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

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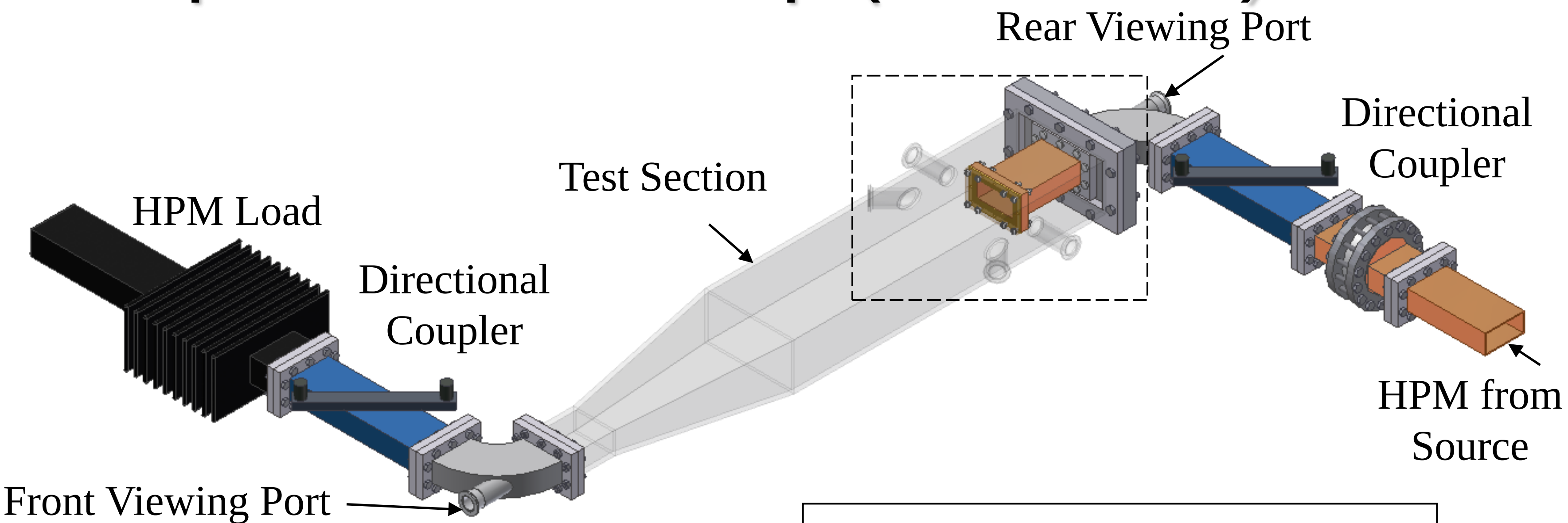
# Goals

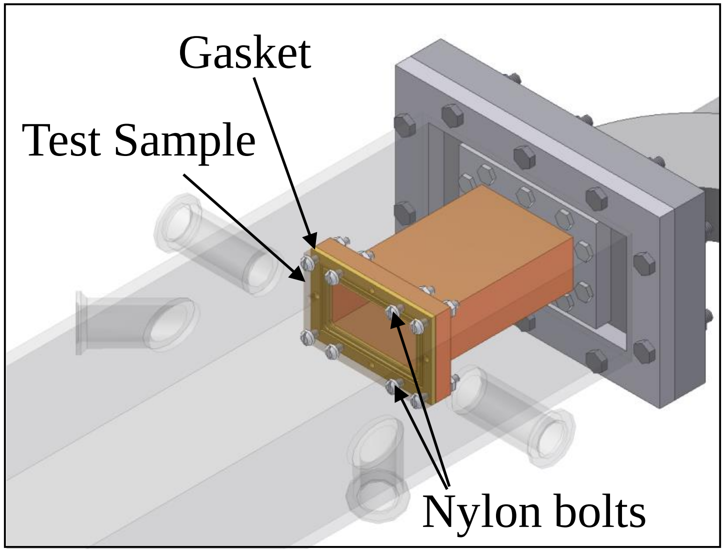
- Understand basic physics of microwave-driven breakdown
  - Breakdown threshold dependence on pressure, gas composition, geometric features
  - Low Pressure Dielectric Multipactor
  - Transition to Ionization Discharge
  - Compare Experiments and Theory

# Experimental Setup (2.85 GHz)

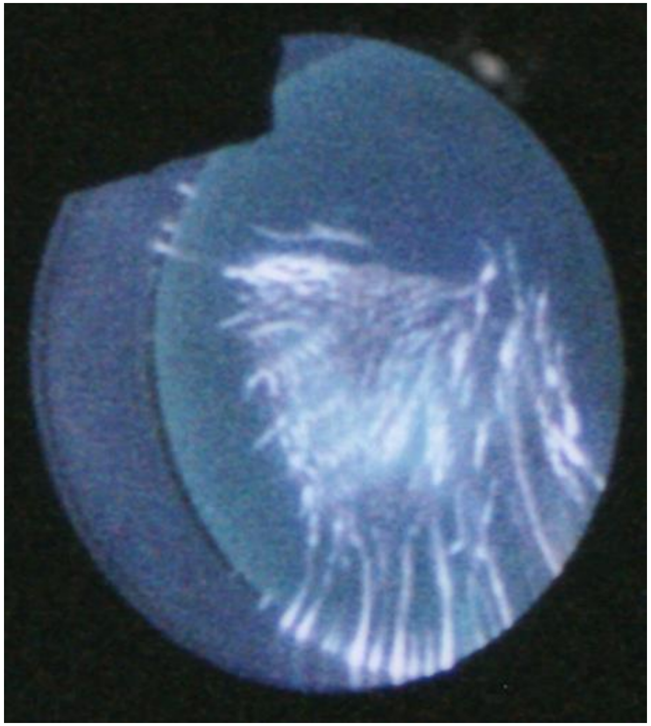


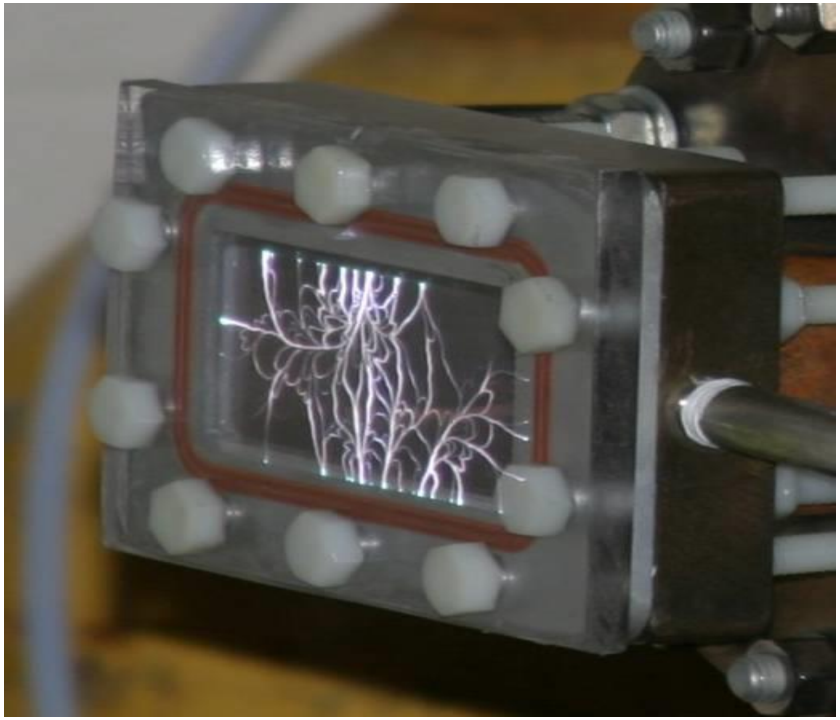

**Test Section Features**

- 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

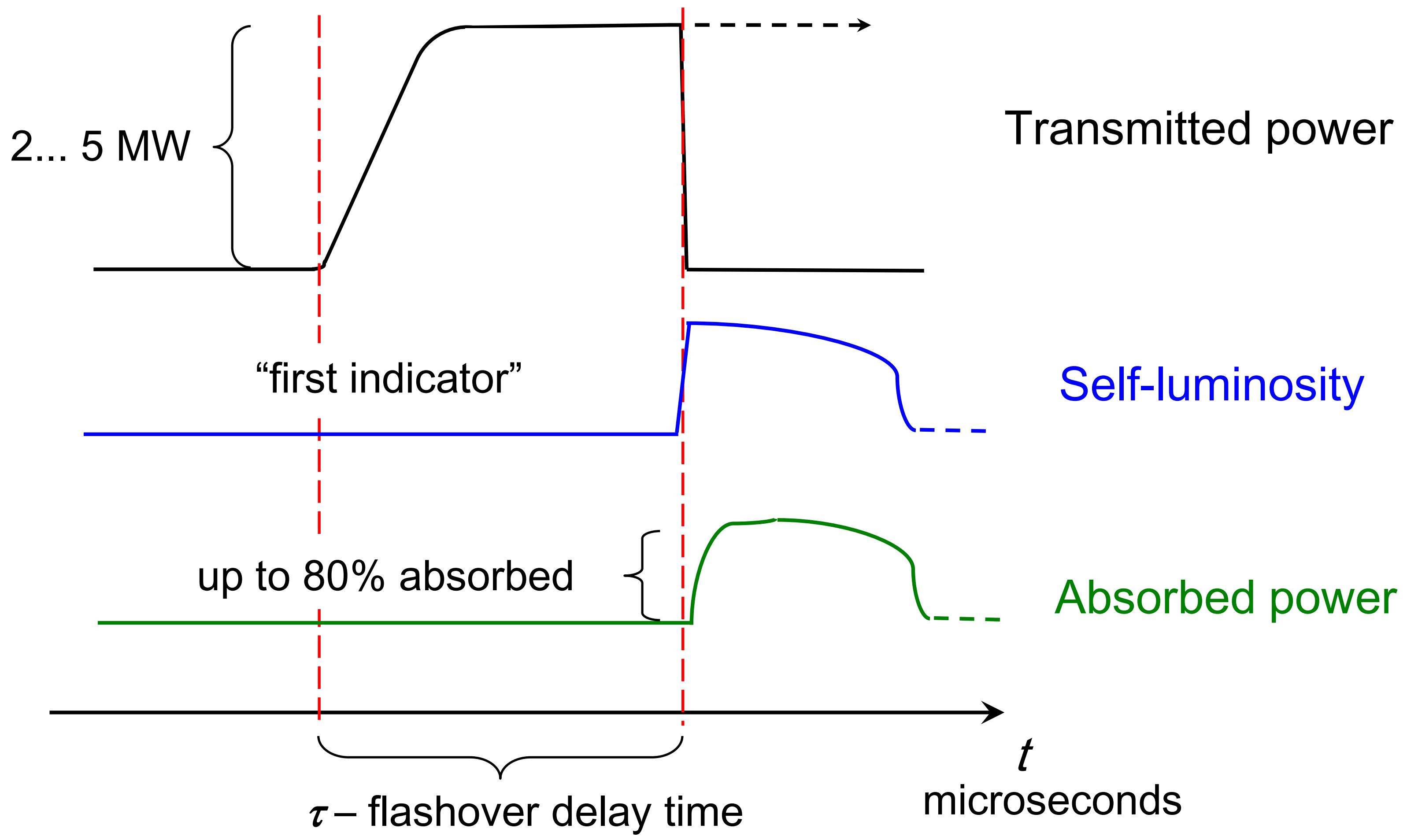




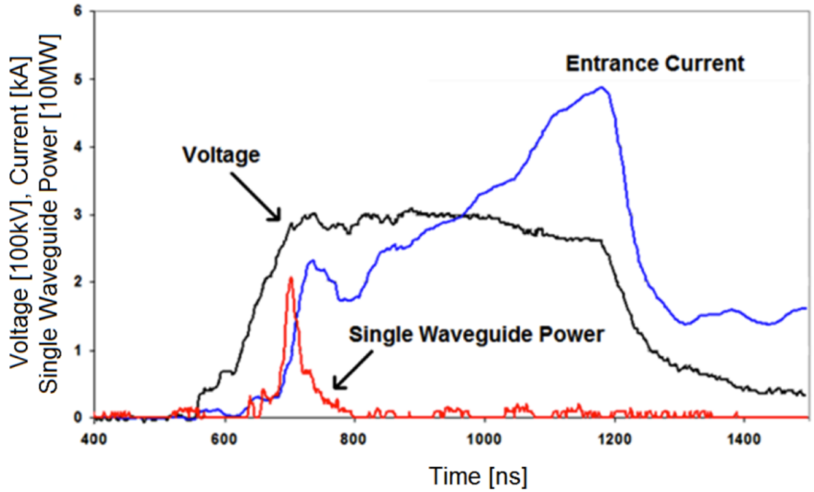
> MW transmitted power (High Power Microwaves, HPM)
→ Field amplitudes in excess of several 10 kV/cm

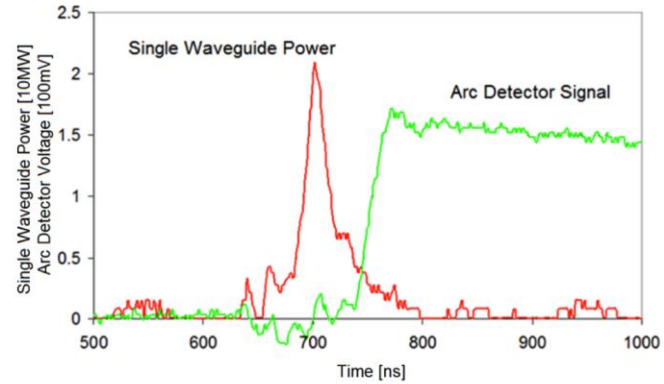
**Flashover can be initiated**
**<u>with</u> or <u>without</u> the presence of a triple point**

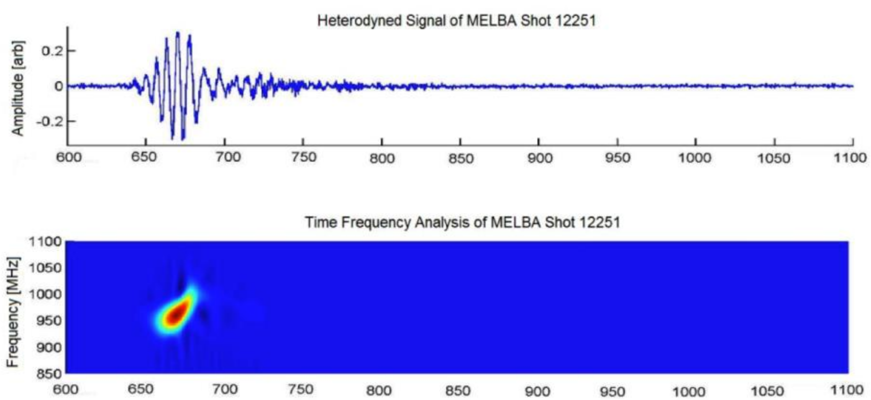
# Observed Waveforms

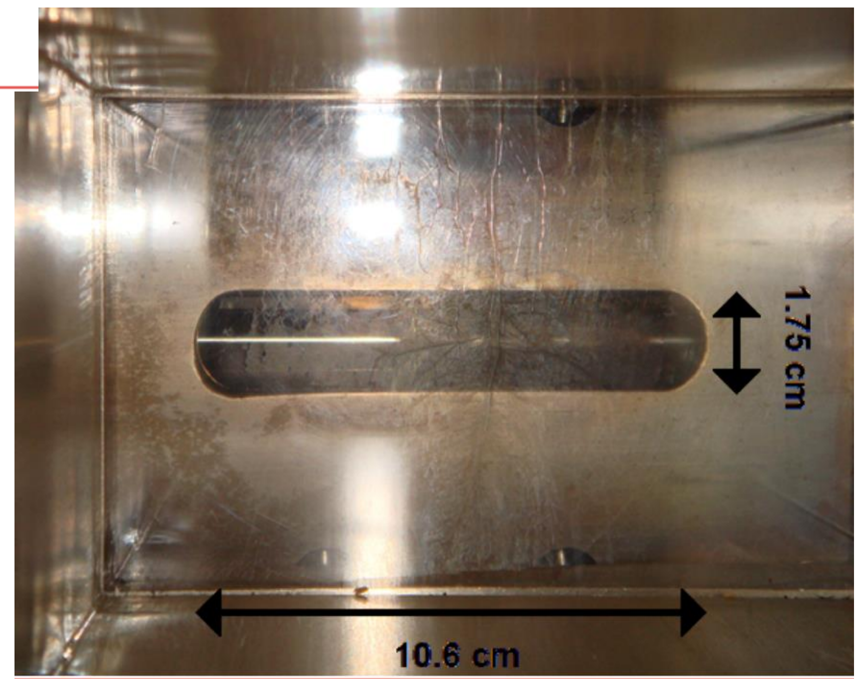


# UM RelMag: old window



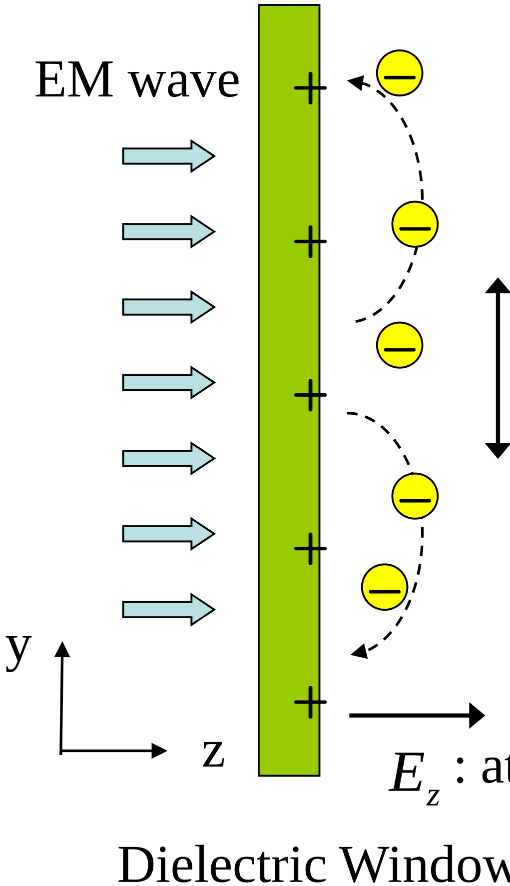



# Single-Surface RF Multipactor

- <u>Multipactor discharge</u> is a <u>secondary electron avalanche</u> 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)

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

Dominates at low pressure

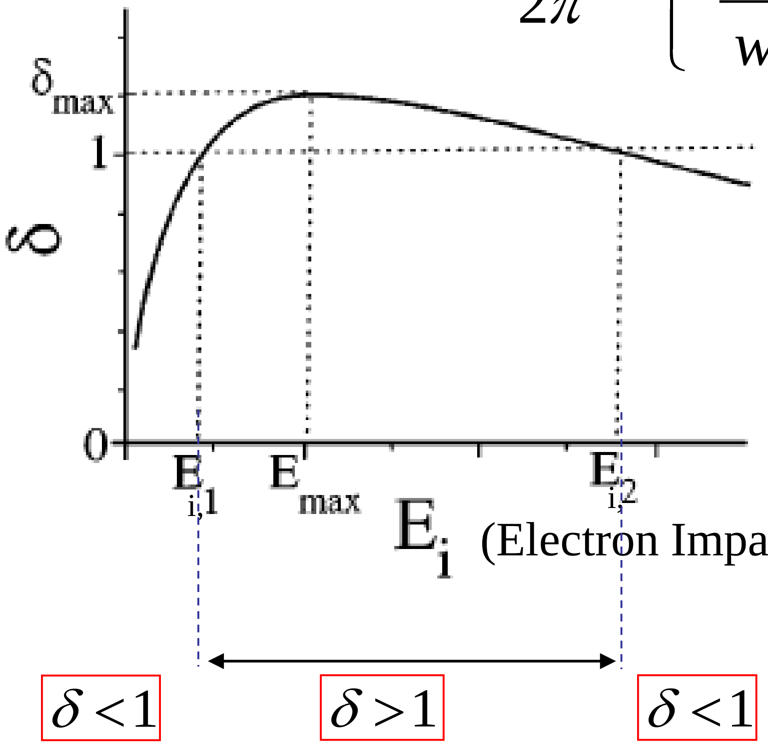
# Secondary Electron Model

- Energy and angular dependence of secondary emission coefficient

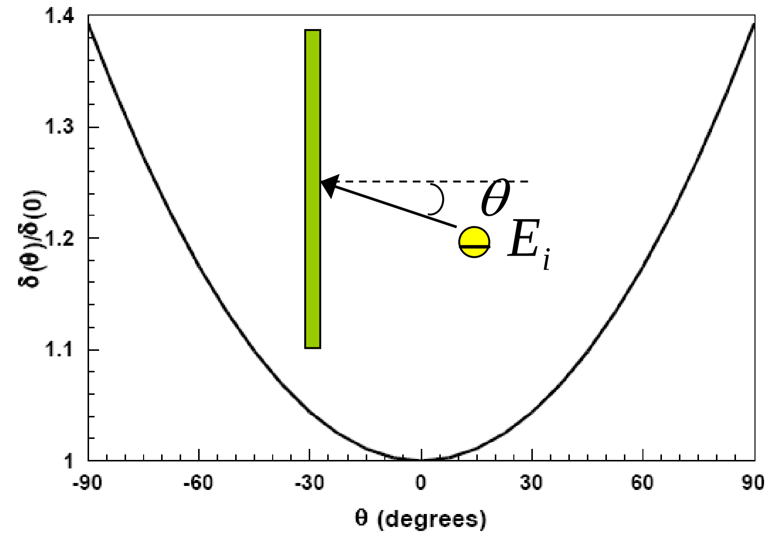
$$\delta(E_i,\theta) = \delta_{\max 0}\left(1+\frac{k_{s\delta}\theta^2}{2\pi}\right)\begin{cases}(we^{1-w})^k, & w \le 3.6 \\ \dfrac{1.125}{w^{0.35}}, & w > 3.6\end{cases}$$

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

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



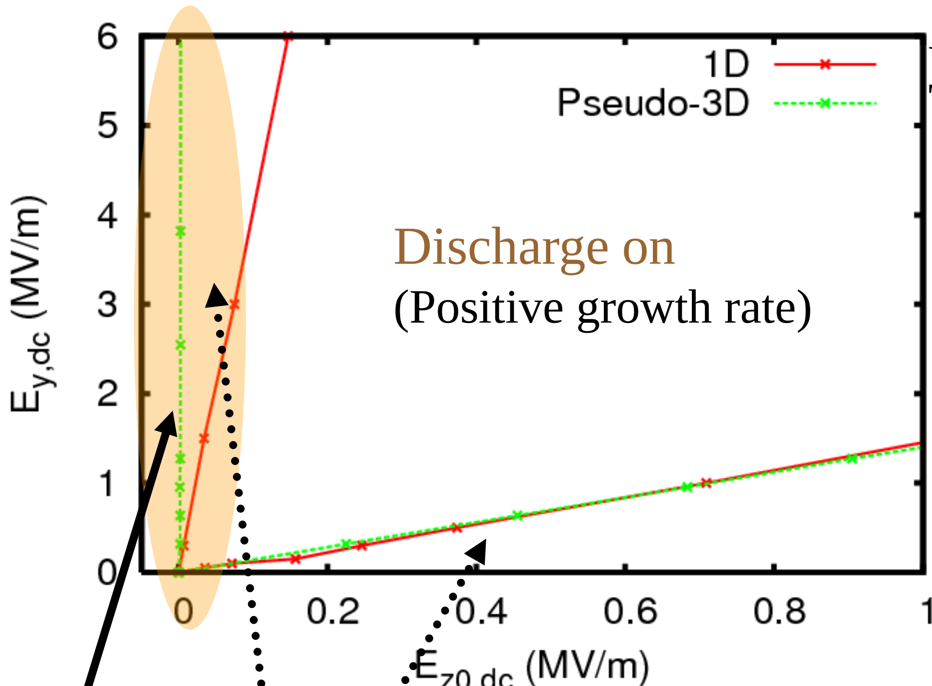

(Electron Impact Energy)




θ (Electron Impact Angle)

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

# PIC Multipactor Susceptibility



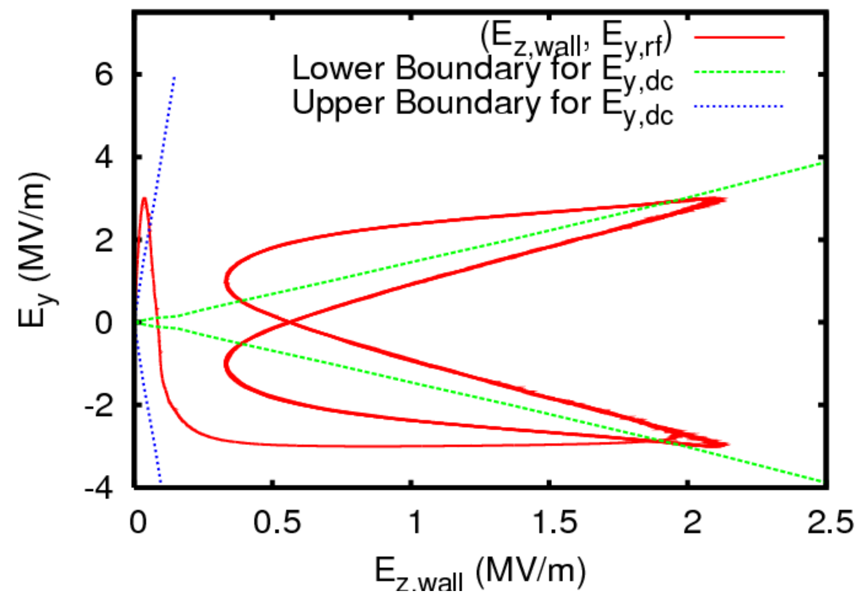

Discharge off : low δ due to

- Too high impact energy
- Too small impact energy

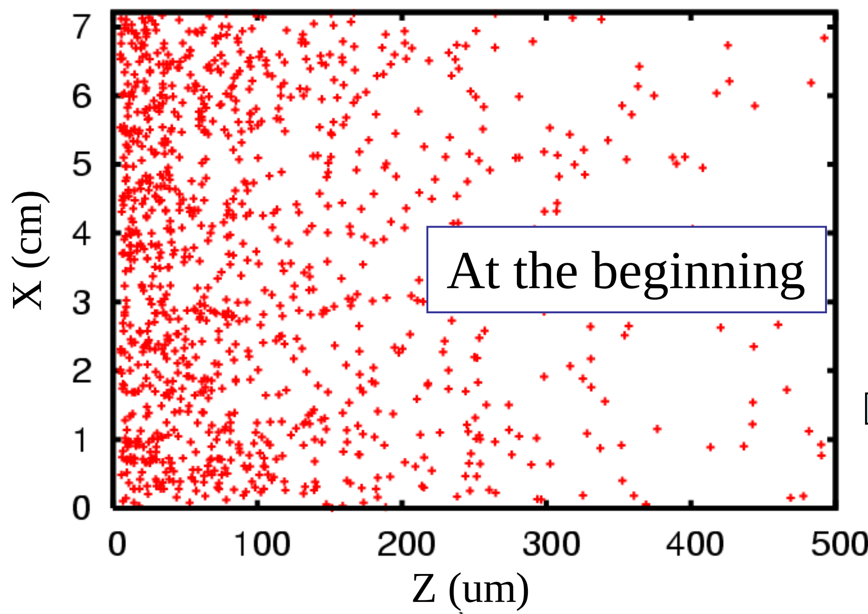
high field susceptibility becomes vertical in waveguide – no upper field cutoff

uniform plane wave
$TE_{10}$ rectangular waveguide

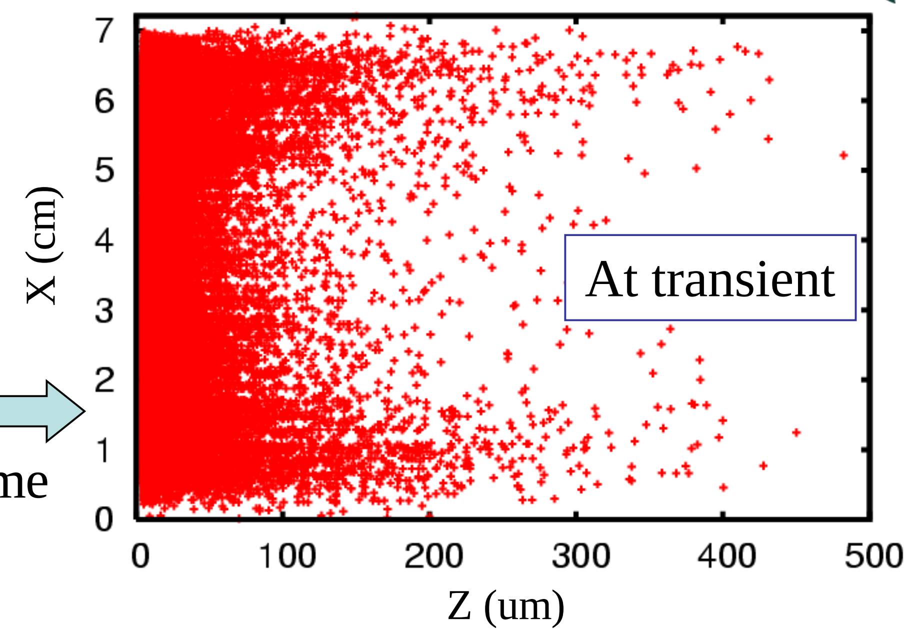
- include transverse variation of $E_{RF}$
- absorb at transverse wall
- neglect transverse space charge



# $TE_{10}$ Multipactor Migration




Time

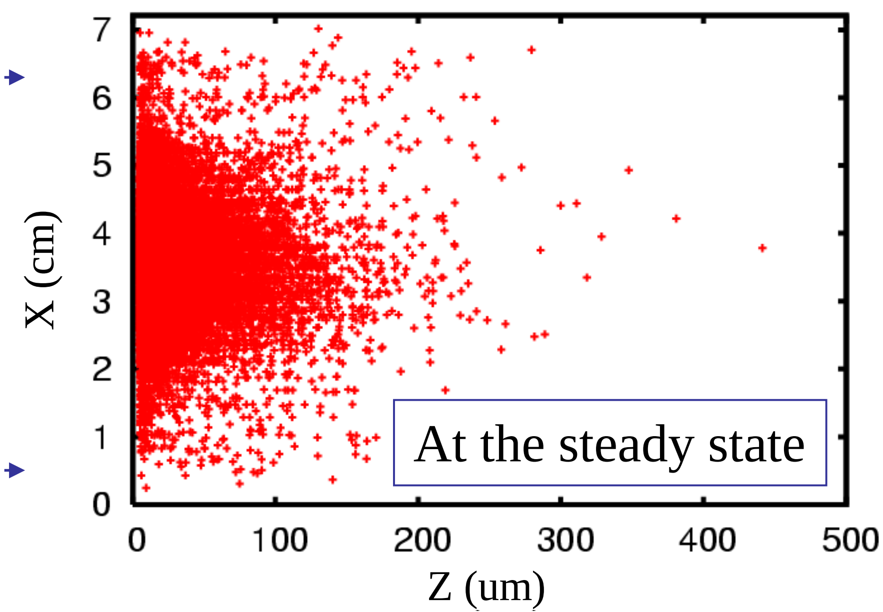



Time

Weak $E_{rf}$

Strong $E_{rf}$

Weak $E_{rf}$




$E_y^0 = 5\ \mathrm{MV/m}$

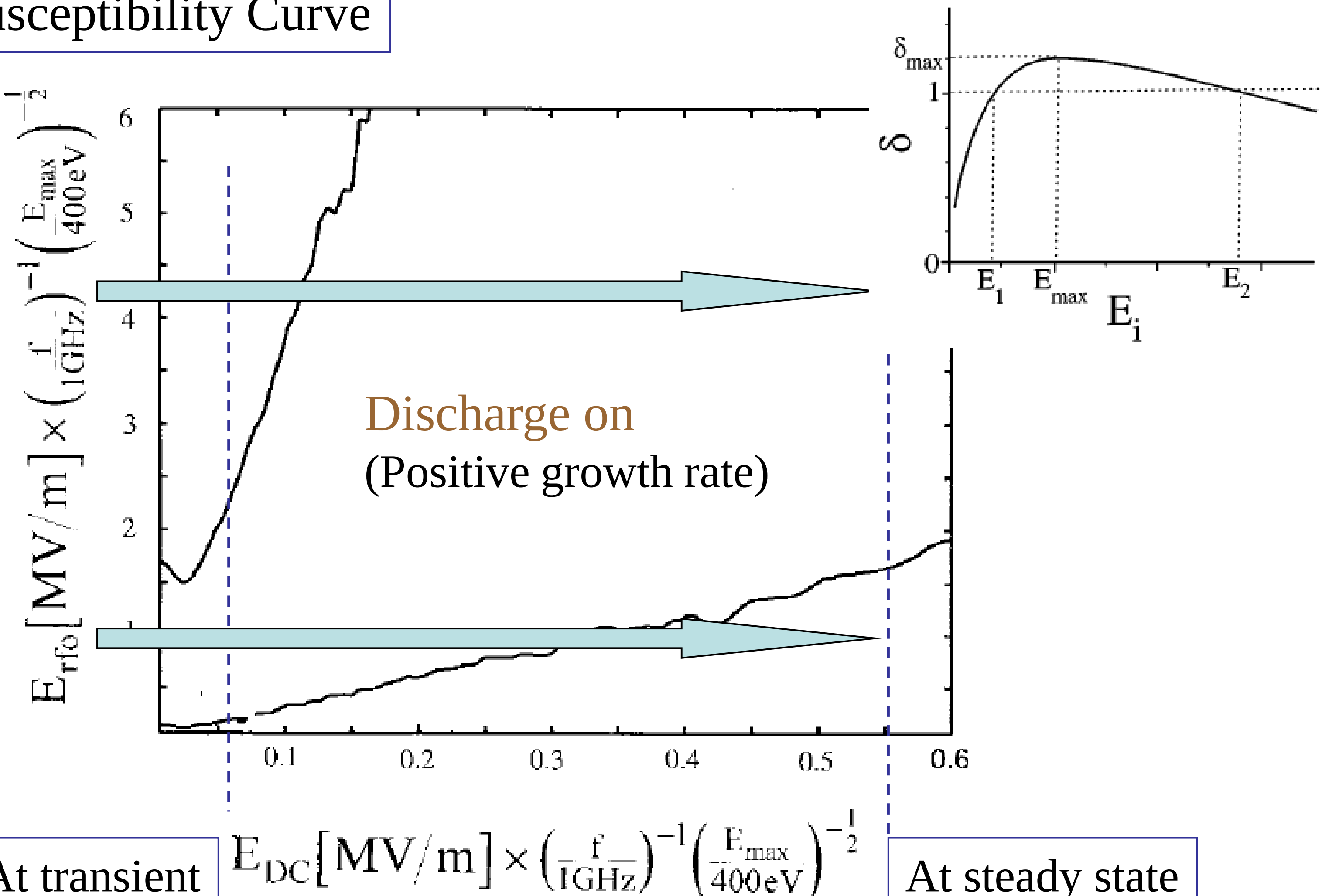
2.85 GHz, Vacuum

# Explanation of Migration

- Susceptibility Curve

Center

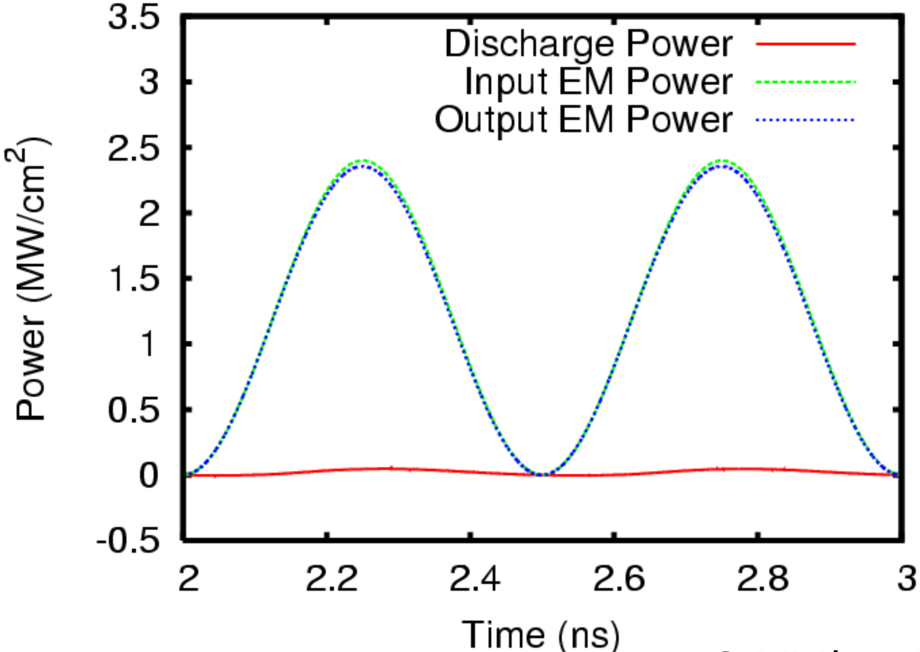
Periphery

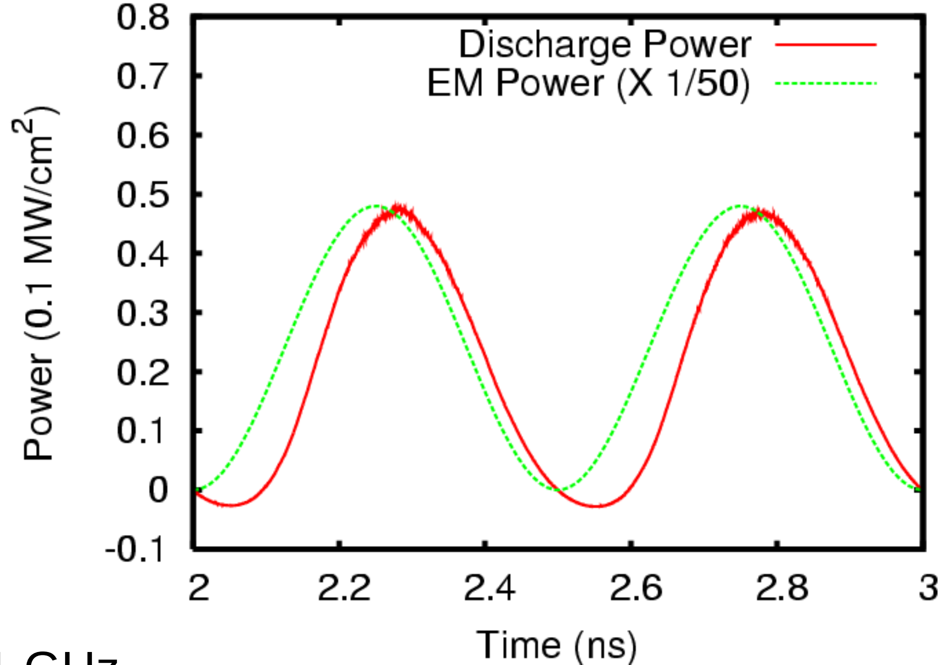



At transient

At steady state

# Multipactor Power

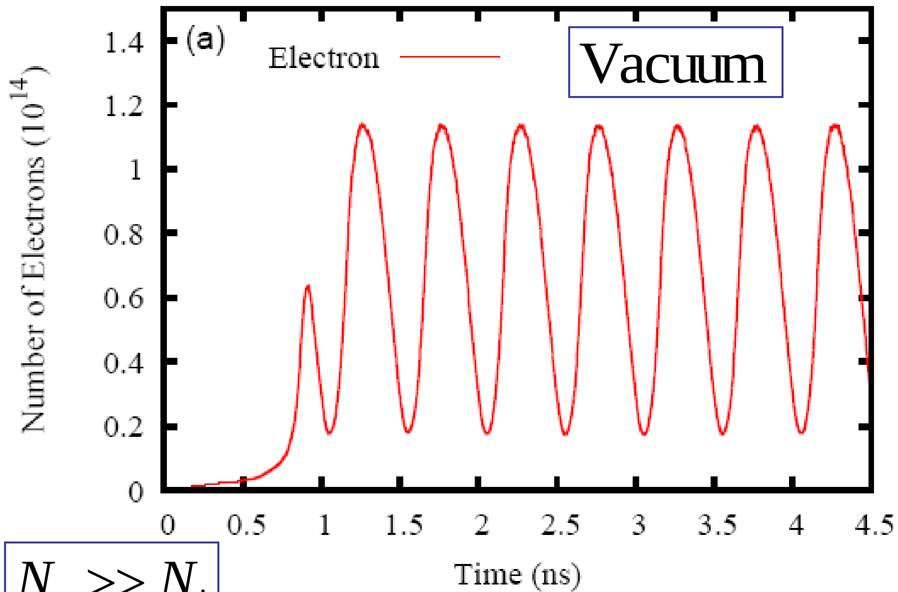


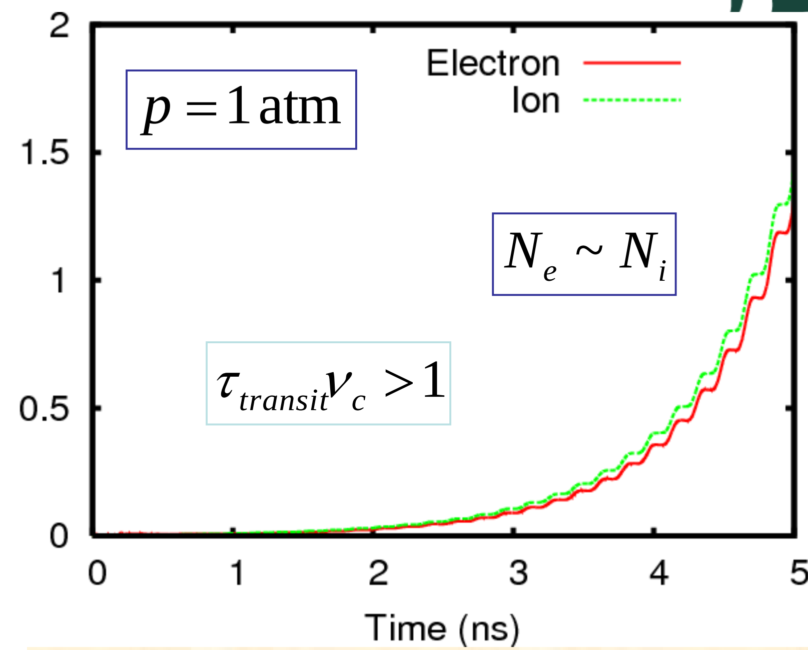

3 MV/m, 1 GHz

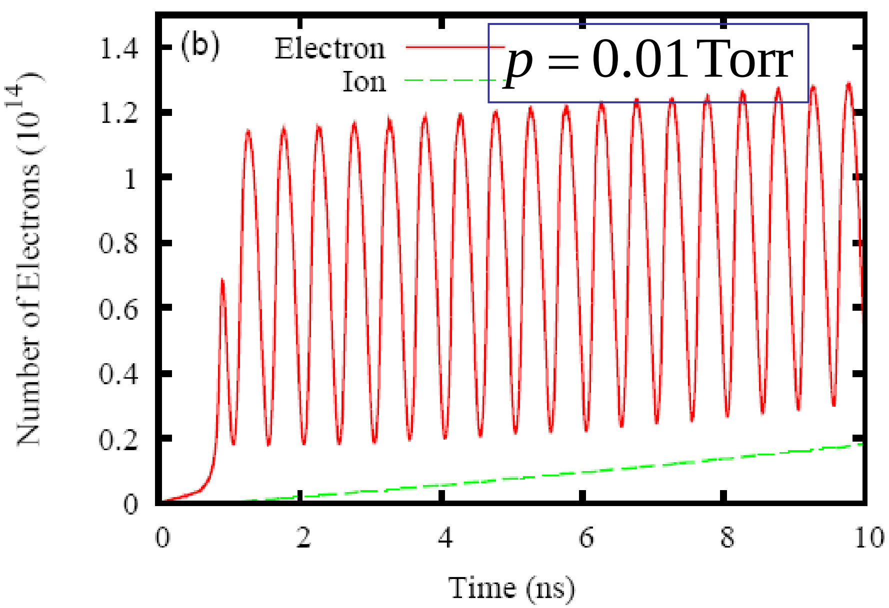
- ~2 % of the input EM power is absorbed
- The phase difference between the discharge power and input EM power means that the electrons are not totally in equilibrium with the local rf electric field.

# Collisional Effects




$N_e >> N_i$

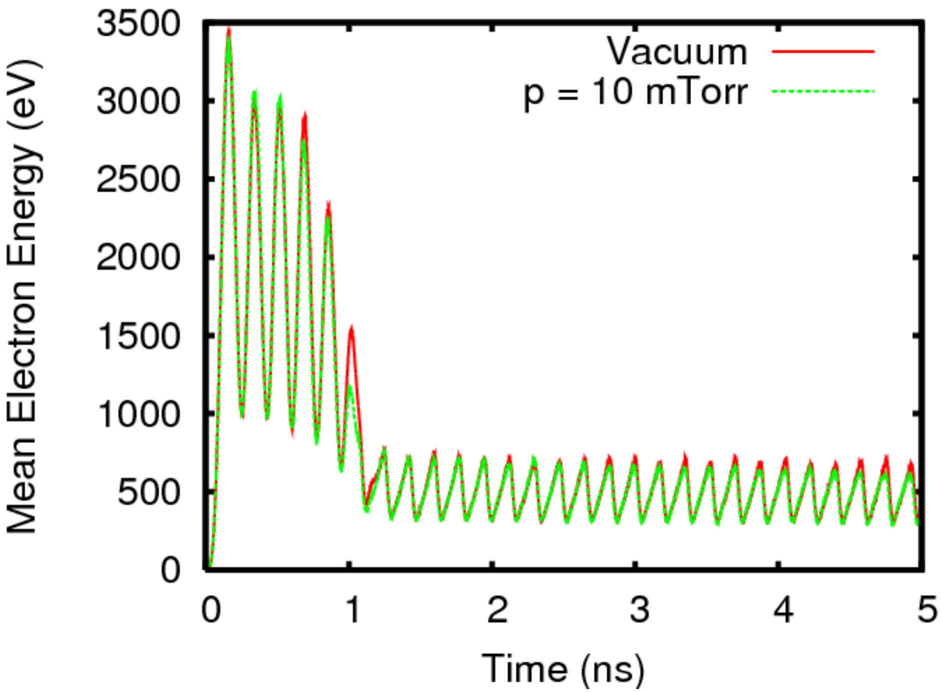


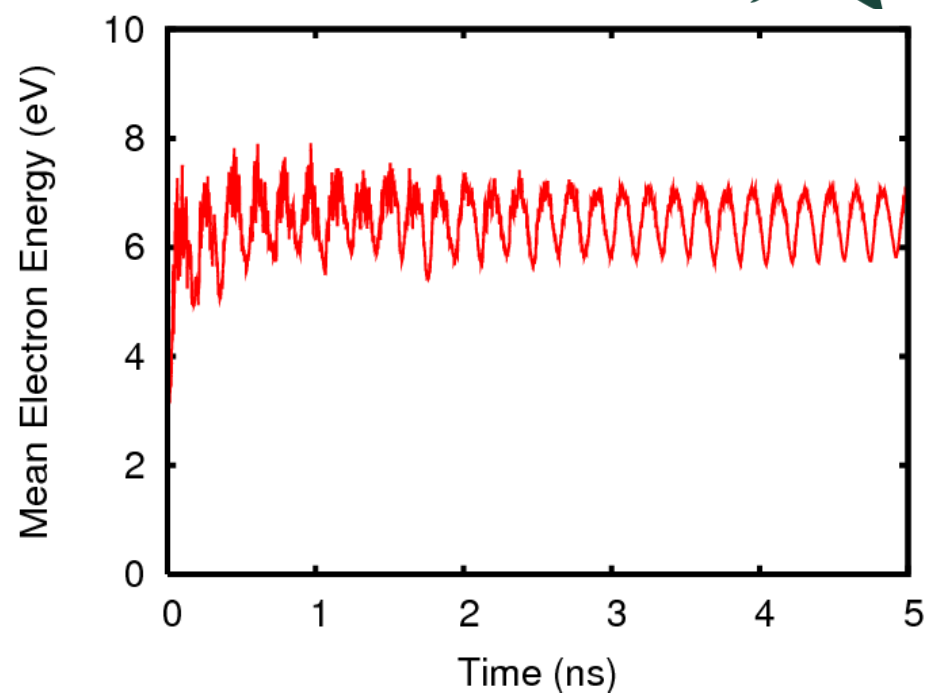

- As the pressure increases, electron-impact ionization collisions dominate secondary electron emission as the electron source.
- At high pressures, the number of ions becomes comparable to that of electrons.

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

# PIC: Electron Mean Energy




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




$p = 1\,\text{atm}$

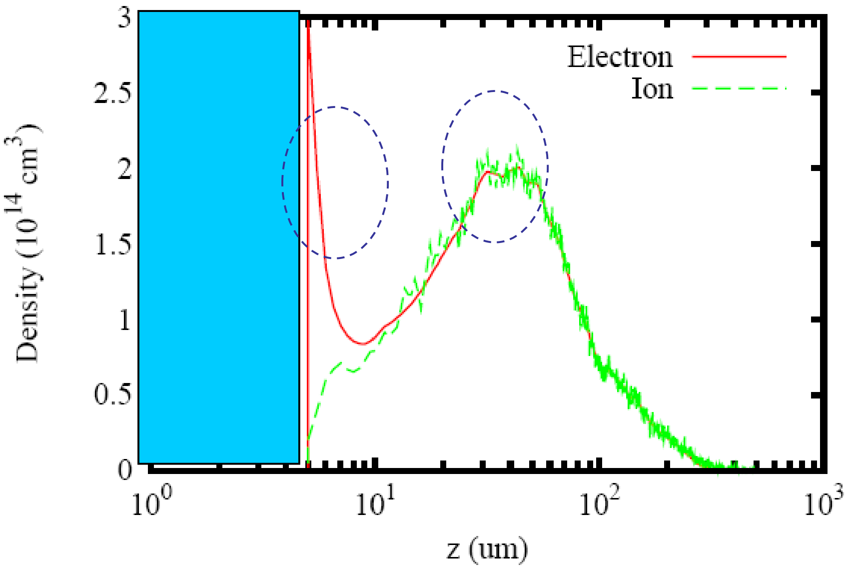
- Electrons in the multipactor discharge gain their energy by being accelerated by <u>the rf electric field during the transit time</u>.

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



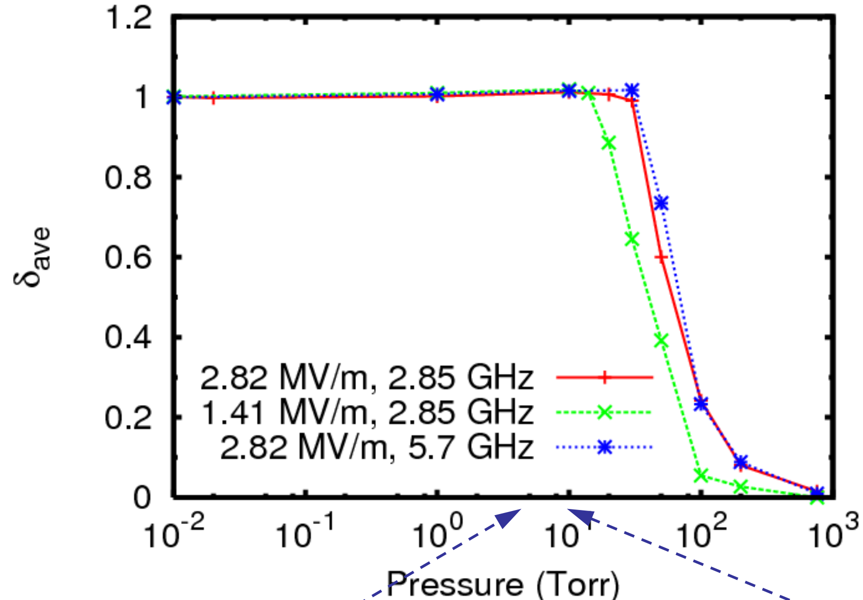
$E_{rf0} = 2.82\,\text{MV/m}$ at $2.85\,\text{GHz}$, Argon

# Transition




1 Torr: surface and volume discharges coexist

Transition Pressure (10~50 Torr Ar)

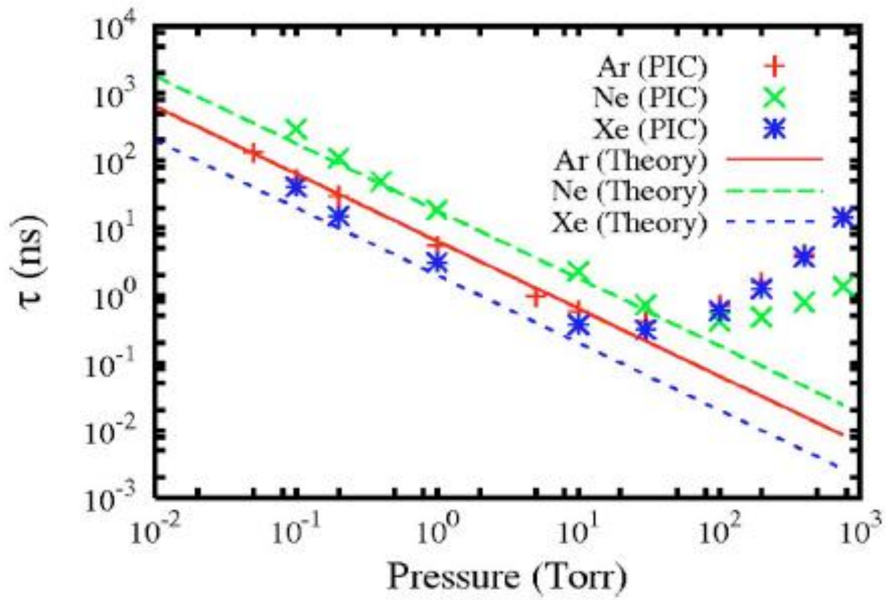


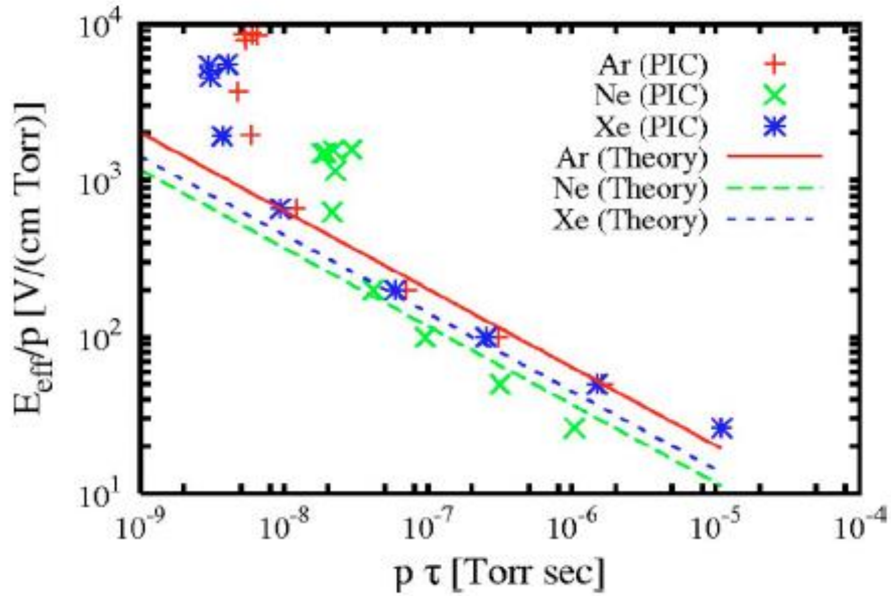

$\omega(2.85\,GHz) \sim \nu_c$

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

- 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

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

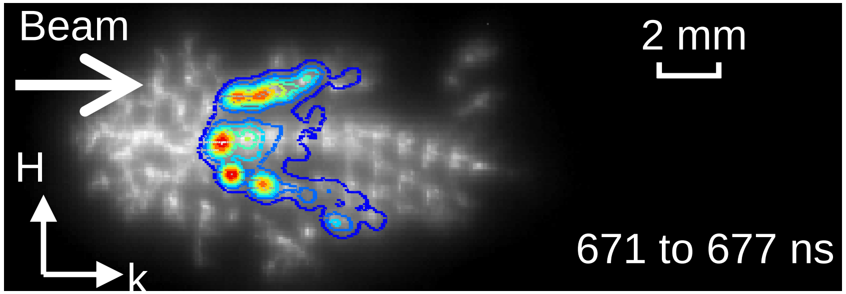
High pressure regime:
collision dominated ($\nu_c >> \omega$)
volumetric discharge

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

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

# Plasma Filamentary Arrays

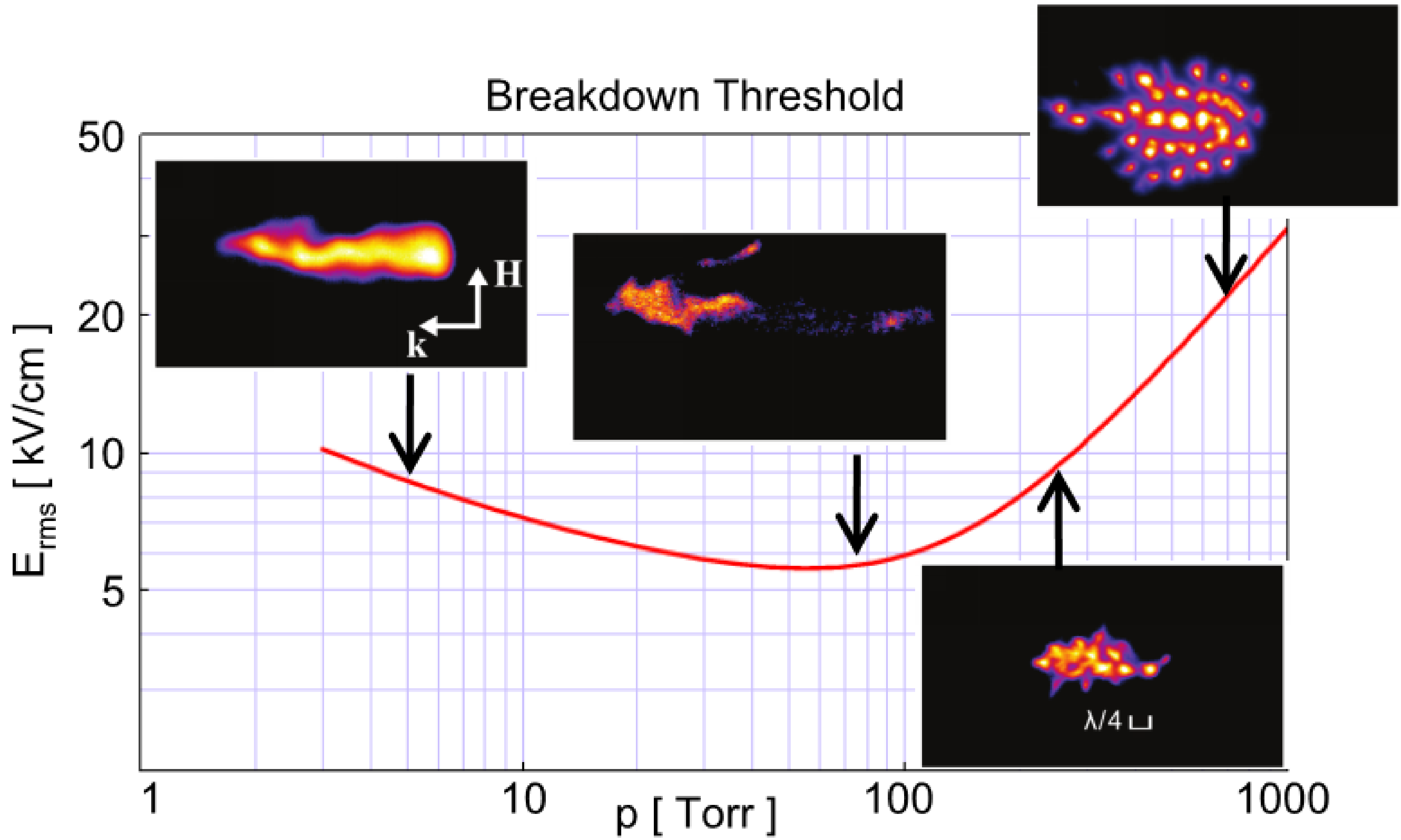
- 1.5 MW, 140 GHz Gyrotron
- 3 shots with slow (B&W) and fast (color) cameras
- Filaments spaced slightly less than $\lambda/4$, propagate towards source
- Hypothesis: constructive interference of reflected/diffracted waves, propagation speed limited by diffusion of seed electrons





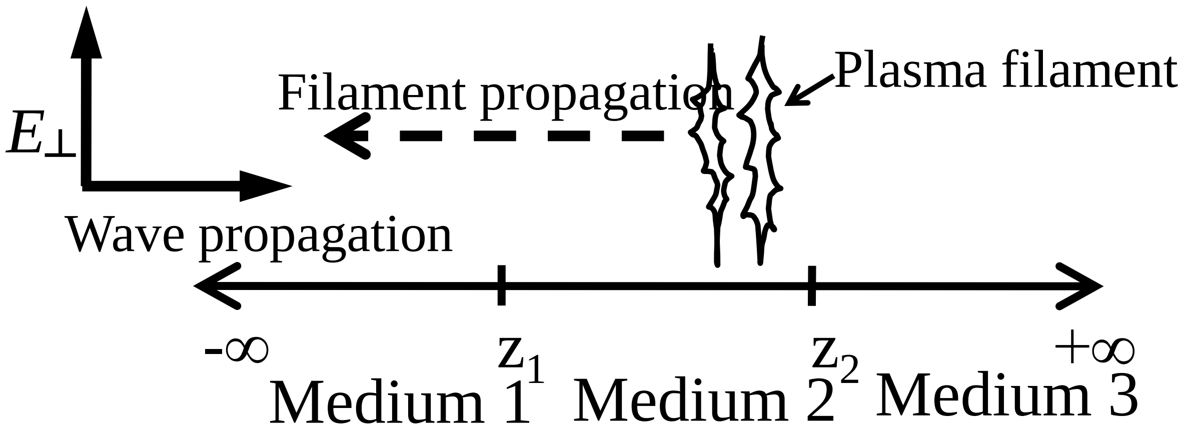
Y. Hidaka, et al., *Phys. Rev. Lett.*, **100**, 035003 (2008).

# 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): $k_1^2 = k_3^2 = \dfrac{\omega}{c}$

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

$\omega_{p,i}$ : 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

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

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

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

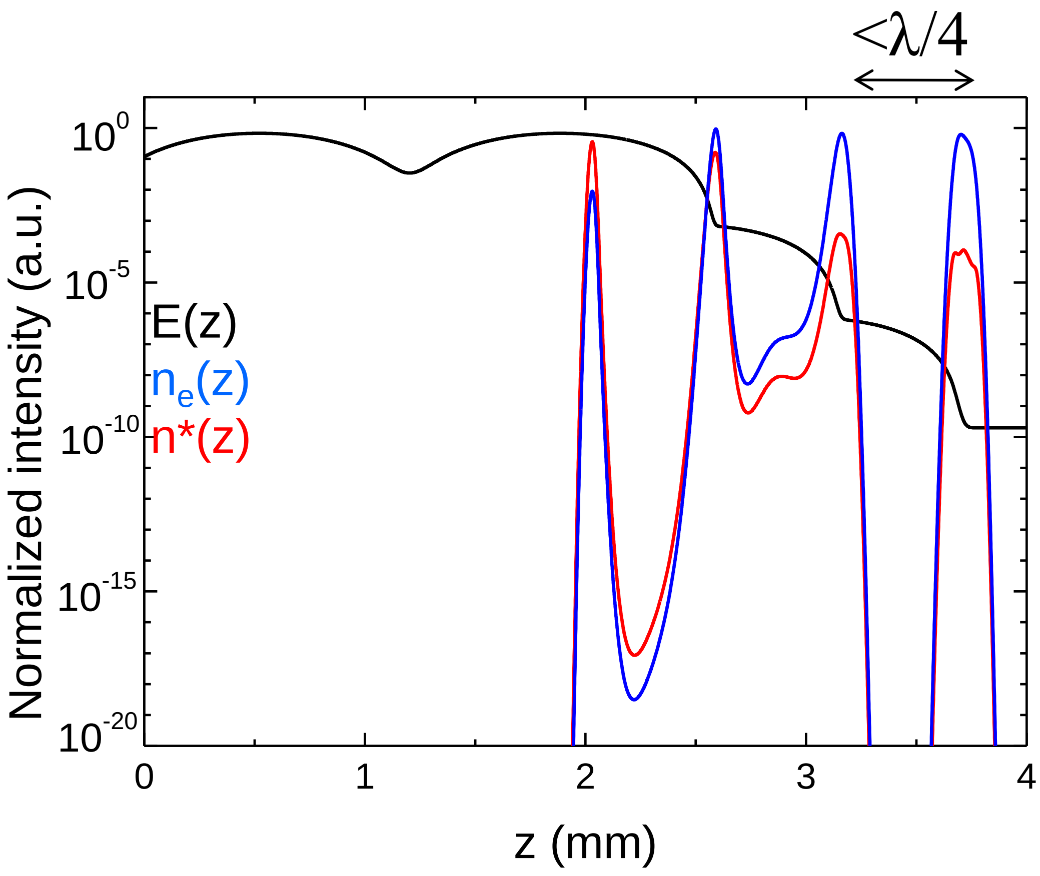
$$q_e = -\frac{3}{2} D_e \nabla n_e T_e + \frac{5}{2} J_e T_e$$

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

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

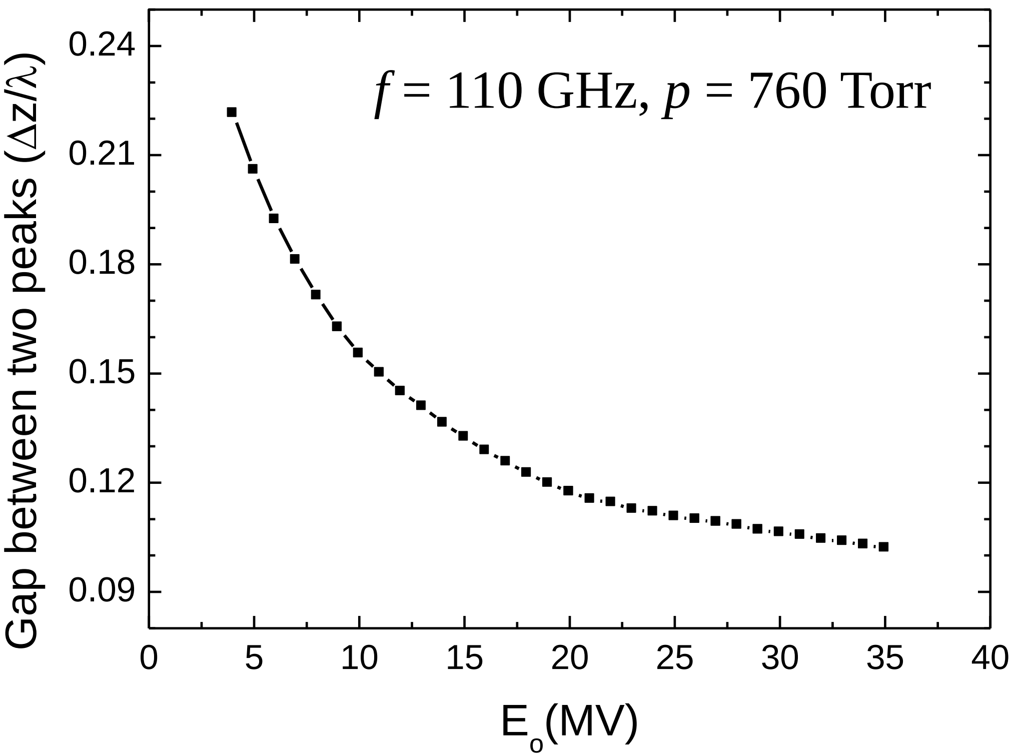
# Filaments: 1D Model

- 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
  - Susceptibility depends on transverse waveform
  - Time dependent behavior understood
  - Multipactor and ionization discharge compete at intermediate pressure (10-50 Torr)
  - Ionization discharge dominates at atmospheric pressure

- Wave-fluid model reproduces filamentary experiment well
  - Filament distance slightly less than $\lambda/4$
  - Propagation speed ~ ambipolar or free diffusion times

# Future Work: Multipactor MURI

- MSU, TT, UM, UNM, UW
- Space device multipactor
- Develop 3 open platforms (model and experiment):
  - Planar
  - Coaxial
  - Stripline