VORPAL Simulation of E-Cloud in the Fermilab Main Injector.

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Project X

Take home message..

- VORPAL provides a fully consistent, truly 3D, simulation of the Electron Cloud (EC) in realistic conditions, for (brief) periods of time. “Precise” density distributions and field maps can be extracted from the simulated data.
- As the secondary emission yield for scrubbed stainless steel is not know with enough accuracy, no “ab-initio”, quantitative prediction about the “EC problem” for current (or Project-X) running conditions can be made
- Yet, if we have “No EC problem” now, this calculation shows that we will **not** have a problem when the proton bunch intensity goes up by a factor 3.

Brief Intro: Scope

- “Mature” project: preliminary results have been presented at PAC09 & IPAC10. Also, POSINST simulations on the same problem have been done years ago. (and still pursued). Yet, detailed comparisons remains to be done.

- Original mandate: simulate (i) the microwave absorption experiment (ii) provide a set of field maps (or code to compute them) such that the effect of the EC on the beam can be simulated in Synergia. In addition: RFA simulation, ideas for new instrumentation, and participation to the future designs of the dedicated EC study region of a straight section of the MI.

Outline

- Relevant parameter of the MI.
- VORPAL specifics...
- Results:
    - Density of EC
    - Field maps, one example
    - Simulation of Phase Shifts and RFA
- Outlook: towards a plan for EC studies @ MI.

Fermilab Main Injector, relevant parameters.

•The Main Injector (MI) consists mostly of dipoles and quadrupoles (warm magnets). EC starts setting in at about 20 GeV, or 0.234 T, when the bunch is shorter. $\rightarrow$ simulation done at that energy.

•• The beam pipe is elliptical (2.38 x 5.88 cm) and made of stainless steel. No coating, except the one gained after ``scrubbing”, or exposing the surface to the electron flux from EC. SEY is assumed to be constant and uniform, except for RFA slits.

•• The bunch charge varies from 0.2 10^{11} to 3.0 10^{11} , the bunch length about 0.3 m. (minimum), the bunch spacing is 18.8 ns.

•• Microwave: TE_{00} mode, E field << field created by the proton beam or the cloud.

Simulation Setup in VORPAL

- VORPAL v4.x, standard scripts except for an extension for the Dey-Mittra boundary conditions, that include magnetic field gradients.
- Extensive use of VORPAL functions to describe the bunch shape, the magnetic "fringe" fields and the SEY RFA slits
- Running on desktop, small cluster (< 32 CPUs) and on Intrepid@alcf.anl.gov , typically 512 nodes. (Not the most efficient use of 512 nodes, but it works, steady throughput.)

POSINST vs VORPAL: Benchmark

- Relevant difference: "2D+" (i.e., slices along Z) vs "truly 3D".

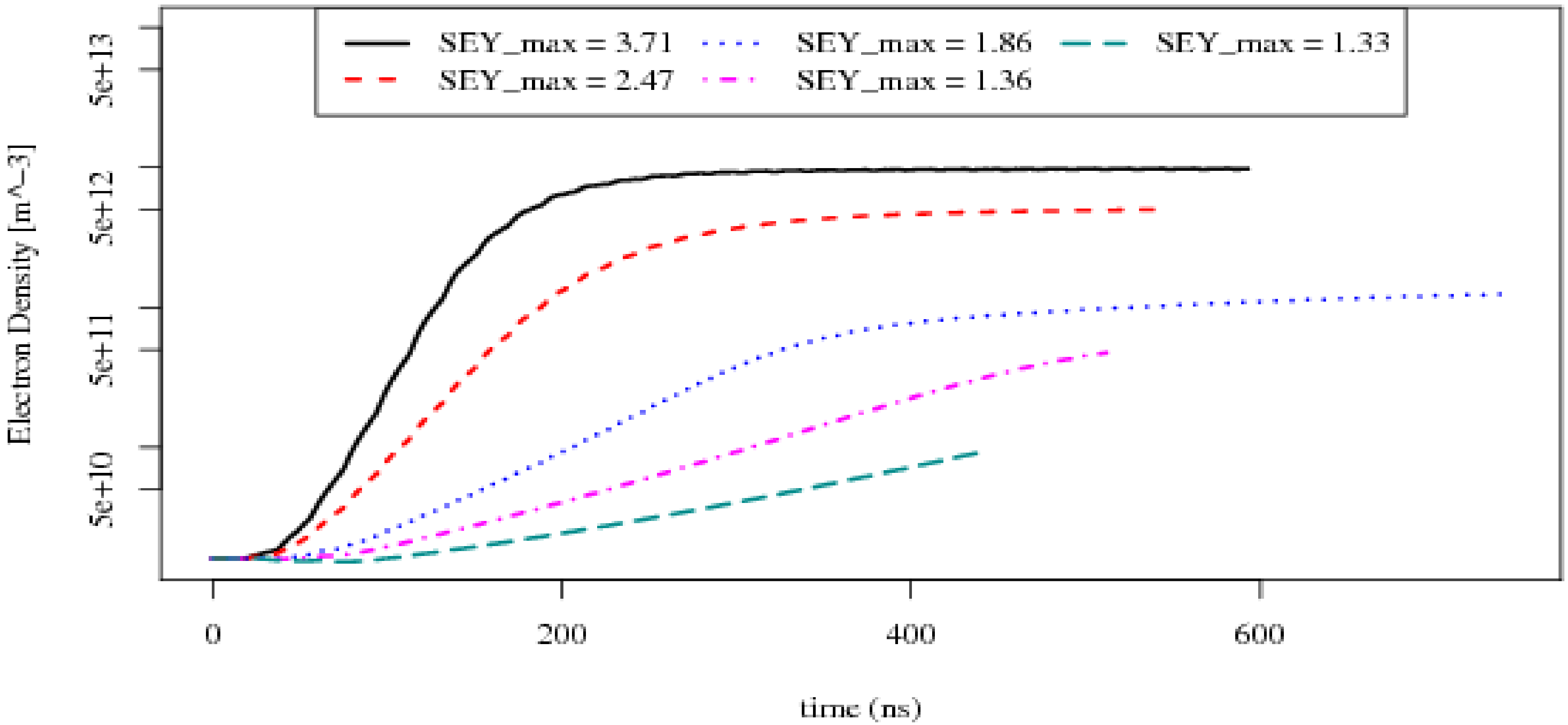
→ e.m. & electrons propagation issues.

- Xiaolong Z. and myself agreed on a simple setup: dipole, elliptical beam beam pipe, same SEY model ("old", VORPAL v3.0, borrowed from POSINST). Ran VORPAL 2D, VORPAL 3D on the same grid size.
- Ongoing effort.
- Hopefully, (please!...) won't last for years...

POSINST vs VORPAL: Benchmark, Results

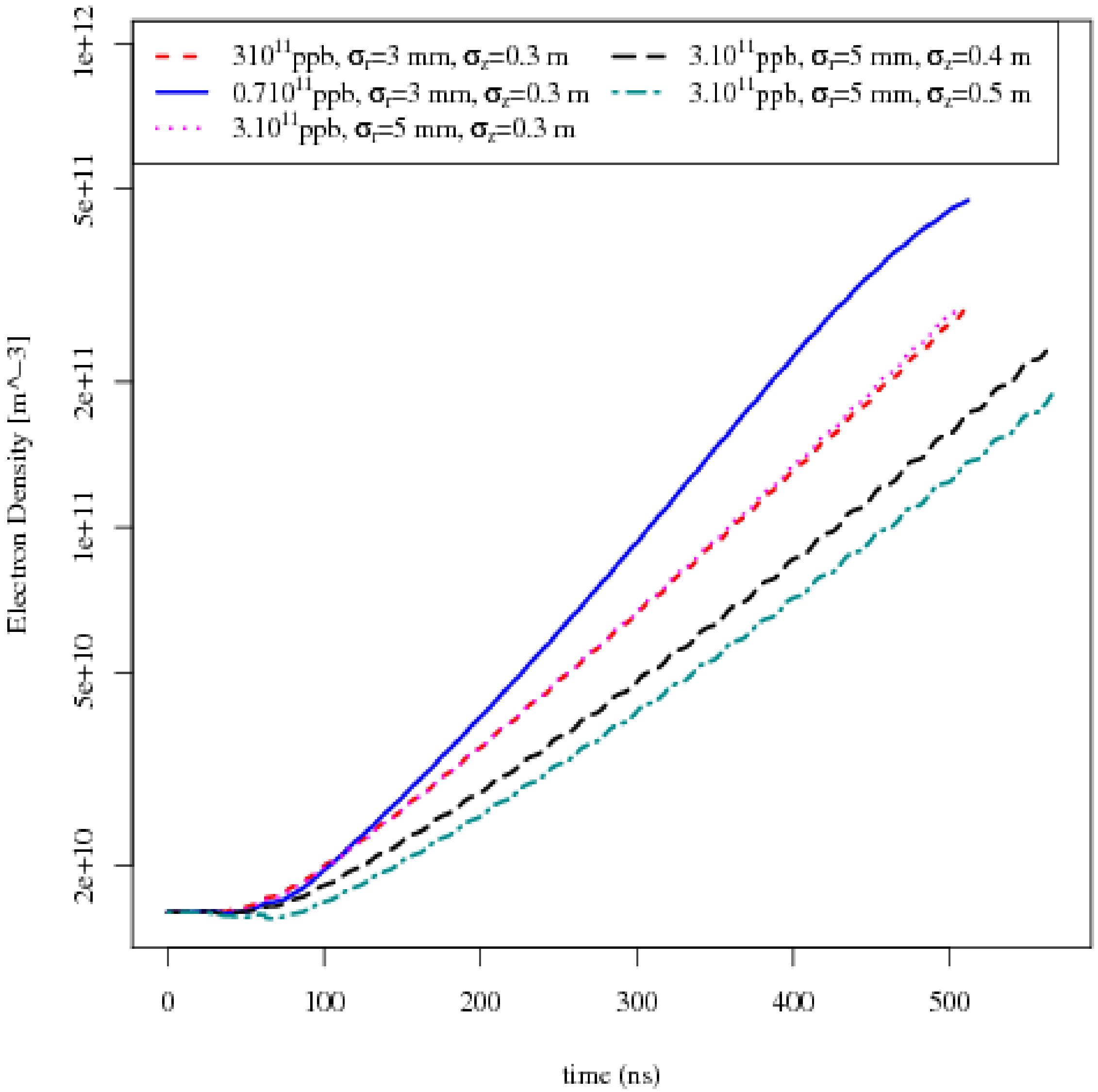
- 2D vs 3D can lead to factor 2 difference in EC density (VORPAL result) , consistent with POSINST/VORPAL differences.
- Growth times also different. VORPAL produce faster EC
- In VORPAL, we see no well defined “trappings” regions in fringe fields of dipole and quadrupole, EC density are diffuse, not sharply define lines.
- Further studies? But, 2D, or 2D+ codes should not produce the same results as 3D!... So, “benchmark” is not the correct concept here..

VORPAL Results: EC density vs time



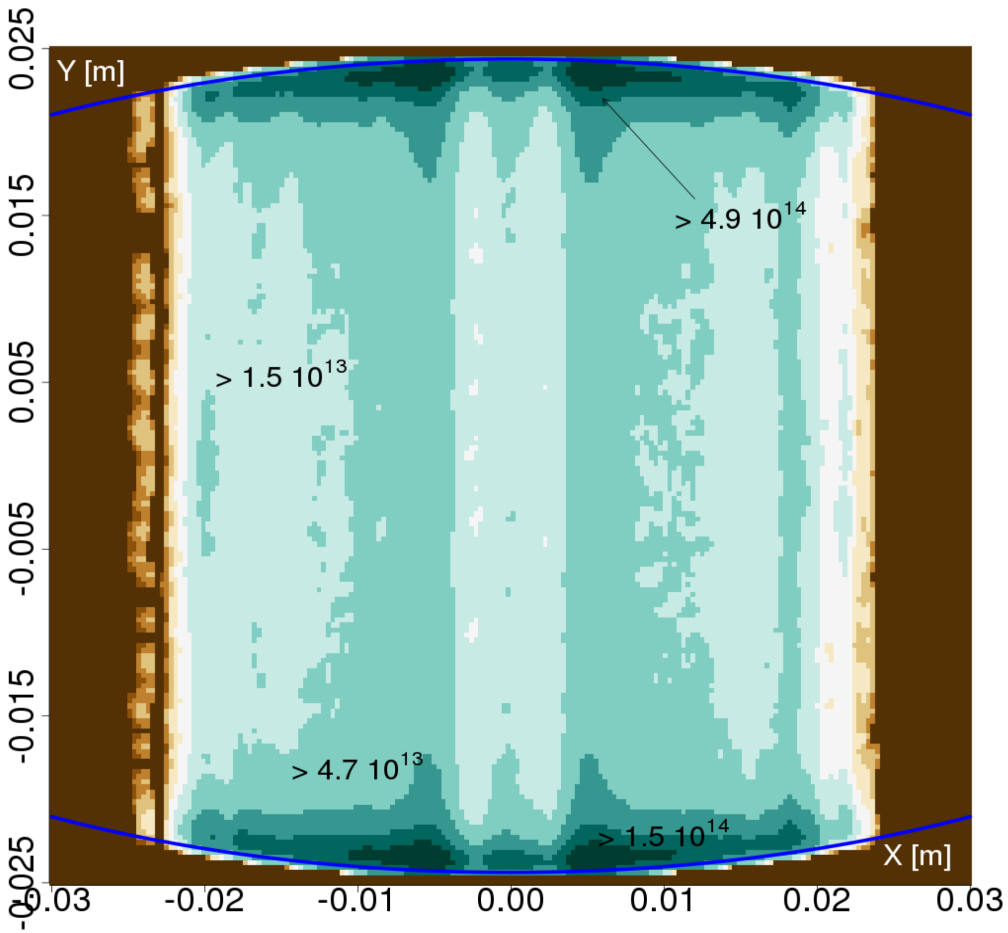
- EC density in a Dipole-Quadrupole-Dipole section of the machine (15 m. long), including fringe field.

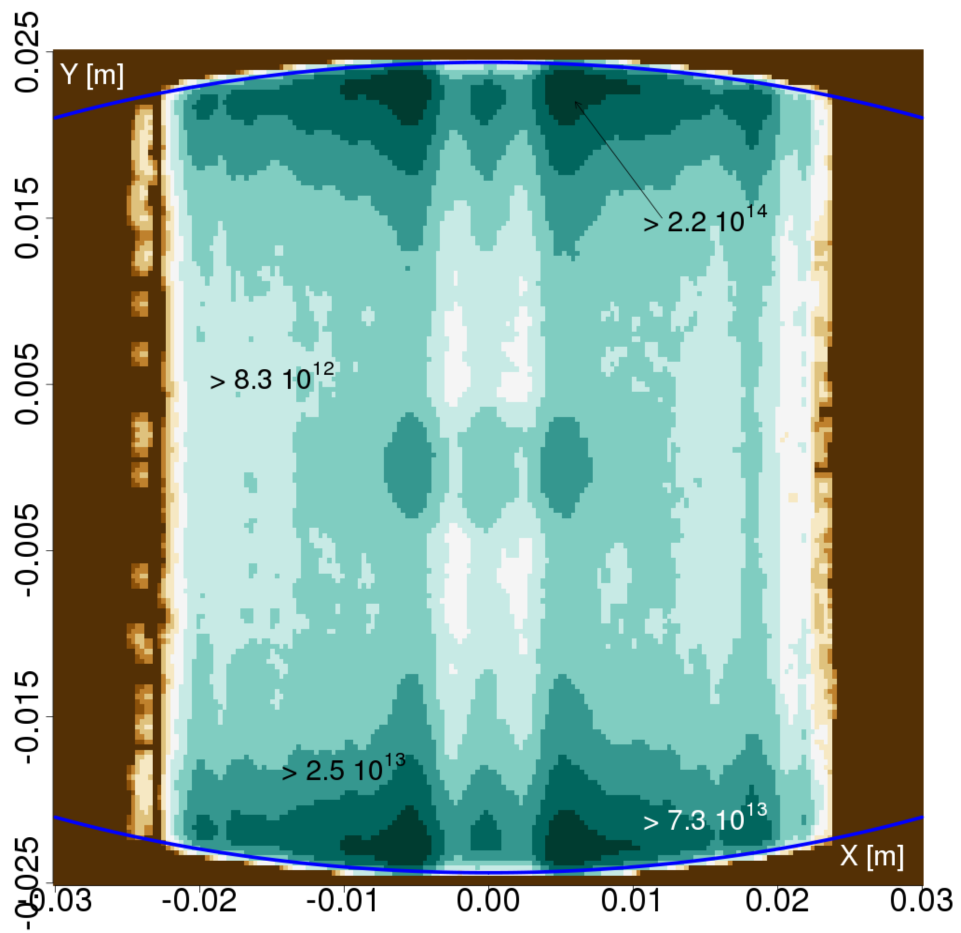
Results: EC density, Project-X era



- EC density, same section of the machine, for different beam conditions.
- At low SEY, below the critical value of SEY_{max} ~ 1.36
- ***No dramatic increase for Project-X intensities.***

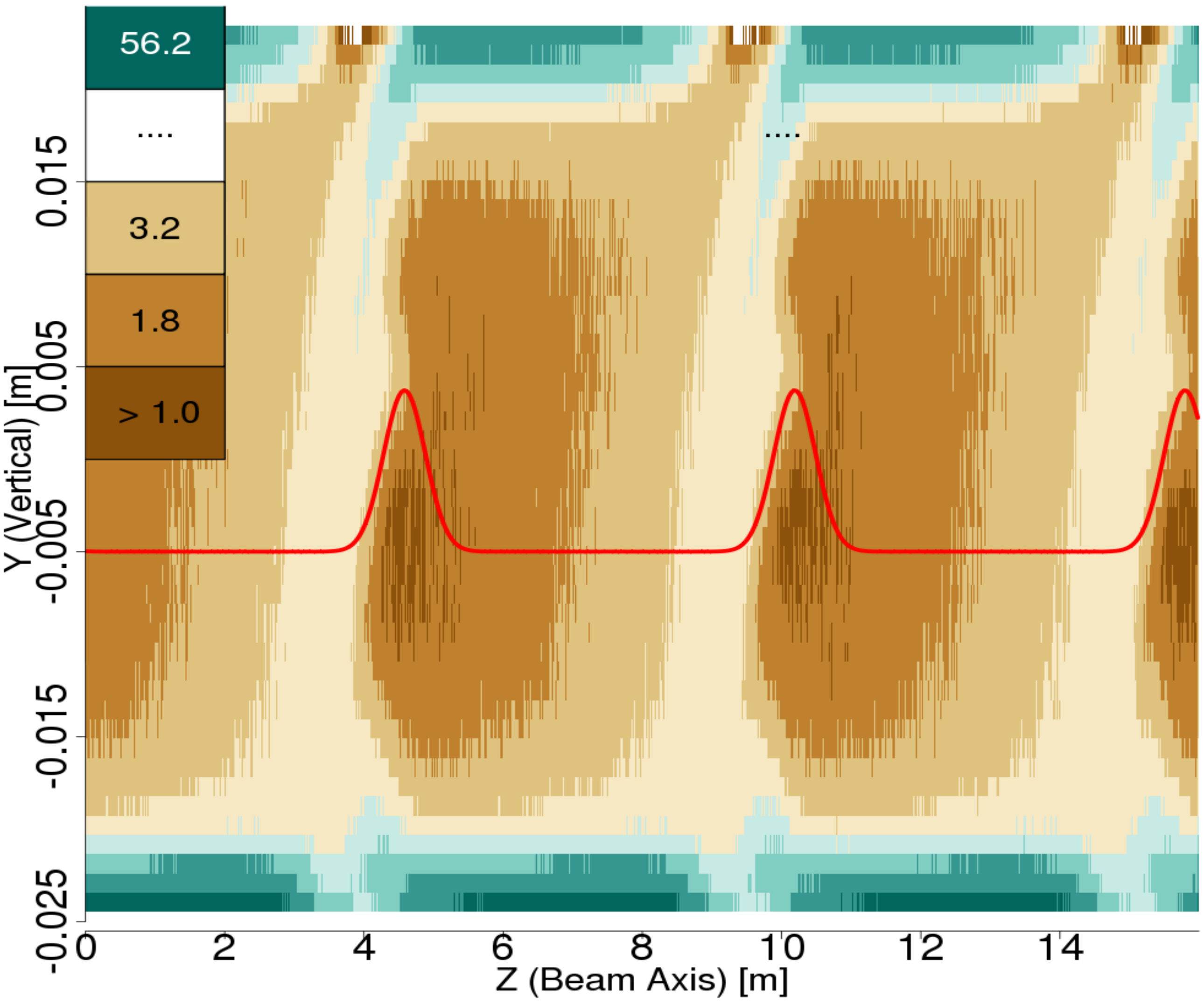
EC density Profiles..





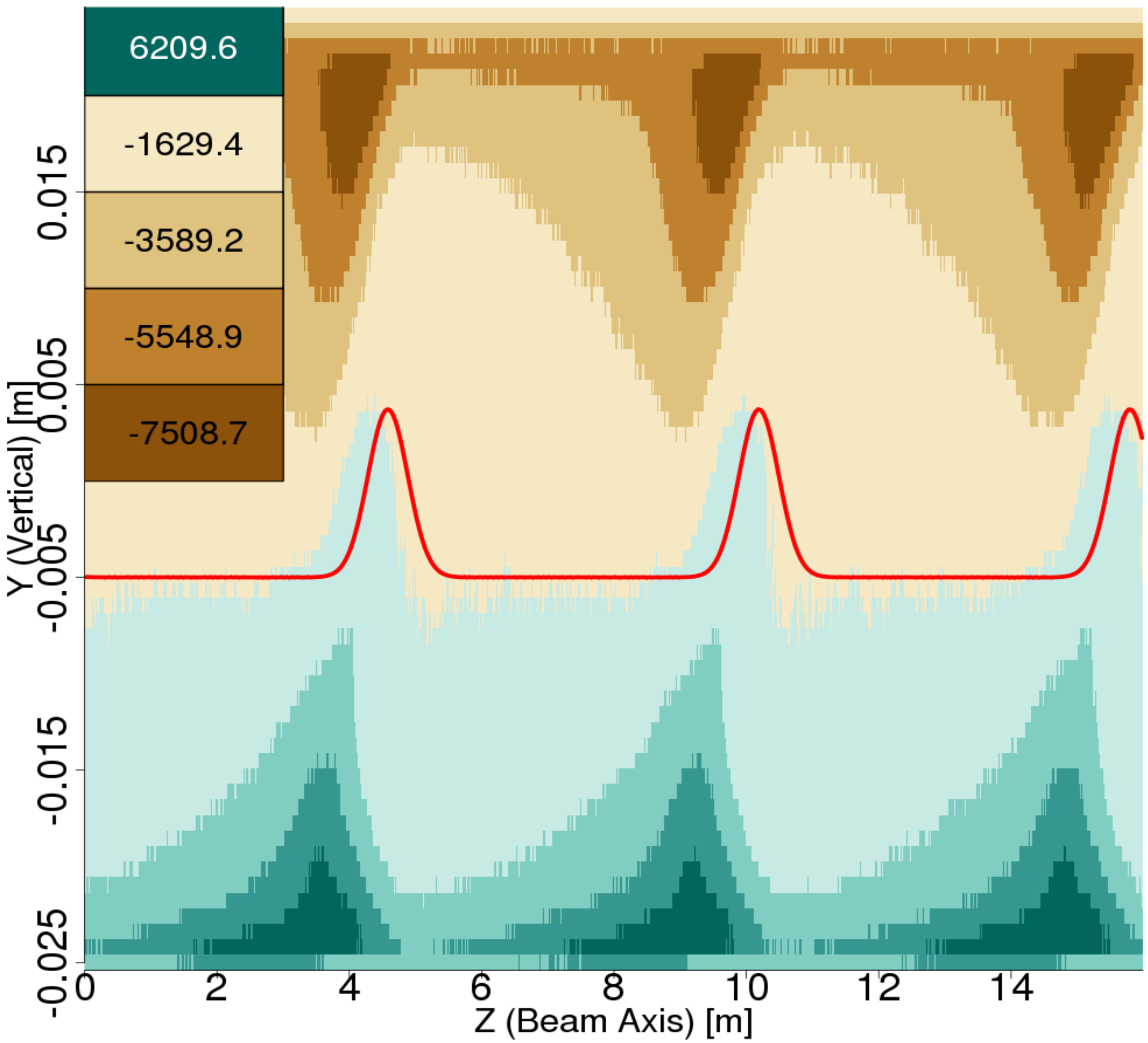
- Transverse profiles, in between bunches (left) and during the "pinch", ~ 1 ns after the passage of the ~ 1. ns bunch

EC density Profiles, Longitudinal



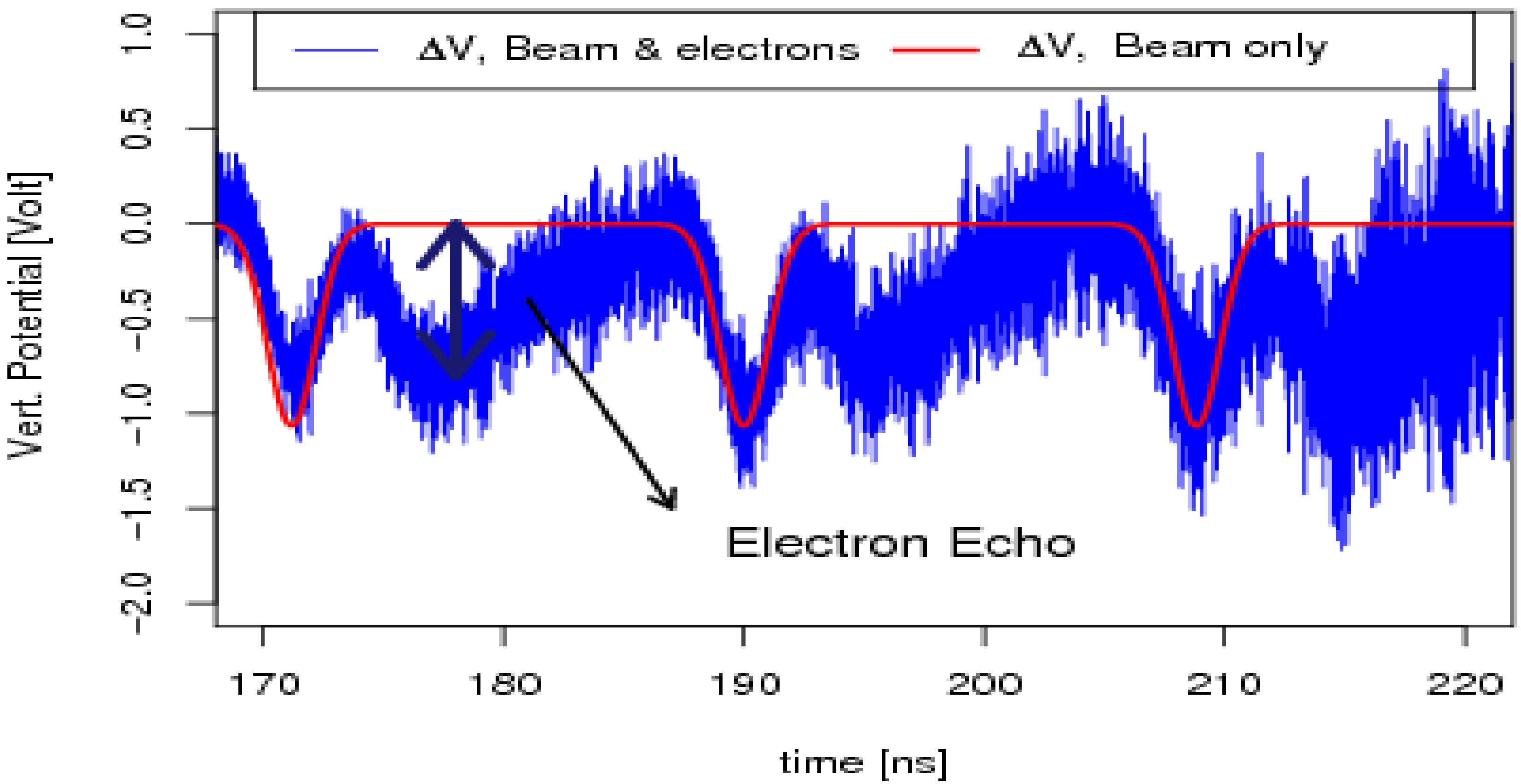
Shown in red is the proton beam profile. The change in density is delayed by ~ 1ns with respect to bunch.

Corresponding Ey Field map.

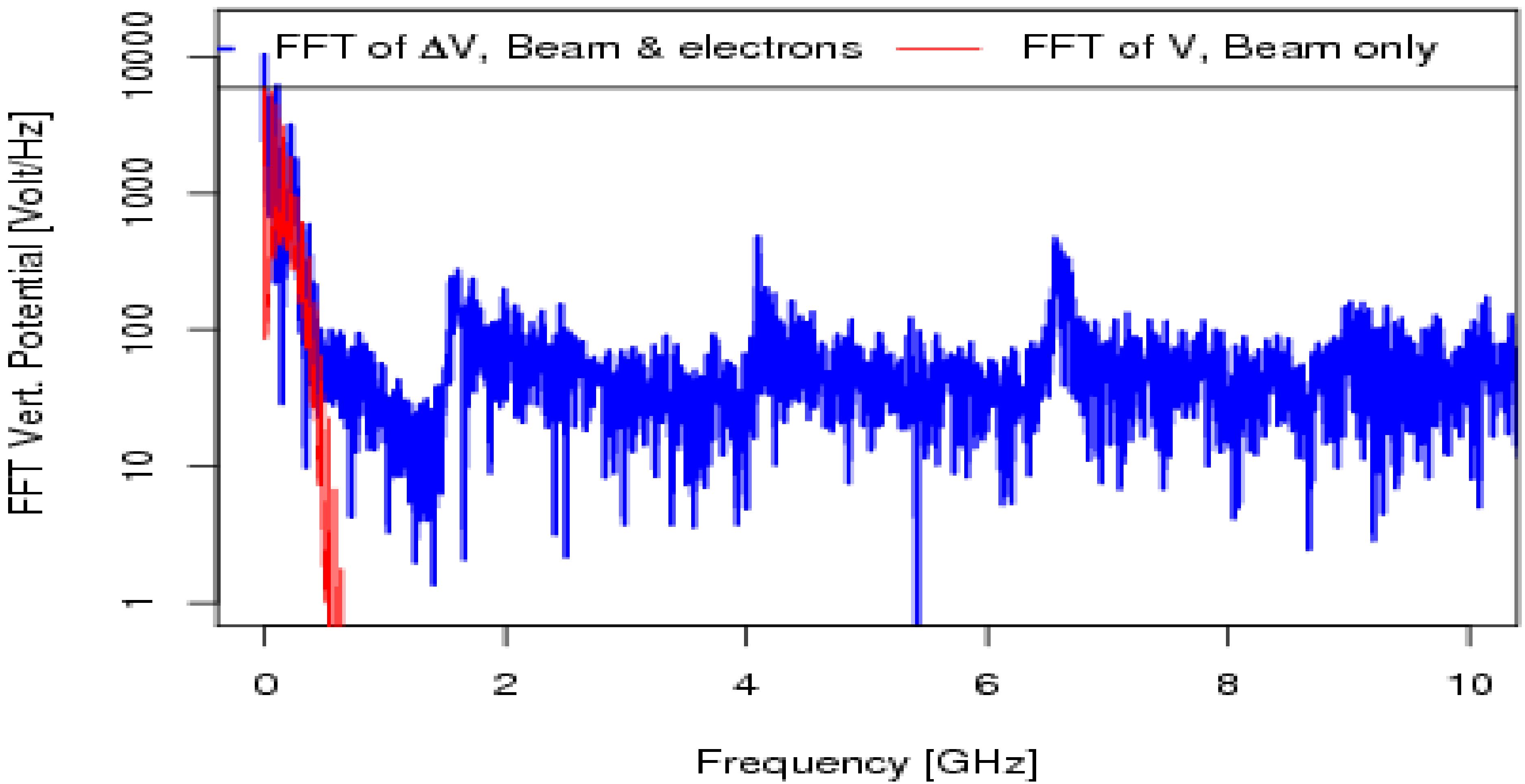


- A false color map of the vertical component of the electric field solely due to the presence of the EC. This field is most intense ~ 2 ns away from the center of the bunch, illustrating the strong head-tail difference in the perturbation.

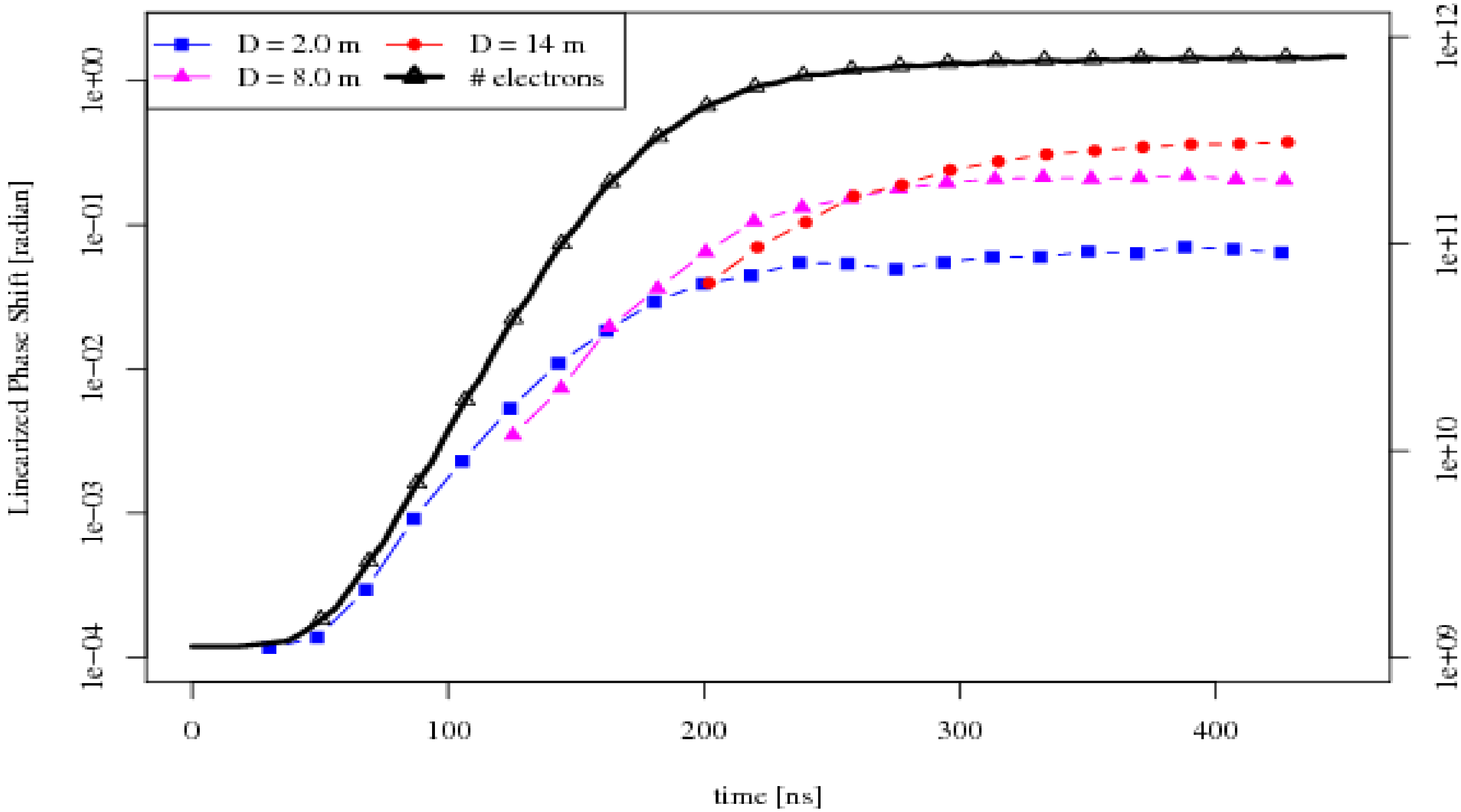
Pseudo Potential: BPM sim.



E.M. Waves..

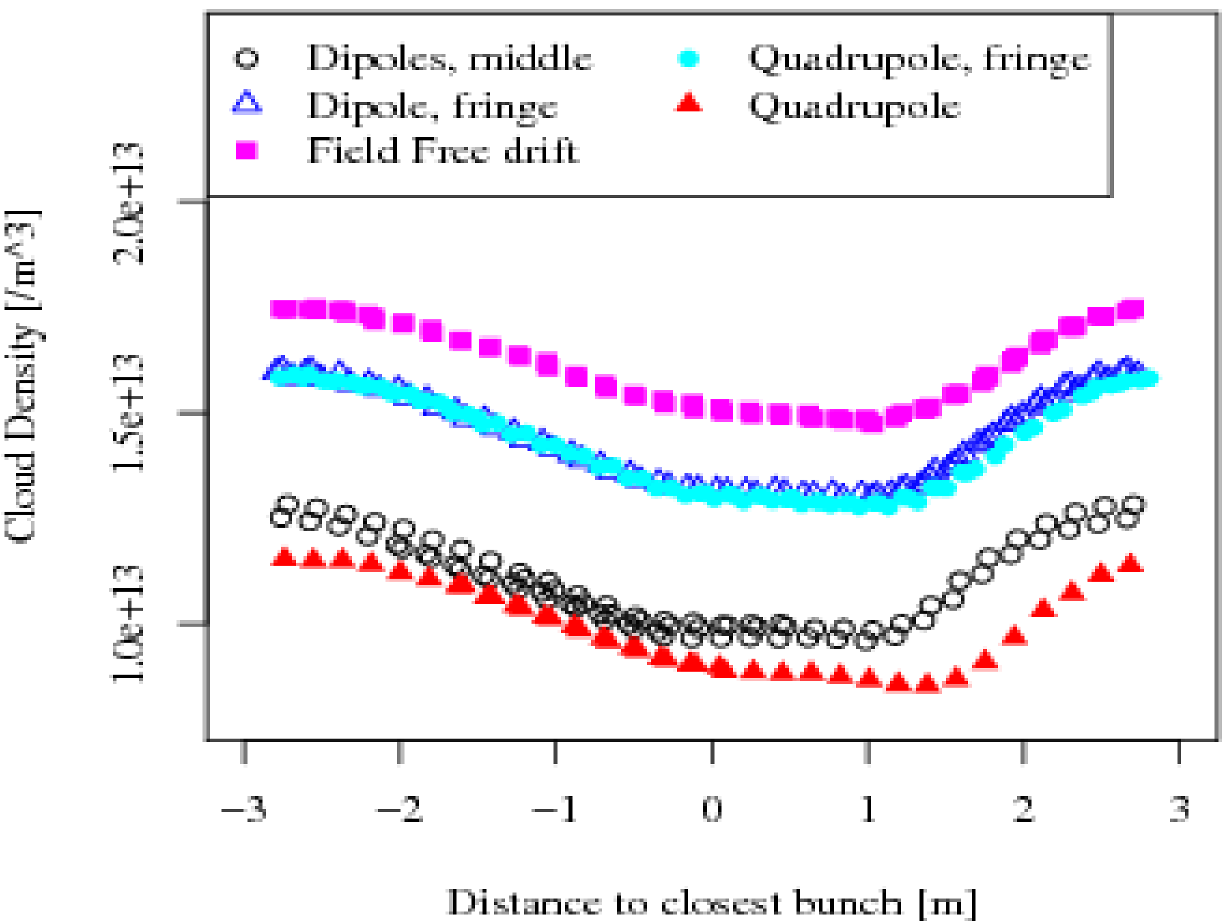

FFT of ΔV, Beam & electrons
FFT of V, Beam only
FFT Vert. Potential [Volt/Hz]
10000
1000
100
10
1
0
2
4
6
8
10
Frequency [GHz]

Time dependence of the Phase shift.



Not rigorously following the number of electrons in the pipe, at the beginning (not sure why). However, steady state observed (Again, using a saturated EC, high SEY)

Density Variations.

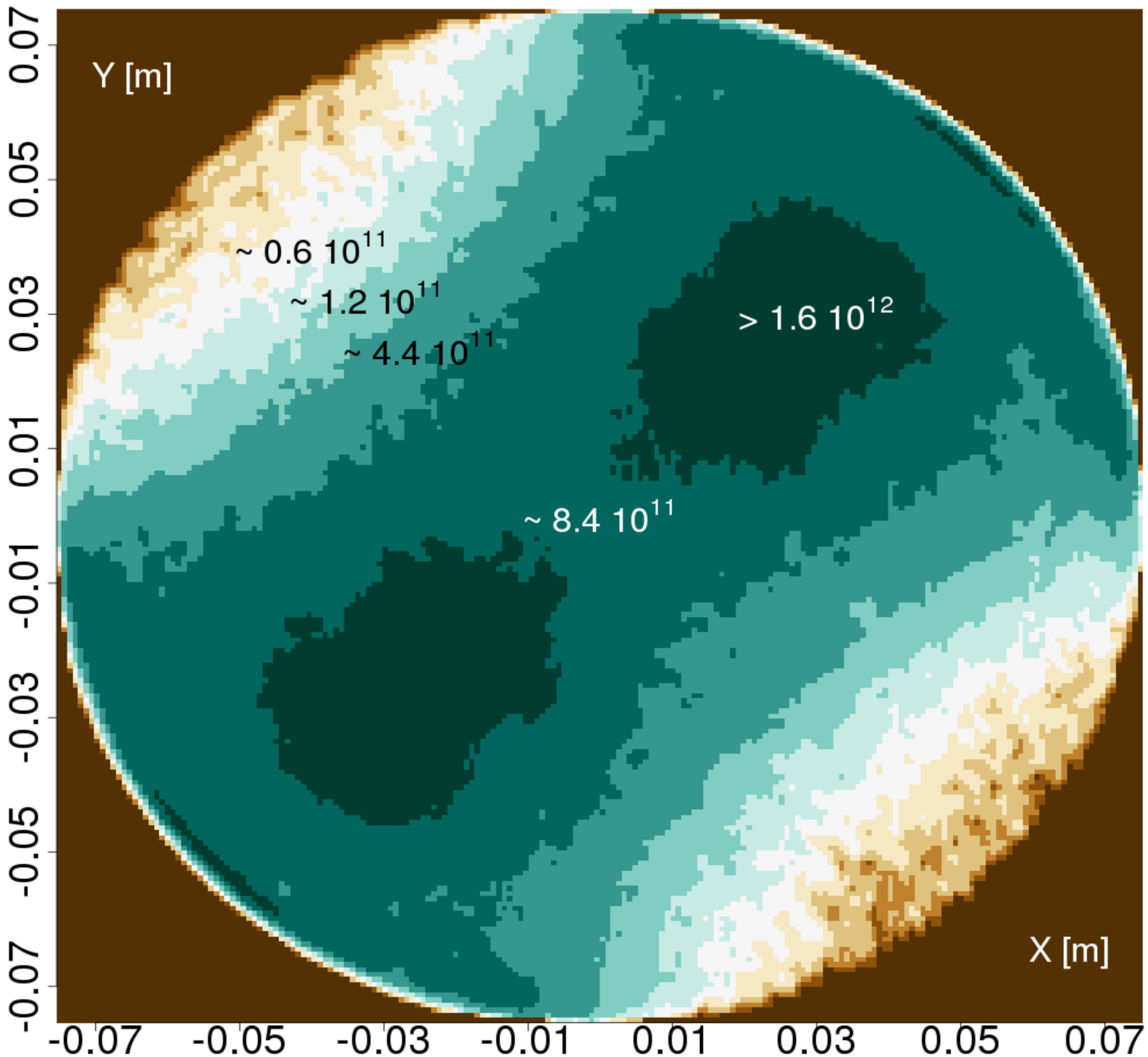


- The charge density fluctuates by ~50% as bunch crossing occurs. Shown here is the EC density in 5 different field configurations, vs the distance to the nearest bunch.
- Obtained for high SEY ("saturated EC")

Simulation of the RFA.

- Installed in straights, where beam pipe is larger. (6” instead of 2”x4”)
- Simulation: simple, but effective: the slits are simply implemented as surfaces where the SEY is zero (perfect absorption, no re-emission.)
- Poorly characterized stray field from the quadrupole and dipole bus do affect the yield of electrons close to the RFA slits.

Transverse density profile below the RFA.



Bx = By = 7 G.

Slits are on top, and do see a biased image of the EC.

Conclusions

- VORPAL provides a fully consistent, truly 3D, simulation of the Electron Cloud (EC)
- As the secondary emission yield for scrubbed stainless steel is not know with enough accuracy, no "ab-initio", quantitative prediction about the "EC problem" for current (or Project-X) running conditions can be made
- Yet, if we have "No EC problem" now, this calculation shows that we will **not** have a problem when the proton bunch intensity goes up by a factor 3.
- Simulation of simplified two EC detectors have been done, but exact, quantitative comparison are pending due to difficult experimental conditions.

Backup: Some details about

(I) Microwave measurements

(ii) Kinematics of the cloud.

Microwave Absorption experiment : Phase Shift w/o electrons

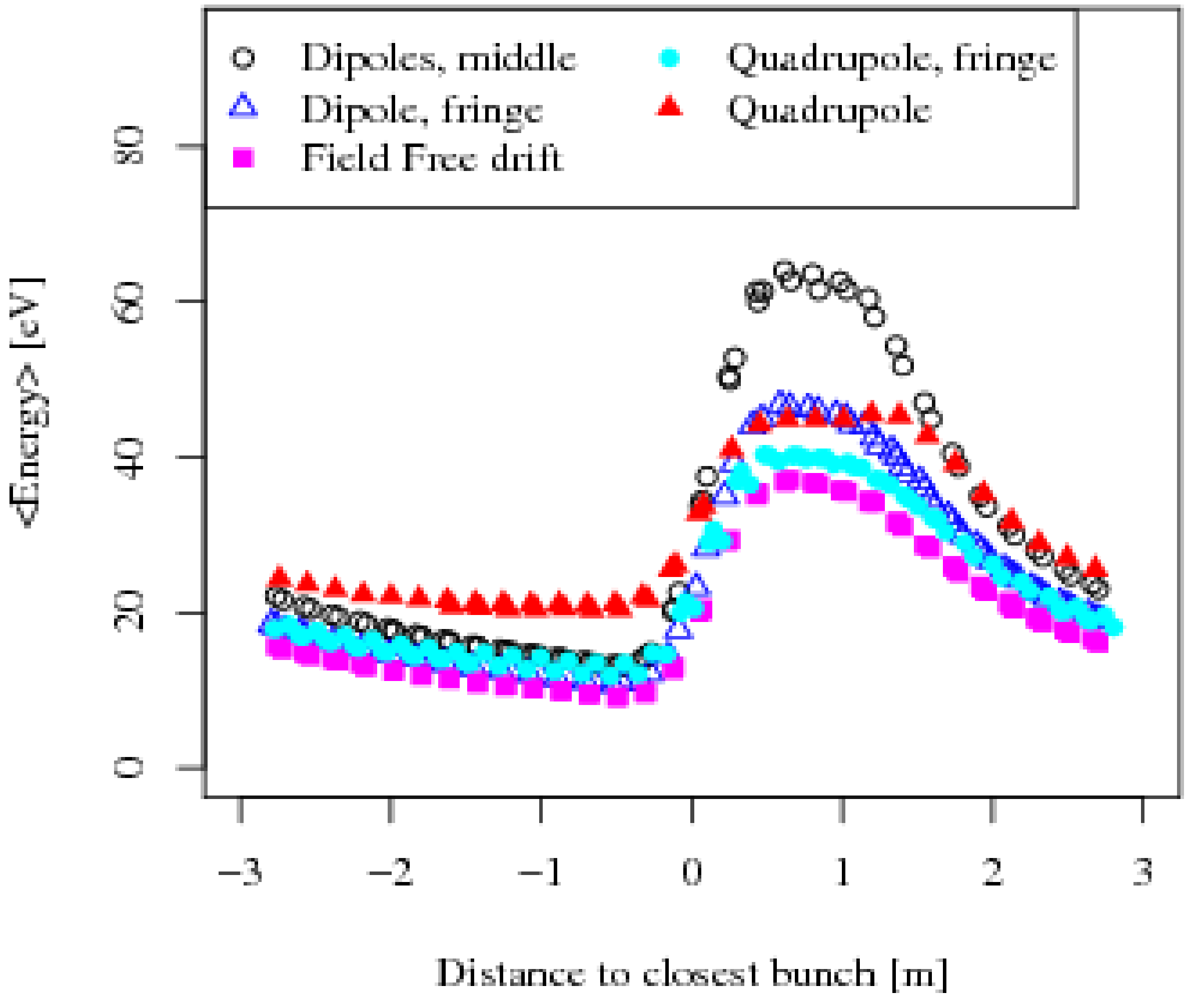
- "Virtual antenna/BPMs installed as VORPAL current sources and PseudoVoltage probes, respectively. No detailed simulation of these devices.
- Running with and without the EC, for the same RF sources, same proton beam. Then subtract the pseudo voltages, FFT, and from the amplitude at 1.6 GH, deduce a "linear Phase shift".
- Caveats:
  - Easy to do in the simulation world, not possible with the real MI.
  - Also, perfectly matched layer absorb all RF wave in the simulation. In reality, reflection(s) of the 1.6 GHz RF on changes of the X-section of the pipe makes life real lifer very complicated
  - No firm experimental results to compare to!.

Linearized Phase Shifts results

BPM Distance (m.)	D $\Delta\varphi$ [radian]	$\Delta\varphi/D$ [radian/m.]
1.8	0.067	0.037
7.8	0.21	0.027
13.8	0.37	0.027

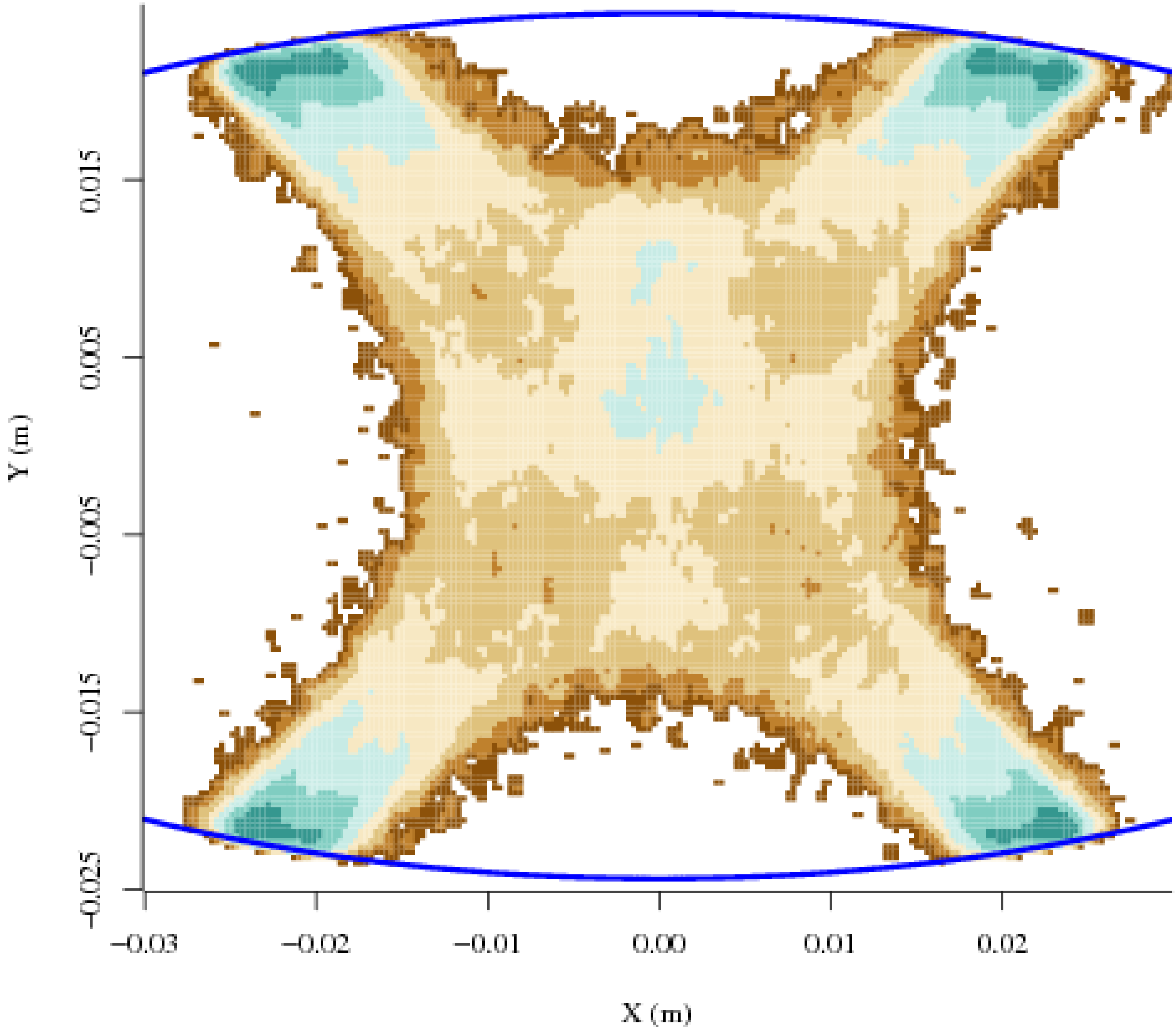
Obtained for a high SEY (~2.2), in dipoles. Results are very similar in quadrupoles. Deviations from simple linear theory for short distances is perhaps due to the fact the wavelength is actually greater than the distance between BPMS, and/or $\Delta\phi$ too big...

Kinematics.



- The average energy versus distance from the nearest bunch, in steady state for the saturated EC.
- This average is dominated by low energy, recently emitted electrons.

Peak energy is a factor 5 to 10 higher.



X-Y distribution of the cloud in a quadrupole.
Note: few electrons where the BPM plates are located.
(Also a good candidate for
"Proect-X logo!)