Computational Study of Field Emission in the MTA 805 MHz RF Cavity

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NFMCC10, Oxford, Mississippi
Jan. 2010

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Introduction

- **The MTA 805 MHz RF cavity has been used for button material tests since 2007. After those tests, damage was observed on the button holder, cavity irises and RF coupler.**

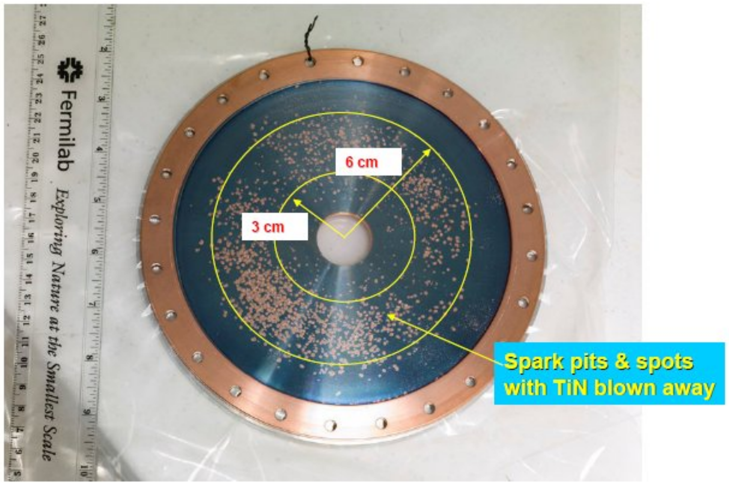
- **The damage on the button holder shows the radial and azimuthal dependence. We also observed damage on the iris and RF coupler (see next slide).**

- **Studies has been carried out in order to explain the damage pattern. The purpose of this study is *not* to discuss the RF breakdown mechanism, but to provide some additional information for the breakdown study.**

- **The study is still ongoing and all the results are *preliminary*; more accurate/detailed simulations will be done.**

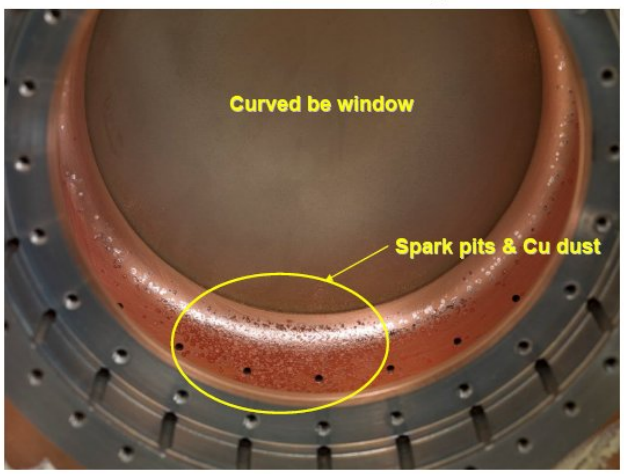
Button test: cavity damage

Button holder

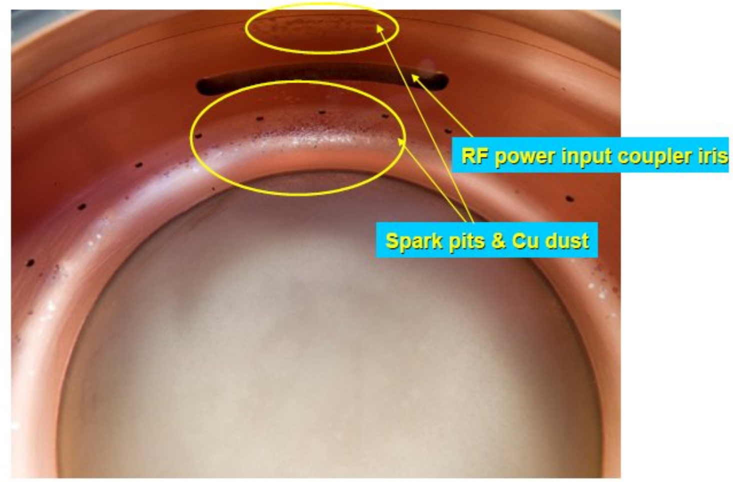


- After opening up the cavity, we observed damage on the button holder, the iris and the RF coupler.
- The cavity is still being remanufactured at JLab now.

Inner surface of cavity



Inner surface of cavity



Field emission

- A field emission model based on the Fowler-Nordheim field emission (FE) law is applied.

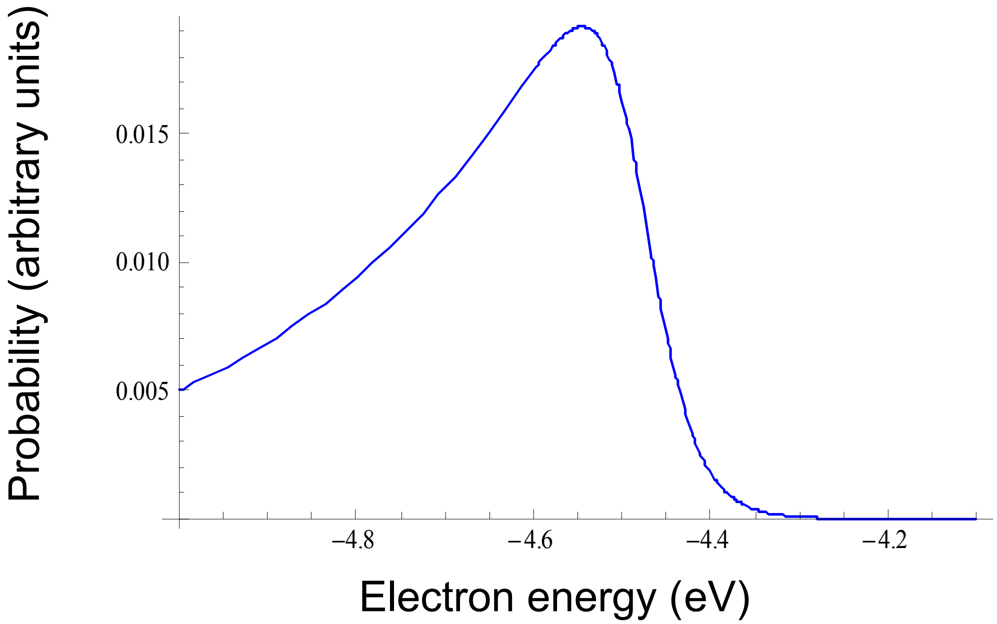
- The energy spectrum of the FE electrons can be expressed as [1]

$$P(E)d(E) = f(\phi, \zeta, \beta\mathbf{E}) \frac{e^{E/d}}{\exp[(E-\zeta)/kT]+1} dE$$

where ϕ is the work function, ζ is the Fermi energy $(\zeta = -\phi)$, $\mathbf{E}$ is the electric field on surface, E Is the electron energy.

- Assuming the local field enhancement [2] $\beta = 184$, and the surface electric field to be 40 MV/m, for Cu with work function 4.48 eV [3], we have the spectrum:

Field emission (cont.)

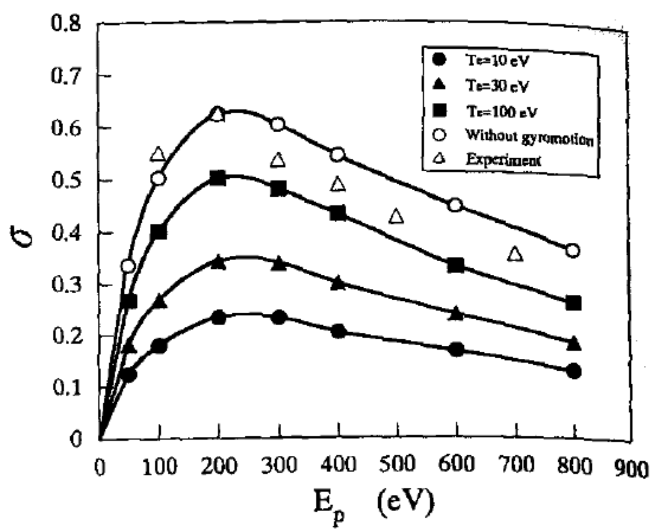


- In the plot, the abscissa is the field-emitted electron energy in eV, the vertical axis is the probability. The maximum is at 4.55 eV. Note that the energy is negative due to the negative sign of electron charge.

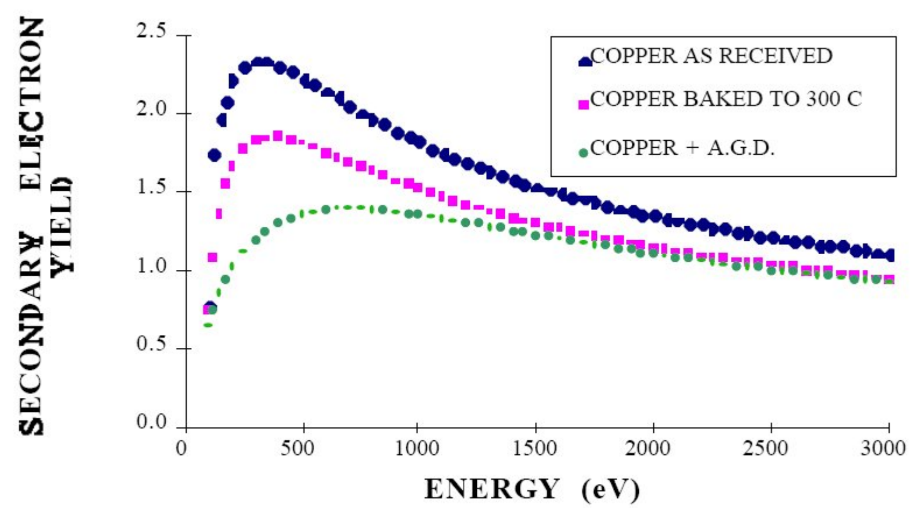
- Additional computations show that for the surface fields from 0.5 MV/m to 40 MV/m, the maximum goes from 1 eV to 4.55 eV.

Field emission (cont.)

- **Another important factor is the Secondary Emission Yield (SEY). It is a function of the energy of the primary electron, temperature and incident angle. For Be, the maximum is ~ 0.6 (< 1!) at 200 eV [4]. Thus in our case, the high energy electrons will mostly penetrate the Be window and introduce negligible SE. For Cu, the maximum is ~ 2.4 at ~ 400 eV [5].**



SEY of Be [4]



SEY of Cu [5]

Particle Studio (PS) simulation

- **The CST Particle Studio is a part of the CST studio suite [6]. We use it to do the study. In the study, I am focused on multiple field emitters on surface instead of an individual one.**

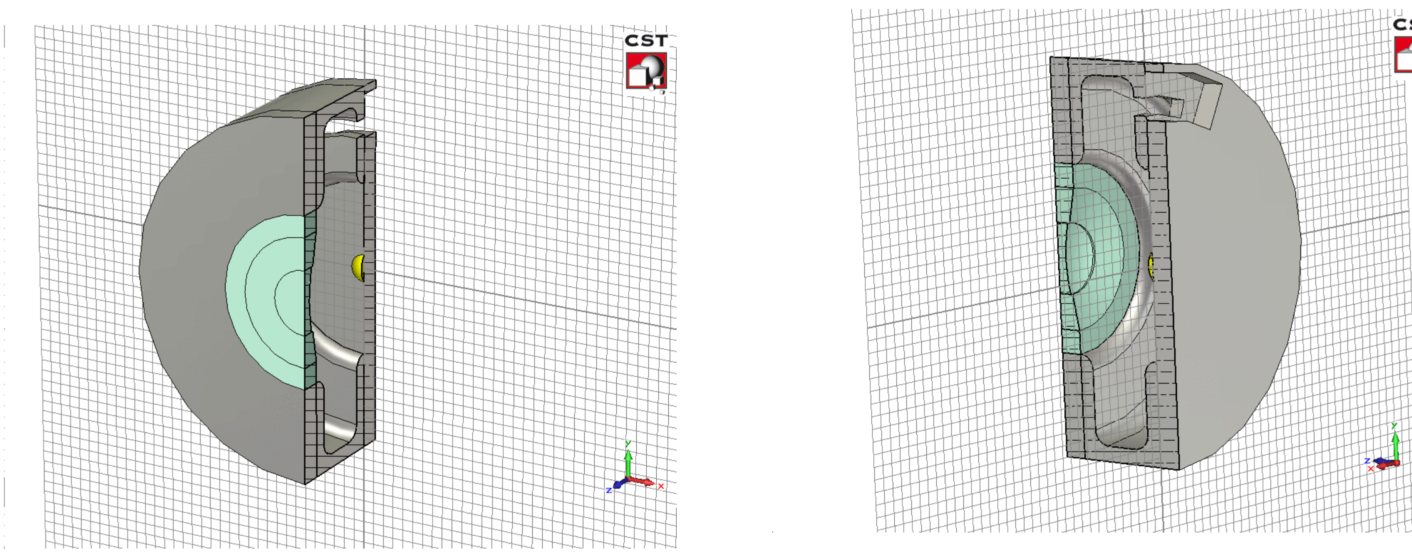
- **In the simulation, one needs to define the surface material, choose the surfaces of emission, FE electron energy (±25% uniform spread around the maximum), and the number of emitters on the surfaces. As a preliminary study, the number of emitters is chosen for the best computation efficiency and the clearest results. It does not matter too much because we are mostly concerned about the secondary yield in the cavity.**

- **As the first step, *only* the fundamental mode, i.e., 805 MHz TM_{010} , is used in the simulation.**

- **All the accelerating gradients in the following discussions are the maximum on axis.**

PS simulation (cont.)

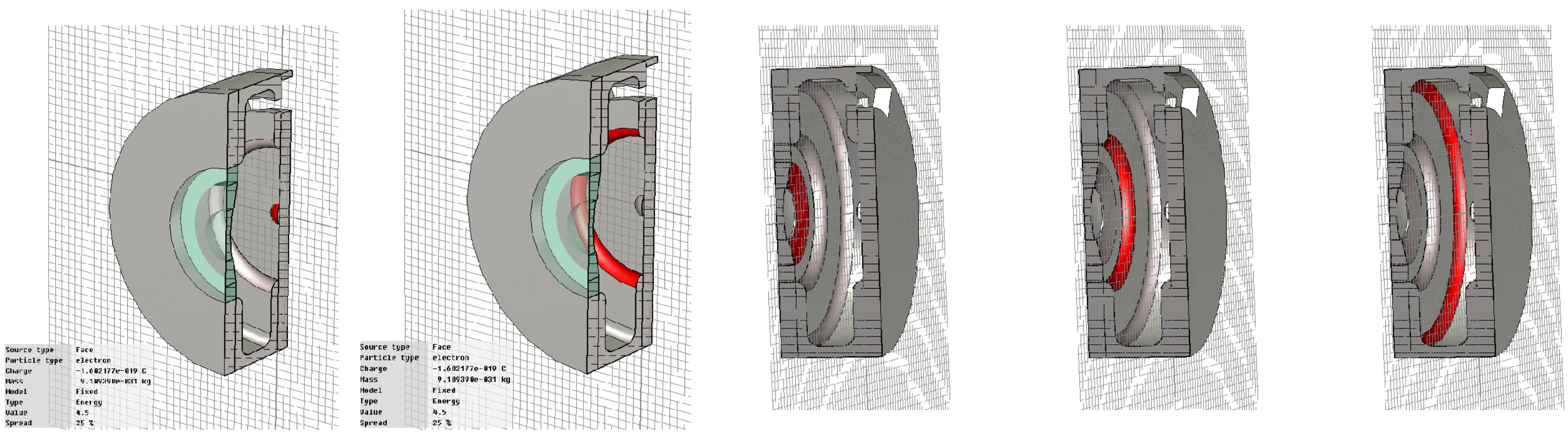
- **A 3D model of the 805 MHz cavity with the curved Be window is built in CST Particle Studio. Because only the inner surfaces of the cavity are of concern, the real thickness is not taken into account.**



3D cutting view of the cavity: the curved Be window is highlighted in light green and the button is in yellow

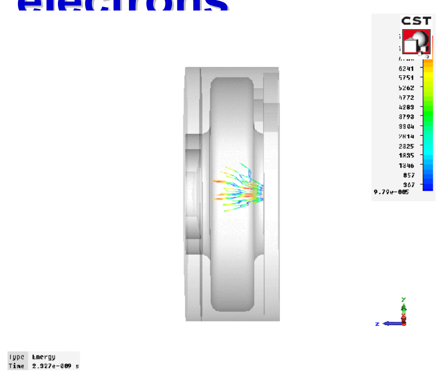
PS simulation (cont.)

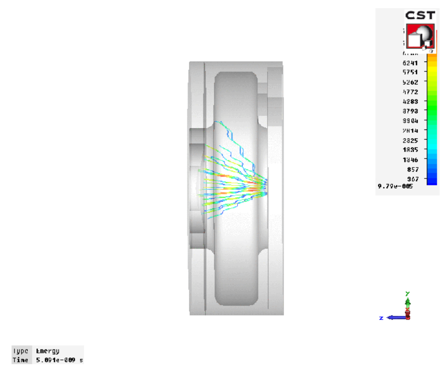
- In the simulation, the surfaces of emission (red) are chosen to be (from left to right): button surface, the iris on the button side, the 3 – 6 cm region on the Curved Be window, the iris on the Be window side, and a corner of the cavity.

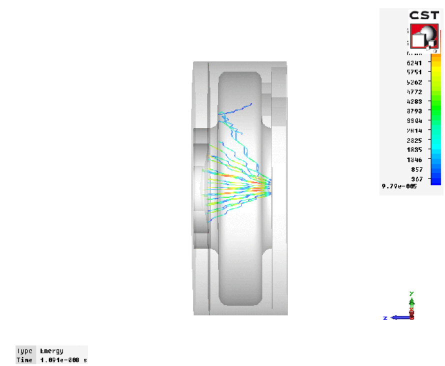


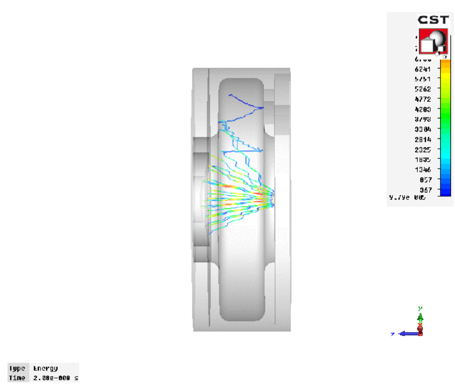
PS simulation (cont.)

- **Without the magnetic field, the trajectories of the FE electrons are spread out. The plots below show the FE electrons of 5 generations starting from the button at 0.5 MV/m and B =0. The color is the energy of electrons**







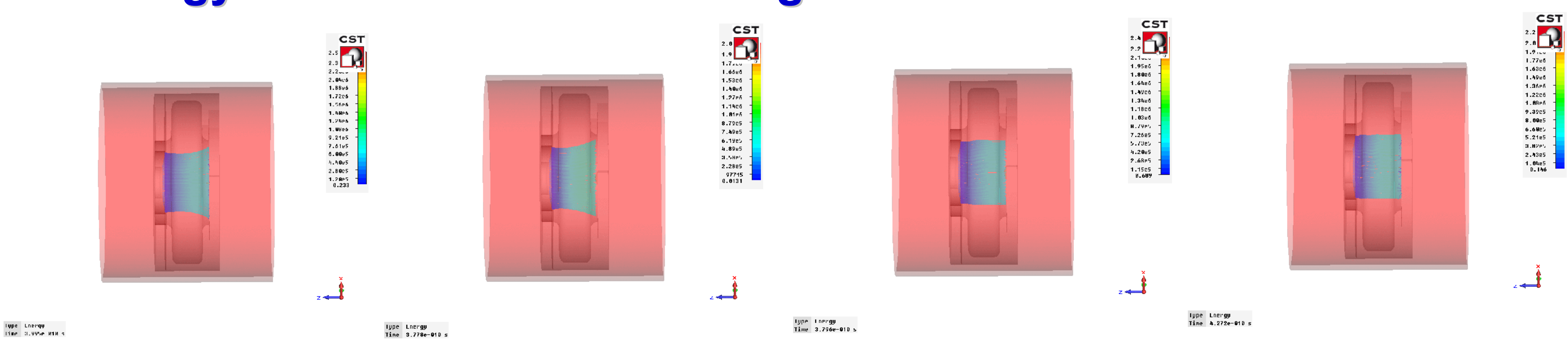


- **The energy of the electrons from the button when hitting the Be window is ~ 42 keV. We can see that their trajectories are terminated at the Be surface, which means no secondaries were generated. This is consistent with the SEY curve.**

PS simulation (cont.)

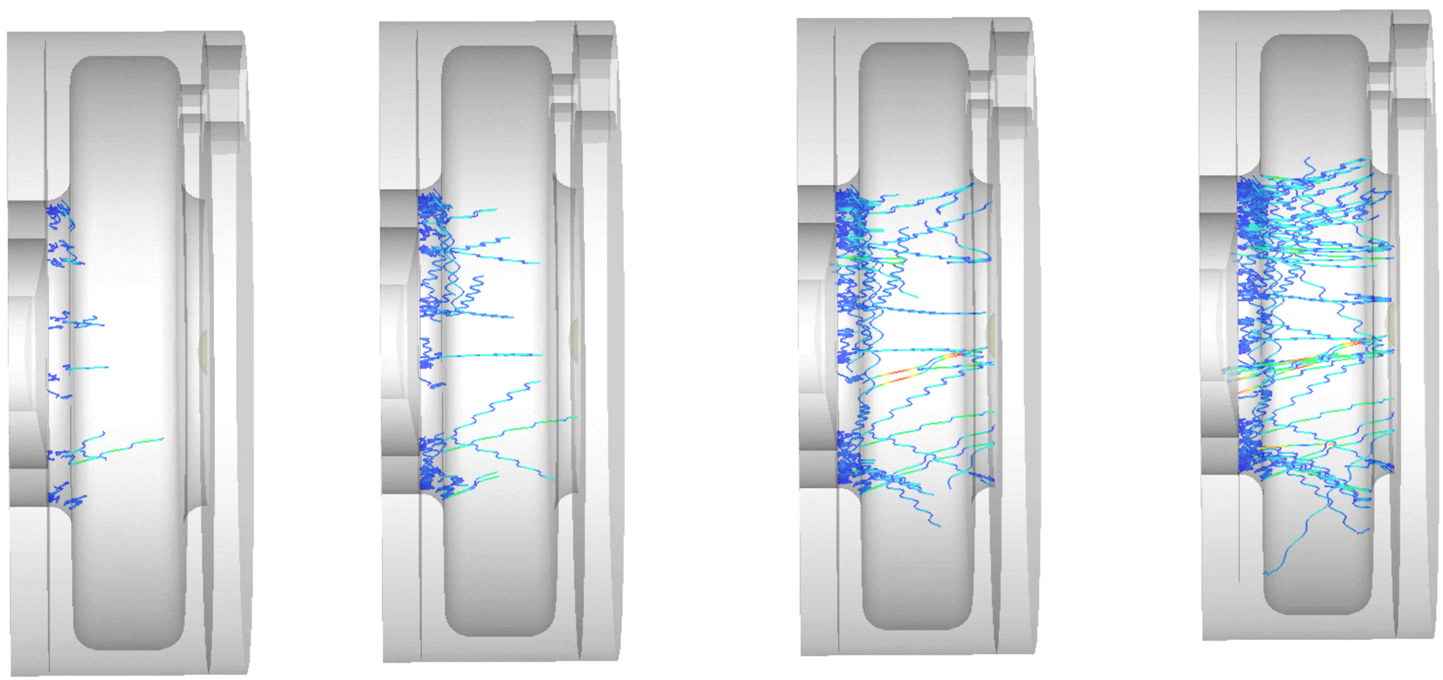
- ***Magnetic focusing:***

  With magnetic field, the trajectories of the FE electrons will be focused. The following is the trajectories of the FE electrons from the 3 – 6 cm region on the Be window up to their arrival at the button holder, at 20 MV/m gradient and various magnetic fields (from left to right: 0, 0.1 T, 0.25 T, and 0.5 T) , note that the energy of electrons when hitting the holder is ~ 1 MeV.



PS simulation (cont.)

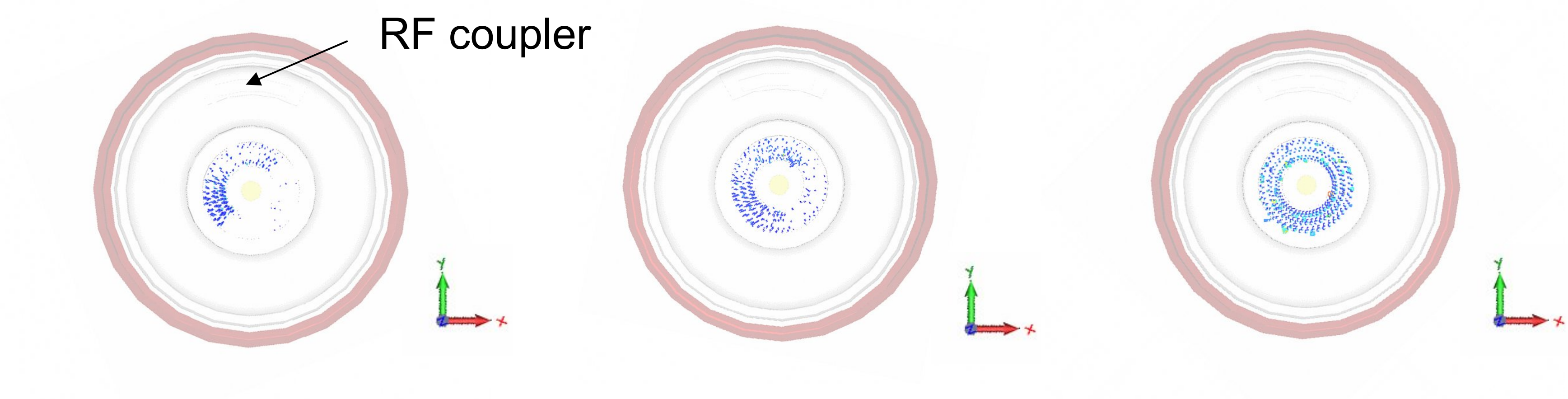
- **As a conclusion, with magnetic field, the FE electrons will be focused and follow the magnetic field lines. Without the magnetic focusing, their trajectories are spread-out. *Another example:* the plots below are the trajectories of the FE electrons from the iris on the Be side at 0.5 MV/m and 0 magnetic field at various time.**



3.74 RF cycle | 7.28 RF cycle | 11.26 RF cycle | 15.12 RF cycle

PS simulation (cont.)

- ***Radial & azimuthal distribution:***
  - **In the simulation, we can see that the FE electrons from the region of 3 – 6 cm in radius on the Be window are focused by the magnetic field directly to the region of 3 - 6 cm in radius on the button holder. As Palmer pointed out [7], this may be the reason that we observe the *radial* dependence of damage on the button holder.**
  - **Moreover, we can also see the *azimuthal* distribution of the FE electrons at various electric gradients (B = 1 T).**



E = 0.5 MV/m　　E = 1.5 MV/m　　E = 9 MV/m

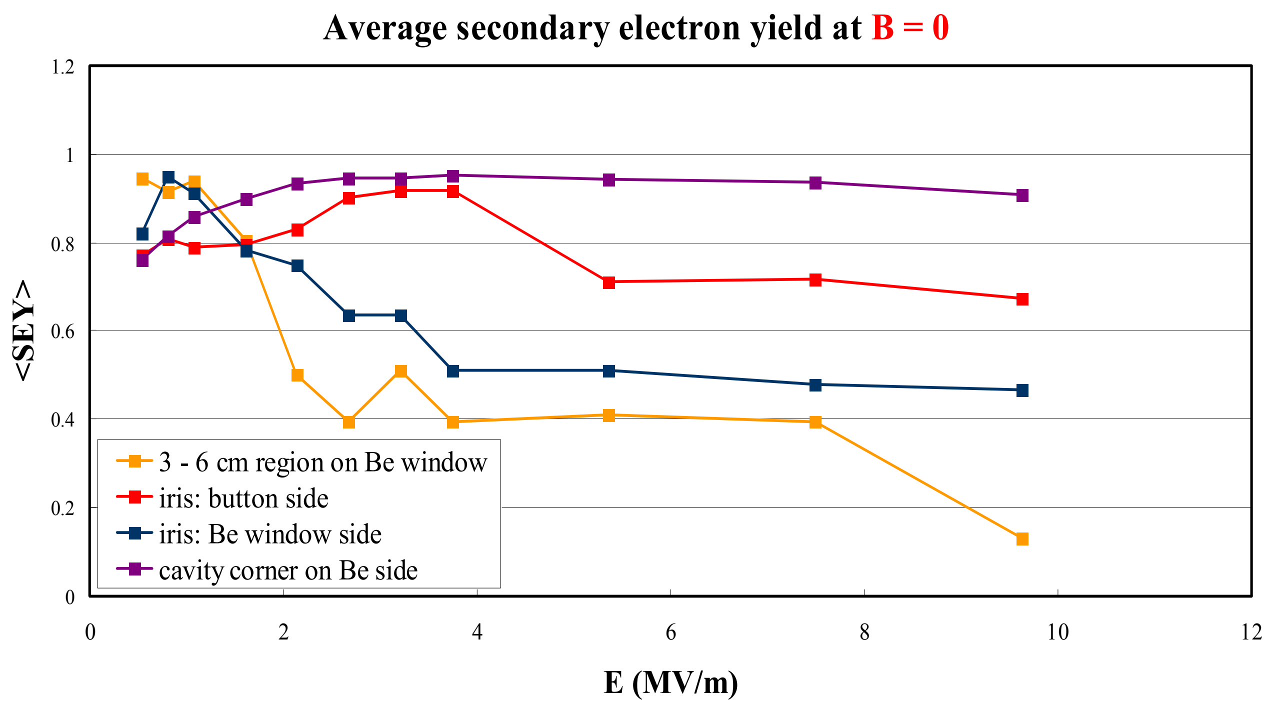
PS simulation (cont.)

- **Therefore because of the magnetic focusing, the azimuthal distribution of the damage on the other side may be introduced by that of the FE electrons on the Be window.**

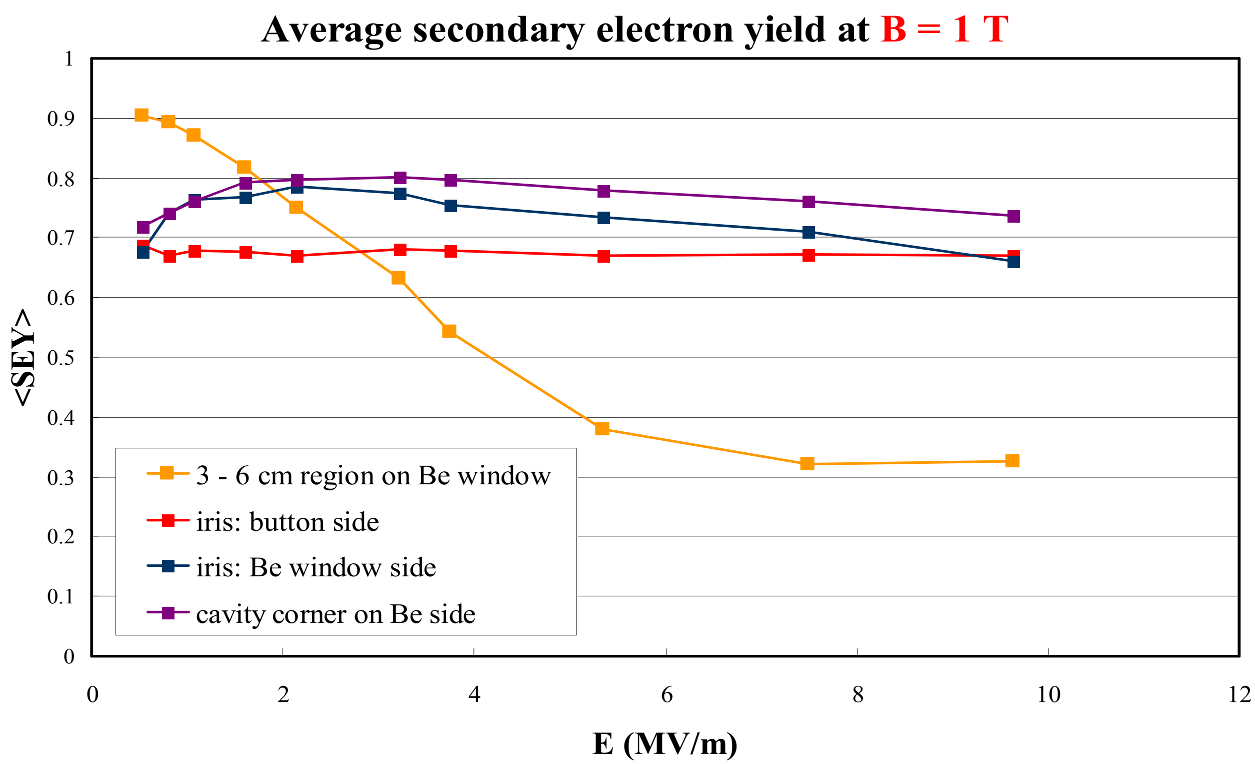
- ***Why is there the azimuthal distribution of the FE electrons?***
  - **A possible reason could be the energy distribution of the FE electrons. As has been pointed out, the FE electrons are not monochromatic, therefore electrons at different locations have different energies. Because some low energy electrons can not gain enough energy when the accelerating gradient is positive and will be pushed back to the surface as the gradient changes sign, thus we cannot see those electrons in the simulation. This effect is significant at low gradient, therefore we see a nonuniform azimuthal distribution when the gradient is low.**

Average Secondary Yield

As primary electrons hit the surfaces, secondary electrons will be generated. The plots below show the secondary yield averaged over all the surfaces hit by the secondary electrons as a function of field gradient: *<SEY>=total number of secondaries / total hits on all surfaces*, 5 generations of electrons are included:



Average Secondary Yield (cont.)



- **Note: the results are very interesting because all the yields are less than 1. If it is true, multipacting possibly did not happen in the cavity.**

Conclusions

- **The simulations show the magnetic focusing effect.**
- **The simulations show the azimuthal distribution of the FE electrons, which could be the reason why the damages on the button holder also have the azimuthal pattern.**
- **The simulations show the average secondary yields are all less than one. If it is true, the multipacting effect may not be as important as we assumed in the MTA 805 MHz cavity.**
- **Since the work is preliminary, more detailed / sophisticated works need to be done to obtain more accurate / confident results. e.g., finer time step, more generations of electrons, finer mesh, high order modes, etc.**

References

- [1] Russell D. Young, Physical Review, v. 113, no. 1 (110) 1959
- [2] J. Norem et al., PRSTAB, v. 6, 072001 (2003)
- [3] H. L. Skriver and N. M. Rosengaard, Physical Review B, v. 46, no. 11 (7157) 1992
- [4] K. Nishimura et al., Vacuum, v. 47, no. 6 – 8 (959) 1996
- [5] V. Baglin et al., EPAC2000 proceeding, page 217, Vienna, Austria
- [6] CST Computer Simulation Technology http://www.cst.com/
- [7] R. Palmer, NFMCC09 talk, LBL