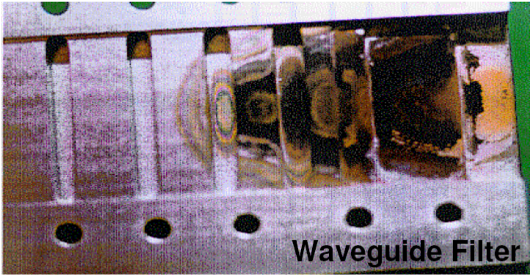
THE DARK CURRENT AND MULTIPACTING CAPABILITIES IN OPAL: MODEL, BENCHMARKS AND APPLICATIONS

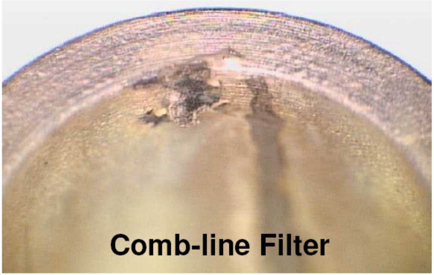
C. Wang, A. Adelmann, Y. Ineichen
Z. G. Yin, T. J. Zhang, M. Seidel

23-08-2012

Outline

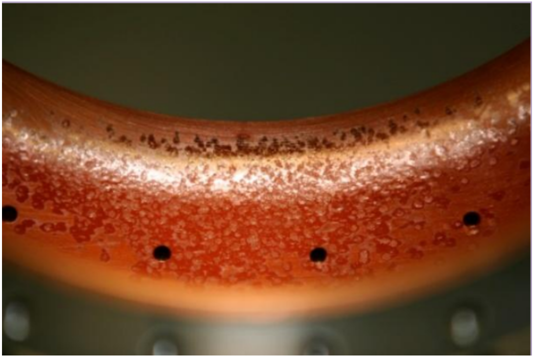
Experimental Observations

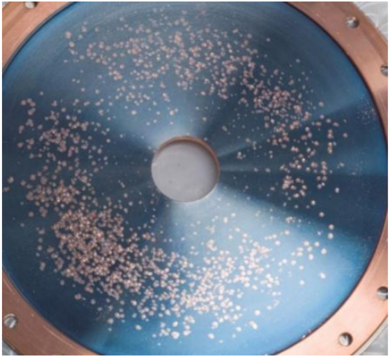




- Multipacting observed in RF/microwave components in the aerospace community.

Experimental Observations





- Dark current observed in a RF cavity and a Be window in the Linac community.

Experimental Observations

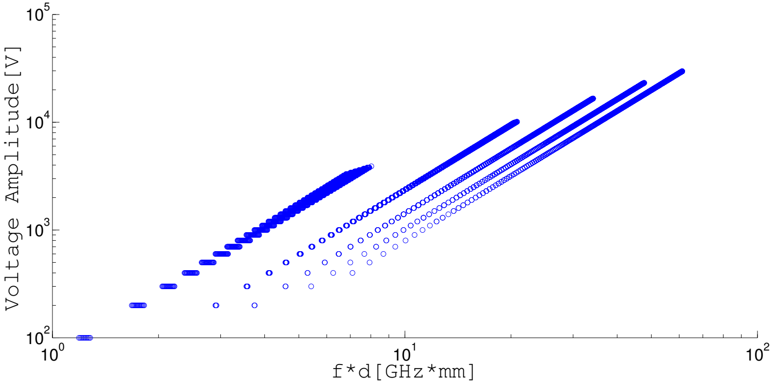
- Multipacting is also a very disturbing phenomenon appearing in high-Q RF cavities in the cyclotron community.
- Electrons are pulled out-off the walls of resonators by the RF field. If these electrons then hitting other metallic surfaces, more new secondary electrons are produced.
- This kind of electron multiplication will limit the power level until the surfaces will be cleaned through a conditioning process.
- Conditioning can be a very time-consuming process.

Outline

Classic Multipacting Theory I

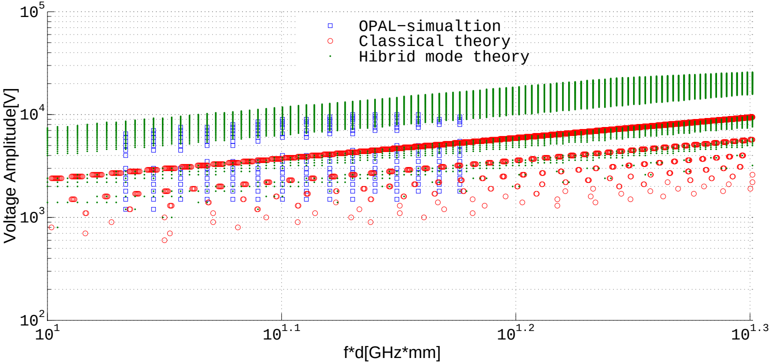
- Simple geometries (parallel plate, rectangular waveguide or coaxial line)
- Deterministic: the emission energy is a constant fraction of the impact energy
- Multipacting is contributed only by the electrons whose transit times through the gap are equal to an odd number of half-periods of the high-frequency field

Classic Multipacting Theory II



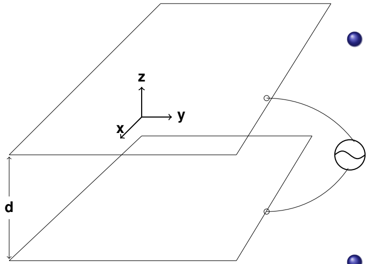
- Example resonant zone in phase space

Classic Multipacting Theory III



- Fail to predict multipacting zone due to missing the single side impact which also plays an important role in multiplication

Non-stationary Multipacting Theory I



- First published in S.Anza's paper.
- Parallel Plate:

$$\frac{d^2 z}{dt^2} = -\frac{e}{m} E_0 \sin \omega t = -\frac{e}{m} \frac{V_0}{d} \sin \omega t \qquad (1)$$

- Random nature of emission energy(velocity): random impact phase, energy ...

S. Anza et al., Phys. Plasmas 17, 062110 2010

Non-stationary Multipacting Theory(2)

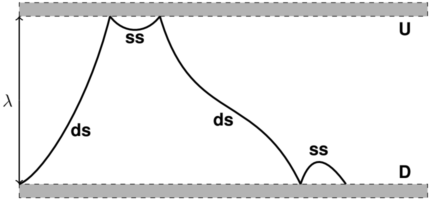
- Integrating equation (1) w.r.t variable t, and using initial conditions $\frac{dz}{dt}|_{t=t_0} = v_0$, $z|_{t=t_0} = 0$, normalized variables: $v_\omega = eV_0/m\omega d$, $\lambda = \omega d/v_\omega$, $u = v_0/v_\omega$, $\omega t_0 = \varphi_0$, $\omega t = \varphi$

$$z = -\frac{d}{\lambda}\sin\omega t + \frac{d}{\lambda}(u + \cos\varphi_0)\omega t + \frac{d}{\lambda}\sin\varphi_0 - \frac{d}{\lambda}(u + \cos\varphi_0)\varphi_0. \quad (2)$$

- if we define $\xi = \omega z/v_\omega$ and $\tau = \varphi - \varphi_0$ in consequence (2) can be rewritten by using this new variable as:

$$\xi(\varphi, \varphi_0, u) = (u + \cos\varphi_0)\tau + \sin\varphi_0 - \sin(\varphi_0 + \tau). \quad (3)$$

Non-stationary Multipacting Theory(3)



- Now double-side(ds) and single-side(ss) impacting exist: $\xi(\varphi, \varphi_0, u) = \lambda$ and $\xi(\varphi, \varphi_0, u) = 0$ in equation (3)
- More (most!) complete description of multipacting in PP

Non-stationary Multipacting Theory(4)

- The initial velocity u of emitted particles is a random variable, the solution of equation (3) w.r.t time τ that particles hit the plates is also a random variable.
- As long as we know the probability density function (PDF) of the initial velocity u, which usually is a thermal distribution, then the PDF of time τ can be derived according to the rule of change of variable in probability theory.

Non-stationary Multipacting Theory(5)

- The electron emission rates and impact rates in each plate can be described by the PDF of τ, at which particles hitting the plates, and the secondary emission yield coefficient w.r.t τ and u.
- The particle number can be obtained by integrating the emission rates and impact rates w.r.t time (details are in the appendix of this talk and also in S. Anza's paper).

Code Review

	Code Name	EM Field Solver	Tracking Algorithm	Emission Effects[&]	Geometry	Scanning Parameters[$]	Multipacting Decision[+]
Helsinki	MultiPac	Included	Runge-Kutta	SE, E_{kin}= user	2D	s, ϕ, α, E_a	CF/ECF/DF
Saclay	MUPAC	Superfish[*]	Runge-Kutta	α=0, SE E_{kin}= user	2D	s, ϕ, E_a	ECF/DF
Genoa	TRAJEC TTWTR AJ	OSCAR2D[*]	Standard Newton	SE, scattering, E_{kin}= user	2D	s, ϕ, α, E_a	Spatial/time focusing
Cornell I	MULTIP	SUPERLAN S (Superfish[*])	Runge-Kutta	SE, FE, E_{kin}= user	2D	s, ϕ, α, E_a	Time focusing
Cornell II	XING	MAFIA, analytic	Leapfrog Runge-Kutta	α=0, SE E_{kin}= 2eV	3D	s, ϕ, E_a	CF/ECF/DF
Albuquerque	TRAK-3D	Included	Runge-Kutta	SE, FE, E_{kin}= user	3D	s, ϕ, α, E_a	Spatial Focusing
Moscow	MULTP	Superfish, MAFIA[*]	Adams-2D Leapfrog-3D	SE, E_{kin}= user	2D, 3D	s, ϕ, α, E_a	Phase Focusing

- F.L.Krawczyk's review paper in the 10th Workshop on RF Superconductivity, 2001, Tsukuba, Japan.
- CST, Vorpal and Track3p.

Outline

Motivation

- Dark current problem in SwissFEL project at PSI
- Mutipactor prediction for the RF cavities of the CYCIAE-100 cyclotron at CIAE

Goal

- Extend the 3D parallel particle tracking code OPAL with complex geometry handling capabilities
- Add dark current and multipacting simulation capabilities in OPAL to handle complex RF structures with arbitrary geometries
- Post processing and visualization

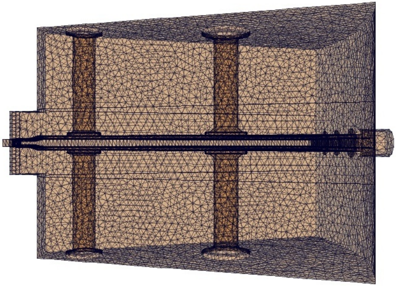
Outline

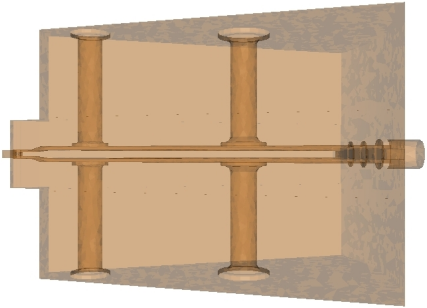
3D Geometry Handling Capability for OPAL

- Read in surface mesh generated by GMSH (step-file) in H5hut format
- Triangle-line segment intersection test and boundary box strategy based collision test
- Handle arbitrary structure as long as it is closed, or more generally speaking: arbitrary structure with pre-defined inward normals

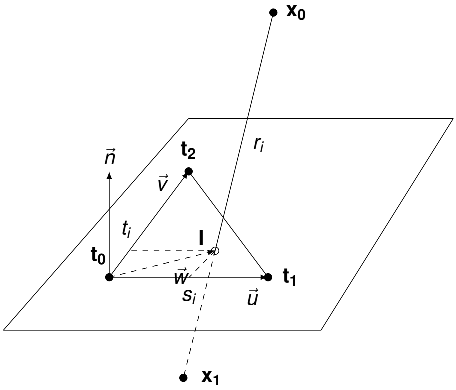
3D Geometry model in OPAL I

- Geometry represented by triangulated surface



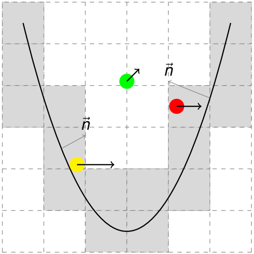


3D Geometry model in OPAL II



- Line segment-Triangle intersection test

3D Geometry model in OPAL III



- Boundary bounding box to speedup the collision tests

Outline

Field Emission Model

- Fowler-Nordheim formula introduced by R. H. Fowler, L. Nordheim: $J(\mathbf{r},t) = \frac{A(\beta E)^2}{\varphi t(y)^2} \exp\left(\frac{-Bv(y)\varphi^{3/2}}{\beta E}\right)$
- Child-Langmuir law: space charge limited current at the surface

$$J(\mathbf{r},t) = \frac{4\varepsilon_0}{9}\sqrt{2\frac{e}{m}}\left(\frac{V^{3/2}}{d^2}\right)$$
$$= \frac{4\varepsilon_0}{9}\sqrt{2\frac{e}{m}}\left(\frac{E^{3/2}}{d^{1/2}}\right)$$

Secondary Emission Model by Furman & Pivi

- Mathematically self-consistent
- Phenomenological- don't involve secondary physics but fit the data
- A number of parameters to fit the measured SEY data
- Built-in SEY data for copper and stainless steel
- Monte Carlo technique has been used
- Detailed description on algorithms can be found in M. A. Furman and M. Pivi's paper.

M. A. Furman and M. Pivi, Phys. Rev. ST Accel. Beams 5, 124404 (2002)

Secondary Emission Model: Vaughan's Formula I

- For material other than copper and stainless steel or material with different SEY curve from the built-in SEY curve in Furman-Pivi's model, Vaughan's model has less parameters than Furman-Pivi's model thus relatively easier to be adjusted to fit the new SEY curve
- Vaughan's formula:

$$\delta(E,\theta) = \delta_{max}(\theta)\cdot(ve^{1-v})^k, \text{ for } v \leq 3.6 \quad (4a)$$

$$\delta(E,\theta) = \delta_{max}(\theta)\cdot 1.125/v^{0.35}, \text{ for } v > 3.6 \quad (4b)$$

where

$$v = \frac{E-E_0}{E_{max}(\theta)-E_0},$$

$$k = 0.56, \text{ for } v < 1,$$

Secondary Emission Model: Vaughan's Formula II

$$k = 0.25, \quad \text{for } 1 < v \leq 3.6,$$

$$\delta_{max}(\theta) = \delta_{max}(0) \cdot (1 + k_\theta \theta^2 / 2\pi),$$

$$E_{max}(\theta) = E_{max}(0) \cdot (1 + k_E \theta^2 / 2\pi).$$

- User adjustable parameters: $E_{max}(0)$, E_0, $\delta_{max}(0)$, δ_0, k_θ and k_E

Outline

Layout of OPAL library

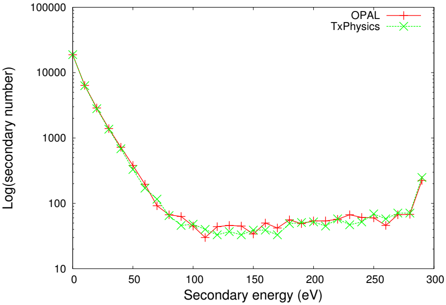
- OPAL is the short for “Object-Oriented Parallel Accelerator Library”.
- Based on the CLASSIC library and the IP^2L framework.
- CLASSIC: building portable accelerator models and algorithms, MAD input language to specify complicated accelerator systems in general.
- IP^2L: providing an integrated, layered system of parallel objects relayed to large scale 3D particle and field calculations.

Dark current and multipacting module in OPAL

- Implemented in one of the flavors of OPAL, the object-oriented parallel ESPIC code OPAL-t.
- Geometry, particle position, momentum and particle type (primary bunch, field emitted electrons or secondaries), are stored in the H5hut file format.
- A re-normalization of simulation particle number approach is used to prevent the exponentially growth of particles in the computational domain.
- Post processing tools are provided in the H5hut library and by the use of Paraview or Visit.

Outline

Benchmark Against the TxPhysics Library

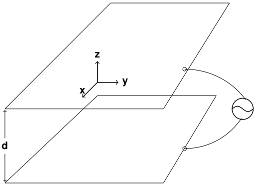


- Validate the implementation of Furman-Pivi's model
- Logarithm of total secondary emission number (backscattered + re-diffused + true secondaries) vs. energy of emitted particles

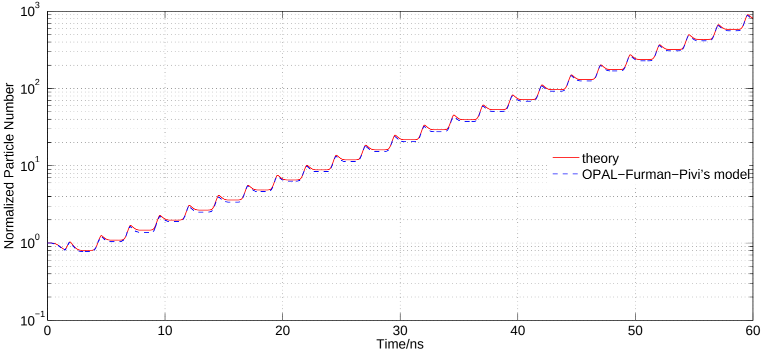
Outline

Why the Non-stationary Theory?

- Only benchmarking the implementation of secondary emission model is not sufficient, the tracking process and the non-trivial geometry handling algorithms need also to be benchmarked
- Simple geometry

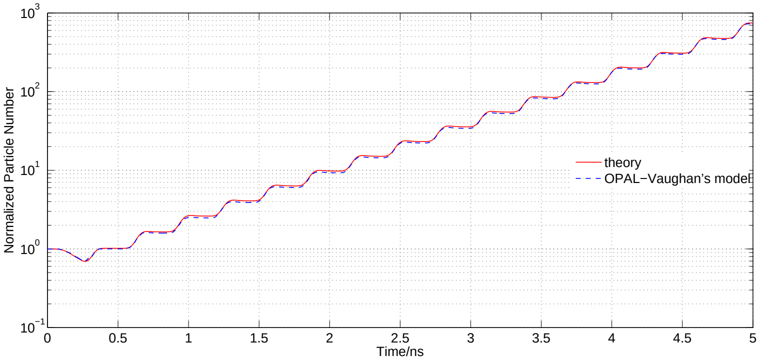


Real Number of Simulation Particles



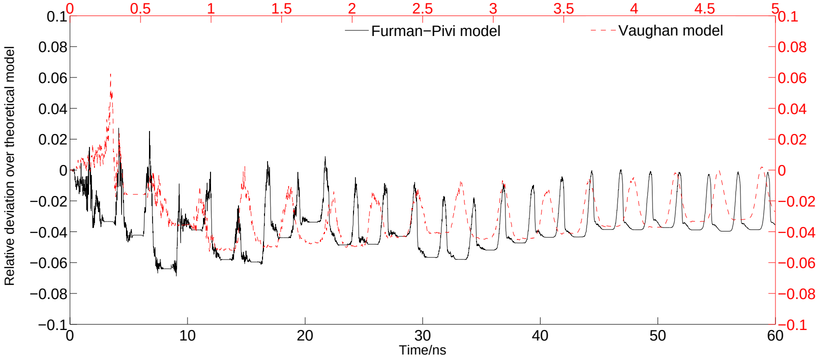
- $f = 200MHz$, $V_0 = 120V$, $d = 5mm$, Furman and Pivi's model and copper's SEY data

Real Number of Simulation Particles



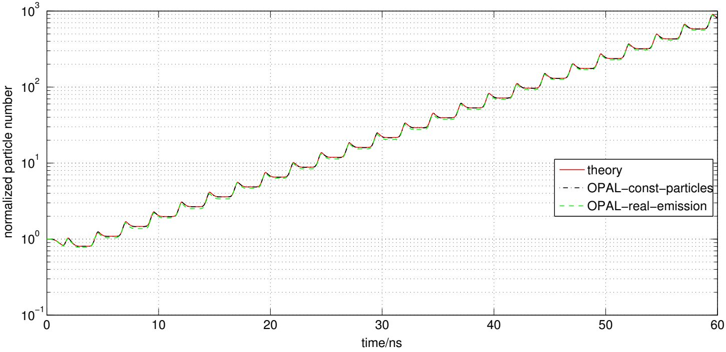
- $f = 1640MHz$, $V_0 = 120\,V$, $d = 1mm$, using Vaughan's model and silver's SEY data

Real Number of Simulation Particles



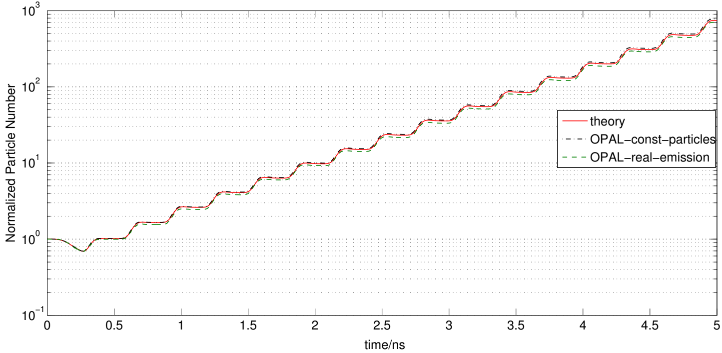
- Relative deviations from the above simulation results w.r.t the theoretical model predictions

Renormalized Simulation Particles I



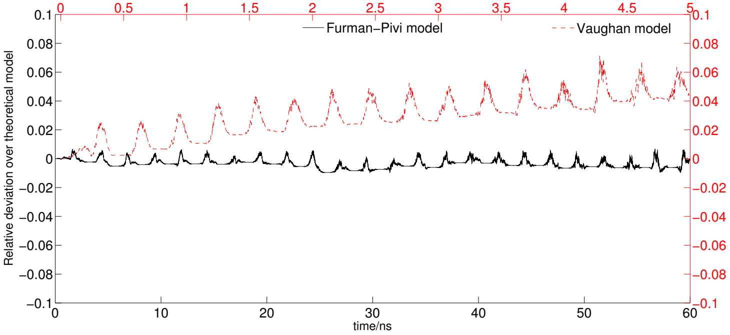
- $f = 200MHz$, $V_0 = 120V$, $d = 5mm$, Furman-Pivi's model, copper and re-normalize to a constant number of simulation particles

Renormalized Simulation Particles II



- $f = 1640 MHz$, $V_0 = 120 V$, $d = 1 mm$, Vaughan's model, silver and re-normalize to a constant number of simulation particles

Renormalized Simulation Particles III



- Relative deviations of simulation results from the theoretical predicted values (re-normalize to const. simulation particle)

Outline

- Why did we do a benchmark experiment after we have already done a perfectly matched code-theory benchmark?

- The ultimate test of a model/code is the comparison with "Nature"!

Experiment configurations I

- The experiment has been done on a 73 MHz, $\lambda/4$ transmission line resonator.

Figure: The RF resonator after installation

Experiment configurations II

- Electron pickup with the vacuum feed-through is mounted through a small hole in the middle of ground plate.

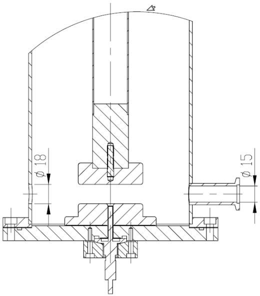


Figure: The configuration of parallel plates and pickup

- Nano-second time resolved measurement circuit.

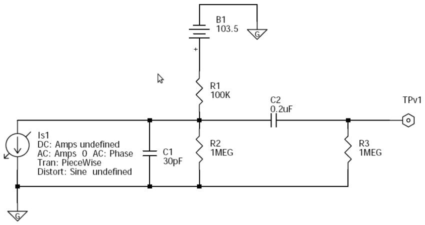


Figure: Sketch of measurement circuit

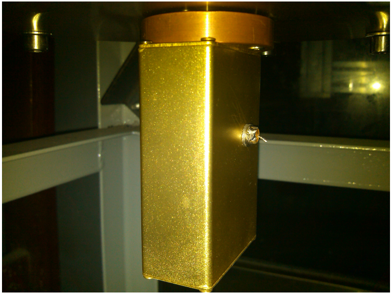


Figure: Real measurement circuit in a sealed metal box

Experiment configurations IV

- The current source of the measurement circuit for SPICE simulation is the electron impact rate which can be predicted either by the none-stationary theory or by OPAL simulation and simulated output can be directly compared with the signal in the oscilloscope.

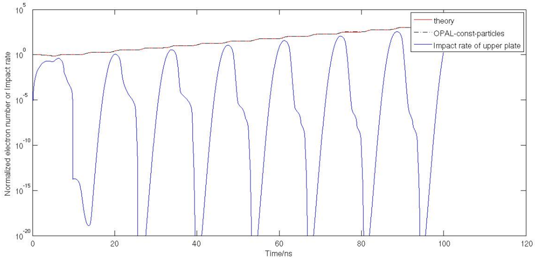


Figure: Simulated impact rate as current source of the measurement circuit

- Signal directly from the oscilloscope.

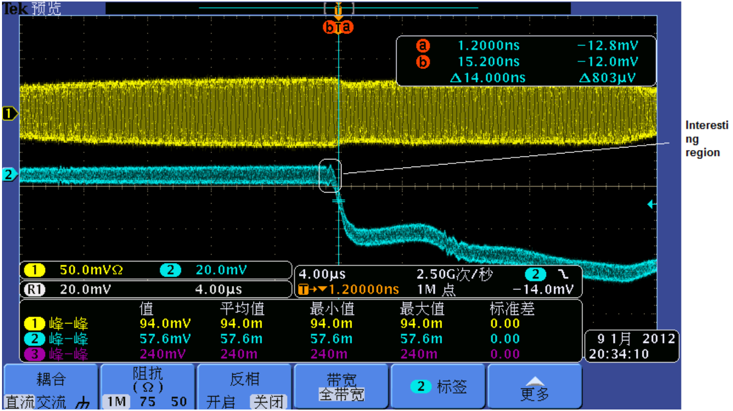


Figure: The measured multipacting signal

Results of the experiment II

- Comparison between simulation and measurement.

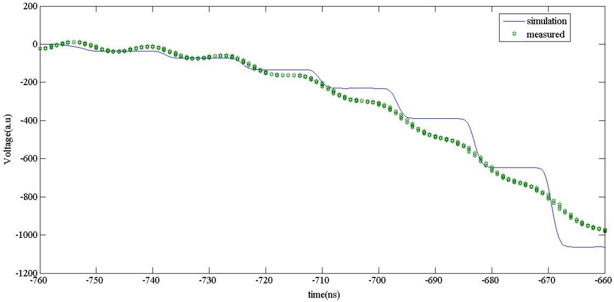


Figure: The comparison between measured multipacting signal after digital filtering and the simulated one

Outline

ANIMATION OF DARK CURRENT SIMULATION

- We add a post processing feature which shows the origin positions and phase of dark current particles which are alive beyond user specified positions
- Animation of CTF3 gun

Outline

Multipacting of CYCIAE-100MeV Cyclotron I

- Preliminary results only on full RF power case, further extension needed to evaluate prone multipacting conditions on different power level

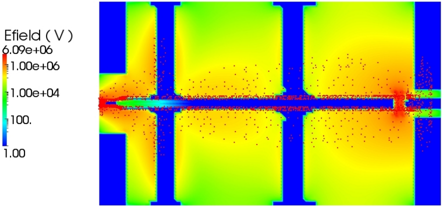


Figure: The electric field in the cavity and initial distribution of electrons (projection view at the symmetric plane of the cavity along the radius)

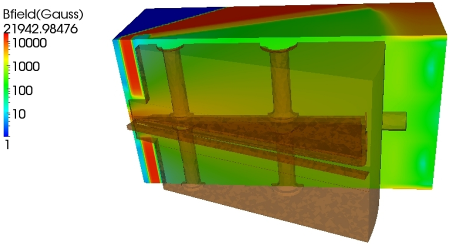
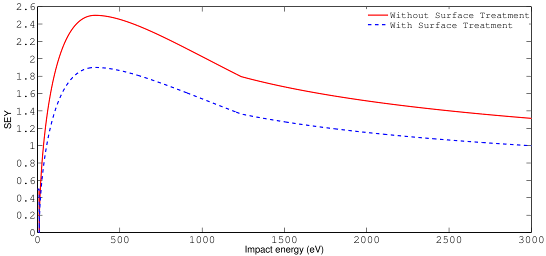


Figure: The RF cavity of CYCIAE-100 cyclotron under the magnetic stray field

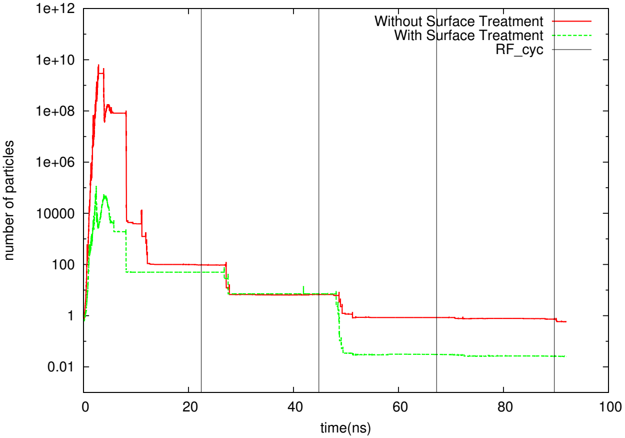
Multipacting of CYCIAE-100MeV Cyclotron II

- According to experiments done by LHC project in CERN, the secondary emission curve for copper varies for different surface treatments:



- Multiplication within 1 RF cycle has been observed:

Multipacting of CYCIAE-100MeV Cyclotron III



- Hot spot: Animation of hot spot where particle hit the surface
- Dumped for each 100 time steps (0.4ns)

Conclusions

- We have successfully modeled, implemented and benchmarked dark current and multipacting modeling capabilities in OPAL
- Thanks to the parallel nature of OPAL, large scale structures can be analyzed
- A full set of pre- and post-processing tools are available in order to enable complex studies **[arXiv:1205.3098v2]**

Future Plan

- Further multipacting study on different RF power level is useful to predict and understand the behavior of the cavities of CYCIAE-100
- Obtain hot spots in different RF power level by simulations to determine the position where a special surface treatment is needed to suppress multipacting
- Add GUI to pre-define different surface materials on a geometry, in order to make multiple surface material simulation possible.

ACKNOWLEDGMENTS

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Appendix: Formulas for Non-Stationary Theory I

- The solution of (3) when electron hit the plates, i.e., when $\xi(\varphi, \varphi_0, u) = \lambda$ or 0, is a probabilistic number, as the emission velocity u is a random number
- The probability density of the least root(on variable τ) of equation (3) can be expressed by the known distribution $f_u = \frac{uv_\omega^2}{v_t^2} \exp\left(-\frac{u^2 v_\omega^2}{2v_t^2}\right)$ of velocity u:

$$G(\tau|\varphi_0;\lambda) = \left|\frac{\mathrm{d}g(\tau|\varphi_0;\lambda)}{\mathrm{d}\tau}\right| f_u[g(\tau|\varphi_0;\lambda)]$$

$$G(\tau|\varphi_0;0) = \left|\frac{\mathrm{d}g(\tau|\varphi_0;0)}{\mathrm{d}\tau}\right| f_u[g(\tau|\varphi_0;0)]$$

where, $u = g(\tau|\varphi_0;\lambda)$ and $u = g(\tau|\varphi_0;0)$ respectively (monotonic function)

Appendix: Formulas for Non-Stationary Theory II

- Emission rate (electrons/radian) in plate U/D at phase φ:

$$C_U(\varphi) = \int_0^{\varphi} C_D(\varphi')G_{ds,D}(\varphi - \varphi'|\varphi')\delta_{ds,D}(\varphi - \varphi'|\varphi')\mathrm{d}\varphi' + \int_0^{\varphi} C_U(\varphi')G_{ss,U}(\varphi - \varphi'|\varphi')\delta_{ss,U}(\varphi - \varphi'|\varphi')\mathrm{d}\varphi' + \Psi_U(\varphi)$$

$$C_D(\varphi) = \int_0^{\varphi} C_D(\varphi')G_{ss,D}(\varphi - \varphi'|\varphi')\delta_{ss,D}(\varphi - \varphi'|\varphi')\mathrm{d}\varphi' + \int_0^{\varphi} C_U(\varphi')G_{ds,U}(\varphi - \varphi'|\varphi')\delta_{ds,U}(\varphi - \varphi'|\varphi')\mathrm{d}\varphi' + \Psi_D(\varphi)$$

- Volterra integral equations of the second

Appendix: Formulas for Non-Stationary Theory III

- Impact rate (electrons/radian) in plate U/D at phase φ:

$$
\begin{aligned}
I_U(\varphi) = & \int_0^{\varphi} C_D(\varphi') G_{ds,D}(\varphi - \varphi' | \varphi') \mathrm{d}\varphi' \\
& + \int_0^{\varphi} C_U(\varphi') G_{ss,U}(\varphi - \varphi' | \varphi') \mathrm{d}\varphi'
\end{aligned}
$$

$$
\begin{aligned}
I_D(\varphi) = & \int_0^{\varphi} C_D(\varphi') G_{ss,D}(\varphi - \varphi' | \varphi') \mathrm{d}\varphi' \\
& + \int_0^{\varphi} C_U(\varphi') G_{ds,U}(\varphi - \varphi' | \varphi') \mathrm{d}\varphi'
\end{aligned}
$$

- Number of particles:

$$
N(\varphi) = \int_0^{\varphi} \left(C_U(\varphi') + C_D(\varphi') - I_U(\varphi') - I_D(\varphi') \right) \mathrm{d}\varphi'
$$