Detonation to Deflagration-mode Transitions in Pulsed Plasma Accelerators

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I. Abstract

PULSED plasma accelerators typically operate by storing energy in a capacitor bank and then discharging this energy through a gas. The current in such discharges will ionize the gas and produce a strong magnetic field, which interacts with the flowing current to accelerate the plasma through the Lorentz body force. For the present work, two plasma accelerator types employing this general scheme are of interest: the gas-fed pulsed plasma thruster (PPT) [1] and the quasi-steady magnetoplasmadynamic (MPD) accelerator. [2]

The gas-fed pulsed plasma accelerator is generally understood as a completely transient device discharging in $\sim$1-10 μs. When the capacitor bank is discharged through the gas, a current sheet forms at the breech of the thruster and propagates forward under a $\mathbf{j} \times \mathbf{B}$ body force, entraining and accelerating propellant it encounters. This process is sometimes referred to in literature as 'snowplowing' the propellant or accelerating the gas in a detonation-mode because the current sheet representation approximates that of a strong detonation shockwave propagating through the gas. For these devices, acceleration of the initial current sheet ceases when either the current sheet reaches the end of the device and is ejected or when the current in the circuit reverses, striking a new 'crowbar' discharge at the breech and depriving the initial sheet of additional acceleration. In general, PPTs typically claim thrust efficiencies (ratio of jet kinetic energy to input electrical energy) registering in the teens or lower. [3]

In the quasi-steady MPD accelerator, the pulse is lengthened to $\sim$1 ms or longer and maintained at an approximately constant level during discharge through the use of a pulse-forming network (PFN) of capacitors. After an initial transient discharge, which is typically short relative to the overall discharge period, the plasma assumes a relatively steady-state configuration, known as 'quasi-steady' MPD operation. [2] In this state, ionized gas flows through a stationary current channel in a manner that is sometimes referred to as deflagration-mode operation owing to the similarities to deflagration waves in gases. The plasma experiences electromagnetic acceleration as the plasma flows through the current channel towards the exit of the device. Quasi-steady MPD thrusters claim efficiencies up to 50% for certain propellants.[4]

There has been significant and sustained research over several decades on both gas-fed PPTs and quasi-steady MPD thrusters, however there have been pulsed thrusters that do not appear to exactly fit either classification, instead possessing a mixture of operational qualities characteristic of both thruster variants. The Coaxial High ENerGy (CHENG) thruster by Cheng, *et al*.[5] operated on the short 10 μs timescales characteristic of PPTs, but claimed the high thrust densities, high efficiencies, and low electrode erosion rates that are more consistent with the MPD/deflagration mode of plasma acceleration. Gas-fed PPT research by Ziemer, *et al.*[3,6] identified two separate regimes of performance in those thrusters. The regime at higher mass bits (termed Mode I in that work) possessed relatively constant thrust efficiency as a function of mass bit, while the second regime at very low mass bits (termed Mode II) exhibited an increase in efficiency with decreasing mass bit.

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Work by Poehlmann *et al.*[7] and by Sitaraman and Raja[8] sought to understand the performance of the CHENG thruster and the Mode I/Mode II performance in PPTs by modeling the acceleration using the Hugoniot Relation, with the detonation and deflagration modes of plasma acceleration representing two distinct sets of solutions to the relevant conservation laws. In these works, it was proposed that the values of the various controllable parameters determined whether the accelerator would operate in detonation or deflagration mode.

Our hypothesized view of the acceleration process in the CHENG thruster and in PPTs experiencing a transition from Mode I to Mode II is inspired by observations of the transition from the PPT mode of operation to the quasi-steady MPD mode. Specifically, the quasi-steady MPD was discovered by driving a PPT to extended pulse lengths. Above a certain pulse length threshold the transient plasma current sheet transitions into a stable plasma acceleration mode that 'replicates in every observable detail steady flow self-field magnetoplasmadynamic acceleration.'[9] In the present work, instead of treating the accelerator as if it were only operating in a single mode during a pulse, we consider the initial stage of the discharge in all cases as a current sheet forming at the breach of the accelerator and moving towards the exit as a detonation wave. If the current sheet reaches the exit of the accelerator before the discharge is completed, the view of the acceleration mode transitions to the deflagration mode-type found in quasi-steady MPD thrusters.

In previous work[10] we presented a modeling framework that first captured the time-evolution of the current sheet (detonation) mode of the thruster and then transitioned into the quasi-steady MPD (deflagration) mode of plasma acceleration. In the present work, variations of the controllable parameters – specifically the pulsed circuit properties, the amount of mass injected into the thruster, and the relative timing between the initial gas injection and the initiation of the plasma current sheet – will be used to explore the thruster performance. A range of parameters are explored to demonstrate that standard gas-fed pulsed plasma accelerators, the CHENG thruster, and the quasi-steady MPD accelerator are variations of the same device, with the overall acceleration of the plasma depending upon the behavior of the plasma discharge during initial transient phase and the relative lengths of the detonation and deflagration modes of operation.

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