

# REPORT DOCUMENTATION PAGE

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# Air Force Research Laboratory



***Integrity ★ Service ★ Excellence***

## Time-Resolved Emission Spectroscopy of Field Reversed Configuration Thruster

August 31<sup>st</sup>, 2016

**Gary Z. Li**

In-Space Propulsion Branch (RQRS)  
Aerospace Systems Directorate  
Edwards AFB, CA



# Outline



- **About Me**
- **Objective**
- **Introduction**
- **Experimental Setup**
- **Data Processing**
- **Results**
- **Conclusions**



# About Me



- **3<sup>rd</sup> year Ph.D. candidate in Aerospace Eng. at UCLA**
- **B.A. in Astrophysics and Physics from UC Berkeley**
  - **Senior thesis on detection of faint supernovae in ultra-luminous infrared galaxies (ULIRGs)**





# Objective



**To study the formation mechanisms of an FRC thruster using time-resolved optical emission spectroscopy.**



# Introduction



- **Field Reversed Configuration (FRC) thrusters are candidates for next generation **high-powered** electric propulsion (EP)**
- **Advantages over competing technologies in same power range (*Hall thrusters, MPDs, VASIMR*)<sup>1</sup>**

[1] Brown, D., Beal, B., Haas, J. (2010) AFRL High Power Electric Propulsion Technology Development



# Introduction



- **Field Reversed Configuration (FRC) thrusters are candidates for next generation **high-powered** electric propulsion (EP)**
- **Advantages over competing technologies in same power range (*Hall thrusters, MPDs, VASIMR*)<sup>1</sup>**
  - **Throttleable** → **momentum transfer control**
  - **Electrodeless** → **near zero erosion**
  - **Low specific mass** → **less thruster, more payload**
  - **Alternative propellants** → **green (AF-M315), ISRU (Martian air)**
  - **Higher overall efficiency\*** → **more bang for your buck**

*\*projected*

[1] Brown, D., Beal, B., Haas, J. (2010) AFRL High Power Electric Propulsion Technology Development



# Introduction



- Field Reversed Configuration (FRC) thrusters are candidates for next generation **high-powered** electric propulsion (EP)
- Advantages over competing technologies in same power range (*Hall thrusters, MPDs, VASIMR*)<sup>1</sup>
  - Throttleable → **control momentum transfer**

**High-powered thruster in a flexible, efficient, and light-weight package.**

*\*projected*

[1] Brown, D., Beal, B., Haas, J. (2010) AFRL High Power Electric Propulsion Technology Development



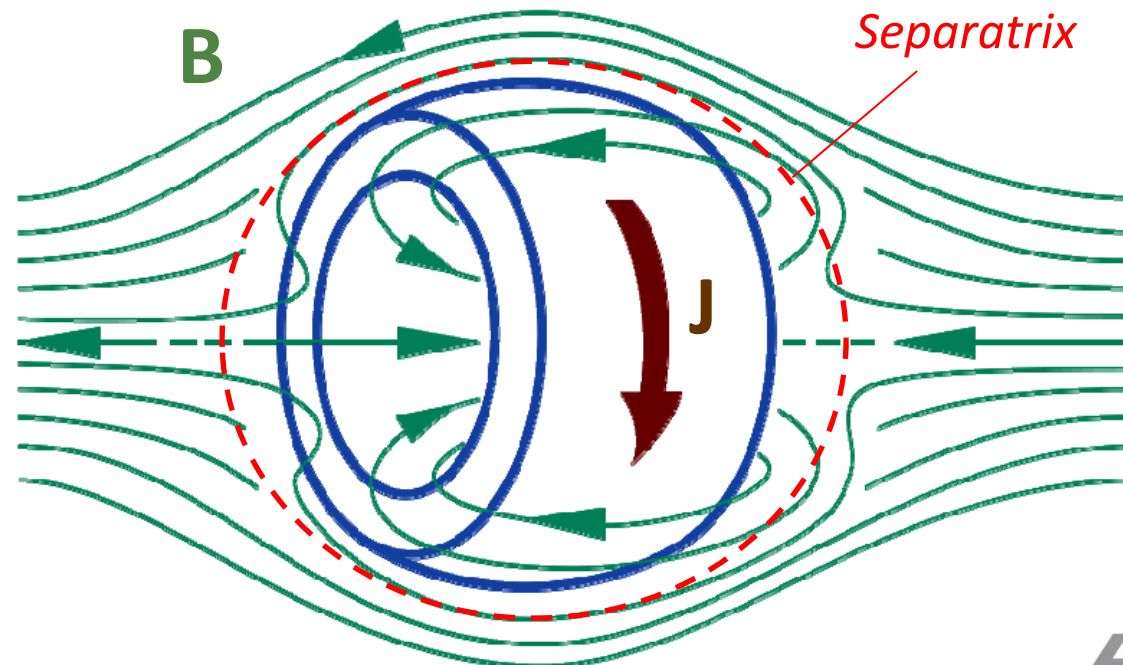


# What is an FRC?



An **FRC** is a plasma blob characterized by

1. Large azimuthal current ( $e^-$  or ions)
2. Closed magnetic surface
3. Reversed internal magnetic field



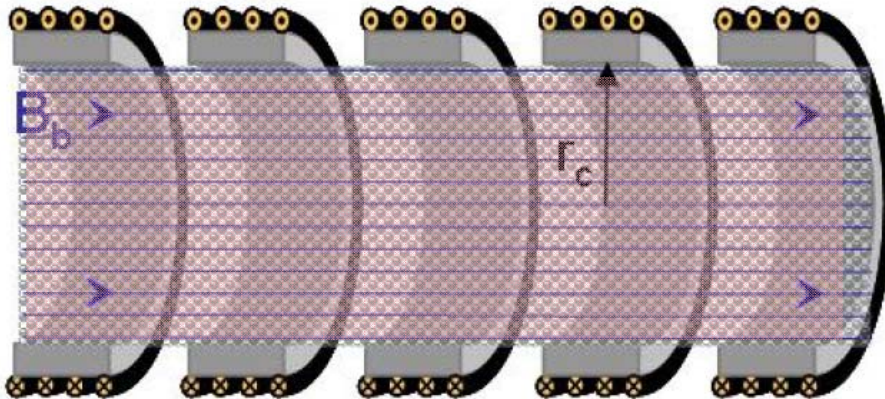


# Formation Stages



## 1. Preionization

*Creates a uniform, low density plasma*



[2] Slough, J. and Kirtley, D. (2009) Pulsed Plasmoid Propulsion – The ELF Thruster

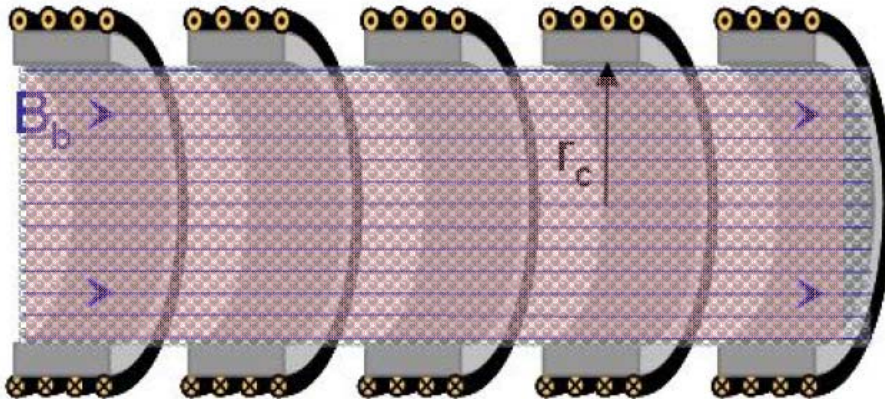


# Formation Stages



## 1. Preionization

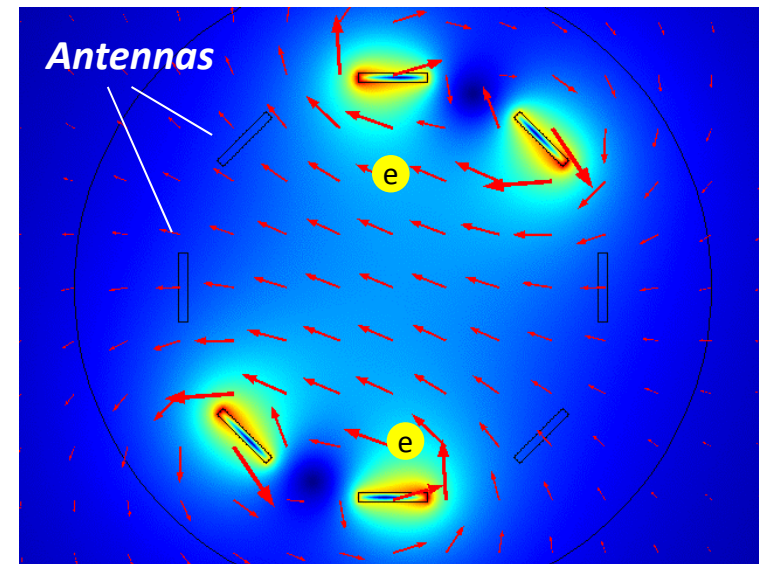
*Creates a uniform, low density plasma*



[2] Slough, J. and Kirtley, D. (2009) Pulsed Plasmoid Propulsion – The ELF Thruster

## 2. Rotating Magnetic Field

*Electrons tied to rotating field lines → azimuthal current*



Source: Nolan Uchizono

Condition:  $\omega_{ci} < \omega_{RMF} < \omega_{ce}$

$\omega_c$  = cyclotron frequency





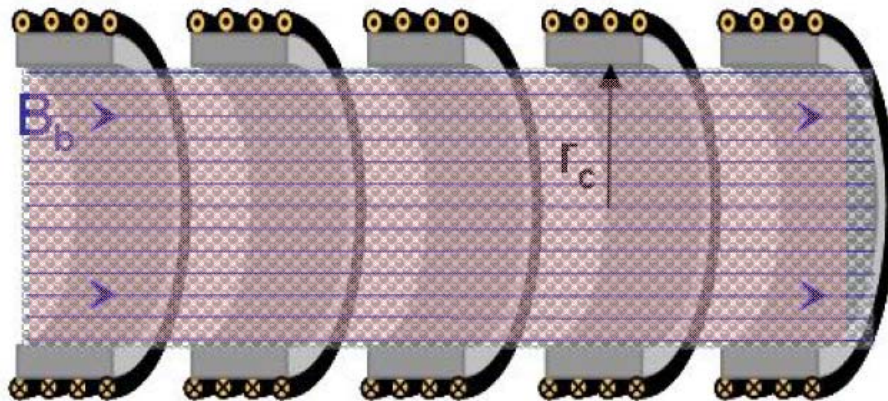


# Formation Stages



## 1. Preionization

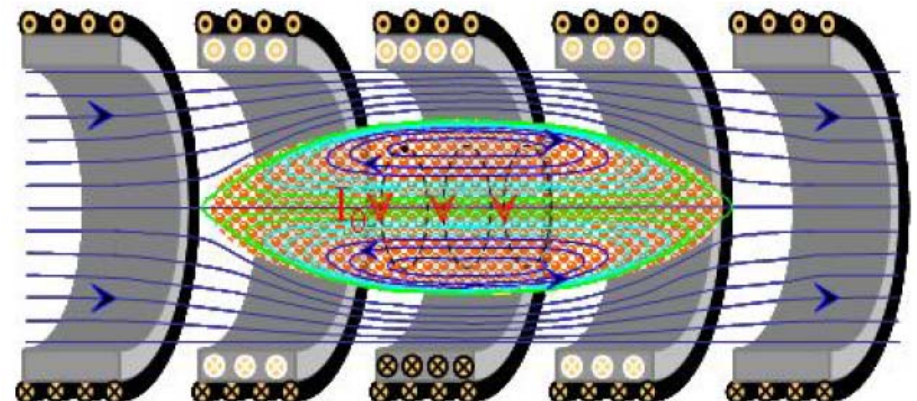
*Creates a uniform, low density plasma*



[2] Slough, J. and Kirtley, D. (2009) Pulsed Plasmoid Propulsion – The ELF Thruster

## 2. Rotating Magnetic Field

*Azimuthal current **reverses** internal magnetic field*



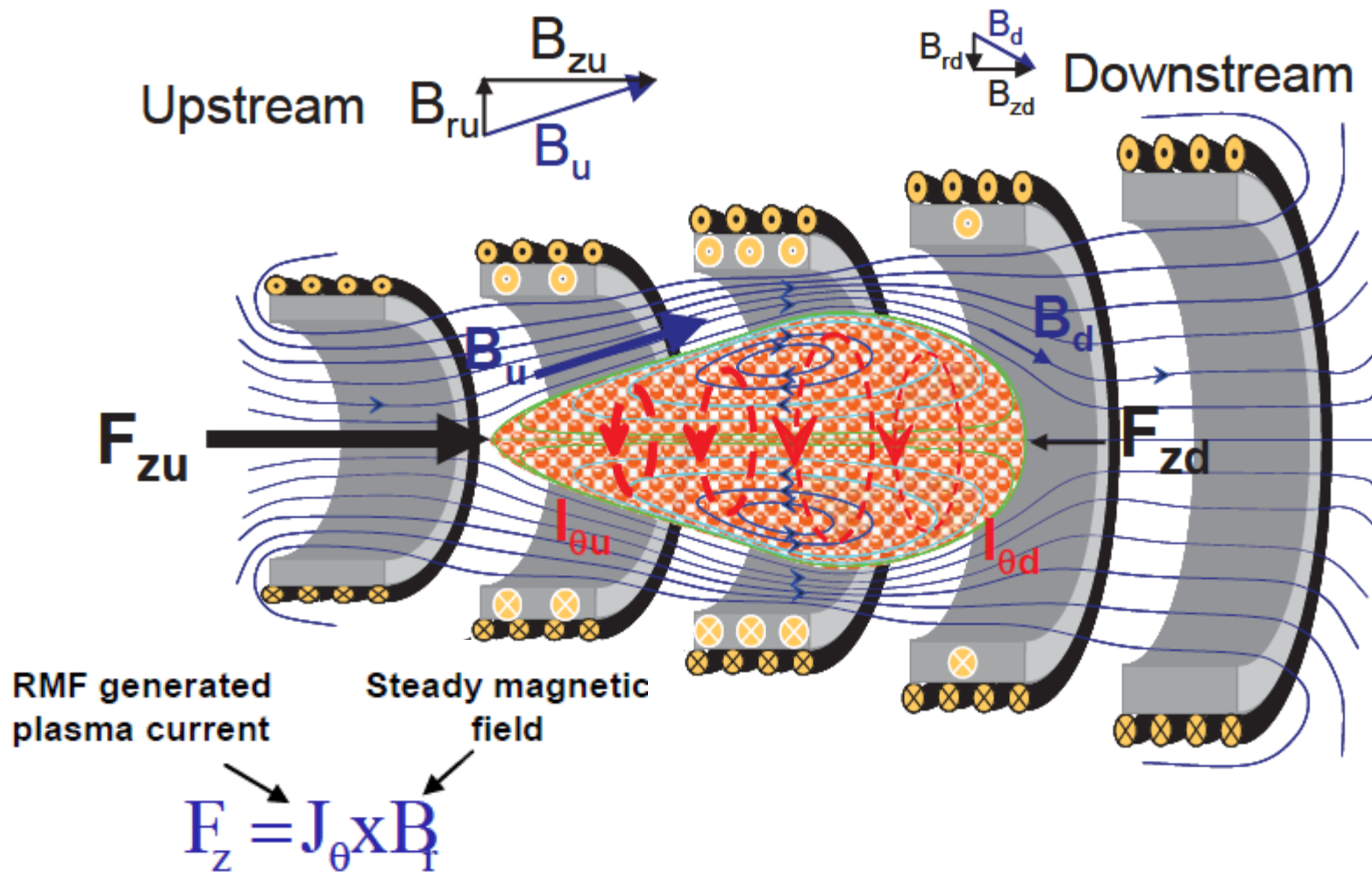
*Magnetic field lines reconnect and form **closed-surface FRC***

$\omega_c = \text{cyclotron frequency}$





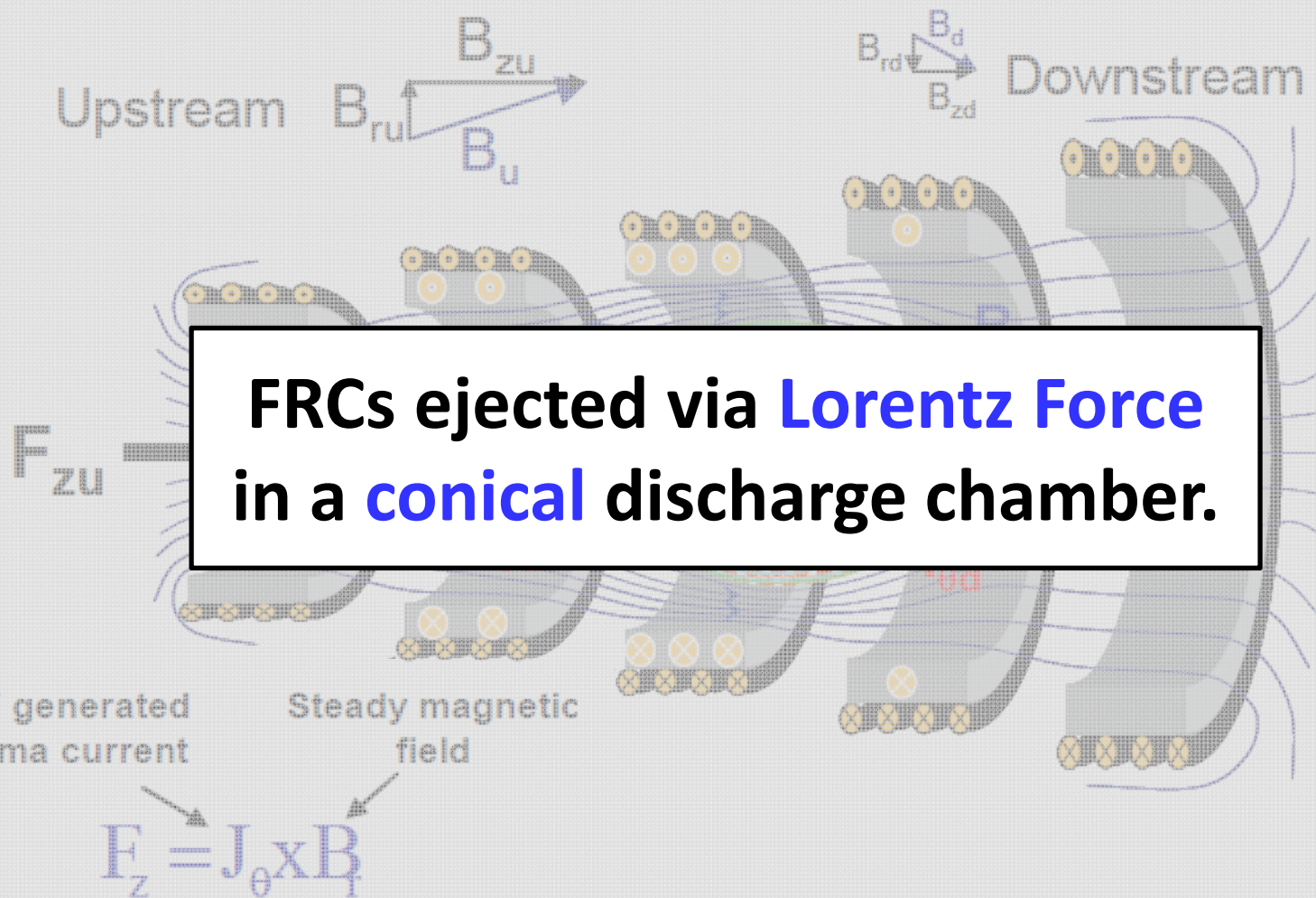
# Translation



[3] Kirtley, D. et al. (2011) Steady Operation of an Electromagnetic Plasmoid Thruster



# Translation

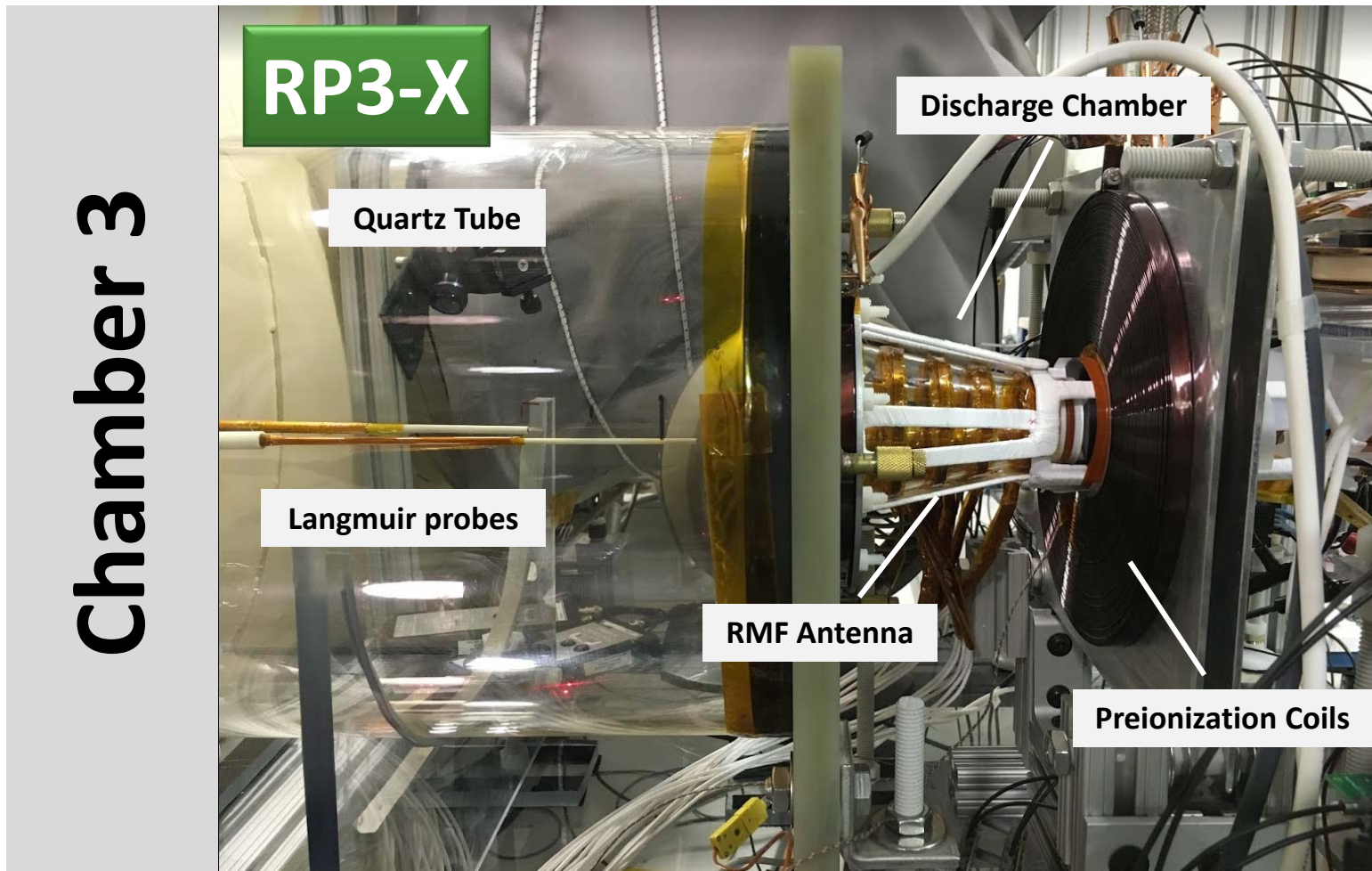


[3] Kirtley, D. et al. (2011) Steady Operation of an Electromagnetic Plasmoid Thruster



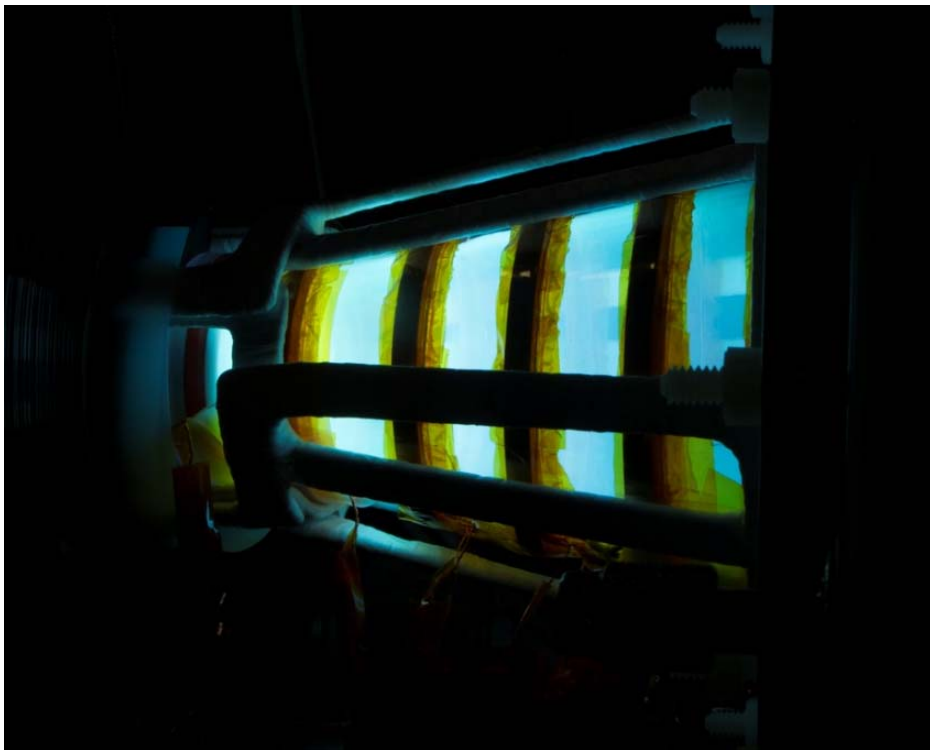


# Experimental Setup





# RP3-X Operation



Source: Mike Holmes

## FRC Settings

**Flow Rate:** 40 sccm

**Operating Gas:** xenon

**Working Pressure:**  $4.6 \times 10^{-5}$  Torr

**FRC Energy (per pulse):** 5 J

**Pulse Frequency:** 10 kHz

**Time Delay btwn PI & RMF:** 10  $\mu$ s

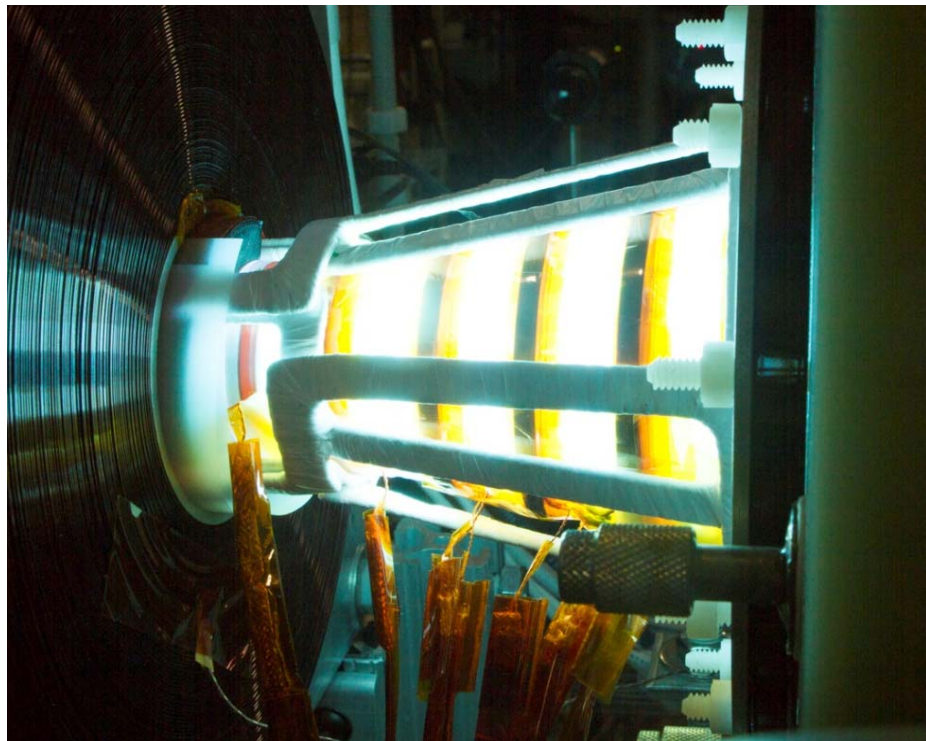
**RMF Phase Delay:**  $-5^\circ$

**Bias Magnetic Field:** 300 G

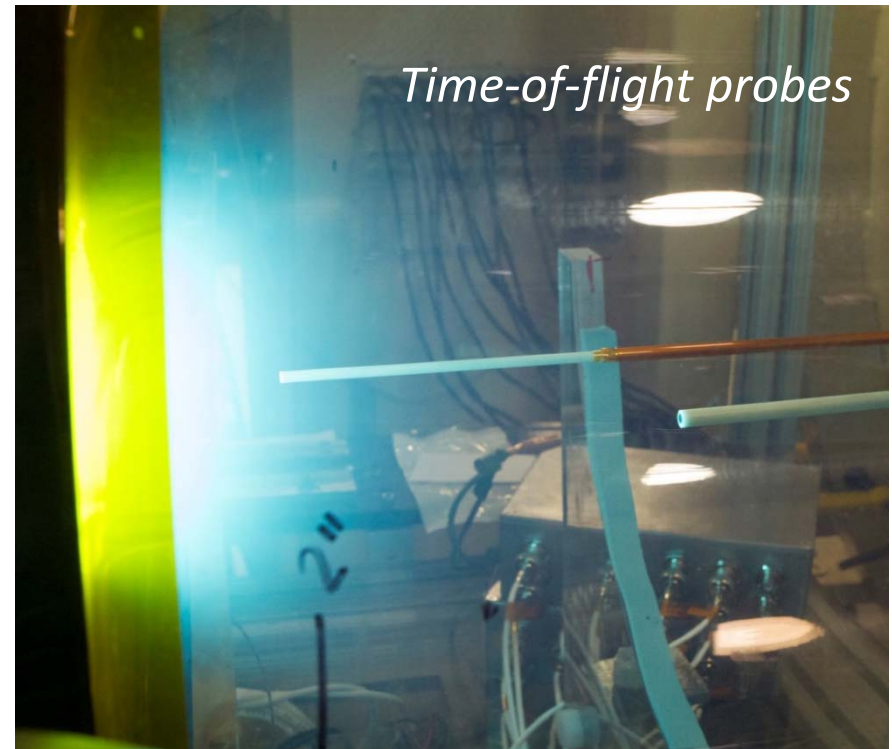




# RP3-X Operation



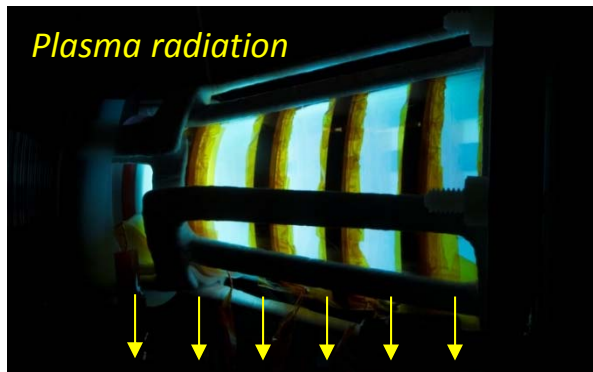
Source: Mike Holmes



Source: Mike Holmes



# Optical Emission Spectroscopy (OES)



Collection Optics  
to 600um fiber

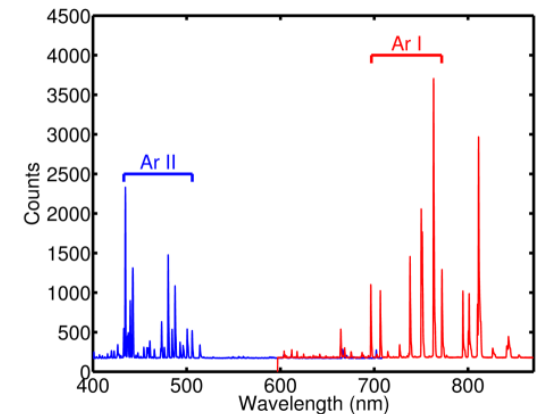
Spectrometer  
(iHR 320)

Ion Streak Camera  
(Hamamatsu C7700)

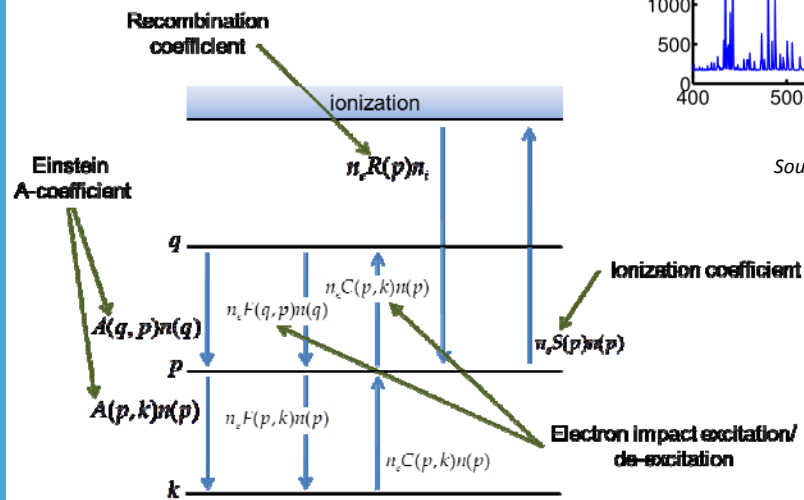
CCD Camera  
(C10600)

Time-resolved OES allows for **non-invasive** measurements of plasma properties ( $n_e$ ,  $T_e$ ) in time.

## 1. Acquire Spectrum



Source: Scherer Research Group



Source: PEARL

## 2. Compare to Collisional-Radiative Model (CRM)

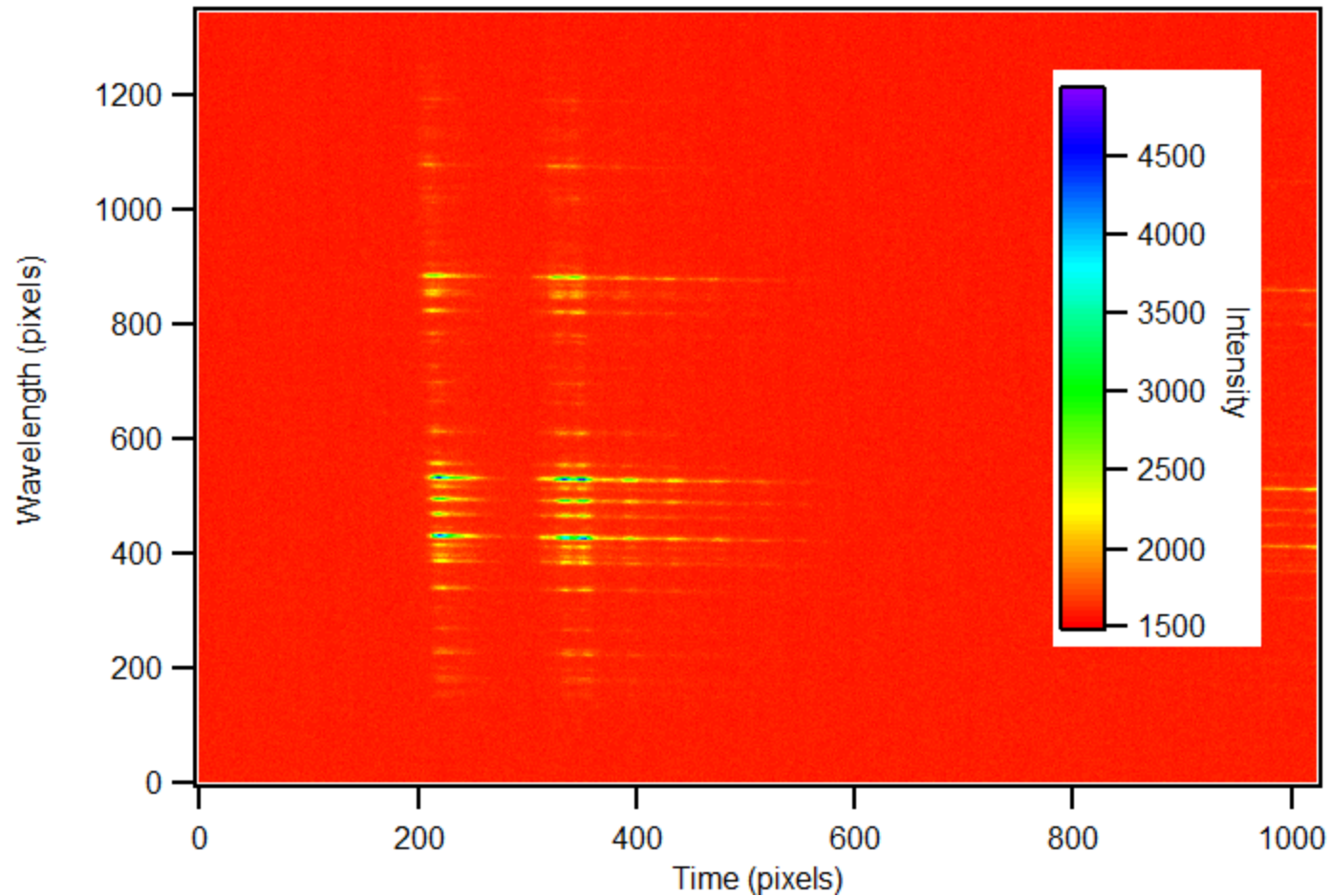




# Data Processing



## Raw Data

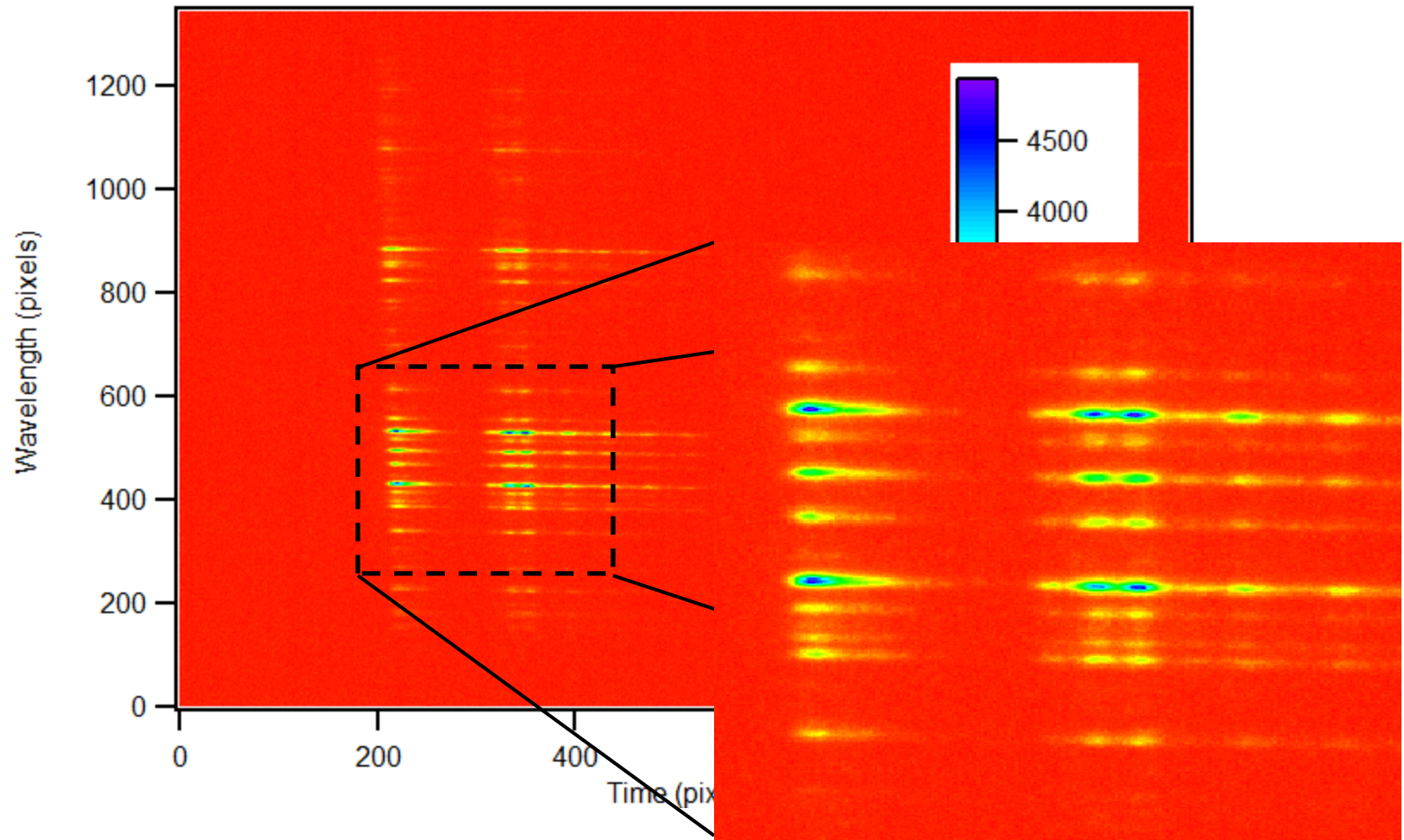




# Data Processing



## Raw Data



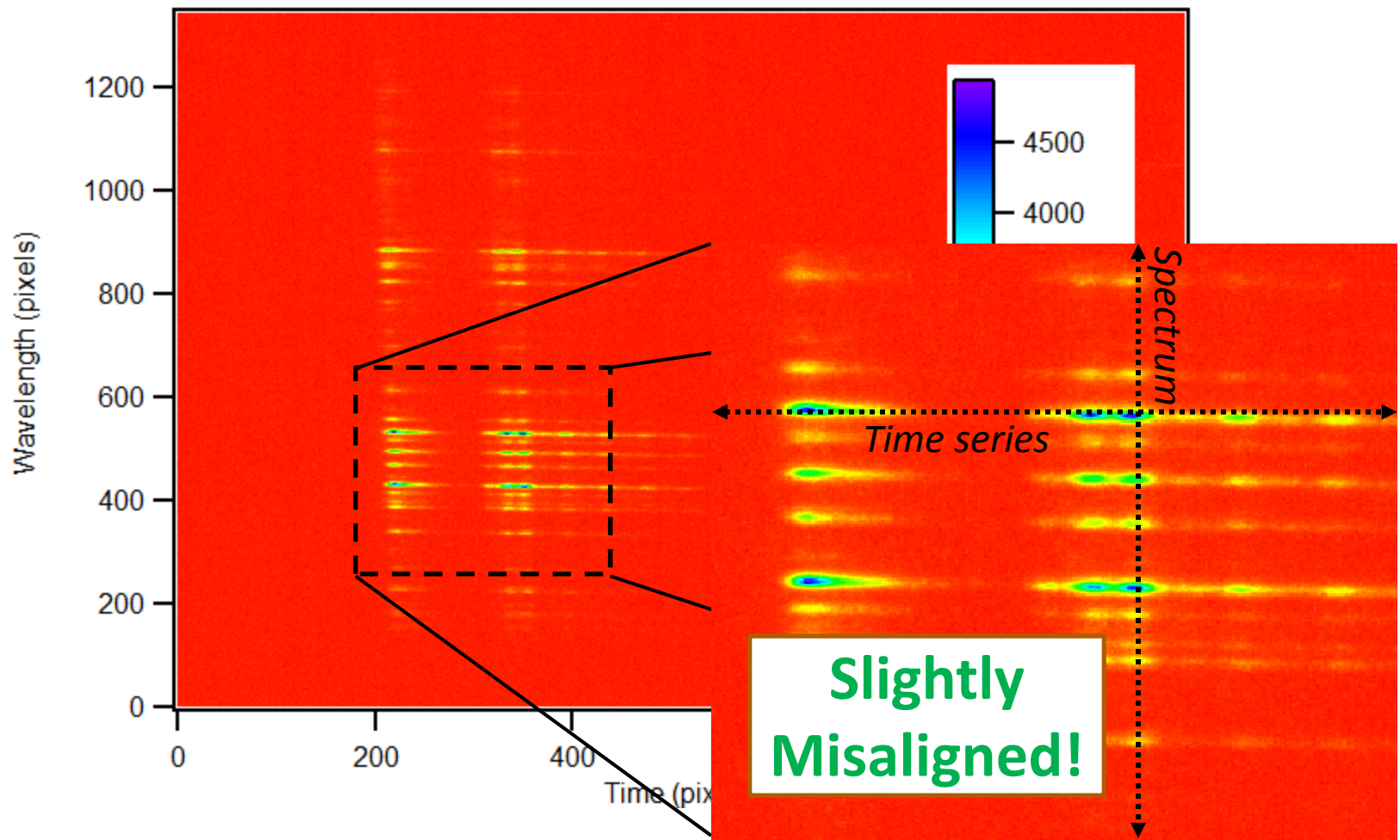




# Data Processing



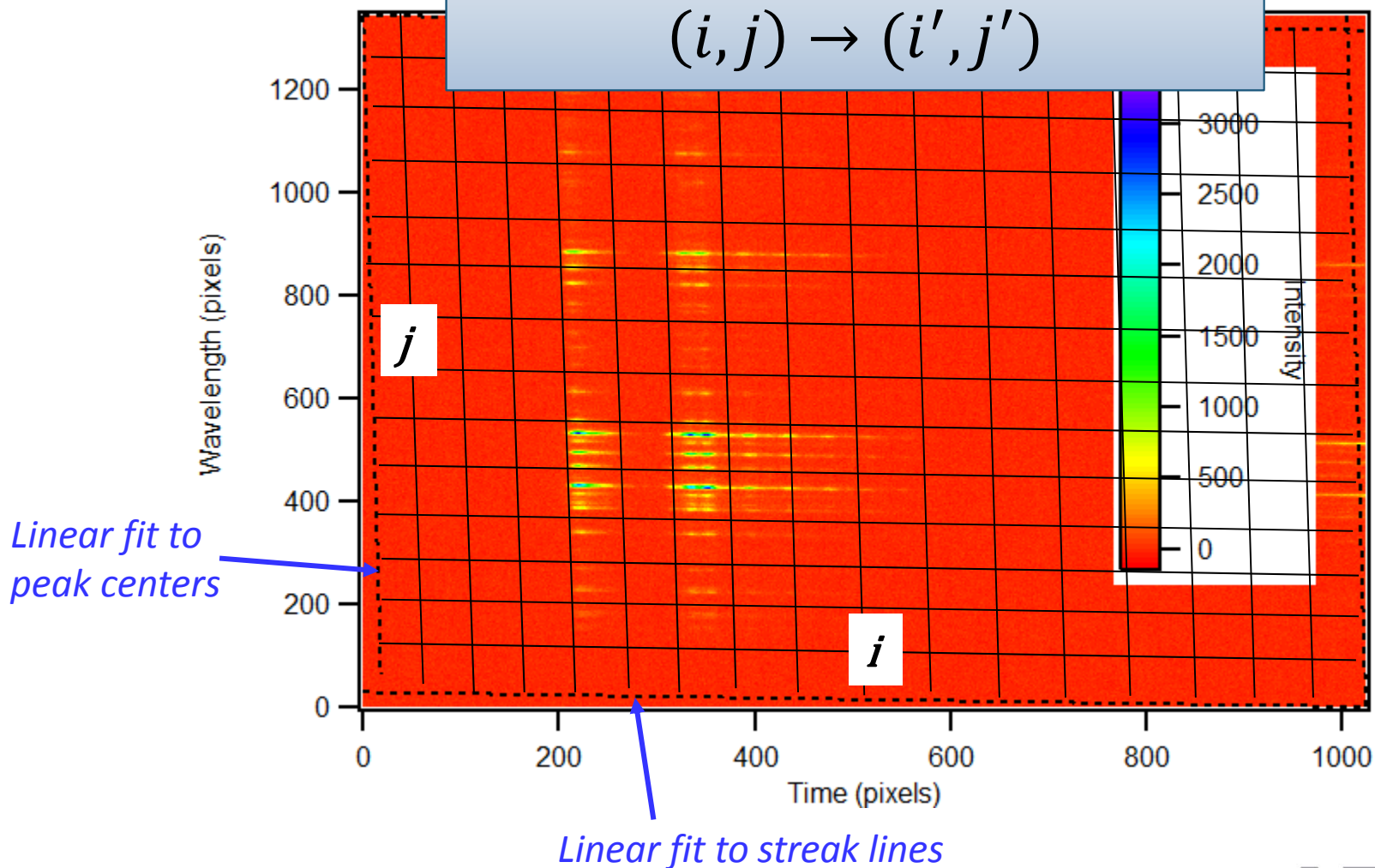
## Raw Data





# Data Processing

*Mapping structured grid  
 $(i, j) \rightarrow (i', j')$*

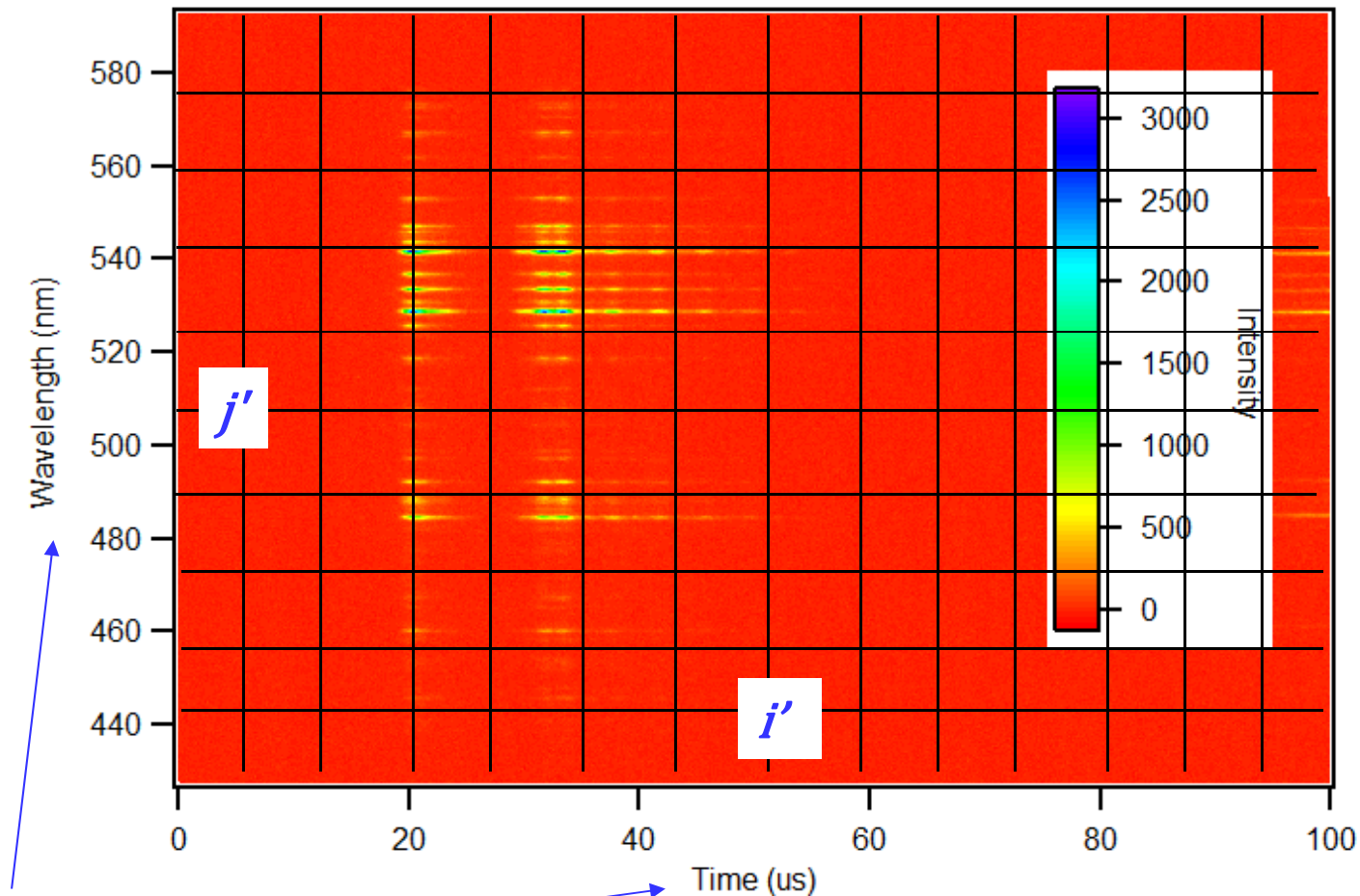




# Data Processing



## Corrected Data



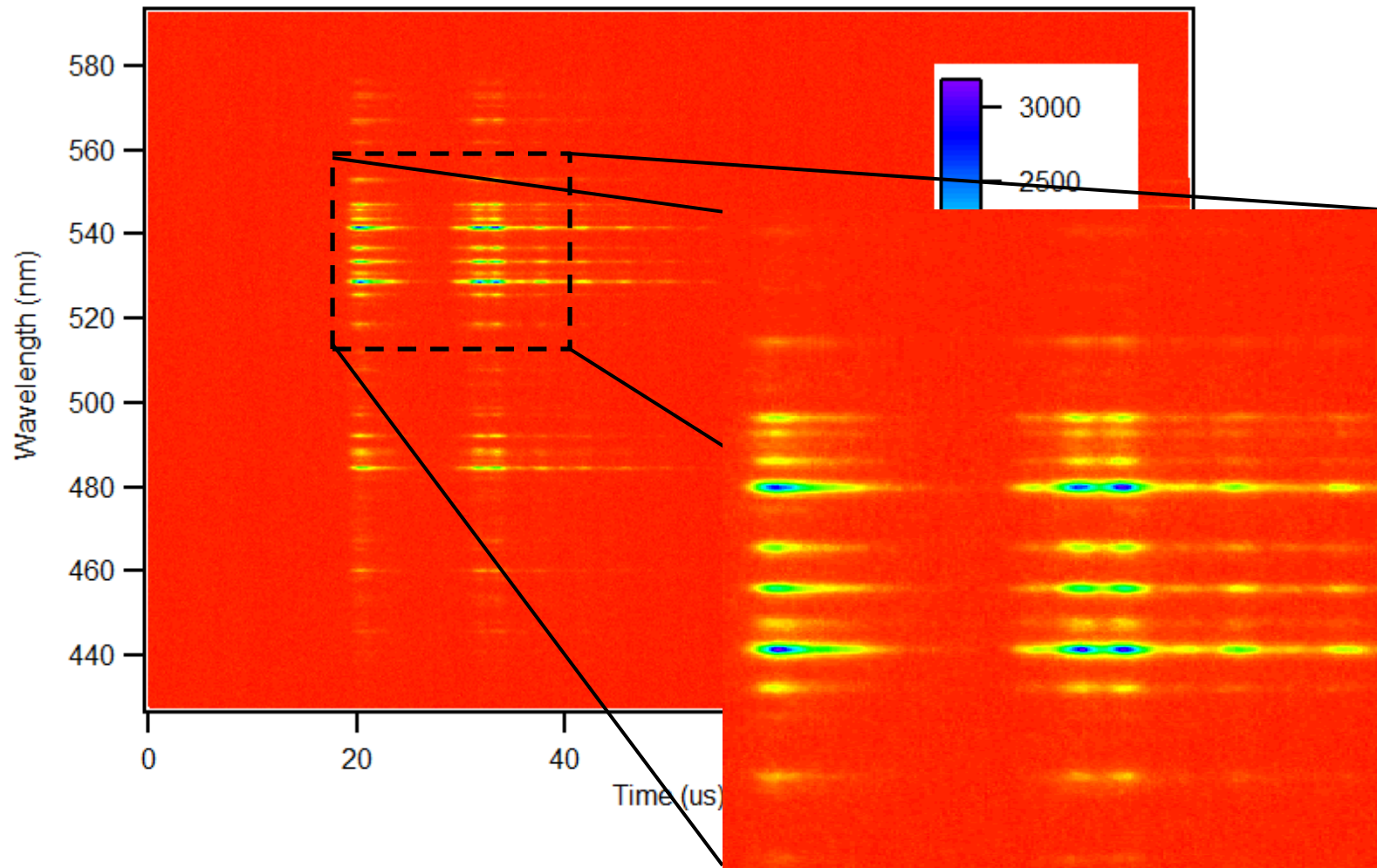
*Calibrated axes*



# Data Processing



## Corrected Data



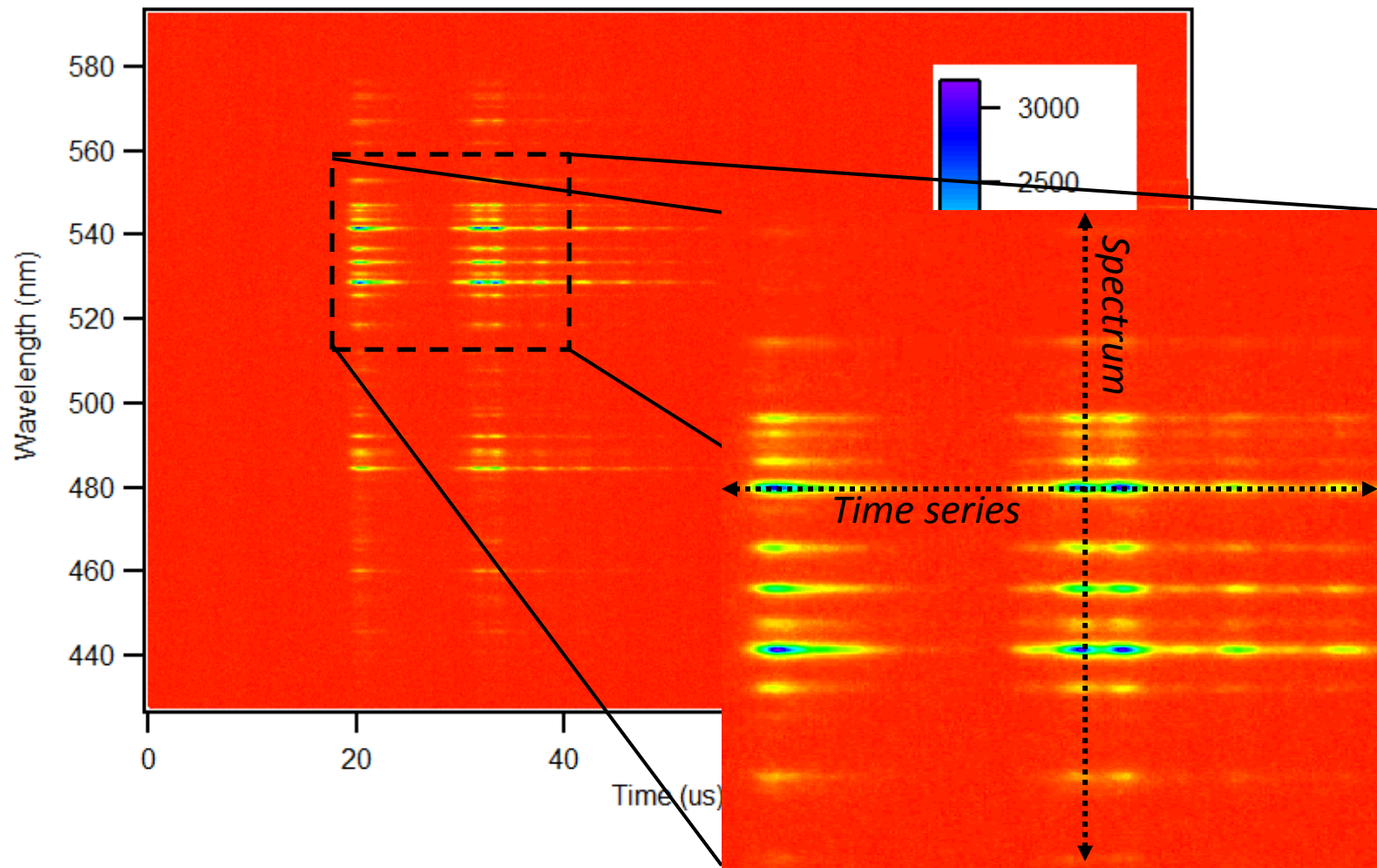




# Data Processing



## Corrected Data

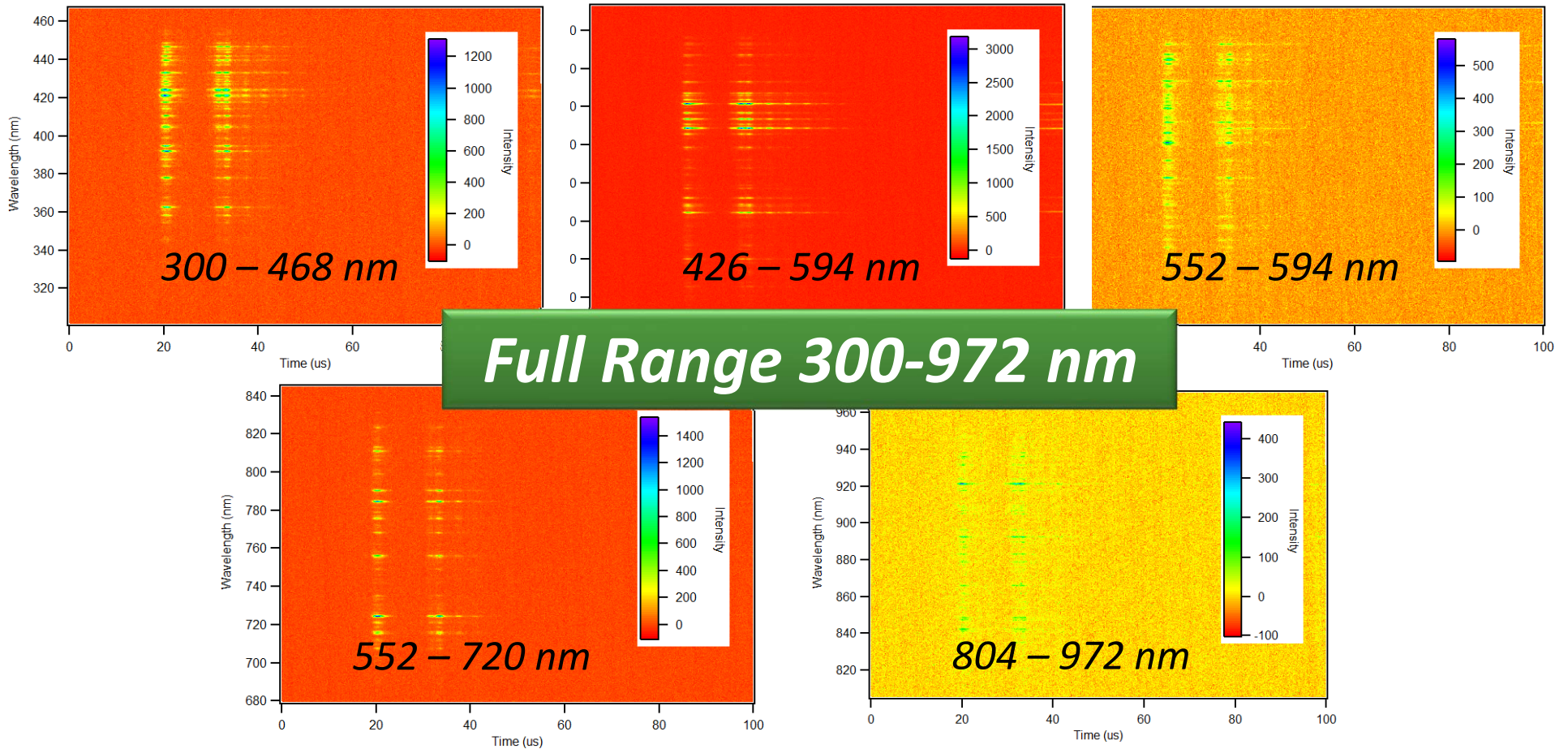




# Data Processing

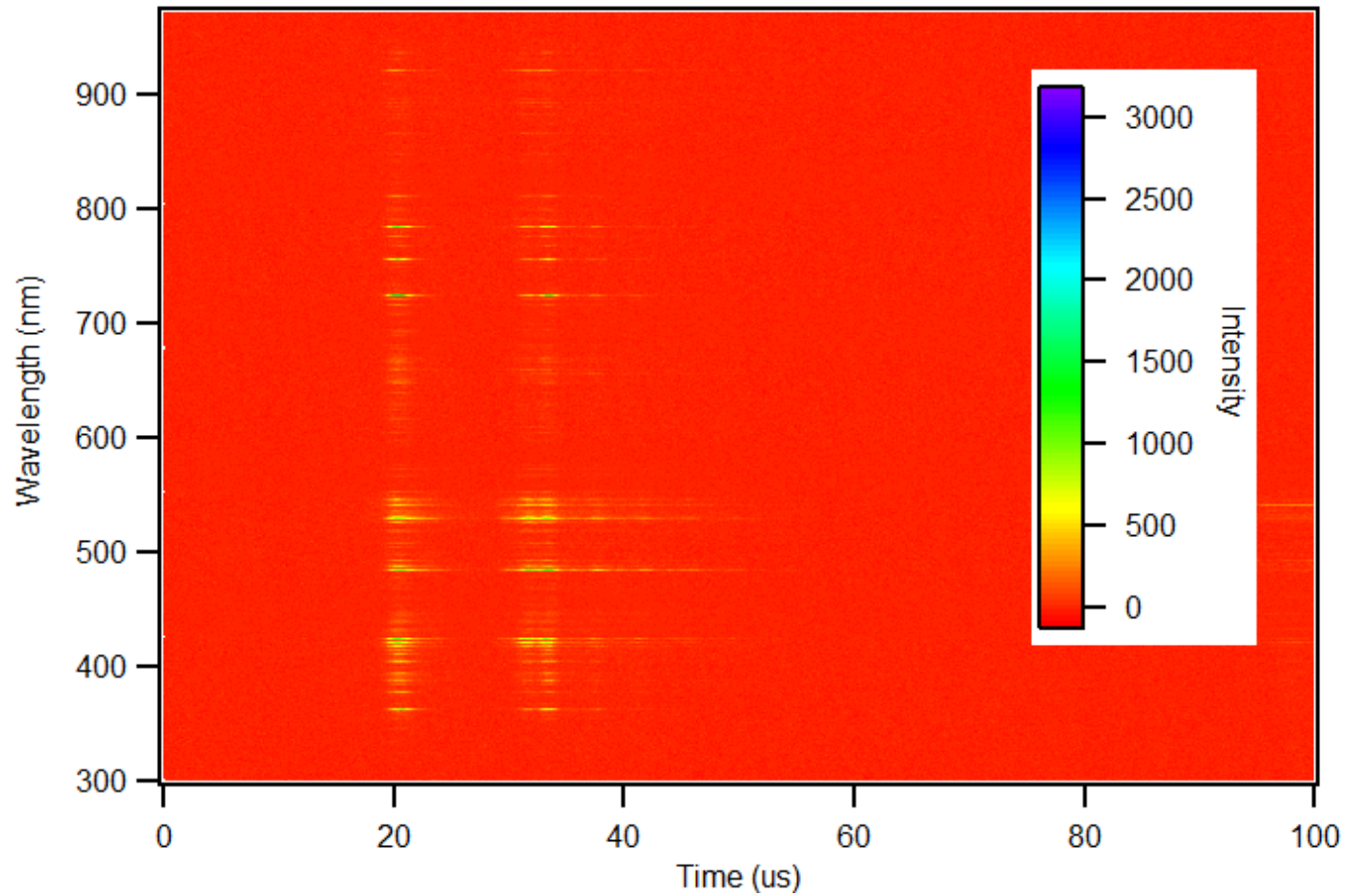


## Mosaicking





# Results

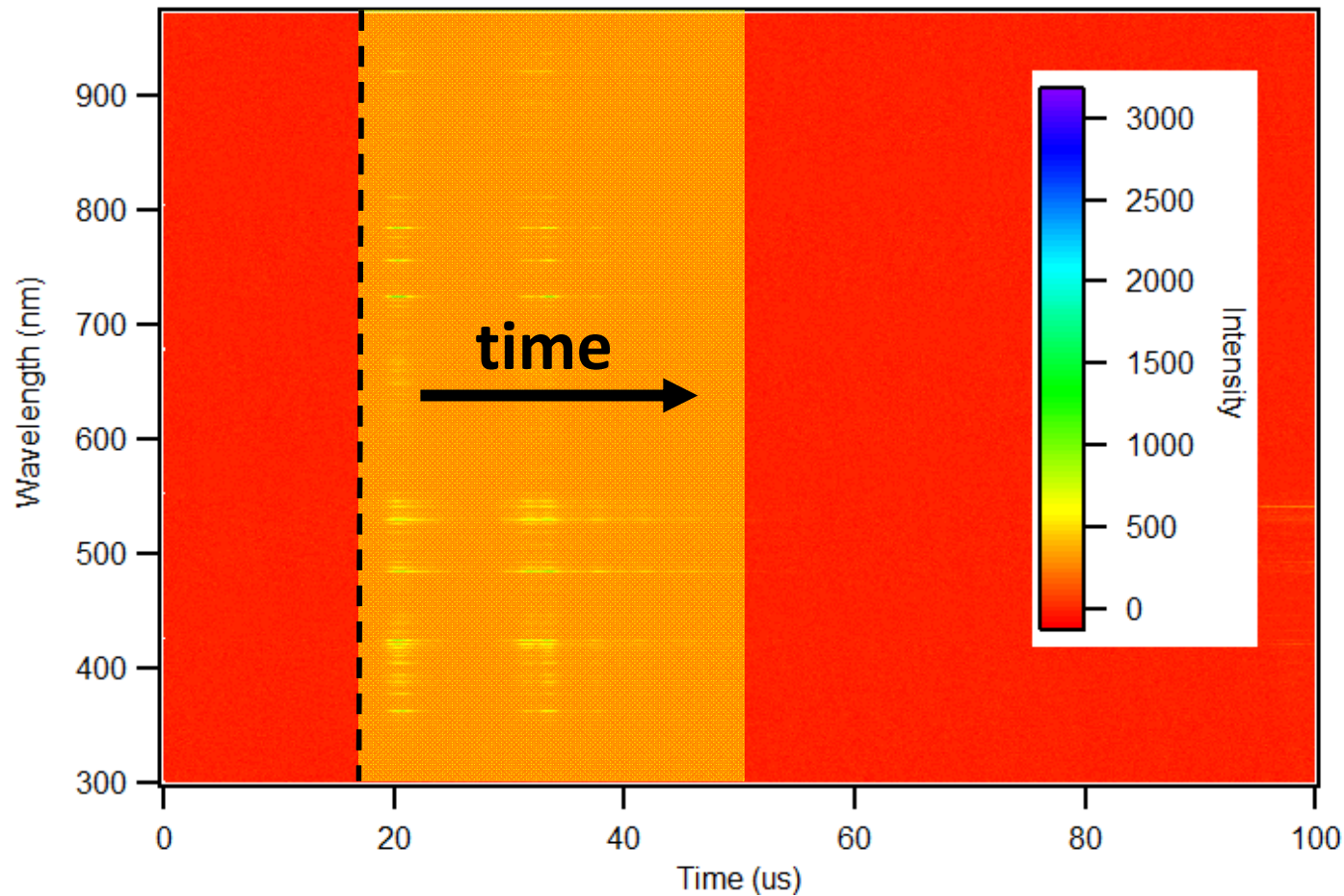




# Results



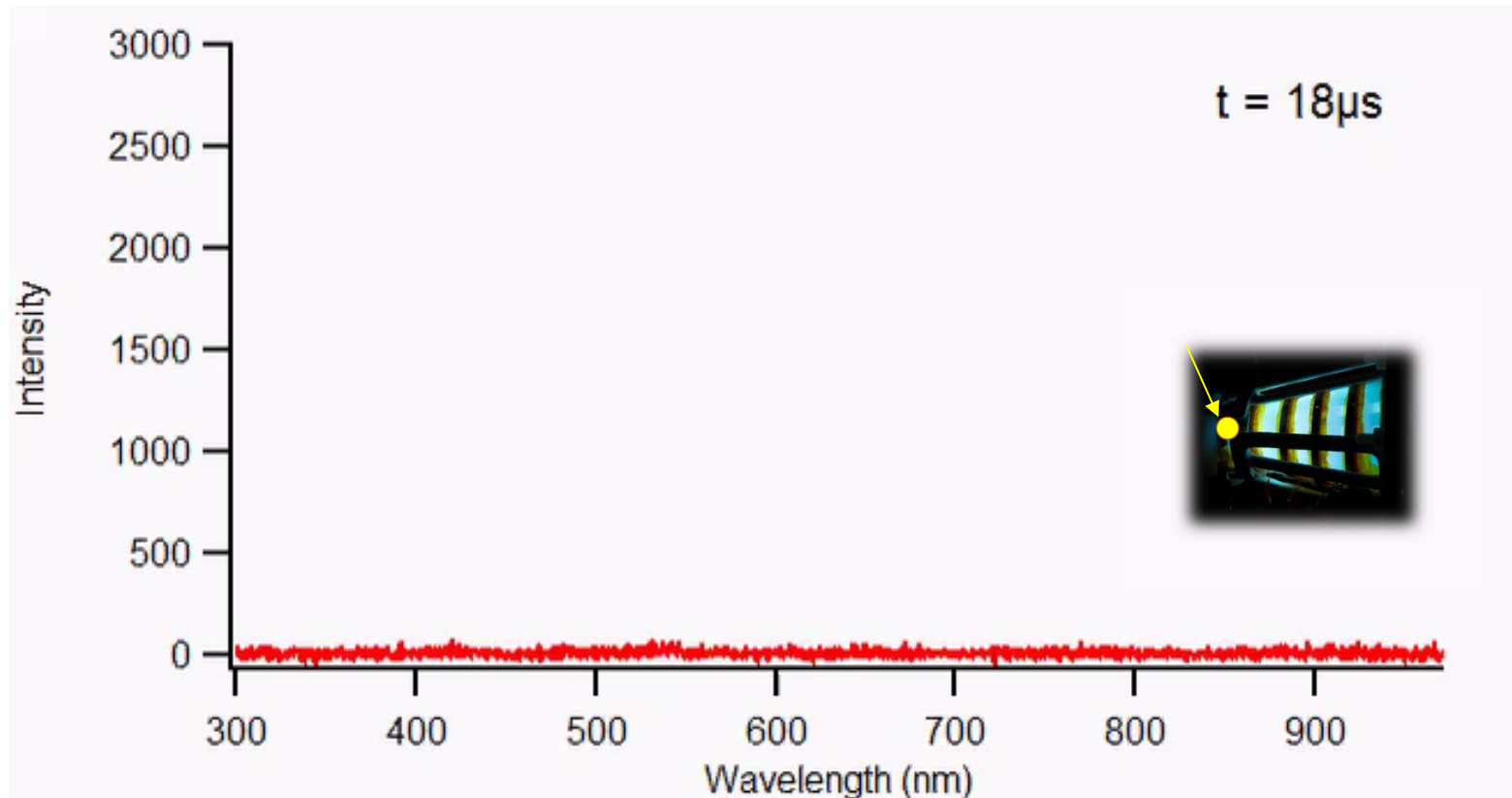
Vertical slice = spectrum at time  $t$







# Results





# Results



**Time-resolved OES** will allow us to answer the following questions:

Is the preionization **efficient**?

How much gas is **ionized**?

How **hot** is the plasma?

How **dense** is the plasma?

Intensity



# Conclusions



- Designed and setup **collection optics**
- Established **data processing** pipeline
- Demonstrated capability of streak camera to capture **time-dependent FRC spectra**



# Future Work



- **Line identification** of xenon spectrum
- Perform **intensity calibration** (deuterium lamp)
- Obtain **Argon FRC data** and use **Collisional Radiative Model (CRM)** to extract **plasma properties**
- Apply knowledge to **improve FRC thruster design**





# Acknowledgments



- **Carrie Hill**
- **Mike Holmes**
- **Nolan Uchizono**
- **ERC**
- **Cece's Cuisine**



# Backup Slides

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# Data Analysis



## Background Subtraction

