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

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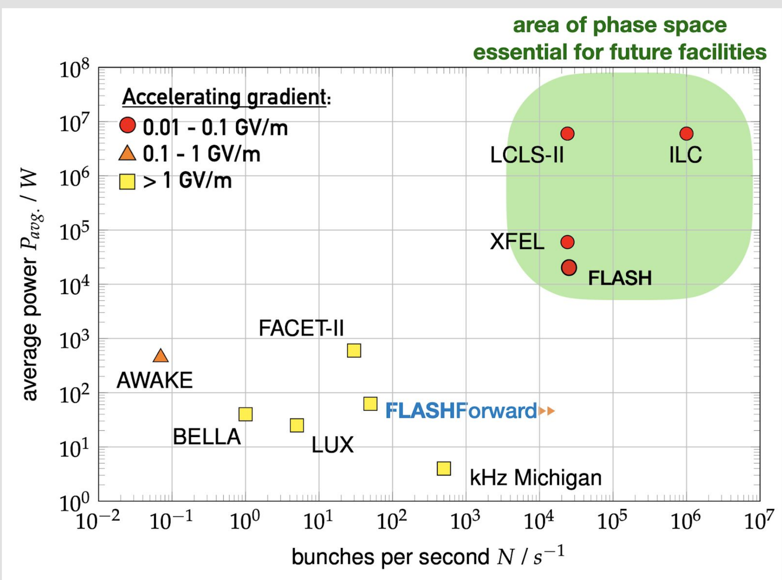
FLASHFORWARD

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 Ⴢ(10 ns) [1], therefore MHz operation is possible. The FLASH front end is capable of producing electron bunches at 3 MHz.



Courtesy of R. D'Arcy

2. Discharge capillaries

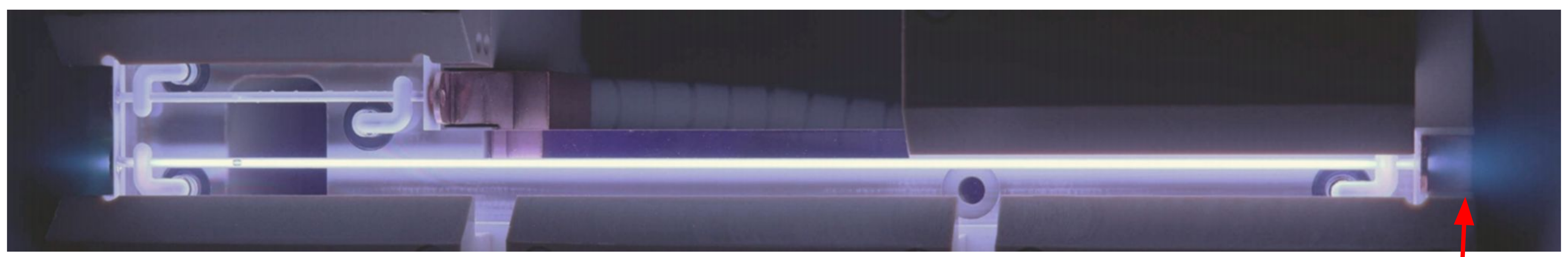


Photo: C. A. Lindstrøm

- Open ended discharge capillaries to reduce emittance growth
- Filled with neutral gas: Argon/Hydrogen…
- Ionised via discharge - (5-20 kV)
- 1.5 mm diameter, 50/200 mm length
- Optimise cell design for high repetition rate operation
- Discharge is very energetic and causes expulsion of the plasma. This can be seen visually

3. Decrease of plasma density

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

- Expulsion
- Recombination

Need to understand underlying physics of this decrease to be able to design high repetition rate cells.

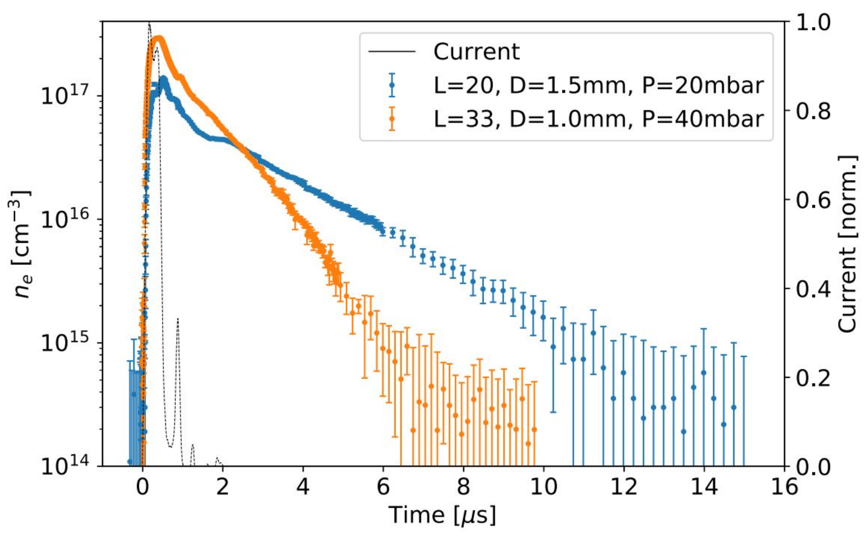


Figure showing decrease in plasma density after discharge for two cell designs [2]

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

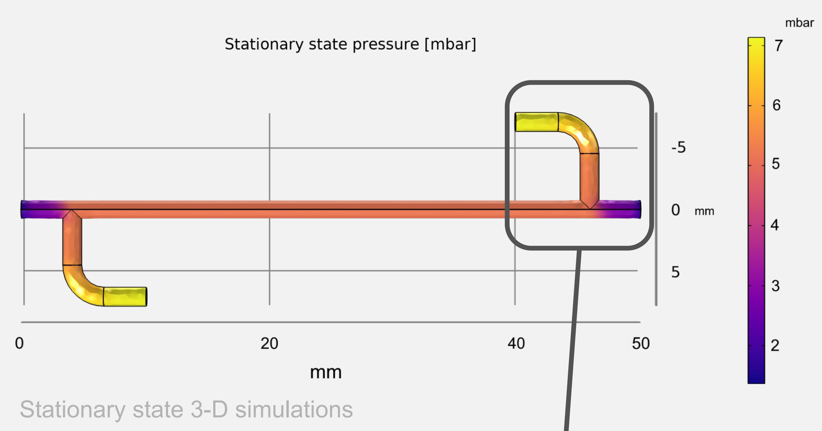
Two ways to reduce plasma reset time:

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

4. Aim of discharge capillary design

Model the filling of discharge capillaries in COMSOL Multiphysics.

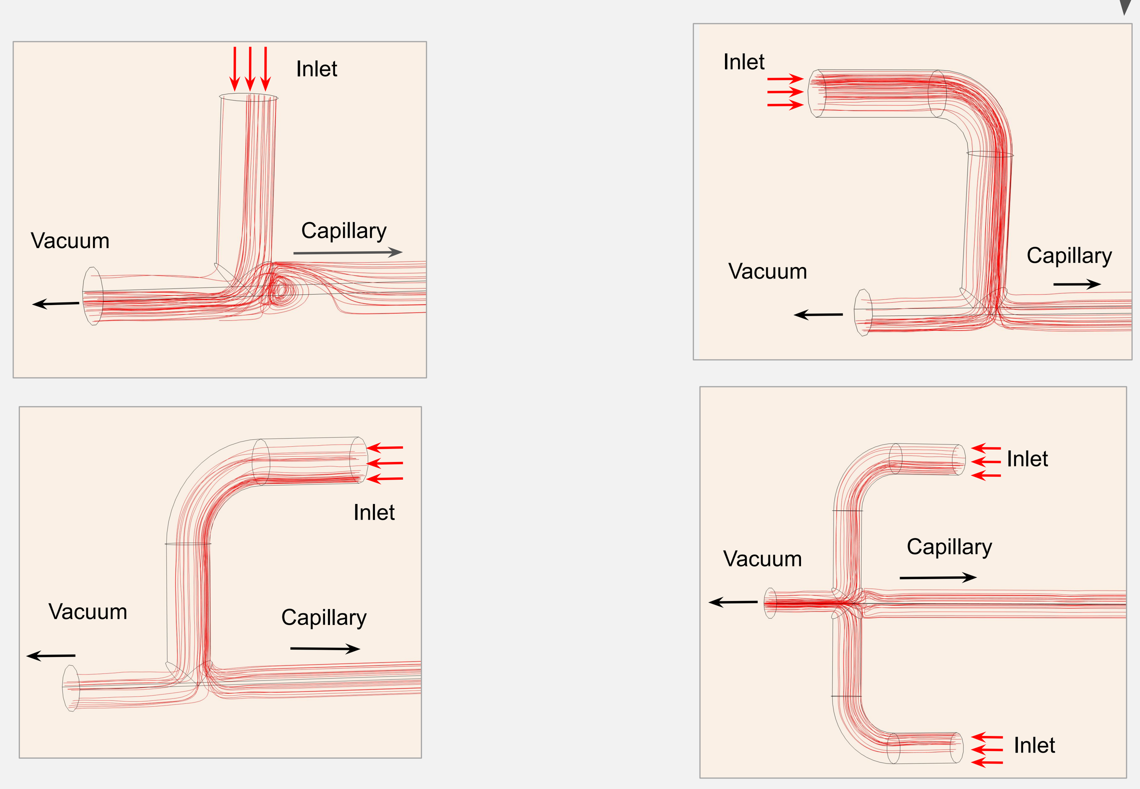
- Compressible turbulent flow (k-ω)
- Slip boundary condition at the wall
- 3D and 2D simulations
- Fill from empty (10^{-3} mbar)
- Test different cell geometries
  - Condition the flow at the inlet to optimise the time to fill the cell



Stationary state 3-D simulations

Flow conditioning at the inlets via 3-D simulations

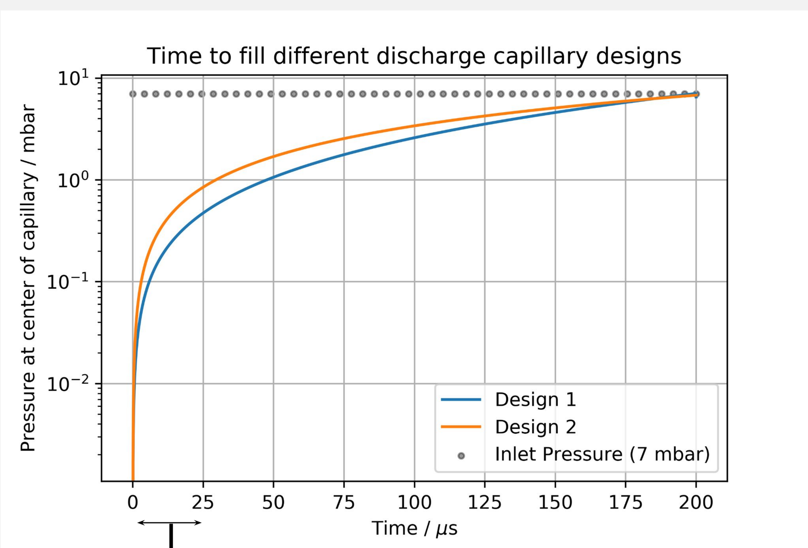
Visualisation of how flow of gas is affected by differing inlet designs.



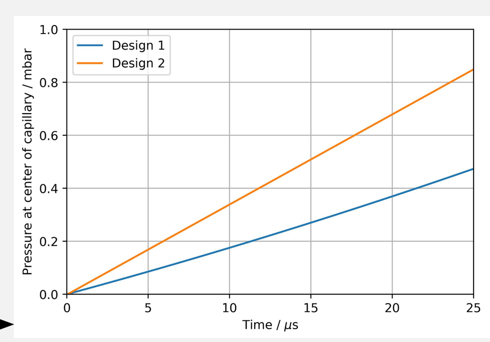
Here we display the streamlines for the flow of Hydrogen in different cell geometries. Conditioning the flow before the capillary improves flow.

5. 2-D time evolution studies

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 2 different inlet designs.



Inlet design 1 Inlet design 2



6. Outlook

- Begin time dependent 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.
- Combine these gas flow simulations with a plasma hydrodynamic simulation code that is currently being developed at DESY
  - This will make it possible to run simulations for multiple discharges and filling events
  - This is a more representative simulation and will better inform capillary design

[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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