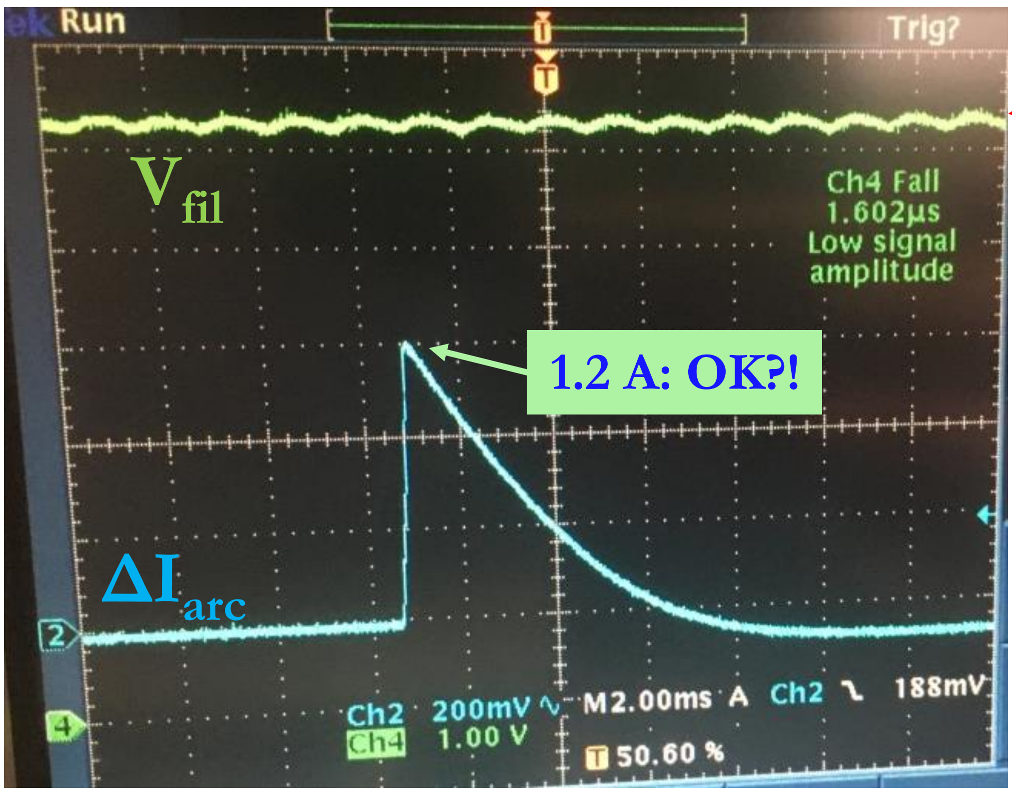
Re-staring plasma



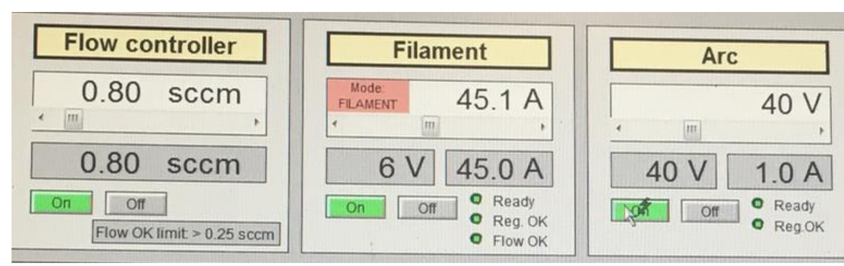
Filament voltage stability during ignition

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

- I_{arc} measured with Pearson 150 on **arc PC** output
- V_{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.



Open questions here (2020)

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

Measure instabilities of 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.

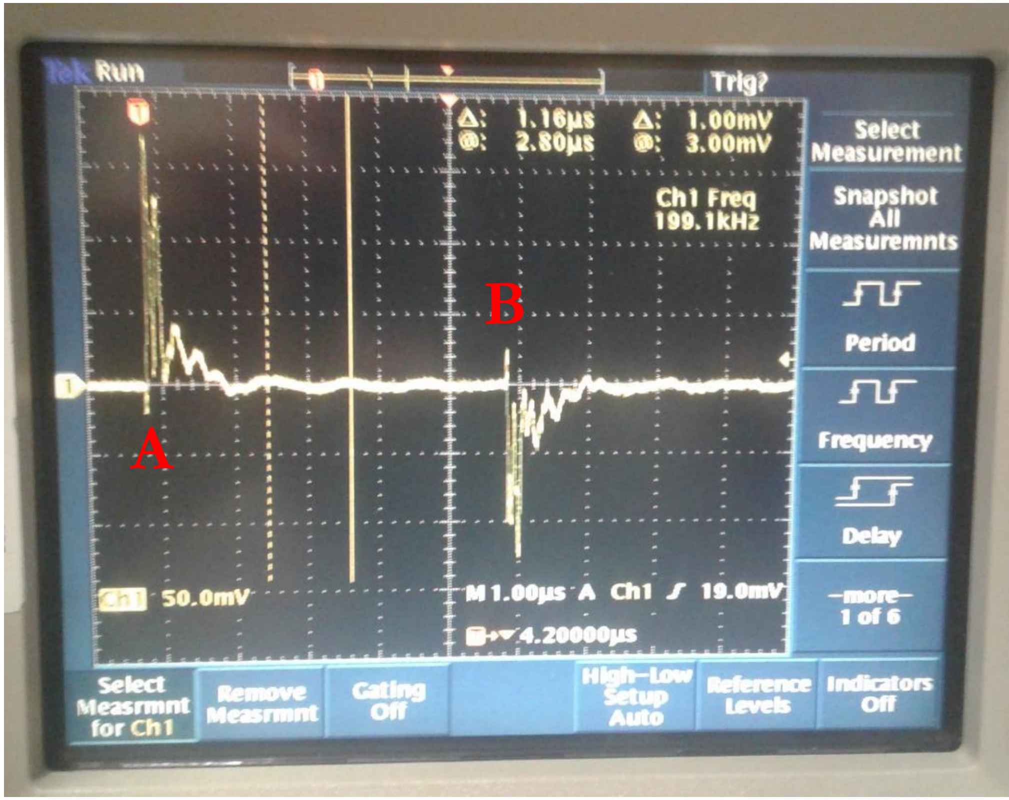
Measure instabilities of arc current

1 us / div
5 mA / div

A & B – switching of puller voltage

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.

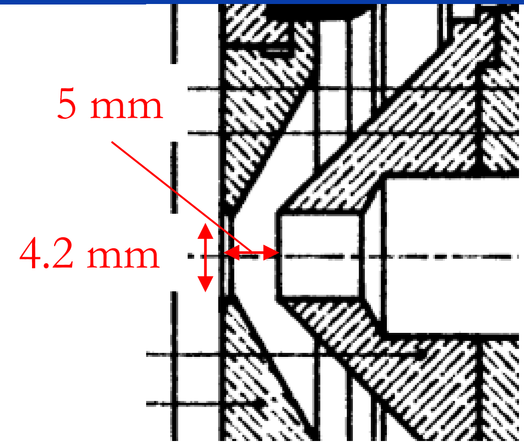
The first peaks in the damped oscillation corresponds to 170 mV*0.1 A/V= 17 mA, which is still significantly lower than the average 1 A arc current. The noise is related to the switching of the puller electrode in time.



! No erratic noise corresponding to the signal seen on the extracted current !

Other parameters

Source perveance

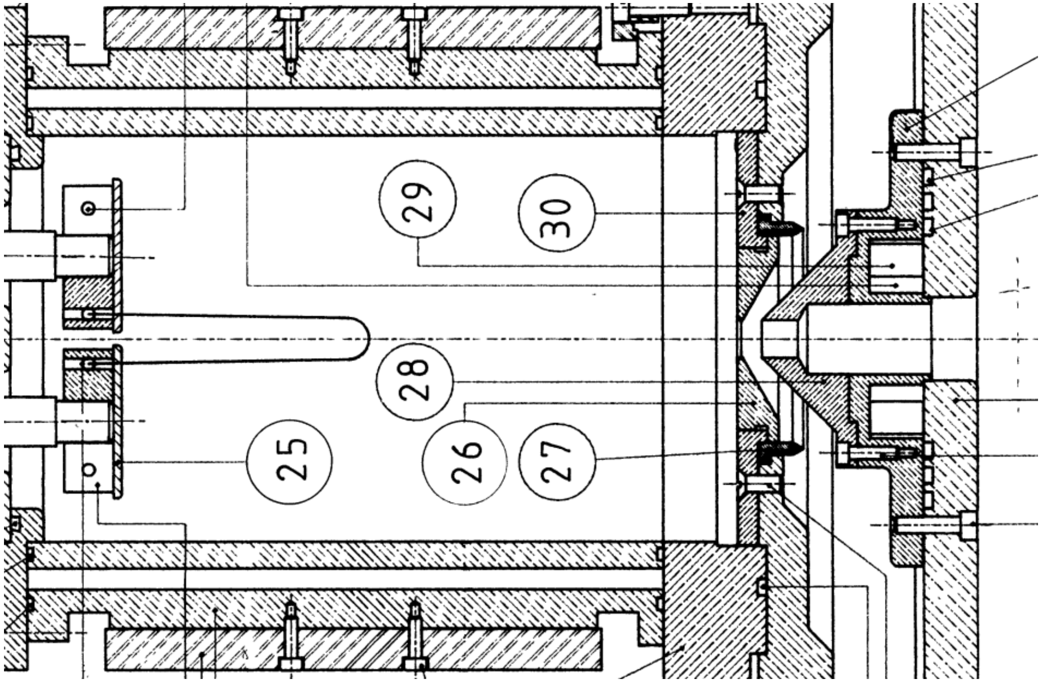


4 mA extractable H- current

- 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

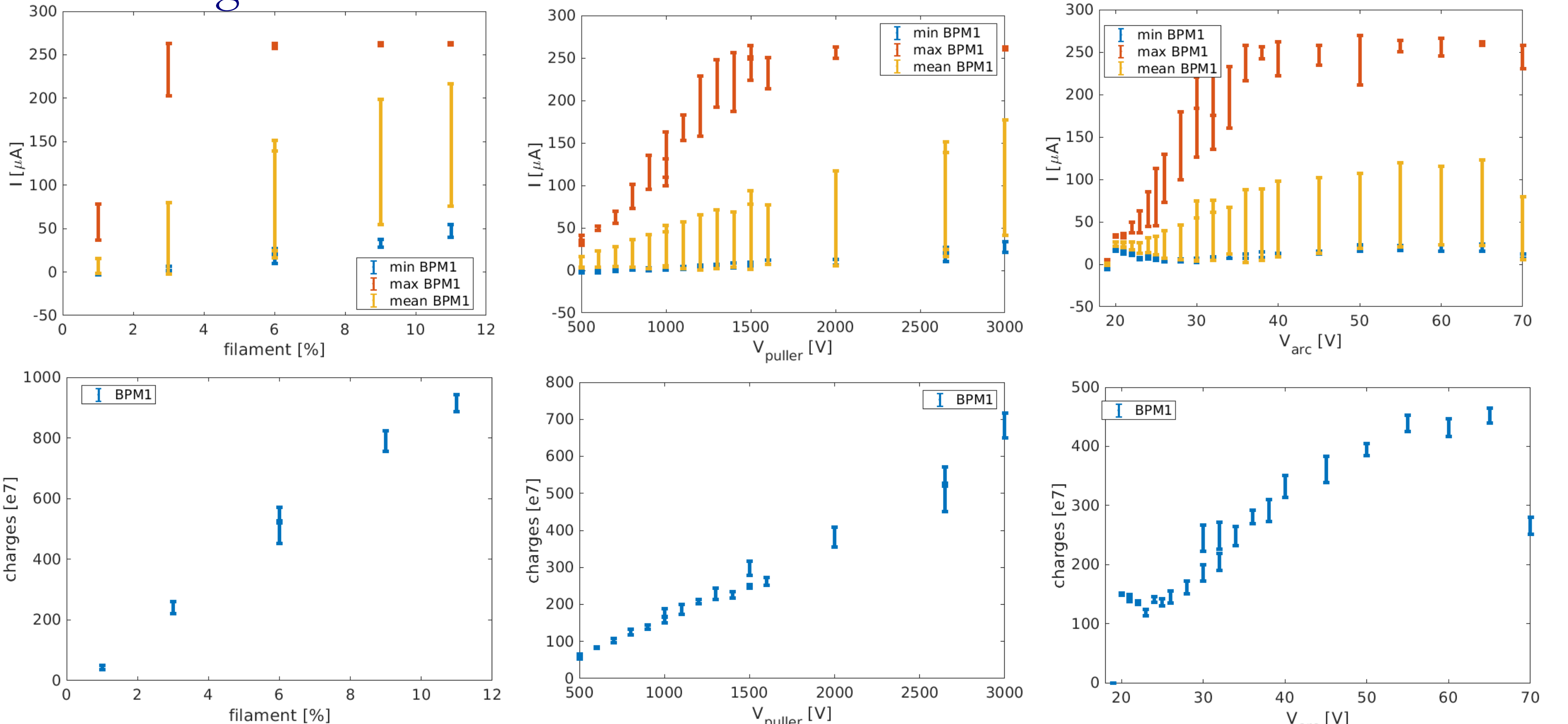


Logbook of other measurements/results

Scan over parameters (old)

Scan over some parameters

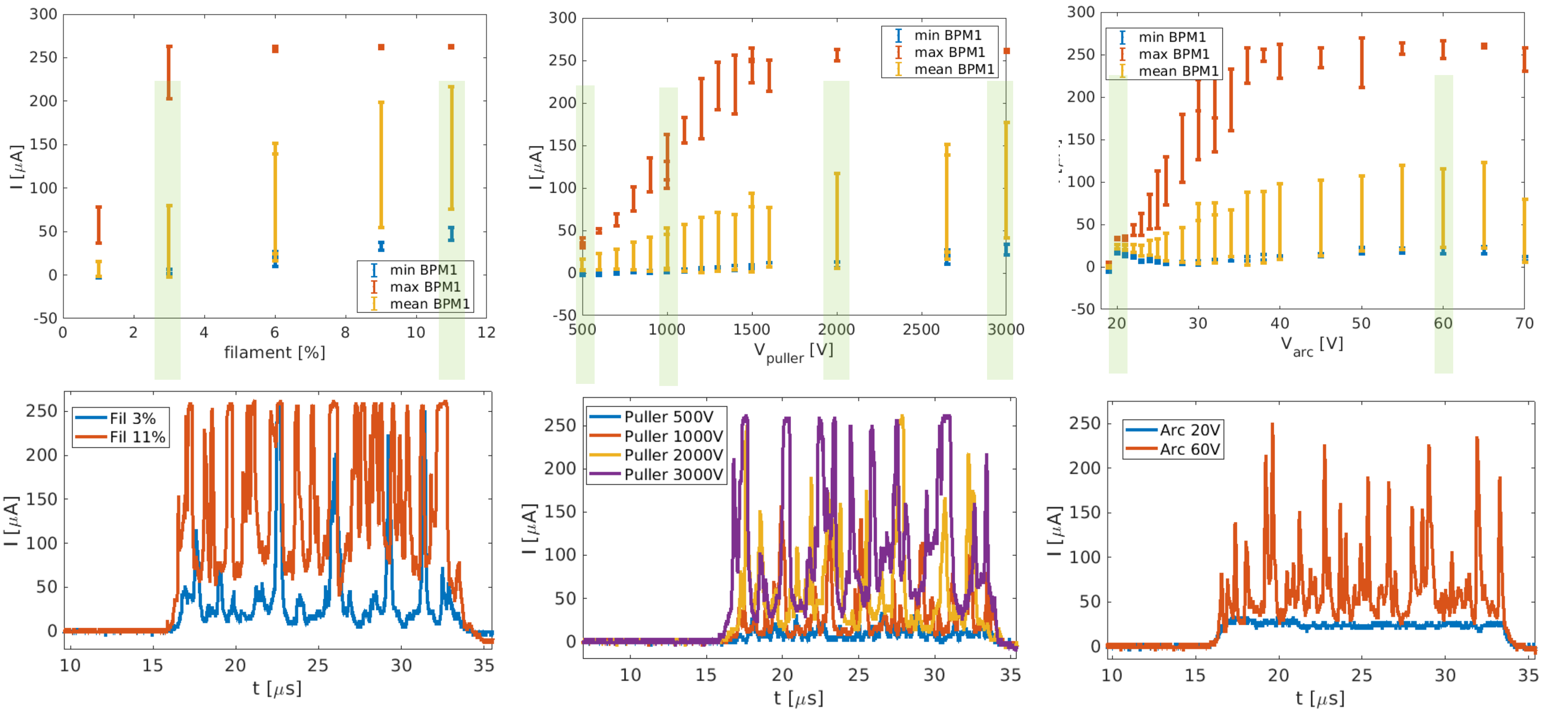
- Basic parameters: 0.8 sccm; 2650 V_{puller}; 6% filament; 70 V_{arc}
- Looking at 10us window for min, mean, max and integrated charges over several shots



BPM saturation @~250 uA.
+should scale everything by ~1/2.5, i.e. max=100 uA

Scan over some parameters

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



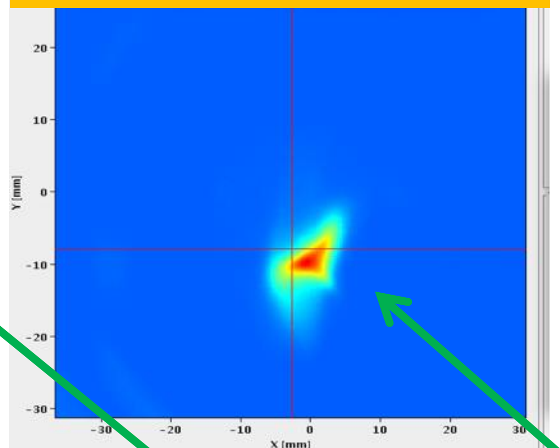
BPM saturation @~250 uA.
+should scale everything by ~1/2.5, i.e. max=100 uA

Seeing the instability elsewhere

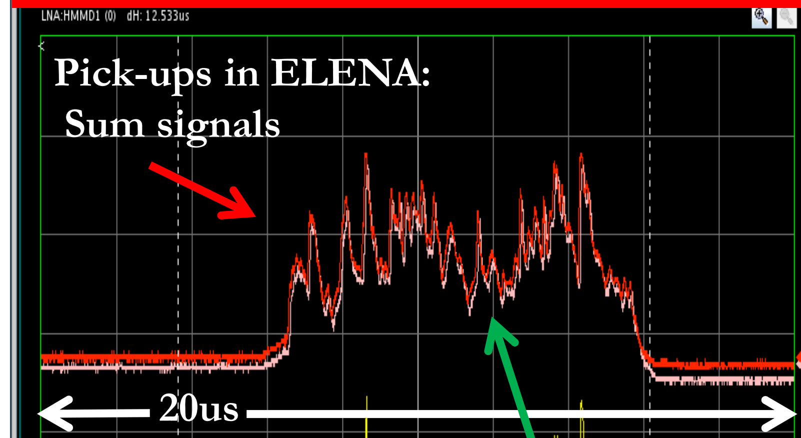
Possible beam observations

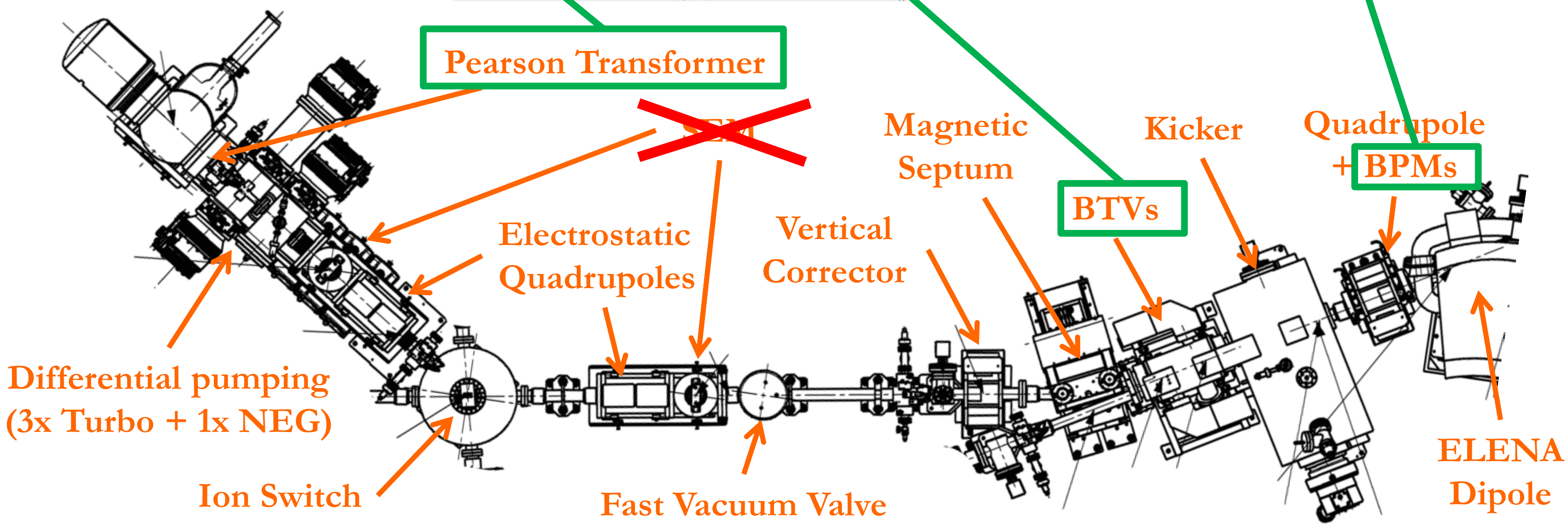
Possible to make ~100 uA beams @source

Poor pointing stability after some time, sometimes

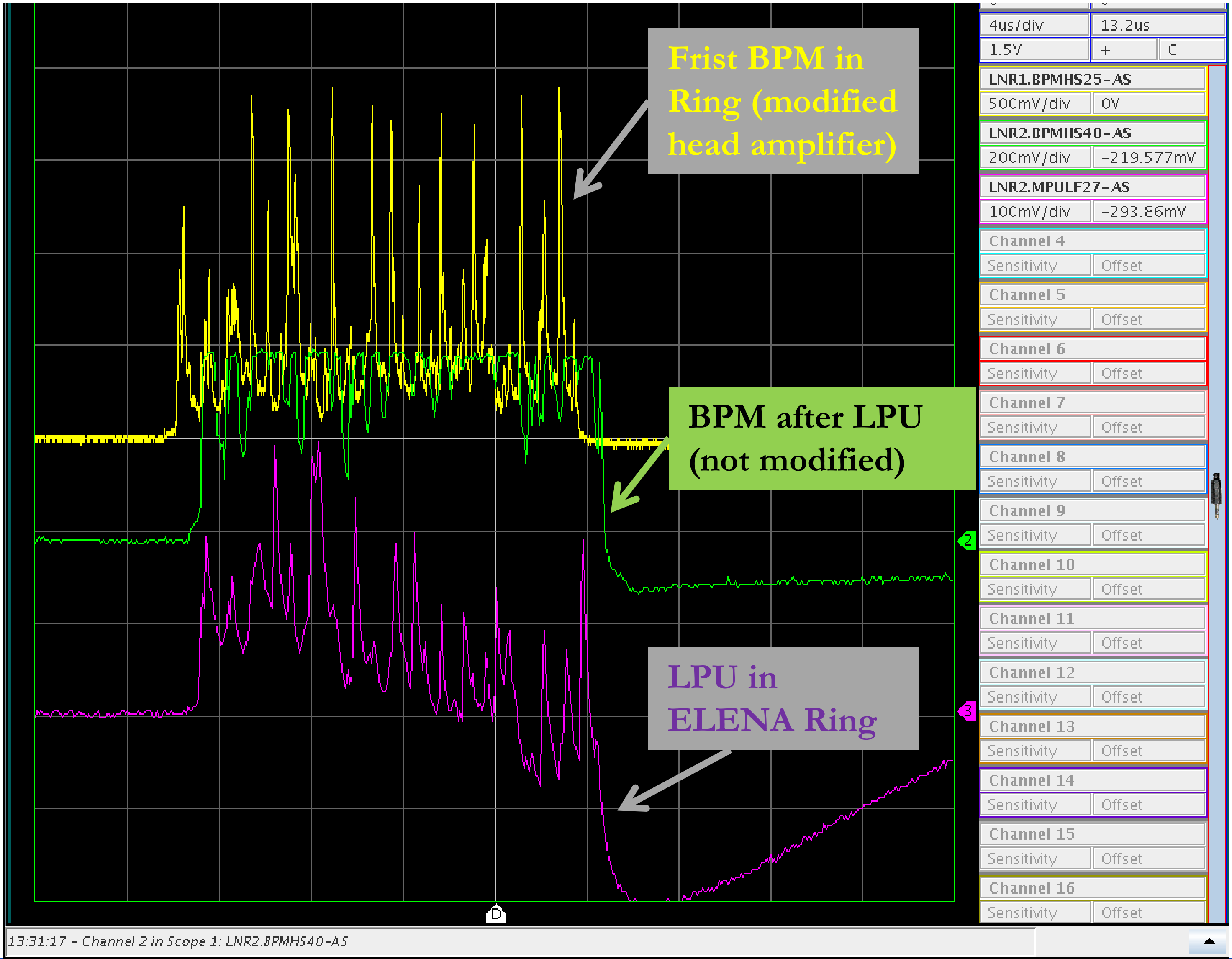


Shot-to-shot, Intra-pulse, Intensity Instability in ELENA



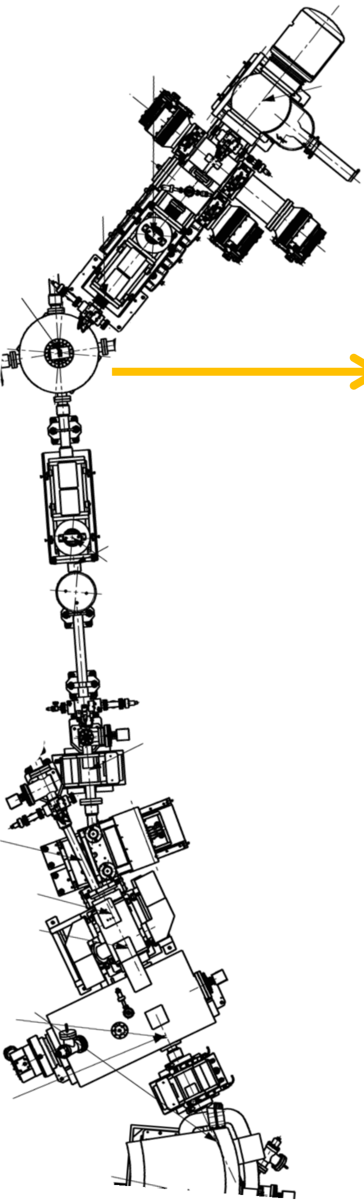


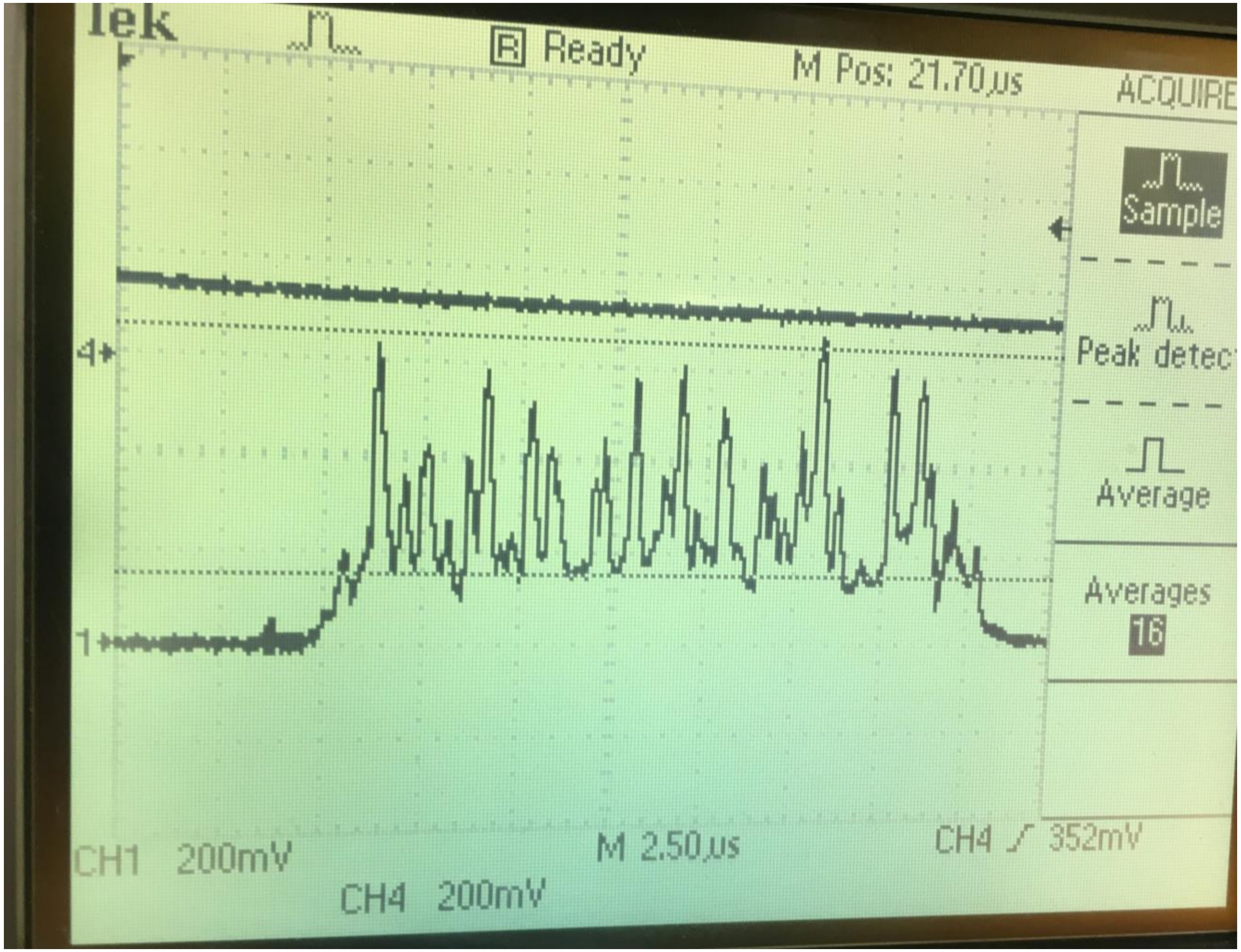
Looking at other signals



Looking at other signals

Using one plate of Ion Switch as Faraday Cup

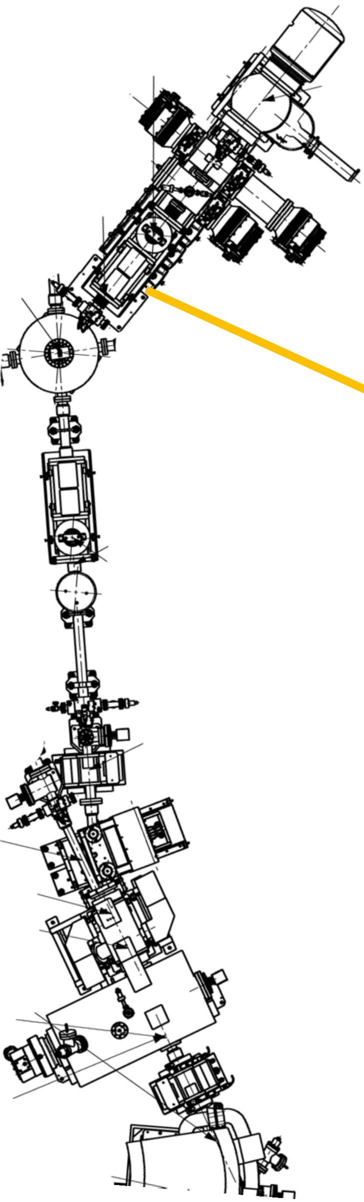


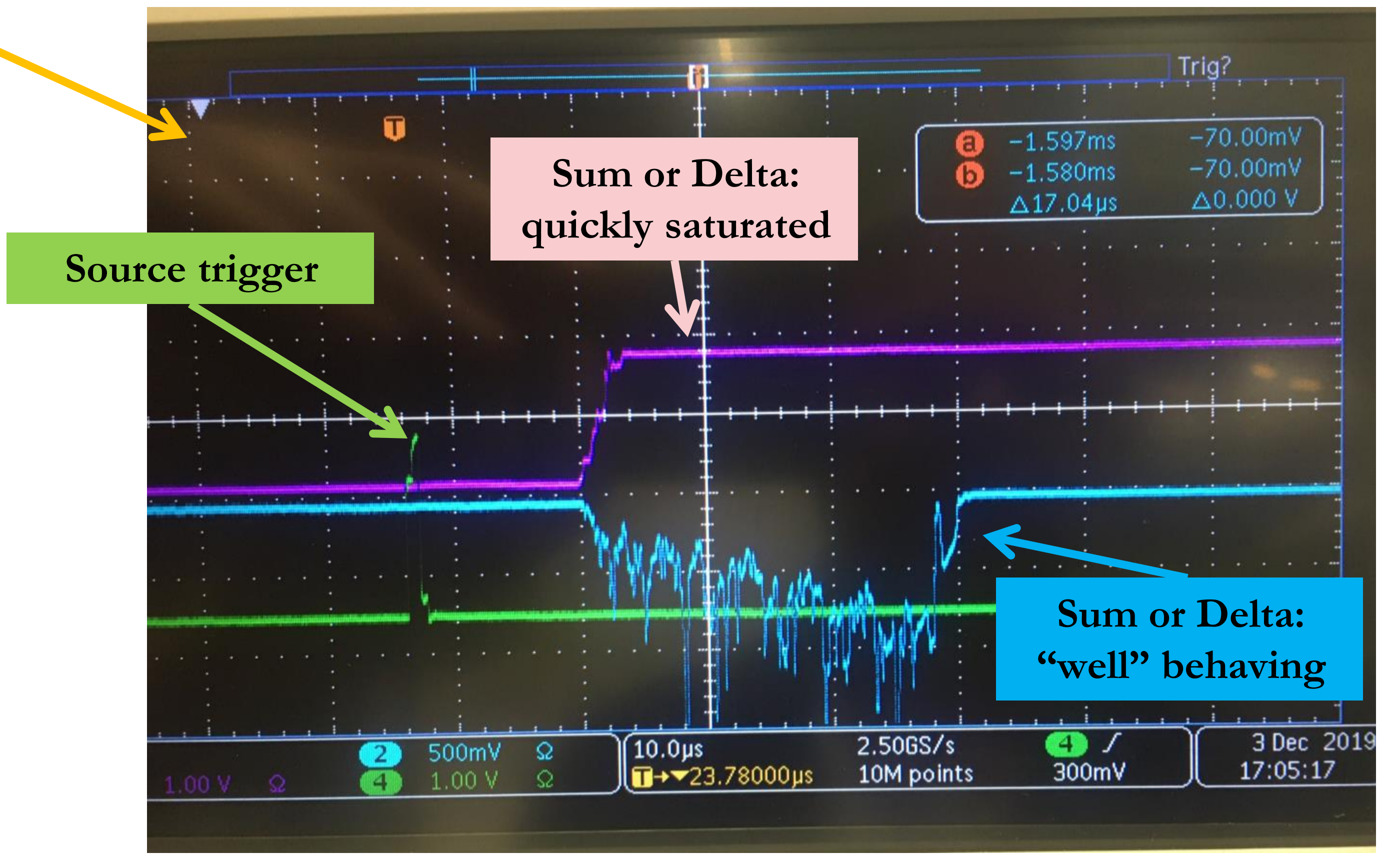


Looking at other signals

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

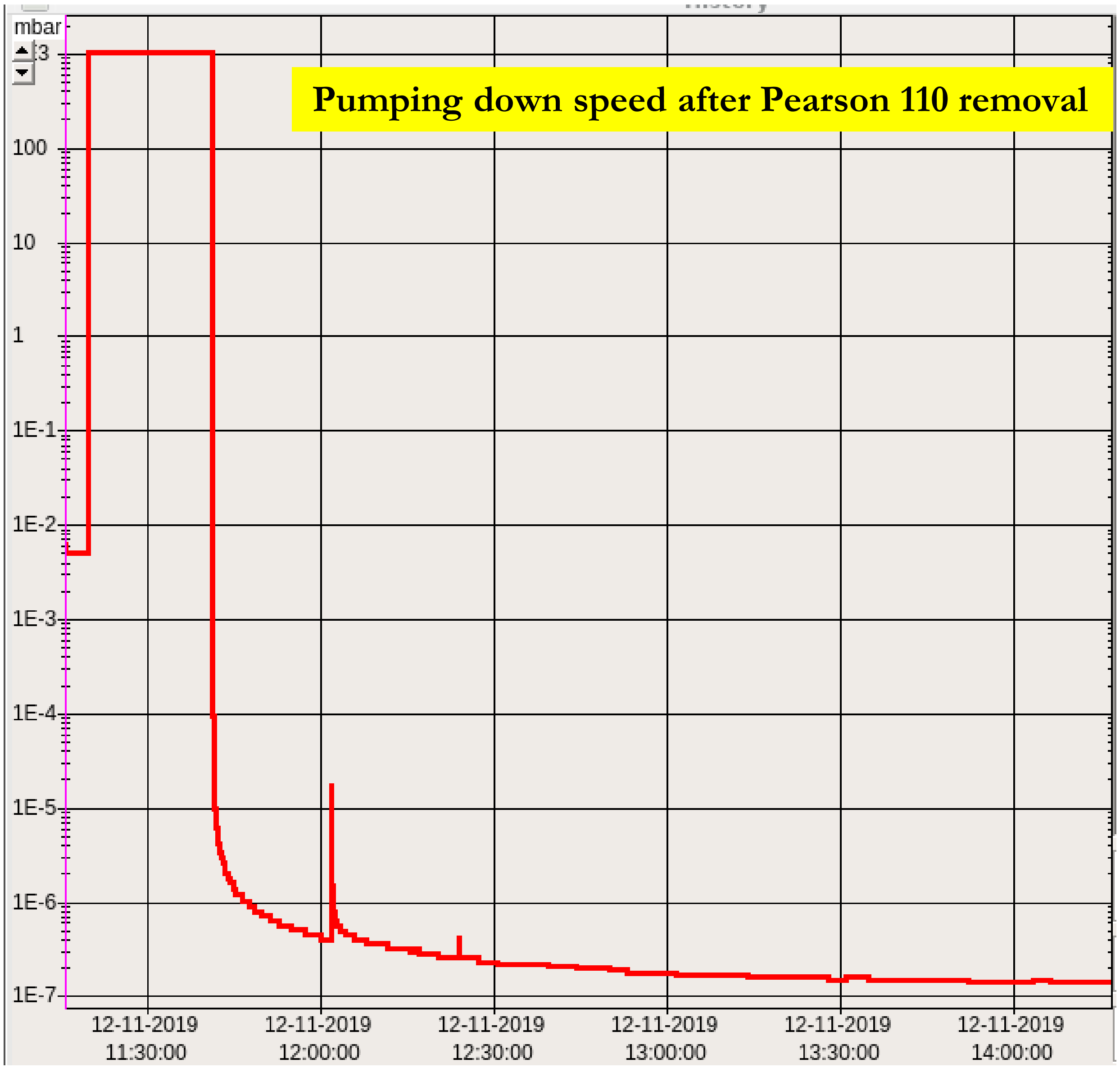
Difficult measurement, as amplifiers saturates quickly if there are losses on the electrodes.



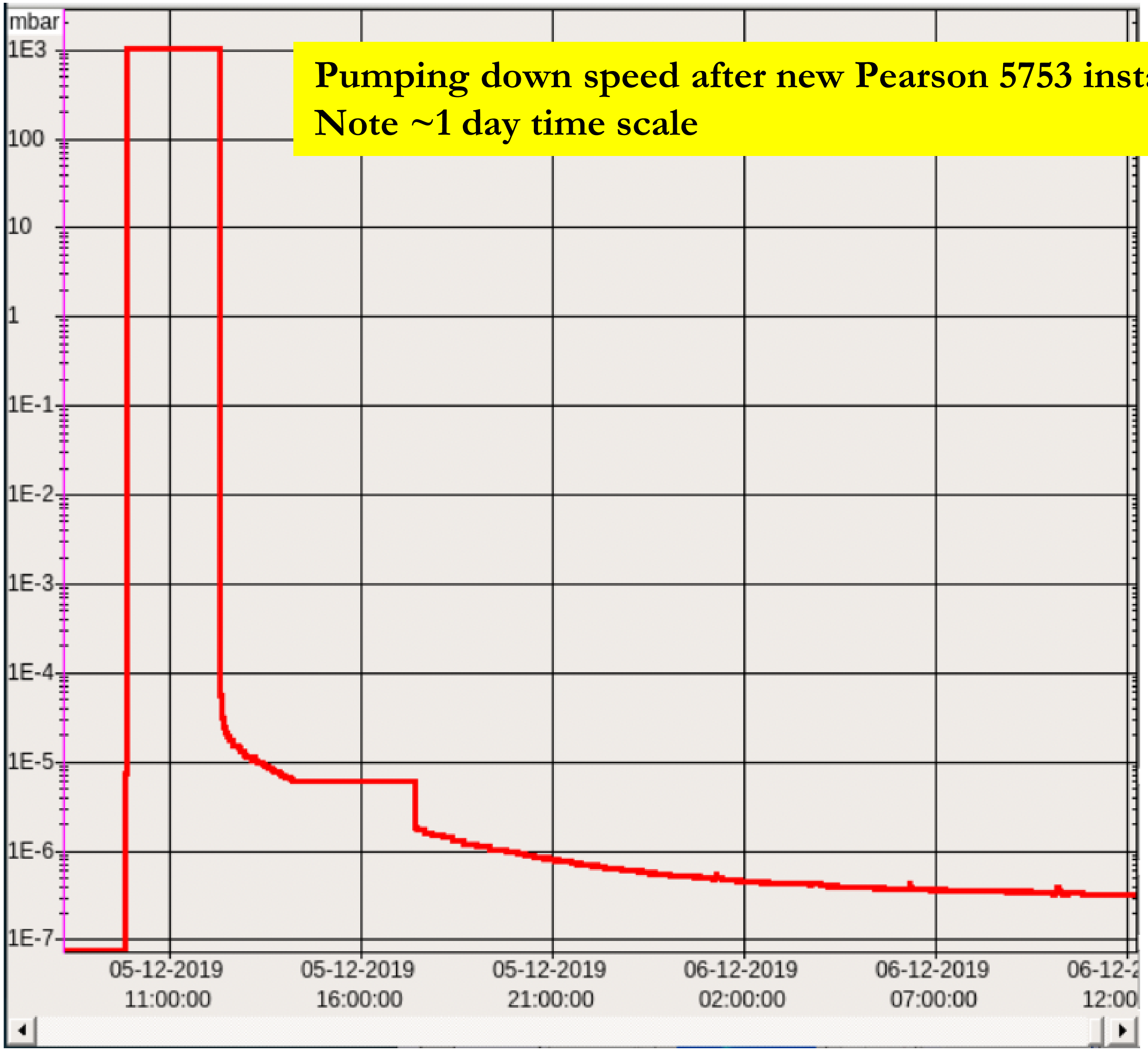


Vacuum: installation of new Pearson

Vacuum measurements 1/2



Vacuum measurements 2/2



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

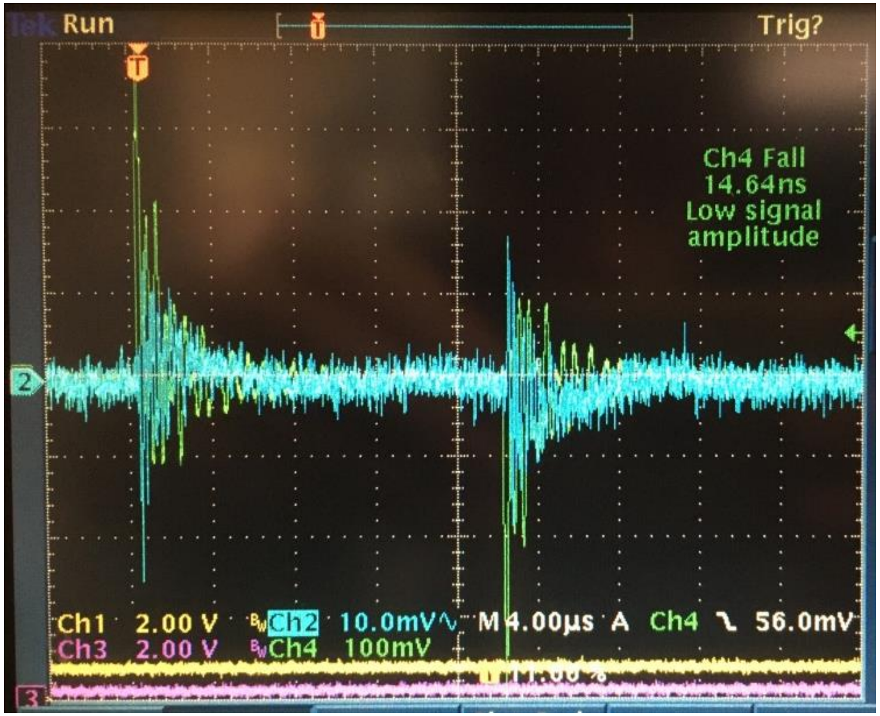
Puller current
WRONG! CALBE IS SHIELDED…

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

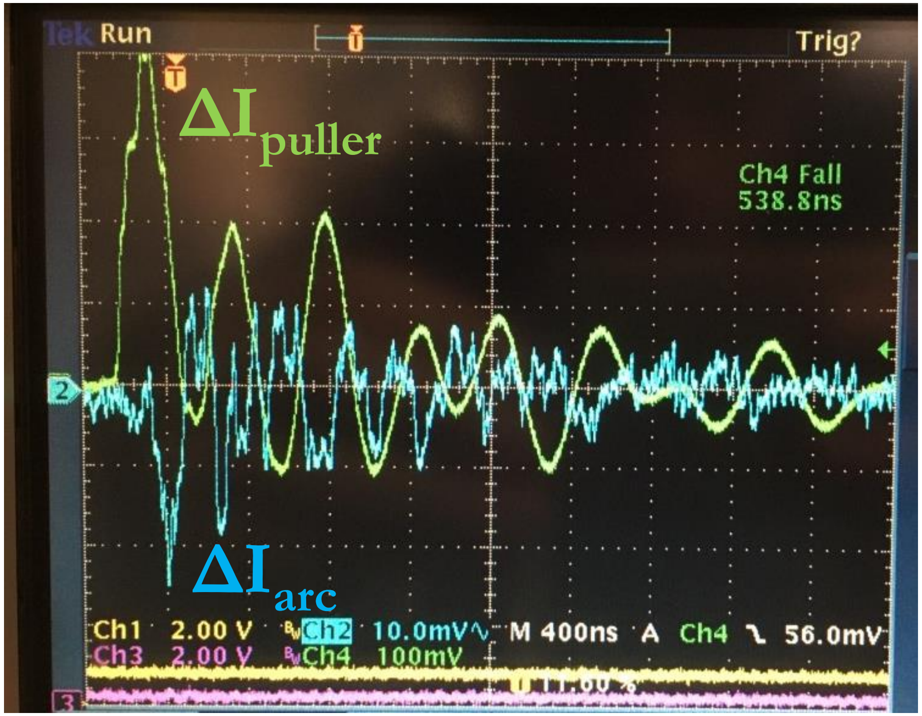
- Current measured with Pearson 150 on **puller switch** output (peak ~200 mA)
- Current measured with Pearson 150 on **arc PC negative** output (peak ~15 mA)

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

Overview



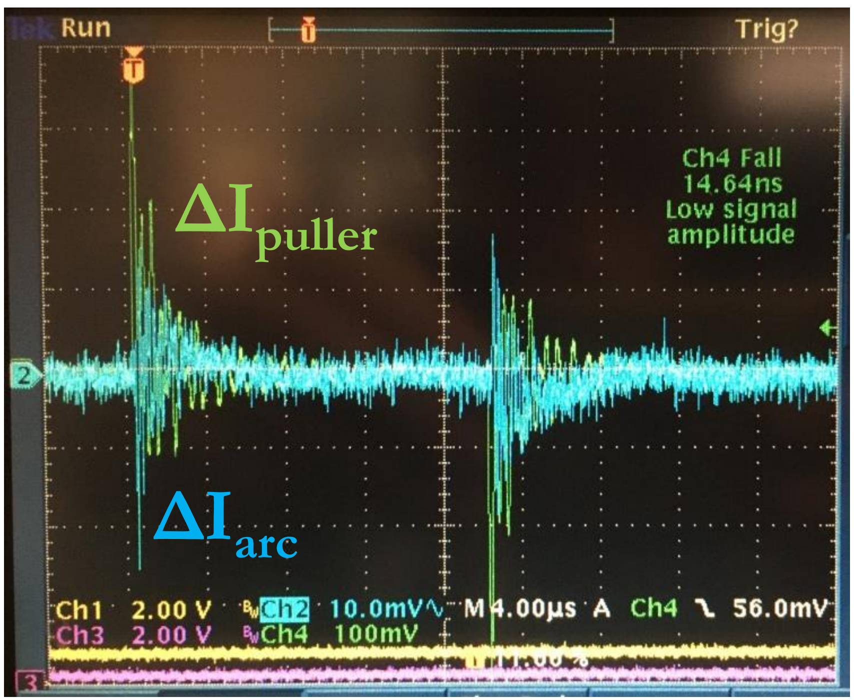
Zoom at start of pulse



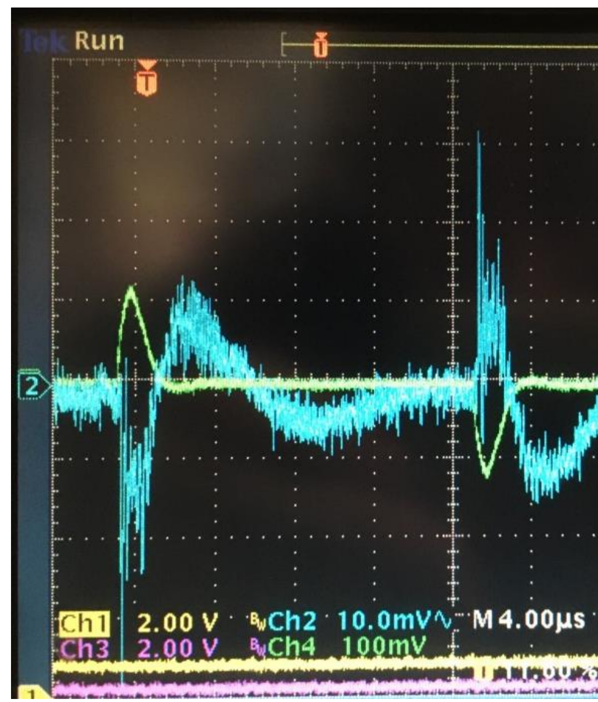
Puller current
WRONG! CALBE IS SHIELDED…

- 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.

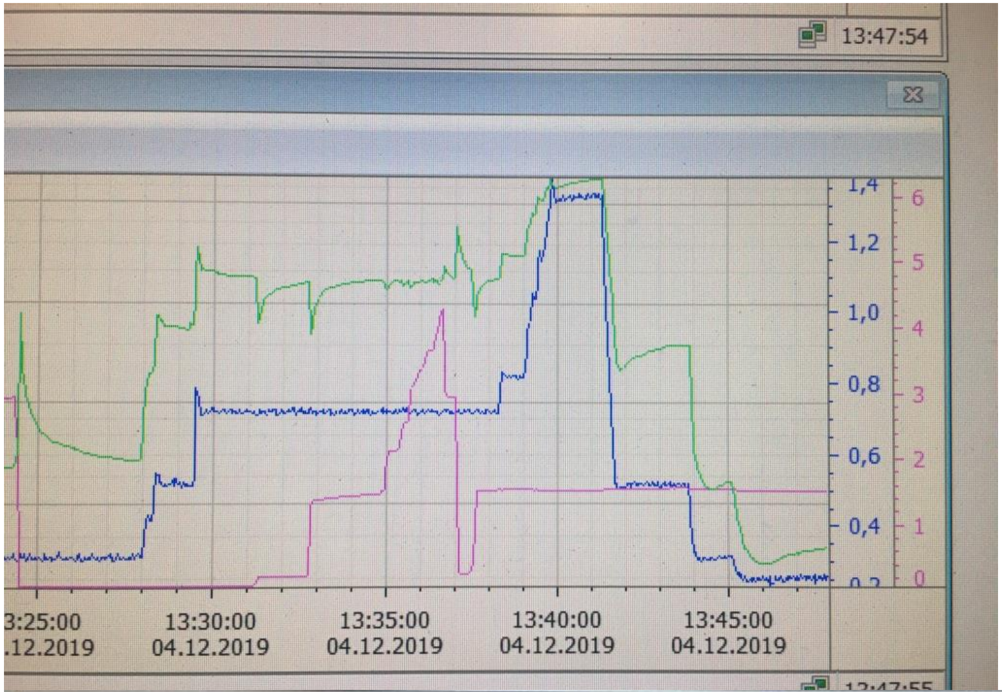
Without ferrite

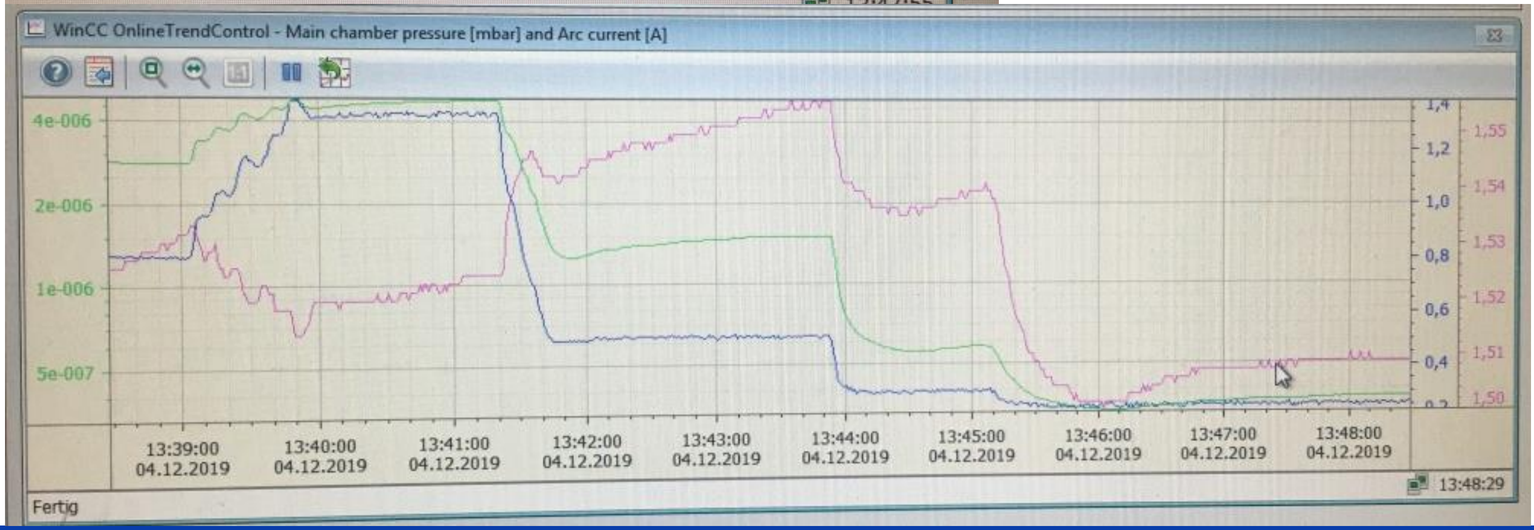


With ferrite



Some tests on source parameters
4 Dec 2019

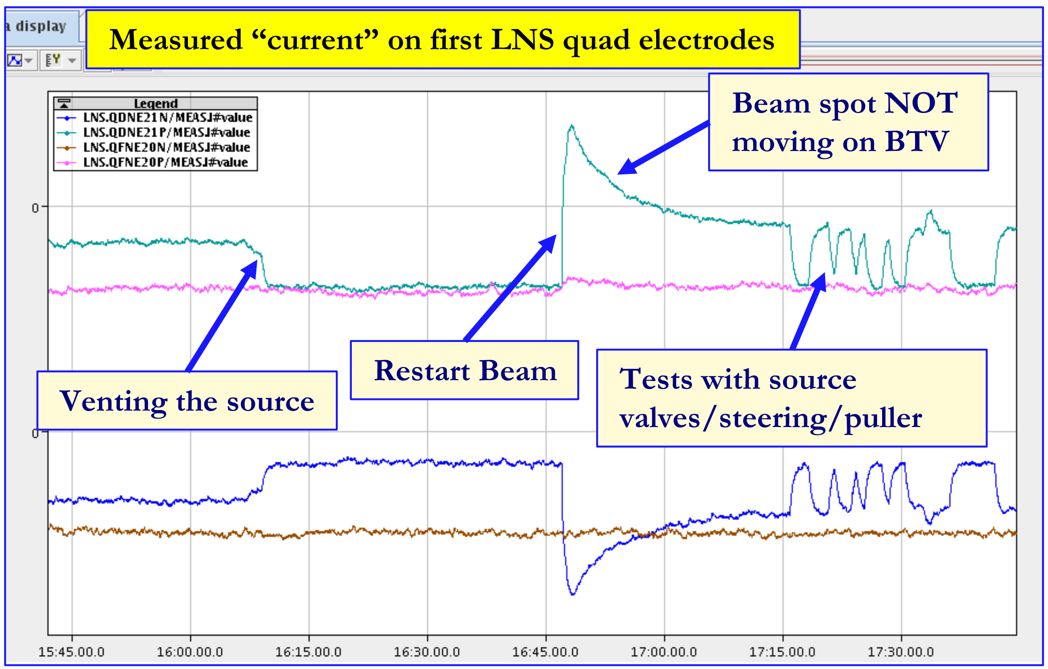


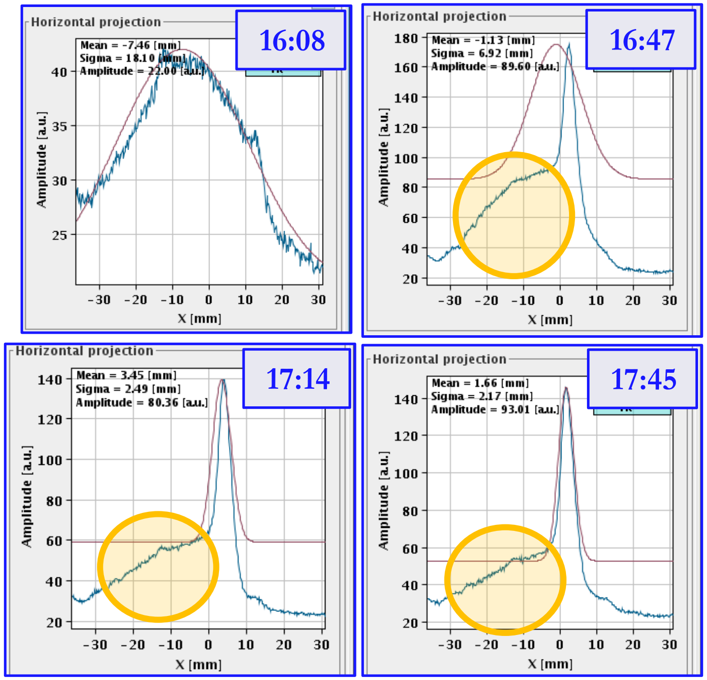


Logbook of CHARGING UP Effects

Beam disappearing after some time

- 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 H_2 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.





- 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.