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Creating low jitter plasma channel in a 3D–printed capillary, filled with gas

Towards a Plasma Particle Accelerator

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Introduction

The goal: design a low–jitter plasma channel for a meter–scale particle accelerator.

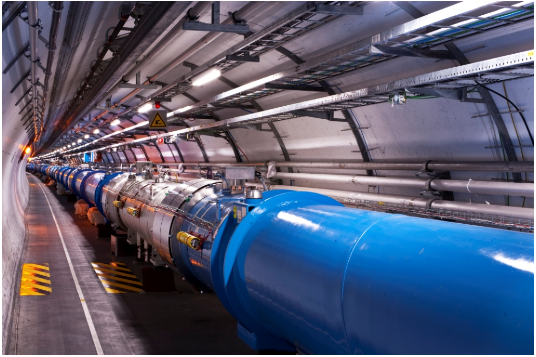
Applications:

- Experiments on the behaviour of nuclear matter
- Creating radiation sources for medical use

Linear accelerators

At present, all high energy accelerators run into limits.

- The accelerating electric fields must be less than 100 MV/m, to avoid material breakdown.
- Each GeV of energy requires $\sim$100 m of acceleration length.

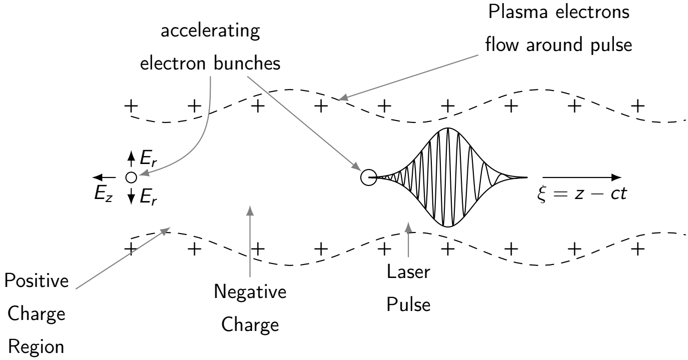


Laser Wake–Field Acceleration (LWFA)

A plasma–based charged particles accelerator

Electrical breakdown is part of the design.

The power source is a laser beam or a charged particle beam.

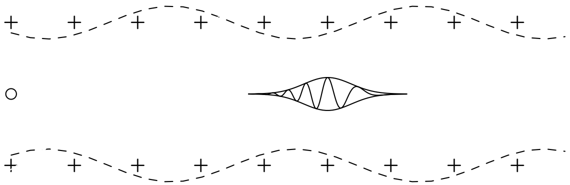


Same as CERN, but in smaller scale.

Limitations of LWFA

Laser defocusing

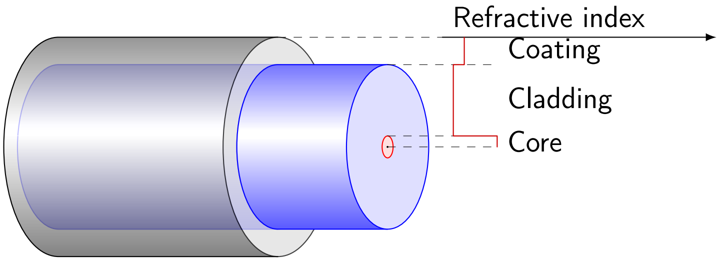
Acceleration is achieved only when the laser beam is focused to $\sim$ tens of μm in diameter.



Solution: Use a wave–guide.

Waveguide

Basic concept

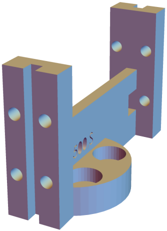


Light confined in core, cladding with a smaller refractive index.

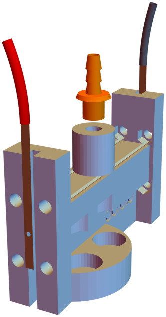
Construct a plasma waveguide

Capillary Discharge

Generate a plasma channel by means of electrical discharge.



Ablated capillary



Gas—filled capillary

Apply voltage (∼kV) on the capillary ends to start a discharge.

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The Plasma state

Ionised gas, electrically neutral.

Defined by $N_e\,(\mathrm{cm}^{-3})$ and $T_e\,(\mathrm{eV})$.

Characteristic quantities:

Debye length $\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{N_e e^2}}$

Plasma Frequency $\omega_p = \sqrt{\frac{N_e e^2}{m_e \varepsilon_0}}\,\mathrm{rad/sec}$

Parabolic density profile

Plasma dispersion relation:

$$\omega^2 = \omega_p^2 + c^2 k^2$$

The index of refraction $\tilde{n}$ is

$$\tilde{n} = \frac{ck}{\omega} = \sqrt{1 - \frac{\omega_p^2}{\omega_L^2}} \approx 1 - \frac{\omega_p^2}{2\omega_L^2} = 1 - \frac{N_e}{2N_{cr}}$$

where

$$N_{cr} = \frac{\omega_L^2 \varepsilon_0 m_e}{e^2}$$

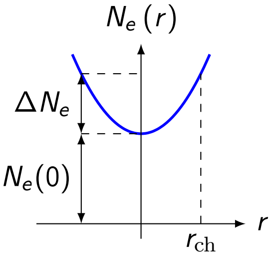
is the critical plasma density.

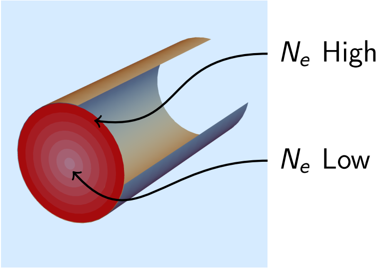
Parabolic density profile

To achieve guiding, we need variation in $\tilde{n}$.

Ideally, the radial density profile (RDP) is parabolic:

$$N_e(r) = N_e(0) + \Delta N_e \left(\frac{r}{r_{\mathrm{ch}}}\right)^2$$



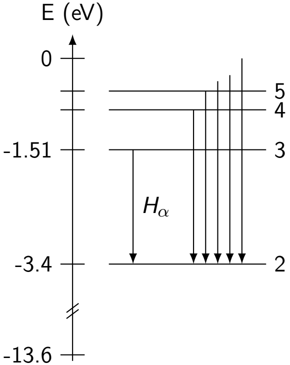


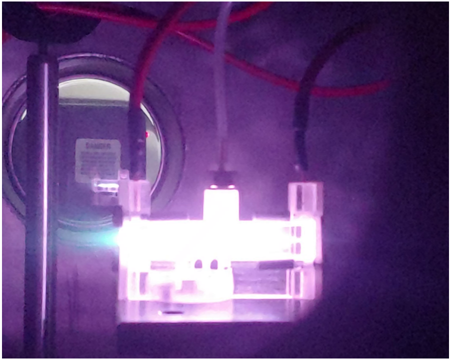
Characterisation of the plasma

Hydrogen Spectrum

Hot plasma emits light.

The emitted spectra can give information about N_e and T_e.





$$H_\alpha : \ \lambda = 656.28\,\mathrm{nm}$$

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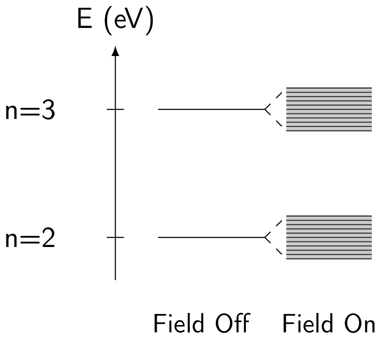
Stark Broadening

Plasma is a charged medium.

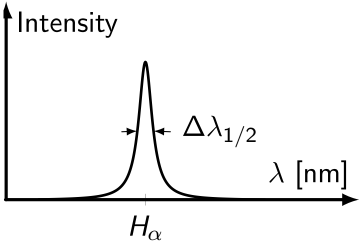
Electric micro–fields perturb the atomic energy levels.

Averaging over different neighbours converts the Stark splitting to Stark broadening.



Stark Broadening

Line shape — a Lorentzian



Relation between N_e and $\Delta\lambda_{1/2}$ is tabulated:

$$N_e = \left(\frac{\Delta\lambda_{1/2}}{\gamma\left(N_e, T_e\right)}\right)^{3/2}.$$

Weak dependence on temperature, in our experiment:

$$N_e\left[10^{18}\,\mathrm{cm}^{-3}\right] = \left(\frac{\Delta\lambda_{1/2}\,[\mathrm{nm}]}{5.4}\right)^{3/2}.$$

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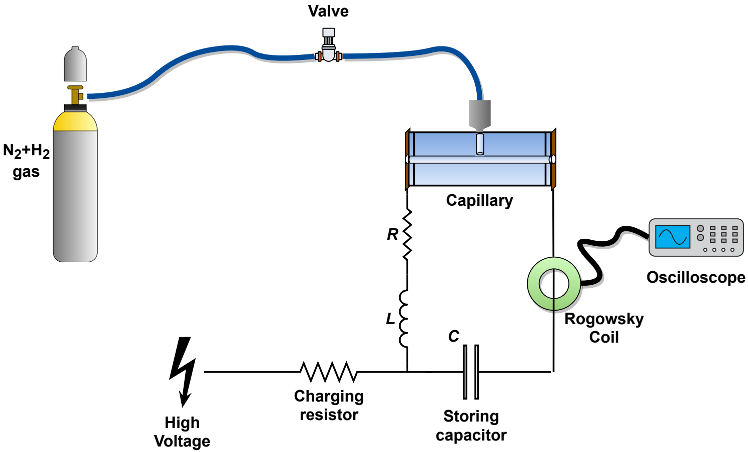
Research Goals

1. Study of discharge evolution, low jitter of discharge ignition
2. Characterisation of the discharge, utilizing Stark broadening
3. Demonstration of optical guiding

Experiment Scheme



Capillary inside a vacuum chamber, maintained at 10^{-4} torr.

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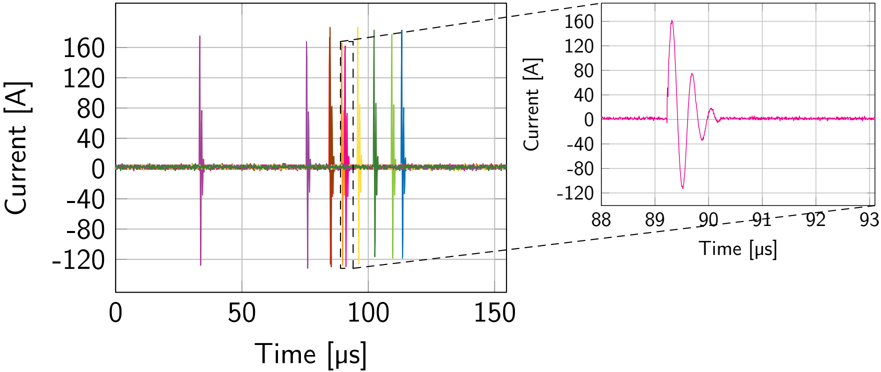
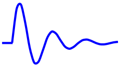
Results

Low Jitter

Plasma is generated, but not in a stable regime.



 — Rogowsky coil reading

jitter ≈ 80 μs

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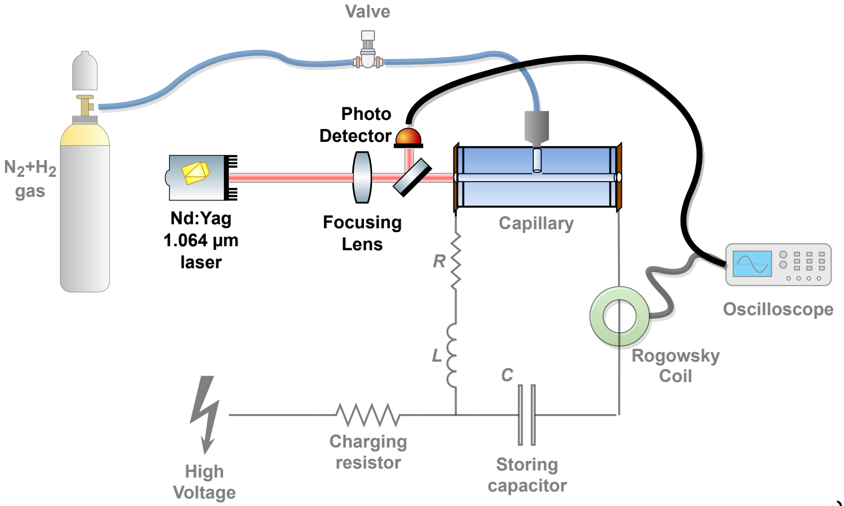
Use a laser pulse to ignite the plasma

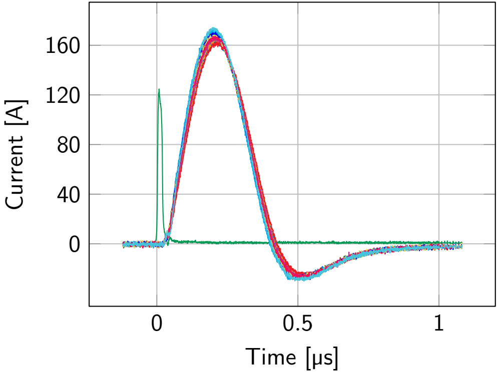
The Nd:Yag laser pulse ionizes matter and detaches electrons.

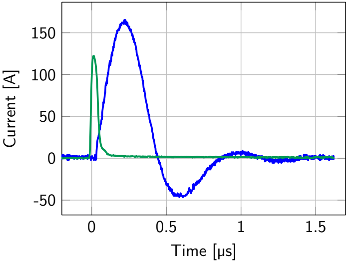


Experimental Results

Low Jitter

12 consecutive capillary discharges. Demonstrating low ignition jitter.





— Nd:Yag laser pulse

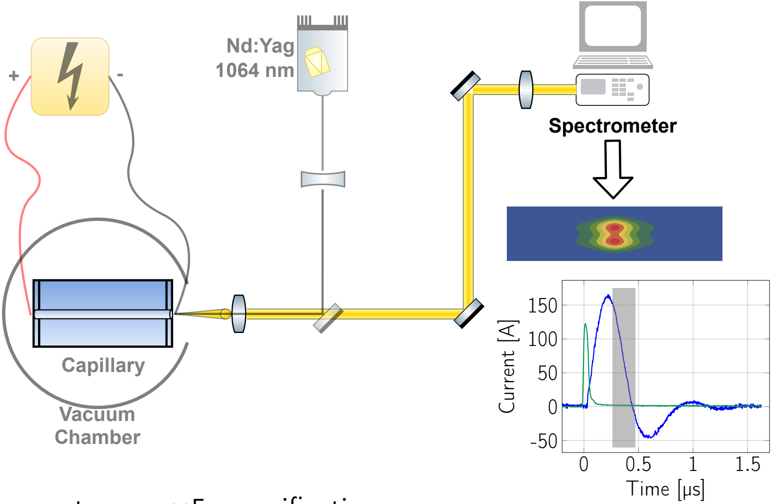
— Rogowsky coil reading

$\text{jitter} \approx 1 \pm 0.36\text{ns}$

Spectroscopy measurements

- Plasma channel depth and density measurement
- Radial and longitudinal density profile
- Means: A spectrometer and a fast camera

Radial density profile



Imaging system — $\times 5$ magnification.

iCCD camera 40 ns gate–on time.

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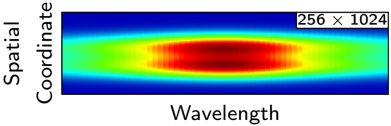
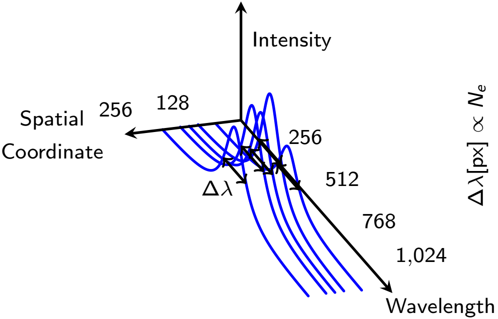
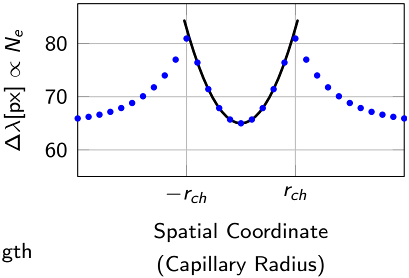
Data Analysis





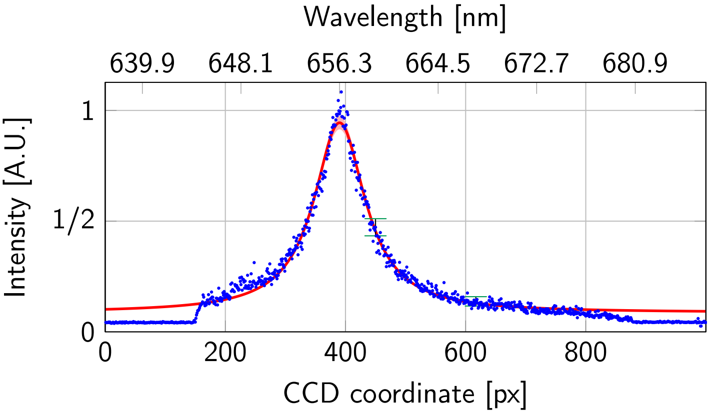


pixel size $= 26\,\mu m \times 26\,\mu m$

Spectroscopy Analysis

cont.

Fit a Lorentzian to each row of the data.



Stark Broadening on the order of 3 nm.

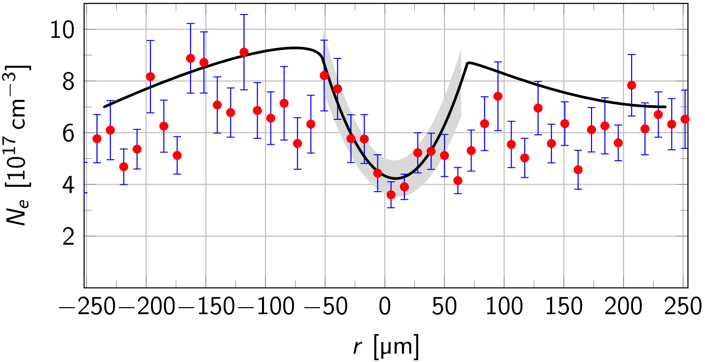
Spectroscopy measurements

Radial density profile

Density minimum on the axis of the capillary.

$$\Delta N_e \sim 4 \times 10^{17}\,\mathrm{cm}^{-3}$$

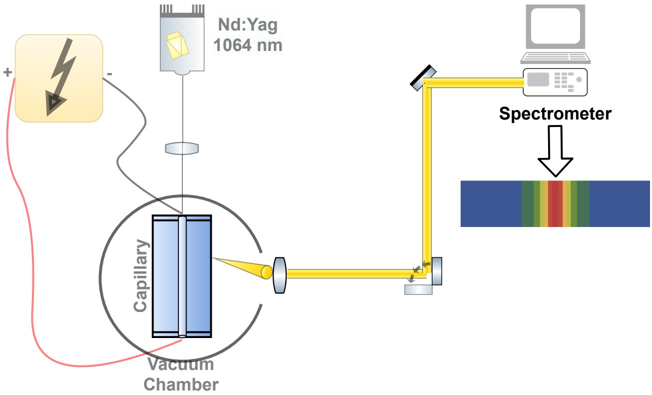
$$\text{with } r_{ch} \approx 50\,\mu\mathrm{m} \text{ and } N_e(0) \approx 4 \times 10^{17}\,\mathrm{cm}^{-3}.$$



Longitudinal density profile

System setup

Verify longitudinal homogeneity of the plasma density.



The entire capillary length was imaged.

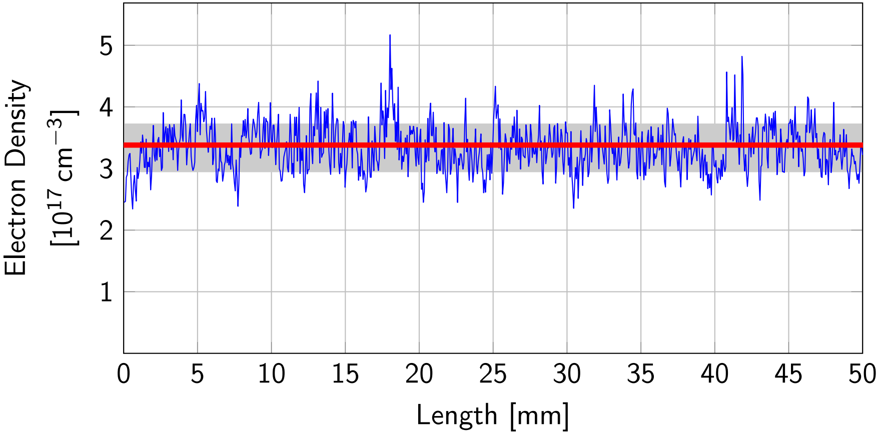
iCCD camera 1 µs gate–on time.

Longitudinal density profile

Result

Mean plasma density $\bar{N}_e$ of

$$\bar{N}_e \sim 3.3 \pm 0.8 \times 10^{17}\,\mathrm{cm}^{-3}.$$

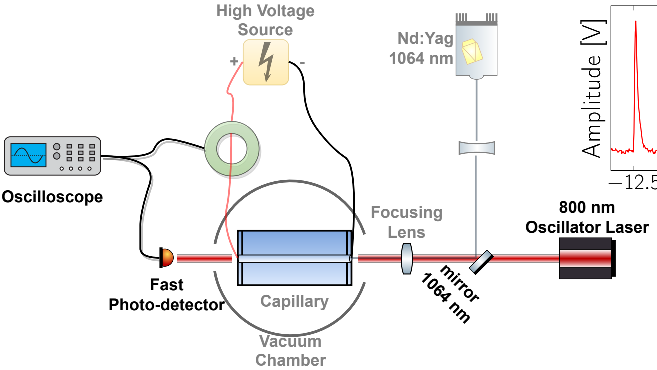


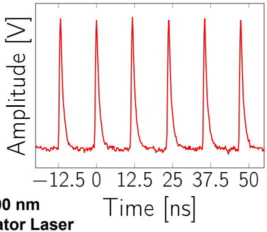
Optical guiding

System setup

System setup as before, but now adding an oscillator laser.

Pulses at a 84 MHz rate.





Beam aligned through the capillary, to a fast photo–diode.

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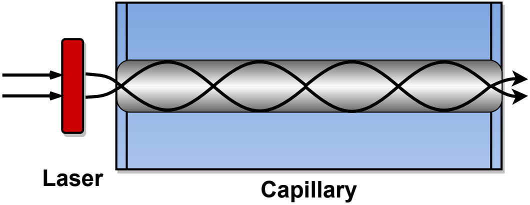
Optical Guiding

Upon plasma discharge, we look for an increase in the detected amplitude — optical guiding.

$$\text{transmission ratio} = \frac{A_{t<0}}{A_{\text{max}}}$$

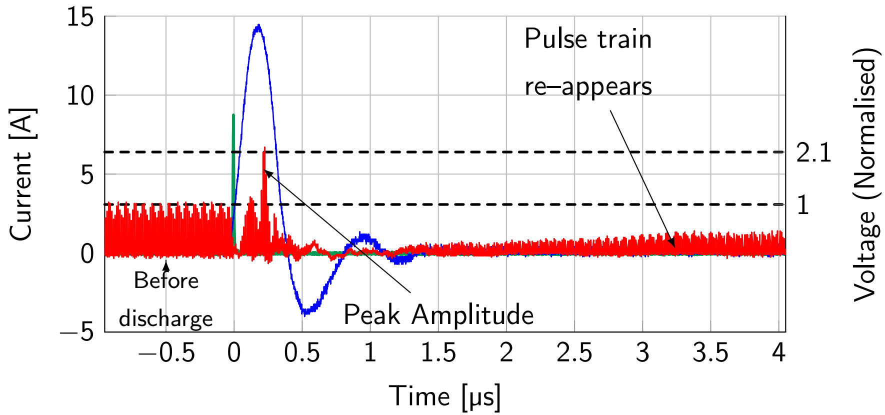
The explanation:

A plasma lens forms, the radiation is focused and trapped by the plasma.



Optical guiding

Results



— Nd:Yag laser pulse

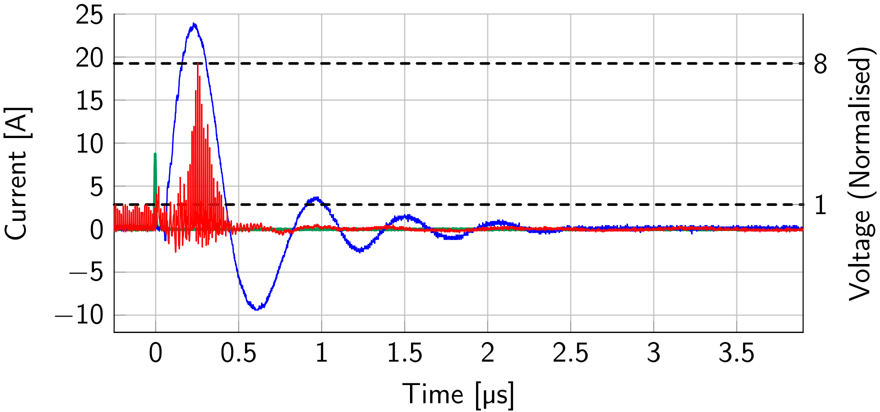
— Rogowsky coil reading

— detected oscillator signal

$$\frac{A_{t<0}}{A_{max}} \approx 2.1$$

Optical Guiding

Higher voltage difference



— Nd:Yag laser pulse

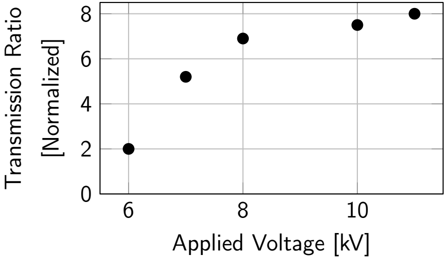
— Rogowsky coil reading

— detected oscillator signal

$$\frac{A_{t<0}}{A_{max}} \approx 8$$

Duration of the plasma channel

Correlation between applied voltage and the transmission ratio:



Duration of the plasma channel:

$$\Delta t_{\text{channel}} = 50 - 100 \text{ ns}.$$

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Summary

Study of plasma channels generated in gas filled–capillaries.

- Low jitter of discharge ignition
- Verification of plasma conditions by spectroscopy means
- Demonstration of optical guiding

Future experiments —

Incorporating these capillaries in a LWFA scheme.