ELECTRON CLOUD SIMULATIONS IN THE FERMILAB RECYCLER

A.P. Schreckenberger | 2022-08 | NAPAC 2022
THE FERMILAB COMPLEX

• **Recycler Ring**: essential piece of robust FNAL chain to accelerate protons
  - Feeds the Main Injector—the bedrock of the higher energy neutrino beam programs
  - Serves beam to Muon Campus—Muon g-2 and Mu2e

• PIP-II and future upgrades will challenge what the current machines can handle
  - **What could potentially destabilize the Recycler?**
  - **Can we develop a stability metric and find limits?**
WHY THE QUESTIONS?

• Recycler Ring has faced instability issues
  • Driven by use of combined function magnets (CFMs) in accelerator lattice
    • Fields trap electrons, possible accumulation

P. Karns et al., “Recycler Rookie Book”
WHY THE QUESTIONS?

- Recycler Ring has faced instability issues
  - Driven by use of combined function magnets (CFMs) in accelerator lattice
    - Fields trap electrons, possible accumulation

- Secondary emission yield (SEY) fuels clouds
  - Interactions between in-vacuum electrons and beam pipe material
  - Electron-cloud instabilities previously studied
    - S. Antipov, University of Chicago Thesis, 2017
    - Y. Ji, IIT Chicago Thesis, 2019

J. Eldred et al., “Fast transverse instability and electron cloud measurements in Fermilab Recycler"
THE CHALLENGES LEFT BEHIND

- Electron cloud studies rely on simulations of the SEY effect as well
  - Typically mapped as an SEY strength ($\delta_{SEY}$) vs. electron energy + incidence angle
    - Maximum value ($\delta_{Max}$) used as assessor
- J. Eldred et al. established the e-cloud as the Recycler instability source
- S. Antipov studied the CFMs and developed models with the SEY context
  - Predicted $\delta_{Max} < 2.2$ suppressed buildup
  - Predicted $\delta_{Max} > 2.5$ needed for beam-driven accumulation mechanism
THE CHALLENGES LEFT BEHIND

• S. Antipov analyzed the CFMs and developed models with the SEY context
  • “Fast Transverse Beam Instability Caused by Electron Cloud Trapped in Combined Function Magnets,” University of Chicago, 2017
  • Predicted $\delta_{\text{Max}} < 2.2$ suppressed buildup
  • Predicted $\delta_{\text{Max}} > 2.5$ needed for beam-driven accumulation mechanism

• Accelerator SEY measurements yield $1.3 < \delta_{\text{Max}} < 1.7$ during 2021 Run
  • We observe effects of conditioning
  • Feb. 2022 instability observed with $\delta_{\text{Max}} \sim 1.7$
  • Test stand — measurement verification

• Point of reconciliation for the new study
THE CHALLENGES LEFT BEHIND

• Y. Ji investigated SEY thresholds in the Main Injector using a combination of POSINST and the Furman-Pivi (FP) Model
  • “Electron Cloud Studies at Fermilab,” IIT Chicago, 2019
• **FP Model is the current standard for simulating SEY effects**
  • Phenomenological fit considers three categories
    • Elastic, rediffused, and true-secondary electrons
  • **Range of $\delta_{Max}$ shifted to values more consistent with measured SEY strengths**
    • Thesis set safe thresholds for $\delta$ below running range
      • Reconcile with rapid-resolving nature of instability
• **POSINST also does not simulate CFMs**
  • Need new solution to reinvestigate Recycler
• **Deployed PyECLoud + FP combination**
ANALYSIS ROADMAP

• Utilize FP Model to simulate SEY
• Use PyECLOUD v8.6.0 to simulate e-cloud density in Recycler
• Massive thanks to G. Iadarola
• Develop stability metric as a function of $\delta_{SEY}(\theta, E)$
• Map stability space by varying simulation parameters
• Write a paper and fly to NAPAC…

FP Model injects material considerations
• Generate $\delta_{SEY}(\theta, E)$ given FP inputs
  • Extract $\delta_{Max}(15^\circ, E)$ for final mapping
  • $15^\circ$ is the mean incident angle in Recycler, shown in Antipov’s thesis

Simulated SEY Curve
ANALYSIS ROADMAP

- Utilize FP Model to simulate SEY
- Use PyECLOUD v8.6.0 to simulate e-cloud density in Recycler
  - Massive thanks to G. Iadarola

Nominal Recycler Beam Input for PyECLOUD

<table>
<thead>
<tr>
<th>Input Name</th>
<th>Input Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>8.885 GeV</td>
</tr>
<tr>
<td>$\sigma_{x,y}$</td>
<td>0.003 m</td>
</tr>
<tr>
<td>Bunch Spacing</td>
<td>18.936 ns</td>
</tr>
<tr>
<td>Nominal Intensity</td>
<td>$5 \times 10^{10}$ ppb</td>
</tr>
<tr>
<td>Nominal Bunch Length</td>
<td>0.4 m</td>
</tr>
<tr>
<td>Nominal $n_i$</td>
<td>3000</td>
</tr>
<tr>
<td>Beam Filling Profile</td>
<td>84·[5e10 ppb]+504·[0 ppb]</td>
</tr>
</tbody>
</table>

- Beam inputs + FP(SEY) + Variables
  - Numerous simulations for cloud density
  - Examples demonstrate impact scaling $\delta_{Max}$ has on the density
ANALYSIS ROADMAP

- Utilize FP Model to simulate SEY
- Use PyECLOUD v8.6.0 to simulate e-cloud density in Recycler
  - Massive thanks to G. Iadarola
- Develop stability metric as a function of $\delta_{Max}(15^\circ, E)$

Simplest metric is a matter of math...
If $n_i > n_f$, mathematically impossible for SEY-driven instability.
If $n_f > n_i$, continued electron cloud accumulation is possible!

$R_s = n_f/n_i$, $R_s < 1.0$ sets stability region

- Beam inputs + FP(SEY) + Variables
  - Numerous simulations for cloud density
- Examples demonstrate impact scaling $\delta_{Max}$ has on the density

Density in Beam Region for Sampled SEY Curves

**Diagram:**
- $\delta_{SEY} = 1.3$
- $\delta_{SEY} = 1.7$
- $\delta_{SEY} = 2.0$

$n_f$, $n_i$, $R_s$ vs Time (s)
• Many points to digest from this plot

• Follows conditioning trend from the SEY data measurements
  • And general expectation of behavior

• Simulation properly assesses the observed instabilities

• Simulation insight aligns with February 2022 conditions

• Bunch Length considerations
  • Conditioned Recycler capped at ~8 \times 10^{10} ppb
  • Upgrade to higher intensities might require new solutions

• Important to lab's future

• Deployed PyECLOUD+FP analysis that answered existing challenges
  • Aligned with accelerator measurements
• Many points to digest from this plot

• Follows conditioning trend from the SEY data measurements
  • And general expectation of behavior

• Simulation properly assesses the observed instabilities
  • Simulation insight aligns with February 2022 conditions
  • Bunch Length considerations

THE TAKE-AWAY

Stability Region: Beam Parameter Study

$R_s = n_r/n_i \approx 3000$

$\delta(0^\circ)$ Uniform Scaling

0.5m Bunch Length

0.3m Bunch Length

304L Data Range

$\delta_{Max}(\theta \approx 15^\circ, E)$

Bunch Length considerations
• Many points to digest from this plot

• Follows conditioning trend from the SEY data measurements
  • And general expectation of behavior

• Simulation properly assesses the observed instabilities
  • Simulation insight aligns with February 2022 conditions
  • Bunch Length considerations

• Conditioned Recycler capped at \( \sim 8 \cdot 10^{10} \) ppb
  • Upgrade to higher intensities might require new solutions/ramp procedure
  • Important to lab’s future
• Many points to digest from this plot

• Follows conditioning trend from the SEY data measurements
  • And general expectation of behavior

• Simulation properly assesses the observed instabilities
  • Simulation insight aligns with February 2022 conditions
  • Bunch Length considerations

• Conditioned Recycler capped at \(~8 \cdot 10^{10}\) ppb
  • Upgrade to higher intensities might require new solutions/ramp procedure
  • Important to lab’s future

• Deployed PyECLOUD+FP analysis that answered existing challenges
  • Aligned with accelerator measurements
OVERFLOW

My effort to make 12+3
ANALYSIS ROADMAP

• Utilize FP Model to simulate SEY
  • FP Model injects material considerations
    • Different materials = different values
  • Introduces many knobs to adjust shapes and amplitudes
    • Scrutinize at future stage of analysis

[Graph showing SEY for stainless steel normal incidence]
ANALYSIS ROADMAP

• Utilize FP Model to simulate SEY

• FP Model injects material considerations
  • Different materials = different values
• Introduces many knobs to adjust shapes and amplitudes
  • Scrutinize at future stage of analysis

• Use PyECLOUD v8.6.0 to simulate e-cloud density in Recycler

• Massive thanks to G. Iadarola

• Develop stability metric as a function of $\delta \delta_M$

• Map stability space by varying simulation parameters

• Write a paper and fly to NAPAC…
ANALYSIS ROADMAP

- Utilize FP Model to simulate SEY
- Use PyECLoud v8.6.0 to simulate e-cloud density in Recycler
  - Massive thanks to G. Iadarola
- Develop stability metric as a function of $\delta_{\text{Max}}$
- Map stability space by varying simulation parameters
  - Scrutinizing FP Model...

Scanned $\delta_{\text{Max}}$ in range of interest
Nominal position in $R_s$, $\delta_{\text{Max}}$ space is stable
Induced 25% shifts on FP parameters
Full material swap required to cross $R_s = 1$
ANALYSIS ROADMAP

- Utilize FP Model to simulate SEY
- Use PyECLOUD v8.6.0 to simulate e-cloud density in Recycler
  - Massive thanks to G. Iadarola
- Develop stability metric as a function of $\delta_{Max}$
- Map stability space by varying simulation parameters
  - FP Scan built confidence small aberrations will not affect the beam study
- Write a paper and fly to NAPAC…

Stability Region: Furman-Pivi Parameter Study

- $R_s = n_f/n_i \approx 3000$
- $\delta_{Max}(\theta \approx 15^\circ, E)$
- $\delta(0^\circ)$ Uniform Scaling
- $s$ - T.S. Shape [±25%]
- $E_0$ - T.S. Shape [±25%]
- $\delta_r$ - Rediff. Amplitude
- $E_r$ - Rediff. Shape [±25%]
- $r$ - Rediff. Shape [±25%]
- $W$ - Elastic Shape [±25%]
- $p$ - Elastic Shape [±25%]
- 304L Data Range

Nominal FP values