A Study of Multipacting Effects in Large Cyclotron Cavities

by Means of Fully 3-Dimensional Simulations

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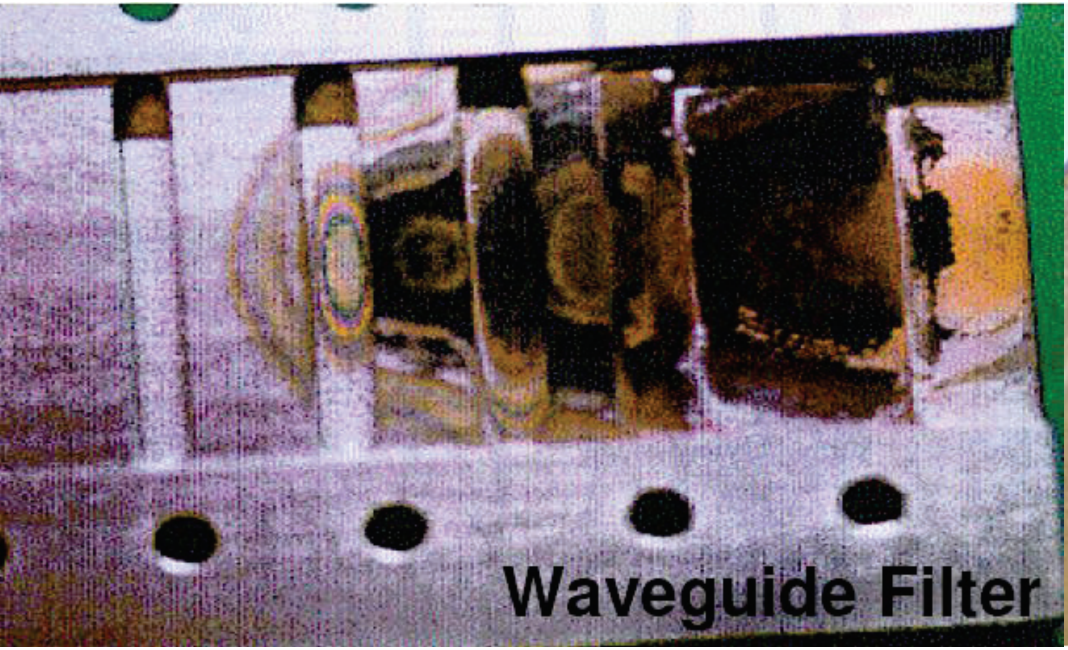
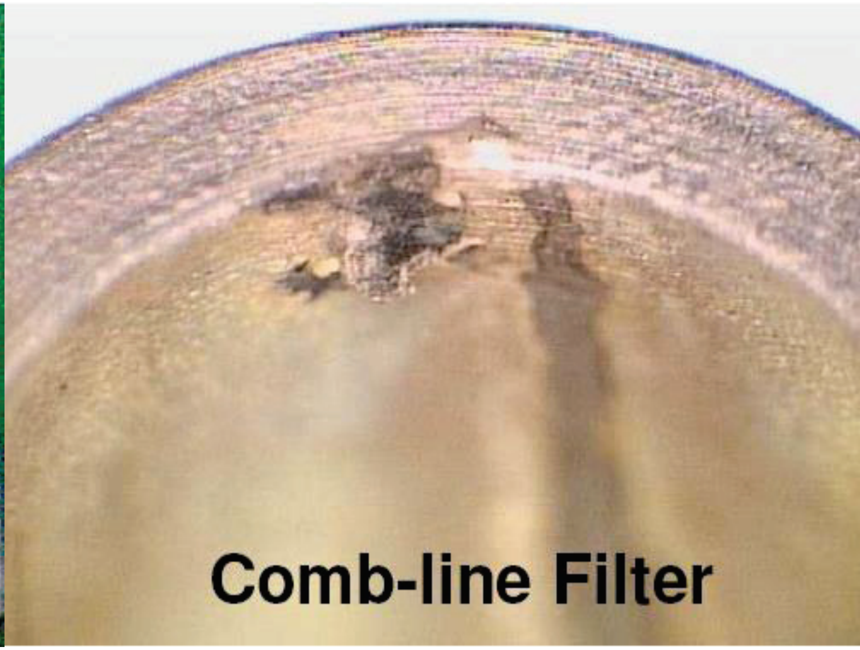
Outline:

- ❑ Background of Multipacting Phenomena
- ❑ Implementations and Benchmark of Models in OPAL
- ❑ RF Conditioning Tests and Observations in CIAE Cyclotrons
- ❑ Multipacting simulation of the CYCIAE-100 cavities
- ❑ Conclusions

Multipacting in Various RF Structures

- The multipactor were discovered by Gutons in 1924 and in 1934 Philo T.Farnsworth confirmed it with experiments.

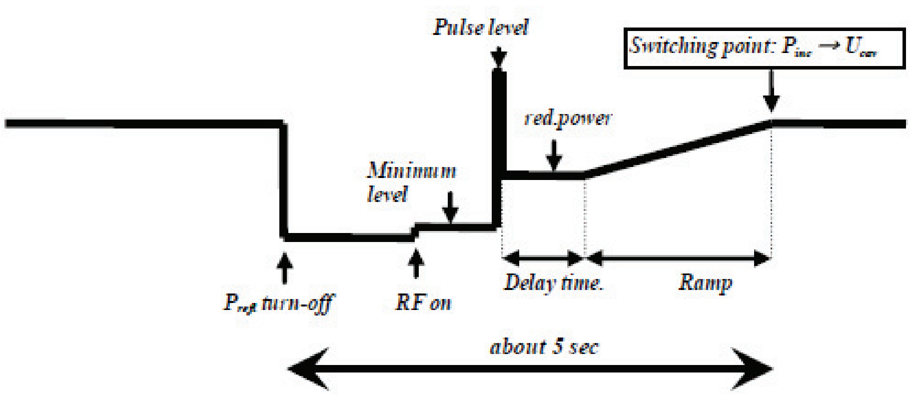




- Multipacting observed in RF/microwave components in aerospace community

- Risk : difficult to remote conditioning on satellites

- In cyclotrons, coupled with strong magnetic stray field, multipacting will limit the power level until the surfaces will be cleaned through a conditioning process.
- Very time-consuming !



Proposed by J. Cherix and P. Sigg @ PSI - Scientific and Technical Report 2004 / Volume VI

Other conditioning process like: CIAE (Lei et al., TUPPT026, this conference)

Multipacting Codes

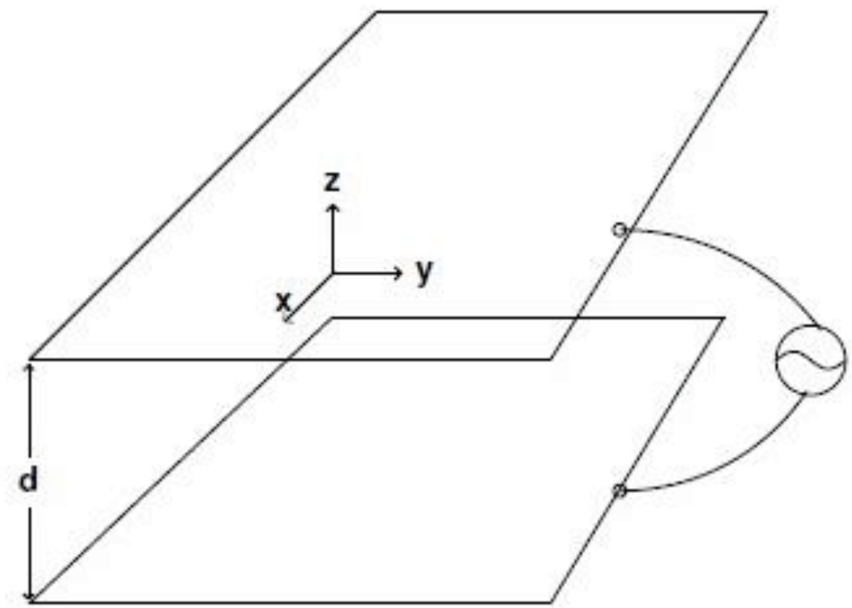
	Code Name	EM Field Solver	Tracking Algorithm	Emission Effects[&]	Geometry	Scanning Parameters[$]	Multipacting Decision[+]
Helsinki	MultiPac	Included	Runge-Kutta	SE, E_{kin}= user	2D	s, ϕ, α, E_a	CF/ECF/DF
Saclay	MUPAC	Superfish*	Runge-Kutta	α=0, SE E_{kin}= user	2D	s, ϕ, E_a	ECF/DF
Genoa	TRAJEC TTWTR AJ	OSCAR2D*	Standard Newton	SE, scattering, E_{kin}= user	2D	s, ϕ, α, E_a	Spatial/time focusing
Cornell I	MULTIP	SUPERLANS (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 et al. Most codes calculate electron trajectories and CF, ECF, DF.

- Track 3p from SLAC; Vorpal, CST

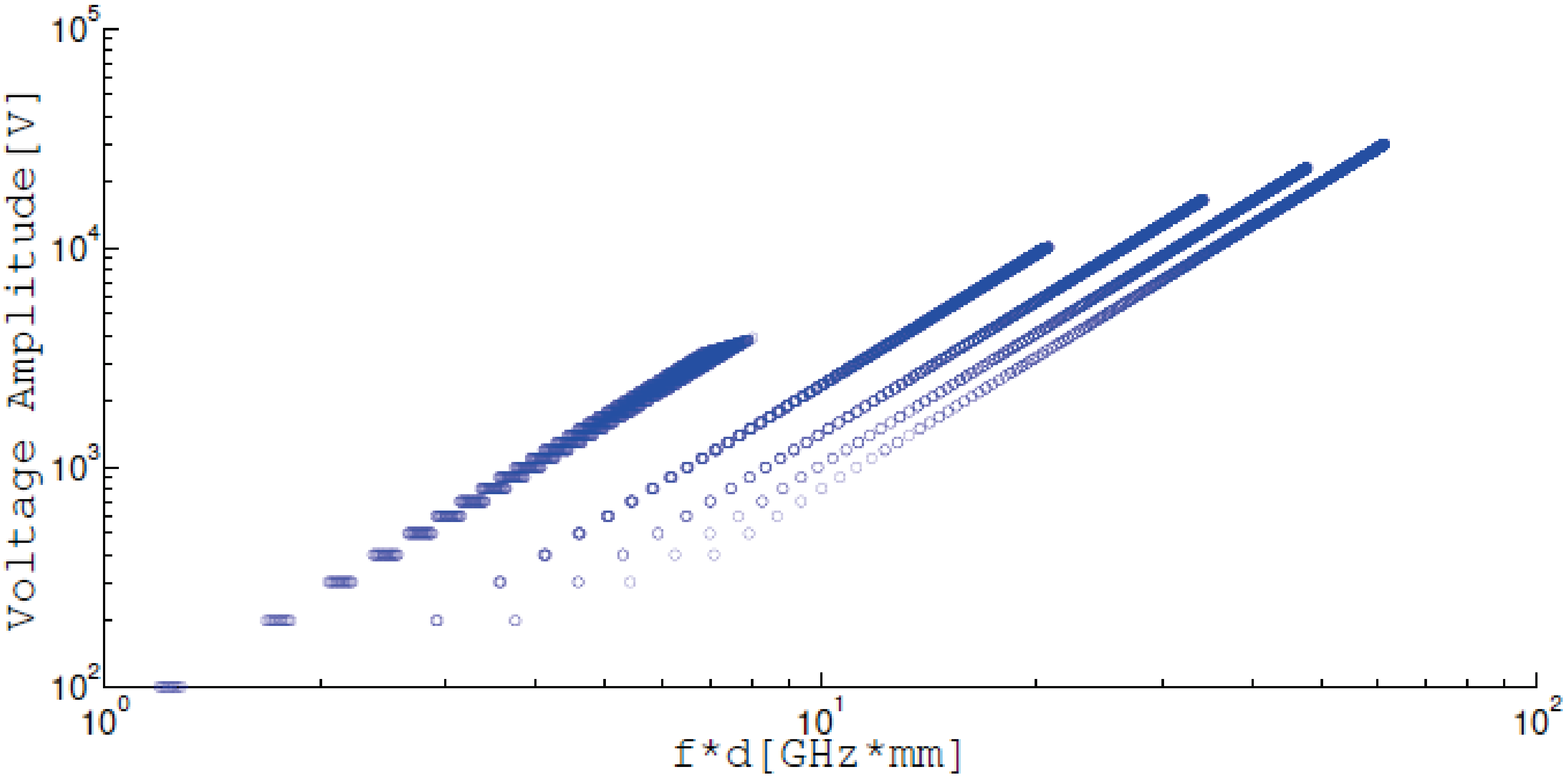
Multipacting Theory

- Simple geometries
- Deterministic

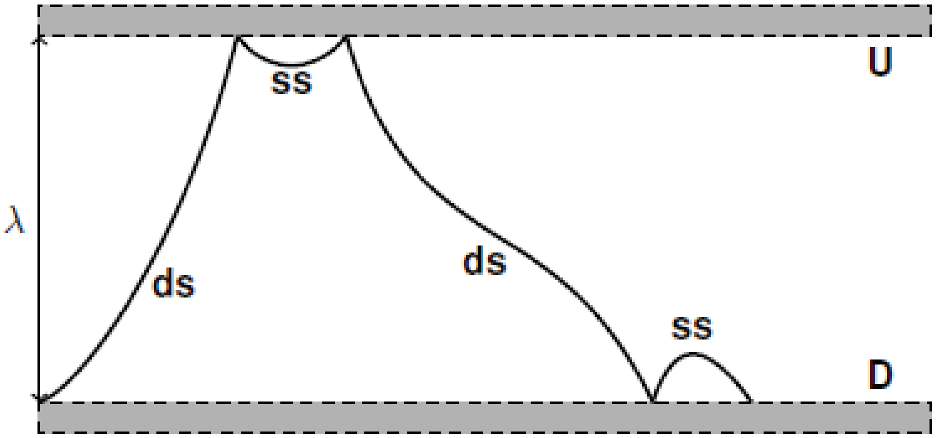


- Transit times equal to an odd number of half-periods of the high-frequency field (classical theory)

Multipacting Theory



- Non-stationary Multipacting Theory (S.Anza et al.)
  - Random nature of emission energy (velocity): random impact phase, energy . . .
  - double-side (ds) and single-side (ss)
  - Time evolution of particle numbers



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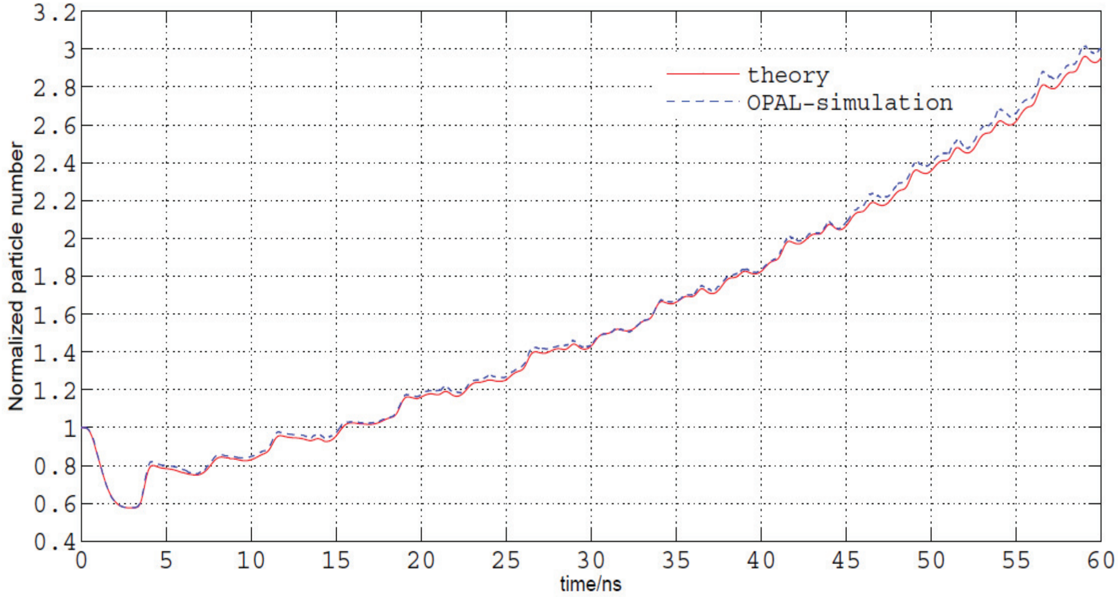

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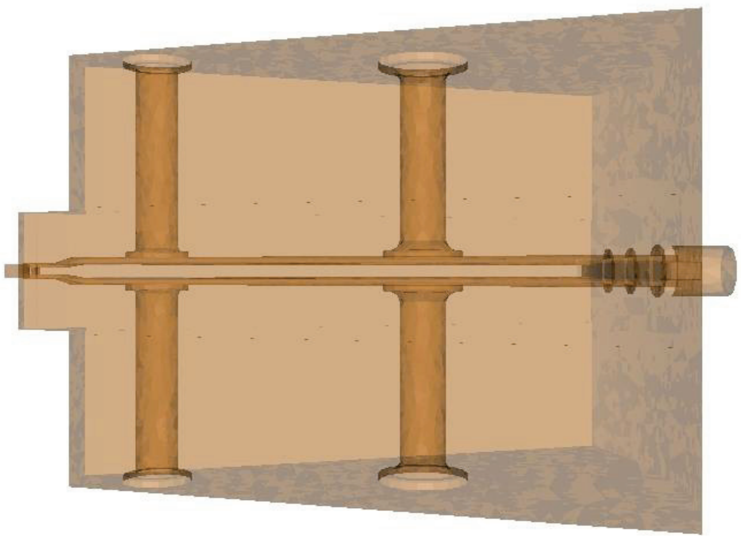
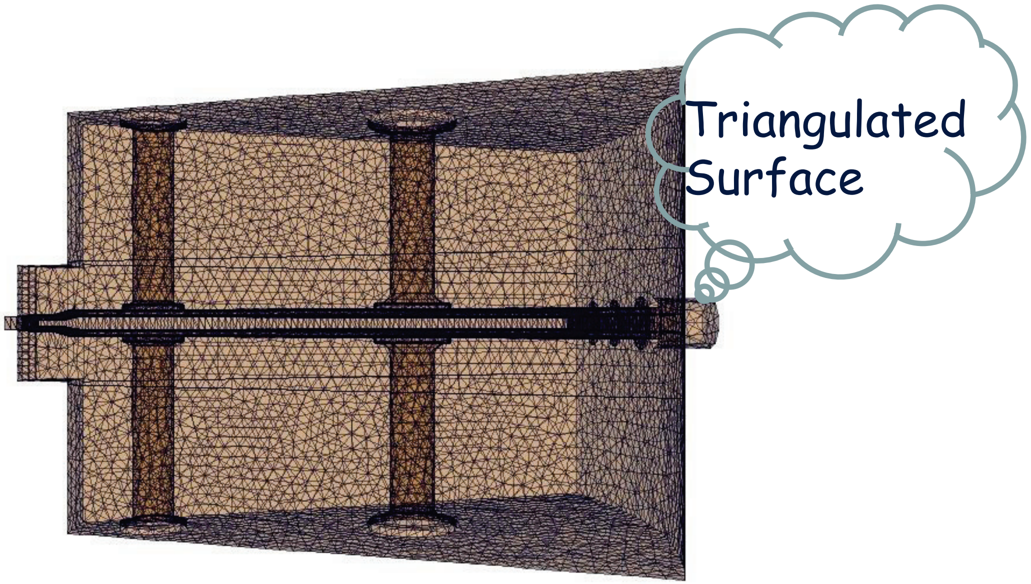
Geometry Handling

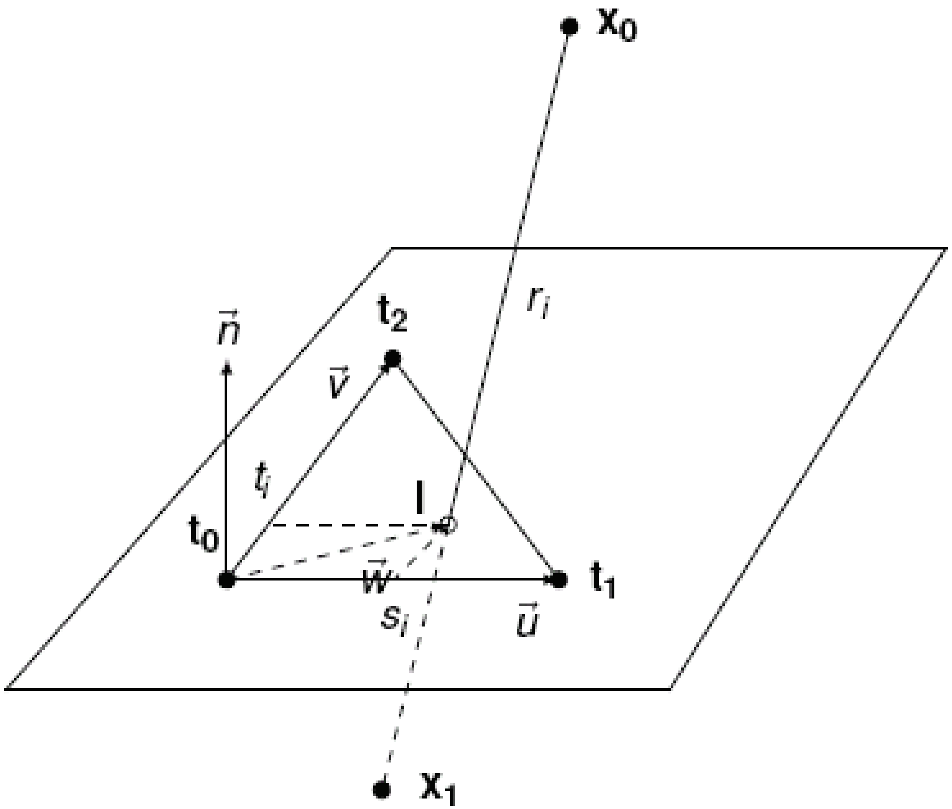
- OPAL:

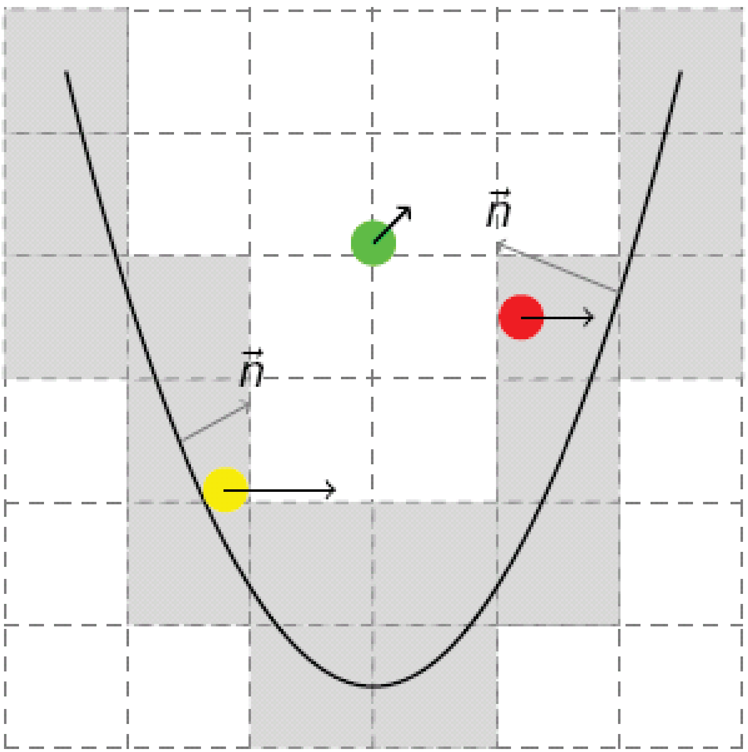
CAD model → GMSH triangulation → H5Hut format





Collision Test





Field Emission

- Fowler-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:

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

Secondary Emission

- Furman & Pivi Model

- Vaughan Model

$$
\begin{aligned}
\delta(E,\theta) &= \delta_{max}(\theta)\cdot(ve^{1-v})^k, \text{ for } v \le 3.6 \\
\delta(E,\theta) &= \delta_{max}(\theta)\cdot 1.125/v^{0.35}, \text{ for } v > 3.6
\end{aligned}
$$

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

$$
k = 0.56, \quad \text{for } v < 1, \quad k = 0.25, \quad \text{for } 1 < v \le 3.6,
$$

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

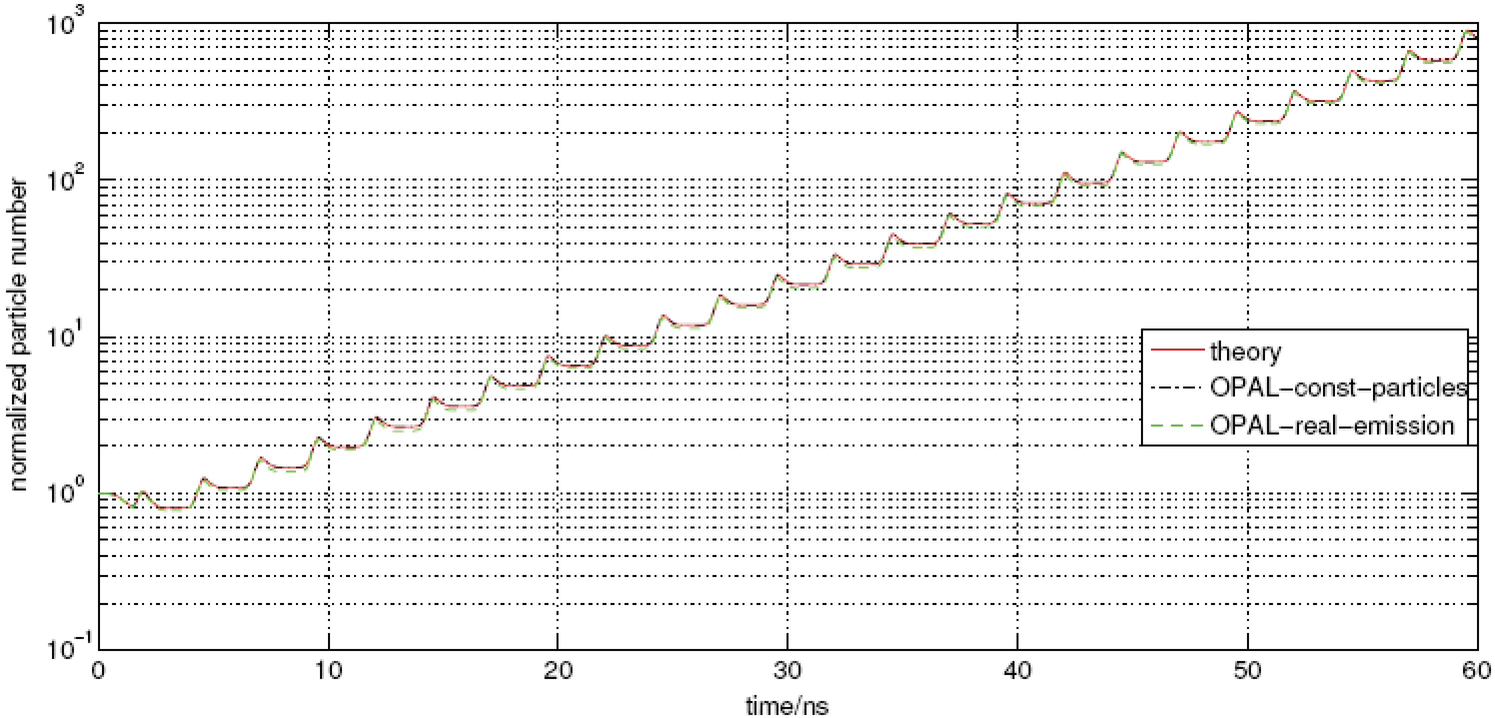
$$
E_{max}(\theta) = E_{max}(0)\cdot(1 + k_E \theta^2/2\pi).
$$

OPAL code

OPAL is a tool for charged-particle optics in large accelerator structures and beam lines including 3D space charge and particle matter interaction

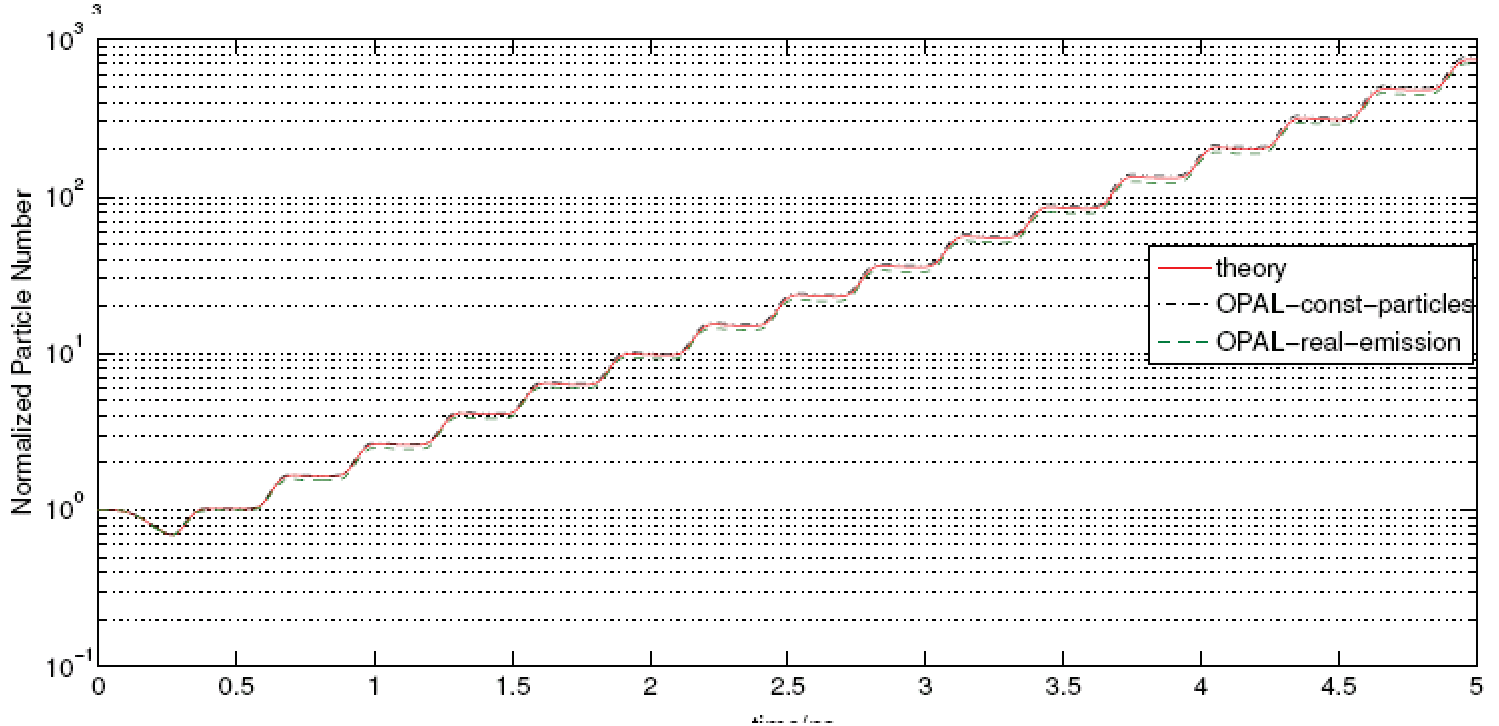
- OPAL is built from the ground up as a parallel application exemplifying the fact that HPC (High Performance Computing) is the third leg of science, complementing theory and the experiment
- OPAL runs on your laptop as well as on the largest HPC clusters
- OPAL uses the mad language with extensions
- OPAL (and all other used frameworks) are written in C++ using OO-techniques, hence OPAL is very easy to extend.
- Open-Source, with ~ 10 developers around the world

Benchmark: Against none stationary theory



$f = 200\,MHz$, $V_0 = 120\,V$, $d = 5mm$, Furman-Pivi's model, copper and re-normalize to const simulation particle

Benchmark: Against none stationary theory



$f = 1640\,MHz$, $V_0 = 120\,V$, $d = 1\,mm$, Vaughan's model, silver and re-normalize to const simulation particle

Benchmark: nanosecond time resolved experiment

- 73MHz、 λ/4 coaxial resonator

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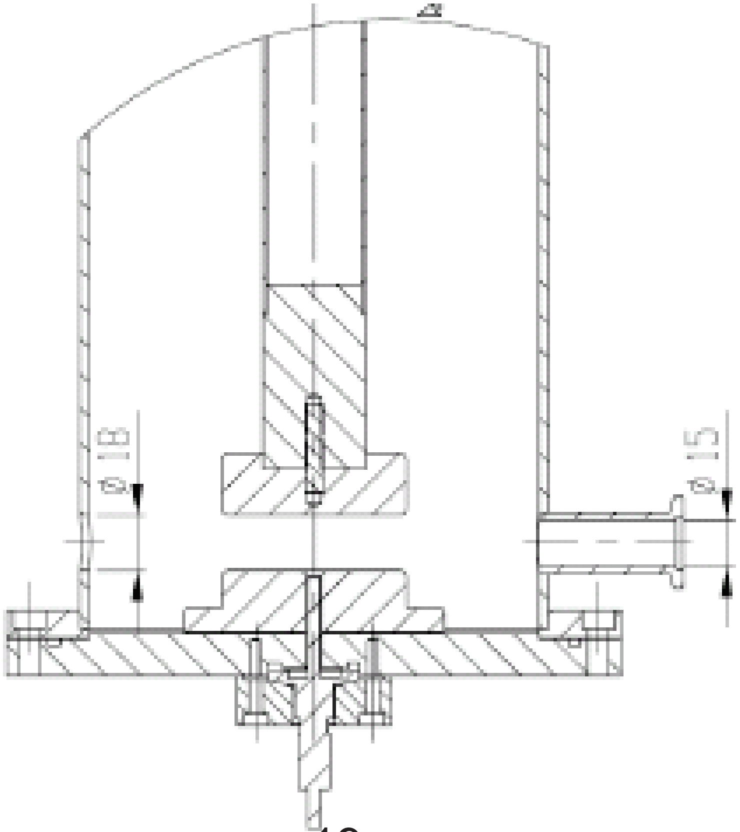
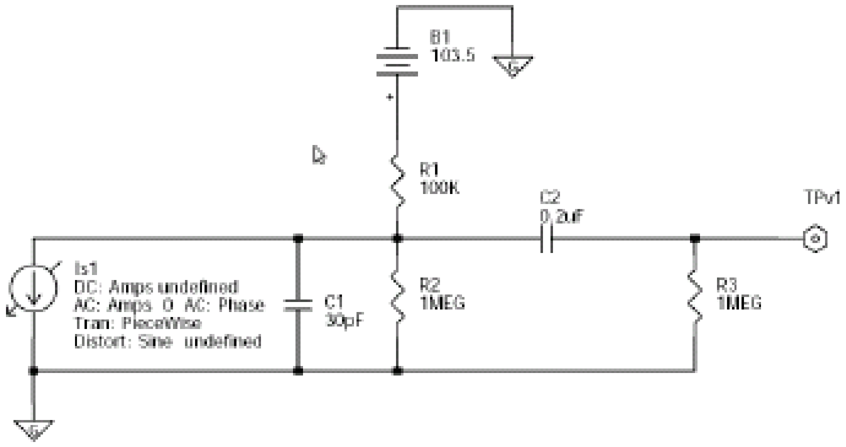
- 73MHz、 λ/4 coaxial resonator

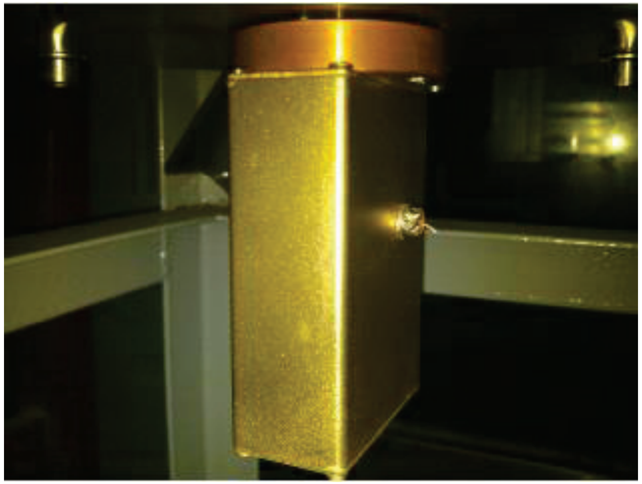
- A probe to collect the impact current



Benchmark: nanosecond time resolved experiment

- 73MHz、 λ/4 coaxial resonator
- A probe to collect the impact current
- Shielded measurement circuit

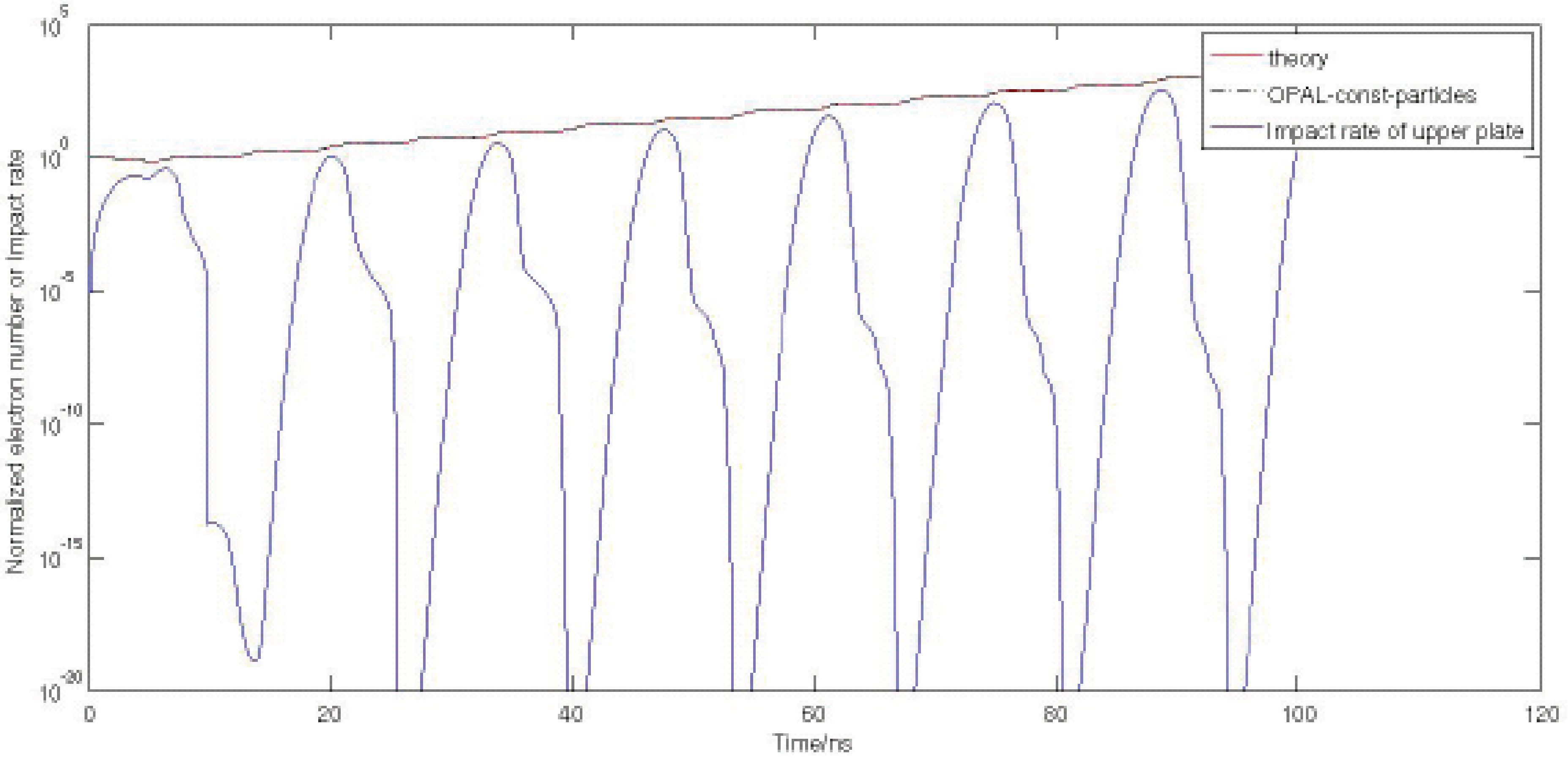




Benchmark: nanosecond time resolved experiment

- 73MHz、 λ/4 coaxial resonator
- A probe to collect the impact current
- Shielded measurement circuit
- Impact rate as current source

Benchmark: nanosecond time resolved experiment



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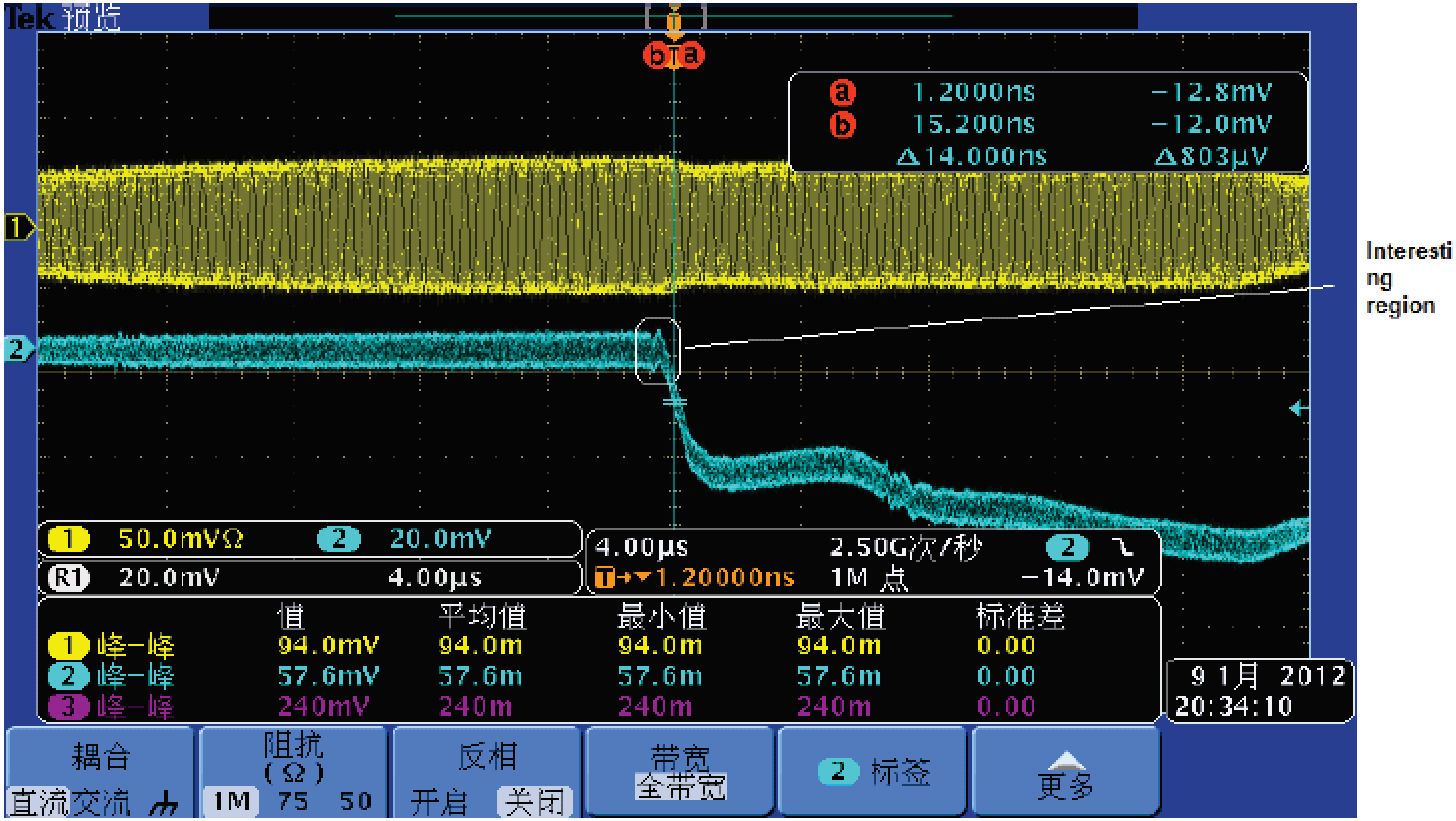

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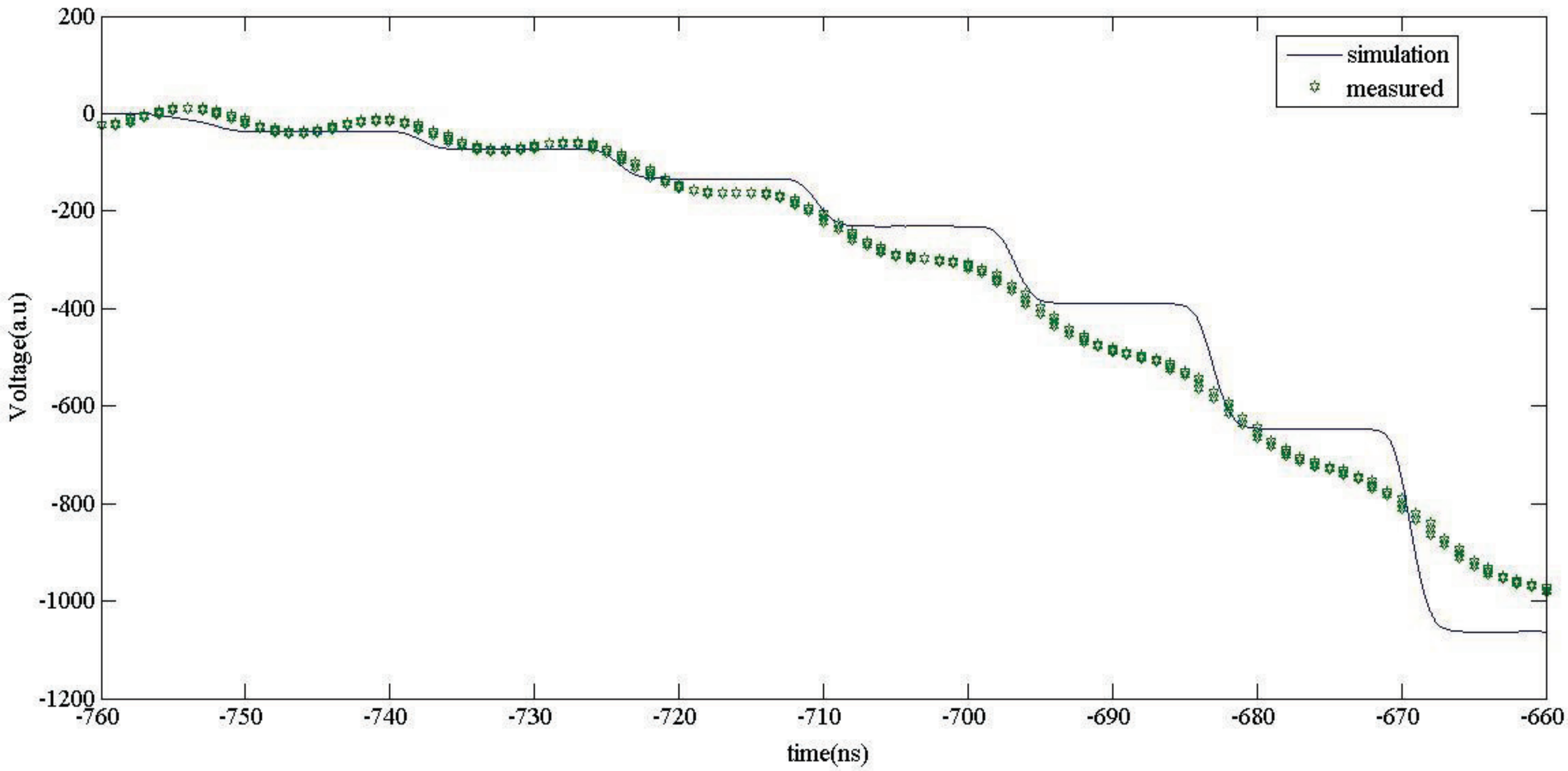

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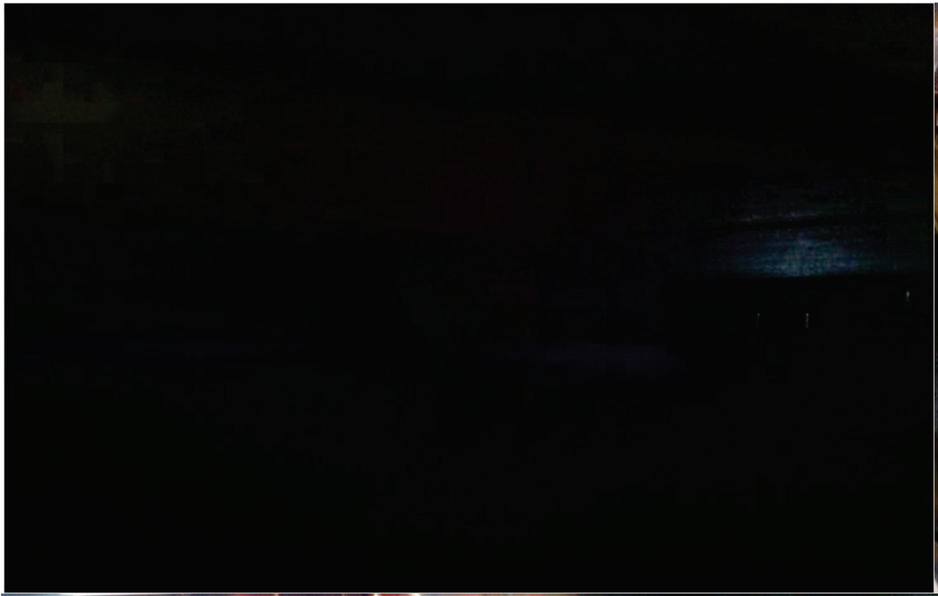
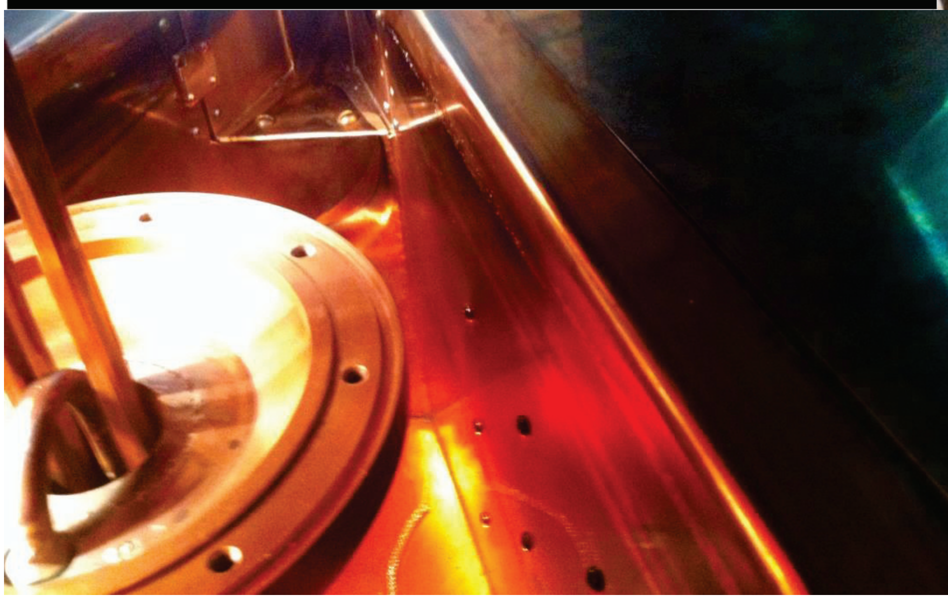
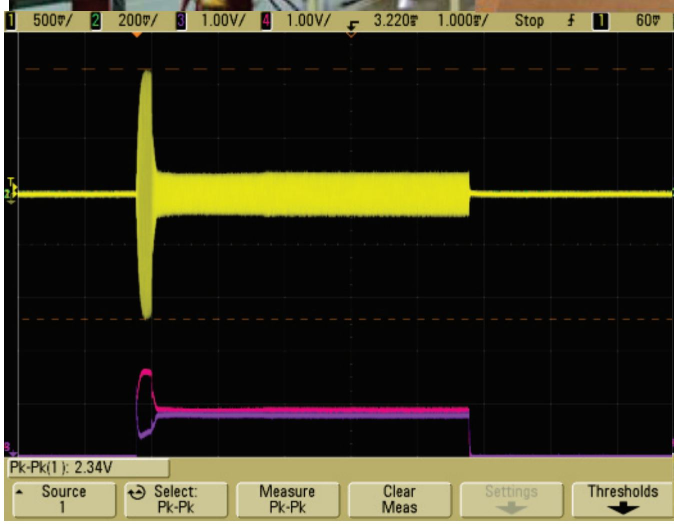
RF Conditioning of CYCIAE-14





RF Conditioning of CYCIAE-100 Test Cavity



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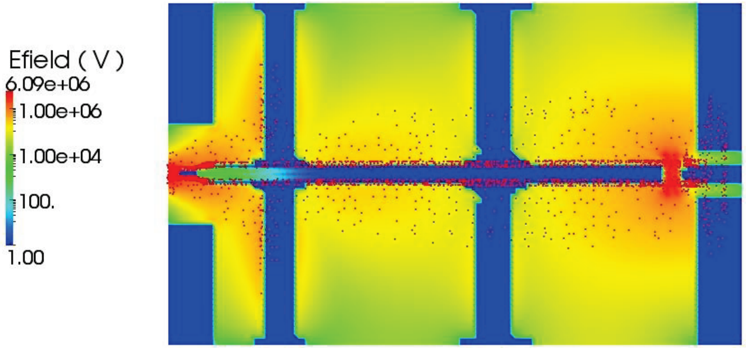
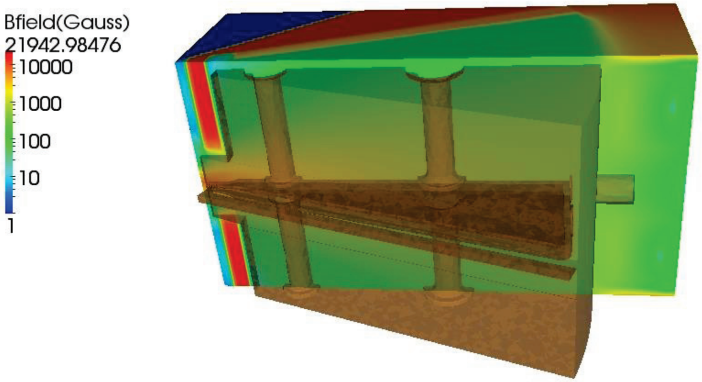
Large Scale Multipacting Simulation

- Magnetic stray field in the cyclotron valley is included





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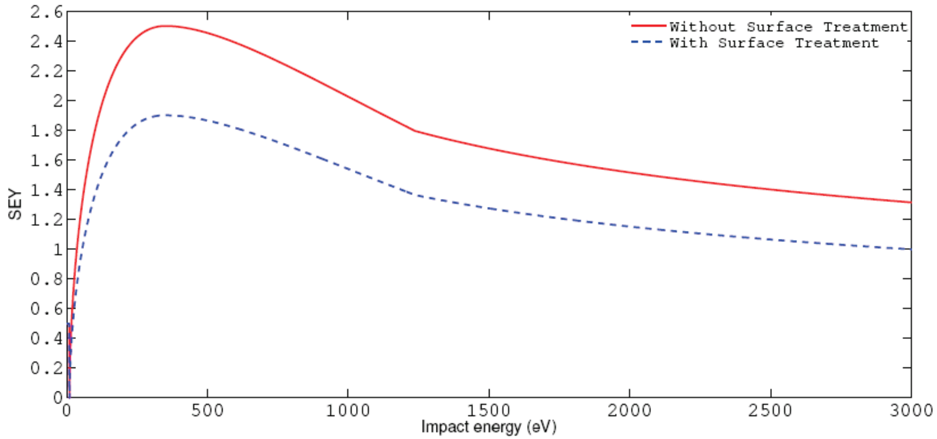
- Magnetic stray field in the cyclotron valley is included
- Effect of SEY Curves on the multipacting behavior



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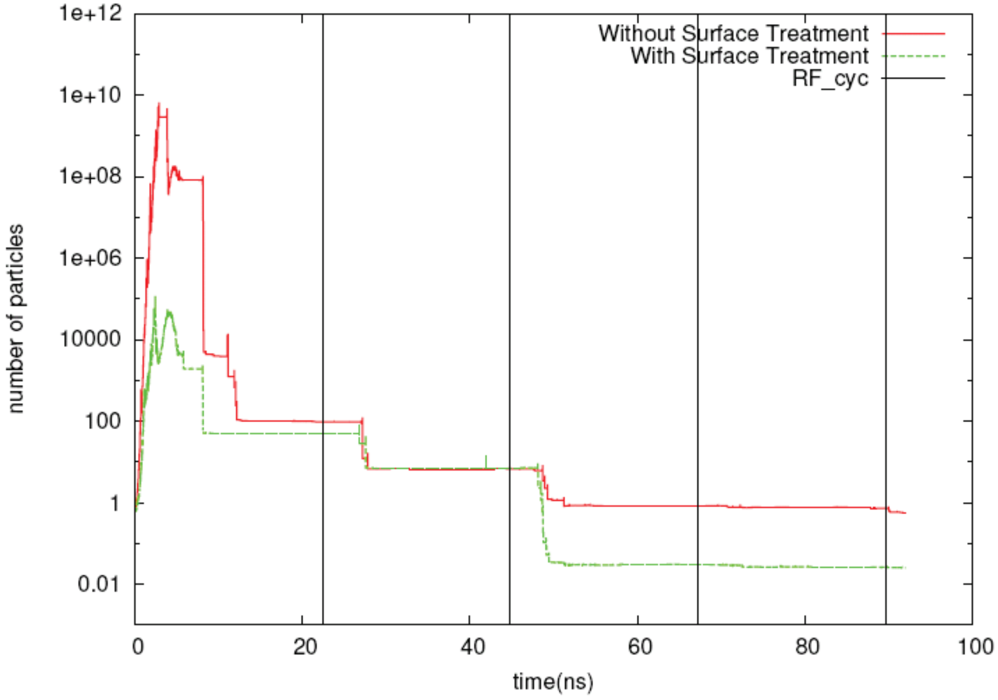
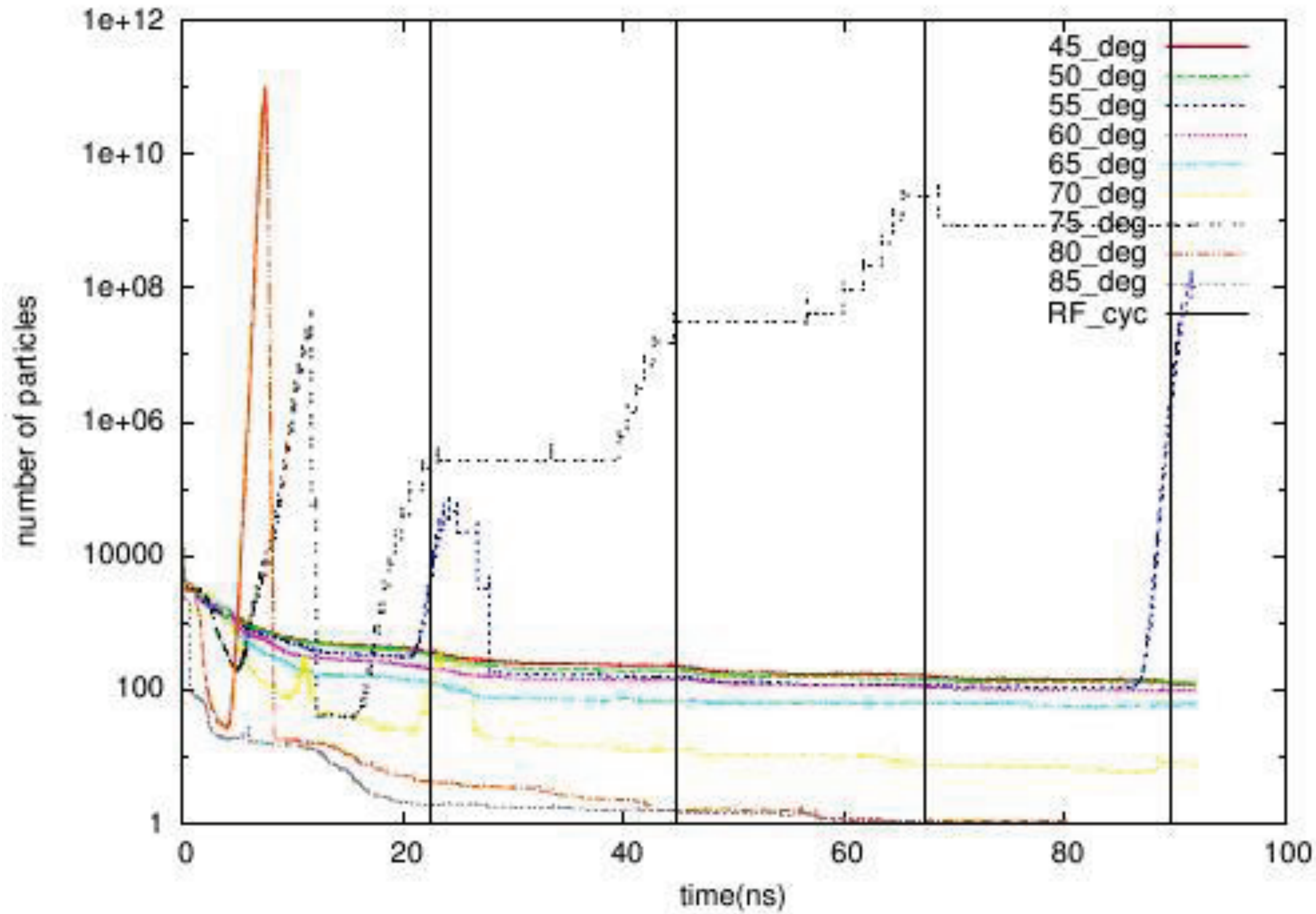


Large Scale Multipacting Simulation

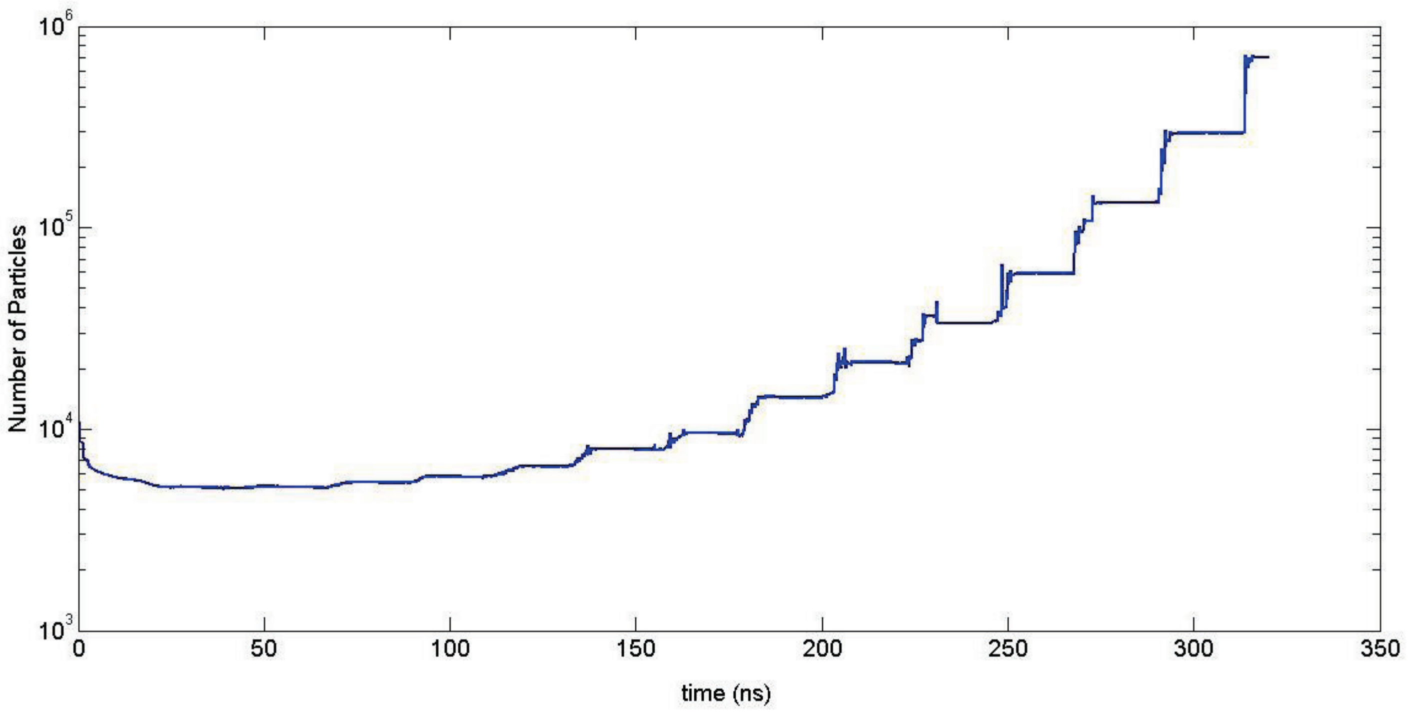
- Phase dependence at full RF power



Large Scale Multipacting Simulation

- Phase dependence at full RF power

- Multipacting in lower power



Large Scale Multipacting Simulation

- ❑ Phase dependence at full RF power

- ❑ Multipacting in lower power

- ❑ Animation

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Conclusions

1. We developed multipacting simulation capabilities for OPAL, including full 3D magnetic and electric fields.

2. The model is carefully benchmarked against the non-stationary multipacting theory and our dedicated nanosecond time resolved multipacting experiment

3. The aim of the multipacting studies in the CYCIAE-100 cyclotron is to shorten the time consuming RF conditioning process by utilizing a localized coating.

Thank you