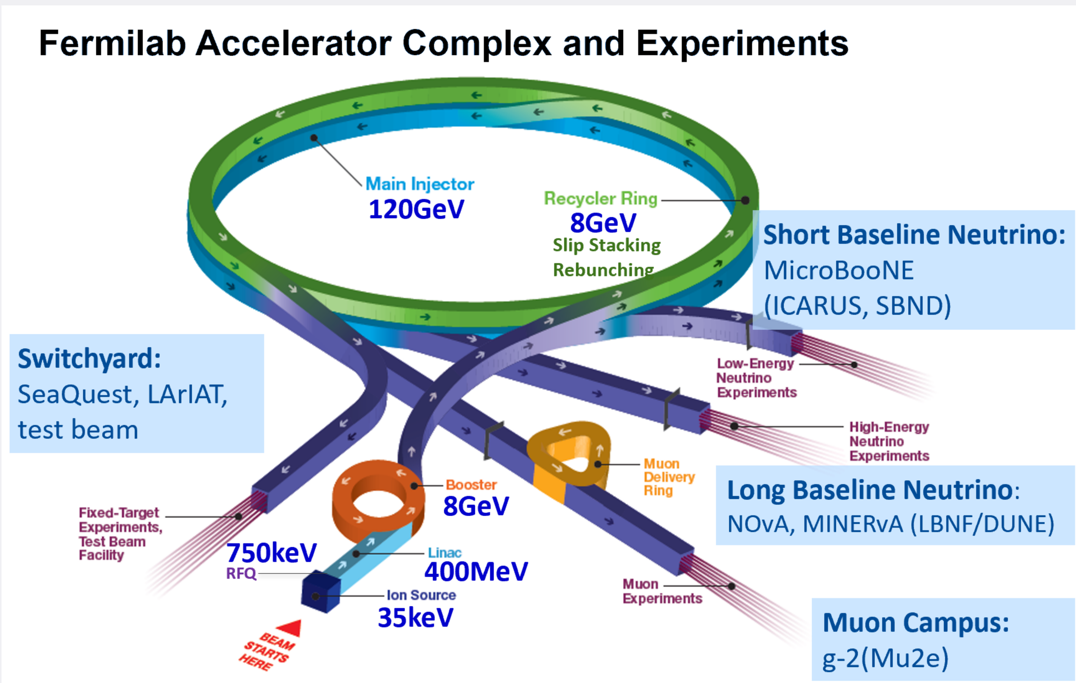
Physics Studies for High Intensity Proton Beams at the Fermilab Booster

Jeffrey Eldred,
for Fermilab Booster

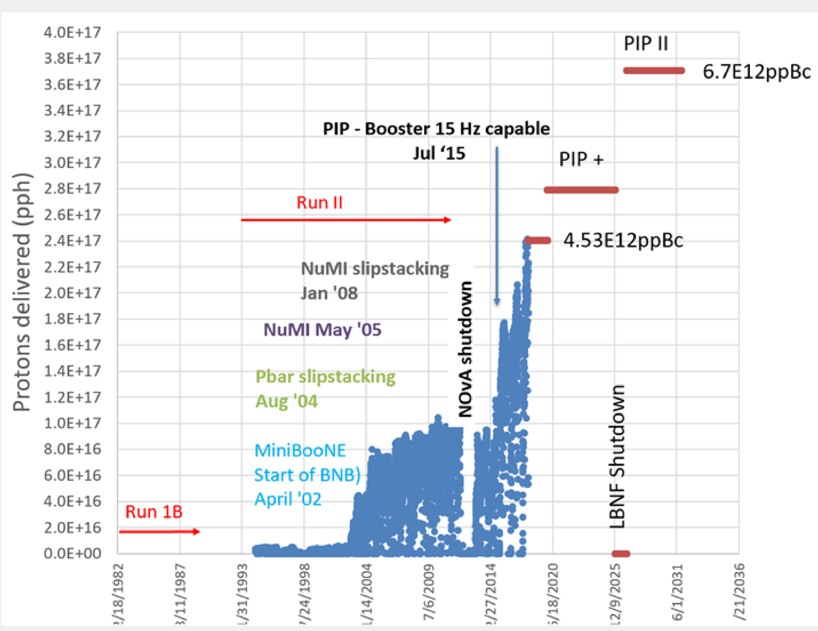
Fermilab

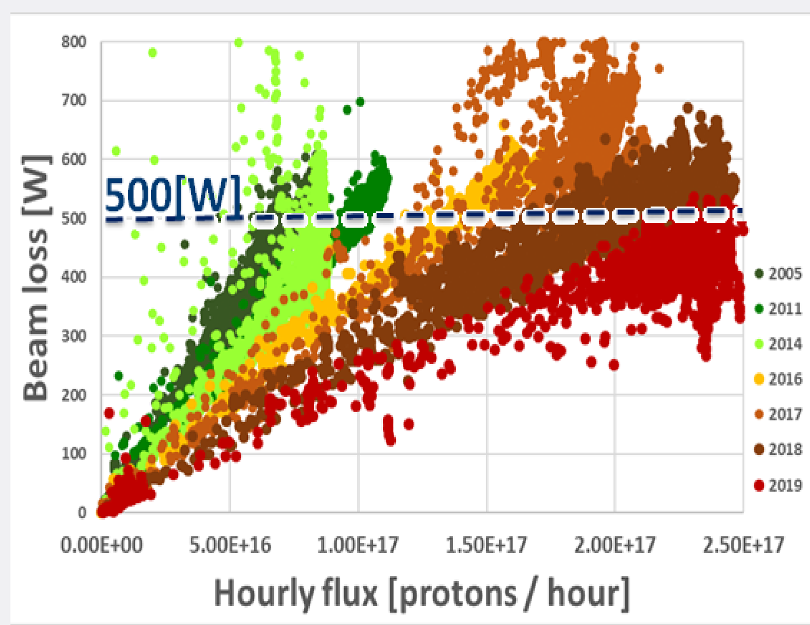
Fermilab Proton Complex & Intensity Upgrades



The Fermilab accelerator complex delivers **high intensity hadron beams** to a variety of HEP experiments.

In the present configuration, beam from the 400 MeV H– Linac is accumulated in the Booster via through a charge-stripping injection foil. Every **15 Hz, 4.5e12** protons are accelerated in the Booster to 8 GeV to power the Muon Campus, Short-baseline Neutrino Program, and the Main Injector programs.





The Proton Improvement Program (PIP) and its successor program **PIP-II** require increasing performance requirements for the Fermilab Booster.

In the PIP-II era, a new 0.8 GeV SRF linac will provide beam to the Booster and the Booster will provide **6.5e12 protons every 20 Hz.**

Proton Improvement	PIP	PIP-PIP II	PIP-II
Target	**750 kW (700kW)**	**900 kW (1MW)**	**1.2MW**
Beam line	NuMI	NuMI	LBNF
Main Injector / Recycler	54 e12 protons every 1.333 s	60 e12 protons every 1.2 s	65 e12 protons every 1.2 s
Booster	4.5 e12 protons at 15Hz	5.4 e12 protons at 15Hz	6.5 e12 protons at 20Hz
LINAC	25mA	30mA	PIP-II SC LINAC

New Program for Booster Studies

Achieving and exceeding our PIP-II performance goals will require identifying and mitigating **sources of Booster loss**. The necessary Booster beam studies must include a broad investigation of the underlying physics that constrains the Booster.

Starting in 2019, the Fermilab Accelerator Division allocates one day per month for dedicated Booster & Linac development and studies.

This study effort supported the results for Section 1 & 2 (below).

From June 17– July 2 we held a special Booster Studies event spanning six study topics with nine visiting scientists. Photo right:

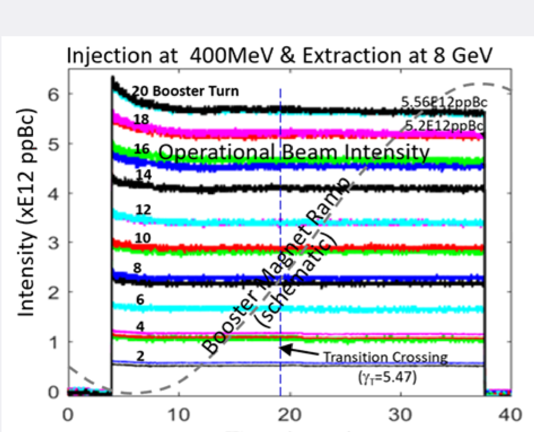
Participants for June Booster Studies Event:

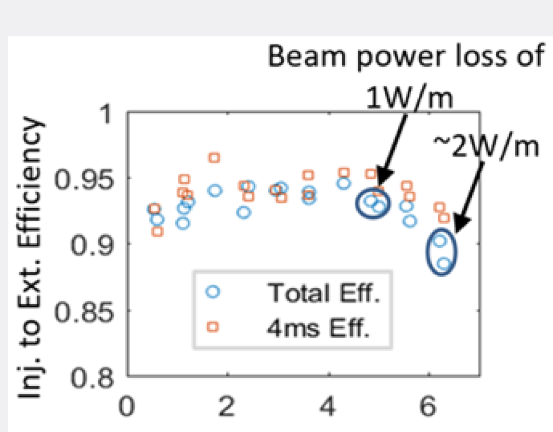
Fermilab: J. Eldred, Y. Alexahin, C. Bhat, A. Burov, S. Chaurize, N. Eddy, C. Jensen, V. Kapin, J. Larson, V. Lebedev, H. Pfeffer, K. Seiya, V. Shiltsev, C.Y. Tan, K. Triplett. S. Valishev

CERN: H. Bartosik, N. Biancacci, M. Carla, A. Saa Hernandex, A. Huschauer, F. Schmidt, **Radiasoft:** D. Bruhwiler, J. Edelen, **GSI:** V. Kornlov

This study effort supported the results for Section 3 - 5 (right-side).

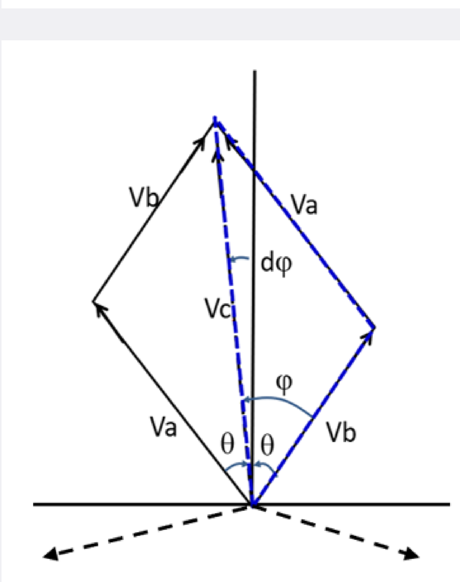
1: Adiabatic Capture Improvement





The Fermilab Booster suffers from injection losses at the few percent level, independent of beam intensity.

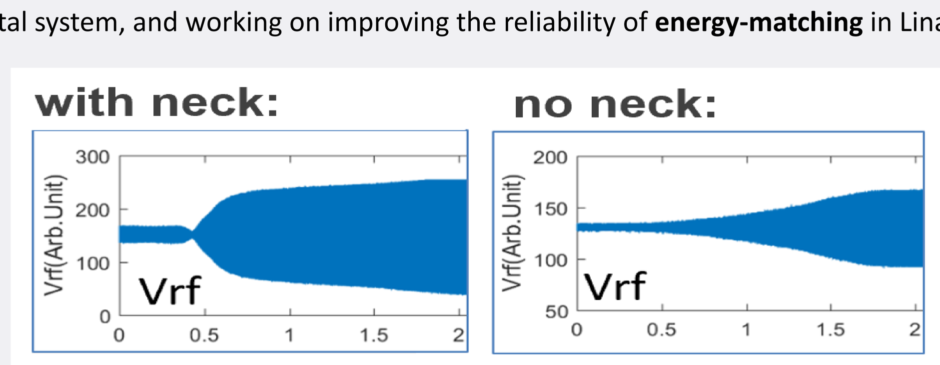
Simulations and beam studies have traced these losses to imperfections in the **adiabatic capture** process.



Adiabatic capture matches the debunched beam from the linac to the Booster RF buckets by gradually increasing the total Booster RF capture voltage. This is accomplished by dividing the Booster RF cavities A & B stations, which start out of phase and gradually phase in.

Present operation finds best efficiency with a "neck" in which the total voltage decreases from a small value before it increases. We believe that neck may be covering for mismatched errors and if we can re-optimize without the neck we can increase the adiabatic capture time.

We also in the process of **upgrading our LLRF** to improve amplitude and phase control with a digital system, and working on improving the reliability of **energy-matching** in Linac & Booster.



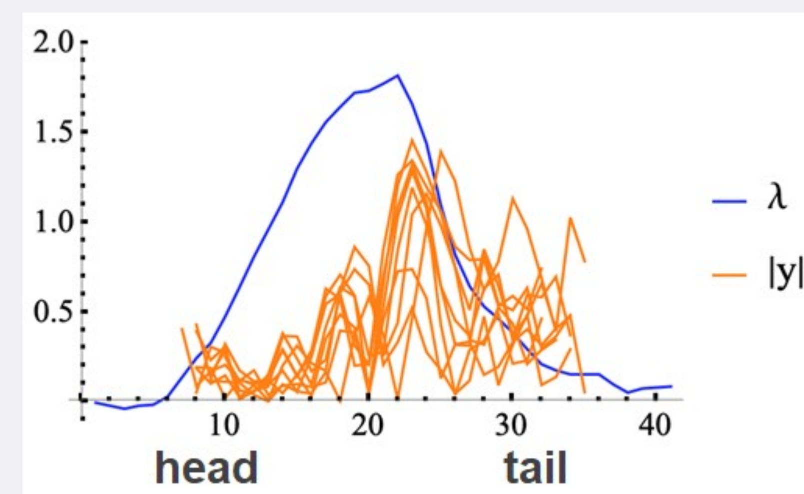
2: Foil Scattering Measurements

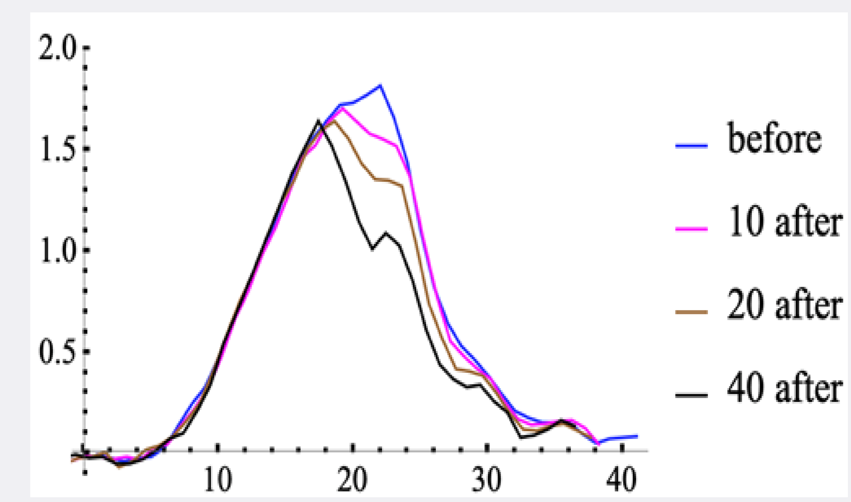
See **WEYBB3** "Foil Scattering Model for Fermilab Booster" presented at these proceedings.

3: Convective Instability

The **convective beam instability** is a recently discovered instability, first identified by Burov in SPS data and confirmed by this dedicated study of the Fermilab Booster. New Physics! The convective instability is **a single-bunch collective instability** with significant head-to-tail amplification, driven by **strong wake forces** in the presence of **strong space-charge**. The instability occurs at transition, because it is damped by synchrotron oscillations and chromaticity.

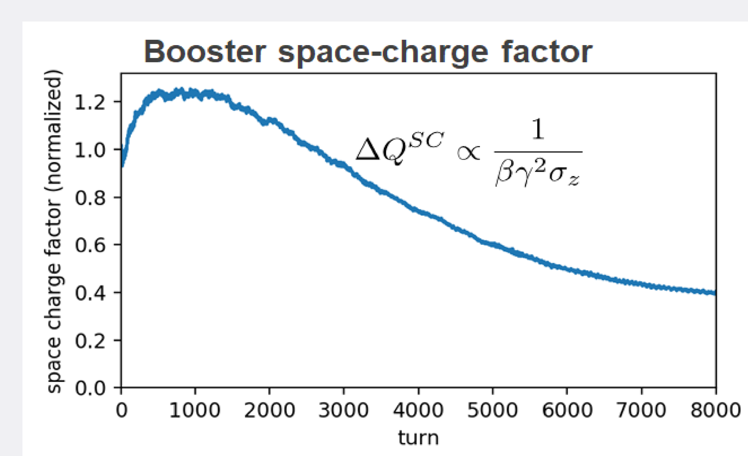
Low-chromaticity transition crossing conditions were prepared in the Booster and the intrabunch motion was recorded at 10 gigasamples per second and under varying intensity. The instability showed the predicted characteristics — the timing of the instability was uncorrelated between bunches, the oscillation progressed from the core to the tail, rapid catastrophic beam losses on the tail-edge, and exponential dependence on intensity. Also the instability was most severe in the vertical plane, as predicted by the impedance model.





Currently the Booster changes from negative to positive chromaticity at transition, and we are looking into designing new chromaticity curves. As the amplitude of the intrabunch motion rises exponentially with intensity, follow-up work will determine the chromaticity needed to mitigate the instability at PIP-II intensities.

4: Space-charge Emittance Growth

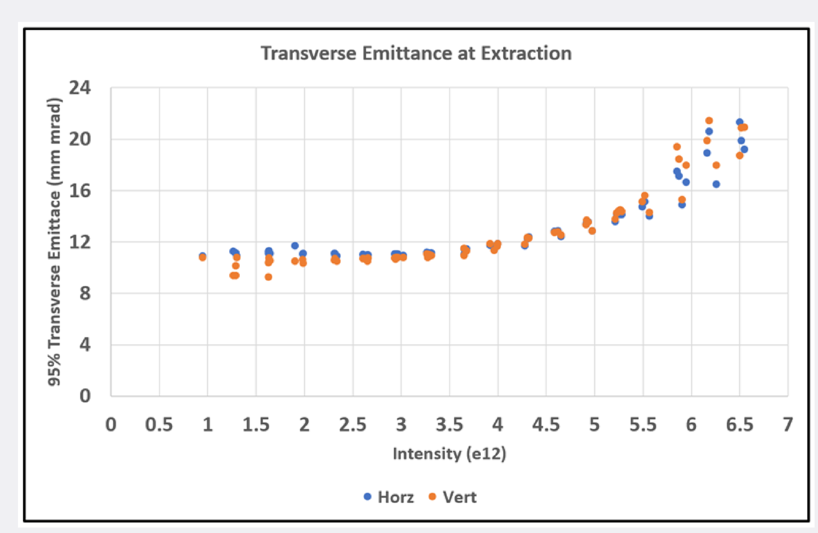


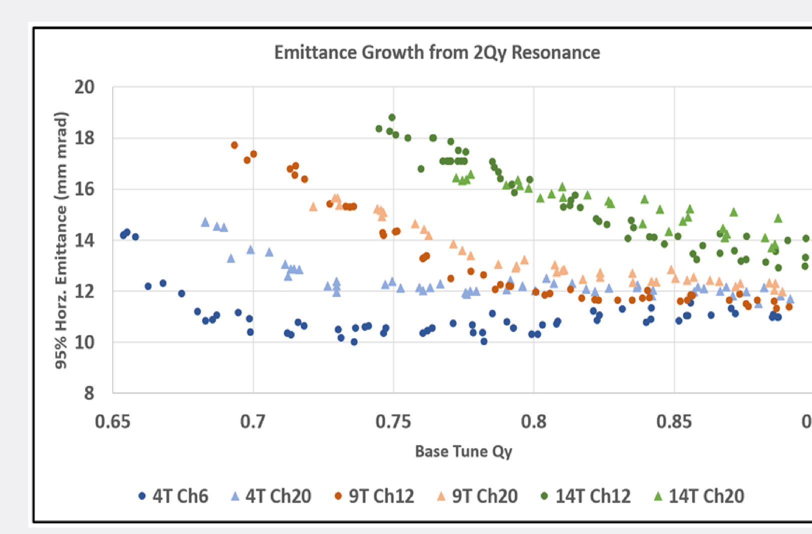
The space-charge tune-spread is largest in the 1000 revolutions after beam injection capture; when the tune-spread crosses resonances, leading to rapid emittance growth; until the emittance growth leads to an equilibrium which no longer crosses major resonances.

Space-charge induced emittance growth is connected to losses at injection, transition, extraction, and transfer to the Recycler / Main Injector. The vertical tune-spread exceeds the horizontal tune-spread and the **half-integer resonances** dominate. At nominal beam intensities (4.5e12 protons or 14 turns) and beyond, the vertical tune-space shrinks to zero and losses begin immediately.

The next step is to implement a half-integer correction program with a properly phased subset of quadrupoles.

The variation in the intensity and emittance will also make an ideal for **calibrating the ionization profile monitors** (IPMs) in the Booster against the multiwire emittance diagnostics in the extraction line.



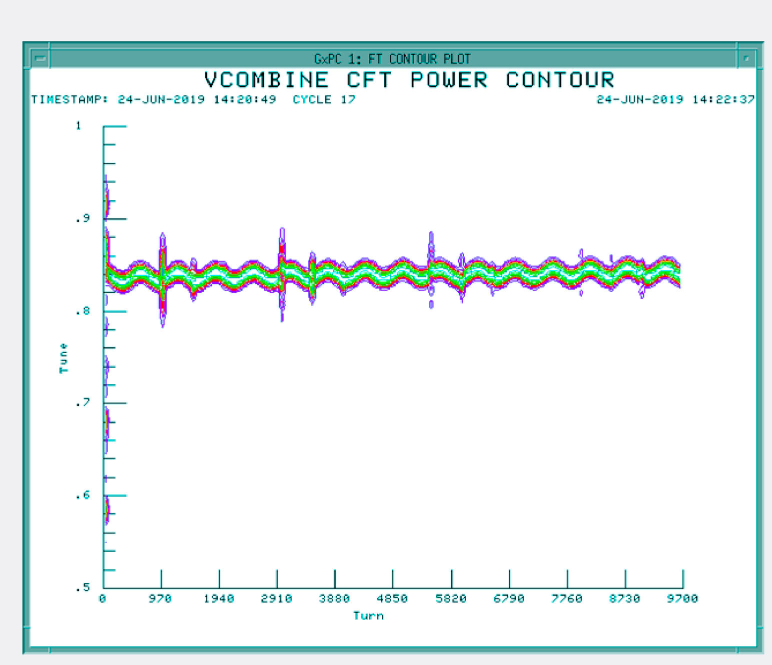


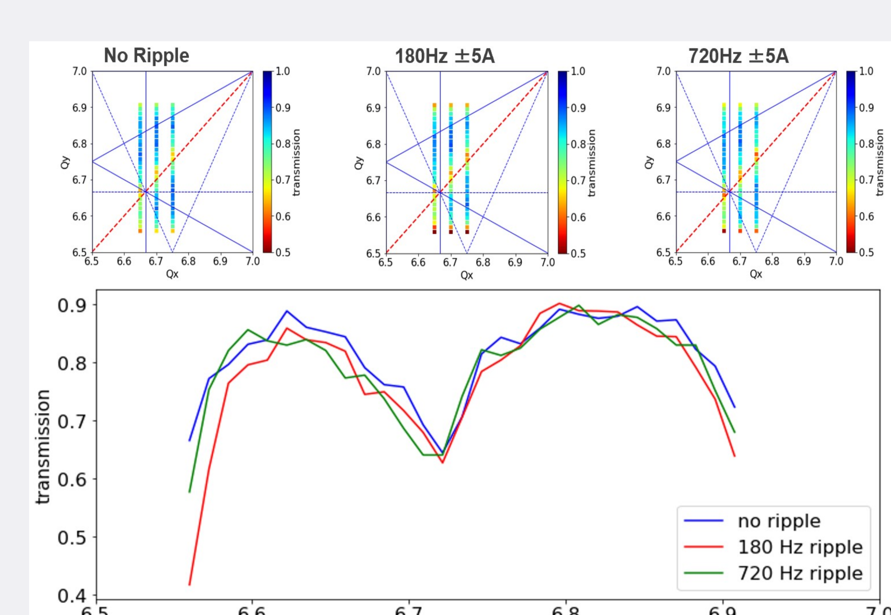
5: Power-supply Tune-Ripple

Any frequency ripple in the gradient magnet power supply would cause both displacement of the beam orbit and modulation of the betatron tune. Neither characteristic was observed in the beam behavior under normal operating conditions, however when the gradient magnet power supply has malfunctioned in the past the effect has been catastrophic.

We **induced a tune modulation** effect to study the impact on the beam. One quadrupole had been excited with a sinesoidal oscillation of 180 Hz or 720 Hz and a tune modulation depth of ~0.01. The half-integer resonance width increased commensurately, but no observed impact on other resonances. We activated a skew-sextupole corrector to induce nonlinear resonances, but **no significant interaction** was observed between the nonlinear resonances, tune-modulation and/or space-charge.

Analysis of the Booster circuit indicates that the power-supply ripple might have more impact at frequencies above 1 GHz, and subsequent measurements should follow-up at these higher frequencies.





Outlook

The coming PIP-II intensity upgrades for the Fermilab proton complex will require the Booster to perform at a factor of two higher beam power and commensurate reduction in beam losses. A new Booster beam study program has been initiated to study the scope of the physics challenges and to ensure the PIP-II upgrades are not limited by Booster performance.

The 2019 Booster studies have examined a variety of important topics. A systematic study is underway to understand the injection losses that have been traced to adiabatic capture process and how energy mismatch and LLRF regulation errors contribute. The foil scattering loss was studied under varying injection condition. The existence of a convective instability was confirmed in the Fermilab Booster. Space -charge induced emittance growth was shown to be driven by the vertical half-integer resonance. The power-supply tune-ripple was demonstrated not to have an operational impact below 1 GHz under nominal conditions.

Upcoming work will focus on the accurate characterization of Booster linear optics, correction of the half-integer resonance, calibration of ionization profile monitors, measurement of convective instability at higher intensity with nonzero chromaticity, and installation of fast loss monitors for the foil-scattering study. The Booster collaboration invites you to participate in the ongoing beam studies!