Computational fluid dynamics simulations of discharge capillary waveguides at FLASHForward for high-repetition-rate plasma-wakefield acceleration

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FLASHFORWARD

To operate a plasma-wakefield accelerator at a high repetition rate, it is crucial to produce the same plasma conditions at the corresponding timescales.

1. FLASHForward uniquely positioned to probe high repetition rate PWFA

High repetition operation of plasma-wakefield accelerators is crucial to achieve good luminosity and brilliance for HEP and FEL applications. Ion motion currently defines the fundamental limit for repetition rate for a plasma-wakefield accelerator. Studies at FLASHForward have shown that ion motion subsides after $\mathcal{O}$(10 ns) [1], therefore MHz operation is possible. The FLASH front end is capable of producing electron bunches at 3 MHz.

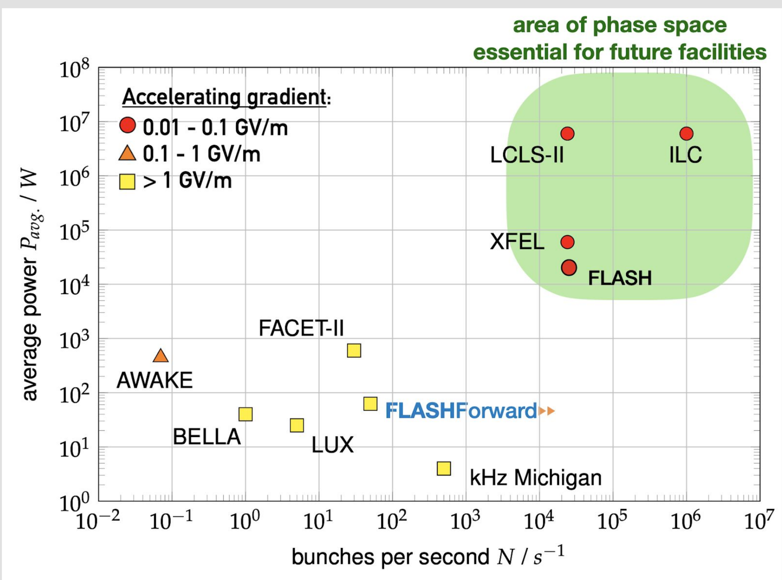


Figure 1: Courtesy of R. D'Arcy

2. Discharge capillaries

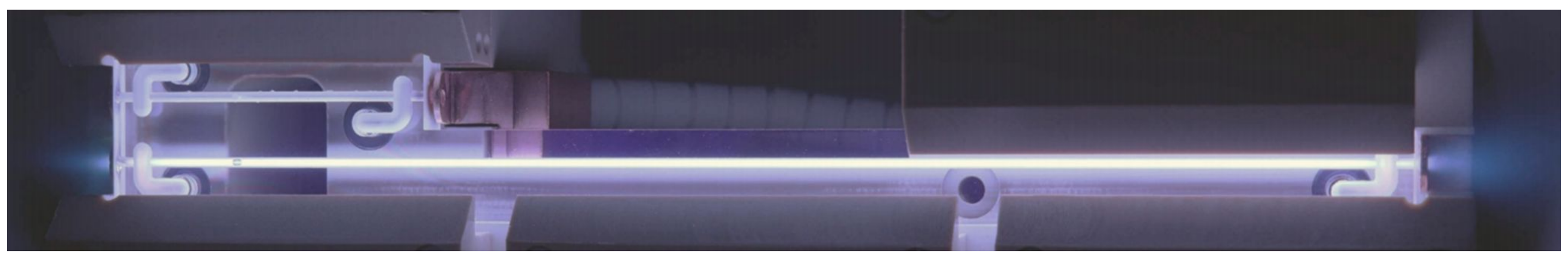


Figure 2: Plasma Targets used at FLASHForward. Expulsion of gas/plasma can be seen at the ends of the capillary. Photo: C. A. Lindstrøm

- Open ended discharge capillaries to reduce increased emittance before entering plasma.
- Filled with neutral gas: Hydrogen, Nitrogen, Argon…
- Gas ionised via discharge at 10 Hz - (5-20 kV).
- 1.5 mm diameter, 50/195 mm length.
- Discharge is very energetic and causes expulsion of the plasma/gas.

3. Measured decrease of plasma density

After a discharge the plasma density initially rises and then falls. Due to a combination of expulsion and recombination

Define plasma reset as: *Time to reach equivalent plasma conditions for suitable for acceleration.*

Two ways to reduce plasma reset time:

1. Contain existing plasma as much as possible.
2. Allow to expel and refill as fast as possible.

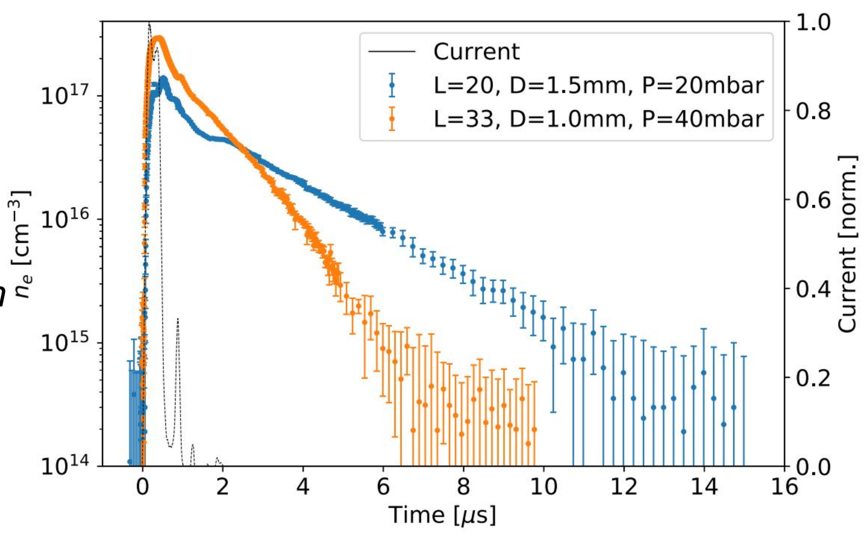


Figure 3: Measured electron density decay in discharge capillaries filled with Argon/ Hydrogen mix (95/5). Current profile used for discharge represented by black line. [2]

4. Filling simulations

Model the filling of discharge capillaries in COMSOL Multiphysics.

- Compressible turbulent flow (k-ω)
- Slip boundary condition at the wall
- 3D and 2D simulations
- Fill from empty (10^{-3} mbar)
- Test different cell geometries
  - Condition the flow at the inlet to optimise the time to fill the cell

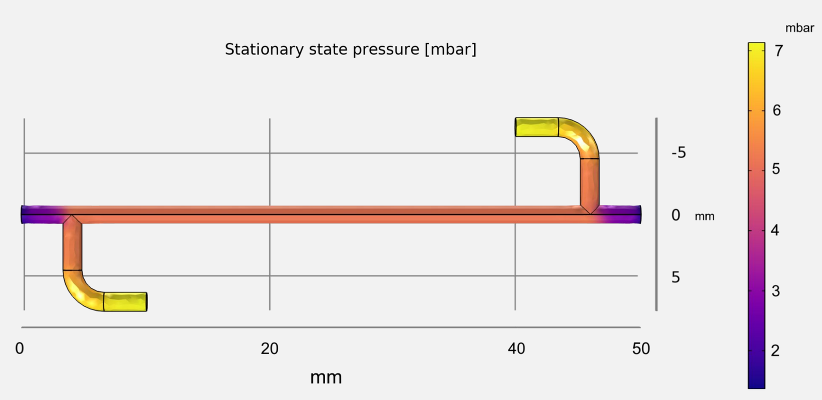


Figure 4: Stationary state 3-D simulations

Investigating how inlet design affects the time to fill discharge capillary. Comparing how quickly the pressure at the centre of the capillary rises for different two different inlet designs.

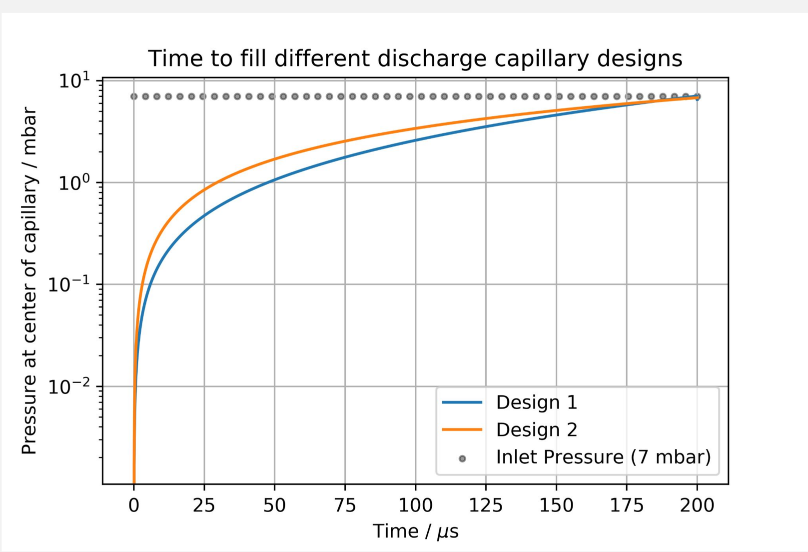
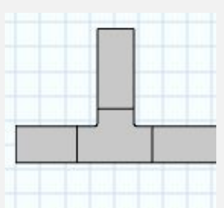
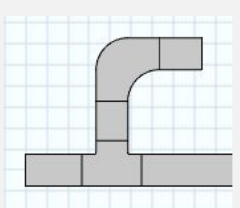


Figure 5a: Gas filling simulation results: long timescale.



Inlet design 1



Inlet design 2

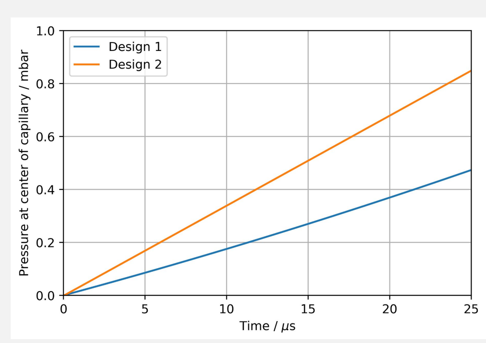
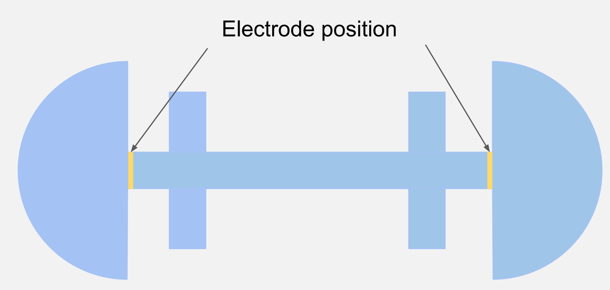


Figure 5b: Gas filling simulation results: short timescale.

5. Discharge and expulsion simulations

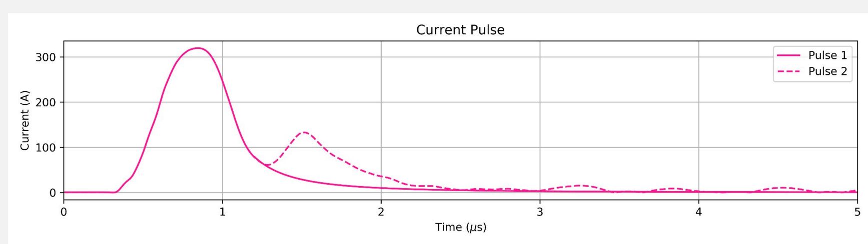
Investigating the effect of a reflection in the discharge profile used to ionise gas at FLASHForward. The discharge is simulated using a Hydrodynamic Plasma model that is being developed at DESY.

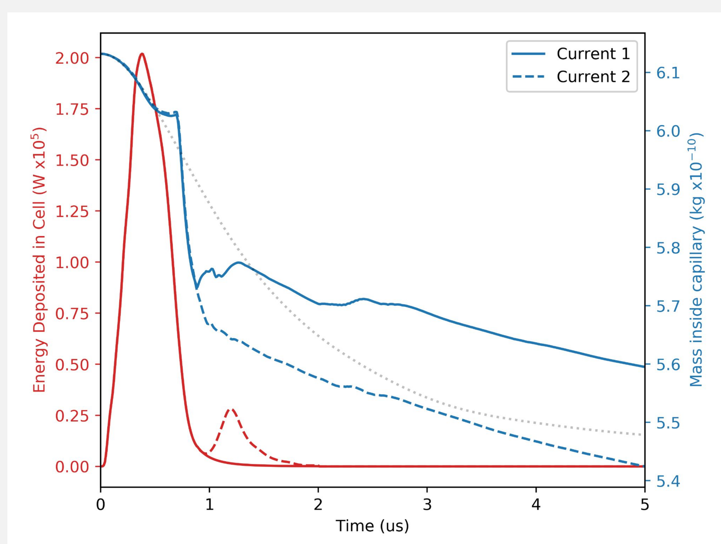
- Single Fluid, two temperature, non-local thermal equilibrium (Ionisation state is tracked with collisional rates) plasma
- 2D axisymmetric geometry
- Physics models included: laminar flow, electric currents, transport of species, heat transfer, electromagnetic heating.
- Simulate various discharges through a capillary filled with Hydrogen gas and allow resulting plasma to expel

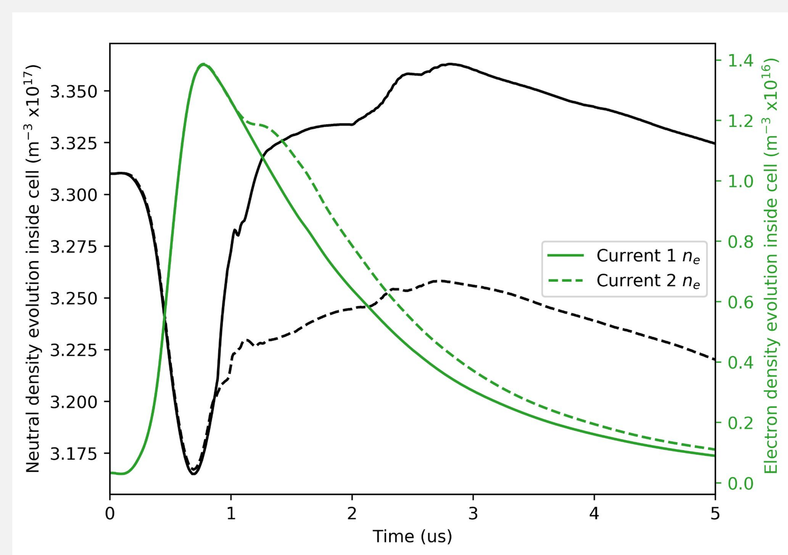


Dimensions of test capillary:

- 50 mm length
- 1.5 mm diameter
- Gas inlets 4 mm from exits
- 3 mm inlet width







6. Outlook

- Begin studies of 3-D capillary geometries
  - Largest obstacle is creating a robust routine to mesh different geometries effectively
- Explore more quantitatively the effects of different geometries
  - Define figures of merit to judge the performance of designs; i.e fill time, gas density achieved, etc.
- Explore more geometries
  - Understanding the influence of capillary diameter, length, inlet position & size, etc. on gas expulsion
- Benchmark these simulation results with experiments in the lab
  - Need to manufacture various cell geometries and characterise them in the lab to see if simulations correlate to real world performance

[1] R. D'Arcy et al., Nature 603, 58–62, 2022
[2] M. J. Garland et al, Review of Scientific Instruments 92, 013505, 2021

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