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ELECTRON CLOUD SIMULATIONS IN THE FERMILAB BOOSTER

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ABSTRACT

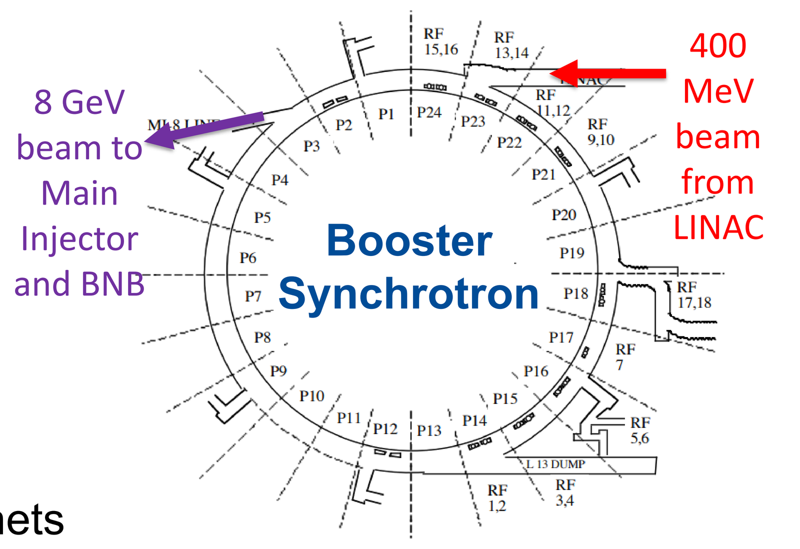
As part of Fermilab's Proton Improvement Plan-II (PIP-II), the Fermilab Booster synchrotron will operate at a higher intensity, increasing from 4.5×10^{12} to 6.7×10^{12} protons per pulse [ppp]. A potential challenge for achieving high-intensity performance arises from rapid transverse instabilities induced by electron cloud (EC). This research presents EC simulations using PyECLOUD, which is an advanced computational tool that incorporates measurements of the secondary electron yield (SEY) from the Booster's combined function magnet material. By systematically varying beam parameters in PyECLOUD, such as bunch structure, bunch length, and intensity, the EC effects on beam stability and overall performance of Booster can be predicted.

INTRODUCTION

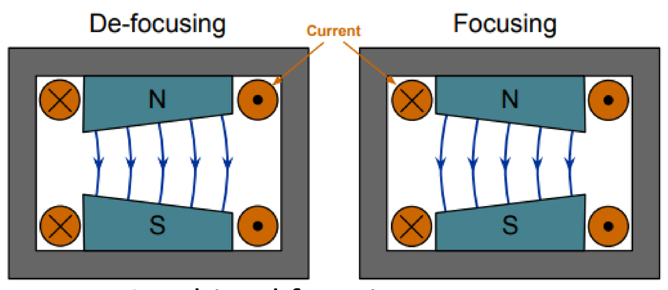
Booster layout

- Booster is a synchrotron that accelerates protons from 400 MeV to 8 GeV.

Parameter	Value
Circumference [m]	474.20
Cycle time [s]	1/15
Harmonic number	84
Number of cells	24
Transition energy [GeV]	4.2
Intensity for 14-turn injection, [ppp]	~4.5×10^{12}



- Booster contains 96 combined function magnets
- Combined function magnets can trap the EC due to its magnetic mirror effect.
- EC accumulates over many revolutions inside a combined function magnet and can reach final densities orders of magnitudes higher than inside a pure dipole.

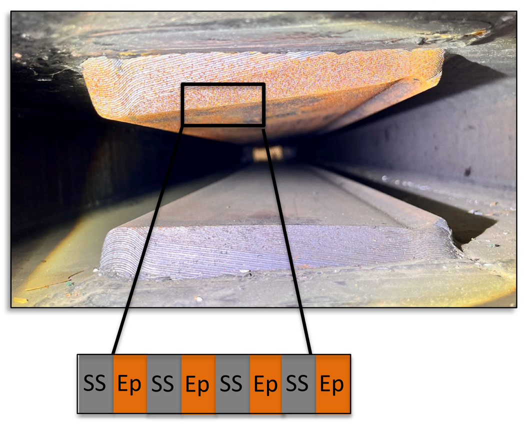


Combined function magnets

SEY MEASUREMENTS

- SEY of a combined function magnet material greatly influences the build-up of the free electrons, which ultimately leads to an EC.
- Booster combined function magnets consist of stainless steel sheets stacked using epoxy layers in between (to minimize eddy currents).
- Thus, the accelerated free electrons in the beam pipe have the potential to interact with both the stainless steel and epoxy components of these magnets.
- As a result, the δ_{SEY} of the combined function magnet material should be that of stainless steel and epoxy.

Booster combined function magnet

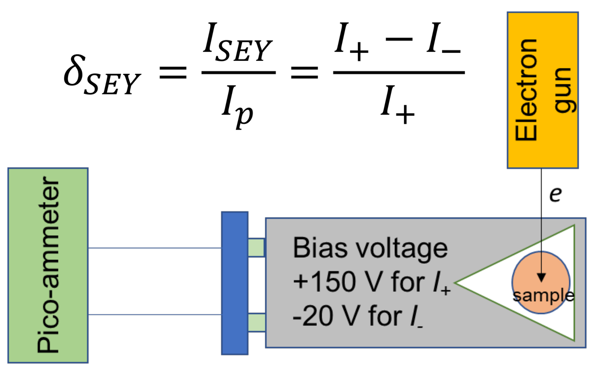


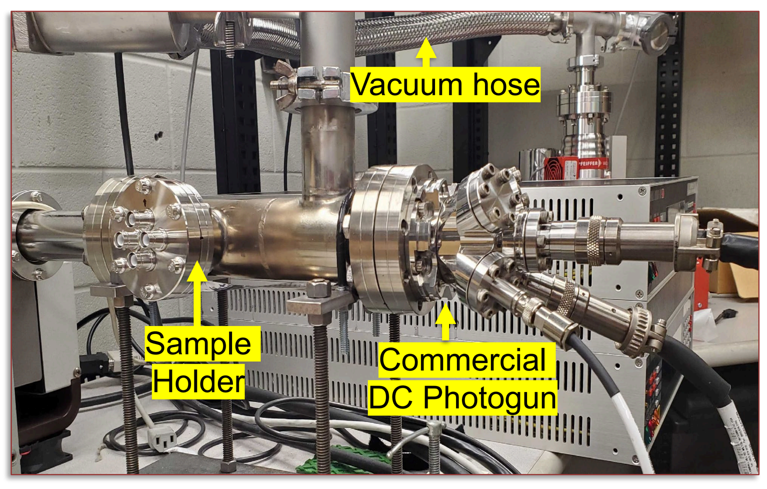
SEY measurement setup

- The SEY test stand is a dedicated setup situated in the XGW-003 area for measuring the SEY of various samples.
- Setup mainly consists of a Kimball electron gun driven by a 1022B-type power supply, associated vacuum chamber and pumping equipment (to keep pressure < 1e-5 torr), and a Keithley pico-ammeter.

Experimental technique

$$\delta_{SEY}=\frac{I_{SEY}}{I_p}=\frac{I_+-I_-}{I_+}$$



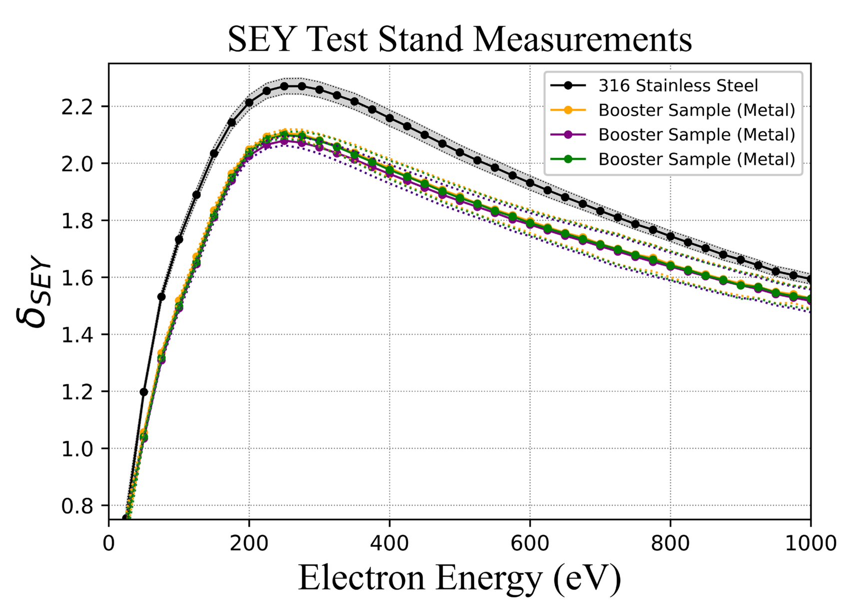


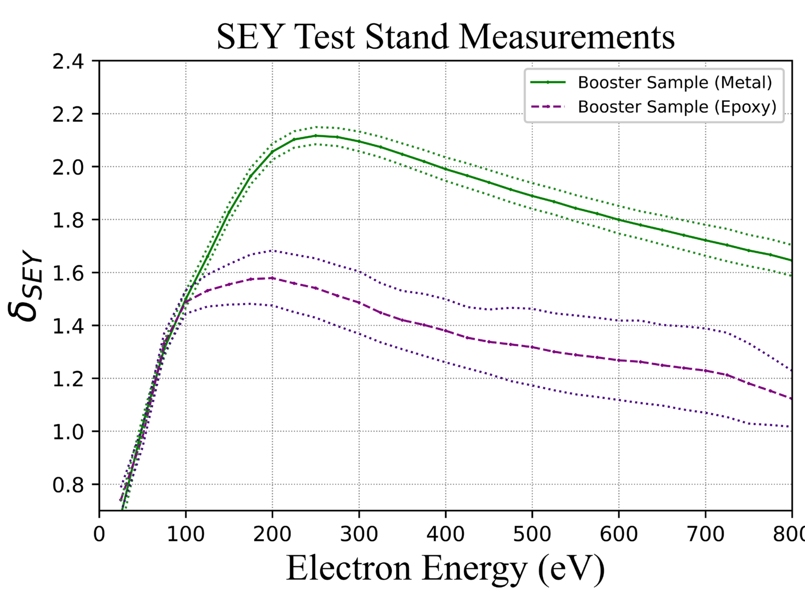
stainless steel sample

Epoxy sample

Bias Voltage Settings:

- Bias voltage of +150 V recaptures the secondary electrons (SEs) that have escaped from the surface. This provides the primary electron current, I_+.
- Bias voltage of -20 V sweeps away the low-energy SEs, enabling the measurement of I_-.





- According to the measurement, δ_{SEY}(epoxy) ≈1.6 and δ_{SEY}(stainless steel) ≈2.1

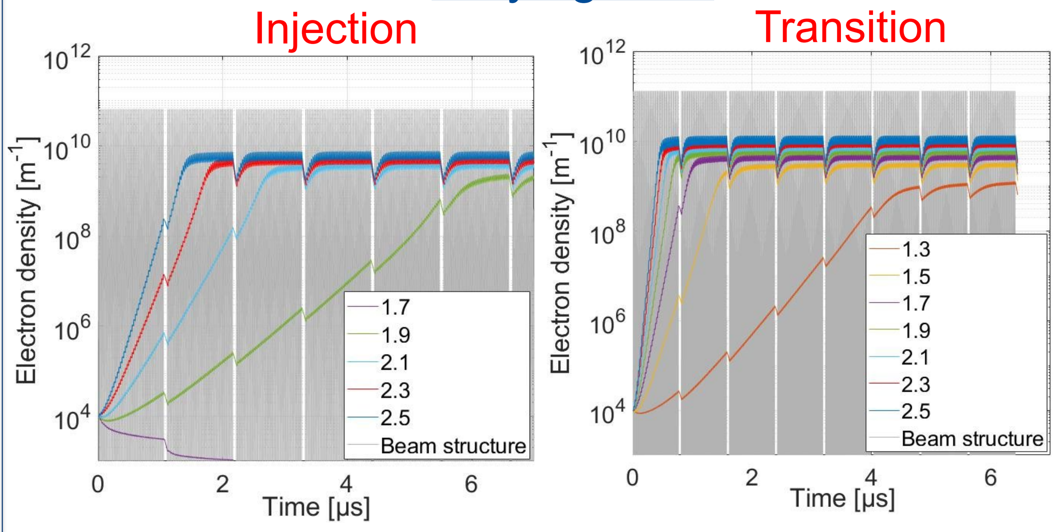
SIMULATIONS

- PyECLOUD code was used to simulate the EC build-up inside a combined function magnet located in the Booster synchrotron.
- Cross-section of the combined function magnet was modelled as a rectangular aperture with dipole and quadrupole magnetic fields.
- Relation between the tune shift ΔQ and the corresponding EC density ρ

$$\Delta Q=\frac{r_p}{\gamma\beta^2}\langle\beta\rangle\rho C\frac{x^2}{(x+y)^2}$$

r_p - classical proton radius
C - circumference
$\langle\beta\rangle$ - average beta function
β - relativistic beta, γ -Lorentz factor
x and y - semi-aperture dimensions

Varying SEY



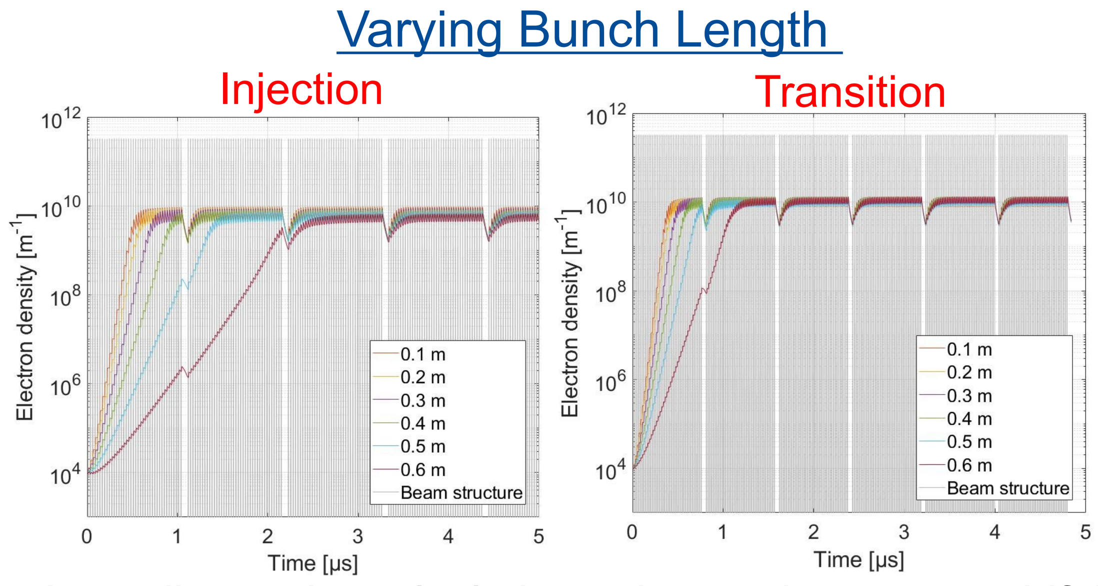
Simulation parameters

Parameter	Transition	Injection
Beam energy [GeV]	4.2	0.4
Bunch length, σ [m]	0.25	0.57
Intensity [ppp]	6.7E12	

PyECLOUD shows the EC accumulation when SEY is > 1.9 at injection.

- According to the calculations, for δ_{SEY} = 2.1 the maximum tune shift is ~0.007 at injection and 0.003 at transition.

Varying Bunch Length



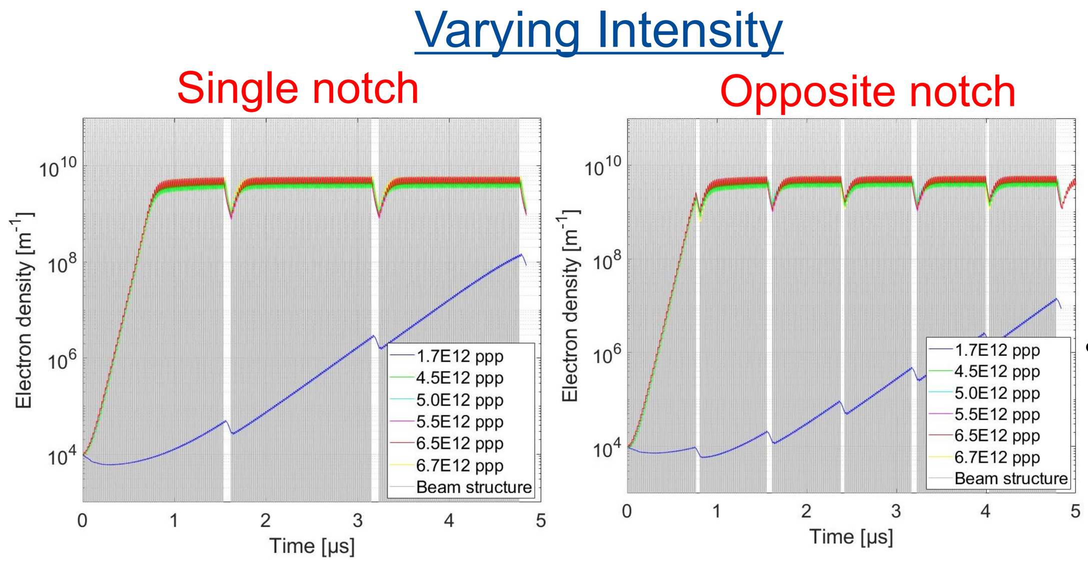
Simulation parameters

Parameter	Transition	Injection
Beam energy [GeV]	4.2	0.4
Intensity [ppp]	6.7E12	
SEY, δ	2.1	

- EC saturation is almost identical irrespective of their bunch length at the transition.

- According to the calculations, the maximum tune shift is ~0.02 at injection and ~0.005 at transition only when the bunch length is 0.1 m (rms).

Varying Intensity



Simulation parameters

Parameter	Transition	Injection
Beam energy [GeV]	4.2	0.4
Bunch length, σ [m]	0.25	0.57
SEY, δ	1.8	

- PyECLOUD did not show meaningful EC accumulation near injection with δ_{SEY}=1.8 and 0.57 m (rms) bunch length.
- EC saturation is almost identical for all the high-intensity beams, irrespective of their bunch structure, *i.e.*, notch configurations that were used minimally clears EC.
- According to the calculations, the maximum tune shift near transition of about 0.001 (with δ_{SEY}=1.8).

SUMMARY AND CONCLUSIONS

- Successfully conducted SEY measurements of the metal and epoxy sides of the combined function magnet material. δ_{SEY}(epoxy) ≈1.6 and δ_{SEY}(stainless steel) ≈2.1.
- Due to beam pipe conditioning over the years, we assume that the δ_{SEY} of the magnet material may have slightly changed from our measurements.
- According to the literature and previous experience, the tune shifts calculated for the maximum δ_{SEY} and minimum bunch length are not large enough to be a major reason for instabilities.
- The density of the accumulated EC is nearly the same for intensities > 4.5×10^{12} [ppp]. We have operated the Booster at 6.1×10^{12} [ppp] with instabilities resulting from impedances controlled by both dampers and chromaticities.
- Contribution to instability from EC is small.
- EC accumulation should not be a problem in the PIP-II era Booster.

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