Microwave-driven breakdown: from dielectric surface multipactor to ionization discharge†

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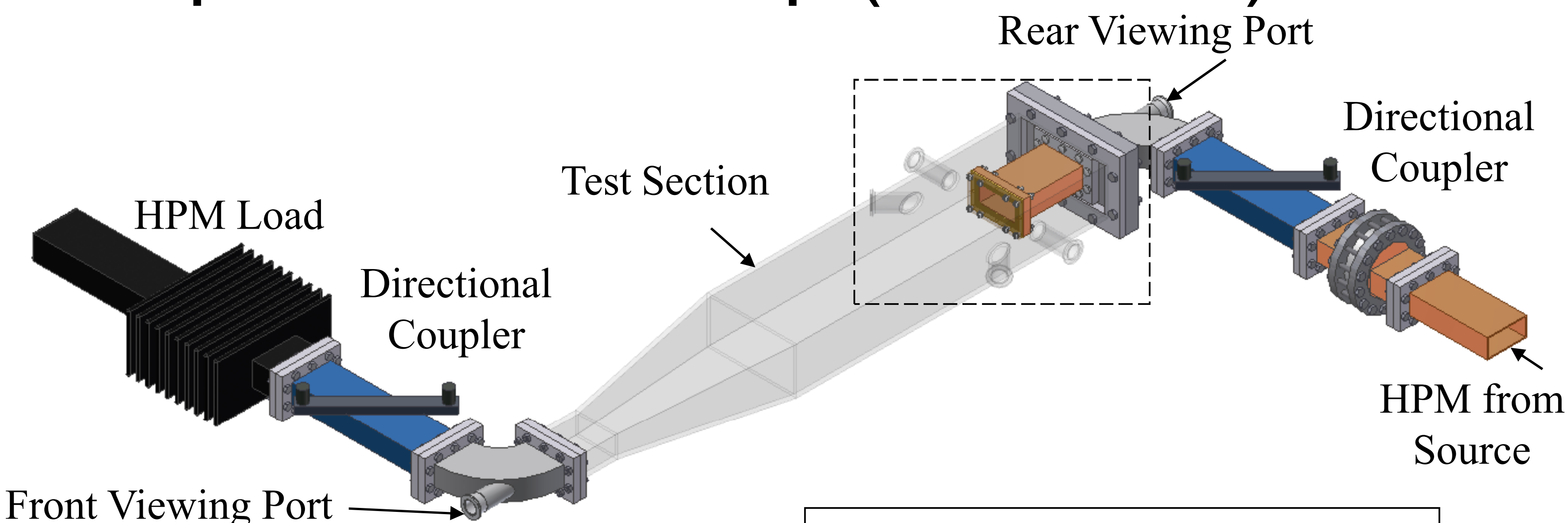
Goals

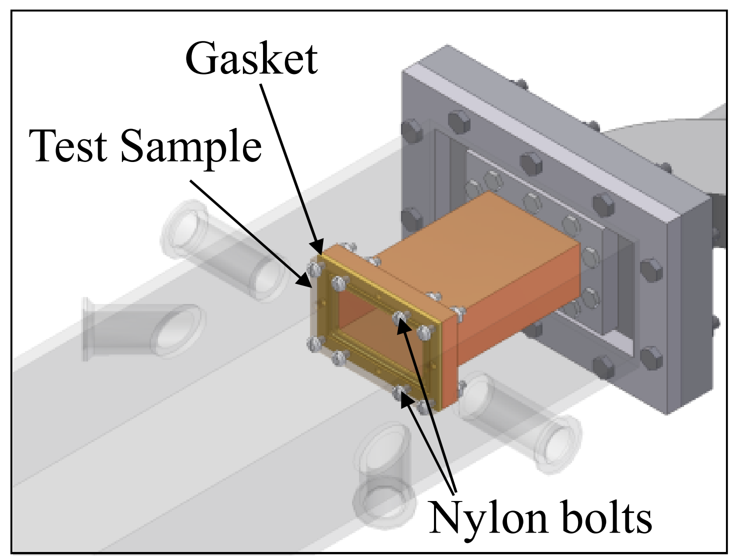
- Understand basic physics of microwave-driven breakdown
  - Breakdown threshold dependence on pressure, gas composition, geometric features
  - Low Pressure Dielectric Multipactor
  - Transition to Ionization Discharge
  - Compare Experiments and Theory

Experimental Setup (2.85 GHz)

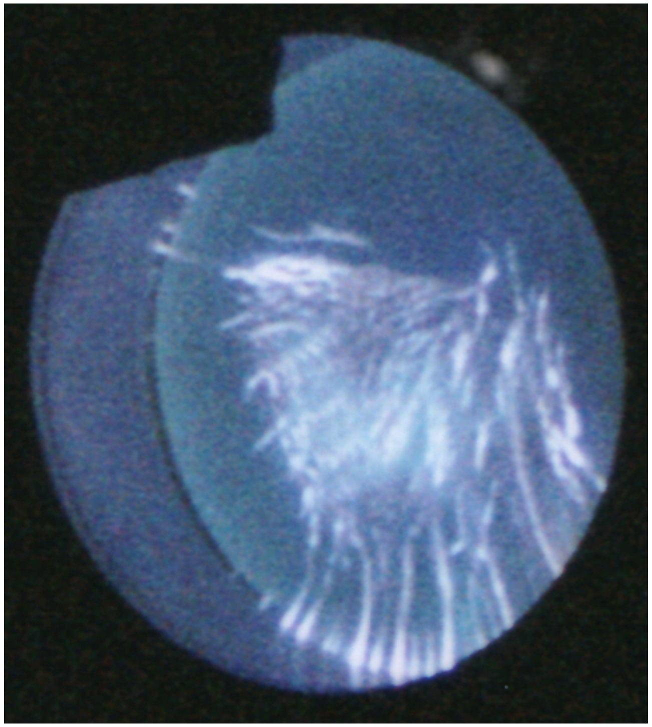


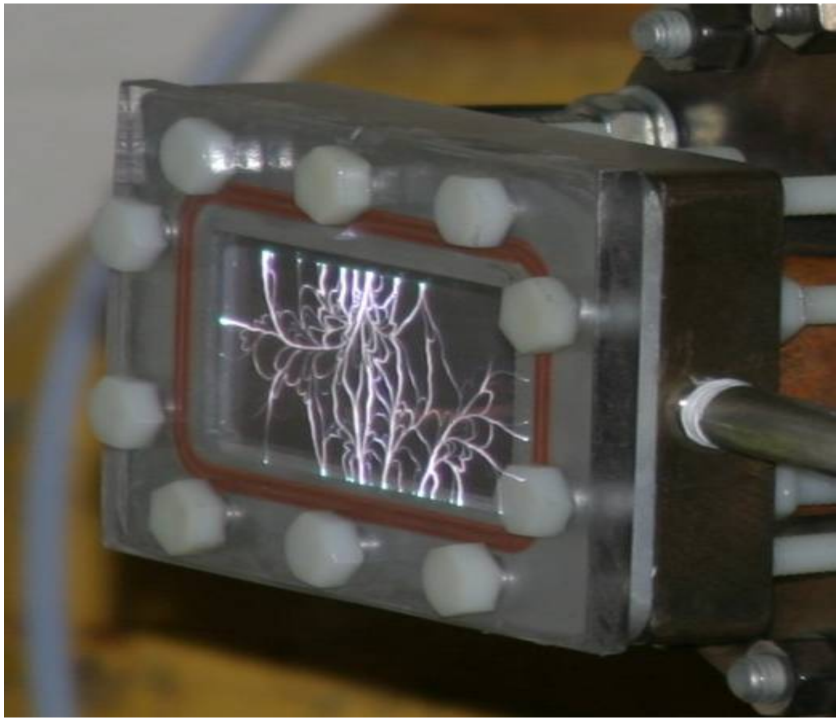
Test Section Features

- WR284-WR650 Standards
- Not optimized for transmission (Simple geometry to study effects)
- High-loss silicone rubber sheets
- Side and 45° Viewing Ports
- Atmospheric Control



RF Window Flashover

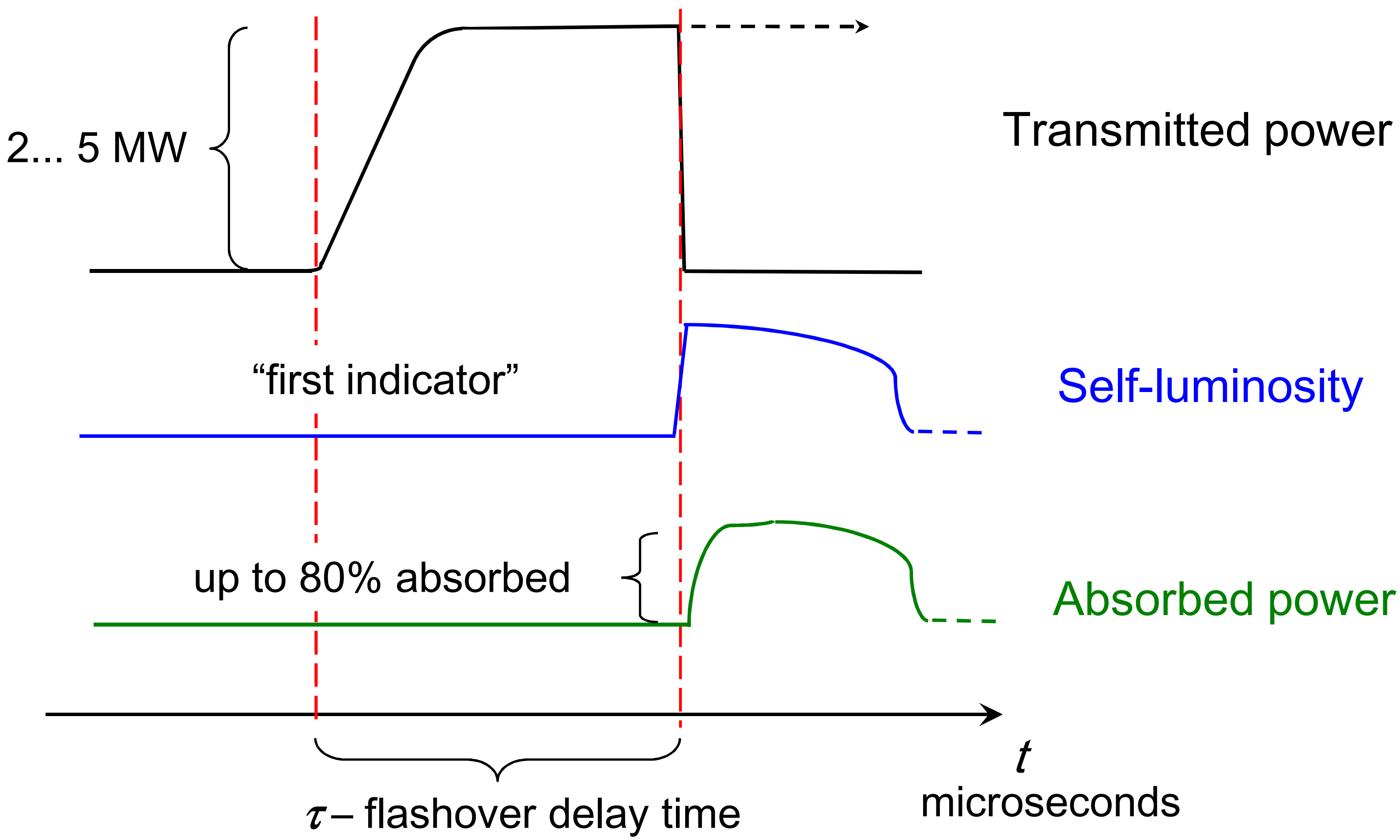




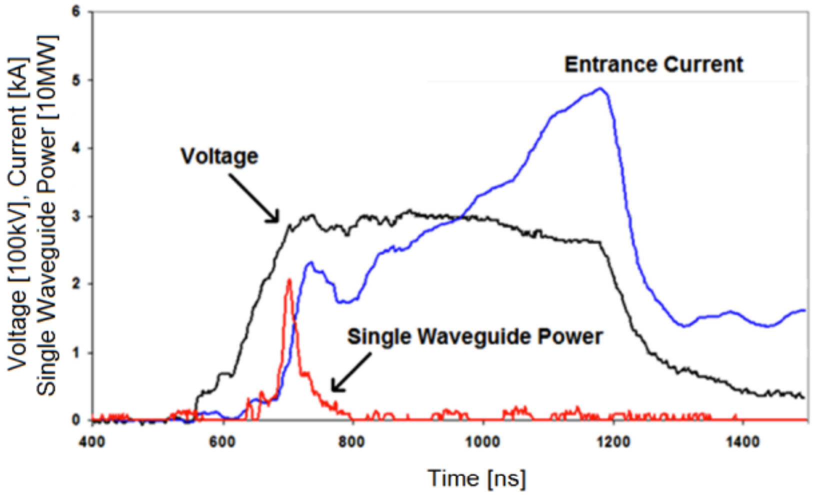
> MW transmitted power (High Power Microwaves, HPM)
→ Field amplitudes in excess of several 10 kV/cm

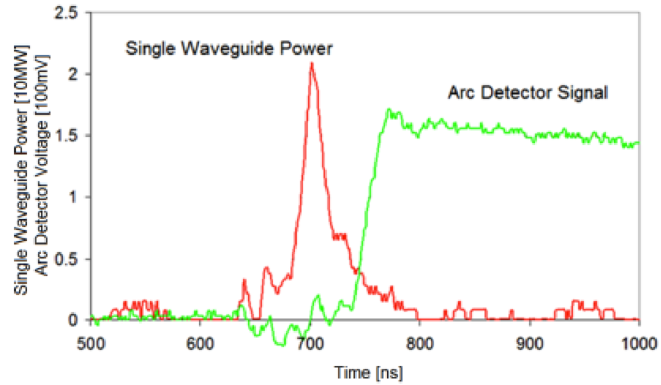
Flashover can be initiated
with or without the presence of a triple point

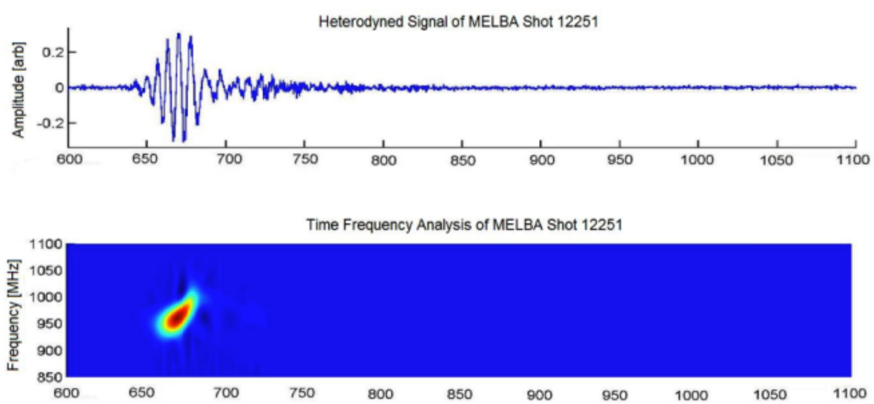
Observed Waveforms

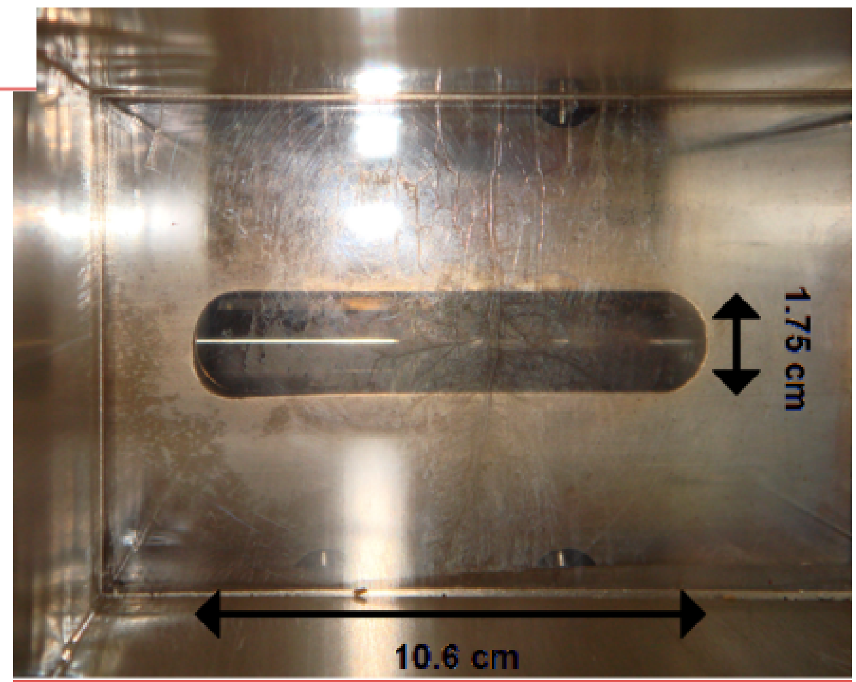


UM RelMag: old window

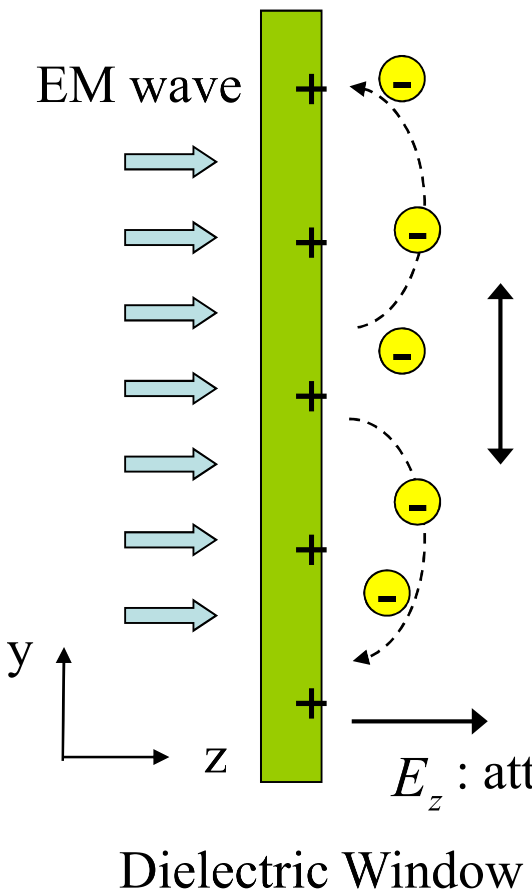








Single-Surface RF Multipactor



- Multipactor discharge is a secondary electron avalanche frequently observed in microwave systems.

$E_y = E_{rf0} \sin(\omega t)$: leads to electron energy gain.

E_z : attracts electrons

$\tau_{transit} = 2m \, \mathrm{v}_{z,0} / eE_{z0}$ (electron life time)

$z_{transit} = \frac{m}{2} \frac{\mathrm{v}_{z,0}^2}{eE_{z0}}$ (maximum distance)

$\mathrm{E}_{iy} = f\,(E_{rf0}/\omega,\ \omega\tau_{transit}, \phi_0 = \omega t_0)$

Dominates at low pressure

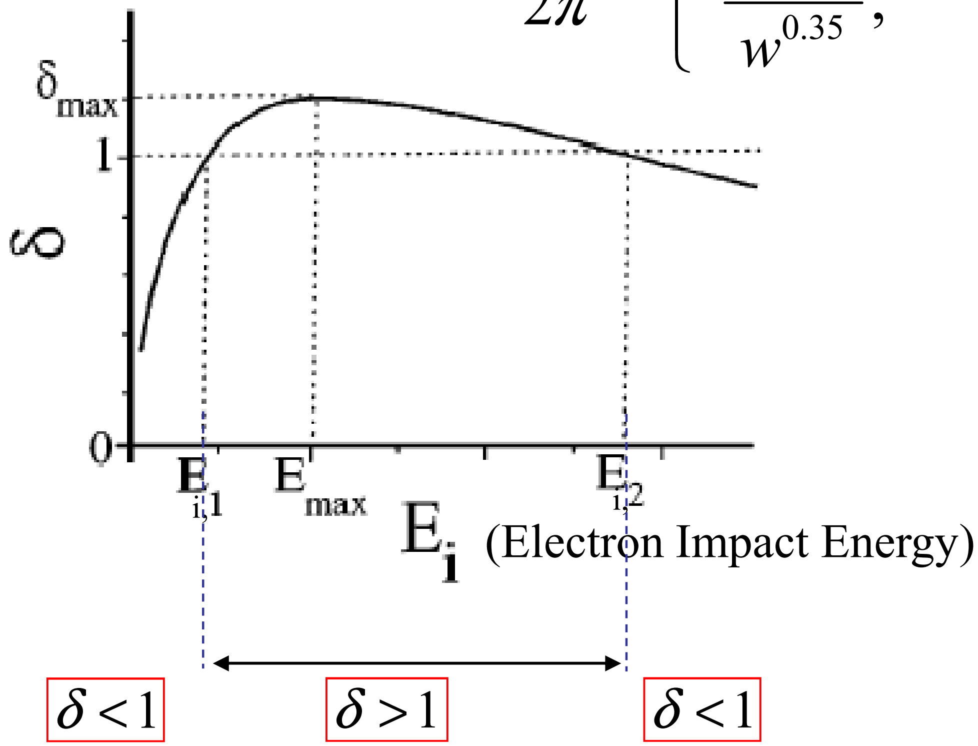
Secondary Electron Model

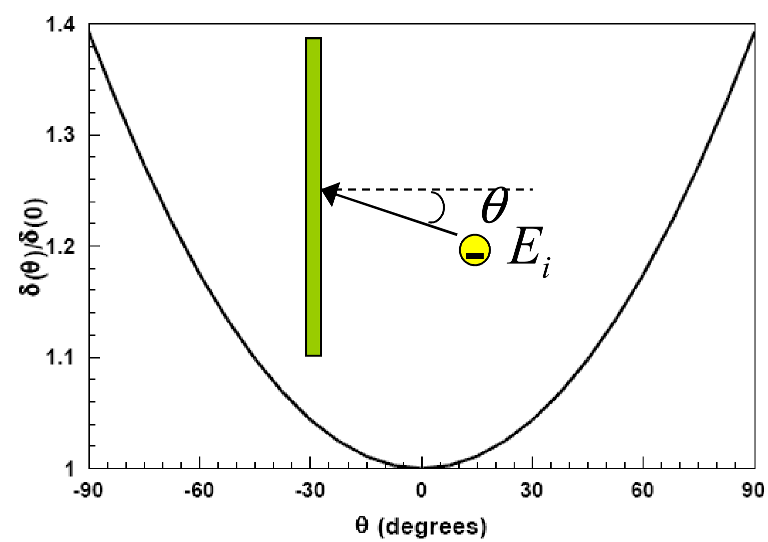
- Energy and angular dependence of secondary emission coefficient

$$\delta(E_i,\theta) = \delta_{\max 0}\left(1+\frac{k_{s\delta}\theta^2}{2\pi}\right)\begin{cases}(we^{1-w})^k, & w \le 3.6 \\ \dfrac{1.125}{w^{0.35}}, & w > 3.6\end{cases}$$

$$w = \frac{E_i - E_0}{E_{\max 0}(1+k_{sw}\theta^2/2\pi) - E_0}$$

$$k = \begin{cases} 0.56, & w<1 \\ 0.25, & 1 \le w \le 3.6 \end{cases}$$

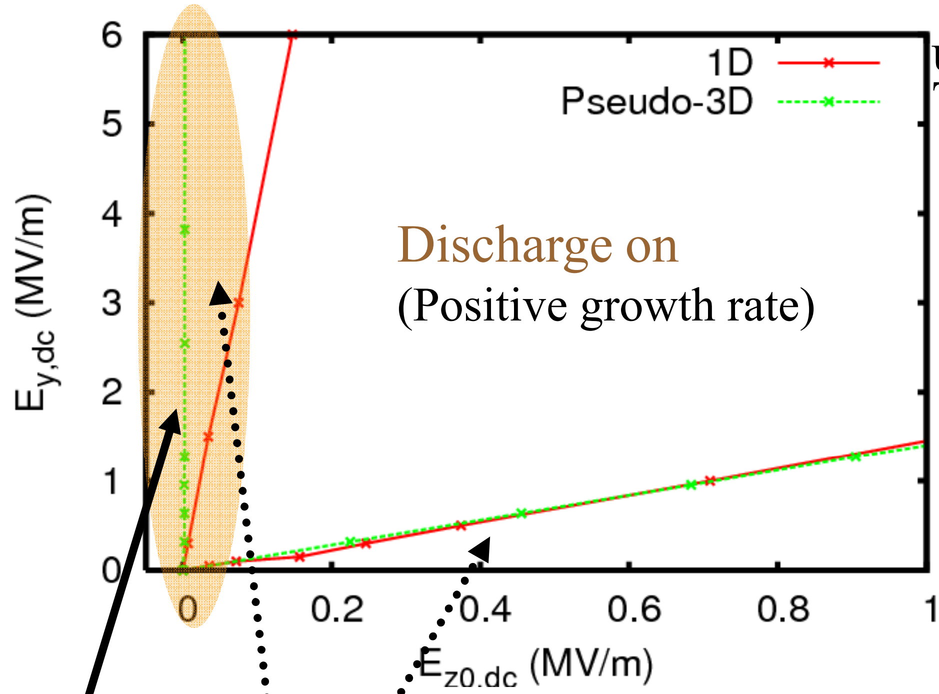




θ (Electron Impact Angle)

Vaughan *et al*, IEEE-TED (1989); IEEE-TED (1993)

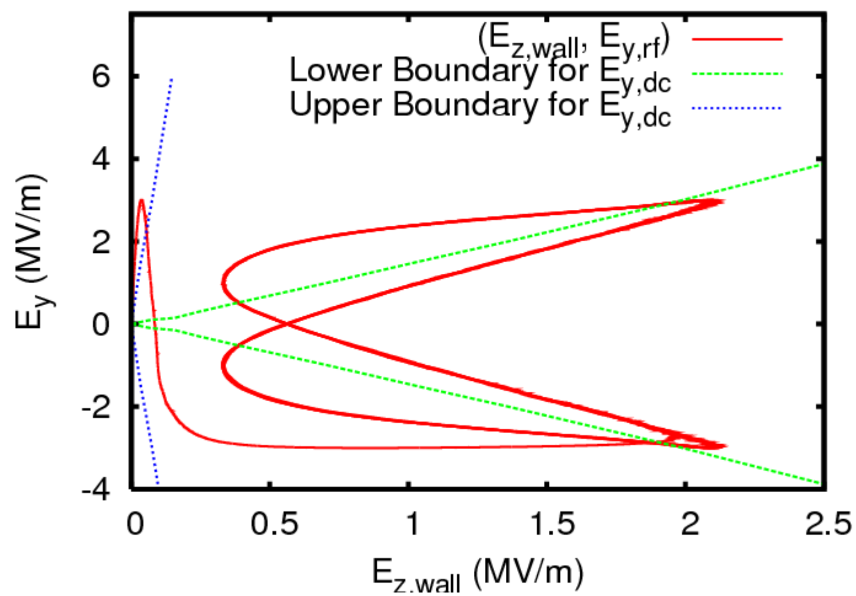
PIC Multipactor Susceptibility



uniform plane wave
TE10 rectangular waveguide

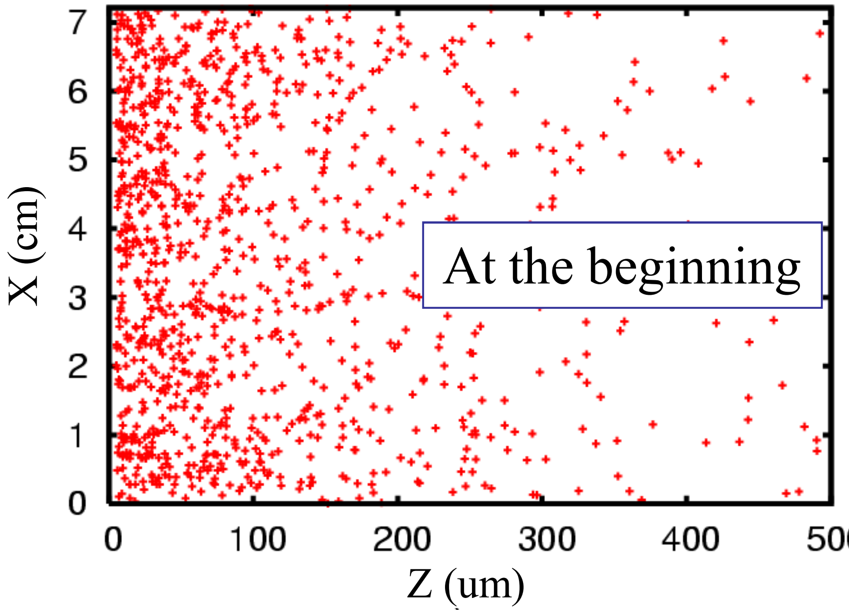
- include transverse variation of E_{RF}
- absorb at transverse wall
- neglect transverse space charge

Discharge off : low δ due to
- Too high impact energy
- Too small impact energy

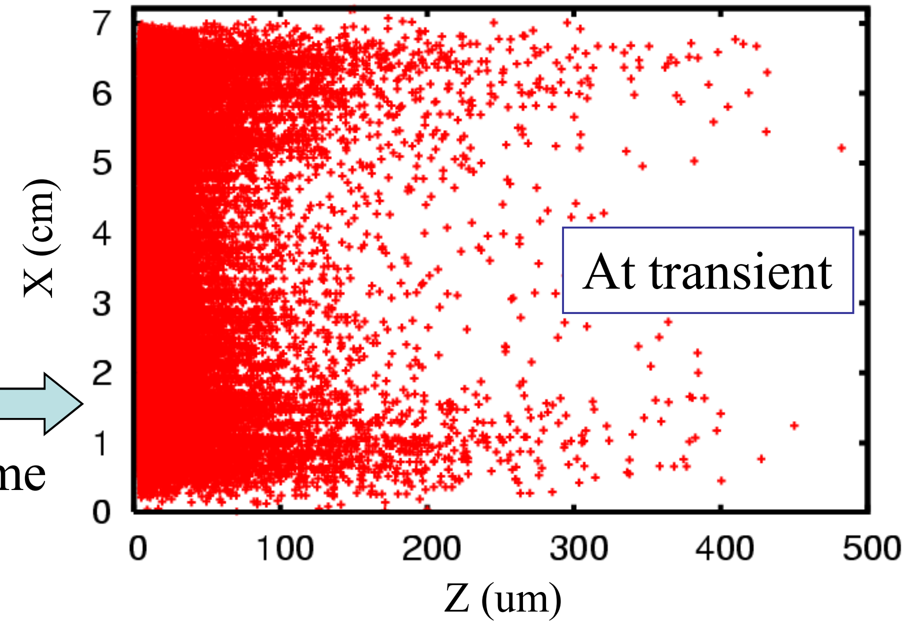


high field susceptibility becomes vertical in waveguide – no upper field cutoff

TE_{10} Multipactor Migration



Time

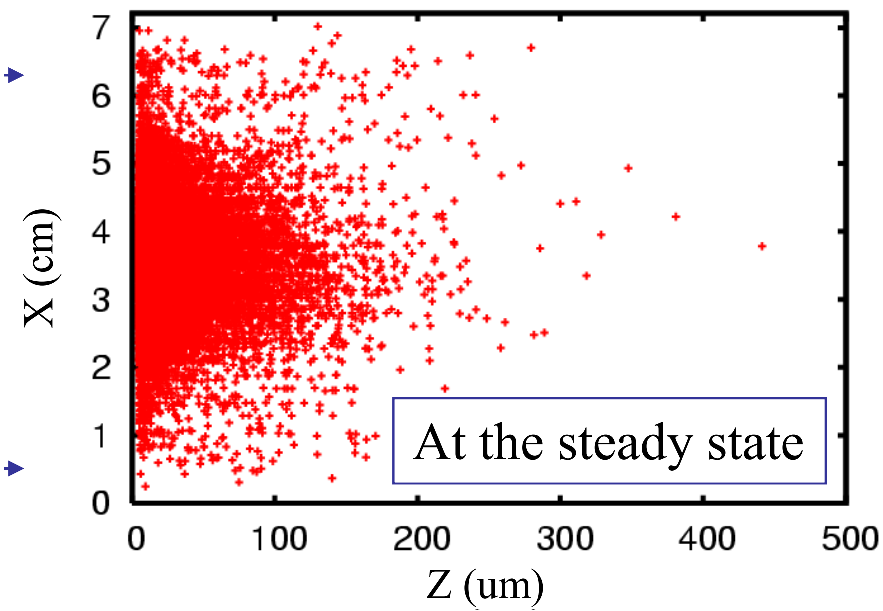


Time

Weak E_{rf}

Strong E_{rf}

Weak E_{rf}

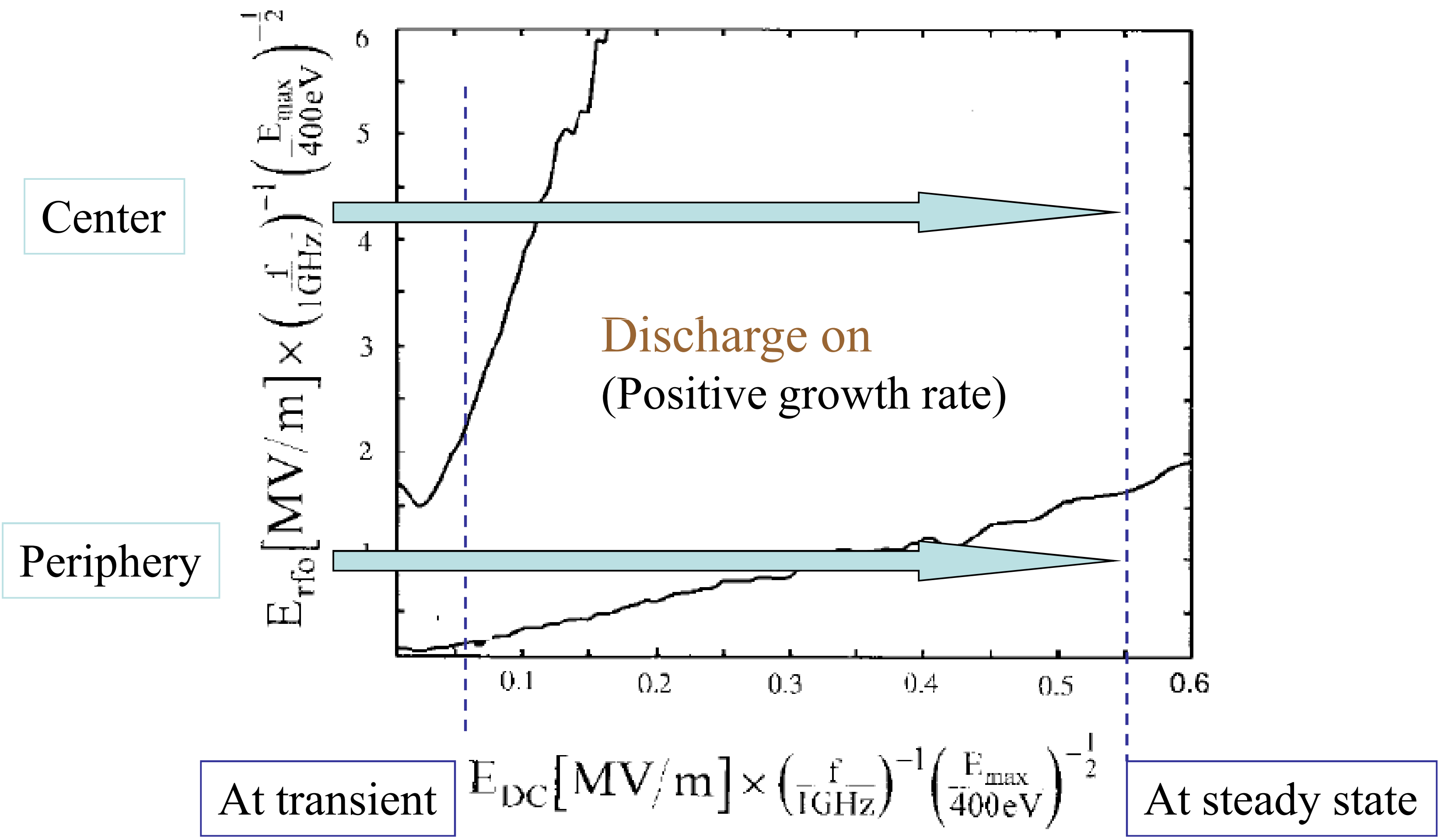


$E_y^0 = 5$ MV/m

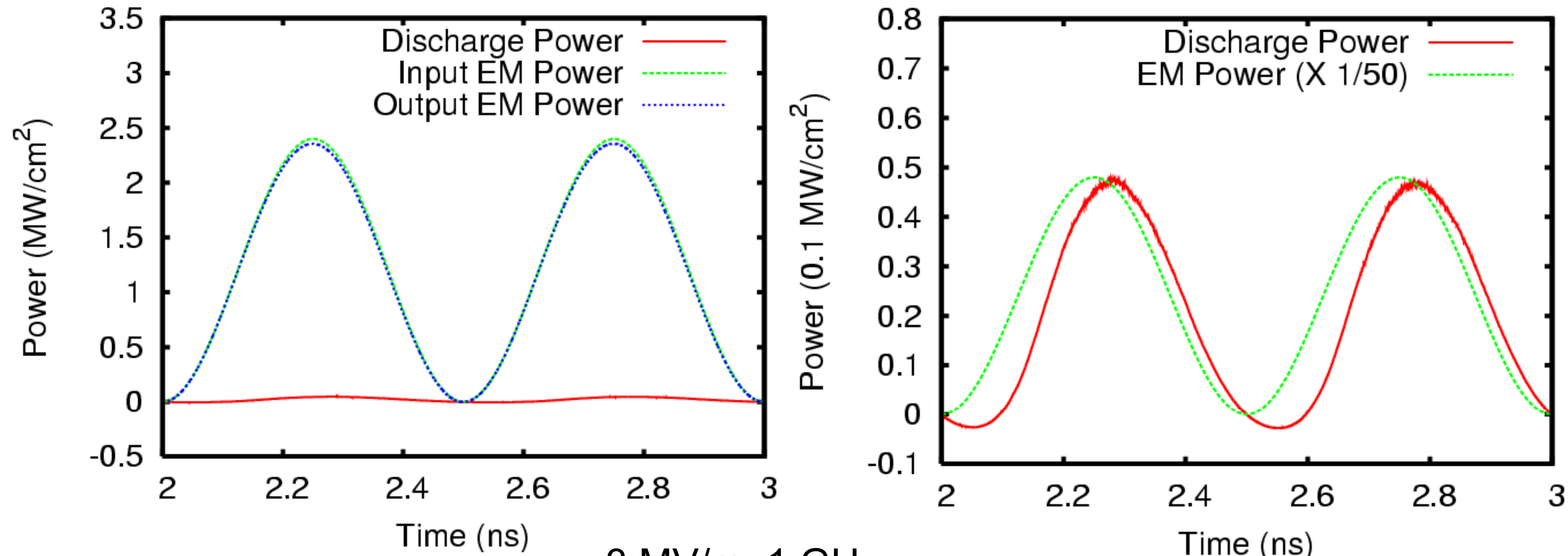
2.85 GHz, Vacuum

Explanation of Migration

- Susceptibility Curve



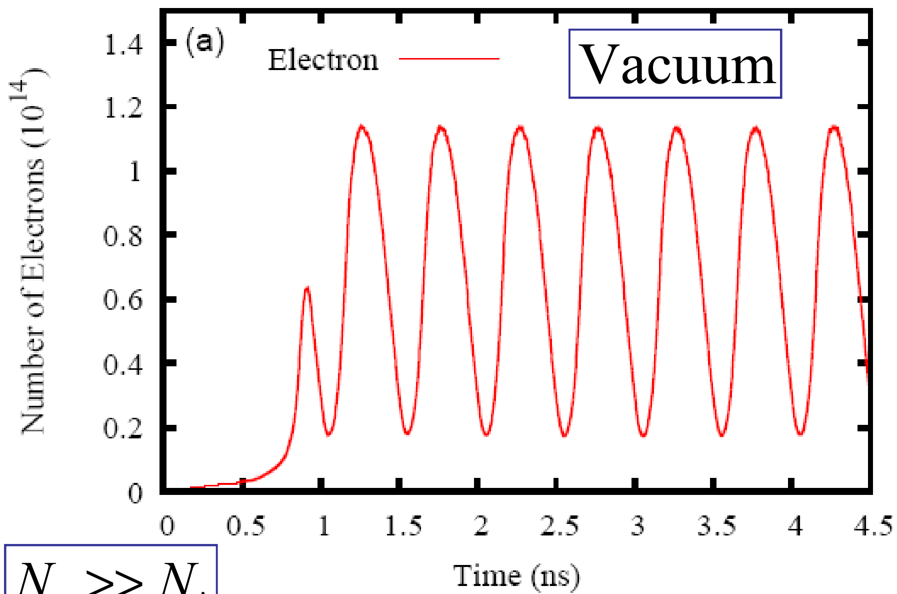
Multipactor Power



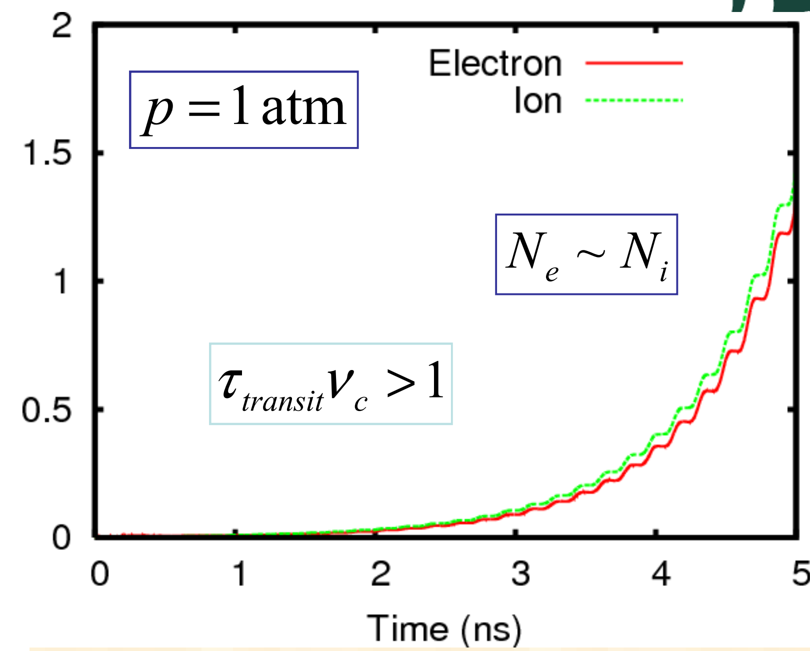
3 MV/m, 1 GHz

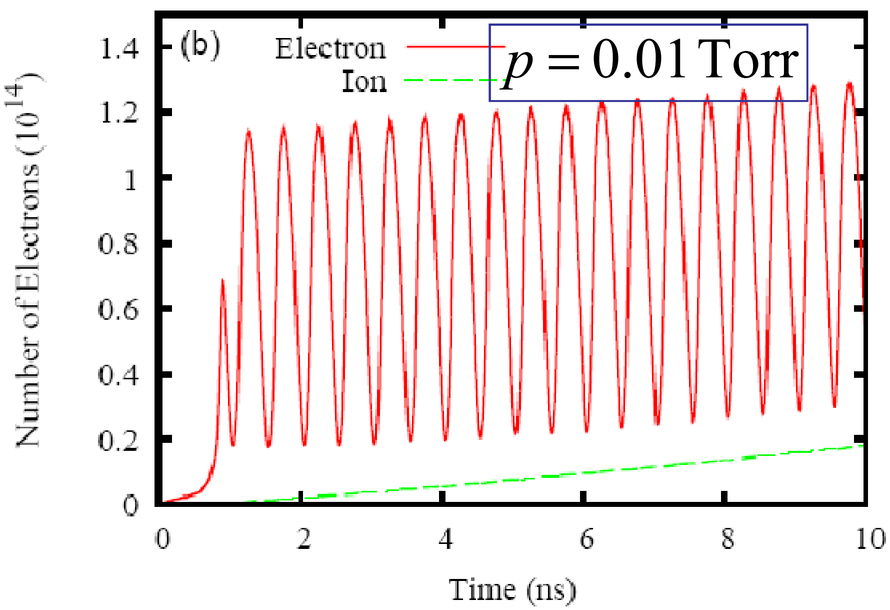
- ~2 % of the input EM power is absorbed
- The phase difference between the discharge power and input EM power means that the electrons are not totally in equilibrium with the local rf electric field.

Collisional Effects



$N_e >> N_i$

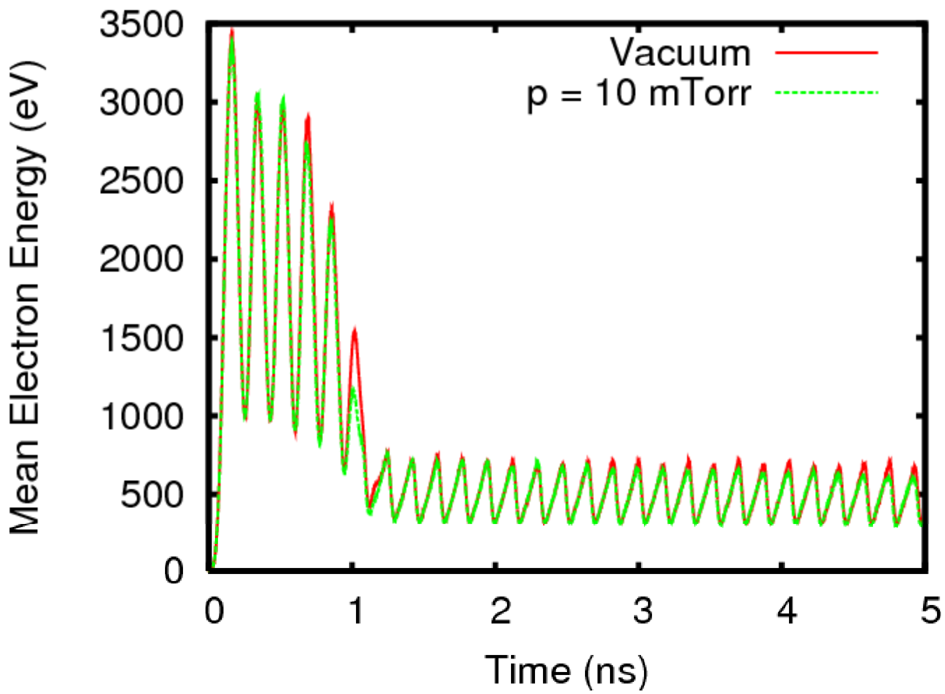


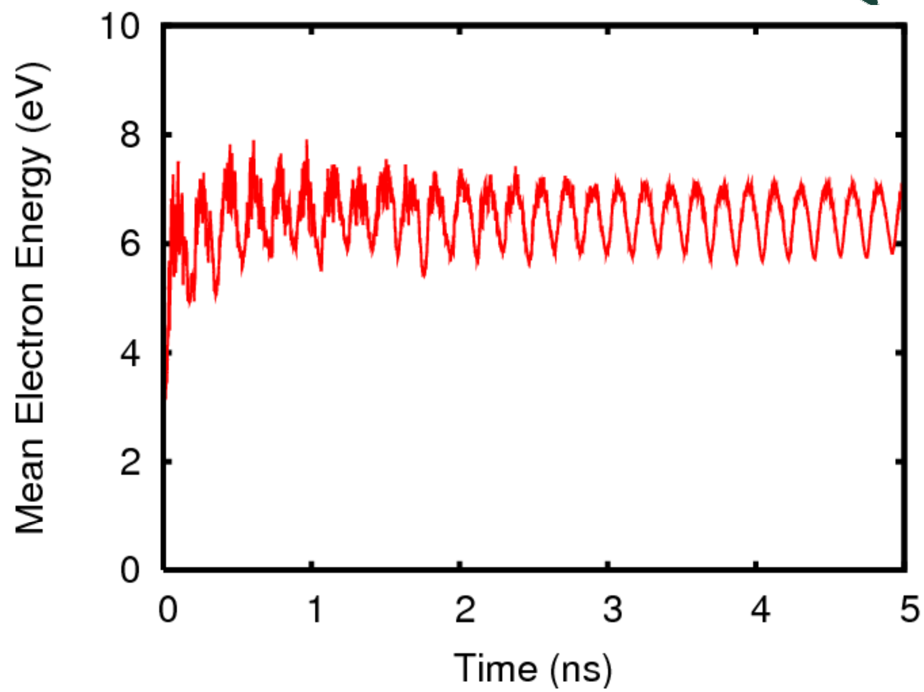


- As the pressure increases, electron-impact ionization collisions dominate secondary electron emission as the electron source.
- At high pressures, the number of ions becomes comparable to that of electrons.

$E_{rf0} = 3\,\text{MV/m at } 1\,\text{GHz, Argon}$

PIC: Electron Mean Energy





Vacuum and $p = 10\,\mathrm{mTorr}$

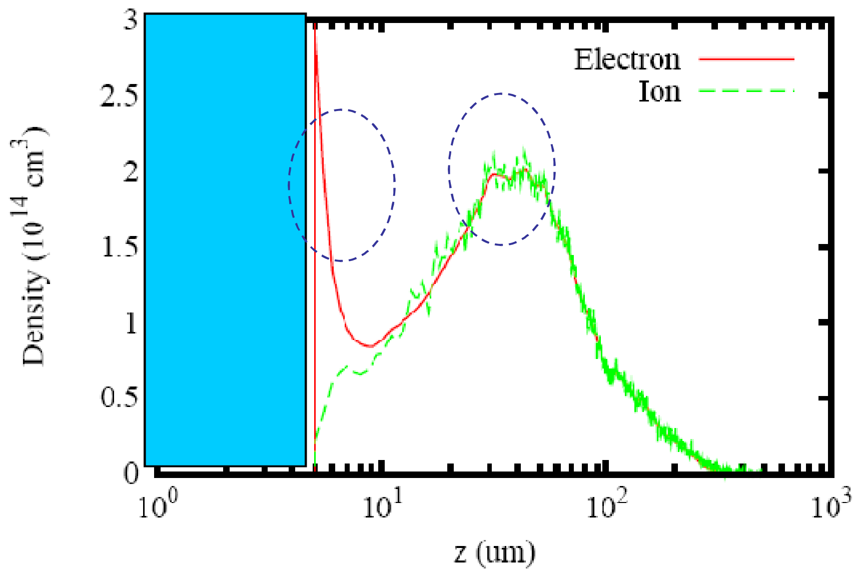
$p = 1\ \mathrm{atm}$

- Electrons in the multipactor discharge gain their energy by being accelerated by <u>the rf electric field during the transit time</u>.

- At high pressures, electrons <u>suffer many collisions</u> and lose a significant amount of energy gained from the rf electric field.

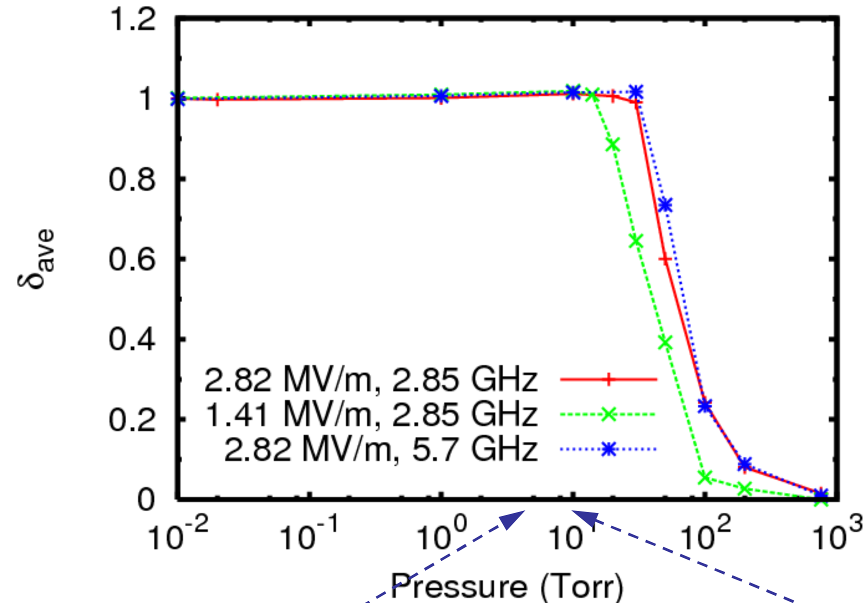
$E_{rf0} = 2.82\,\mathrm{MV/m}$ at $2.85\,\mathrm{GHz}$, Argon

Transition



1 Torr: surface and volume discharges coexist

Transition Pressure (10~50 Torr Ar)

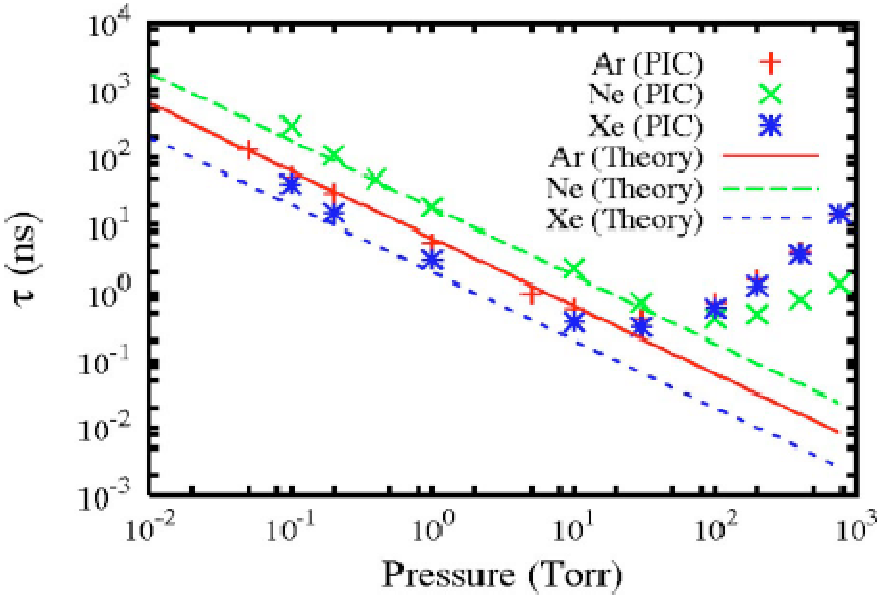


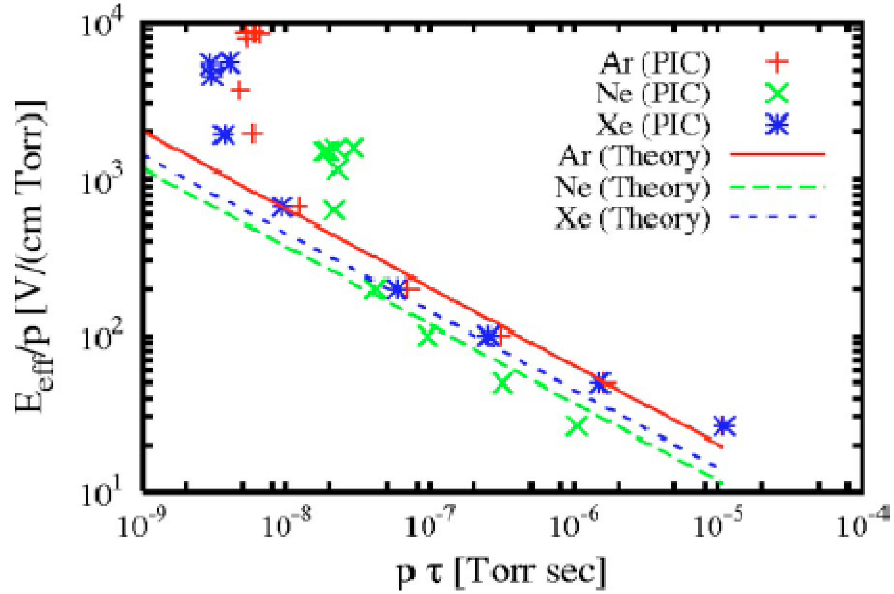
$\omega(2.85\ GHz) \sim \nu_c$

$\omega(5.7\ GHz) \sim \nu_c$

- Below 10 Torr, the secondary yield is nearly unity so multipactor is dominant.
- As the pressure increases and hence the volume discharge suppresses the secondary electron emission, it decreases to nearly zero.

Breakdown Scaling Law





Low pressure regime:
surface multipactor dominated

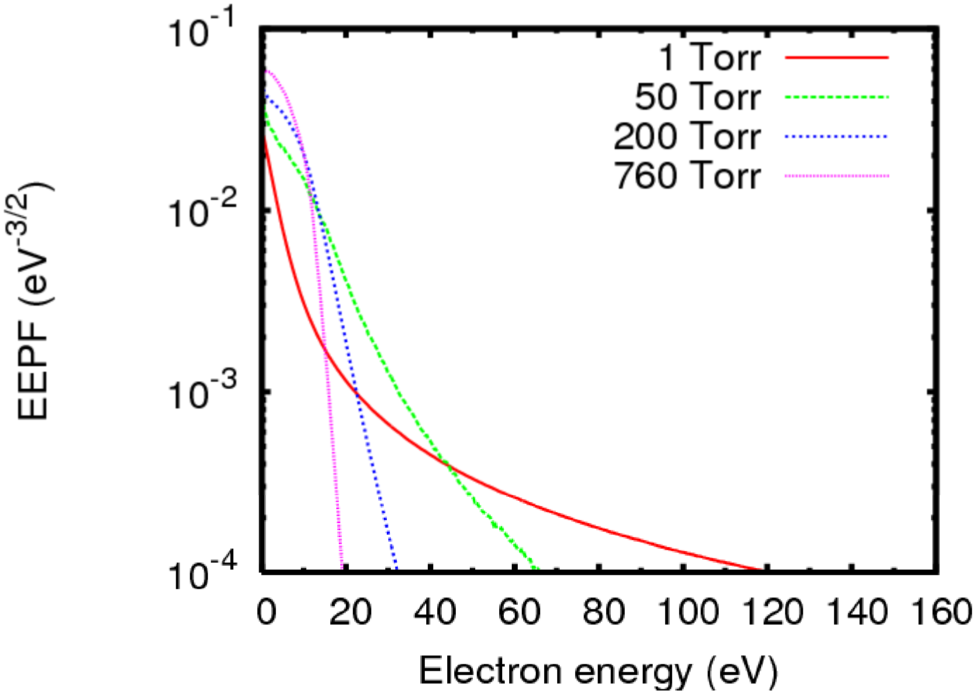
$$\tau \sim \frac{1}{\nu_i} \sim \frac{1}{n_g \langle \sigma v \rangle} \sim \frac{1}{p}$$

High pressure regime:
collision dominated ($\nu_c >> \omega$)
volumetric discharge

$$\frac{E_{eff}}{p} \sim \frac{1}{\sqrt{p\tau}}$$

Lau, Verboncoeur, and Kim, **APL**, 89, 261501 (2006)

PIC: Electron Energy Distribution

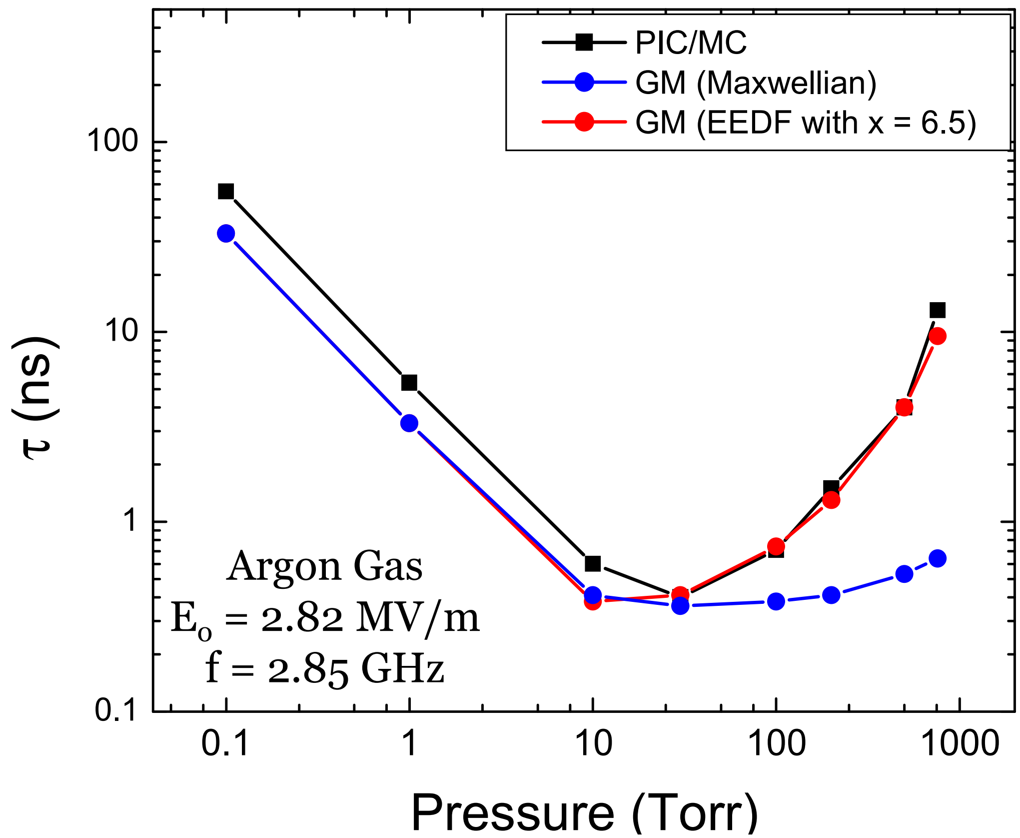


Spatially averaged

- Below 50 Torr, the EEPF is bi-Maxwellian like
- At high pressures, the EEPF becomes cutoff, with the depletion of high-energy electrons $\nu_c > \omega$

$E_{rf0} = 2.82\,\mathrm{MV/m}$ at $2.85\,\mathrm{GHz}$, Argon

Kinetic Global Model



Assume general distribution function:

$$f(\varepsilon) = c_1 \varepsilon^{1/2} e^{-c_2 \varepsilon^x}$$

Solve continuity, energy, and power absorption equations for each species

Get x for distribution function from PIC: Good over 4 orders in pressure!

Works for all gases tried – shape depends only on cross sections

From PIC: $$K_{ion}\big|_{PIC} = \int_{\varepsilon_{ion}} \sqrt{\frac{2e\varepsilon}{m_e}} \cdot \sigma_{ion}(\varepsilon) \cdot c_1 \varepsilon^{1/2} e^{-c_2 \varepsilon^x} d\varepsilon \qquad \text{(Ar)}$$

Kinetic Global Model* II

- Coupled continuity equations for all species, e.g. for oxygen:

$$\frac{dn_e}{dt} = K_{ion} n_e n_{gas} - K_{att} n_e n_{gas} - K_{rec} n_e n_{O_2^+} + K_{\det} n_e n_{O^-} + K_{\det 2} n_{O_2^+} n_{O^-}$$

$$\frac{dn_{O_2^+}}{dt} = K_{ion} n_e n_{gas} - K_{rec} n_e n_{O_2^+} - K_{mut} n_{O^-} n_{O_2^+}$$

$$\frac{dn_{O^-}}{dt} = K_{att} n_e n_{gas} - K_{\det} n_e n_{O^-} - K_{mut} n_{O^-} n_{O_2^+} - K_{\det 2} n_{O_2^+} n_{O^-}$$

where $K = \int_{\varepsilon} \sqrt{\frac{2e\varepsilon}{m_e}} \sigma(\varepsilon) f(\varepsilon) d\varepsilon$

* Nam and Verboncoeur, *APL* **23**, 231502 (2008)

Oxygen Reactions

$1)\ e+O_2 \rightarrow e+O_2$

$2)\ e+O_2 \rightarrow e+O_2(r)$

$3\text{-}6)\ e+O_2 \rightarrow e+O_2(\upsilon=n, n=1,2,3,4)$

$7)\ e+O_2 \rightarrow e+O_2(a^1\Delta_g)$

$8)\ e+O_2 \rightarrow e+O_2(b^1\Sigma_g^+)$

$9)\ e+O_2 \rightarrow O+O^-$

$10)\ e+O_2 \rightarrow e+O_2(c^1\Sigma_u^-, A^3\Sigma_u^+)$

$11)\ e+O_2 \rightarrow e+O(3P)+O(3P)$

$12)\ e+O_2 \rightarrow e+O(3P)+O(1D)$

$13)\ e+O_2 \rightarrow e+O(1D)+O(1D)$

$14)\ e+O_2 \rightarrow e+O_2^+ + e$

$15)\ e+O_2 \rightarrow e+O+O^*(3p^3P)$

$16)\ e+O_2^+ \rightarrow O+O$

$17)\ e+O^- \rightarrow e+O+e$

$18)\ O^- + O_2^+ \rightarrow O+O_2$

$19)\ O^- + O_2 \rightarrow O+O_2+e$

Enhanced Global Model III

- Electron energy equation:

$$\frac{d}{dt}\left(\frac{3}{2}n_e kT_{eff}\right) = P_{abs} - (\varepsilon_{ion}K_{ion}n_e n_{gas} + \sum_{exc}\varepsilon_{exc}K_{exc}n_e n_{gas} + \widetilde{K}_{mom}n_e n_{gas})$$

- Improved RF power absorption model:

$$P_{abs} = \int \frac{e^2 n_e}{m\nu_m}\left(\frac{E_0}{\sqrt{2}}\frac{\nu_m}{\sqrt{\nu_m^2 + \omega^2}}\right)^2 f(\varepsilon)d\varepsilon$$

Enhanced Global Model IV

- The general EEDF equation in the isotropic velocity space *:

$$f(\varepsilon) = c_1 \varepsilon^{1/2} e^{-c_2 \varepsilon^x}$$

- Maxwellian: x=1, Druyvestyn: x=2
- Determine x by the ionization and dissociative attachment from PIC model:

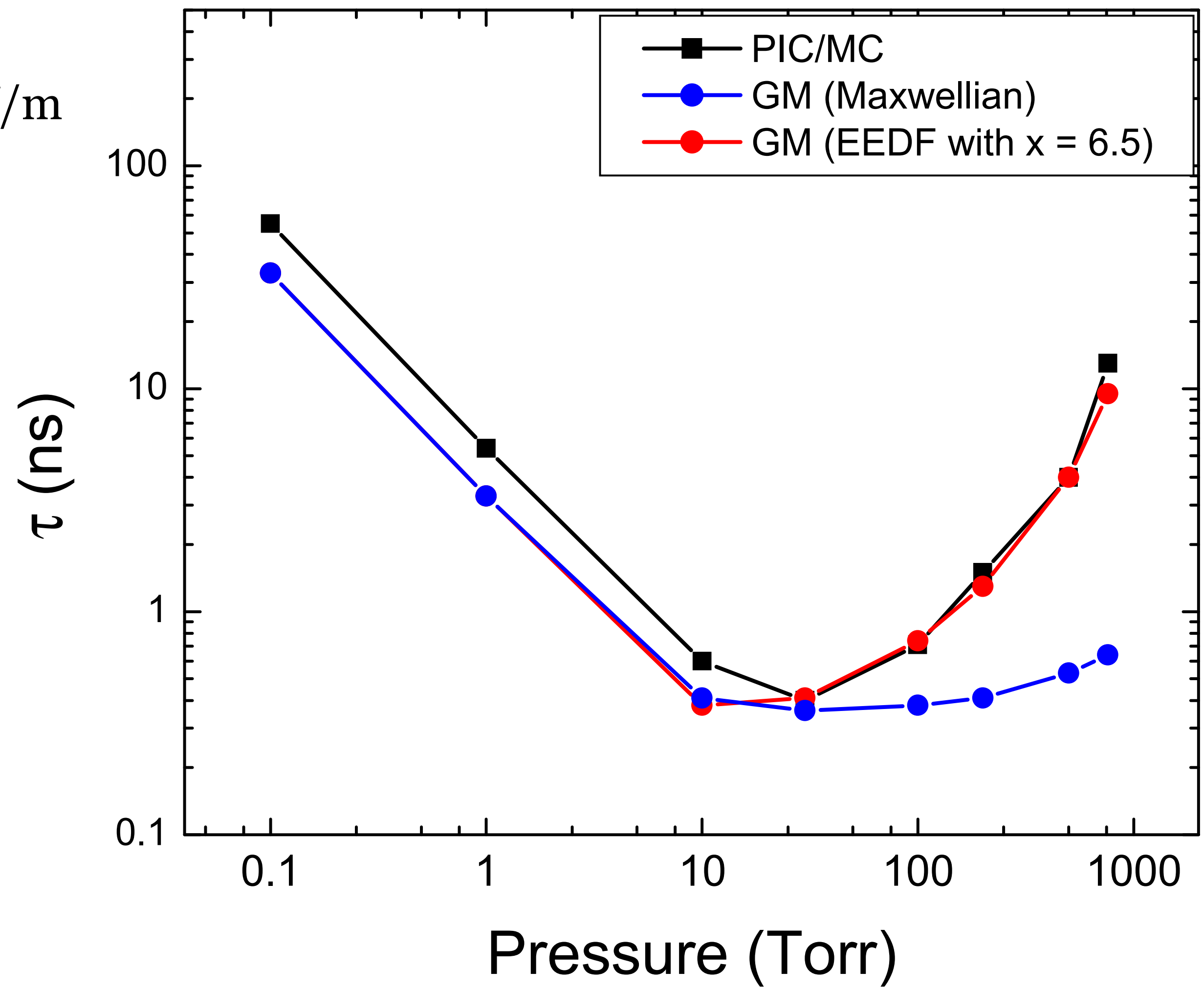
$$K_{ion}\big|_{PIC} - K_{att}\big|_{PIC} =$$

$$\int_{\varepsilon_{\text{ion}}} \sqrt{\frac{2e\varepsilon}{m_e}} \cdot \sigma_{ion}(\varepsilon) \cdot c_1 \varepsilon^{1/2} e^{-c\left(\frac{\varepsilon}{T_{eff}}\right)^x} d\varepsilon - \int_{\varepsilon_{\text{att}}} \sqrt{\frac{2e\varepsilon}{m_e}} \cdot \sigma_{att}(\varepsilon) \cdot c_1 \varepsilon^{1/2} e^{-c\left(\frac{\varepsilon}{T_{eff}}\right)^x} d\varepsilon$$

* J. T. Gudmundsson, *Plasma Sources Sci. Technol.*, **10**, 76 (2001).

Enhanced Global Model in Ar

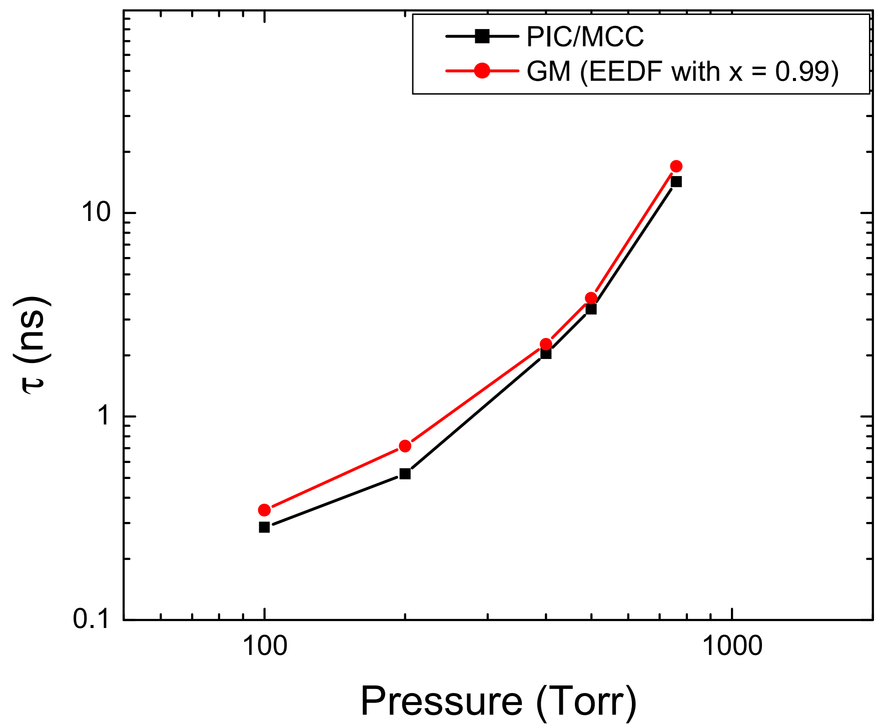
Argon Gas
E_o = 2.82 MV/m
f = 2.85 GHz



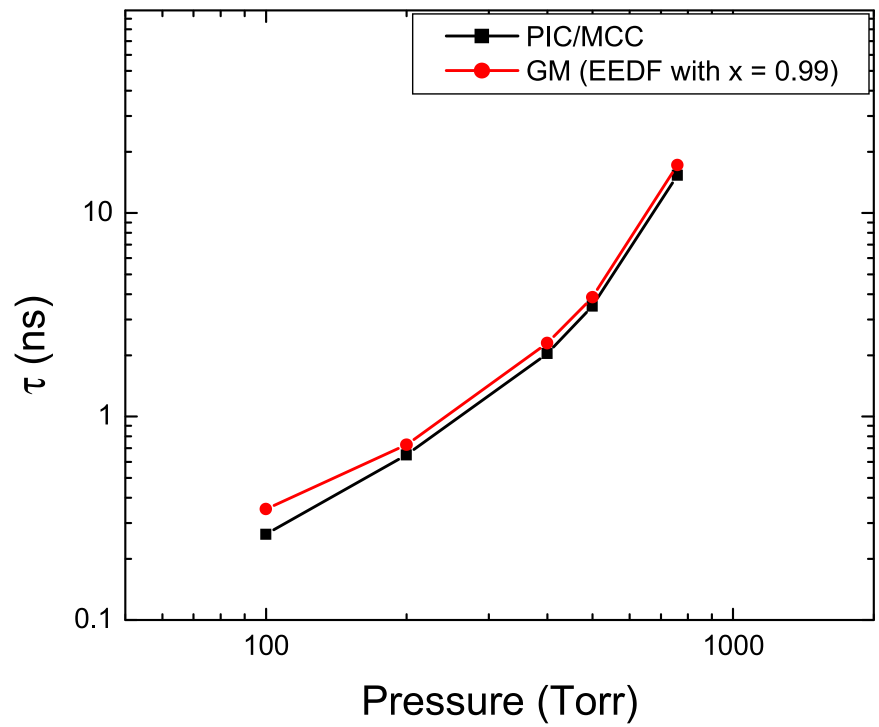
Breakdown Time in Air

Air
E_o = 4.23 MV/m

f = 2.85 GHz



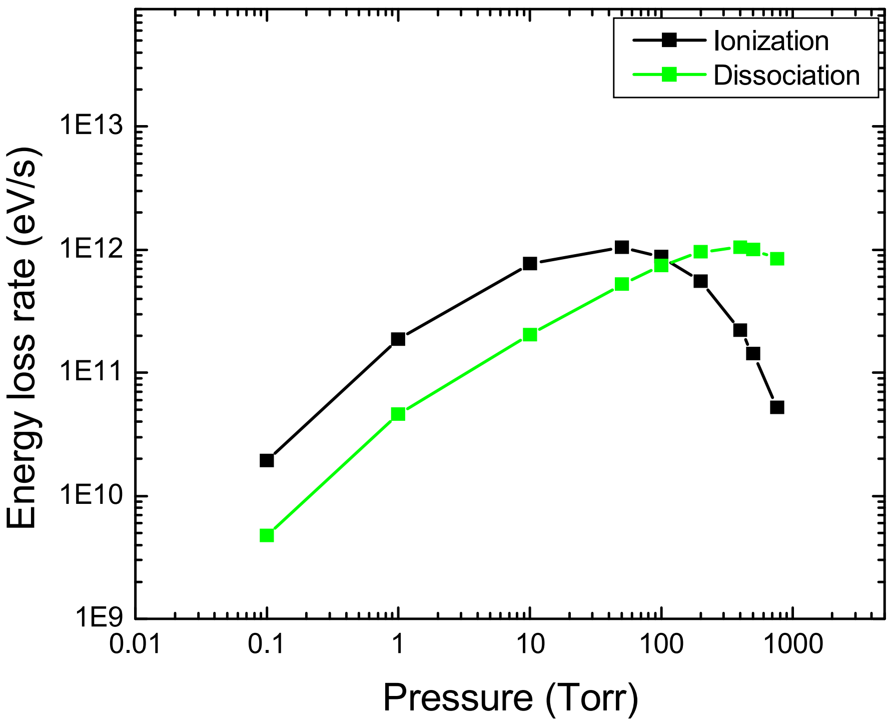
f = 5.70 GHz

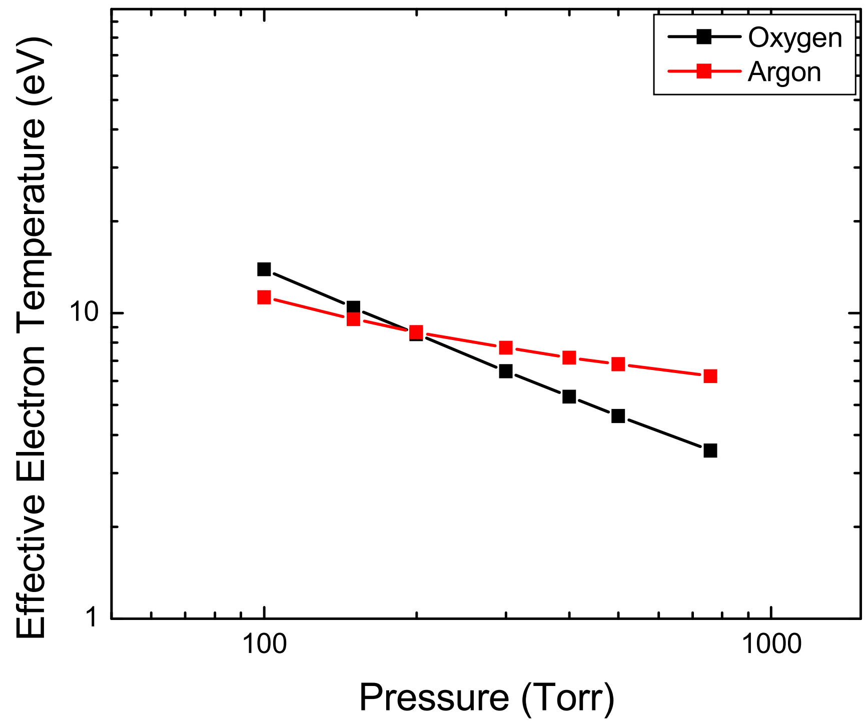


Energy loss rate and T_{eff}

$E_0 = 4.23$ MV/m
$f = 2.85$ GHz

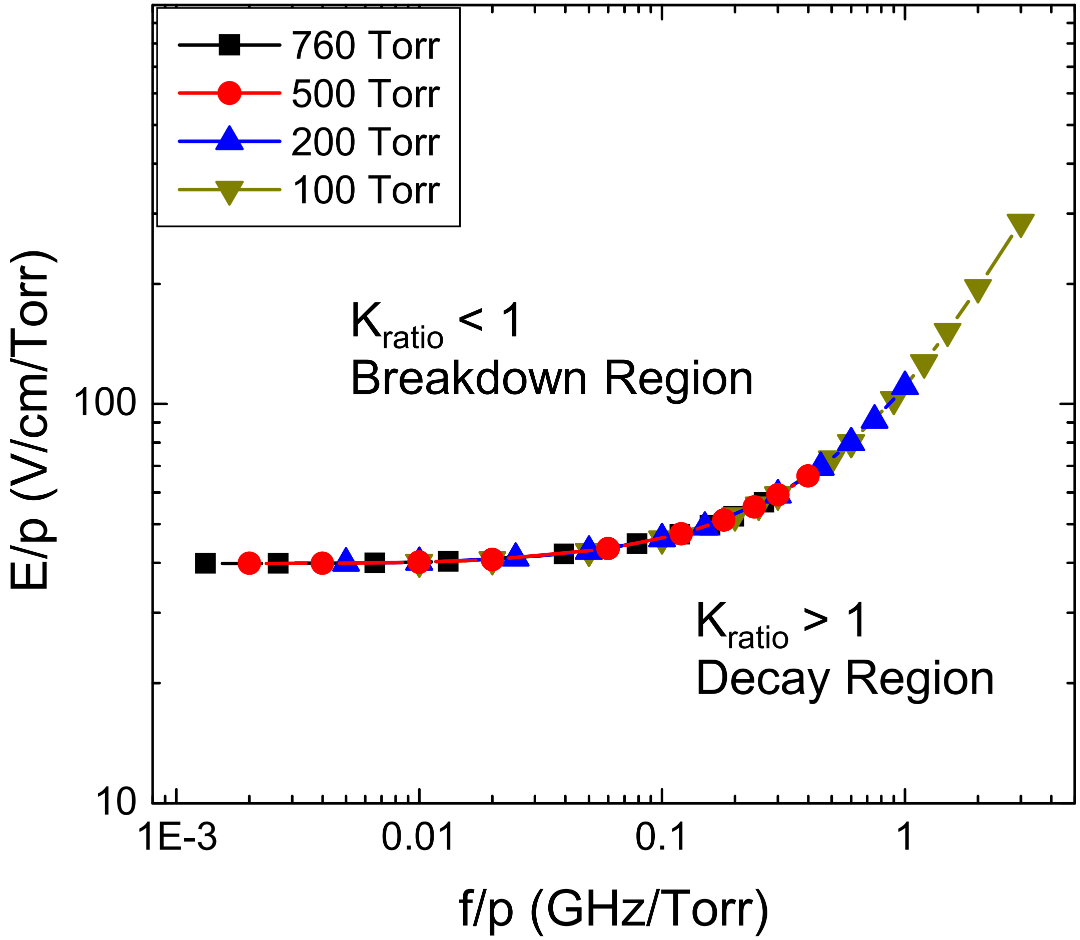
oxygen





Applied E vs f for K_{ratio}=1 in air

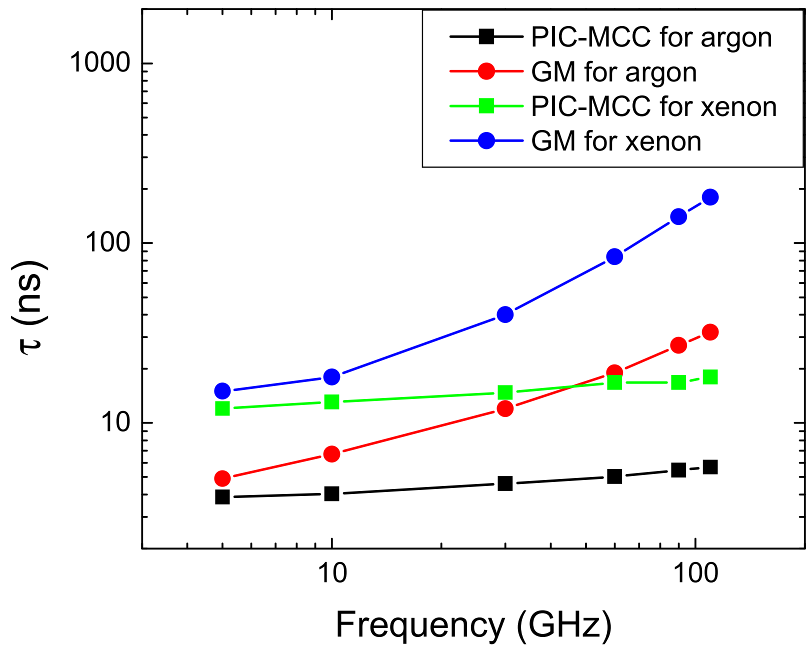
$$K_{ratio} = \frac{K_{att}}{K_{ion}}$$



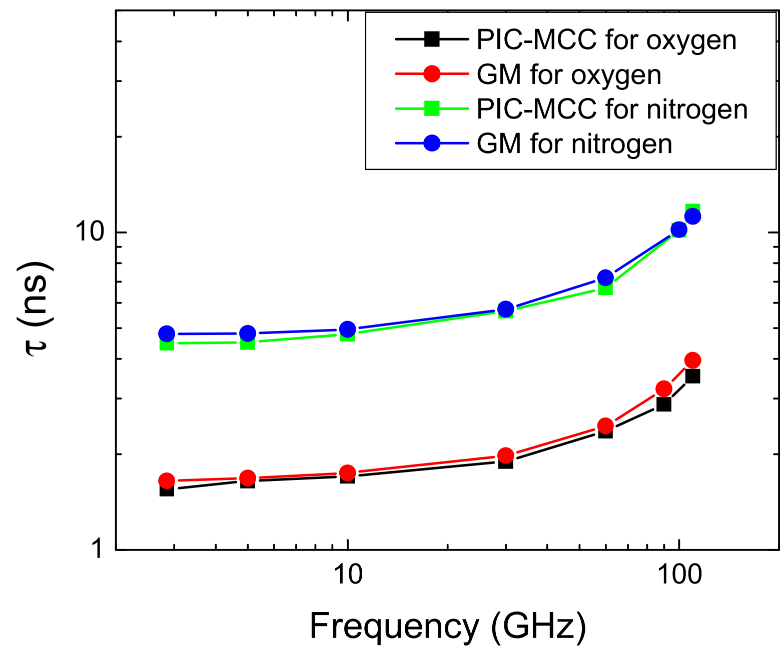
Effect of Frequency

Constant x is inadequate at high frequency for Ramsauer gases

Argon
E_0 = 2.82 MV/m, p=500 Torr
Xenon
E_0 = 2.82 MV/m, p = 700 Torr



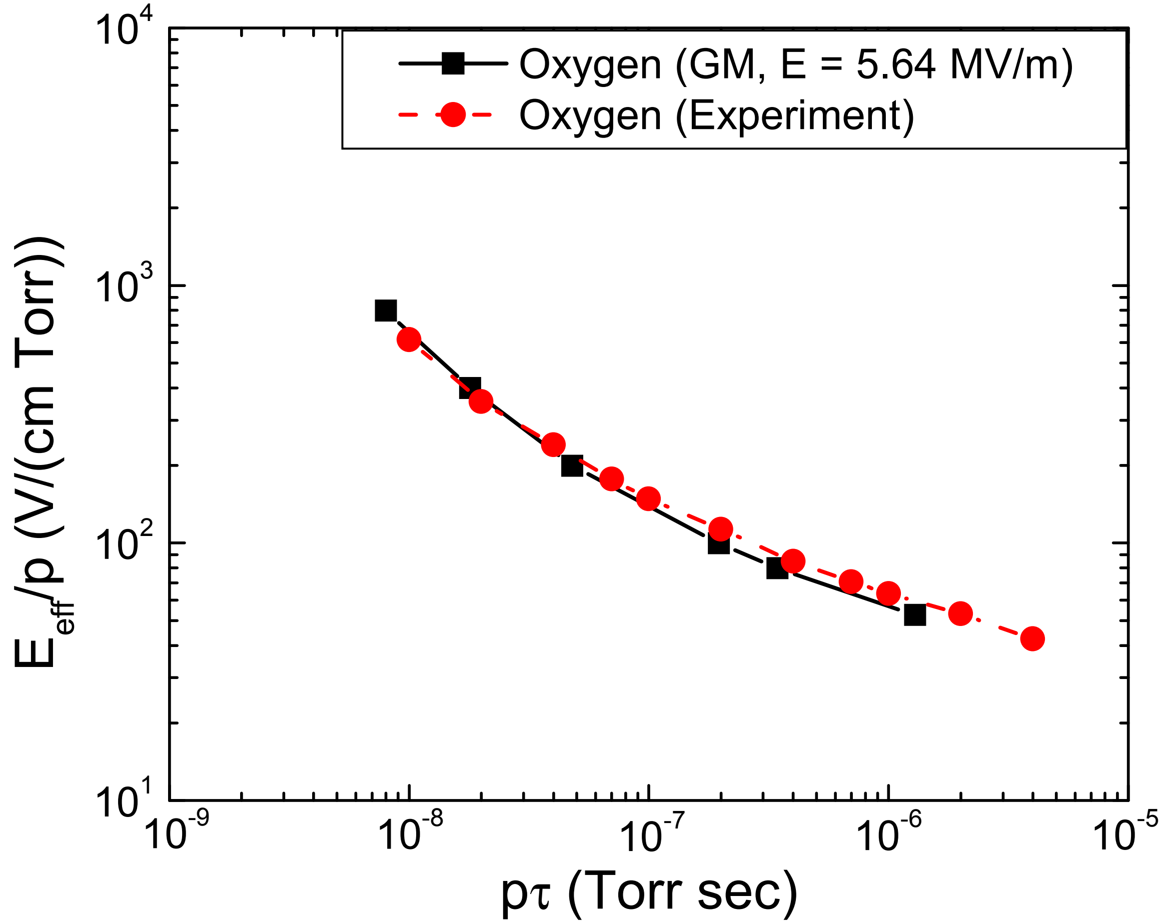
Oxygen and Nitrogen
E_0 = 4.23 MV/m
p = 500 Torr



Sang Ki Nam and J. P. Verboncoeur, *Appl. Phys. Lett.*, **93**, 151504 (2008).

Argon: frequency dependence of x

Comparison to Experiment



* P. Felsenthal and J. M. Proud, *Phys. Rev.*, **139**, A 1796 (1965).

UV Illumination of Windows

Reduction in flashover delay time and standard deviation

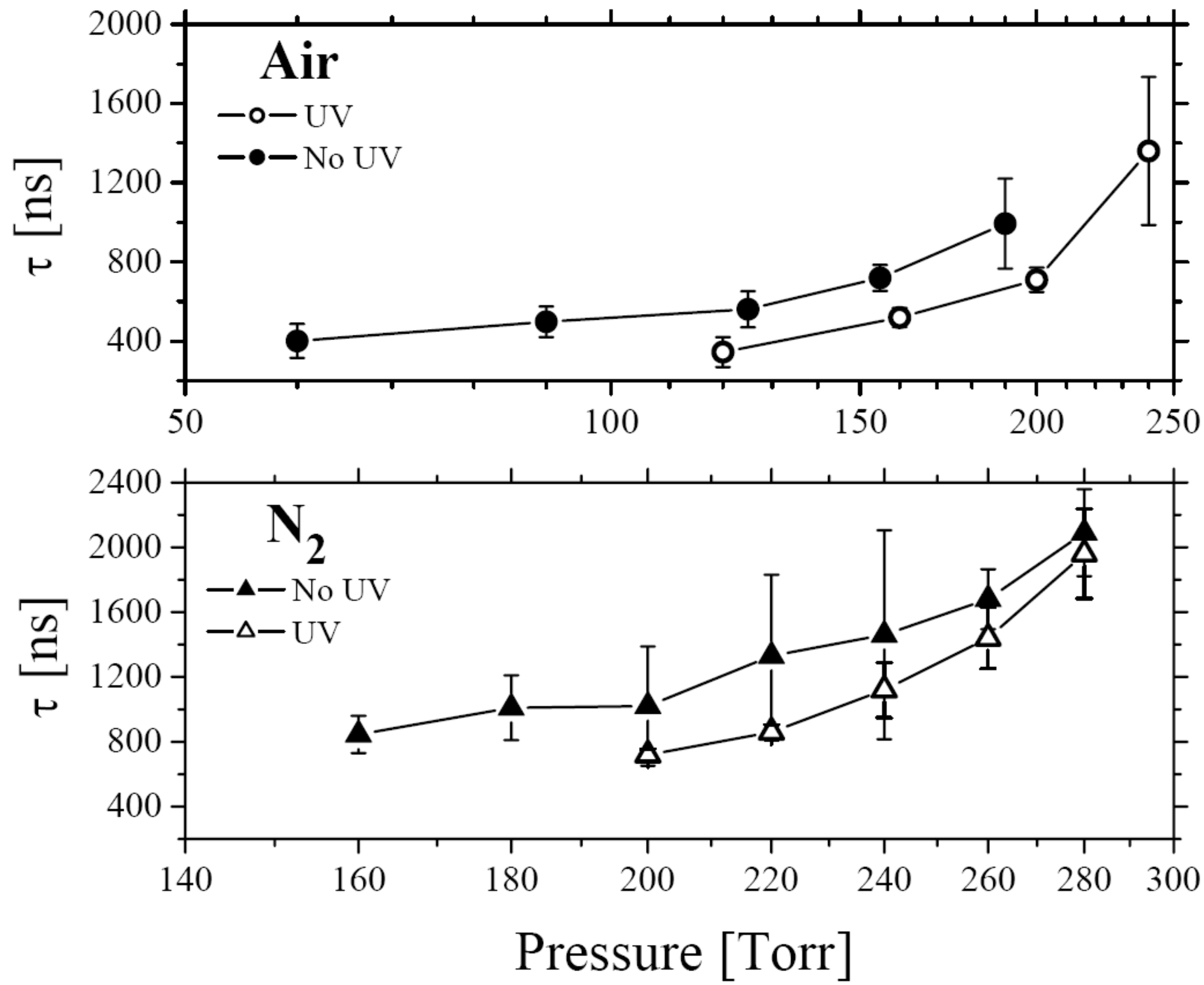
•4 MW, 2.5 μs incident pulse

•Illumination intensity of approximately 4 mW/cm^2 over 240-400 nm range

•Equivalent illumination of "sunny" day at 3000 ft. above sea level

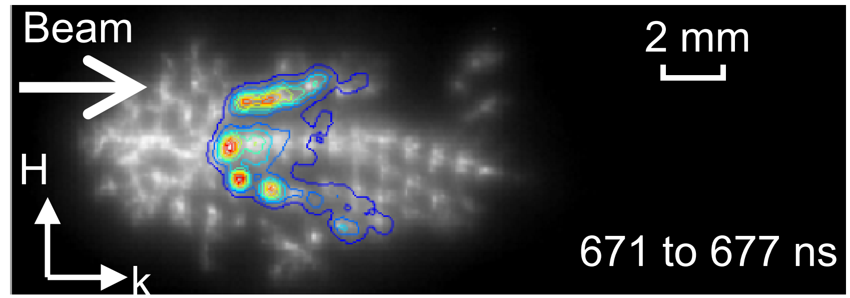
•Breakdown delay times exhibit less fluctuations with UV illumination

•Sample-to-sample variance also somewhat reduced



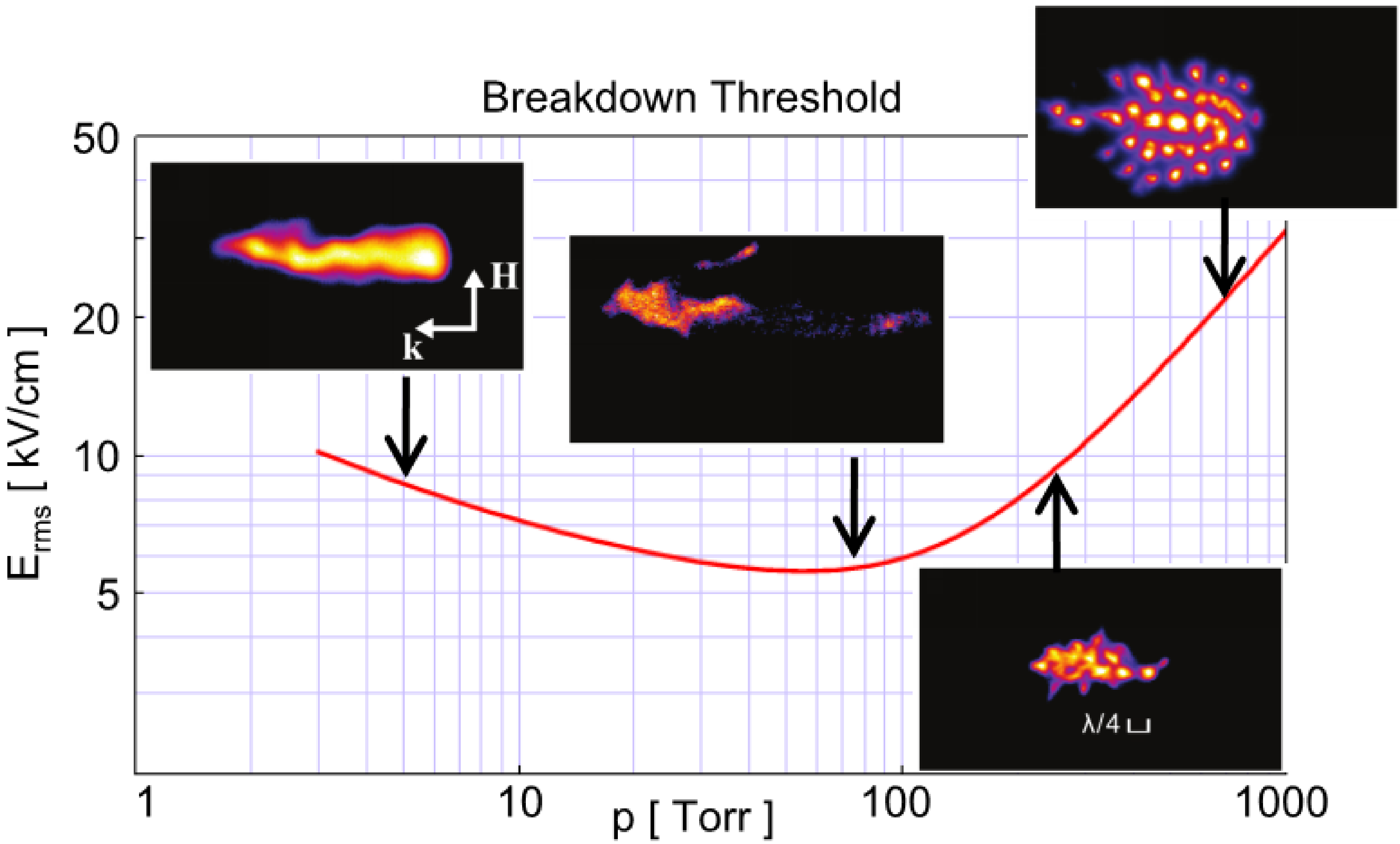
Plasma Filamentary Arrays

- 1.5 MW, 140 GHz Gyrotron
- 3 shots with slow (B&W) and fast (color) cameras
- Filaments spaced slightly less than $\lambda/4$, propagate towards source
- Hypothesis: constructive interference of reflected/diffracted waves, propagation speed limited by diffusion of seed electrons



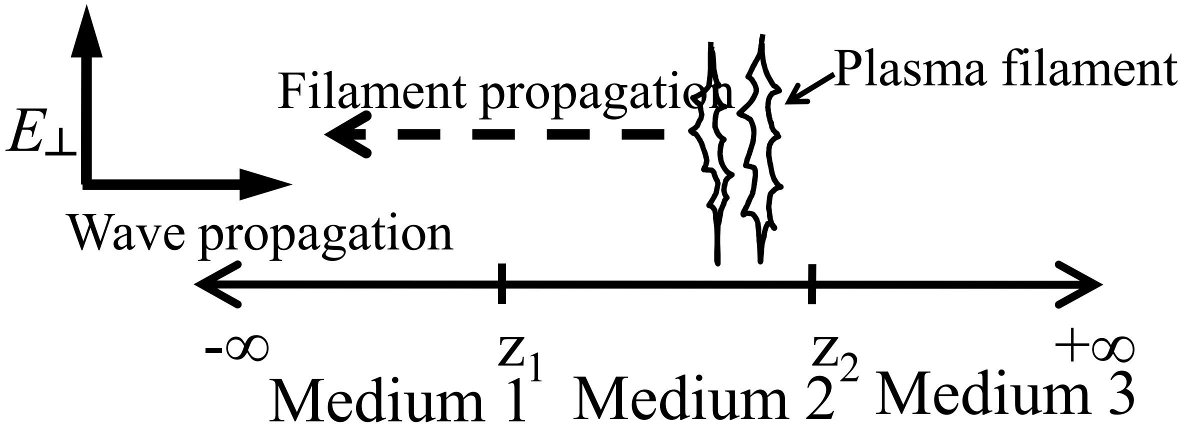
Y. Hidaka, et al., *Phys. Rev. Lett.*, **100**, 035003 (2008).

Pressure Dependence



distinct filaments appear at high pressure

EM Wave Model



$$\frac{\partial^2 Z}{\partial z^2} + k_z^2 Z = 0$$

$$k_z = k^2 - (k_{x,m}^2 + k_{y,n}^2)$$

$$E_\perp = \mathrm{Re}(E_0 Z e^{-j\omega t})$$

Z is spatial profile of $E_\perp$

vacuum (1 and 3): $k_1^2 = k_3^2 = \frac{\omega}{c}$

plasma (2): $k_2^2 = \frac{\omega}{c}\left(1 - \sum_i \frac{\omega_{p,i}^2(z)}{\omega(\omega + j\nu_{m,i}(z))}\right)^{1/2}$

$\omega_{p,i}$: plasma frequency

$\nu_{m,i}$: momentum transfer frequency

* H.C. Kim and J. P. Verboncoeur, *Comp. Phys. Comm.* 177 (2007) 118-121

Fluid Model

Particle Continuity and Electron Energy Equations

$$\frac{\partial n_e}{\partial t} = -\nabla \cdot J_e + K_{ion} n_e n_{gas}, \; J_e = -D_e \nabla n_e - \mu_e n_e E_{\parallel}$$

$$E_{\parallel} = \frac{D_i - D_e}{\mu_i + \mu_e} \frac{\nabla n_e}{n_e}$$

$$\frac{\partial}{\partial t}\left(\frac{3}{2} n_e T_e\right) = -\nabla \cdot q_e + P_{abs} - (\varepsilon_{ion} K_{ion} n_e n_{gas} + \varepsilon_{exc} K_{exc} n_e n_{gas} + \widetilde{K}_{mom} n_e n_{gas})$$

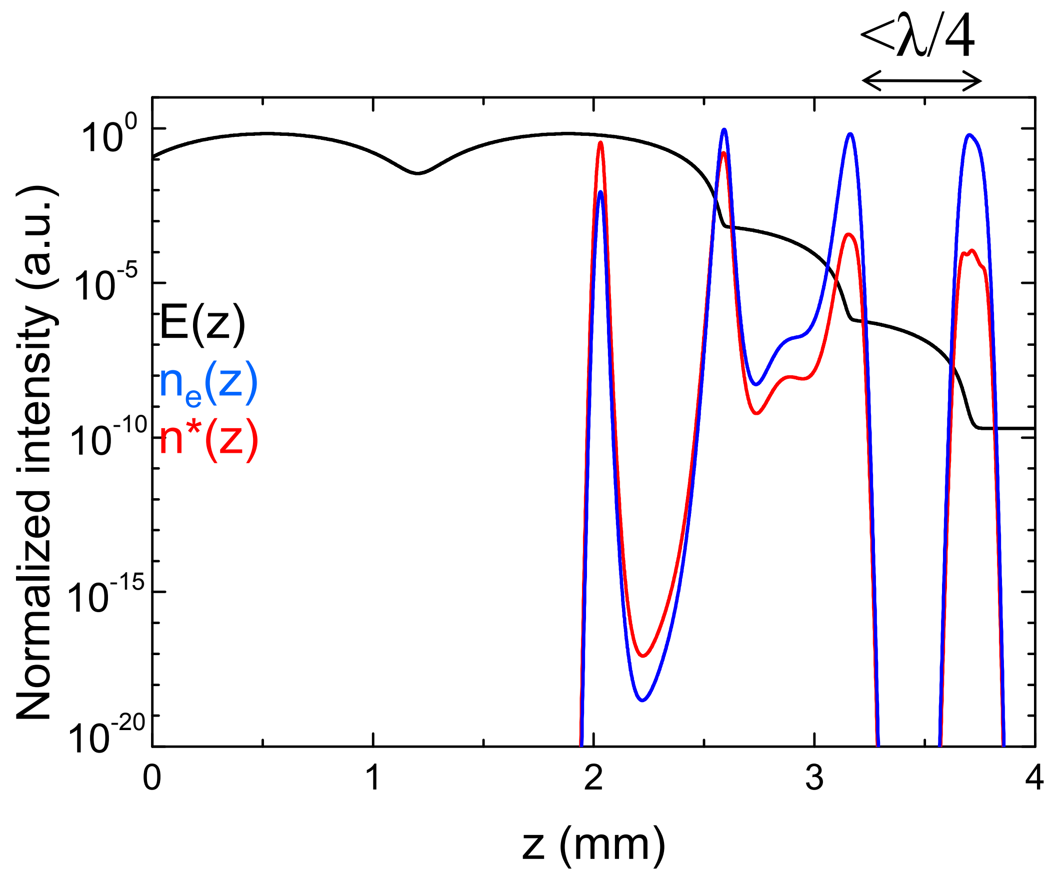
$$q_e = -\frac{3}{2} D_e \nabla n_e T_e + \frac{5}{2} J_e T_e$$

$$P_{abs} = \frac{e n_e}{m_e \nu_m} E_{\perp}^2 = \mu_e n_e E_{\perp}^2$$

S. K. Nam and J. P. Verboncoeur, *Phys. Rev. Lett.*, **103**, 055004 (2009)

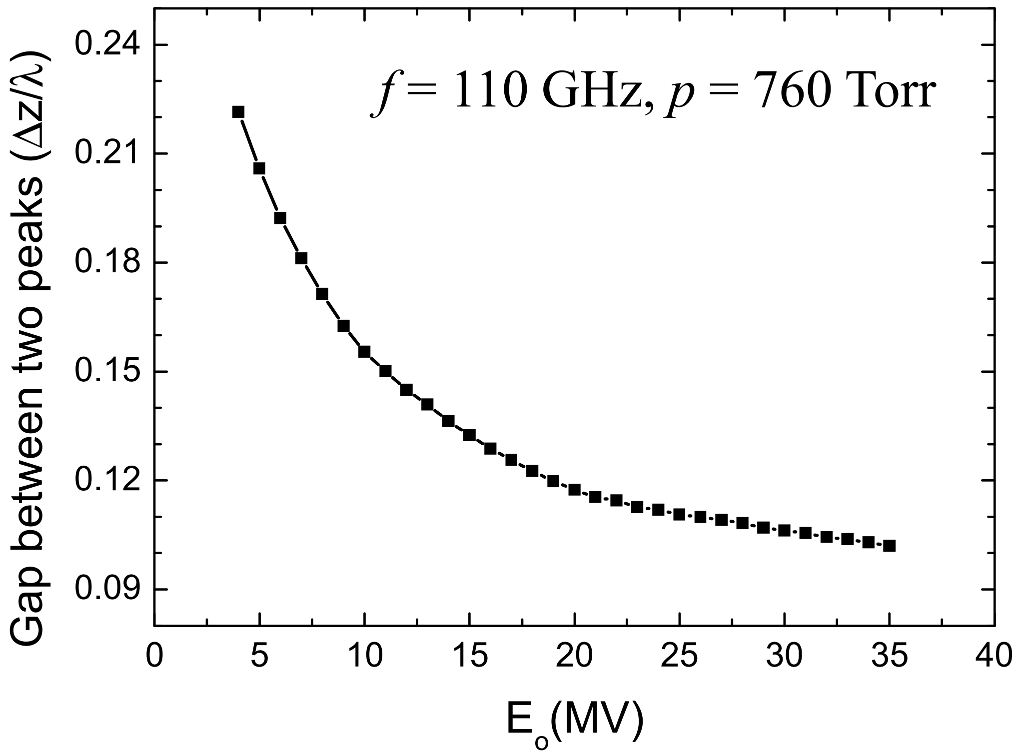
Filaments: 1D Model

- Filaments propagate slowly toward source
- Explained via 1D fluid-EM model
- Ionization by electrons heated by EM absorption
- Standing waves via reflection
- Filament spacing depends on E, ω, gas



Kim et al., Comput. Phys. Comm. 177 (2007)
Nam et al., Phys. Rev. Lett. 103 (2009)

Filament Spacing



Increasing field strength decreases filament spacing as breakdown threshold is exceeded closer to the previous filament.

Conclusions

- Modeling breakdown phenomena across a wide parameter regime
  - Multipactor dominates at low p
  - Multipactor and ionization discharge compete at intermediate pressure (10-50 Torr)
  - Ionization discharge dominates at atmospheric pressure
- Enhanced kinetic global model agrees with PIC model over 4 orders in pressure, 3 orders in f
  - EEDF shape nearly independent of p, E
  - EEDF shows some dependence on f for Ramsauer gases
- UV reduces statistical delay time
- Wave-fluid model reproduces filamentary experiment well
  - Filament distance slightly less than $\lambda/4$
  - Propagation speed ~ ambipolar or free diffusion times