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Analytical and Numerical Studies of Dark Current in Radiofrequency Structures for Wakefield Acceleration

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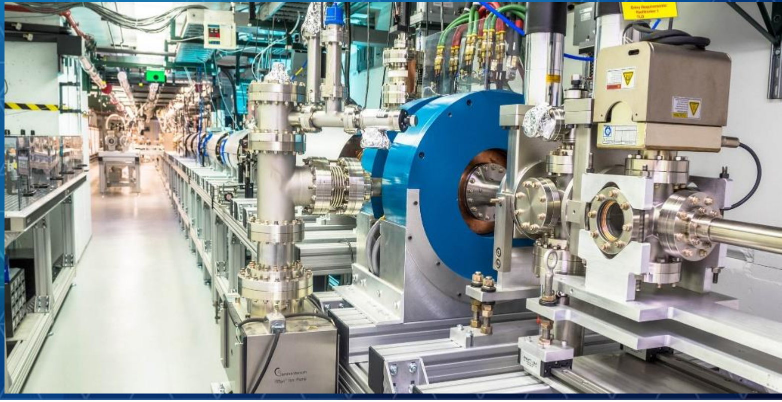

OUTLINE

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DARK CURRENT SIMULATIONS IN ACCELERATING STRUCTURES OPERATING WITH SHORT RF PULSES

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- Motivation
- Short Pulse Acceleration
  - Short pulse → High gradient → Compact Accelerators
  - Understanding RF breakdown phenomena with short RF pulses
- Dark Current Modeling
  - Two breakdown processes under investigation:
    - Field emission
    - Multipacting
      - Two approaches: Analytical modeling + PIC simulations
- Conclusions

MOTIVATION

- Recent experimental demonstration of high accelerating gradient in RF structures powered by short RF pulses at AWA
  - Close to 400 MV/m achieved on the surface of an X-band photocathode with ~9 ns RF pulses

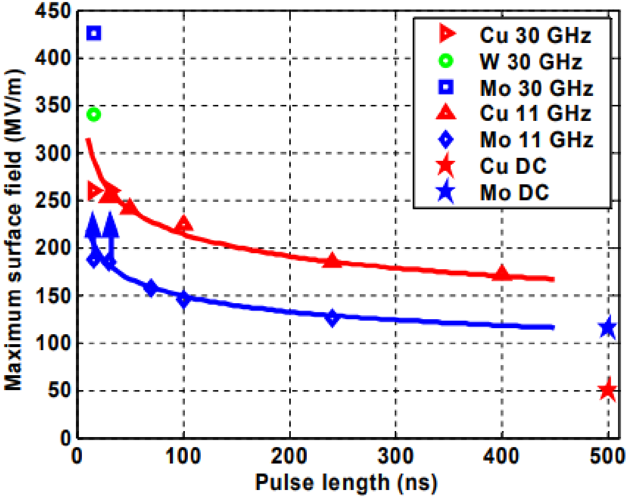
- RF breakdown with nanosecond-long pulses has not been carefully characterized
  - Previous studies mostly cover a range of ~100 ns to ~1 μs

- Goals:
  - Understanding of RF breakdown physics on various time scales
  - Experimental strategies to mitigate breakdown using short pulses

SHORT-PULSE ACCELERATION

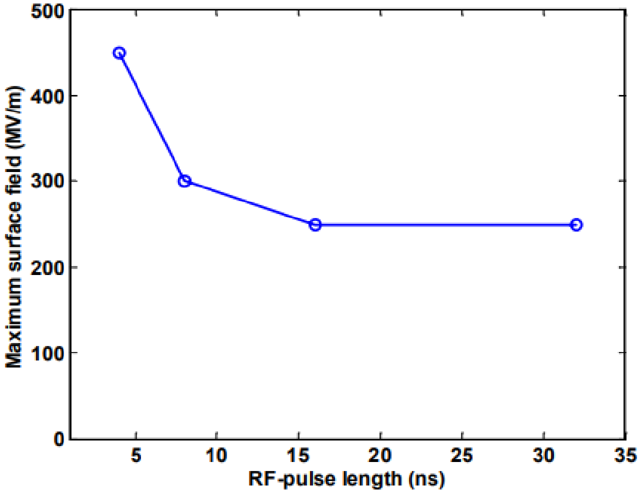
- Evidence of the benefits of short-pulse acceleration from:
  - Empirical scaling law
  - Early experiments

Breakdown rate (BDR) $\propto E^{30}\tau^{5}$



@NLCTA, 11.424 GHz

S. Döbert *et al*., SLAC-PUB-10551 (2004)



@CTFII, 30 GHz

W. Wuensch *et al*., Proc. PAC 2003, ROAA011

DARK CURRENT STUDIES

Dark current

- Unwanted current in accelerators that limits the gradient

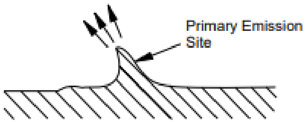
Consequences

- Energy loss and beam instabilities
- Emittance growth
- Secondary radiation

Sources of dark current

- Field emission
- Secondary electron emission
- Multipacting

THEORY OF FIELD EMISSION



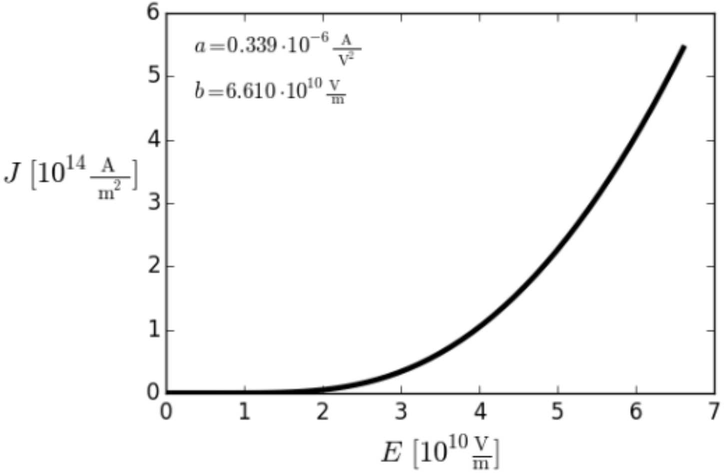
- Field emission of electrons
  - Fowler-Nordheim field emission model
    - Solution of Schrödinger equation by considering an electron in conduction band in presence of triangular potential.

$$I_{\mathrm{FN}} = \frac{1.54 \times 10^{-6} \times 10^{4.52/\sqrt{\phi}} \times A_e \times \beta^2 E^2}{\phi} \times \exp\left(-\frac{6.53 \times 10^9 \phi^{1.5}}{\beta E}\right).$$

Emission current

Work function

Electric Field

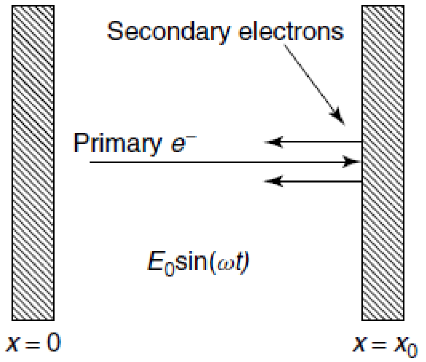


Emission current density vs field gradient plot.

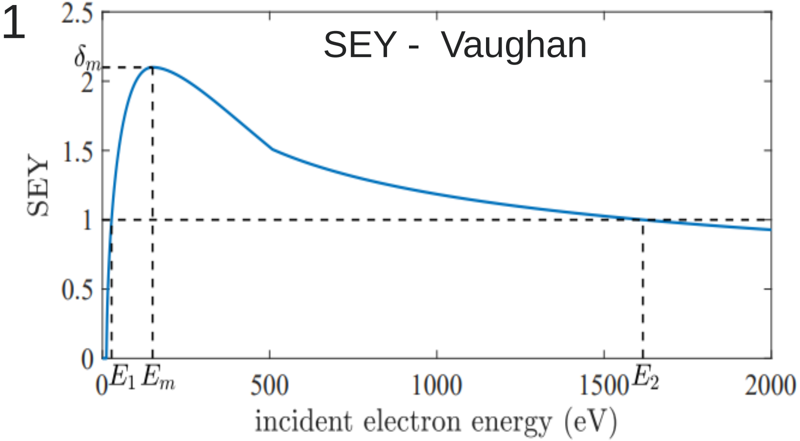
MULTIPACTING

- Multipacting resonance
  - Synchronization between electron motion and RF field

  → Exponential growth of dark current
- Two conditions for electron multipactor
  - Resonant electron motion
  - Average secondary electron yield (SEY) > 1
- Secondary electron emission
  - SEE yield depends on incident electron energy
  - Multipacting often plays a larger role at lower gradients

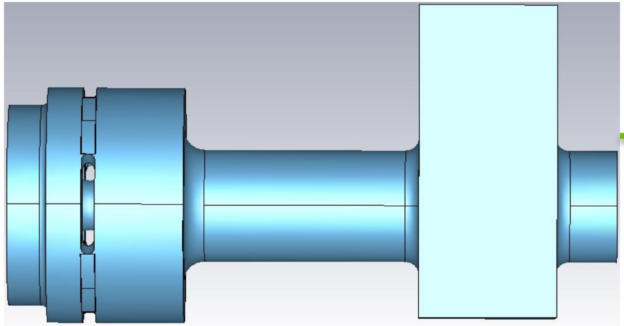


Parallel plate model of multipacting

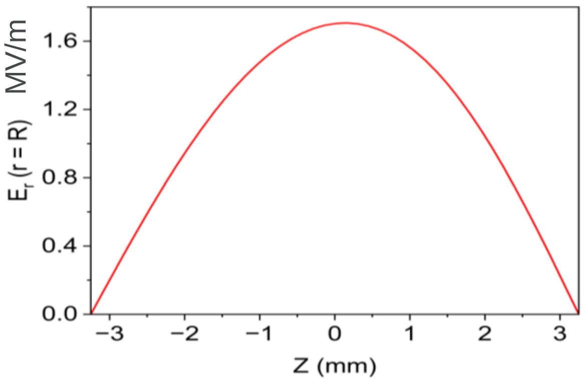


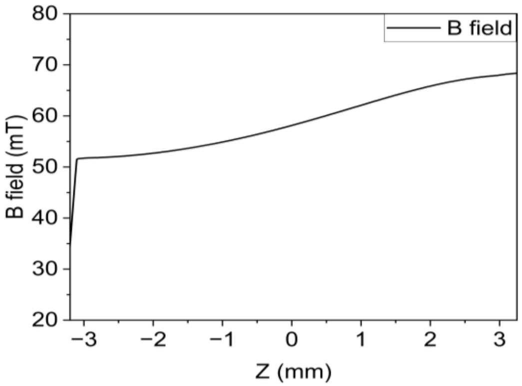
ANALYTICAL MODELING OF MULTIPACTOR

Field distribution in the X-band photocathode



Vacuum model of the x-band photocathode cavity





Good approximation of the realistic cavity geometry: pill-box cavity

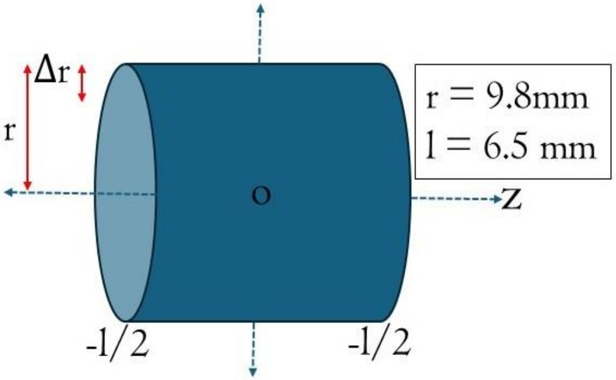
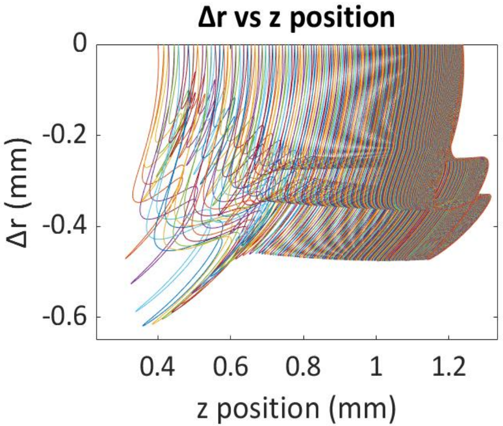
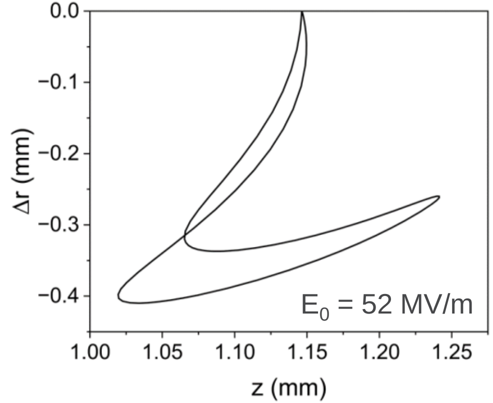
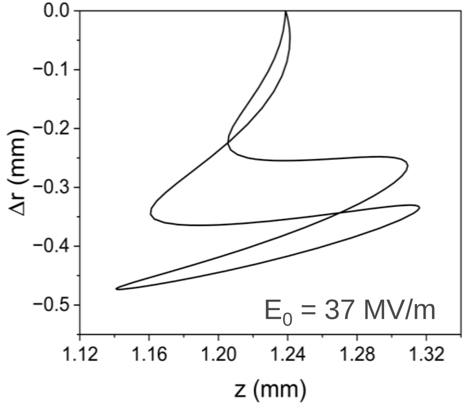


Fig: 11.7 GHz Pillbox cavity

ANALYTICAL RESULTS OF MULTIPACTOR







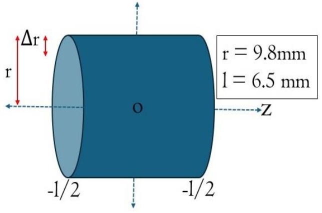
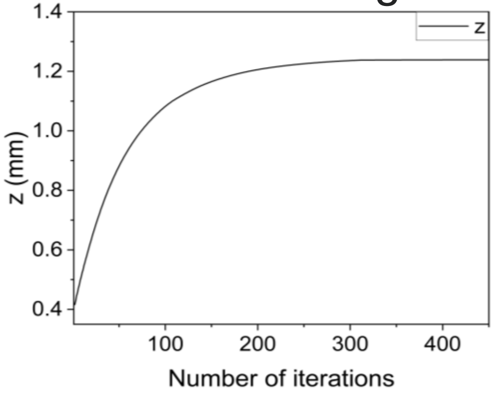
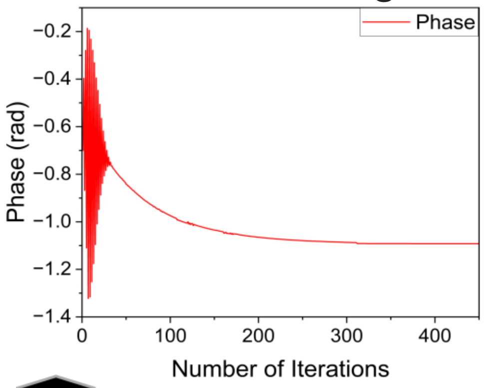


Fig: 11.7 GHz Pillbox cavity

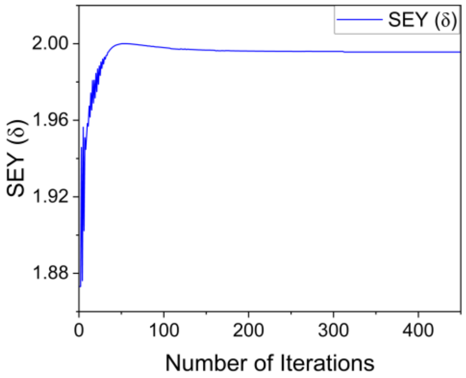
Position convergence



Phase convergence

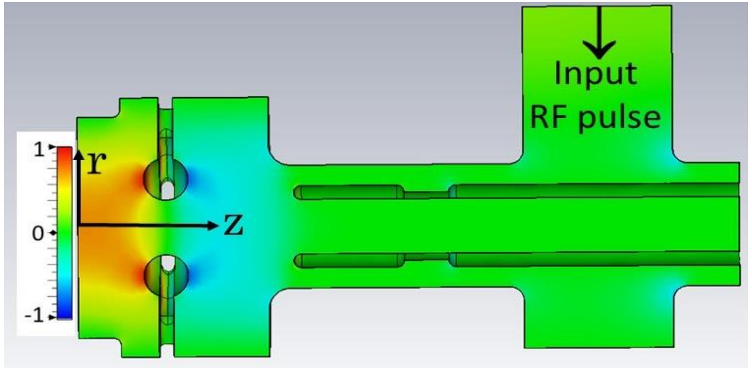


SEY convergence

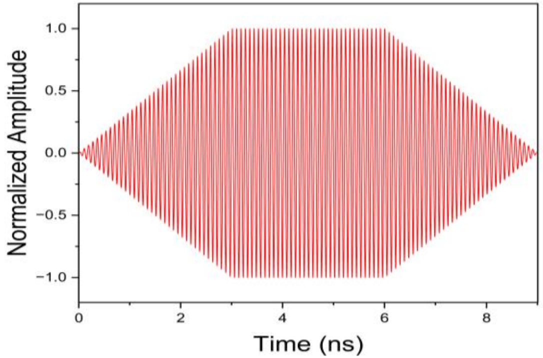


DARK CURRENT SIMULATIONS

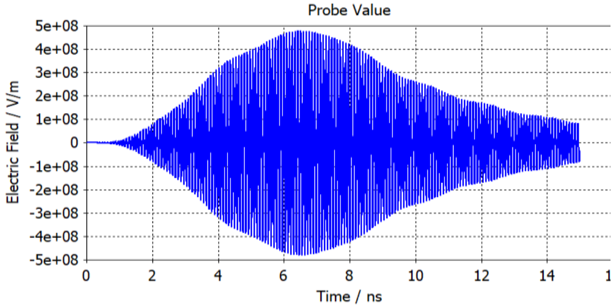
- Short-Pulse photocathode
  - X band, 1.5 cell RF gun
  - Operating in π mode, 11.7 GHz
  - Strongly over-coupled



Normalized longitudinal electric field distribution in the X-band photocathode cavities at 11.7 GHz

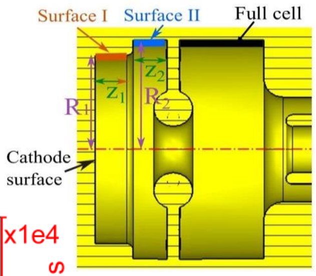


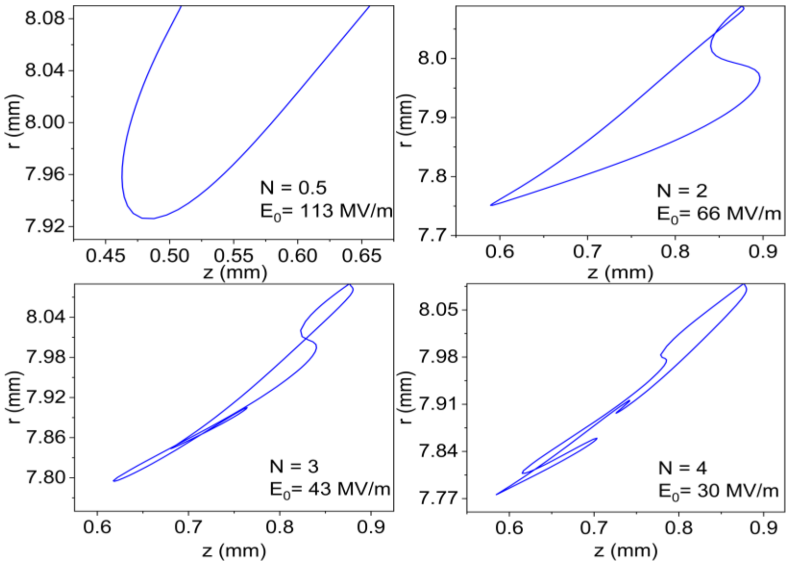
6 ns long FWHM RF pulse used to excite the cavities



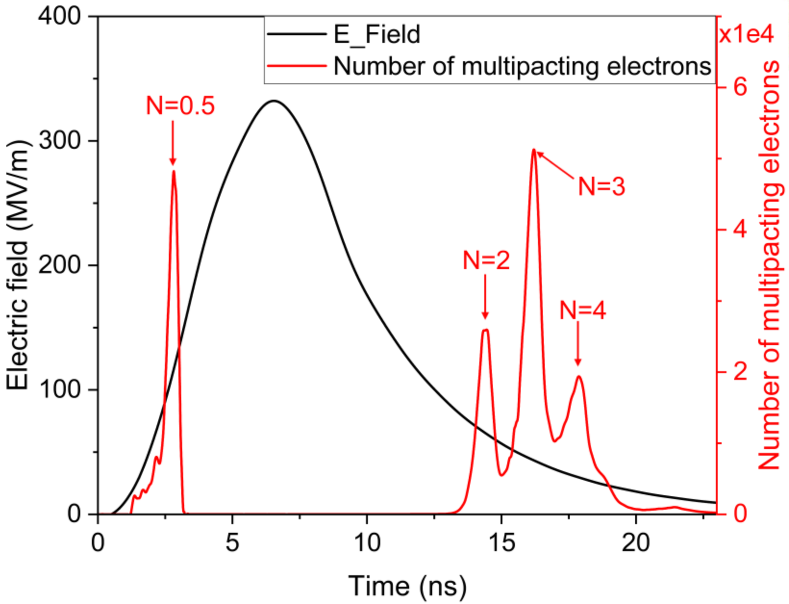
Time probe signal nearby photocathode surface with 400 MW input power

SIMULATIONS OF MULTIPACTING



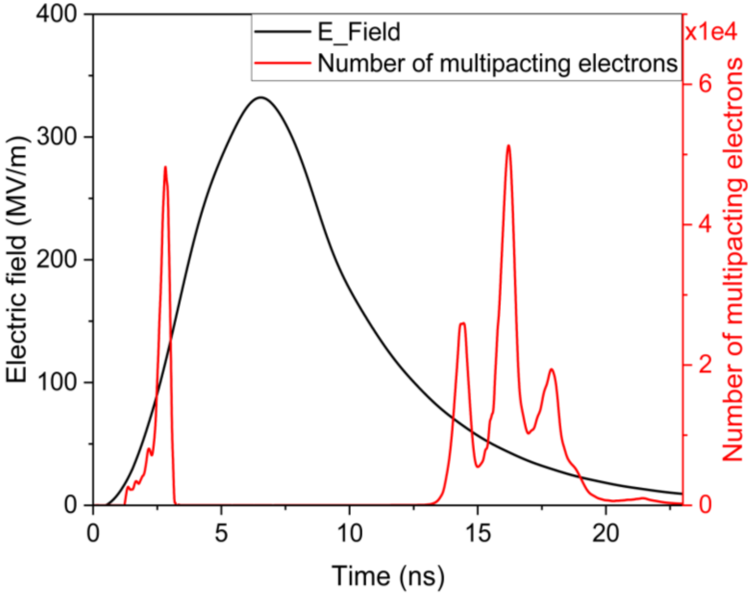


Multipacting electron trajectories in surface I sidewall

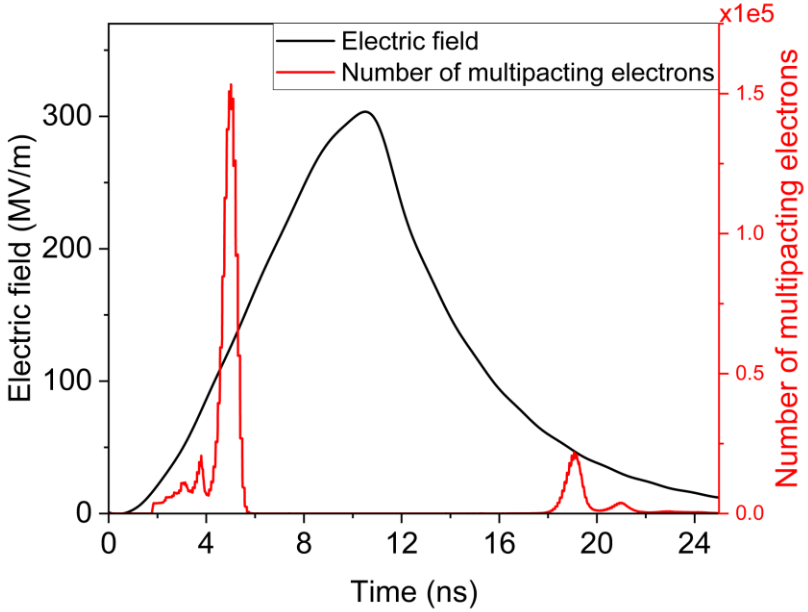


The number of multipactor electrons with Surface I

DEPENDENCE ON PULSE SHAPE

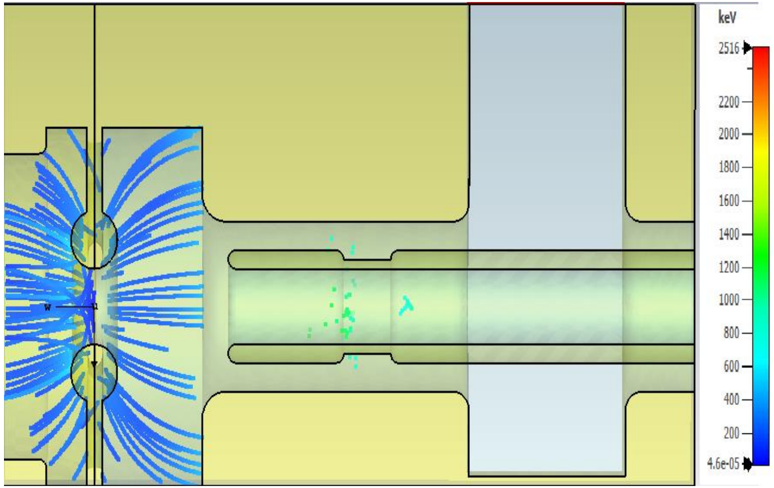


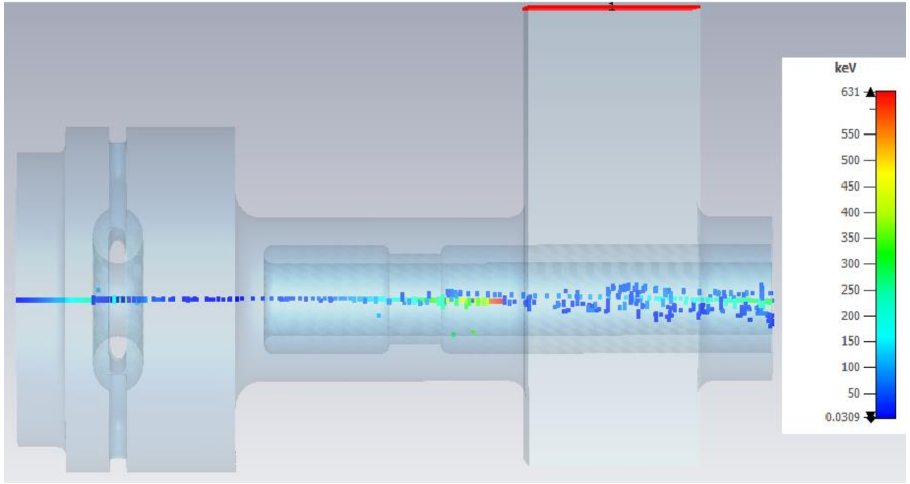
The number of multipactor electrons with surface I sidewall with 3-3-3 ns pulse



The number of multipactor electrons with surface I sidewall with 8-2-2 ns pulse

FIELD EMISSION SIMULATIONS





Field emitted electrons from the iris

- Dark electrons blocked on the path

Field emitted electrons from photocathode surface
At Field 120 MV/m and beta 5

CONCLUSIONS

- Short-pulse acceleration is promising
  - An 11.7 GHz traveling wave gun powered by short pulses recently demonstrated at AWA with close to 400 MV/m on the cathode
- Modeling and experimental characterization of RF breakdown phenomena with short nanosecond RF pulses
  - Multipacting simulations
    - Comparisons of analytical and numerical dark current results
    - Multipactor current growth depends on the pulse shape
  - Field emission simulations
- **Future plans**: Study on plasma related processes in the cavity, improved diagnostics

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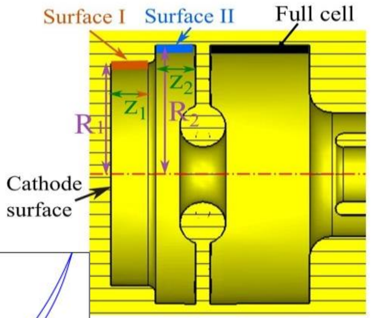
Backup

MULTIPACTING ON CAVITY SIDEWALLS



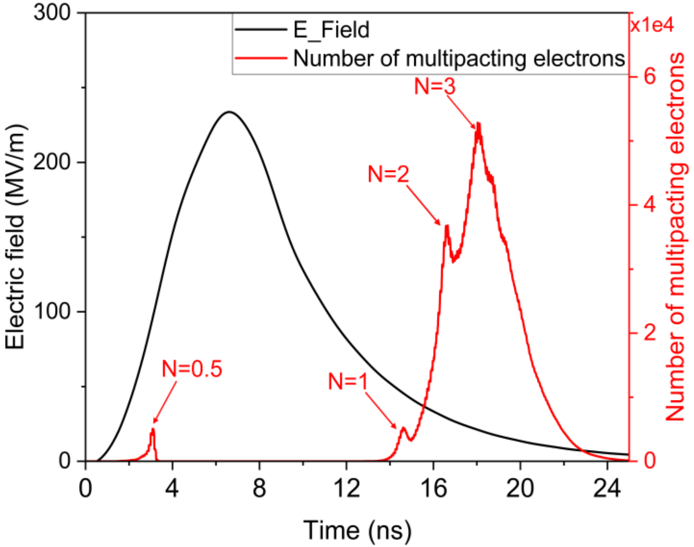


Fig: The number of multipactor electrons with Surface II

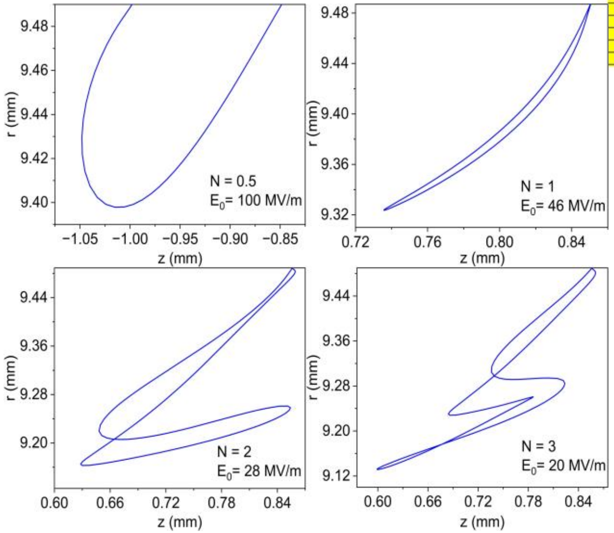
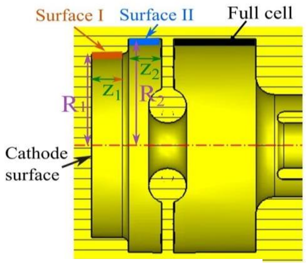


Fig: Multipactor electron trajectories in surface II sidewall

MULTIPACTING ON CAVITY SIDEWALLS



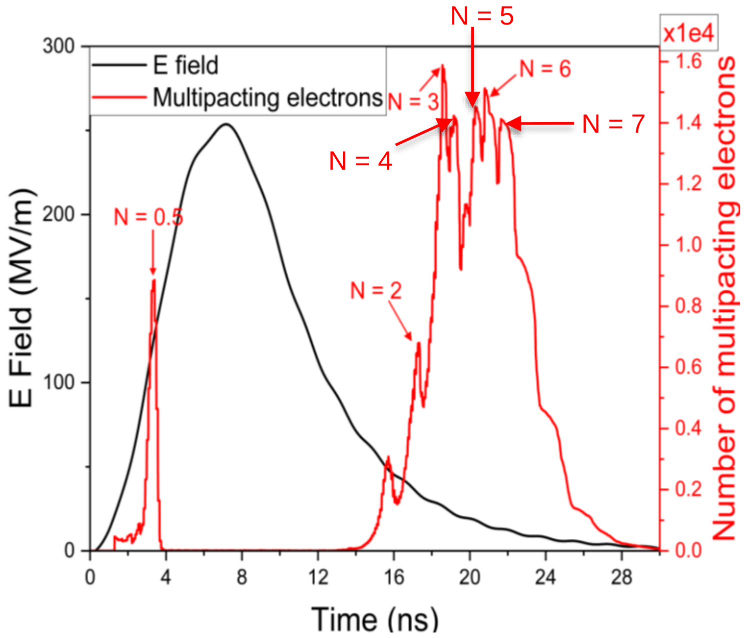


Fig: The number of multipactor electrons with full cell sidewall

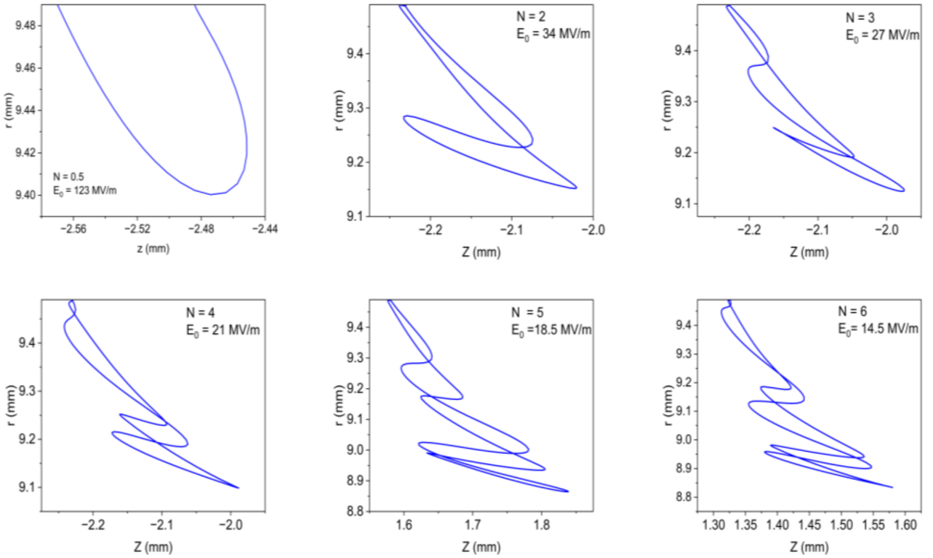


Fig: Multipactor electron trajectories in full cell sidewall

ANALYTICAL MODELING OF MULTIPACTOR

The motion equations are:

$$m\frac{d\vec{v}}{dt} = -e\vec{E} - e\mu_0\vec{v} \times \vec{H}$$

$$\vec{V} \times \vec{H} = -\vec{r}V_z H_\theta + \vec{Z}V_r H_\theta$$

$$m\frac{dv_z}{dt} = -eE_z - e\mu_0 v_r H_\theta$$

$$m\frac{dv_r}{dt} = -eE_r + e\mu_0 v_z H_\theta$$

The Secondary Electron Yield (SEY) is calculated as follows:

$$\sigma = \sigma_m \left[w \exp(1 - w)\right]^k$$

where $w = \frac{W_i}{W_m}$, $k = \begin{cases} 0.56 & \text{if } w < 1 \\ 0.25 & \text{if } w > 1 \end{cases}$

$$W_m = W_{\max}\left(1 + \frac{\theta_i^2}{2\pi}\right),\ W_{\max} = 200\,\text{eV}$$

$$\sigma_m = \sigma_{\max}\left(1 + \frac{\theta_i^2}{2\pi}\right),\ \sigma_{\max} = 2.0$$

- ✓ Motion equations are integrated for V_r and V_z to obtain r and z applying initial condition
- ✓ Vaughan's secondary emission model is implemented to track the secondary emitted particle and SEY.

BACKUP SLIDES