ACCURATE SIMULATION OF THE ELECTRON CLOUD IN THE FERMILAB MAIN INJECTOR WITH VORPAL*

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Abstract

Precision simulations of the electron cloud at the Fermilab Main Injector (MI) have been studied using the plasma simulation code VORPAL. The physical model is fully 3D and self consistent on the time scale of a few hundred nanosec. Solutions that include Yee-type E.M. field maps, electron spatial distributions and the time evolution of the cloud have been generated. By "precision simulations", we mean that systematic uncertainties in the calculation are studied and quantified. Preliminary results on the comparison between our results and those obtained by the POSINST code are discussed. Based on the results of these simulations and the ongoing experimental program, two distinct new experimental techniques are briefly mentioned. The first one is based on the use BPM plates placed in dipole fields that are made of material(s) for which the secondary emission is well characterized. The second technique would be based on the optical, or ultra-violet, detection of the radiation emitted (inverse photo-electric effect) when the cloud interacts with the inner surface of the beam pipe. As the microwave absorption experiment, this technique is non-invasive and has the advantage of providing spatial images of the cloud as well as accurate timing (ns) information. However, our first priority should be to measure the secondary emission yield for the scrubbed stainless steel beam pipe, in-situ, as this is the most basic unknown quantity in the problem. While mechanically challenging, this in-situ measurement is required, as the secondary emission yield depends on the exposure to the beam and other factors.

MOTIVATION AND SCOPE

As previously stated, the electron cloud (EC) effect in high intensity proton storage rings and synchrotrons can seriously limit the performance of such machines [1, 2]. The Fermilab Main Injector (MI) is no exception, although no definite indication of a degradation of the machine performance due to this effect has been documented thus far. While the machine currently delivers the designed beam intensity, the factor ~ 3 increase in beam power projected for the **Project X** [6] era could induce stronger beam instabilities and related beam losses. A simulation effort in the context of the ComPASS [7] aimed at supporting the experimental studies currently being pursued at the Main Injector [8, 3] has been initiated a few years ago. More recent progress reports have been presented [3, 4]. In this brief paper, our goal is limited to a brief reminder of the salient results regarding Project X, a discussion of the systematic uncertainties in the calculation in relation to POSINST, a 2D PIC simulation code used in previous calculation [2]. Finally, some suggestions for the experimental program are presented.

SIMULATION CONDITIONS

Relevant details on the Main Injector configuration are listed in reference [5]. Briefly: VORPAL [9] is a Particle In Cell (PIC) simulation code used for advanced beam or plasma problems. Our physical configuration consists of a elliptical stainless steel beam pipe (minor and major axis are 2.34 and 5.88 cm or a cylindrical pipe (radius 7.5 cm), respectively located in a static magnetic field or in a straight section with small stray fields. Multiple configurations were studied in details: a short section (~ 0.25 m long) and a longer section (16 m.) of a typical MI arc, consisting a 5 m. long dipole, followed by a quadrupole, followed by a dipole, separated by a field free region. The magnetic fields are approximately those corresponding to a MI energy of 20 GeV. This is close to the transition energy, where the bunch length is the shortest, and, therefore, when the EC problem is most acute. The proton bunches are 3D Gaussian-shaped, 0.3 m long (1 σ) and about 3 mm radius. The number of particles per bunch ranges from a few 10^{10}, to $0.7\,10^{11}$ (maximum allowable under current running condition), to $3.0\,10^{11}$ the designed value for Project X. The bunch spacing is 18.8 ns.

SUMMARY OF RESULTS AND SYSTEMATICS

The spatial density, averaged over the entire beam pipe, is shown versus time on figure 1, for various beam conditions. The maximum of the secondary emission yield (SEY_{max}) here is assumed to be rather low. This choice is based on the fact that, under current beam condition, the MI does not suffer from and EC problem. Other simulation runs have been produced for higher SEY_{max} and show a faster growth and much higher densities. However, if the SEY_{max} is such that EC density remains much lower that the proton charge density (averaged over a few bunches),

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under current beam condition, then, our calculation indicates that it will remain relatively low when the bunch charge increases by a factor three. This paradoxical results stems from the fact that SEY is relatively flat vs electron incident energy above SEY_{max}. Under current conditions, the proton bunches already generate a sufficiently high accelerating field to be well above the secondary emission yield threshold.

In presence of an external strong confining magnetic field , the magnetic field due to the beam current becomes negligible. Moreover, this strong field generated by the machine dipoles or quadrupole magnets is perpendicular to the beam. Since the bunch length is long compared to the transverse dimensions of the pipe, the problem becomes de-facto two-dimensional: the bulk motion of the electrons is always perpendicular to the proton beam direction. The synchrotron motion is a small (microns size) perturbation on the trajectory. In addition, for the considered bunch length and charge per bunch, the E-fields are such that the maximum velocity of the accelerated electrons does not exceeds $\approx 5\%$ of c. Thus, in concordance with POSINST, a set of VORPAL scripts have been written to reduce the 3D, self-consistent and relativistic PIC simulation to a 2D electrostatic PIC simulation, performed in the time domain. For the dipole case, this simplified (and much faster) problem was found to give consistent answers with the 3D case to better than $\approx 10\%$ percent relative accuracy in EC density. This accuracy is adequate for the estimate of the EC densities in the MI arcs. However, this simplification is not expected to be valid for straight sections where the stray magentic fields are weak.

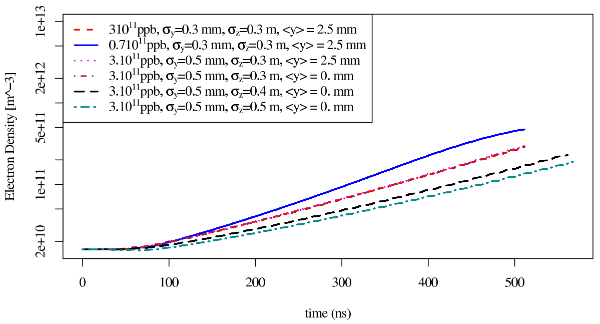

Figure 1: The EC density vs time, at the beginning of a bunch train, for about 10 to 25 MI bunch spacing and for various beam conditions. σ_r and σ_z corresponds to the average beam radius and bunch length, respectively. Displacements along the vertical axis have little impact on the EC density. Regarding the SEY_{max}, this data refers to the cases where this parameter is low and nearly critical: The EC is nearly evanescent and the growth time is anomalously long. For a moderate value of SEY of 1.36, the worst case scenario corresponds to the current operating conditions and not those expected in the Project-X era.

Evidently, the SEY_{max} is the most important parameter in the problem. However, other uncertainties are worth reporting. The first systematic uncertainty to be discussed here is a fairly common one to all PIC problems: one has to show that the grid resolution is adequate for the target accuracy. This is particularly justified in our case because the peak density occurs close to wall and the density changes by more than a factor two over once cell, which is 808μm, in vertical size for the 64x64 grid. The time step was 2.511 ps. A run with a 128X128 grid, time step of 1.25 ps, was also performed. The resulting electric field map were compared. Relative differences in the integrated electrical field ranges from 3% to a maximum of 15%, for vertical or radial paths in the beam region.

The difference between the Trilinos (with the "Dey-Mittra" cut cell method[10] at the wall pipe boundary) E.M. Poisson solver used in the VORPAL was also compared to the solver used in POSINST. The biggest difference (8%, relative) was found the near the wall, as expected. Note that the accuracy could be improved by running bigger grids, 2D only, on a super-computer.

However, we have yet an other, bigger uncertainty: The saturated cloud density and its associated electric field do depend on the assumed spatial distribution of the seed electrons. Such seed electrons trapped in the beam pipe can be produced by either ionization of the residual gas, or produced at the wall by beam losses. While the density for such electrons is typically at least 2 or 3 orders of magnitude smaller than the EC density reached at saturation, the spatial distribution of these seed electrons does influence the final EC density at saturation, as shown on figure 2. Although a bit paradoxical, this phenomena has been reproducibly seen running the VORPAL and POSINST codes. A putative explanation could be based on the existence of long time scale in the diffusion properties of the cloud. More specifically, for a dipole field of 0.234 T, an electron temperature of the ≈ 40 eV, a spatial scale of 1 cm, the Bohm diffusion time scale (transverse to the beam) is $\approx 5\,\mu$sec. So, once the EC develops, it's pattern is nearly frozen transverse to the beam, suggesting a dependency on the initial conditions of the cloud. Various distributions of the seed electrons have been considered: (i) solely dictated by the proton beam spot (labeled "beam focused" on figure 2); (ii) Conversely, electrons floating very close to the top and bottom beam pipe walls, above the beam region (2 mm away and about 2 mm thick) (iii) as done in the previous VORPAL simulation [4], a diffused seed cloud centered on the beam, occupying almost the entire pipe (3 times the sigma of the transverse dimension of the beam). Note that the density of the seed cloud matters less than the geometry of the seed cloud (the case "beam focused, HD corresponds to a density one order of magnitude higher than the seed density for the simulation ran previously).

OUTCOME:SUGGESTIONS FOR THE EXPERIMENTAL PROGRAM

As detailed in reference [5],two distinct experiments aimed at characterizing the EC at the Fermilab MI have

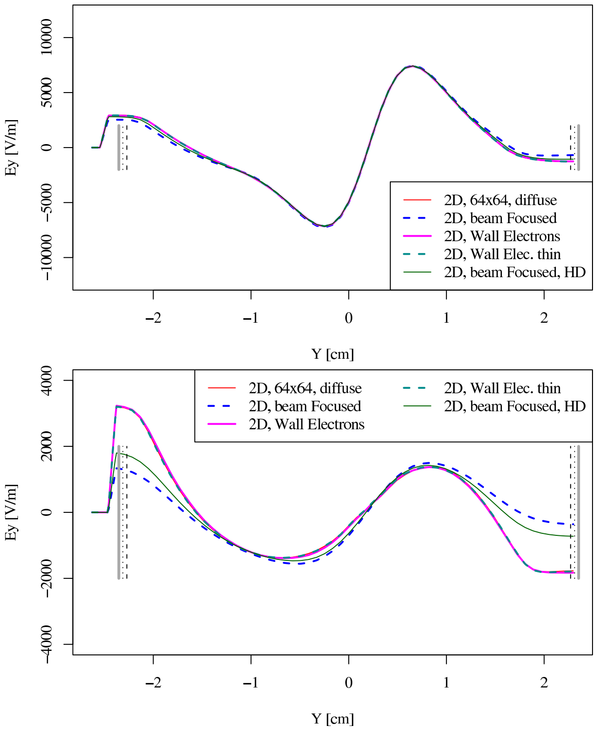

Figure 2: The vertical electric field created by both the proton bunch and the e-Cloud at at t=524.085, for different initial conditions of the seed electrons. Top: at X=0. (symmetry axis) Middle: at X = 1.0 cm (3.3 σ away from the beam). The grey thick line indicate the location of the beam pipe walls and the dotted line the cell boudary that is closest to the wall.

simulated with VORPAL: the transmission and detection of a 1.5 GHz microwave and the response of Retarding Field Analyzer.

Despite the systematic uncertainties on the final EC density, this simulation effort is worthwhile, as it provides guidance in establish a robust experimental program. For instance, the value of the stray magnetic field at the RFA position must be determined, as it influences the yield of electron collected in a relatively small region of the pipe. Note that this problem is no longer 2D, as symmetries along the beam pipe are lost due to the complicated patterns of the weak stray magnetic fields. Finally, since the SEY_{max} depends on the beam induced scrubbing, this most crucial parameter must be determined *in-situ* and inside a magnetic field commensurate with the one used in the dipole or quadrupole. A dedicate set of two small dipoles equipped with instrumentations, retractable sample holder and an electron gun (to measure this SEY) should be installed in one of the available straight section of the MI. In addition, an optical (U.V.) detection of the interaction of the cloud with the beam pipe surfaces (i.e., plasmon decays) should be feasible and could be investigated.

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REFERENCES

[1] G. Franchetti *et al* Phys. Rev. ST Accel. Beams 12, 124401 (2009).

[2] M. T. Pivi and M. A. Furman, Phys. Rev. ST Accel. Beams 6, 034201 (2003).

[3] P. Lebrun *et al*, “Microwave Transmission through the Electron Cloud at the Fermilab Main Injector: Simulation and Comparison With experiment” PAC’09, Vancouver, `http://jacow.org/PAC2009/papers/th5pfp019.pdf`

[4] P. Lebrun *et al*, “Accurate Simulation of the Electron Cloud in the Fermilab Main Injector with VORPAL” IPAC’10, Kyoto, May 2010, `http://jacow.org/IPAC10/papers/tupd015.pdf`

[5] P. Lebrun *et al*, “Accurate Simulation of the Electron Cloud in the Fermilab Main Injector with VORPAL”, FERMILAB-CONF-11-009-APC-CD (Jan 2011) 10p

[6] Stephen D. Holmes, “Project X at Fermilab”, PAC’09, Vancouver, May 2009, ID-1167, `http://www.JACoW.org/PAC2009/papers/fr1gri02.pdf`.

[7] P. Spentzouris *et al* `https://compass.fnal.gov/`

[8] N. Eddy *et al* “Measurement of Electron Cloud Development in the Fermilab Main Injector Using Microwave Transmission” PAC’09, Vancouver, May 2009, `http://jacow.org/PAC2009/papers/we4grc02.pdf`.

[9] C. Nieter and J. R. Cary,“VORPAL: a versatile plasma simulation code”, J. Comp. Phys. 196, 448-472 (2004).

[10] See for instance C. Nieter *et al*, Journal of Computational Physics Volume 228, Issue 21, 20 November 2009, Pages 7902-7916