

# REPORT DOCUMENTATION PAGE

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# CAPILLARY DISCHARGE THRUSTER EXPERIMENTS AND MODELING

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Electric propulsion systems  
June 2016, Rhode-Saint-Genèse, Belgium



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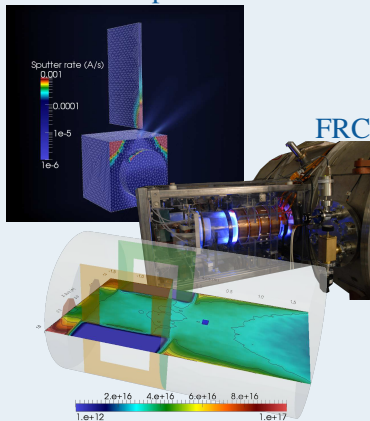
- 1 INTRODUCTION
- 2 AFRL CDT EXPERIMENTS
- 3 CDT AND RELATED MODELS
- 4 CURRENT STATUS & FUTURE WORK
- 5 CONCLUSION



## Spacecraft Propulsion Relevant Plasma:

- From hall thrusters to plumes and fluxes on components
- Complex reaction physics i.e. Discharge and Breakdown in FRC
- Relevant Densities often Span 6+ Orders of Magnitude
- Spatial scales of interest span  $\mu m$ - $100m$  range

## Electric Propulsion Plumets



## Chamber Environment

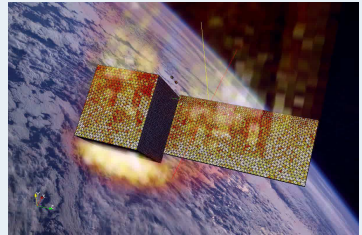


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All Relatively Low Energy Density...  
Connection to HEDP Capillary Discharge?

## All Rarefied Gas and Plasma



...and Highly Non-Equilibrium

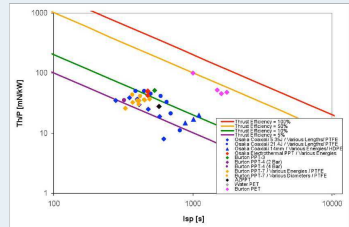


# INTEREST IN PULSED PLASMA THRUSTERS



## Need Efficiency Across Thrust Range:

- Spacecraft Power is Constrained
- Fundamental Tradeoff: Isp vs. Thrust
- Optimal Trade Mission Dependent (i.e. Station Keeping vs. Orbit Insertion)

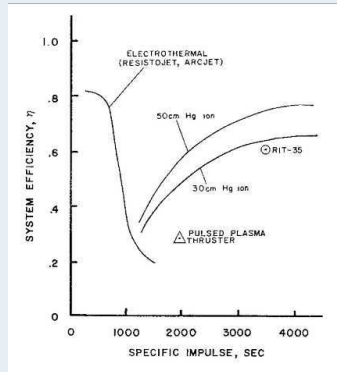


Pancotti, PhD Dissertation, USC, 2009.



## Need Efficiency Across Thrust Range:

- Spacecraft Power is Constrained
- Fundamental Tradeoff: Isp vs. Thrust
- Optimal Trade Mission Dependent (i.e. Station Keeping vs. Orbit Insertion)
- Electrothermal - Electrostatic Gap



Burton, et. al., AIAA Paper, (TDS83-10), 1983.



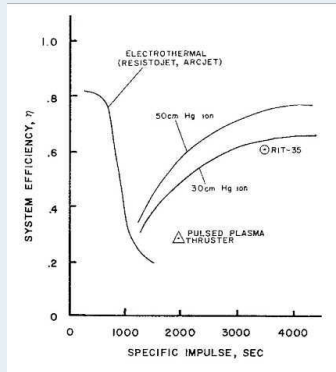


## Capillary Discharge Thruster Viability:

- Efficiency Gap for Moderate ISP EP (750s-3000s)
- Capillary Discharge Conceptually Efficient ( $\eta_t > 65\%$ ) in this Range
- Burton Predicted  $\eta_t \approx 80\%$
- Burton Observed only 56% Max (0.085 Ns @ 1600s Isp)
- Realizing full Efficiency requires Deeper HED Physics Understanding
- CDTs are Simple Small Devices Accessible to Lab Experiments

Must Converge...

Theory, Models, and Experiments

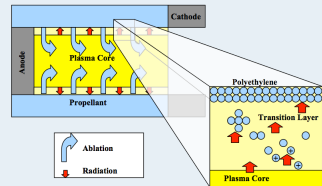


Burton, et. al., AIAA Paper, (TDS83-10), 1983.



## Key Processes for Design & Efficiency:

- Assumptions
  - Unmagnetized/LTE/Coupling
- Energy Balance
  - Conduct/Evaporate/Bond Break/Ionize
- Ablation
  - Photo-ablation/Macro-particles/Pyrolysis
- Radiative Transport
  - Optical Depth/Spectrum
- Ionization/Recombination
  - Breakdown/Recombination Rate



Pancotti, PhD Dissertation, USC, 2009.



## Key Processes for Design & Efficiency:

- Magnetization
  - Essentially Electrothermal
  - Weaker Assumption if  $n=\mathcal{O}(1e24/m^3)$

### Plasma- $\beta$ :

$$\beta = \frac{P_T}{P_B}$$

$$P_T = nkT \quad \& \quad P_B = \frac{B^2}{2\mu_0}$$

$$B = \frac{\mu_0 I}{2\pi r}$$

$$\beta = \frac{8nkT}{\mu_0} \left(\frac{\pi r}{I}\right)^2$$

Using:

$$T=2eV, n=1e25/m^3, r=2mm, I=6kA$$

$$\beta=22 \gg 1$$



## Key Processes for Design & Efficiency:

- Magnetization
- Local Thermodynamic Equilibrium
  - LTE: Acceleration/Collision Balance
  - Highly Collisional After Breakdown

## LTE Parameter:

$$K = \frac{\Delta\epsilon_{e\leftrightarrow i}}{\Delta\epsilon_E}$$

$$\Delta\epsilon_{e\leftarrow i} = T \left( \frac{2m_e}{m_i} \right)$$

$$\Delta\epsilon_E = \frac{e^2 E}{m_e \nu_{ei}}$$

$$K = \frac{1}{128} \frac{e^6}{\pi^2 \epsilon_0^4 k^3} \frac{m_e}{m_i} \left( \frac{n}{ET} \right)^2$$

Using:

$$T=2eV, n=1e25/m^3, E=1e5V/m$$

$$K \approx 2.5e8$$



## Key Processes for Design & Efficiency:

- Magnetization
- Local Thermodynamic Equilibrium
- Plasma Coupling
  - Potential/Kinetic Energy Balance
  - Degree Ideal Plasma EOS Applies

## Non-Ideal Parameter:

$$\Gamma = \frac{U_{PE}}{U_{KE}}$$

$$U_{PE} = \frac{e^2}{4\pi\epsilon_0\bar{r}} = \frac{e^2n^{1/3}}{4\pi\epsilon_0}$$

$$U_{KE} = kT$$

$$\Gamma = \frac{e^2n^{1/3}}{4\pi\epsilon_0kT}$$

Using:

$$T=2\text{eV}, n=1\text{e}25/\text{m}^3$$

$$\Gamma \approx 0.16$$

Non-Ideal?  $\Gamma < 1$ , but not  
 $\Gamma \ll 1$ ?

Ideal Assumption Used, but  
Should be Revisited.



# CD PROCESS: ENERGY

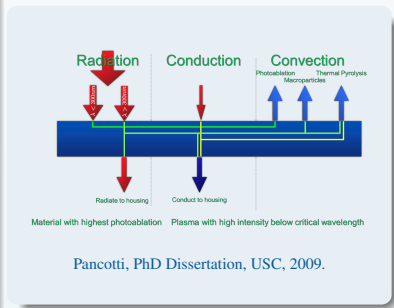
## Key Processes for Design & Efficiency:

### • Energy Balance

-Evaporate $C_2H_4$ from wall:	0.5eV
-Break C-C Bond:	4.5ev
-Break 4 C-H Bond:	14.0eV
<hr/>	
Total 6 Atoms:	19.0ev
-Dissociation Energy/Atom:	3.2eV
-Mean Ionization Energy/Atom:	12.8ev
<hr/>	
Total Energy/Ion:	16.0ev

Would be Energy Sink Inhibiting Efficiency... but  
Recombination before Exit Captures Ion Energy!

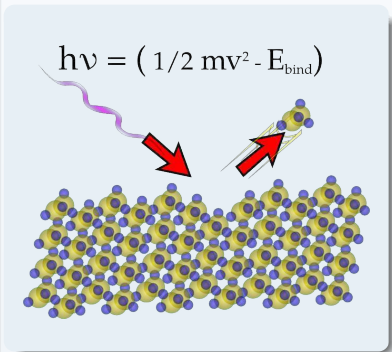
Losses via Radiation/Conduction to Housing...  
Limited on Discharge Timescales





## Key Processes for Design & Efficiency:

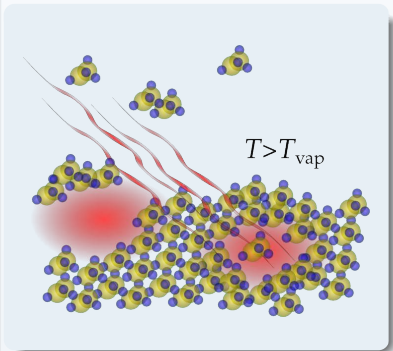
- **Photo-Ablation**
  - Direct Ablation by Photon Energy
  - Polymers Highly Susceptible to Photo-Ablation
  - Still Requires  $\lesssim 300\text{nm}$  Photons





## Key Processes for Design & Efficiency:

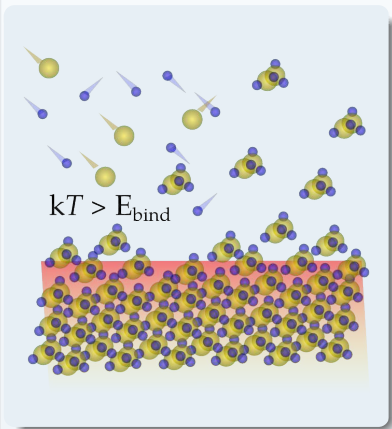
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- **Macro-Particles**
  - Subsurface Energy Deposition
  - Vaporization Ejects Macro-particles
  - Particles Evaporate Quickly (S/V ratio)





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- **Pyrolysis**
  - Thermal Evaporation
  - Surface Temperature must Exceed  $T_{vap}$
  - Conductive Losses with  $T_{vap}$

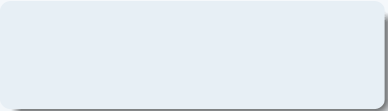




## Key Processes for Design & Efficiency:

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Direct Ablation Preferable... Spectrum?





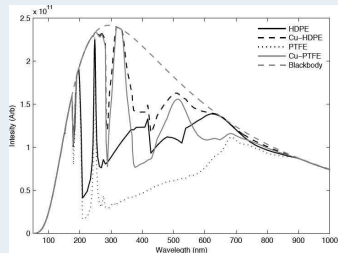
## Key Processes for Design & Efficiency:

### • Spectrum

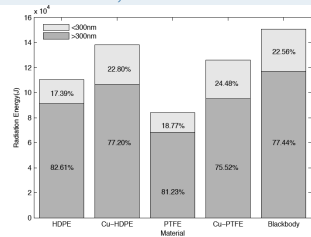
- Several Materials Investigated
- Spectra Generated using PrismSpect<sup>®</sup>

### • Optical Depth

- $\lambda_{mfp}^{rad} \approx \mathcal{O}(1)R - \mathcal{O}(0.1)R$
- High Radiation Conductivity  $\rightarrow$  Uniform  $T$



$$T=1.5\text{ev}, n=1.5e25 \text{ m}^{-3}$$

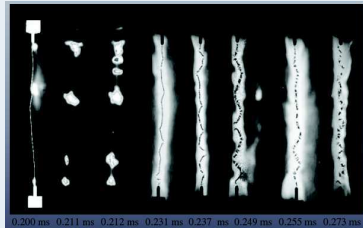


Pancotti, PhD Dissertation, USC, 2009.



## Key Processes for Design & Efficiency:

- Ionization Process
  - Wire Breakdown is Chaotic



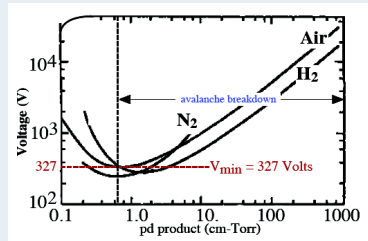
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## Key Processes for Design & Efficiency:

- Ionization Process

- Wire Breakdown is Chaotic
- Paschen Breakdown more Predictable
- Breakdown Voltage Density Dependent



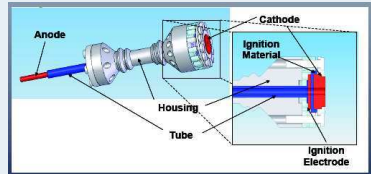
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## Key Processes for Design & Efficiency:

### ● Ionization Process

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- Paschen Breakdown more Predictable
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- Spark



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## Key Processes for Design & Efficiency:

### ● Ionization Process

- Wire Breakdown is Chaotic
- Paschen Breakdown more Predictable
- Breakdown Voltage Density Dependent
- Spark

### ● Recombination

-Recombination Rate:

$$\nu_e = \alpha_3 n^2 = 8.75 \times 10^{-27} T^{-9/2} n^2 \text{ Hz}$$

(T in eV, n in  $\text{cm}^{-3}$ )

-Thermal Velocity / Mean Free Path:

$$u = \sqrt{\frac{8kT}{\pi m}} \quad \lambda = \frac{u}{\nu_e}$$

Device	Burton PET
Density, $n^*$	$5.4e27/\text{m}^3$
Temp, $T^*$	4ev
Rate, $\nu_e$	$5.0e14 \text{ Hz}$
Velocity, $u^*$	$1.2e4 \text{ m/s}$
MFP, $\lambda^*$	$2.4e-11 \text{ m}$

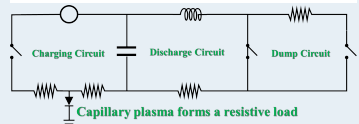
Device	Pancotti CDT <sup>(Est.)</sup>
Density, $n^*$	$1.0e25/\text{m}^3$
Temp, $T^*$	2ev
Rate, $\nu_e$	$3.9e10 \text{ Hz}$
Velocity, $u^*$	$9.6e3 \text{ m/s}$
MFP, $\lambda^*$	$2.5e-7 \text{ m}$

$$2.5e-7 \text{ m} \ll 2\text{mm}$$



## Thruster Design & Ignition:

- Baseline

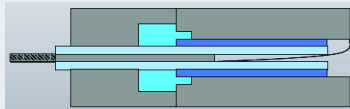


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## Thruster Design & Ignition:

- Baseline
- Wire Ignition
  - Simple and Reliable
  - Chaotic Process
  - Random Ignition Delays
  - Bi-Modal Performance
  - Only Single Use

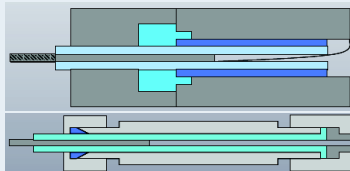


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## Thruster Design & Ignition:

- **Baseline**
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  - Only Single Use
- **Paschen Ignition**
  - More Repeatable
  - Enabled Use of Thrust Stand
  - Requires some Background Density

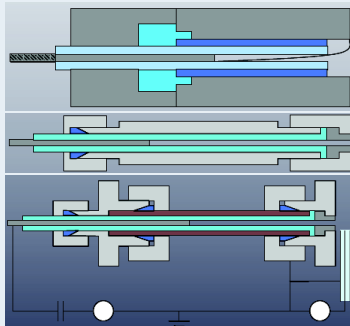


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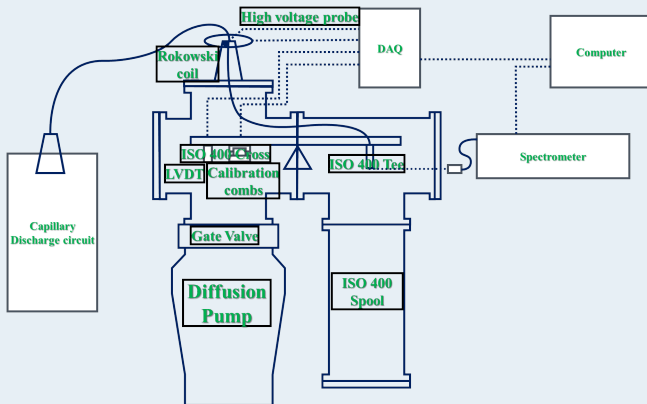


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- **Baseline**
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  - Bi-Modal Performance
  - Only Single Use
- **Paschen Ignition**
  - More Repeatable
  - Enabled Use of Thrust Stand
  - Requires some Background Density
- **3-Electrode Ignition**
  - More Applicable to Space Vacuum
  - Dielectric Flashover
  - Less Electrode Erosion



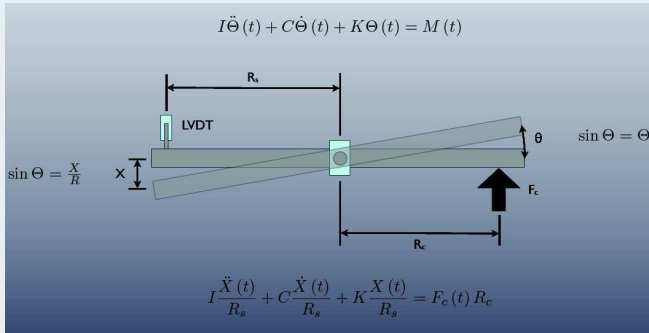
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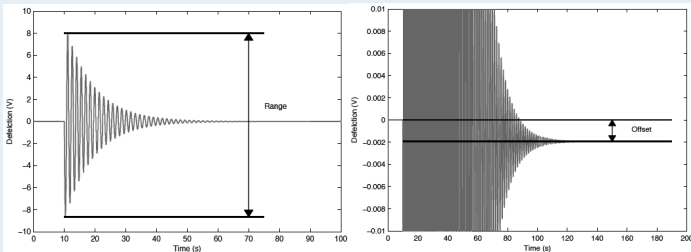
# TORSIONAL THRUST STAND



Pancotti, PhD Dissertation, USC, 2009.



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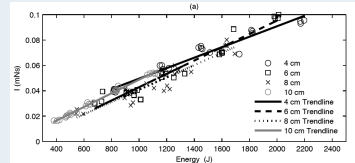


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## Key Processes for Design & Efficiency:

- Linear Impulse with Energy

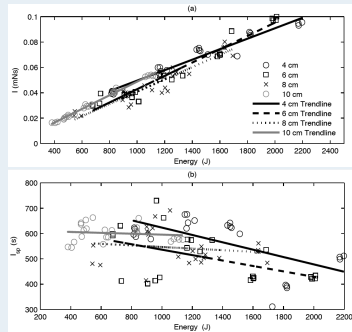


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## Key Processes for Design & Efficiency:

- Linear Impulse with Energy
- Large Scatter in Isp

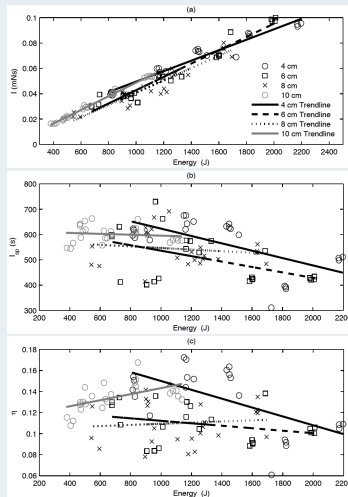


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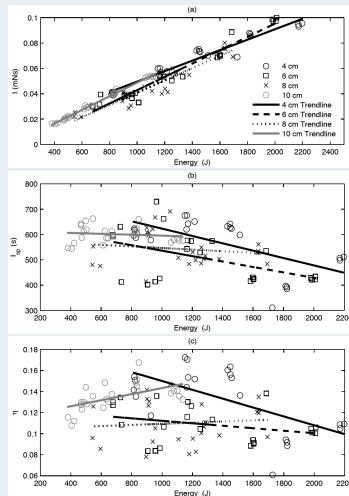
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## Key Processes for Design & Efficiency:

- Linear Impulse with Energy
- Large Scatter in Isp
- Large Scatter in Efficiency
- Performance:
  - Impulse: 20-100 mNs
  - Specific Impulse: 350-700s
  - Efficiency: 8-17% (Nozzleless Design)

Scatter due to Electrode Erosion?

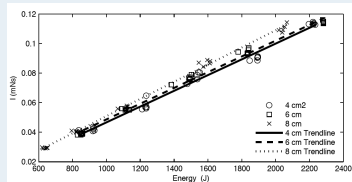


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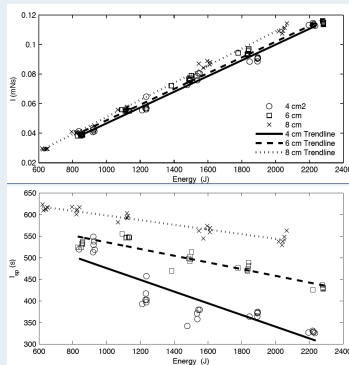
- Same Linear Impulse with Energy
- Better Correlated





## Key Processes for Design & Efficiency:

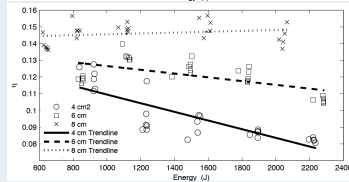
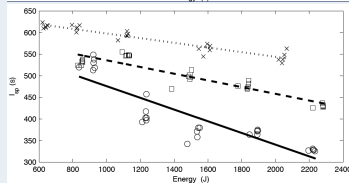
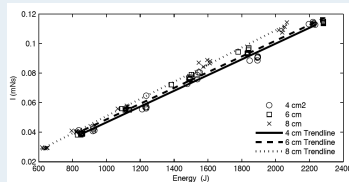
- Same Linear Impulse with Energy
- Better Correlated
- Clearer Isp Trends
- Higher Isp when Longer





## Key Processes for Design & Efficiency:

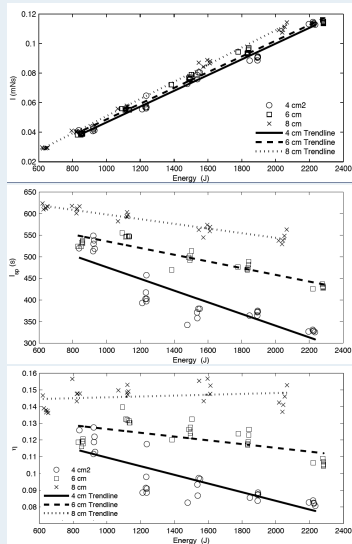
- Same Linear Impulse with Energy
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- Clearer Isp Trends
- Higher Isp when Longer
- Longer also Higher Efficiency





## Key Processes for Design & Efficiency:

- Same Linear Impulse with Energy
- Better Correlated
- Clearer Isp Trends
- Higher Isp when Longer
- Longer also Higher Efficiency
- 8cm Efficiency Constant with Energy
- Performance:
  - Impulse: 30-120 mNs
  - Specific Impulse: 350-650s
  - Efficiency: 9-17% (Nozzleless Design)





## Spitzer Resistivity:

- Ratio of Rate Electron Momentum Exchange to Current Density:

$$\eta = 1/\sigma = \frac{P_{ei}}{j}$$

- For a Lorentz Gas:

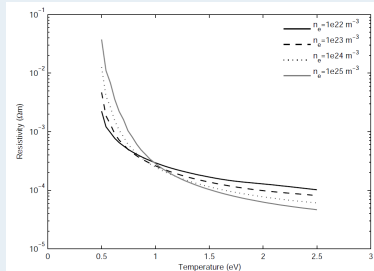
(Stationary Ions/Noninteracting Electrons)

$$\eta_L = \frac{\pi^{3/2} Z m_e^2 c^2 \nu \ln \Lambda}{2(2kT)^{3/2}}$$

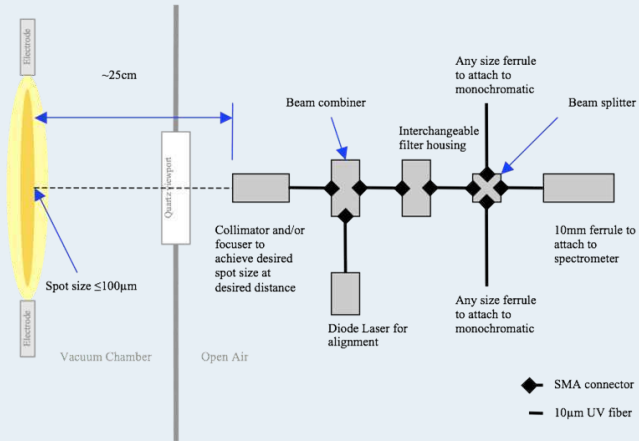
- With e-e Collisions (Spitzer-Härm)

$$\eta = \frac{\eta_L}{\gamma_E}$$

Ionic Charge $Z$	1	2	4	16	$\infty$
$\gamma_E$	0.582	0.683	0.785	0.923	1.000



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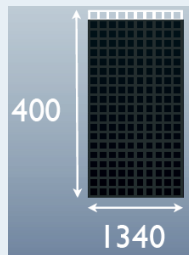


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## Time Resolved OES:

- Uses Spectral Line Shape not Intensity
  - Simpler Calibration
- Pulsed Device Requires Time Resolved
- Kinetics Mode via Pixel Time Shifts
  - 5pixel/Spectra
  - 16 $\mu$ s/Spectra
  - 0.1nm/Pixel

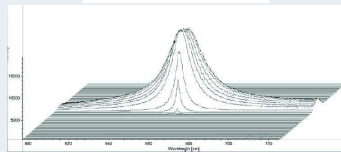
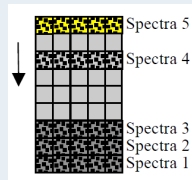


Pancotti, PhD Dissertation, USC, 2009.



## Time Resolved OES:

- Uses Spectral Line Shape not Intensity
  - Simpler Calibration
- Pulsed Device Requires Time Resolved
- Kinetics Mode via Pixel Time Shifts
  - 5pixel/Spectra
  - 16 $\mu$ s/Spectra
  - 0.1nm/Pixel



Pancotti, PhD Dissertation, USC, 2009.



## Hydrogen- $\alpha$ Line Broadening:

- Neutral Broadening (Small)
- Doppler Broadening ( $H_\alpha, H_\beta: < 1\text{\AA}$ )
- Resonance Broadening (N-N Collisions)
- Van der Waals Broadening (Also N-N Collisions)
- **Stark Broadening**  
 **$\mathcal{O}(10\text{nm})$**

$$\Delta_{1/2}^N \approx 1 \times 10^{-4} [\text{\AA}]$$

$$\Delta_{1/2}^D = 7.16 \times 10^{-7} \lambda_0 \sqrt{\frac{T}{M}} [\text{\AA}]$$

$$\Delta_{1/2}^R = 8.6 \times 10^{-30} \sqrt{\frac{g_i}{g_k}} \lambda_0^2 \lambda_r f_r N_i [\text{\AA}]$$

$$\Delta_{1/2}^W \approx 3 \times 10^{-30} \lambda_0^2 C_6^{2/5} \left(\frac{T}{\mu}\right)^{3/10} N [\text{\AA}]$$

$$\Delta_{1/2}^{S,H} \approx 2.5 \times 10^{-9} \alpha_{1/2} N_e^{2/3} [\text{\AA}]$$



## Hydrogen- $\alpha$ Line Broadening:

- Neutral Broadening
- Doppler Broadening
- Resonance Broadening
- Van der Waals Broadening
- Stark Broadening

Table 3.3: Fractional Intensity Widths[48]

T (K)	T (eV)	N (#/m <sup>3</sup> )	$\alpha_{1/2}$
5000	0.431	1 × 10 <sup>21</sup>	9.69 × 10 <sup>-3</sup>
5000	0.431	1 × 10 <sup>22</sup>	14.9 × 10 <sup>-3</sup>
5000	0.431	1 × 10 <sup>23</sup>	18.9 × 10 <sup>-3</sup>
5000	0.431	1 × 10 <sup>24</sup>	N/A
5000	0.431	1 × 10 <sup>25</sup>	N/A
10000	0.862	1 × 10 <sup>21</sup>	7.77 × 10 <sup>-3</sup>
10000	0.862	1 × 10 <sup>22</sup>	13.4 × 10 <sup>-3</sup>
10000	0.862	1 × 10 <sup>23</sup>	18.6 × 10 <sup>-3</sup>
10000	0.862	1 × 10 <sup>24</sup>	21.8 × 10 <sup>-3</sup>
10000	0.862	1 × 10 <sup>25</sup>	N/A
20000	1.723	1 × 10 <sup>21</sup>	6.01 × 10 <sup>-3</sup>
20000	1.723	1 × 10 <sup>22</sup>	11.4 × 10 <sup>-3</sup>
20000	1.723	1 × 10 <sup>23</sup>	17.5 × 10 <sup>-3</sup>
20000	1.723	1 × 10 <sup>24</sup>	22.0 × 10 <sup>-3</sup>
20000	1.723	1 × 10 <sup>25</sup>	23.5 × 10 <sup>-3</sup>
30000	2.585	1 × 10 <sup>21</sup>	4.98 × 10 <sup>-3</sup>
30000	2.585	1 × 10 <sup>22</sup>	10.0 × 10 <sup>-3</sup>
30000	2.585	1 × 10 <sup>23</sup>	16.6 × 10 <sup>-3</sup>
30000	2.585	1 × 10 <sup>24</sup>	22.9 × 10 <sup>-3</sup>
30000	2.585	1 × 10 <sup>25</sup>	25.7 × 10 <sup>-3</sup>
40000	3.447	1 × 10 <sup>21</sup>	4.50 × 10 <sup>-3</sup>
40000	3.447	1 × 10 <sup>22</sup>	9.22 × 10 <sup>-3</sup>
40000	3.447	1 × 10 <sup>23</sup>	15.8 × 10 <sup>-3</sup>
40000	3.447	1 × 10 <sup>24</sup>	22.3 × 10 <sup>-3</sup>
40000	3.447	1 × 10 <sup>25</sup>	26.9 × 10 <sup>-3</sup>

Huddlestone & Leonard, *Plasma Diagnostic Techniques*, Academic Press, '65.

$$\Delta_{1/2}^{S,H} \approx 2.5 \times 10^{-9} \alpha_{1/2} N_e^{2/3} [\text{\AA}]$$



## Hydrogen- $\alpha$ Line Broadening:

- Neutral Broadening
- Doppler Broadening
- Resonance Broadening
- Van der Waals Broadening
- Stark Broadening

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5000	0.431	$1 \times 10^{23}$	$18.9 \times 10^{-3}$
5000	0.431	$1 \times 10^{24}$	N/A
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10000	0.862	$1 \times 10^{21}$	$7.77 \times 10^{-3}$
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10000	0.862	$1 \times 10^{25}$	N/A
20000	1.723	$1 \times 10^{21}$	$6.01 \times 10^{-3}$
20000	1.723	$1 \times 10^{22}$	$11.4 \times 10^{-3}$
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30000	2.585	$1 \times 10^{24}$	$22.5 \times 10^{-3}$
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40000	3.447	$1 \times 10^{21}$	$4.50 \times 10^{-3}$
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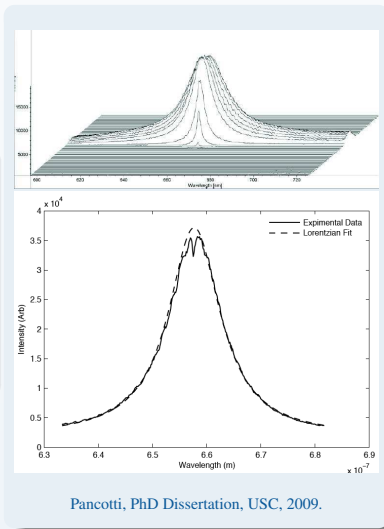
$$\Delta_{1/2}^{S,H} \approx 2.5 \times 10^{-9} \alpha_{1/2} N_e^{2/3} [\text{\AA}]$$



## Time Resolved Electron Density:

- Spectrum fit to Lorentzian Profile:

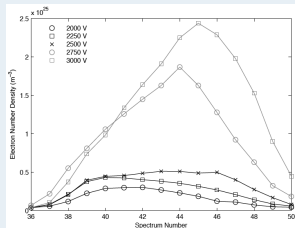
$$f(\lambda - \lambda_0) = \frac{1}{\pi\gamma} \left[ \frac{\gamma^2}{\lambda^2 + \gamma^2} \right] \text{ where } 2\gamma = \text{FWHM}$$



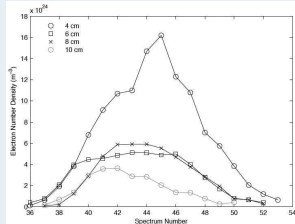


## Time Resolved Electron Density:

- Spectrum fit to Lorentzian Profile:  
$$f(\lambda - \lambda_0) = \frac{1}{\pi\gamma} \left[ \frac{\gamma^2}{\lambda^2 + \gamma^2} \right]$$
 where  $2\gamma = \text{FWHM}$
- Fit inverted for  $n_e$  vs. Time
  - Density  $\rightarrow 1e25/m^3$  Estimate
  - Optical Depth  $\rightarrow \approx$  Exit Plane  $n_e$ ?



$n_e$  vs. Time, 6cm Capillary



$n_e$  vs. Time, 2500V Discharge

Pancotti, PhD Dissertation, USC, 2009.



## 0D Slab Model:

- Conservation of Mass:

$$V \cdot \frac{dn}{dt} = 2A_w \cdot \Gamma - A_e n^e C_s^e$$

- Conservation of Energy:

$$V \cdot \frac{d(n\epsilon)}{dt} = V \cdot \frac{I^2/A_e^2}{\sigma(n,T)} - A_e n^e C_s^e h - 2A_w \Theta$$

Where:

$n$  is the Plasma/Gas Density

$V$  is the Slab Volume

$A_w$  is the Wall Area

$A_e$  is the Exit Area

$\Gamma$  is the Ablation Flux

$C_s$  is Sound Speed (at the Exit)

Superscript- $()^e$  is Isentropically Expanded Exit Value

$\epsilon$  is the Energy Density

$I$  is Current

$\sigma(n, T)$  is the Conductivity

$h$  is the Enthalpy

$C_s$  is the Sound Speed

$\Theta$  is the Wall Energy Flux

Pekker, 40th AIAA Plasmadynamics and Laser Conference, 2009.



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Slab Capillary, La = 8 cm, Da = 4 mm

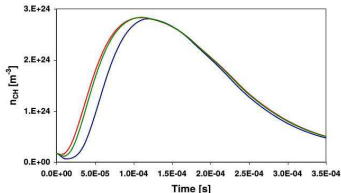


Fig. 6. Polyethylene number density in the plasma core region:  
blue -  $\eta = 0.5\text{mm}$ , green -  $\eta = 0.1\text{mm}$ , red -  $\eta = 0.02\text{mm}$

Slab Capillary, La = 8 cm, Da = 4 mm

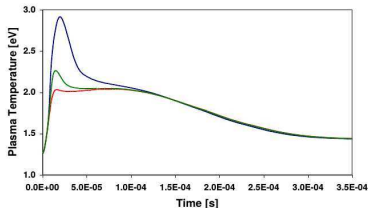


Fig. 8. Plasma temperature: blue -  $\eta = 0.5\text{mm}$ , green -  $\eta = 0.1\text{mm}$ , red -  $\eta = 0.02\text{mm}$

Pekker, 40th AIAA Plasmadynamics and Laser Conference, 2009.



## 1D PDE Model:

- Conservation of Mass:

$$\frac{\partial(A\rho)}{\partial t} + \frac{\partial}{\partial x} [(A\rho u)] = A_w \cdot \Gamma$$

- Conservation of Momentum:

$$\frac{\partial(A\rho u)}{\partial t} + \frac{\partial}{\partial x} [(A(\rho u + p))] = p \frac{\partial A}{\partial x} - A_w f$$

- Conservation of Energy:

$$\frac{\partial(Ae)}{\partial t} + \frac{\partial}{\partial x} [(Au(e + p))] = A (Q_j - Q_{rad} - Q_{conv} - Q_{ab} - \Phi)$$

Where:

$A$  is the Cross Section Area

$\rho$  is the Mass Density

$u$  is the Velocity

$A_w$  is the Wall Surface Area

$\Gamma$  is the Ablation Mass Flux

$p$  is the Pressure

$f$  is the Viscous Wall Friction

$e$  is the Total Energy

$Q_j$  is the Joule Heating

$Q_{rad}$  is the Radiant Energy Losses

$Q_{conv}$  is the Convection Energy Losses

$Q_{ab}$  is the Ablation Energy

$\Phi$  is Viscous Wall Energy Loss

Pancotti, PhD Dissertation, USC, 2009.



## 1D PDE Model:

- Conservation of Mass:

$$\frac{\partial(A\rho)}{\partial t} + \frac{\partial}{\partial x} [(A\rho u)] = A_w \cdot \Gamma$$

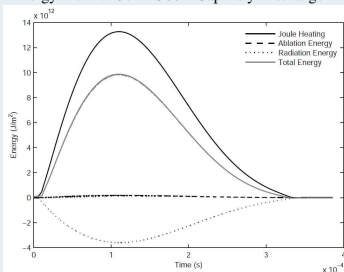
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$$\frac{\partial(A\rho u)}{\partial t} + \frac{\partial}{\partial x} [(A(\rho u + p))] = p \frac{\partial A}{\partial x} - A_w f$$

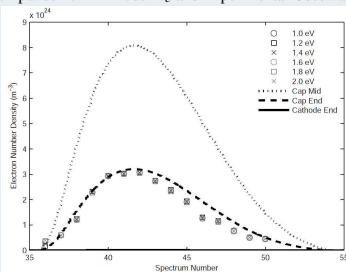
- Conservation of Energy:

$$\frac{\partial(Ae)}{\partial t} + \frac{\partial}{\partial x} [(Au(e + p))] = A (Q_j - Q_{rad} - Q_{conv} - Q_{ab} - \Phi)$$

Energy Flux for 5cm 2500V Capillary Discharge



Comparison of 1D Model- $n_e$  and Experimental Observation

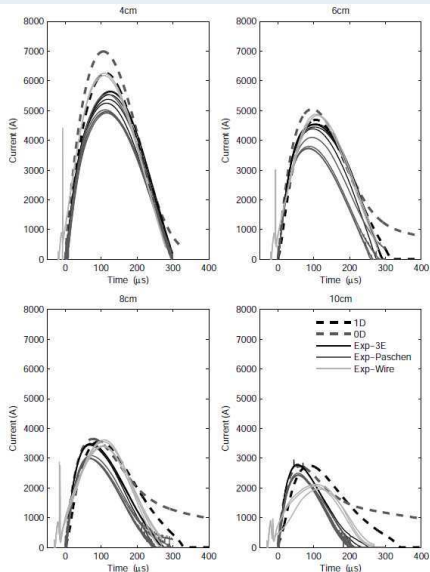


Pancotti, PhD Dissertation, USC, 2009.



## Discharge Current Predictions:

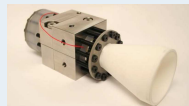
- Comparison of 2500V Discharge
- Similar Profiles/Trends
- Wire Highest Current
- Paschen Lowest Current
- Models Over-Predict Tail (Especially 0D)
- Initial  $dI/dt$  Incorrect





## For Proof-of-Concept Demonstration:

- Repeatable Ignition
  - 3-Electrode System developed by Pancotti
- Desired Isp &  $\eta$ 
  - Nozzle added for Efficient Energy Conversion**
  - Additional Propellant Materials were Studied
  - High Efficiencies Demonstrated, Isp $\approx$ 1000s

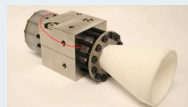


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## For Proof-of-Concept Demonstration:

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  - High Efficiencies Demonstrated, Isp $\approx$ 1000s



Tested Capillary Discharge Materials

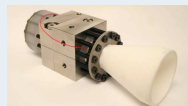
<ul style="list-style-type: none"><li>• HDPE</li><li>• Nylon 6/6</li><li>• Molybdenum Disulfide Nylon</li><li>• Teflon</li><li>• Graphite Teflon</li><li>• Fluorosint LF207</li><li>• Fluorosint HPV</li></ul>	<ul style="list-style-type: none"><li>• PEEK</li><li>• Pyropet HD</li><li>• Vespel</li><li>• K-Fel</li><li>• Rulon 123</li><li>• Rulon 142</li><li>• Teflon</li><li>• Radel</li></ul>	<ul style="list-style-type: none"><li>• FEP</li><li>• PPS</li><li>• Delrin</li><li>• PTFE Delrin</li><li>• POM</li><li>• Acetal Copolymer</li><li>• Tuncite</li><li>• PVDF</li></ul>
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## For Proof-of-Concept Demonstration:

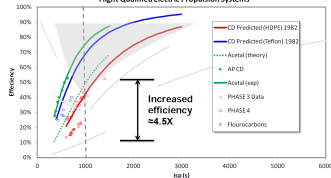
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Tested Capillary Discharge Materials

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Flight Qualified Electric Propulsion Systems

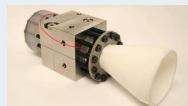


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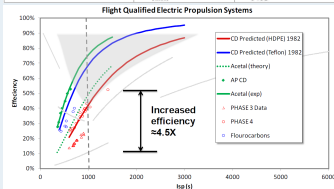


## For Proof-of-Concept Demonstration:

- Repeatable Ignition
  - 3-Electrode System developed by Pancotti
- Desired Isp &  $\eta$ 
  - Nozzle added for Efficient Energy Conversion
  - Additional Propellant Materials were Studied
  - High Efficiencies Demonstrated, Isp  $\approx$  1000s
- Robust Propellant feed Mechanism
  - Remains Unresolved
  - Burton studied Liquid/Gas Schemes
  - Additional research Required



Tested Capillary Discharge Materials		
<ul style="list-style-type: none"><li>• HDPE</li><li>• Nylon 6/6</li><li>• Molybdenum Disulfide Nylon</li><li>• Teflon</li><li>• Graphite Teflon</li><li>• Fluoroalloy LF207</li><li>• Fluoroalloy HPV</li></ul>	<ul style="list-style-type: none"><li>• PEEK</li><li>• Pyrogel HD</li><li>• Vespel</li><li>• K-Fel</li><li>• Rulon 123</li><li>• Rulon 142</li><li>• Teflon</li><li>• Radel</li></ul>	<ul style="list-style-type: none"><li>• FEP</li><li>• PPS</li><li>• Delrin</li><li>• PTFE Delrin</li><li>• POM</li><li>• Acetal Copolymer</li><li>• Tuncite</li><li>• PVDF</li></ul>



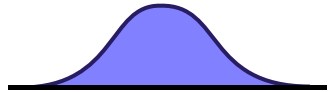
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## Breakdown non-LTE:

- Many Particles  $\rightarrow \approx$ Continuous Distribution

VDF





## Breakdown non-LTE:

- Many Particles  $\rightarrow \approx$ Continuous Distribution
- Discretized VDF yields Vlasov Models  
But 3D3V Severe Dimensionality Curse

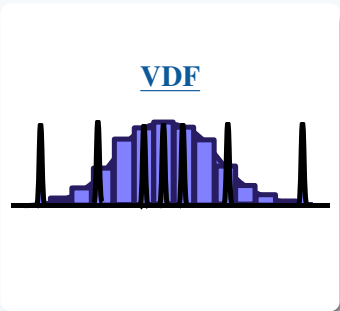
VDF





## Breakdown non-LTE:

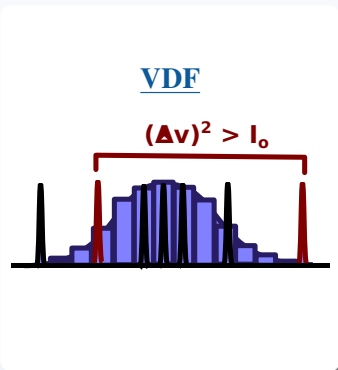
- Many Particles  $\rightarrow \approx$ Continuous Distribution
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But 3D3V Severe Dimensionality Curse
- Particle Methods (i.e. PIC) Simplify to Delta Functions
- Sparse Representation in 3D3V Phase Space  
But Added Noise and Low Dynamic Range





## Breakdown non-LTE:

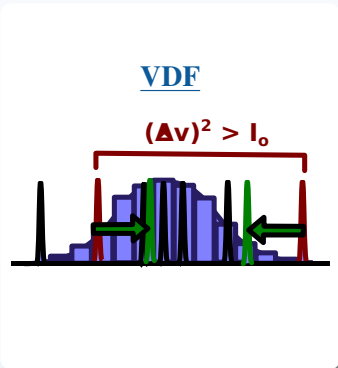
- Many Particles  $\rightarrow \approx$ Continuous Distribution
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- Collisions between Discrete Velocities
- Inelastic Collisions in Tail Impact High Moments





## Breakdown non-LTE:

- Many Particles  $\rightarrow \approx$ Continuous Distribution
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- Inelastic Collisions in Tail Impact High Moments
- All-or-Nothing Collision  $\rightarrow$  Rare Large Events





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But Added Noise and Low Dynamic Range
- Collisions between Discrete Velocities
- Inelastic Collisions in Tail Impact High Moments
- All-or-Nothing Collision  $\rightarrow$  Rare Large Events
- Variable Weights  $\rightarrow$  more DOF representing Tails

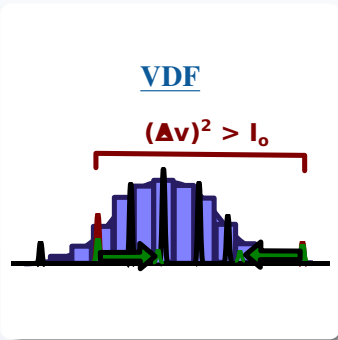
## VDF





## Breakdown non-LTE:

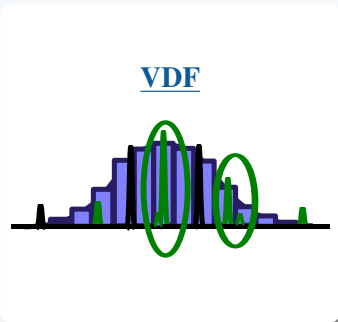
- Many Particles  $\rightarrow \approx$ Continuous Distribution
- Discretized VDF yields Vlasov Models  
But 3D3V Severe Dimensionality Curse
- Particle Methods (i.e. PIC) Simplify to Delta Functions
- Sparse Representation in 3D3V Phase Space  
But Added Noise and Low Dynamic Range
- Collisions between Discrete Velocities
- Inelastic Collisions in Tail Impact High Moments
- All-or-Nothing Collision  $\rightarrow$  Rare Large Events
- Variable Weights  $\rightarrow$  more DOF representing Tails
- Fractional Collisions  $\rightarrow$  New Numerical Particles





## Breakdown non-LTE:

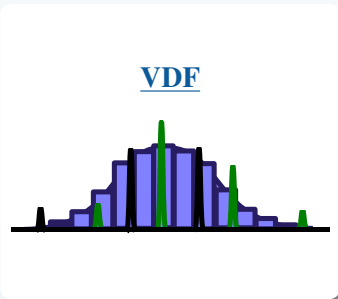
- Many Particles  $\rightarrow \approx$ Continuous Distribution
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- Particle Methods (i.e. PIC) Simplify to Delta Functions
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- Collisions between Discrete Velocities
- Inelastic Collisions in Tail Impact High Moments
- All-or-Nothing Collision  $\rightarrow$  Rare Large Events
- Variable Weights  $\rightarrow$  more DOF representing Tails
- Fractional Collisions  $\rightarrow$  New Numerical Particles
- Conservative Merge Needed to Control Growth





## Breakdown non-LTE:

- Many Particles  $\rightarrow \approx$ Continuous Distribution
- Discretized VDF yields Vlasov Models  
But 3D3V Severe Dimensionality Curse
- Particle Methods (i.e. PIC) Simplify to Delta Functions
- Sparse Representation in 3D3V Phase Space  
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- Collisions between Discrete Velocities
- Inelastic Collisions in Tail Impact High Moments
- All-or-Nothing Collision  $\rightarrow$  Rare Large Events
- Variable Weights  $\rightarrow$  more DOF representing Tails
- Fractional Collisions  $\rightarrow$  New Numerical Particles
- Conservative Merge Needed to Control Growth





## Phase-Space Decomposition

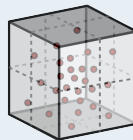
- Given a Set of Particles...





## Phase-Space Decomposition

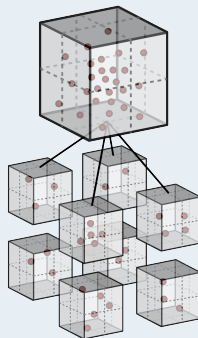
- Given a Set of Particles...
- Particles Binned in Octants





## Phase-Space Decomposition

- Given a Set of Particles...
- Particles Binned in Octants
- Octants Recursively Sub-Divided



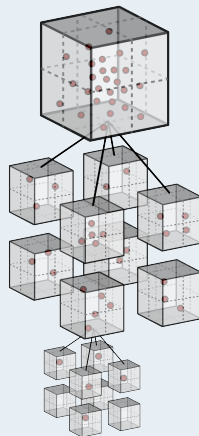


## Phase-Space Decomposition

- Given a Set of Particles...
- Particles Binned in Octants
- Octants Recursively Sub-Divided
- Recursion Halted at 1-Particle/Bin or Other Criteria such as Bin-Density

Restricts Phase-Space Diffusion to  
Within Local Bins

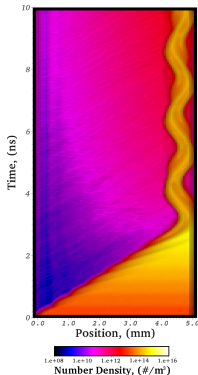
(Entropy,  $\sum n \log(n)$ , Constant within Octree Adaptive Quadrature )



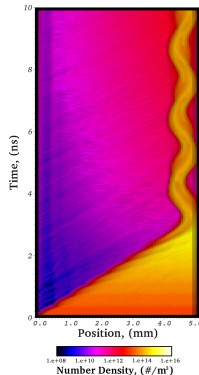


## 250V DC-Diode Test Case:

- Full 3D Electrostatic-PIC
- Averaged to 1D XT-Plot
- 250V Cathode → Anode
- MCC-Ionization Collisions
- Secondary Emission at Cathode



Control

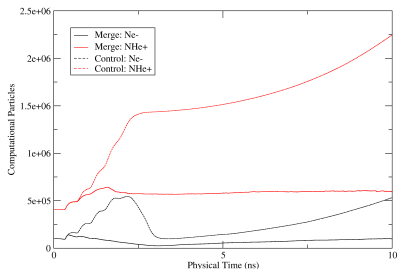


Merged



## 250V DC-Diode Test Case:

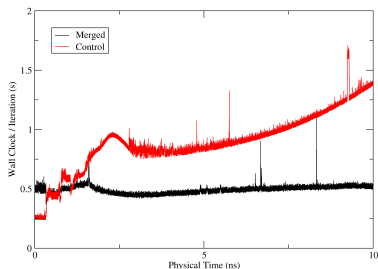
- Full 3D Electrostatic-PIC
- Averaged to 1D XT-Plot
- 250V Cathode → Anode
- MCC-Ionization Collisions
- Secondary Emission at Cathode
- Weak Chain-Branching (Marginal on Paschen Curve)





## 250V DC-Diode Test Case:

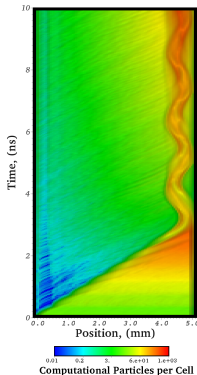
- Full 3D Electrostatic-PIC
- Averaged to 1D XT-Plot
- 250V Cathode → Anode
- MCC-Ionization Collisions
- Secondary Emission at Cathode
- Weak Chain-Branching (Marginal on Paschen Curve)
- Negligible Merge Overhead





## 250V DC-Diode Test Case:

- Full 3D Electrostatic-PIC
- Averaged to 1D XT-Plot
- 250V Cathode → Anode
- MCC-Ionization Collisions
- Secondary Emission at Cathode
- Weak Chain-Branching (Marginal on Paschen Curve)
- Negligible Merge Overhead
- Control: Parts/Cell  $\propto$  Density



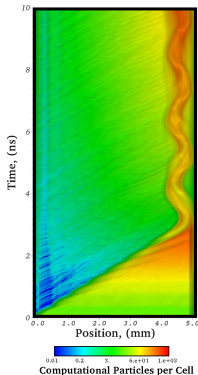
Control

Merged

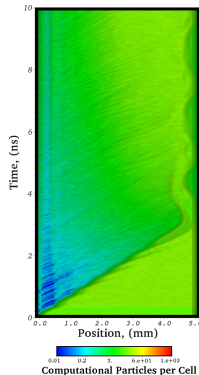


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- 250V Cathode → Anode
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- Secondary Emission at Cathode
- Weak Chain-Branching (Marginal on Paschen Curve)
- Negligible Merge Overhead
- Control: Parts/Cell  $\propto$  Density
- Merge: Parts/Cell **Reduced**



Control

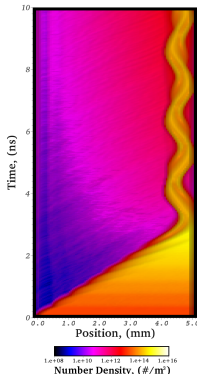


Merged

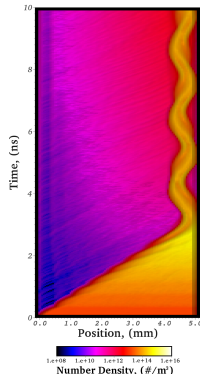


## 250V DC-Diode Test Case:

- Full 3D Electrostatic-PIC
- Averaged to 1D XT-Plot
- 250V Cathode → Anode
- MCC-Ionization Collisions
- Secondary Emission at Cathode
- Weak Chain-Branching (Marginal on Paschen Curve)
- Negligible Merge Overhead
- Control: Parts/Cell  $\propto$  Density
- Merge: Parts/Cell **Reduced**
- Despite Identical Densities



Control

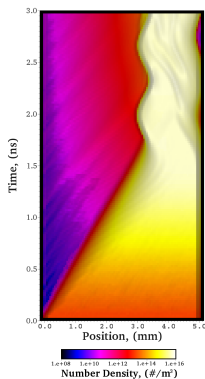


Merged



## 1KV DC-Diode Test Case:

- Voltage increased to 1KV
- Otherwise Identical to 250V
- Much Stronger Ionization



Control

Merged

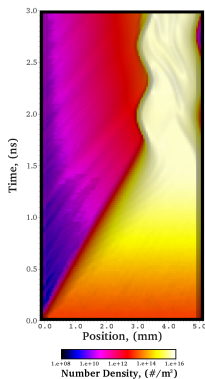
Martin, Cambier, JCP, (accepted), 2016.

(doi:10.1016/j.jcp.2016.01.020)

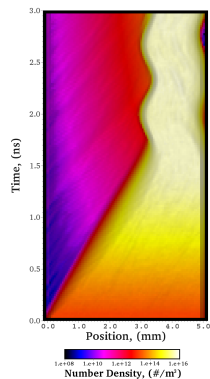


## 1KV DC-Diode Test Case:

- Voltage increased to 1KV
- Otherwise Identical to 250V
- Much Stronger Ionization
- Major Features Captured



Control



Merged

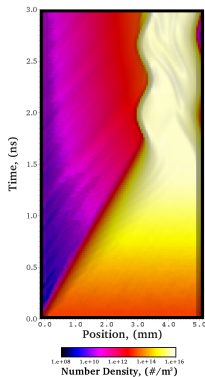
Martin, Cambier, JCP, (accepted), 2016.

(doi:10.1016/j.jcp.2016.01.020)

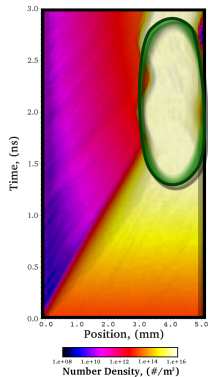


## 1KV DC-Diode Test Case:

- Voltage increased to 1KV
- Otherwise Identical to 250V
- Much Stronger Ionization
- Major Features Captured
- Some Features Lost...



Control



Merged

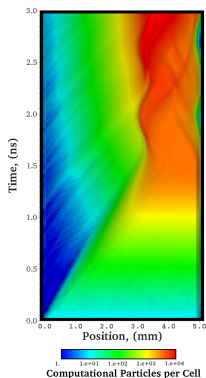
Martin, Cambier, JCP, (accepted), 2016.

(doi:10.1016/j.jcp.2016.01.020)

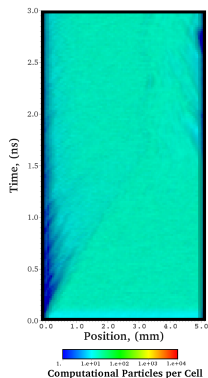


## 1KV DC-Diode Test Case:

- Voltage increased to 1KV
- Otherwise Identical to 250V
- Much Stronger Ionization
- Major Features Captured
- Some Features Lost...
- Might be Captured by Increasing Target #/cell?



Control



Merged

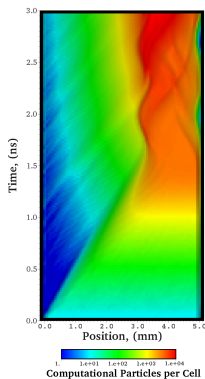
Martin, Cambier, JCP, (accepted), 2016.

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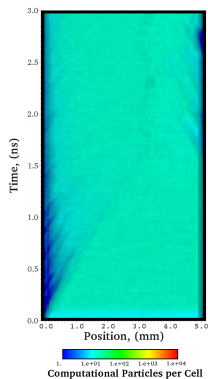


## 1KV DC-Diode Test Case:

- Voltage increased to 1KV
- Otherwise Identical to 250V
- Much Stronger Ionization
- Major Features Captured
- Some Features Lost...
- Might be Captured by Increasing Target #/cell?
- 26x Speedup



Control  
Run: 6hr12min



Merged  
Run: 14min

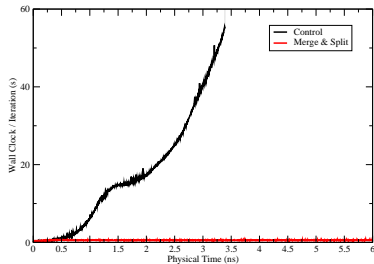
Martin, Cambier, JCP, (accepted), 2016.

(doi:10.1016/j.jcp.2016.01.020)



## 1KV DC-Diode Test Case:

- Voltage increased to 1KV
- Otherwise Identical to 250V
- Much Stronger Ionization
- Major Features Captured
- Some Features Lost...
- Might be Captured by Increasing Target #/cell?
- 26x Speedup
- Control Halted Mem>15GB



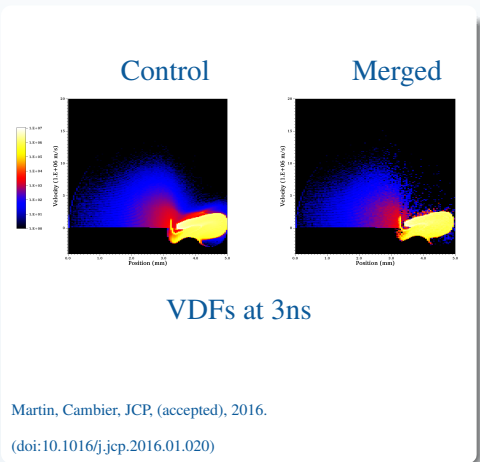
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## 1KV DC-Diode Test Case:

- Voltage increased to 1KV
- Otherwise Identical to 250V
- Much Stronger Ionization
- Major Features Captured
- Some Features Lost...
- Might be Captured by Increasing Target #/cell?
- 26x Speedup
- Control Halted Mem>15GB
- Major VDF Features Captured
- Future? Hybrid Kinetic/Fluid





## Thank You

This Presentation is derived from Anthony Pancotti's Dissertation Work:

### **A Study of Ignition Effects on Thruster Performance of a Multi-Electrode Capillary Discharge using Visible Emission Spectroscopy Diagnostics**

(<http://digitalibrary.usc.edu/cdm/ref/collection/p15799coll127/id/270907>)

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## Questions?