FERMILAB-SLIDES-19-060-AD

Physics Studies for High Intensity Proton Beams at the Fermilab Booster

J. Eldred, for Fermilab Booster Group

NAPAC 2019 - Lansing

Sept 5th, 2019

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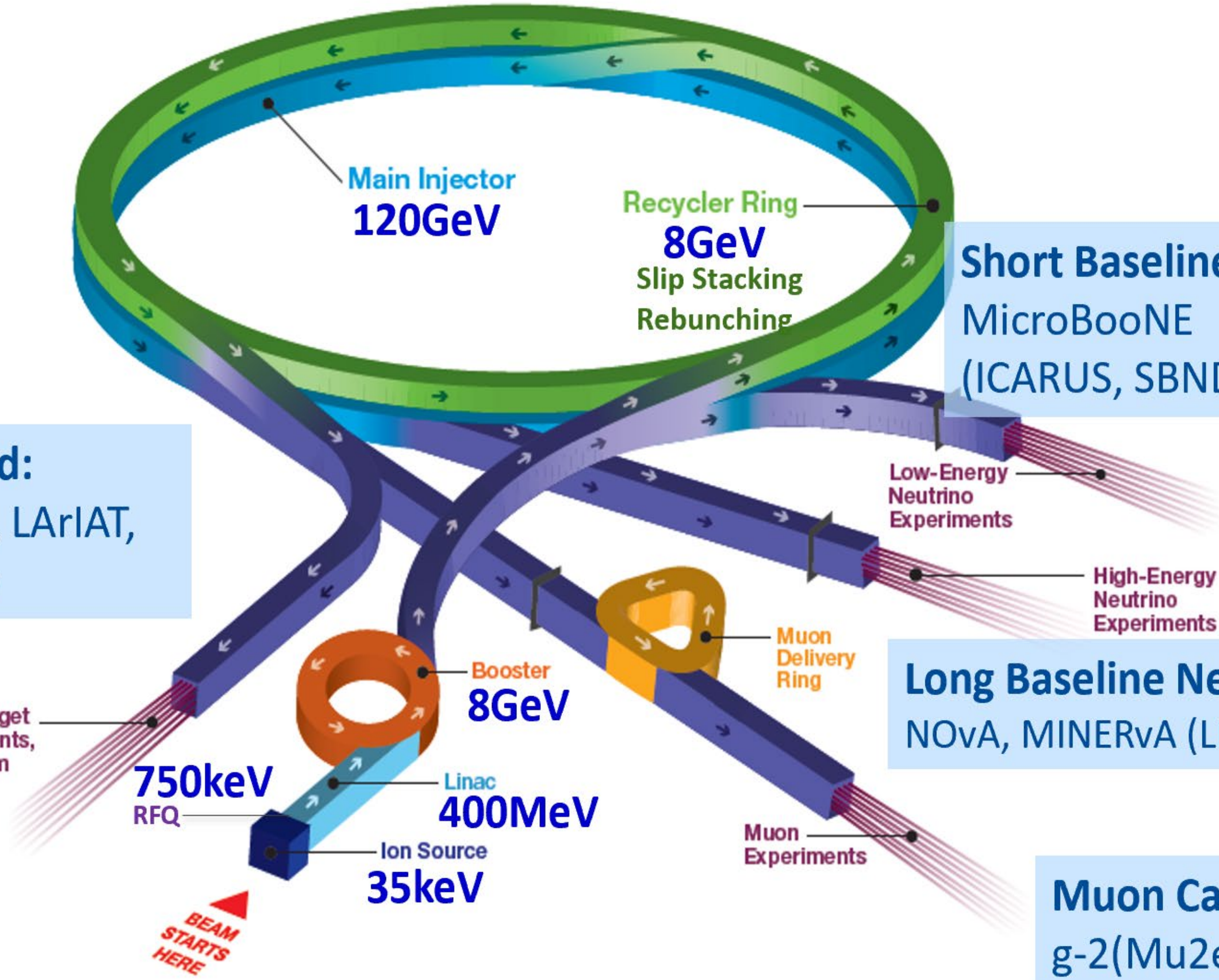
Fermilab Accelerator Complex and Experiments



Short Baseline Neutrino:
MicroBooNE
(ICARUS, SBND)

Switchyard:
SeaQuest, LArIAT,
test beam

Long Baseline Neutrino:
NOvA, MINERvA (LBNF/DUNE)

Muon Campus:
g-2(Mu2e)

PIP-II Intensity Upgrades

2019 --> ~2021 --> ~2027

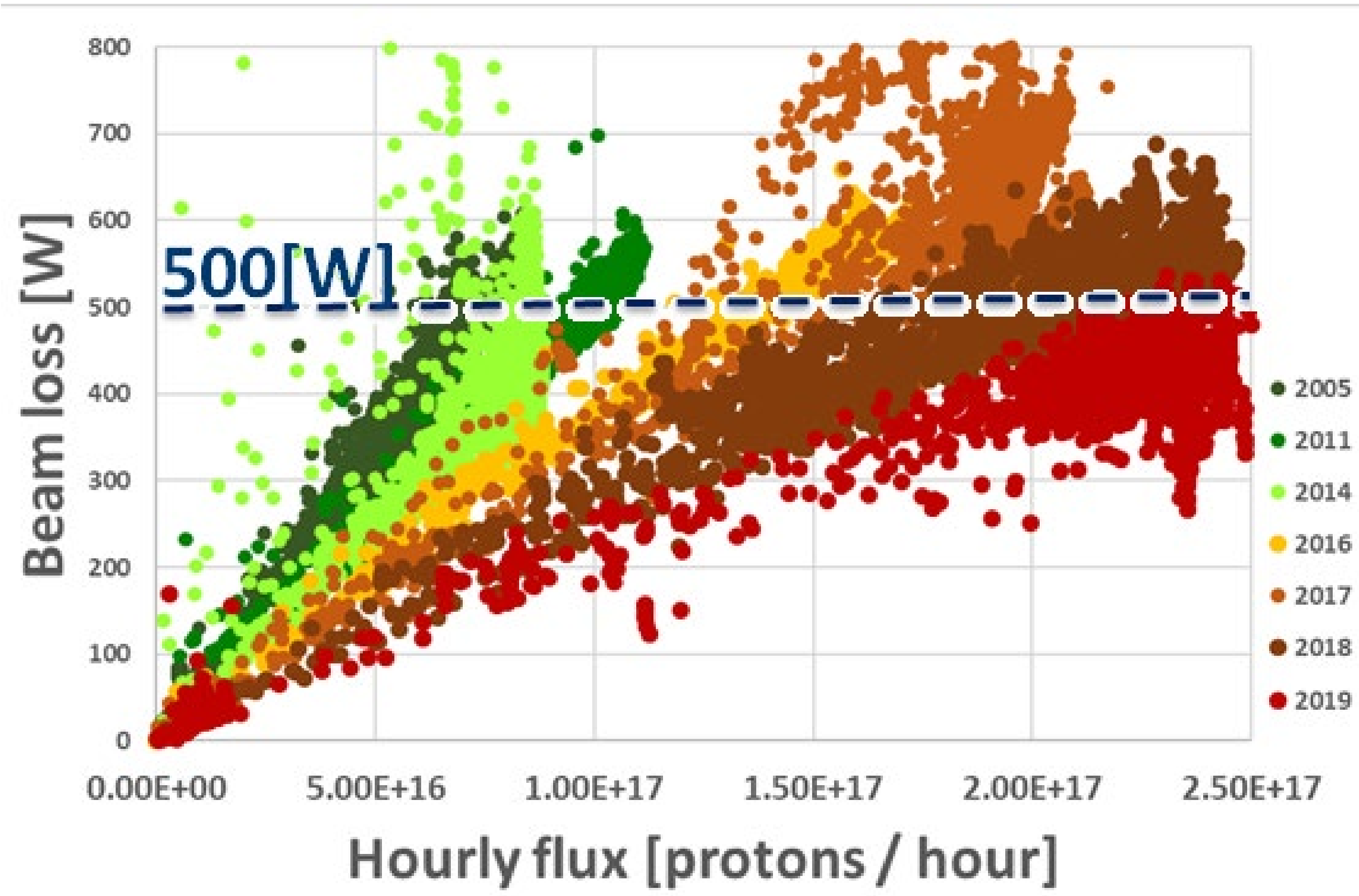
Proton Improvement

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

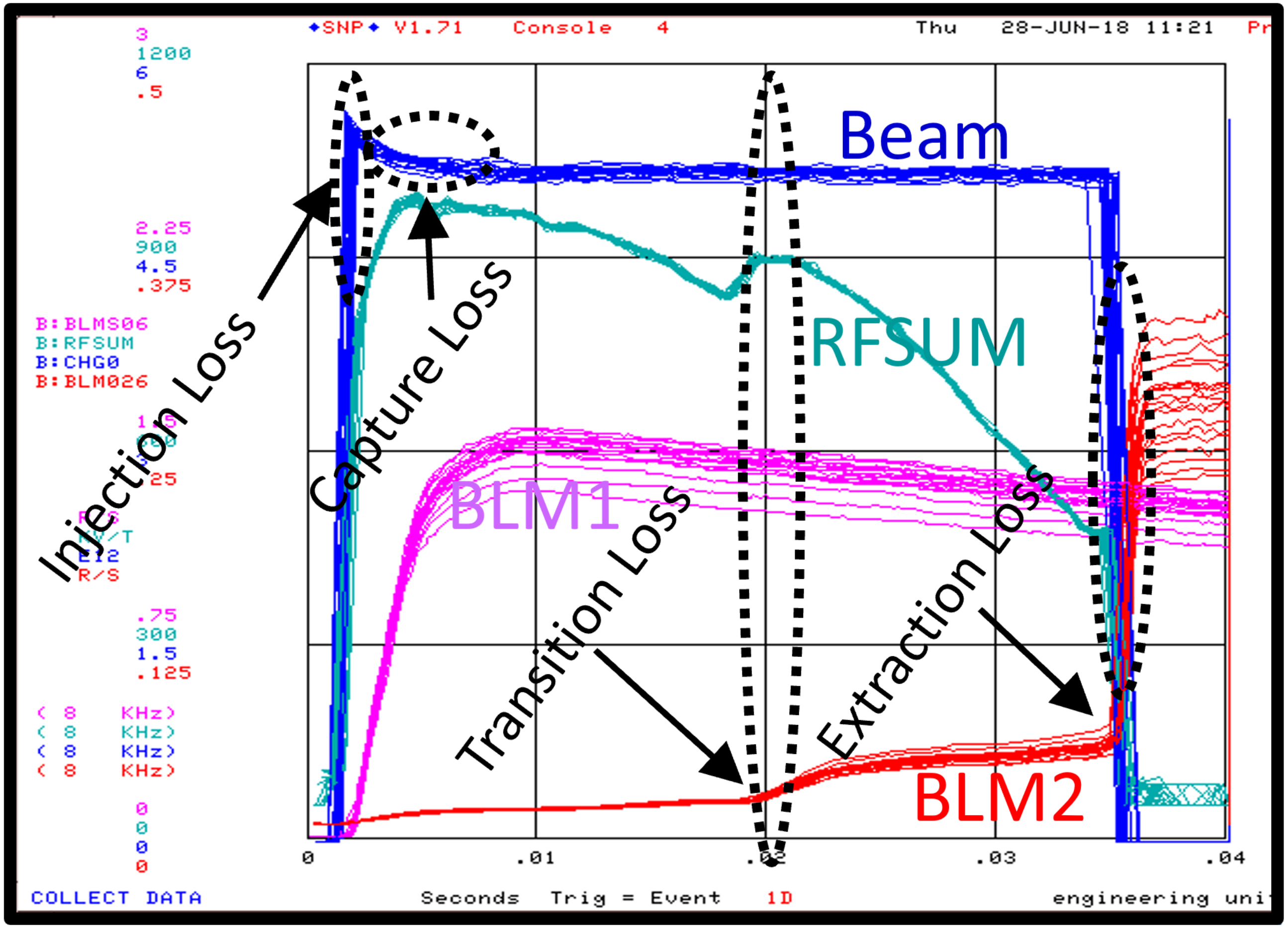
PIP-II intensity upgrade, and intermediate upgrades, will require increasing performance requirements for the Fermilab Booster.

Losses per flux



Pellico

Losses over cycle



Bhat

At nominal intensity, about half the power loss is at inflection and about half at extraction.

New Initatives for Booster Physics Studies

Starting this year, one day/month for dedicated PS development.

- In addition to everyday parasitic studies/tuning.

Annual US-Japan Collaboration - Mar 18-22

- Included one day of parasitic Booster studies focusing on lattice measurement & resonance correction.

June Booster Studies – June 17- July 2nd

- Five dedicated study days, plus eight parasitic study days.
- Six separate study proposals.
- Nine visiting scientists – CERN, Radiasoft, GSI.

Participants for June 2019 Studies

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, CY Tan, K. Triplett

CERN

H. Bartosik, N. Biancacci, M. Carla, A. Saa Hernandez, A. Huschauer, F. Schmidt

Radiasoft

D. Bruhwiler, J. Edelen

GSI

V. Kornilov

A Group Photo

(also Angela, David, Jon, and many key Fermilab participants.)

Booster Physics Studies

Booster Physics Studies

from Monthly Dedicated Studies:

1 Adiabatic Capture

2 Foil Scattering

- **WEYBB3** “Foil Scattering Model for Fermilab Booster”

from June 2019 Studies Event:

3 Convective Instability

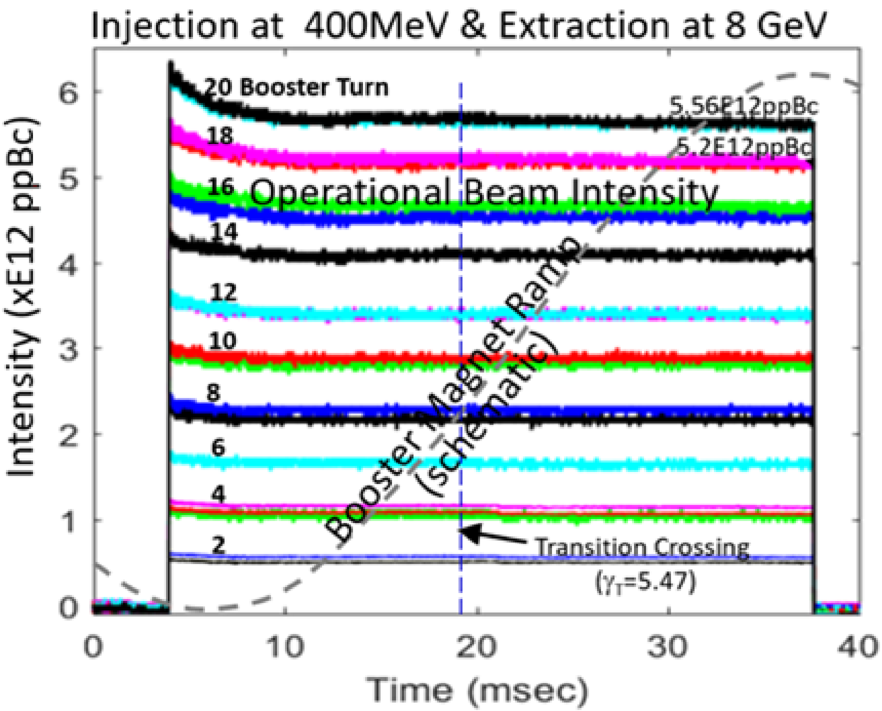
4 Space-charge Emittance Growth

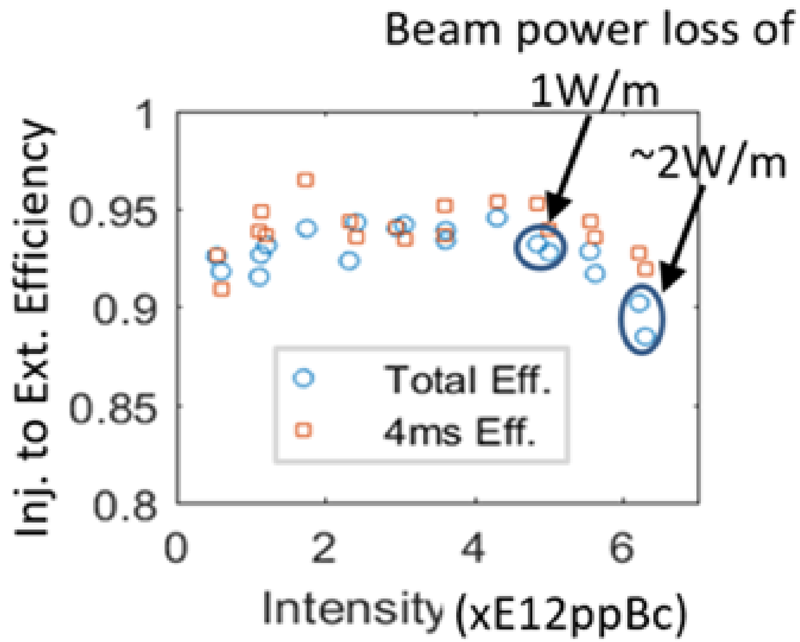
5 Power-Supply Ripple

1 Adiabatic Capture

Chandra Bhat, Salah Chaurize, Cheng-Yang Tan, Victor Grzelak, Bill Pellico, Brian Schupbach, Kiyomi Seiya, Kent Triplett

Losses with Intensity



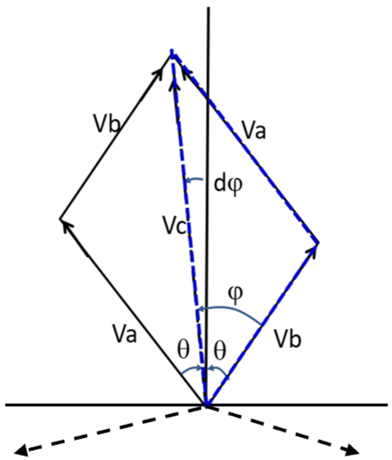


Bhat

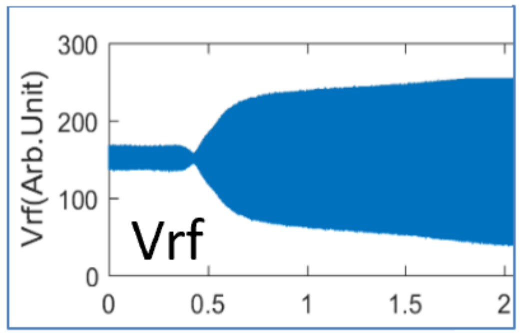
At or below nominal intensity, injection losses are at a few percent level and independent of beam intensity.

Longitudinal Capture

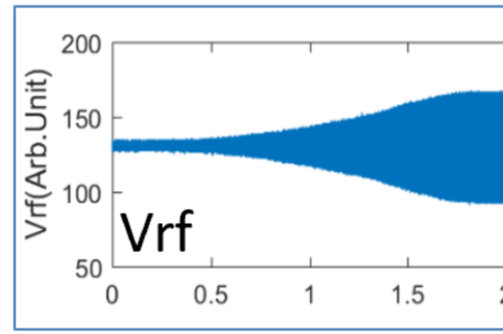
- Adiabatic capture by paraphasing
  - A & B RF stations start out of phase and slowly phase in.



with neck:



no neck:



- Currently we implement a feature we call the "neck"
  - RF starts greater than pi out of phase, then phases in.
  - Is the effect of the neck to cover for energy mismatch errors?
  - If we remove the neck, more time for paraphrasing normally.

- LLRF to be upgraded to a digital system, expected to improve amplitude and phase control.

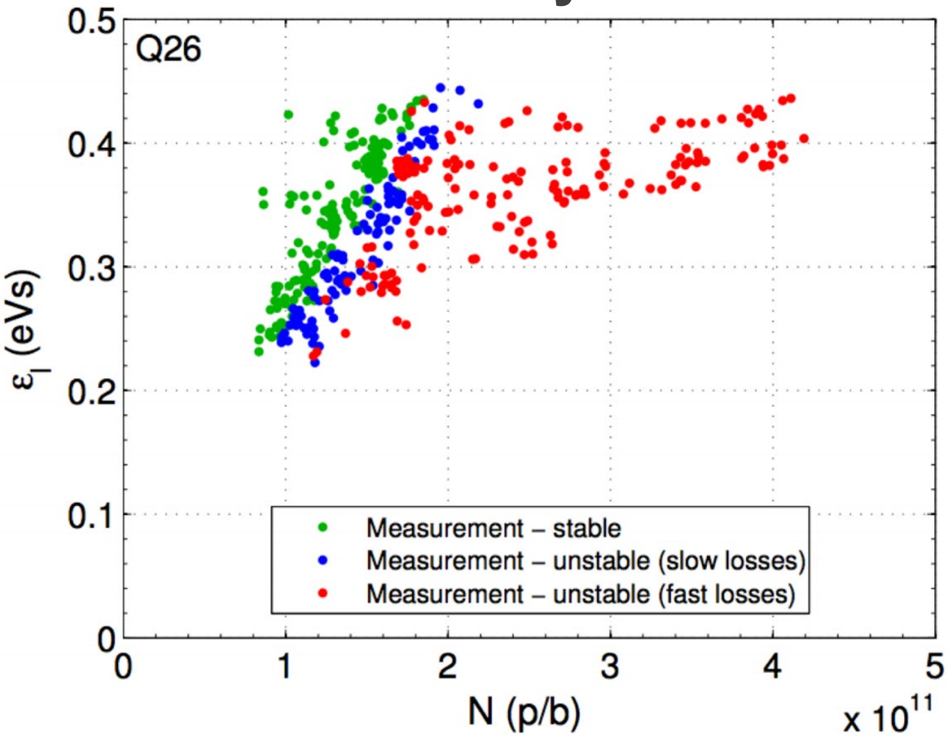
3 Convective Instability

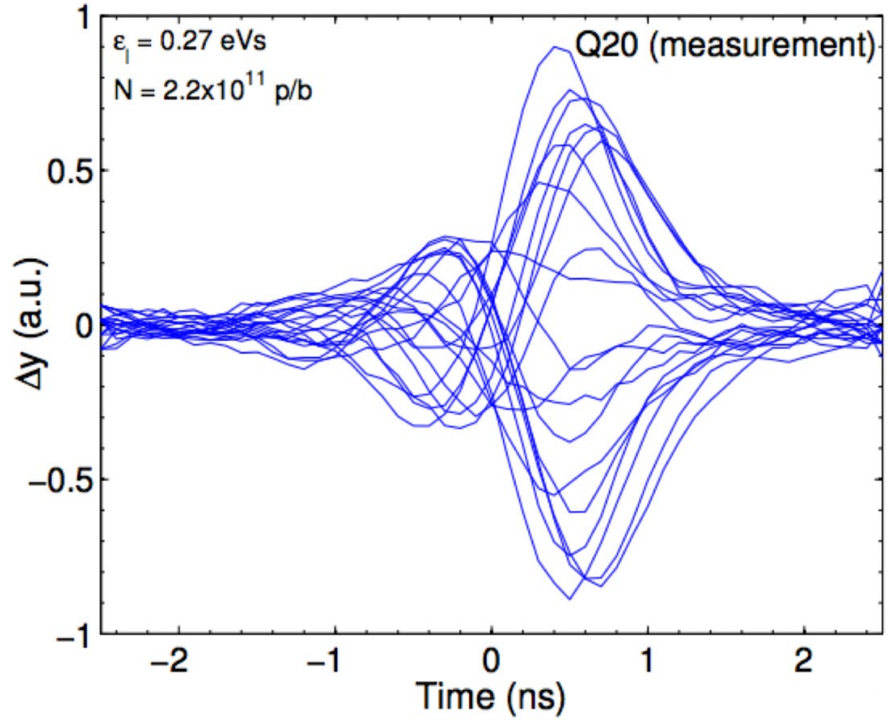
Alexey Burov, Jeffrey Eldred, Valeri Lebedev

Convective Instability in SPS

SPS Instability:

Burov





Burov identified a CERN SPS instability as a convective instability, and derived the properties for the new instability.

Convective Instability Study

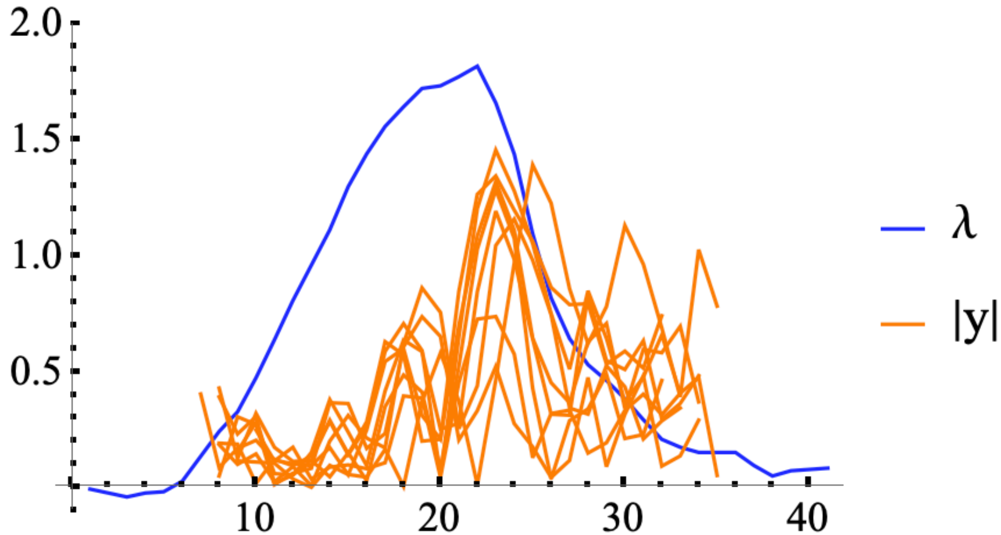
A. Burov "Convective instabilities of bunched beams with space charge" PRAB 2019. link

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**.

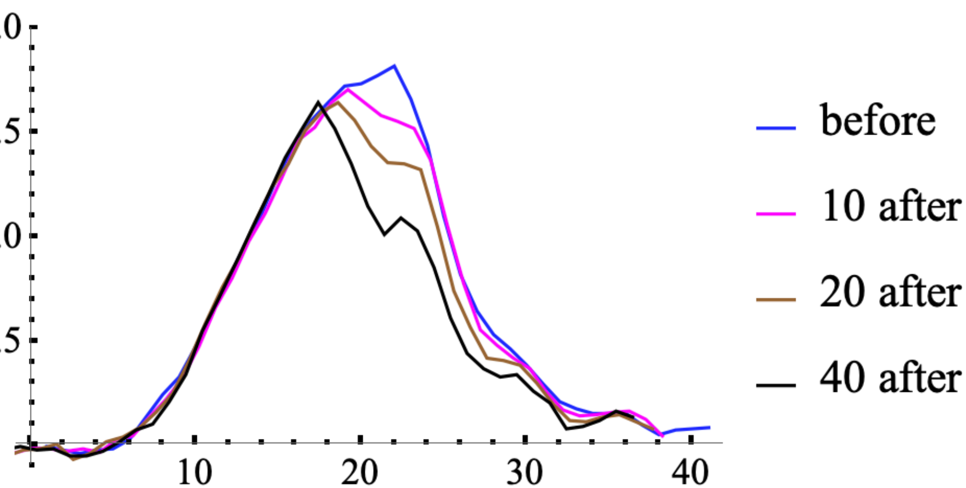
The instability is damped by synchrotron oscillations and chromaticity, therefore a ramp curve with a low-chromaticity transition-crossing was prepared.

We were able to confirm the existence of the convective instability in the Booster, with its predicted properties. **New Physics!**

Signature of Convective Instability



head **tail**



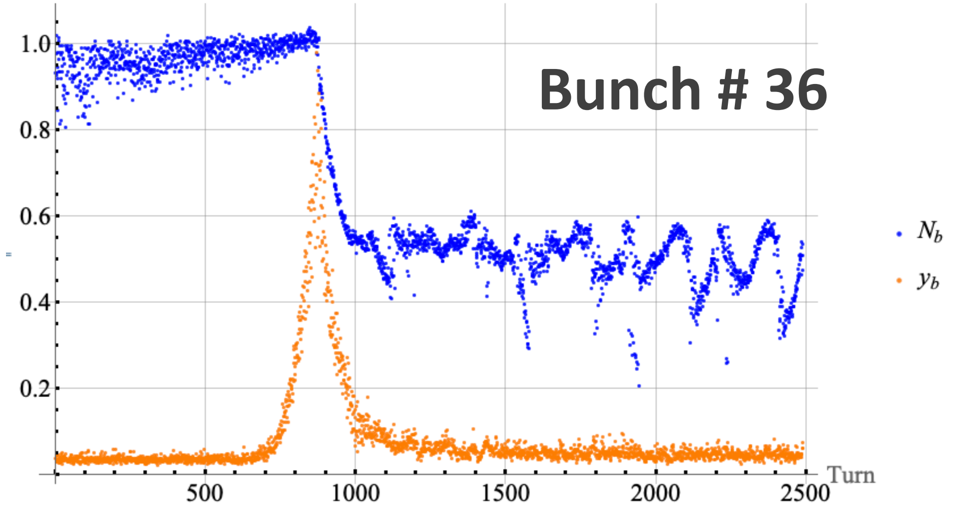
Transverse intrabunch motion propagating from head to tail.

Each bunch blows up to a different amplitude and becomes unstable at a different time.

Massive beam loss rapidly occurs in tail-edge of the bunch.

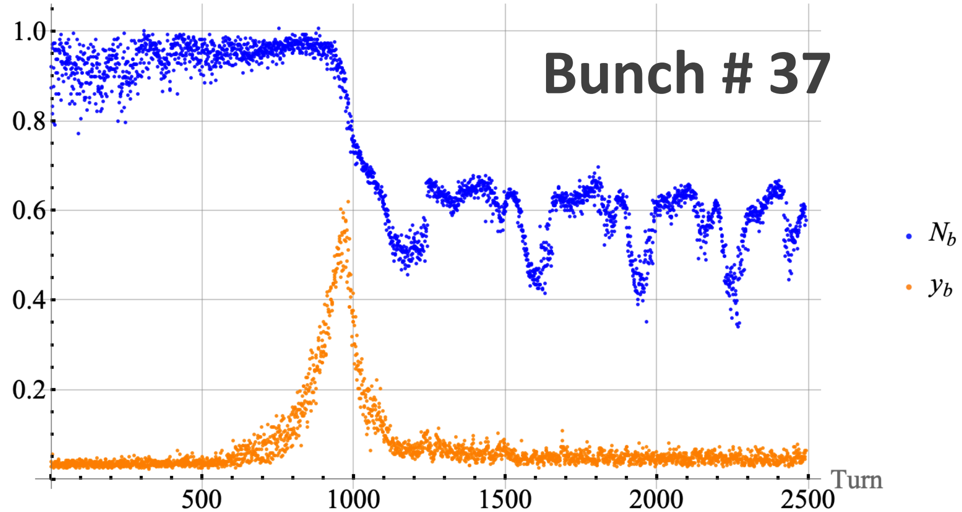
Burov

Vertical Instability for two neighboring bunches



Blue: Estimated Bunch Charge

Orange: Vertical Oscillation



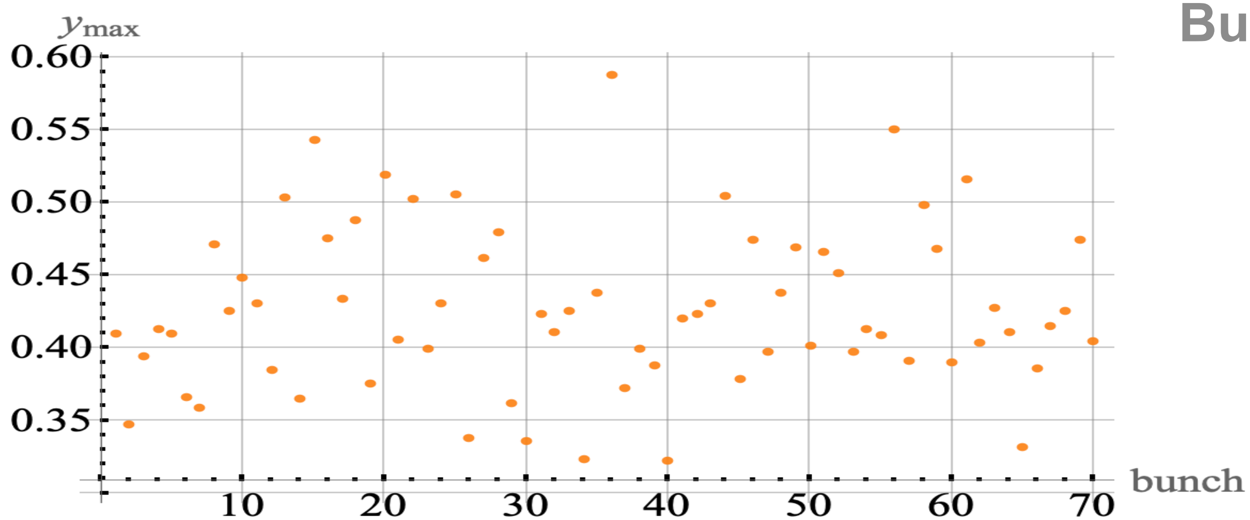
Neighboring bunch
same instability,
~100 revolutions later.

Burov

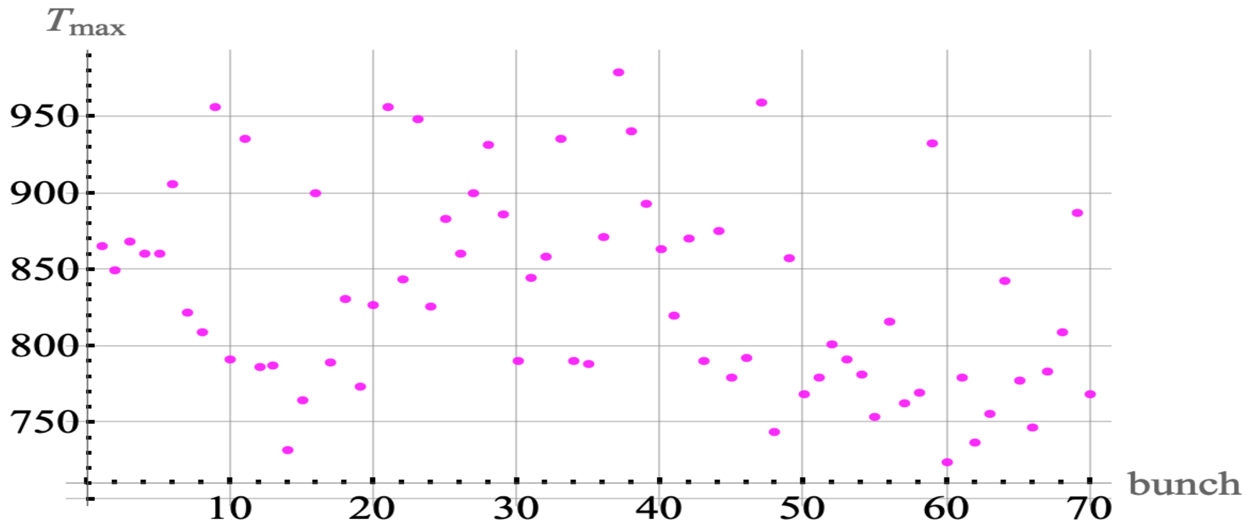
Intrabunch instability completely independent

Burov

Amplitude of Maximum Vertical Signal



Timing of Maximum Vertical Signal



Convective Instability – Outlook

Under nominal intensity and chromaticity, the instability is observable but has a negligible impact on the beam.

Critical Question:
What chromaticity is needed to mitigate the instability for PIP-II?

In present operation we switch from negative to positive chromaticity at transition – we should revise our approach.

Note: We have a bunch-by-bunch damper, but it does not have enough bandwidth to damp this intrabunch instability.

4 Space-Charge Emittance Growth

Vladimir Shiltsev, Hannes Bartosik, Salah Chaurize, Jeffrey Eldred, Alex Huschauer, Valery Kapin, Vladimir Kornilov, Frank Schmidt, Kiyomi Seiya, Cheng-Yang Tan, Kent Triplett

Space-charge Emittance Growth Study

Loss Mechanism:

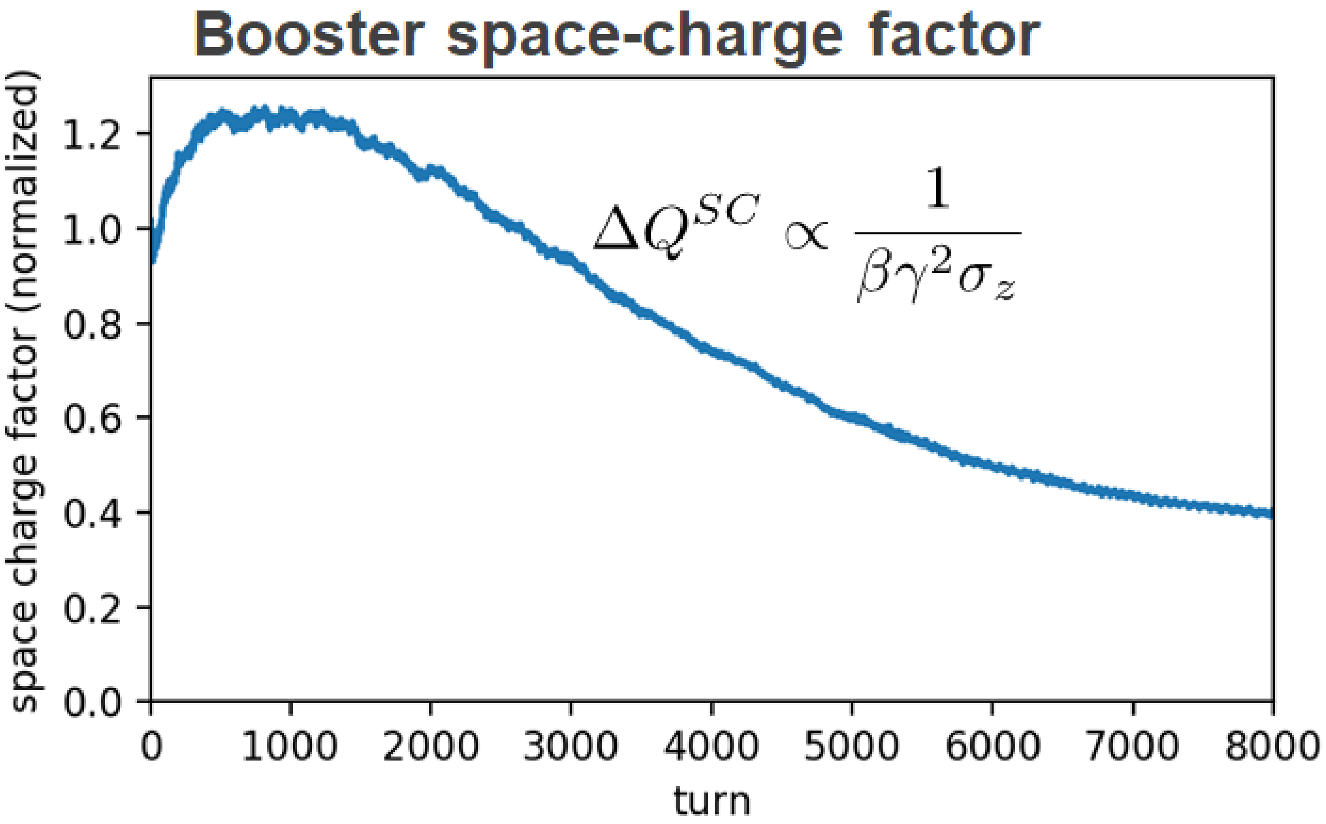
- After capture, space-charge tune-spread is very large.
- The tune-spread crosses resonances, leading to emittance growth.
- Until the emittance growth, and losses, reduce the tune-spread.
- Losses occur at injection, transition, extraction, and transfer.

Method:

- Scan betatron tune at injection, vary intensity, chromaticity.
- Measure losses after capture, losses by extraction.
- Measure emittance with multiwires by extraction.
- Measure emittance with IPMs throughout cycle.

Evolution of space charge along the cycle

For fixed transverse emittance and intensity, space charge scales as

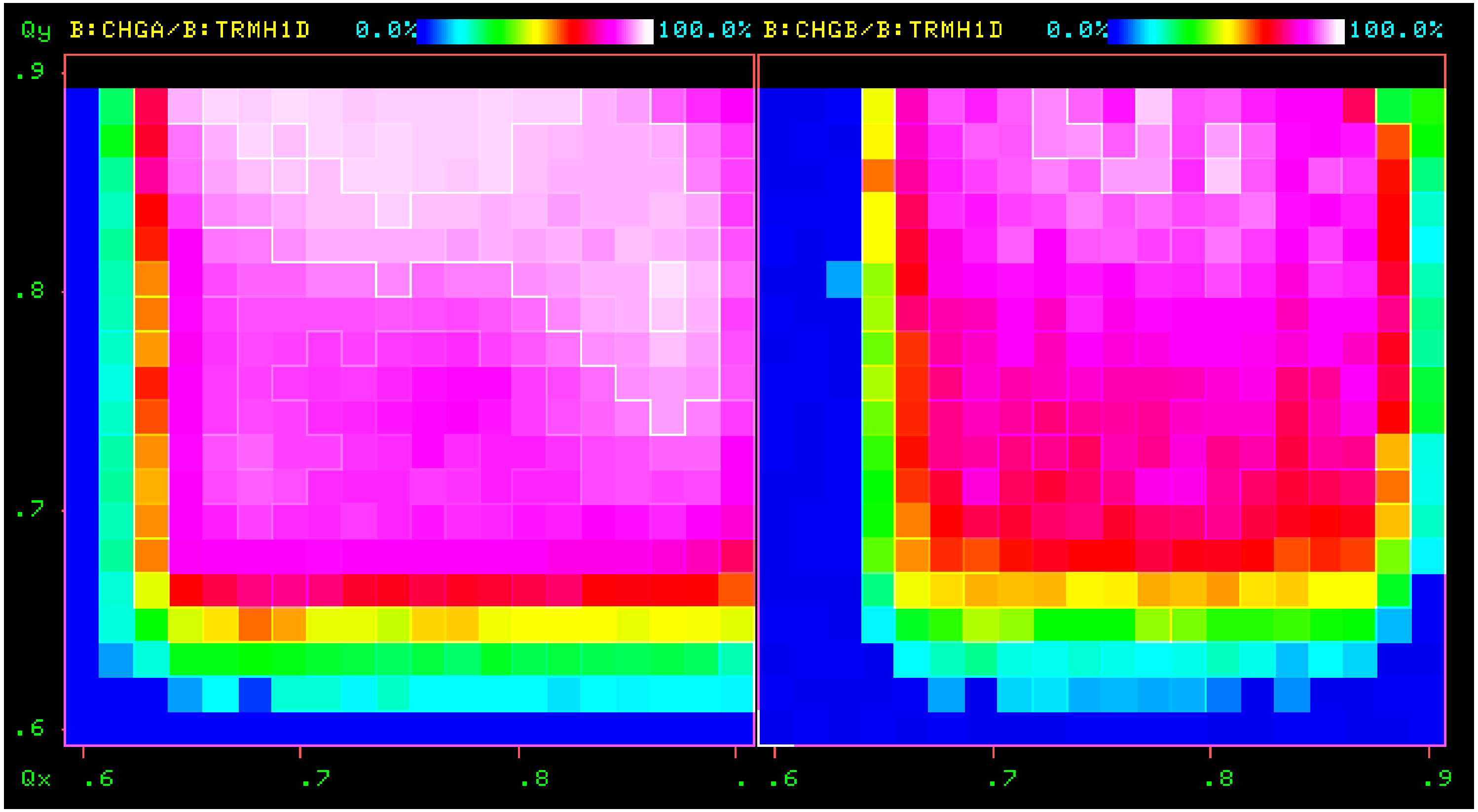


H. Bartosik, A. Huschauer

Intensity Reduces Tunespace

Losses at Capture

Losses by Extraction

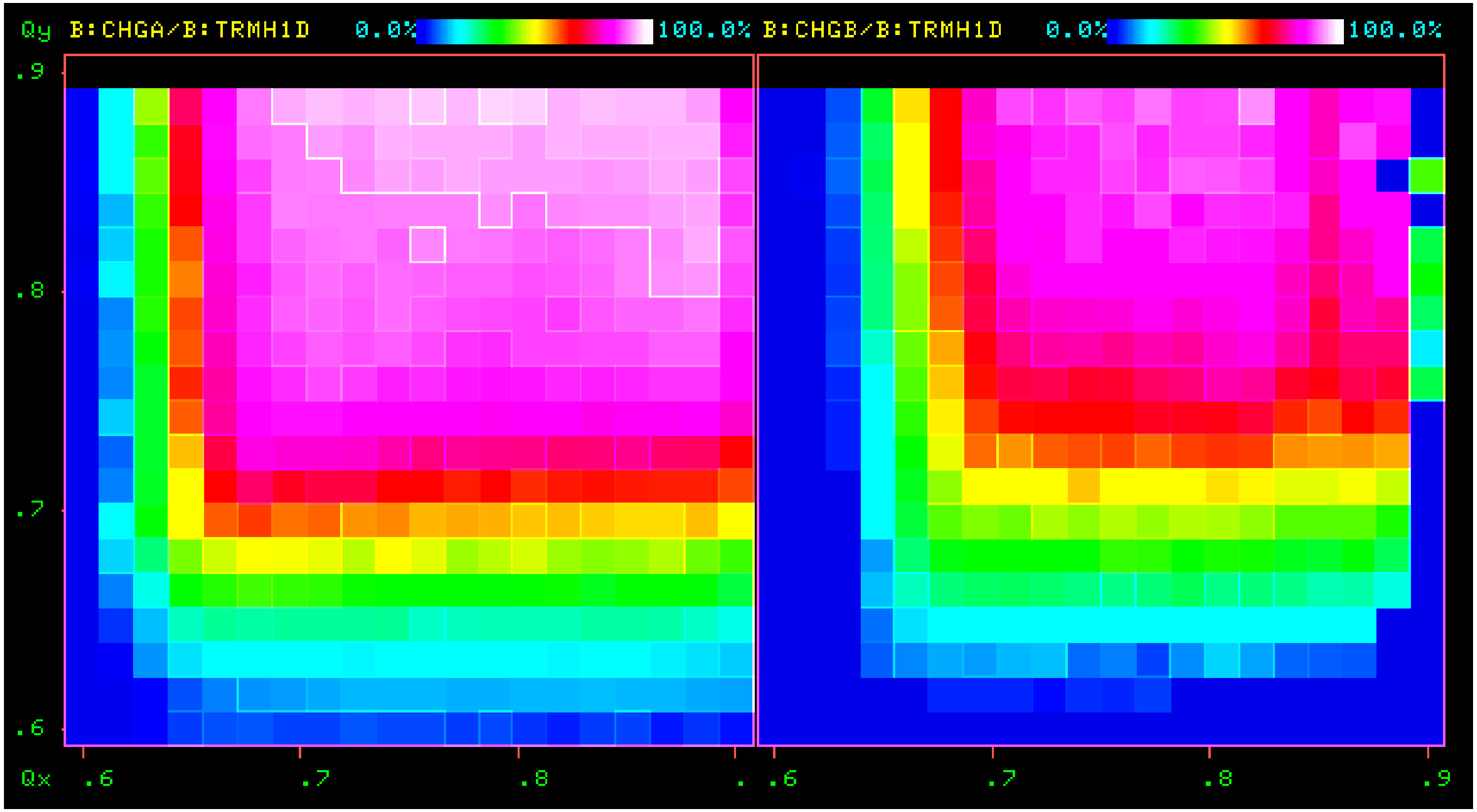


4-turns intensity, chromaticity -20 at injection

Intensity Reduces Tunespace

Losses at Capture

Losses by Extraction



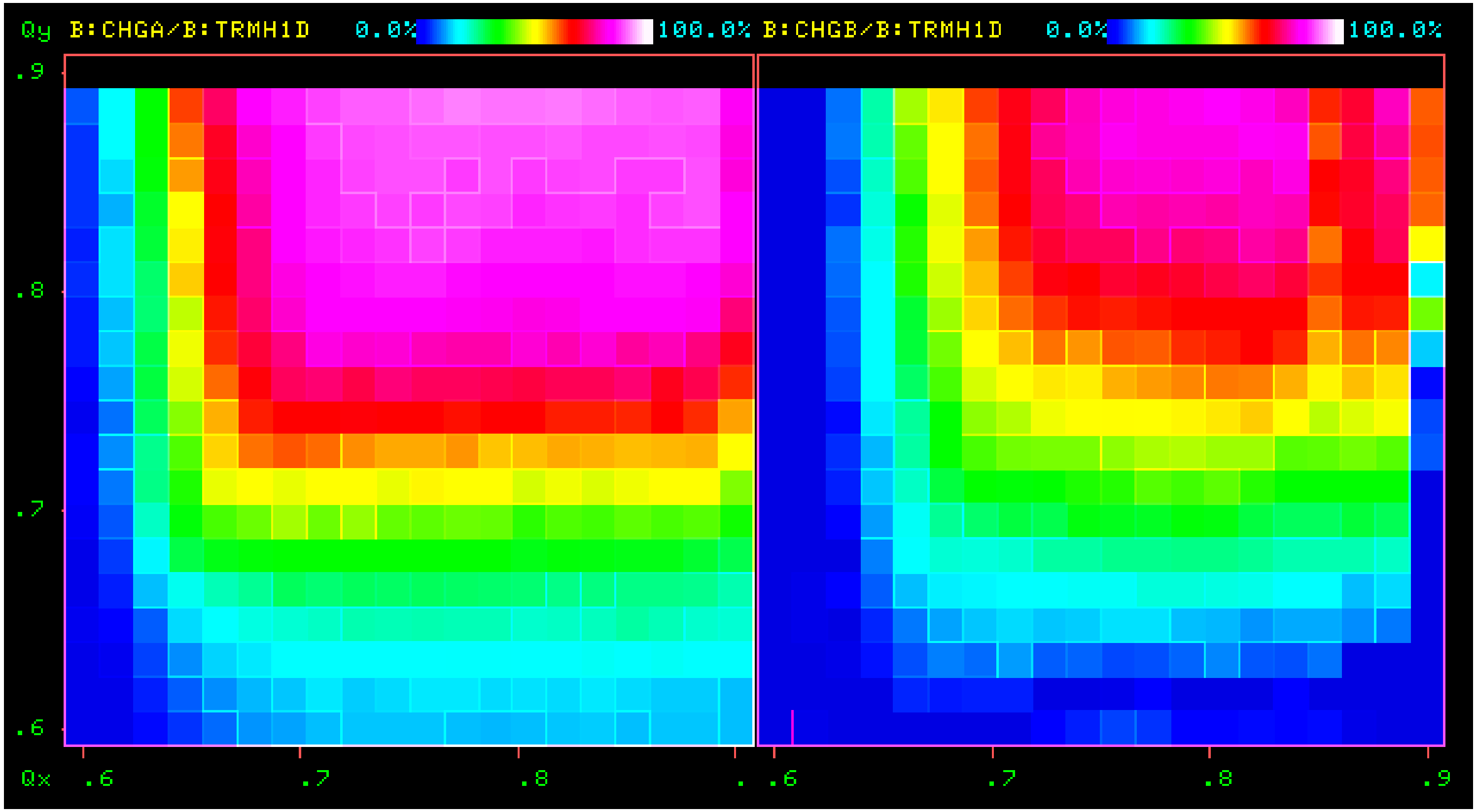
9-turns intensity, chromaticity -20 at injection

Fermilab

Intensity Reduces Tunespace

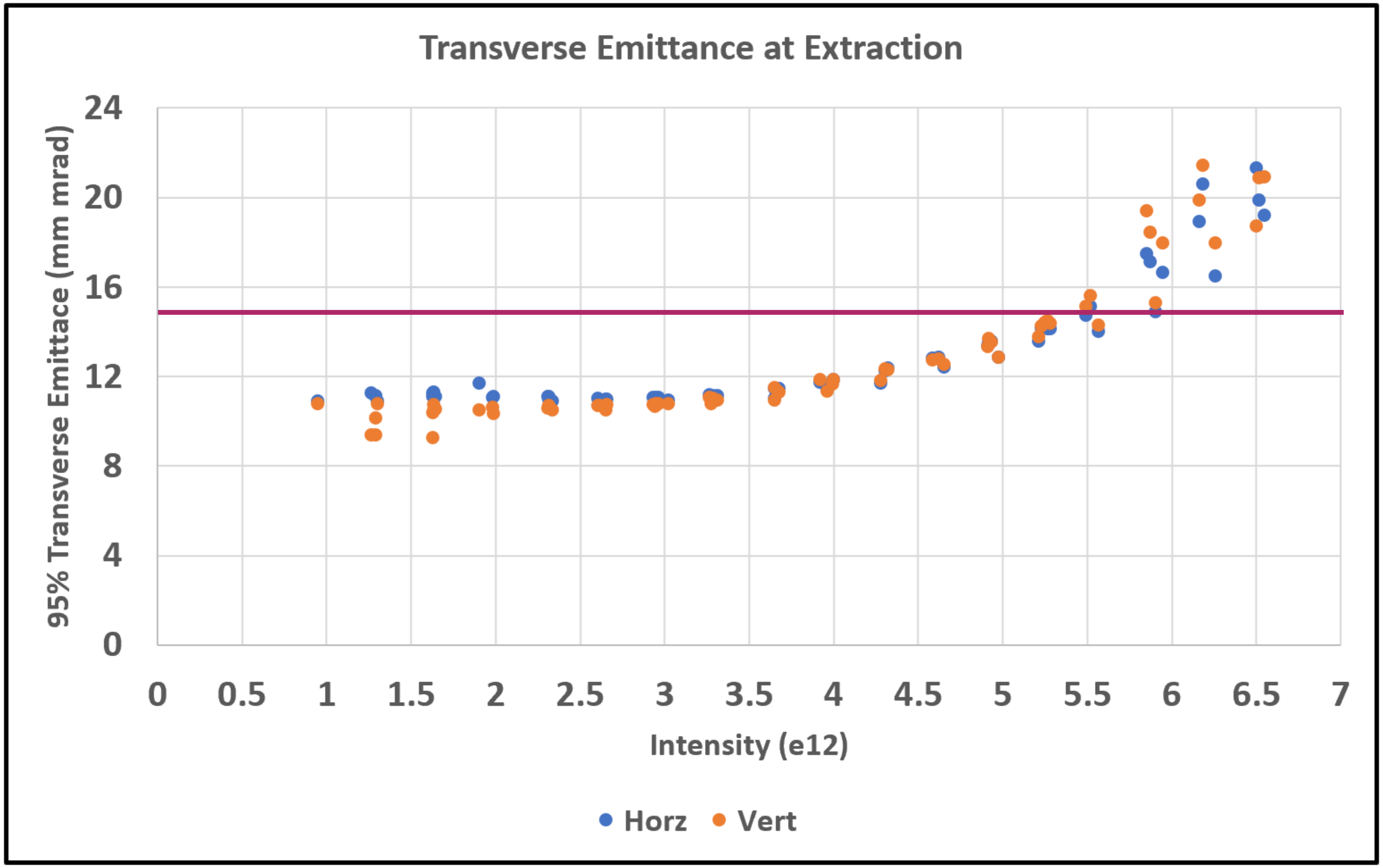
Losses at Capture

Losses by Extraction

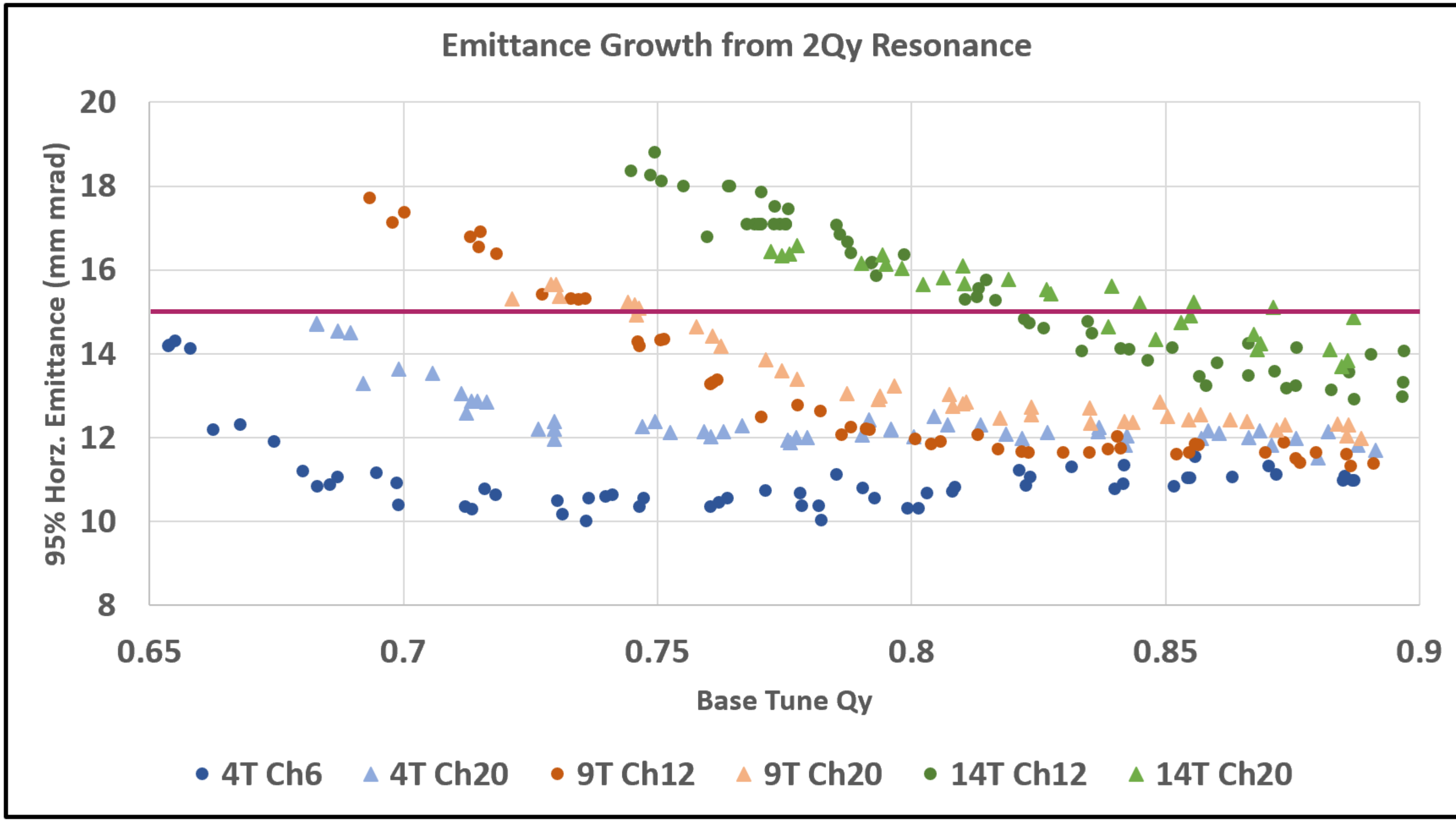


14-turns intensity, chromaticity -20 at injection

Emittance vs. Intensity

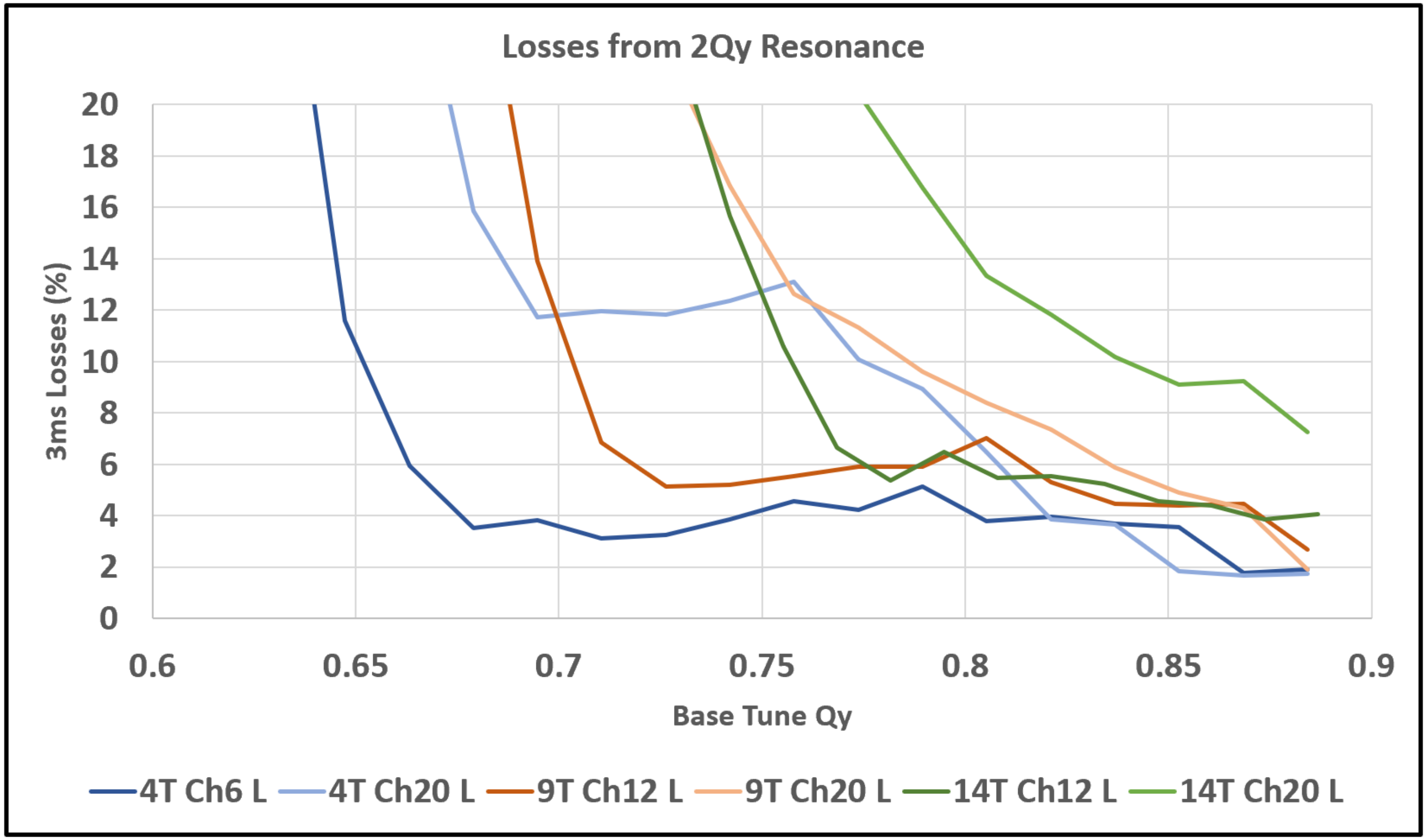


Emittance Growth from 2Qy Resonance



At highest intensity, emittance already connected to 2Qy resonance.

Losses from 2Qy Resonance



Practical loss limits are encountered immediately, dramatic losses follow.

Losses are much more sensitive to chromaticity.

Ionization Profile Monitor Calibration

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 6, 102801 (2003)

Calibration of the Fermilab Booster ionization profile monitor

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G. Jungman
Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

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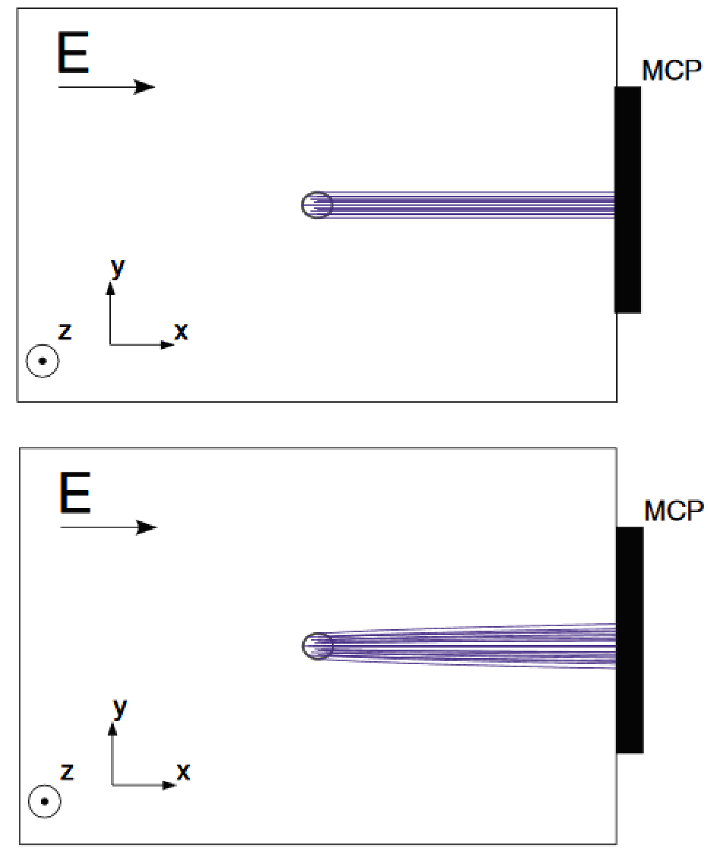
Department of Biological, Chemical, and Physical Sciences, Illinois Institute of Technology, Chicago, Illinois 60616, USA
(Received 20 May 2003; published 9 October 2003)



relation between the raw beamwidth seen in the IPM and the real width is well described by the function

$$\sigma_{\text{measured}} = \sigma_{\text{real}} + C_1 N \sigma_{\text{real}}^{p_1}, \tag{8}$$

where N is the current in units of 10^{12} protons in the machine, $C_1 = (1.13 \pm 0.06) \times 10^{-5}\ \text{m}^{1-p_1}/10^{12}$, and $p_1 = -0.615 \pm 0.013$. The range of validity in

While AGS IPM (PAC1987):

SPACE-CHARGE DISTORTION IN THE BROOKHAVEN IONIZATION PROFILE MONITOR*

R.E. Thern
AGS Department,

$$\sigma_m = \sigma + 0.302 \frac{N^{1.065}}{\sigma^{2.065}} (1 + 3.6\ R^{1.54})^{-0.435}$$

Emittance Growth – Outlook

Results:

- The vertical half-integer resonance already drives emittance growth and loss at nominal intensity.

Next Steps:

- Calibrate ionization profile monitors vs. multiwire.
- Verify and improve Booster linear optics measurements.
- Implement harmonic-correction of 2Qy with a properly phased subset of quadrupoles.

5 Booster Power Supply Ripple

Frank Schmidt, Hannes Bartosik, Salah Chaurize, Jeffrey Eldred, Angela Saa Hernandez, C. Jensen, Jeff Larson, Howard Pfeffer, Kent Triplett

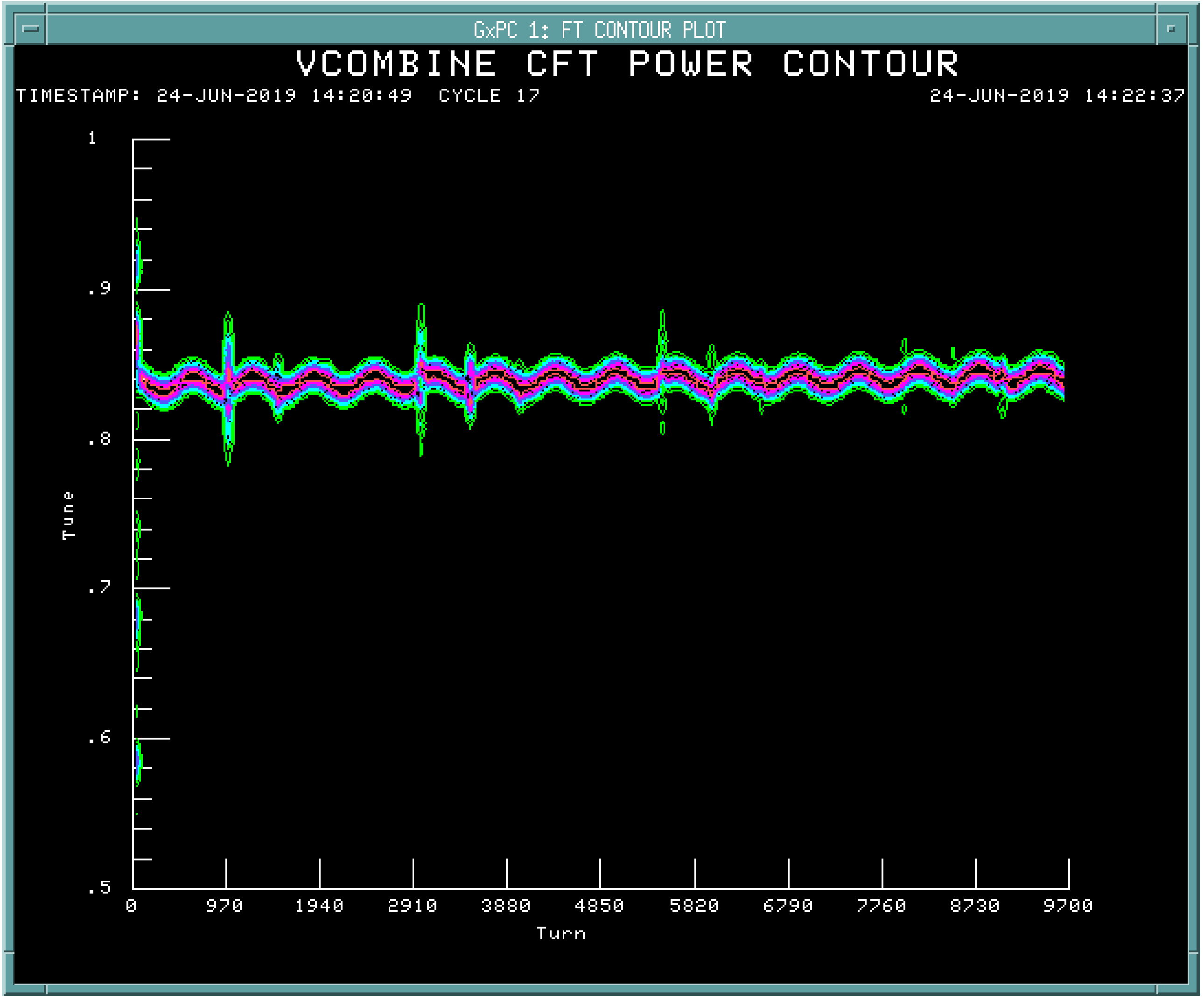
Booster Power Supply Ripple

Any frequency ripple in the gradient magnet power supply would cause modulation of the betatron tune.

No apparent power supply ripple problem at the moment – beam was measured, gradient magnet power supply was measured, Booster resonant magnet circuit was modeled.

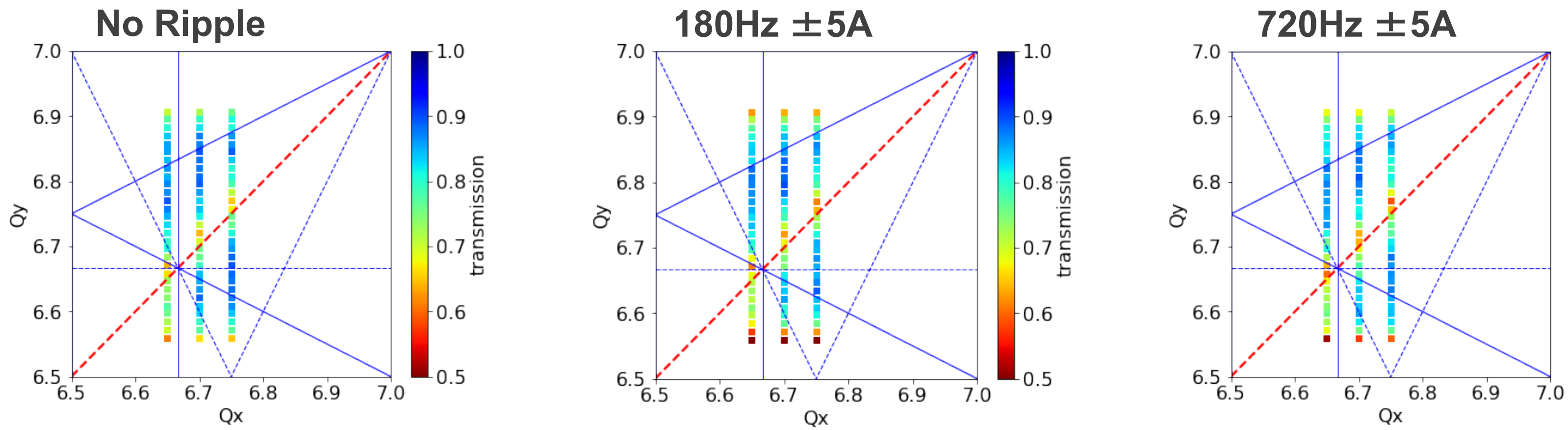
We **induced a tune modulation** effect to study the impact on the beam. One quadrupole was excited with a sinesoidal oscillation of 180 Hz or 720 Hz and a tune modulation depth of ~0.01.

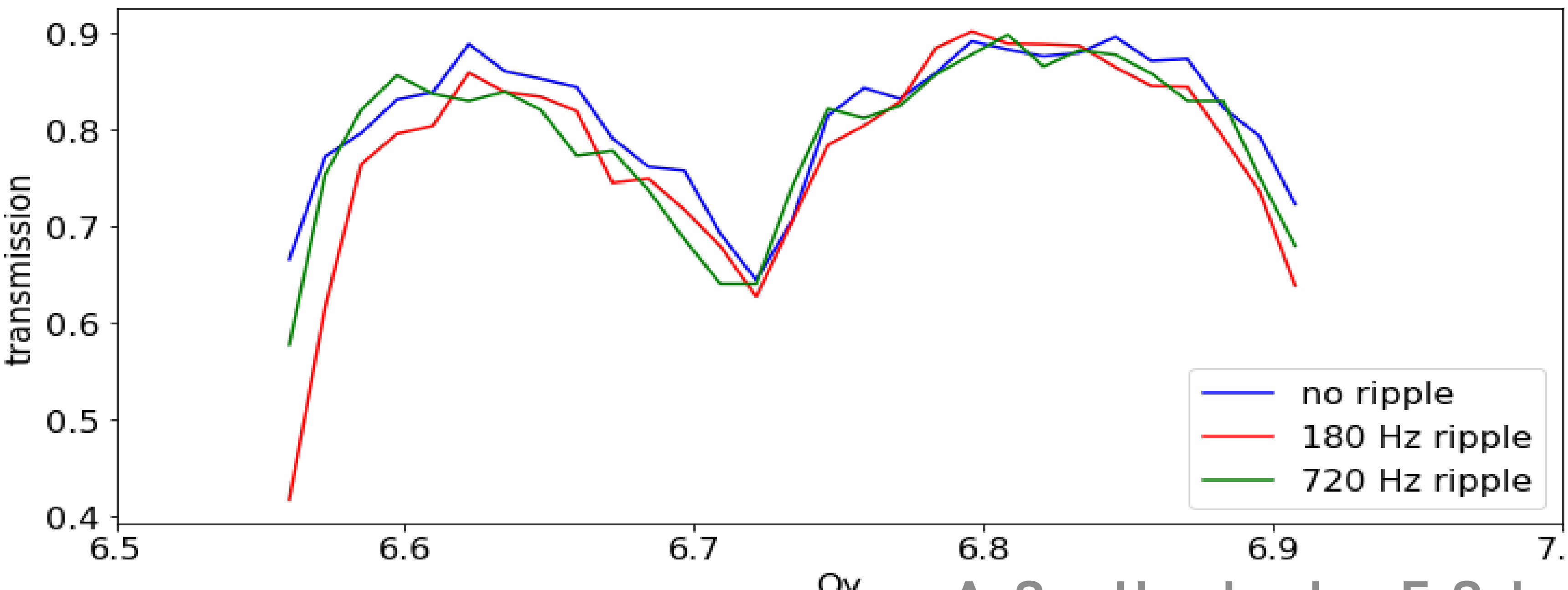
Tune Modulation



~0.01 Tune Modulation

Losses induced by Tune Modulation

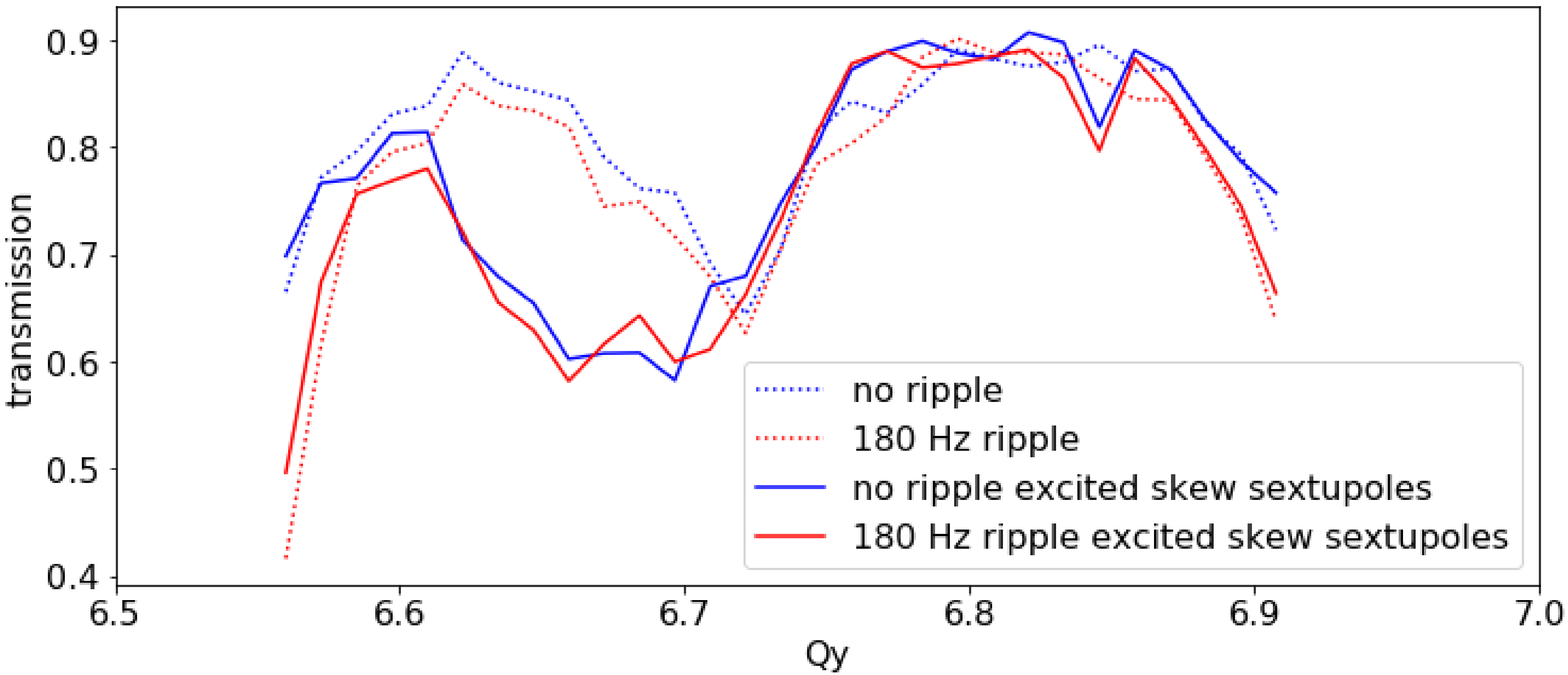




A. Saa Hendandez, F. Schmidt

Losses induced by Tune Modulation & Skew Sextupole

A. Saa Hendandez, F. Schmidt



Tune-modulation broadens half-integer and integer resonances only.

Skew-sextupole resonance has no interaction with tune modulation.

Booster Power Supply Ripple – Outlook

Results:
- No evidence of significant orbit or tune modulation in beam.
- No significant interaction was observed between the tune-modulation, nonlinear resonances, and/or space-charge.

Next Steps:
- Booster circuit model suggests that ripple may have a greater impact at frequencies about 1 kHz, need to measure the gradient magnet power-supply at higher frequencies.

Booster Studies – Next Steps

Booster intensity upgrades motivate us to study the scope of the physics challenges and to mitigate known sources of beam loss.

Results:

1 Injection losses traced to adiabatic capture.

3 Space-charge emittance growth traced to 2Qy resonance.

4 First verification of convective instability.

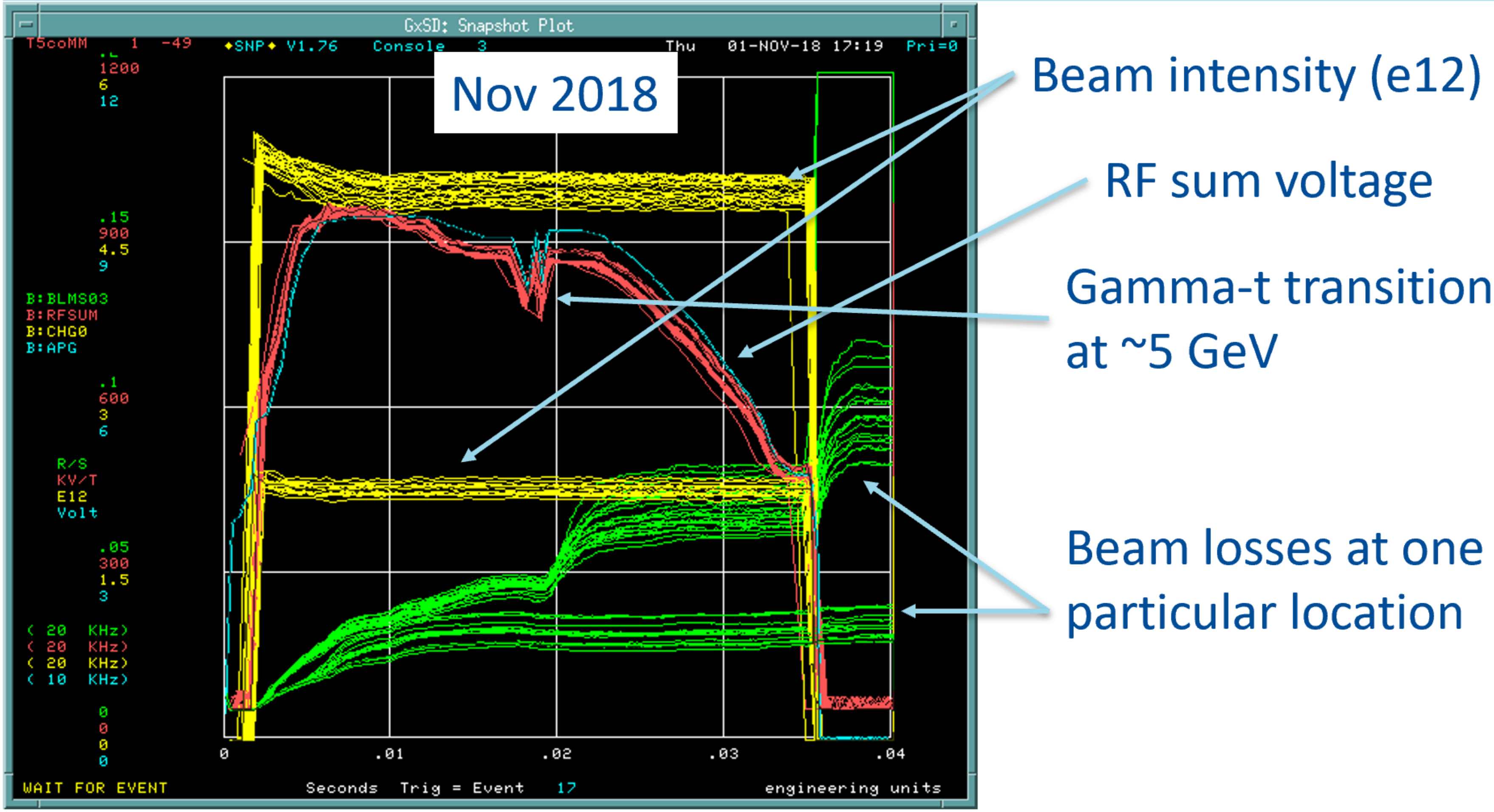
5 Power supply ripple does not threaten Booster operation.

Upcoming focus:

- 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
- Investigation of transition crossing losses.

Backup

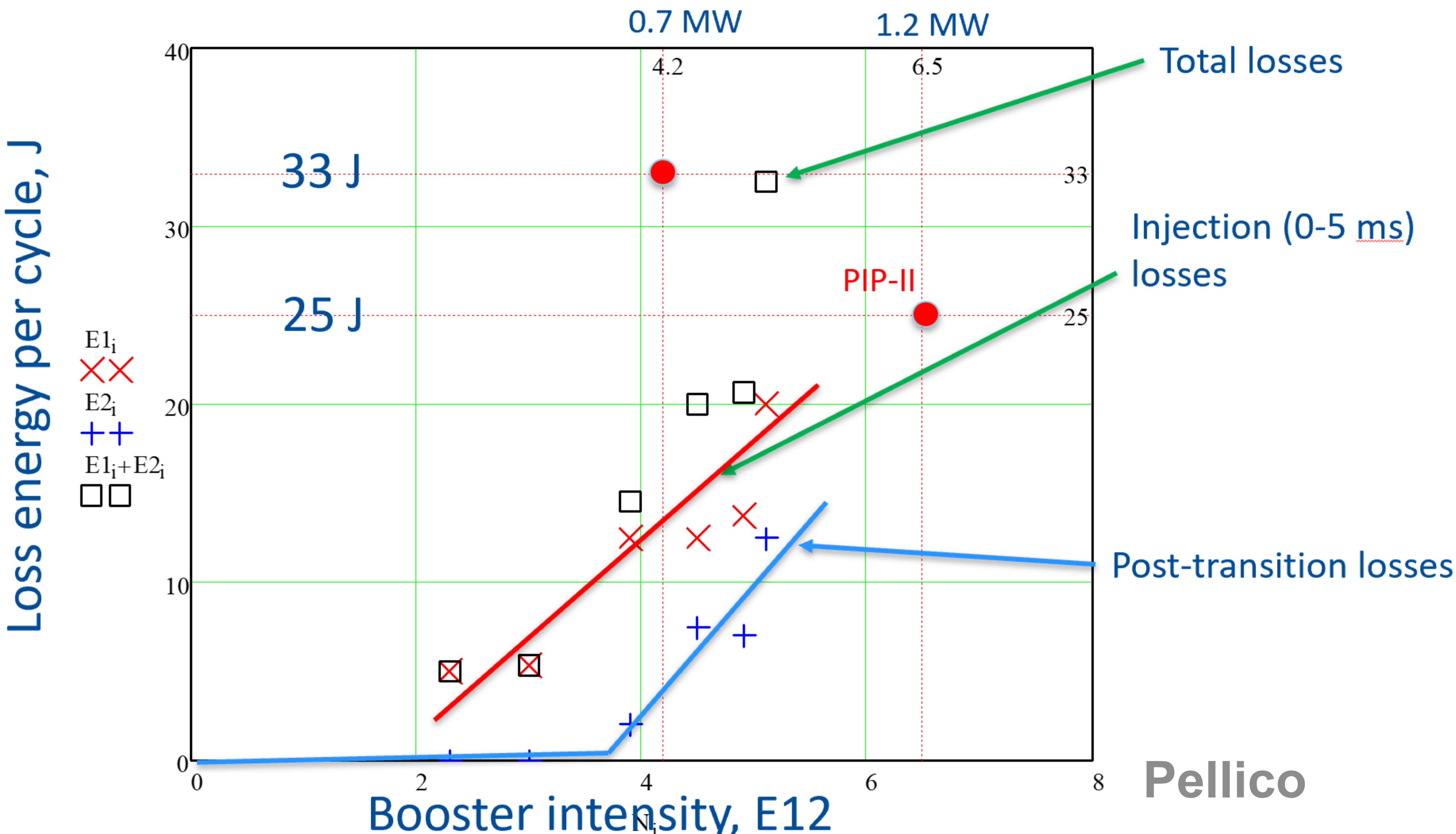
Losses over Cycle



Beam losses for two different intensities (green lines).

Losses above gamma-t transition appear only above 3e12.

Injection & Transition Losses



Pellico

Nagaitsev

PIP-II at 400 MeV

Two-stage collimators – conceptual design.

Wide-bore RF cavities, 60 kV and 3-inch aperture.

GMPS regulation using ML learning (LDRD).

Flat Injection – correct dipole ramp during injection.

LLRF system upgraded to digital.

Longitudinal & transverse damper amplifier upgrades.

Booster shielding assessment

Magnet girder test-stand for 20 Hz.