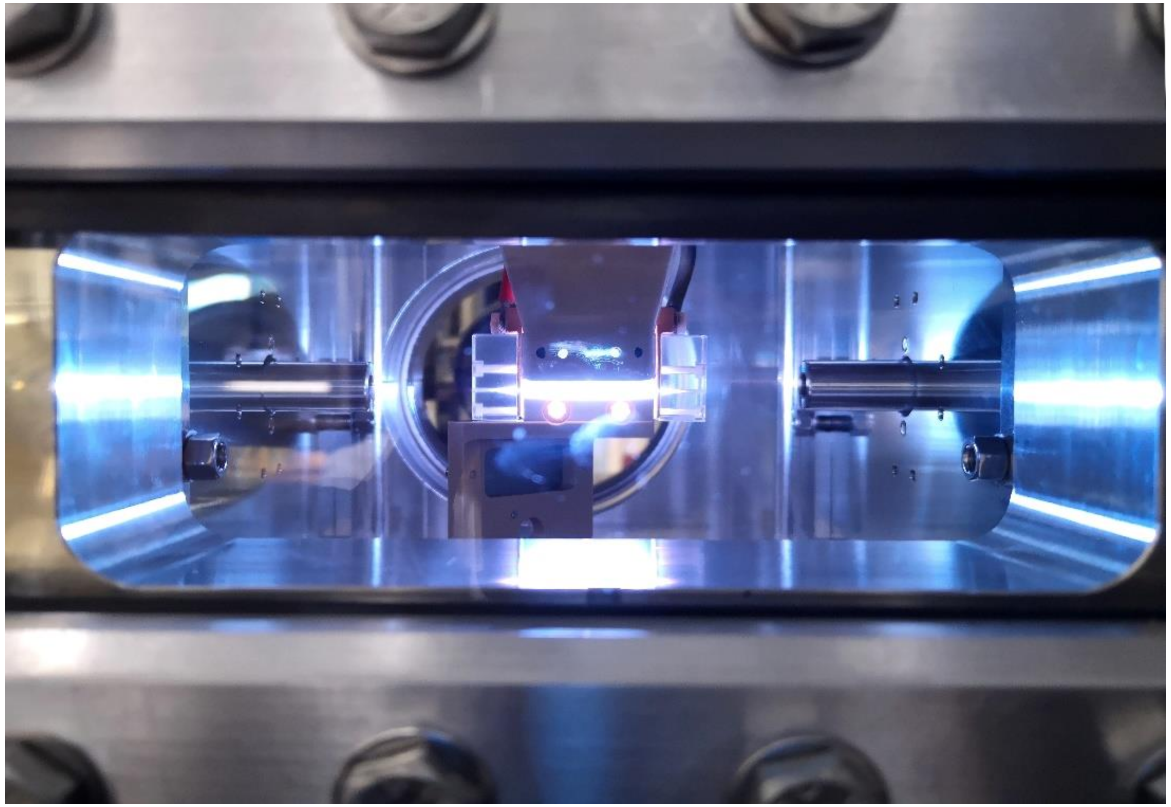
TDR Review Committee meeting

Plasma section

30th November-2nd December 2022

A. Biagioni, R.Pompili



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2.8 Plasma Section

Very good progress was made with the plasma source for the ~500MeV energy gain. An ~40 cm capillary discharge now operates at the plasma laboratory. It is similar to the ~3 cm discharge, also occurring in a 3D-printed capillary, but with six gas inputs, instead of two. It produces a plasma with density varying. longitudinally between ~1.5 and 3×1017 cm−3. Surprisingly, the plasma density variation is comparable to that observed with the 3-cm-long capillary and also occurs over the entire half length of the discharge. The hypothesis is that the variation in plasma density over the length of the discharge can be compensated by varying the diameter of the discharge tube.

Vacuum measurements show that operating at 100 Hz requires an almost continuous gas flow. Operating at 400 Hz requires a continuous flow, posing a challenge for maintaining good vacuum before and after the plasma source.
Measurements also show that the density of the discharge in a 3D-printed capillary decreases as a function of the number of discharges, e.g., 30% over one hundred thousand events. On the contrary, it remains constant over that number of discharges in a sapphire capillary. A cheaper, 3D-printed glass capillary may offer the same lifetime as a sapphire capillary.

A plasma length allowing for 5 GeV energy gain, longer but also with a larger transformer ratio acceleration maybe possible by stacking three 40-cm-long discharges.
The use of a laser pulse to decrease time jitter of the discharge with respect to the electrical trigger and reduce variations of plasma density from event to event was presented at previous meetings. Is this method applicable to the longer discharge and will it be implemented (if needed)?

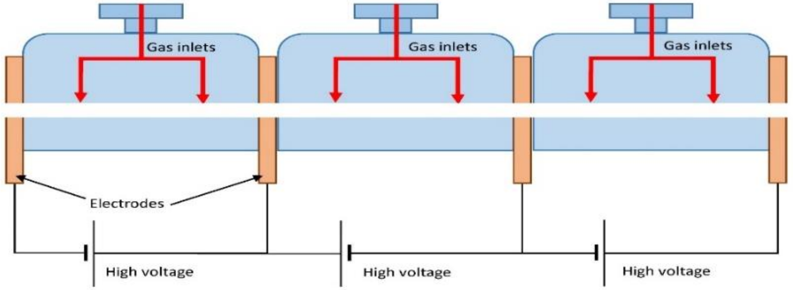
The RC recommends that capillaries with tapered radius to compensate for the (non constant) longitudinal plasma density profile measured in the constant-radius capillaries be tested very soon. This test can be done with the short capillary. For consistency, requirements in terms of uniformity of the longitudinal plasma density should be determined from simulation studies. Alternatively, numerical simulations may be performed to determine the effect of the observed non-uniformity on the beam and FEL parameters. Density ramps at the plasma entrance and exit of the capillary should also be carefully characterized and included in numerical simulations.

Plasma module for EuPraxia project

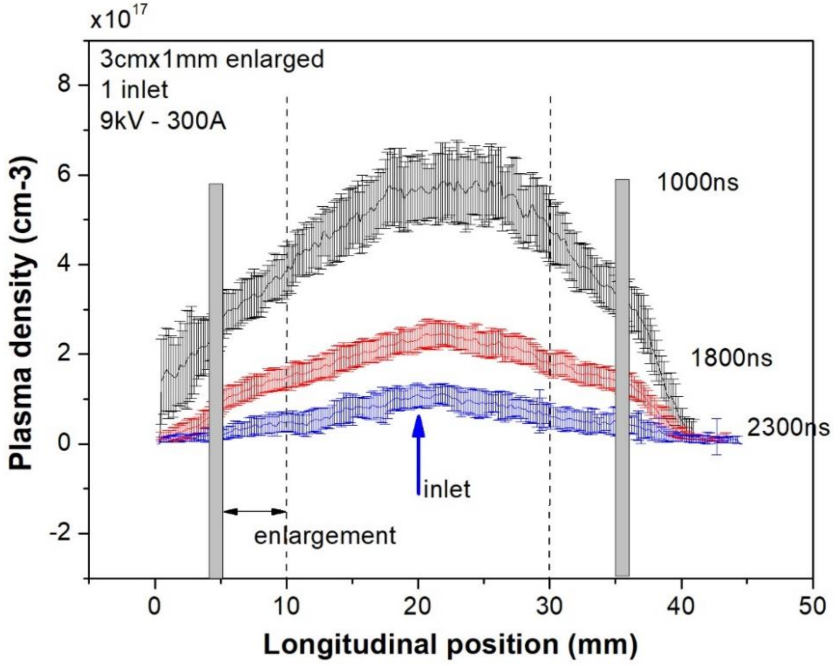
- **1.1 GeV** (1.5 GV/m 40cm capillary - density 10^{16} cm-3)
  - Direct plasma discharge for 40cm long capillary
    - Stability
    - Longitudinal profiles
  - Plasma sources operating at 100 – 400 Hz
    - Vacuum system
    - Study on materal science to increase capillary's longevity
    - High-voltage sources for plasma formation

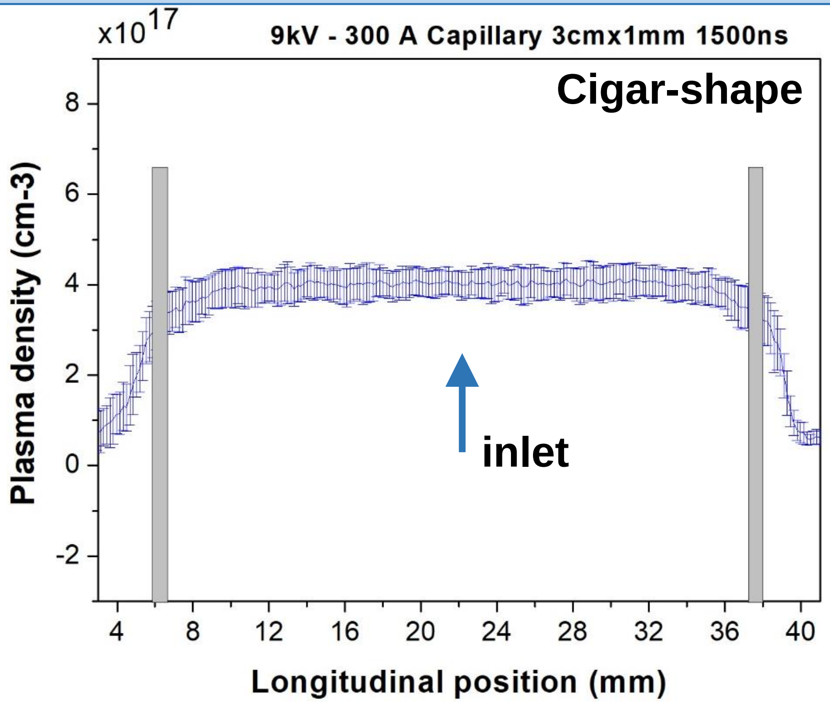
40cm capillary is working

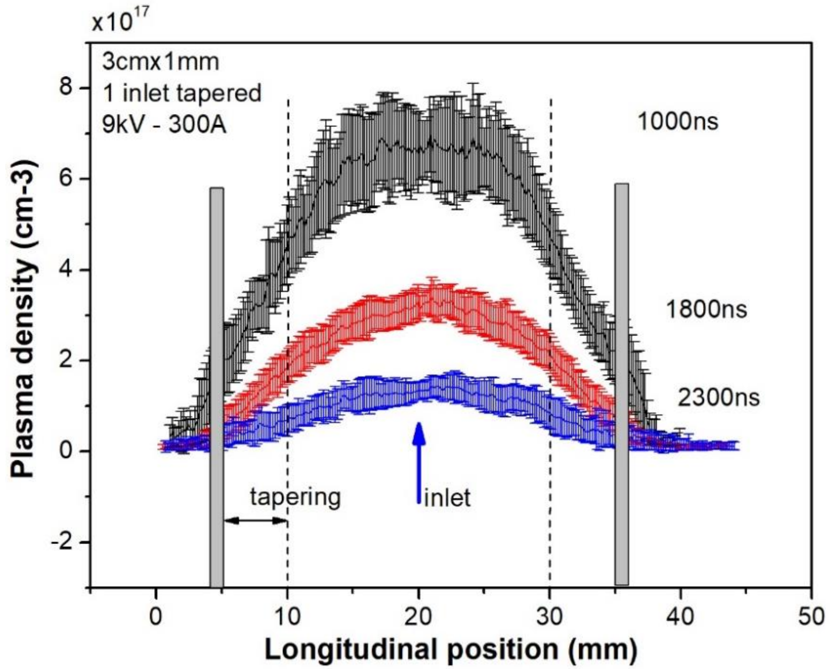
- Segmented capillary
    - Plasma sources larger than 40 cm (m-scale)
    - Longitudinal density modulation
    - **5 GeV** case for EuPRAXIA (1.5 GV/m m-scale capillary - density 10^{16} cm-3)

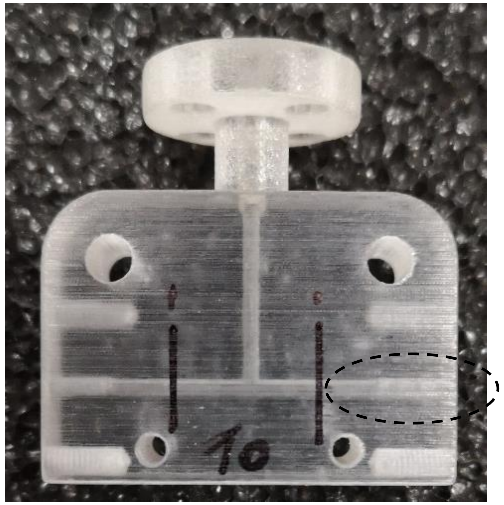


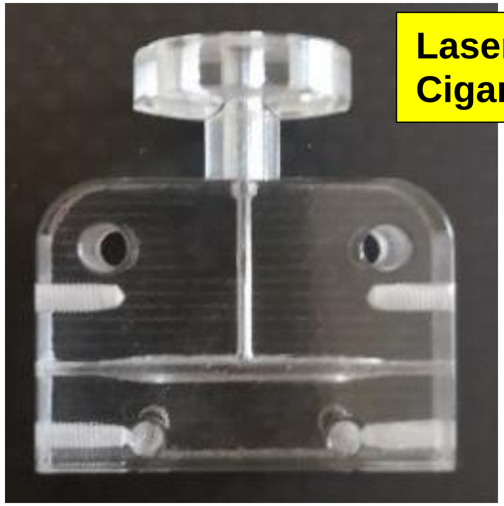
Presented in the previous RC 26 - 27th October 2021



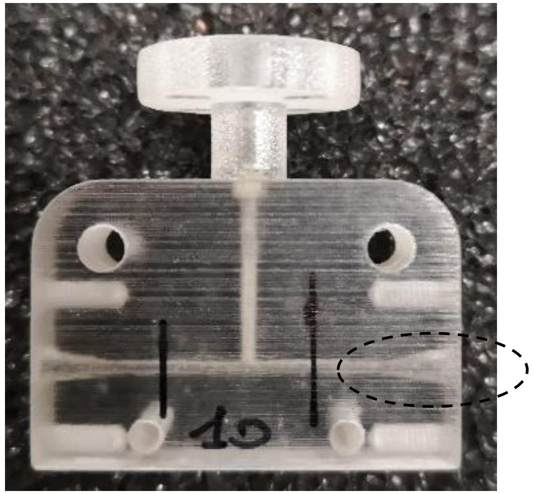


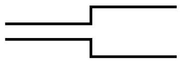


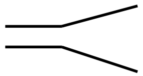




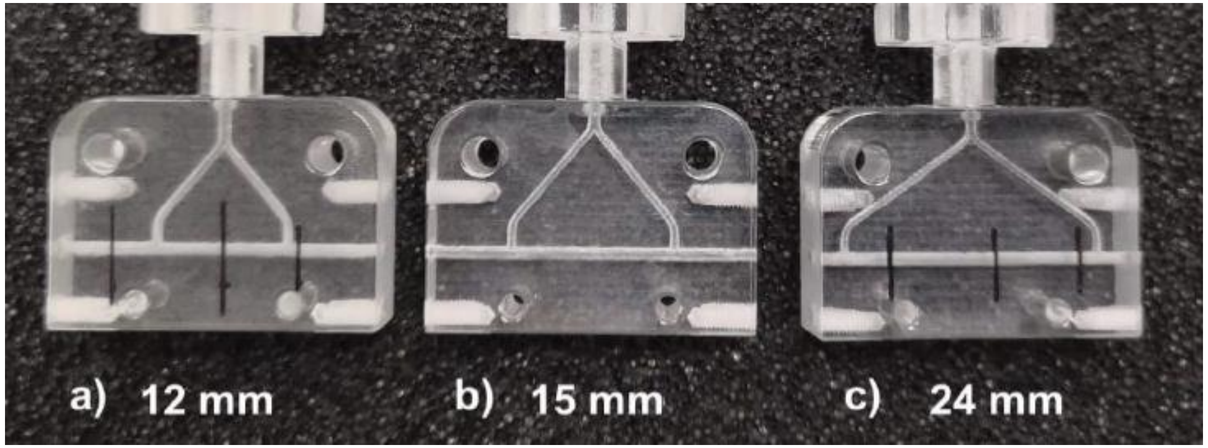
Laser trigger and Cigar-shape capillary

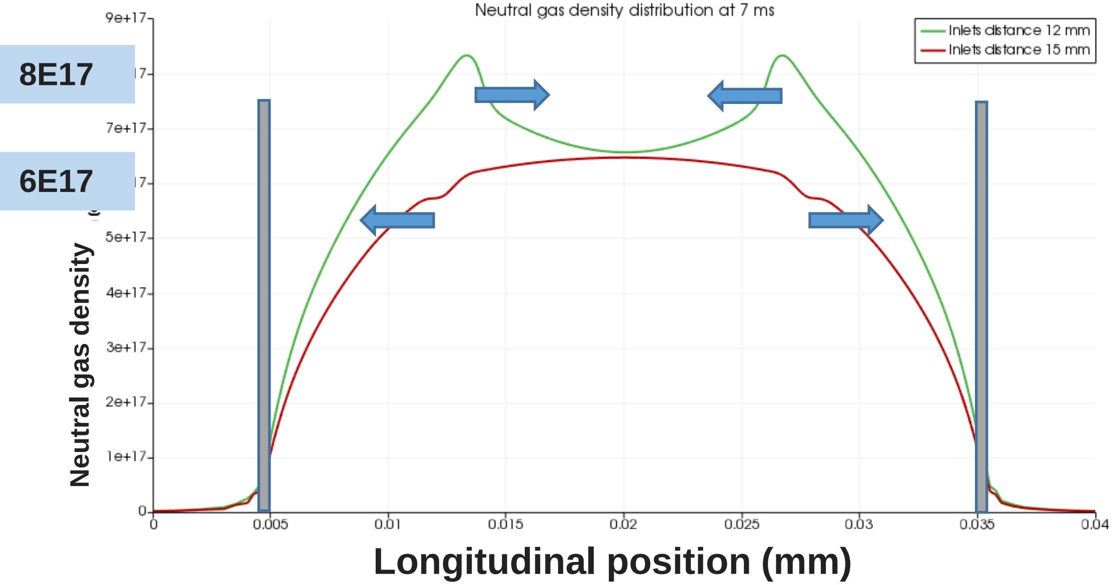




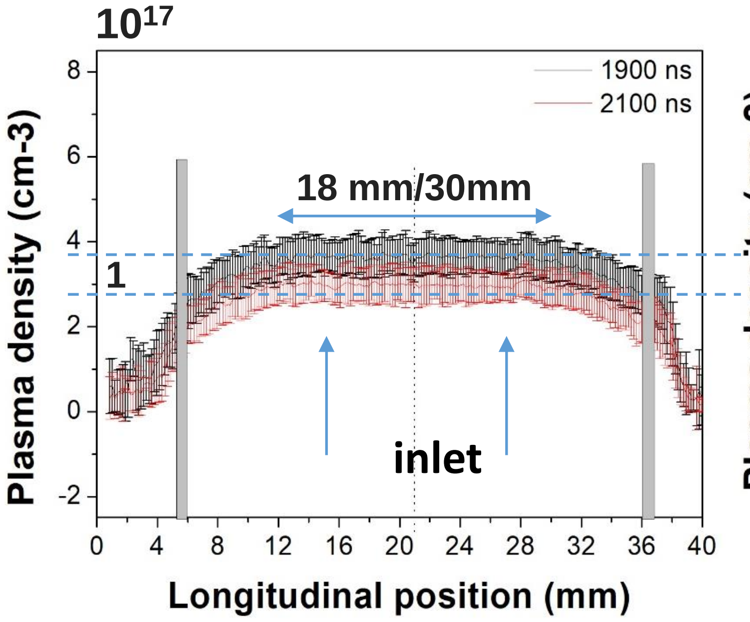


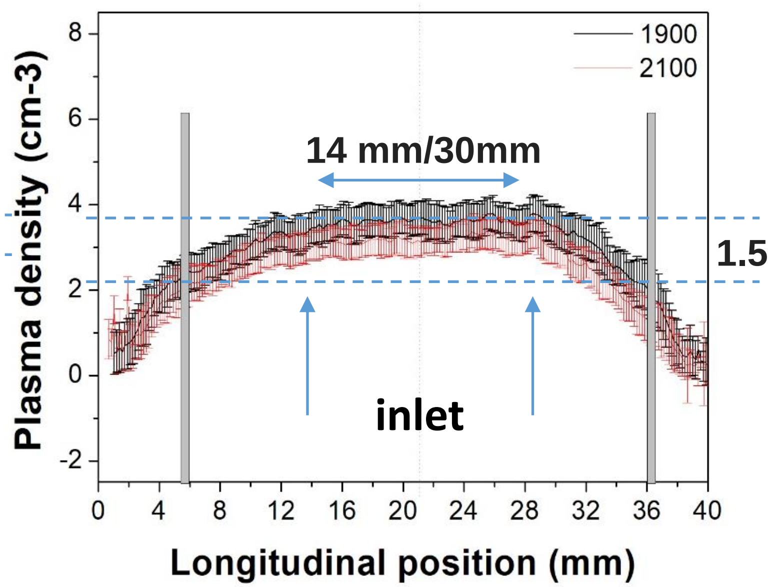
Plasma module developments: channel shaping

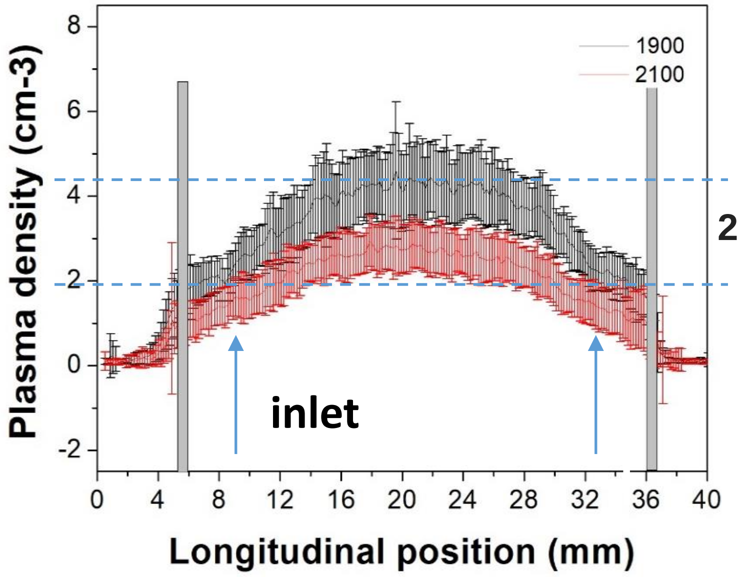




12kV 300 A







INFN LNF Istituto Nazionale di Fisica Nucleare — EuPRAXIA

Mitigation of erosion of the capillary walls can be achieved by reducing the *heat flux*

PWFA	
$5x10^{16}cm^{-3}$	Pgas=20mbar
Ip=300A	Rcap=500um
Lcap=30mm	Δt=600ns

$$T_e(\mathrm{eV}) = 5.7\left[\frac{I(\mathrm{kA})}{r_{\mathrm{cap}}(\mathrm{mm})}\right]^{2/5}$$ **≈ 4.6 eV**

the energy deposited into the capillary per shot:

E = Rp Ip² Δt = 50 mJ/shot

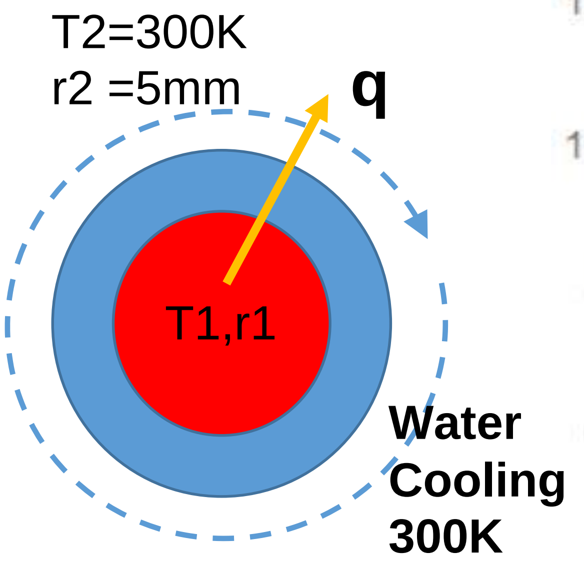
Spitzer plasma resistance

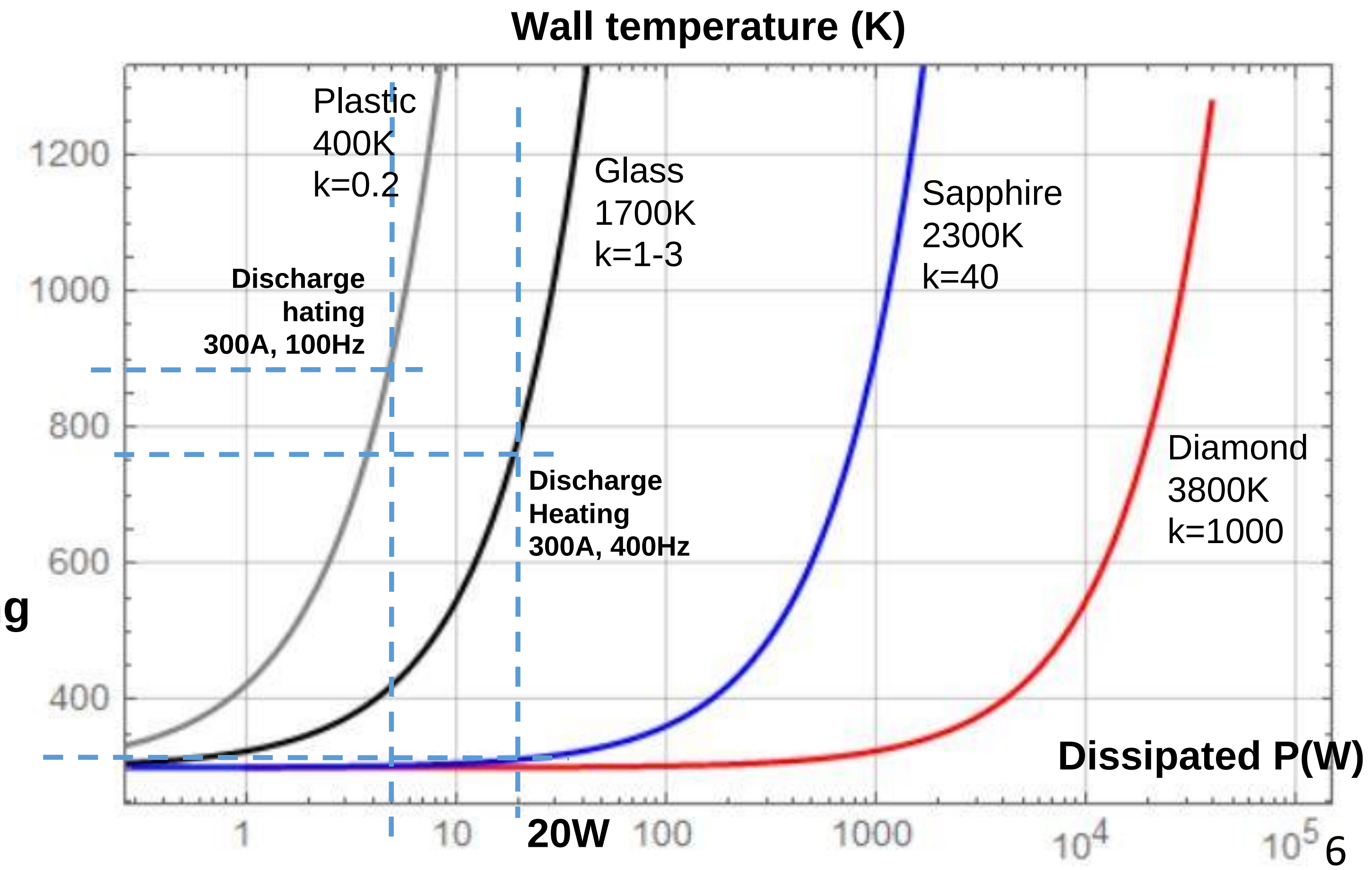
Conductive heat transfer law:

$$\mathbf{q} = -k(T)\,\nabla T$$

$$2\pi L k \frac{T_1 - T_2}{\ln(r_2/r_1)}$$

Cylinder geometry





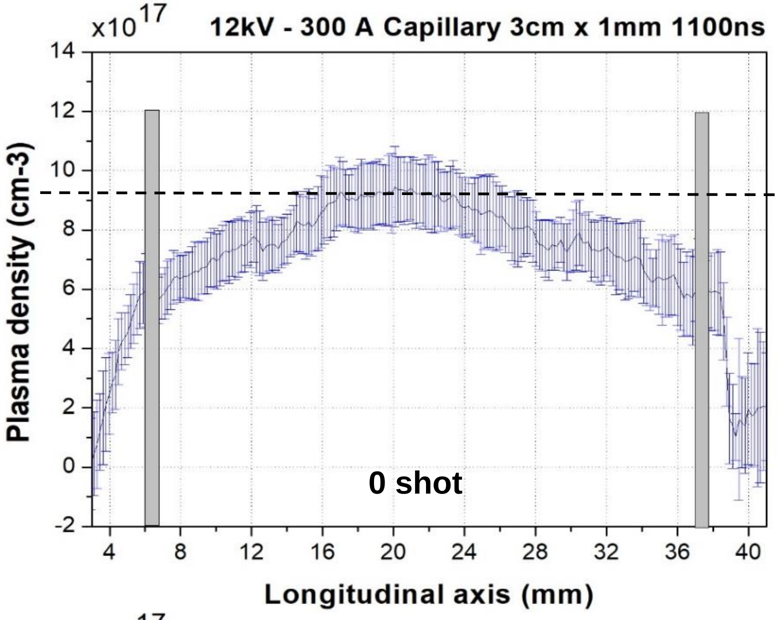
A. Gonsalves, et al, *Demonstration of a high repetition rate capillary discharge waveguide*, JAP, 119,10.1063/1.4940121

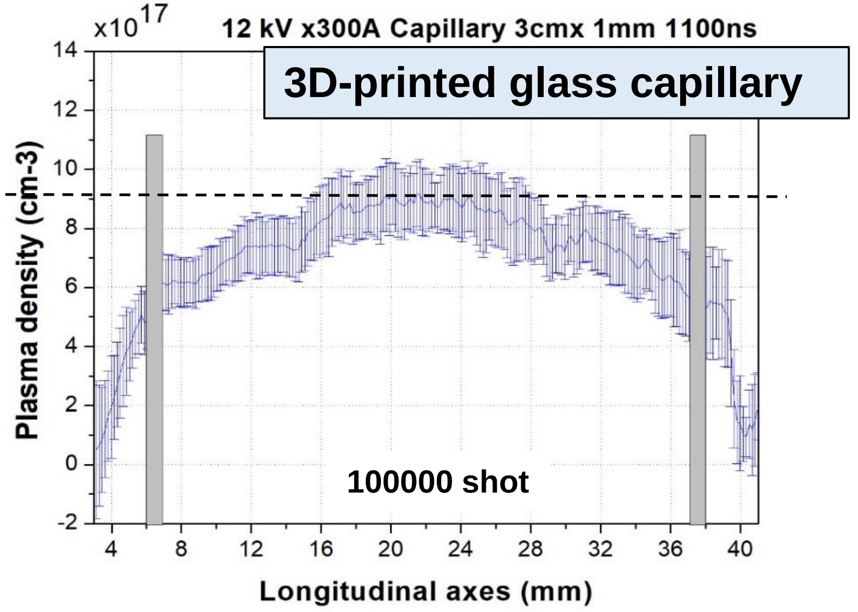
Plasma section developments: erosion of the walls capillary

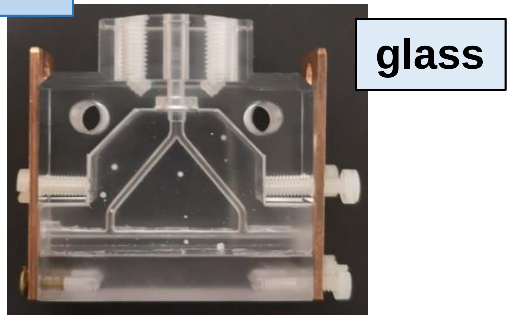
1Hz repetition rate

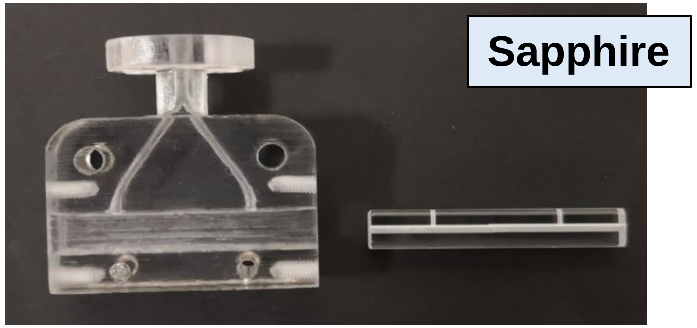
Presented in the previous RC 6 - 7th June 2022

3D-printed glass capillary

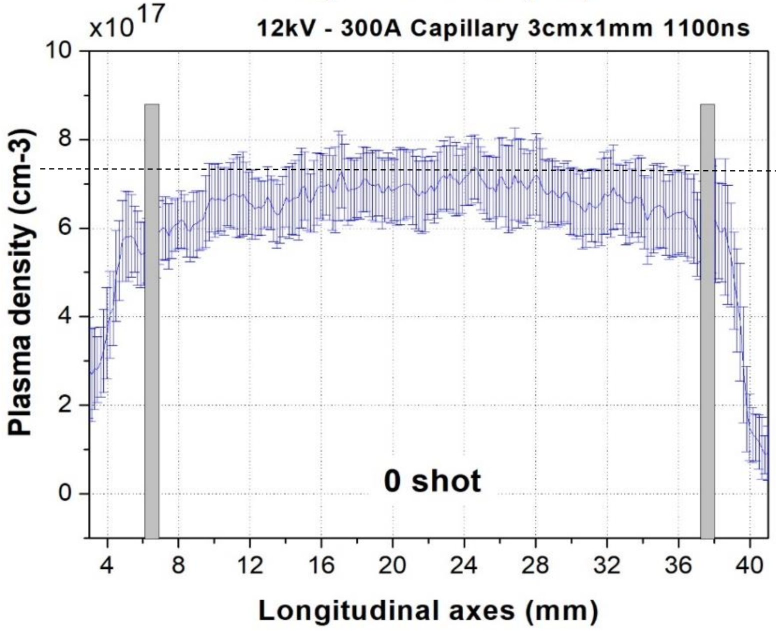


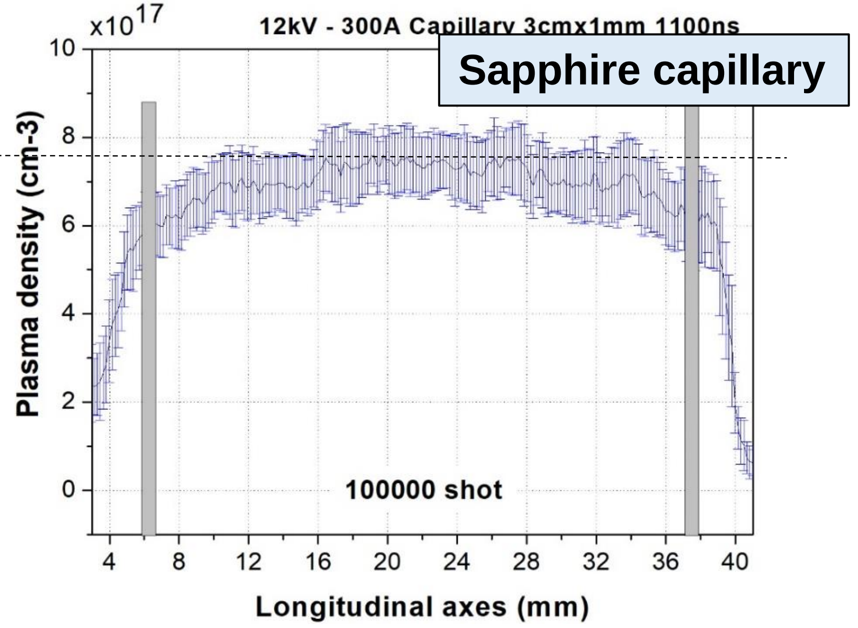


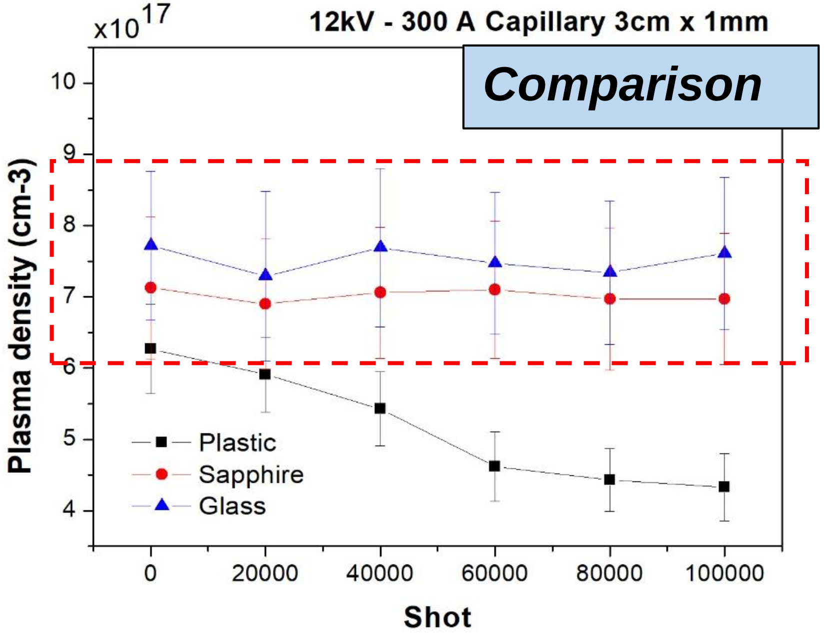




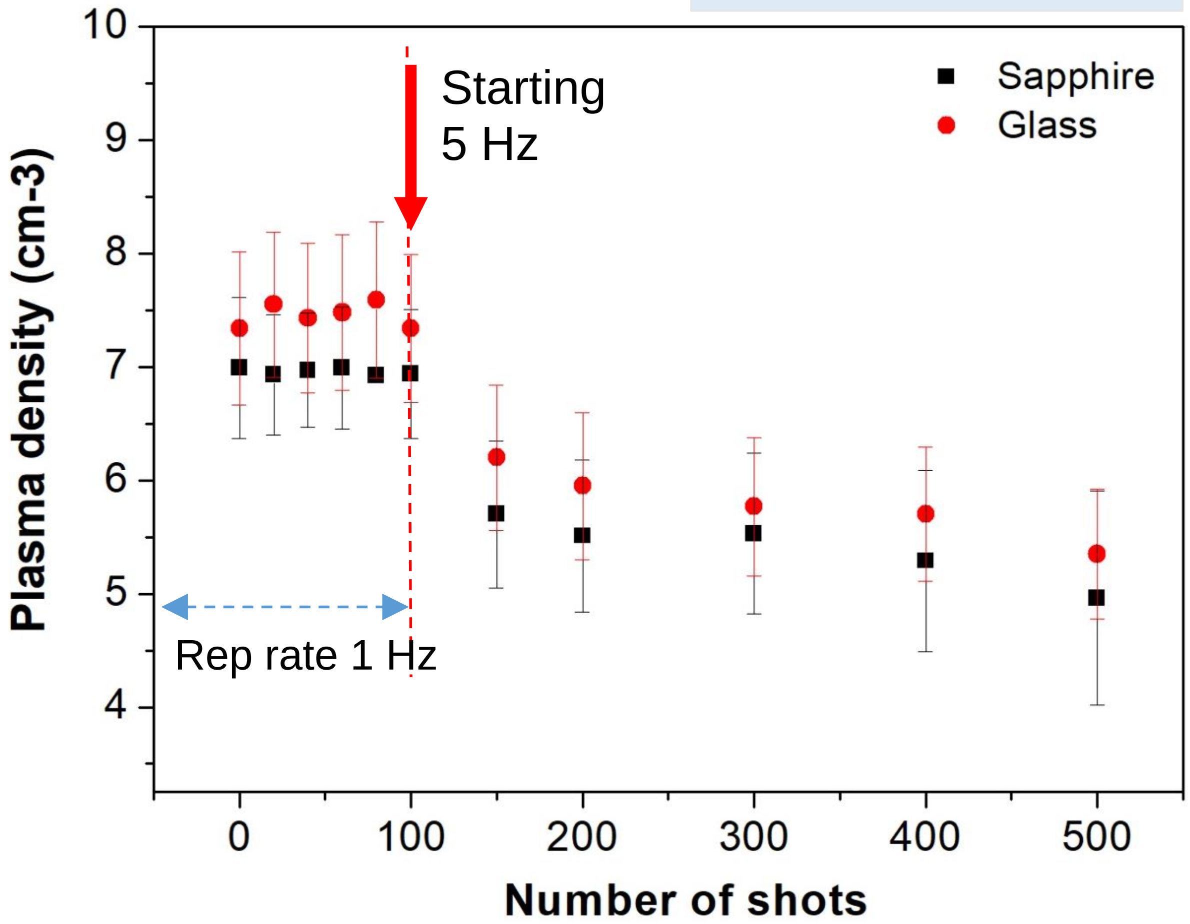
Sapphire capillary



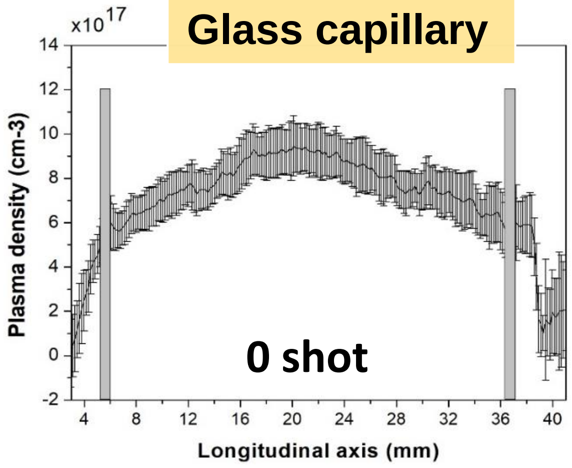


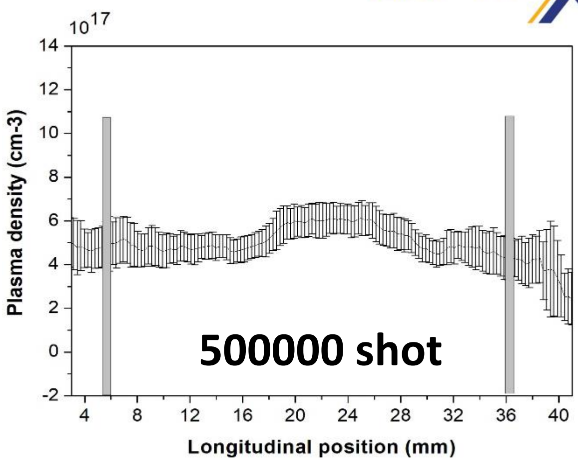


1-5 Hz repetition rate

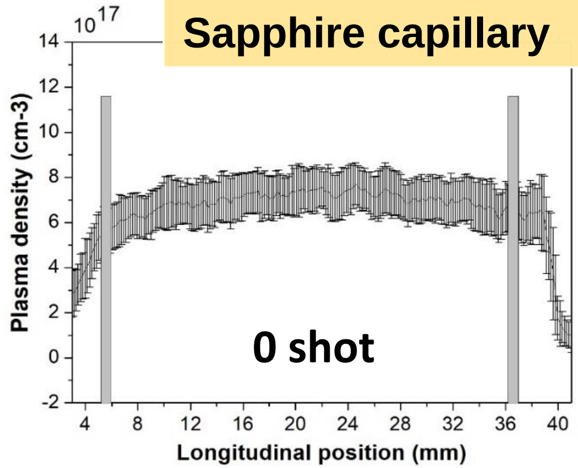


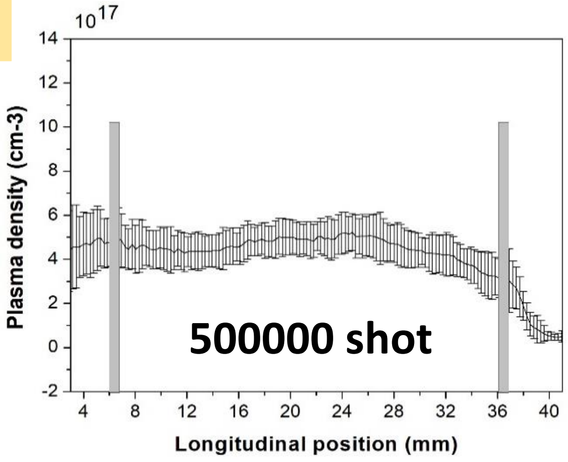
Glass capillary





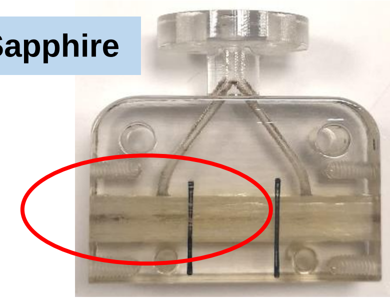
Sapphire capillary



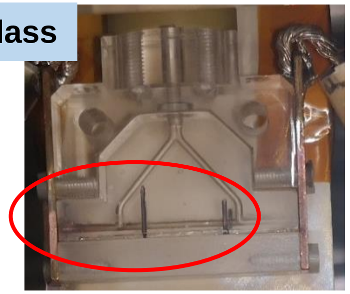


Stronger materials as sapphire or Glass can support a larger number of shots at 1 Hz but higher repetition rates produce a deformation of the channel that in turn changes the longitudinal density profile

Sapphire



Glass



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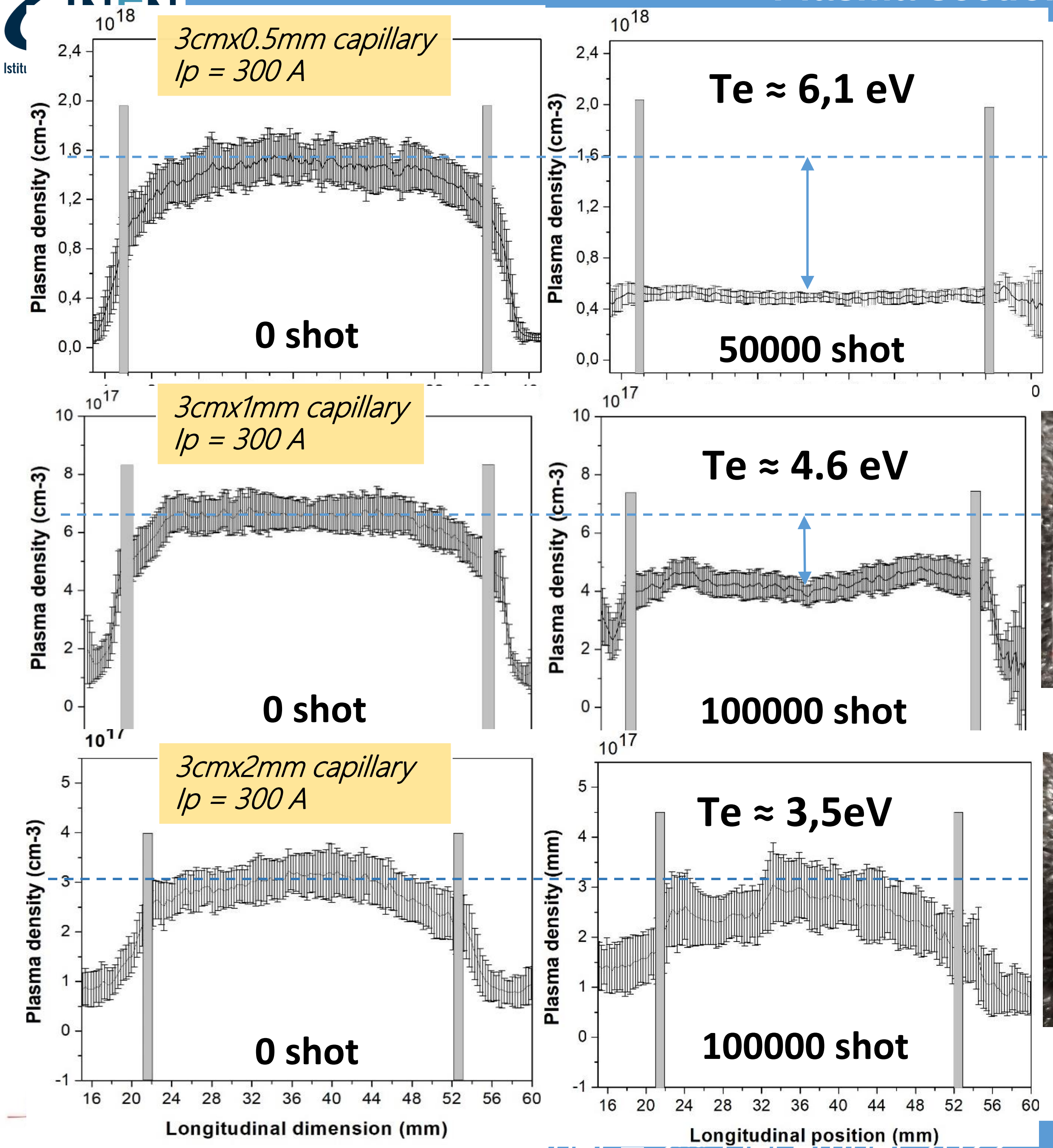
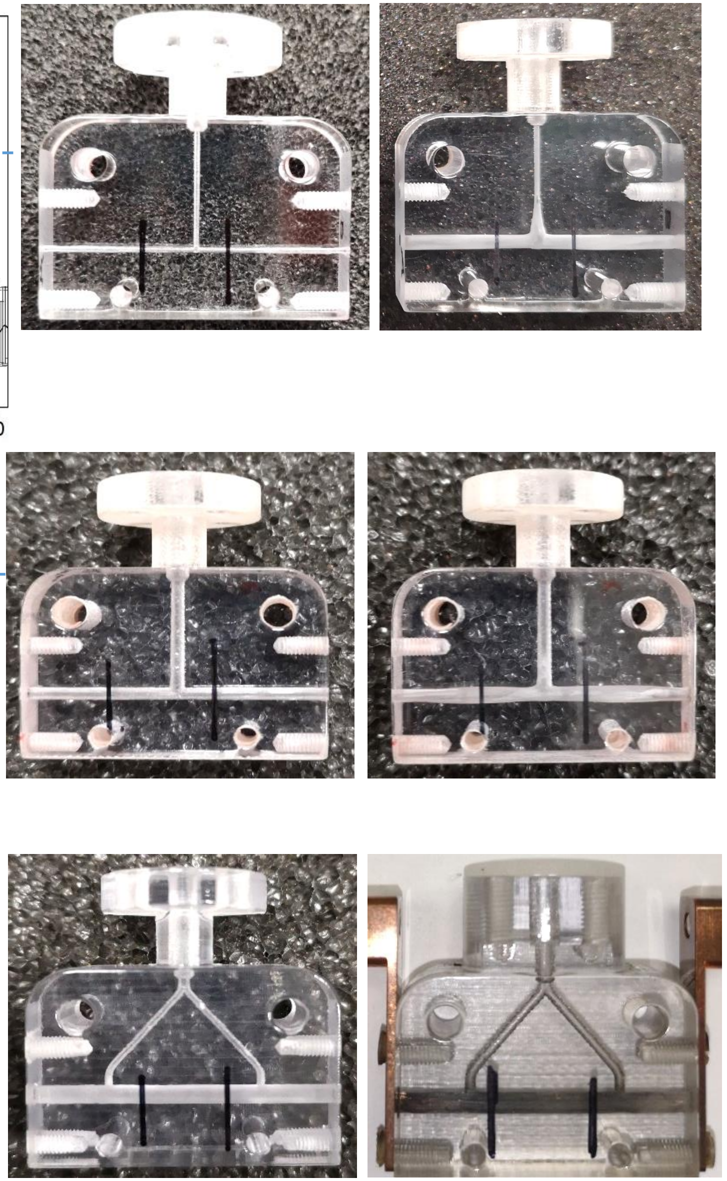


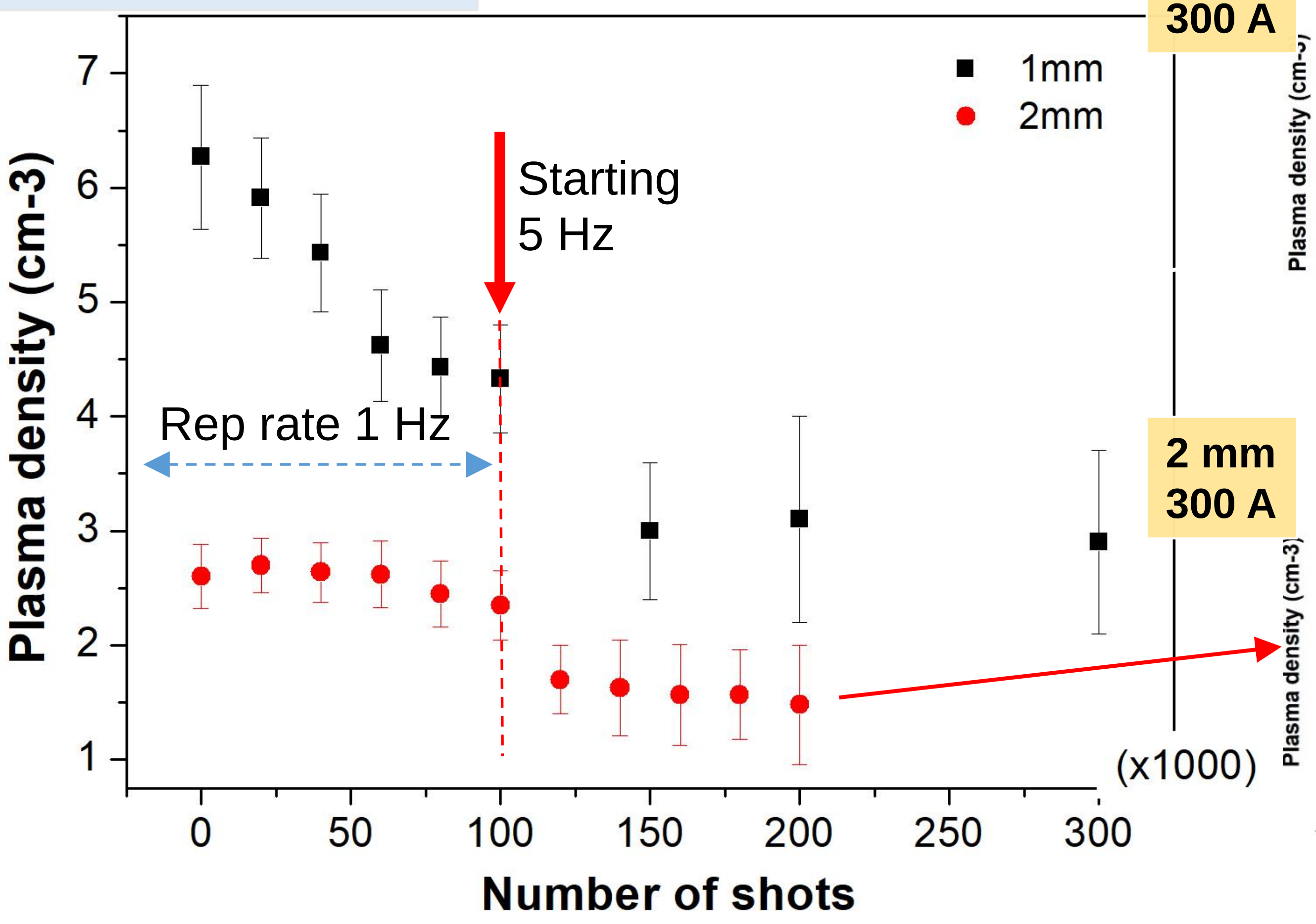


1Hz repetition rate

$$T_e(\mathrm{eV}) = 5.7 \left[\frac{I(\mathrm{kA})}{r_{cap}(\mathrm{mm})}\right]^{2/5}$$

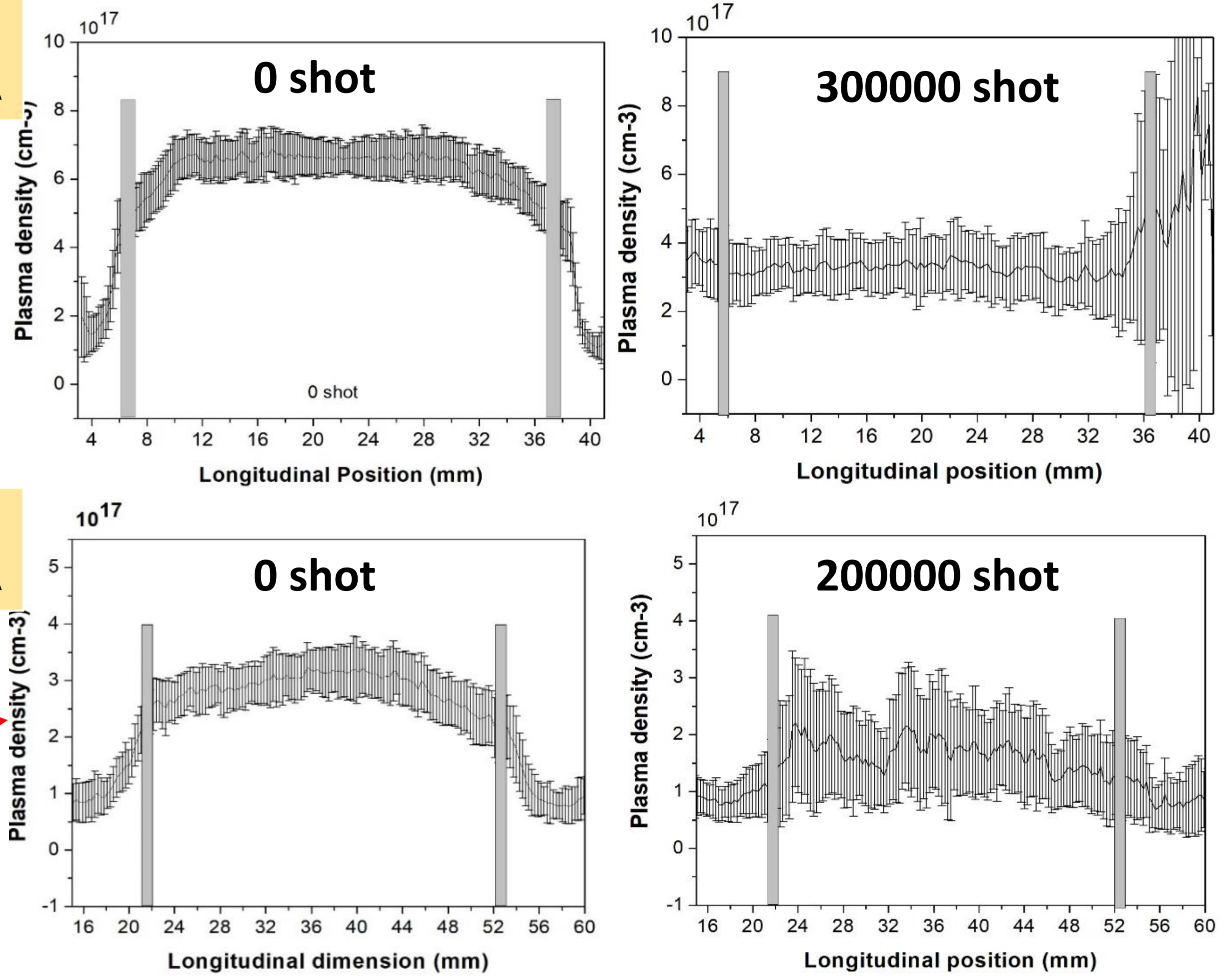
The larger is the current density, the stronger is the damaging of the plasma channel, because the thermal energy to be dissipated by the capillary walls will increase

1-5 Hz repetition rate



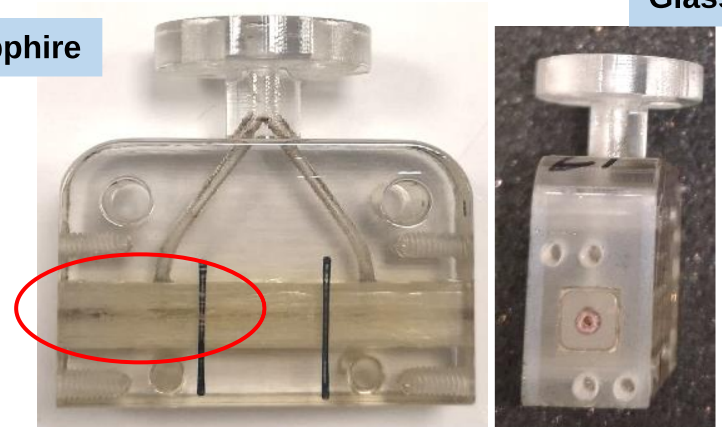
1 mm
300 A

2 mm
300 A

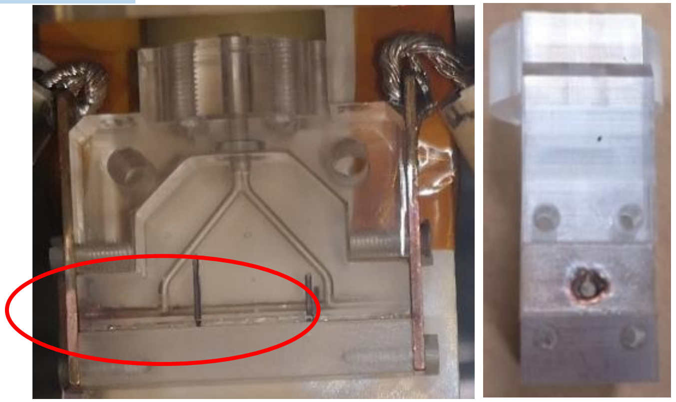


The damaging of the capillary depends on the plasma current density and also on the repetition rate of the discharge, since the higher is the repetition frequency the larger is the thermal energy accumulated on the capillary walls

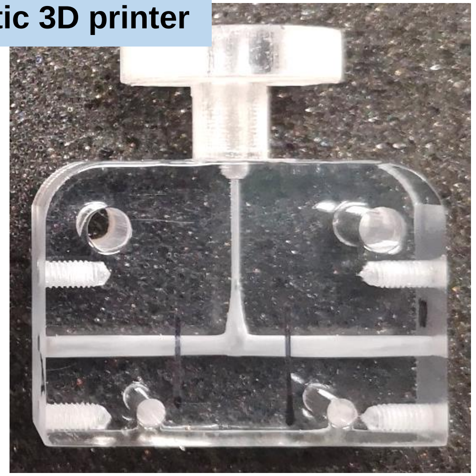
Sapphire



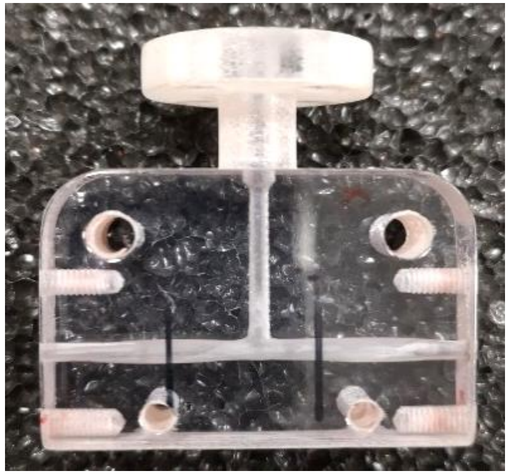
Glass 3D printer



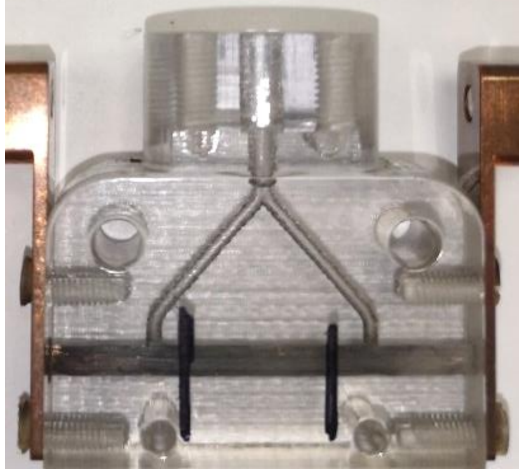
Plastic 3D printer



3cmx0.5mm capillary
Ip = 300 A



3cmx1mm capillary
Ip = 300 A

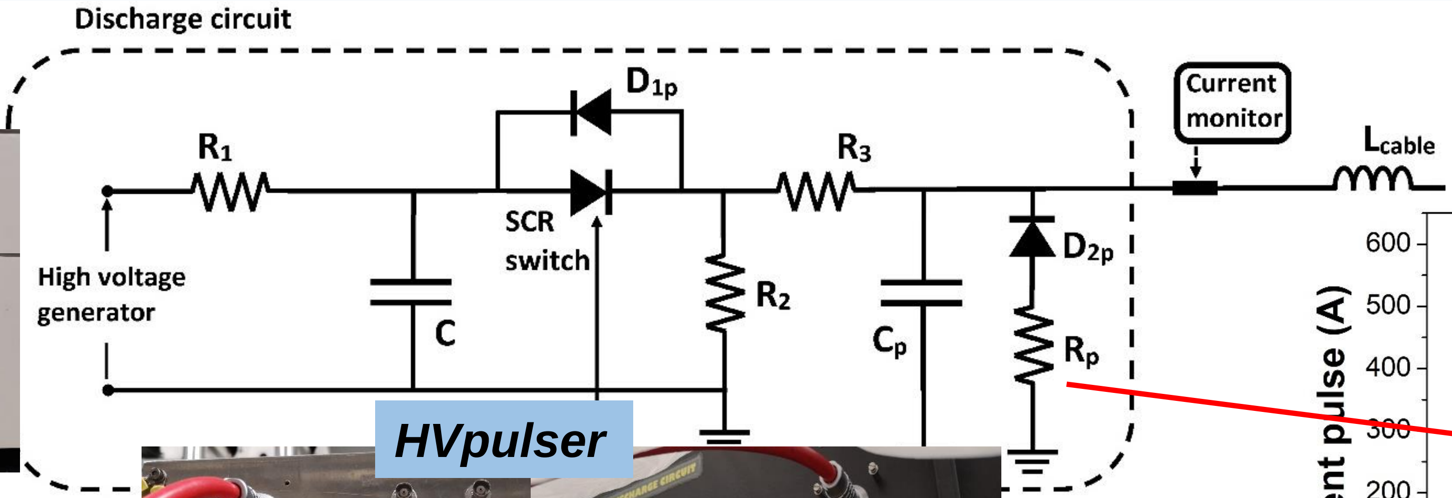


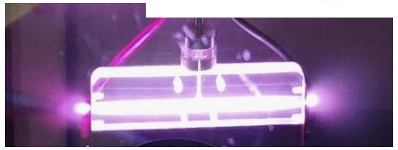
3cmx2mm capillary
Ip = 300 A

- 3cmx0.5 mm and 3cmx1mm show a strong deformation but no blackened parts
- Sapphire and glass materials do not show a deformation along the longitudinal coordinate like the plastic capillary composed of plastic but have a blackened parts on the positive electrode
- Also the 3cmx2mm channel does not show a strong deformation but it is completely blackened

Plasma section developments: high voltage source for plasma formation

HV gen

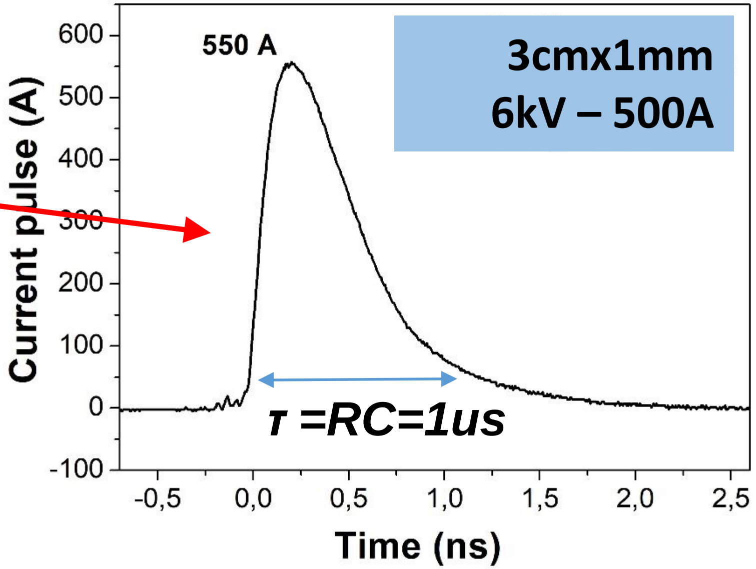




HVpulser

1.2 kA **2.5 kA**

3cmx1mm
6kV – 500A

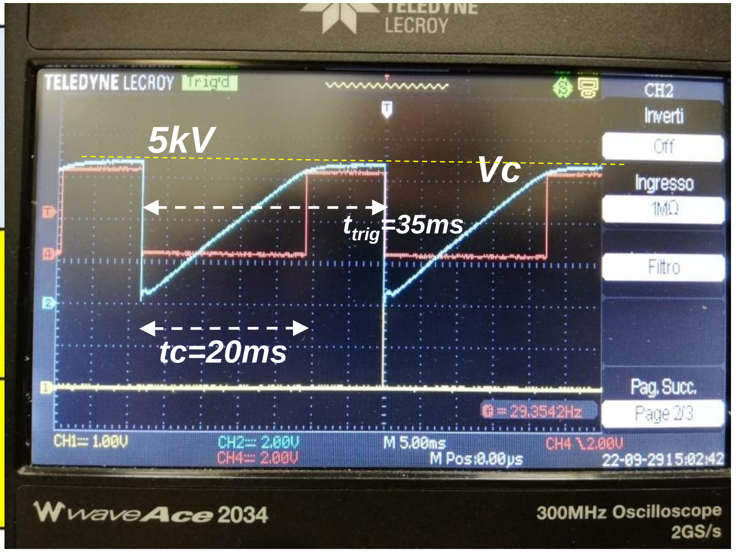


20/40 Hz Rep rate (measured) is the current limit Due to HV gen

In priciple, the HV pulser is able to support 400 Hz RepRate, heating issues can limit the RepRate, but the primary electric source could represent a limit to operate at High rep rate:

Q=CV=10kV x 40nF = 0.4x10^{-3} C
t_c = dQ/I_c = 20 ms per pulse (with I_c=20 mA)
Max Rep rate 50 Hz with the current HV gen

RepRate (Hz)	40cmx2mm (10kV) (EuPRAXIA plasma source)	3cmx2mm (5kV)(Current plasma source)
Current HV gen 35kV-20mA	50 Hz	100 Hz
New HV gen 25kV-200mA	500 Hz tc = 2 ms	1 kHz tc = 1 ms



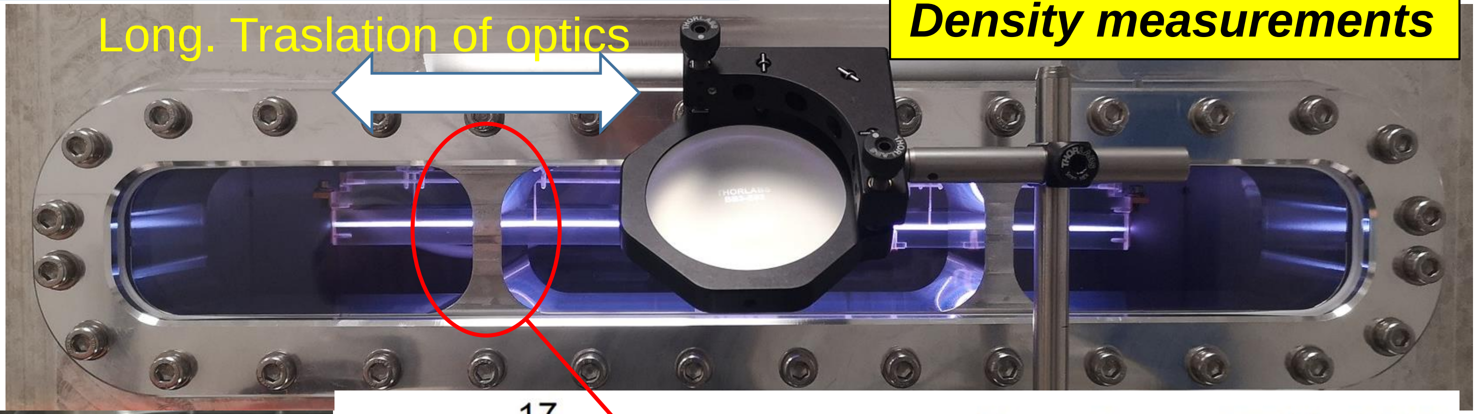
Presented in the previous RC 6 - 7th June 2022

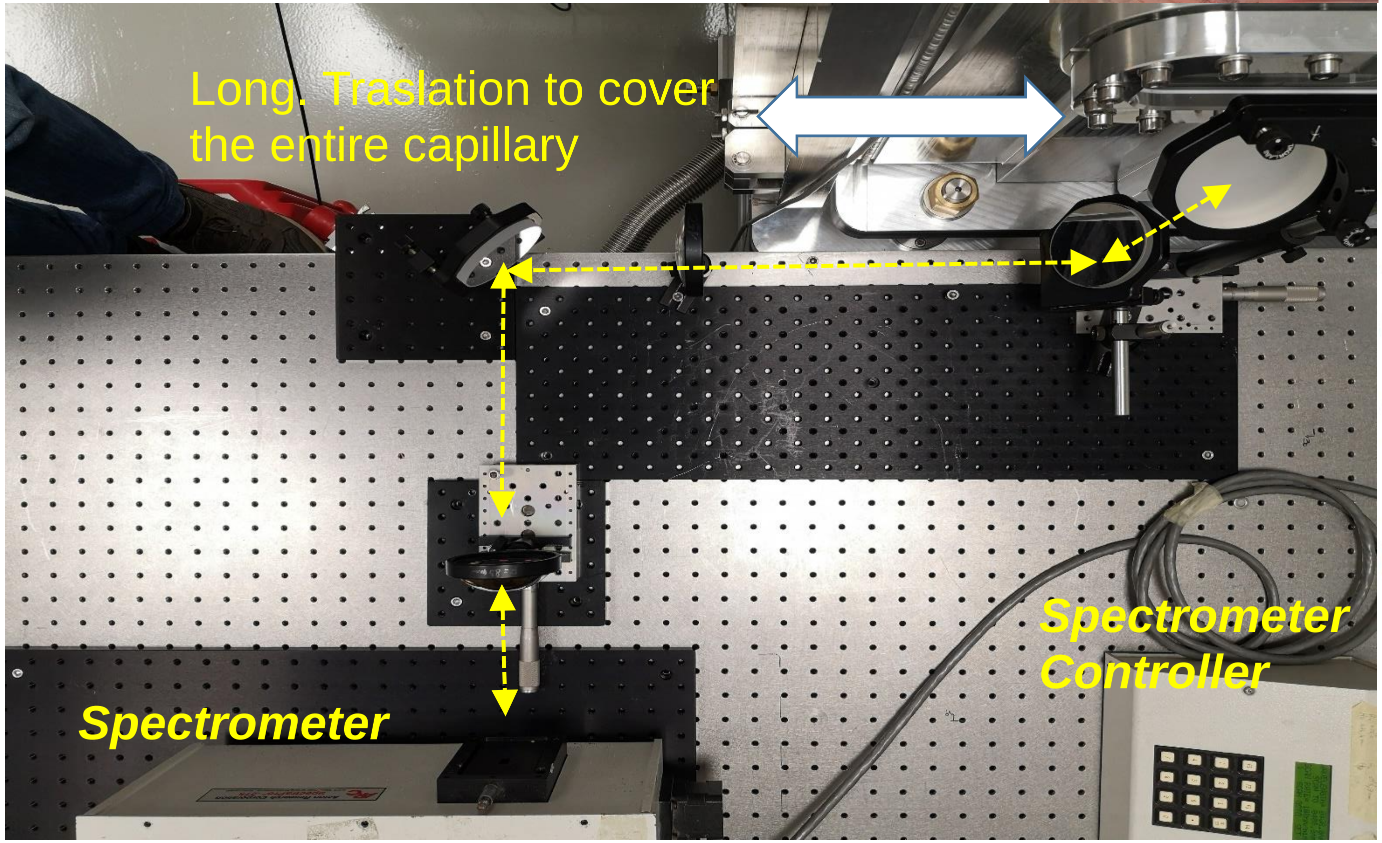
Operating conditions:

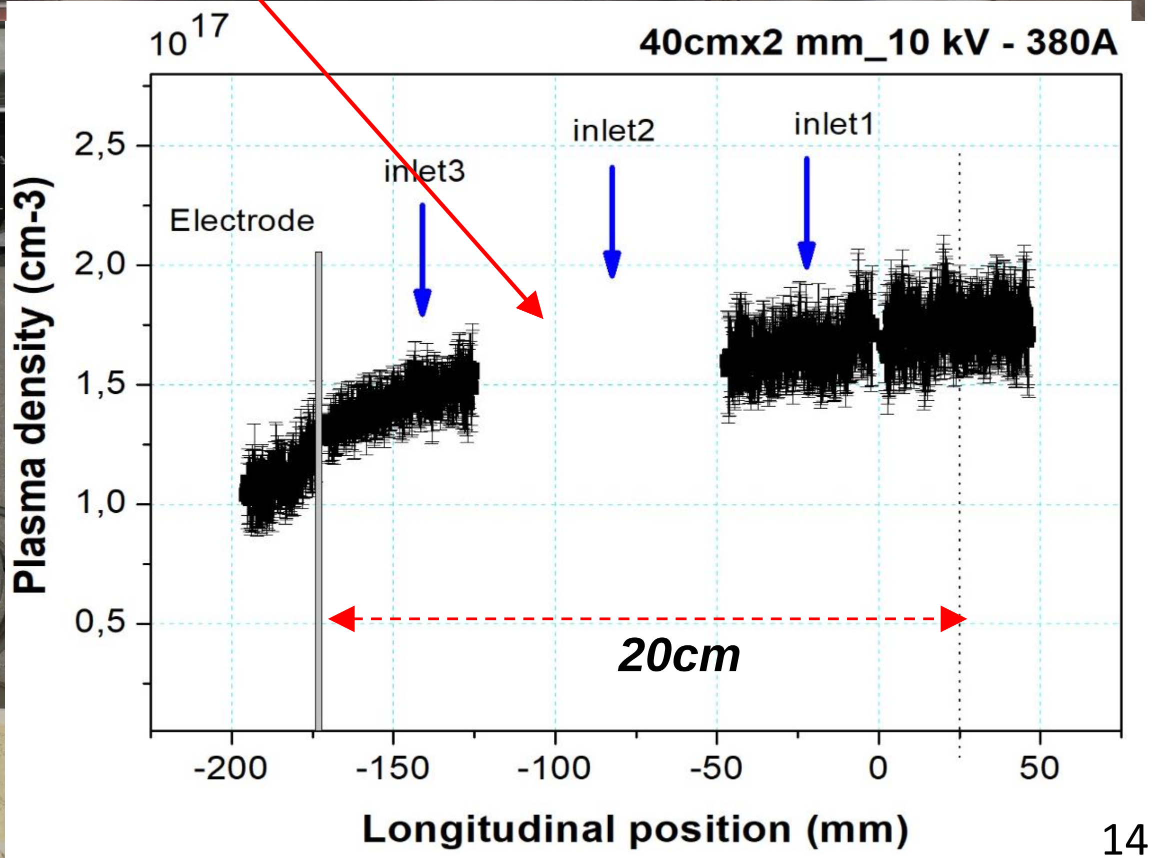
- **Rep rate at 1 Hz**
- **10 kV – 380 A minimum values to have the ionization (3 kV – 140 A for 3cmx2mm)**
- **Aperture time E-valve/Voltage delay is 8ms/12 ms (3-4 ms/5-6 ms for 3cmx2mm)**
- **6 inlets of 1 mm in diameter separated by 60mm/80mm (1 or 2 inlets for 3cmx2mm)**

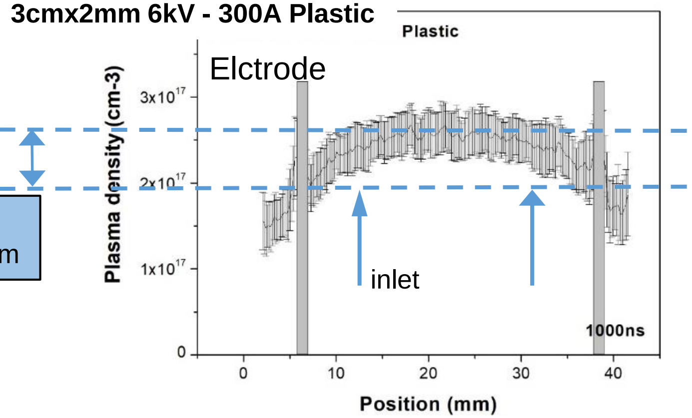
Presented in the previous RC 6 - 7th June 2022

- All mirrors and lenses have been mounted on movable breadboards In order to scan the entire lenght of the capillary
- Blind area where there is windwow supports (could be reduced)
- **10^{16} - 10^{17} cm-3 range (EuPRAXIA goal)**

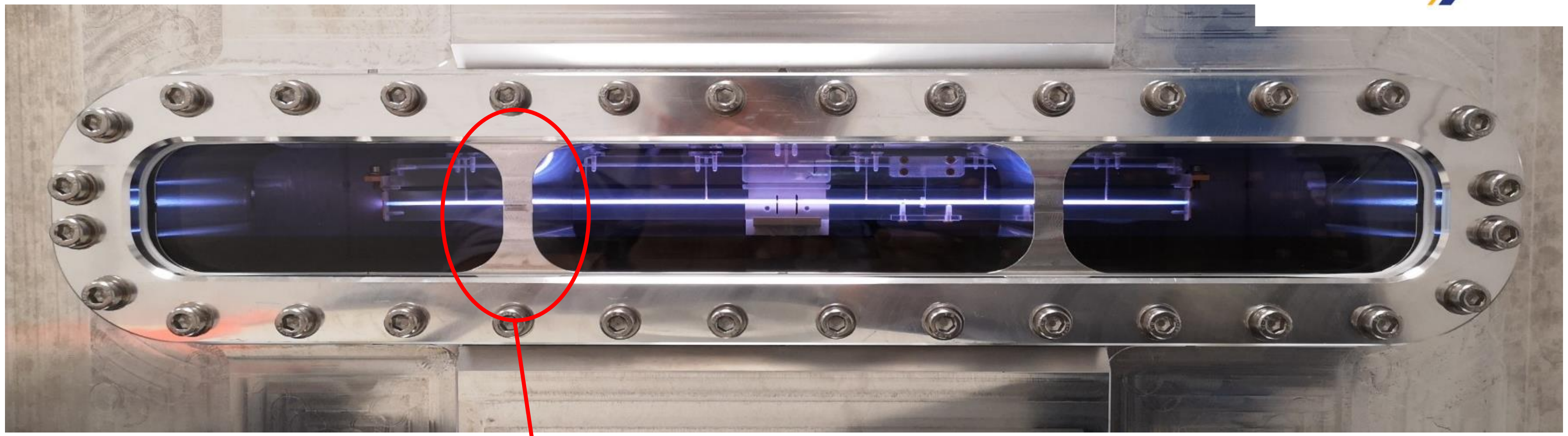


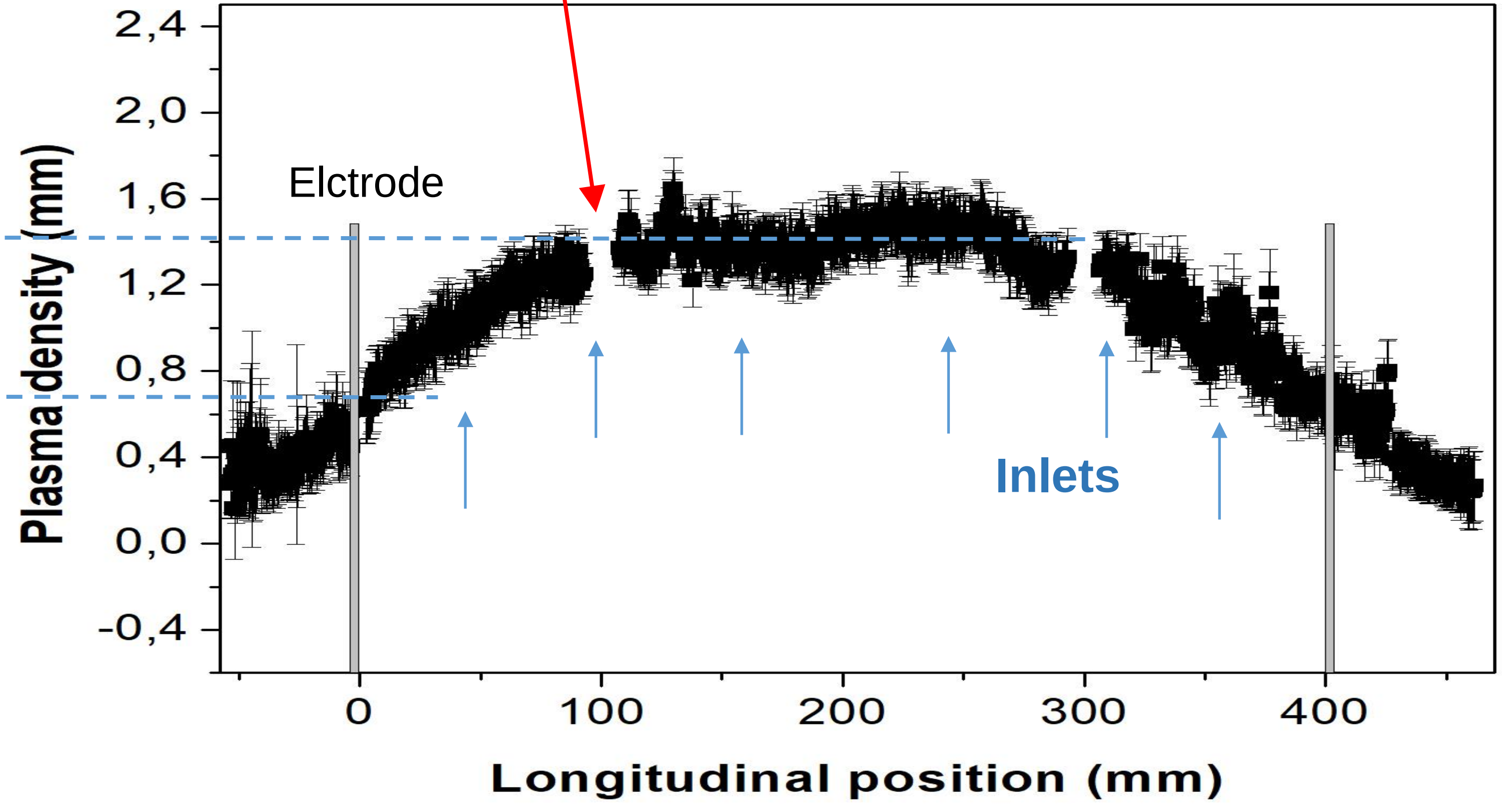






0.7x10^{17} cm-3
related to 15mm

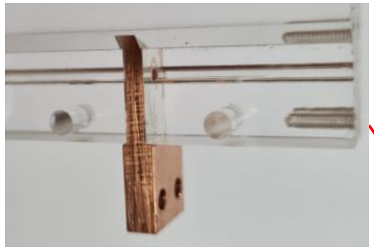




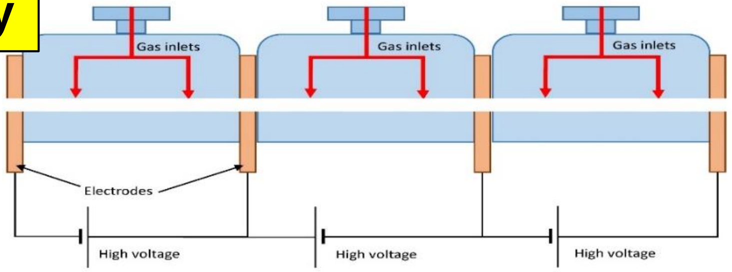
0.6x10^{17} cm-3
related to 200mm

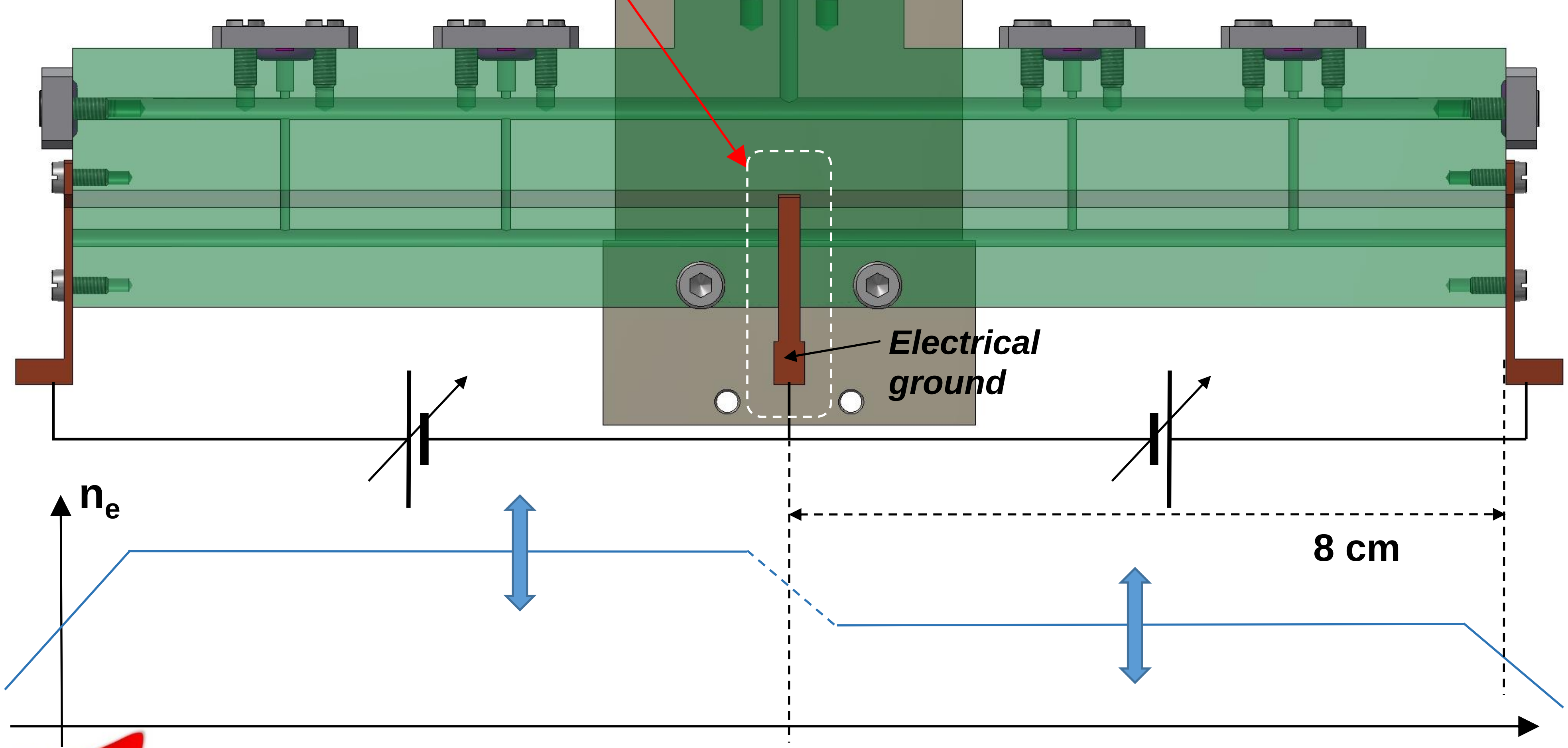
EuPRAXIA plasma sources: segmented capillary

The critical point is the electrode insertion to avoid gas leaks (two prototypes already produced)

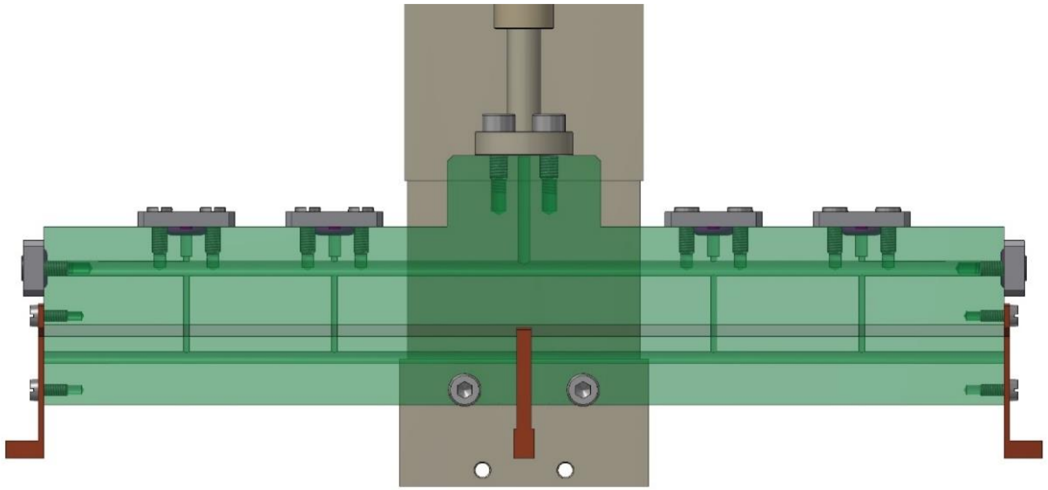


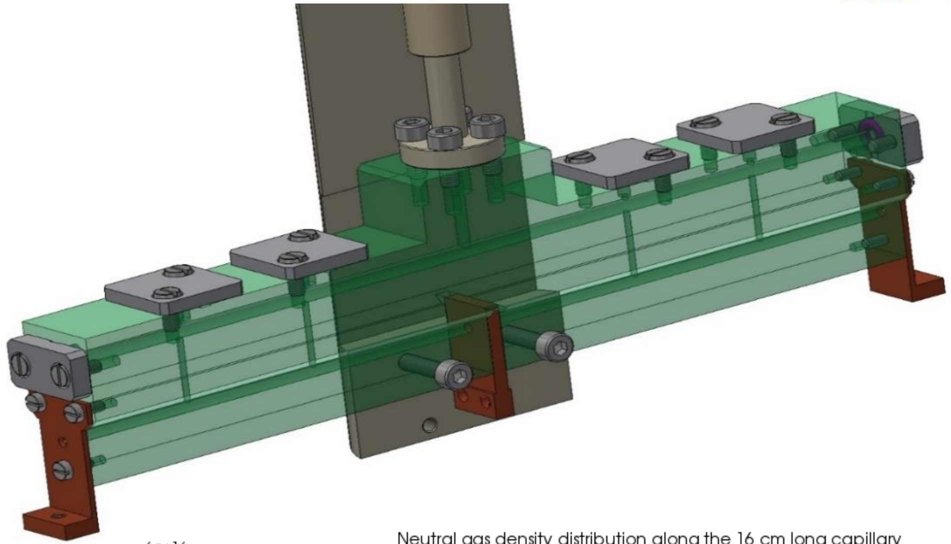
Segmented capillary

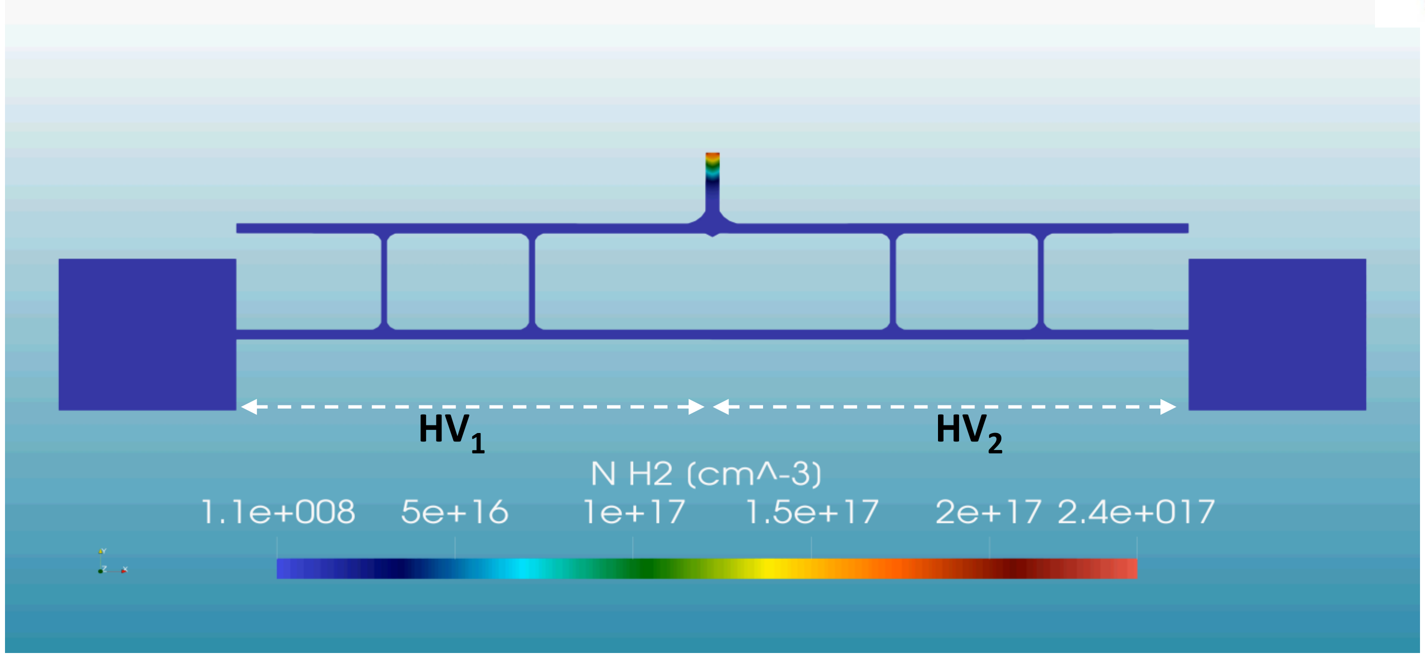


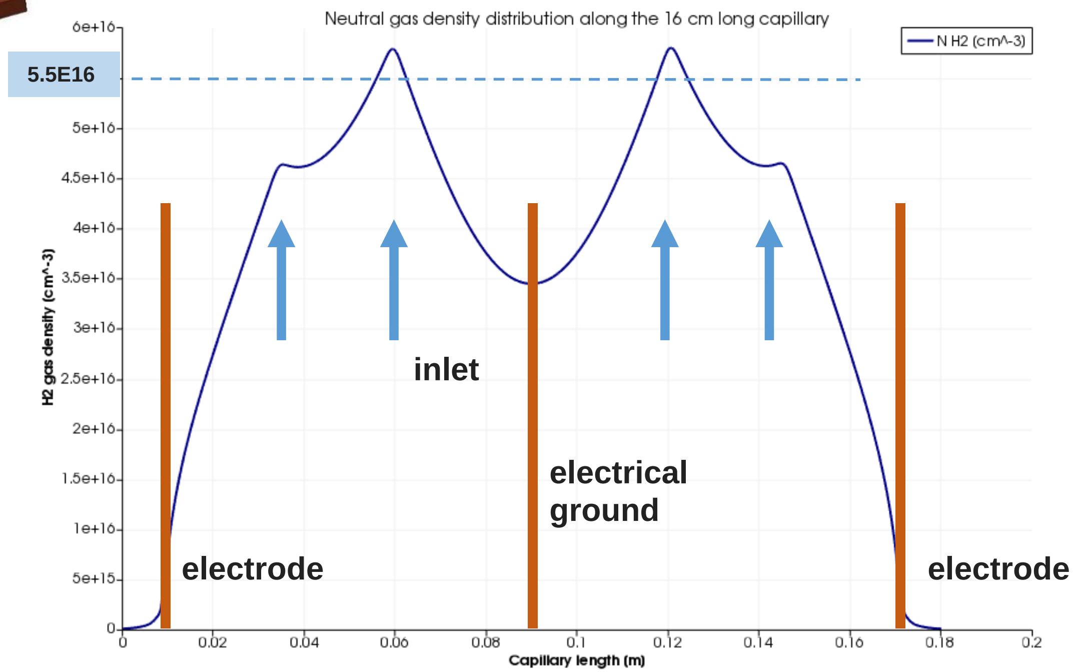


- **Elongation of the maximum length of plasma sources up to m-scale with HV pulses less tahn 10 kV**
- **Longitudinal density modulation by changing voltage or delay time**
- **Transition area of the plasma density around the electrical gorund has to be characterized**









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All sections of the Plasma module for EuPraxia project are ongoing

40cm capillary is working

- **1.1 GeV** (1.5 GV/m 40cm capillary - density 10^{16} cm-3)
  - Direct plasma discharge for 40cm long capillary
    - Stability
    - Longitudinal profiles
  - Plasma sources operating at 100 – 400 Hz
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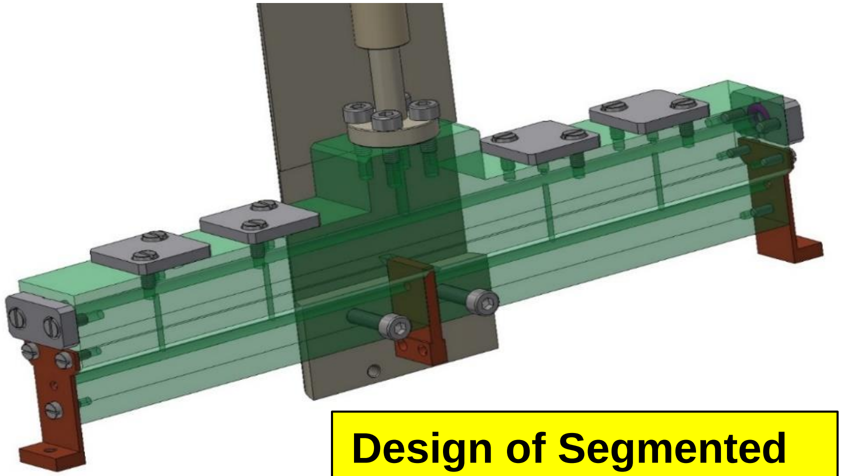
    - Plasma sources larger than 40 cm (m-scale)
    - Longitudinal density modulation
    - **5 GeV** case for EuPRAXIA (1.5 GV/m m-scale capillary - density 10^{16} cm-3)



Design of Segmented capillary

Thank you for your attention