Long-term evolution of conditions within plasma capillary discharge devices, with application to plasma accelerators

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Introduction

The ability to characterise and manipulate the plasma conditions within capillary discharge devices, such as plasma accelerator modules, laser waveguides, and active plasma lenses, is paramount to the development and optimization of next generation compact particle accelerator technology [1]. For example, the FLASHForward [2] experiment at DESY aspires to use beam-driven plasma wakes to accelerate GeV electron beams of sufficient quality to generate free-electron laser gain. Experimental parameters, such as the discharge current pulse shape, alter the plasma properties, and the relaxation time of these properties limits the repetition rate [3].

In this work, QUEST [4] simulations are used to investigate the long-term evolution of hydrogen capillary discharge plasmas, with a particular focus on high-repetition-rate discharges. Both the conditions of the plasma and capillary wall material are considered.

Model description

Following Refs. [5, 6], the discharge dynamics of a confined cylindrical hydrogen plasma of radius R and length $L \gg R$ are considered. The dynamics of the plasma discharge system are largely dictated by the local plasma temperature [4]. The radial energy balance equation is

$$\frac{\partial \varepsilon}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\left[\varepsilon + P\right]v\right) = Q - \frac{1}{r}\frac{\partial}{\partial r}\left(rq\right), \tag{1}$$

where r and t are the radial position and time respectively, ε is the total energy, P is the total pressure, v is the radial velocity, and q is the heat flux, all defined for a single-fluid plasma. Q represents the combined remaining sources and sinks of thermal energy. The key to QUEST [4] is to assume a specific form of radial temperature and density profiles, such that the radial average of Eq. (1) reduces to

$$C_v'\left(\overline{T}, \overline{n}_a\right)\frac{d\overline{T}}{dt} = \frac{1}{\sigma\left(\overline{T}, \overline{n}_a\right)}\left(\frac{I}{\pi R^2}\right)^2 - \frac{2}{R}q(R), \tag{2}$$

where $\overline{T}$ and $\overline{n}_a$ are the (radial) average plasma temperature and atomic density respectively, C_v' represents and effective heat capacity which accounts for the effects of ionisation and recombination, σ is the electrical conductivity, I is the discharge current, and $q(R)$ represents the heat flux at the capillary wall. For details of the QUEST method and workflow, see Ref. [4].

The heat flux per unit length at the plasma-wall interface, $Q_w = \frac{2}{R}q(R)$, can be calculated from Eq. (2), then used as the input into a separate heat-flow simulation to model the temperature evolution of the capillary walls. For consistency, the temperature boundary condition used in the QUEST calculation should vary as the wall temperature evolves, but for a preliminary investigation we treat the temperature in the QUEST simulation as separate, and constant.

Long-term plasma evolution

The long-term evolution of a 750 μm radius hydrogen capillary plasma, with an initial 2 mbar backing pressure, subject to a sine-wave discharge is shown in Fig. 1. These parameters have been chosen to be approximately consistent with the ongoing plasma source investigations at FLASHForward [2].

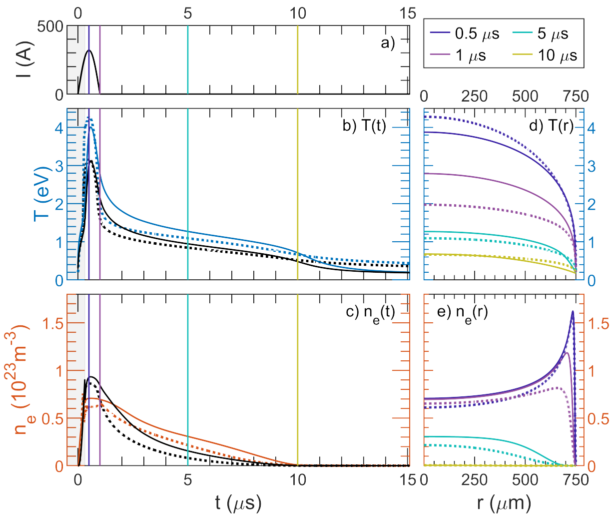

Figure 1: *Comparison of QUEST [4] (solid) and plasma fluid [7] (dashed) simulation results for plasma temperature and electron density. The subplots are:* ***a)*** *Discharge current profile I,* ***b)*** *Average (black) and on-axis (blue) electron temperature T_0,* ***c)*** *Average (black) and on-axis (red) electron density n_{e0},* ***d)*** *Radial electron temperature profiles $T(r)$ for select times corresponding to the vertical lines in b),* ***e)*** *Radial electron density profiles $n_e(r)$ for select times corresponding to the vertical lines in c). The shaded grey in a)-e) indicates the times at which the QUEST algorithm assumes uniform conditions.*

Both during and after the discharge, reasonable agreement is demonstrated between the QUEST and 1D plasma fluid [7] simulations for the average and on-axis temperature (Fig. 1b)), and the average and on-axis electron density (Fig. 1c)). However, at approx. 10 μs, the QUEST method temperature drops much faster than the fluid simulation. This appears to be due to calculating the ionic state populations from the average temperature, rather than from a temperature profile, and is to be investigated in future studies.

The radial temperature (Fig. 1d)) and radial electron density (Fig. 1e)) show some significant differences between QUEST and fluid results, but this is largely a consequence of the difference in average temperature at those times. The general radial profile shapes are consistent between the two models. Overall, the QUEST method still works well long after the current discharge has terminated.

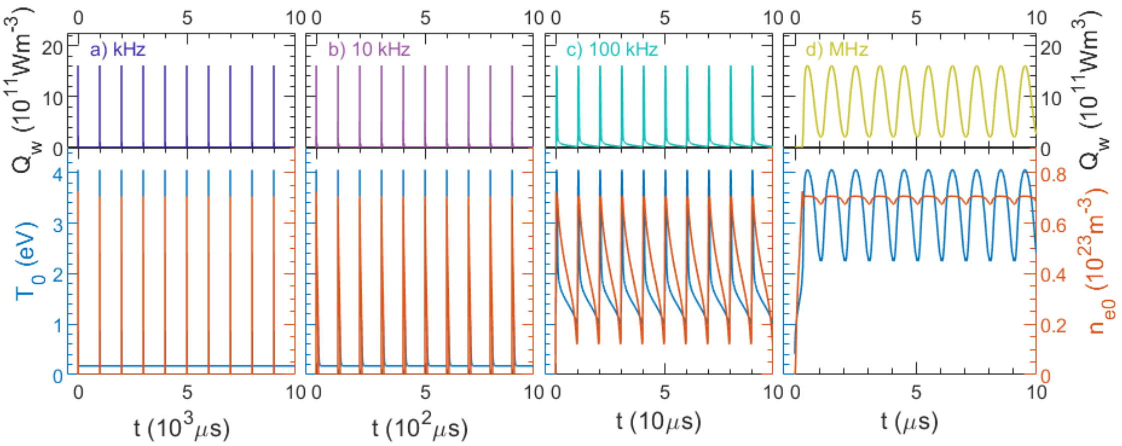

Figure 2: *QUEST simulations for the discharge in Fig. 1a) operated at kHz–MHz repetition rates. **(Top)** Heat flux per unit length at capillary wall, **(Bottom)** On-axis electron temperature and density.*

Repeated discharges

QUEST simulations were used to investigate the response of the capillary plasma to repeated discharges. The on-axis plasma temperature and density, as well as the heat flux per unit length at the plasma-wall interface, are shown for a range of discharge repetition rates in Fig. 2. At low repetition rates (1-10 kHz), the discharges act essentially independently. At high repetition rates (100 kHz -1 MHz) the plasma relaxation overlaps with subsequent discharges, and a new periodic steady-state is established. The peak plasma property values are independent of the repetition rate, which reflects the assumption of a quasistatic steady-state inherent in the QUEST method when using a Dirichlet temperature boundary condition.

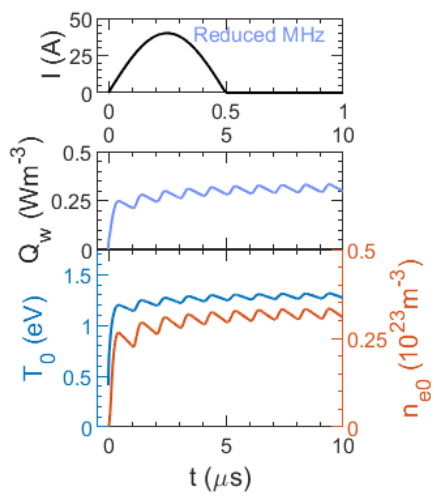

Figure 3: *QUEST simulations for the Reduced MHz discharge profile (discussed in text). **(Top)** Current profile, **(Middle)** Heat flux per unit length at capillary wall, **(Bottom)** On-axis electron temperature and density.*

To minimise the wall heat load, we have also considered a discharge profile with reduced total power yet still sufficient to produce an electron density suitable for FF. The 'Reduced MHz' mode employs a short pulse and a reduced current amplitude operated at a MHz repetition rate, as shown in Fig 3. Only partial (approx. 30%) ionization is achieved under these conditions, and lower peak temperature values than those shown in Fig 2.

To investigate the wall temperature variation due to repeated discharges, Fig. 4, the heat flux calculated in Figs. 2-3. were used as inputs in a COMSOL heat-flow simulation for a sapphire cylinder with 750 μm< r <7.5 mm. This represents an upper limit as there can be significant heat loss during plasma expulsion out the open capillary ends. In Figs. 4a) and 4b) the wall temperature for kHz and MHz rates are compared to the equivalent constant heat flux rates. The constant heat flux simulations accurately reproduce the general temperature evolution and are less computationally expensive. In Fig. 4c), the temperature evolution up to 10 s is shown. The 1 kHz and 10 kHz rates reach a steady-state value well below the sapphire melting point of 2326 K, while the 100 kHz and 1 MHz values far exceed it. The 'Reduced MHz' was tailored to operate at at 1 MHz while staying below the melting point. These results are consistent with Ref. [6].

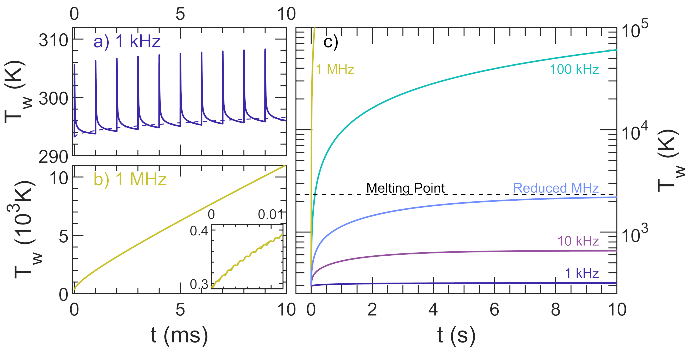

Figure 4: *Plasma-wall interface temperature for different discharge repetition rates. The subplots are:* ***a)*** *Temperature comparison for the heat flux in Fig. 2a) with the equivalent constant heat flux,* ***b)*** *Same as a), but for the heat flux in Fig. 2d),* ***c)*** *Temperature for various constant heat fluxes.*

Summary

This work represents the first long-term (μs+) simulations of capillary discharge devices, made feasible by the computationally inexpensive QUEST algorithm [4]. We have demonstrated that QUEST gives comparable results to full plasma fluid simulations both during and long after the discharge has terminated. Using QUEST, the heat flow through the plasma-wall interface was simulated for discharge current conditions relevant to the FLASHForward experiment [2], operated at kHz-MHz repetition rates. The model showed that 1 kHz and 10 kHz repetition rates could be sustained indefinitely, but that 100 kHz and MHz rates quickly exceeded the sapphire capillary melting point. By reducing the pulse length and amplitude, MHz repetition rates can feasibly be sustained while providing plasma conditions suitable for accelerator applications.

References

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