# Electron-Cloud Build-Up Simulations for the FNAL Main Injector: Dependence on Train Length and Bunch Intensity at 53 MHz*

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## *Abstract*

We present simulation results of the electron-cloud build-up in a field-free region and in a dipole bending magnet of the Fermilab Main Injector (MI) in which the beam is represented by a simplified fill pattern consisting of a single continuous train of $M$ bunches followed by a single gap of length $h - M$ buckets, where $h = 588$ is the MI harmonic number corresponding to the RF frequency $f_{\rm RF} = 53$ MHz. We carry out the simulations only at injection energy, $E_b = 8.9$ GeV, and explore three values for the bunch intensity, namely $N_b = (10, 15, 30) \times 10^{10}$ for $M = 5,\ 10, \cdots, 588$. Most of the results presented here are obtained under the assumption that the peak secondary emission yield (SEY) is $\delta_{\rm max} = 1.3$, since this is the currently favored estimate in the MI chamber region where a retarding-field analyzer (RFA) is installed [1]; however, spot checks with $\delta_{\rm max} = 1.2$ and 1.4 indicate qualitatively similar results. The simulations show a clear threshold of the electron cloud buildup in $M$, where the threshold value, $M_{\rm th}$, is a strong function of $N_b$. For example, in the field-free region, $M_{\rm th} \simeq 50$ at $N_b = 30 \times 10^{10}$, and $M_{\rm th} \simeq 200$ at $N_b = 15 \times 10^{10}$. All else being equal, $M_{\rm th}$ is significantly higher in the dipole magnet than in the field-free region. We provide simple explanations for these threshold values based on the electron-cloud growth rates. As a corollary, we conclude that the electron cloud will probably not be a significant problem in the Recycler Ring even at $N_b = 30 \times 10^{10}$.


## INTRODUCTION

The desire to assess the impact of the electron-cloud effect on the MI upgrade [2] has motivated the measurement of the incident electron flux $J_e$ on the walls of the MI vacuum chamber by means of a RFA electron detector in a field-free region [3] for various high-intensity beam fill patterns [4]. In Ref. 1 we presented electron-cloud build-up simulations for the MI for several fill patterns consisting of 3–5 trains, each of which had 81 consecutive bunches ($f_{\rm RF} = 53$ MHz) with a bunch intensity in the range $N_b \sim (7 - 10) \times 10^{10}$. By comparing the measured RFA signal obtained with these fill patterns against our simulations, and using some reasonable assumptions, we were able to constraint the value of the peak SEY to the range $\delta_{\rm max} \sim 1.25 - 1.35$.

At present, it is difficult or impossible to obtain bunch intensities much higher than $\sim 10 \times 10^{10}$ except for beams consisting of one, or very few, bunches. Motivated by this possibility, we then simulated the electron-cloud effect for a beam consisting of only 4 bunches, each of intensity $N_b = 30 \times 10^{10}$, spaced by 21 RF buckets (398 ns) [5], since such a fill pattern is presently feasible without ramping the beam energy [6]. Our conclusion was that the electron-cloud effect in this case is expected to be very weak, with an RFA signal several orders of magnitude below what has been measured for fill patterns with $N_b \lesssim 10 \times 10^{10}$ hence undetectable in practice.

In this note we attempt to further map out the region of parameter space where the electron-cloud effect is expected to be strong for the MI upgrade. For these purposes we assume a simplified beam fill pattern, consisting of a single train of $M$ bunches followed by a single gap, and we explore only three values of the bunch intensity. The beam energy is held fixed at its injection value. The peak SEY is assumed to be, in most cases, $\delta_{\rm max} = 1.3$. Table 1 summarizes the most relevant physical and numerical parameters. The value of the RMS bunch length is approximately what is measured in practice at injection energy. Although the transverse RMS beam sizes are different in the field-free region and the dipole, we set them equal for the purposes of the exercises carried out in this note.

The results in this note are a logical continuation of the studies initiated in early 2006 [7]. The complete publication list can be found in Ref. 8.

## RESULTS

As in our previous studies, we use here the 2D build-up simulation code POSINST [9–12]. We only simulate the beam for one full turn at injection energy, and extract from this the one-turn average of $J_e$ as well as the electron-cloud average number density $n_e$, along with many other instantaneous and time-averaged quantities that characterize the electron distribution.

### *Field-free region*

Results for $J_e$ as a function of $M$ for $N_b = 30 \times 10^{10}$ and $\delta_{\rm max} = 1.2$, 1.3 and 1.4 are shown in Fig. 1. It is clear that there is a threshold $M_{\rm th} \simeq 50$ above which $J_e$ rises linearly with $M$, and is not very sensitive to $\delta_{\rm max}$. This threshold is a simple consequences of the fact that it takes $\sim 50$ bunches ($\sim 1\ \mu$s following injection) for the build-up of the electron-cloud density $n_e$ to reach saturation, as seen in Fig. 2. Once $n_e$ reaches saturation, its one-turn average is simply proportional to $M$.

It seems worth noting that the values of $J_e$ near $M_{\rm th}$ are

* Work supported by the FNAL MI upgrade R&D effort and by the US DOE under contract DE-AC02-05CH11231.

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on the scale of the largest values obtained from the RFA measurements last year [1, 3, 4], namely a few mA/m$^2$.

Since the measurements with the RFA strongly indicate a preferred value of $\sim 1.3$ for $\delta_{\max}$ [1], we constrain our remaining simulations to this value. Figure 3 shows the one-turn averages of $J_e$ as a function of $M$ for three values of $N_b$. One observes that, for $N_b = 15 \times 10^{10}$, the threshold is $M_{\rm th} \simeq 200$, which is $\sim 4$ times larger than for $N_b = 30 \times 10^{10}$, and also that, for $N_b = 10 \times 10^{10}$, there is no threshold behavior in $M$. For the same conditions, Fig. 4 shows the corresponding one-turn average values of the density $n_e$. As before, these values can be simply explained by the time evolution of $n_e$, as shown in Fig. 5.

## *Dipole magnet*

In a dipole magnet the motion of the electrons is strongly confined to tight vertical spirals leading to qualitative differences with the field-free region, where the electrons are free to move uniformly around the chamber cross-section (see, eg., Figs. 3 and 7 in Ref. 1).

Figure 6 shows the one-turn average of $J_e$. Comparing with Fig. 3 for the field-free region, one sees a weaker effect by $\sim 1$ order of magnitude at $N_b = 30 \times 10^{10}$, and no threshold in $M$ for $N_b \leq 15 \times 10^{10}$. However, in this case, there is a large difference in the value of $J_e$ computed from an overall chamber average and the value computed by averaging over the RFA location. Fig. 7 shows that, for the field-free region, there is virtually no difference between the RFA value of $J_e$ and the overall value of $J_e$, while for the dipole bending magnet the former is $\sim 5$ times larger than the latter.

The one-turn average density $n_e$ for the dipole is shown in Fig. 8, and its time evolution in Fig. 9. In this case, for $N_b = 30 \times 10^{10}$ the threshold $M_{\rm th}$ is $\simeq 200$, which

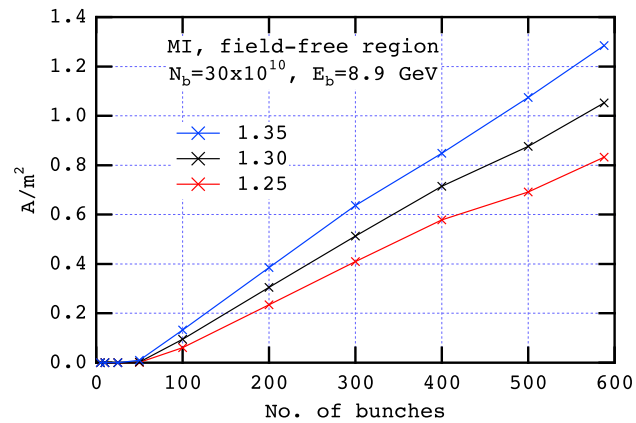


Figure 1: One-turn average of $J_e$ in the field-free region as a function of $M$ for $N_b = 30 \times 10^{10}$ and $\delta_{\max} = 1.25 - 1.35$, as indicated.

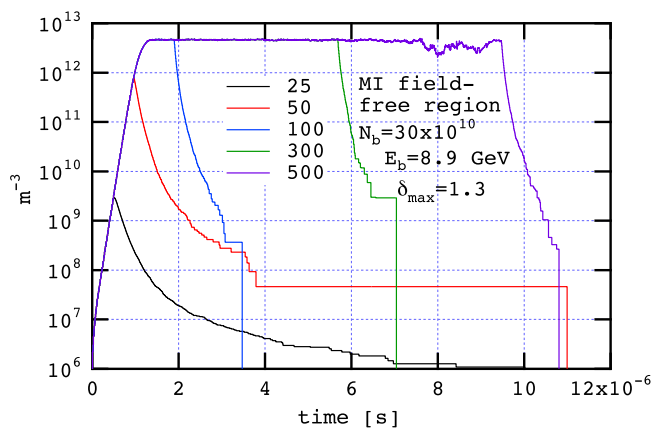


Figure 2: Build-up and dissipation of $n_e$ during one MI turn for pulses of $M = 25, \cdots, 500$ bunches, as indicated, assuming $N_b = 30 \times 10^{10}$ and $\delta_{\max} = 1.3$. The fluctuations at $t \sim 8 - 9$ $\mu$s for $M = 500$ are a consequence of the appearence of a "virtual cathode."

Table 1: Assumed MI parameters for EC simulations.

| | |
|---|---|
| **Ring and beam** | |
| Ring circumference | $C = 3319.419$ m |
| Revolution period | $T_0 = 11.13$ $\mu$s |
| RF frequency | $f_{\rm RF} = 52.809$ MHz |
| Harmonic number | $h = 588$ |
| Beam energy | $E_b = 8.9$ GeV |
| Bunch profile | 3D gaussian |
| Tr. RMS bunch sizes | $(\sigma_x, \sigma_y) = (2.3, 2.8)$ mm |
| 95% bunch duration | $\tau_{95} = 10$ ns |
| RMS bunch length | $\sigma_z = 0.75$ m |
| Bunch intensity | $N_b = (10 - 30) \times 10^{10}$ |
| No. bunches per train | $M = 5 - 588$ |
| Pipe cross sect. at RFA | round |
| Pipe radius at RFA | $a = 7.3$ cm |
| Pipe cross sect. at dipole | elliptical |
| Pipe semiaxes at dipole | $(a, b) = (6.15, 2.45)$ cm |
| Dipole field at $E_b = 8.9$ GeV | $B = 0.092$ T |
| **Primary e$^-$ sources** | |
| Resid. gas pressure | $P = 20$ nTorr |
| Temperature | $T = 305$ K |
| Ioniz. cross-section | $\sigma_i = 2$ Mbarns |
| Ioniz. e$^-$ creation rate | $1.266 \times 10^{-7}$ (e/p)/m |
| **Secondary e$^-$ parameters** | |
| Range of peak SEY | $\delta_{\max} = 1.2 - 1.4$ |
| Energy at $\delta_{\max}$ | $E_{\max} = 292.6$ eV |
| SEY at 0 energy | $\delta(0) = 0.2438 \times \delta_{\max}$ |
| **Simulation parameters** | |
| Primary macroelectrons/bunch | 100 |
| Max. no. of macroelectrons | 20000 |
| Full bunch length | $L_b = 5\sigma_z$ |
| No. kicks in $L_b$ | $N_k = 357$ |
| Integration time step | $5 \times 10^{-11}$ s |
| Space-charge grid | $64 \times 64$ |

corresponds to the build-up time $\sim 5\ \mu$s, as seen in this last figure.

The weaker electron-cloud effect in the dipole compared with the field-free region can be qualitatively correlated with the electron-wall impact energy. In the former case, for $N_b = 30 \times 10^{10}$, the average impact energy is $\sim 50\%$ of that in the latter, as shown in Fig. 10. Given that the SEY function $\delta(E_0)$ peaks at $E_0 = E_{\max} = 293$ eV in our model, and that $\delta(E_0)$ falls rapidly as the incident electron energy $E_0 \to 0$ below $E_{\max}$, one expects the effective SEY to drop significantly; this is probably the origin of the relative weakness of the effect in the dipole as compared with the field-free region.

## DISCUSSION

In this note we have simulated the electron-cloud build-up in the MI at injection energy, $E_b = 8.9$ GeV, for an idealized beam pulse consisting of a single train of $M$ bunches followed by a single gap of $588 - M$ empty buckets. The main results are:

1. Threshold behavior: $M$ needs to be larger than a threshold $M_{\rm th}$ for the electron cloud to become significant. For $M > M_{\rm th}$, both the one-turn everage electron density $n_e$ and incident electron flux $J_e$ rise linearly with $M$.

2. $M_{\rm th}$ has a strong inverse dependence on the bunch intensity $N_b$:

   - In a field-free region, $M_{\rm th} \simeq 50$ for $N_b = 30 \times 10^{10}$ and $M_{\rm th} \simeq 200$ for $N_b = 15 \times 10^{10}$. There is no discernible threshold for $N_b = 10 \times 10^{10}$.
   - In a dipole bending magnet, $M_{\rm th} \simeq 200$ for $N_b = 30 \times 10^{10}$. There is no discernible threshold for $N_b \leq 15 \times 10^{10}$.

3. In the field-free region, the average value of $n_e$ is roughly 5 times higher than in the bending magnet for above-threshold conditions.

4. Both for the field-free region and the dipole bending magnet, the simulated values of $J_e$ at $N_b = 30 \times 10^{10}$ and $M \simeq M_{\rm th}$ are on the scale of mA/m$^2$'s. This is comparable to the highest values measured with the RFA last year using trains of $N_b \simeq 10 \times 10^{10}$ and $M \simeq 400$.

Our results are obtained under the assumption that the peak SEY is $\delta_{\max} = 1.3$. However, spot-checks with $\delta_{\max} = 1.2$ and 1.4 suggest qualitatively similar results.

Given that the Recycler Ring (RR) is mostly composed of dipole bending magnets and that the beam energy is fixed at $E_b = 8.9$ GeV, our results provide a strong indication that the electron cloud will probably not be a significant problem in the RR even at $N_b = 30 \times 10^{10}$. This conclusion assumes that the vacuum chamber in the RR is similar in shape, size and conditioning state as in the MI, and that the beam in the RR is also similar to the MI (ie., similar bunch sizes and fill pattern).

## ACKNOWLEDGMENTS

I am indebted to I. Kourbanis and R. Zwaska for experimental results, many discussions and guidance.

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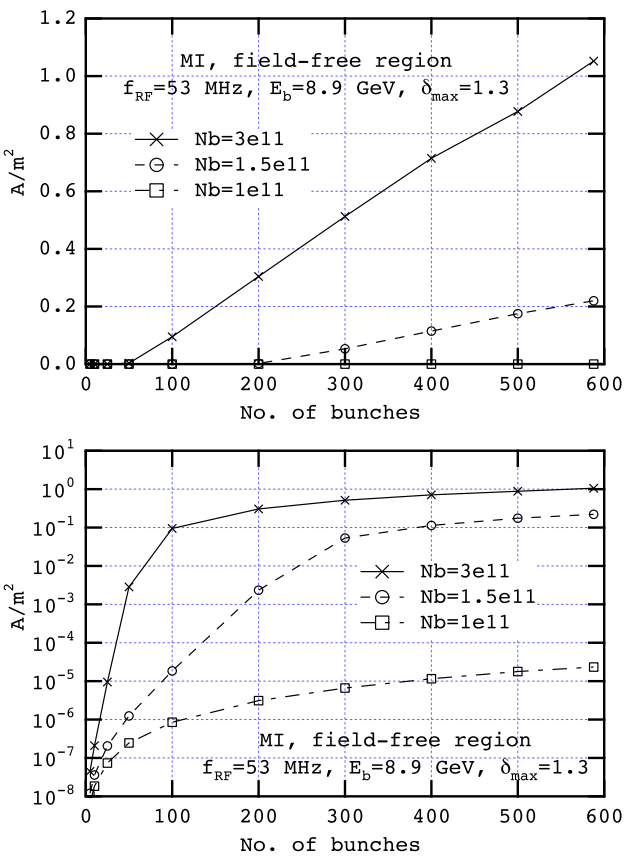


Figure 3: One-turn average of $J_e$ in a field-free region as a function of the number of bunches in the pulse, assuming $\delta_{\max} = 1.3$. Top: linear scale; bottom: log scale (same data).

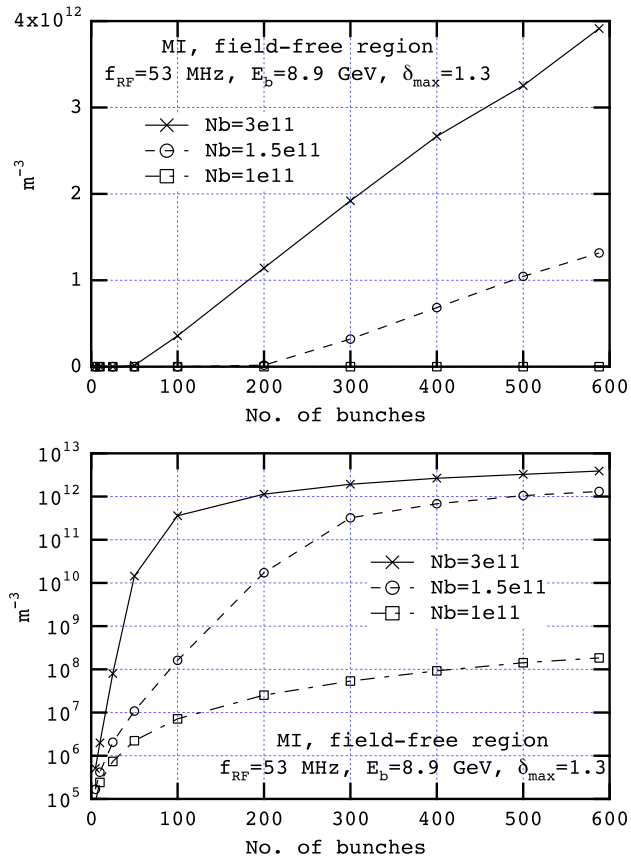


Figure 4: One-turn average of $n_e$ in a field-free region as a function of the number of bunches in the pulse, assuming $\delta_{\max} = 1.3$. Top: linear scale; bottom: log scale (same data).

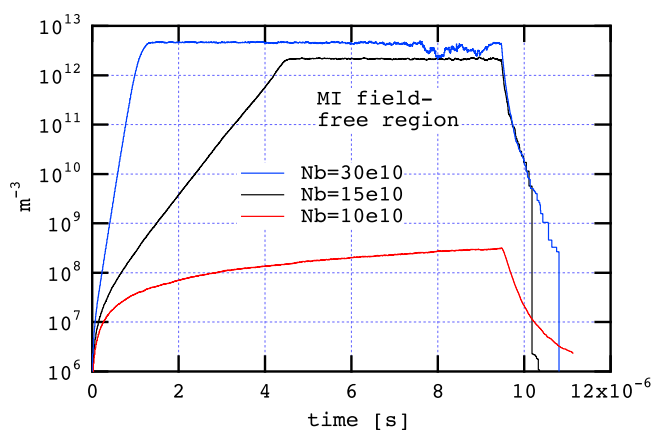


Figure 5: Build-up and dissipation of $n_e$ during one MI turn for a pulse of $M = 500$ bunches, for three values of $N_b$, as indicated, assuming $\delta_{\max} = 1.3$.

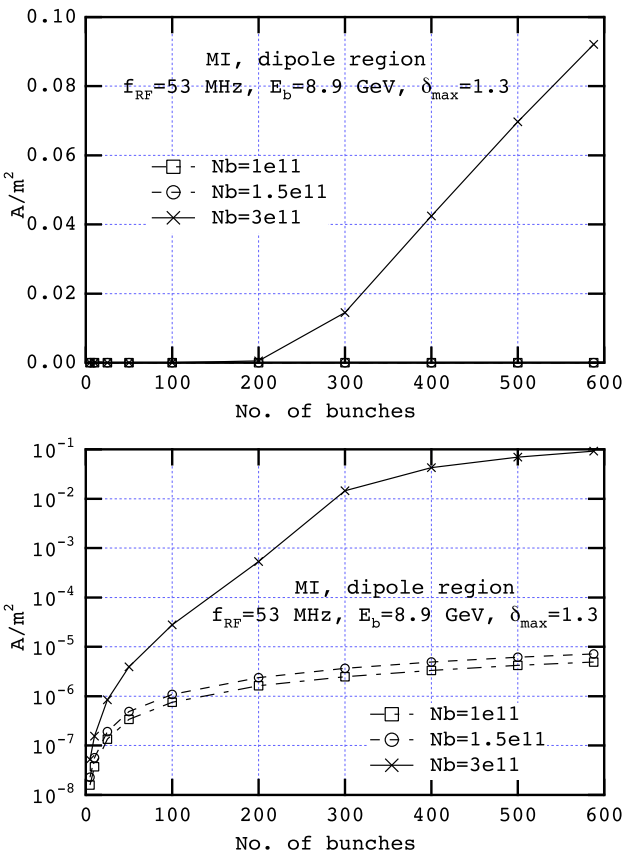


Figure 6: One-turn average of $J_e$ in a bending dipole as a function of the number of bunches in the pulse, assuming $\delta_{\max} = 1.3$. Top: linear scale; bottom: log scale (same data).

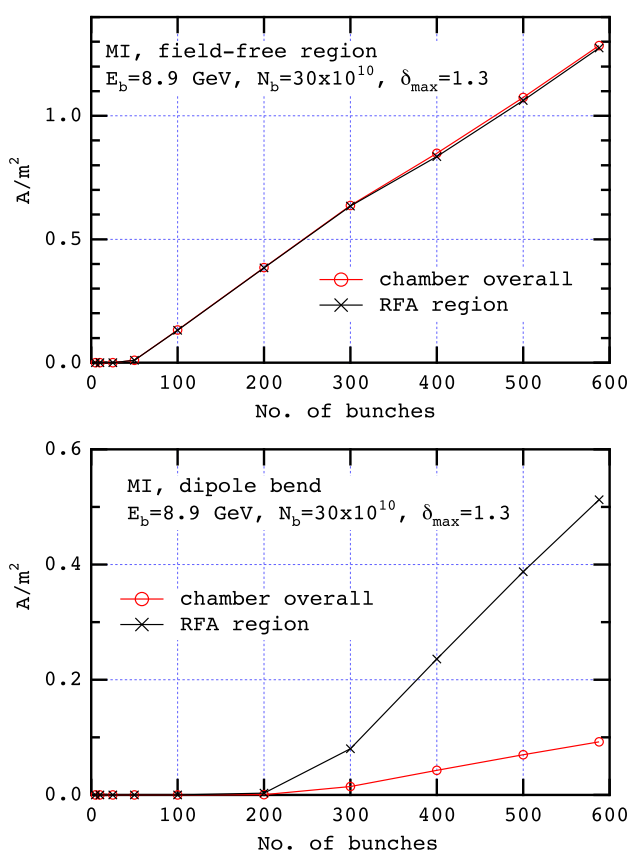


Figure 7: One-turn average of $J_e$ obtained by averaging in the chamber overall, and by averaging only in the RFA region, assuming $N_b = 30 \times 10^{10}$ and $\delta_{\max} = 1.3$. For these purposes, "RFA region" is defined as the combined top and bottom of the chamber within $-0.5'' \leq x \leq +0.5''$, where $x = 0$ is the geometrical center of the chamber in the horizontal dimension. Top: field-free region; bottom: dipole bending magnet.

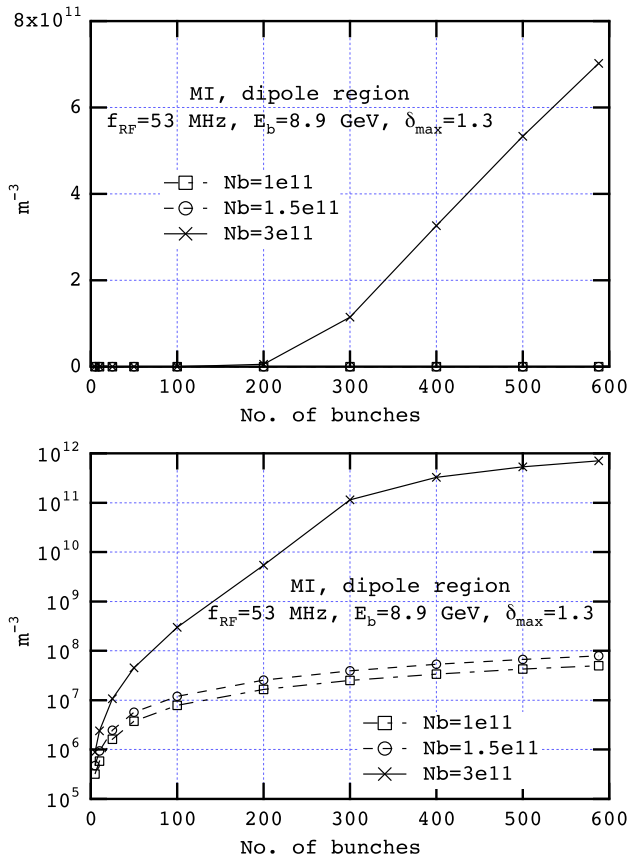


Figure 8: One-turn average of $n_e$ in a bending dipole as a function of the number of bunches in the pulse, assuming $\delta_{\max} = 1.3$. Top: linear scale; bottom: log scale (same data).

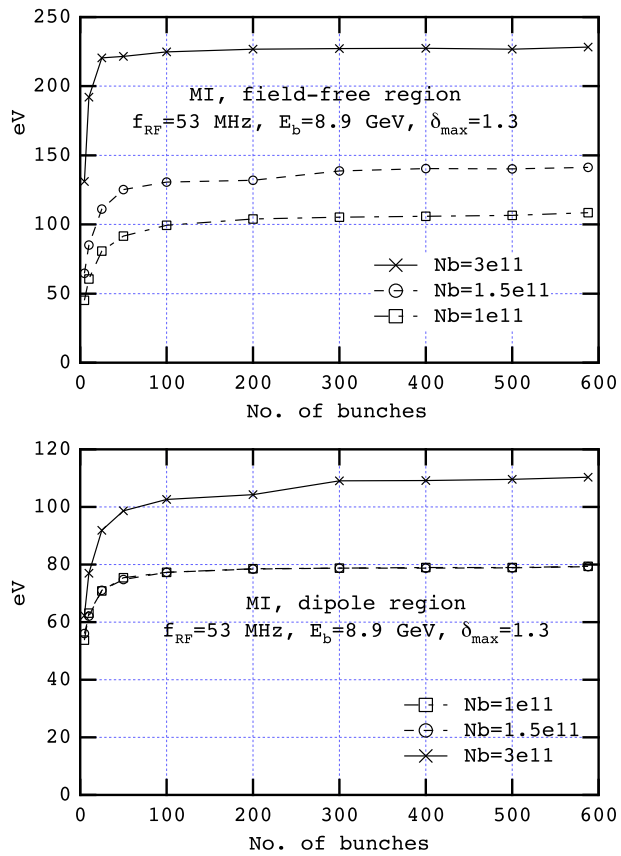


Figure 10: One-turn average of the simulated electron-wall impact energy in a field-free region and in a bending dipole as a function of the number of bunches in the pulse, assuming a peak SEY $\delta_{\max} = 1.3$.

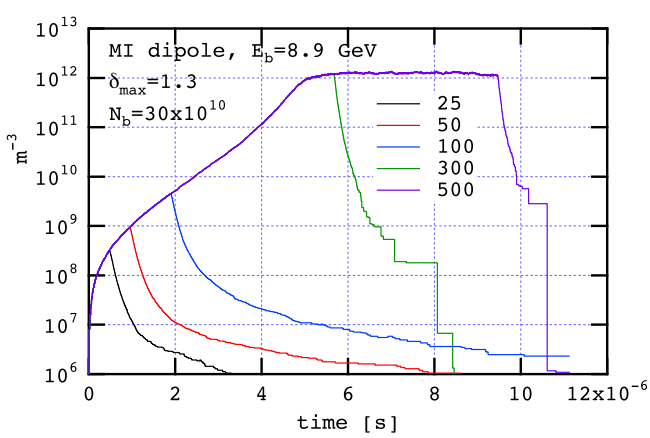


Figure 9: Build-up and dissipation of $n_e$ during one MI turn for pulses of $M = 25,\ 50, \cdots, 500$ bunches, as indicated, assuming $N_b = 30 \times 10^{10}$ and $\delta_{\max} = 1.3$.