Warp-PyECLOUD simulations for 3D RF structures

L. Giacomel, G. Iadarola, J.-L. Vay

September 26, 2022

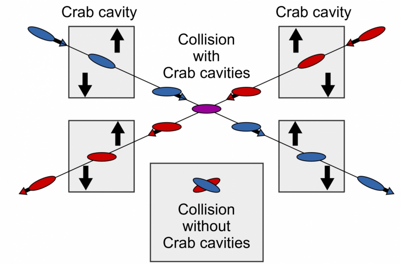
Many thanks to: R. Calaga, M. Carlà, M. Furman, E. Mètral, K. Paraschou, G. Penn, G. Rumolo, B. Salvant, L. Sabato, C. Zannini

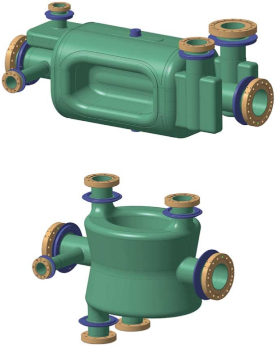
And to the WarpX development team, in particular: D. Grote, A. Huebl, R. Lehe, A. Myers, W. Zhang, E. Zoni

Outline

The Crab Cavities

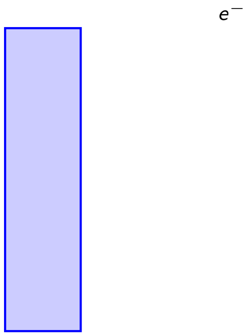
The Crab Cavities are new RF cavities which will be installed in the LHC with the High-Luminosity upgrade





Principle: tilt the bunches to maximize their overlap.

Multipacting in the Crab Cavities



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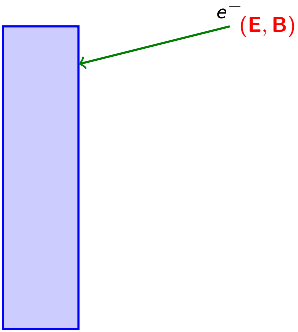

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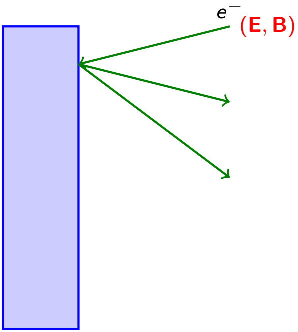

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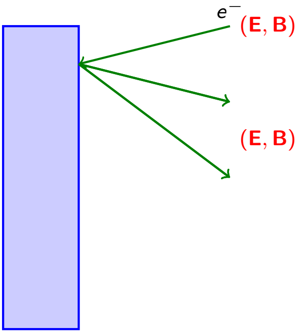

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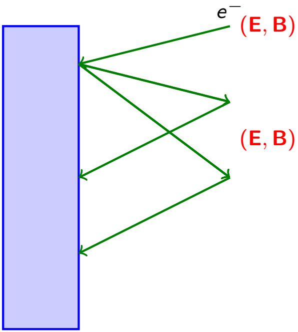

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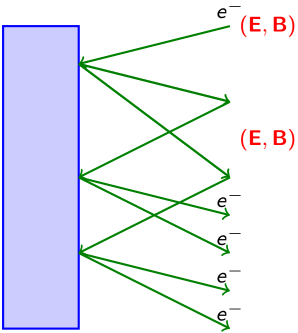

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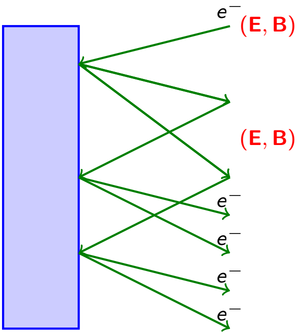
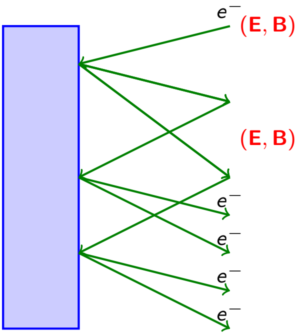


Multipacting in the Crab Cavities



Electrons can be pushed by:

- A beam $\longrightarrow$ beam-induced multipacting
- An RF field $\longrightarrow$ RF-induced multipacting

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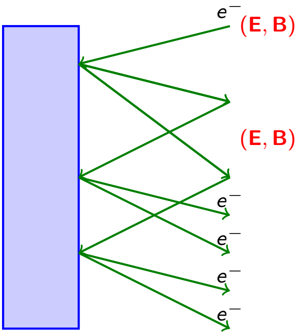

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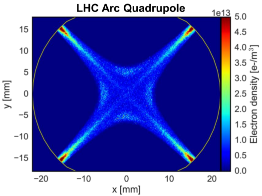
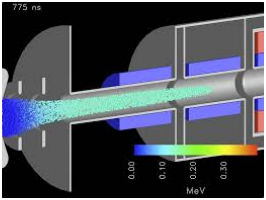
In the CCs there are three contributions to the electromagnetic field:

- RF mode
- beam-induced field
- self-fields of the ECloud

Can the interplay between the three contributions enhance multipacting?

PyECLOUD and Warp





PyECLOUD	Warp

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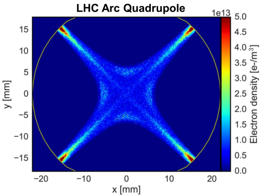

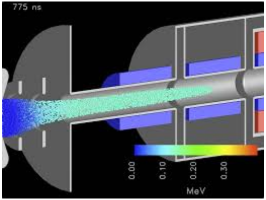

PyECLOUD

- 2D PIC code

Warp

- 3D PIC code

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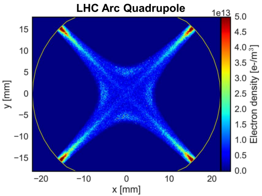

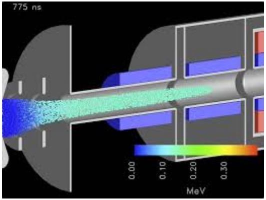

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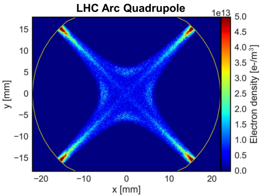

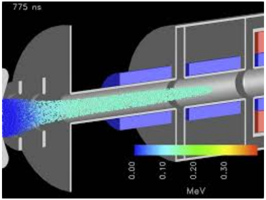

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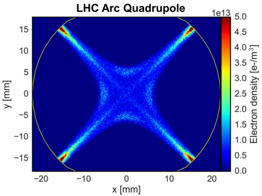

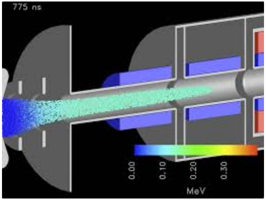

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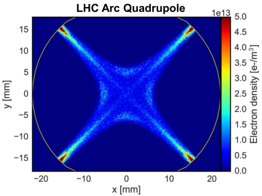
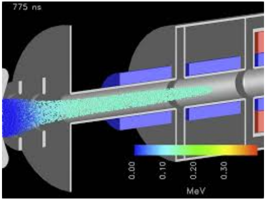
PyECLOUD and Warp





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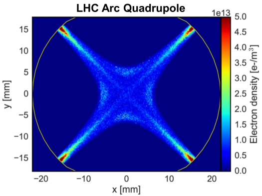

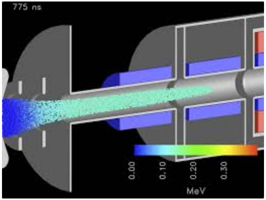

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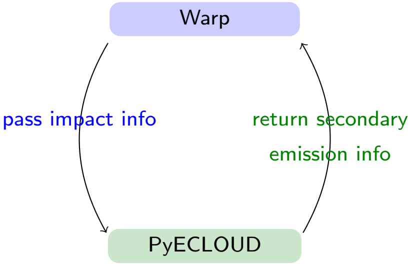
We decided couple Warp and PyECLOUD to take advantage of the nice features both codes.

Warp-PyECLOUD

We interfaced the two codes to use the PIC from Warp and the secondary emission models from PyECLOUD.



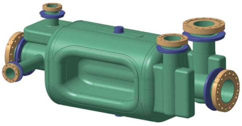
Details can be found in the presentation "Development of WARP simulations for 3D RF structures" given at the Electron Cloud Meeting #73

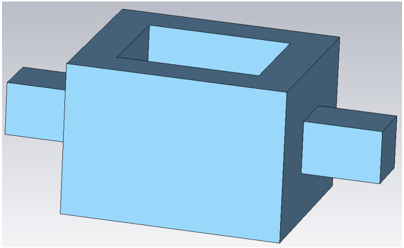
Outline

Simplification of the Crab Cavities

We initially simplified the structure of the Crab Cavities in order to avoid the numerical artifacts given by the staircasing approximations.

This has been useful to simply study the dynamics in the cavities and the properties of the different solvers.





Self-consistent Simulations

The RF field can either be imported from an external software (CST) or it can be computed directly in Warp.

Simulations with externally computed fields have been discussed in "Development of WARP simulations for 3D RF structures", Electron Cloud Meeting #73

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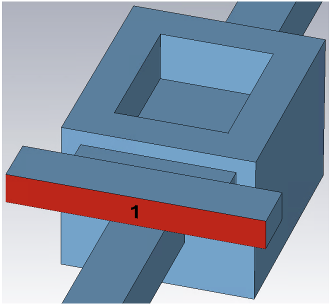
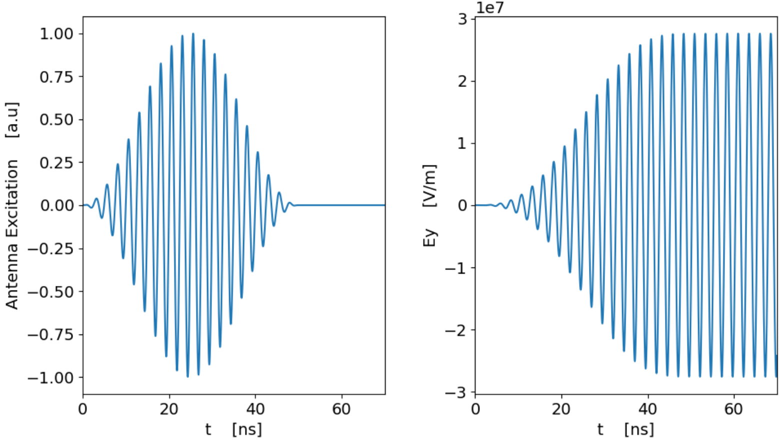
In Warp we can feed the cavity through a waveguide in which we place a time-varying current sheet ("laser antenna") which excites the cavity mode.



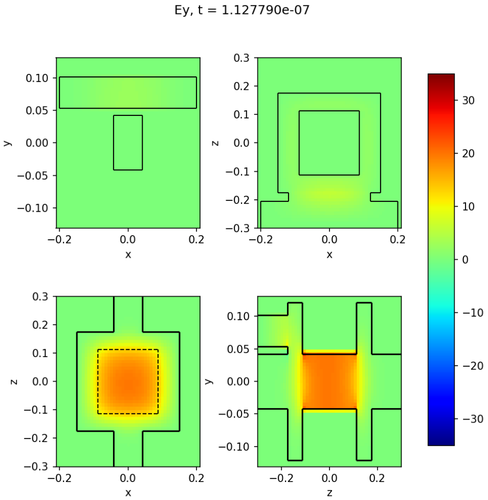
The Field in the Cavity

We probe E_y at the cavity center to visualize its time evolution compared to the antenna excitation.



The electric field increases when the antenna is on and keeps resonating as the antenna is turned off. Since the cavity is lossless, we can keep the antenna off for the rest of the simulation.

RF Field



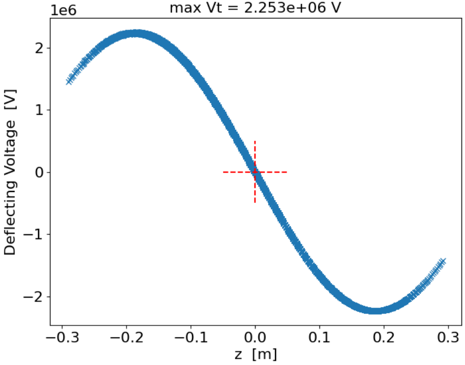
MOVIE

Bunch Deflection - Transverse Kick

To test our computation of the RF fields we measure the deflecting voltage directly on a p^+ bunch.

$$V_t = \frac{E_{beam}}{q_e}\Delta y' \qquad\qquad E_{beam} = \text{beam energy}$$

This test is very useful to phase the bunches correctly with the cavity.

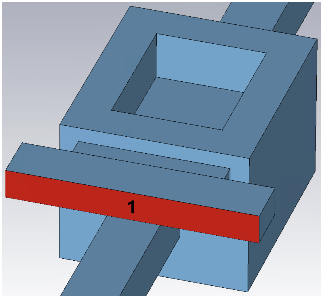


We clearly see that the head and tail of the bunches are kicked in opposite directions.

Outline of a Self-Consistent Ecloud Simulations

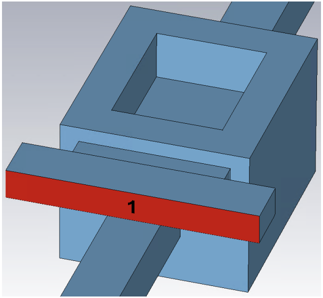
Outline of a Self-Consistent Ecloud Simulations

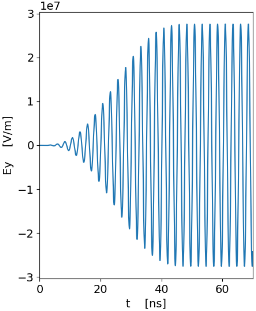
- Initialize the simulation



Outline of a Self-Consistent Ecloud Simulations

- Initialize the simulation
- Turn on the antenna and simulate the transient that excites the cavity mode





Outline of a Self-Consistent Ecloud Simulations

- Initialize the simulation
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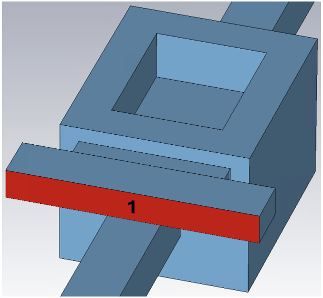
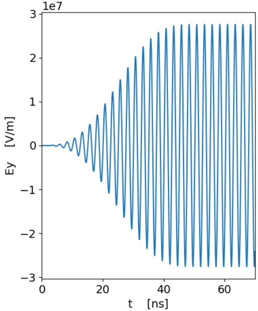
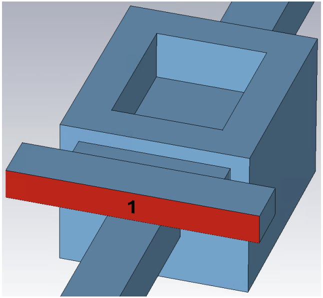
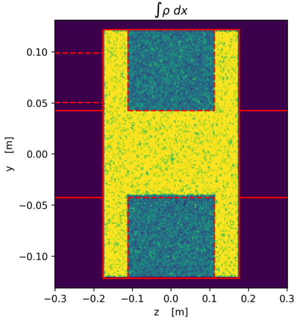


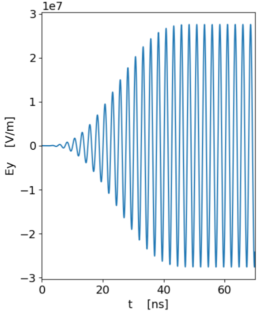


Outline of a Self-Consistent Ecloud Simulations

- Initialize the simulation
- Turn on the antenna and simulate the transient that excites the cavity mode
- Turn off the antenna
- Introduce a uniform distribution of seed electrons

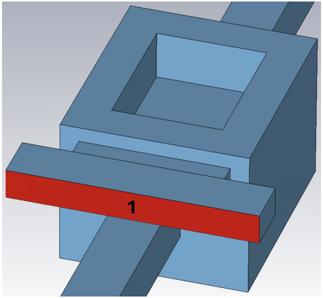


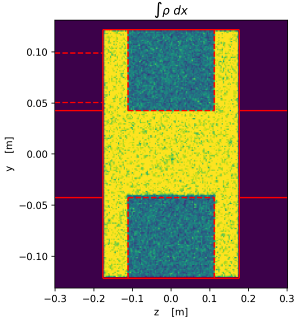


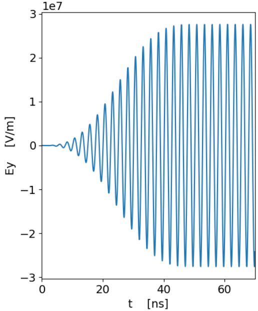


Outline of a Self-Consistent Ecloud Simulations

- Initialize the simulation
- Turn on the antenna and simulate the transient that excites the cavity mode
- Turn off the antenna
- Introduce a uniform distribution of seed electrons
- Inject bunches



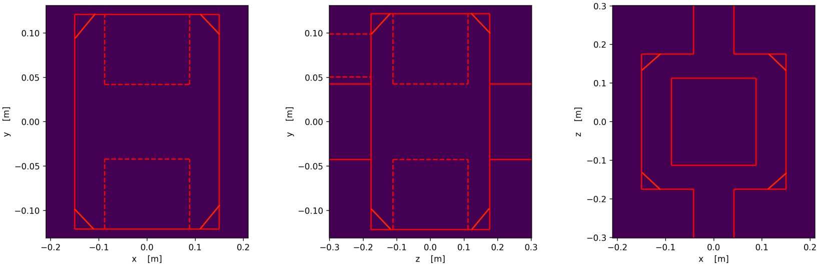




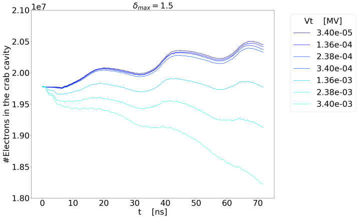
Outline

Carving the corners

By carrying out simulations for high voltages we see that the electrons tend to cluster in the corners of the cavity. As the real cavity has no corners, we prevent the electrons from reaching these areas inserting additional planes into the domain.



Build-Up VS Transverse Voltage



Multipacting "period": 25 ns

- Low voltages: beam-induced multipacting is observed

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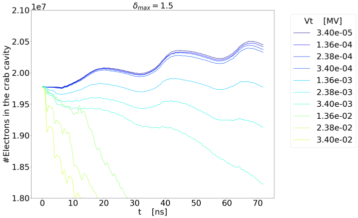

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- Low voltages: beam-induced multipacting is observed
- Medium voltages: the RF field suppresses the beam-induced multipacting

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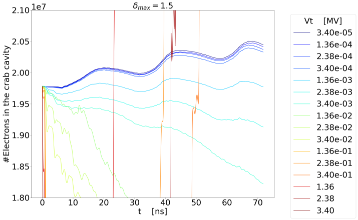

Multipacting "period": 25 ns

- Low voltages: beam-induced multipacting is observed
- Medium voltages: the RF field suppresses the beam-induced multipacting
- High voltages (up to nominal): RF-induced multipacting arises

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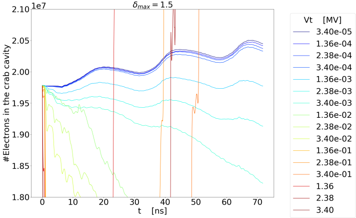

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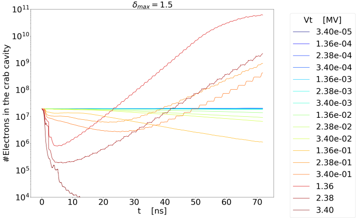

Multipacting "period": 2.5 ns

- Low voltages: beam-induced multipacting is observed
- Medium voltages: the RF field suppresses the beam-induced multipacting
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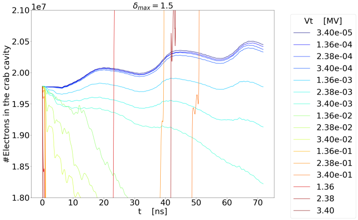

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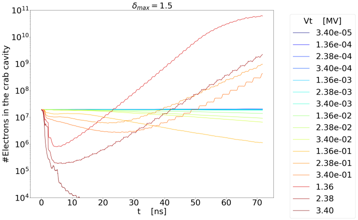

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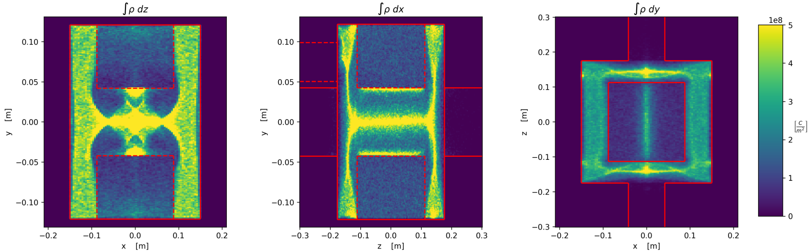
Let's visualize the distribution of the electrons.

Electrons Distribution - $V_t = 34V$

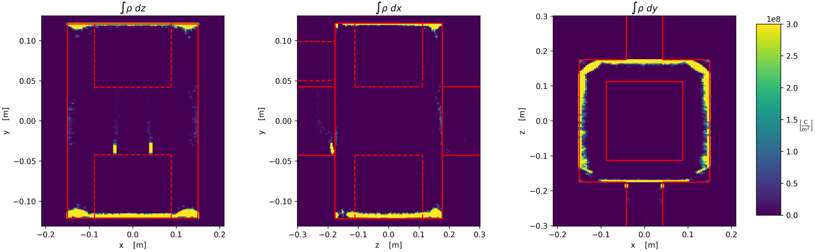
The electrons are only pushed by the beam and multipacting happens in the poles region.



MOVIE

Electrons Distribution - $V_t = 1.36MV$

The electrons are concentrated around the upper/lower edges of the cavity.



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This is compatible with what has been observed in [1]

[1] Verdú-Andrés et al., "Design and vertical tests of double-quarter wave cavity prototypes for the high-luminosity LHC crab cavity system".

Electromagnetic or Electrostatic ECloud Field?

We analysed the properties of different solvers by comparing the following two approaches:

- RF
- Beam
- ECloud

} EM solver

- RF
- Beam

} EM solver

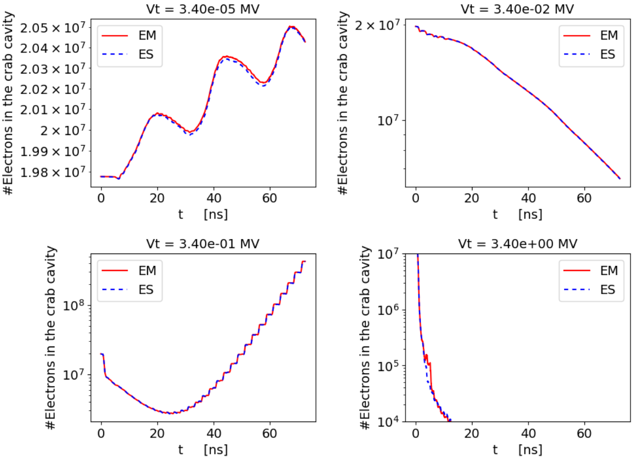
- ECloud

} ES solver

In the following we compare them.

Electrostatic VS Electromagnetic

Plots for increased values of the deflecting voltage:



The ES and EM solvers agree really well, thus we conclude that the self-interaction of the electrons can be approximated as electrostatic.
This is particularly convenient in sight of computations in realistic geometries (as the EM solver in Warp doesn't handle properly curved boundaries).

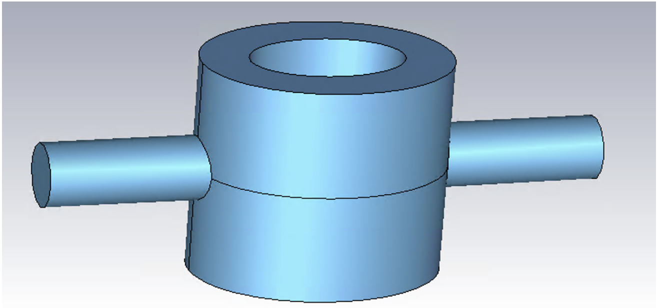
Outline

Realistic Geometry

To study beam-induced multipacting the DQW CC can be simplified a lot.
The main differences with the actual design are:

- Sharp edges (no weldings)
- Missing FPC, HOM couplers..
- Cylindrical geometry

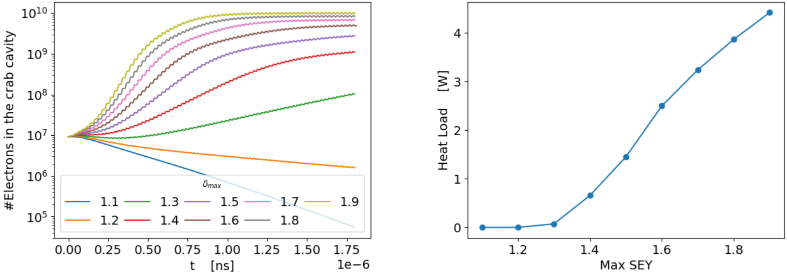
These simplifications are made to speed up the simulations, but in principles the procedure can be extended to the full model.



In Warp the cavity is modelled as an assembly of cylinders.

ECloud Build-up and Heat Loads

We simulated the electron cloud buildup for a 72 bunches train.



- For the heat load estimate we used the last 10 bunches, in order to have a pessimistic estimate (i.e. as if the whole LHC was filled and as if the ECloud was always at saturation)
- Other multipacting studies assume $\delta_{max} = 1.5$ for niobium cavities

Outline

From Warp to WarpX

Main limits of the simulations with Warp-PyECLOUD:

- The EM solver cannot resolve properly curved boundaries (staricasing)
- Cannot import directly a CAD geometry

Main issue: we cannot simulate accurately the RF mode due to staircasing.

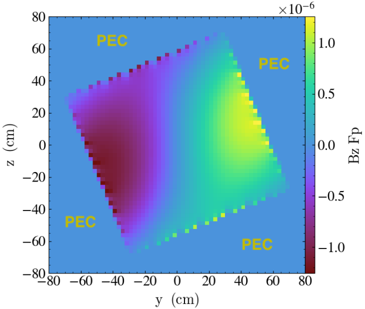
We decided to start tackling these issues in the new code WarpX (see J-L. Vay's talk on Tuesday) since it offers interesting new features such as GPU acceleration.

Conformal FDTD solver

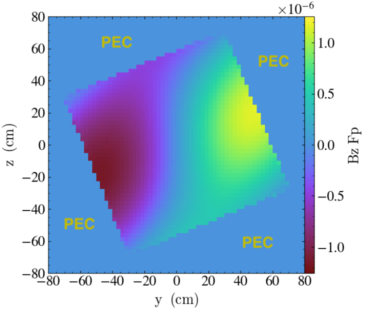
We implemented a new conformal (non-staircased) solver in WarpX based on the Enlarged Cell Technique (see paper by paper by Tian Xiao and Qing Huo Liu).

Example: simulating a resonant mode in a cubic cavity

Staircased solver:



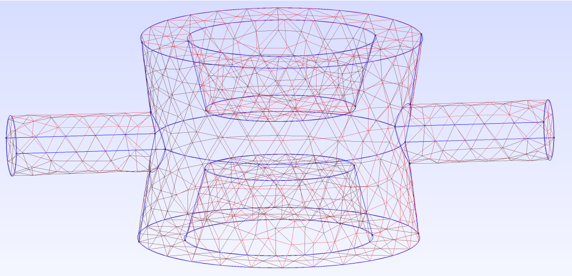
Conformal solver:



MOVIE

Importing CAD Geometries

Thanks to recent developments of WarpX (by W. Zhang) it is possible to specify the geometry directly as a STL file (i.e. triangular mesh).



The actual design of the Crab Cavities can now be imported in WarpX!

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  - Quasi-static solver for the electrons self-fields;
  - Electromagnetic solver for the electrons self-fields;

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- Simulated beam-induced multipacting in a realistic DQW cavity;
- Implemented a conformal Electromagnetic solver in WarpX
- For future studies it would be useful to couple WarpX with PyECLOUD