CERN

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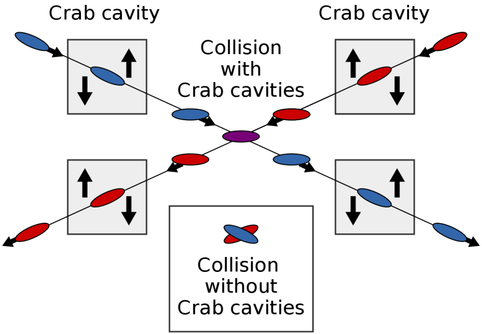
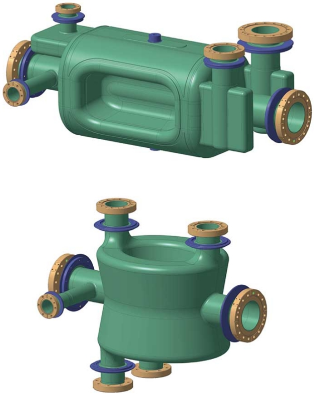
Development of Warp Simulations for 3D RF Structures

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

Many thanks to: R. Calaga, M. Carlà, S. De Santis, M. Furman, D. Grote, T. Luo, E. Metral, K. Paraschou, G. Penn, L. Sabato, B. Salvant, M. Schwinzerl, C. Zannini

The Crab Cavities





Computational challenge:

- Complex 3D Geometry
- Cavity EM Mode + Proton Bunch E-field + ECloud self-fields

PyECLOUD Is Not Enough

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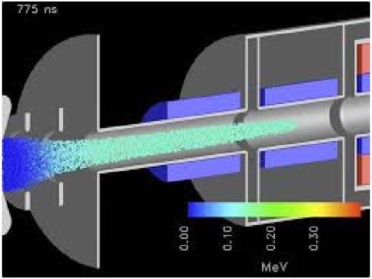
Warp, a 3D PIC framework developed at LBNL, offers many of the requeired features.

Outline

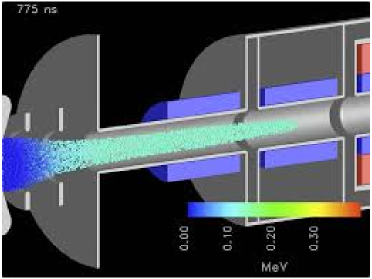
Warp



Warp

Numerical tools:

- FD 2D/3D electrostatic solver
- Several electromagnetic FDTD/PS solvers
- Lorentz-boosted frame
- Boris tracking (classic and relativistic)



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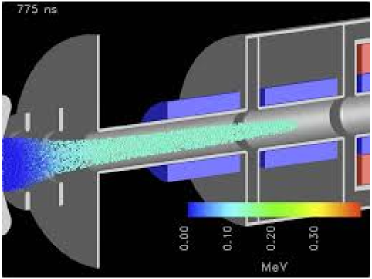

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- ECloud in static 3d structures (coupled with POSINST)

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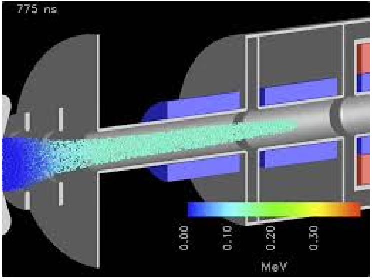

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ST)

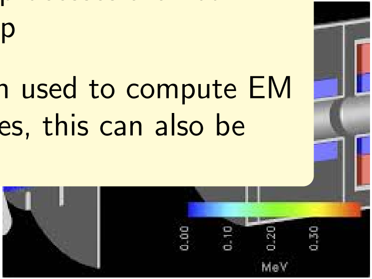
But:

- Secondary emission processes are not implemented in Warp
- Warp has never been used to compute EM fields in RF structures, this can also be handled externally

Geo

any

Multi-CPU parallel simulations (MPI)



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In the past Warp has been used to simulate the electron cloud in **static structures** jointly with POSINST.

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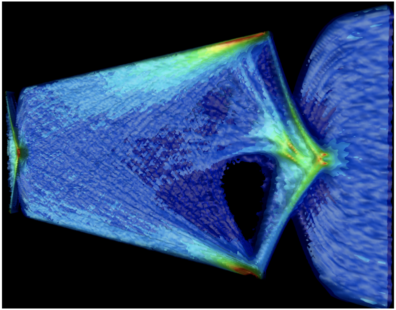

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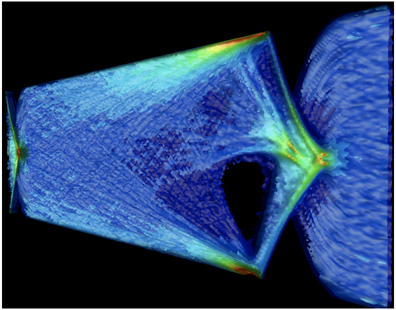

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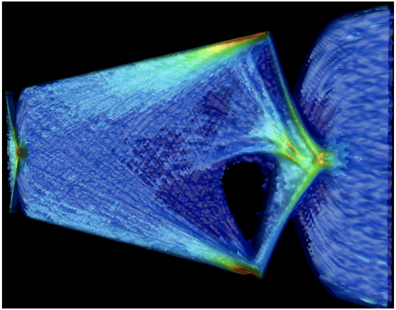

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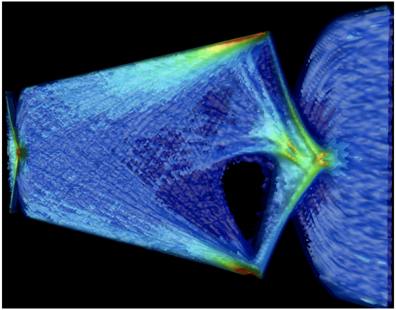

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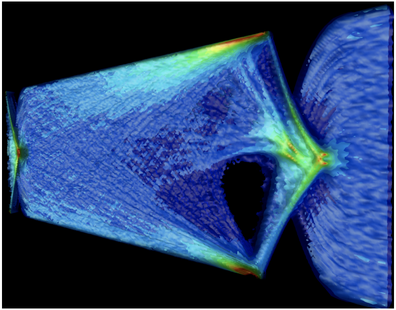

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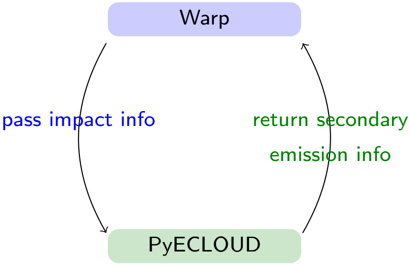
We can use PyECLOUD instead!

Outline

Warp-PyECLOUD

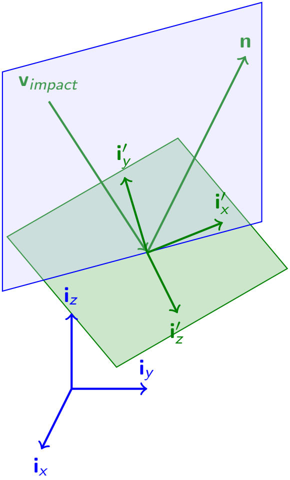
Warp has a Python wrapper from which we can call routines belonging to other Python packages.

We decided to exploit this feature to interface Warp with PyECLOUD.



The interface has been developed by L. Giacomel, G. Iadarola, J-L Vay during Gianni's visit at LBNL in October.

Warp-PyECLOUD interface



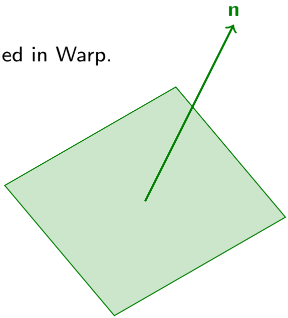
The interface which we wrote implements the transformation between the two reference systems

$$\{\mathbf{i}_x, \mathbf{i}_y, \mathbf{i}_z\} \rightarrow \text{Warp}$$
$$\{\mathbf{i}'_x, \mathbf{i}'_y, \mathbf{i}'_z\} \rightarrow \text{PyECLOUD}$$

We report the transformation in the next slides (also for documentation purposes)

Warp-PyECLOUD Interface

We want to find a normal plane which is easily defined in Warp.



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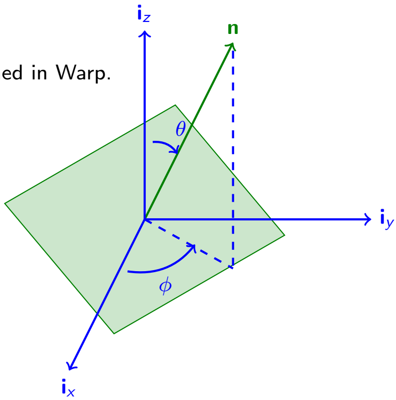

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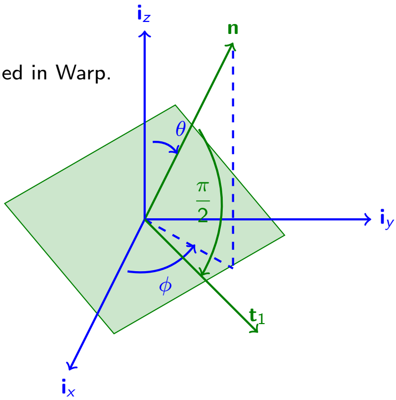
For every impact Warp returns (ϕ,θ), in terms of which the normal vector and a tangential vector are defined respectively as

$$\mathbf{n} = \begin{bmatrix} \cos(\phi)\sin(\theta) \\ \sin(\phi)\sin(\theta) \\ \cos(\theta) \end{bmatrix}, \mathbf{t}_1 = \begin{bmatrix} \cos(\phi)\cos(\theta) \\ \sin(\phi)\cos\theta) \\ -\sin(\theta) \end{bmatrix}.$$



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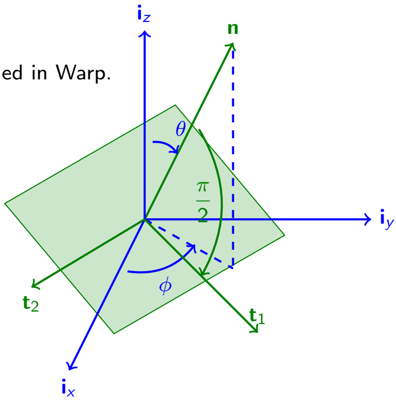

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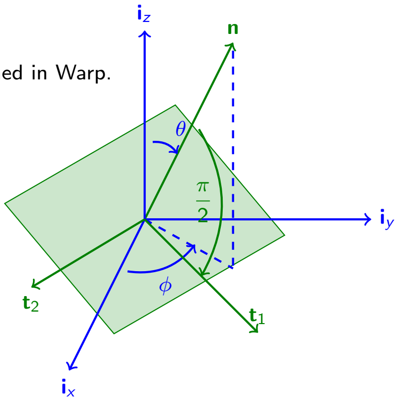

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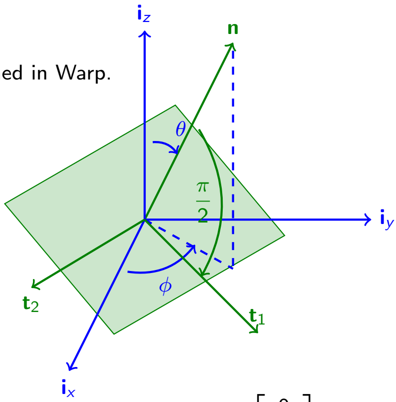

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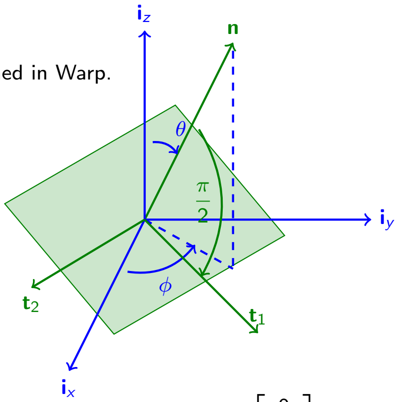

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Transformation of velocities:
$$v'_x = \mathbf{v} \cdot \mathbf{i}'_\mathbf{x}$$
$$v'_y = \mathbf{v} \cdot \mathbf{i}'_\mathbf{y}$$
$$v'_z = \mathbf{v} \cdot \mathbf{i}'_\mathbf{z}$$

Additionally Implemented Features

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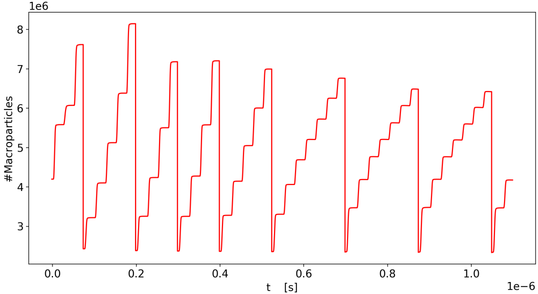
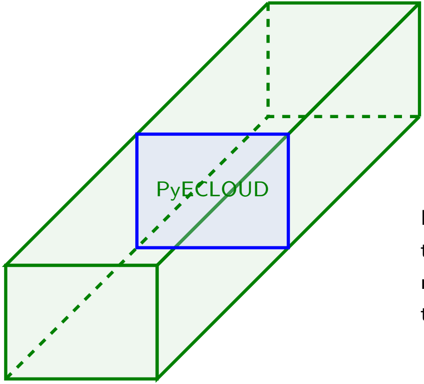
- **Regenerations**: during the buildup the number of MPs increases exponentially. When the number of MPs becomes too high, a fraction of the MPs is killed and the weight of the others is increased accordingly;



Warp-PyECLOUD benchmark

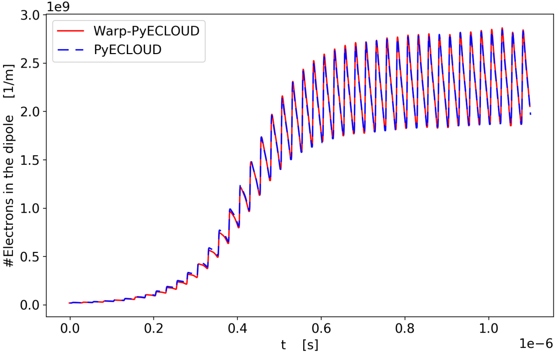
We use as a benchmark case a one-meter-long dipole with rectangular beam pipe.



In this case, we can reasonably compare the PyECLOUD 2D simulation with the middle section of the Warp 3D simulation.

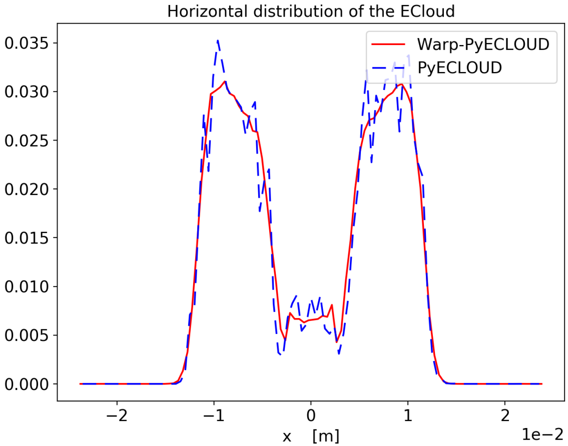
Warp-PyECLOUD benchmark

We compare the number of electrons per meter of dipole.



Warp-PyECLOUD benchmark (cont'd)

Comparing a 2D PyECLOUD simulation with a 3D simulation in a one-meter-long rectangular dipole magnet.



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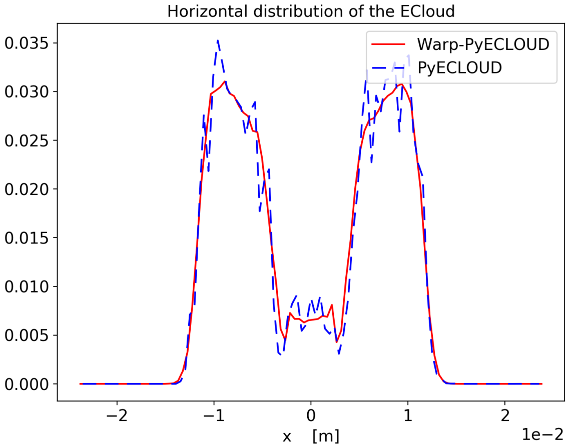
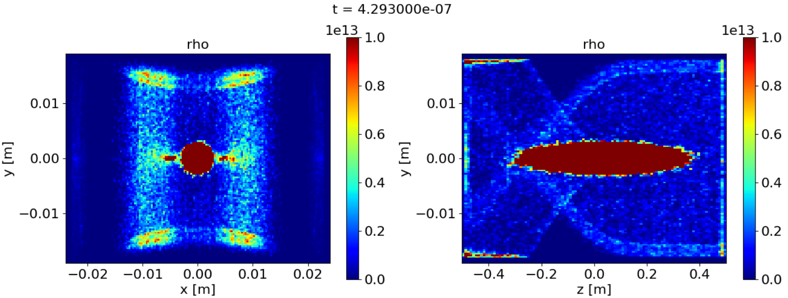


Warp results are less noisy because they consist of the averaging of many sections of the dipole.

3D Pinch


t = 4.293000e-07
rho
1e13
y [m]
x [m]
0.01
0.00
−0.01
−0.02
−0.01
0.00
0.01
0.02
1.0
0.8
0.6
0.4
0.2
0.0
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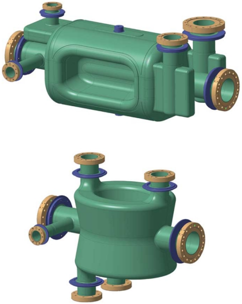
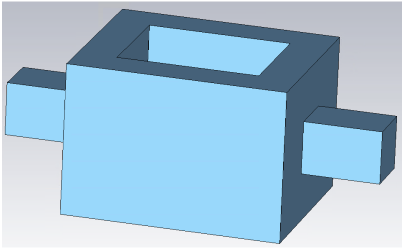
Outline

Simplification of the Crab Cavities

The structure of the Crab Cavities has been heavily simplified to carry out some preliminary simulations (the electromagnetic solver of Warp has troubles with curved boundaries).





RF Fields

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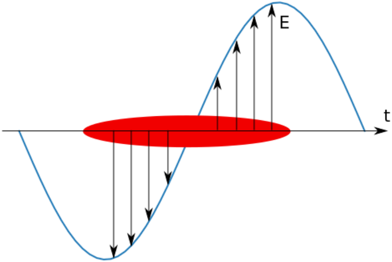

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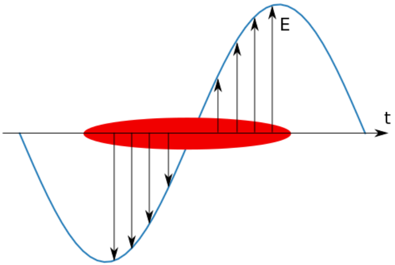
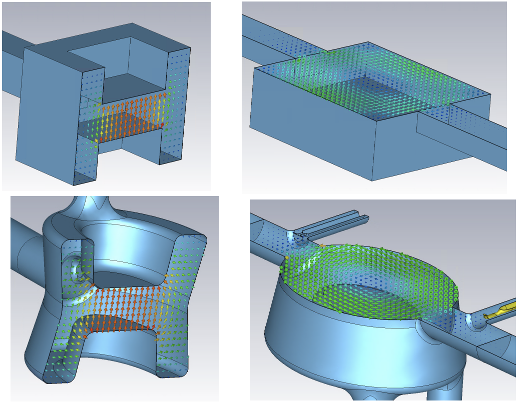


The simulation of these fields require an electromagnetic solver. For now the fields can be computed externally using CST and imported into Warp. In the future the fields will be computed directly in Warp.

Fundamental Mode

We can carry out eigenmode simulations to qualitatively check that fields of the squared cavity is similar to that of the DQW cavity and to tune the frequency.



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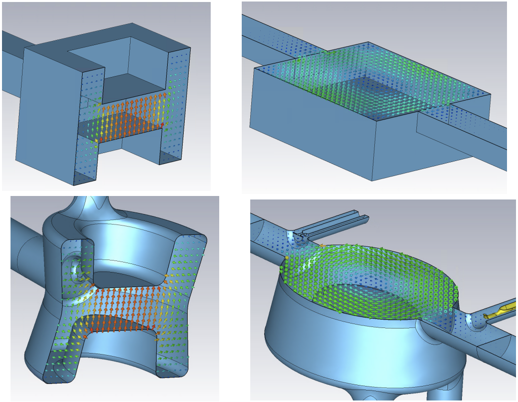


Many thanks B. Salvant and C. Zannini

Moreover, the the fields computed in the frequency domain can be converted to time domain and imported into Warp.

Import the Fields into Warp

We need to pass from frequency domain to time domain

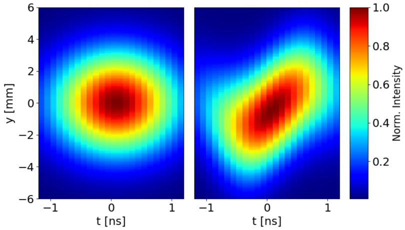
$$\tilde{\mathbf{F}}(\mathbf{x}, t) = \mathrm{Re}[\mathbf{F}(\mathbf{x}) e^{i\omega_{RF} t}] = \mathrm{Re}[\mathbf{F}(\mathbf{x})] \cos(\omega_{RF} t) - \mathrm{Im}[\mathbf{F}(\mathbf{x})] \sin(\omega_{RF} t)$$

```
### Import the fields as vectors
[x,y,z,ReEx,ReEy,ReEz] = getdatafromtextfile("ReE_field.txt",dims=[6,None])
[_,_,_,ImEx,ImEy,ImEz] = getdatafromtextfile("ImE_field.txt",dims=[6,None])

### Map to 3D arrays and interpolate to cell centers
[ReExx,ReEyy,ReEzz,ImExx,ImEyy,ImEzz] =
    preprocessFields(ReFx,ReFy,ReFz, ImFx,ImFy,ImFz)

### Create time vectors
time_array = linspace(0.,Tf,Nt)
sin_array = sin(time_array*freq*2*pi)
cos_array = cos(time_array*freq*2*pi)

### Create overlapped lattice elements for ReE and ImE
addnewegrd(...,time=time_array,data=cos_array,ex=ReExx,ey=ReEyy,ez=ReEzz)
addnewegrd(...,time=time_array,data=sin_array,bx=ImExx,by=ImEyy,bz=ImEzz)

### Repeat for B
```

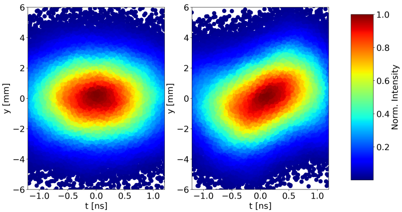
Tilting bunches

We verified that the squared cavity can crab a bunch similarly to the real DQW cavities tested in the SPS. This shows that we are injecting the bunches with the right phase.

SPS tests:



CST+Warp:



Warp-PyECLOUD-CST

Warp

Initialization:

- set up the domain

Warp-PyECLOUD-CST

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Initialization:

- set up the domain
- background electrons MPs distribution

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Warp

Initialization:

- set up the domain
- background electrons MPs distribution
- import RF fields

read field maps

field.txt

export field maps

CST

EM 3d simulation

Warp-PyECLOUD-CST

Warp

Initialization:

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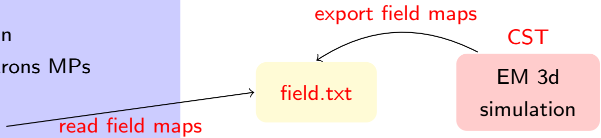
- import RF fields

For every time step:



Warp-PyECLOUD-CST

Warp

Initialization:

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- background electrons MPs distribution
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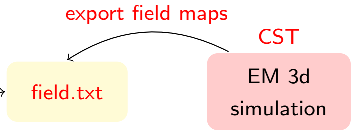
read field maps

For every time step:

- inject protons (or not)



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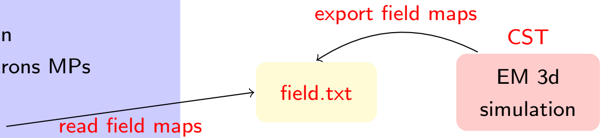

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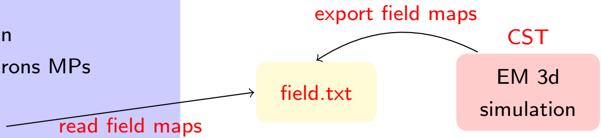

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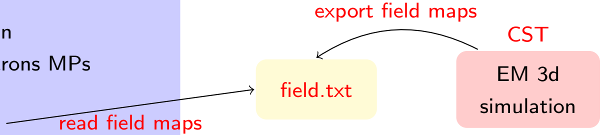
- push MPs



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- push MPs
- detect impact of electrons against the wall

read field maps

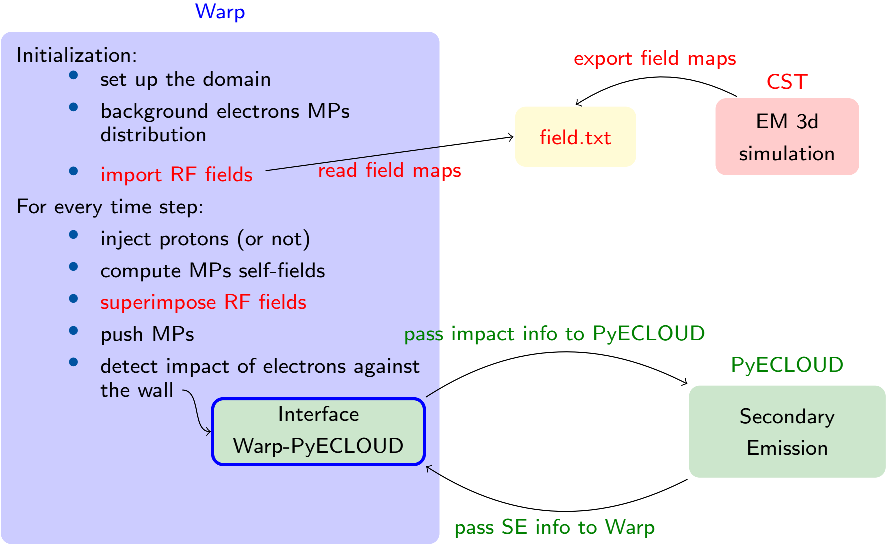
field.txt

export field maps

CST

EM 3d simulation

Warp-PyECLOUD-CST



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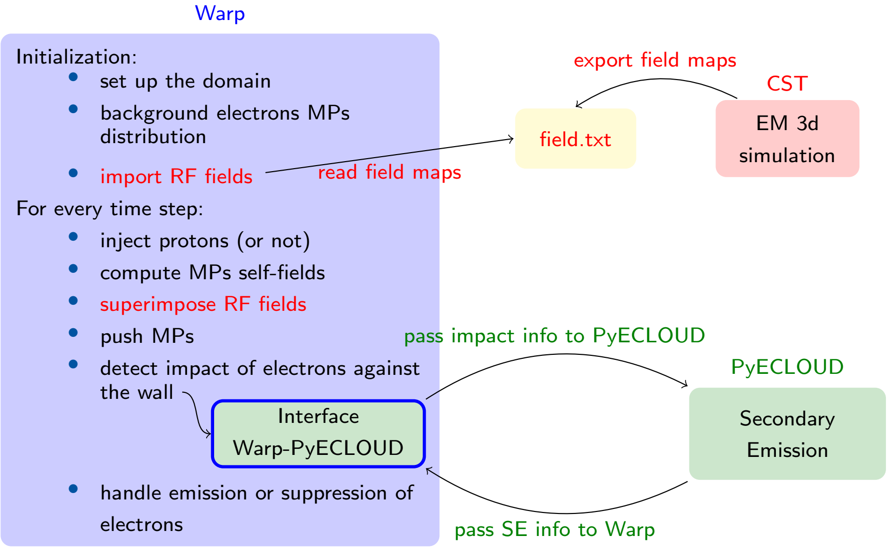
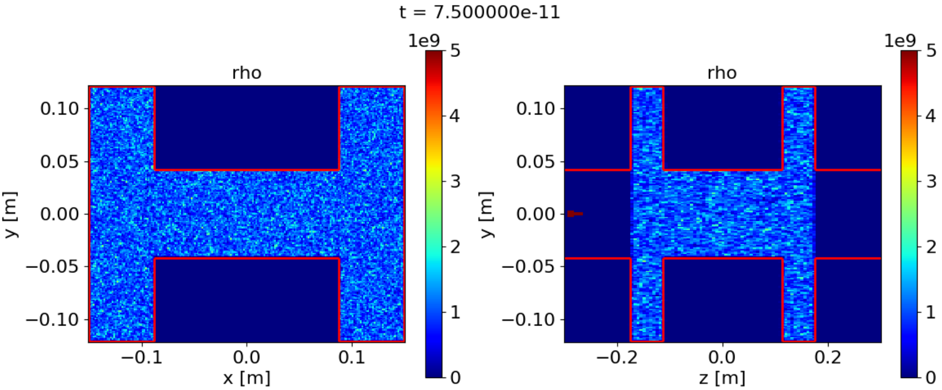
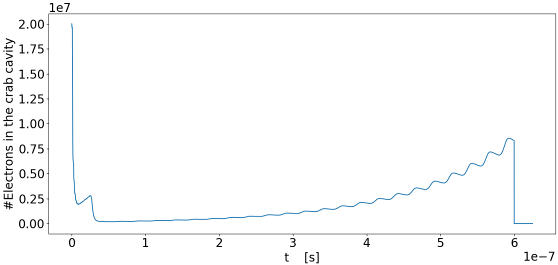


Simulation in the Cavity



Buildup Curve

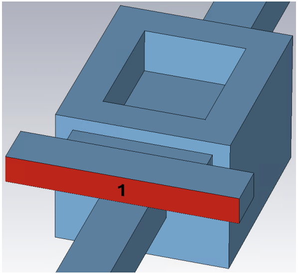


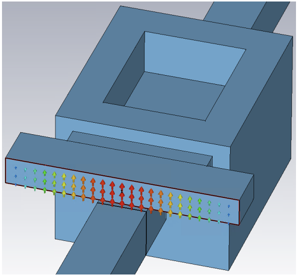
The electrons are pushed by the cavity with an energy that doesn't allow multipacting, therefore most of them are absorbed by the wall during the first RF period. On the other hand, some electrons are pushed to the adjacent drifts giving raise to multipacting in there.

Outline

Time Domain Simulations in the Crab Cavities

In CST the cavity can be fed with a simple rectangular Waveguide Port.





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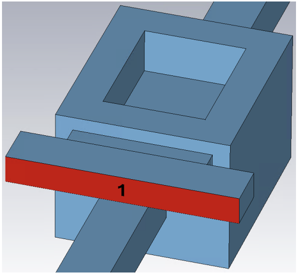

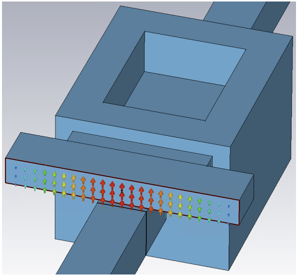

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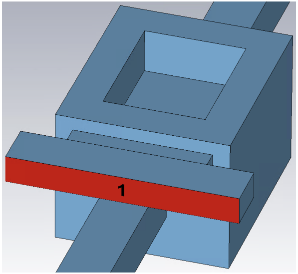

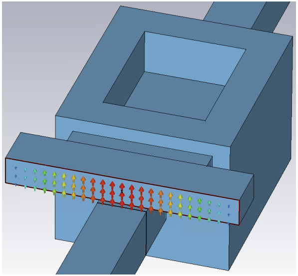

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Warp has no eigenmode solver. We need a different strategy.

Computation of the RF fields in Warp

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In addition to the standard PIC iteration:

- Place a macro-particle with unitary charge in each mesh cell of a given region
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- Scatter current to the mesh
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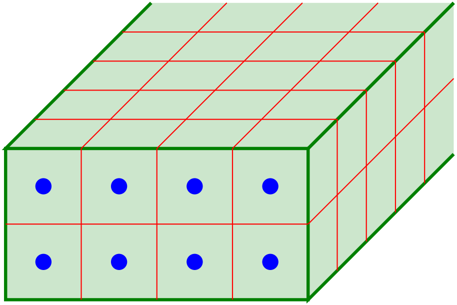

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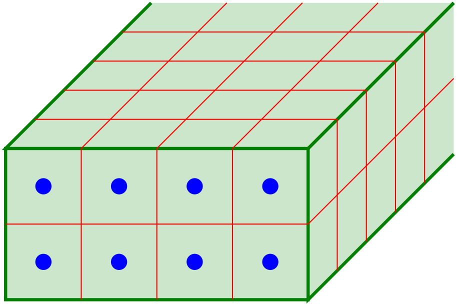
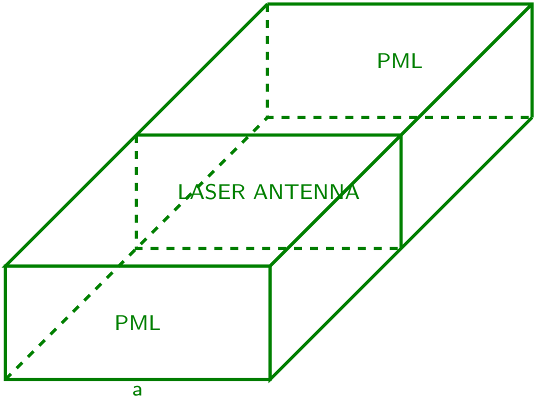


By choosing properly the velocity distribution of the macro-particles we can excite a specific mode of a waveguide.

TE10 in a Rectangular Waveguide

Numerical experiment: excite a TE10 mode in a rectangular waveguide.



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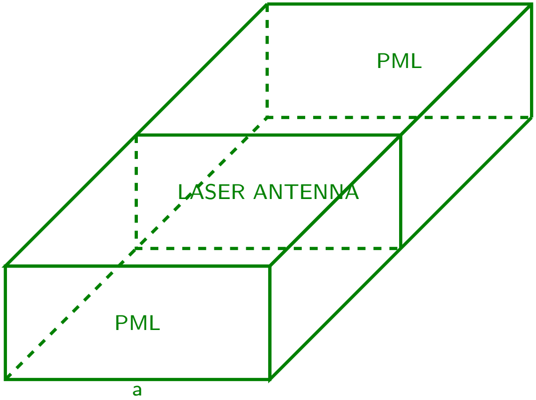

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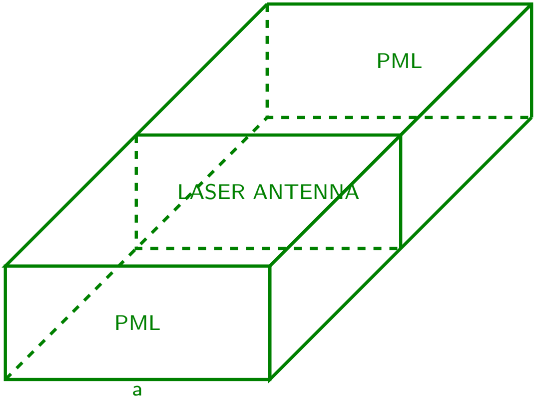

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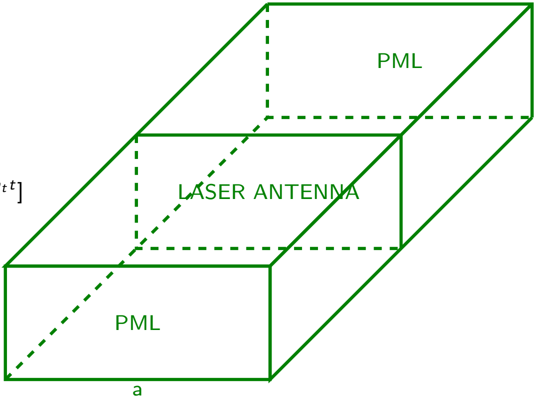
- Field on the antenna plane:

$$\mathbf{E}(\mathbf{x}) = \mathrm{Re}[E_0 \sin \frac{\pi x}{a} e^{-i\omega_z z} e^{-i\omega_t t}]$$

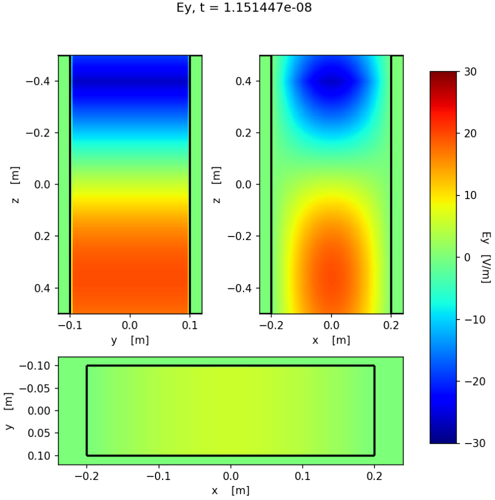
$$\omega_t = 2\pi f$$

$$f = 400 MHz$$

$$\omega_z = c\sqrt{\left(\frac{\omega_t}{c}\right)^2 - \left(\frac{\pi}{a}\right)^2}$$



TE10 in a Rectangular Waveguide - Results



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