Pulsed Plasma Acceleration Modeling in Detonation and Deflagration Modes

Kurt Polzin

NASA-Marshall Space Flight Center

Christine Greve

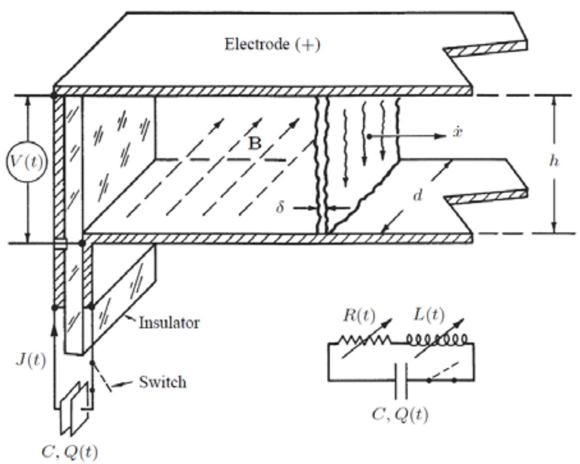
Texas A&M University

Kamesh Sankaran

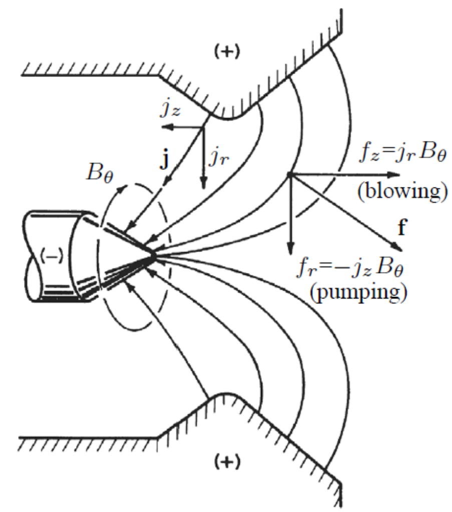
Whitworth University

Introduction

- Pulsed Plasma Accelerators
    - Pulsed Plasma Thrusters (PPT)
    - Quasi-Steady Magnetoplasmadynamic (MPD) Thrusters



Jahn, *Physics of Electric Propulsion* (1968)



Jahn, *Physics of Electric Propulsion* (1968)

- PPT (typically)
    - Transient, ~1-10 μs
    - Snowplow / Detonation mode acceleration
    - Low efficiency (relative to MPD)

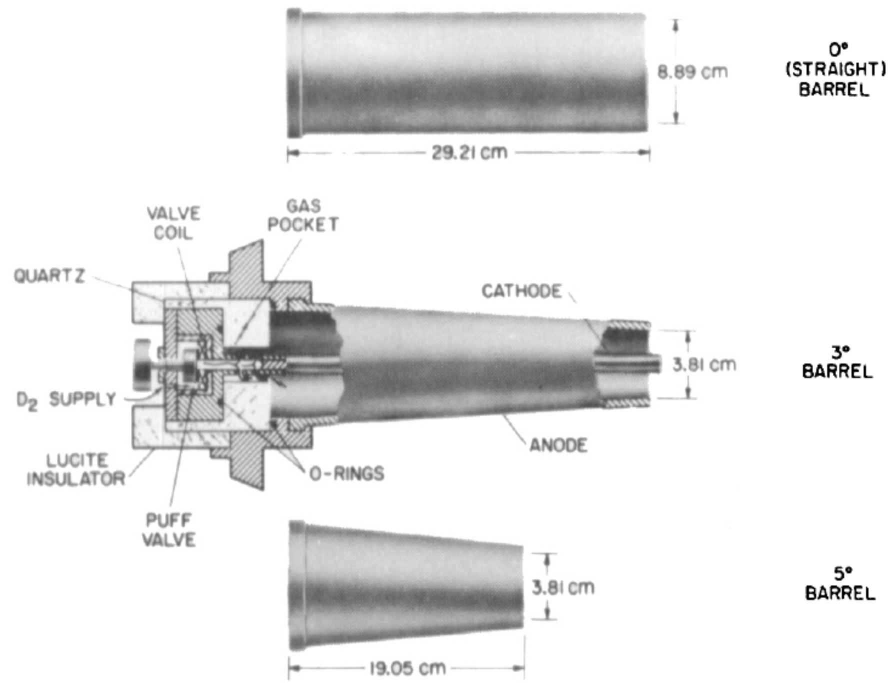
- MPD (typically)
    - Quasi-steady, ~1 ms or longer pulse
    - Blowing / Deflagration mode acceleration
    - Higher efficiency (approaching 50% at high power)

Motivation for Present Work

- Thrusters that don't fit either category or have performance that deviates from expectations
- Coaxial High ENerGy (CHENG) "Deflagration Gun"

  - ~10 μs timescale pulses
  - Claimed high thrust density, high efficiency
  - More consistent with deflagration mode acceleration

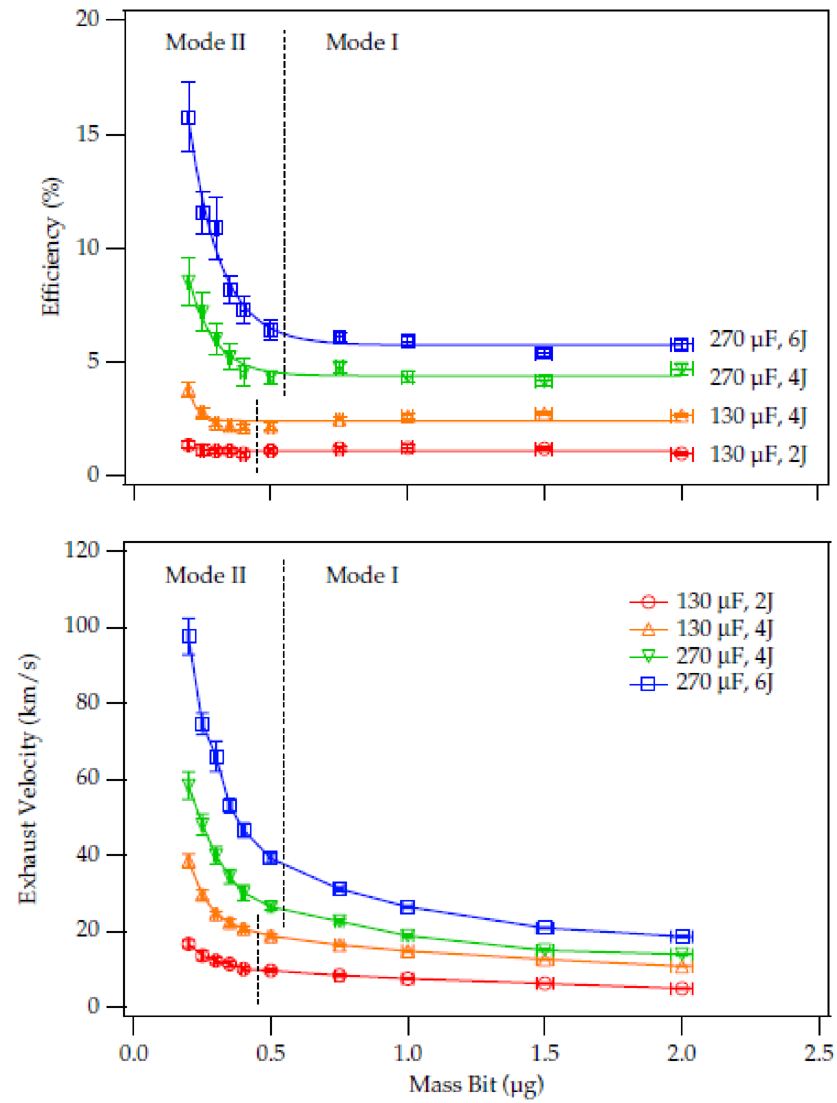
  - Gas injection initiates/switches discharge



Cheng, *Nuclear Fusion* **10** (1970)

Motivation for Present Work

- Gas-Fed PPT
  - Two performance regimes as a a function of mass bit (Mode I, Mode II)
  - Electrode erosion not enough to explain increase as a function of decreased mass bit in Mode II
  - Spark plug initiates discharge



Ziemer, *Performance Scaling of Gas-Fed Pulsed Plasma Thrusters*, Princeton Ph.D. Dissertation (2001)

Modeling & Experiments - Literature

- Cheng (1970), *Nuclear Fusion* (1970)
- Poehlmann, *et al*. (2007-2010), AIAA Paper 2007-5263 (2007), *Phys. Plasmas* (2010), Ph.D. dissertation (2010)
  - Used Rankine-Hugoniot model for pulsed plasma acceleration
  - Selectable parameters determined where on the graph one resided (detonation or deflagration)

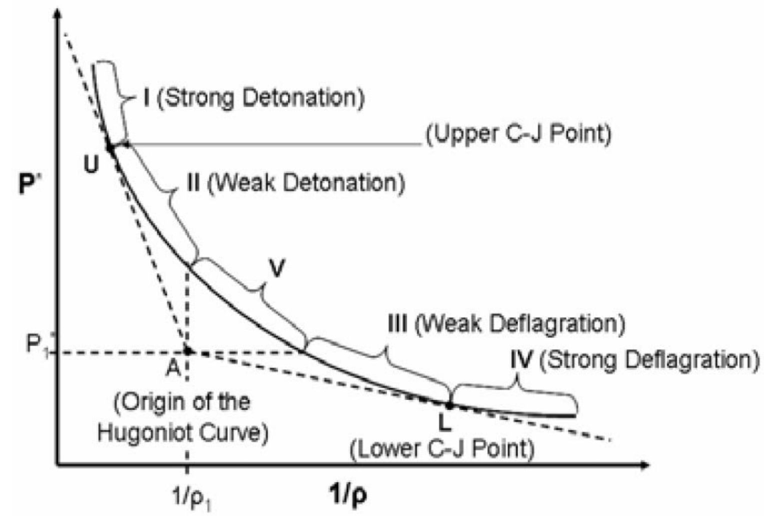


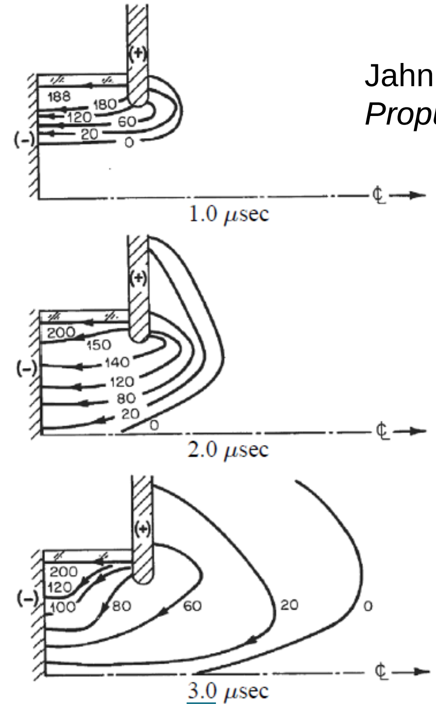
Figure 2: Hugoniot relation.
Poehlmann, *et al.*, AIAA Paper 2007-5263

- Woodall and Len, *J. Appl. Phys.* (1985)
- Sitaraman and Raja, *Phys. Plasmas* (2014)
  - MHD simulations
  - Adjusted plasma temperature and conductivity to gain agreement between the models and data
  - Low Conductivity → Deflagration Mode
  - High Conductivity → Detonation Mode

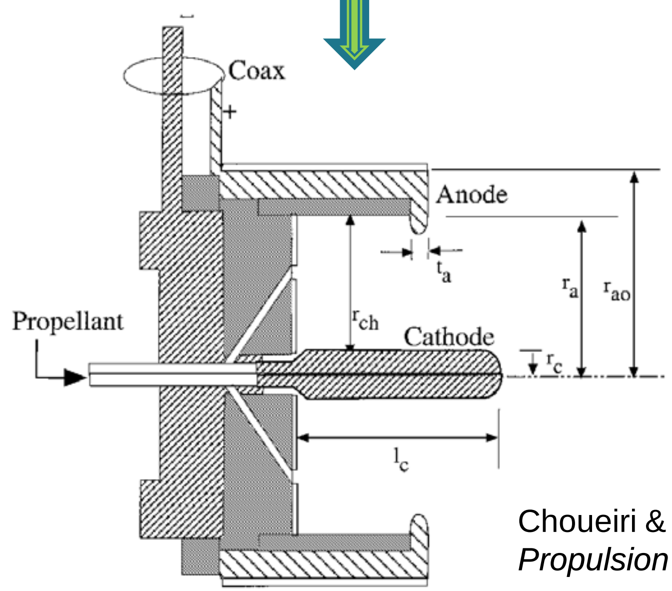
- Subramaniam, *et al.*, *Phys. Plasmas* (2017), *Plasma Sources Sci. Tech.* (2018)
  - Resistive MHD simulations
  - Modeled discharge as sequence of events
  - Compared to Schlieren measurements as plasma jet impacted downstream object
  - Varied time between gas injection and current pulse
  - Short Delay → Low Conductivity → Deflagration Mode
    - Deflagration to Detonation after first half-cycle
  - Long Delay → High Conductivity → Detonation Mode

The Quasi-Steady Arc

- Princeton gas-fed z-pinch work
  - Purely pulsed detonation-mode device
- Lengthened pulse with a PFN
- Extended cathode
- Quasi-steady MPD thruster
  - Initial pulsed detonation-mode current sheet
  - Becomes a deflagration-mode current channel if pulse is long enough (~1-3 ms or greater for Q-S operation)

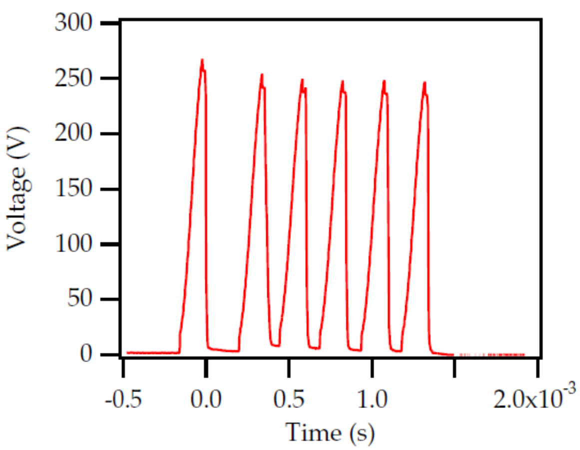


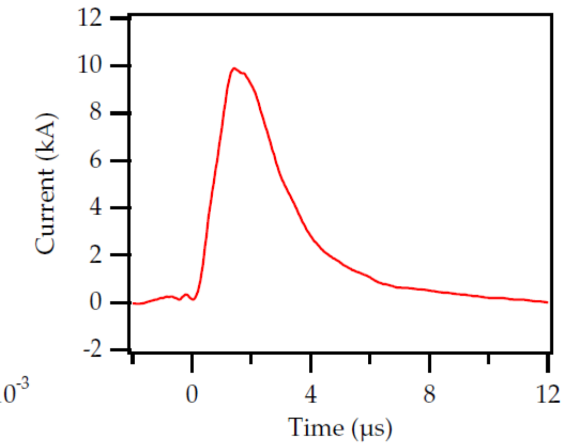
Jahn, *Physics of Electric Propulsion* (1968)



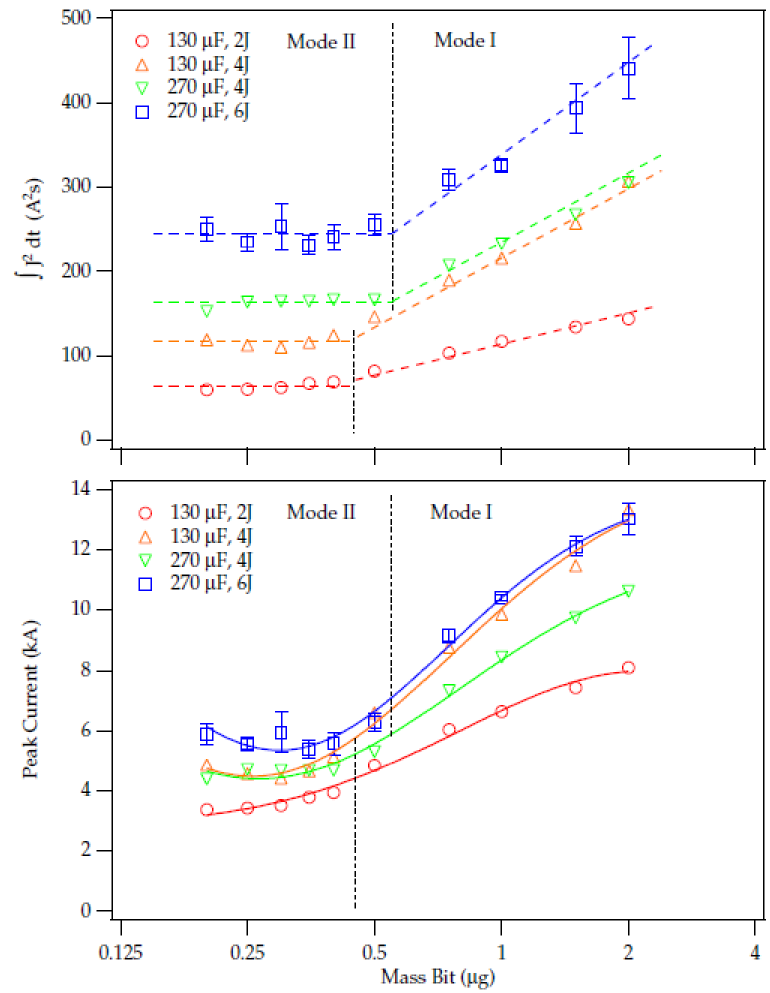
Choueiri & Ziemer, *J. Propulsion Power* (2001)

GF-PPT - Revisited





- No ringing in this circuit
- Scaling of peak current and $\int I^2 \, dt$ with mass bit
- Implies mass loading has an effect on the nature of the discharge waveform
- Integral indicative of the overall impulse imparted to the gas over the course of the discharge



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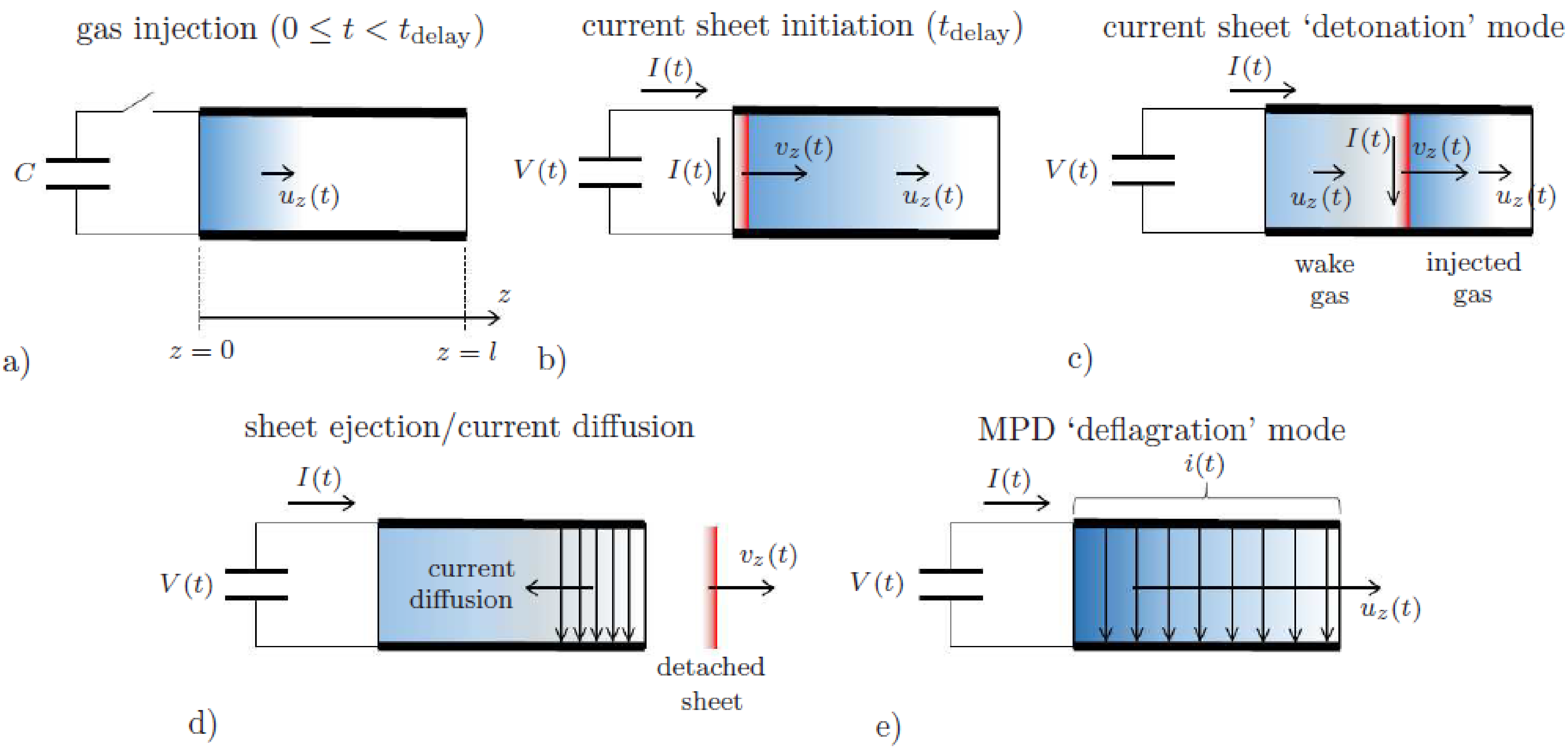
Proposed Model



Model of Processes

- Neutral fluid species (Eulerian reference frame)
  - Initial gas injection and current sheet wake

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}\left(\rho u_z\right) = 0$$

$$\frac{\partial \left(\rho u_z\right)}{\partial t} + \frac{\partial}{\partial z}\left(\rho u_z^2 + P\right) = \left(f_z\right)_{\text{ext}}$$

$$\frac{P}{\rho^\gamma} = \text{constant}$$

- Current sheet plasma acceleration (Lagrangian reference frame)

$$\frac{dV}{dt} = -\frac{I}{C}$$

$$\frac{dI}{dt} = \frac{V - I\left[\left(R_e + R_{\text{p,deton}}\right) + L_1 v_z\right]}{\left(L_0 + L_1 z\right)}$$

$$\frac{dz}{dt} = v_z$$

$$\frac{dv_z}{dt} = \left(\frac{L_1 I^2}{2} - {v_z}^2 \lambda_e A \rho\left(z\right)\right)/m$$

$$\frac{dm}{dt} = \lambda_e v_z A \rho\left(z\right) - \nu_L m$$

Model of Processes

- Stationary Discharge Plasma Acceleration

Circuit equations

$$\frac{dV}{dt} = -\frac{I}{C},$$
$$\frac{dI}{dt} = \frac{V - I\left(R_e + R_{\mathrm{p,deflag}}\right)}{\left(L_0 + L_1 l\right)},$$

Assumption for Transition
Detonation to Deflagration

$$R_{\mathrm{p,deflag}} = R_{\mathrm{p,deton}} + \left.\frac{dL}{dt}\right|_{\mathrm{sheet\ ejection}} = R_{\mathrm{p,deton}} + L_1 v_z\big|_{\mathrm{sheet\ ejection}}$$

Accelerating Force

$$\left(F_z\right)_{\mathrm{ext}}(t) = \frac{L_1\, i(t)^2}{2}$$

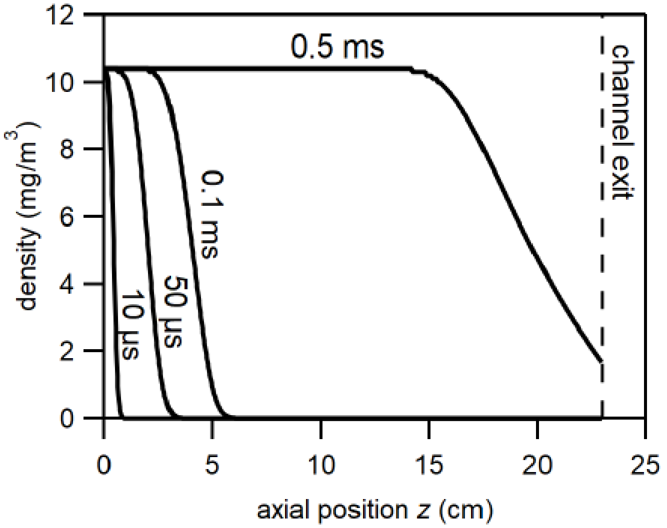
$$\left(f_z\right)_{\mathrm{ext}}(t) = \frac{L_1\, i(t)^2}{2\, A\, \Delta z}$$

Thruster Length	23 cm
Inner electrode diameter	5 mm
Outer electrode diameter	5 cm
Capacitance C	112 μF
Stray inductance L_0	50 nH
Stray resistance R_e	5 mΩ
'Detonation' plasma resistance $R_{\mathrm{p,deton}}$	2.5 mΩ
Initial charge voltage	1000 V
Inlet gas temperature	298 K

contributor to I_{bit}	amount of contribution	location/time of evaluation
plasma sheet	$m_{\mathrm{sheet}} v_z$	evaluated at detachment
exit gas flux	$\int \dot{m} u_z\, dt$	at the exit
gas in channel after pulse	$\int \rho u_z\, A\, dz$	entire domain

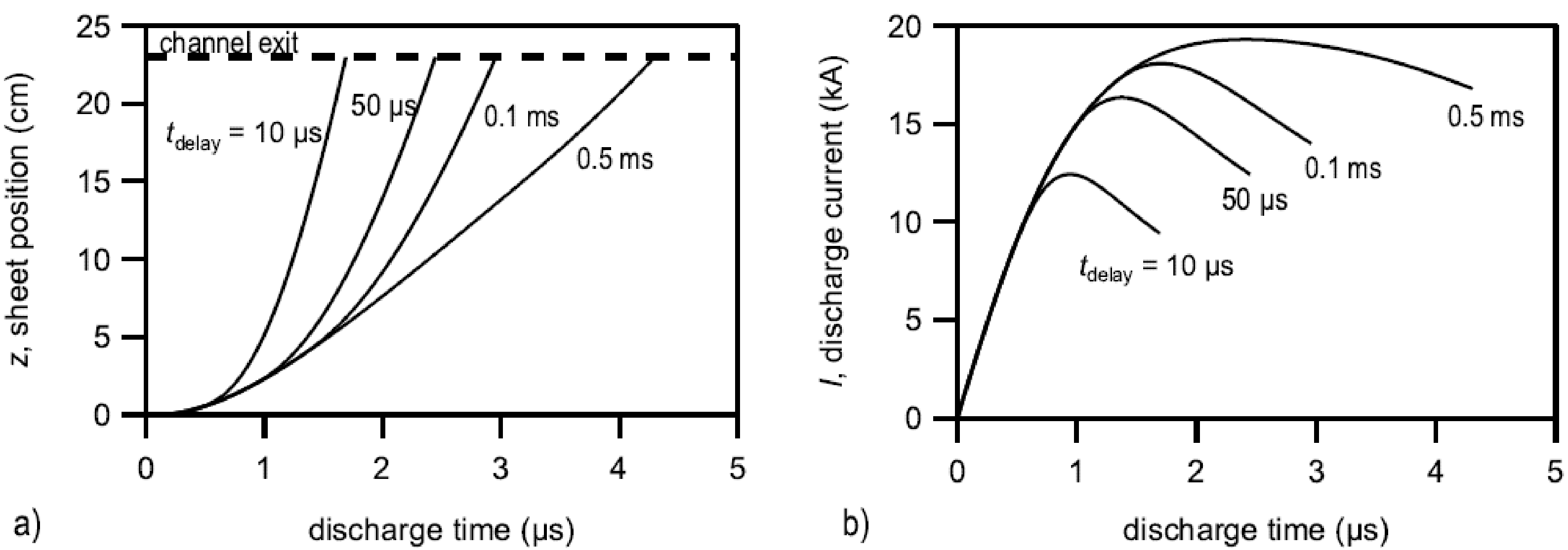
Results – Injection and Detonation Mode

Gas Injection Timing



Amount of gas encountered has a major effect on the discharge current and trajectory (current sheet drag)

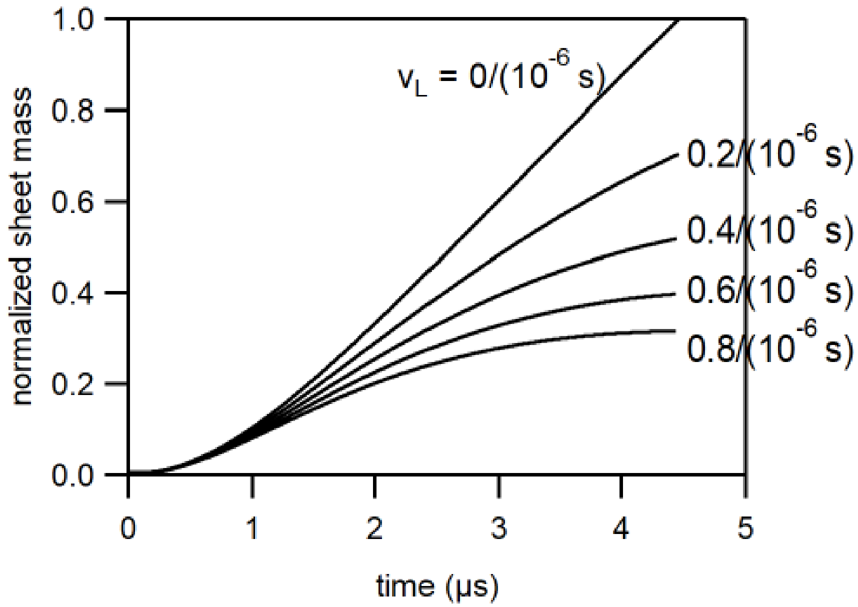
Position and discharge current as a function of t_{delay} ($\lambda_e = 1$)



Polzin & Greve, AIAA-2018-4728

Results – Detonation Mode

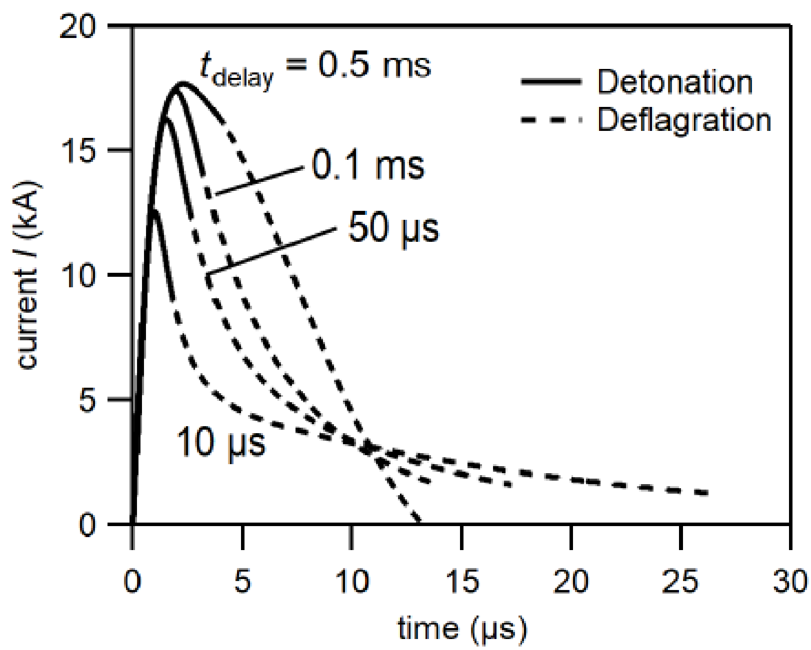
Current Sheet Mass Shedding ($\lambda_e = 0.6$)



Reduction in sheet inertia through shedding does not affect time to reach the end of the channel (still encountering mass the whole way – drag)

Results – Detonation to Deflagration

Discharge Current (λ_e = 0.6, ν_L = 0.1/(10^{-6} s))

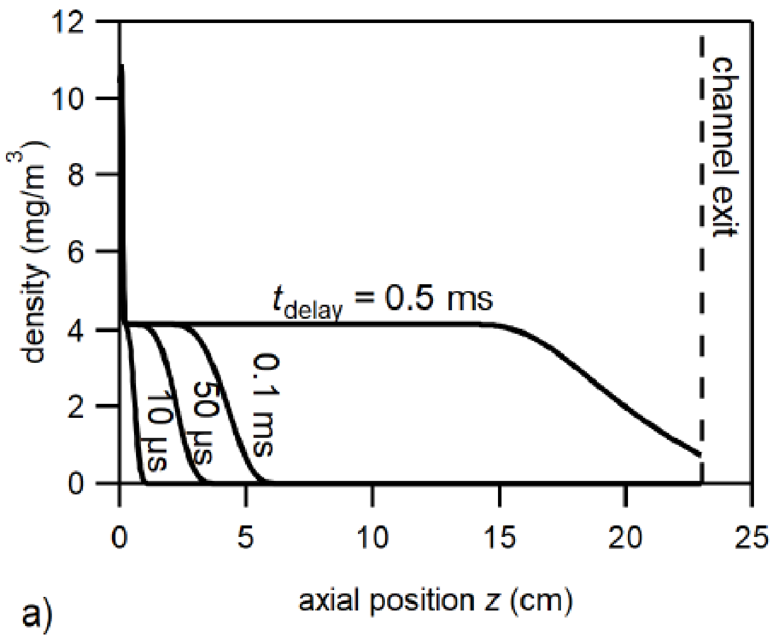


Resistance assumption successful in developing a patched solution (unclear if it is correct, though)

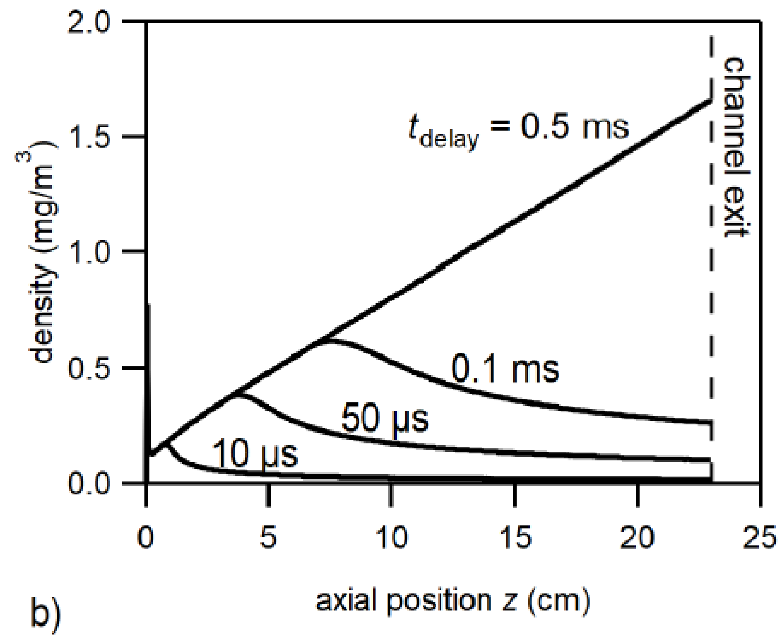
Pushes curves into the overdamped regime

Results – Detonation Mode Wake

($\lambda_e = 0.6$, $\nu_L = 0.1/(10^{-6}$ s))

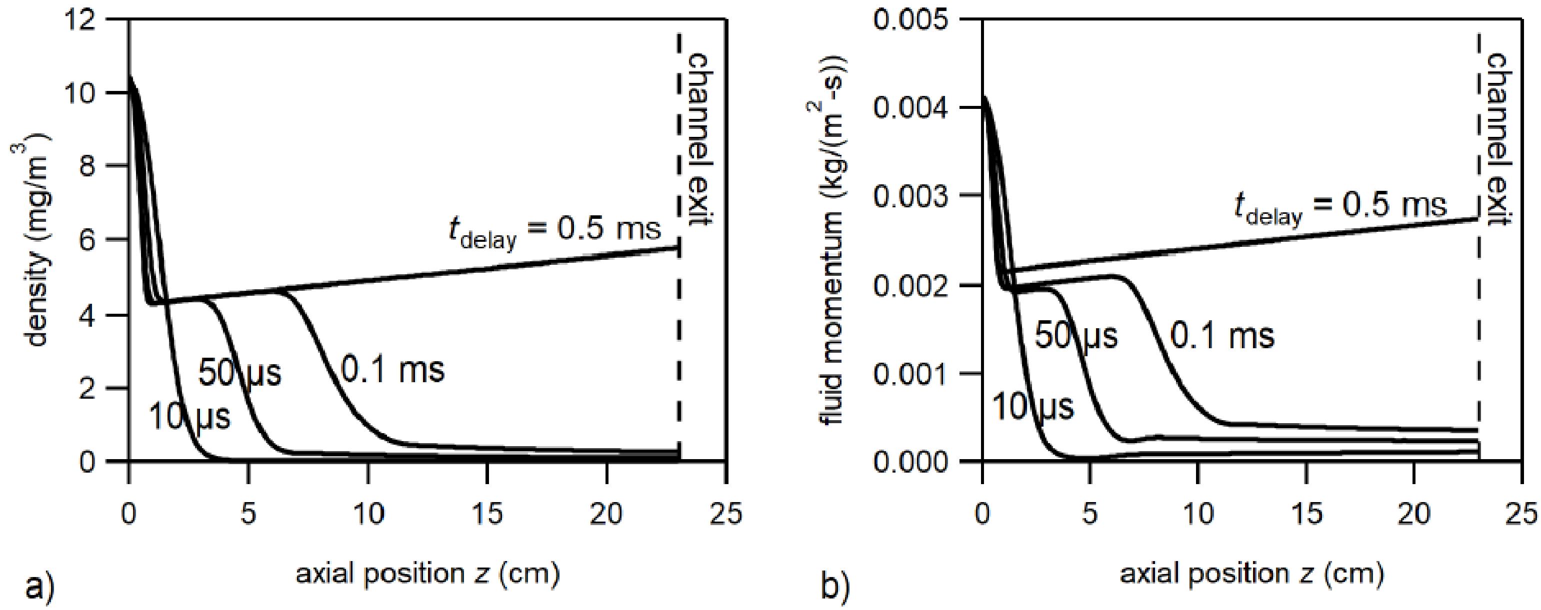


Unentrained



Shed gas

Results – Deflagration Mode



Fluid hasn't advanced far in this time-period … very little noticeable electromagnetic acceleration

Calculated results indicate very little contribution to the impulse bit

t_{delay}	Detonation I_{bit} $(\mu N - s)$	Deflagration I_{bit} $(\mu N - s)$
10 μs	36.8	1.0
50 μs	91.9	0.30
0.1 ms	132	0.21
0.5 ms	179	0.15

Conclusions

- One-D coupled circuit / momentum equation model
- Based upon history of QS-MPD, model assumes the plasma is accelerated in a series of steps starting with a detonation mode (current sheet) and, if the current has not crossed zero yet, transitioning to a deflagration mode (MPD)
- Enhancements on the detonation mode portion appear to be working properly, and the impulse bit computed is in-line with expectations
- Gas loading in the channel has a major impact on the trajectory of the current sheet, which affects the response of the pulsed circuit
- Deflagration mode modeling was not in-line with expectations (much too low)
  - Assumptions used to 'patch' the detonation and deflagration modes for one continuous solution merit significant further investigation (resistance assumption, current distribution assumption)
  - In part, running against the limits of what a one-D circuit-model-based theory can capture