Vacuum Breakdown at 110 GHz

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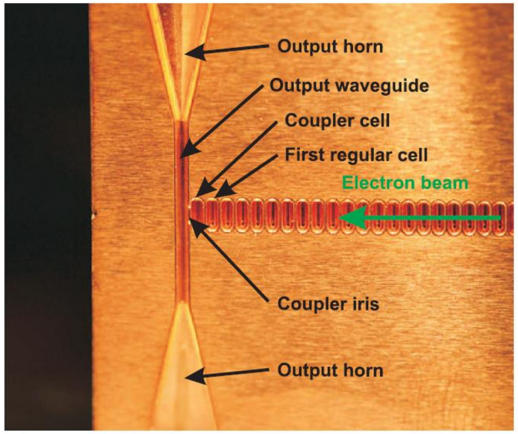
October 11, 2016

Motivations and Goals



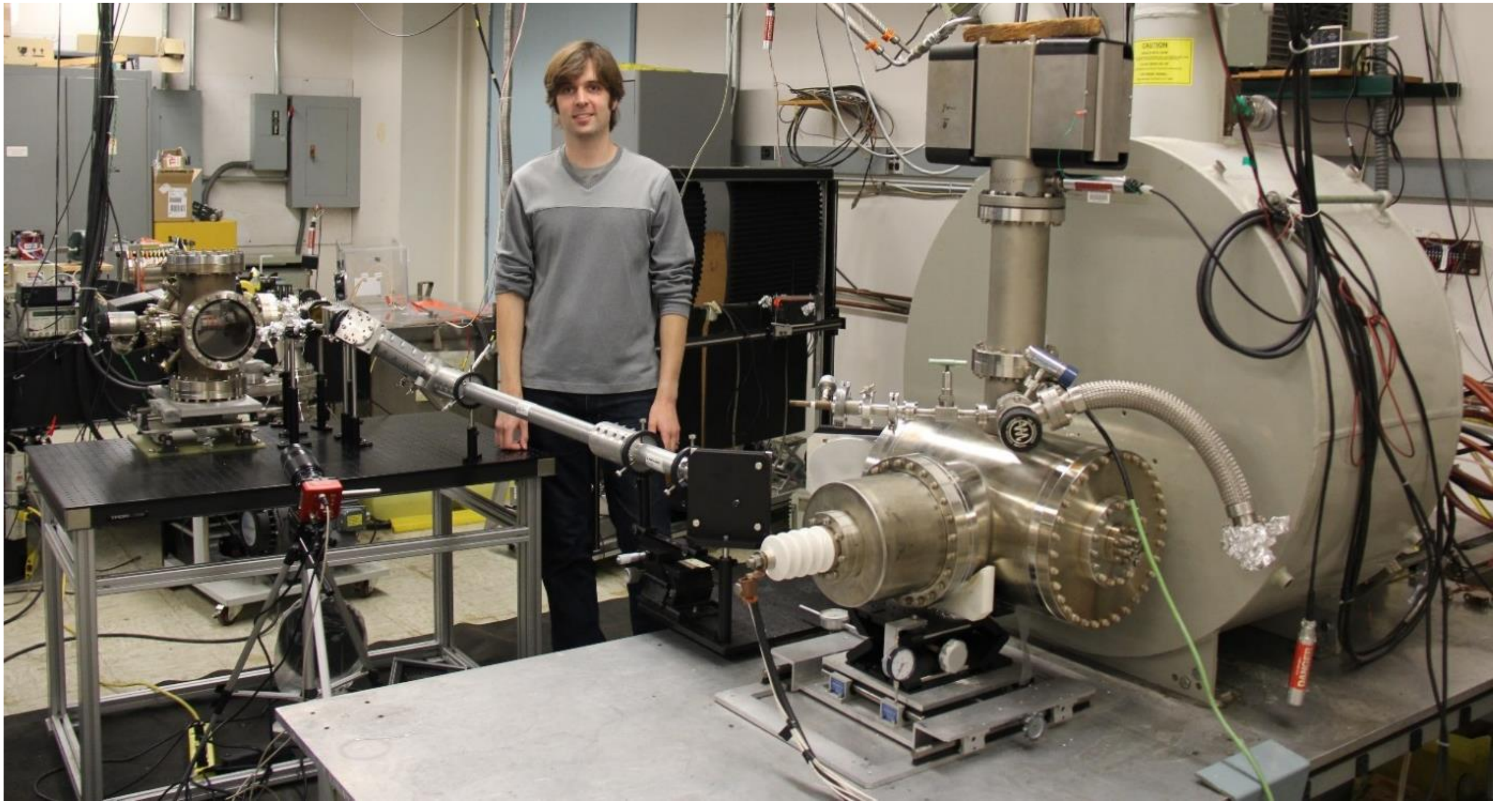
- Millimeter-wave RF LINAC structures have been the subject of recent research
  - Wakefield structures tested by SLAC at FACET facility[1]
  - THz-driven electron LINAC demonstrated at MIT[2]
- There is a lack of experimental data on breakdown thresholds of materials at these frequencies (> 100 GHz)
  - Due to historical lack of sources
  - Megawatt gyrotrons have been developed for fusion applications
- Goals: Test breakdown thresholds of materials in physically simple geometries using a 110 GHz, 1.5 MW gyrotron
  - Multipactor breakdown of dielectrics
  - RF breakdown in simple metallic cavity in collaboration with SLAC[3]

1. M. Dal Forno et al., "Experimental measurements of rf breakdowns and deflecting gradients in mm-wave metallic accelerating structures," Phys. Rev. Accel. Beams, vol. 19, p. 051302, (2016).

2. E. Nanni et al., "Terahertz-driven linear electron acceleration," Nature Communications, vol. 6, p. 8486, (2016).

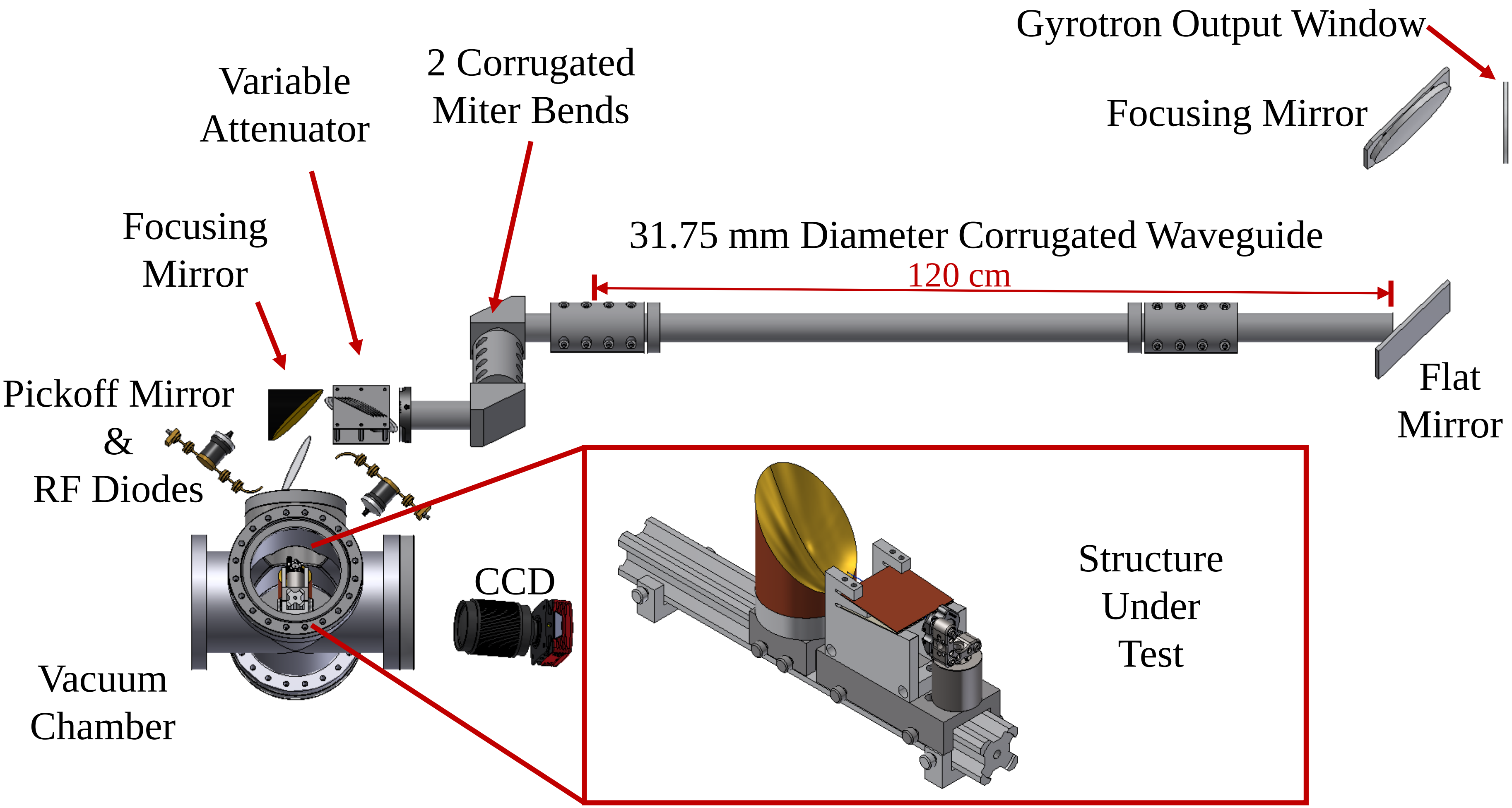
3. E. Nanni et al., "mm-Wave Standing-Wave Accelerating Structures for High-Gradient Tests" presented at IPAC16, Busan, Korea (2016)

Experiment Overview



- Gyrotron
  - Up to 1.5 MW
  - 110 GHz
  - 3 μs pulses
  - 1 Hz rep. rate
  - Gaussian beam output in free space

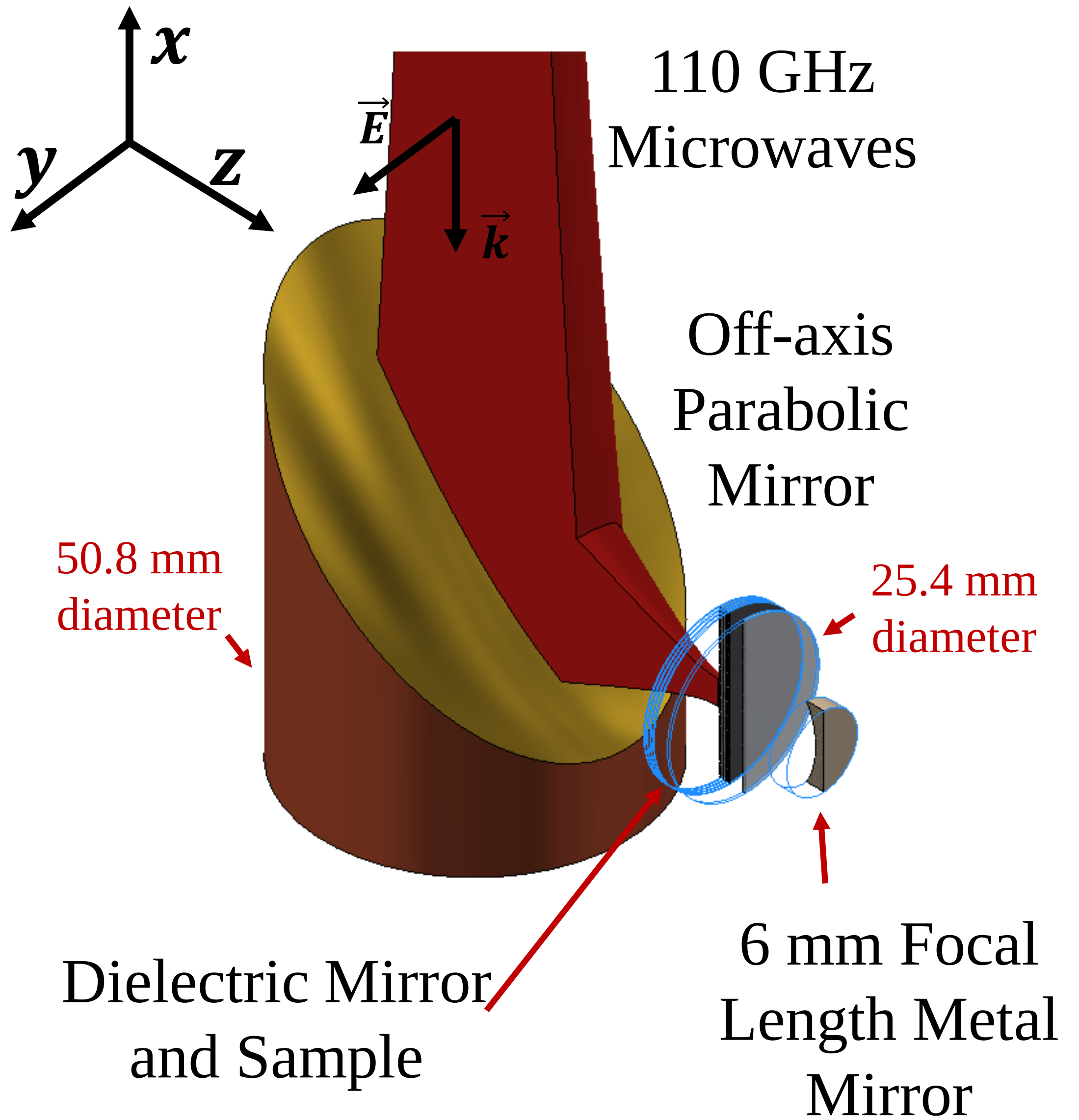
Experiment Overview



- Diagnostics
  - Forward and Reverse RF diode
  - Pressure Monitor
  - Visible light CCD imager

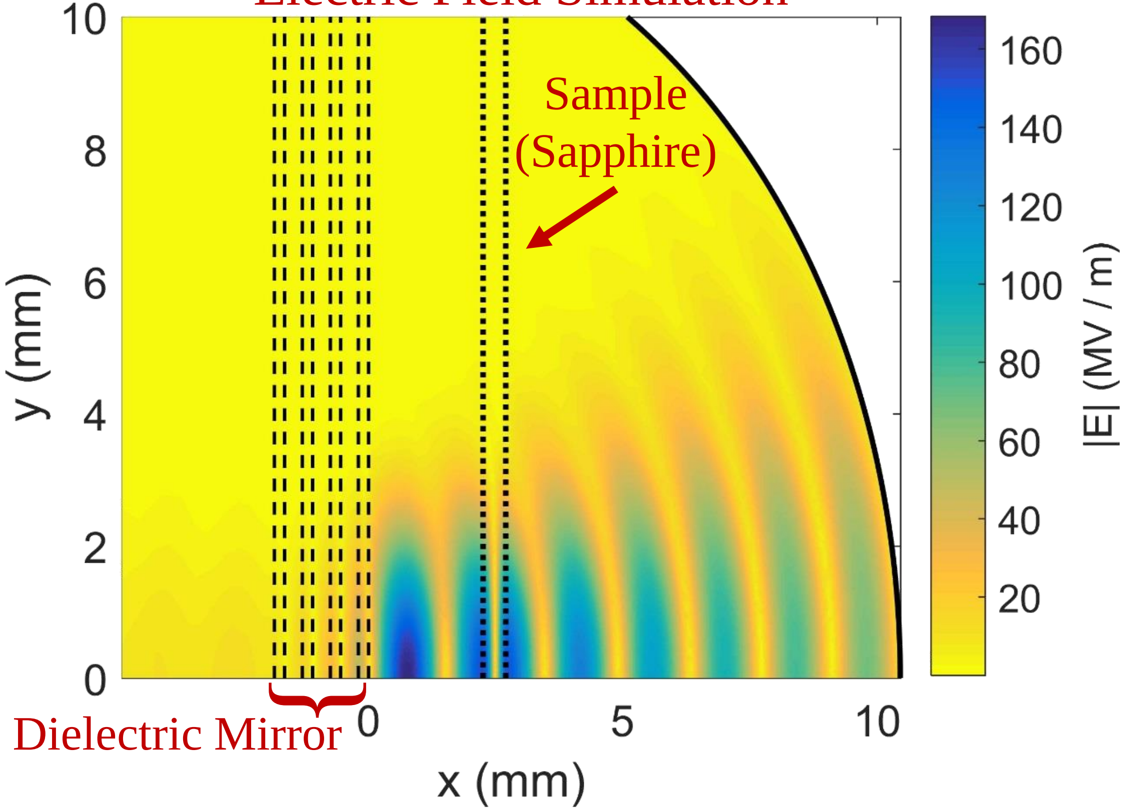
Parallel E-field Configuration

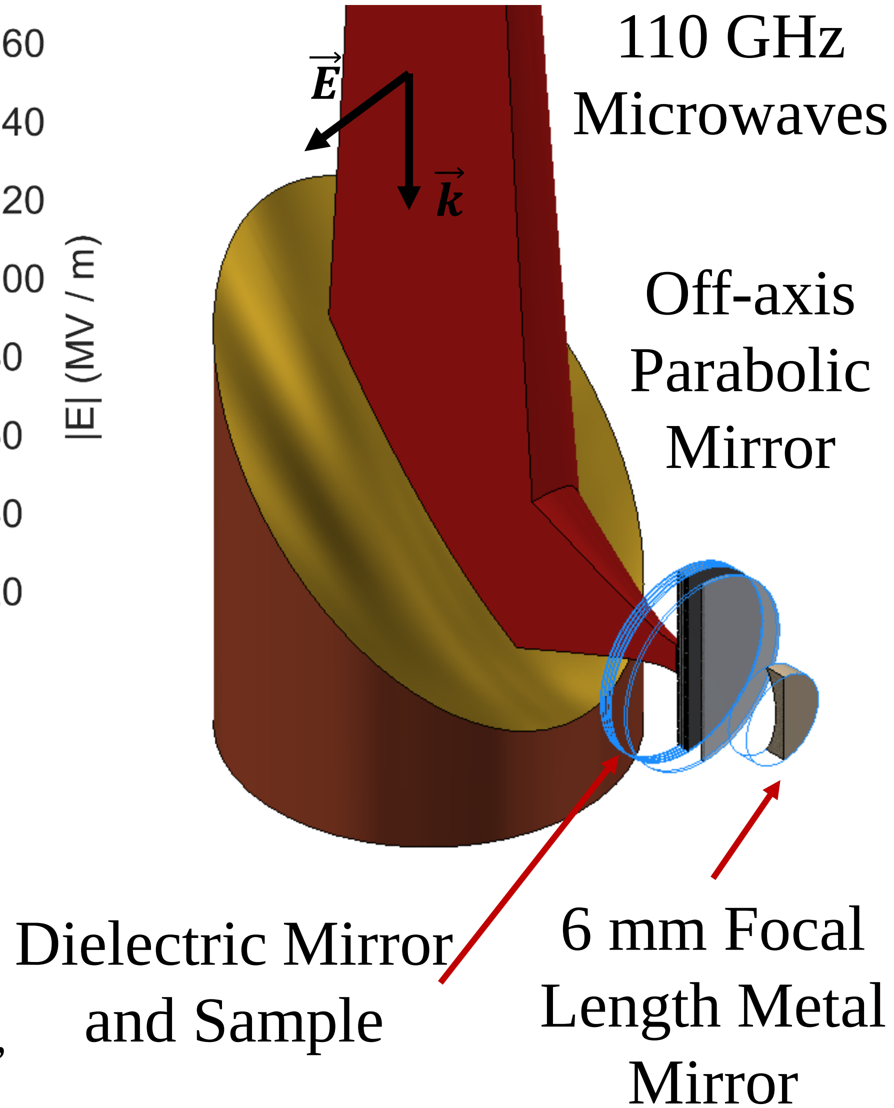
- Structure placed in vacuum chamber
- Fabry-Pérot cavity
  - Cavity formed between a layered dielectric mirror and a spherical mirror
  - Dielectric mirror
    - Alternating layers of polished HRFZ Si and fused quartz wafers
    - 25.4 mm diameter
- Gaussian microwave beam incident from $+x$
  - Linearly polarized in y
  - Focused to 2 mm spot size radius (0.7 λ)



Parallel E-field Configuration

Electric Field Simulation





- 1 MW incident from right
- 150 MV/m on sample surface (< 30 MV/m on mirrors)
- Samples to be tested: crystal quartz, fused quartz, sapphire, 96% alumina, 99.9% alumina, HRFZ silicon

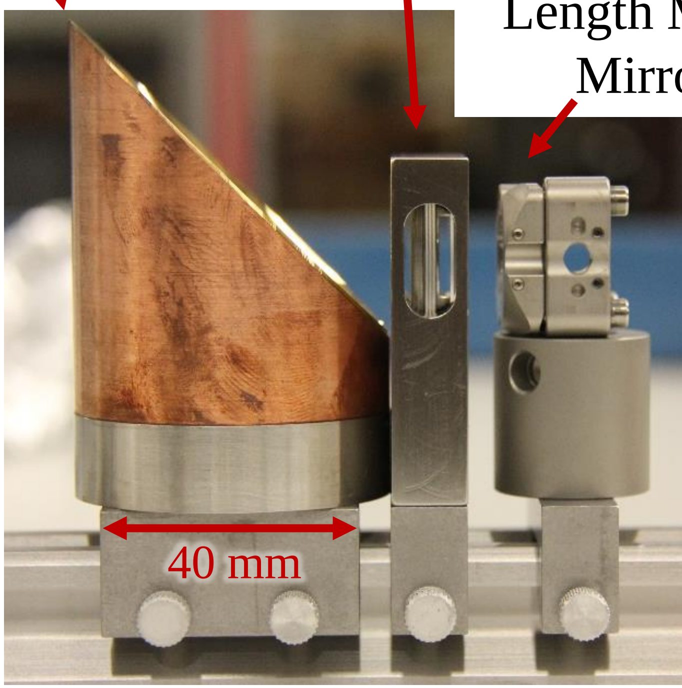
Parallel E-field Configuration

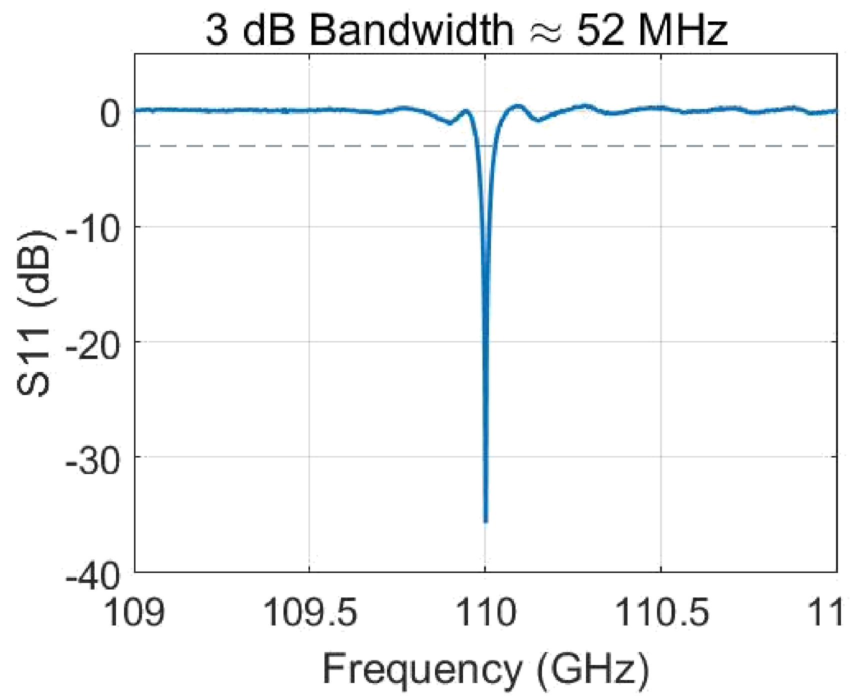
Low Power Test

Off-axis Parabolic Mirror

Dielectric Mirror, Spacer, and Sample

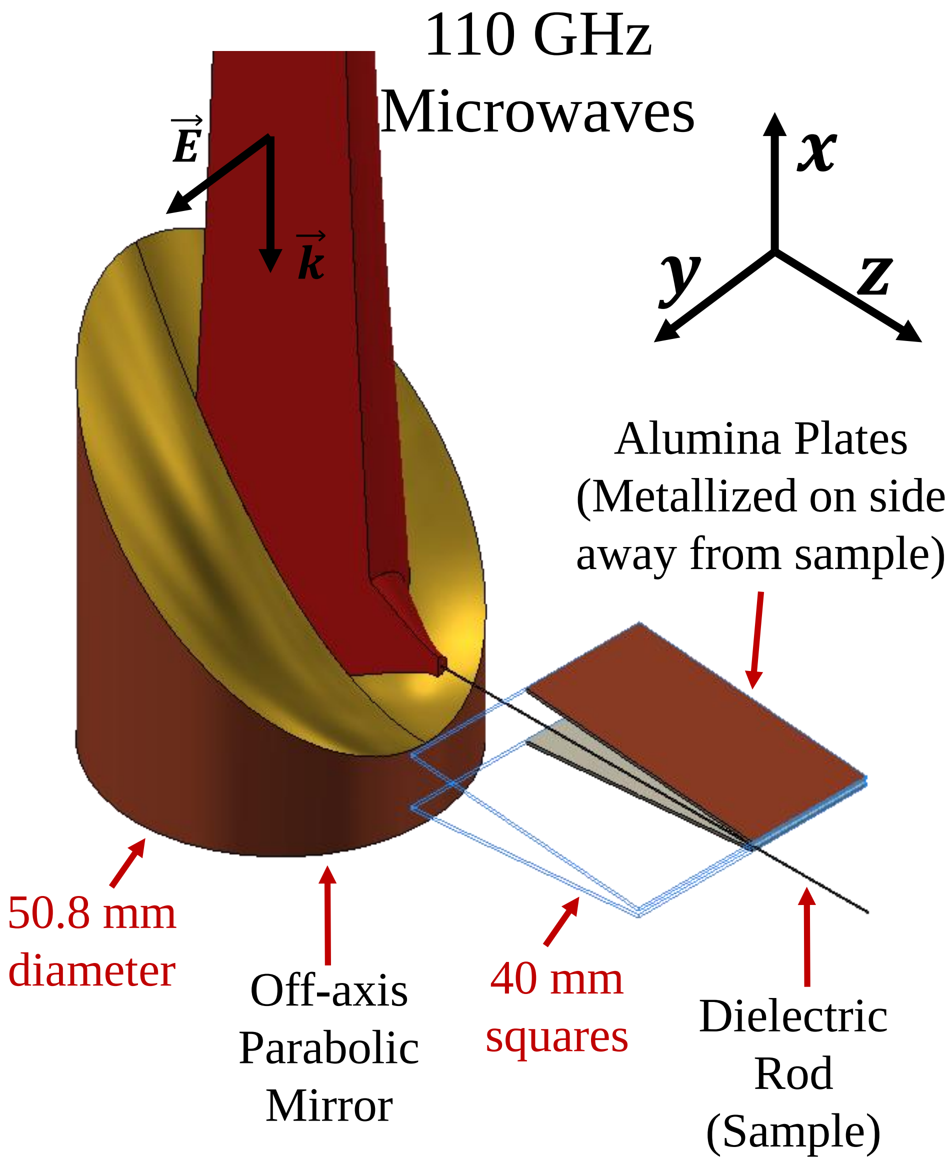
6 mm Focal Length Metal Mirror





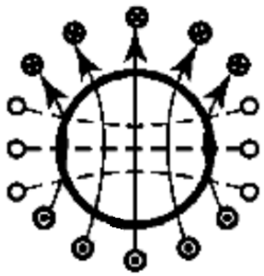
Perpendicular E-Field Configuration

- Gaussian beam incident from $+x$ direction
  - Linearly polarized in y direction
  - Focused to 1.5 mm spot size (0.55λ)
  - Focused on end of thin dielectric rod
- Sample is thin dielectric rod
  - 0.5 mm diameter for 99.8% alumina and sapphire
  - 0.8 mm diameter for fused quartz
- ~90% coupling to single propagating mode of dielectric rod waveguide
- Mode squeezed between two polished 99.9% alumina plates
  - Plates metalized with silver on sides away from sample



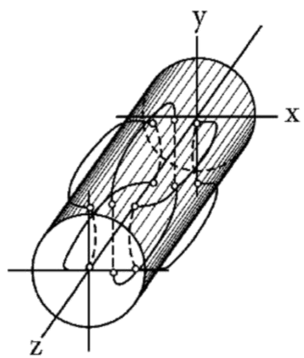
Perpendicular E-Field Configuration

- HE_{11} mode on a dielectric rod:
  - E-field concentrated on two sides

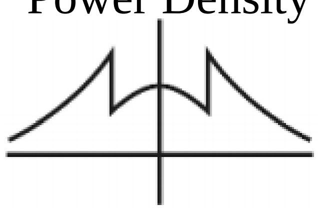


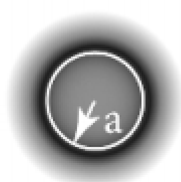
Solid: E-field
Dashed: H-field

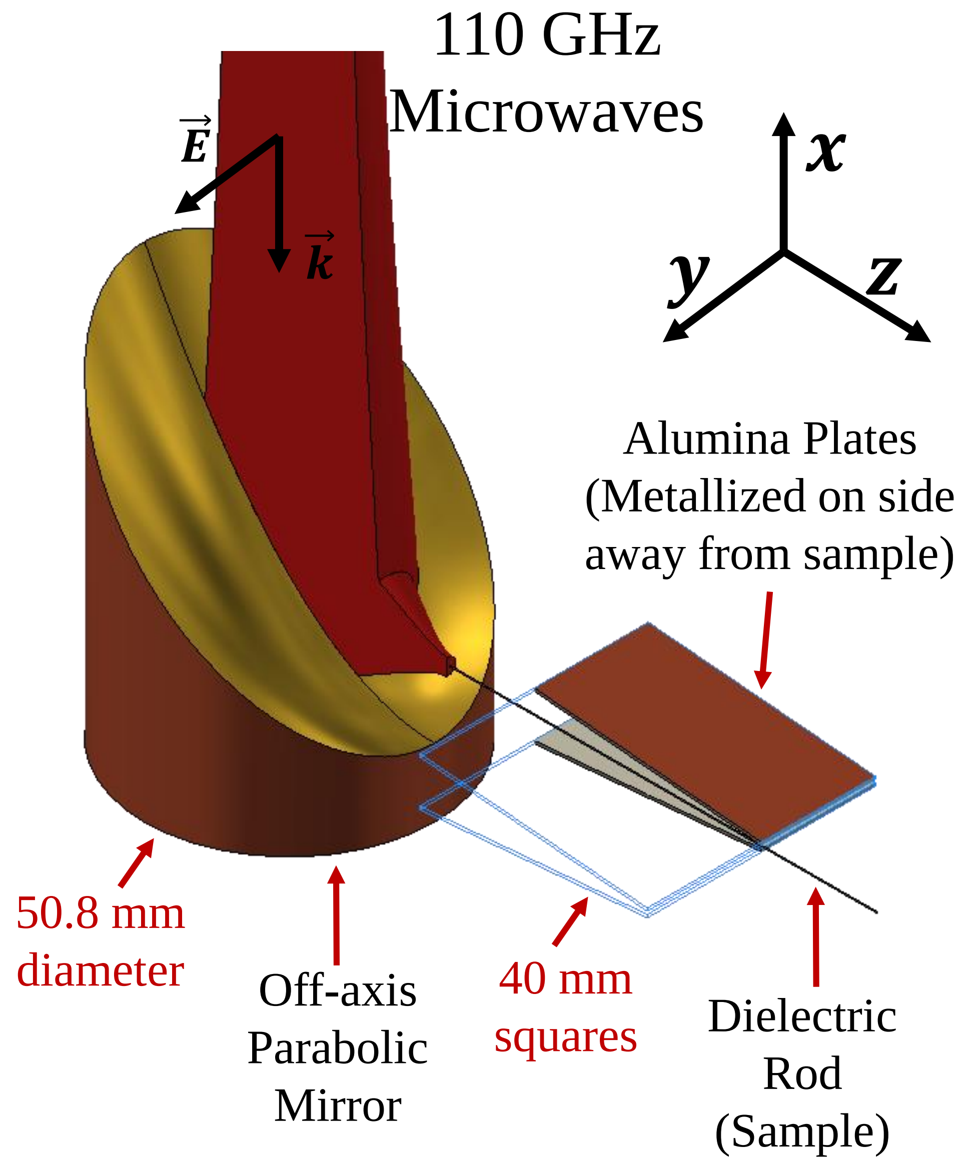
  - E-field lines form loops along rod



  - Power density concentrated along surface of thin rods

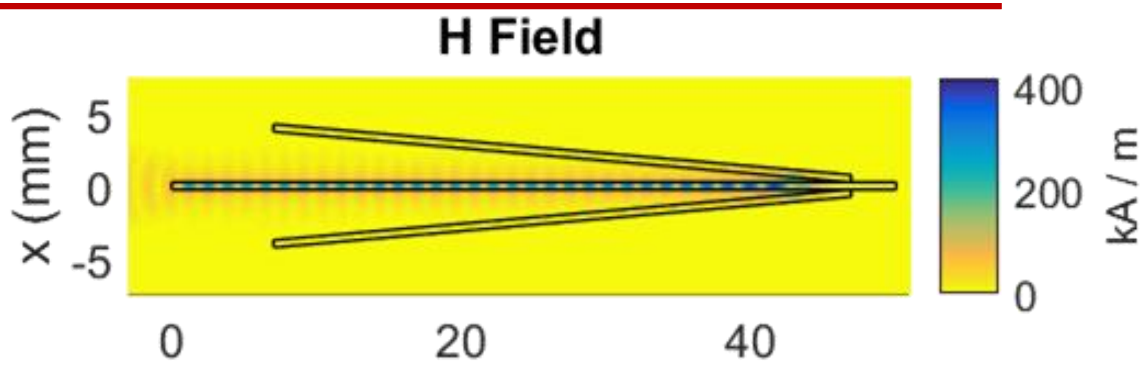


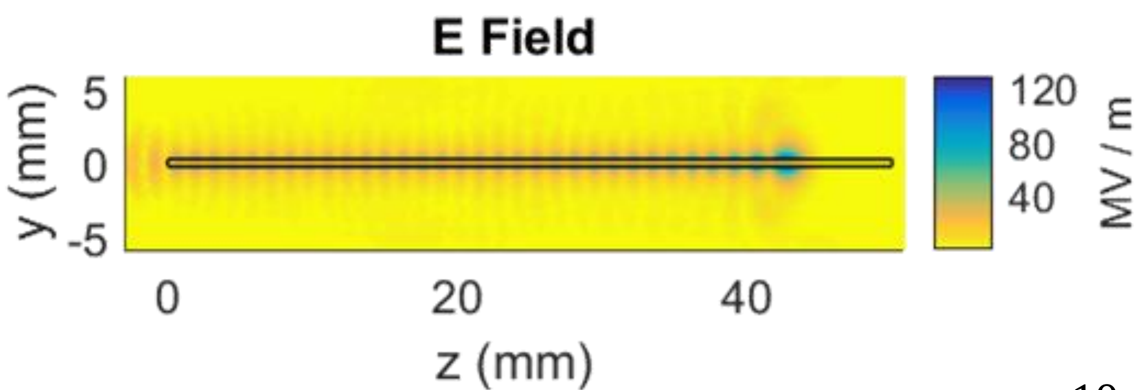




Perpendicular E-Field Configuration

- Gaussian beam incident from left
  - 1 MW of power
- Fields polarized in *y*
  - Strong E-fields on sides of rod (away from alumina plates)
- Alumina plates squeeze magnetic field of dielectric rod waveguide mode
  - Plates are metalized on sides away from the rod
  - Cutoff mode near end of plates
  - Creates standing wave on rod
- Max field on surface of sapphire and alumina rods: 125 MV/m (lower for fused quartz)





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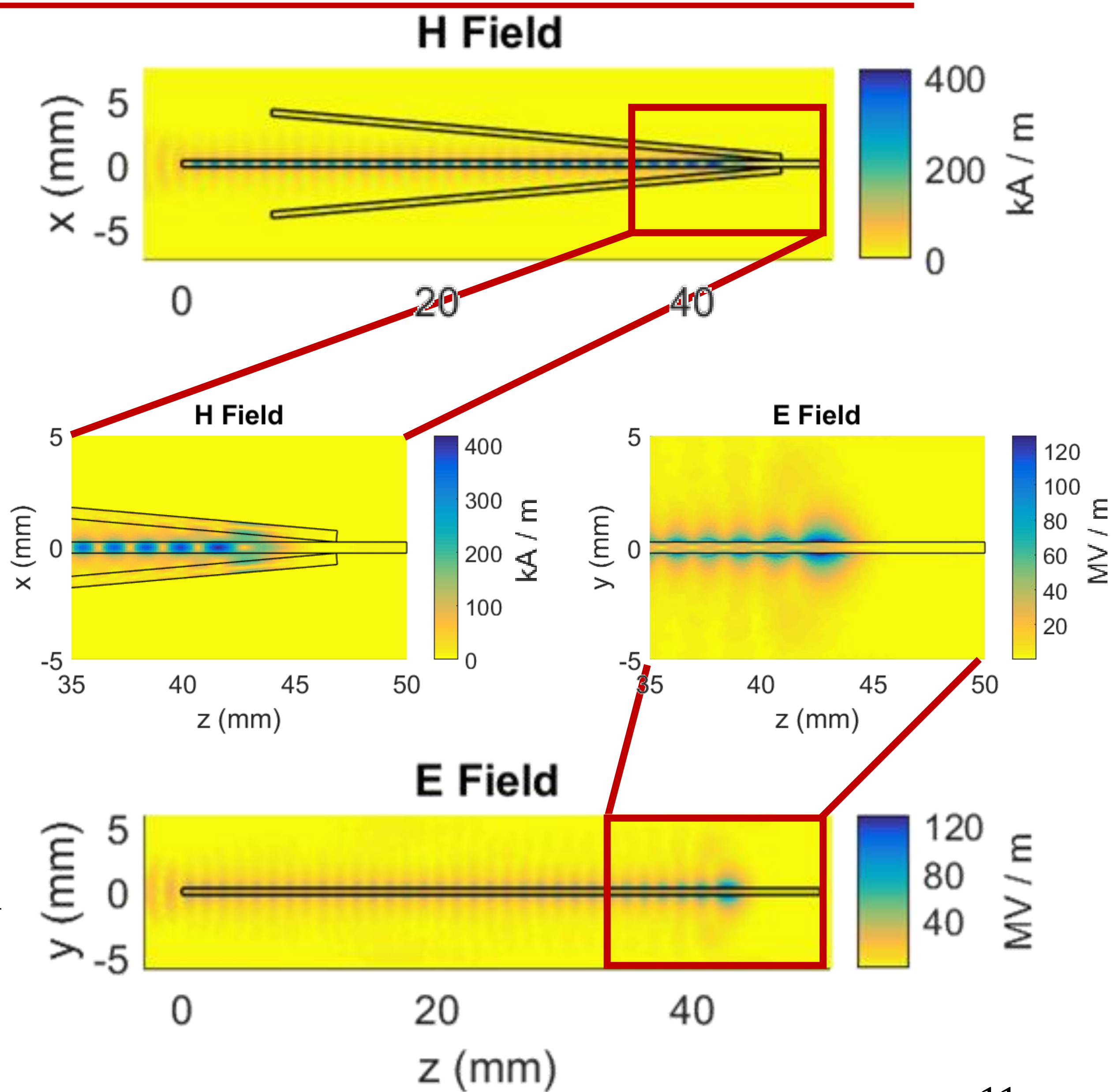
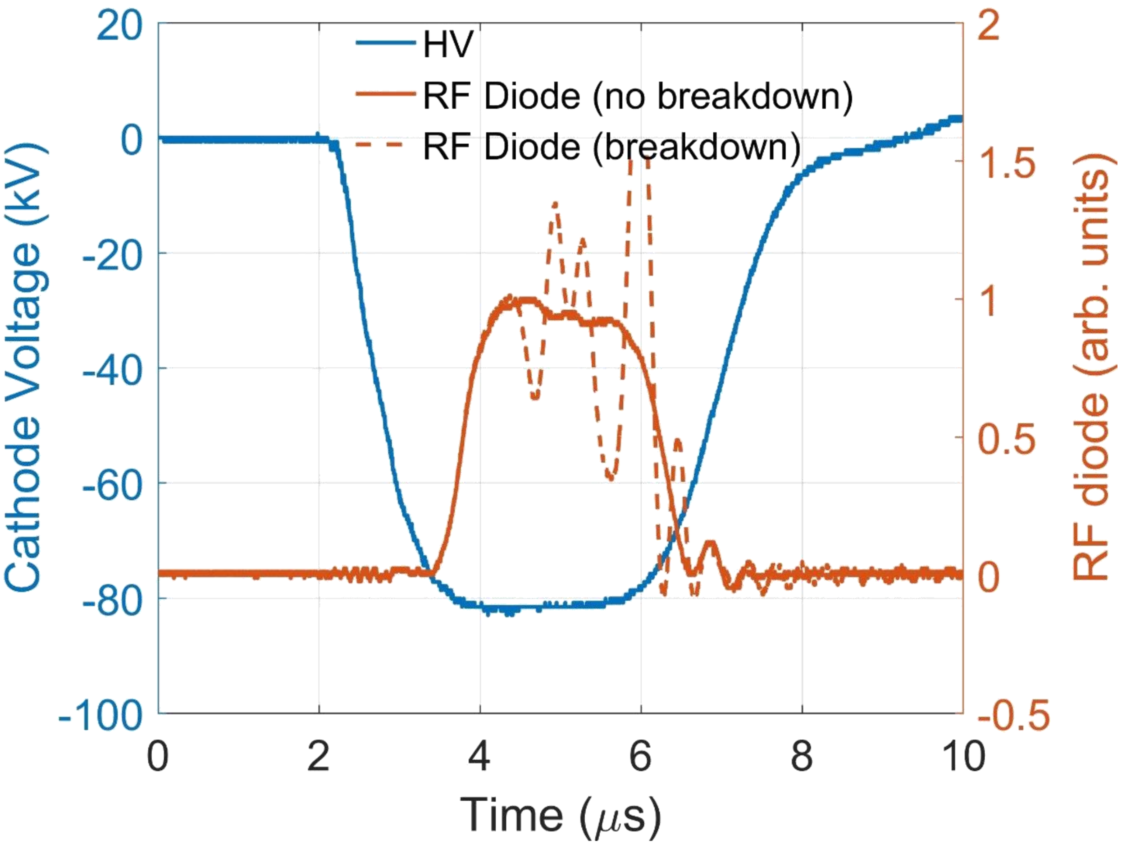


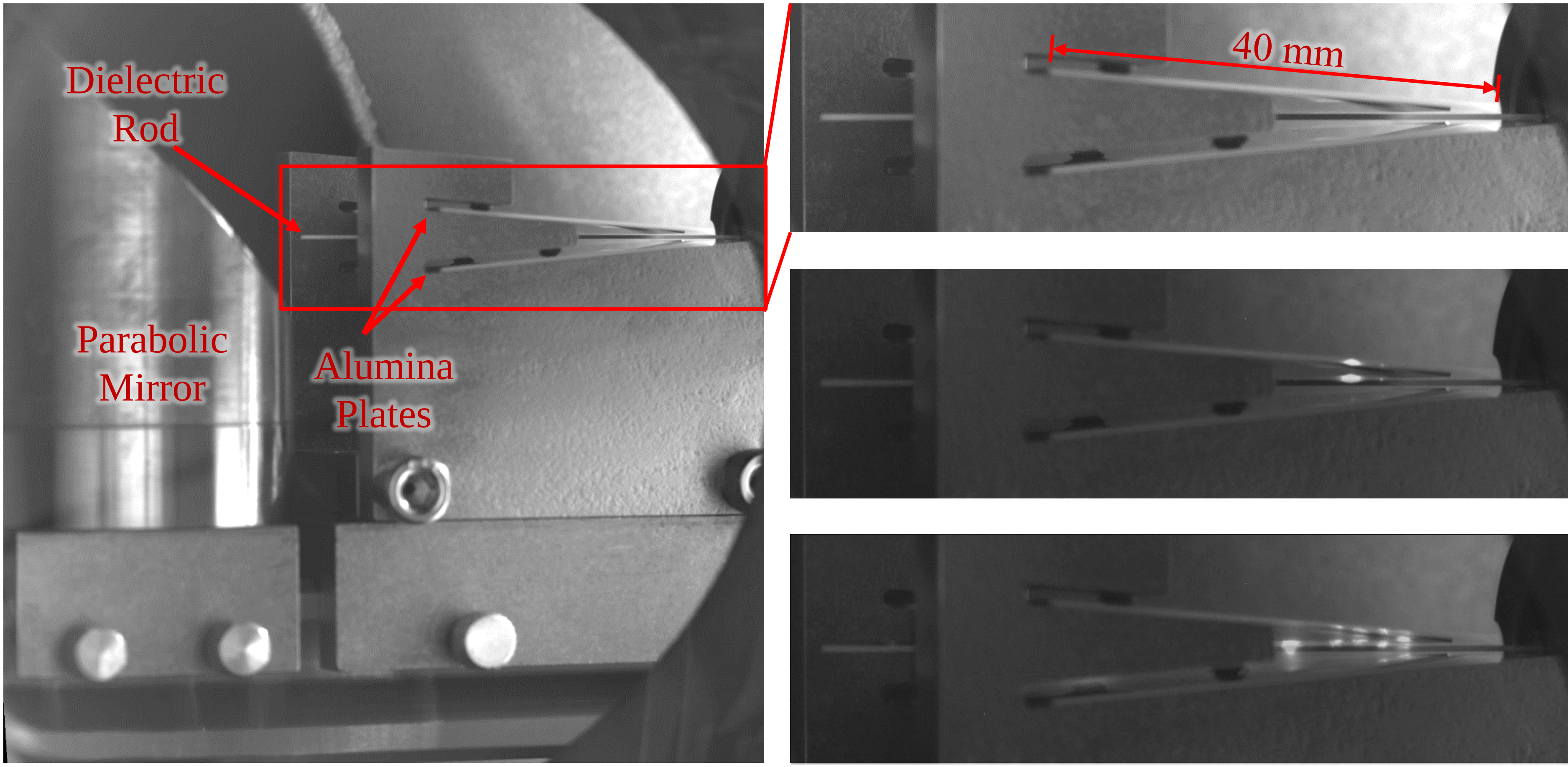
High Power Testing (Perp E-field)

- High power testing has begun on the dielectric rod (perpendicular E-field) configuration
- Base vacuum pressure
  - 1×10^{-8} Torr
- Breakdown detection
  - Pressure rises to a few $\times 10^{-7}$ Torr
- Breakdown visible on reverse power RF diode trace

Reflected Power Traces



High Power Testing (Perp E-field)



- Visible light images capture breakdowns
- Breakdowns occur reproducibly at the same locations along the rod

High Power Testing (Perp E-field)

- First tests on 99.8% alumina rod
- Currently tested up to 25 MV/m fields
  - Breakdowns from outgassing as power is ramped up
  - Breakdown rate at a given power drops to zero after < 100 shots
  - Threshold for multipactor breakdown not yet reached
- Testing is ongoing

- Current result: for 99.8% alumina with E-fields perpendicular to the surface, multipactor breakdown threshold > 25 MV/m

Future Work

- Continue high power tests on dielectric rods (Perpendicular E-field)
- Begin high power tests on dielectric windows (Parallel E-field)
- Install additional diagnostics
  - Photodiode
  - Spectroscopy
  - Dark current probe
  - ICCD imager (2 ns exposures)
- Test RF breakdown threshold in metallic cavity in collaboration with SLAC
  - S. Tantawi group
  - Gaussian beam to TM_{01} mode converter and TM_{01} cavity designed by SLAC
  - Will require shortening gyrotron pulse from 3 μs to ns timescale

Summary

- Experiments have been designed to test multipactor breakdown thresholds of dielectrics
  - Two designs for testing fields either parallel to or perpendicular to the sample surface
  - Testing with high power, 110 GHz has begun
  - Materials to be tested
    - Parallel E-field: crystal quartz, fused quartz, 96% and 99.9% alumina, sapphire, HRFZ Silicon
    - Perpendicular E-field: fused quartz, 99.8% alumina, sapphire
  - Currently functioning diagnostics
    - Forward and reverse power RF diodes, pressure monitor, visible light CCD imager
  - Additional diagnostics will be added
    - Photodiode for time resolution
    - Dark current probe
- More high power testing to be done
- Future testing of metallic structures will be done in collaboration with SLAC

Acknowledgements

- Waves and Beams Division at MIT Plasma Science and Fusion Center

Graduate Students	Postdocs	Faculty and Staff
Hannah Hoffmann	Guy Rosenzweig	William Guss
Xueying Lu	Jacob Stephens	Sudheer Jawla
Julian Picard		Ivan Mastovsky
Alexander Soane		Michael Shapiro
Haoran Xu		Richard Temkin
		Paul Woskov

- S. Tantawi's group at SLAC
  - V. Dolgashev and E. Nanni
- Department of Energy High Energy Physics Grant DE-SC0015566