Plasma density profile measurements for ultra-short high power laser beam guiding experiments at SPARC_LAB

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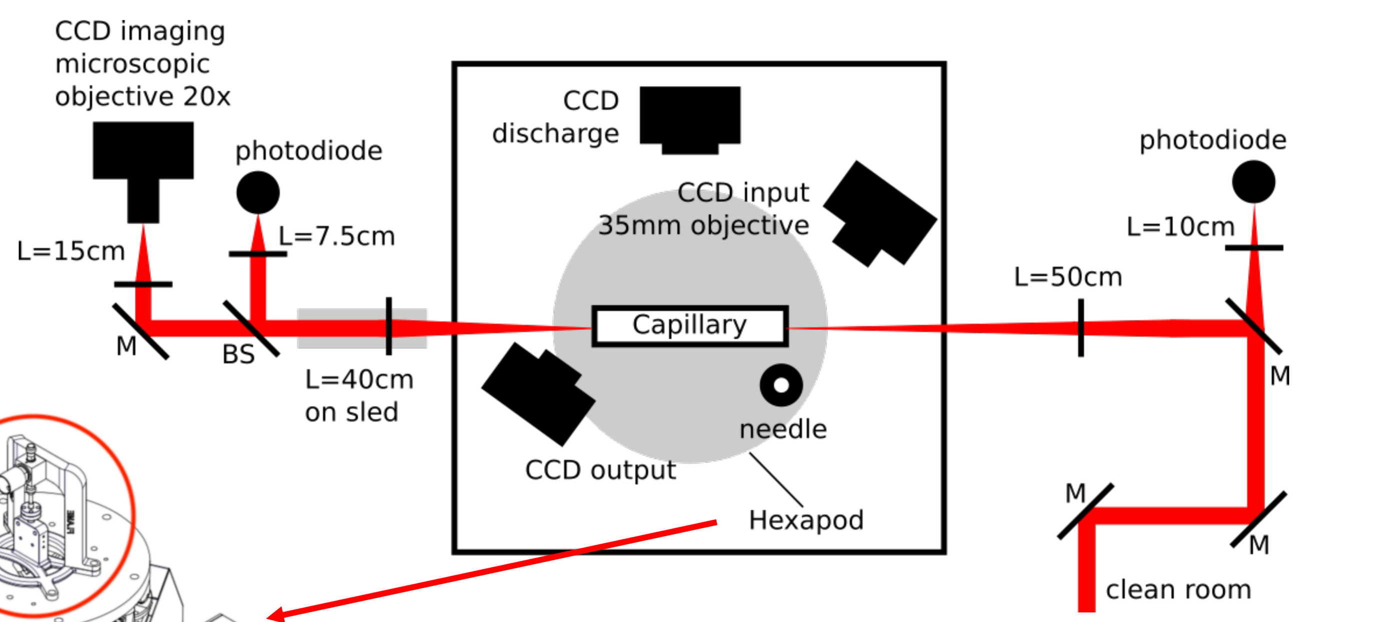
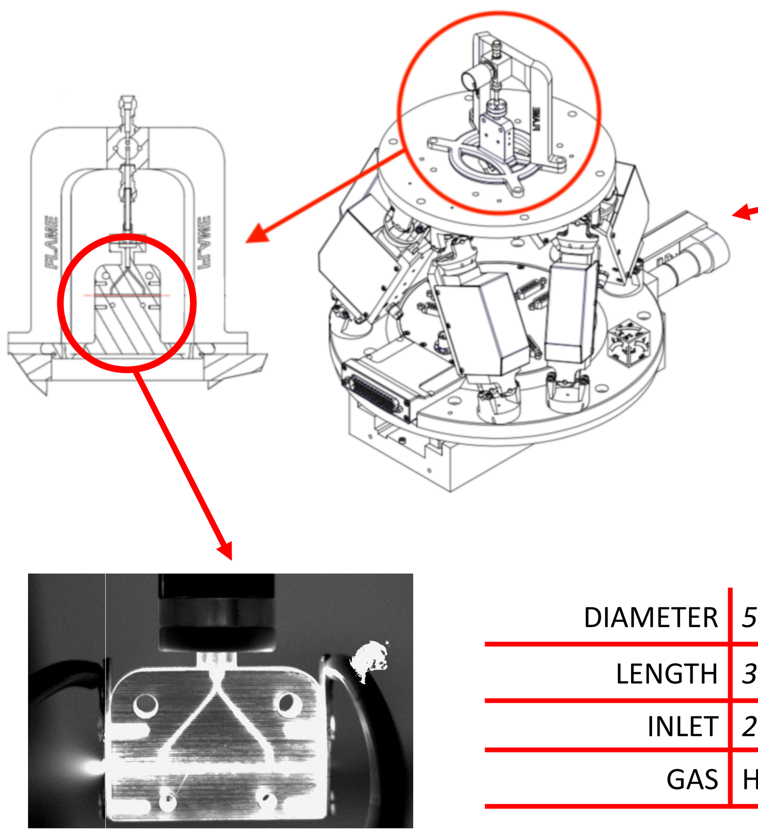
Abstract:
The External injection, i.e a drive laser exciting a plasma wake followed by an electron bunch, is a promising method to achieve high accelerating gradients and to control the beam properties. The energy gain of an electron via the wakefield is proportional to the product of the accelerating field multiplied by the effective propagation distance of the laser, which is approximately equal to πZ_R, where Z_R is the diffraction length of the laser pulse (Rayleigh length), typically in the millimetre range. Therefore, in order to bring the electron energy to the order of the *GeV*, a longer propagation length is required, which can be obtained by guiding the laser pulse in a wave-guide. In the case of SPARC_LAB, a *500 μm* diameter hydrogen-filled capillary discharge is used. To guide the laser beam it is necessary to act on the refractive index of the plasma, depending on its density. Therefore, to correctly match the laser pulse and the guide, time-resolved measurements of the electronic density profile inside the capillary are essential: in this case a spectrometer was used to detect the gas emission line enlargement produced by the Stark effect.
In this work measurements of the trend over time of longitudinal and transverse profiles of plasma density within the capillary used for guiding experiments are presented, compared with the results of MHD simulations based on initial gas profiles obtained in OpenFOAM and on the real discharge profile. Preliminary tests of laser guiding are also shown, taking particular care of the discharge process, detecting the behaviour of the laser beam at the exit of the capillary with respect to the discharge current value.

LASER GUIDING AND PLASMA DENSITY: SETUP AND MEASUREMENTS

Motivation:
Laser guiding tests are of fundamental importance for the external injection configuration; in fact it is essential to study the laser-plasma matching, according to the type of capillary used and to the type and the intensity of discharge generated inside of it. For this reason, we study the plasma density during and after the discharge, analyzing the longitudinal and transverse profiles, with the aim of obtaining a temporal zone of longitudinal uniformity of plasma density along the whole capillary, and with a transversal parabolic distribution. In this plasma zone it is possible to guide a laser pulse, matched with the guide radius and with the plasma density difference axis-walls.

PULSE ENERGY	*2 mJ*
TEMPORAL LENGTH	*50 fs*
SPOT@FOCUS	*~ 50 μm*

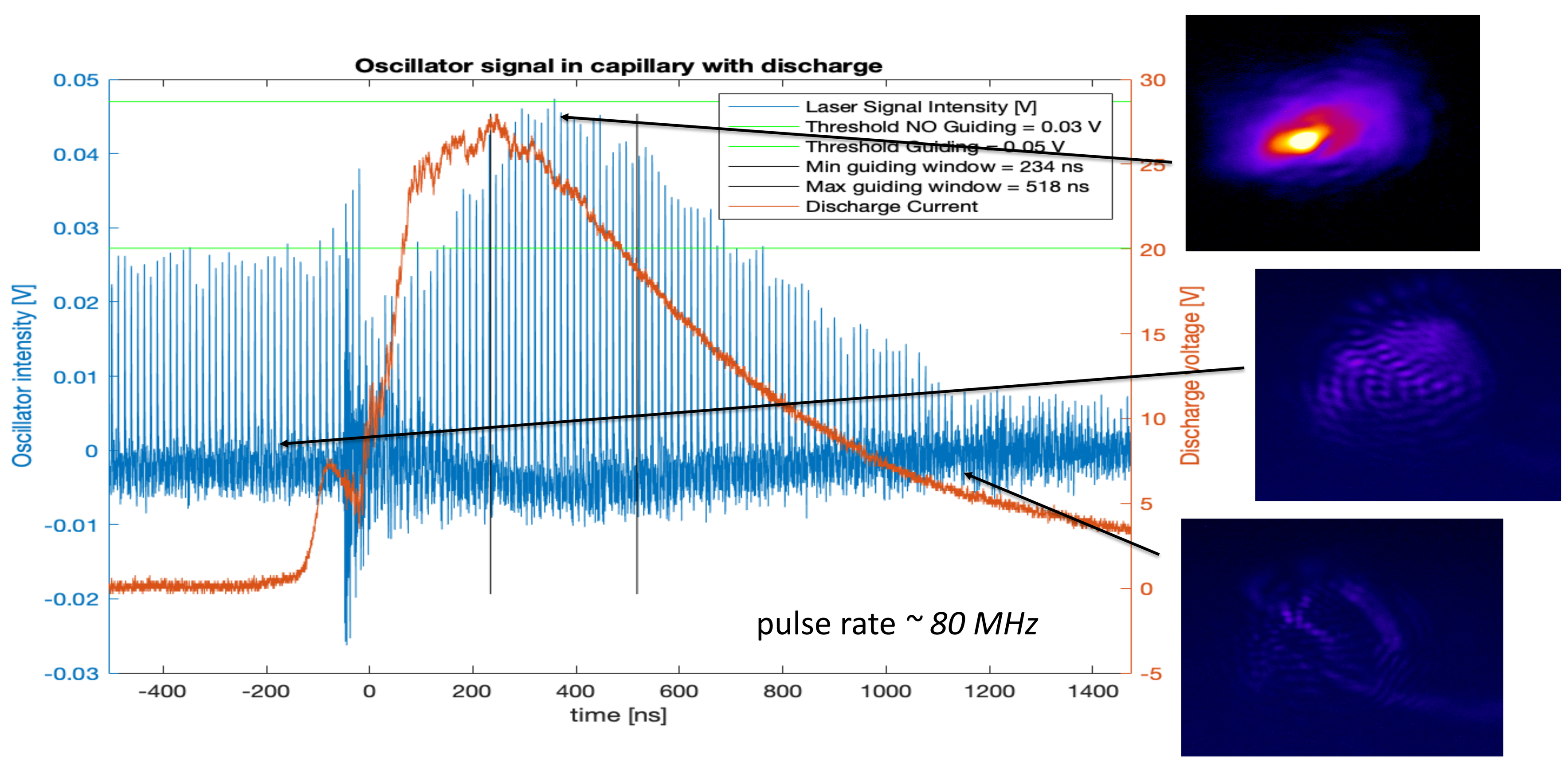




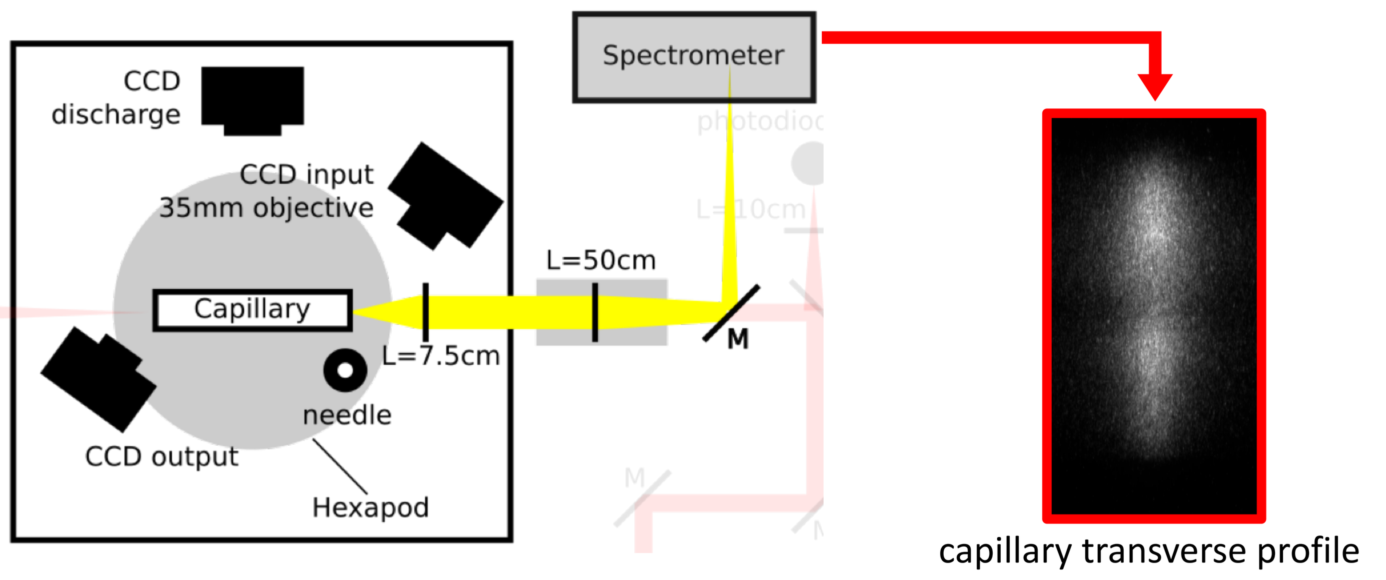
The laser is focused with a *50 cm* lens at the entrance of the capillary. The imaging system is composed of a *20 cm* lens, joined to a CCD with a microscopic objective.

DIAMETER	*500 μm*
LENGTH	*3 cm*
INLET	*2*
GAS	H

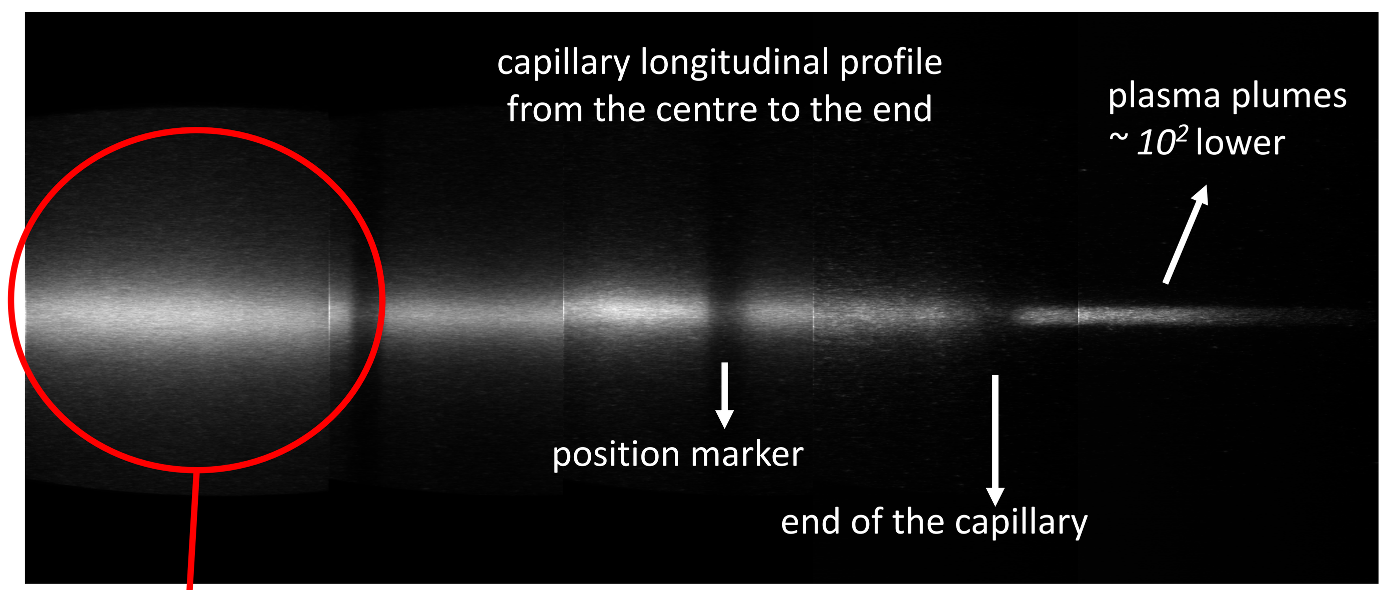
MAIN LASER ENERGY	7 J
MAIN LASER DURATION	25 fs
MAIN LASER SPOT@FOCUS	20 μm
MAIN LASER PEAK POWER	250 TW
WAVELENGTH	800 nm
BANDWIDTH	60/80 nm
CONTRAST RATIO	10^{10}
REPETITION RATE	10 Hz

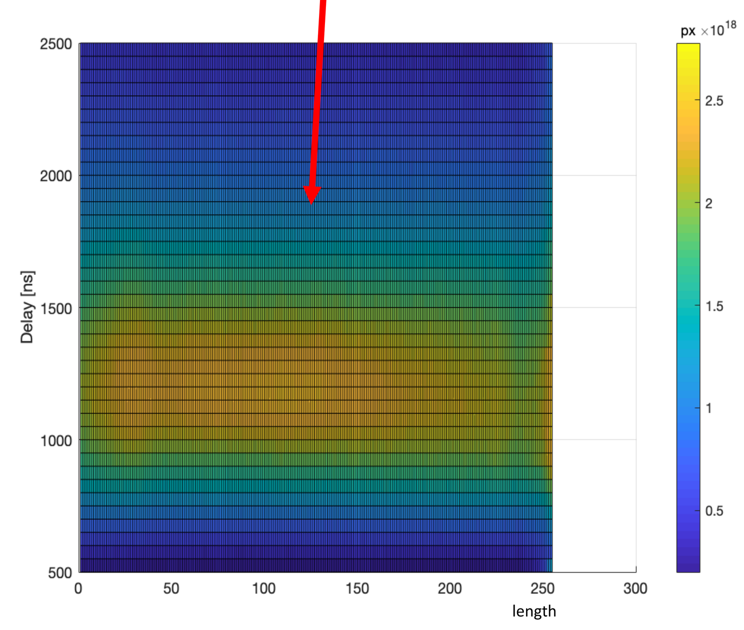


A photodiode detects the time arrival of the laser with respect to the discharge signal. By means of the oscillator laser we are able to understand where is the guiding window: here there is an increase of the signal intensity, with a transmission efficiency of about 80% of the original pulse. On the right, the probe spots at fixed time delays: inside the guiding window and before and after the discharge.



Measurements of the enlargement of the emission lines of the gas, caused by the Stark effect. The electric field of electrons and ions generates a spectral enlargement $dL \sim \alpha n_e^{2/3}$.
The system uses a first lens that reproduces the longitudinal or transverse profile of the capillary, transported by an optical system on the slit of the spectrometer, on the diffractive grating and a second lens that, subsequently, conveys the scattered light on a CCD that must be equipped with an intensifier to increase the signal/noise ratio. In this way it is possible to make a measurement resolved in time of the electronic density profile present within the capillary.
To guide the laser beam it is necessary to operate on the plasma refractive index, which depends on plasma density. The plasma channel is formed by the temperature profile during the discharge, which is higher at the center than it is at the walls, so since the pressure of the gas is almost uniform, plasma density radially has a parabolic profile, which means lower density on the axis.



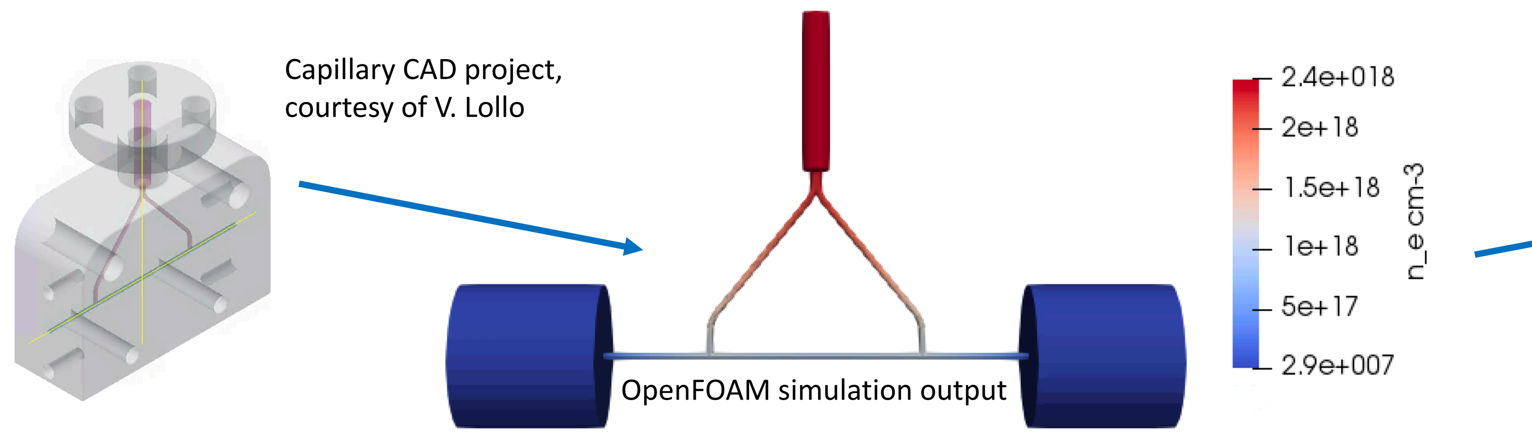


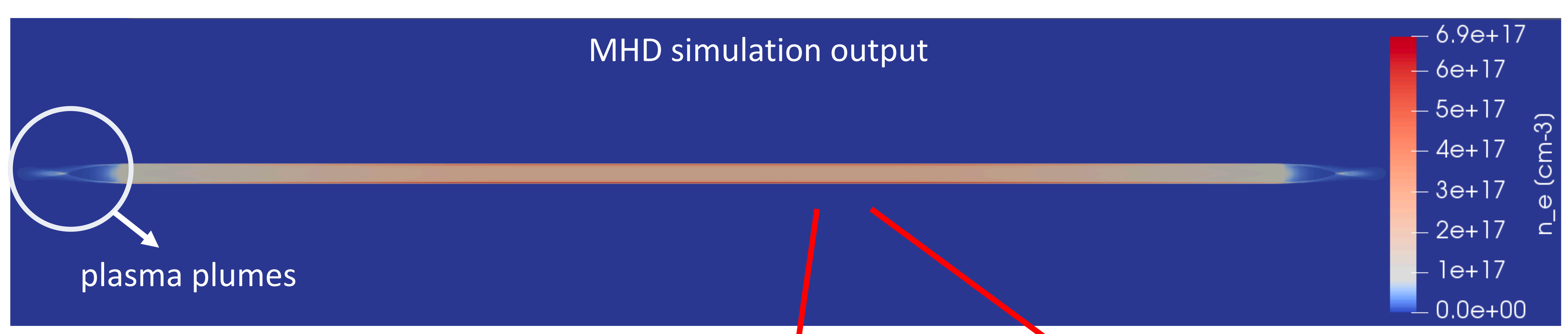
Portion of the capillary longitudinal profile: statistical analysis of the evolution of plasma density at different delays after discharge

CURRENT	*250 A*
H	*1.9 bar*
RATE	*0.2 Hz*

$H_\alpha = 655\ nm$, $H_\beta = 486\ nm$

OpenFOAM AND MHD SIMULATIONS





Starting from the CAD projects with which the capillaries used in the laboratory are printed in 3D, simulations have been built in OpenFOAM (Open-source Field Operation And Manipulation), with the aim of obtaining the distribution of the density of gas inside and immediately outside the capillary, from the moment in which the gas is injected to the moment in which the discharge begins. In the geometry there is an inlet that simulates the electro-valve open, and two outlets that simulate the vacuum coming out of the capillary; the thermal conductivity boundary condition is set on the capillary surface. The main parameters are used in this case:

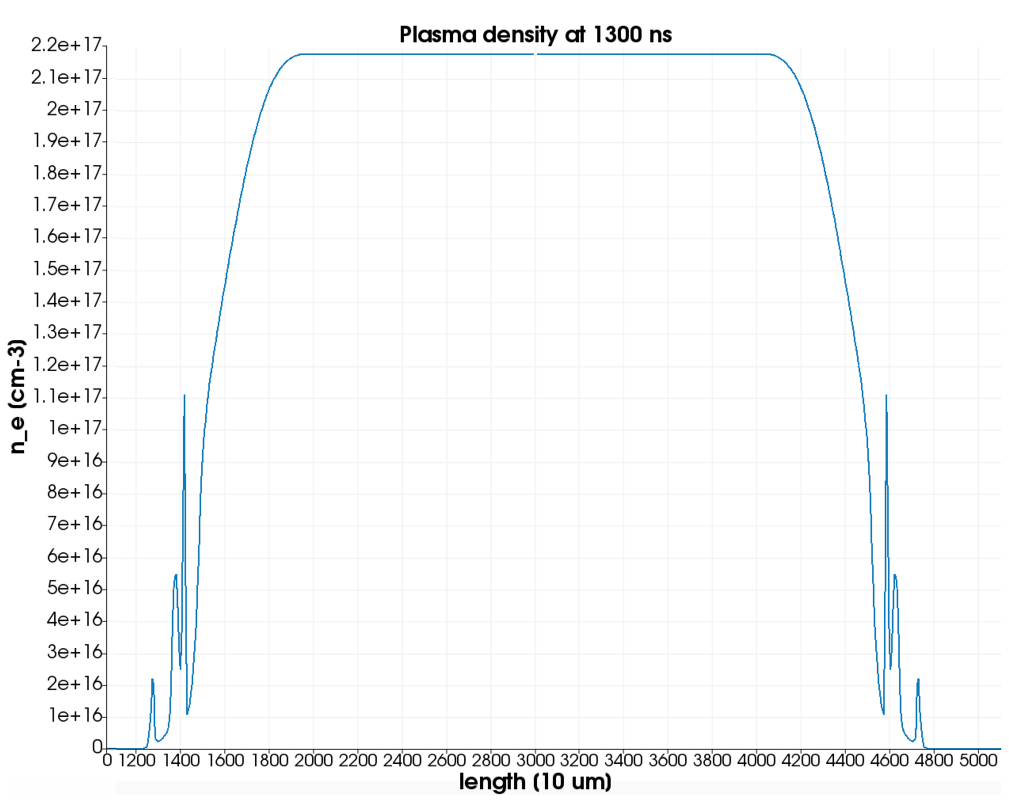
opening time interval electro-valve	*3 ms*
pressure on the inlet	*100 mbar*
Courant parameter	*0.1*
Δt simulation	$10^{-15} - 10^{-7}$

The fluid-dynamic simulations of the discharge process and of the evolution of the plasma density are carried out by means of a modified version of PLUTO, an open source Euler MHD code (therefore with a fixed grid). The main properties set in the model are:

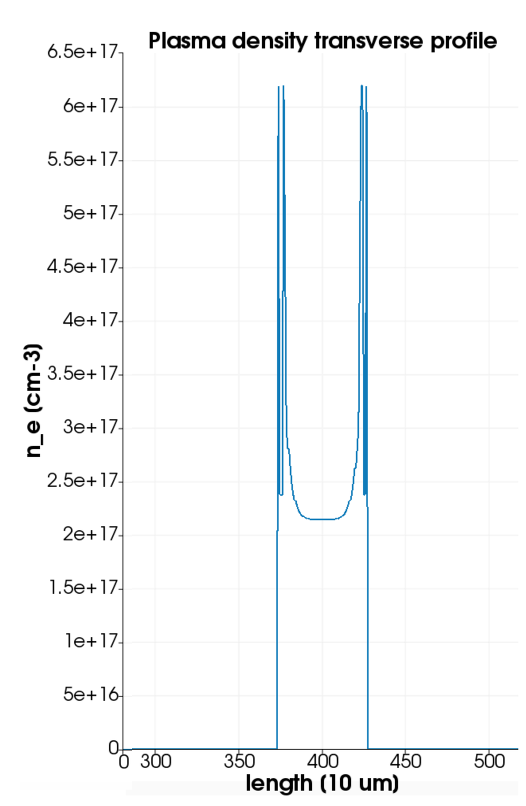
- axial symmetry
- fixed mesh (rectangles)
- resolution of MHD equations by means of a temperature curve
- current imposition ∀ t
- Ionisation calculated as an approximation of LTE (local thermal equilibrium) with the Saha equation
- electrical resistivity and thermal conductivity calculated according to a rigorous process

The code imports pressure, temperature and speed data from OpenFOAM simulations at the final time, along with the real current profile of the discharge circuit.

Plasma longitudinal profile



Plasma transverse profile



One order of magnitude lower due to different initial conditions set: gas pressure and discharge curve.

Future developments: In order to study the best laser-plasma matching conditions, new simulations, Stark broadening measurements and imaging measurements of laser profiles at the output of the capillary in the guiding time window will be carried out, even on capillaries with diameters of *300 μm* and *700 μm* . A study on the density of the neutral gas and the plasma density at the output of the capillary will be performed to understand the effect it has on a high-power laser pulse focused at the entrance to the capillary. Guiding tests of the full power laser pulse with the setup in this way chosen will follow, inside the interaction chamber of the Flame laser. After that the first experiments of external injection in Flame with electrons produced by self-injection will begin, then the experiment of external injection using the high brightness electron beam of SPARC as witness beam for the plasma wakefield acceleration will start.