EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

High repetition rate plasma sources

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On behalf of the EuPRAXIA@SPARC_LAB collaboration

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Outline

Funded by the European Union

Introduction

- Plasma module limitations in high repetition rate operation

Ceramic Plasma Discharge Capillaries

- Design and experimental setup
- High repetition rate testing and characterization
- Heat transfer numerical analysis

Laser-induced plasma filaments

- Experimental setup and characterization

Conclusions

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Limitations in high repetition rate

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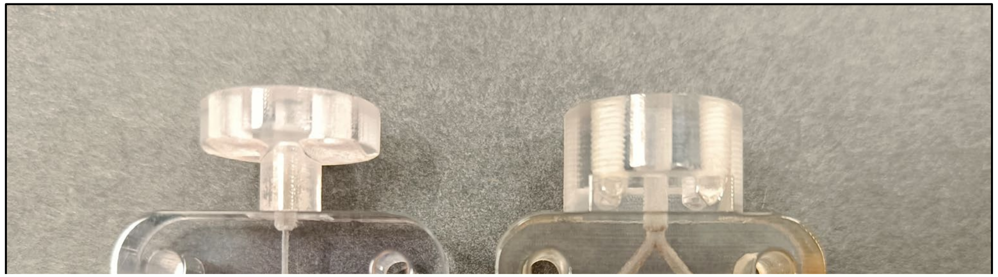
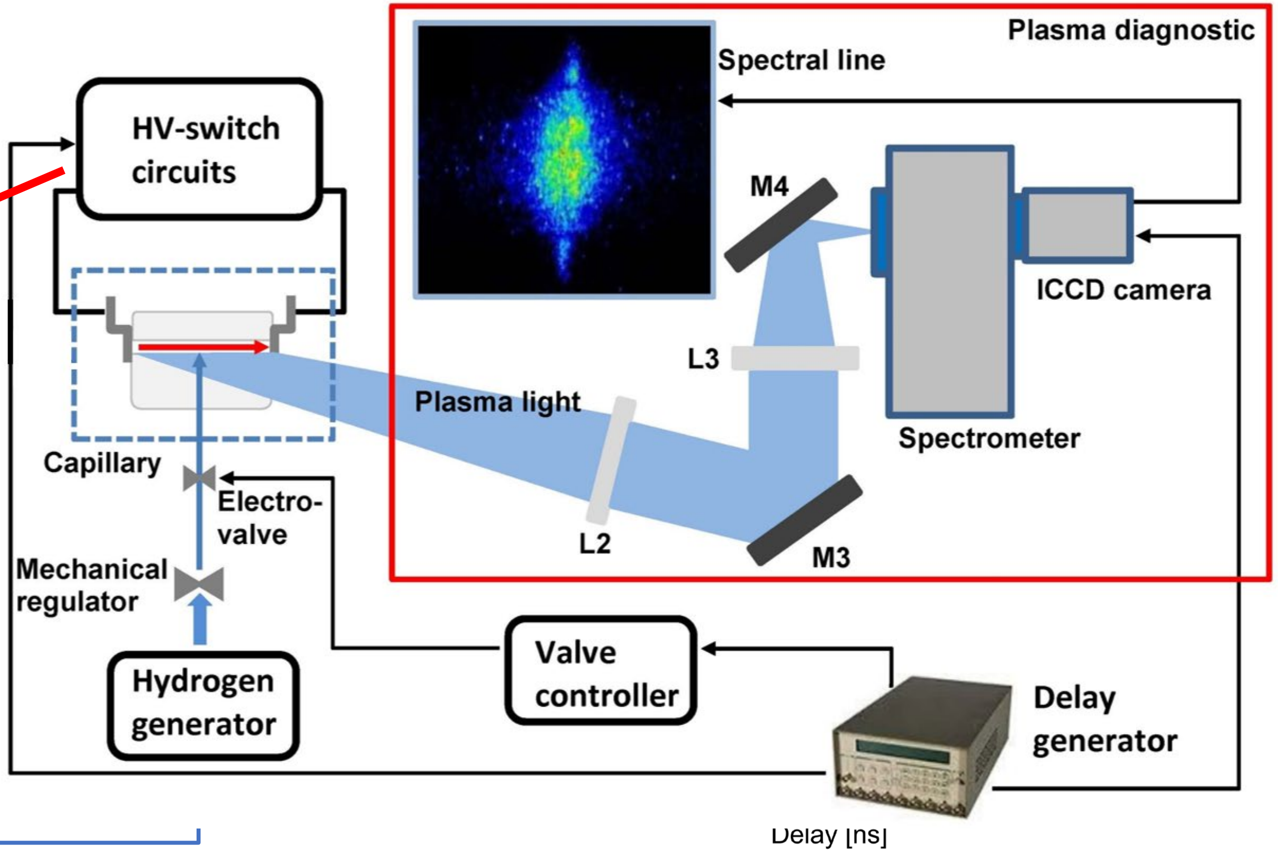
Plasma module operation at high repetition rate

1. Heating of HV discharge system
2. Effort required from vacuum systems for gas injection in continuous flow
3. Capillary erosion/damage





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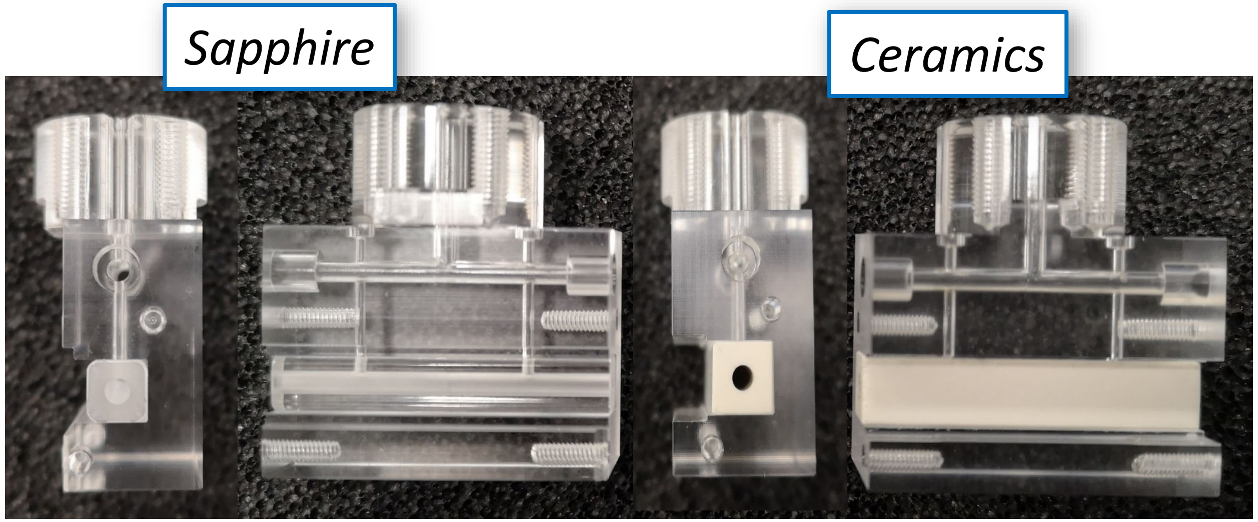
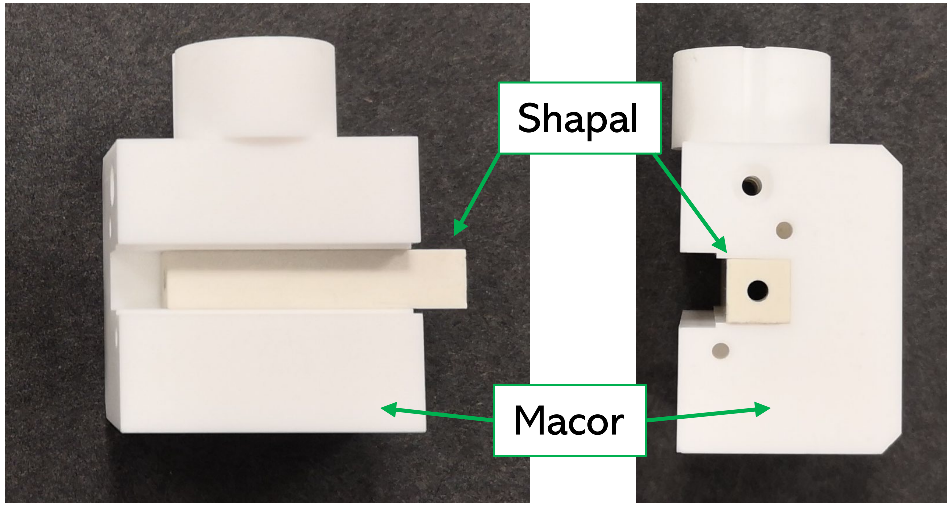
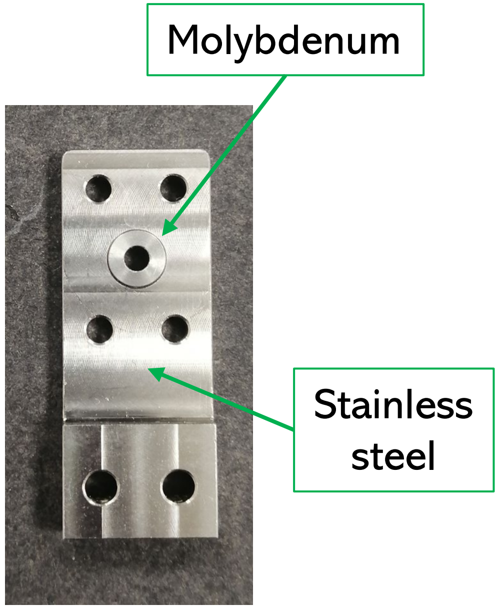
Advanced Ceramic capillaries

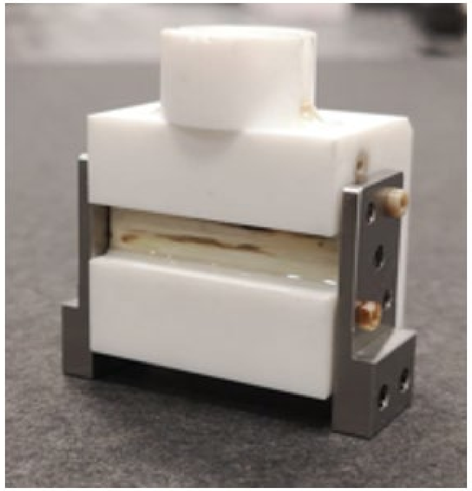
High temperature resistant materials

- High thermal conductivity
- High max operating temperature
- Good machinability, cost-effectiveness and availability for large geometries









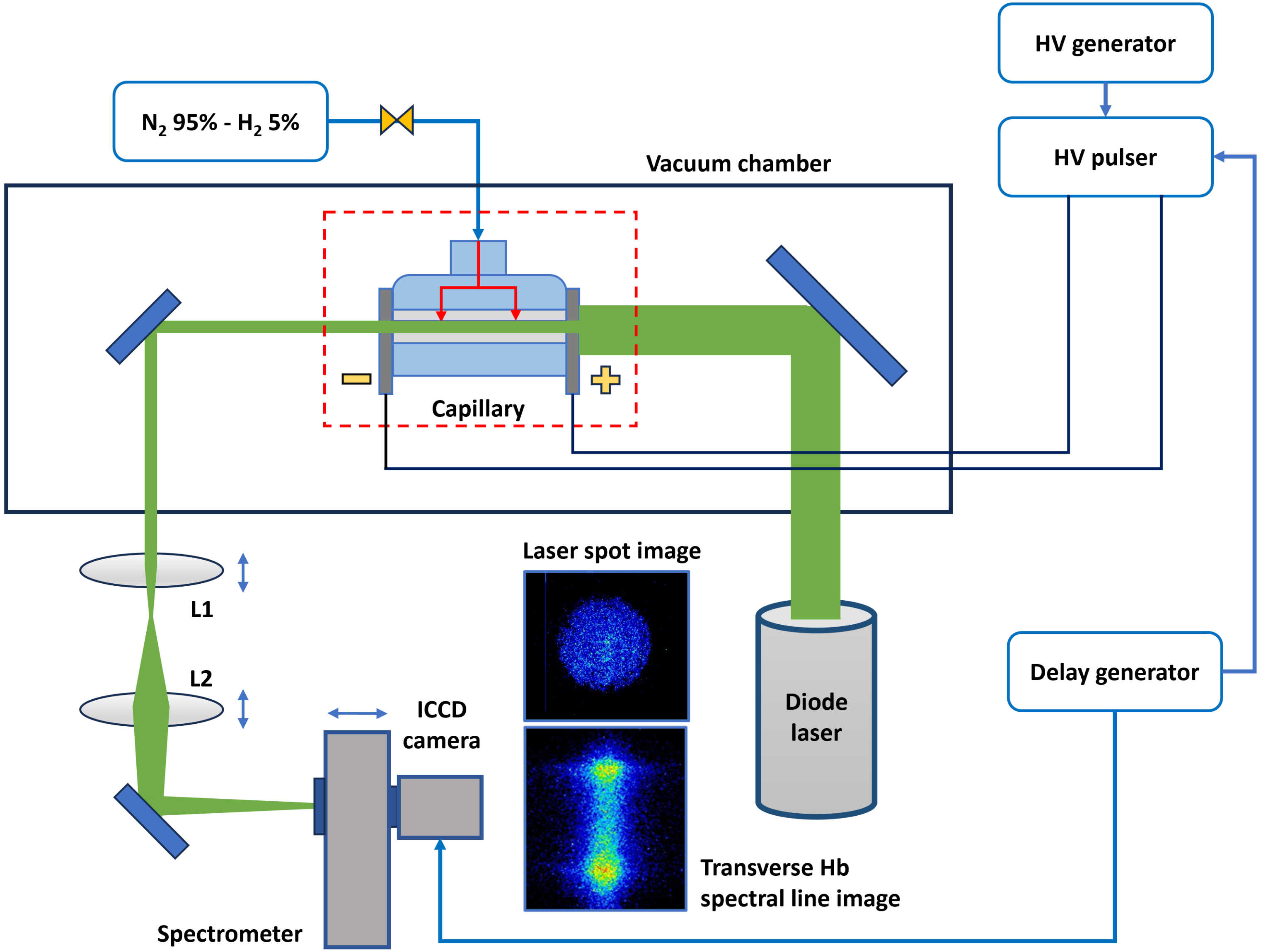
3 cm long, 2 mm diameter

Advanced Ceramic capillaries

Experimental testing

- 10-150 Hz operation
- N_2 80-100 mbar in continuous flow
- 5 kV – 400 A

100 Hz repetition rate discharges

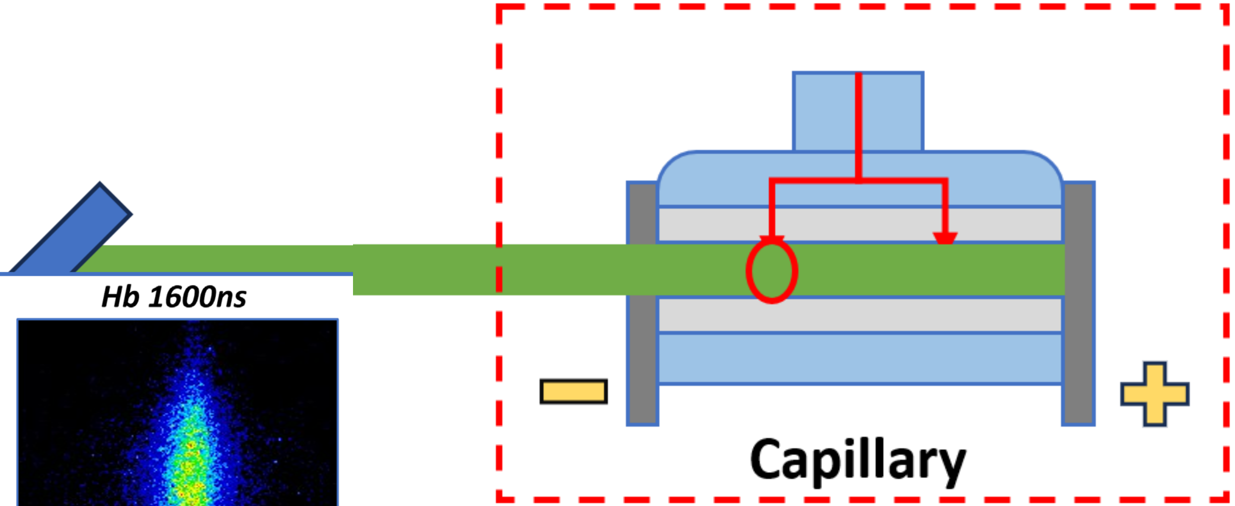


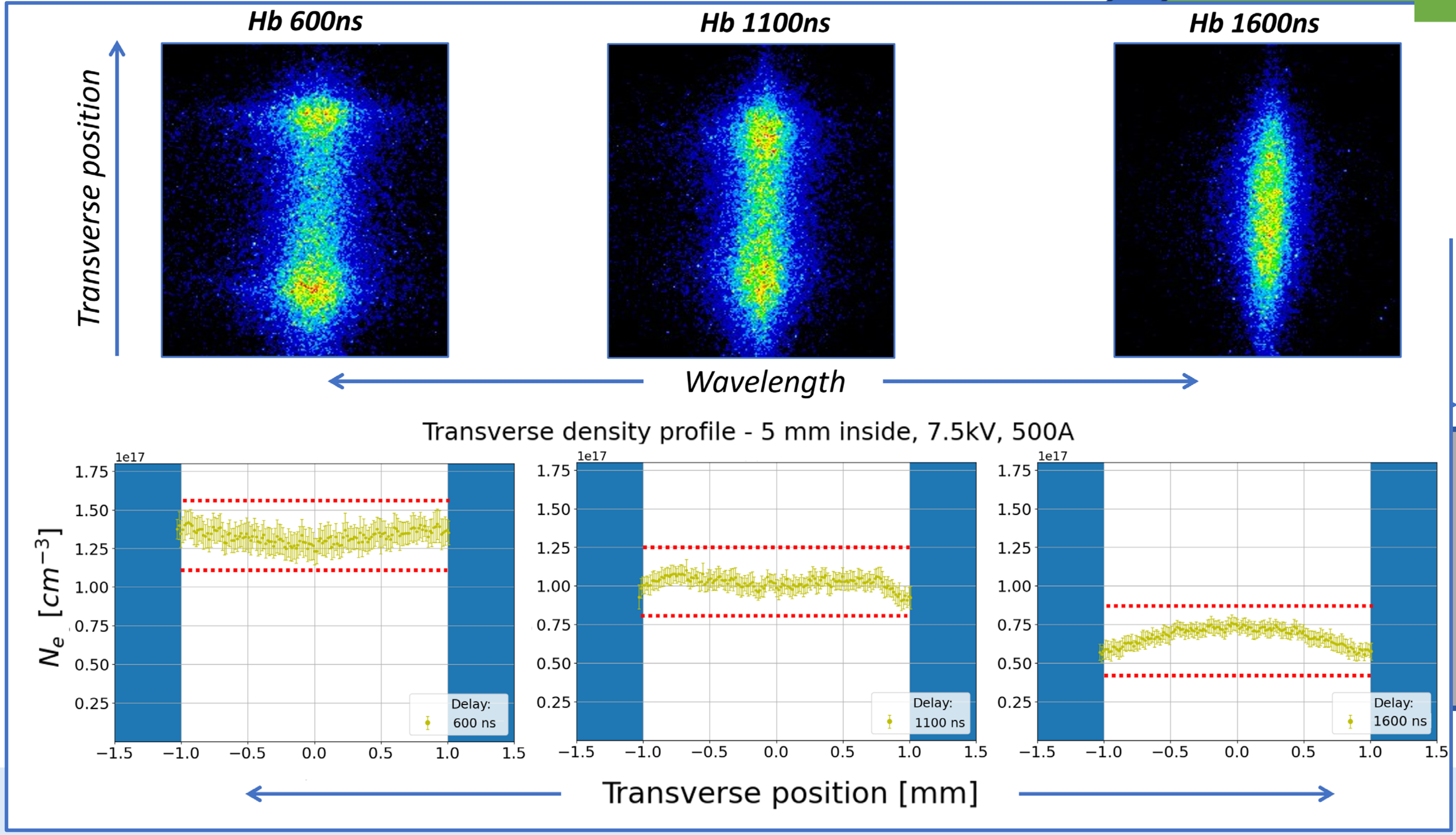
Plasma density measurements

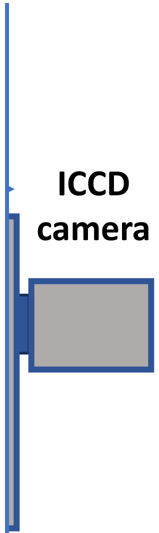
Funded by the European Union

Transverse Stark broadening

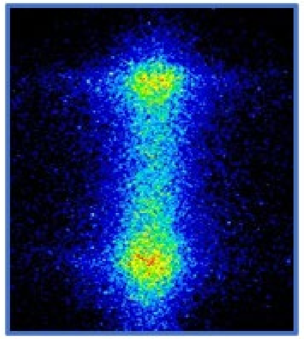
- 1 Hz operation
- H_2 80-100 mbar in pulsed







Transverse Hb spectral line image

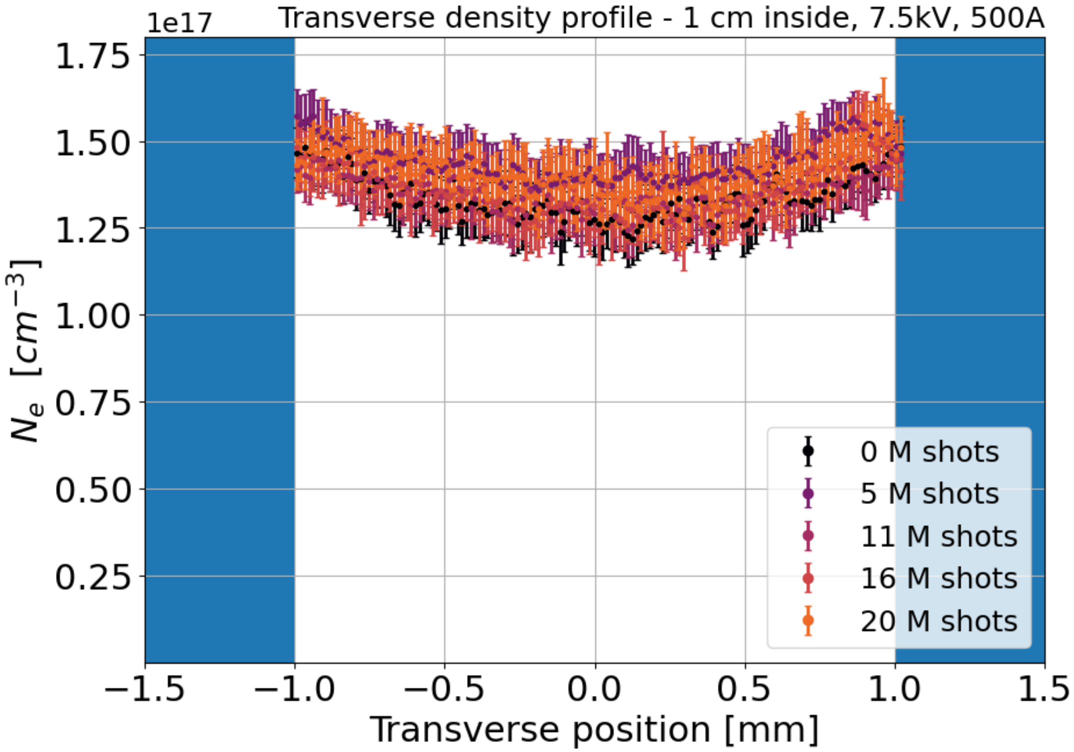


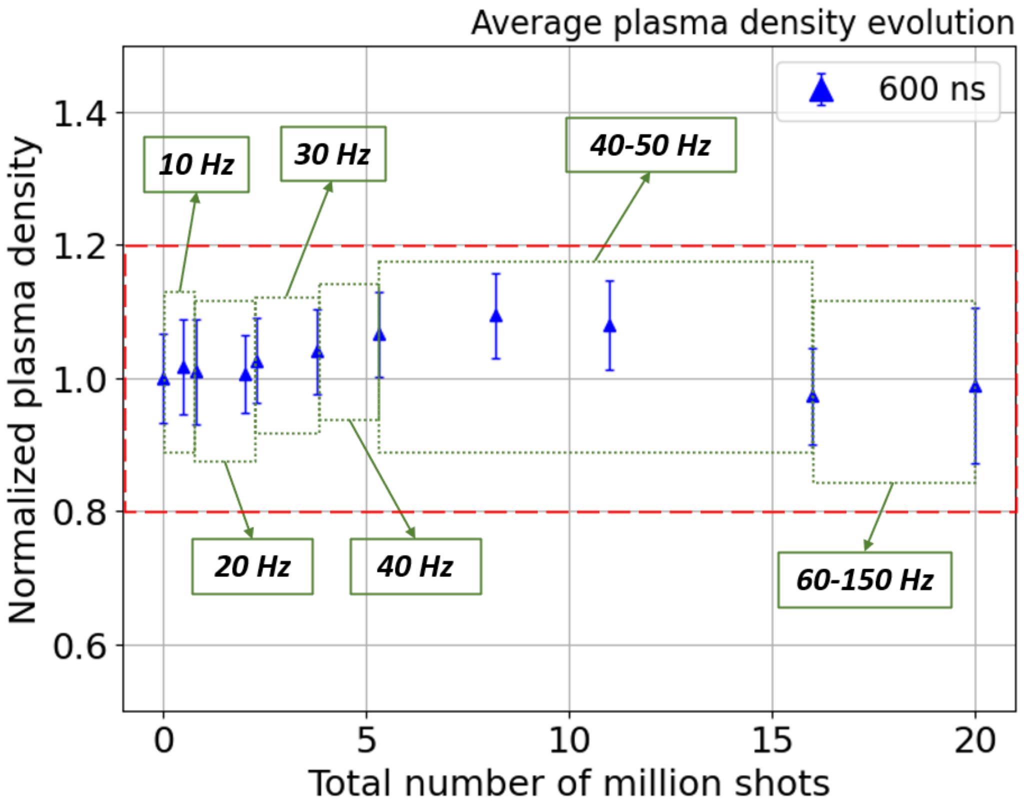
Plasma density measurements

Funded by the European Union

Experimental results

- ➢ Transverse density profile at the density peak
- ✓ No alteration in plasma density distribution



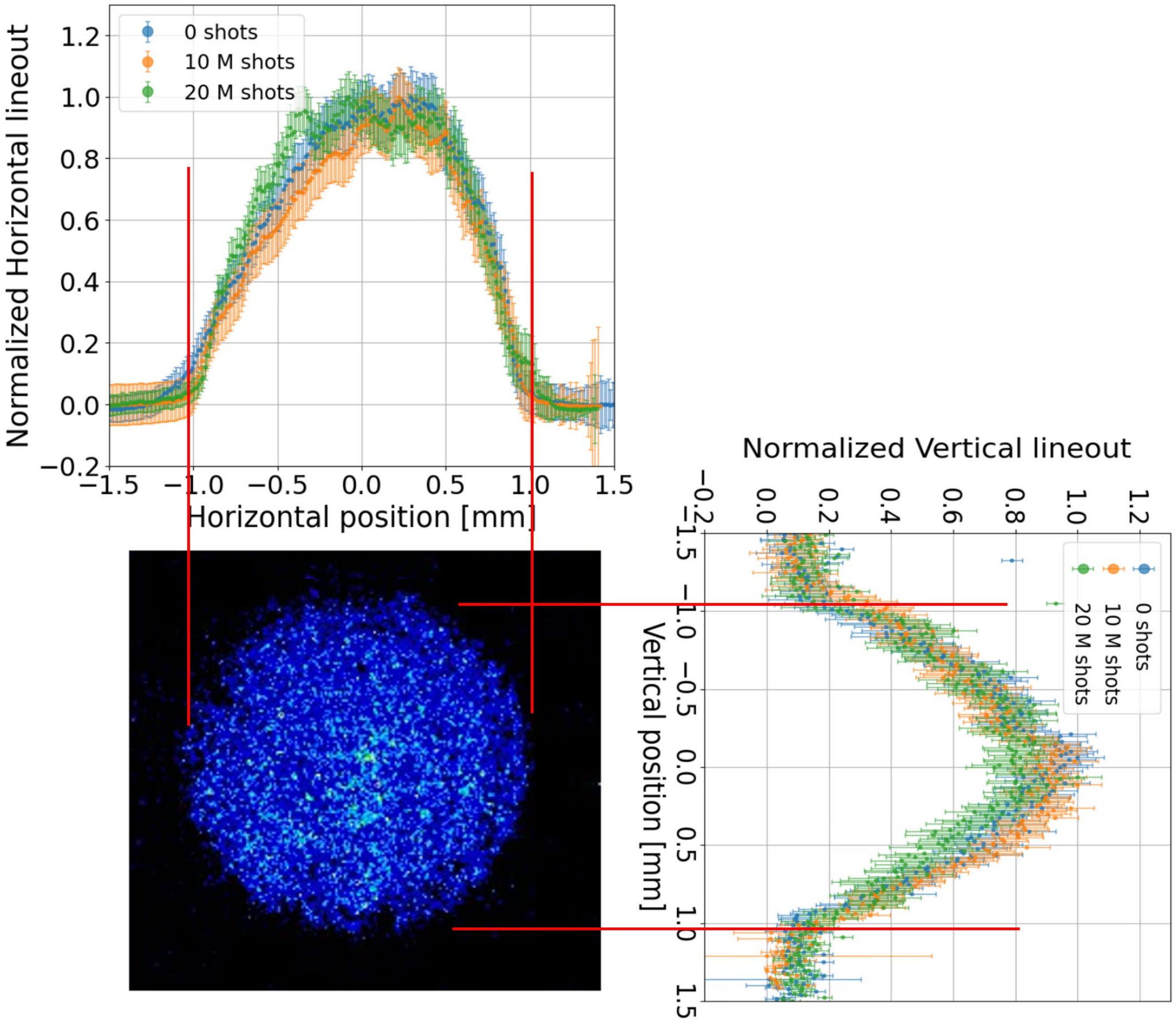


Laser spot imaging

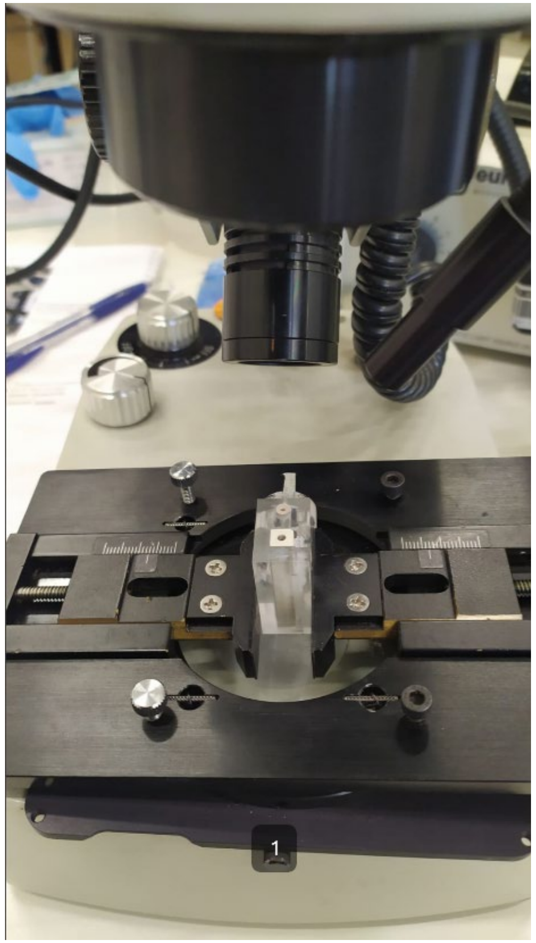
Funded by the European Union

Experimental results

- ➢ Laser spot size lineouts measured during the experimental campaign
- ✓ No alteration in laser spot size

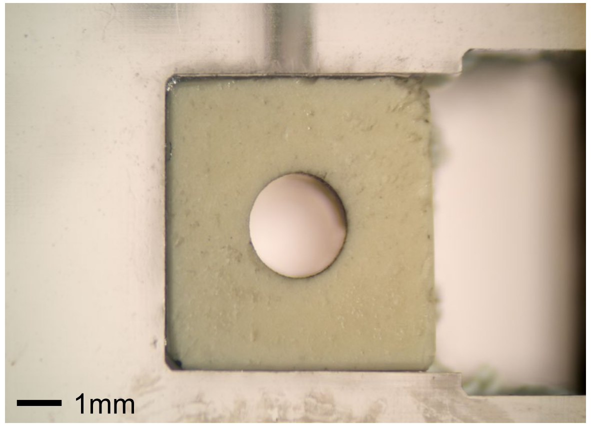


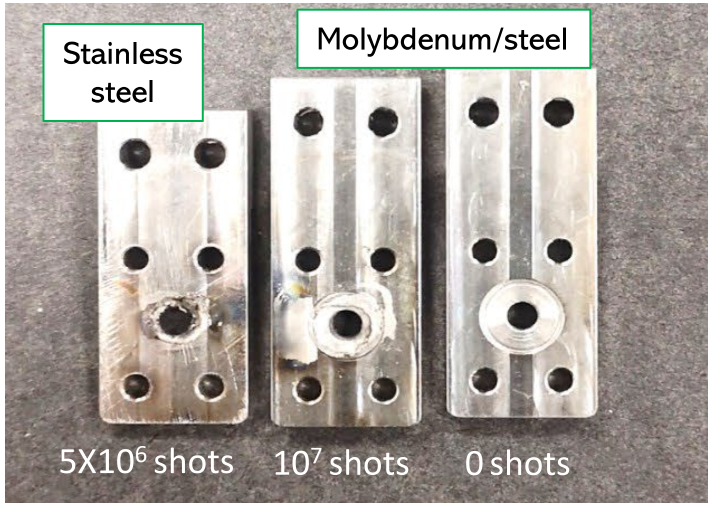
Microscopic analysis



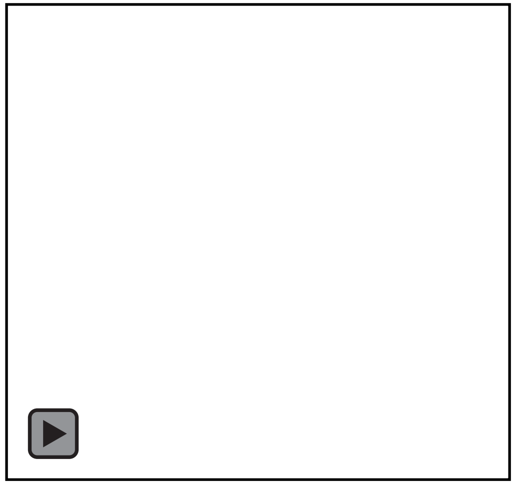
Optical Stereomicroscope - Euromex

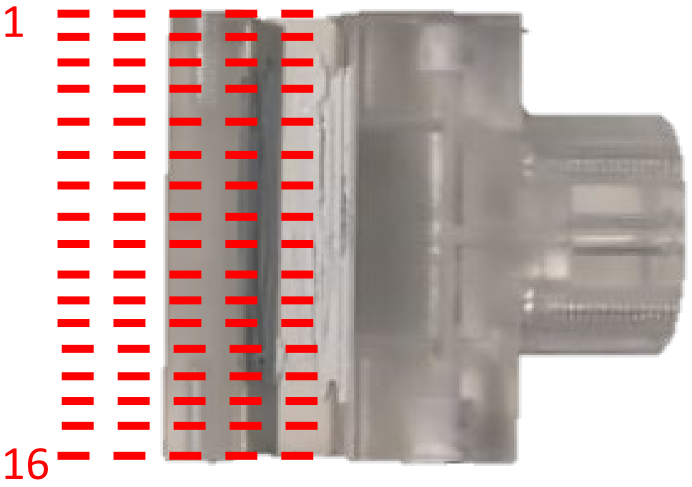
Magnification: 1x

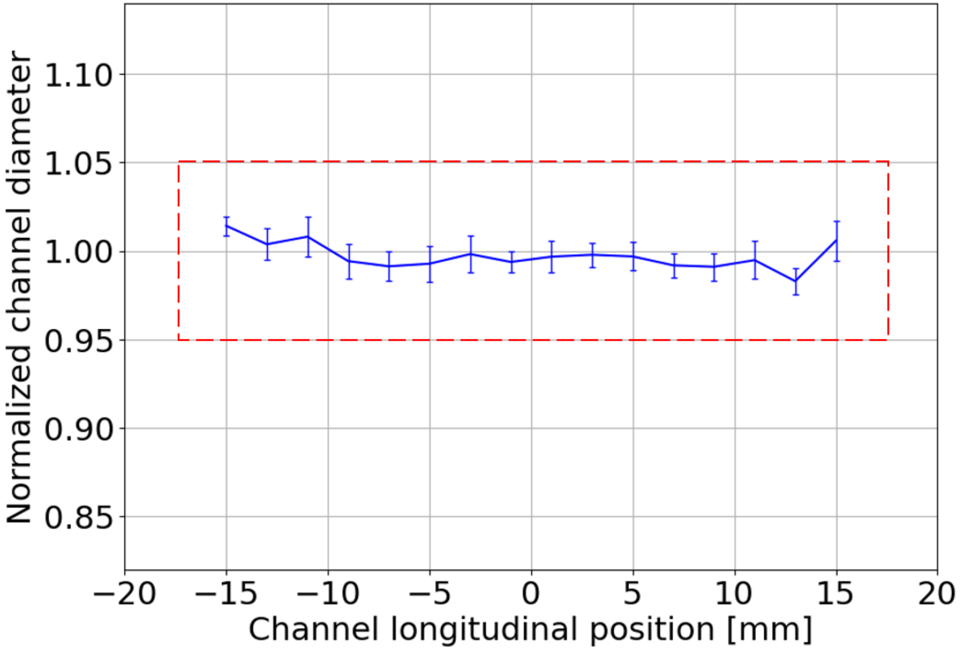




Magnification: 3.5x







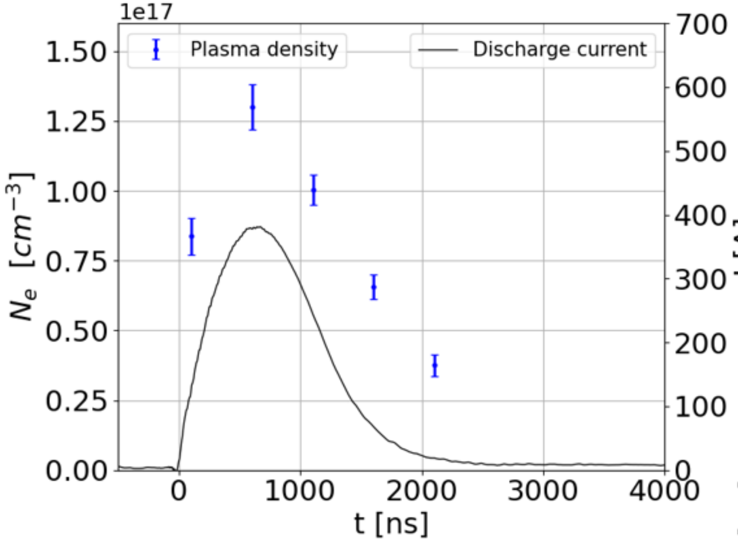
Analytical estimate

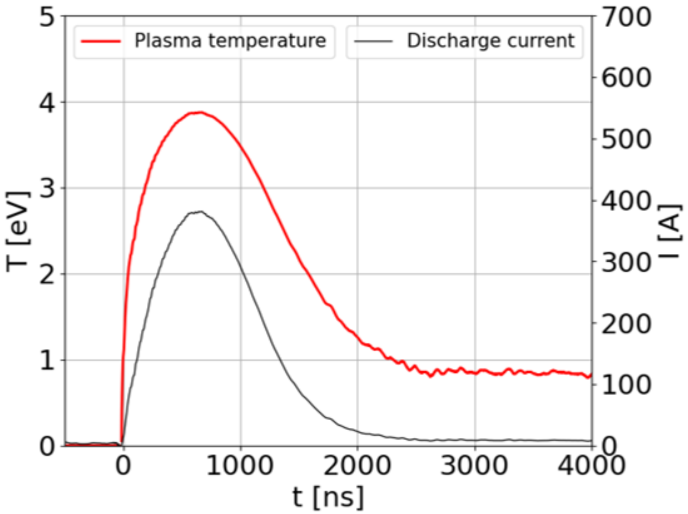
$$T_e = 5.7 \left(\frac{I[kA]}{R_0[mm]} \right)^{2/5} eV$$

Ohmic heating inside the plasma channel:

$$P(t) = R_p(t) I_p^2(t)$$

- $R_p(t) = \rho_{ei}(t) \frac{L}{S}$
- $\rho_{ei}(t) = \frac{m_e}{n_e(t) e^2} \upsilon_{ei}$
- $\upsilon_{ei} = \frac{4}{3} \sqrt{\frac{2\pi}{m_e}} \frac{e^4 n_e ln\lambda_{ei}}{(4\pi\varepsilon_0)^2 (k_B T)^{3/2}}$
- $ln\lambda_{ei} = ln \left[\frac{3}{2\sqrt{2\pi}} \frac{(4\pi\varepsilon_0)^{3/2} (k_B T)^{3/2}}{e^3 n_e^{1/2}} \right]$





Gonsalves, A. J. et al. J. Appl. Phys. 119, 033302, 10.1063/1.4940121 (2016).

Analytical estimate

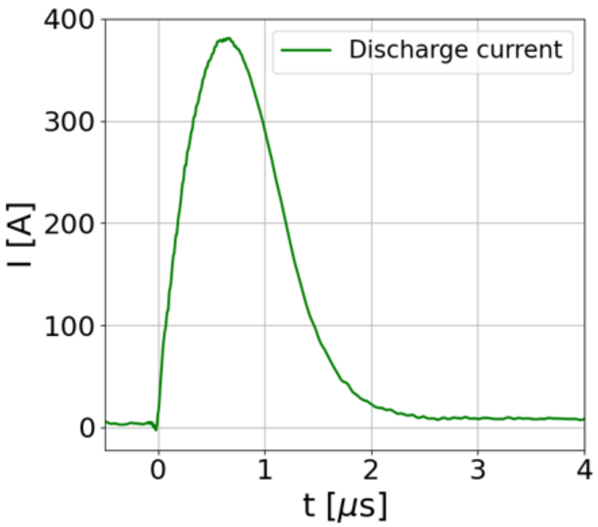
Ohmic heating inside the plasma channel:

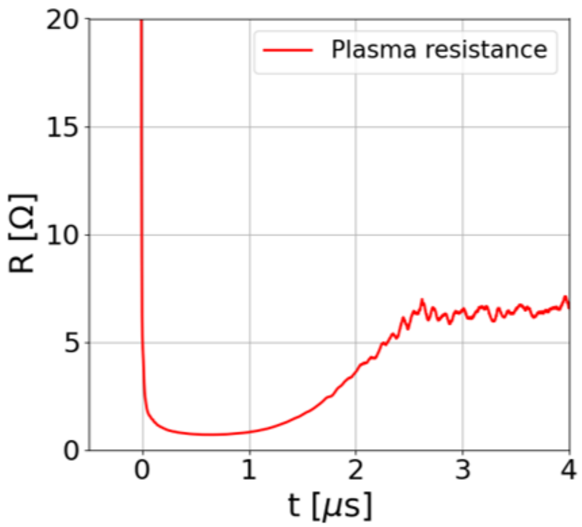
$$P(t) = R_p(t) I_p^2(t)$$

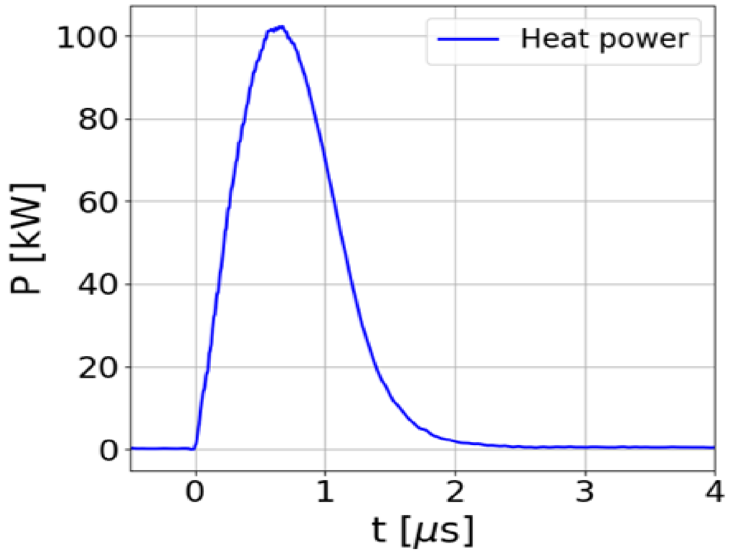
$$Q_p = \int_0^{\tau} P(t) \approx 100\ mJ$$

$$f = 10, 100, 1000\ Hz$$

$$P_{avg} = 1, 10, 100\ W$$





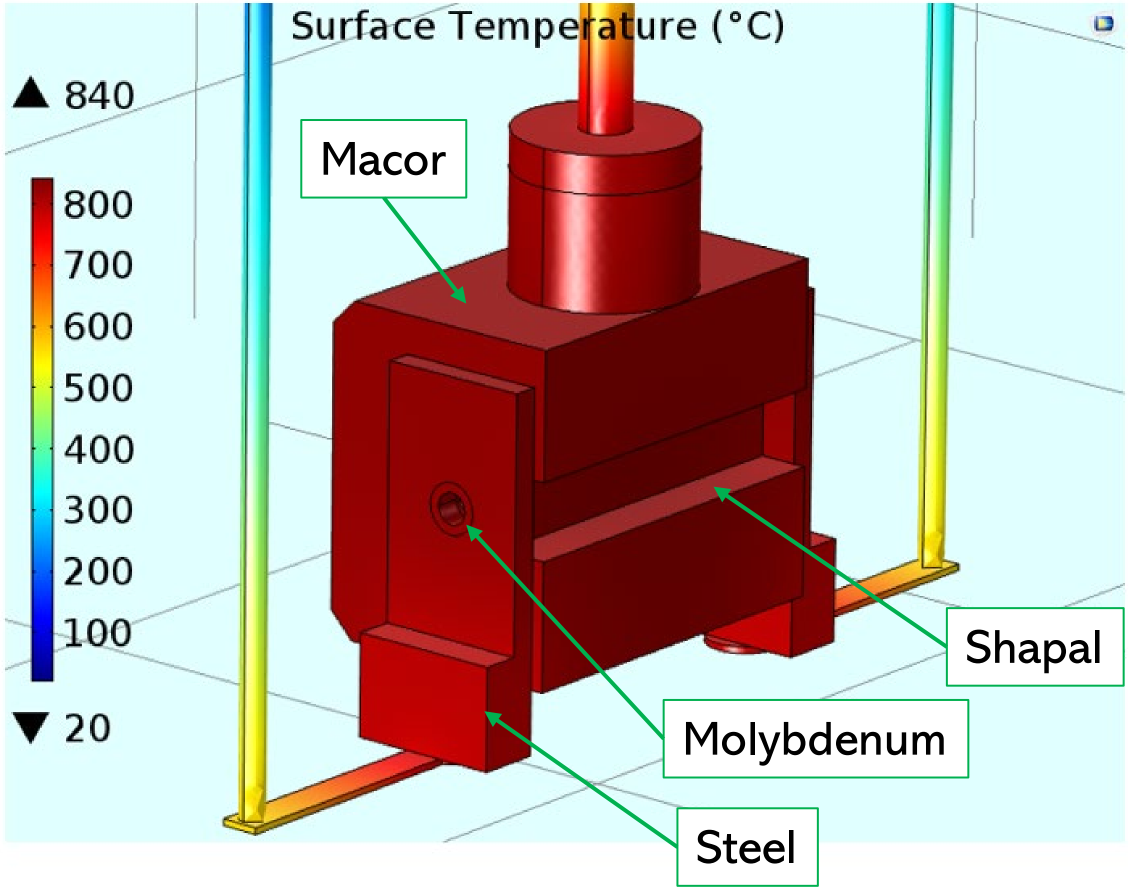


Heat transfer simulations

Fourier's Law:

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

- Heat transfer within the entire plasma source

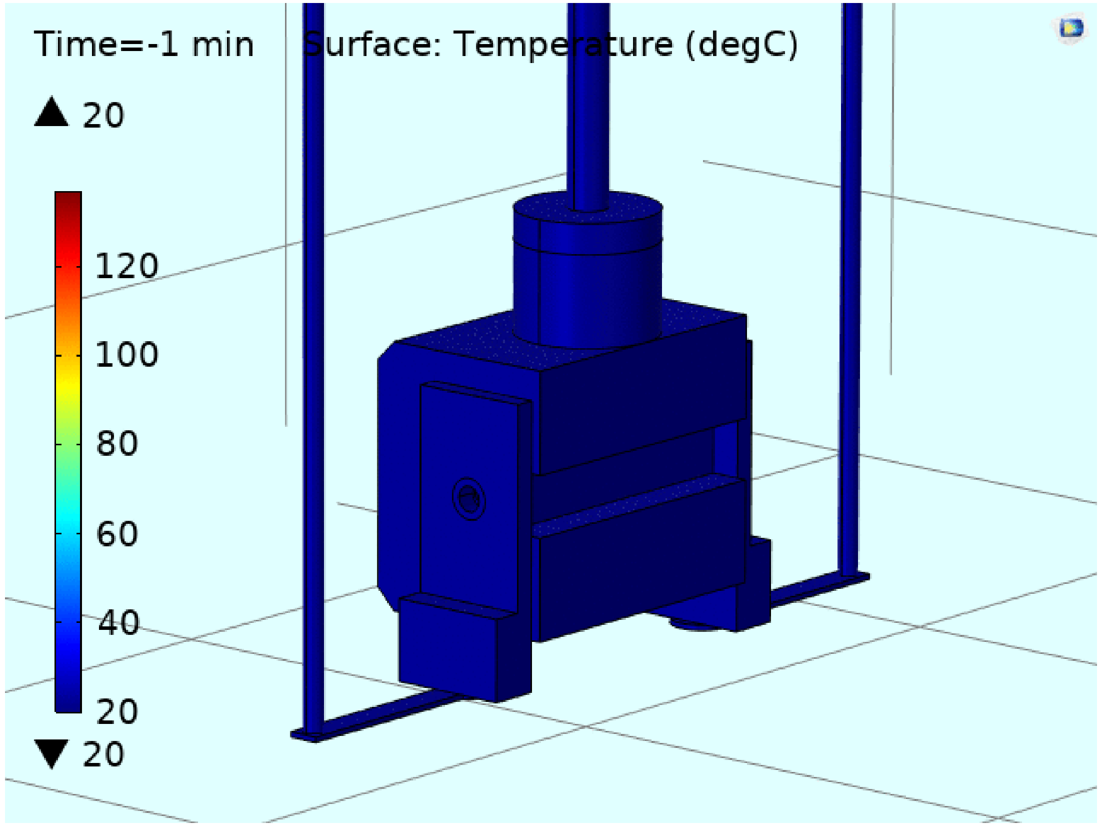


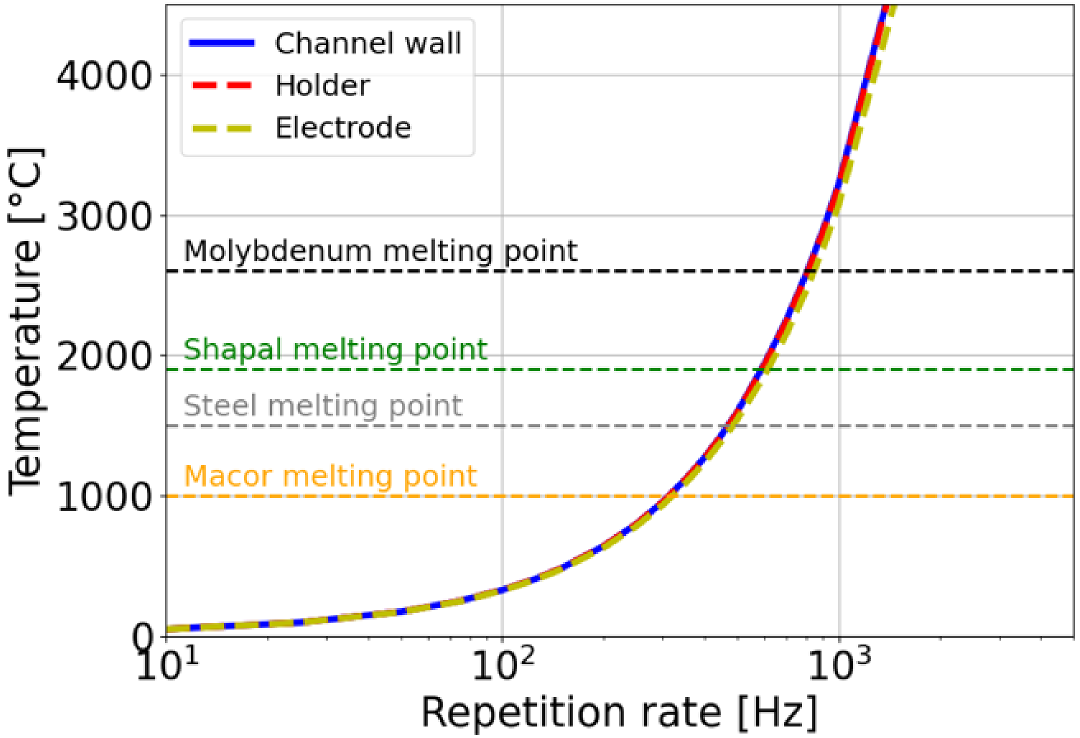
Heat transfer analysis

EuPRAXIA@SPARC_LAB goal
100 Hz

$$P_{avg} = f \cdot Q_p$$

$$f \nearrow \Longrightarrow Q_p \searrow \Longrightarrow I, \tau \searrow$$





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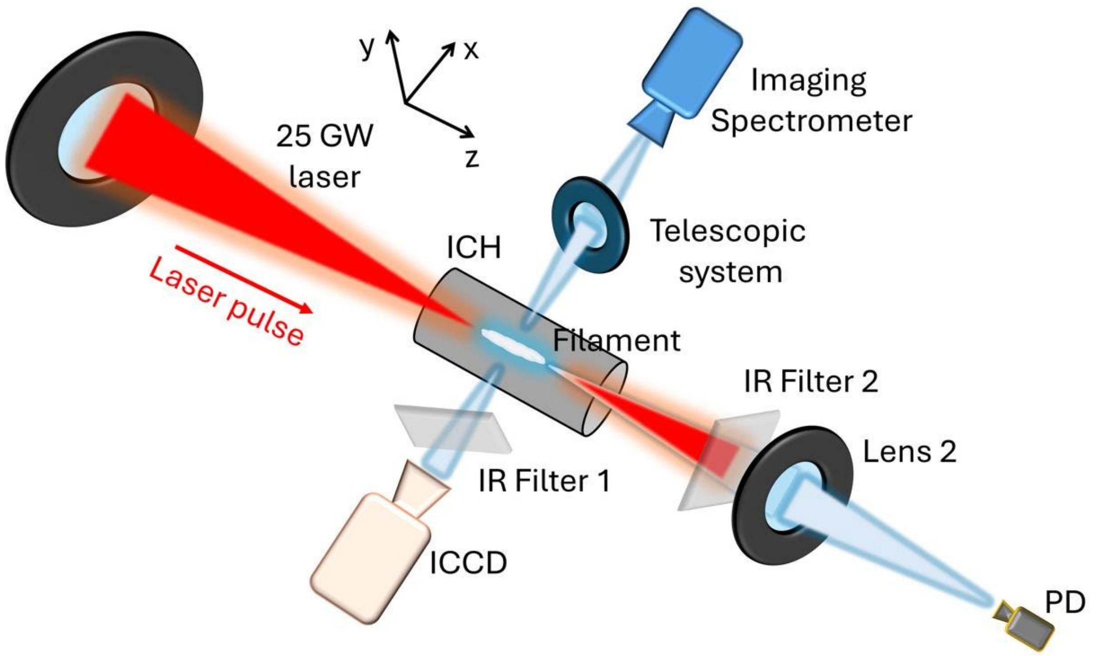
Experimental setup

- Ti:Sapphire laser system:
  - 10 mJ, 350 fs FWHM, 10 Hz
- 10 cm X 1 m gas cell
- 1 mbar N_2 95% - H_2 5%

Experimental characterization

- Side imaging fluorescence technique
  - Filament size
- Spectral analysis
  - Plasma density and temperature distribution
- Photodiode
  - Decay time



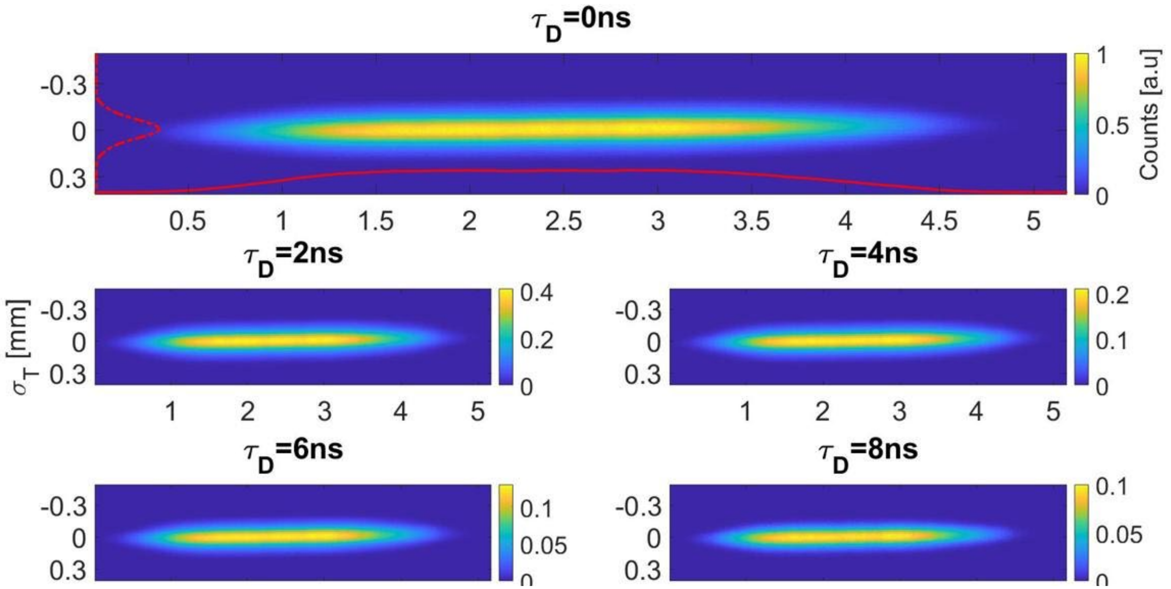
Laser-induced plasma filaments

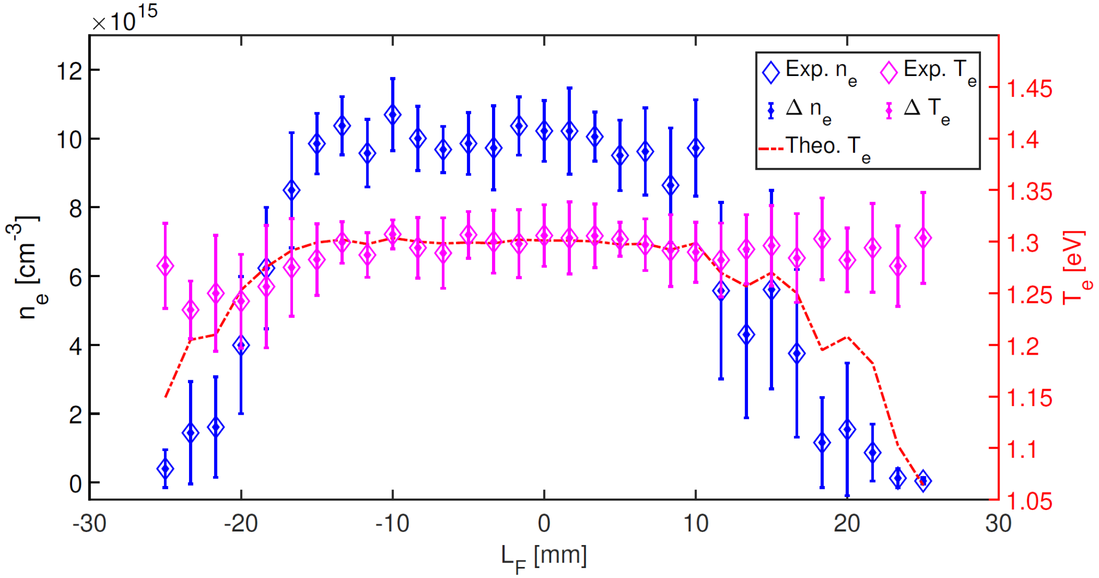
Plasma filament properties

- 4cm x 300 um
- $n_e = 10^{16}$ cm^{-3}
- T_e = 1.3 eV
- Decay time 8 ns

Advantages

- Low energy deposition
- Tunable dimensions and density
- No time-jitter
- Low gas injection





Conclusions

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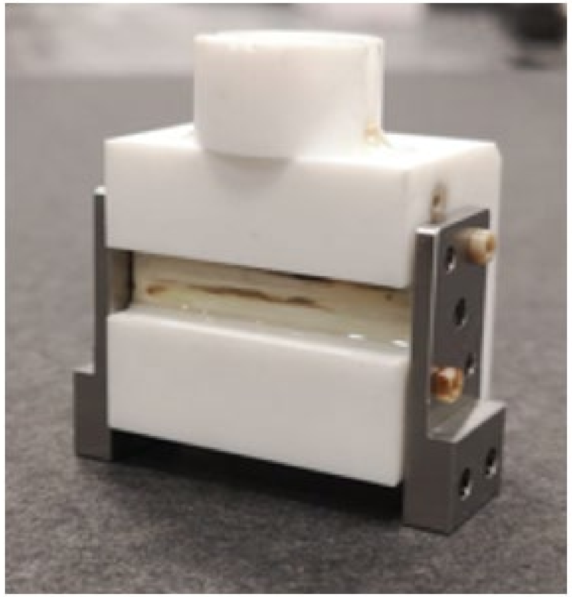
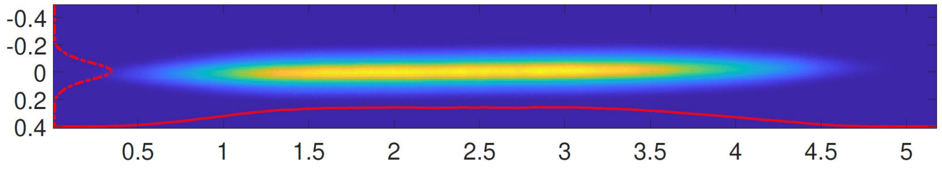
High repetition rate plasma sources

- Upgrade of the entire plasma module is required
- High temperature resistant ceramics are machinable, cost-effective and available for large geometries
- Preservation of plasma properties and source integrity is demonstrated at 150 Hz
- Laser-induced plasma filaments represent a promising alternative





Thanks to EuPRAXIA@SPARC_LAB team!

Thank you for the attention!