E-Cloud Studies at the Fermilab Main Injector

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1 Tech-X

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Project X

A Status/Update report, since Ecloud'10, In Summary..

- Currently, the e-Cloud at the Main Injector is not a limiting factor in reaching our physics goals. Nor will it be during the upcoming Nova run (starting in less than a year from now).
- However, in the Project-X era, where the bunch intensity will be 3 times higher, previous calculations have shown that the a potentially detrimental threshold could be reached, leading to unacceptable beam loss due to e-cloud induced instabilities.
- New simulations showed that this might not be the case, as the anticipated electron cloud density close to the beam will not scale linearly with the bunch charge: a more moderate increase will occur. These findings prompted a new round of simulation benchmarking, which confirmed the findings gotten in 2010 with the VORPAL simulation code.

The differences between POSINST and VORPAL being understood, the E-Cloud densities and field maps were generated for bunch intensities expected under Project-X (phase 0,... or last phase), using the 2D approximation.

Retarding Field Analyzer (RFA) simulations have been performed.

Discussions on the proposed experimental plan have occurred.

Outline

- VORPAL-POSINST benchmark: Results and lessons learned.
- Highlights on e-cloud densities in M.I. Dipoles (or quadrupoles)
- RFA simulations (if time permits)
- Short and long term plans for EC studies at MI.

VORPAL-POSINST benchmark, success

• Goal: compare the electron densities at the beam location, POSINST vs VORPAL. They should be with ~ 10 % of each others. (The density of electron very close to the surfaces where secondary emission occurs being a bit ill-defined and ultimately not that consequential).
• First results (Jan 2011): discrepancy!.
• Worth pursuing... (~2 to 3 man months extra)
• ~ July 2011 : Even with the same initial conditions, the “dynamical” EC, i.e., replenished bunch after bunch, did not had the same density in Vorpal (2D or 3D) vs POSINST. ==> presented “redux” benchmark: space charge field calculation for a given cloud and EC lifetime, in absence of secondary emission at the wall.
•Aug-Sept 11: Not good enough!. Back to detailed studies of the POSINST vs tech-X code... As previously mentioned by M. Furman, indeed, the “true” secondary emission in POSINST was not quite adequate for high SEY (2.2) .. Yet, such SEY are not necessarily unrealistic (and, for SEY ~< 1.35, no EC).

POSINST: Code modifications.

- Expand the array sizes for the EC 6D phase space (kinematics of the macro electrons). Provides protection against memory over-write.
- Sub-component testing: Allow to upload a given EC from VORPAL, and re-start a POSINST simulation.
- Complete re-coding of the generation of secondary electrons, to fix the non-poissonian behavior at high SEY. Based on *Numerical Recipes* rather then ``own code”
- Numerous “scaffolding” code to debug the differences, one by one (kick calculation, Poisson solvers, SEY routines, etc...
- Maintained in the Synergia ``git”, for posterity.

Old POSINST results.., LBNL-4251E

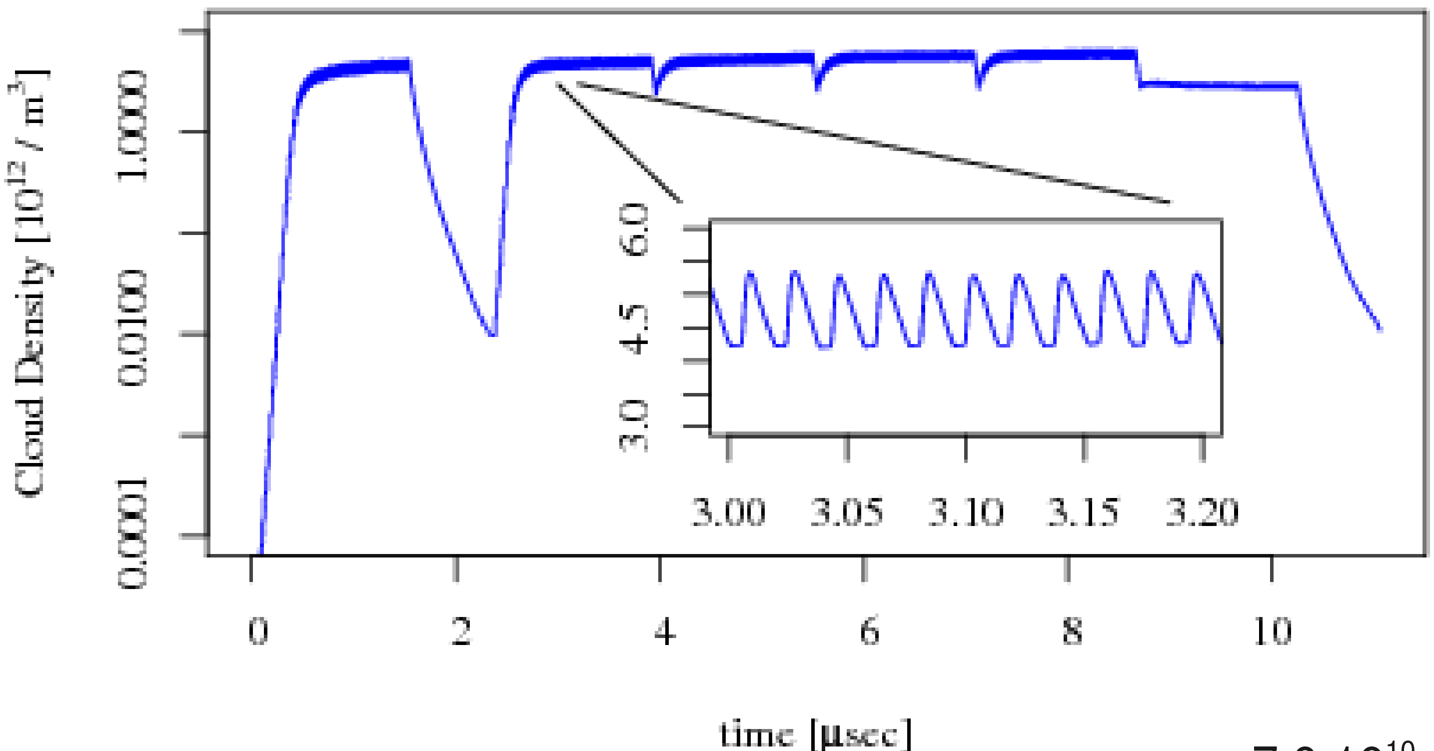
- Delivered in late 2010 to the Main-Injector..
- Conclusions
  - Critical SEY ~ 1.2 to 1.4 ==> **O.K.**
  - For high SEY (>~ 1.3), threshold behavior in proton current... ***Not seen in VORPAL.***
  - Weak dependence on beam energy => **O.K.**
  - Virtual Cathode effect: sudden change in EC density ***Not seen in VORPAL.***

Suggested changes to POSINST 15.3

- Expand (or make them dynamical) the arrays that contain the phase space, to defeat unwanted limitation on the number of macro electrons.
- Improve the simulation of true secondary electrons at high SEY, following Poisson distribution.
- Note:

  Most of the work in this benchmark exercise was to install plenty of ``scaffolding”, or interfaces, , such that detailed comparisons with other code(s) can be done, via the exchange of phase space describing the e-cloud, Poisson solver(s), etc...

New POSINST result, higher SEY. Same beam conditions.. (Fermilab TM-2524-APC)



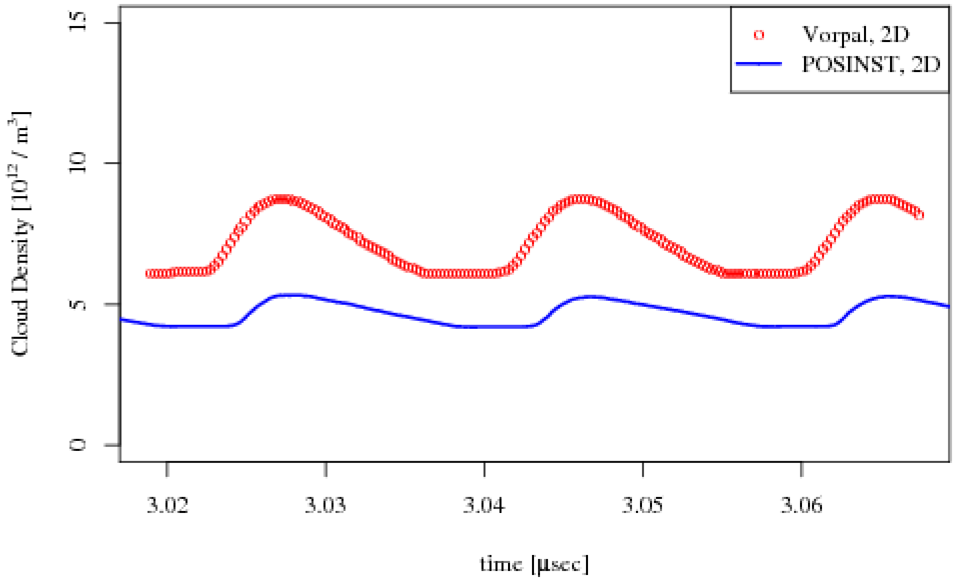
Smooth..

With sufficiently high number of macro electrons..
.
Grid size 64x64.

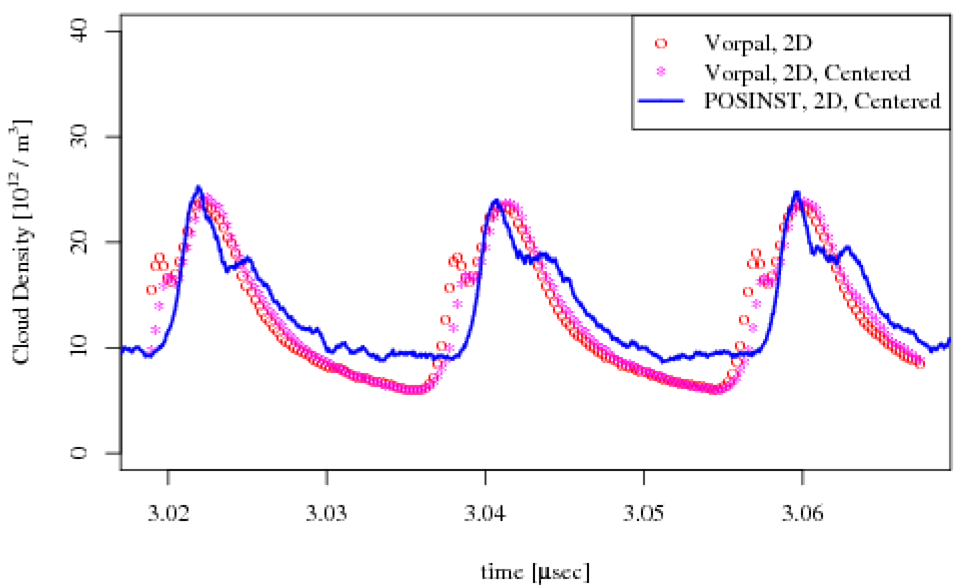
Sey ~ 2.2 (High!) Mean “true secondary” ~ 8.!

7.0 10^{10} protons/bunch, Δ y = 2.5 mm. In the MI dipoles.

New POSINST vs VORPAL.



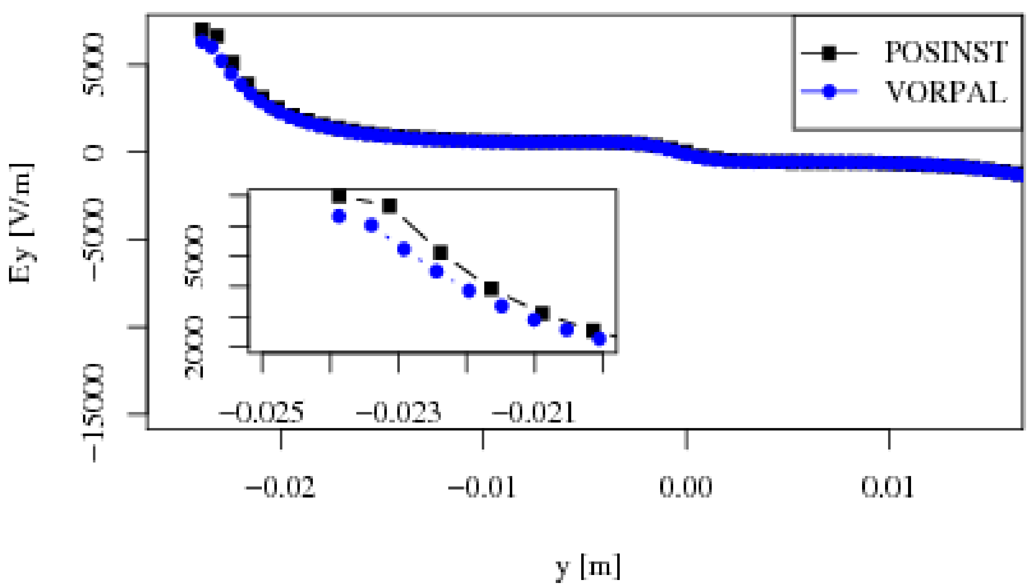
Averaged over the whole volume of the pipe.
Same beam condition as previous, in saturation phase.



Density in the center of the pipe, where it counts (i.e. near the beam..)

VORPAL is a bit more precise, as the time step is about a factor ten smaller. Also, more macro -particle.

New POSINST vs VORPAL, remaining diffferences.

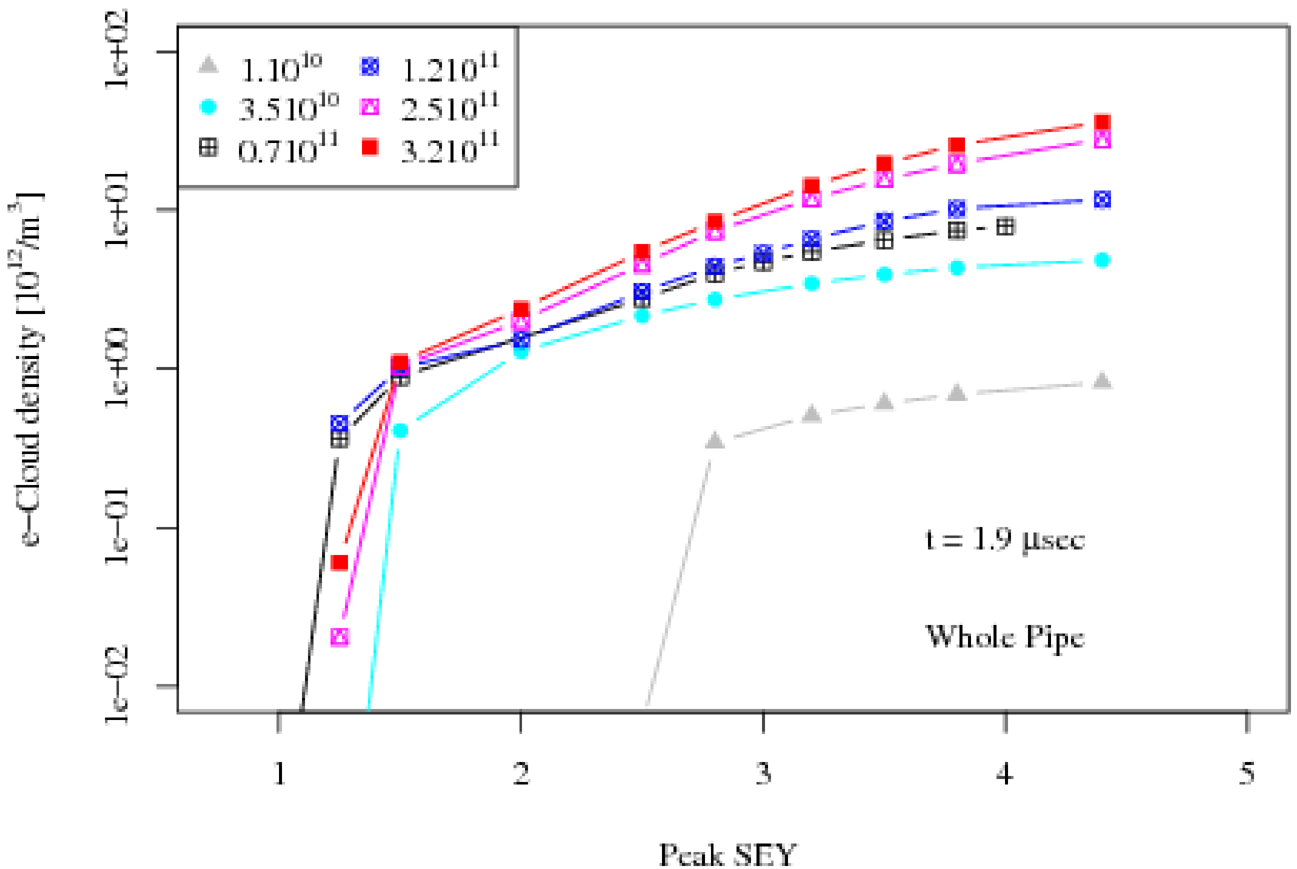


Electric field, vertical component, as a function of the vertical from the center of the beam pipe.

The Poisson solvers in POSINST and VORPAL are different, as well the approximations close to the beam pipe wall, where there is a discontinuity. (skin depth at MHz → GHz range much smaller than cell size).

Although this is essentially an electrostatic problem, neither code uses an adaptive grid to tackle the steep gradients in EC density and E fields near the wall...

On the e-Cloud density vs bunch intensity and SEY.

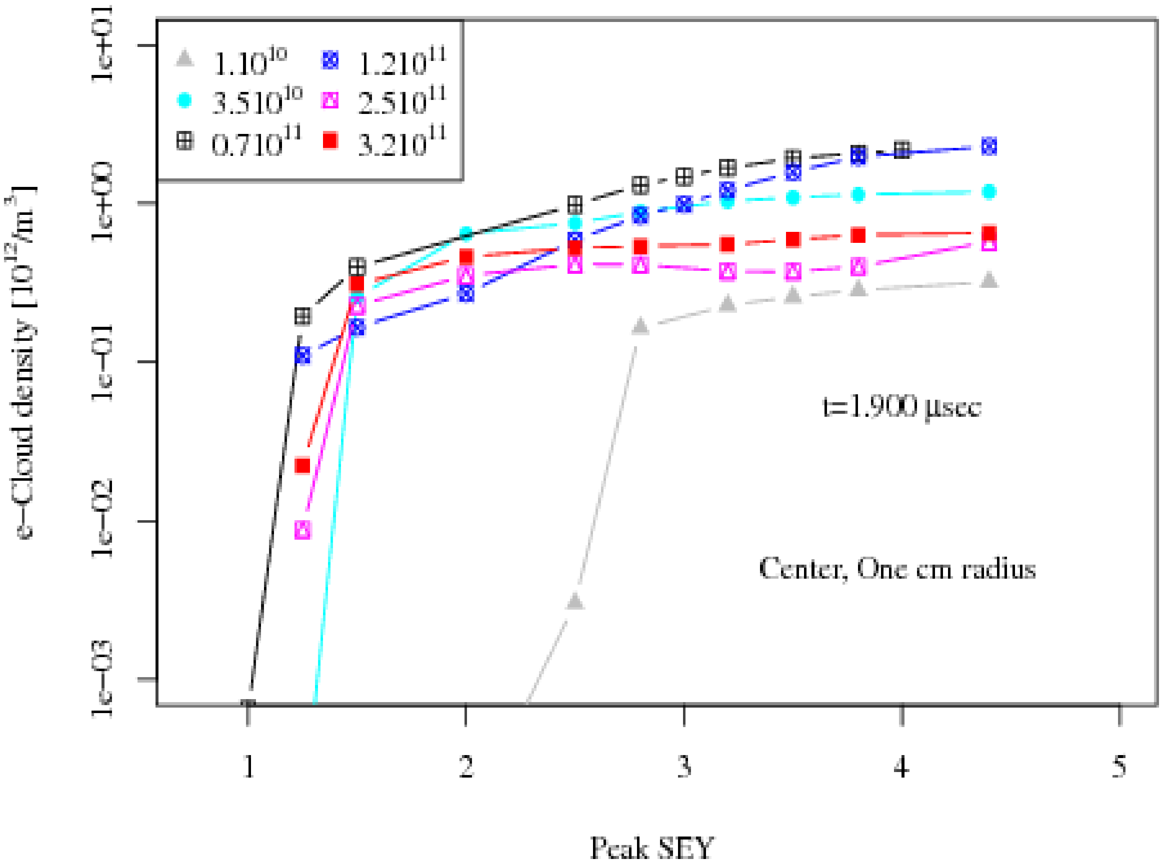


Ecloud density as a function of SEY for different bunch intensity.

The bunch spacing is 18.8 ns, bunch witdth 1 ns (realistic at 20 GeV).

Averaged over the whole volume..,
snapshot taken 3ns after the passage of the bunch

On the e-Cloud density, close to the beam



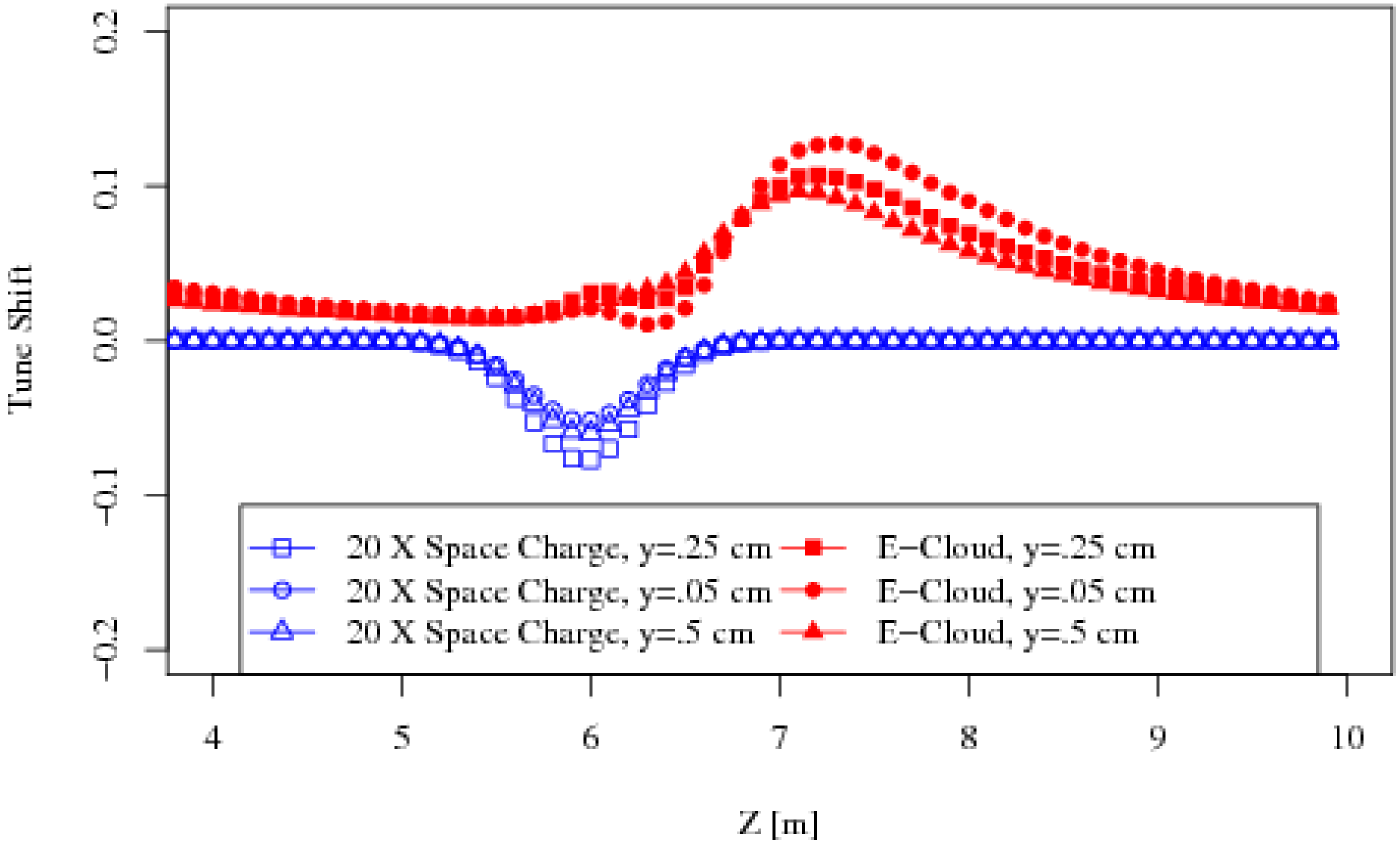
Beam dynamics is unlikely to be directly affected by the density close to the beam pipe walls.

So let us look closer to the beam, at ~ 1 cm.

There

The current operating point is between 0.75 and 1 10^{11} protons per bunch.
Close to the optimum to get maximum density, should the SEY be large.

Approximate e-Cloud Tune shift with respect to Space Charge Tune shift. At 20 GeV, 0.7 e11



Note: longitudinal motion simply ignored.

EC Beam Dynamics in Synergia

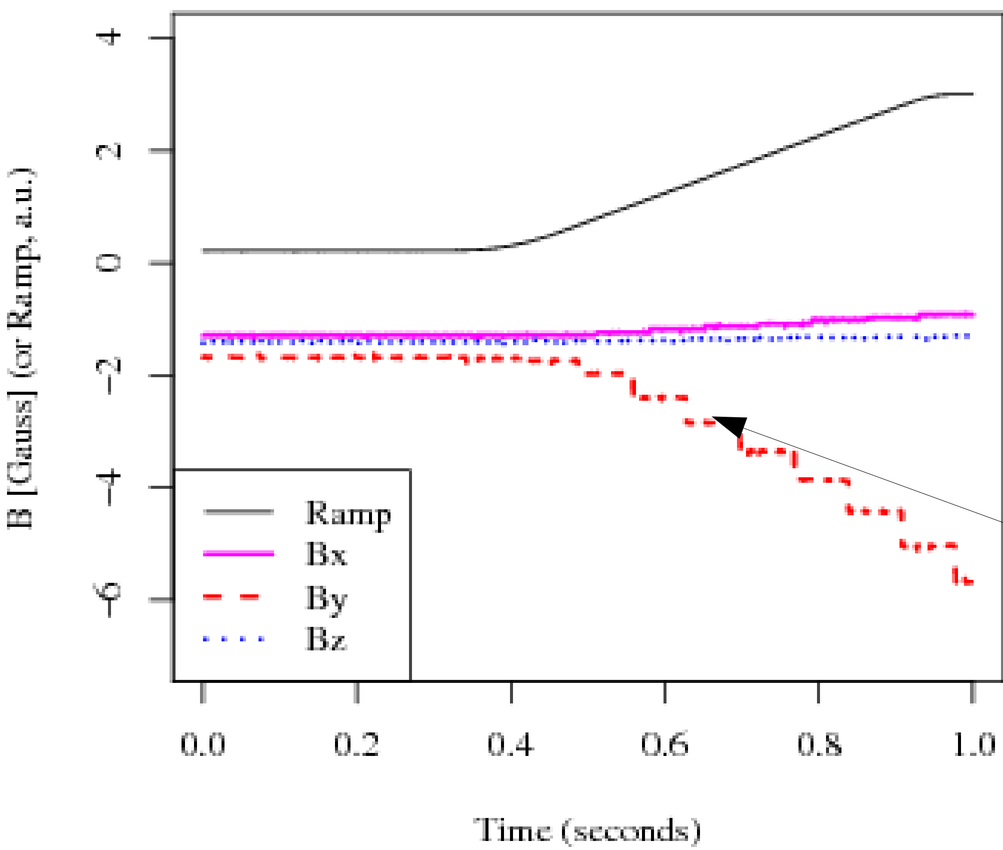
- Previously: based on the VORPAL 2D electric field maps, an effective tune shift has been estimated, using the same reasoning as for getting an estimate of the space charge tune shift. Found large ($\delta\nu$ ~ 0.1) effect, but only in the tail of the bunch, at 3 to 5 sigma away from centroid. The cloud, too close to the walls, does not move fast enough to get to the beam region when the bunch is going through.
- Crude calculation: must be confirm this by tracking. With the correct lattice optics, and at low energy, with space charge. Status:
  - Converted VORPAL 2D maps to Synergia “rectangular grid” fields, ready to be integrated.
  - When the MI model is fully implemented, with space charge, then install these fields and track...
  - Regenerate EC maps if need be. Iterate...

E-Cloud in Synergia: 2 strategies.

- Vorpal based E-fields.
  - Extract e-Cloud field maps from VORPAL, 2D or 3D sims.
  - Read these maps in Synergia, use to compute elements by elements, steps by steps kicks for all macro-particles.
- Re-implement POSINST in Synergia using the existing low-level tools (2D Poisson solver, I/O, tools for handling collection of macro-particles)
  - And link against the Tx-Physics library for secondary electron generation.
- These are in a sense the “short term” vs “long term” approaches. Both are worth doing/implementing.
- In any event, perform the final proton beam (beam dynamics) simulation and analysis in Synergia.

Support of the E-Cloud studies @ MI: RFA Simulation.

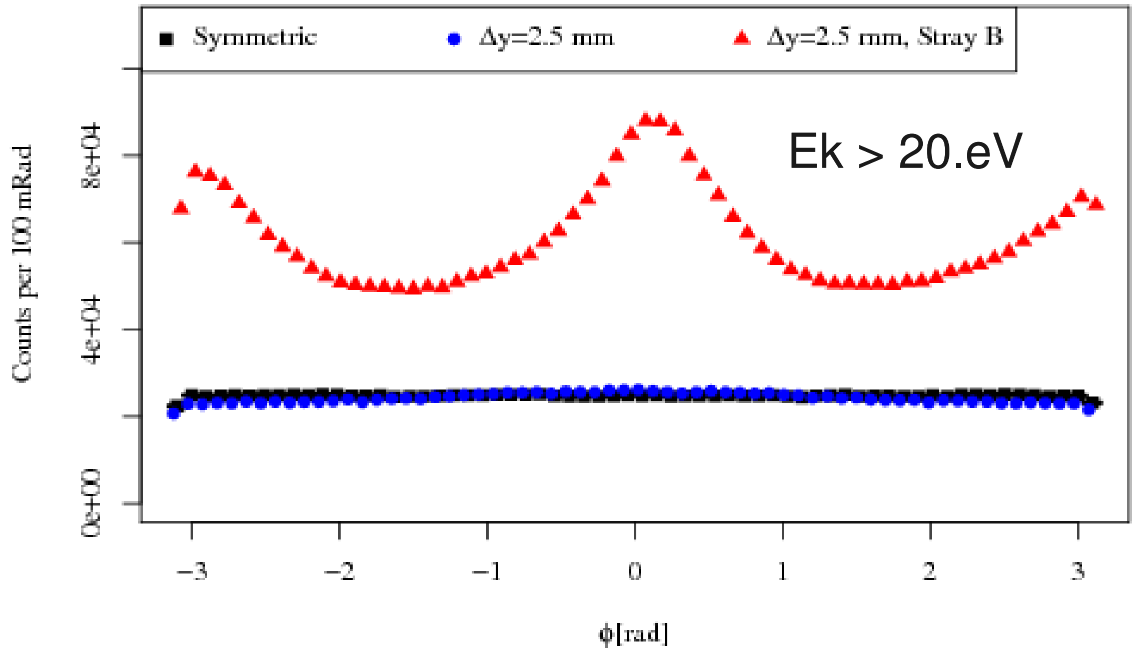
- New measurements of the stray magnetic field near the RFA

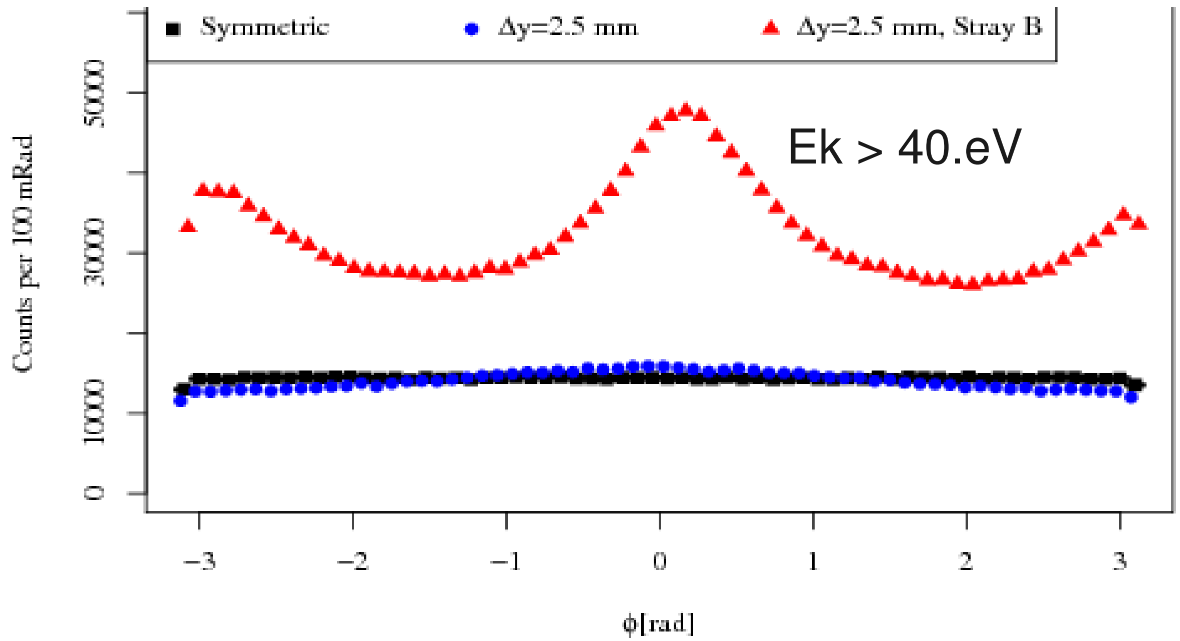


Bx ~ -1.7 G
By = 2 to 6 G.

Not completely negligible: at ~ 3 sigma away from the beam, the field created by the proton beam is about 1 Gauss.

At about ~ 20 to 30 GeV... let us simulate.. By ~ 3.3 G





At time t=201 ns,
No stray field
With stray field

The kinetic energy of the electrons also matters.

The ϕ spectrum for E > 20 eV and E > 40 eV look similar.

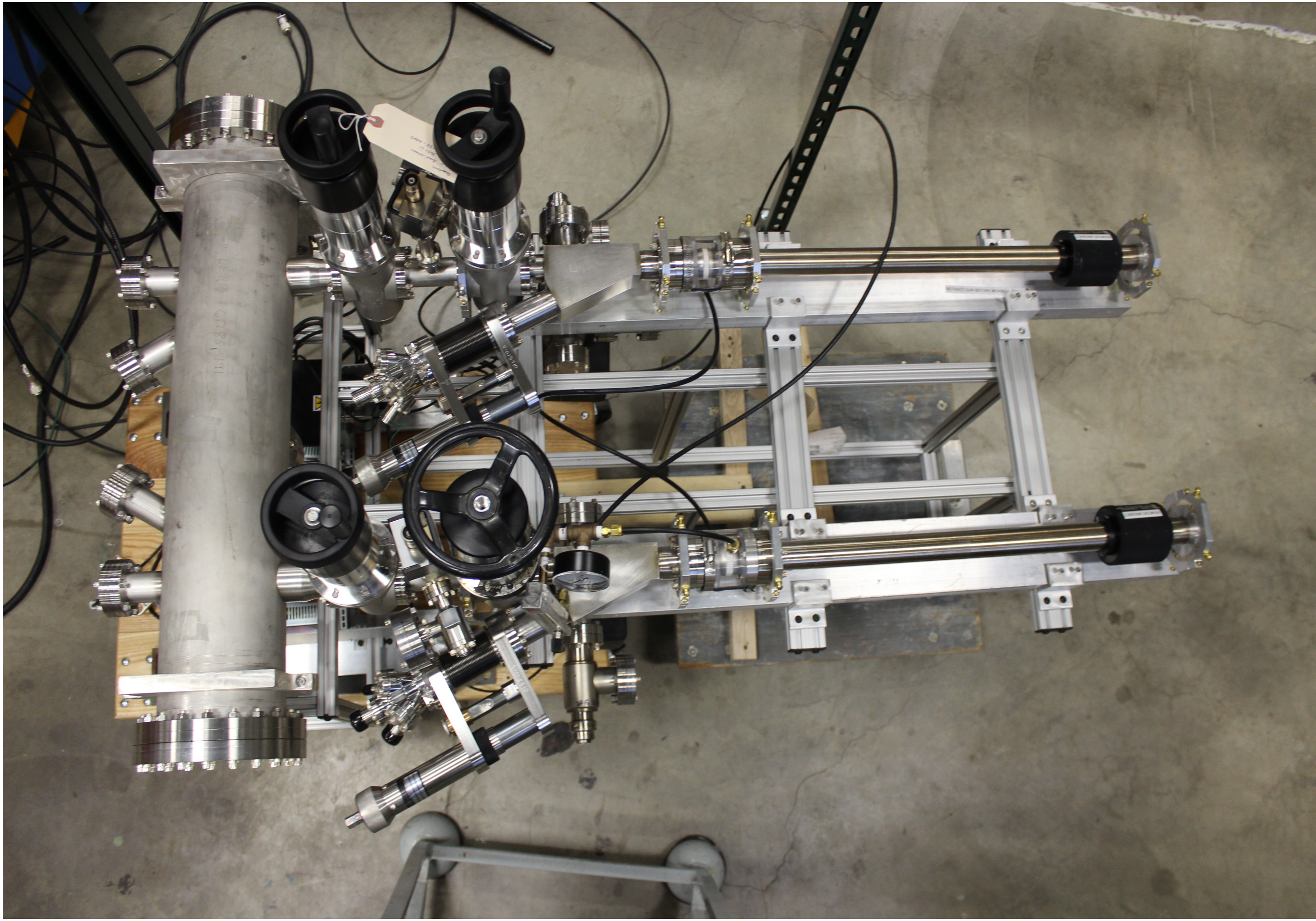
But of course the RFA count should decrease going from 20 V to 40 V bias field.

Note the slight offset in Phi, due to the non-zero Bx field.

Note 190 real electrons per Macro-electrons.

Proposed experimental plan: 2012 shutdown

- Installation of SEY measurements device “in situ” in a “low stray magnetic field ” region.
- Install an extension solenoid close to the RFA, to make sure we are counting electrons from “the cloud”.
- Install a faster high gain pre-amplifier such that we can resolve booster batches (~10 MHz ?) Difficult, as tunnel environment noisy... Not yet worked on...
- If not working, resurrect the idea of installing image amplifier, or optical detection of ~50 eV electrons on ad-hoc scintillator. Or borrow detectors from Cornell???



Proposed experimental plan: Long term

- RFA and current beam dynamics indicate that “scrubbing” helps.
- If so, it must depend on the fluence of ions, electrons, hitting the pipe.
- Which depend on the magnetic field configuration. Indeed, the local EC density changes by orders of magnitude when the magnetic field changes.
- => need to measure the changing SEY in-situ,
  - i.e., in a dipole, as our (potential) EC problem is in the arcs!.

Dedicated EC dipole at the MI.

- Acquire two short (leaving the lattice invariant) dipoles, ~.2 to .3 T. field.
- Relatively wide gaps, such that the top/bottom of the pipe (same as in the arc dipole!) can be instrumented.
- Such magnets exist (or did existed) : Old TeV IPM magnets (it not already called for..)
    - -Adapt the SEY setup (add, if need be, a set of compensating coils to be activated during SEY measurement, with EC dipole off).
    - Add adhoc instrumentation.
- Understand the current mystery about the vanishing RFA signal above ~25 to 30 GeV in the MI ramp. Are we sure the SEY stays constant on “fast” (few seconds!) time scale?

This is more important than finessing the simulations!...

Conclusions

- VORPAL & POSINST differences fully understood. No changes to the VORPAL code are needed. Previous conclusions stands.
- Tentative explanation for the disappearance of the RFA e-Cloud signals above some MI energy: not confirmed, if the field direction measured by the probes are correct. This remaining ``mystery" should be addressed...
- Next set of simulation and Synergia (beam dynamics) calculation in preparation.
- Suggested experimental program at MI, based on the following observations: E-Cloud still a complex phenomena, where beam pipe geometry, timing consideration and magnetic field do play a role. Meanwhile SEY remains largely unknown. And it must be measured in-situ, i.e., with the actual B field in place.

Backup slides

Sudden change in the density..

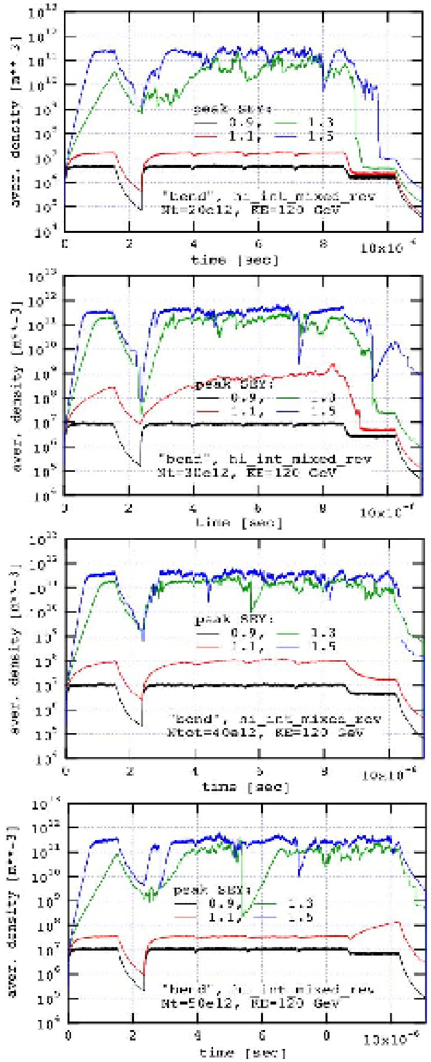


Figure 5: Build-up of the average ecloud density during one turn in a "bend" region, at $E_k = 120$ GeV, for the fill pattern "hi_int_mixed_rev" for $N_t = (2, 3, 4, 5) \times 10^{13}$, as labeled. Each trace corresponds to the indicated value of the peak SEY $\delta_{\max}$.

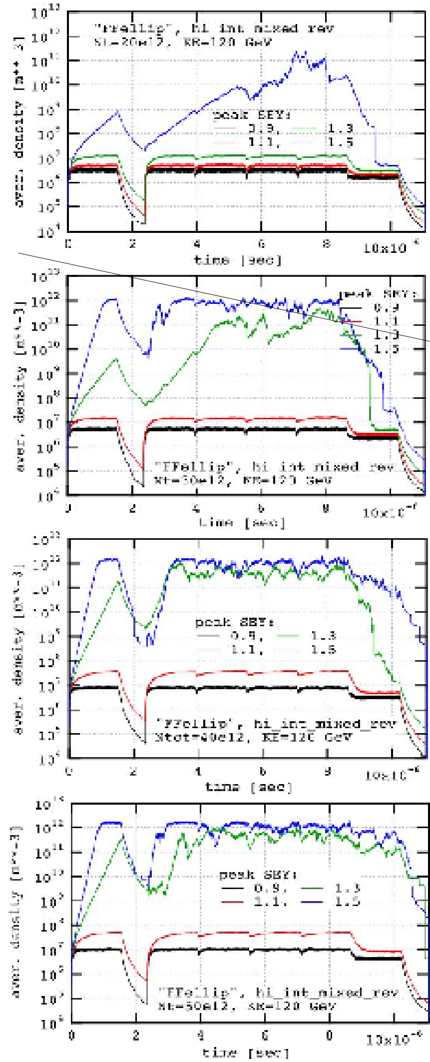
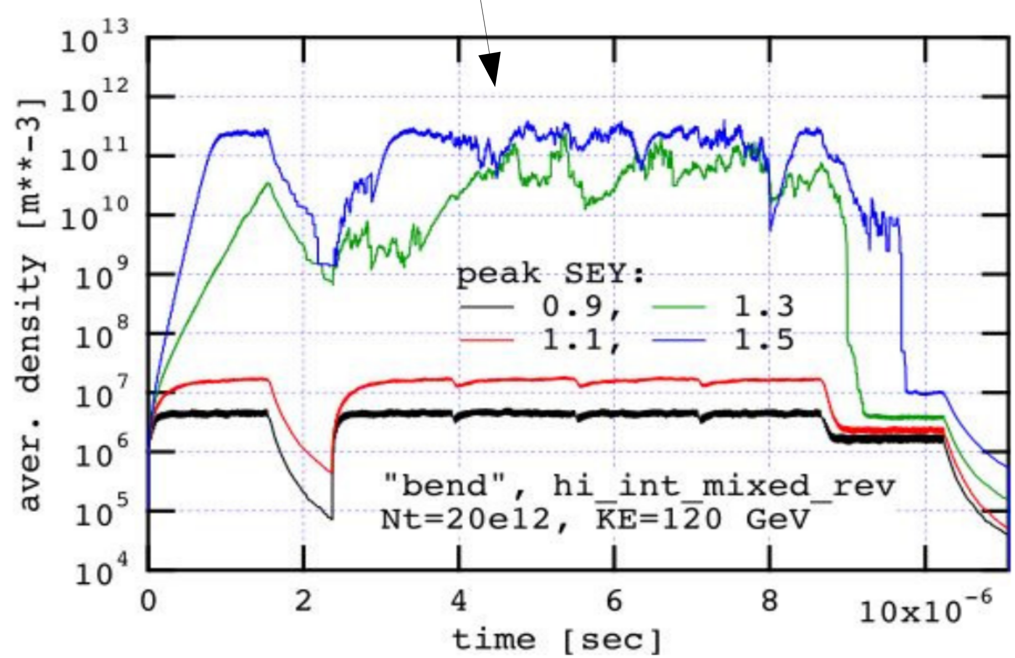


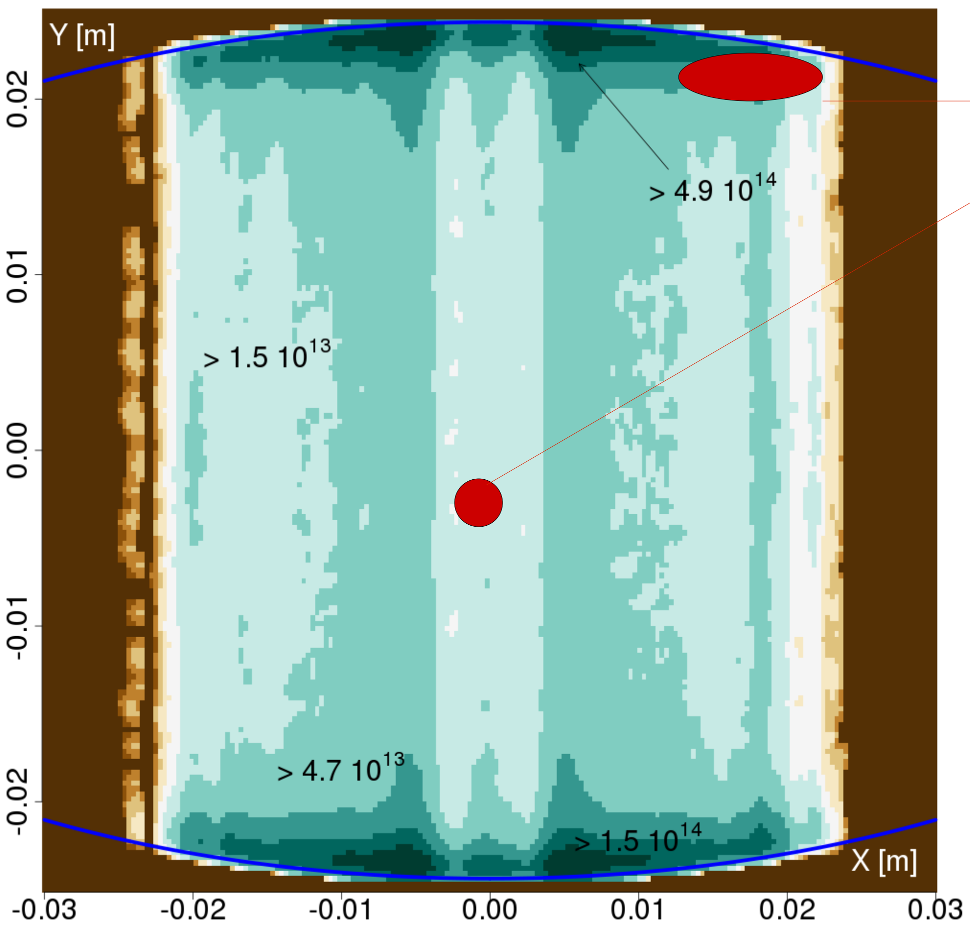
Figure 6: Build-up of the average ecloud density during one turn in a "FFellip" region, at $E_k = 120$ GeV, for the fill pattern "hi_int_mixed_rev" for $N_t = (2, 3, 4, 5) \times 10^{13}$, as labeled. Each trace corresponds to the indicated value of the peak SEY $\delta_{\max}$.



POSINST, Prospects...

- Having a 2D code, for problem where there is a symmetry that allows us to reduce the dimensionality, good to have a EC simulation tools that belongs to the community. (open software. ***This is very valuable***).
- Must have well defined run interface such that it can be used in conjunction with Beam Instability code, such as Synergia. Must also be able to run stand-alone.
- Still a CPU intensive problem. Parallelism is a must. For instance, transport for macro-electrons in the field can be run in //. So do modern POISSON solvers..
- Requires almost a complete re-write. However, algorithms needs to be simply adapted, but not re-invented from scratch. Manageable task.

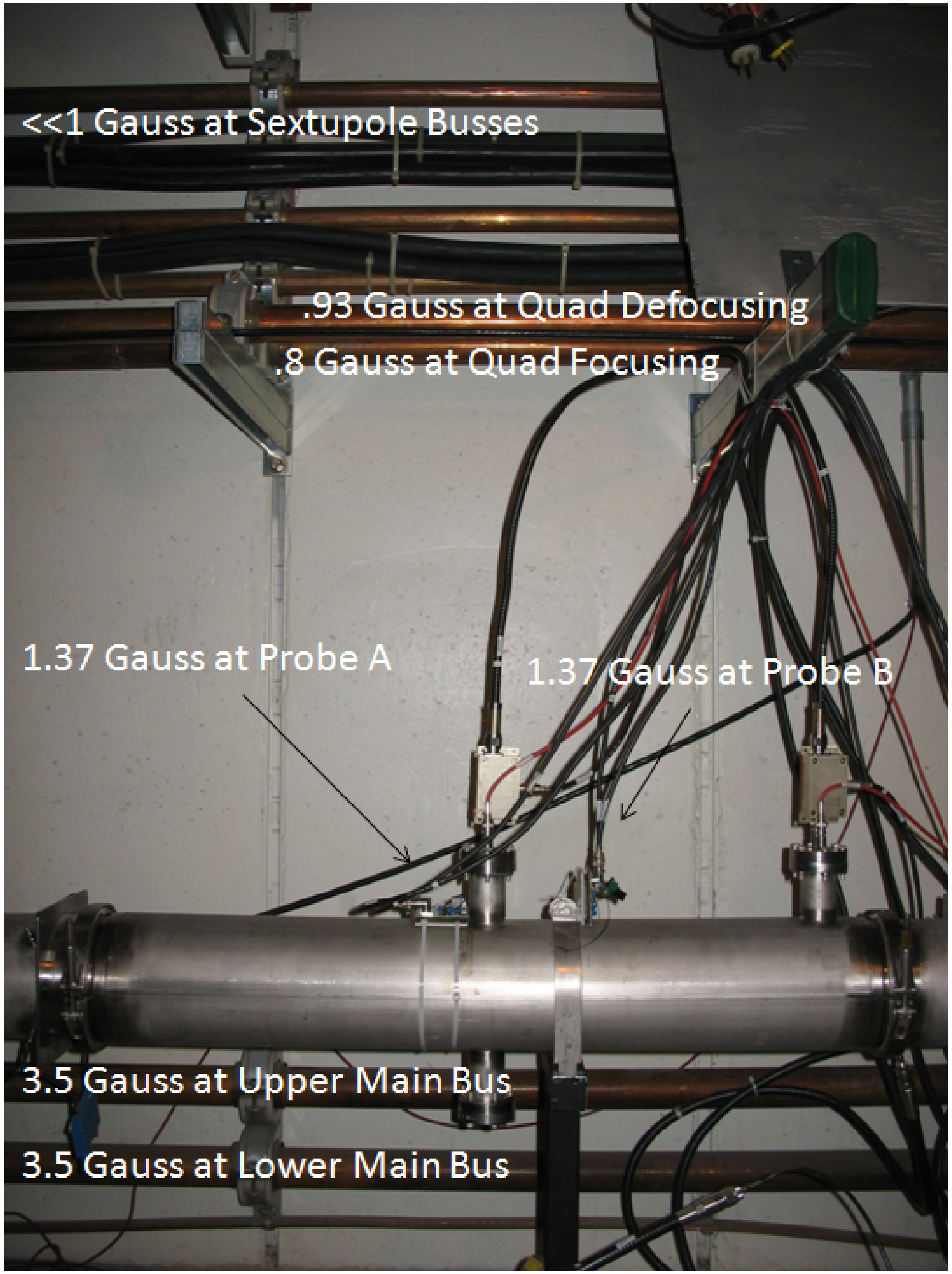
On Initial Conditions...

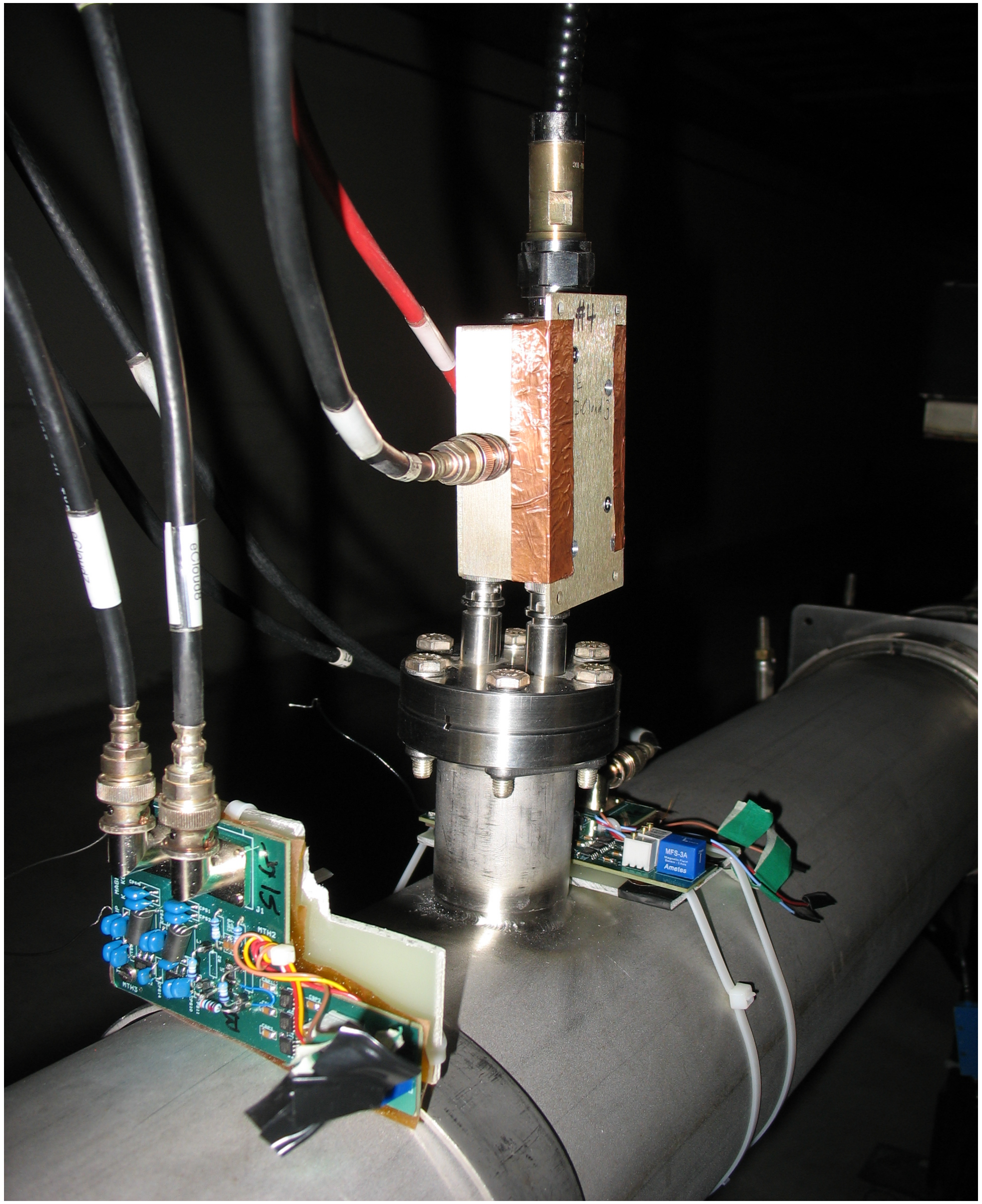


Typical Vorpal e-density map, transverse

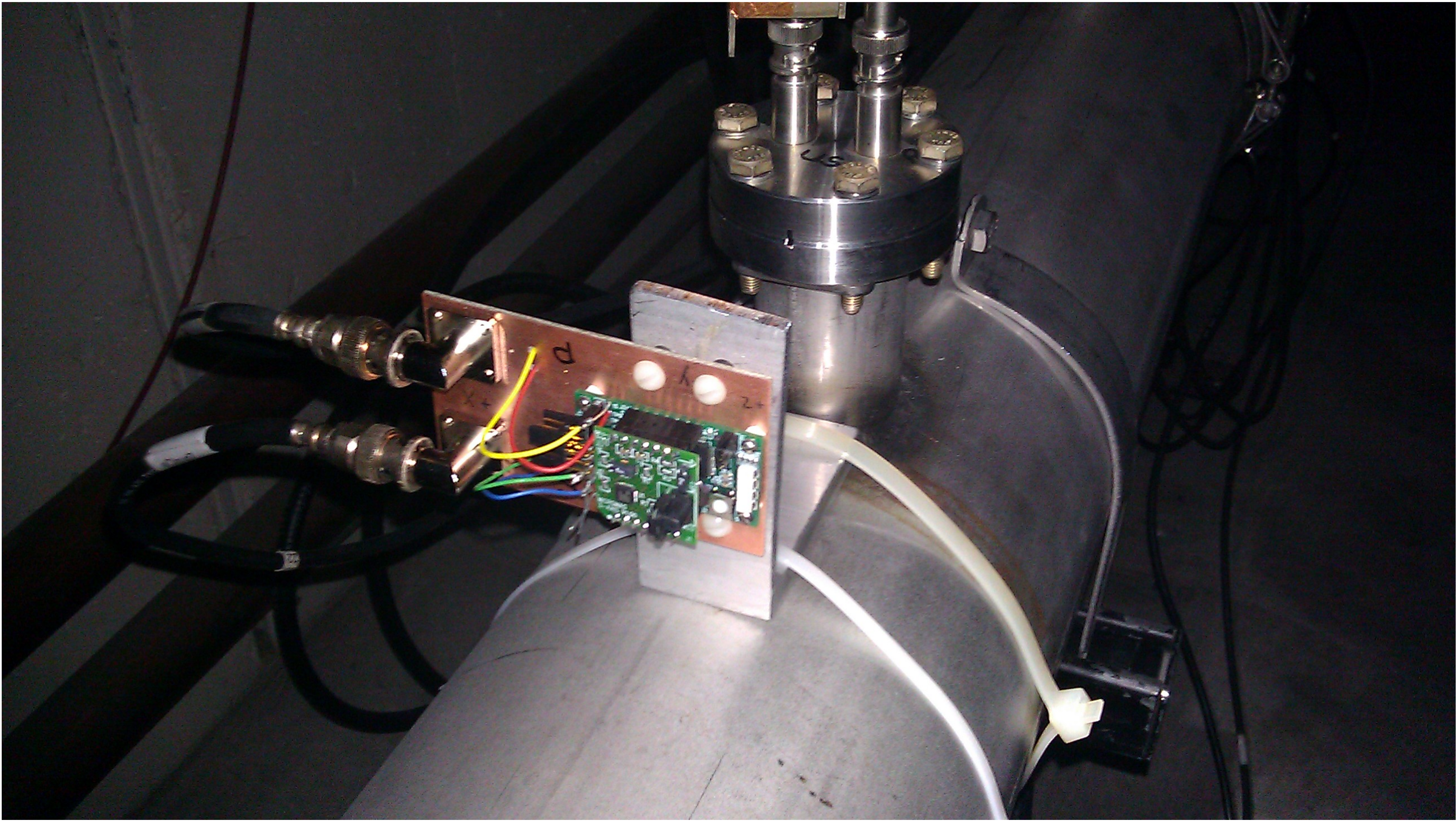
Possible locations of seed sources:
- Beam region (ionization of residual gas)
- Beam loss induced at highly localized hot spots.

Electrons are confined to move up and down along to the magnetic field lines, to first order. But, close to the beam, strong fields can “mix-up” the cloud and spread the cloud. On the other hand, if the hot spot located too far away from the center of the pipe along the X direction, the electrical fields are weaker, kinetic energy of electrons are smaller, less efficient wall-emitted emissions of secondary electrons. Averaged density changes... This effect has been seen in both codes.


<<1 Gauss at Sextupole Busses
.93 Gauss at Quad Defocusing
.8 Gauss at Quad Focusing
1.37 Gauss at Probe A
1.37 Gauss at Probe B
3.5 Gauss at Upper Main Bus
3.5 Gauss at Lower Main Bus



Upgraded to....



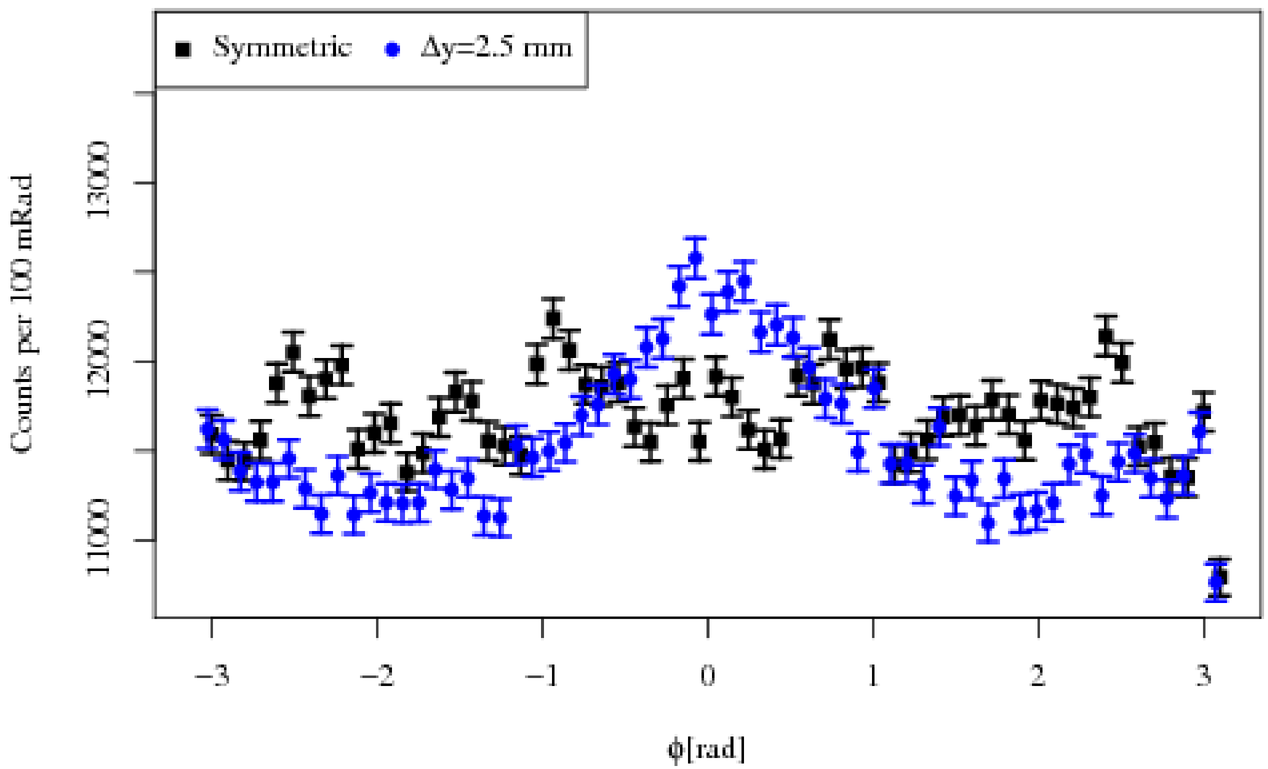
RFA Simulation details..

- 2D or 3D ? This stray magnetic field brakes the symmetry along the beam axis. A small beam offset brakes the ϕ symmetry. ==> go for the 3D treatment.
- Adjust the cell size such that, for centered beam, stray field off, the electron density is ϕ symmetric and flat along beam line, as the beam pipe upstream/downstream edges are far away (with respect to the beam pipe radius) from the RFA, located at the center of the setup. ==> 1.7 mm cell size. Obtained by trial & error.
- Install Perfectly Matched Layers at upstream/downstream edges such that the ~GHz E.M. waves generated by the EC are propagated correctly, as if the beam pipe was infinite. (Perhaps I am too picky, as the electrons are fairly non-relativistic..)
- Set the number of macro-particles such that the E field and density profile are smoothed. At the start!
- Culling required, as the density change by 2 to 3 orders of magnitude as the cloud builds up

Simulation of ~ 0.8 μsec : tedious

- Requires patience: a run takes easily one to two weeks on 16 cores. For detailed investigations, need to “dump” the state of the plasma (macro-particle coordinates and fields)
- Reduce the frequency of dumps during the exponential growth of the cloud, more detailed picture close to saturation (no patience to wait for a complete booster batch...)
- Total L = 2 m. + PMLs, Leff = 1.5 m., .075 x .075 transverse
- At: BX = -1.75 , By= 3.3 , Bz = 1.65 Gauss.
- Grid size 768x96x96 => ~1.7 mm transverse, and time step = 3.6 ps. => ~200,000 steps..

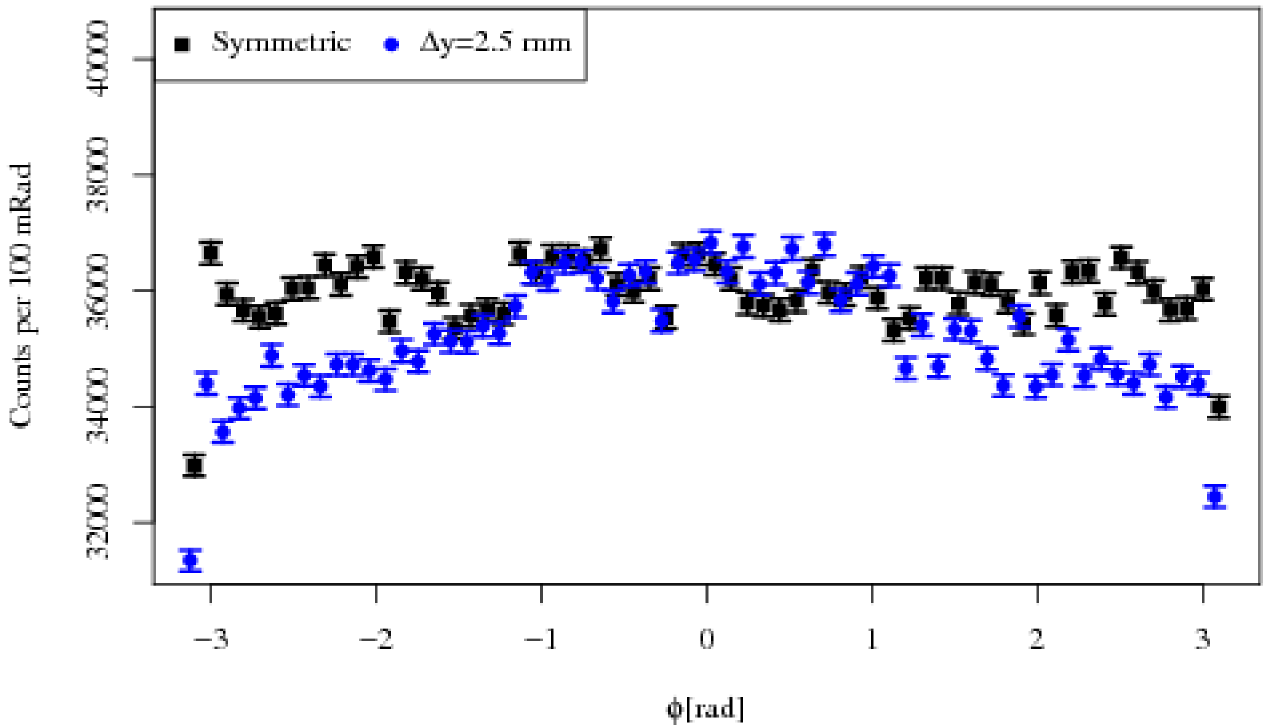
Azimuthal (ϕ) profile, t=128 ns



Symmetric case:
Some residual (~%) differences due to finite cells grid.

Beam Offset effect:
Prior to space charge saturation effects, a vertical beam displacement enhances the flux towards the RFA (located on top of the pipe..). Small effect..

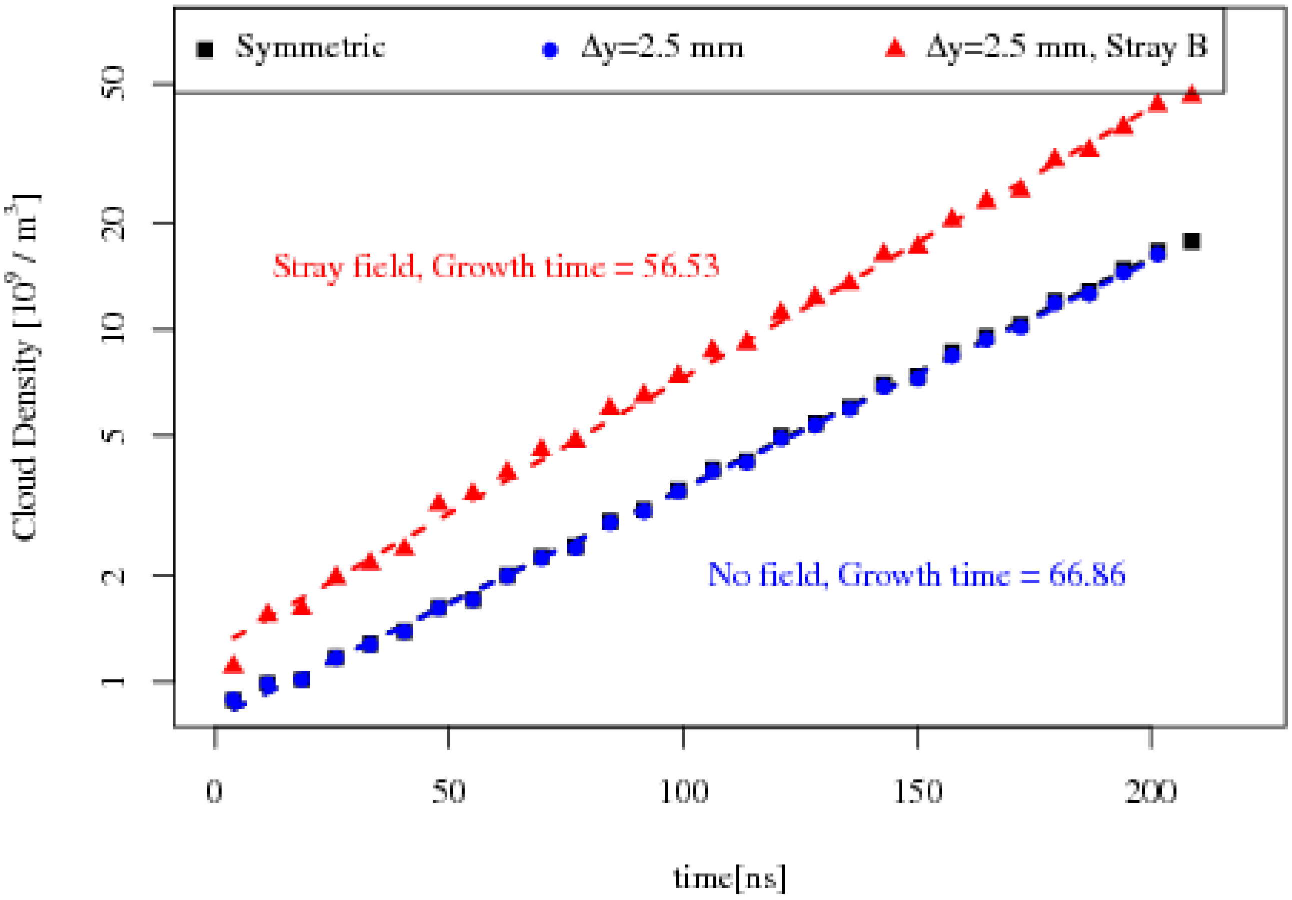
Azimuthal (ϕ) profile, t=135 ns



Symmetric case:
Some residual (~%) differences due to finite cells grid.

Beam Offset effect:
Prior to space charge saturation effects, a vertical beam displacement enhances the flux towards the RFA (located on top of the pipe..). Small effect..

Growth time: early after the gap.

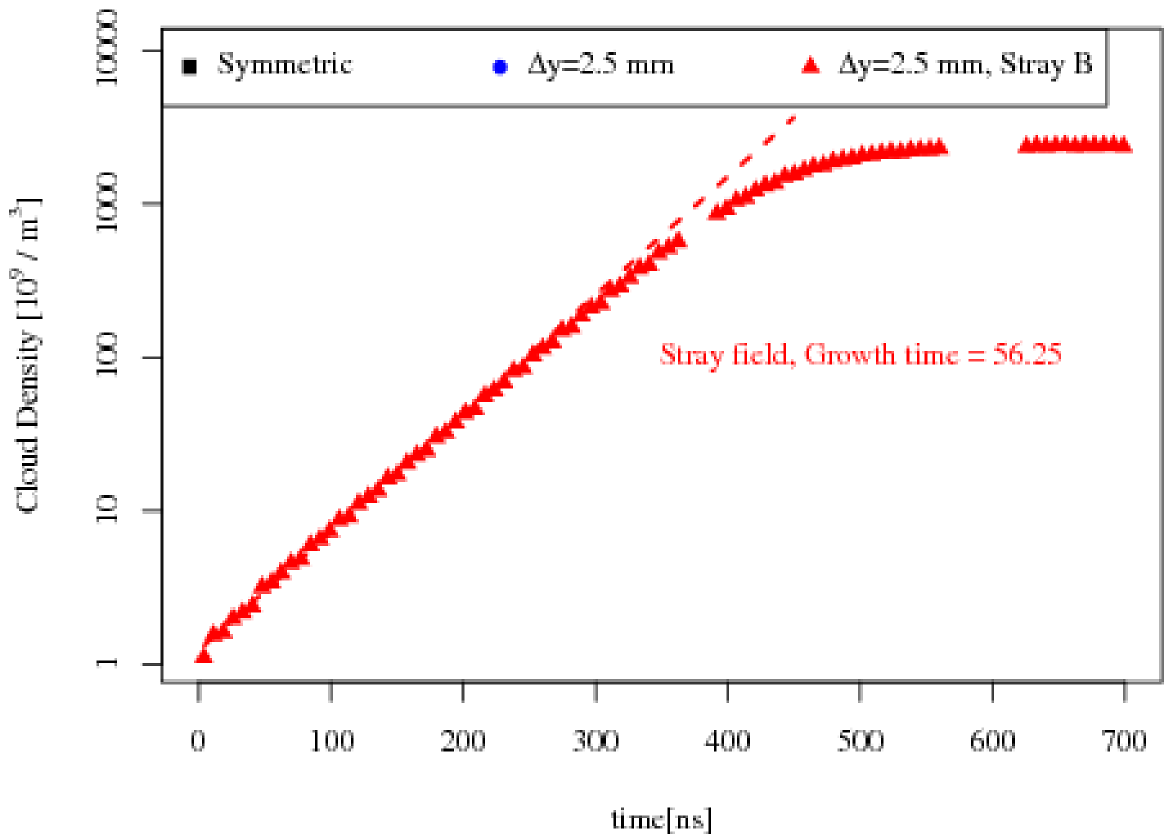


About 10 bunches, starting after a long gap, i.e., from the low EC density dictated by beam gas ionization rate.

The diffusion time in this regime is a bit longer with the stray magnetic field and the first bunch blows the cold EC more efficiently in absence of such a field..
Different starting points.

Yet, Growth time are different..

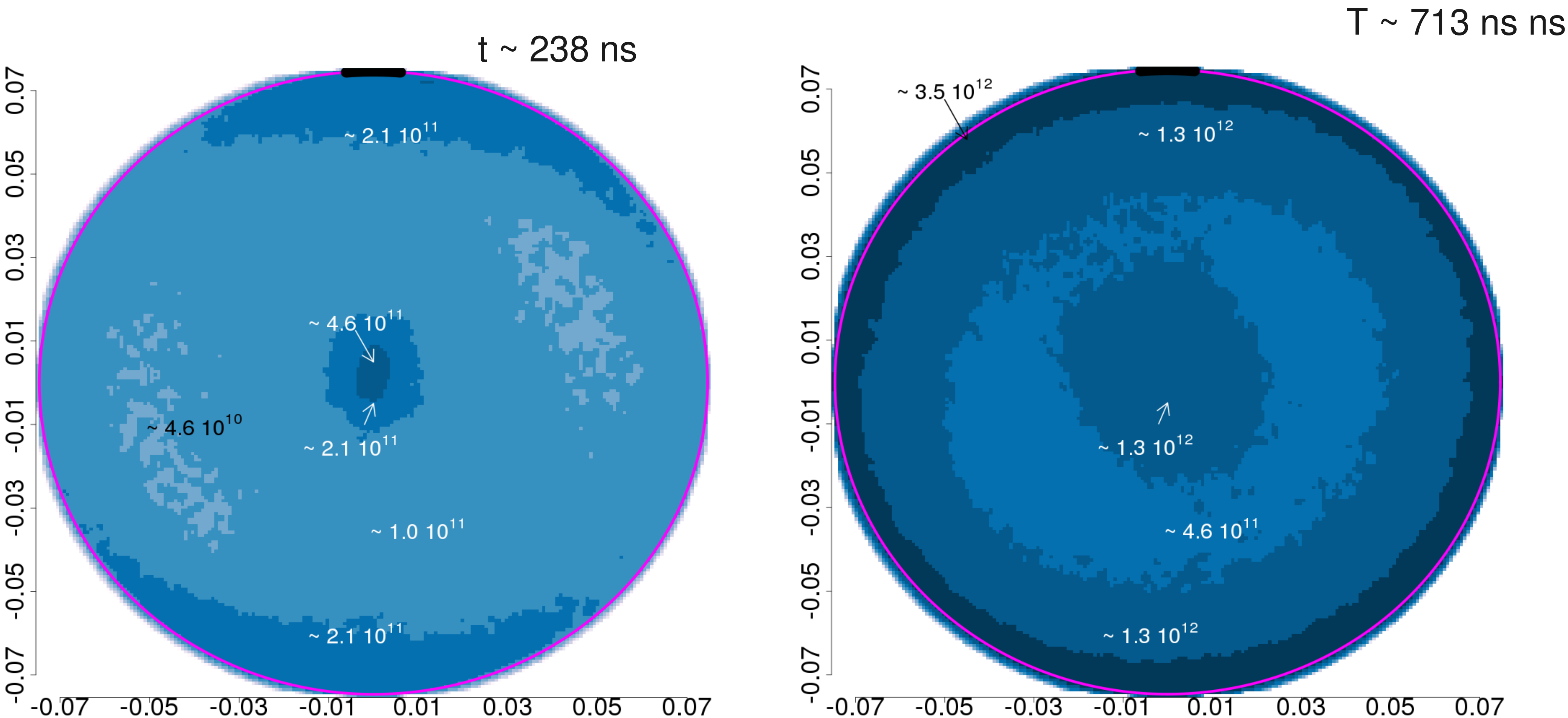
EC self space charge ==> saturation



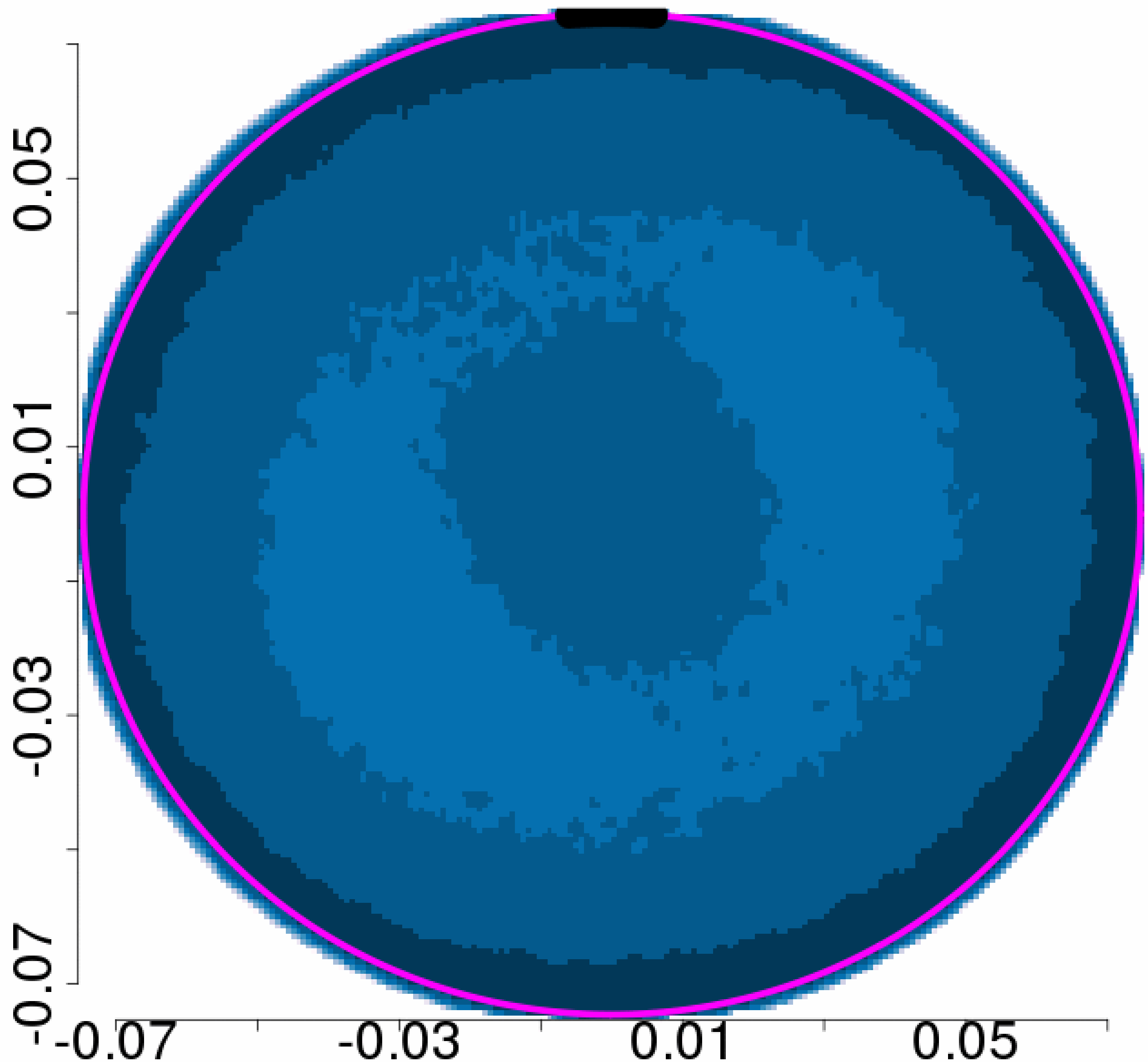
Obtained by just letting the cloud grow.
The weight of a given macro-particle changes gradually, to avoid excessive memory (and disk space!) usage. At the beginning, one macro electron represent 190 real electrons and at the 144 times that number .

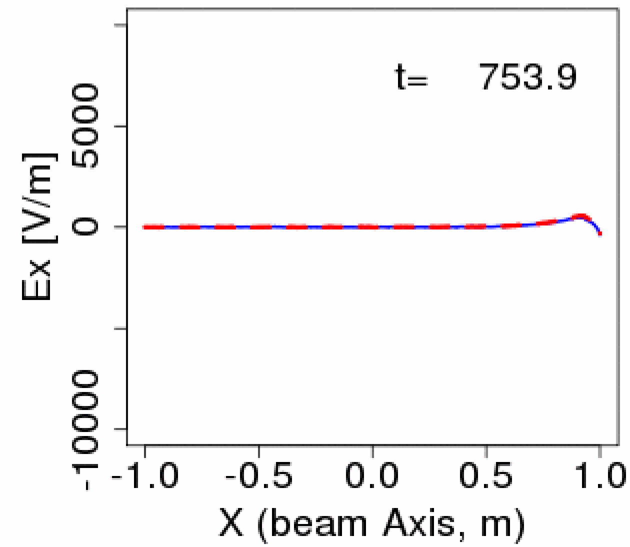
Clear change in the growth rate 20 to 30 bunches.

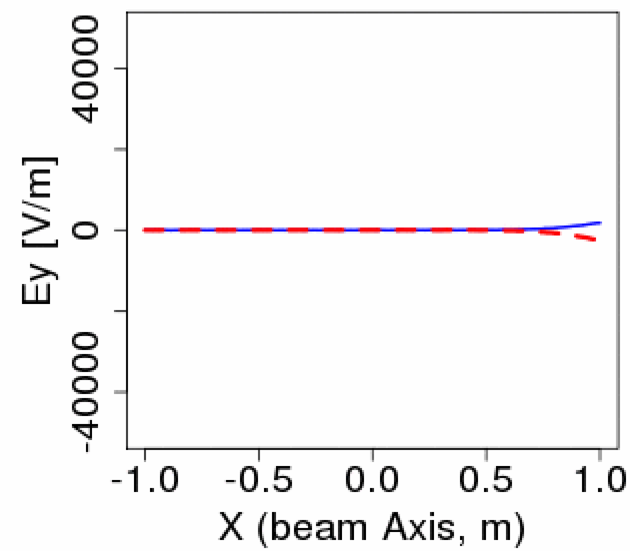
Projections of the EC, transverse



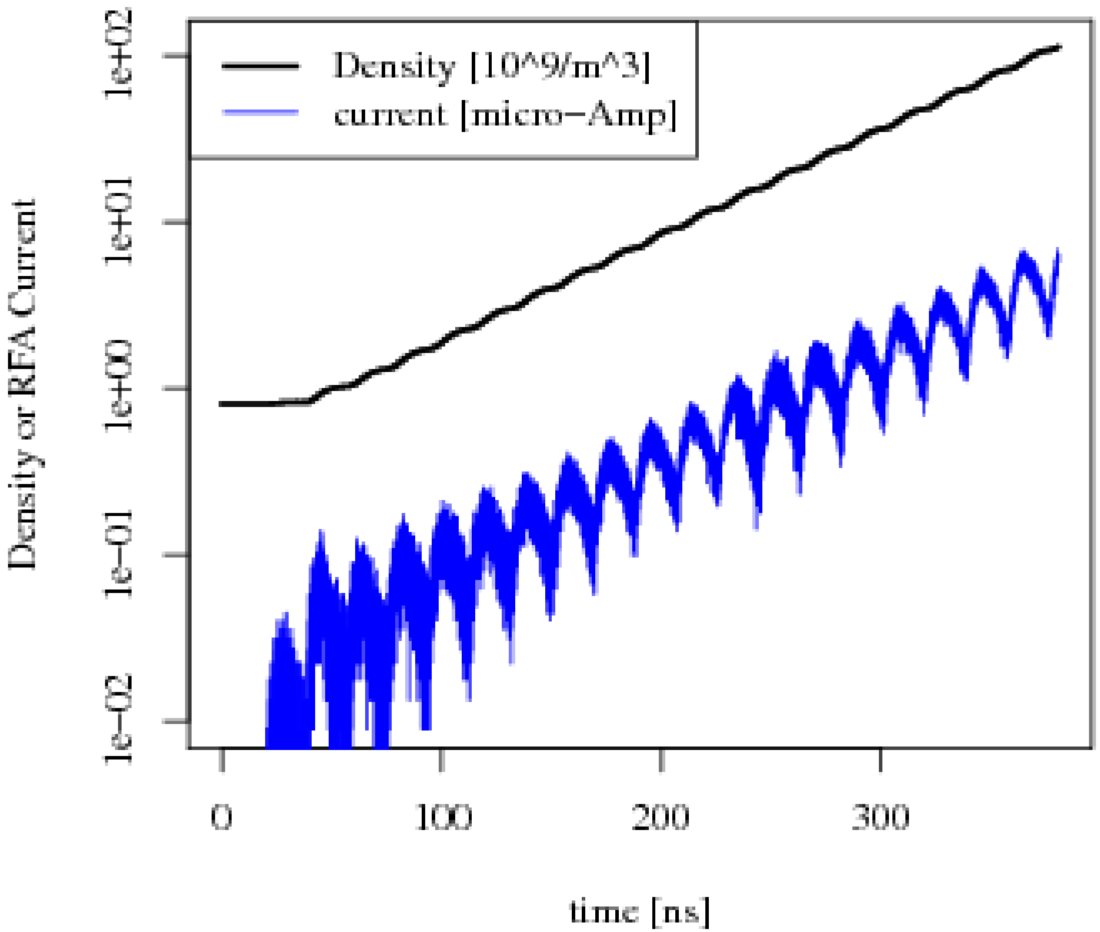
“X” in VORPAL is along the beam!







An estimate of the current detected by the RFA



Implementation in VORPAL, for the nearly ϕ-symmetric case: Count the number of macro-electron hitting the wall, rescale by the ratio of the geometrical aperture of the RFA to the beam pipe surface.

Numerical noise depends on the mumber of macroelectrons in the simulation.

The bunch structure seen here is a non-trivial expression of the dynamics.
Would be nice to confirm this experimentally.

RFA Simulation, learned lessons

- The growth time after a ~100 ns gap is different w/o a stray field of only a few Gauss.
- Complex spatial EC distribution with such field, prediction on EC density, although quite accurate, are irrelevant if the field direction is unknown (factor of few in EC density)
- Stray field measurement give a stronger vertical dipole componenent, wich boost the yield into the RFA. This component increases during the ramp => no longer a viable explanation for the disappearance of the cloud above 20 to 30 GeV. Still a mystery..
  - ***Are we really detecting the EC in the RFA?***