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Characterization of a Diverging Cusped Field Thruster Operating on Krypton

67th Gaseous Electronics Conference
Tuesday, November 4, 2014



**Integrity ★ Service ★
Excellence**

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Outline



- **Motivation for using krypton**
- **Diverging Cusped Field Thruster (DCFT)**
 - Operation on krypton vs. xenon
 - Frequency characteristics
- **Krypton Laser Induced Fluorescence (LIF)**
 - Time-Averaged LIF Velocimetry
 - Time-Synchronized LIF Velocimetry
- **Summary and continuing work**



Motivation for Using Krypton



- **Xenon has been expensive recently**

- Prices peaked at \$40 per std liter
- Increasing industrial use, scarcity
- ~50,000 liters per GEO comsat
- 200-500k liters for SOTV...

- **Krypton less expensive**

- 1/10 cost per volume, 1/6 by mass
- 150% tankage required (vs Xe)
- GEO comsat savings

Property	Units	Xe	Kr
Atomic Mass	amu	131.3	83.8
1 st Ionization Energy	eV	12.1	14.0
2 nd Ionization Energy	eV	21	24
3 rd Ionization Energy	eV	32	37
Atmospheric Concentration	ppb	87	1000
Stable Isotopes		9	6
Odd Isotopes		2	1
Critical Pressure	MPa	5.84	5.50
Critical Temperature	K	290	209
Boiling Point (1 atm)	K	161	120

- **Krypton Similar to Xenon**

- Noble gases
- Similar physical properties
- Electrons bound more tightly
 - Less electron shielding
 - Higher ionization energies, +15%
- More ideal gas behavior
 - Less compressible
 - More difficult pressurized storage
 - 150% tankage required for Kr (vs Xe)

- **Kr is nearly a “drop in” replacement for Xe**

- Some loss in efficiency
 - 25% gain in Isp (vs Xe)
 - 80% thrust (vs Xe)
 - Advantageous for station keeping
- No changes required to thruster
- Minimal changes required to propellant management
- No increased likelihood of S/C contamination

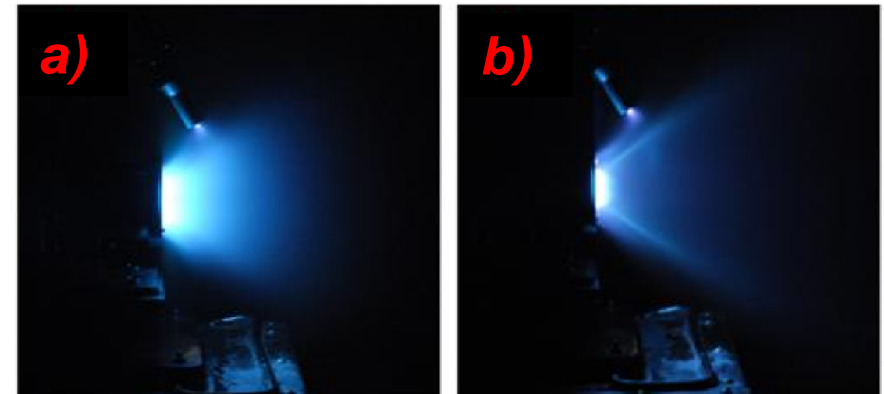


Diverging Cusped Field Thruster

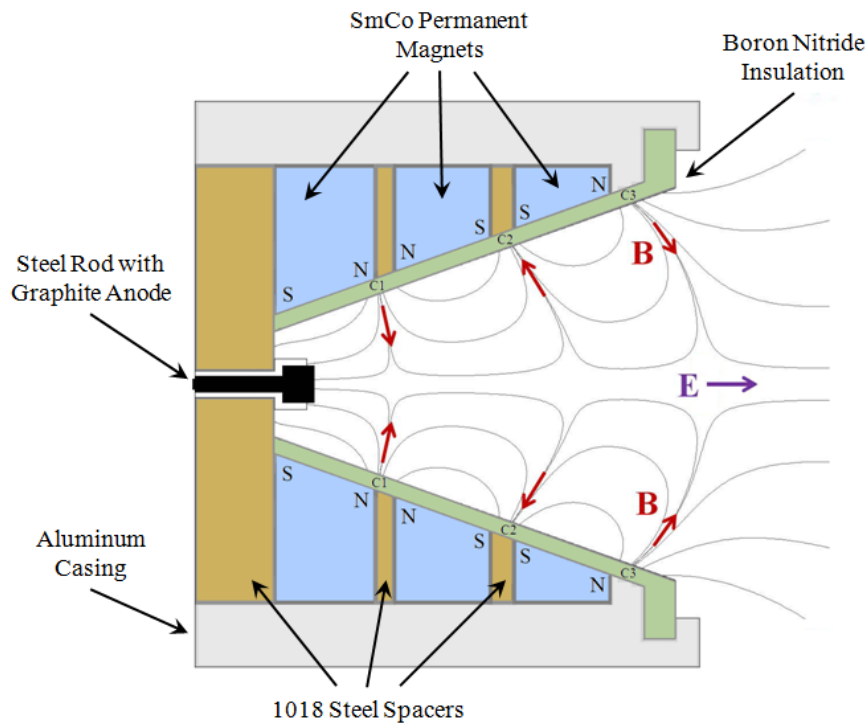


Two, distinct operating modes:

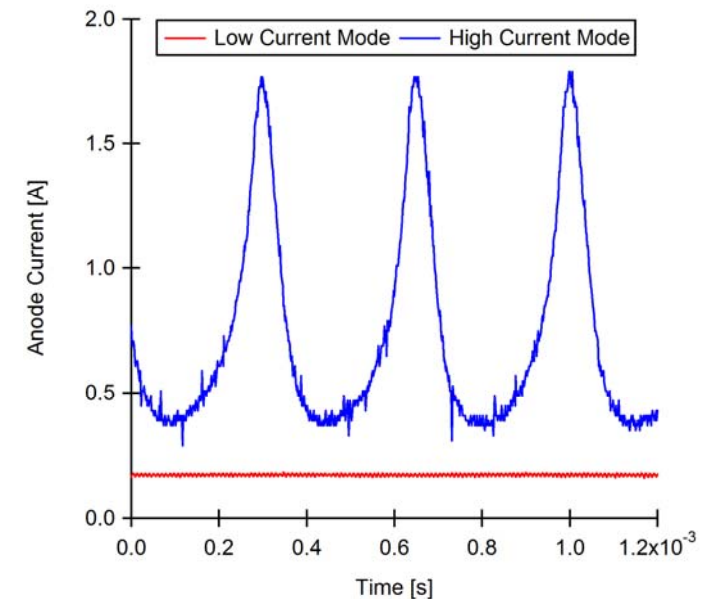
- **Low Current Mode**
 - Quiescent, time averaged measurements are relevant
- **High current mode with**
 - Strong, quasi-periodic discharge current oscillations
 - Fluctuations in position of ionization and acceleration regions
 - Dynamics not resolved with time averaged measurements



DCFT operating in: a) High current mode, b) Low current mode



Schematic of DCFT



DCFT Current Traces



DCFT Operation on Krypton vs Xenon



● Current-Voltage Characteristics

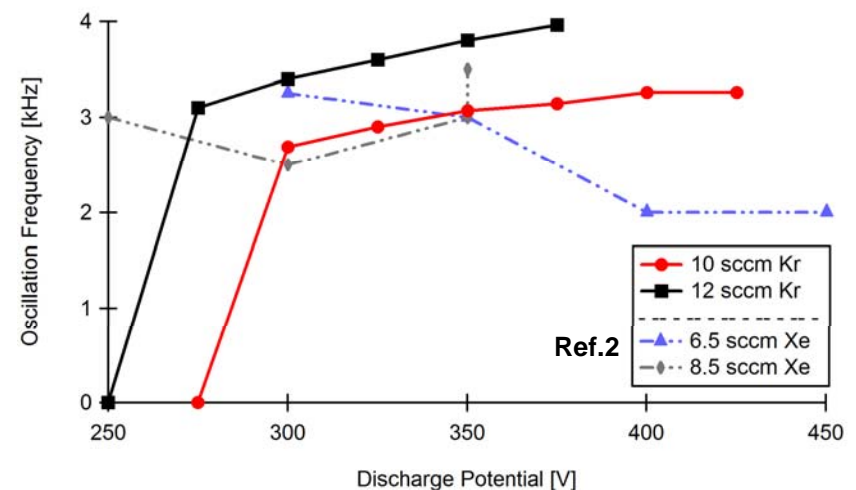
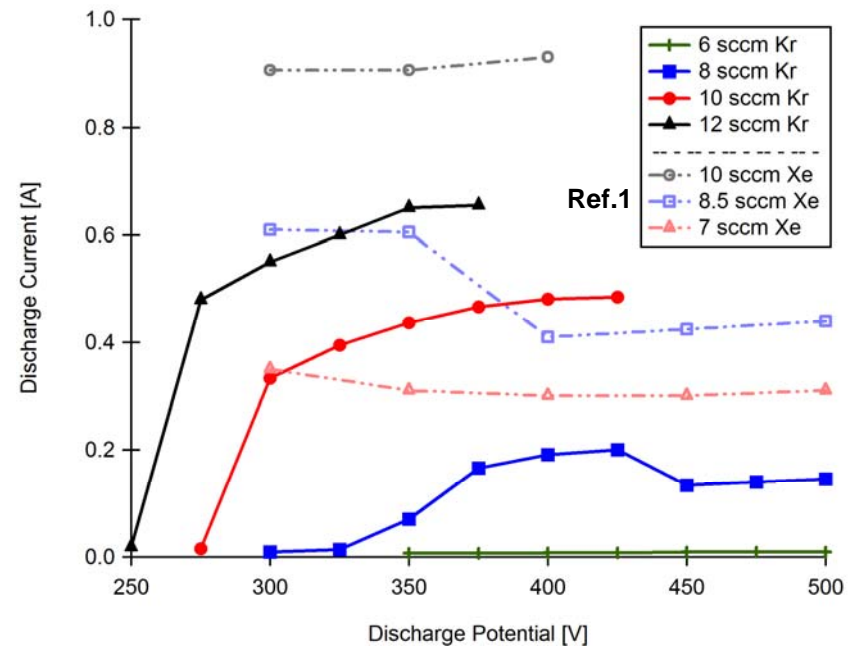
- Kr able to operate in ultra-low current glow mode, not sustainable in Xe
- Kr does not roll off into low current mode at high voltage – stays oscillatory

● Krypton

- Strong correlation between flow rate and frequency
- Linear change in frequency with increased voltage

● Xenon

- Little to no trend in frequency vs. voltage
- Strong linear trend in flow rate vs. frequency



Ref. 1: Gildea, S. R., Matlock, T. S., Lozano, P., and Martínez-Sánchez, M., "Low-Frequency Oscillations in the Diverging Cusped-Field Thruster," AIAA Paper 2010-7014, 2010.

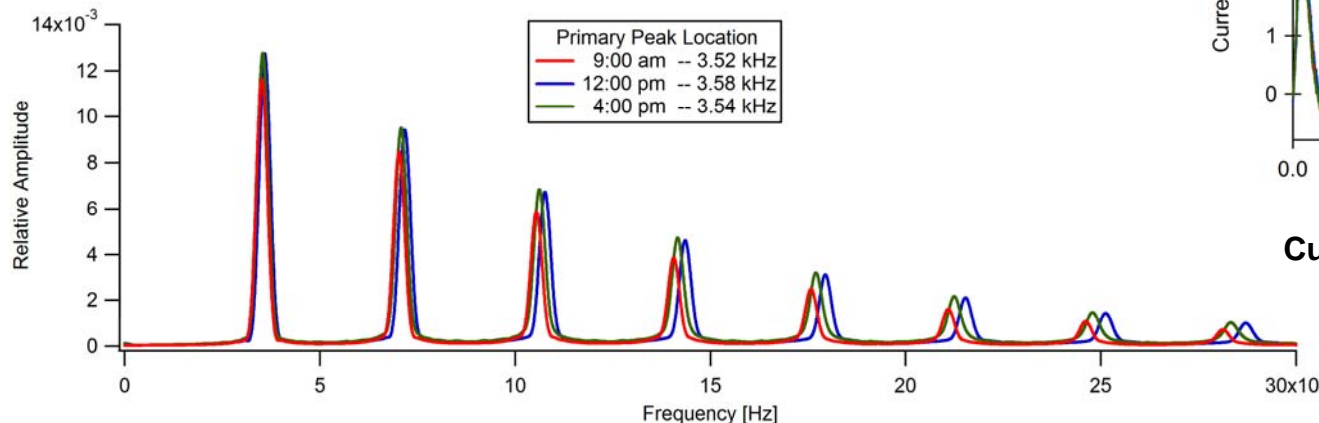
Ref. 2: Courtney, D. G., "Development and Characterization of a Diverging Cusped Field Thruster and a Lanthanum Hexaboride Hollow Cathode," S.M. Thesis, Massachusetts Inst. of Technology, Cambridge, MA, June 2008.



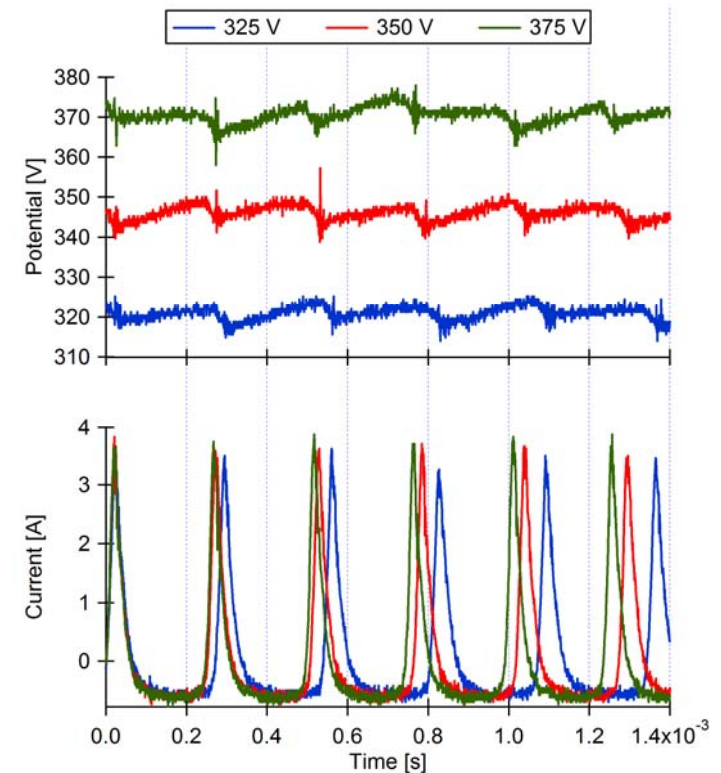
DCFT Frequency Characteristics



- **Operation at 12 sccm Kr**
 - Amplitude and frequency of current oscillations increase with voltage
 - Small dips in discharge voltage corresponding to current peaks
 - Voltage dips also seen in Xe operation
- **FFTs of current signal**
 - Frequency lower at start up
 - Relatively stable after 30 min, slight decrease over course of day



**FFT of current signal at various times throughout the day
DCFT operating at 12 sccm Kr, 350 V, 0.595 A**



**Current and voltage traces of DCFT
operating on 12 sccm Kr**

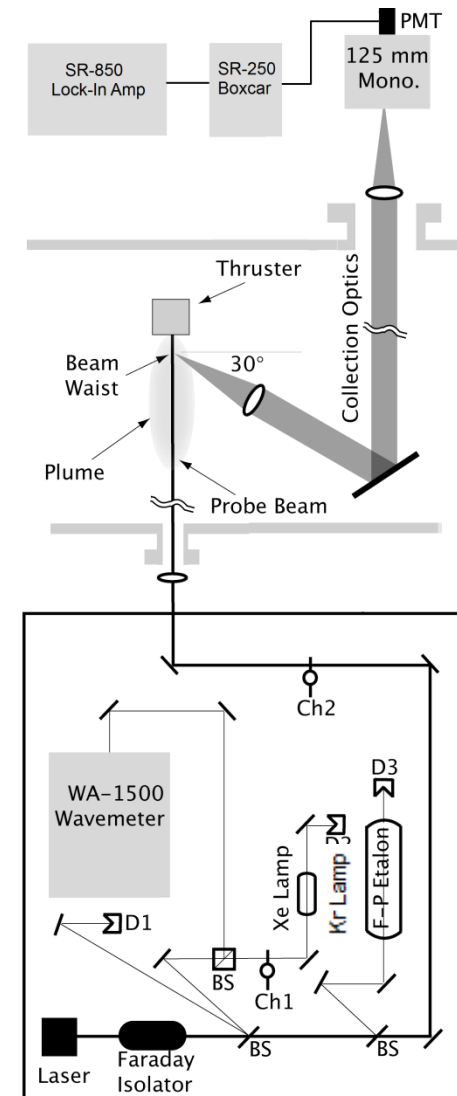
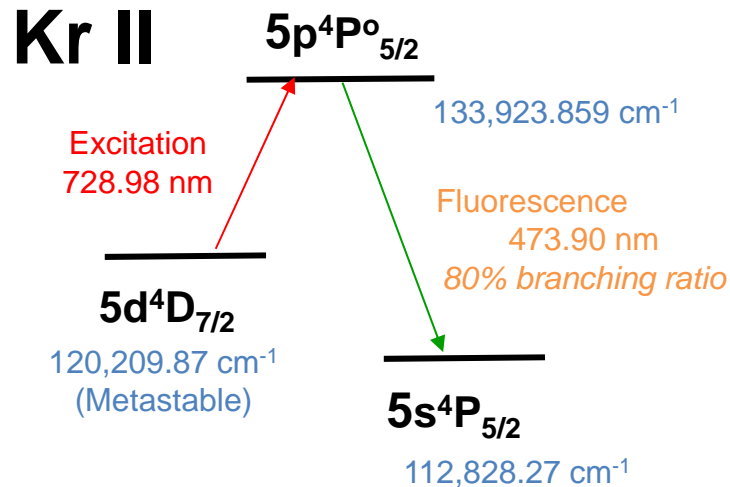


Krypton Laser Induced Fluorescence



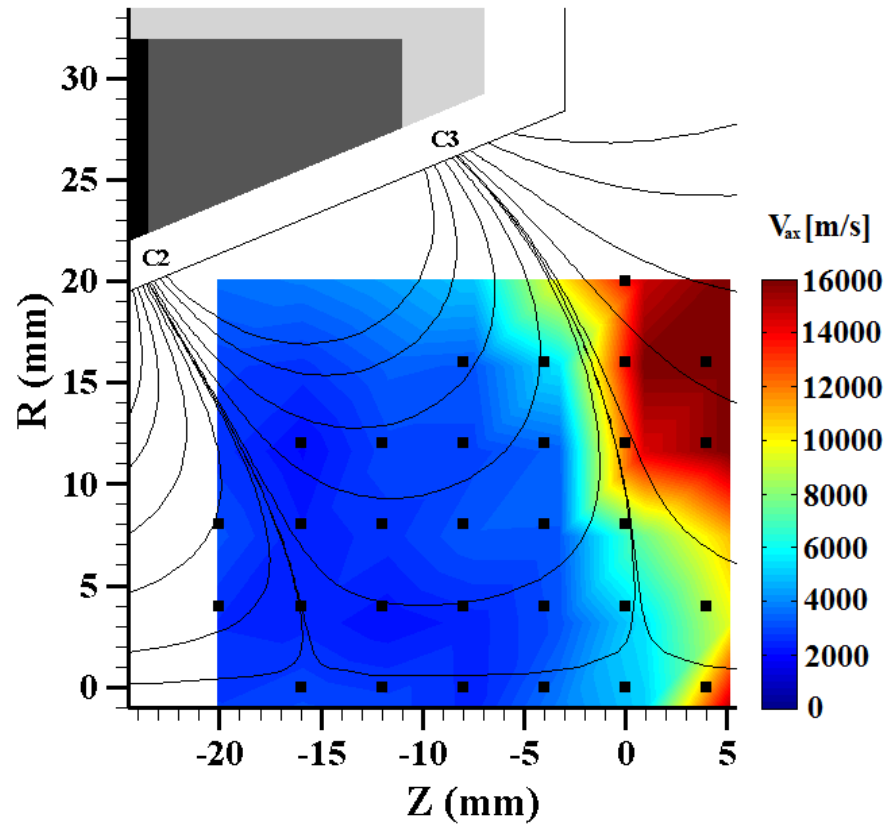
- **Used to measure krypton ion velocities**

- Kr II transition, $5d^4D_{7/2} - 5p^4P_{5/2}^o$
- Wavelength = 728.98 nm
- Non-resonant fluorescence with ~80% branching ratio at 473.90 nm
- Metastable lower electronic state
- Well characterized, hyperfine constants measured

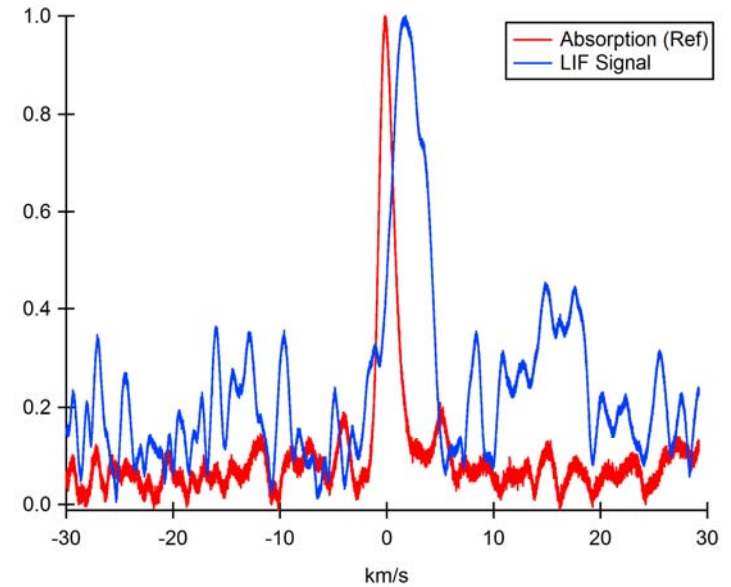




Time-Ave Axial Velocities



DCFT Operating on 12 sccm Kr

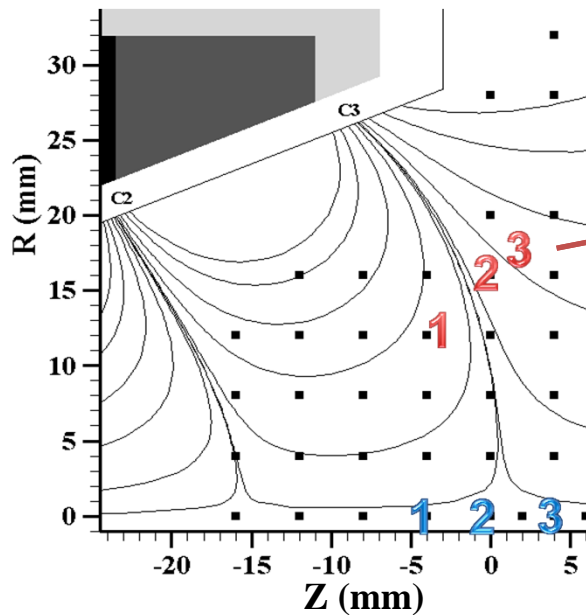


Example LIF Trace (R = 8 mm, Z = -16 mm)

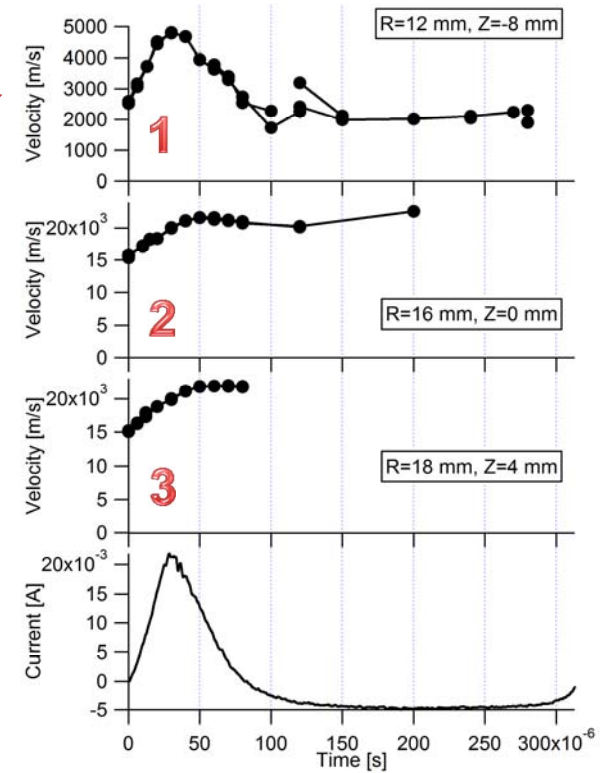
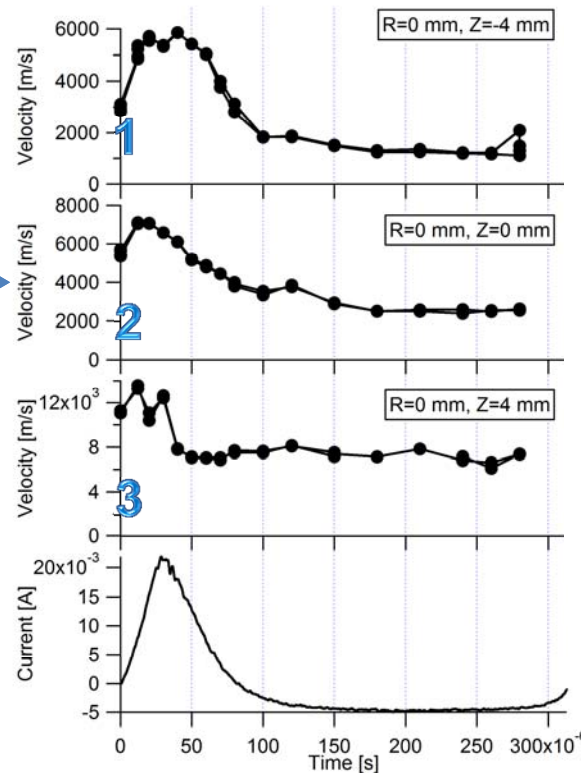
DCFT Operating Conditions	
Anode Flow Rate:	12 sccm Kr
Anode Potential:	350 V
Anode Current:	0.595 A
Background Pressure:	1.2×10^{-5} torr



Time-Sync Axial Velocities



Measurement locations for time-sync LIF on DCFT



Journal article in progress: C. V. Young, N. A. MacDonald, M. A. Cappelli and W. A. Hargus, Jr. "Time-synchronized ion velocimetry of a diverging cusped field thruster operating on krypton" *Physics of Plasmas* (pre-print)



Summary



Summary

- **Characterization of DCFT operating on krypton**
 - Linear changes in flow rate, voltage
 - Amplitude and frequency of current oscillations increase with voltage
- **Time resolved laser-induced fluorescence**
 - Phase synchronization to breathing mode periodicity

Continuing Work

- **Extensive krypton time-sync LIF measurements made on DCFT**
 - Collaboration with Stanford University (Chris Young)
 - Data reduction nearing completion
 - Journal article in progress: “**Time-synchronized ion velocimetry of a diverging cusped field thruster operating on krypton**” Physics of Plasmas (pre-print)
- **Upcoming xenon time-sync LIF measurement campaign**





Comparison of Global Parameters



Krypton Operating Parameters (Time-Sync)

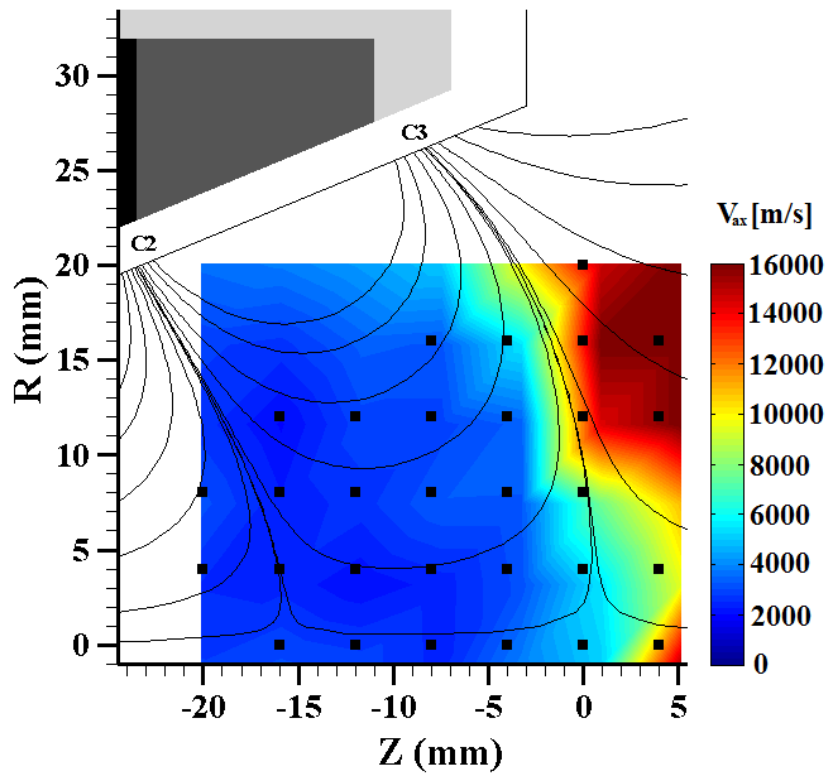
Anode Flow Rate:	12 sccm Kr
Anode Potential:	350 V
Anode Current:	0.595 A
Cathode Flow Rate:	1.5 sccm Kr
Cathode Heater:	4.7 V, 4.00 A
Cathode Keeper:	16 V, 0.500 A
Background Pressure:	1.2×10^{-5} torr

Xenon Operating Parameters (Time-Sync)

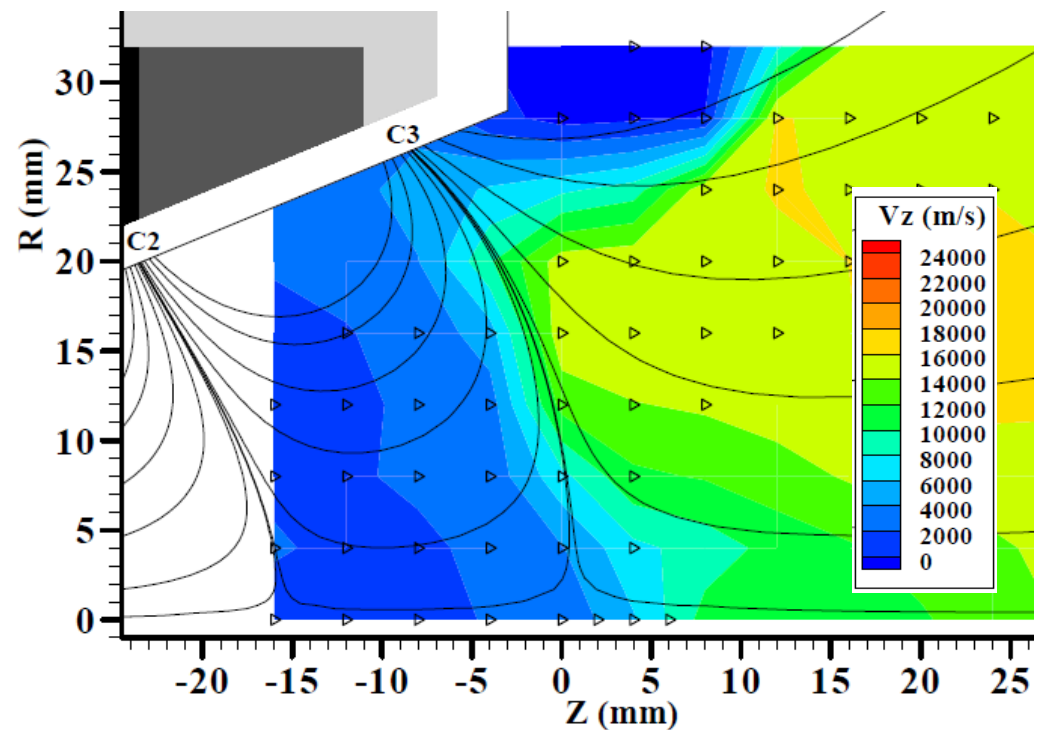
Anode Flow Rate:	8.5 sccm Xe
Anode Potential:	300 V
Anode Current:	0.49 A
Cathode Flow Rate:	1.5 sccm Xe
Cathode Heater:	4.7 V, 4.00 A
Cathode Keeper:	16 V, 0.500 A
Background Pressure:	1.2×10^{-5} torr



Time-Ave Axial Velocities: Kr vs. Xe



DCFT Operating on 12 sccm Kr, 350 V



DCFT Operating on 8.5 sccm Xe, 300V