INTRODUCTION

An upgrade to the MI is being considered that would increase the bunch intensity $N_b$ from the present $\sim 1 \times 10^{11}$ to $3 \times 10^{11}$, corresponding to a total pulse intensity $N_{\text{tot}} = 16.4 \times 10^{13}$, in order to generate intense beams for the neutrino program [1]. Such an increase in beam intensity would place the MI in a parameter regime where other storage rings have seen a significant EC effect. Motivated by this concern, efforts have been undertaken over the recent past to measure [2–5] and simulate [6–15] the magnitude of the effect and to assess its operational implications on the proposed upgrade.

We report here a summary of simulation results obtained with the code POSINST [16, 17], and certain benchmarks against measurements. Unless stated otherwise, the simulation parameters used are shown in Tab. 1. Some of these represent a slightly simplified version of the MI operation.

DEPENDENCE ON SEY

During 2006 an RFA-type electron detector was installed in a field-free straight section of the MI and was used to measure the electron flux $J_e$ incident on the RFA for various bunch intensities $N_b$ and fill patterns [2–5]. Fig. 1 of Ref. [11] summarizes the measurements.

The primary unknown variable in the EC intensity build-up is the peak value of the secondary electron yield (SEY) $\delta_{\text{max}}$. By fixing other variables and then running simulations for various assumed values of $\delta_{\text{max}}$, we were able to fit the measurements [11], as shown in Fig. 1, obtaining $1.25 \lesssim \delta_{\text{max}} \lesssim 1.30$. The close clustering of the solutions, which were obtained for rather varied beam conditions, indicates consistency in the simulation model and the measurements. For all other results presented in this article we assumed $\delta_{\text{max}} = 1.3$.

The EC number density $n_e$ inferred from these measurements is sufficiently low that it is not expected to cause significant detrimental effects on the beams used in the measurements. This absence of an effect is, indeed, consistent with observations.

DEPENDENCE ON $N_b$

The dependence of $n_e$ on $N_b$ is shown in Figs. 2-3, where $n_e$ represents the one-turn average of the electron density in the entire section being simulated (the local density in the neighborhood of the beam is substantially higher) [12–14]. Also shown is the average electron-wall impact energy $E_0$.

Table 1: Selected MI parameters used in most simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring circumference</td>
<td>$C = 3319.419$ m</td>
</tr>
<tr>
<td>RF frequency</td>
<td>$f_{RF} = 52.809$ MHz</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>$h = 588$</td>
</tr>
<tr>
<td>Beam fill pattern</td>
<td>500 full + 88 empty</td>
</tr>
<tr>
<td>Beam energy</td>
<td>$E_b = 8.9 - 120$ GeV</td>
</tr>
<tr>
<td>Bunch profile</td>
<td>3D gaussian</td>
</tr>
<tr>
<td>Transv. RMS bunch sizes</td>
<td></td>
</tr>
<tr>
<td>at 8.9 GeV</td>
<td>$(\sigma_x, \sigma_y) = (2.3, 2.8)$ mm</td>
</tr>
<tr>
<td>RMS bunch length $\sigma_z$</td>
<td>see Fig. 4</td>
</tr>
<tr>
<td>Pipe cross sect. at RFA</td>
<td>round</td>
</tr>
<tr>
<td>Pipe radius at RFA</td>
<td>$a = 7.3$ cm</td>
</tr>
<tr>
<td>Pipe cross sect. at dipole</td>
<td>elliptical</td>
</tr>
<tr>
<td>Pipe semiaxies at dipole</td>
<td>$(a, b) = (6.15, 2.45)$ cm</td>
</tr>
<tr>
<td>Dipole bending field</td>
<td>0.0115 T/(GeV/c)</td>
</tr>
</tbody>
</table>

Secondary $e^-$ parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak SEY</td>
<td>$\delta_{\text{max}} = 1.2 - 1.4$</td>
</tr>
<tr>
<td>Energy at $\delta_{\text{max}}$</td>
<td>$E_{\text{max}} = 292.6$ eV</td>
</tr>
<tr>
<td>SEY at 0 energy</td>
<td>$\delta(0) = 0.2438 \times \delta_{\text{max}}$</td>
</tr>
</tbody>
</table>

1 At other energies, $\sigma_x$ and $\sigma_y$ were assumed to scale as $\gamma^{-1/2}$.

Figure 1: Simulated electron flux $J_e$ vs. $\delta_{\text{max}}$ (curves) and RFA measurements (thick horizontal lines) for the respective fill patterns. The bowties indicate the intersections of the measurements with the simulations for each case [11].

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Figure 2: Average $n_e$ and $E_0$ in the field-free region containing the RFA, at injection and extraction $E_b$.

Figure 3: Average $n_e$ and $E_0$ in a dipole bending magnet at injection and extraction $E_b$.

Figure 5: Average $n_e$ and $E_0$ vs. $E_b$ in the RFA field-free region for two values of $N_b$.

Figure 6: Average $n_e$ and $E_0$ vs. $E_b$ in a dipole bending magnet for two values of $N_b$.

**DEPENDENCE ON $E_b$**

The primary dependence of the EC build-up on beam energy $E_b$ is through the bunch length, which varies substantially as $E_b$ ramps from 8.9 GeV to 120 GeV, as seen in Fig. 4. The simulated density $n_e$ vs. $E_b$ is shown Figs. 5-6 for two selected values of $N_b$. There is appreciable variation of $n_e$ only near transition energy, where $\sigma_z$ is smallest, as expected.

**DEPENDENCE ON $f_{RF}$**

We compared [12] the EC density for the actual RF frequency $f_{RF} = 53$ MHz ($\hbar = 588$) against a hypothetical value of 212 MHz ($\hbar = 4 \times 588 = 2352$). For the purposes of this exercise we assumed, for $f_{RF} = 53$ MHz, a fill pattern consisting of 548 consecutive filled buckets, each with $N_b$ protons and RMS bunch length $\sigma_z$, plus 40 empty buckets. For 212 MHz we assumed 2192 filled buckets, each with $N_b/4$ protons and RMS bunch length $\sigma_z/4$, plus 160 empty buckets. All other quantities were kept fixed. The total number of protons per pulse in either case is $N_{tot} = 548 \times N_b = 2192 \times (N_b/4)$. Results are shown in Fig. 7.

Figure 7: Average $n_e$ vs. $N_{tot}$ in the RFA field-free region for $f_{RF} = 53$ and 212 MHz at injection $E_b$.

**DISCUSSION**

Having simulated various current operational scenarios and compared our results against RFA measurements, we have obtained a reasonably consistent picture indicating $\delta_{max} \sim 1.3$, assuming $E_{max} = 283$ eV. Although this value for $E_{max}$ is realistic, we do not have evidence that it is the actual value for the MI vacuum chamber (a typi-
cal range for $E_{\text{max}}$ is 250–350 eV). It is generally possible to trade off, to some extent, $\delta_{\text{max}}$ and $E_{\text{max}}$ for each other in any given fit to the data. Pinning down both parameters requires a broader set of simultaneous fits than we have carried out, and this exercise remains to be done.

Extrapolating our simulations to higher beam intensities, we predict a significant increase of the electron density $n_e$ in field-free regions. For these, $n_e$ exhibits a threshold behavior in $N_b$, with approximately linear dependence on $(N_b - N_{b,\text{th}})$ above the threshold $N_{b,\text{th}}$. For a dipole bending magnet there is no indication of threshold behavior in $N_b$: $n_e$ increases rather strongly, and non-monotonically, for $N_b$ above $\sim 2 \times 10^{10}$, and further changes are $E_b$-dependent. At the design goal, $N_{\text{tot}} = 16.4 \times 10^{15}$, we estimate the time-averaged, volume-averaged $n_e$ in the range $(0.1 - 1) \times 10^{12}$ m$^{-3}$ (the density in the neighborhood of the beam is substantially higher). The peak exhibited by $n_e$ at $N_b \approx 1 \times 10^{11}$ in a dipole can be explained from the $E_0$ data: when $N_b \approx 1 \times 10^{11}$, $E_0$ crosses 300 eV, the assumed value for the location of the SEY peak. The actual value of $N_b$ where $n_e$ peaks depends on the actual value of $E_{\text{max}}$. The dependence of $E_0$ on $N_b$, however, does not explain all simulation trends; this issue remains to be better understood. In particular, we do not yet have an explanation for the increase of $n_e$ at $N_b \lesssim 3 \times 10^{11}$ at injection $E_b$ in a dipole magnet.

The dependence of $n_e$ on $E_b$ is generally mild except near transition energy, given that the bunch length has strongest variation about this energy. This translates into strong variation of the strength of the beam-electron kick, hence into strong variation of $E_0$, hence of the effective SEY, hence of $n_e$. For $E_b$ significantly larger than $E_{\text{max}}$ the effective SEY is smaller that for $E_0 \sim E_{\text{max}}$. This accounts for the reversal in the dependence of $n_e$ for the two selected values of $N_b$ when comparing the field-free region and the dipole magnet. The mild sensitivity of the EC to $E_b$ is consistent with recent measurements via the microwave dispersion technique [18], but not with RFA measurements. These latter show a rather strong dependence on $E_b$, typically peaking at $E_b \sim 60$ GeV. This issue remains to be clarified.

Going to a hypothetical $f_{\text{RF}}$ four times larger than the present 53 MHz, with 4 times smaller bunch population, leads to a threshold of the EC build-up $\sim 2$ times higher in $N_{\text{tot}}$ in a field-free region relative to the 53 MHz case. Above threshold, including the design goal of $N_{\text{tot}} = 16.4 \times 10^{15}$, the density is $\sim 2 - 4$ times lower for the higher $f_{\text{RF}}$ than for the lower. Preliminary simulations for a dipole bending magnet, however, do not show such a beneficial trend at the higher $f_{\text{RF}}$, and remain to be properly analyzed and understood.

Our overall experience with simulations of proton storage rings, including the MI, consistently show that the vacuum chamber SEY is the main variable that determines $n_e$ and hence the severity of all EC-related effects. The surest way to decrease these effects, therefore, is to decrease the SEY of the vacuum chamber by means of low-emission coatings, grooved surfaces, clearing electrodes, appropriate magnetic fields, etc.

We have checked the numerical stability of our simulation results against computational parameters such as the integration time step, space-charge grid size and number of macroparticles, but not in all combinations. While with have confidence in our results, a final check for any given specific set of physical parameters check remains to be carry out. In any case, a clear qualitative picture of the EC build up in the MI field-free regions and dipole bending magnets is emerging.

Initial simulations of the effects from the EC on the beam have been carried out [15]. These calculations indicate a threshold $n_e \sim 10^{12}$ m$^{-3}$ for significant emittance growth, which is in the range of our EC density estimates. Therefore, it is important to pursue such investigations further.

Recent simulations [19] of the EC build-up for the proposed PS2 storage ring at CERN show results remarkably similar to those summarized here for the MI. Therefore, a program of benchmarks will benefit the beam dynamics studies in both machines.

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REFERENCES

[18] N. Eddy et. al., these proceedings.
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