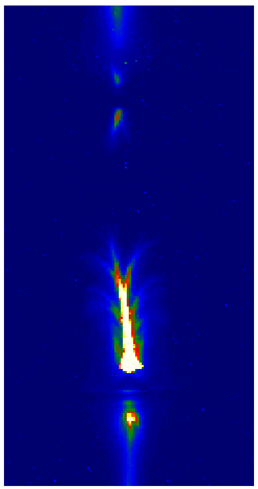
High Power Microwave Breakdown of Dielectric Interfaces*



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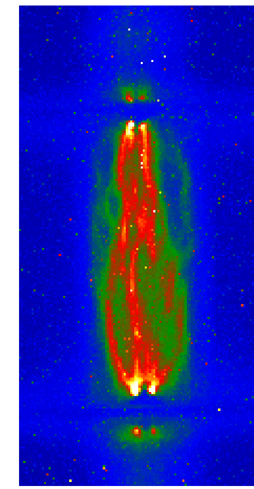
http://p3e.ttu.edu/personnel/faculty/Dr.Andreas/Neuber.htm



* This work was solely funded by the High Energy Microwave Device MURI program funded by the Director of Defense Research & Engineering (DDR&E) and managed by the Air Force Office of Scientific Research (AFOSR).

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Window Failure/History

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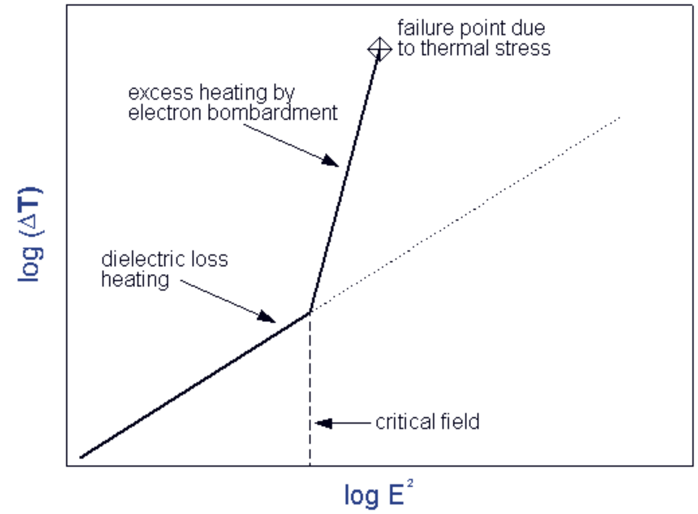
- Early 60's: relatively high continuous wave (cw) power levels
  - Main failure mode: thermal stress



- Mid-1990's: S-band window (pillbox geometry) transmitting 300 MW microwave power in a 2.5 µs pulse at 10 pulses per second (7.5 kW average).

  - **Problem remains:** costly window manufacturing process, HIP
  - Window failure associated with SEE and electron multipactoring (coating with TiN)
  - Especially critical: defect locations with high SEE, local heating, vaporization of window material → window failure.

Objectives

Breakdown phenomena limit generation and transport of high power microwaves:

- internal breakdown in high power microwave generators
- cavity breakdown
- surface breakdown at vacuum/dielectric/vacuum (gas) interfaces
- breakdown phenomena are involved in pulse shortening

Physical mechanisms leading to breakdown of interest:

- generation of free electrons
- amplification/avalanche mechanisms
- interface breakdown ↔ volume breakdown

Clarify basic mechanisms and find ways to increase breakdown thresholds:

- "real-time" high speed diagnostics (electrical, optical, x-rays, ...)
- select materials, coatings, geometries
- apply external electric/magnetic fields

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Method

Setup:

4MW S-Band Magnetron coupled to a traveling wave resonator provides maximum power of 90 MW at 2.85 GHz.
Field amplitude rises to about 10 kV/cm in 150 ns.
Maximum field is about 90 kV/cm

Different window geometries:

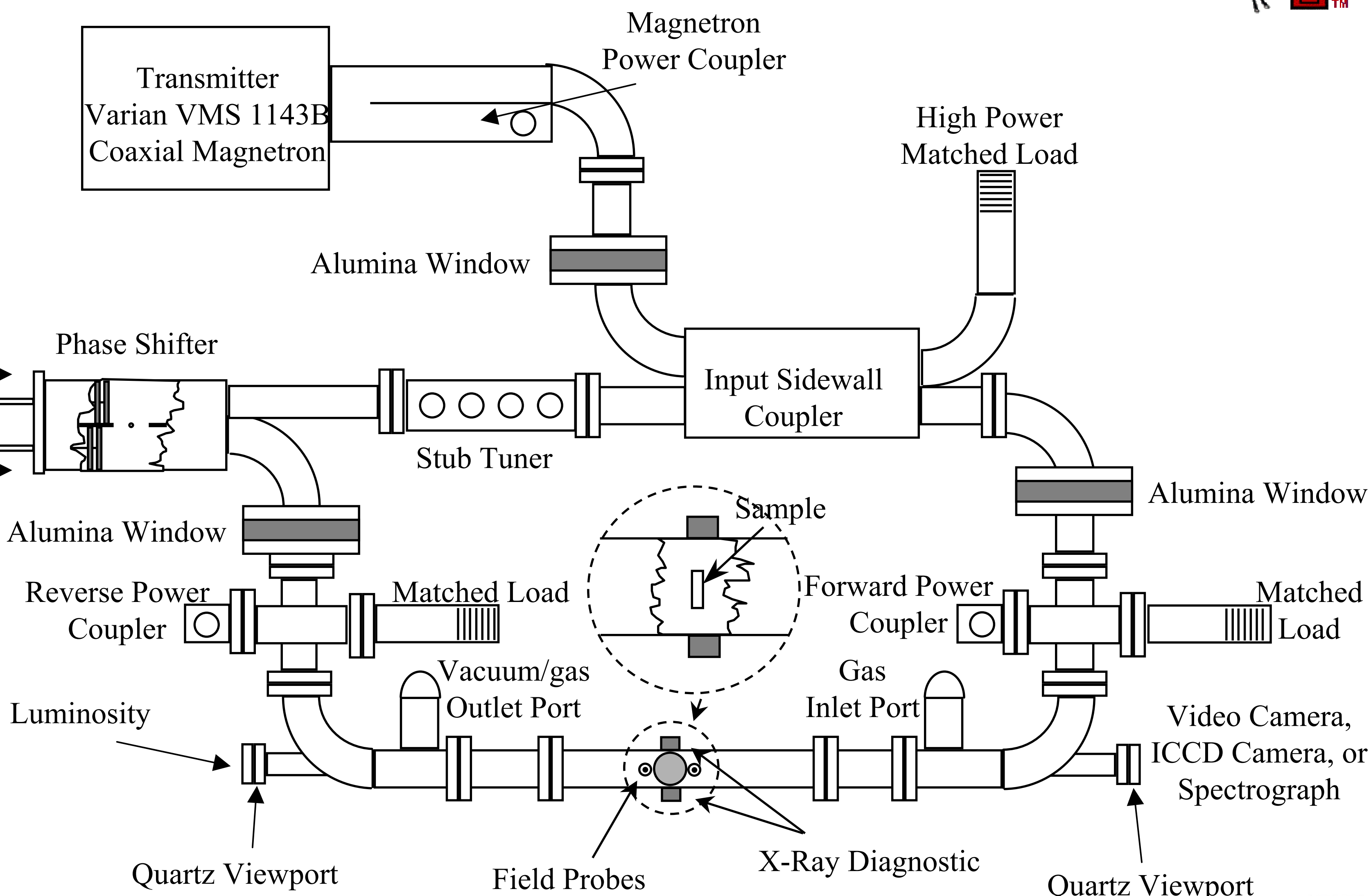
SLAC Pillbox geometry (combination of multipactor and surface discharge)

Planar interface with tangential electric field to simulate high power interfaces

Pressure range:

Variable from 10^{-6} Torr to 1000 Torr
Pure gases and mixtures

Experimental Setup



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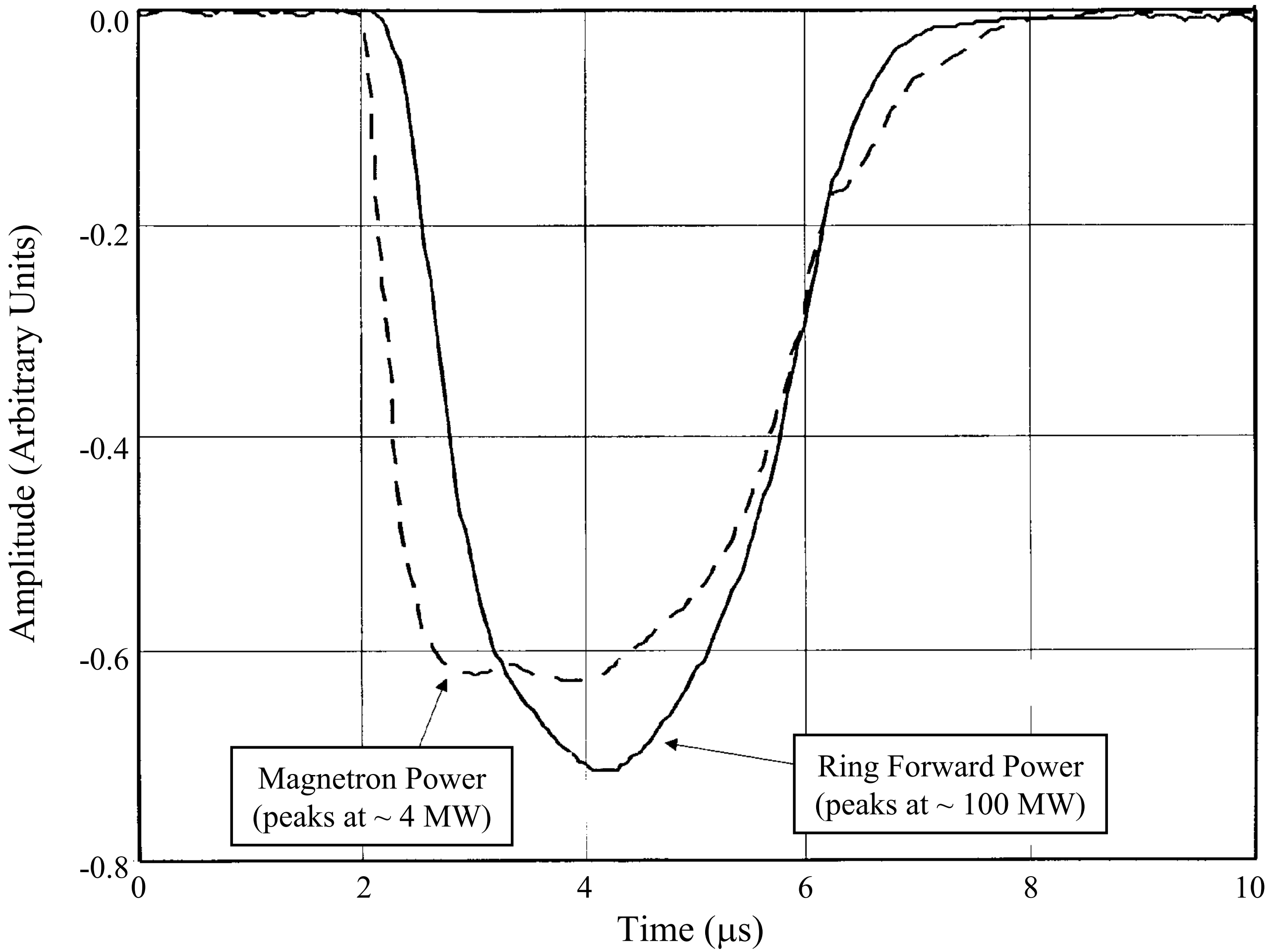
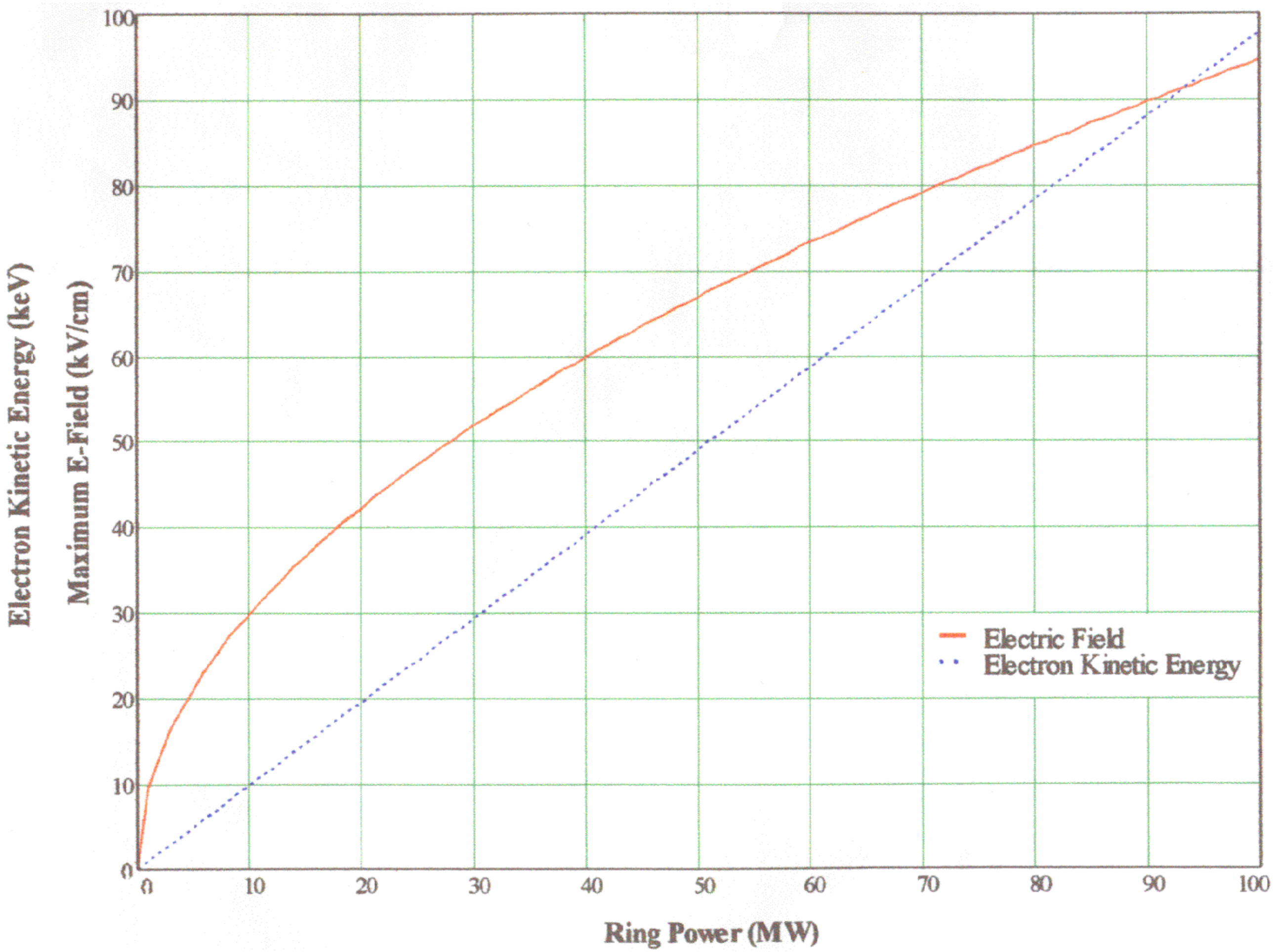
Magnetron Power vs. Ring Forward Power



Pulse energy magnetron: ~ 15 J

Stored energy in ring: < 1.5 J → ***non-destructive testing***

Max E-field And Electron Kinetic Energy vs Ring Power



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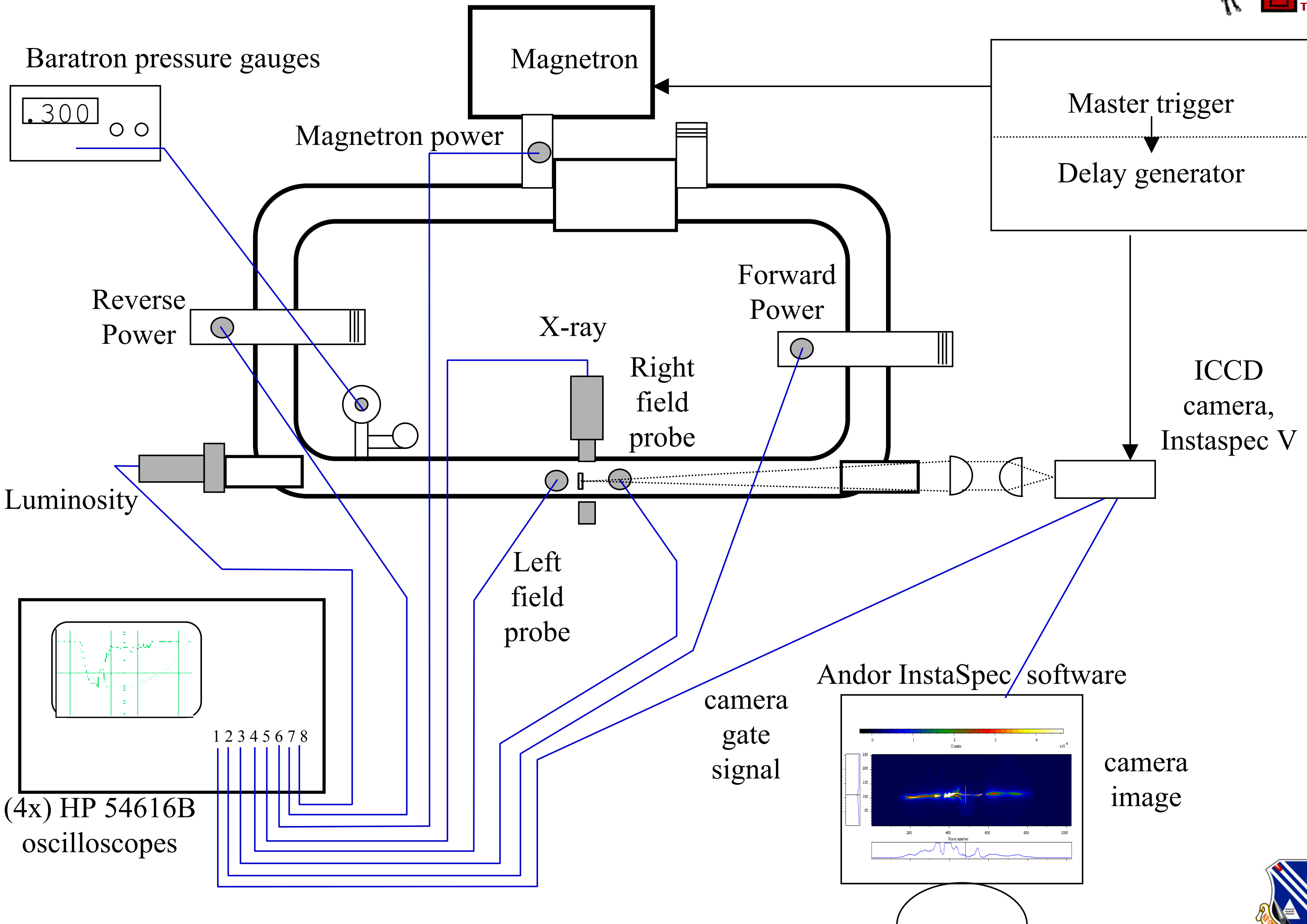
Diagnostics



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DIAGNOSTICS

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Local Field Probes, Forward and Reverse Power

Coaxial microwave detectors with 1 ns risetime

Field distribution across sample (assisted by field calculations with Maxwell Eminence)

Parameters of developing discharge plasma

Luminosity

Photomultipliers (risetime 1 ns, threshold 1 μW)

Gated image intensifier (exposure time >2.5 ns, high sensitivity)

Plasma luminosity as a function of time and position

Development of discharge channel

Power absorption

X-ray Emission

Plastic scintillator/PMT combination, x-rays with E>3keV (risetime 1.5 ns, threshold 10^5 electrons/ns

Existence of free electrons as a function of time

X-ray pinhole camera

Optical Spectroscopy

Spatially and temporally resolved spectral intensity

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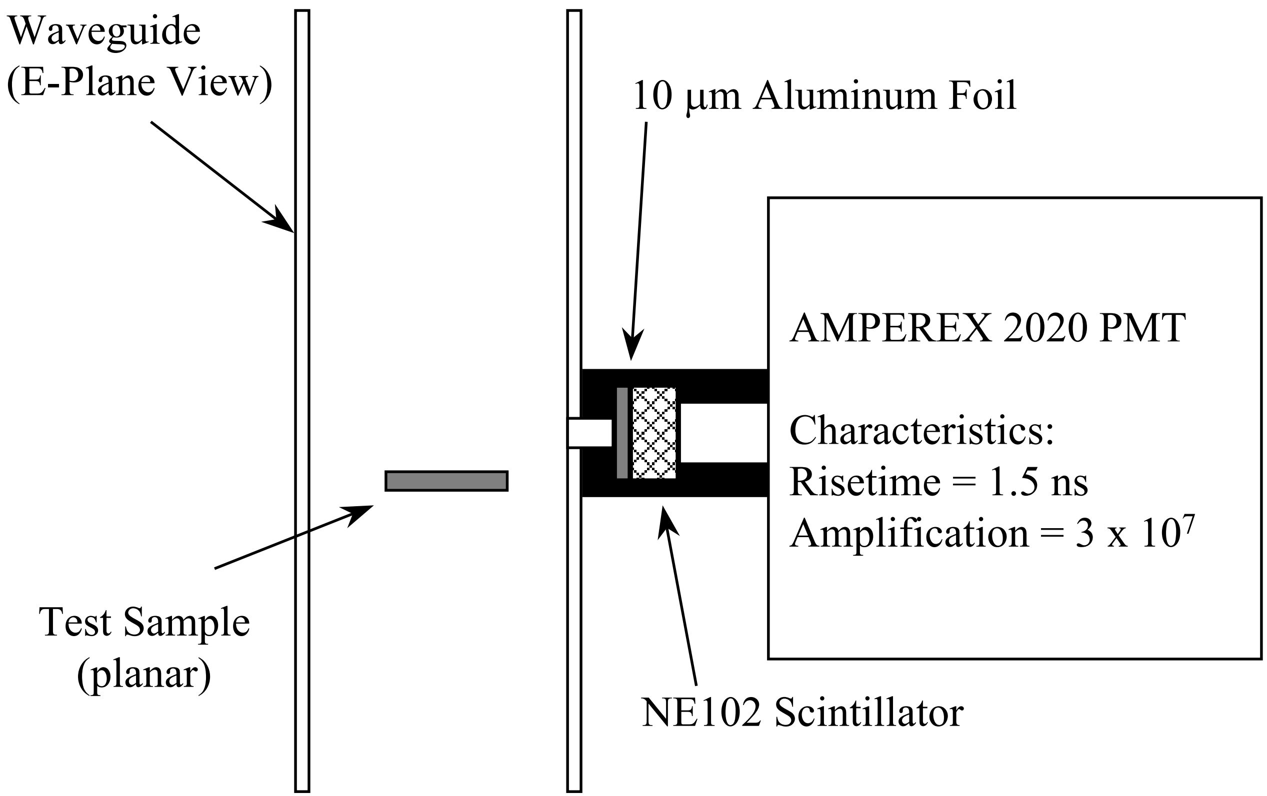
X-ray Diagnostic Setup

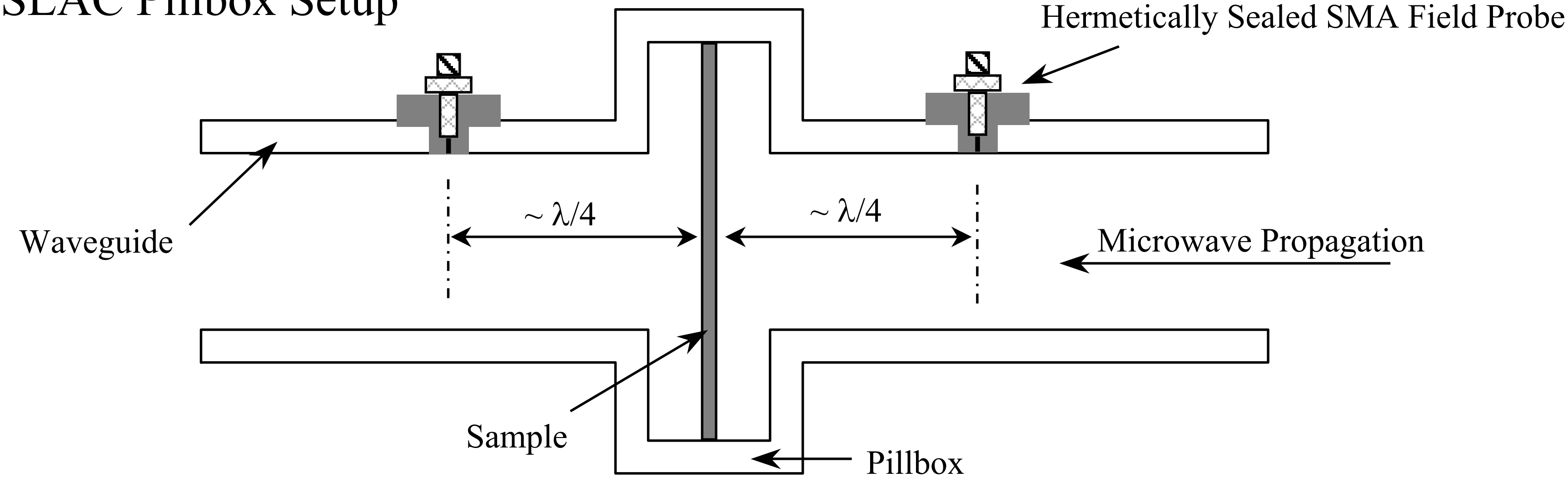


Alternative setup:

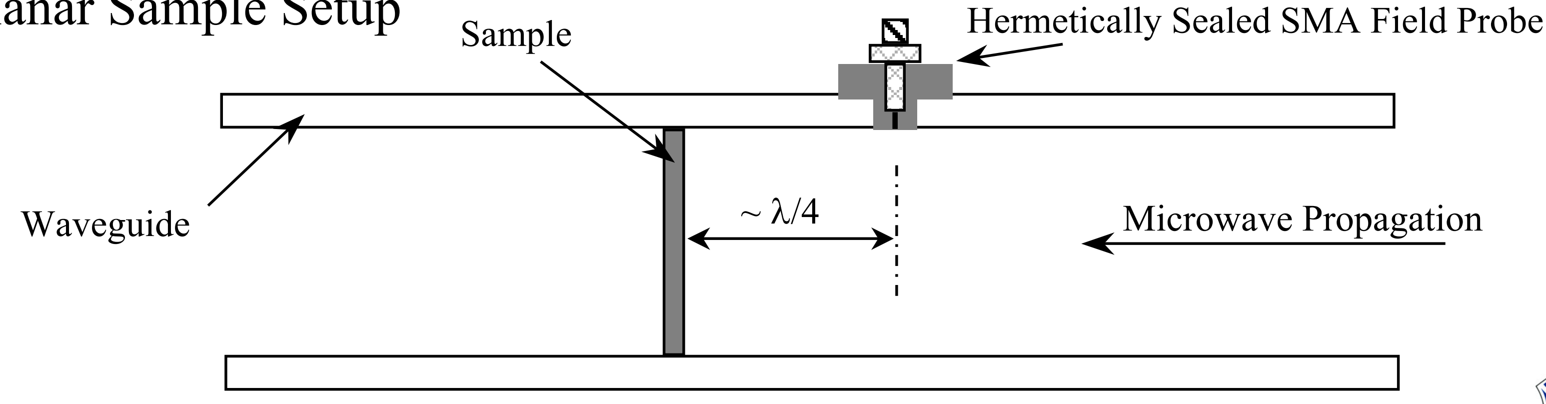
X-ray pinhole camera with 10 µm Be foil and lead iris
MCP with CsI cathode as camera back

Interface Geometries

SLAC Pillbox Setup



Planar Sample Setup



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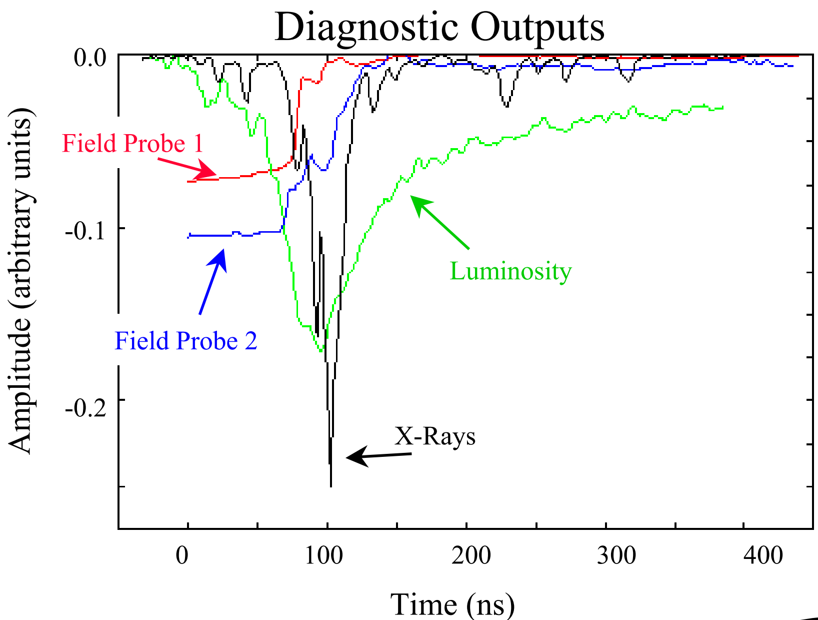
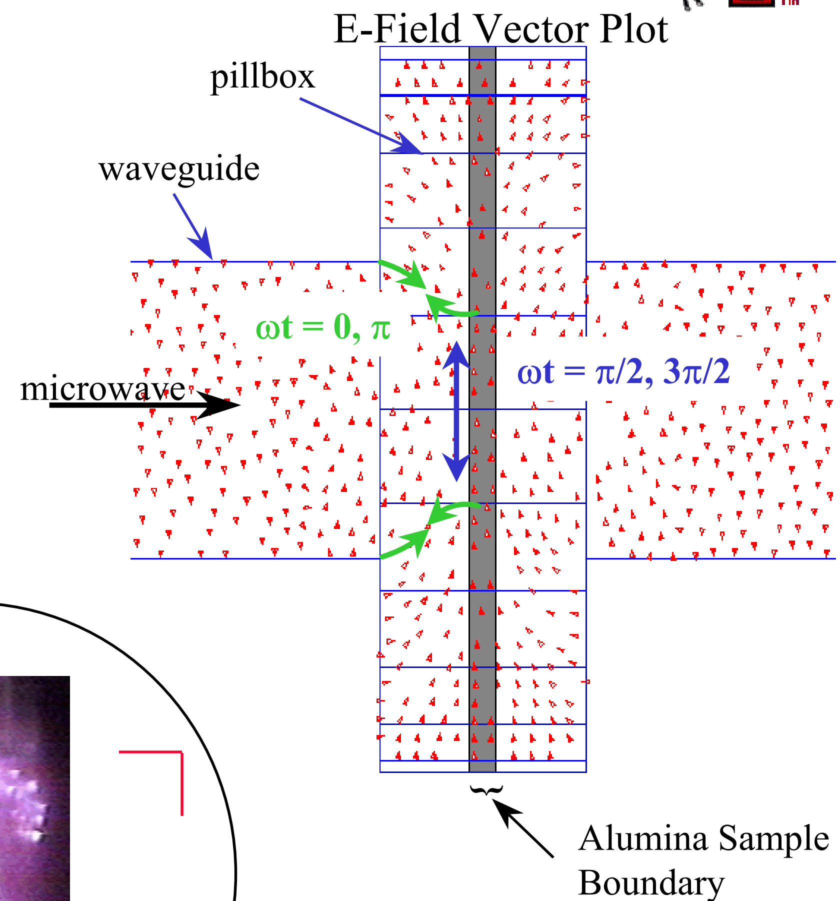
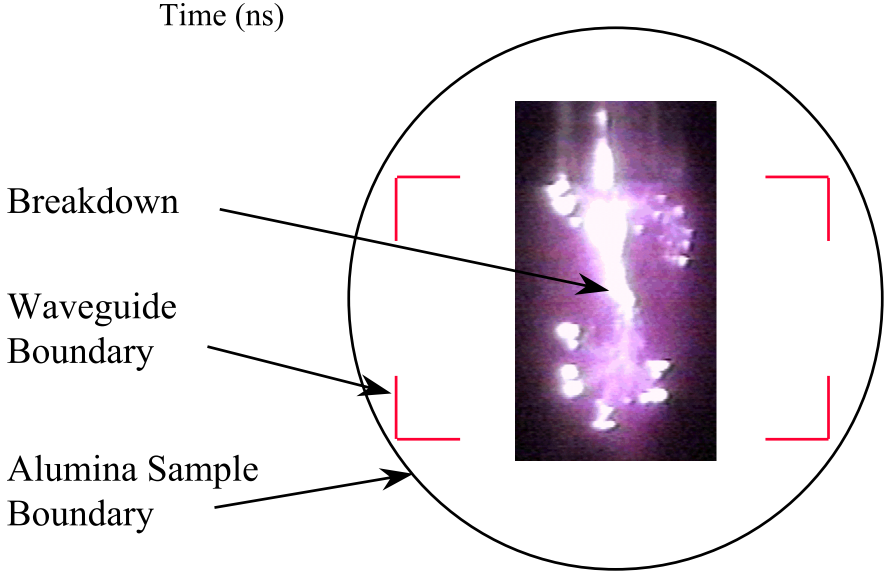
SLAC Pillbox Window







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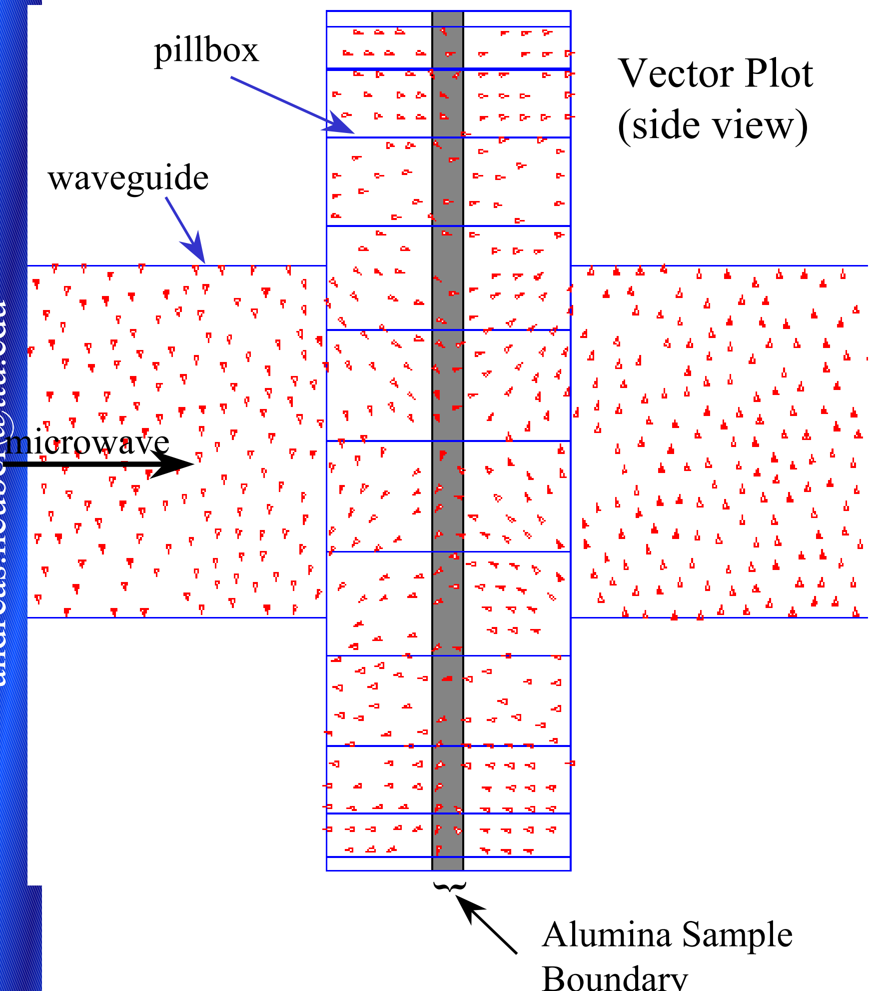
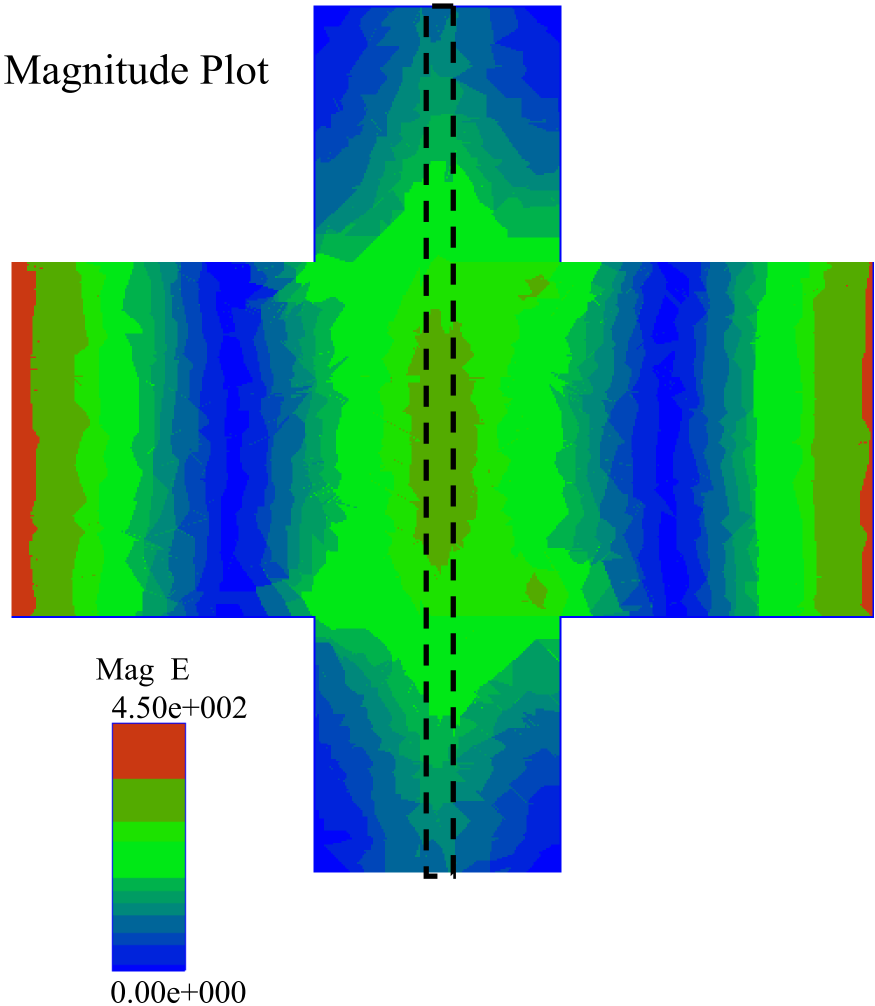
Electric Field Plots

SLAC PILLBOX WINDOW





Complicated field-structure, small tangential field at window.
(Combination of single surface and two surface multipactor)

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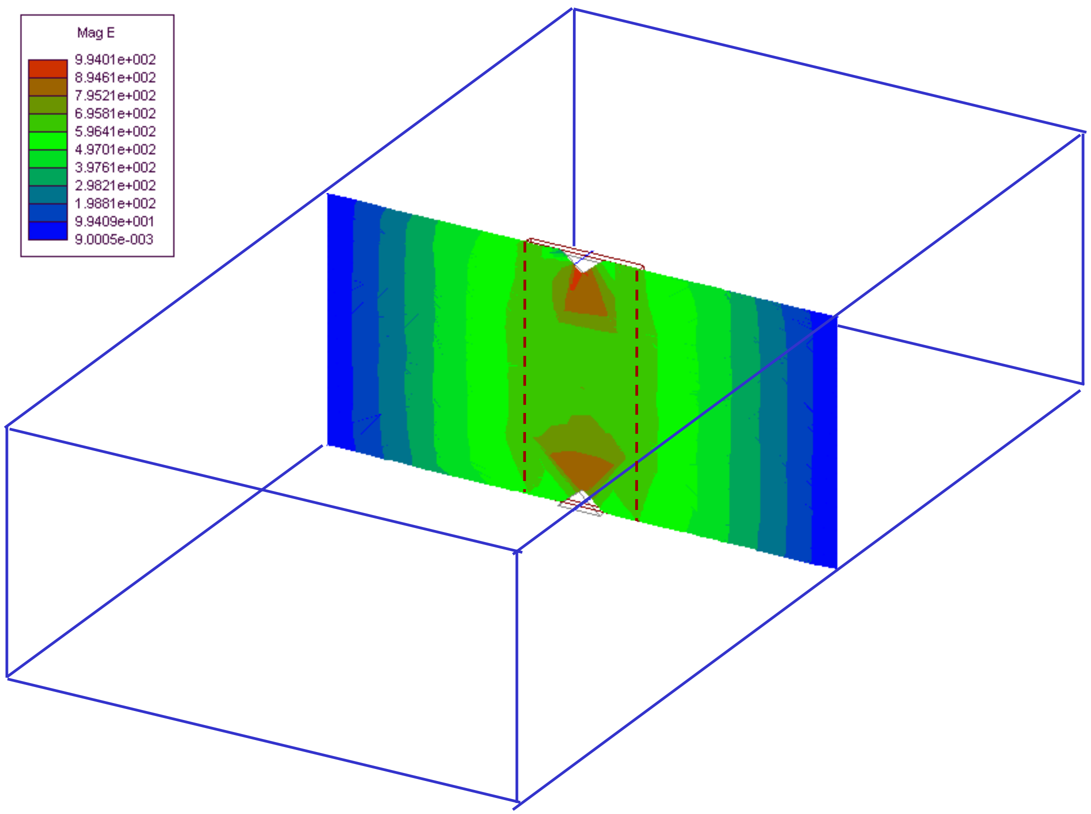
“Slab In Waveguide” Setup



- Dielectric, 1.5 mm thick
  16.0 mm wide
- reflection coefficient without breakdown < 0.3 %
- local field enhancement factor : 1.33
- ring tuned for maximum forward power using HP9719C network analyzer
- series starts with virgin sample, stops after 30 discharges
- energy / discharge < 0.2 J
  --> surface damage negligible

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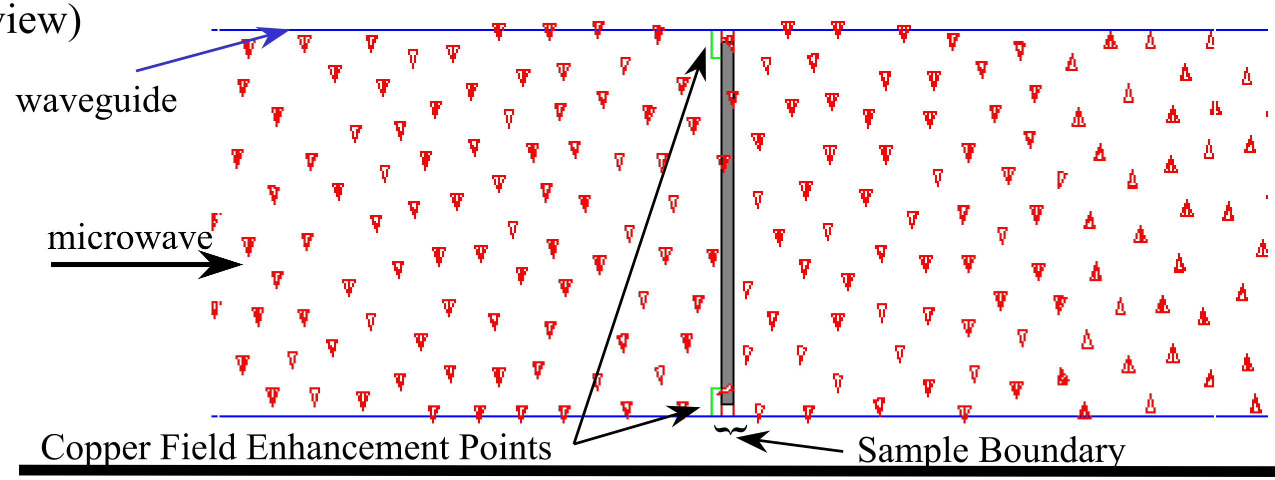
Electric Field Plots

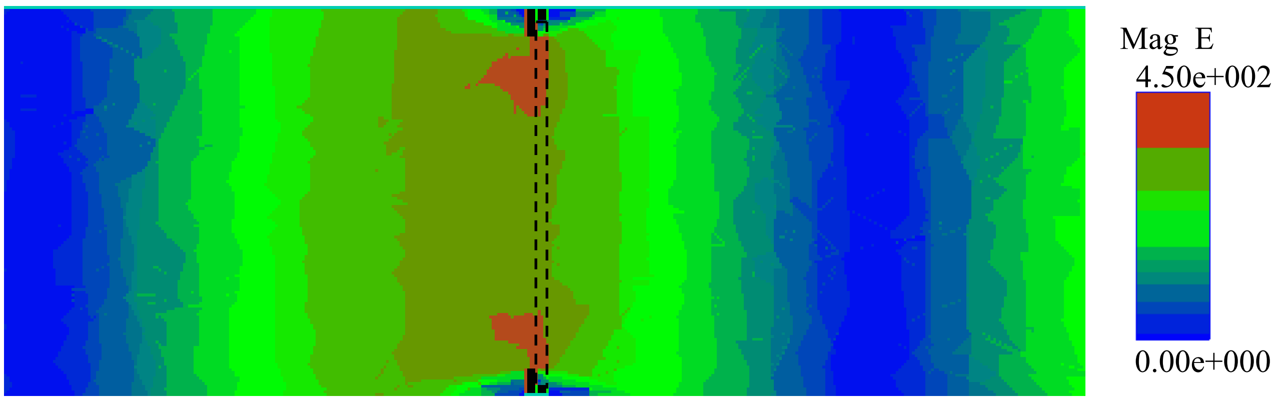
PLANAR SAMPLE

Vector Plot
(side view)



Reflection Coefficient = 2.4×10^{-3}

Magnitude Plot



Simple field geometry, defined breakdown path, good optical access

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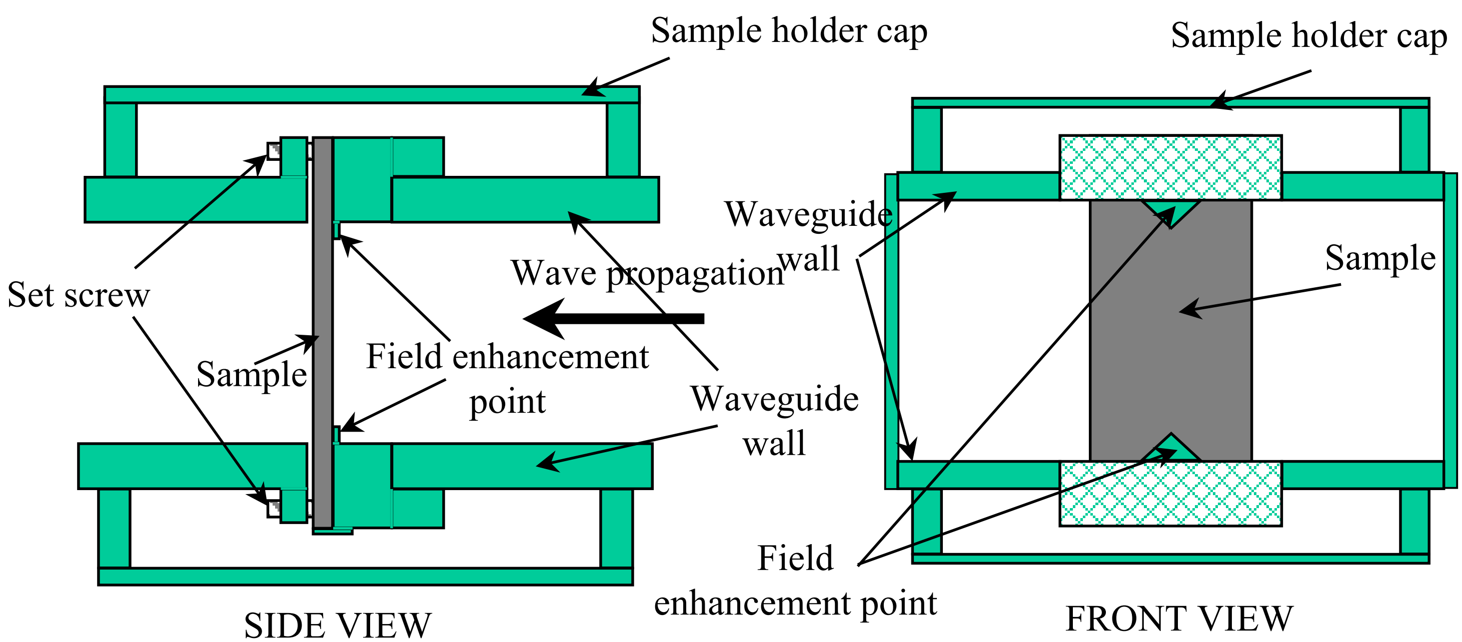
"Slab in Waveguide" Setup



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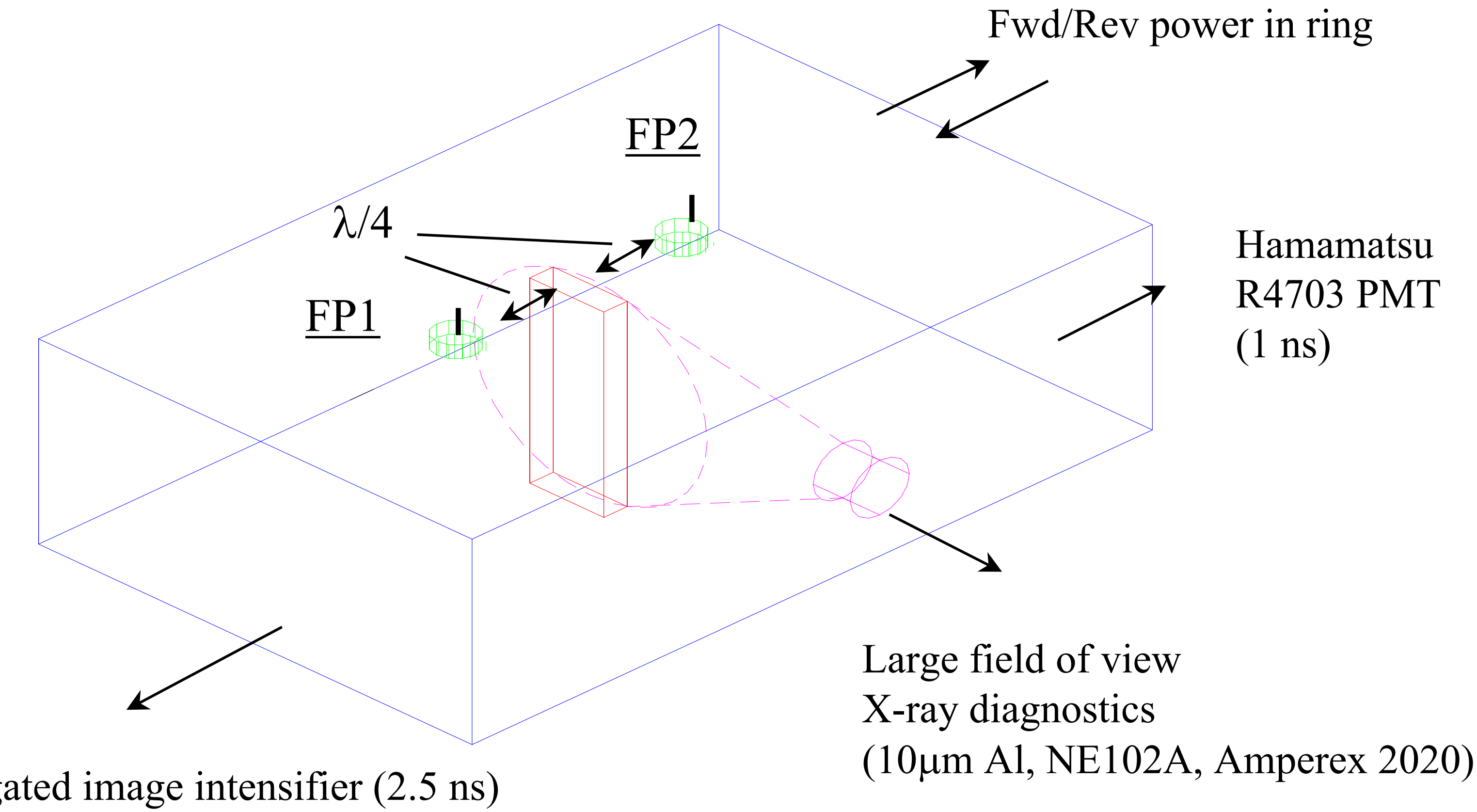
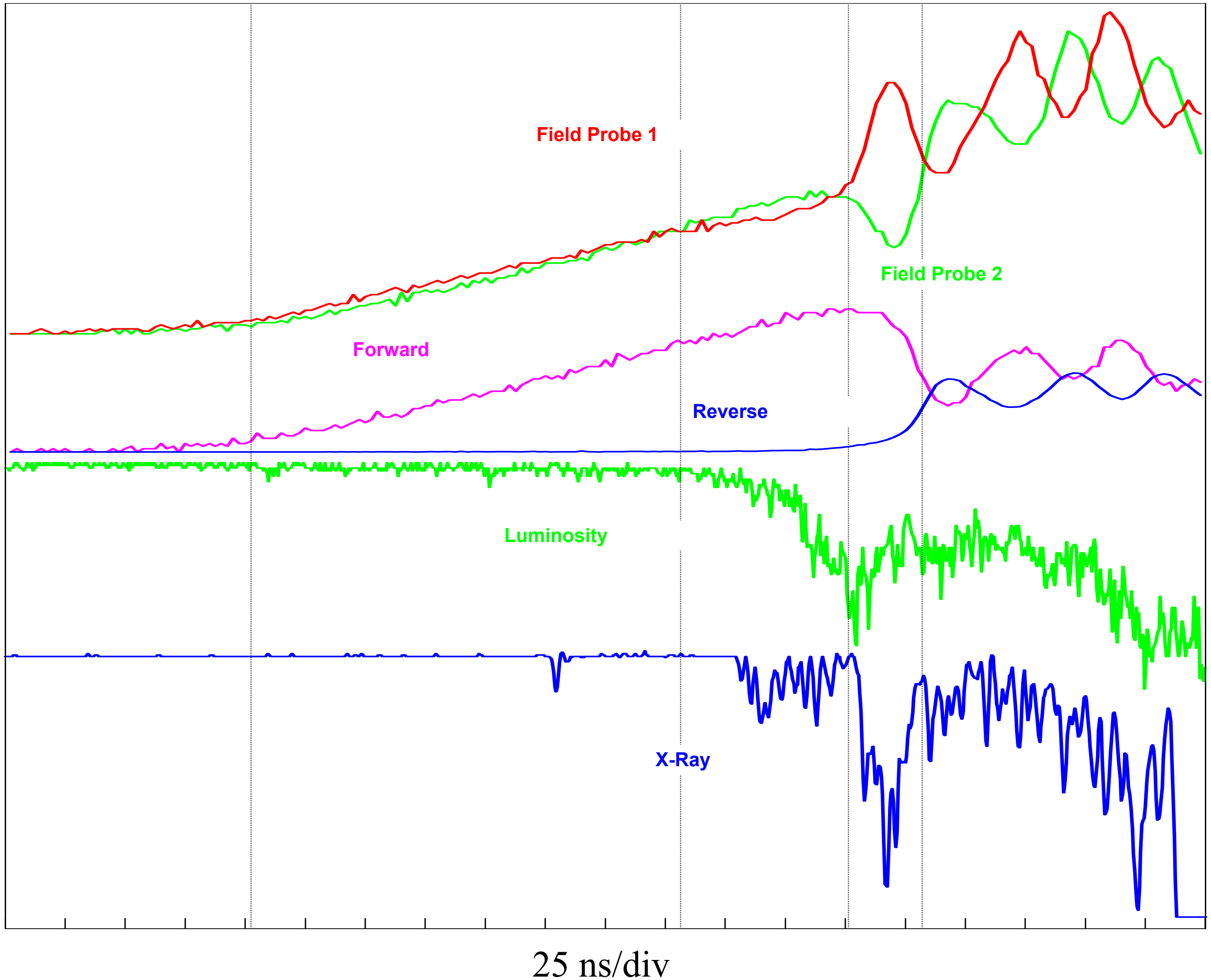
DIAGNOSTICS



Typical Breakdown Signals



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Dielectric/Vacuum Interface Breakdown

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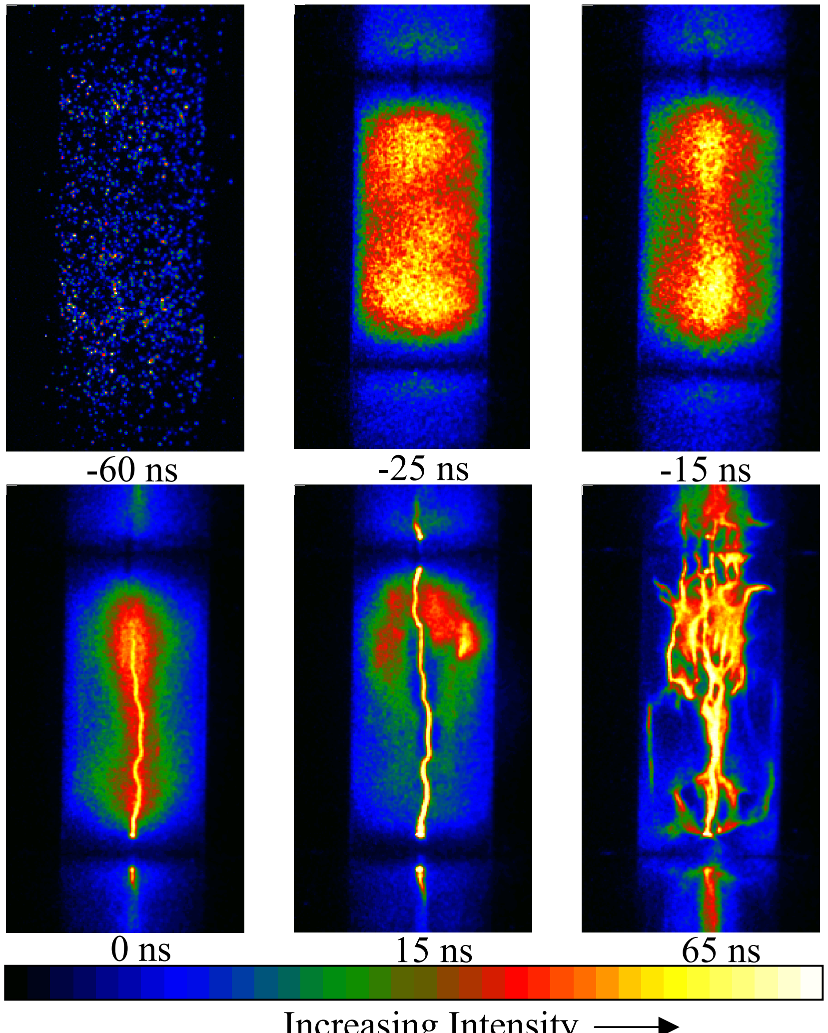
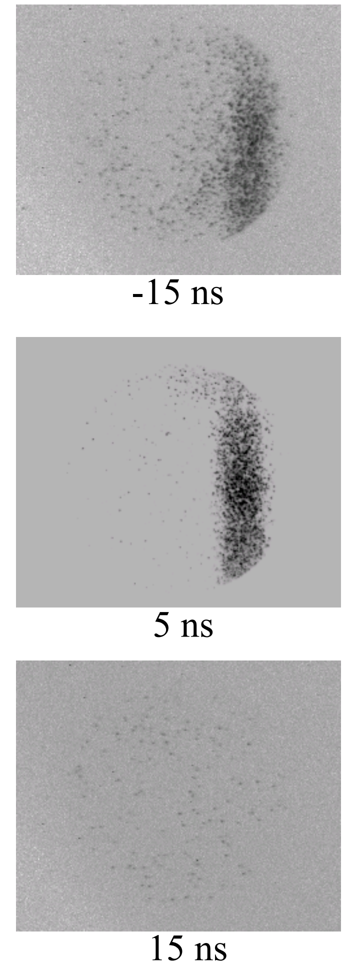
Visible image sequence (color enhanced)



X-ray image sequence



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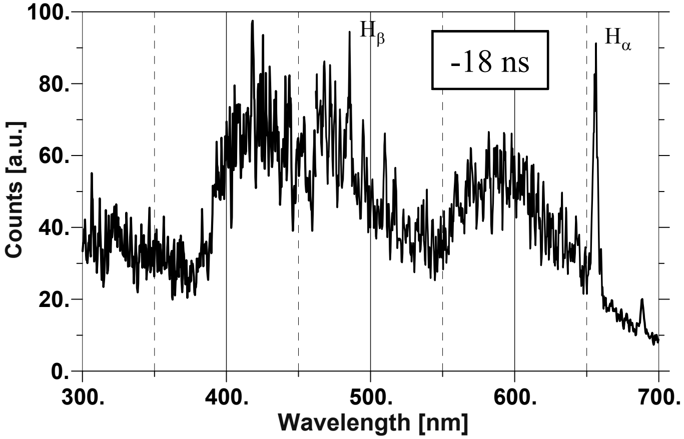
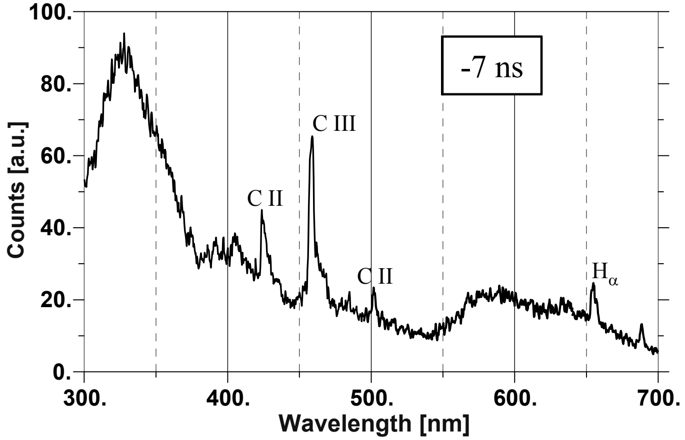
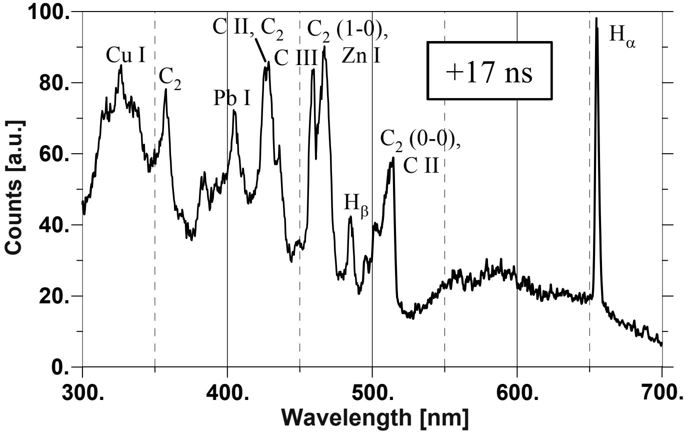
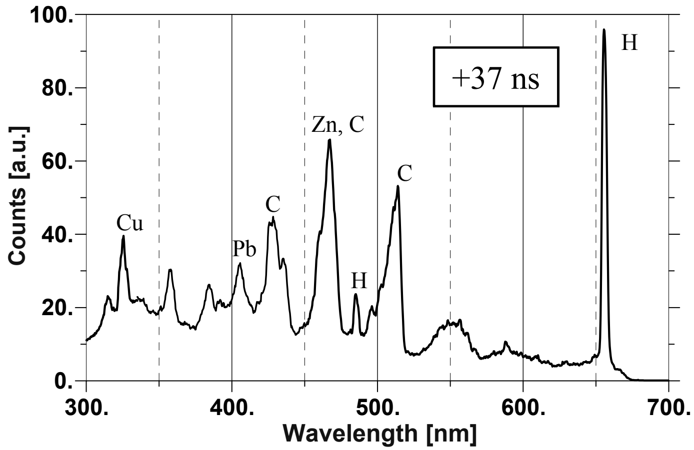
Vacuum/Dielectric Interface Breakdown





Emission Spectra referenced to moment of breakdown





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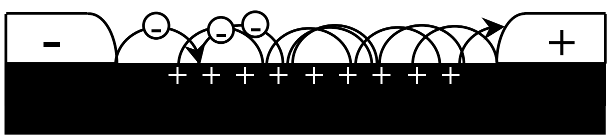
Surface Flashover (Breakdown)

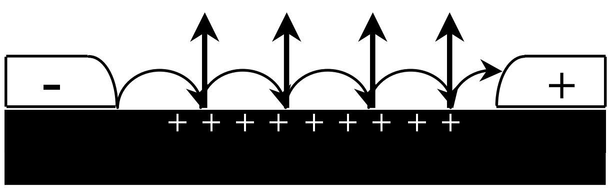
MODEL

1. 

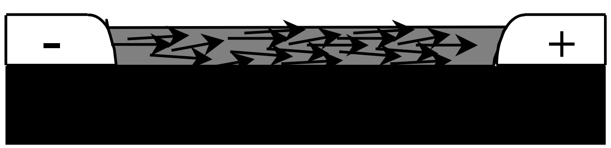
Field Emission from Triple Point

2. 

Saturated Secondary Emission Avalanche

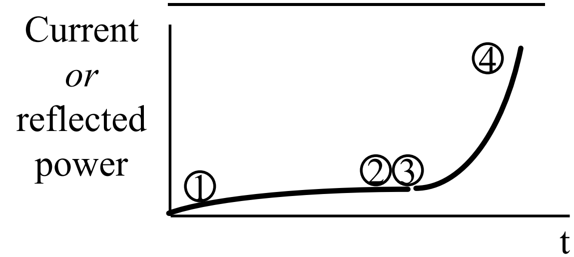
3. 

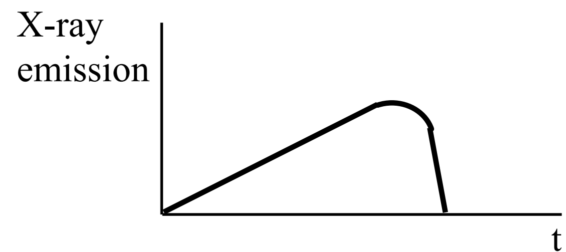
Electron Induced Outgassing

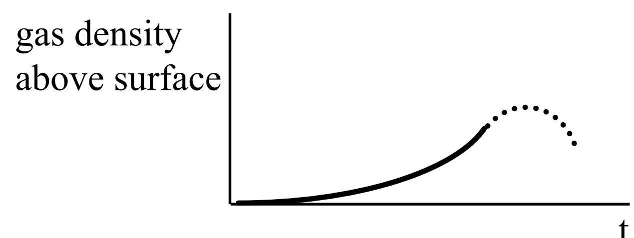
4. 

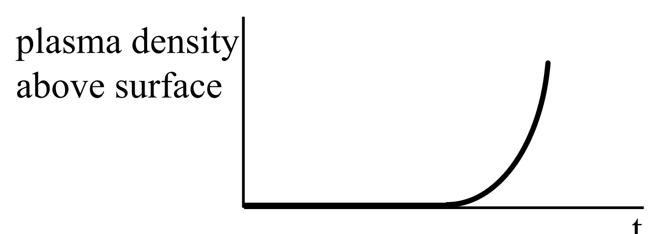
Paschen Breakdown in Desorbed Gas

OBSERVATION

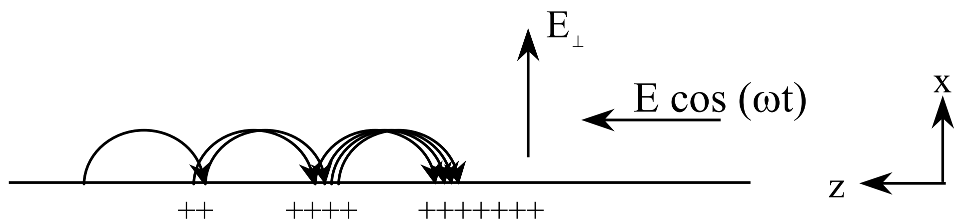








Similarity of AC Flashover and DC Flashover



Equation of motion in direction perpendicular to surface

$$d^2x/dt^2 = -eE_\perp/m$$

$$dx/dt = (-eE_\perp/m)(t - t_0) + v_{x0}$$

$$x = (-eE_\perp/2m)(t - t_0)^2 + v_{x0}(t - t_0), \quad \text{where } x(t=0) = 0$$

$$x = 0 \text{ after "hopping time" } \tau = t - t_0 = 2mv_{x0}/(eE_\perp)$$

Equation of motion parallel to surface, due to AC field

$$d^2z/dt^2 = (-eE/m)\cos(\omega t)$$

$$dz/dt = -v_\omega(\sin(\omega t) - \sin(\omega t_o)) + v_{0z}, \quad \text{where } v_\omega = eE/(m\omega)$$

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Similarity, contd.

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impact energy A_1 (for dz/dt at $t = t_0$)

$$A_1 = \frac{m}{2}[(dz/dt)^2 + v_{0x}^2]$$

$$= \frac{m}{2} v_\omega^2 [\sin^2(\omega t_0 + \omega\tau) + \sin^2(\omega t_0) - 2\sin(\omega t_0 + \omega\tau)\sin(\omega t_0)] + \frac{m}{2} v_{0x}^2$$

average over emission phases" ωt_0:

$$< \sin^2(\omega t_0 + \omega\tau) > = < \sin^2(\omega t_0) > = ½$$

$$< \sin(\omega t_0 + \omega\tau)\sin(\omega t_0) > = ½\cos(\omega\tau)$$

$$< A_1 > = \frac{m}{2} v_\omega^2 2\sin^2(\omega\tau/2) + \frac{m}{2} v_{0x}^2$$

for $\omega\tau/2 \ll 1$, $(m/2)v_{0x}^2 \ll \langle A_1 \rangle$:

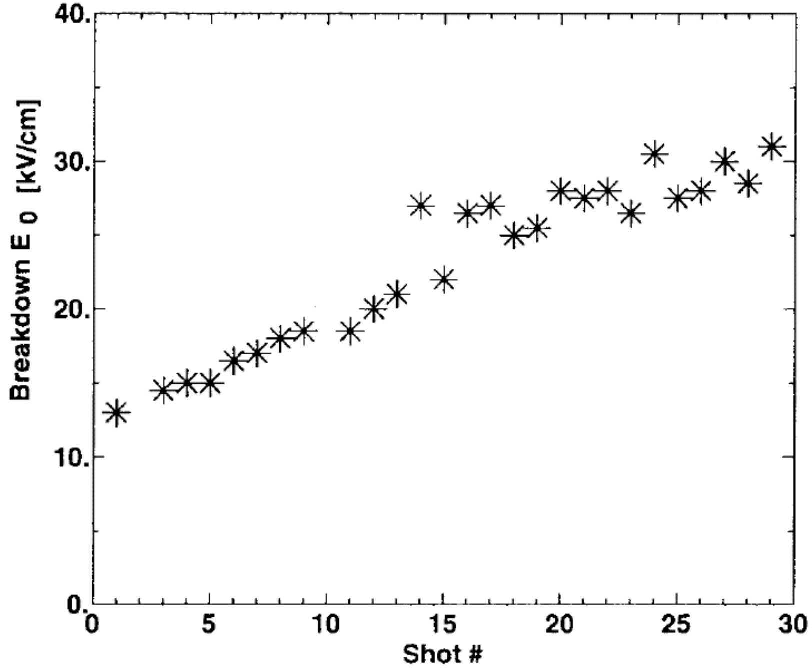
$$< A_1 > = \frac{m}{2} v_\omega^2 2(\omega\tau/2)^2 = 2A_0(E/E_\perp)^2 \text{ , where } A_0 = \frac{m}{2} v_{0x}^2$$

i.e. $E_\perp / E = (2A_0/A_1)^{½}$ if $\omega\tau/2 = \omega(A_1 m)^{½}/(eE) \ll 1$, (for $E = 2\times10^4$ V/cm, this means f < 20 GHz)

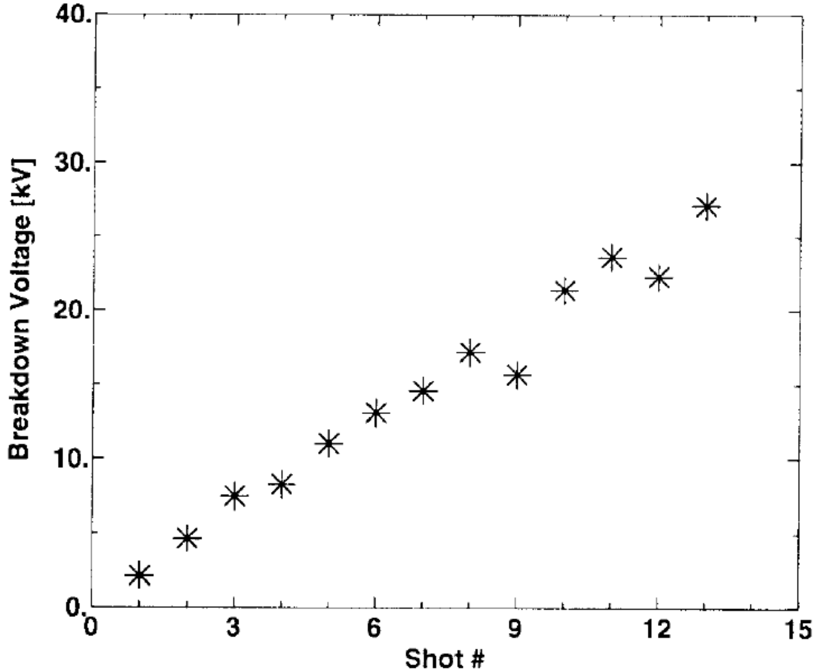
$$\textbf{\textit{If}} \quad \omega(E_{p1}m)^{1/2} / eE_{rfo} \ll 1 \qquad (E_{p1}\text{: first crossover point})$$

Same saturated avalanche parameters (surface charge density etc.) and outgassing rate as for dc flashover!

Similarity, contd.



AC flashover



DC flashover

→ ***Similar dynamics: SEE, induced outgassing, gaseous ionization***

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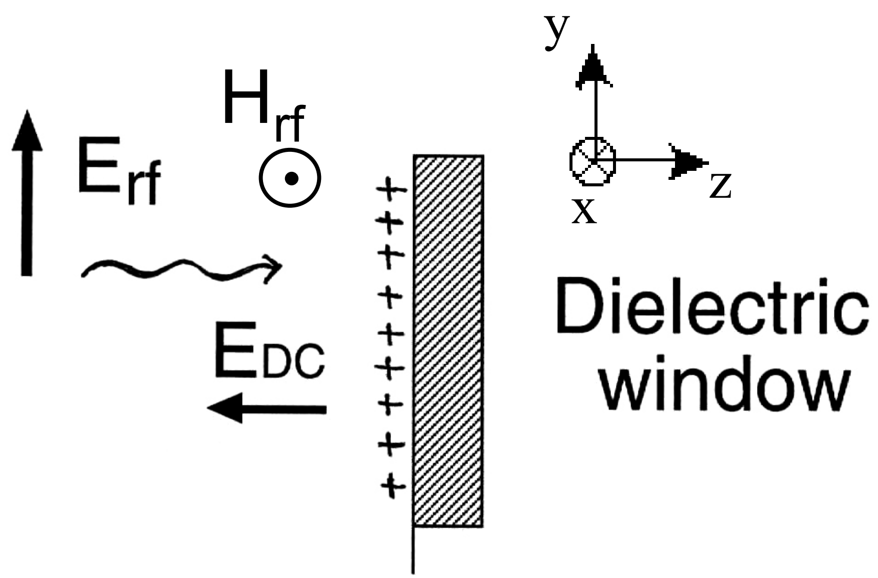
AC Flashover Model (including H_{rf})

JAPPL '99



$$\frac{dv_y}{dt} = -\frac{e}{m} \cdot E_{rf0} \cdot \cos(\omega \cdot t + \theta) \cdot \left(1 - v_z \cdot \frac{\beta_{10}}{\omega}\right)$$

$$\frac{dv_z}{dt} = -\frac{e}{m} \cdot E_{rf0} \cdot \left(-\alpha + v_y \cdot \frac{\beta_{10}}{\omega} \cdot \cos(\omega \cdot t + \theta)\right)$$

with $\alpha = E_{dc}/E_{rf0}$

$$v_y(t_0) = 0$$

$$v_z(t_0) = -\sqrt{2 \cdot E_{emi}/m}$$

with $E_{emi} \sim 2.8$ eV

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AC Flashover Model

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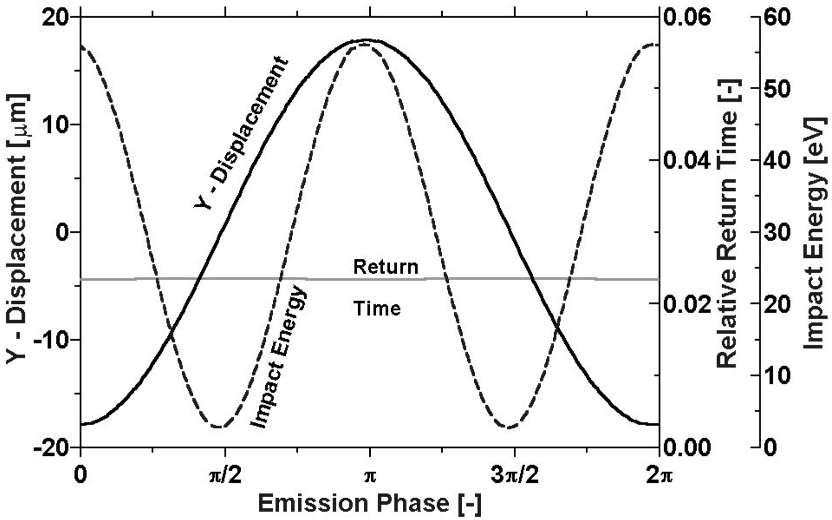
Numerical Solution (E_{rf0} = 30 kV/cm)

Identical result for H_{rf}-field on or off



Impact energy: $E_p = \frac{1}{2}\, m\, (v_y^2 + v_z^2)$

Adjust E_{DC} so that phase averaged $E_p = E_{p1}$ = 29.7 eV (first crossover point)

→ $\alpha^{-1} = 2.2$ (= E_{rf0}/E_{DC})

Compare DC – flashover: $\alpha = \sqrt{2 \cdot E_{emi} / (E_{p1} - E_{emi})}$

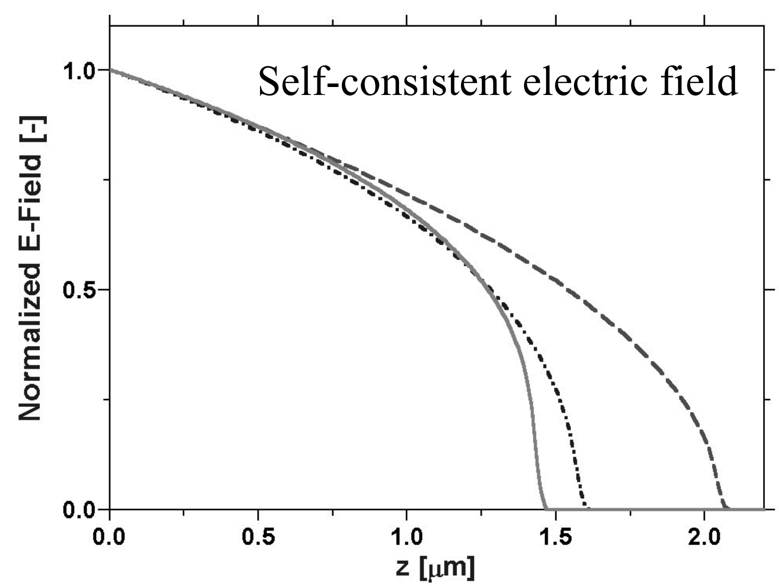
Independent of E_{rf0}, same numerical value

$$E_{DC}(z) = \frac{\rho_0 \cdot e}{\varepsilon_0} \cdot \left(\frac{\gamma}{2} + 1 - \int_0^z pdf(z')\,\mathrm{d}z' \right)$$

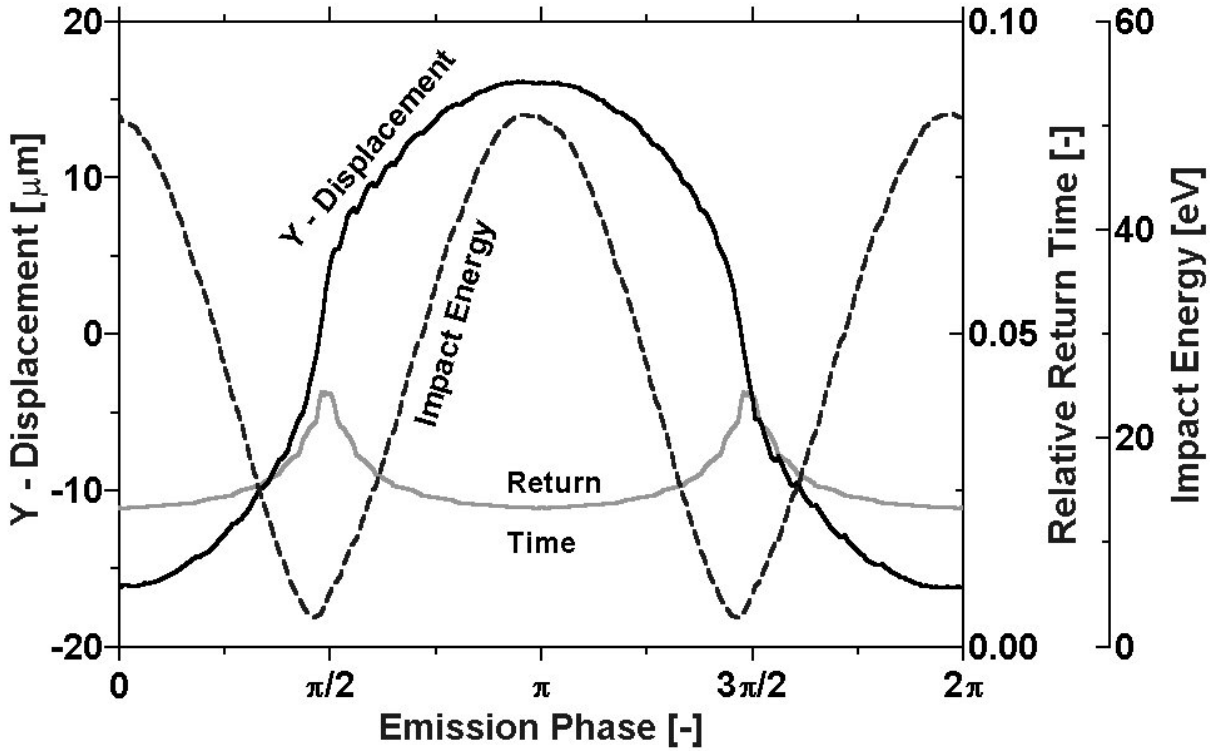
pdf: Electron probability density function, from trajectories averaged with respect to emission phases.

$$\gamma = (N_+ - N_-)/N_-$$

Normalized difference of positive surface charge to total negative space charge.



AC Flashover Model



- Maxima in hopping distance (y-displacement coincide with low E_{rf} at moment of secondary electron emission, $E_{rf} \sim \cos(\omega t + \theta)$).
- Positive surface charge: 2.3 x 10^{10} electrons/cm^2
- Up to this point, no difference between H_{rf} on or off
- Return time τ << microwave period

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AC Flashover Model

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In reality: SEE energy is distributed

→ Account for tail in the emission energy by introducing electrons with $E_{emi}^* = E_{emi} + 10\%$

- Only a few electrons with higher SEE energy will change the *pdf* little
- RF magnetic field has distinct impact on electrons emitted with E_{emi}^*:
  - Upstream: averaged E_p = 3 keV (instead of 29 eV)→ experimentally observed x-ray emission
  - Downstream:
    - Electrons will only return for emission phases close to E_{rf} maximum
    - ExB drift (+initial emission velocity) drives the electrons away from the surface for lower E_{rf} at the moment of emission
    - Faster electrons will only return for 25% higher positive surface charge

→ Hypothesis: Breakdown field on downstream side will be higher

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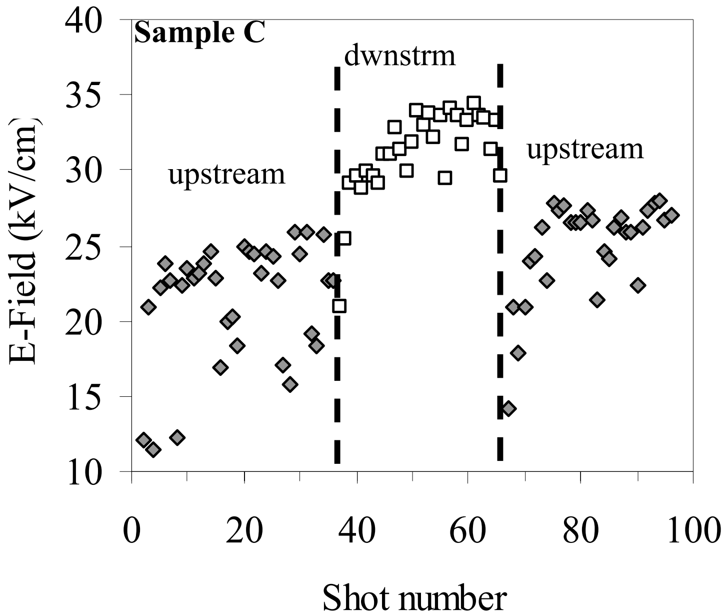
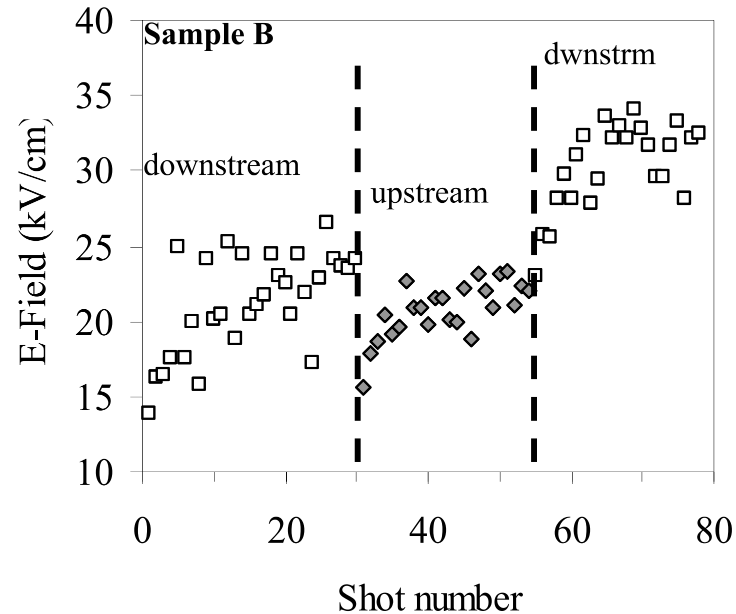
Experimental Verification

- Alumina sample (one-sided coating with antibreakdown coating)
- Sample in cradle rotated after about 30 flashovers (triple point conserved)





Conditioning effects excluded → *~ 20 % higher breakdown field on downstream side*

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CONCLUSIONS

- Magnetron/traveling wave resonator excellent tool for breakdown studies at power density levels of 10 MW/cm^2.

- High speed diagnostics provides detailed information on the breakdown processes.

- Results for "pillbox"-window show complex behavior, i.e. superposition of two-surface multipactor and surface flashover.

- Breakdown phenomena for interfaces in vacuum with TE_{10} mode (pure tangential applied field) are similar to DC surface discharge: same saturated secondary electron dynamics, same outgassing rate, same breakdown in desorbed gas above the surface.

  → Same methods to increase breakdown fields can be used.

- Although the bulk of electrons has energies below 100 eV, the rf magnetic field needs to be included in breakdown simulations.

- 0.5 % to 1 % of the rf energy is dissipated in fully developed single surface multipactor

Outlook: Breakdown at Higher Pressures

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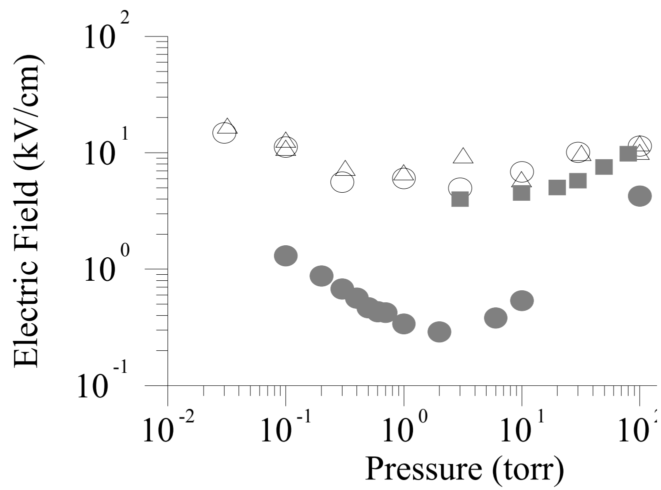
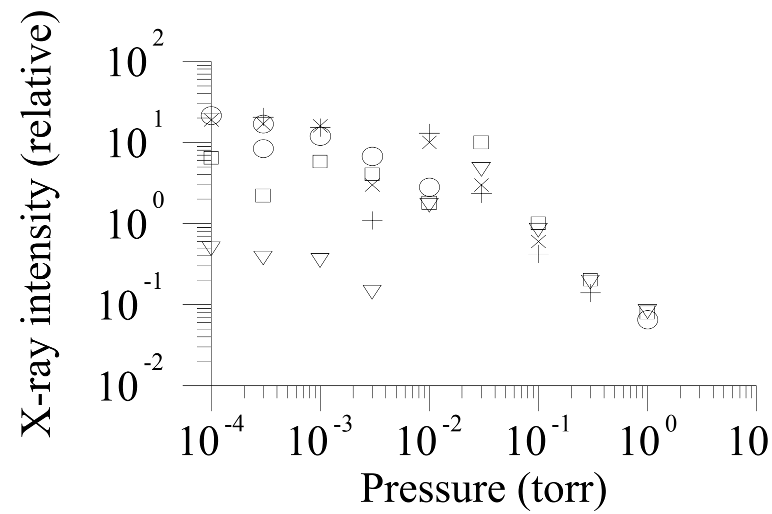
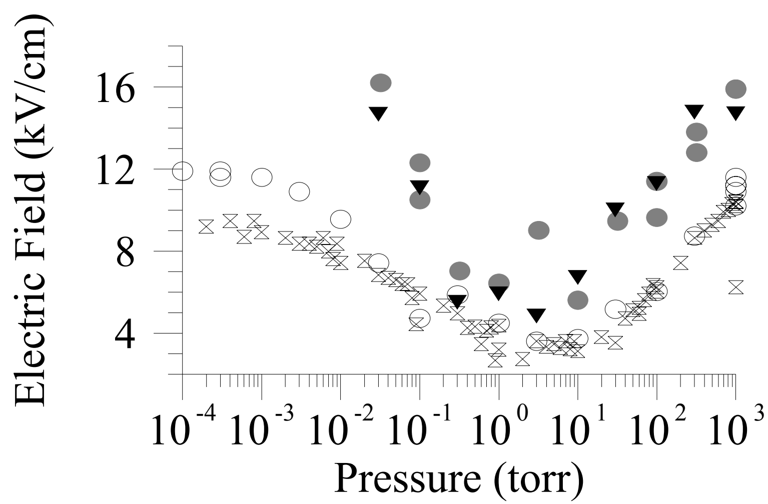


Fig. 3. Comparison of TTU volume breakdown results with literature data for air (o, Δ - TTU data; ■ - Grachev; ● - MacDonald, cw).



Relative x-ray intensity measured at breakdown for different gases (o, sample B-air; +, sample C-SF_6; ×, sample D- SF_6; □, sample E-argon; ∇, sample F-argon).



Alumina surface – volume breakdown

(⧖, sample A-air; o, sample B-air; ●, Air; ▼, Air(2)

→ ***Primarily volume breakdown at p > 1 Torr ?***

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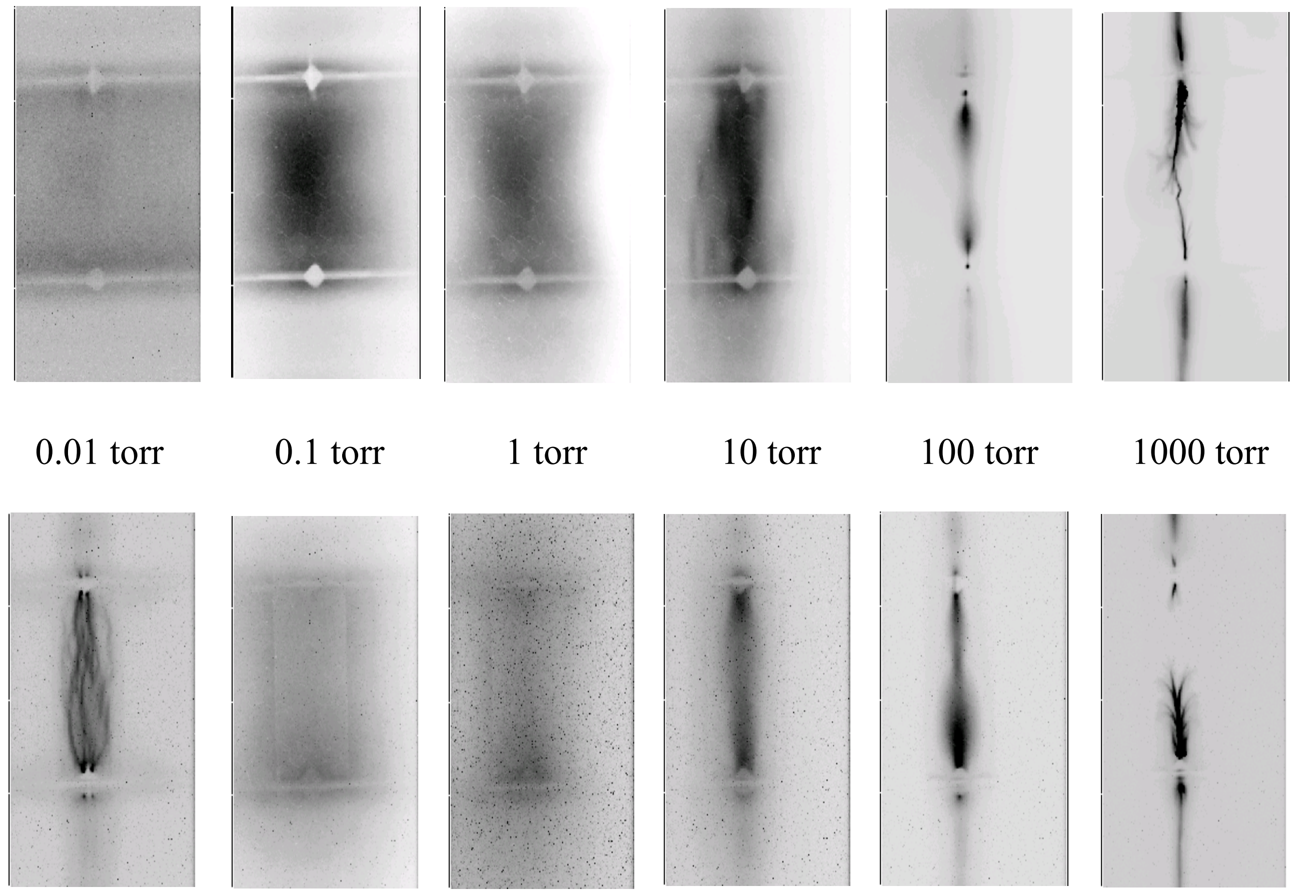
Comparison of Time Integrated Images for Volume Breakdown and Dielectric/Gas Breakdown



Acknowledgement

Texas Tech University:

James Dickens

Magne Kristiansen

Hermann Krompholz

David Hemmert

University of Michigan:

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