SAND2022-7726C

Study of anode-initiated surface flashover in vacuum with spatiotemporally resolved optical emission spectroscopy

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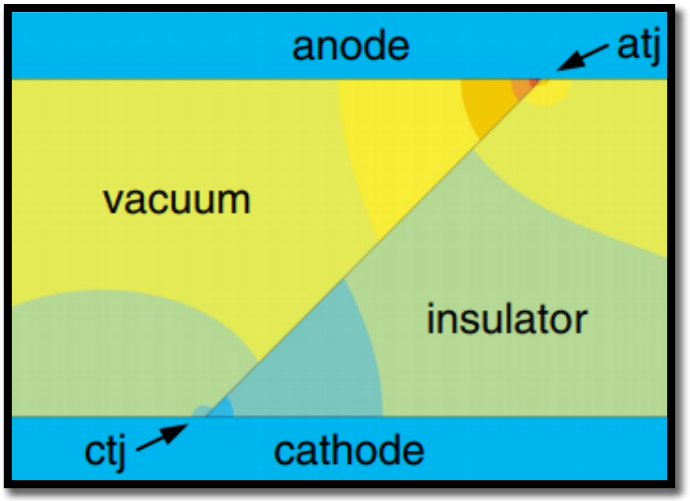
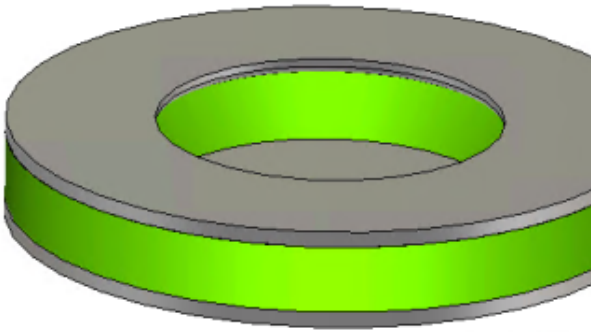
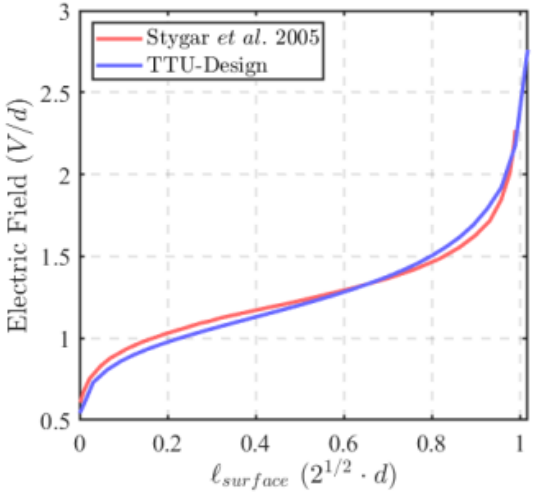
Motivation

- Determine physical mechanisms of flashover initiation in large insulator stack environments in vacuum
  - Improve body of evidence for anode-initiated flashover
    - Desorbed species
    - Bulk insulator involvement
    - Electrode involvement
    - Time scales
  - Support modelling efforts





Stygar-like topology



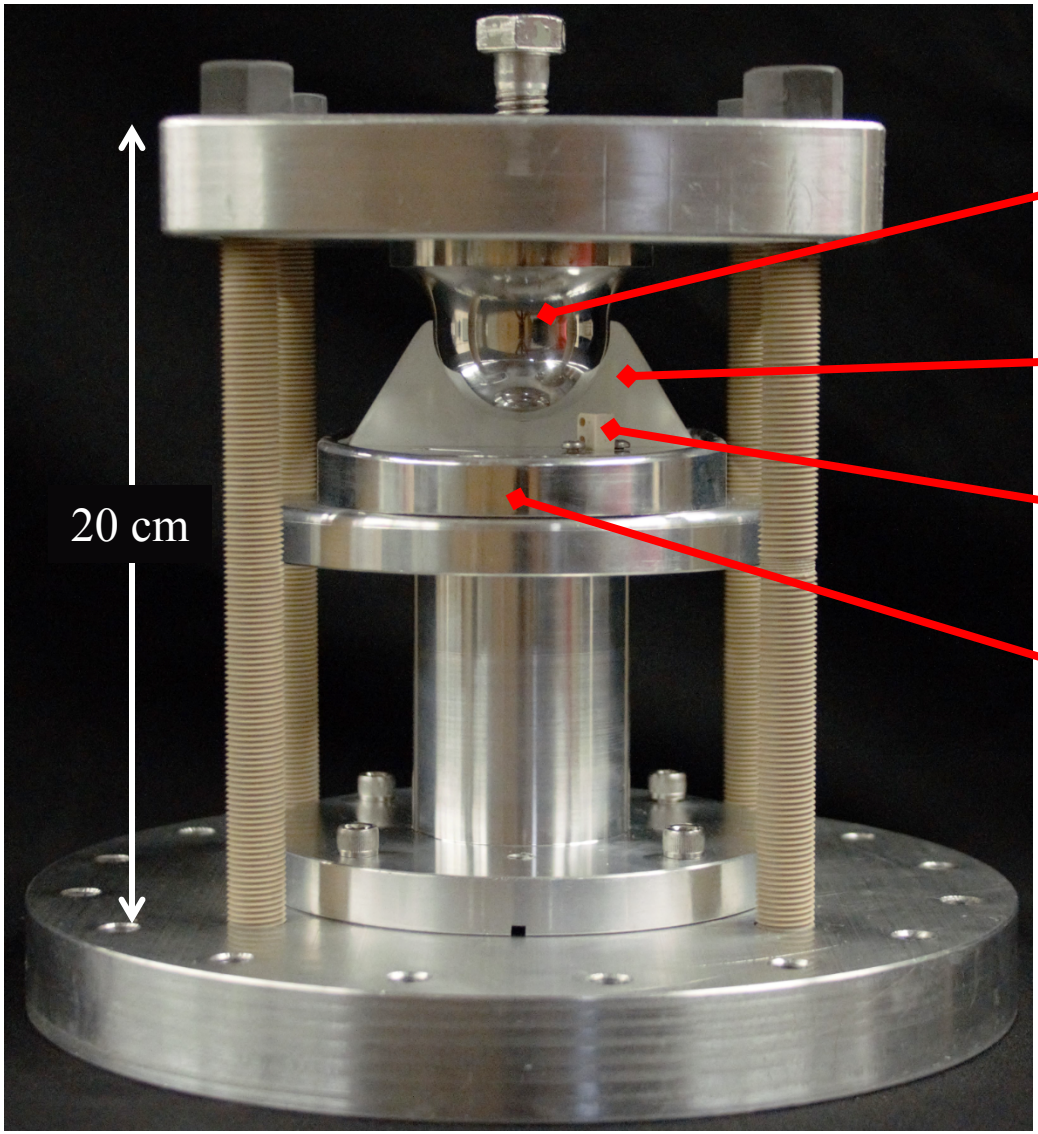
W. A. Stygar et al. 2005, Physical Review Special Topics – Accelerators and Beams 8, 050401 (2005)

Insulator Testbed

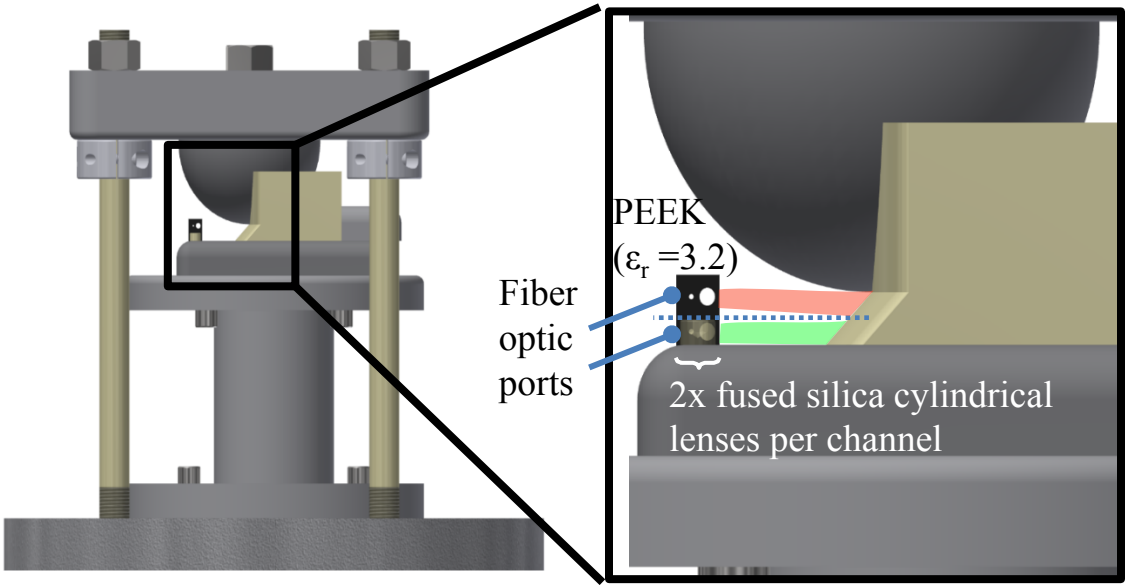
Source:
- 240 kV Marx
- 20-30 ns rise time

Chamber:
- 5×10^{-6} torr typical background pressure
- 22°C typical temperature

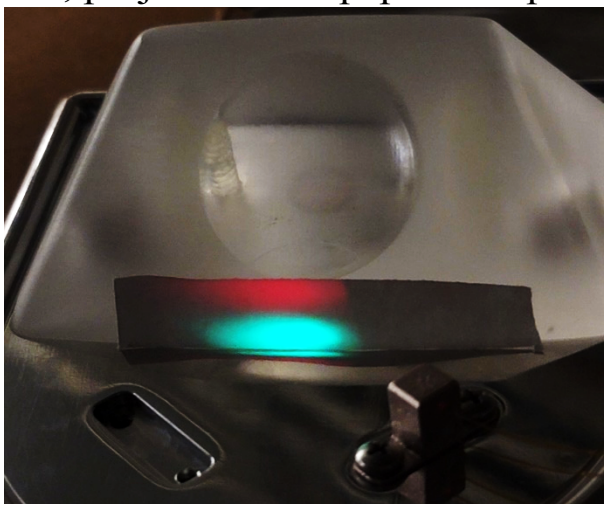
Electrical diagnostics:
- Coaxial CVD
- Coaxial CVR



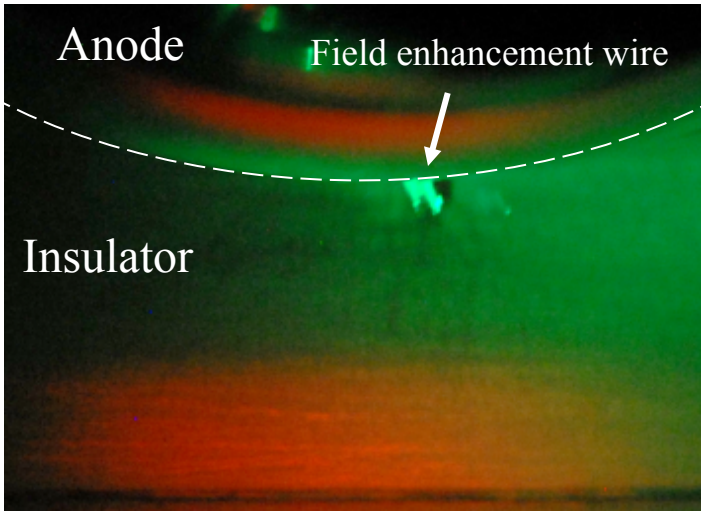
Light Collection



In air, projected onto paper for opacity



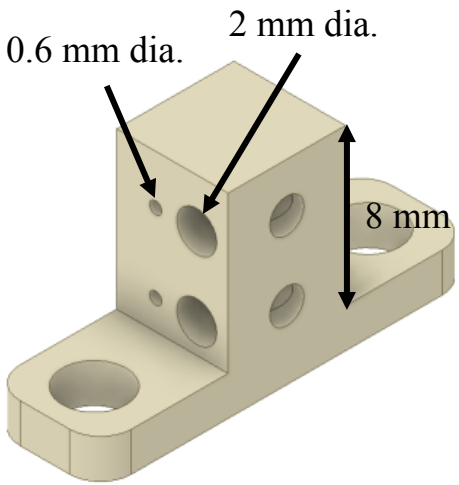
Installed in vacuum chamber



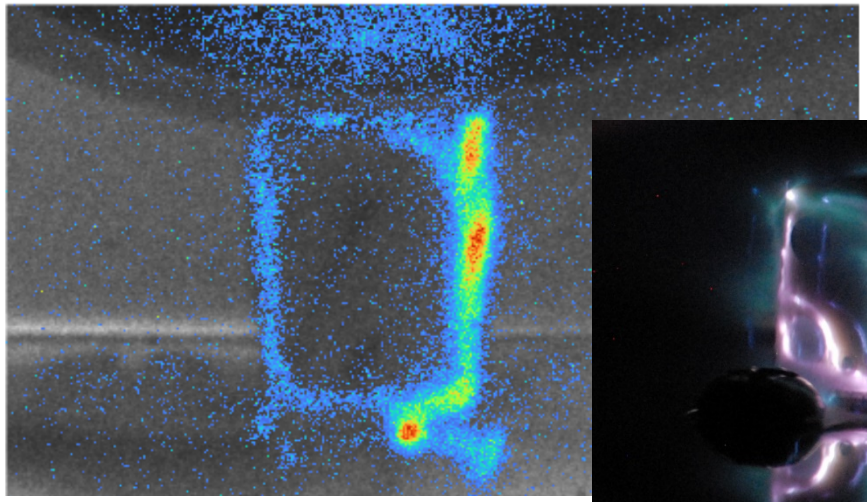
Increased diffusivity due to insulator transparency

Multimode optical fiber
- Solarization resistant
- 180-850 nm transmission
- 200 µm core

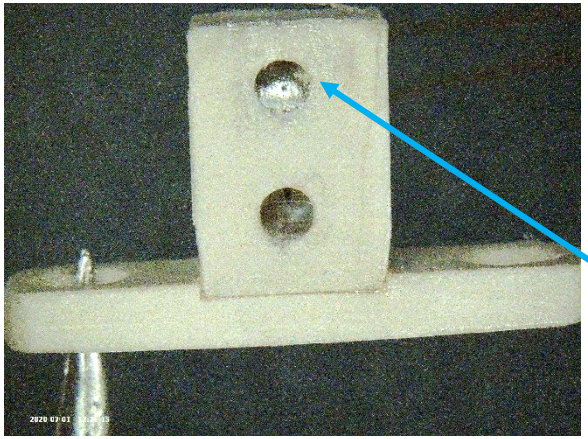
UV-FS Vacuum fiber feedthrough



Optics Holder Protection



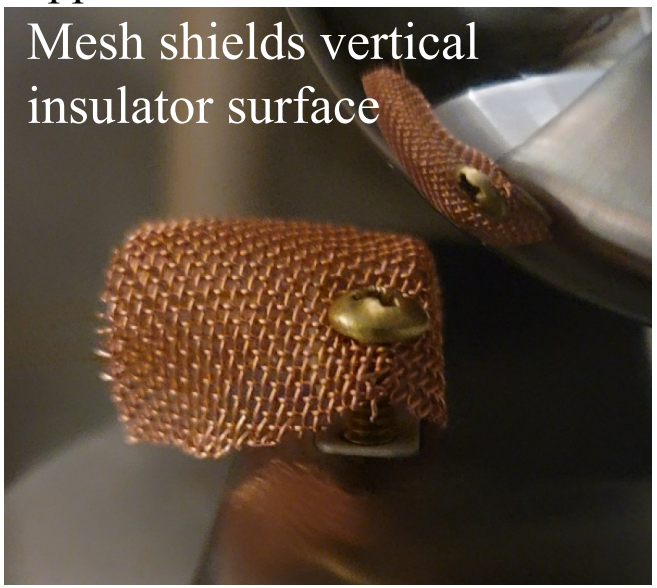
2 ns gate ICCD, false color



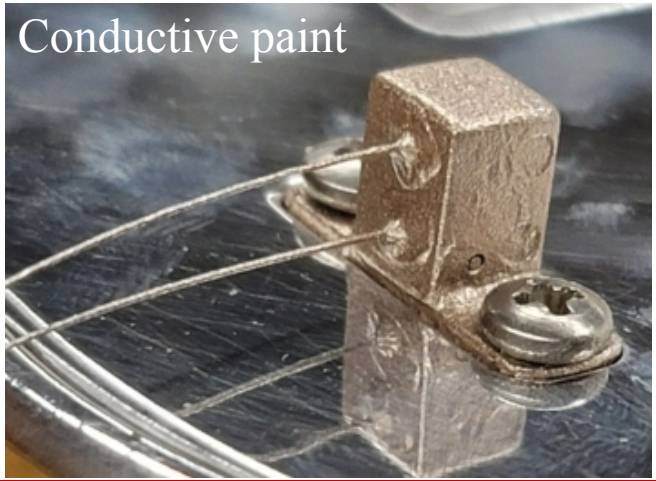
- Flashover along vertical surface of the holder

Debris from anode deposited on and around lenses

Approach 1:



Approach 2:

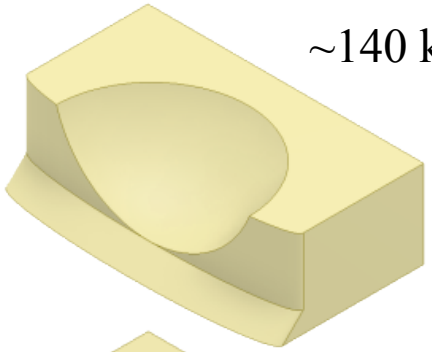


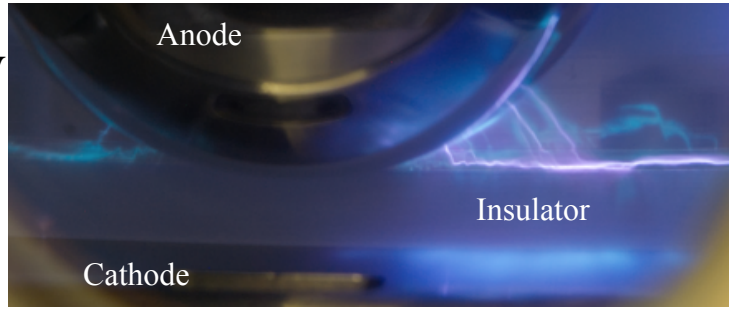
Localizing Flashover

Insulator revisions

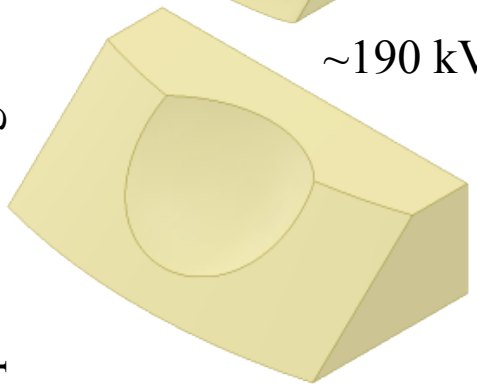
Improved voltage hold-off

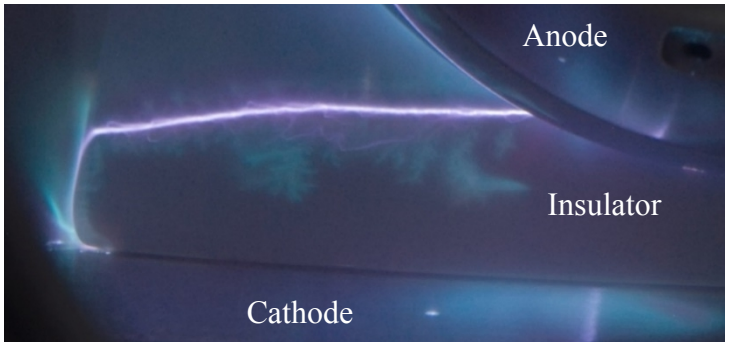
~140 kV



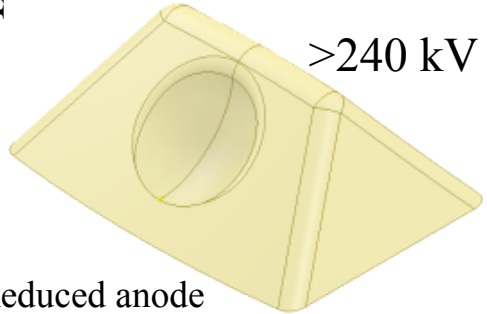


~190 kV





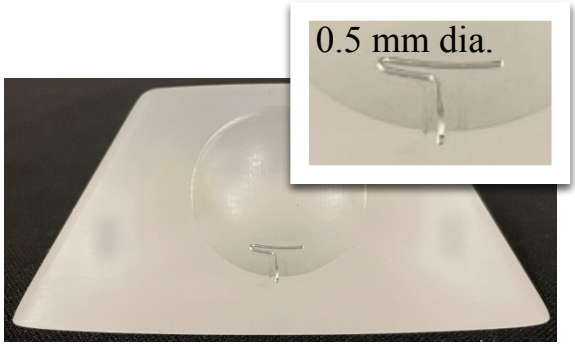
>240 kV



Reduced anode diameter, field shaping

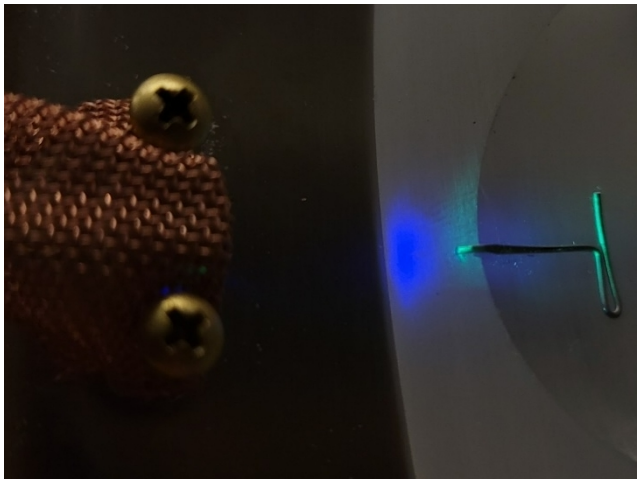
Without initiation point:
Rarely flashes over for 6 mm gap

For repeatable flash-over path initiation, an aluminum wire field enhancement (Al 6061) was added.



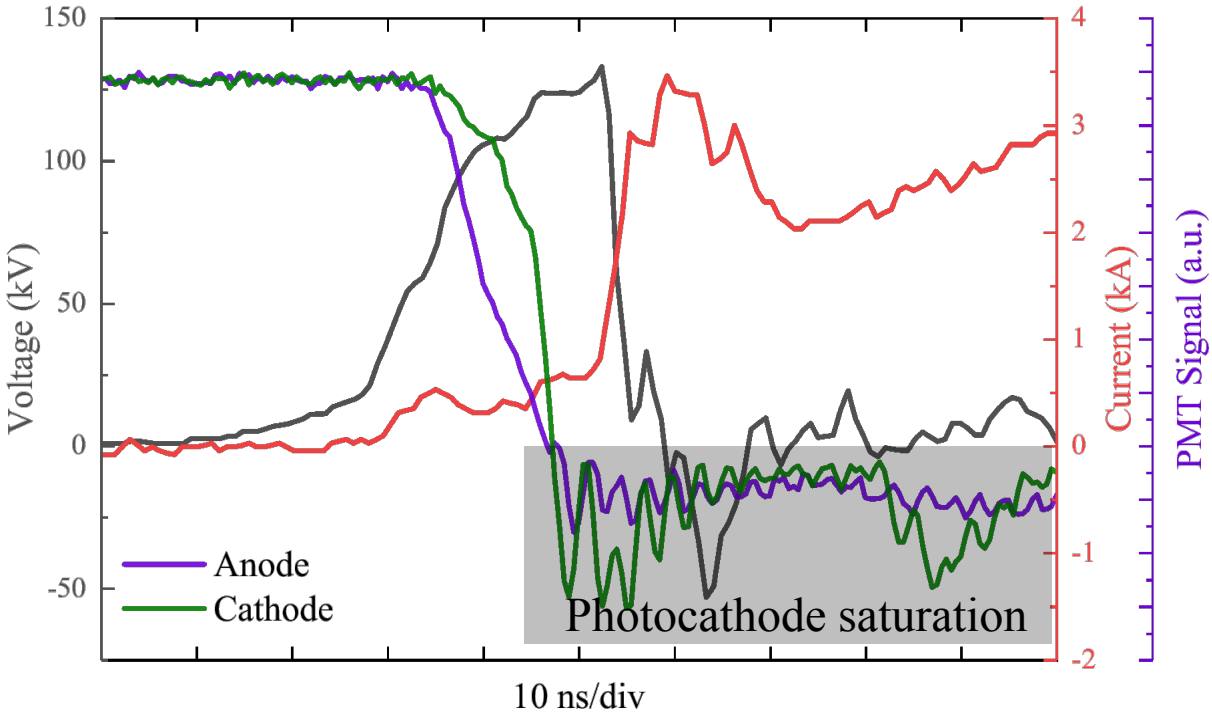
Early Light Emission

- For flashover on pristine insulator, first light appears at anode
- Corroborated by time-resolved imaging
- Voltage, current, and intensity waveforms timed to within ± 1 ns



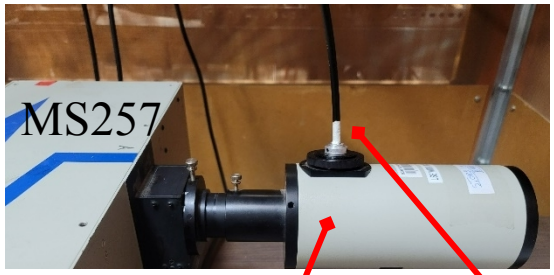
Early light detection with Thorlabs PMTSS

- 1.4 ns rise time
- 185-900 nm spectral response
- Gain > 10^7



Spatially Resolved Spectroscopy

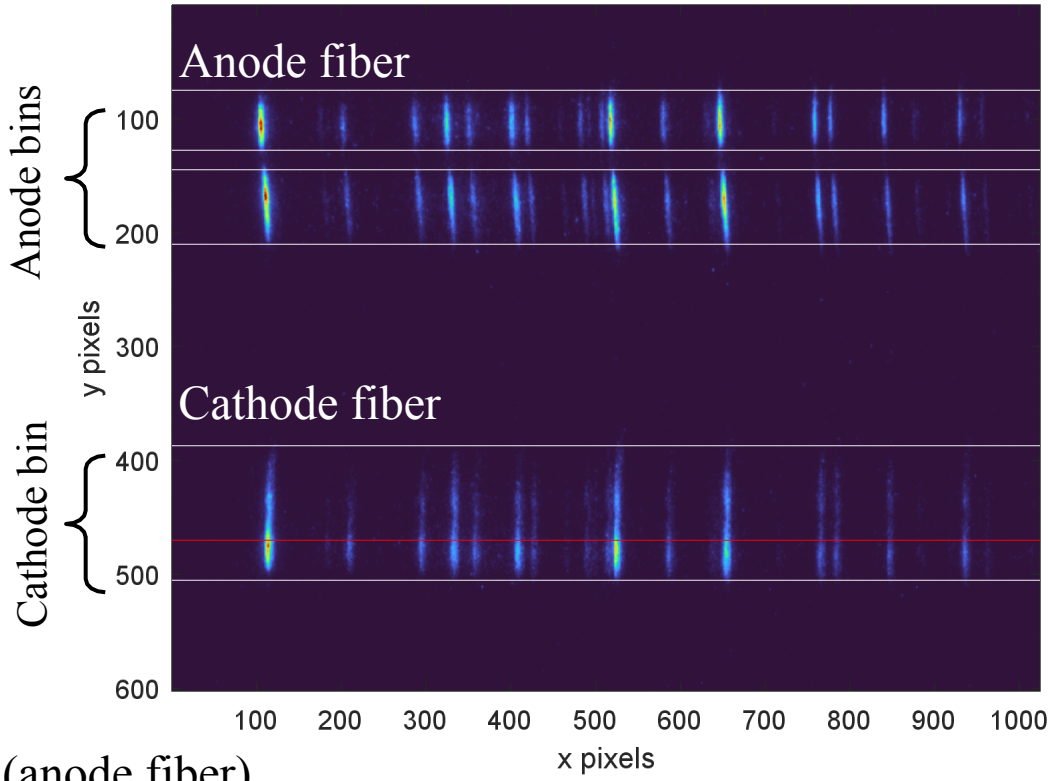
- Oriel MS257 Spectrograph
  - 121.6 lines/mm
  - 413 nm blaze
- Andor iStar DH7 ICCD
  - 3 ns gate capable



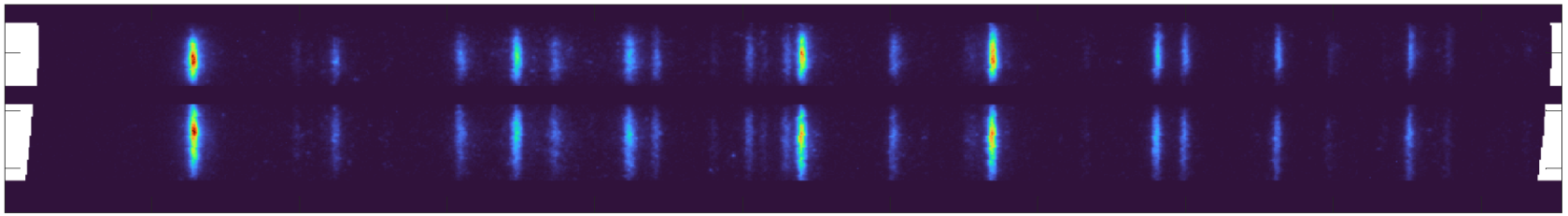
Fiber collimating element

Fiber input

Hg Ar and H He sources fed into fibers to demonstrate spatial resolution on ICCD



Nonlinearity correction example (anode fiber)



Line Identification

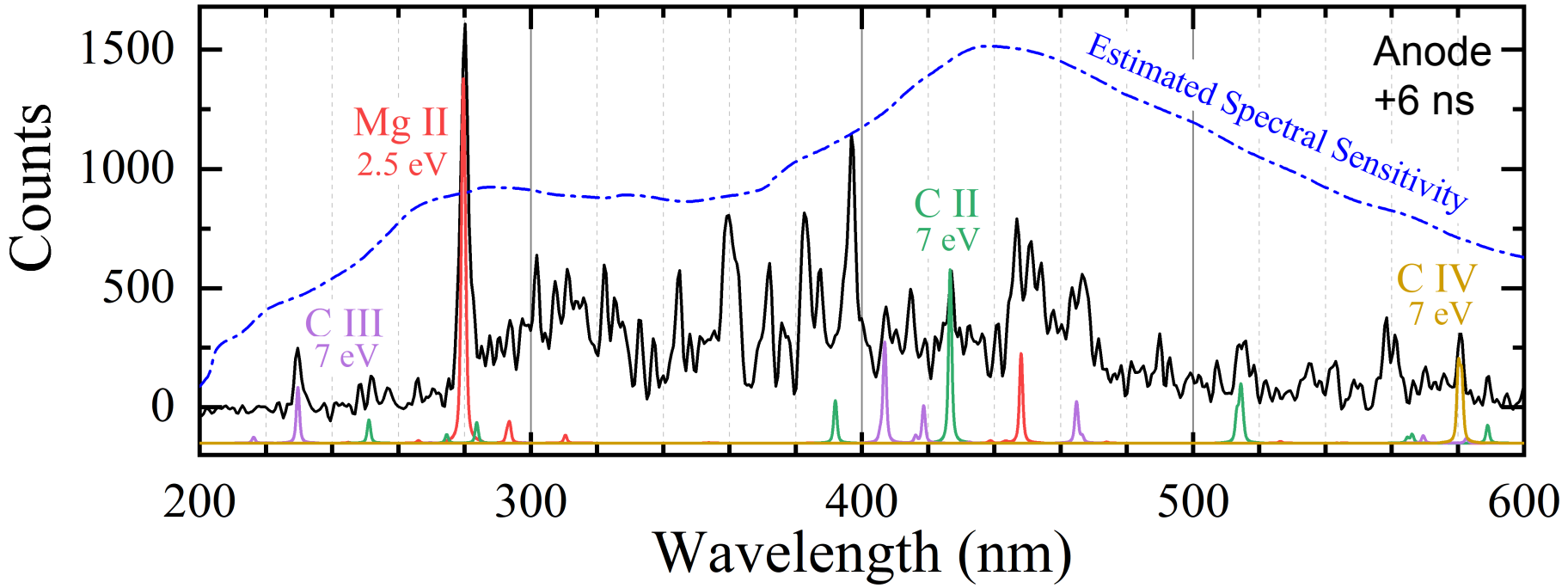
Wavelength accuracy – 0.7 nm/pixel

Spectroscopic notation:
C I – neutral carbon
C II – singly ionized carbon
C III – doubly ionized carbon

Constituents:
Insulator – C, H
Electrodes – Al, Mg, Si
Surface – H_2O, CO, CO_2, O_2
Surface treatment – Si, C

SpectraPlot

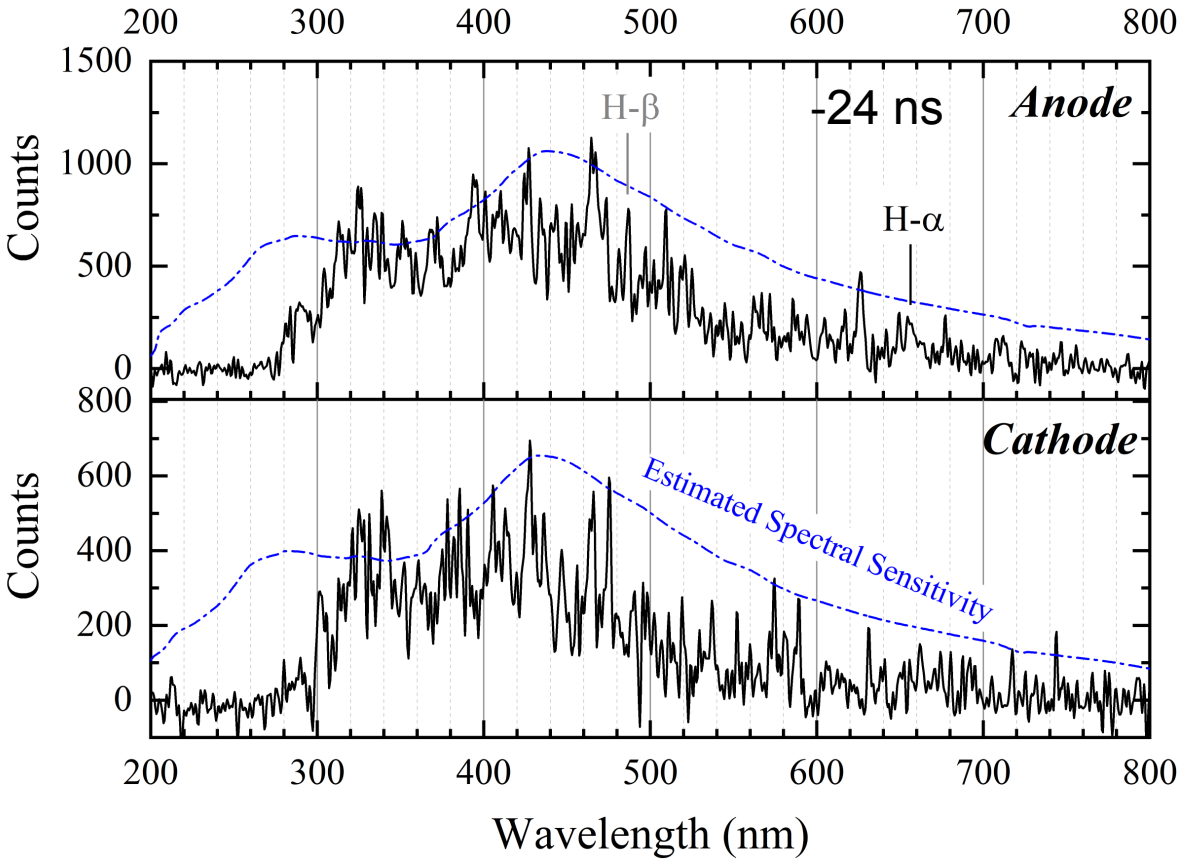
A. Fierro, G. Laity, A. Neuber, "Optical Emission Spectroscopy Study in the VUV-VIS Regimes of a Developing Low-Temperature Plasma in Nitrogen gas," Journal of Physics D: Applied Physics, vol. 45, 495202, 2012.

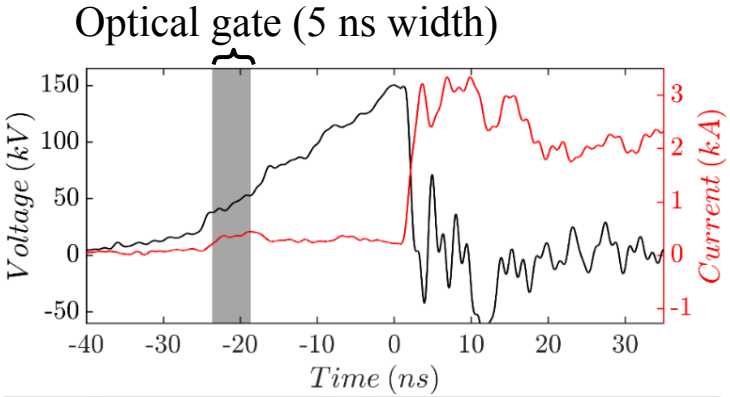


Simulated spectra offset by 150 counts for viewing purposes

OES Time Series (Ins. A, -24 ns)

- Broadband background characteristic of cathodoluminescence or similar
  - Governed by optical characteristics of polystyrene toward the UV

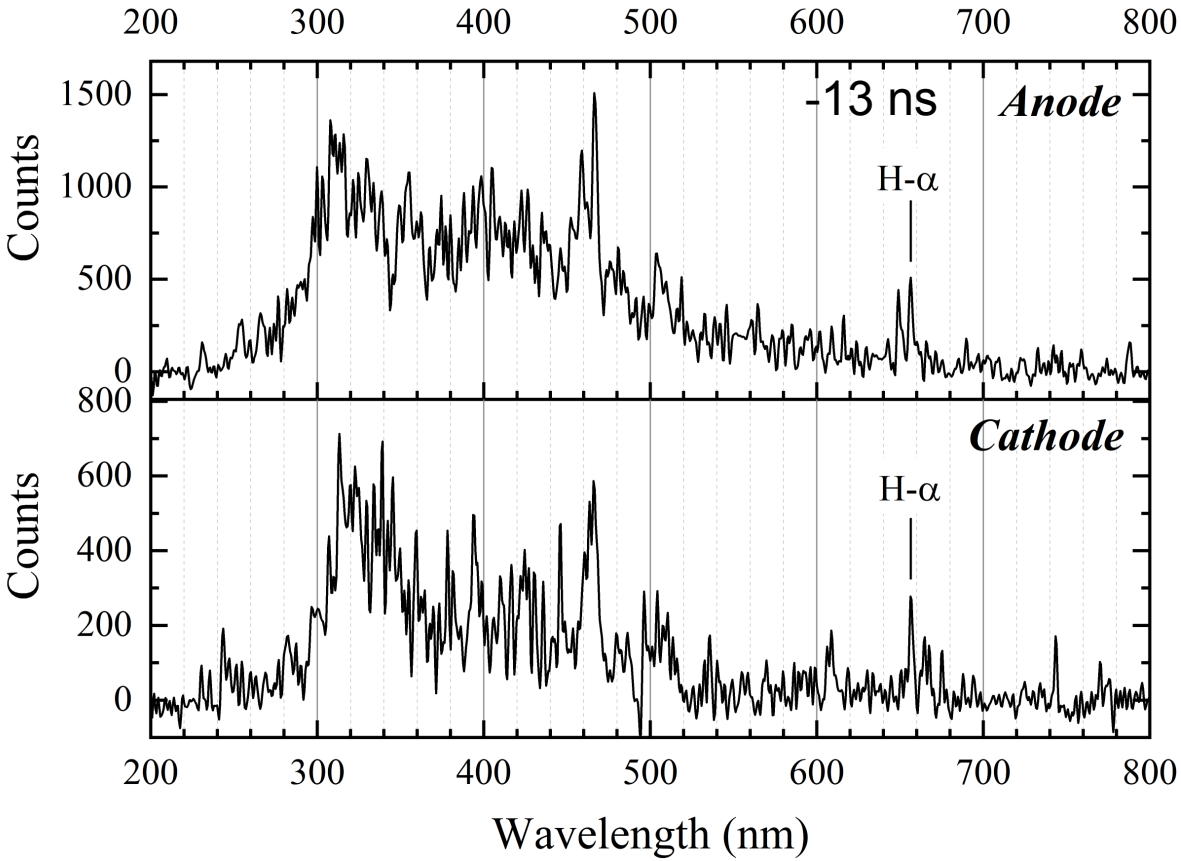




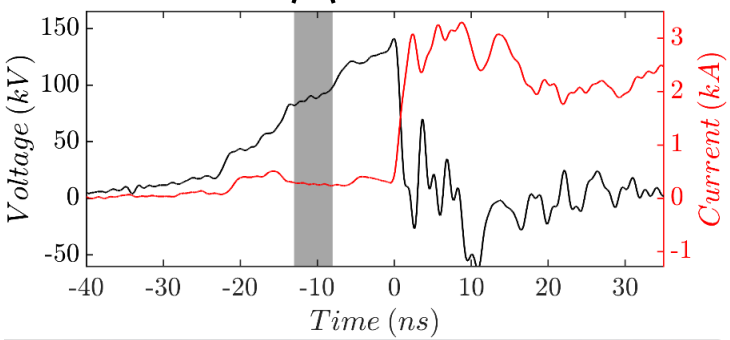
Black: High degree of confidence
Gray: Lesser degree of confidence

OES Time Series (Ins. A, -13 ns)

High confidence transitions (nm):
H - **656.3**



Optical gate (5 ns width)

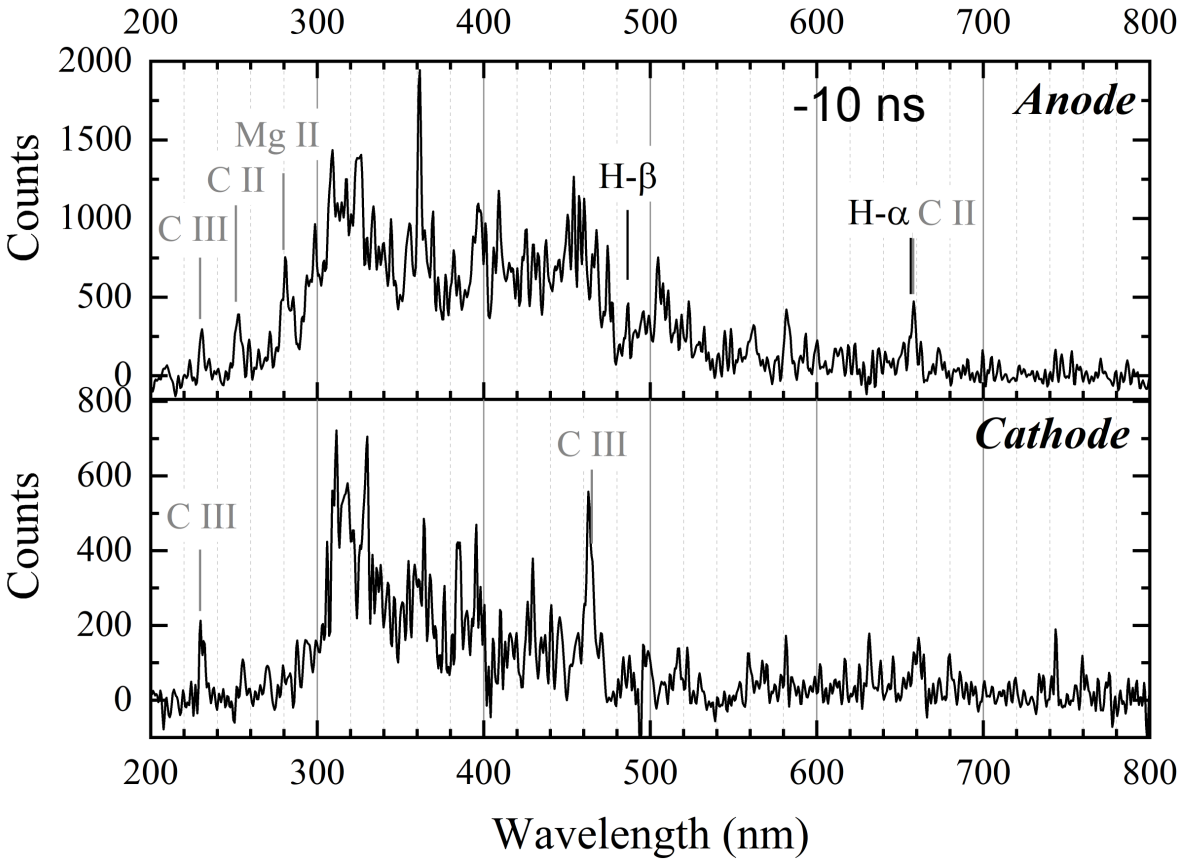


Black: High degree of confidence
Gray: Lesser degree of confidence

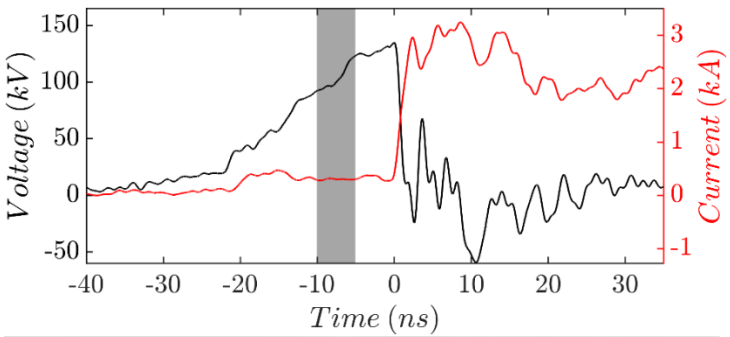
OES Time Series (Ins. A, -10 ns)

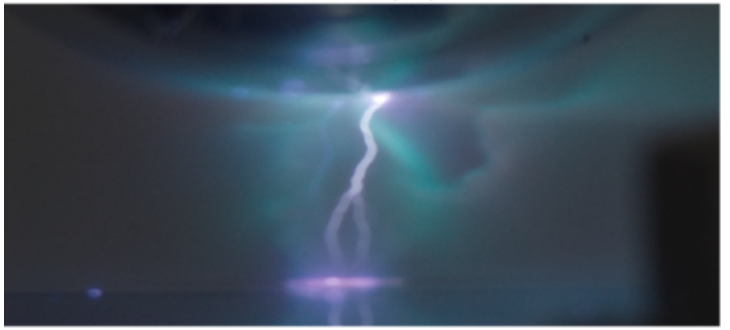
High confidence transitions (nm):
H - **486.1**, **656.3**

Possible transitions (nm):
C II – **251.1**, 283.7, 392.0, 426.7, 514.5, 589.0, **657.9**
C III – **229.7**, 406.9, 418.7, 464.8
Mg II – **279.7**, 448.1



Optical gate (5 ns width)



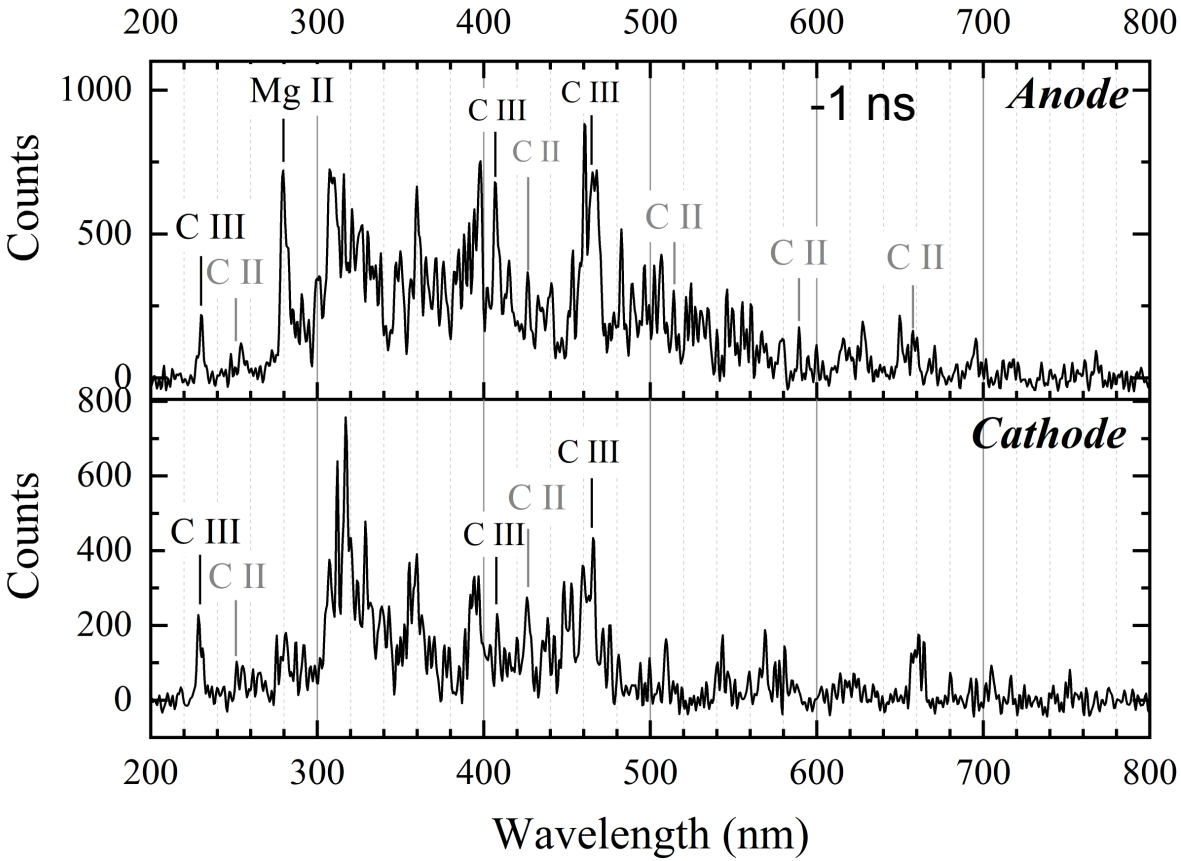


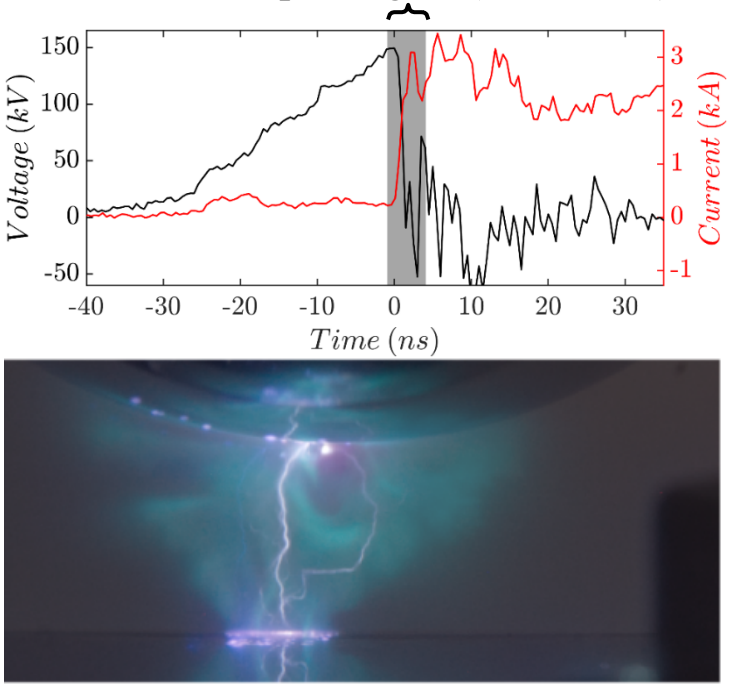
Black: High degree of confidence
Gray: Lesser degree of confidence

OES Time Series (Ins. B, -1 ns)

High confidence transitions (nm):
C III – **229.7**, **406.9**, 418.7, **464.8**
Mg II – **279.7**, 448.1

Possible transitions (nm):
C II – **251.1**, 283.7, 392.0, **426.7**, **514.5**, **589.0**, **657.9**



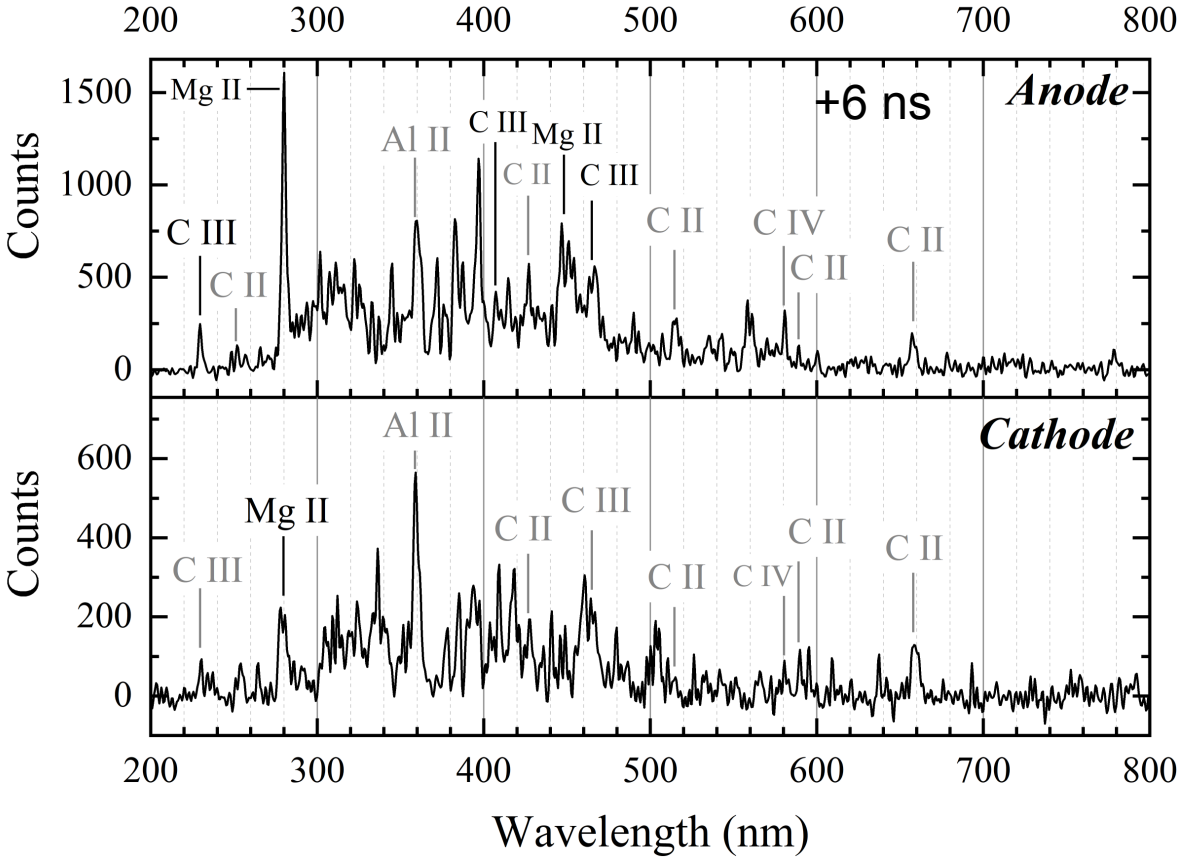


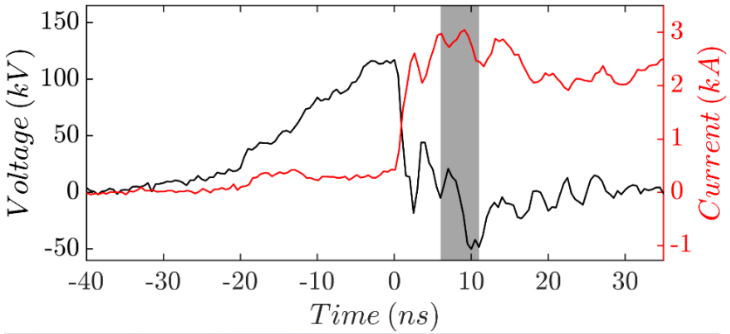
Black: High degree of confidence
Gray: Lesser degree of confidence

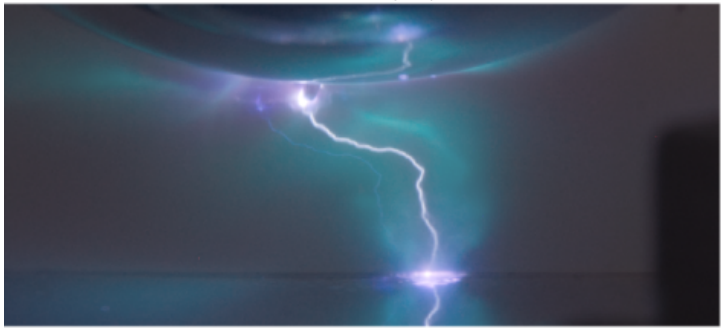
OES Time Series (Ins. B, +6 ns)

High confidence transitions (nm):
C III – **229.7**, **406.9**, 418.7, **464.8**
Mg II – **279.7**, **448.1**

Possible transitions (nm):
C II – **251.1**, 283.7, 392.0, **426.7**, **514.5**, **589.0**, **657.9**
C IV – **580.3**
Al II – **358.7**





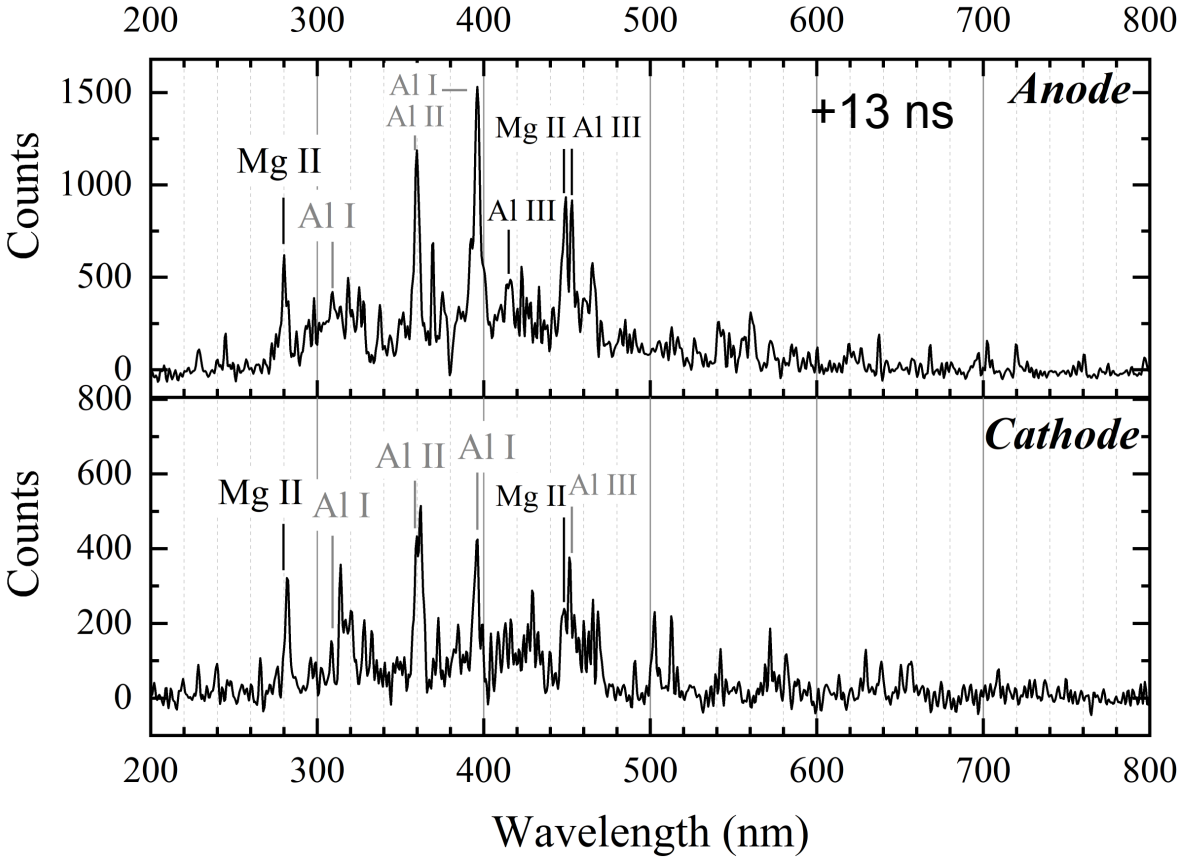


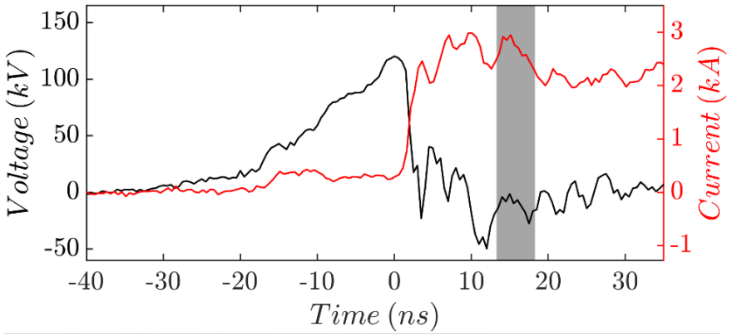
Black: High degree of confidence
Gray: Lesser degree of confidence

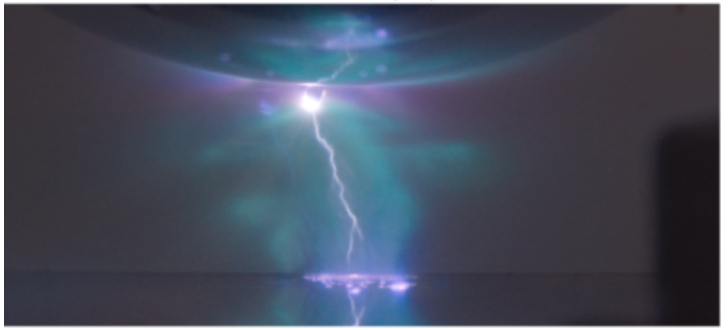
OES Time Series (Ins. B, +13 ns)

High confidence transitions (nm):
Mg II – **279.7**, **448.1**
Al III – **415.0**, **452.9**

Possible transitions (nm):
Al I – **309.2**, **396.2**
Al II – **358.7**







Black: High degree of confidence
Gray: Lesser degree of confidence

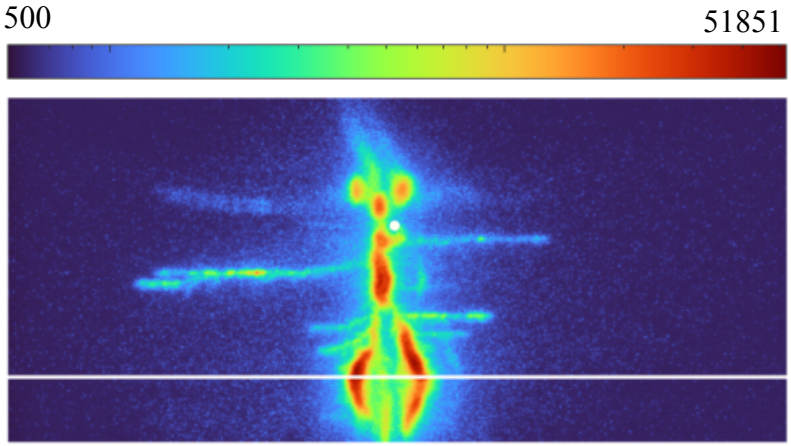
Conclusions

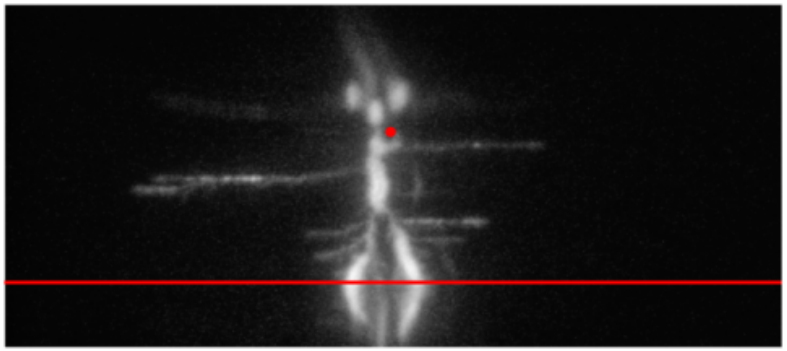
Conclusions:

- Successfully implemented spatially resolved photodetection across insulator surface
- Early anode light precedes cathode light by nanoseconds
- Anode and cathode regions exhibit distinct spectral development

Future Work:

- Detailed characterization of spectral development
- Transition to next generation flashover setup (>600 kV, >1 cm gap)
- Continued development of insulator geometry
  - Localize the breakdown, possibly **without** the need for the wire



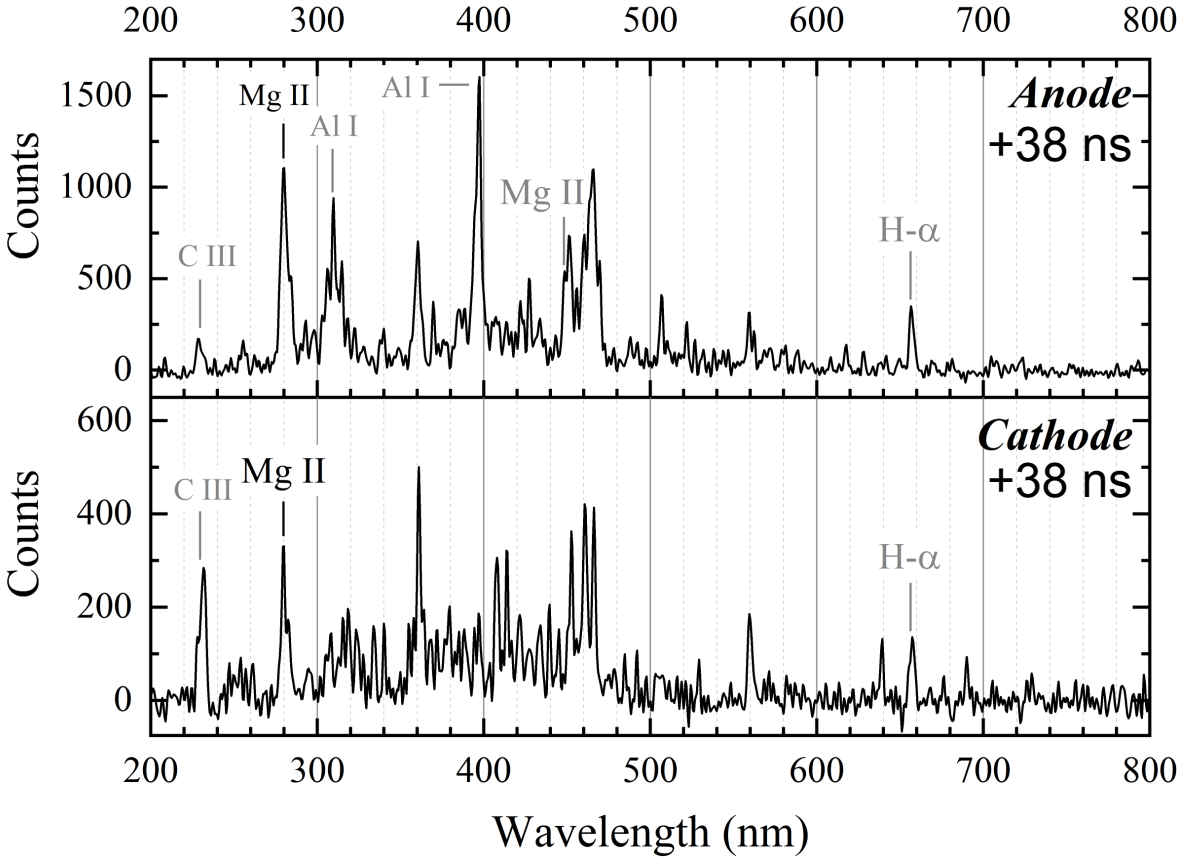


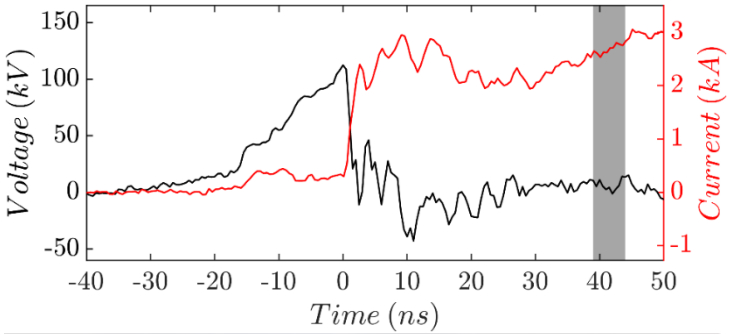
Appendix

OES Time Series (Ins. B, +38 ns)

High confidence transitions (nm):
Mg II – **279.7**, **448.1**

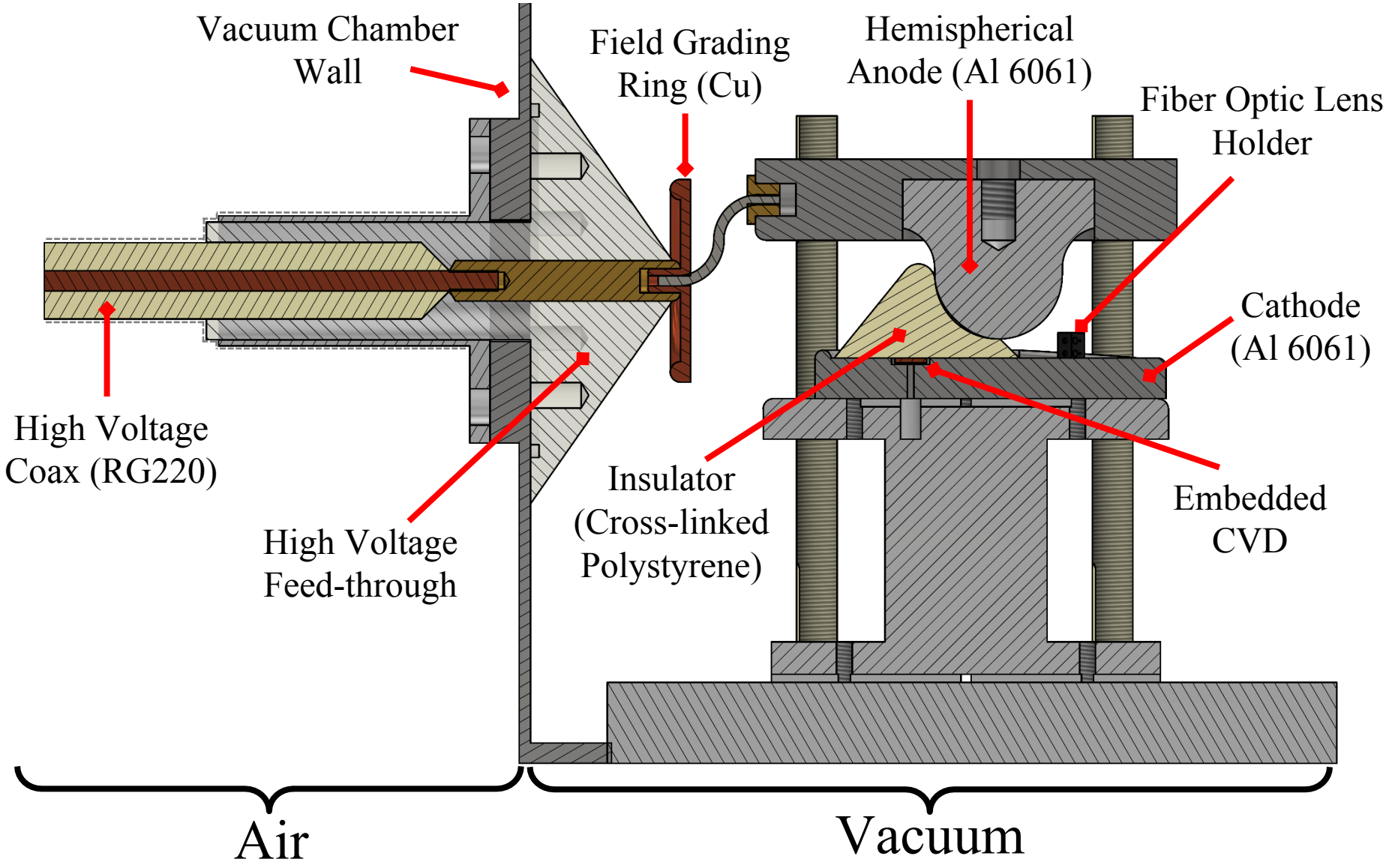
Possible transitions (nm):
H – **656.3**
Al I – **309.2**, **396.2**
C III – **229.7**



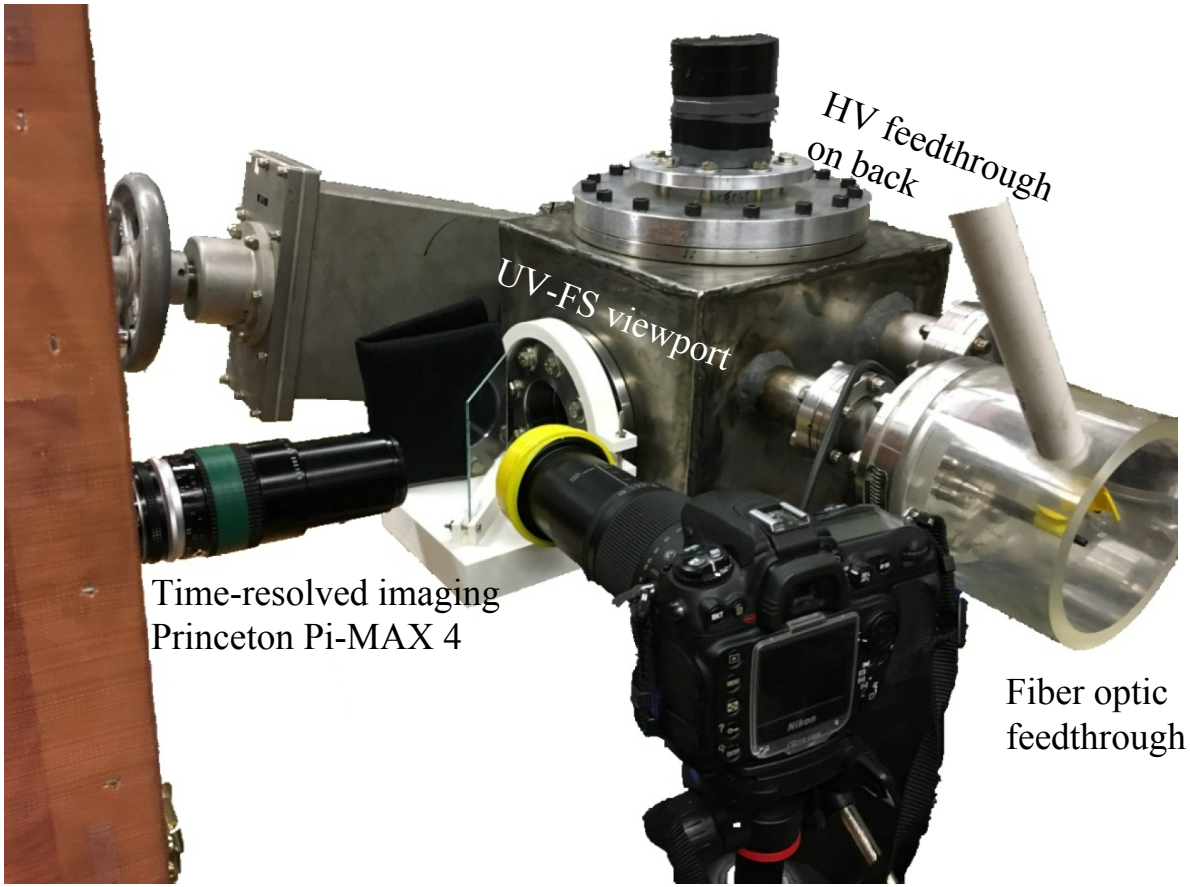


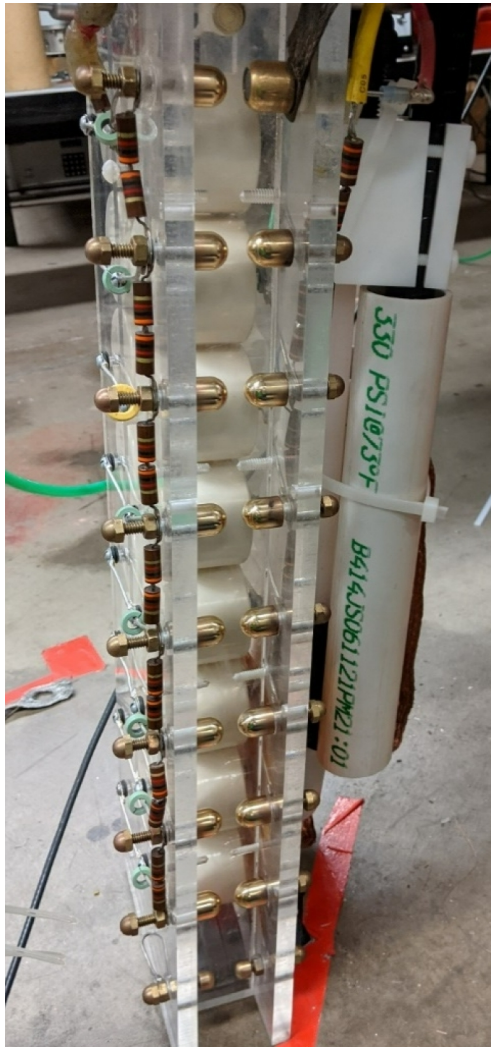
Black: High degree of confidence
Gray: Lesser degree of confidence

Insulator Testbed Cross-Section



Flashover Chamber and Source





30 kV charged, 240 kV, 675 pF erected pressurized Marx

Coaxially integrated electrical diagnostics
- Capacitive voltage divider
- ~50 mΩ current viewing resistor