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 have been studied using the plasma simulation code VORPAL. Fully 3D and self consistent solutions that includes E.M. field maps generated by the cloud and the proton bunches have been obtained, as well detailed distributions of the electron's 6D phase space. We plan to include such maps in the ongoing simulation of the space charge effects in the Main Injector. Simulations of the response of beam position monitors, retarding field analyzers and microwave transmission experiments are ongoing.

MOTIVATION AND SCOPE

The electron cloud (EC) effect in high intensity proton storage rings and synchrotrons can seriously limit the performance of such machines [1, 2, 3]. The Fermilab Main Injector (MI) is no exception. While the machine currently delivers the designed beam intensity, the factor ~ 3 increase in beam power projected for the **Project X** [4] era could induce stronger beam instabilities and related beam losses. A simulation effort in the context of the ComPASS [5] aimed at supporting the experimental studies currently being pursued at the Main Injector [7, 8] has been initiated. In this brief paper, our goal is limited to a quantitative description of the morphology and dynamics of the EC, via full 3D and self-consistent E.M. code, i.e. VORPAL [9]. Such studies are necessary for a detailed and accurate comparison with experiments, and, in fact, do suggest new types of instruments. They are also complementary to other broader simulations, based on the concept of iterative EC maps [10].

SIMULATION CONDITIONS

Relevant details on the Main Injector configuration are listed in reference [8]. 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, respectively located in a static magnetic field. Two configurations were studied in details: a short section ($\sim$ 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 range 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. Therefore, only one bunch can be studied at a given time in the short section, while the long section comprises typically 2 or 3 bunch at any given time. The proton beam current is assumed to be perfectly rigid. Of course, this is incorrect over long time periods, as the beam will ultimately by the field created by the EC. However, over the course of a few hundred nanoseconds, such perturbations can be neglected. At a later stage, we plan to insert the VORPAL electric field maps obtained in this work into the Synergia [13] framework to look at such beam dynamics issues.

In addition to the beam parameters, a key component in the EC problem is the Secondary Emission Yield (SEY) model. Most of our simulations were performed assuming a relatively high SEY [11] for the stainless steel, peaking above slightly two electrons per incident electrons. More recently, a new interface to VORPAL has been provided, allowing the user to set the SEY dependence on incident electron energy. Reduced SEY peak values[12] have been studied.

A microwave field can be used to probe the permittivity of the EC [8]. It has been verified that this field does not affect the shape nor density of this cloud. This allowed us to explicitly simulate the microwave experiment while studying the properties of the EC.

The PIC grid size used has been set to obtain about one percent relative accuracy in the average electron density, and a few percent accuracy in the integrated electric field created by the electron across the vertical gap between the two electrodes of a typical Beam Position Monitor (BPM) used in the microwave absorption experiment. Most of the run where performed with a cell size of $2.6 \times 1.1 \times 2.7$ mm, where the coarse dimension is along the beam line and the finest one along the vertical axis, which is the minor axis

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of the beam pipe.

For the short (long) beam pipe, the typical physical grid size is $384 \times 48 \times 48$ ($6144 \times 48 \times 48$), respectively. Our intent is to simulate the EC in an infinitely long beam pipe. Thus, one must add at both ends of these physical sections two sets of perfectly matched layers to absorb wave energy. Their size must be each at least about 25% as big as the physical region to correctly handle the propagation of E.M. wave close to the frequency cutoff of the pipe. To achieve numerical stability, once the cell size is set, so is the time step, typically 3.1 ps in our case.

The small simulation were performed on a small cluster comprised of 4 nodes, each with 4 cores (16 processes), while the large one ran on the Intrepid system at the Argonne Leadership Computing Facility [14], running on 512 processors. An explicit decomposition of the grid to processor mapping has been used to run optimally, whereby all cells in a given range along the beam axis were running on the same processor.

At the onset of the simulation, the EC density profile is uniform along the beam direction and roughly matched to the transverse beam profile. Fortunately, the seed density profile is quickly (few bunch crossings) forgotten during the exponential growth phase of the EC occuring at the start of the bunch trtain. The seed EC might be too thin early in the bunch train to be detected at that time, the duration of this quiet time is difficult to predict, as one needs to know residual EC density from previous turns and other sources of electrons such as beam losses and residual gas pressures.

As the EC phenomena is analogous to multipacting, there a phase where the EC density is growing exponentially. To get good accuracy from the initiation to the saturation phase, it is necessary to change the ratio of macro particles to real electrons throughout the simulation. To avoid biases, if the number of macro-particles per cell in the dense region is large enough at the onset, it is sufficient to simply cull the entire cloud by the adequate ratio using a flat probability scheme, where each macro particle is kept or discarded for the next stage of the calculation based on the roll of the dice with a fixed probability, irrespectively of the location of the macro-particle location in 6D phase space. Depending of the growth speed of the cloud, from 3 about to 10 culling phases are needed before reaching stable saturation.

RESULTS

By saturation, we mean that the average electron density no longer changes average over the time scale of few bunch crossings. This occurs when the electric field sensed by electrons away from the beam region becomes too small to accelerate them. That is, the space charge on the EC on itself limits the growth of the cloud. The morphology of the EC at the onset and at saturation differ: the fields induced by the proton bunch, this EC space charge effect and the static magnetic field dictate the shape of the cloud. Shown on figure 1 is a transverse profile of the cloud in between bunches and during the pinch caused by the passage of the bunch. This has been obtained at saturation, in the dipole case, with 10^{11} protons per bunch. Averaged over the volume of the beam pipe, the peak density in the beam region is $\approx 2.4\,10^{13}\,m^{-3}$. The linear density of the cloud averaged over $\sim 1\sigma$ of the bunch is about 75% of the average linear density of the proton bunch. This was obtained with the short beam pipe. The fact that the linear density of the EC is commensurate with the linear density of the bunch applies for the long beam line as well. Shown on figure 2 is the longitudinal profile of the EC in the long dipole case.

Similar density maps have been produced for other types of magnetic field configuration. In a quadrupole, as expected, the density stripes at $\sim 3.\sigma$ away from the beam are on a 45° diagonal.

The e-folding time scale of the EC depends on the SEY parameters, the bunch intensity and, to a lesser extend, the magnetic field configuration. Under current conditions, in the MI dipoles, assuming a relatively high value for the maximum SEY (SEY_m) of about 2., this e-folding time is about 50 ns. If SEY_m is less than 1.05, the EC dies away and multipacting does not occur. The e-folding time increases to 60 ns if $SEY_m = 1.7$. Most importantly, the spatial average density at $\sim 700ns$ (1/2 bunch train length) decreases by a factor 9. The decay time of the EC is about 40 ns, in the dipole case. Again, this life time depends on the trapping efficiency in the magnetic field. This is unfortunately not short enough to kill the EC in between MI bunch trains.

Other dynamical properties can be studied from the 6D EC phase space distributions. For instance, one can follow the change in average kinetic energy of the electrons and deduce from this the amount of energy absorbed by the beam pipe wall. Preliminary calculation show that about 40 W/m is transferred from the beam to the wall due to the EC, for an average EC density of $\approx 1.1\,10^{13}\,m^{-3}$. The mean velocity of the EC along the beam axis in field free regions is found to be negligible. Even if not confined by the static magnetic field, the beam does not appreciably "drag" the cloud. The EC phenomena is always localized.

The BPM have been crudely simulated via the use of VORPAL's pseudovoltages. In a dipole, if the beam is displaced vertically and if the EC linear density is large enough with respect to the linear density of the proton beam itself, then one ought to be able to detect the echo of the beam pulse due to the EC. That is, the voltage recorded on the BPM shows the ~ 1 ns beam signal, then, delayed by ~ 3 ns, a second, broader (~ 2 ns wide) signal signaling the spatial re-arrangement of the shocked EC.

A Fast Fourier Transform analysis of BPM response reveal that the EC weakly resonated at the cutoff frequency of the beam pipe. The EC, excited by the beam, caries E.M. waves that can propagate in the beam pipe. The lowest mode is at 1.55 GHz. This frequency does not match with the electron cyclotron frequency in the dipoles. Also, because the kinetic energy distribution of the electrons is very broad, electron cyclotron resonances do not play a significant role in the microwave absorption experiment.

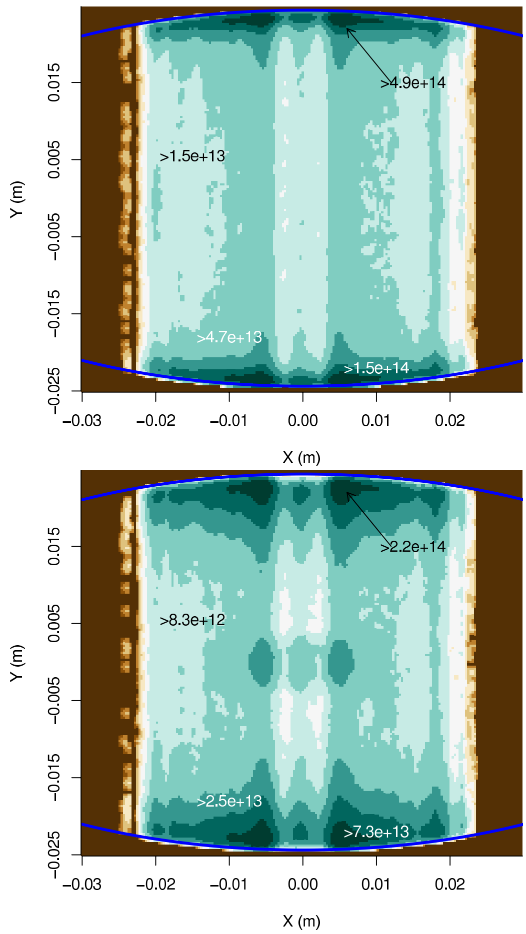

Figure 1: Transverse profile of the EC density. Top: at the beginning of the relaxation phase, when the density reaches a maximum. Bottom: during the pinch phase, when the density is minimum, as the electrons have just migrated away from walls.

As found in previous (2D) simulations [2], uncertainties in the SEY dominates. While our simulation can not predict *ab-initio* the EC density and its impact on the beam, these full 3D, self-consistent simulations provide valuable information used to guide and interpret the ongoing experimental program. For instance, an optical (U.V.) detection of such interaction should be feasible.

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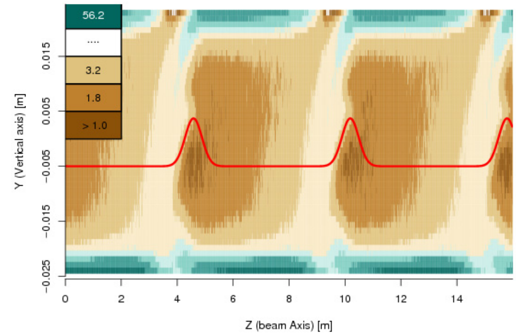

Figure 2: Longitudinal profile of the EC density for an infnitly long dipole and a continuous sequence of bunches, at saturation. The proton bunch intensity is $0.7\,10^{11}$. The proton beam (red line) is displaced by 5 mm downwards, which makes the EC top-down asymmetric.

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