Paving the way for CW kHz operation of a discharge capillary in the DESY ADVANCE lab

H. Jones*, *M. J. Garland, S. Kottler, S. Lederer, G. Loisch, K. Ludwig, F. Obier, T. Parikh, K. Põder, R. Shalloo, J. Björklund Svensson, R. D'Arcy and J. Osterhoff*

*Contact: harry.jones@desy.de

Discharge capillaries are an essential plasma-source for a wealth of different applications in plasma-based accelerators. The long, uniform profiles have been pivotal in both LWFA and PWFA experiments alike. The repetition rate of such sources has thus far been limited to 1-10 Hz, far below the required 10 kHz to MHz of a plasma-based collider or FEL. Development of high repetition rate discharge capillaries is imperative for these and other future applications and is currently being performed in the ADVANCE laboratory at DESY. Our initial goal is to achieve the milestone of continuous, stable, 1 kHz operation from which higher repetition rates might be achieved.

1. Motivation for high repetition rate

Discharge capillaries have myriad applications for plasma-based technology such as guiding high intensity laser light [1] and for active plasma lens applications [2]. Current plasma discharges operate at repetition rates of ≤ 10 Hz. Increased repetition rate can facilitate:

- High frequency statistics and feedback for enhanced optimisation and control.
- Improved Brightness and Luminosity for plasma based light sources and accelerators.
- Better matching of plasma sources to particle accelerators.

Achieving these goals can help to secure the position of plasma-based accelerators for commercial. An initial milestone goal of stable, long life, continuous operation at 1 kHz is set.

·[1] Gonsalves, A. J., et al. "Petawatt laser guiding and electron beam acceleration to 8 GeV in a laser-heated capillary discharge waveguide." Physical review letters 122.8 (2019): 084801.
·[2] Lindstrøm, Carl A., et al. "Emittance preservation in an aberration-free active plasma lens." Physical review letters 121.19 (2018): 194801.

2. What do we need?

Demonstrating stable operation of a 1 kHz repetition rate plasma discharge capillary will require many individual goals to be met. Those in **bold** are discussed here.

- A kHz CW high-voltage current pulse delivery system - currently in development.
- **A plasma source which can produce identical profiles within 1 ms.**
- Ensure the capillary has appropriate longevity to enable long term kHz application.
- Investigate the thermal properties of the capillary (to prevent thermal damage / melting)
- **Develop methods for accurately diagnosing the operation of the capillary plasma.**

3. ADVANCE lab capabilities

The ADVANCE lab hosts a variety of equipment for plasma source testing and characterisation [3]:

- Imaging spectrometer and high sensitivity, electron-multiplying CMOS camera for Optical Emission Spectroscopy (OES). Longitudinally resolved, sub-μs density evolution can be measured.
- Large vacuum system
- High-voltage current pulser capable of generating pseudo-square-wave, high-current pulses.
- A variety of gases: Nitrogen, Argon and Hydrogen.
- A recently re-commissioned kHz repetition rate Ti:Sap capable of producing mJ pulses.

An example of the density evolution in hydrogen produced by a 50 mm long, 500 μm wide cell is given in Figure 1. below.

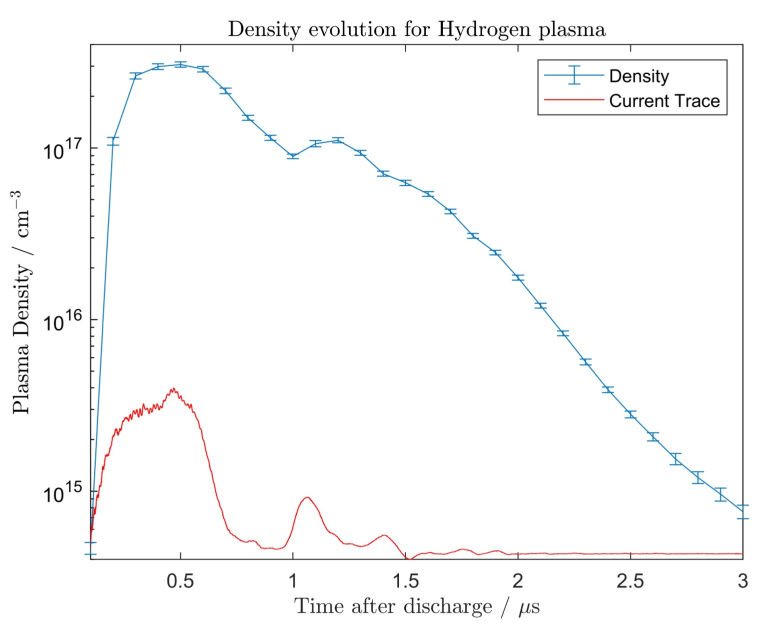

Fig 1 a. Longitudinally averaged density evolution

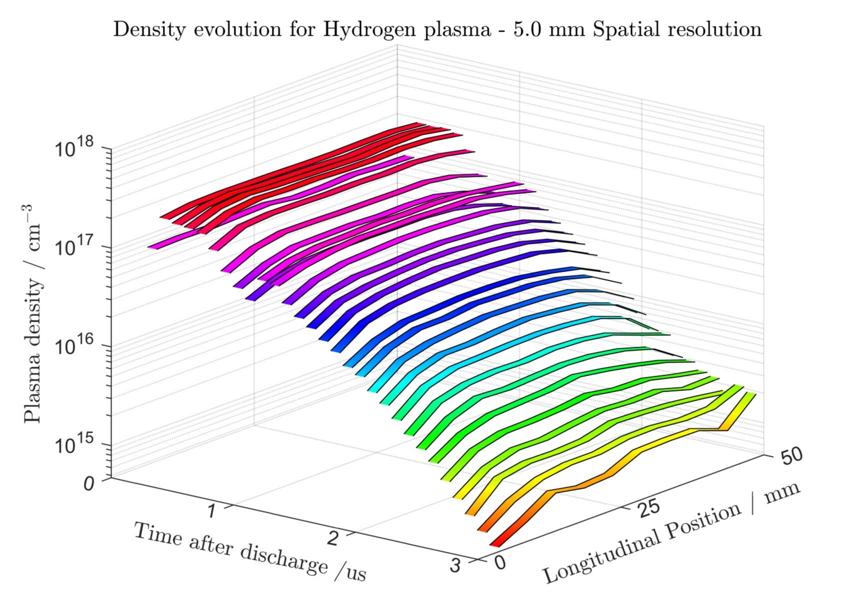

Fig 1 b. Longitudinally resolved density evolution

[3] - Garland, J. M., et al. "A Discharge Plasma Source Development Platform for Accelerators: The ADVANCE Lab at DESY". 10.18429/JACoW-IPAC2022-WEPOPT021

4. kHz Laser

The recently re-commissed kHz laser will allow us to synchronise the laser pulses to the discharge capillary, allowing for additional, laser based, plasma diagnostics to be established, in addition to the OES set-up. One of particular interest to us is Two-Colour Interferometer (TCI).

TCI-OES coupled measurements have a number of advantages over only using OES:

- Allows for temperature calibration [4].
- TCI can be more sensitive at lower densities, important for measuring stability at kHz.
- Sensitivity can boosted by generating higher harmonics.

In addition to TCI, we also plan to use the laser for CW capillary discharge guiding experiments at a kHz repetition rate. This would represent a significant milestone for kHz operation and could be used for an additional figure of merit.

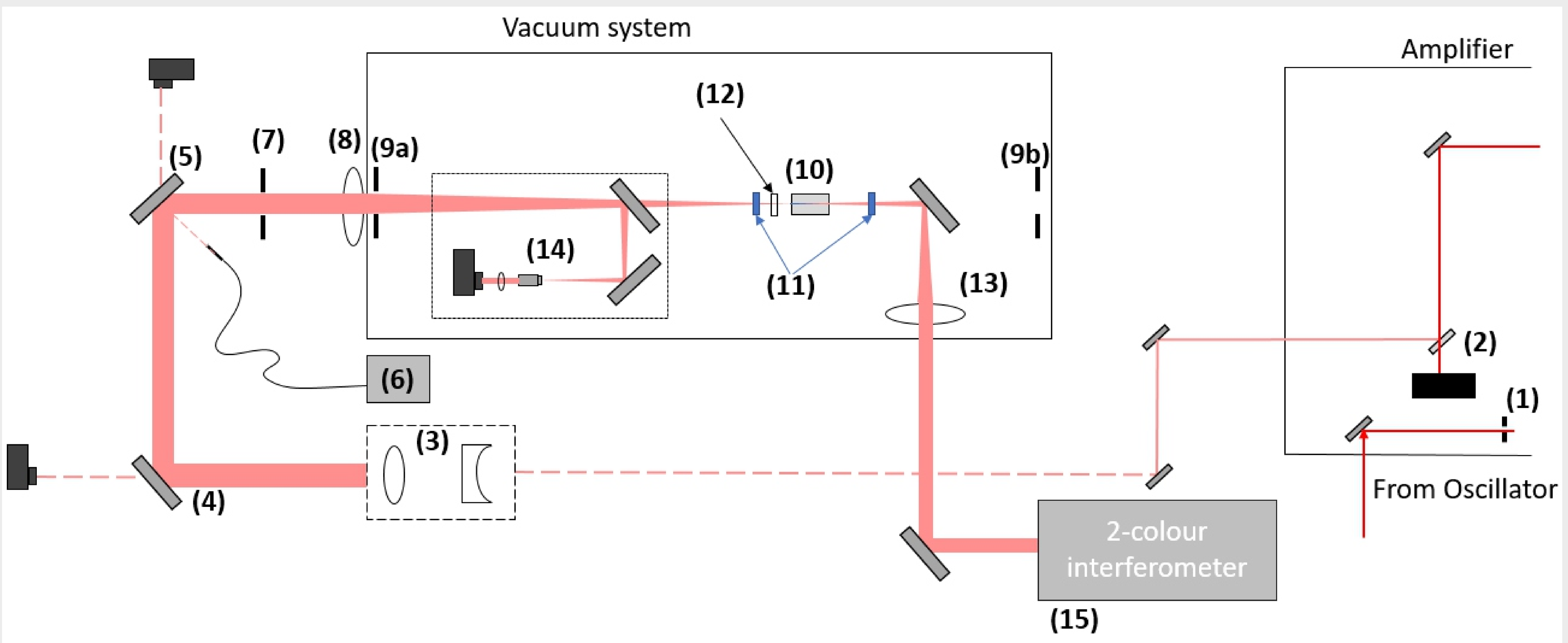

Fig 2. Schematic diagram for a two colour interferometer beamline. **Key:** 1) Alignment iris, 2) Energy control, 3) Beam expander, 4/5) Alignment camera, 6) Spectrometer, 7) Motorised Aperture, 8) Focusing optic, 9) Alignment Iris, 10) Capillary, 11) BBO crystals, 12) phase delay glass, 13) Collimating Optic, 14) Focus camera, 15) two-colour interferometer.

[4] Garland, J. M., et al. "Combining laser interferometry and plasma spectroscopy for spatially resolved high-sensitivity plasma density measurements in discharge capillaries." Review of Scientific Instruments 92.1 (2021): 013505.

5. Cell designs

A 1 kHz CW capillary must be able to reproduce identical plasma profiles within a maximum **1 ms**. After each discharge pulse the density will peak and then decay. This is due to:

- Recombination - This can re-ionised by the next discharge
- Expulsion of the gas/plasma into the vacuum chamber. This gas must be replaced.

The capillary geometry is often fixed by other factors, therefore it is best to alter the inlet geometry to improve the filling times. To produce an identical profile it is necessary not only to **replace** the missing gas, but also to allow for the gas to **equilibrate.**

Some initial simulations were performed, in steady state and temporally resolved, for two different inlet designs. The geometries were set up using 'test cell' parameters: 5 x 50 mm capillaries with 2/4 inlets backed at 1 bar. The ends of the capillary are connected to a 100 x 100 mm 'vacuum chamber'. The results of these simulations are shown in Figure 3. below.

Both designs achieve good uniformity in steady state with 4.3% and 0.8 % variation in density for the 2- and 4-inlet designs respectiely.The temporal evolution simulations indicate that the 2-inlet design reaches this steady state **far** quicker than the 4-inlet design.

Design	Time to reach 5% uniformity	Time to reach 1% uniformity
2 inlets	280 μs	N/A
4 inlets	2300 μs	>10,000 μs

These initial simulations show that temporally resolved simulations are essential. More simulations are needed to understand the driving forces behind the filling and equilibrium times.

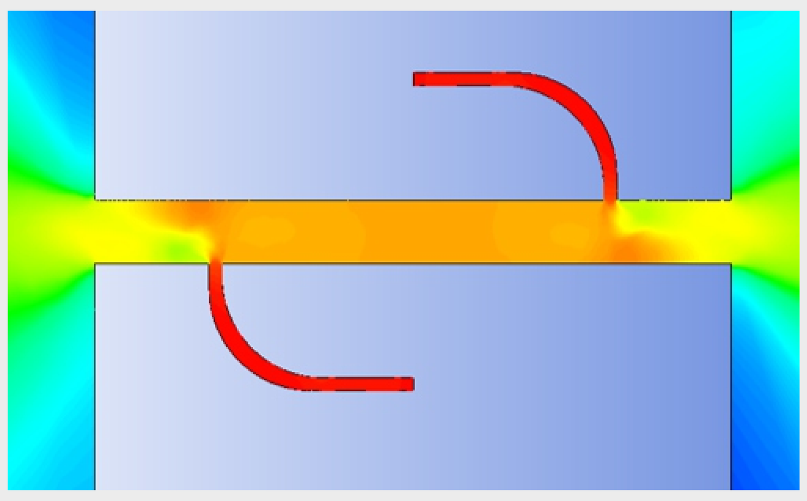

Figure 3.a: 2 inlet neutral density profile - steady state

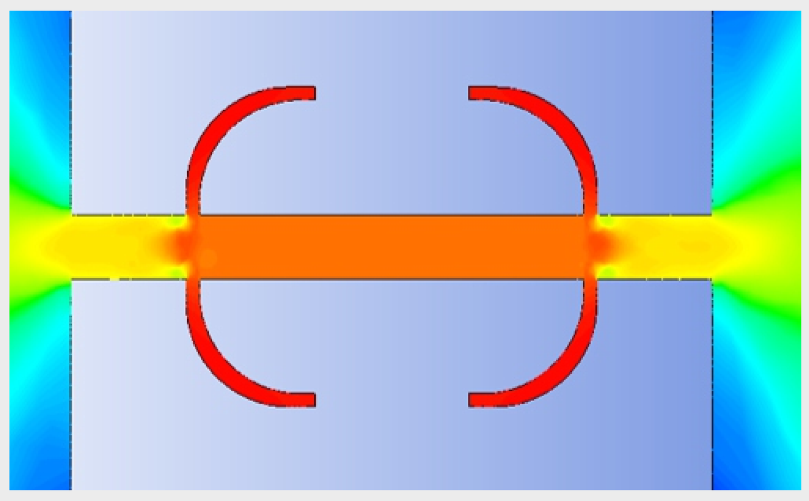

Figure 3.b: 4 inlet neutral density profile - steady state

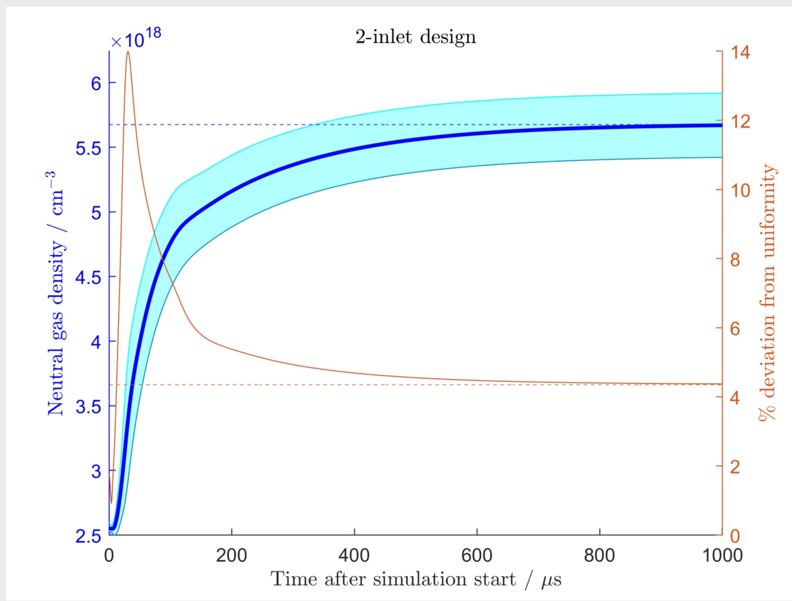

Figure 3.c: Neutral density evolution for 2 inlet design

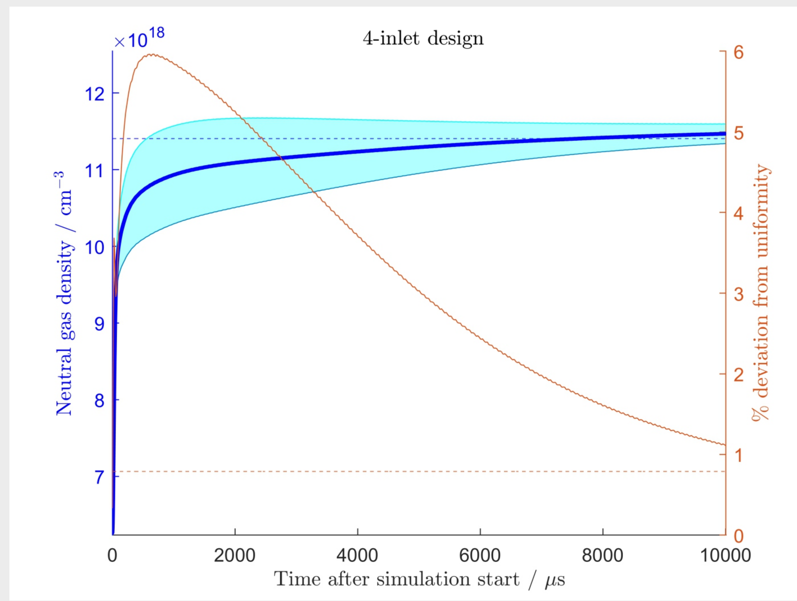

Figure 3.d: Neutral density evolution for 2 inlet design

6. Goals

1. Use Fluent to guide cell design and produce a capillary suitable for high repetition rate.
2. Successfully demonstrate CW, kHz operation.
3. Use both OES and TCI to characterise the capillary with longitudinal and temporal resolution.
4. Demonstrate stable CW, kHz guiding.
5. Quantitatively assess capillary damage and its effect on cell performance.