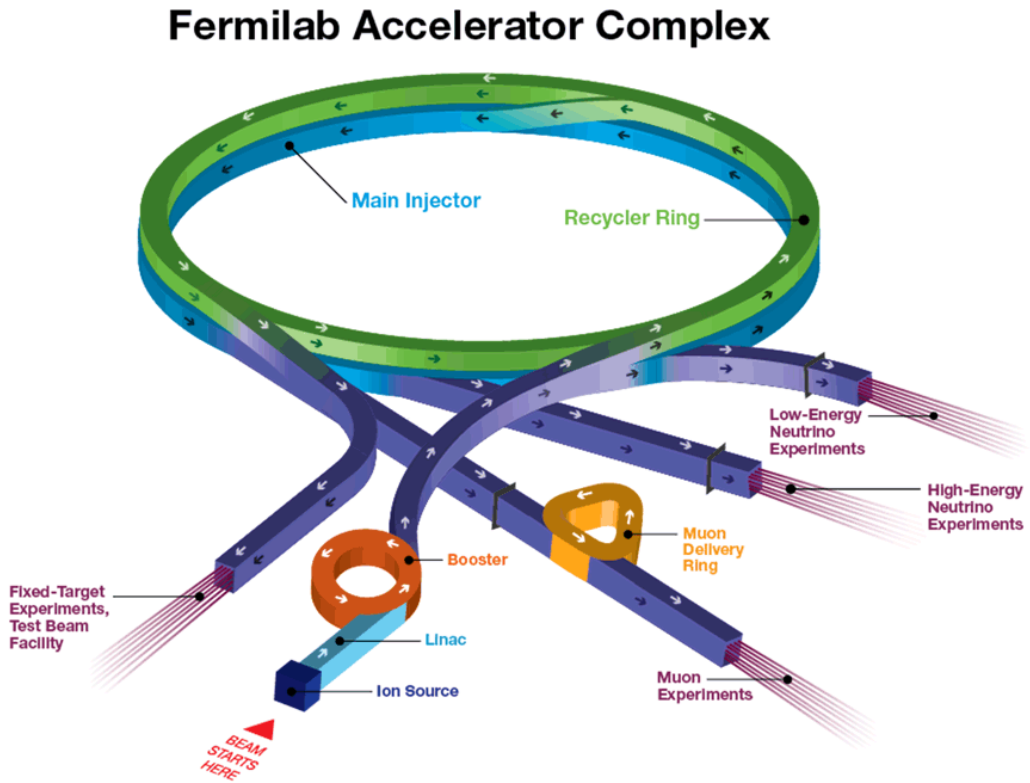
ELECTRON CLOUD SIMULATIONS IN THE FERMILAB RECYCLER

A.P. Schreckenberger | 2022-08 | NAPAC 2022

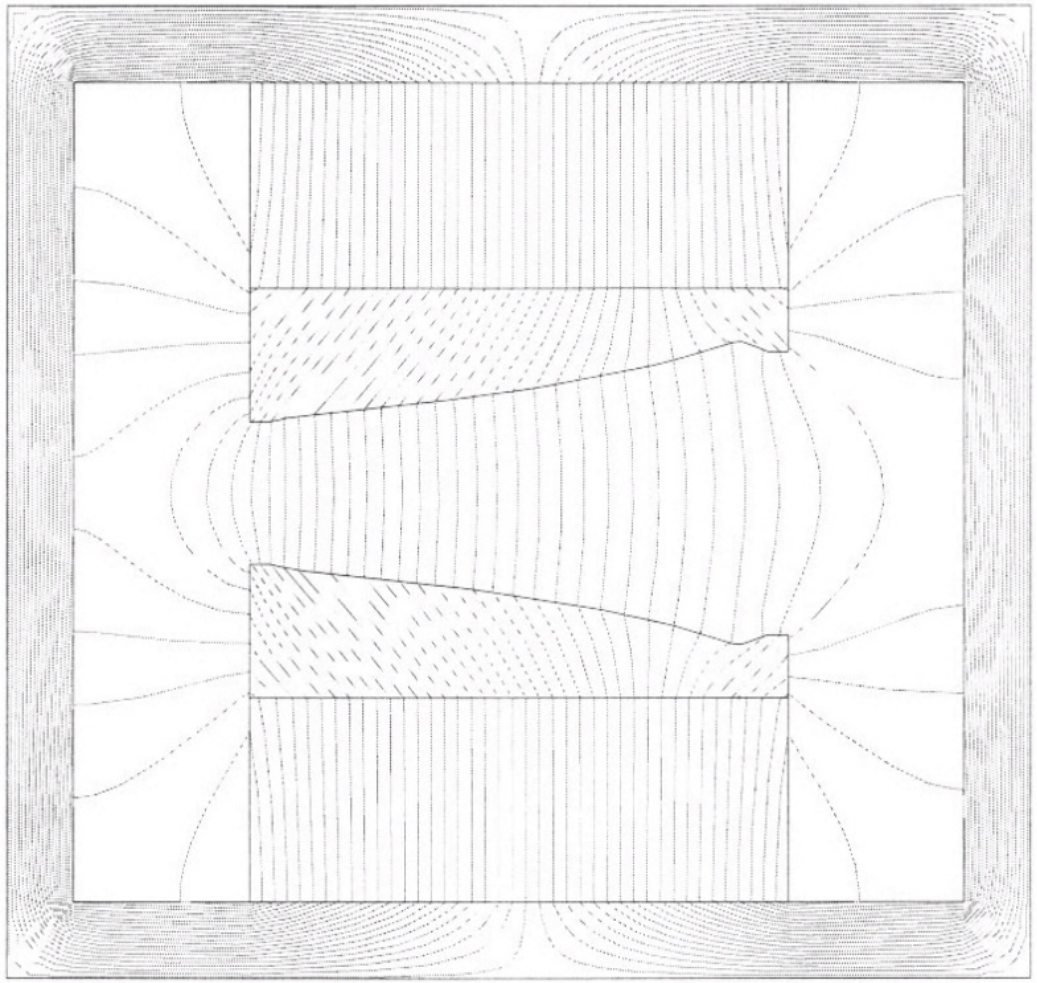
THE FERMILAB COMPLEX

- **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?**

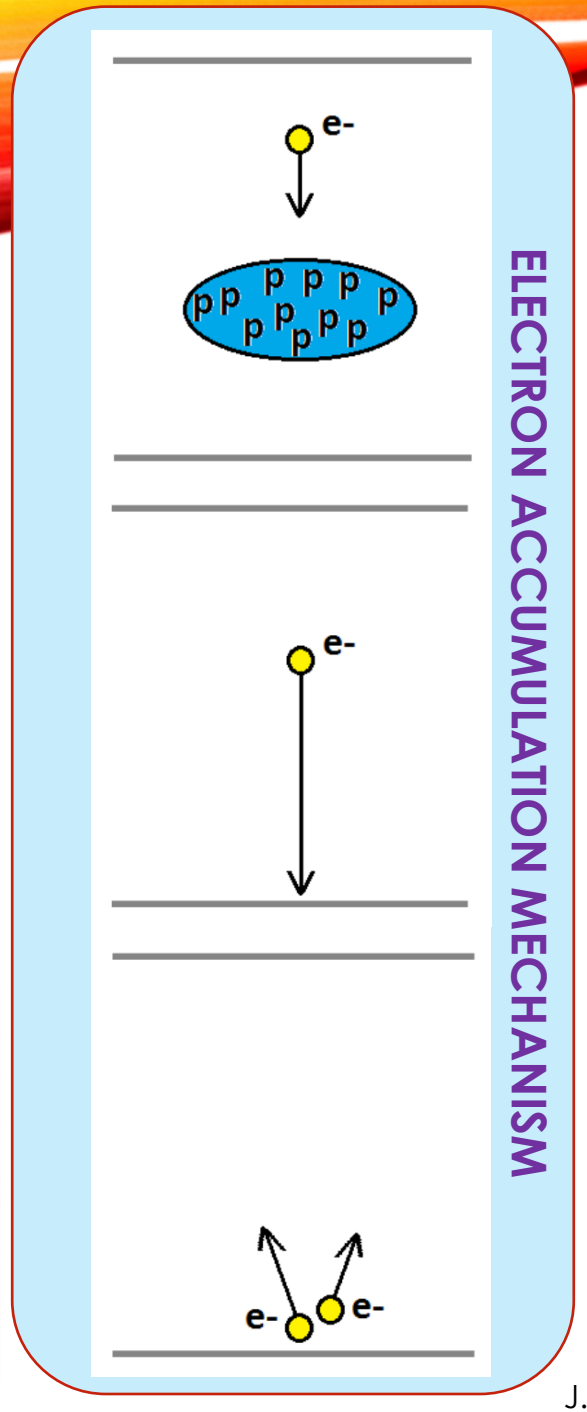


WHY THE QUESTIONS?

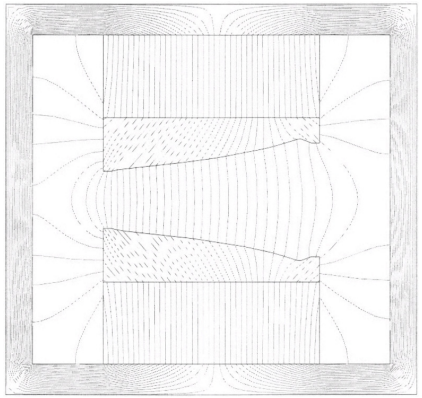


P. Karns *et al.,* "Recycler Rookie Book"

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



MAGNETIC MIRRORS →



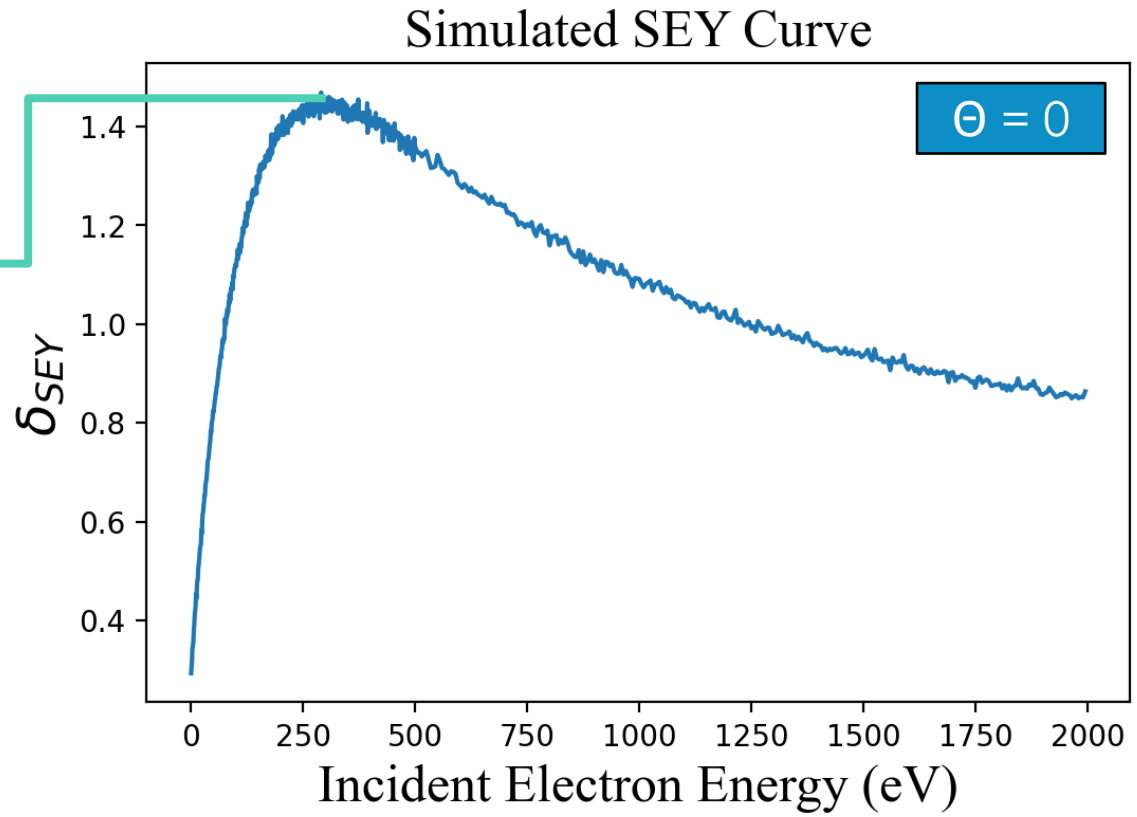
WHY THE QUESTIONS?

- **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 (δ_{SEY}) vs. electron energy + incidence angle
    - **Maximum value (δ_{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* $\boldsymbol{\delta_{Max} < 2.2}$ *suppressed buildup*
  - *Predicted* $\boldsymbol{\delta_{Max} > 2.5}$ *needed for beam-driven accumulation mechanism*



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  - *"Fast Transverse Beam Instability Caused by Electron Cloud Trapped in Combined Function Magnets,"* University of Chicago, 2017
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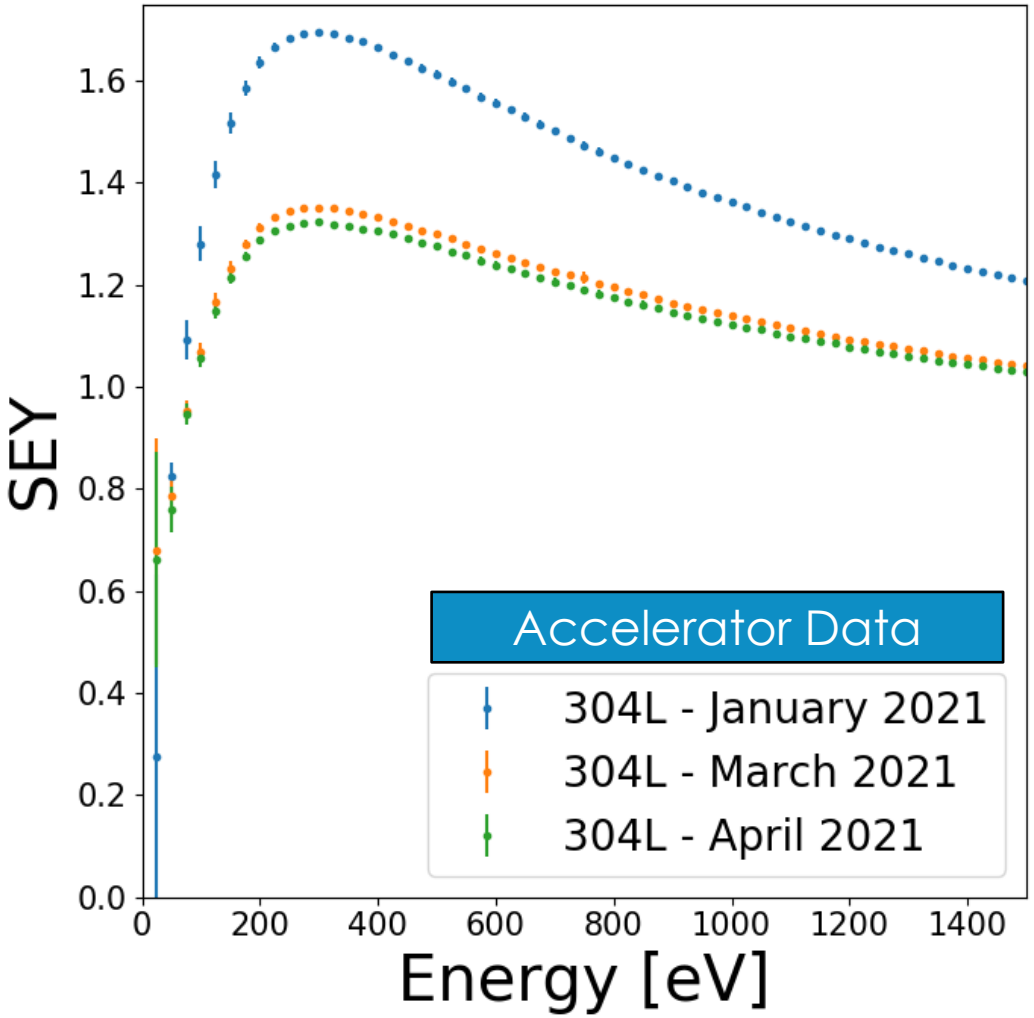
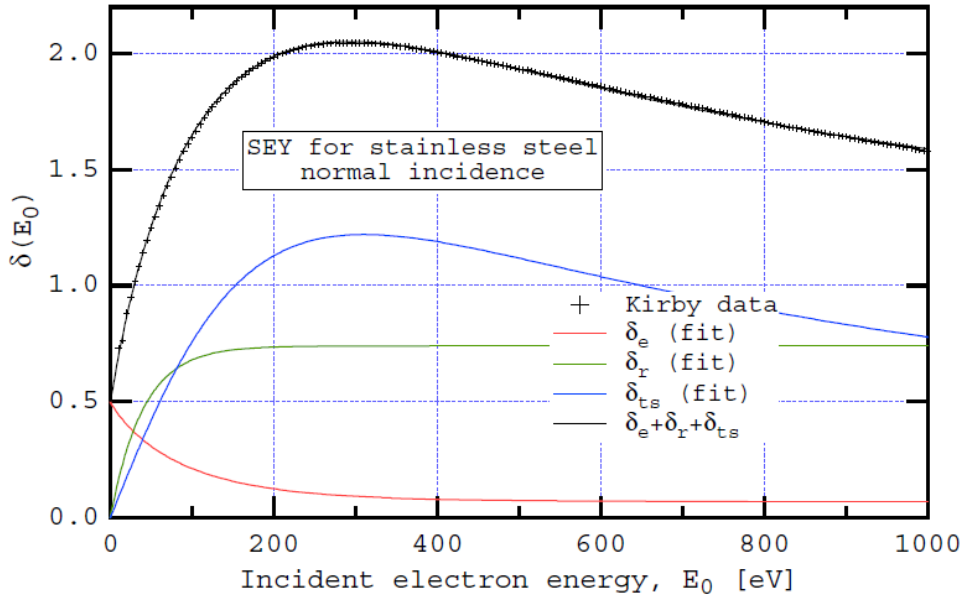
- **Accelerator SEY measurements yield** $\boldsymbol{1.3 < \delta_{Max} < 1.7}$ **during 2021 Run**
  - We observe effects of conditioning
  - Feb. 2022 instability observed with $\delta_{Max} \sim 1.7$
  - Test stand — measurement verification
- **Point of reconciliation for the new study**



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 δ_{Max} shifted to values more consistent with measured SEY strengths**
    - Thesis set safe thresholds for δ 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***

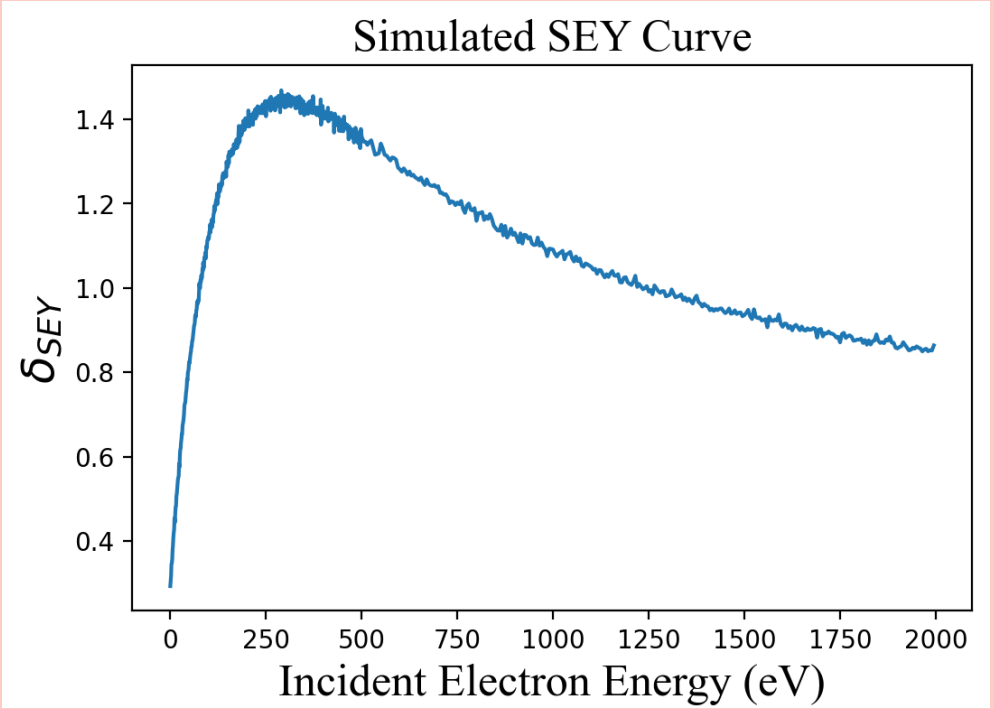


M. A. Furman and M. T. F. Pivi, *"Simulation of Secondary Emission Based on a Phenomenological Probabilistic Model,"* SLAC, 2003.

ANALYSIS ROADMAP

- Utilize FP Model to simulate SEY

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



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 $\delta_{Max}(15°, E)$**

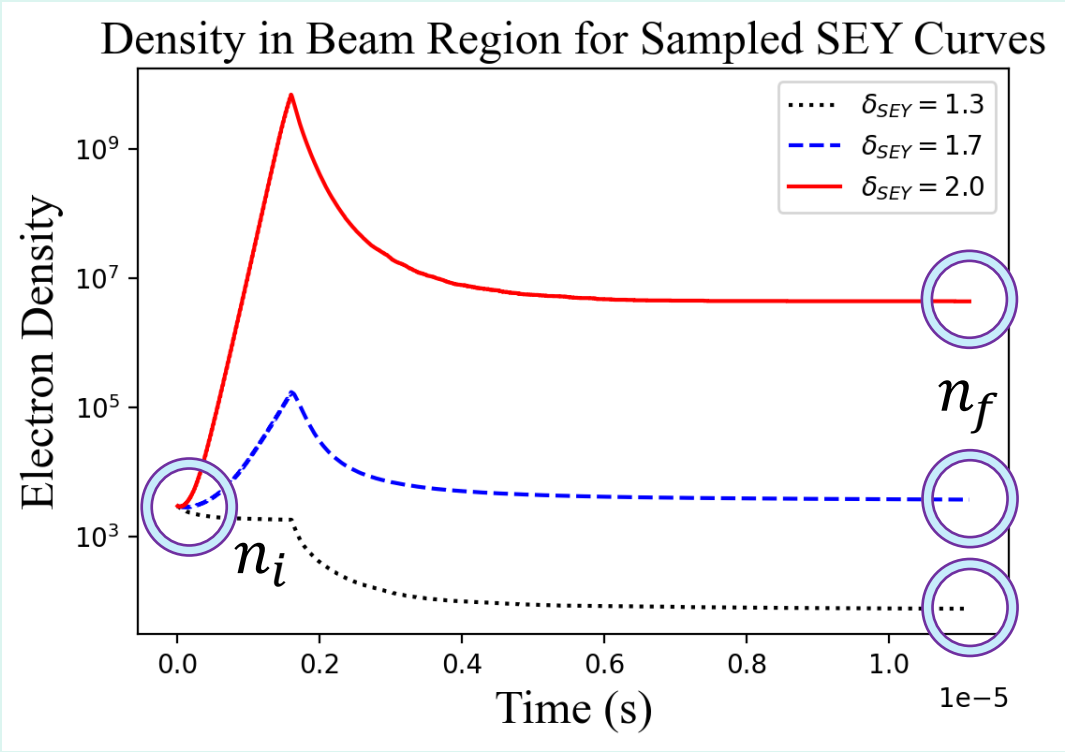
Simplest metric is a matter of math…

If $n_i > n_f$, mathematically impossible for SEY-driven instability.

If $n_f > n_i$, continued electron cloud accumulation is possible!

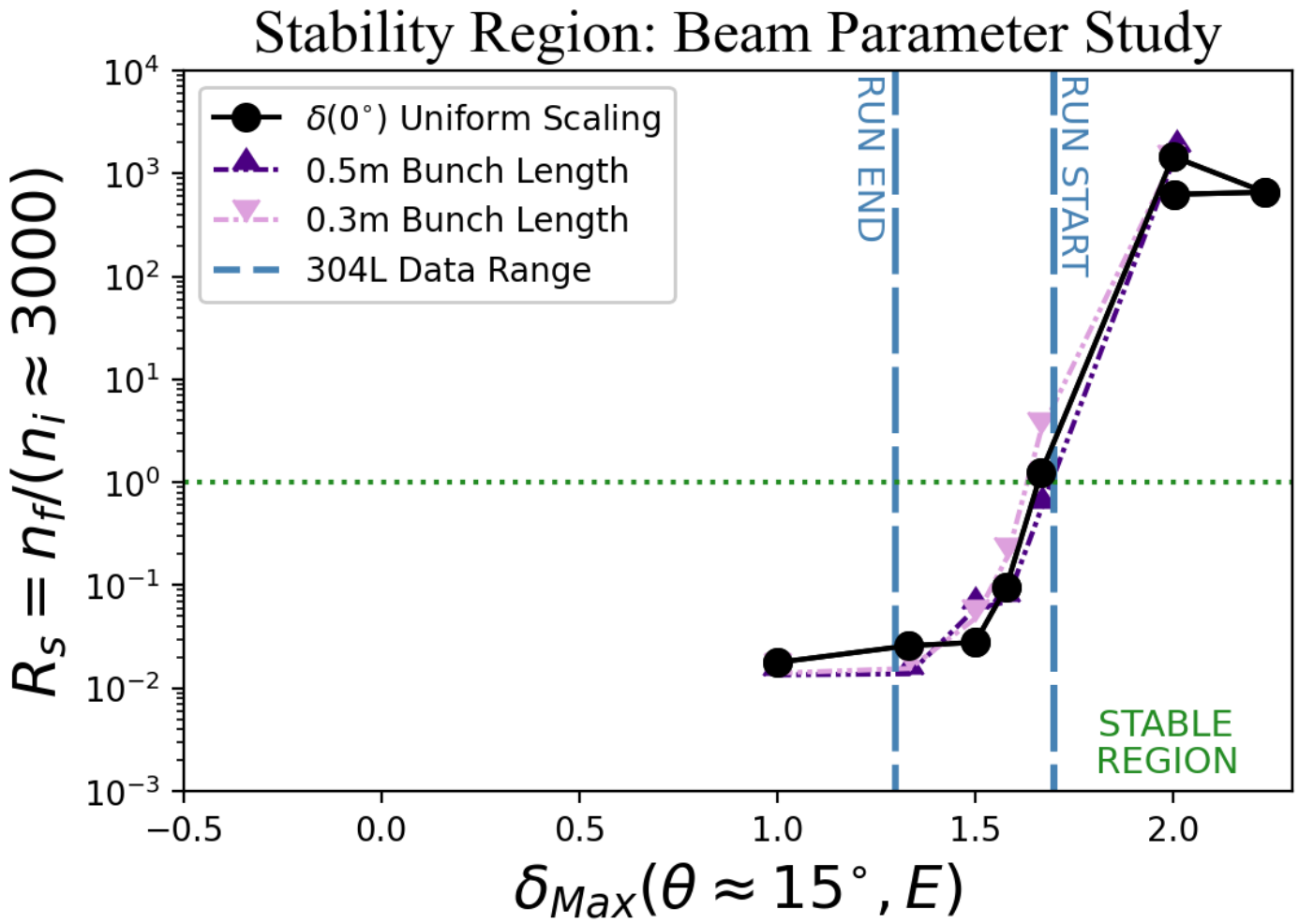
$R_s = n_f/n_i$, $R_s < 1.0$ sets stability region

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



THE TAKE-AWAY

- **Many points to digest from this plot**
- **Follows conditioning trend from the SEY data measurements**
  - *And general expectation of behavior*



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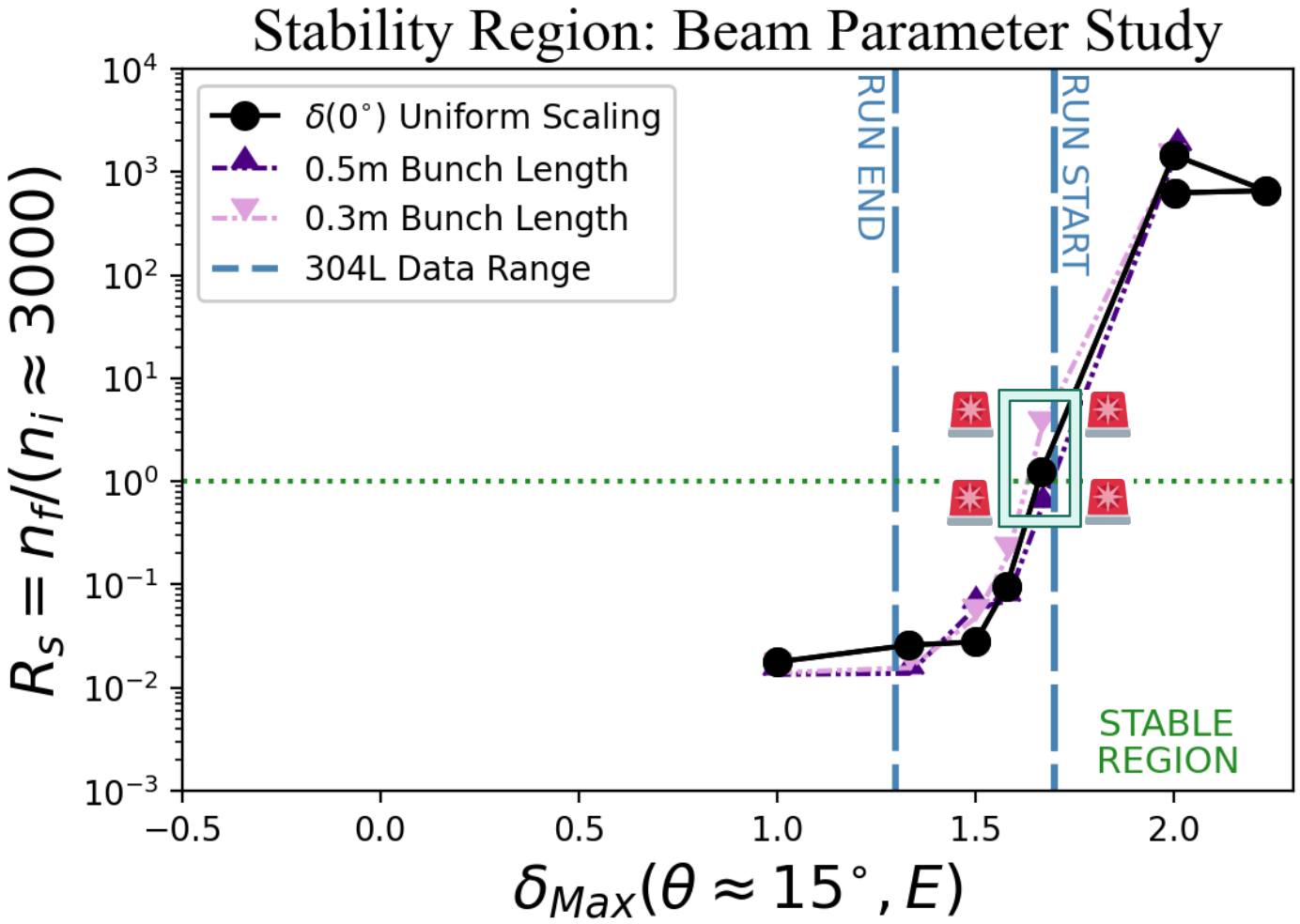
  - Bunch Length considerations



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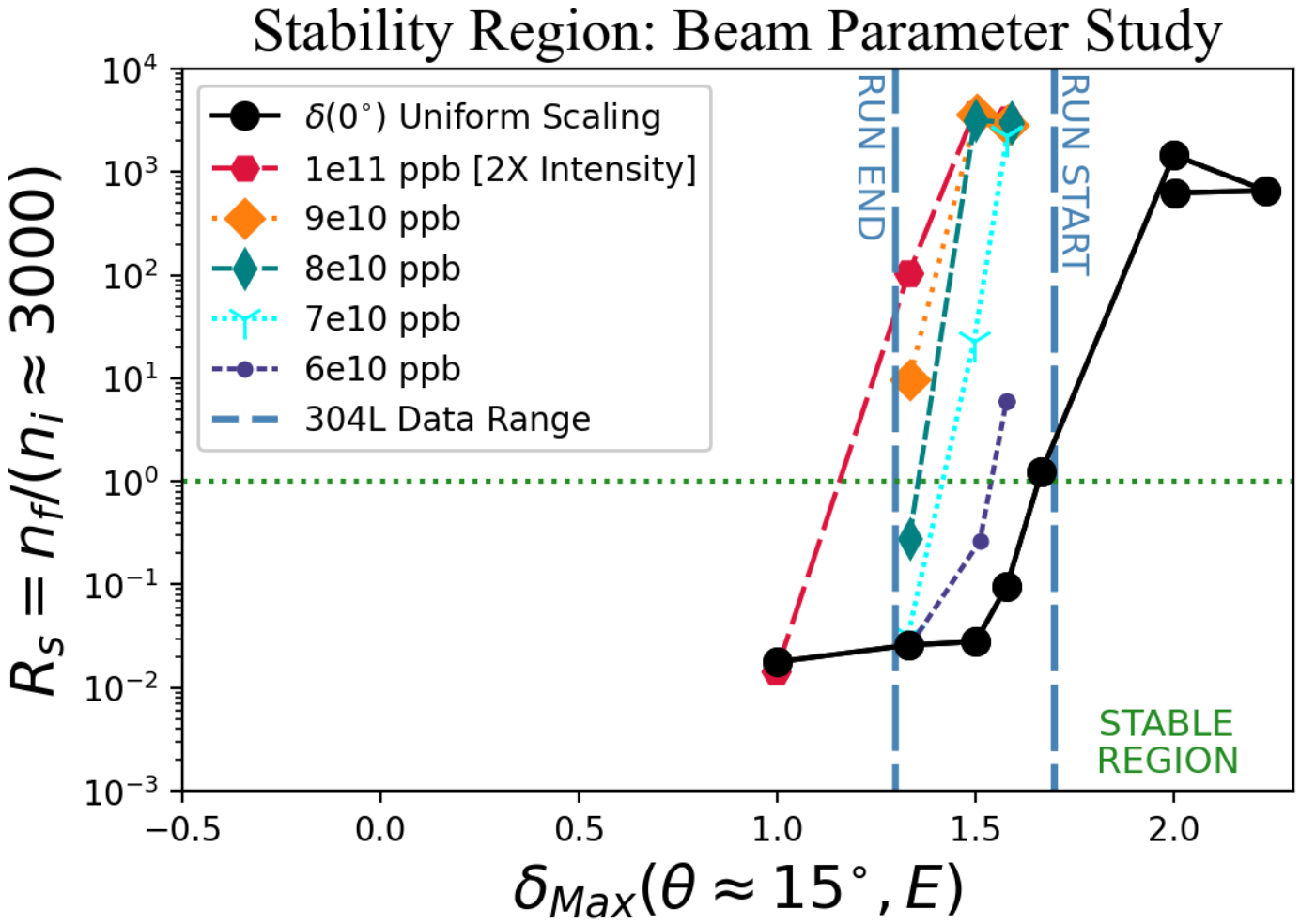
  - Upgrade to higher intensities might require new solutions/ramp procedure
  - *Important to lab's future*



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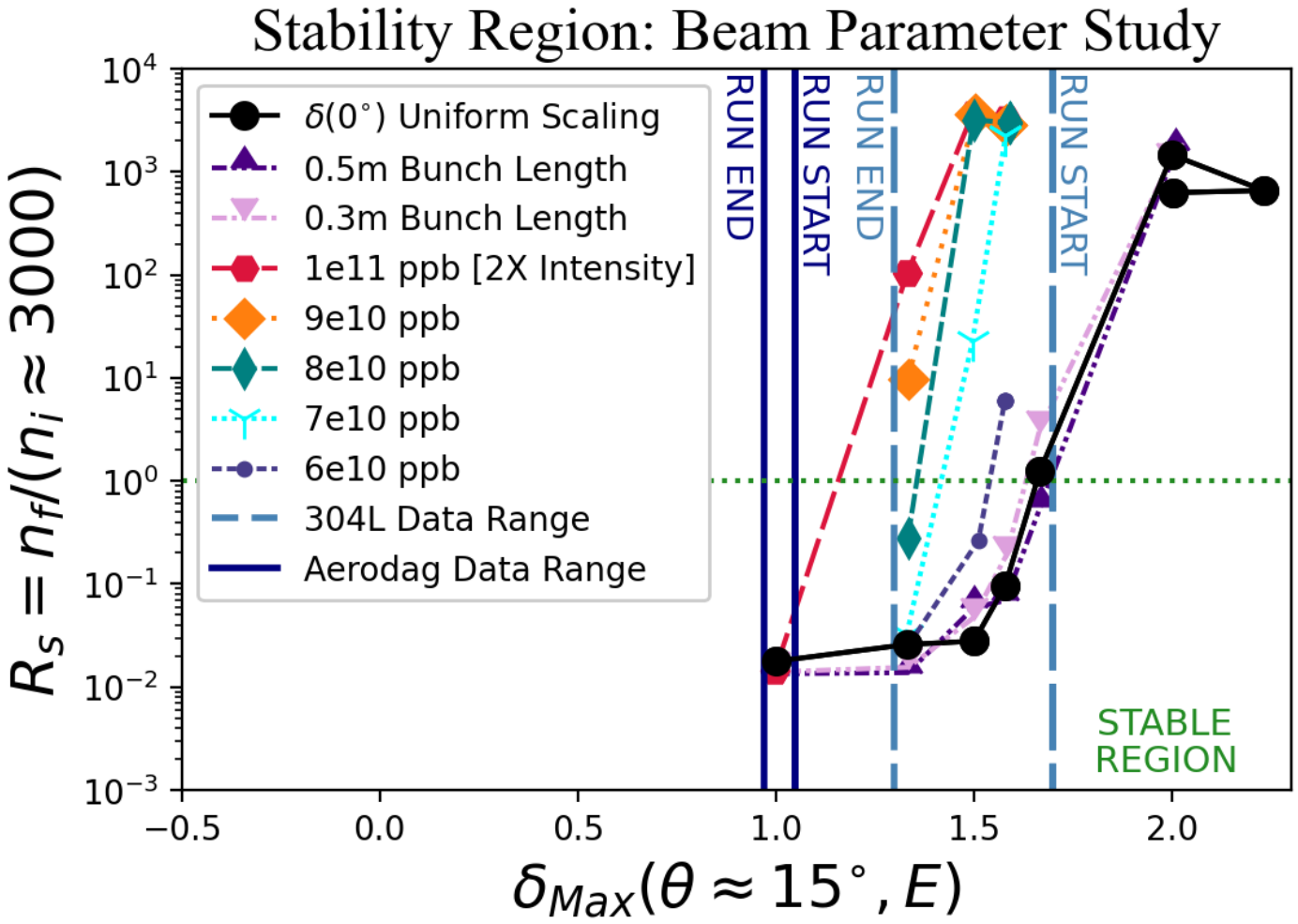
- **Deployed PyECLOUD+FP analysis that answered existing challenges**
  - Aligned with accelerator measurements



OVERFLOW

My effort to make 12+3

ANALYSIS ROADMAP

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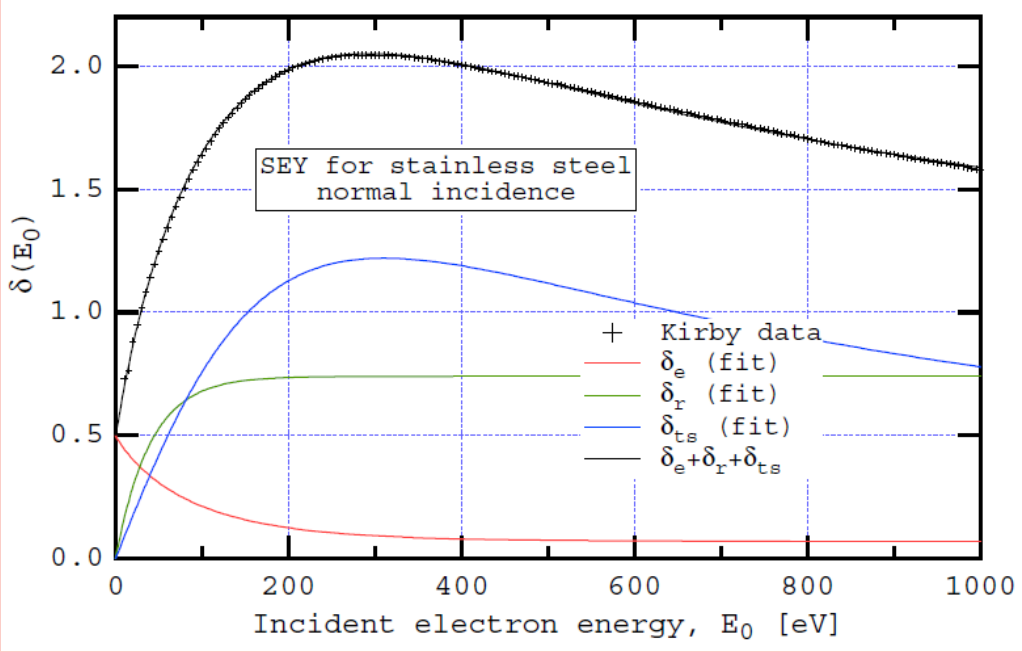
  - Different materials = different values
- Introduces *many* knobs to adjust shapes and amplitudes
  - *Scrutinize at future* stage of analysis



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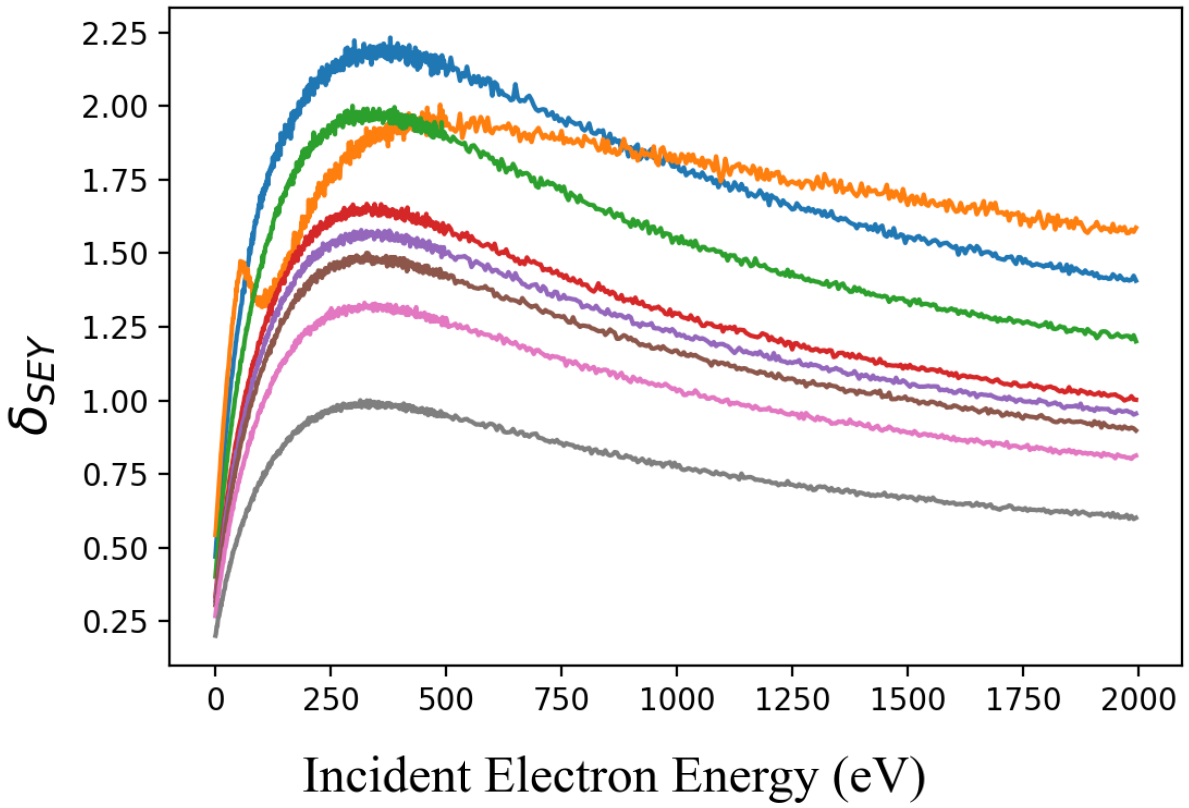

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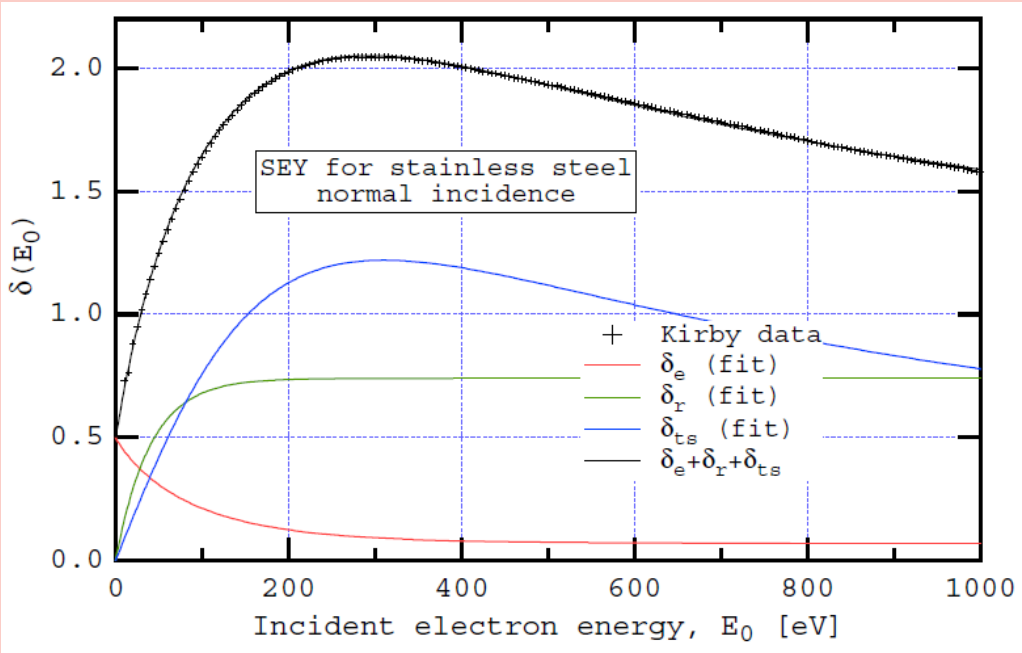

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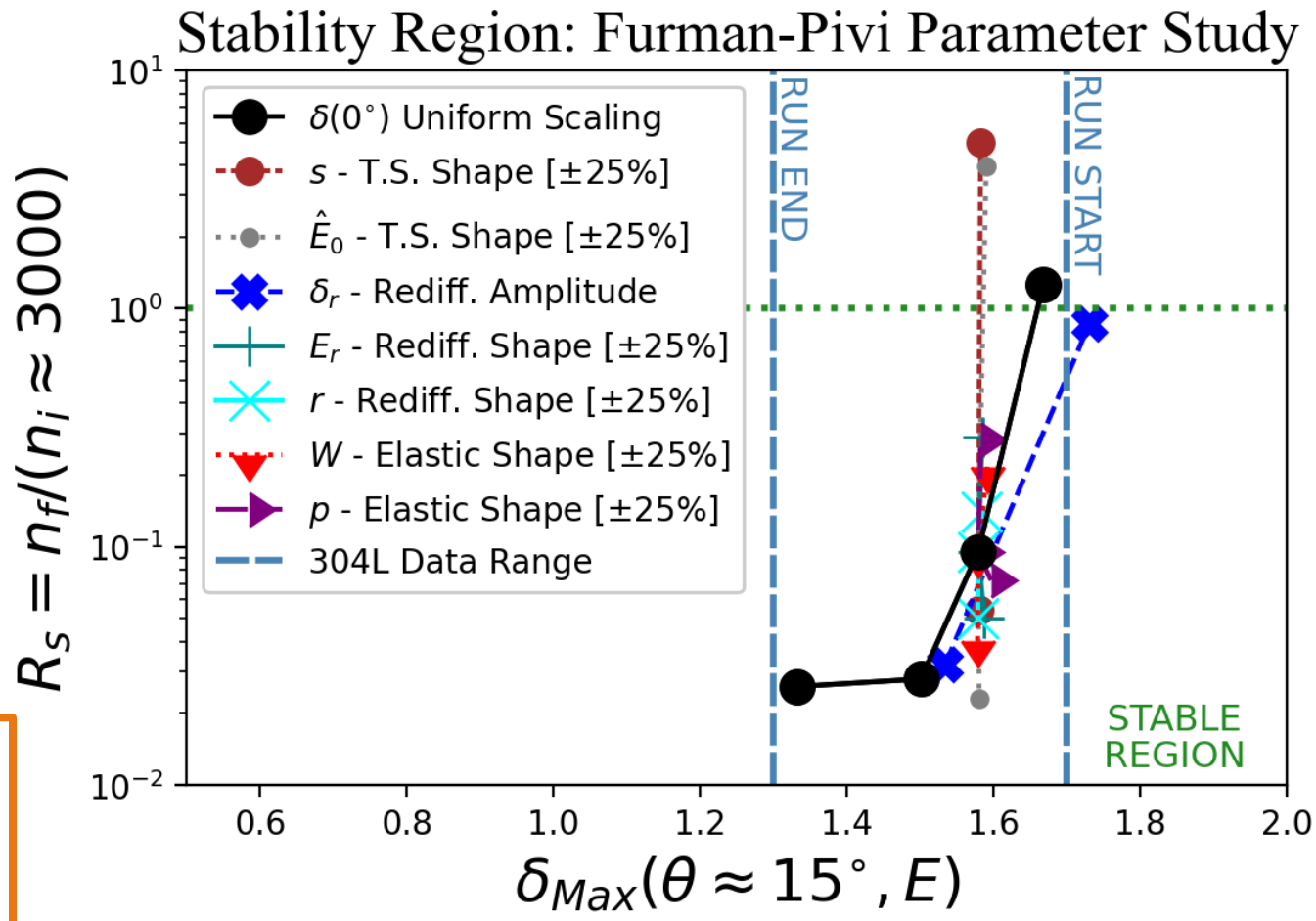
- **Develop stability metric as a function of δ_{Max}**
- **Map stability space by varying simulation parameters**
  - Scrutinizing FP Model…

Scanned δ_{Max} in range of interest

Nominal position in R_s, δ_{Max} space is stable

Induced 25% shifts on FP parameters

Full material swap required to cross $R_s = 1$



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  - FP Scan built confidence small aberrations will not affect the beam study
- Write a paper and fly to NAPAC…