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MICROWAVE TRANSMISSION THROUGH THE ELECTRON CLOUD AT THE FERMILAB MAIN INJECTOR: SIMULATION AND COMPARISON WITH EXPERIMENT[*]

Paul L. G. Lebrun, Fermilab, IL 60510, USA[†]
Seth Andrew Veitzer, Tech-X, Boulder, Colorado, USA[‡]

Abstract

Simulations of the microwave transmission properties through the electron cloud at the Fermilab Main Injector have been implemented using the plasma simulation code “VORPAL”. Phase shifts and attenuation curves have been calculated for the lowest frequency TE mode, slightly above the cutoff frequency, in field free regions, in the dipoles and quadrupoles. Preliminary comparisons with experimental results for the dipole case are showed and will guide the next generation of experiments.

INTRODUCTION AND MOTIVATION

The electron cloud (e-cloud) effect in high intensity proton storage rings and synchrotrons can limit the performance of such machines [2], [3]. The Fermilab Main Injector (MI) is no exception. In the **Project X**[1] era, where the delivered beam power on target will go from the current value of 300 MW to 2.1 GW, fast instabilities due in part to e-cloud problem are predicted by many models. New instruments must be developed to characterized this effect. The absorption and re-emission of microwave photons by the e-cloud causes a detectable phase shift in this microwave field. This phase shift is related to the density of the e-cloud. This paper reports on recent observations based on VORPAL [8] simulations and some comparison with data recently taken at the MI[6]. It is also an extension of previous simulation work, using a new version of the same software [9].

THE ELECTRON CLOUD IN THE MAIN INJECTOR

Current parameters of the MI.

Those are listed on table 1 [7]. The major change for the Project X era will be an increase of two in the repetition rate of the synchrotron and an increase of the bunch intensity by a factor 3 to 6, up to 3 10^{11} protons per bunch [4]. While the former upgrade is irrelevant concerning the e-cloud problem, the latter one raise numerous concerns about potential beam instabilities and subsequent beam losses.

Table 1: Relevant MI machine parameters.

Parameter	**Value**
Total Length	3319.4 m
Length of all dipoles	1842.4 m
Length of all quadrupoles	488 m
Magnetic Field in dipole (8 GeV)	0.010 Tesla
Quadrupole Gradient (8 GeV)	11.9 Tesla/m
Beam Pipe minor/major radii	$2.39 / 5.88$ cm
Beam Pipe Material	stainless steel cm
Max. Num. of Protons per Bunch	$1.0\,10^{11}$
Bunch Length	1 m to 0.3 m
Bunch Spacing	18.9 ns
Number of bunch per batch	70
Beam Pipe Frequency Cutoff	1.49 GHz
MicroWave frequency	1.538 GHz
BPM dist. emitter/receiver	13 m

Tentative phenomenological description of the electron cloud.

Prior to running advanced computer simulations, some expected properties of this e-cloud can be derived from basic principles. The seed for the e-cloud could comes from ionization of the residual gas by the proton beam, or from secondary emission due to beam losses on the beam pipe. In either case, these seed electrons are non-thermal, with kinetic energy of at least one eV or so. By conventional plasma standard, this cloud is also extremely rarefied, and non-neutral. The seed density is expected to be much lower than charge density in the proton bunch. “Plasma” is probably a misnomer: at a density of $\sim 1\%$ of the proton density, the plasma frequency ranges from a few MHz to 10 MHz, and the Debye length is likely to be of the same order of magnitude of the minor radius of the elliptical beam pipe. Thus, the plasma-wall interaction will be a dominant feature. Finally, the re-combination rate with ions can be neglected over the time scale of the passage of a few bunches. Electrons are simply re-absorbed in the beam pipe.

The passage of a $\sim 1.\,10^{11}$ proton bunch, ~ 30 cm long creates an electric field of tens of kV/m at a few σ from the beam center, and can accelerate the electrons to tens if not a few hundred eV. Once released from the attraction of the positively charge bunch, they can drift towards the wall, and generate secondary electrons, which drift in the

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[†] lebrun@fnal.gov

[‡] veitzer@txcorp.com

beam pipe and are then accelerated by the passage of the next bunch (aka, “multipacting”). If the cloud density is high enough, electrons close far the beam region, that is, close to the wall will no longer be accelerate, and the cloud is “saturated”.

It is useful to consider three distinct regimes:

- The weak, cold and linear regime: The cloud is assumed to be homogeneous and cold ($KT_e << 1$ eV), and the proton beam current is negligible. The motion of these electrons is dominated by the field of the microwave. The phase shift is expected to be proportional to the electron density. Although this is evidently not a realistic regime, simulation results can be straightforwardly compared to theory [9]
- An intermediate regime : the proton beam is too diffuse or does not carries enough charge to cause the resonant multipacting effect. However, the perturbations due the passage of these bunches on the e-cloud are bigger than those created the microwave field. This is true well below current operating condition, few 10^8 protons/bunch.
- The strong regime: The field from the proton bunch is capable of accelerating numerous electrons above the threshold for secondary emission at the wall. The density of the cloud increases up to saturation time. The seeding state of the cloud is quickly (~ 100 ns) forgotten.

The critical beam current at which the transition between the intermediate and strong regimes occurs depends on the secondary emission yield, and its dependence on the incident electrons energy. The VORPAL code uses a model identical to the one developed in the POSINT code [10]. Only the strong regime is of interest in terms of pushing the MI beam power: the remnant of intermediate e-cloud is too weak to cause significant perturbations on the proton beam.

VORPAL SIMULATION

As in any simulation of a real experiment, some modeling and simplifications are unavoidable. The length of the beam pipe had to be reduced. The magnetic field has been greatly simplified: a uniform dipole field has been selected[1]. A model from the fringe field of these magnet is available, and could relatively easily be included in the VORPAL scripts.

The chosen dipole field strength corresponds to the time when the bunch are shortest (just before the synchrotron transition). As the microwave field is oriented vertically, i.e., $E//B$, this magnetic field is not expected to play a significant role. The case for quadrupoles, confining solenoidal fields and dipoles/quadrupoles fringe fields are more complicated and will be studied later.

The proton beam is treated as a perfectly rigid current source. The kinetic energy of the protons are much higher than the energy stored in the e-cloud. Proton’s trajectories are not expected to deviate much over such a short distance and such short time scale.However, over many turns in the ring, the e-cloud is expected to have an effect. Since the time scales and relative motions of the e-cloud and proton beam are so different, it makes sense to treat them in separate steps.

Despite their relatively low velocity ($\sim 1\%$ of c) the electrons are treated as relativistic particle using a “Boris” integrator. In the strong regime, weighted particle must be used and the e-cloud density can grow by several orders of magnitude. The spatial distribution of the seed electron is largely unknown, in the results shown below, the radial density is Gaussian, $\sigma \sim 1$ cm.

The simulation parameters are summarized on table 2. This VORPAL simulation ran on a single desktop computer running Scientific Linux [11] and on a Blue Gene®/P system (intrepid) at Argonne National Laboratory [12].

Table 2: Relevant Simulation parameter.

Parameter	**Value**
Phycal Length	5.6 m
Dipole field strength	.0234 Tesla
Beam Pipe geometry	elliptical, as real
Bunch Length	0.3 m
MicroWave frequency	1.538 GHz
MicroWave Ey amplitude	20 to 100 V/m
BPM dist. emitter/receiver	3.5 m
Typical Num. Grid cells	720 X 48 X 24
Time step	5 ps
Typical Num. of time steps	10^5
Typical Num. electrons/cell	20
Typical Nnum of processors	32 to 512

For each configuration, two distinct runs are done: one with seed electrons and one without. The electric field is recorded at every time step at a few location via the VORPAL “History” mechanism. The difference between these two electric fields (ΔEy) is computed. The phase and amplitude of the microwave field recorded at the these virtual antennas, without electrons is extracted from fit (plain sine function) that exclude time periods where the bunches are passing through. ΔEy is then fitted to a cosine function, the integrated phase shift $\Delta\Phi$[2] is extracted.

The signal processing in the real experiment differs a bit from simulation. It is obviously not possible to turn off the real e-cloud, should it be really there. In addition, taking the analog difference between two r.f. signals is difficult. Thus, the signal received at the antenna is mixed with the phase shifted input signal. The simplified mathematical translation of this procedure is :

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[1] However, the VORPAL script also support a quadrupole field. A 1.5 GHz, the Electron Cyclotron Resonance is expected to occur at a field of 570 Gauss, or at a distance of ~ 2 cm from the beam axis, at 20 GeV.

[2] notation are those found in ref. [9]

$$S_m = A\,cos(\omega t) * sin(\omega\,t + \Delta\Phi)$$

or

$$S_m \approx A/2\,sin(2\omega t) + A\,\Delta\Phi\,cos(\omega\,t)^2$$

This assumes that the amplitude of the received signal is dominated by the microwave field and $\Delta\Phi << 1$. This processing has been implemented in our analysis. However, the 2nd important difference between simulation and experiment is the length of time for which S_m can be recorded and Fourier transformed (FFT): About one microsecond and many milliseconds, respectively. Since the down-conversion and subsequent processing of the phase shift signal ($\propto A\Delta\Phi$) is done asynchronously with respect to the MI rf frequency, the beam component cancels out. In the simulation, this is done by performing FFT's on segments of S_m recorded in between bunch crossings.

RESULTS FROM SIMULATION

By starting with a density sufficiently high enough for the initial, cold e-cloud, and a vanishingly small proton current, the linear regime is valid and a simulated phase shift measurement can be obtained during a fraction of one microsecond. The e-cloud has (arbitrarily) a Gaussian shape ($\sigma_r \sim 1$ cm) and a density of $\sim 4.0\,10^{11}\,m^{-3}$ at the center of the beam pipe. The extracted $\Delta\phi \sim 5.8\,10^{-4}$ radians is in good semi-qualitative agreement $\sim 50\%$ with the linear theory. $\Delta\Phi$ does not depend much ($\sim 2\%$, relative) on the transverse position of the antenna.

Keeping the same e-cloud and with a relatively small bunch charge of $5\,10^{-8}$, deviations from the linear model do occur. The FFT of the simulated S_m reconstructed after the third bunch, shortly after the transient due to the beginning of the bunch train is shown on Fig 1. the signal to noise is about xxxx times stronger in this regime than the in linear regime. The phase shift is now of the order of 2 mRad for an initial density of $4.0\,10^{11}\,m^{-3}$, significantly higher then in the previous case. This phase shift also does not scale with this electron density. This clearly shows that this apparent $\Delta\Phi$ signal is not a simple, linear and unambiguous indicator of the e-cloud density. The strong regime is evidently more complex and is currently under study. Yet, as observed in previous simulations, in a dipole field of at least ~ 50 Gauss, the e-cloud take the form of column centered on the beam, with the high charge density located above and below beam, close to the wall. Strong non-linearity of ΔPhi have been observed but systematics in the calculation need to characterized. No firm evaluation on the need for an e-cloud mitigation strategy can currently be made. However, these simulations do help interpreting the data and guide the design of future experiments.

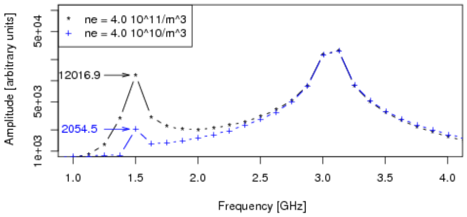

Figure 1: The FFT of the Sm in the linear and intermediate regime, for $5.\,10^8$ protons per bunch, and for two initial density.

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