ELECTRON CLOUD SIMULATIONS IN THE FERMILAB RECYCLER

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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*
    - J. Eldred *et al.*, Proc. HB2014, 2014
    - 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 $\delta_{MМММММ}$
• 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
ANALYSIS ROADMAP

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Nominal Recycler Beam Input for PyECLoud

| Input Name           | Input Value        |
|----------------------|--------------------|
| Beam Energy          | 8.885 GeV          |
| $\sigma_{x,y}$       | 0.003 m            |
| Bunch Spacing        | 18.936 ns          |
| Nominal Intensity    | $5 \times 10^{10}$ ppb |
| Nominal Bunch Length | 0.4 m              |
| Nominal $n_i$        | 3000               |
| Beam Filling Profile | 84-[5e10 ppb]+504-[0 ppb] |

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

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Density in Beam Region for Sampled SEY Curves

$\delta_{SEY} = 1.3$
$\delta_{SEY} = 1.7$
$\delta_{SEY} = 2.0$

$n_f$

$n_i$

$10^3$

$10^5$

$10^7$

$10^9$

Time (s)

0.0

0.2

0.4

0.6

0.8

1.0

$10^{-5}$
• 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
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OVERFLOW

My effort to make $12+3$
• 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
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- Map stability space by varying simulation parameters
- Write a paper and fly to NAPAC…

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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 $R_s = 1$
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  • Massive thanks to G. Iadarola
• Develop stability metric as a function of $\delta_{\text{Max}}$
• Map stability space by varying simulation parameters
  • FP Scan built confidence small aberrations will not affect the beam study
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Stability Region: Furman-Pivi Parameter Study

- $R_s = n_f/(n_i \approx 3000)$
- $\delta(0^\circ)$ Uniform Scaling
- $s$ - T.S. Shape $[\pm 25\%]$
- $\hat{E}_0$ - T.S. Shape $[\pm 25\%]$
- $\delta_r$ - Rediff. Amplitude
- $E_r$ - Rediff. Shape $[\pm 25\%]$
- $r$ - Rediff. Shape $[\pm 25\%]$
- $W$ - Elastic Shape $[\pm 25\%]$
- $p$ - Elastic Shape $[\pm 25\%]$
- 304L Data Range

Nominal FP values