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# SECONDARY ELECTRON YIELD MEASUREMENT AND ELECTRON CLOUD SIMULATION AT FERMILAB

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*Abstract*

Fermilab Main Injector is upgrading the accelerator to double the beam intensity from 24e12 protons to 48e12 protons, which brings the accelerator into a regime where electron cloud effects may limit the accelerator performance. In fact, an instability that could be caused by electron cloud effects has already been observed in the Recycler [1, 2].

Secondary Electron Yield (SEY) is an important property of the vacuum chamber material that has great influence on the process of building up free electrons. The Main Injector of the Fermilab accelerator complex offers the opportunity to measure SEY and conditioning effects in the environment of a running accelerator, since samples of these materials are located at the beampipe wall. The SEY of stainless steel (SS316L) and TiN coated SS316L in the proximity of the proton beam were measured and compared.

A series of simulation studies of electron cloud build up were done for the Main Injector and Recycler using the code POSINST. Parametric studies were done to determine the maximum electron density vs. peak SEY at different beam intensities in the Fermilab Main Injector. Threshold simulations of electron cloud density versus SEY were extended from Main Injector to include the Recycler Ring [3]. It was found that the electron cloud density around the beam depends on bunch location within the bunch train.

## SEY MEASUREMENT

The Secondary Electron Yield (SEY) measures on average how many electrons are emitted when one electron hits the beam chamber surface. SEY is generally dependent on the incident electron energy, $E$, and the incident angle, $\theta$. The SEY of different materials and coatings has been studied for many years; however, the effect of the accumulated dose under actual accelerator conditions has only been studed recently [4].

### *SEY Test Stand*

The SEY measurement stand was originally designed and built by Cornell. Modifications were made to adapt it to the Main Injector, reduce background, and improve signal level for the Main Injector tunnel conditions [4, 5].

The measurement stand has two different arms so that two samples can be exposed to the same dose for comparison. The arms are protected by faraday boxes to eliminate leakage current. Each sample is a small curved piece that sits on the vacuum chamber wall. They are retracted from the vacuum chamber on an electrically isolated arm during measurements. Two Kimball Physics ELG-02 electron guns were installed and are directed towards the sample at a 15° angle, which will increase the measured SEY by 1% compared to normal incidence, according to the Furman-Pivi probabilistic model [6]. The electron guns scan over an energy spectrum of 45 *eV* to 1545 *eV* with a 1 *mm* diameter spot on a 3 × 3 grid. A Keithley 6487 pico-Ammeter is used to indirectly measure the SEY of the sample. A bias voltage must be applied during measurements and the pico-Ammeter is also used to apply this bias voltage.

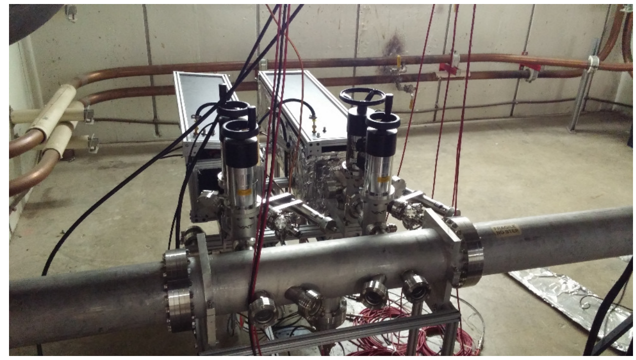

Figure 1: The SEY test stand.

A typical measurement generally takes 6 to 8 hours, which includes transportation of the DAQ-control computer, equipment set-up and warm-up and then the actual measurement. The test stand vacuum vessel is grounded during measurements. The gun was set to to deliver 0.5 to 1.0 *nA* beam at 300 *eV*. The primary current $I_p$ is measured by applying a +150 V bias voltage that recaptures all secondary electrons. The total current $I_t$ is measured by applying -20 V that repels all low energy secondary electrons. Then the secondary emission current is given by $I_{SEY} = I_t - I_p$. The SEY can be calculated by the following equation.

$$SEY = \frac{I_{SEY}}{I_p} = \frac{I_t - I_p}{I_p} \quad (1)$$

### *Leakage Current*

Due to the low signal current measured, the bias voltage induced leakage current can cause a very high background during a measurement. The leakage current can reach as high as tens of nano-Amperes and must be compensated when calculating the SEY from the data. High leakage current generally occurred when the ceramic (used to isolate the vacuum vessel from the sample) got wet due to moisture from the surrounding atmosphere, or there were excessive vibrations around the testing stand, or current leakage from the wire to the faraday box. The following modifications were made to control the leakage current:

1. Implementation of a faraday box.

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2. Implementation of a nitrogen system to keep the ceramic dry.

3. Better isolation of wires from the faraday box.

The leakage current generally takes 2 to 5 minutes to reach a steady level, so before a measurement it is necessary to wait for the leakage current to settle. Recently, the leakage current during measurements have been around 300 *pA* with a variation of 20%.

### *SEY Measurement Results*

Two sets of Main Injector SEY measurements have been taken to monitor changes with beam exposure.

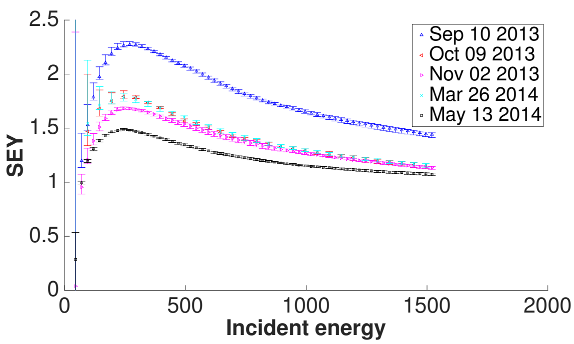


Figure 2: SS316L SEY measurements during 2013-2014.

Figure 2 shows the first data set, which was taken from one sample of stainless steel 316L (SS316L, which makes up most of Main Injector), during 2013-2014. Only one of the two arms of the SEY test stand was functional at the time. Over time, the peak SEY of the sample dropped from 2.2 to 1.5.

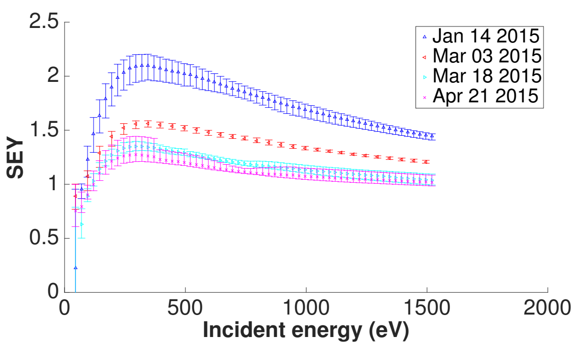


Figure 3: TiN coated SS316L SEY measurements.

The second data set using new samples shows a comparison between the SEY evolution of stainless steel 316L and titanium nitride (TiN) coated SS316L from 2014 till now. Figure 3 shows the TiN result and figure 4 shows SS316L data for comparison. With the same amount of conditioning, the peak SEY of TiN went down below 1.3 compare to a low of 1.5 of SS316L. The final SEY value of TiN would not be as low if the entire chamber were coated with TiN. The presence of SS316L causes electrons to persist due to its higher SEY, so there is more conditioning.

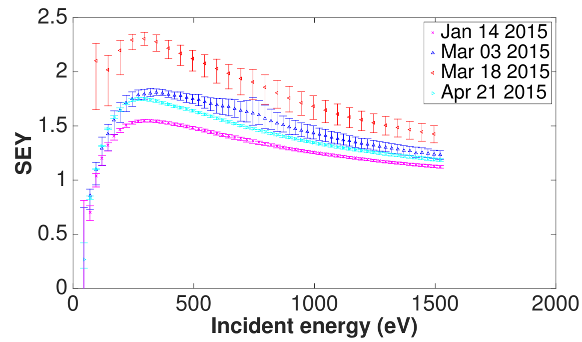


Figure 4: SS316 SEY measurements.

## POSINST SIMULATION

The POSINST code simulates the build-up and dissipation of electron cloud in an accelerator environment described by realistic beam parameters and values for the externally applied magnetic field [6–10]. Simulations of the SEY test stand environment were done to estimate the electron cloud intensity and the number of electrons that hit the vacuum chamber. Simulations were also done for a different machine, the Recycler Ring (RR), since instabilities have been observed there that could be caused by the build up of an electron cloud.

### *Main Injector Simulations*

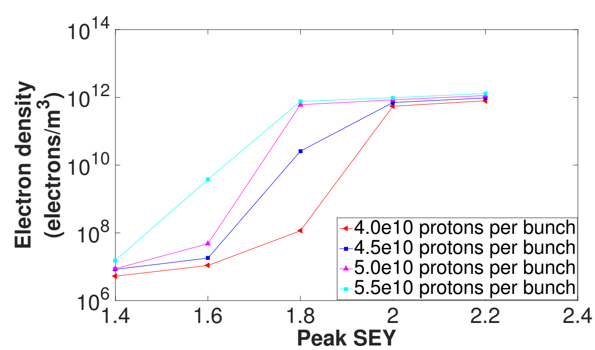


Figure 5: Maximum electron density vs. peak SEY at different beam intensities.

Main Injector (MI) simulations for the SEY-test-stand location were done using the MI circular beam pipe radius 7.3 *cm*. The simulation scanned over peak SEY values from 1.4 to 2.2 with beam intensities varying from $4.0e10$ to $5.5e10$ protons per bunch.

Simulation results are shown in figure 5 and figure 6. They show that the maximum electron cloud intensity will drop five orders of magnitude when the SEY drops from 2.2 to 1.4. The bombardment rate also drops five orders of magnitude when the SEY drops. When the SEY drops below 1.4, the electron cloud does not saturate, and for some cases does not even maintain the seeding electron population.

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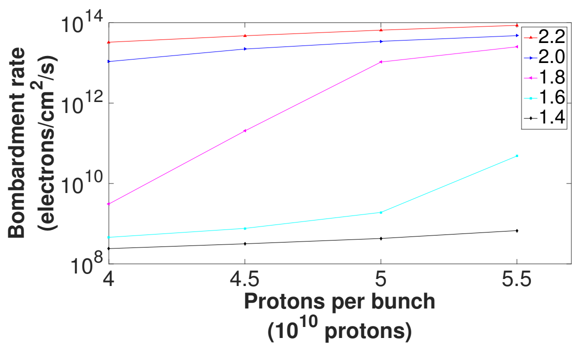


Figure 6: Simulation of bombardment rate on the vacuum chamber with different peak SEY.

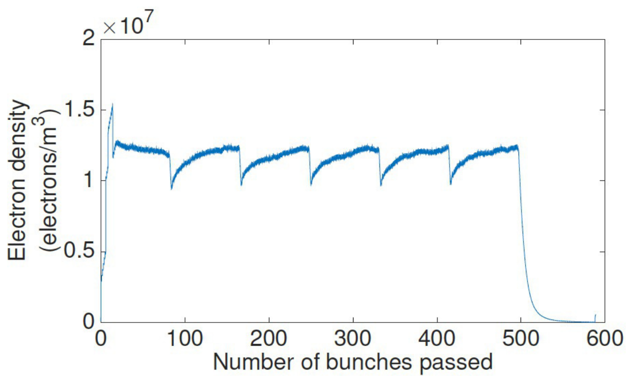


Figure 7: Electron cloud density for peak SEY 1.4 and 4.0e10 protons per bunch.

### *Recycler Simulation*

The Recycler Ring simulation was done using the elliptical vacuum chamber dimensions of 4.7 *cm* semi-major radius in the x-direction and 2.2 *cm* semi-minor radius in the y-direction. The simulation scanned the peak SEY value from 1.6 to 2.2 with a beam intensity of $5.0e10$ protons per bunch with and without a dipole field.

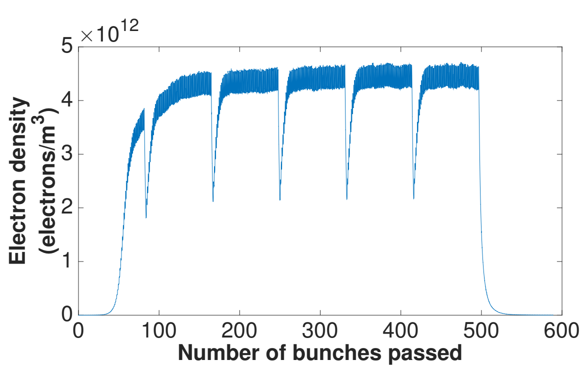


Figure 8: Total electron cloud density.

The simulation shows an interesting bunch selection phenomenon where in a dipole field region. Figure 8 and figure 9 showed that the electron-cloud gathers around the beam during the build-up and spreads out after saturation is reached. Table 1 shows the Recycler simulation results for electron cloud densities and peak density location referenced to bunch number.

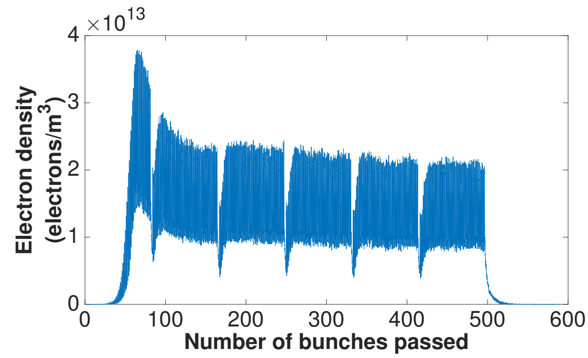


Figure 9: Electron cloud density within one sigma of the proton beam.

Table 1: Recycler Simulation Result

| $SEY$ | $n_{dp}$ $(e^-/m^3)$ | $n_{fr}$ $((e^-/m^3)$ | $n_{os}$ $(e^-/m^3)$ | $b_{os}$ |
|---|---|---|---|---|
| 1.6 | $1.7e84$ | $3.5e8$ | $4.64e9$ | 333 |
| 1.8 | $2.04e12$ | $2.19e12$ | $2.38e13$ | 149 |
| 2.0 | $3.56e12$ | $4.18e12$ | $3.19e13$ | 104 |
| 2.2 | $4.77e12$ | $5.42e12$ | $3.78e13$ | 68 |

First column: $(SEY)$ peak SEY value; Second column: $(n_{dp})$, maximum electron cloud density within dipole field; Third column: $(n_{fr})$, maximum electron cloud density in field free region; Forth column: $(n_{os})$, maximum electron density within one sigma around the beam; Fifth column: $(b_{os})$, maximum one sigma electron density position in the bunch train (bunch number).

## CONCLUSION

The measurement of SEY and the change in SEY due to conditioning in a proton accelerator environment was done for both TiN coated SS316L and SS316L. This was the first time a direct comparison could be done for different materials in a proton beam environment. The measurements were supported with POSINST simulation studies of electron cloud density versus SEY for the Main Injector. Simulations were also done for the Recycler Ring where an electron cloud instability may be occurring [1, 2]. It was found that the position of the maximum electron density along the bunch train depends on peak SEY value.

## ACKNOWLEDGEMENT

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