



# Impact of a Wideband Feedback Prototype System on TMCI in the SPS

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The realisation of the SPS prototype transverse Wideband Feedback system has been a multi-laboratory effort in the frame of the US-LARP program and the SPS-LIU project at CERN.

The contributions from co-workers from SLAC, LBNL, and INFN are gratefully acknowledged.



# Outline

- Motivation for Wideband SPS transverse feedback
- Principle and realisation of prototype system “demonstrator”
- Multi-bunch and single bunch results
- Outlook - conclusions

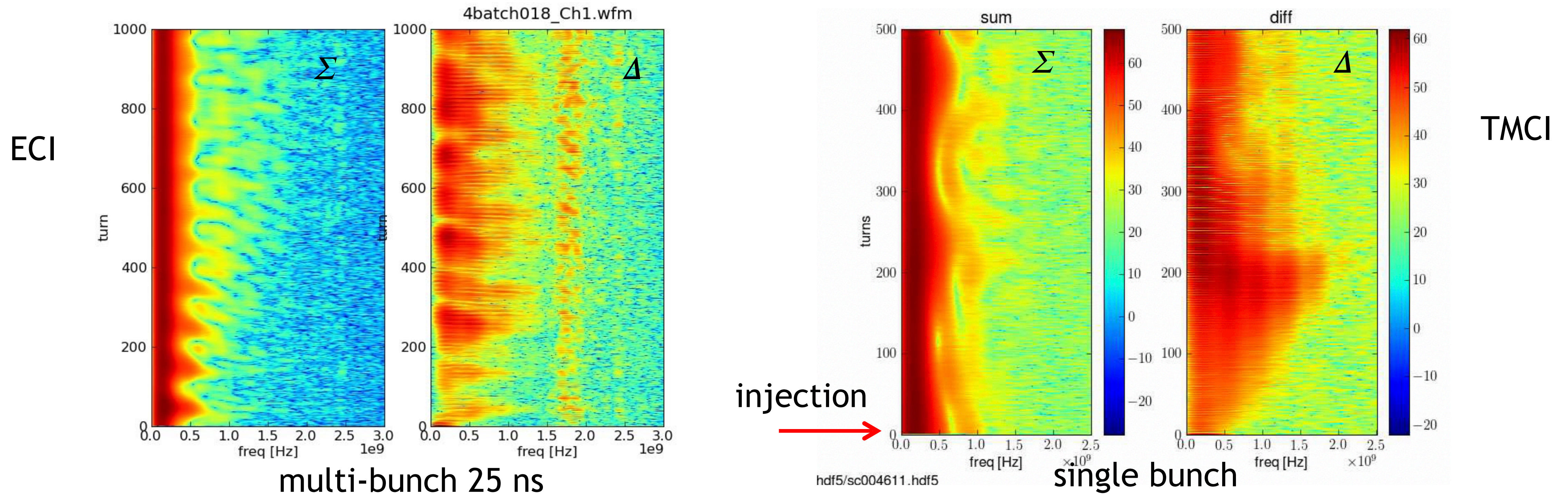


# Motivation for Feedback: SPS as LHC Injector

- SPS operates as LHC injector accelerating protons from 26 GeV/c to 450 GeV/c
  - currently provides up to 288 Bunches per injection into LHC,  $1.3e11$  proton per bunch
- High-lumi upgrade for LHC foresees SPS to deliver  $2.3e11$  per bunch
  - requires single bunch intensities of  $2.6e11$  at SPS injection
  - Limitations today include transverse instabilities that are addressed by the LHC Injector Upgrade program (LIU)
- SPS operates with coupled bunch transverse feedback (20 MHz bandwidth)
  - damps well dipolar oscillations, upgraded in 2014
- intra-bunch oscillations also observed
  - electron cloud driven
  - impedance driven
- possible mitigation by
  - high chromaticity
  - change of optics: lower gamma transition  $\rightarrow$  higher threshold of instability (Q20, Q22, Q26)
  - feedback  $\rightarrow$  prototype system “demonstrator” developed and deployed

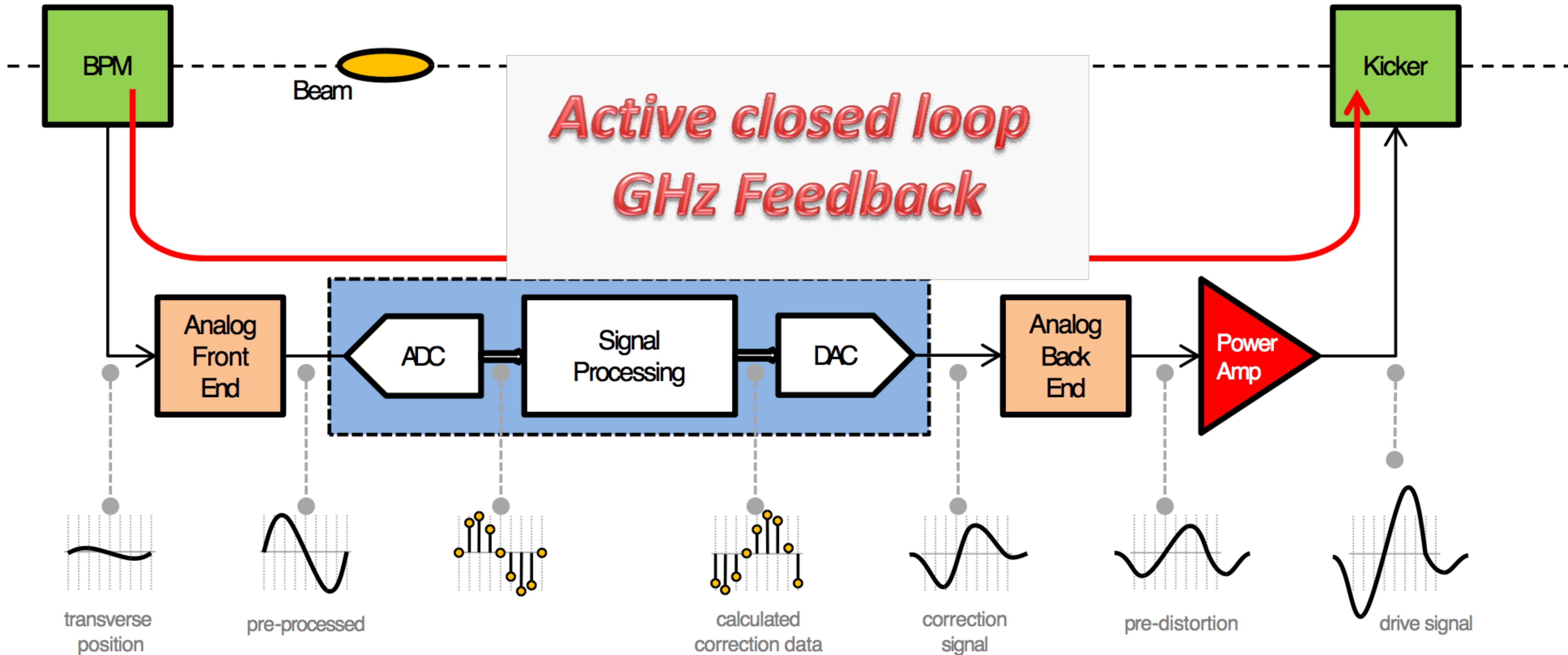
# Motivation and History of SPS intra-bunch Feedback

- Study to mitigate intra-bunch vertical oscillations by feedback started in 2007
- originally motivated by vertical electron cloud driven instability (ECI)
- potential to mitigate impedance driven transverse mode coupling instability (TMCI) recognised from the start



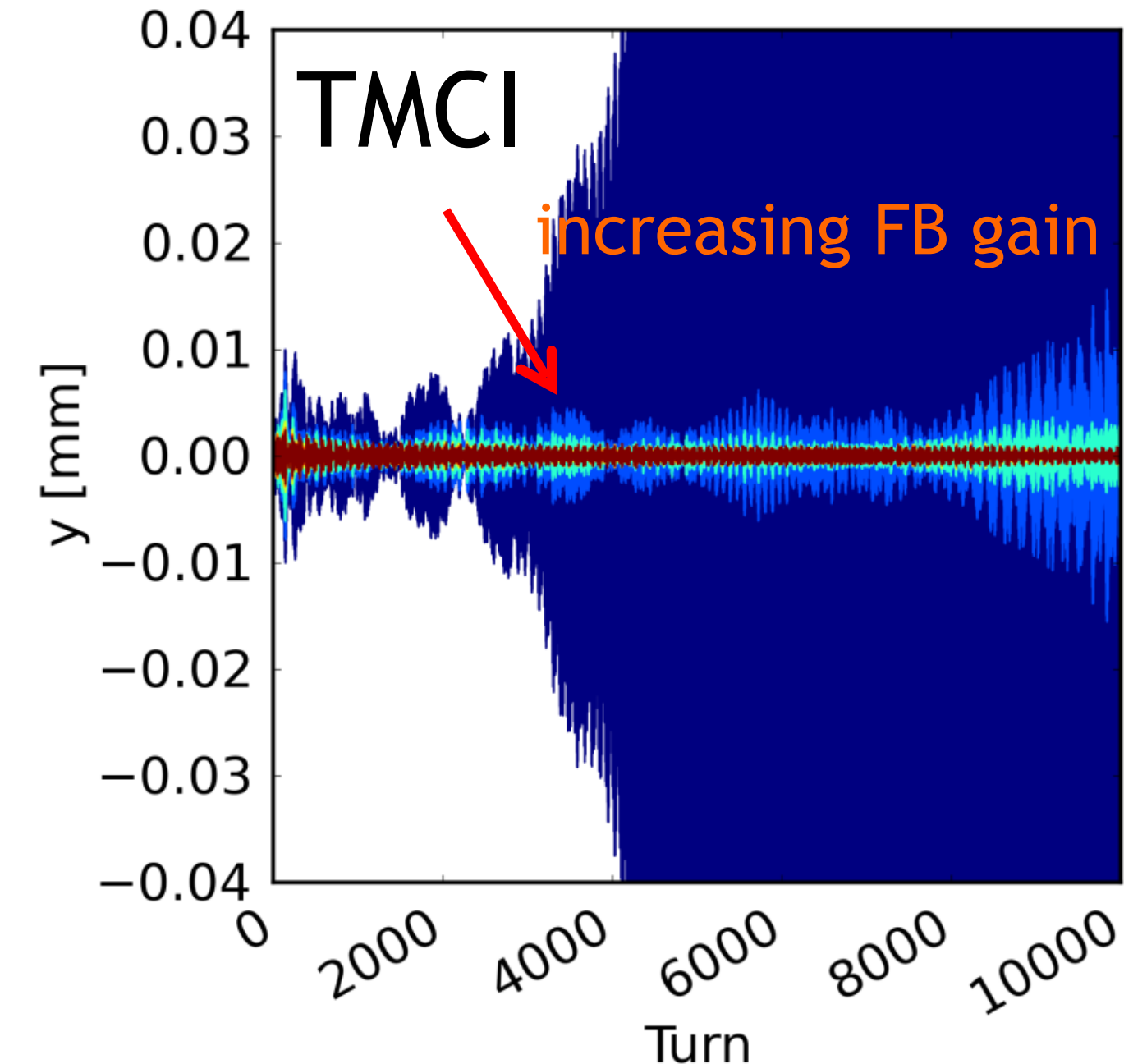
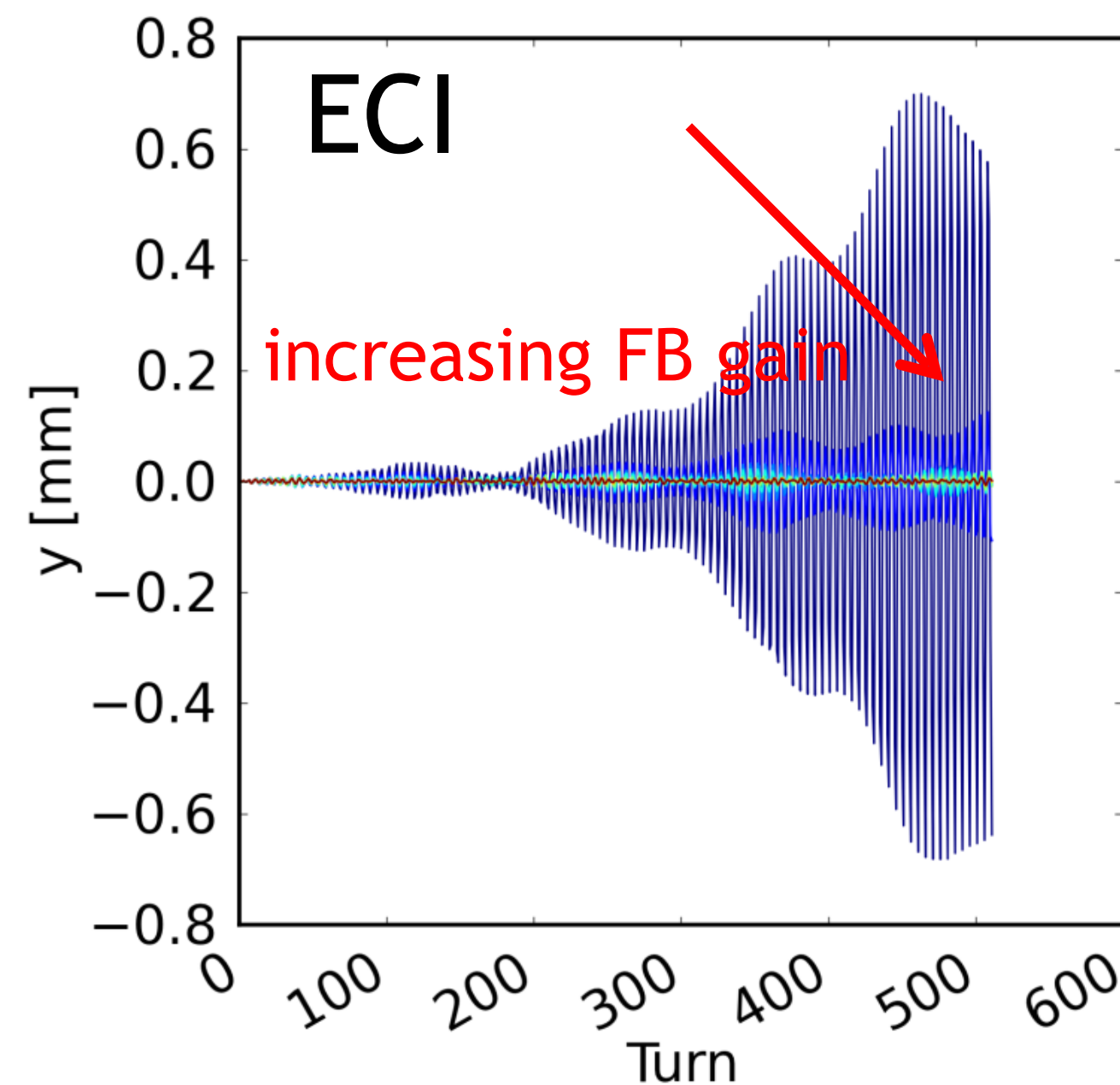
Pick-up signals: evolution of spectra of vertically unstable bunches at SPS at injection: 26 GeV/c

# Principle of Wideband Feedback



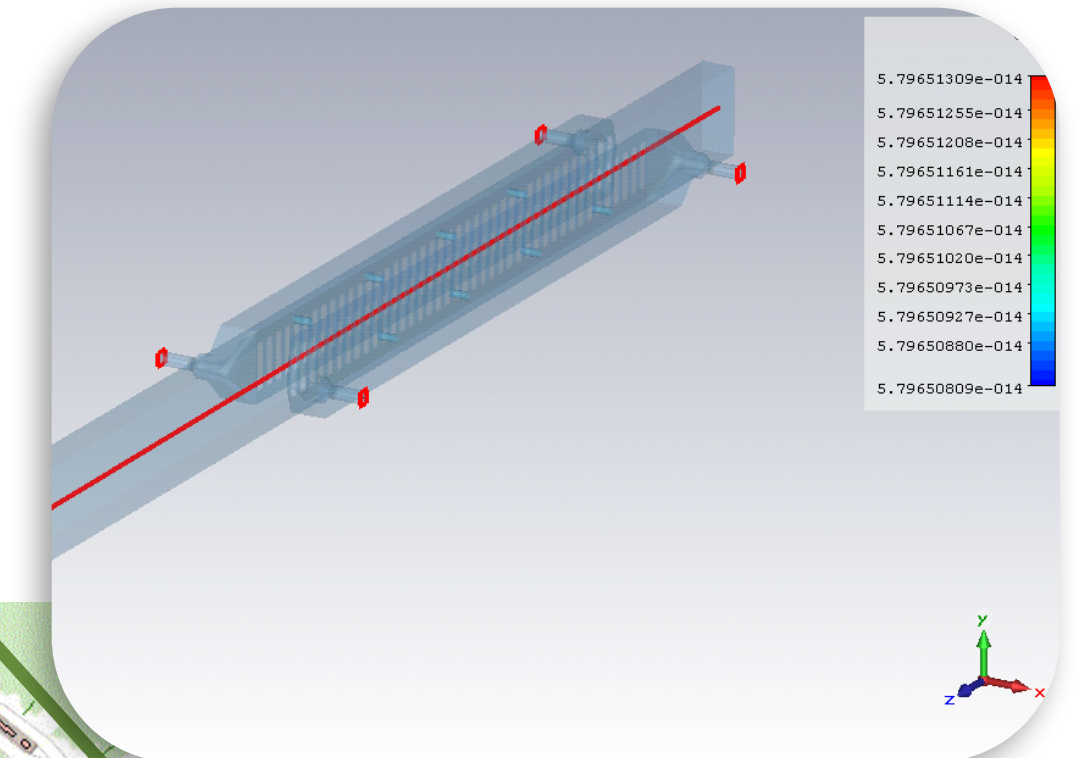
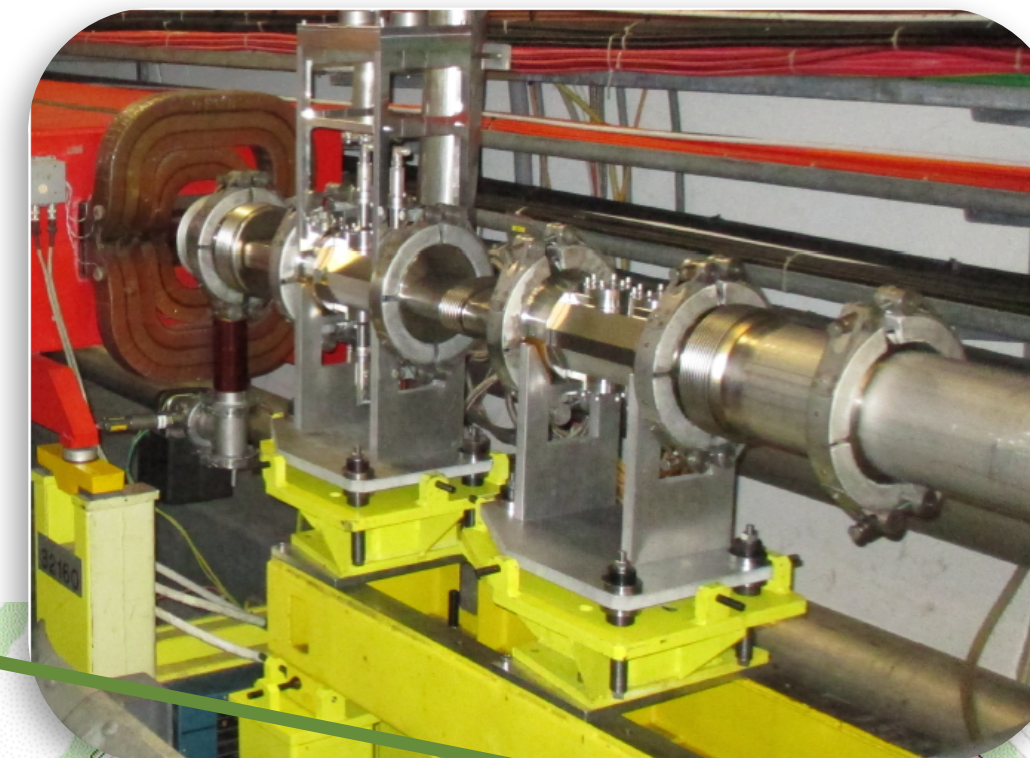
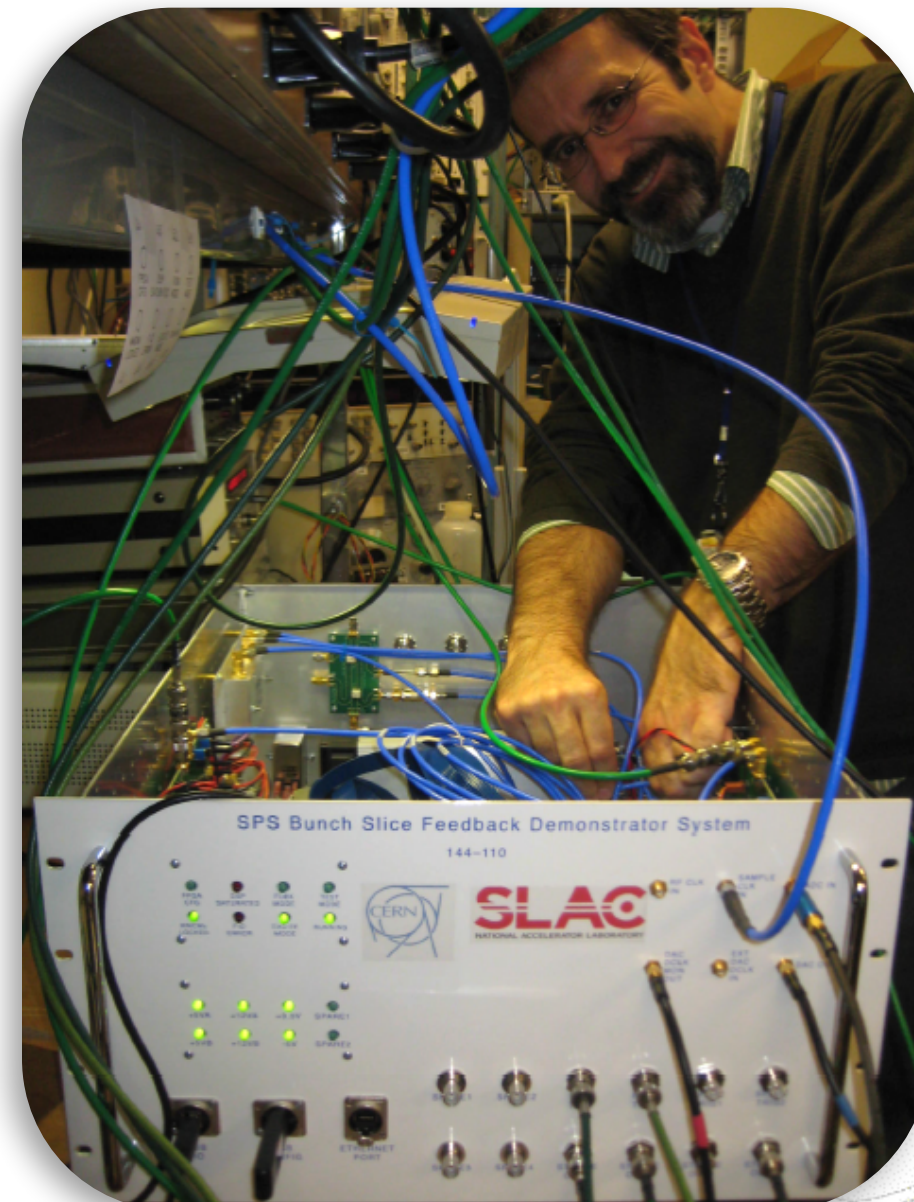
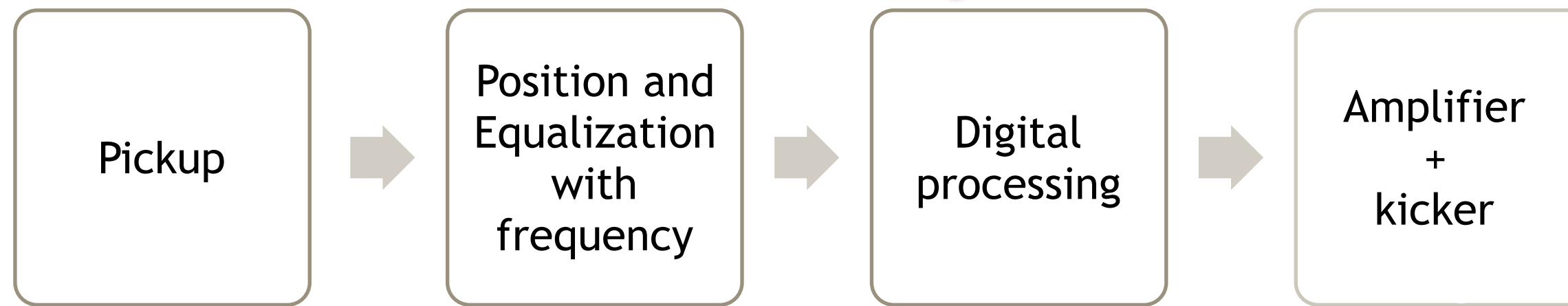
# Numerical Simulations in Q26

- Numerical simulations show the feasibility of feedback to cure the instabilities
- typically done at CERN using the Headtail Code
  - model of machine impedance integrated
  - feedback applied slice-by-slice within the bunch
  - Actual signal processing (e.g. FIR filters) can be integrated in simulation



# Wideband feedback system components

- Complete processing channel from pickups through kicker, running a digital **programmable system up to 4 GS/s** is installed and used at 3.2 Gs/s with 16 samples over the 5 ns bucket
- SLAC built prototype includes **multi-bunch processing** of up to 64 bunches
- Kickers:
  - 2 strip-line kickers
  - 2 x 2 power amplifiers with 250 W, frequency range: 5 - 1000 MHz
  - adding a slotline kicker in 2018 → 1.2 GHz



see poster for more information on prototype performance and possible future evolution

J. Fox et al.; WEPAL079

J. Dusatko, J. Fox; WEPAF073

W. Hofle, TUZGBD4

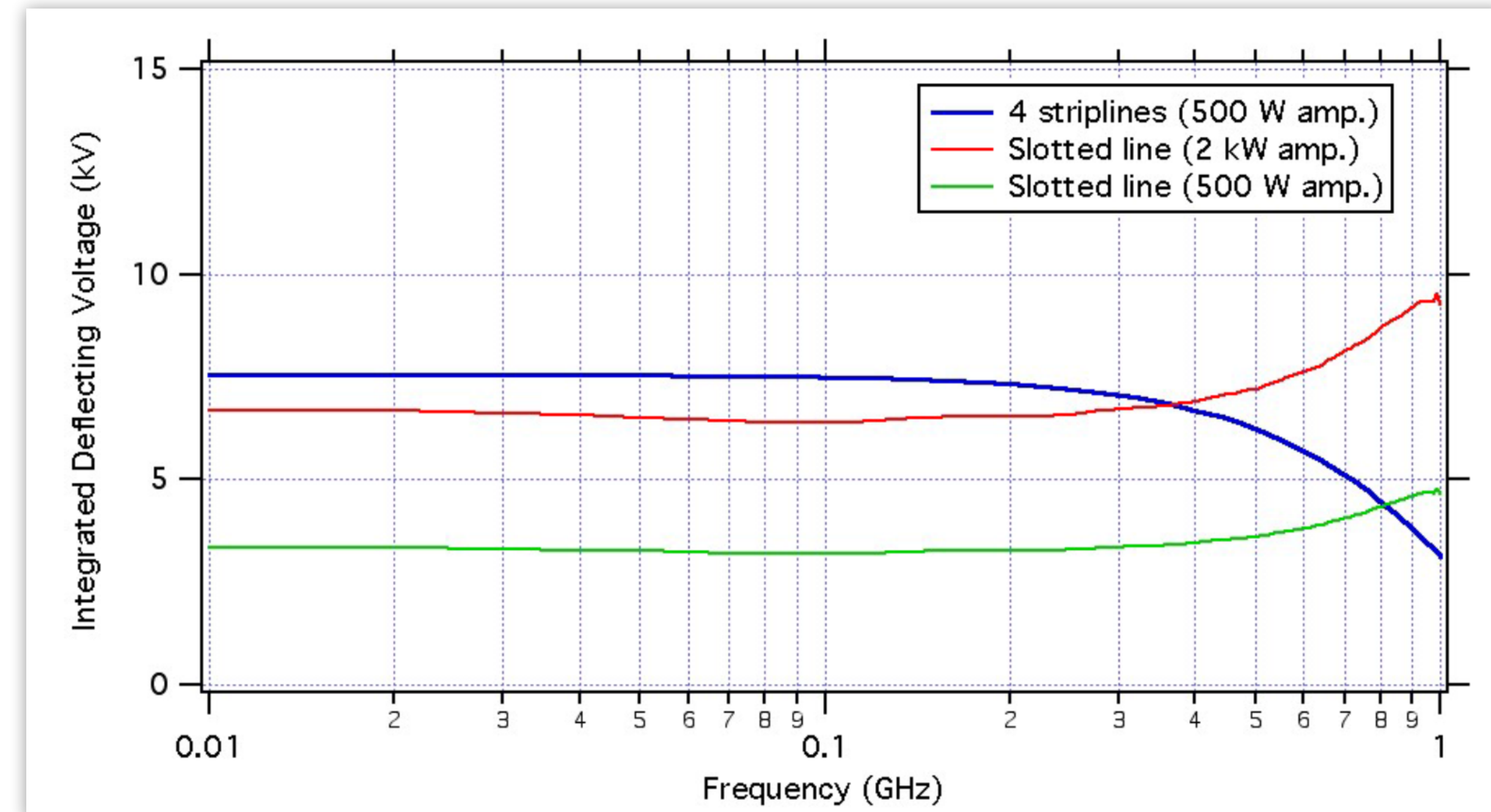
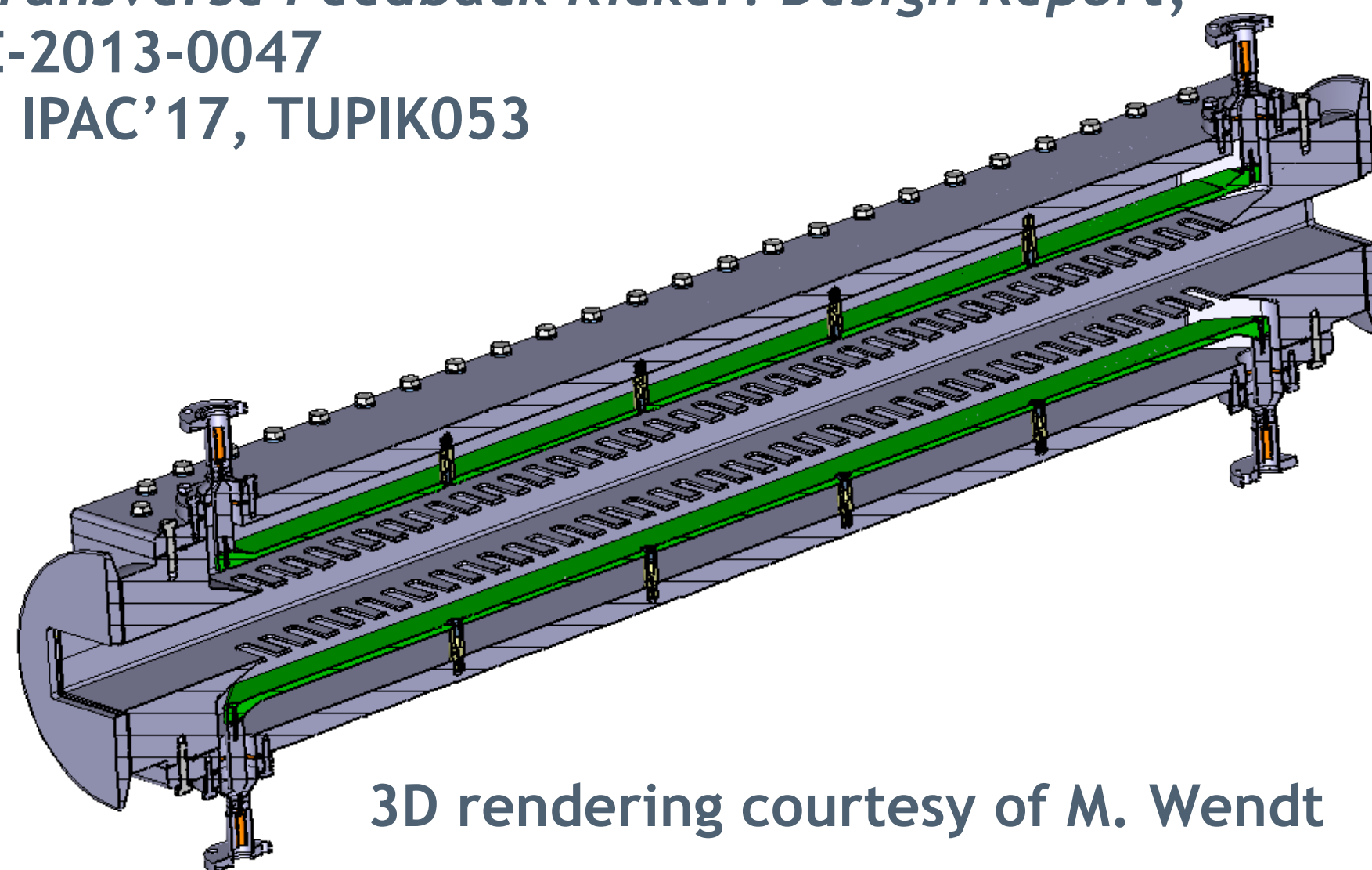
# Comparison of kickers

	$N_{\text{mod}}$	$N_{\text{amp}}$	$P_{\text{amp}}$ (W)	$P_{\text{tot}}$ (W)	$V_{\perp}$ (kV)				
					100 MHz	250 MHz	500 MHz	750 MHz	1000 MHz
Striplines	4	8	500	4000	7.6	7.3	6.3	4.9	3.2
Striplines	44	88	100	8800	37.3	35.9	31.1	23.9	15.5
Slotline	1	2	500	1000	3.2	3.3	3.6	4.2	4.6
Slotline	1	2	2000	4000	6.4	6.6	7.2	8.4	9.3
Slotline	6	12	300	3600	14.8	15.3	16.7	19.4	21.5

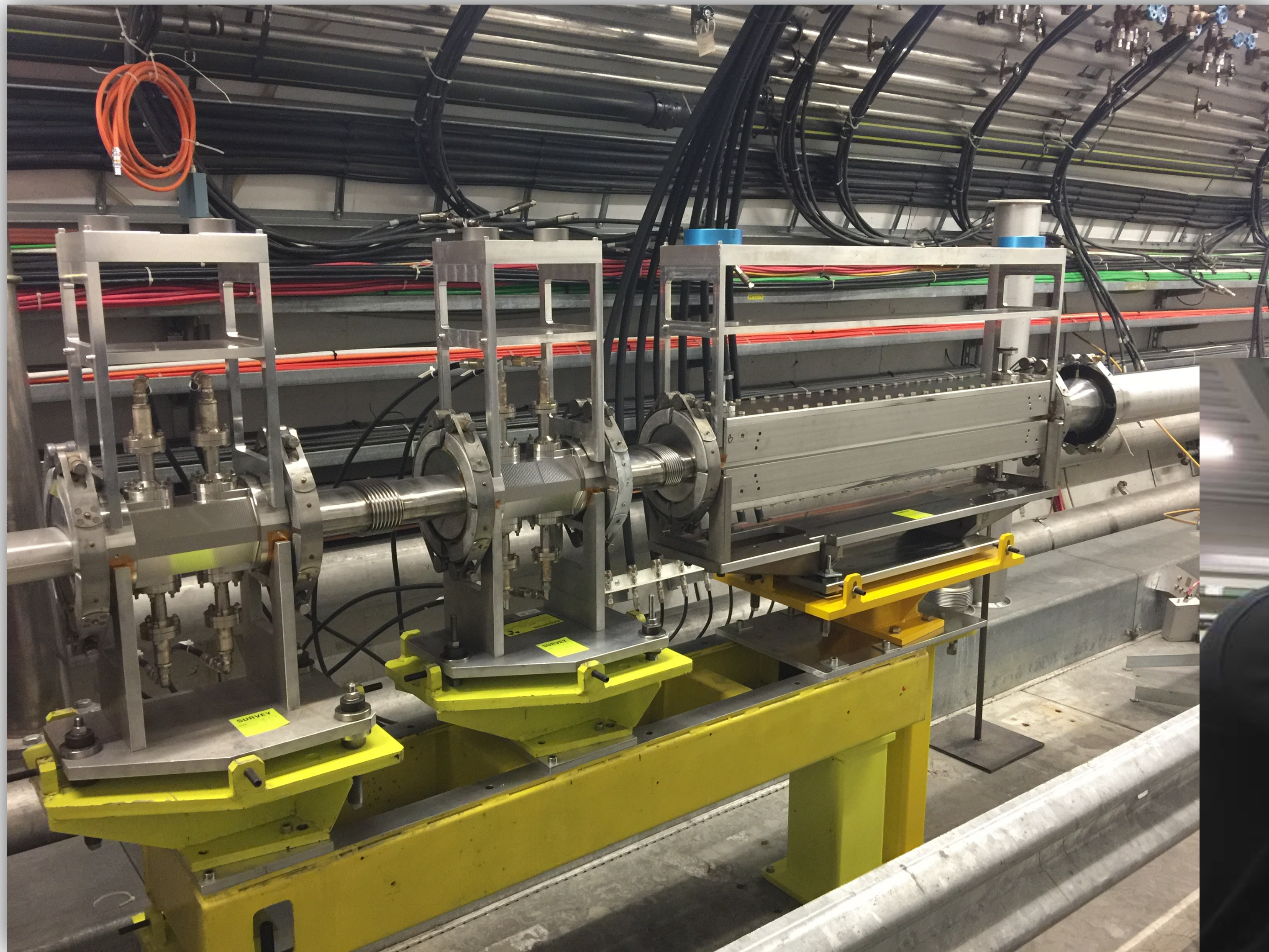
$$\Delta x' \propto \frac{eV_{\perp}}{E}$$

- Stripline - 10 cm
- Slotline - 1 m

J. Cesaratto et al.:  
*SPS Wideband Transverse Feedback Kicker: Design Report,*  
 CERN-ACC-NOTE-2013-0047  
 M. Wendt et al.: IPAC'17, TUPIK053

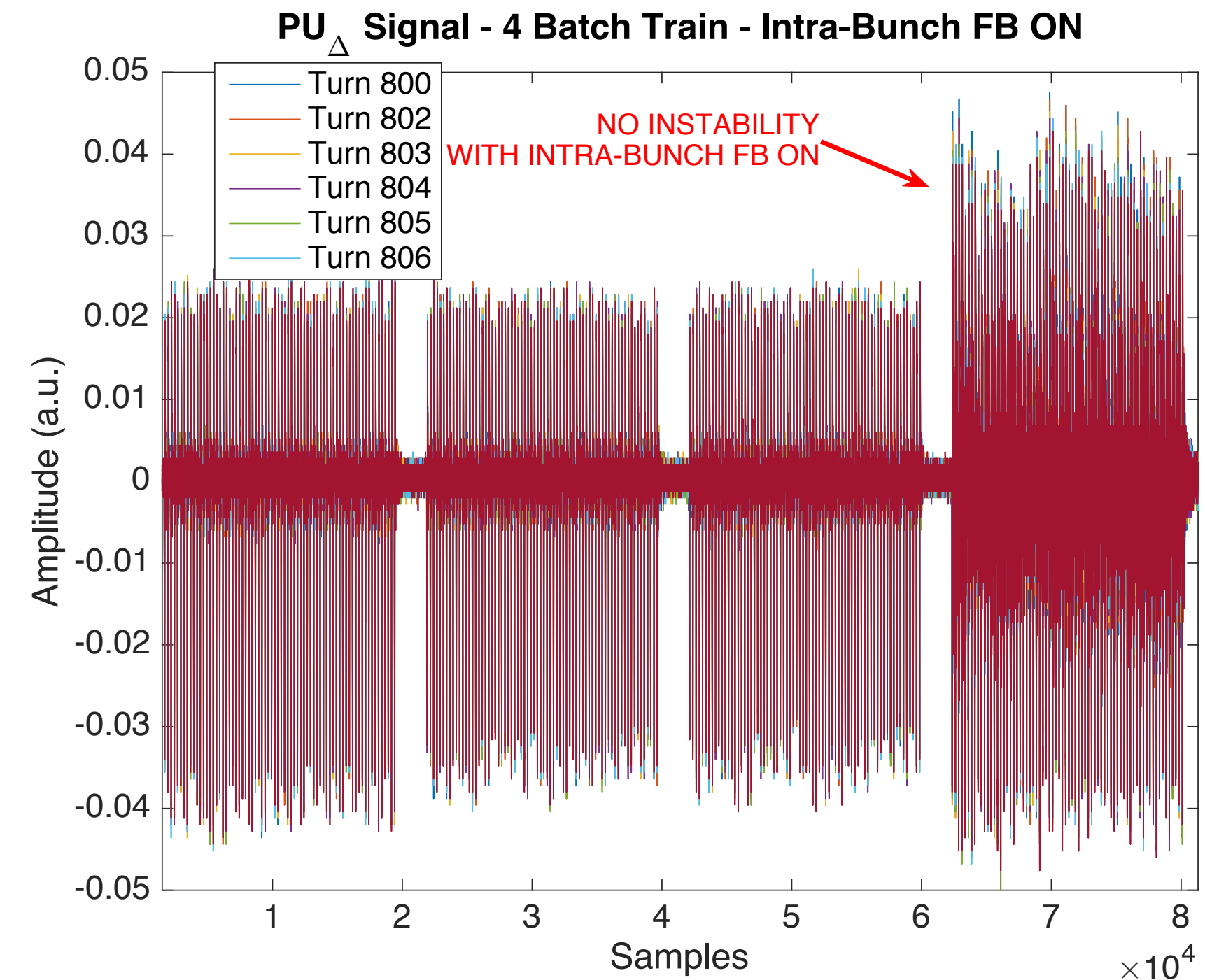
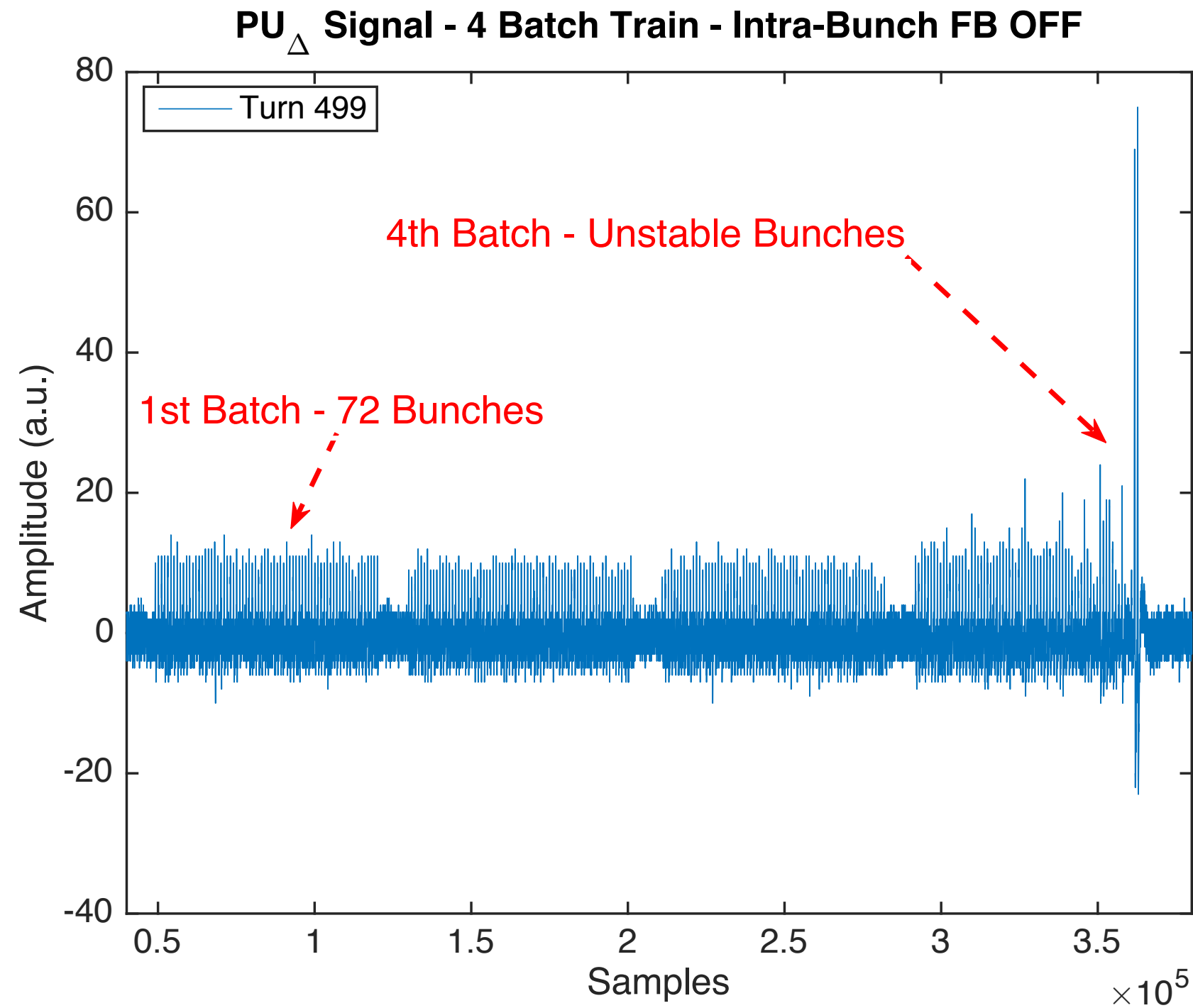


# Installed Kickers in SPS Tunnel



# Results for Multi-bunch Beams: Q20 optics

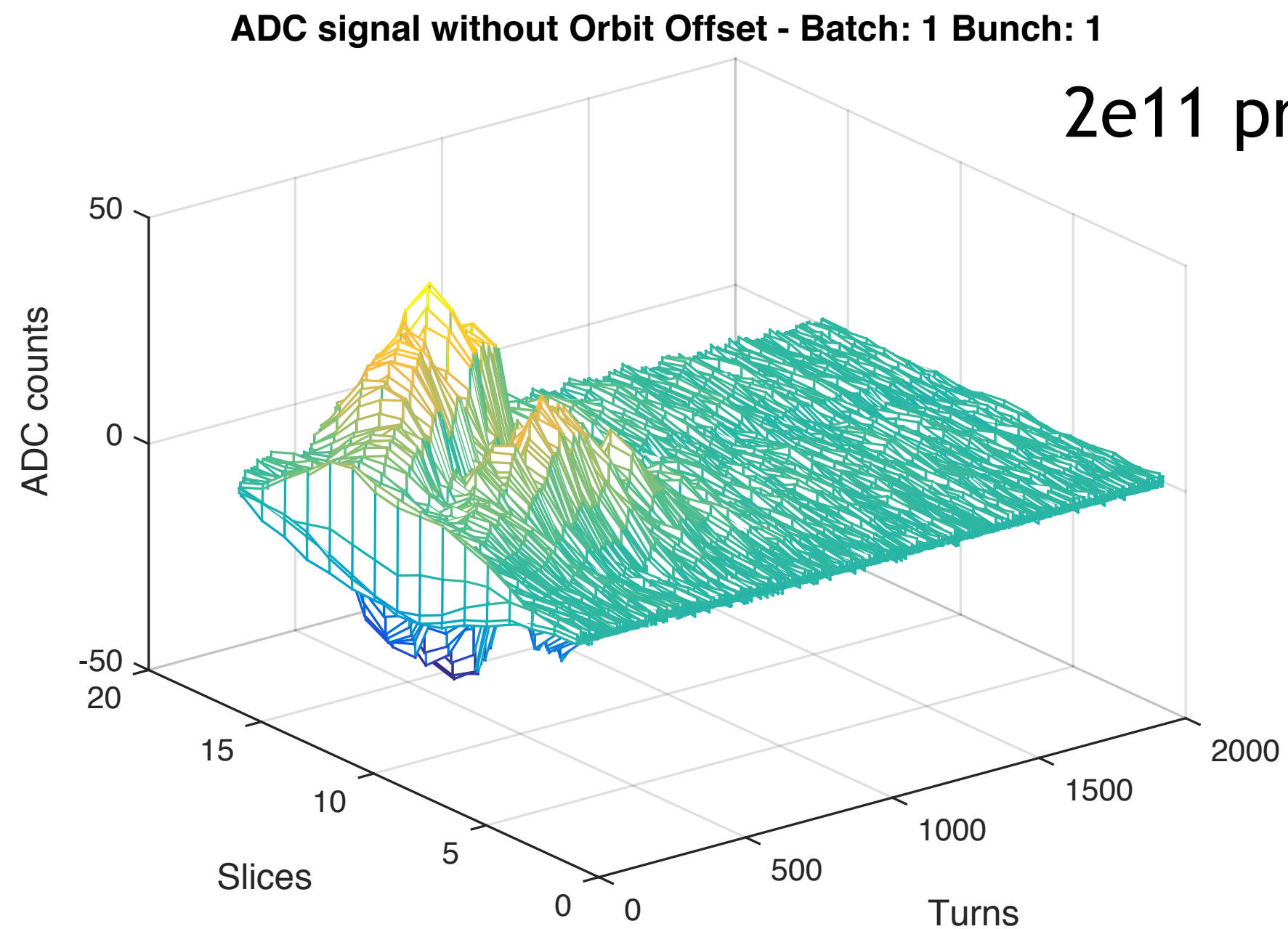
- conventional damper needed to control the coupled bunch instabilities
- single bunch instabilities not well under control by coupled bunch feedback
- appear at low chromaticity and in presence of electron cloud



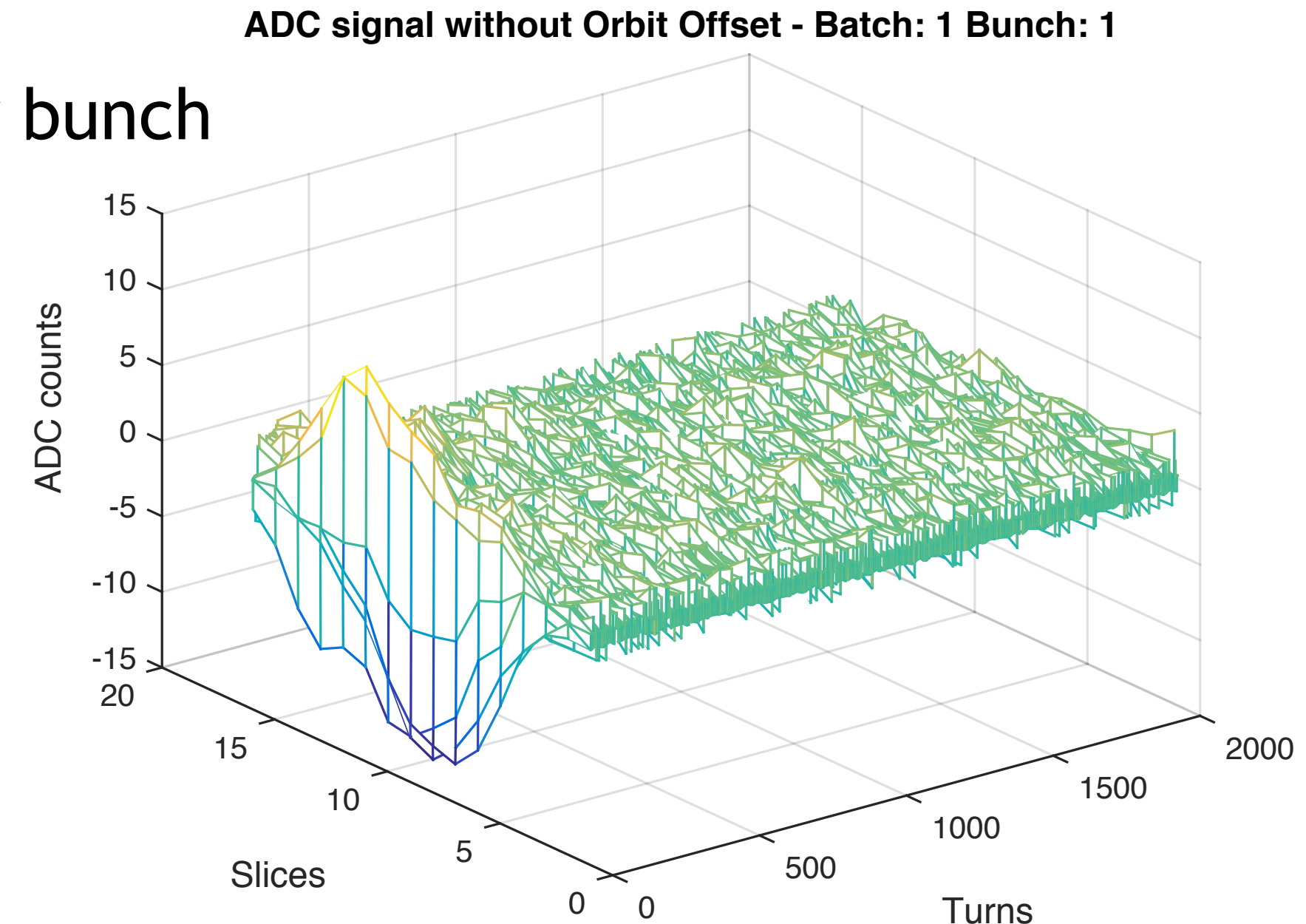
4x72 bunches

# Single Bunch results in Q26 Optics

- Operating at injection with the conventional and the Wideband feedback in conjunction stabilises the beam in the “slow” TMCI regime in Q26 optics



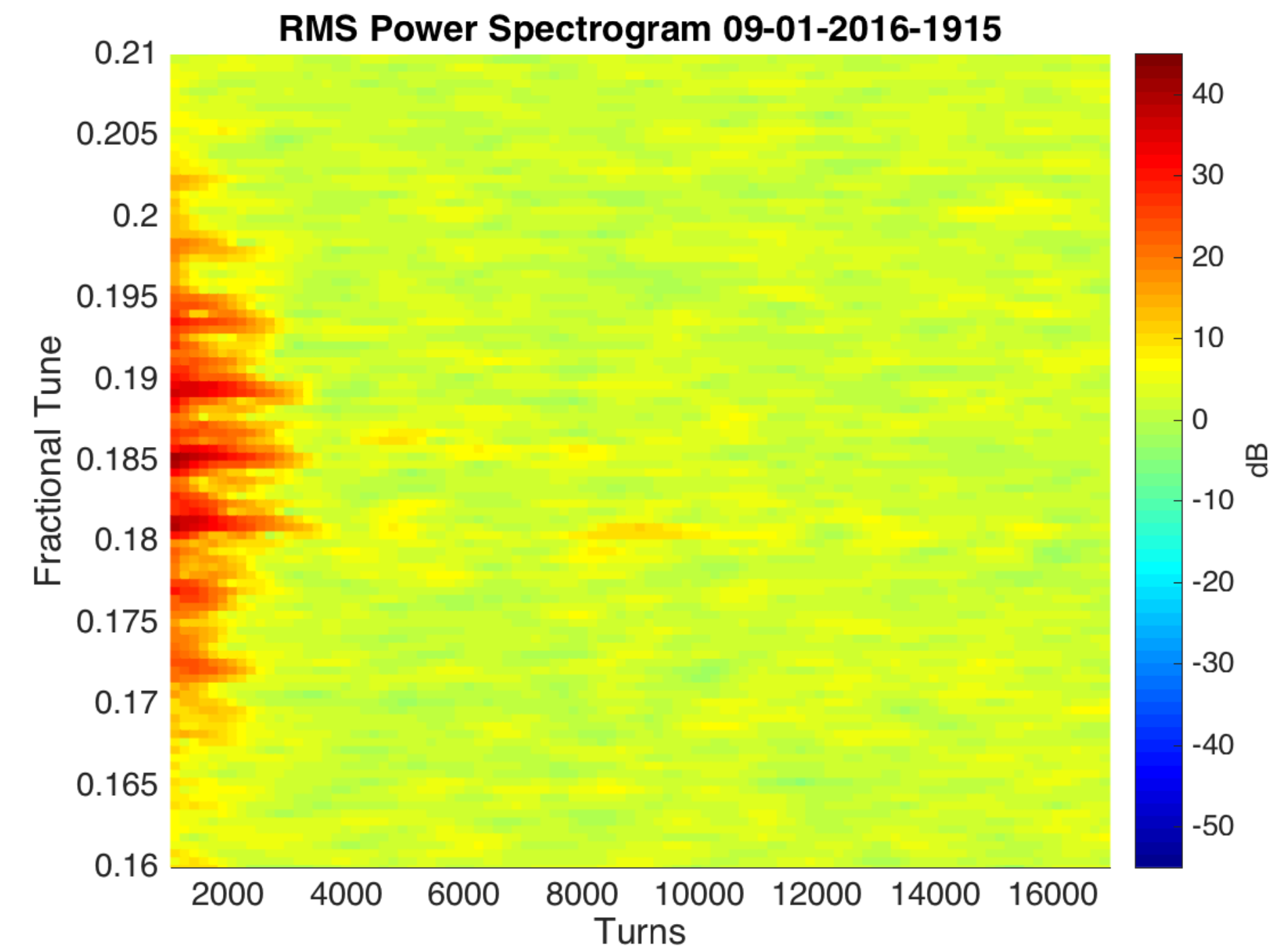
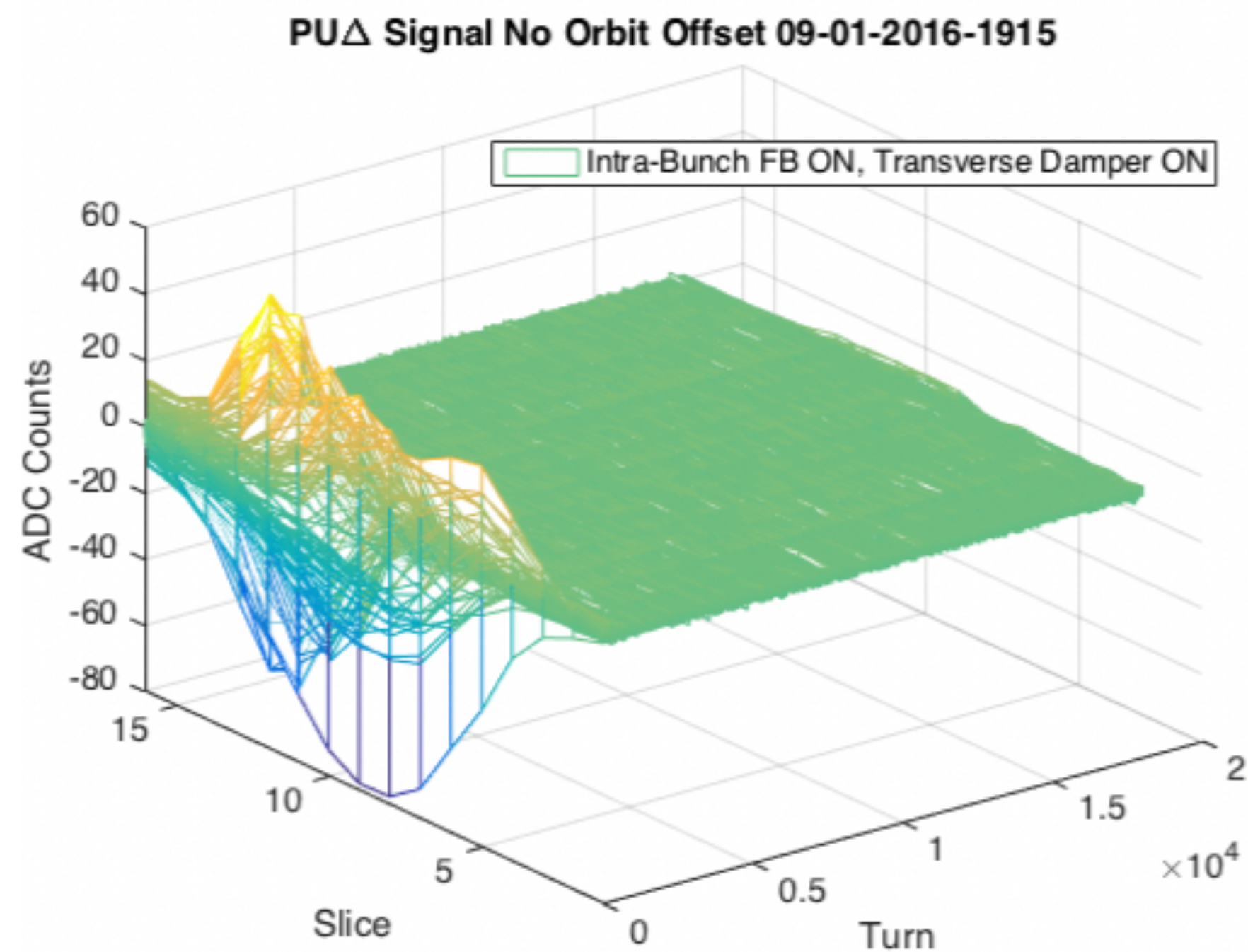
Wideband feedback off  
 —> intra-bunch oscillation, beam lost



Wideband feedback on  
 —> intra-bunch oscillation damped

# Single Bunch Results in Q26 Optics

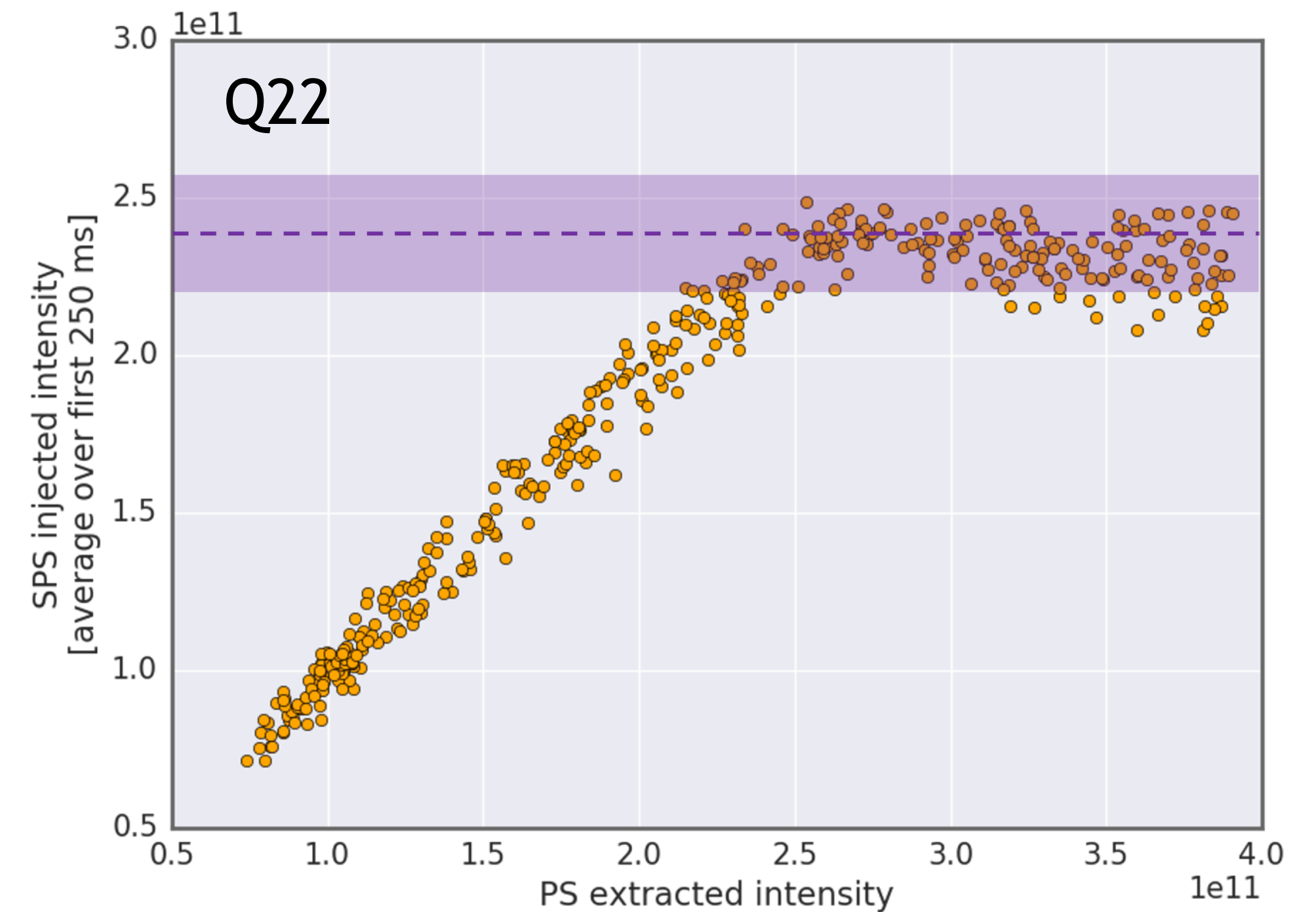
- $2e11$  protons per bunch with Wideband feedback and conventional damper on





# Reminder – SPS TMCI thresholds

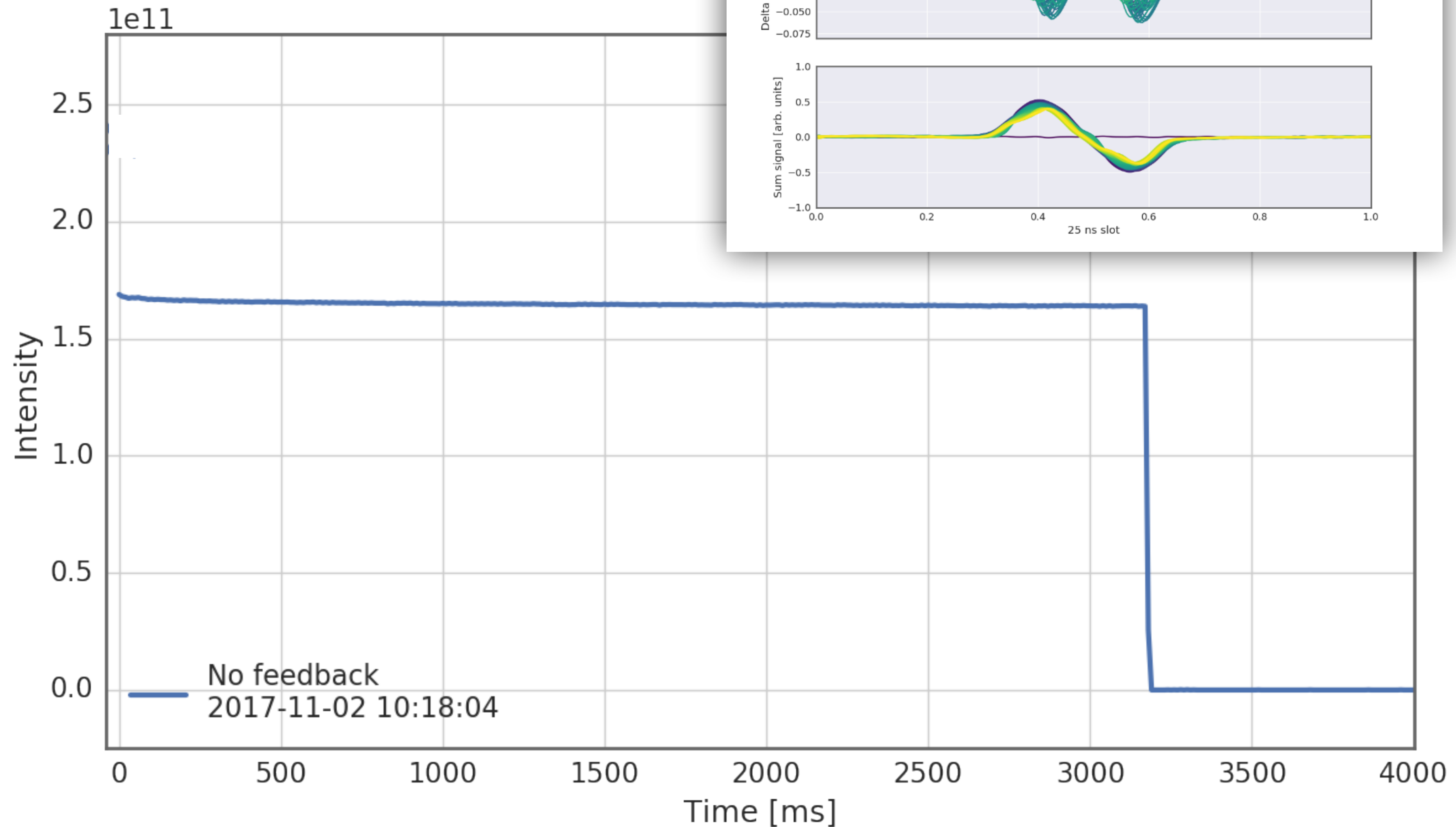
- The SPS standard optics “Q26” has been with integer tune of 26 and gamma transition of 22.8 until 2012 for LHC beams
  - TMCI threshold scales with slippage factor, injection is at gamma of 27.7
  - Threshold is at  $1.5e11$  protons per bunch
- 2013 the “Q20” optics became available operationally; gamma transition of 18
  - tripples instability threshold → future intensities needed are not limited by transverse instabilities
  - more RF voltage and power needed for Q20 than for Q26
- Exploration of a new optics with integer tune of 22 “Q22” and intermediate gamma transition of 20 has started
  - TMCI threshold at  $2.5e11$  per bunch at 0.32 eVs



see poster M. Carla et al.  
TUPAF022

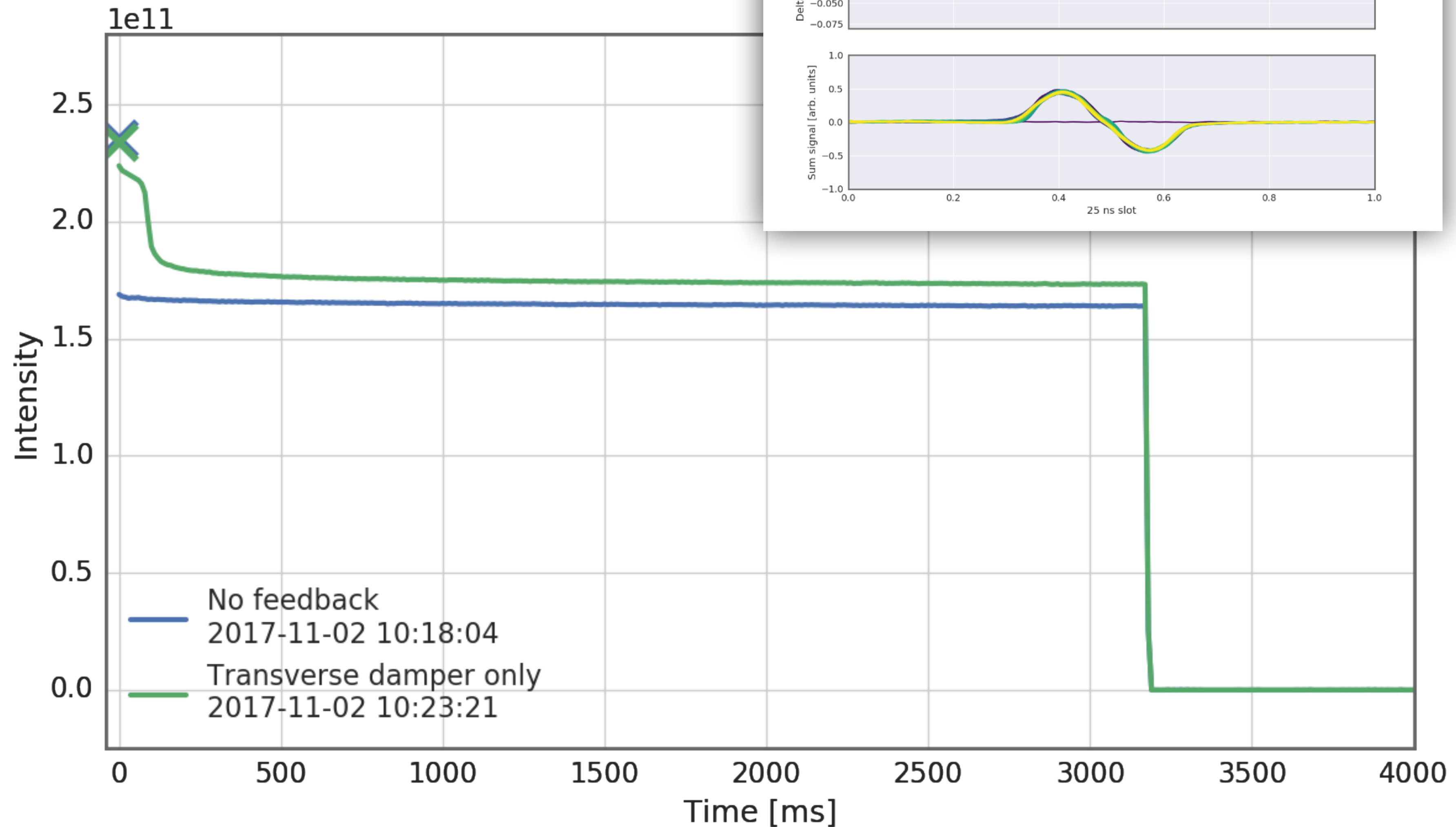
# Q22: Intensity scan 2018

- Due to limitations imposed by the ions cycle the injected intensity had to be reduced → the RF voltage was reduced adequately to obtain TMCI at a lower intensity.
- First test... looking at the BCT, **a constant signal** is observed all along the cycle.
- To be noted that we are **injecting high intensity beams** ( $\sim 2.5e11$  ppb) → TMCI induced losses occur before the first BCT sampling point
- A look into the HEADTAIL monitor **just after injection reveals the TMCI**.



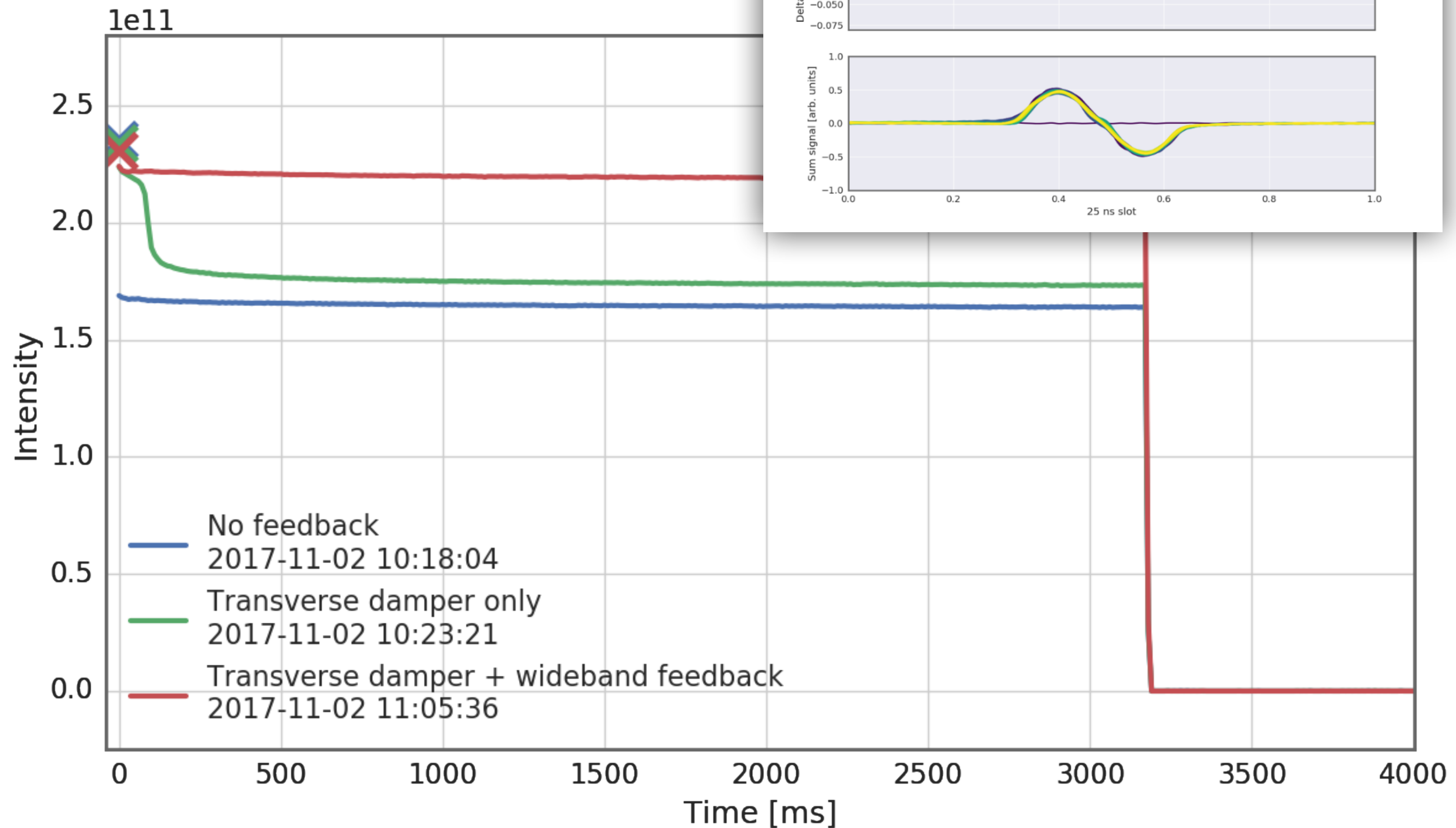
# Q22: Intensity Scan 2018

- The **standard transverse damper** was set up and put into operation in an attempt to mitigate the instability.
- The fast growth was reduced but **could not be stopped**. The losses are ultimately comparable to running without the transverse damper.
- This is expected **due to the bandwidth limitations** of the transverse damper... the high frequency content of the instability remains unaffected.



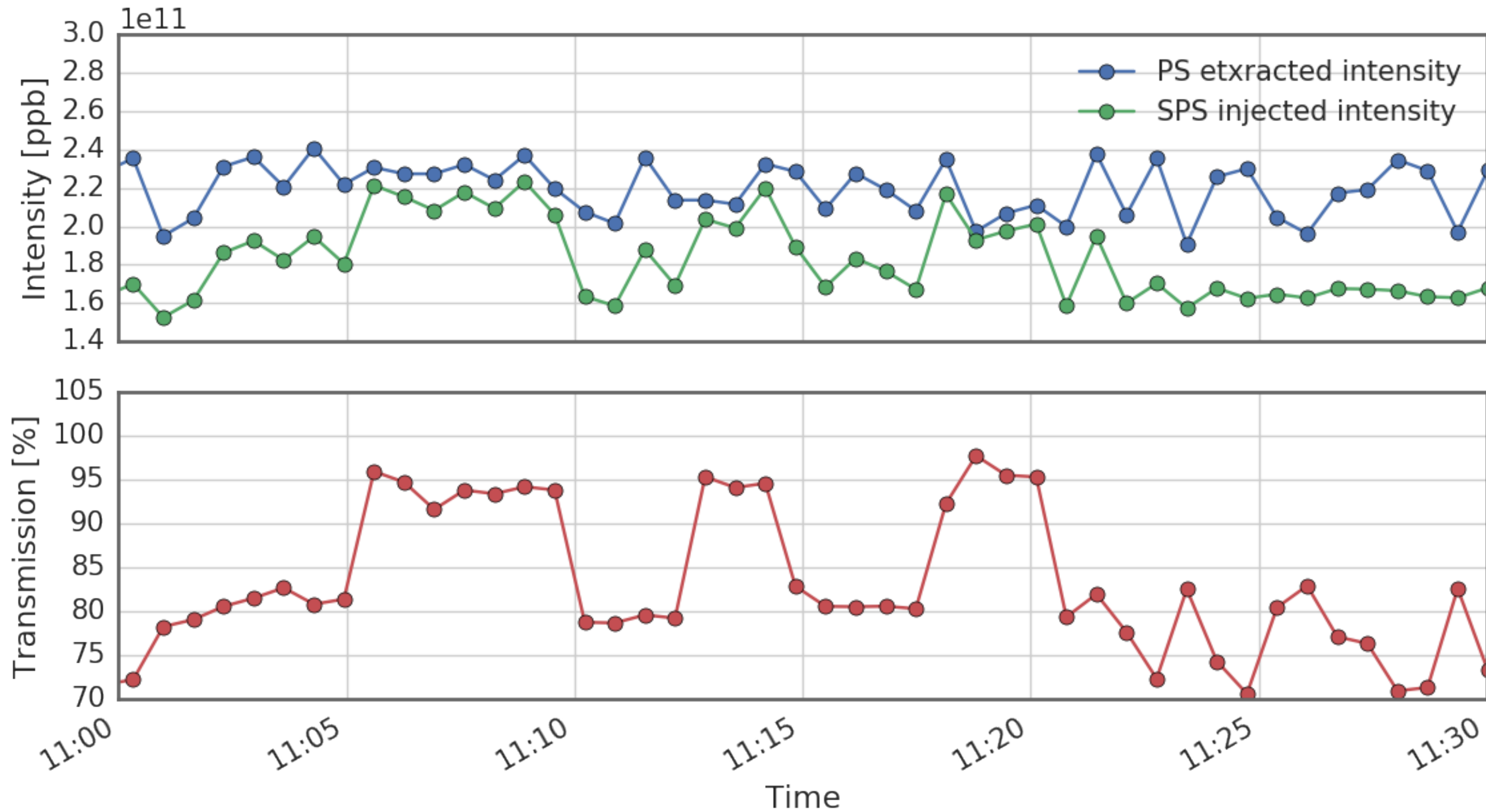
# Intensity Scan 2018

- Finally, the **wideband feedback system** was time aligned, configured and activated by closing the loop over the observed instability.
- The **transverse damper was kept active** to control the large amplitude low frequency motion to prevent saturation of the ADCs which would otherwise render the wideband feedback system ineffective.
- With the **two systems active**, the **losses are significantly reduced** and comparable to what is observed in absence of TMCI.



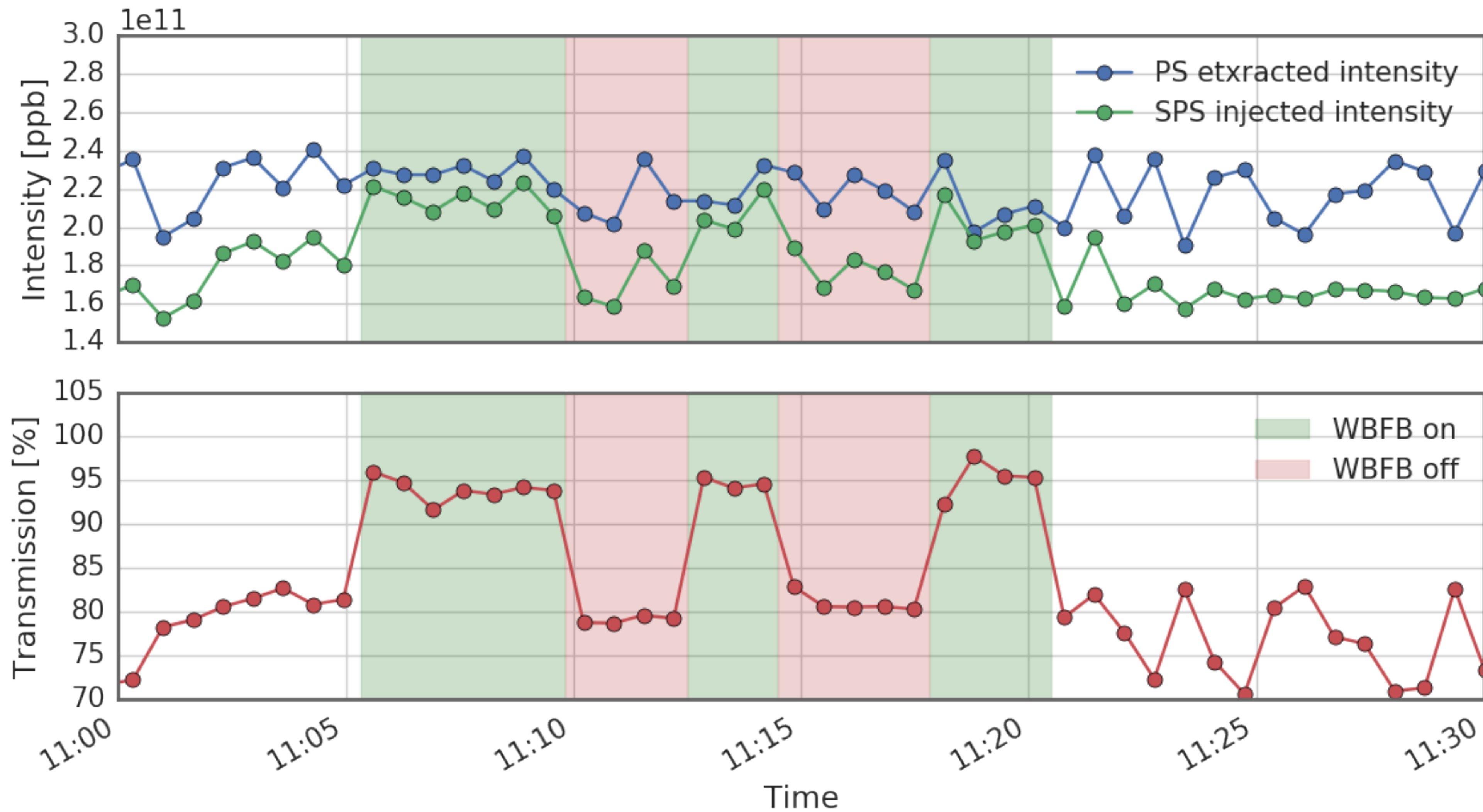
# Q22: Intensity scan 2018

- The wideband feedback loop **was closed and opened several times** over a period of half an hour **to ensure reproducibility** of both the TMCI and the stabilization of the latter.



# Q22: Intensity Scan

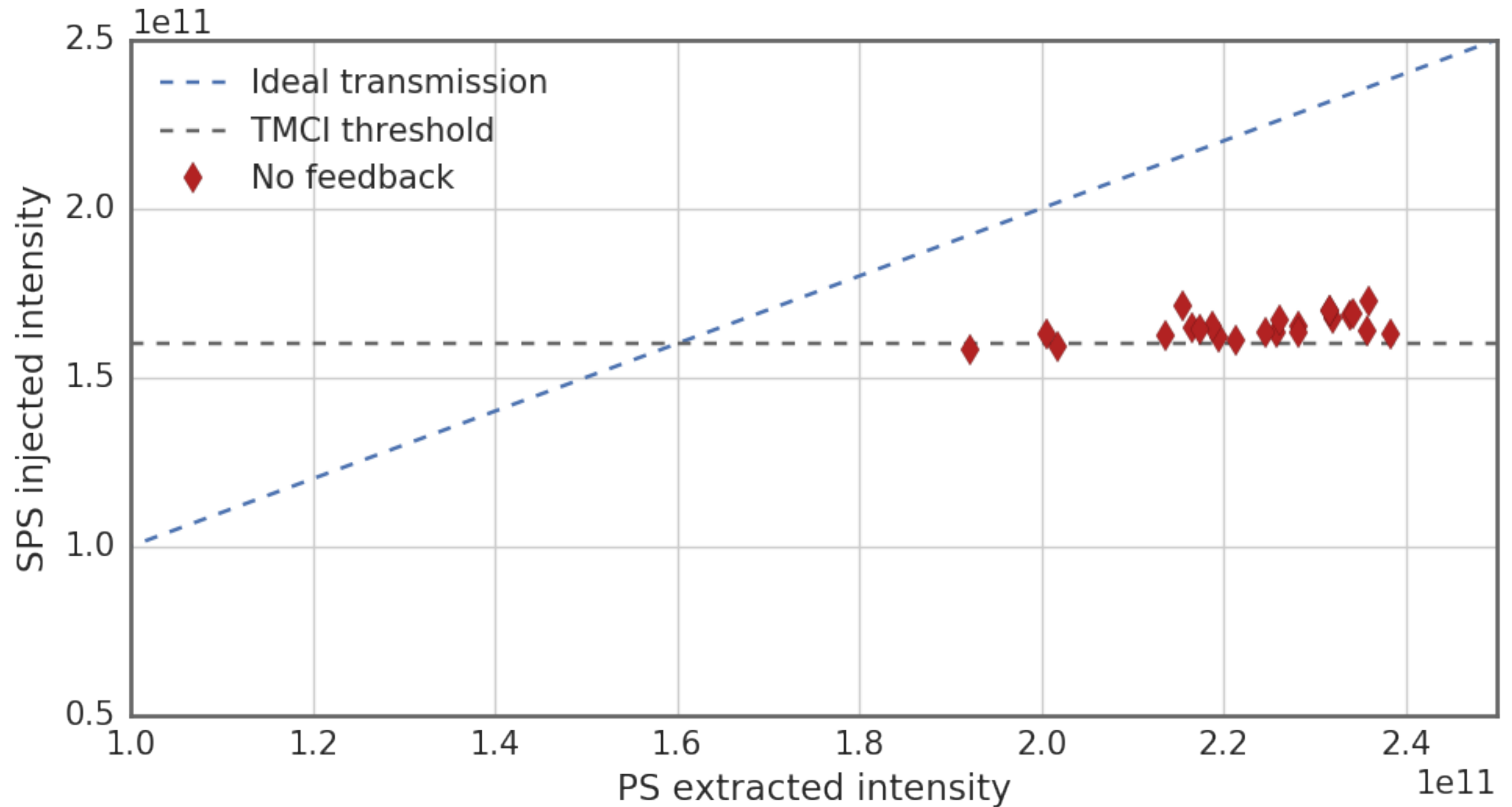
- The wideband feedback loop **was closed and opened several times** over a period of half an hour **to ensure reproducibility** of both the TMCI and the stabilization of the latter.
- There is a **clear correlation** between transmission and open/closed loop configuration.



# Intensity scan

- One can now make a comparison of the intensity reach (average over first 250 ms) in the different configurations:

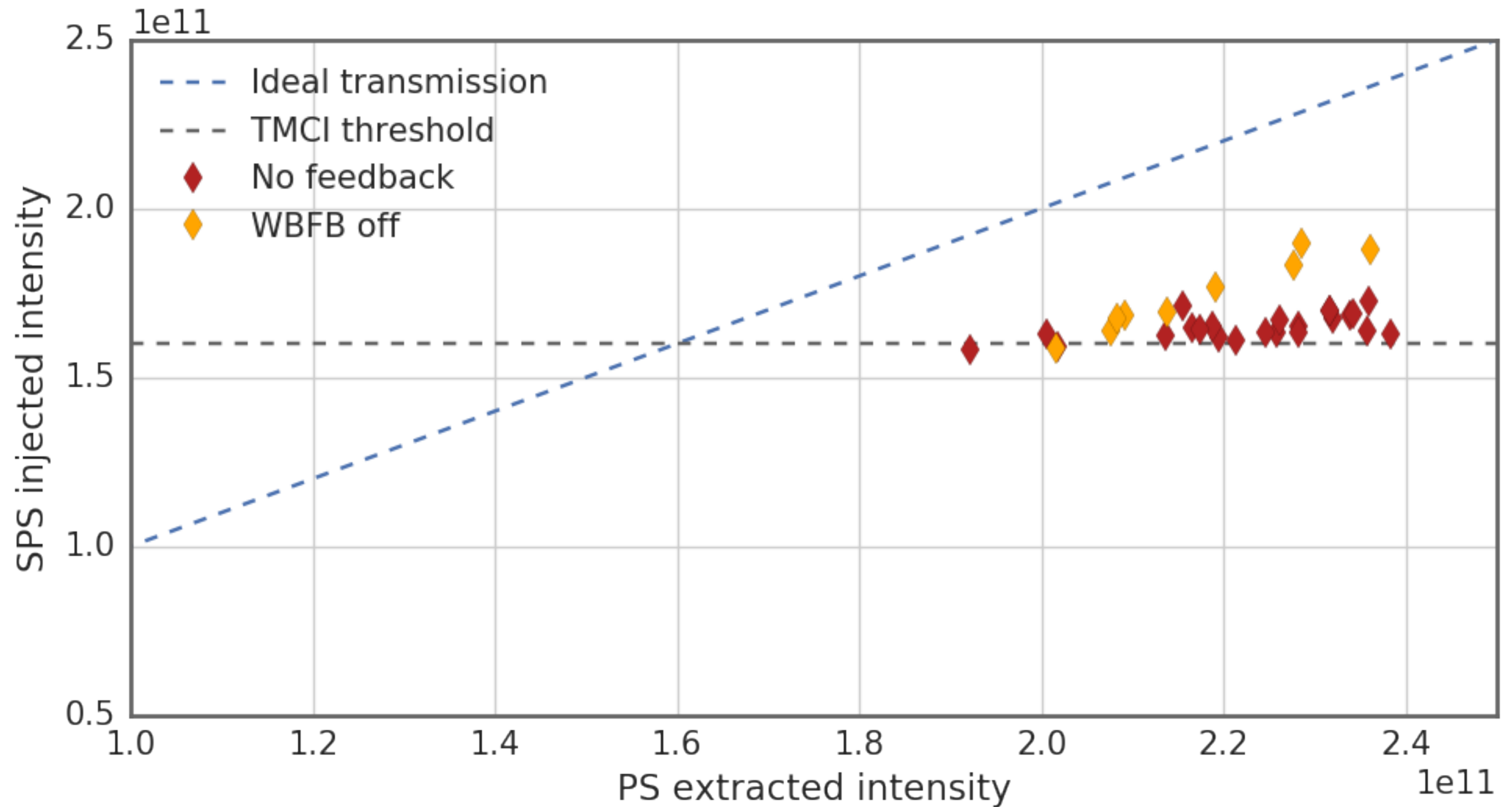
- **No feedback**



# Intensity scan

- One can now make a comparison of the intensity reach (average over first 250 ms) in the different configurations:

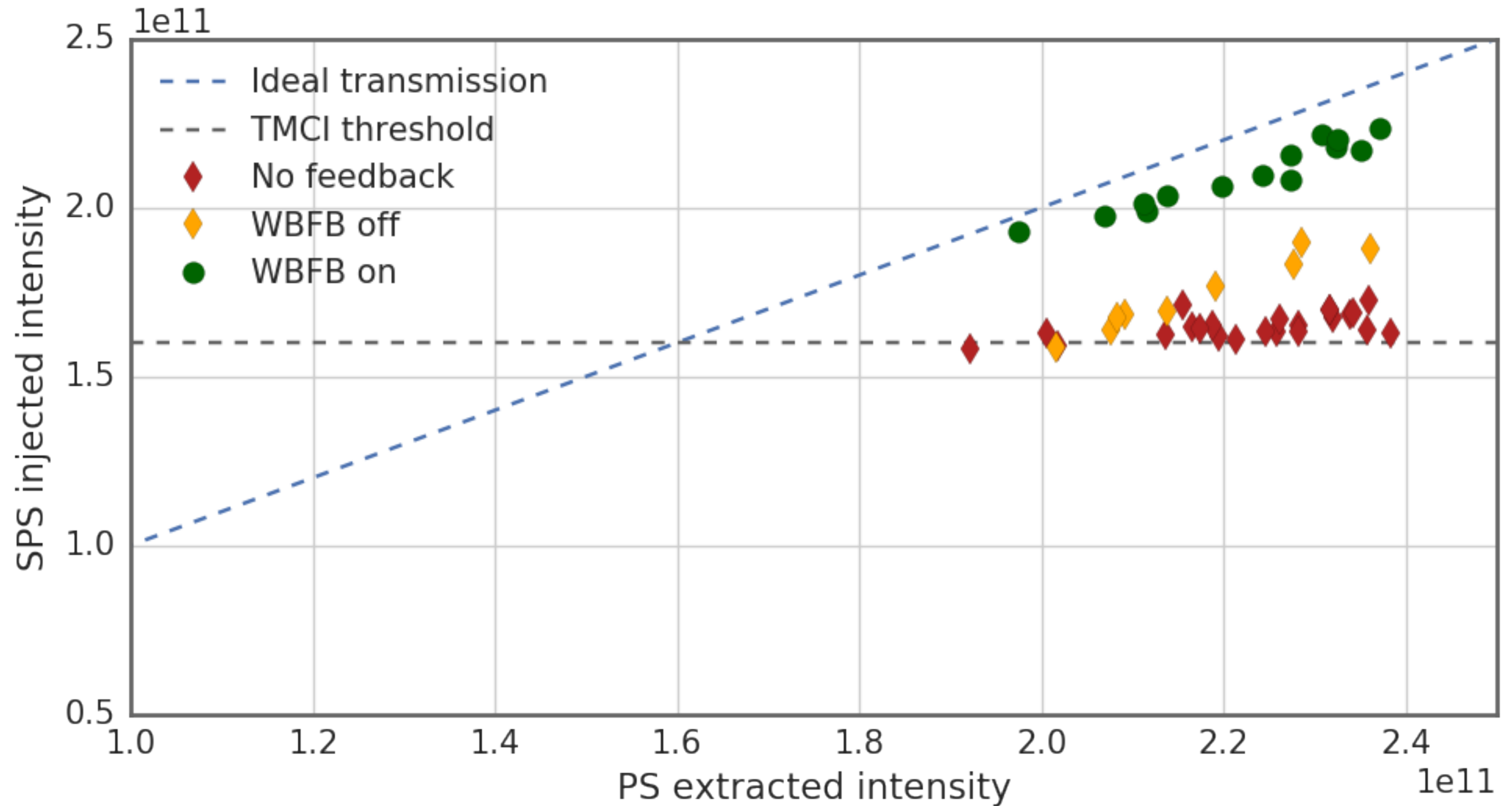
- **No feedback**
- **Transverse damper**



# Intensity scan

- One can now make a comparison of the intensity reach (average over first 250 ms) in the different configurations:

- **No feedback**
- **Transverse damper**
- **Transverse damper + wideband feedback**





# Conclusions and outlook

- Prototype Wideband Transverse Feedback System in SPS for vertical plane deployed
  - Demonstrator as a proof of principle for LHC type beams at injection 26 GeV/c
  - Signal processing operating at 3.2 GS/s, treating up to 64 bunches
- Recent achievements include
  - damping multi-bunch **centroid** (beam instability at low chromaticities)
  - damping of single intra-bunch oscillations in **TMCI regime**
  - demonstrated increase of intensity reach in the SPS Q22 optics
- Next steps
  - Extension of kick strength and frequency reach by commissioning slotline kicker in 2018
  - Machine studies using the nominal beam parameters of the LIU beams



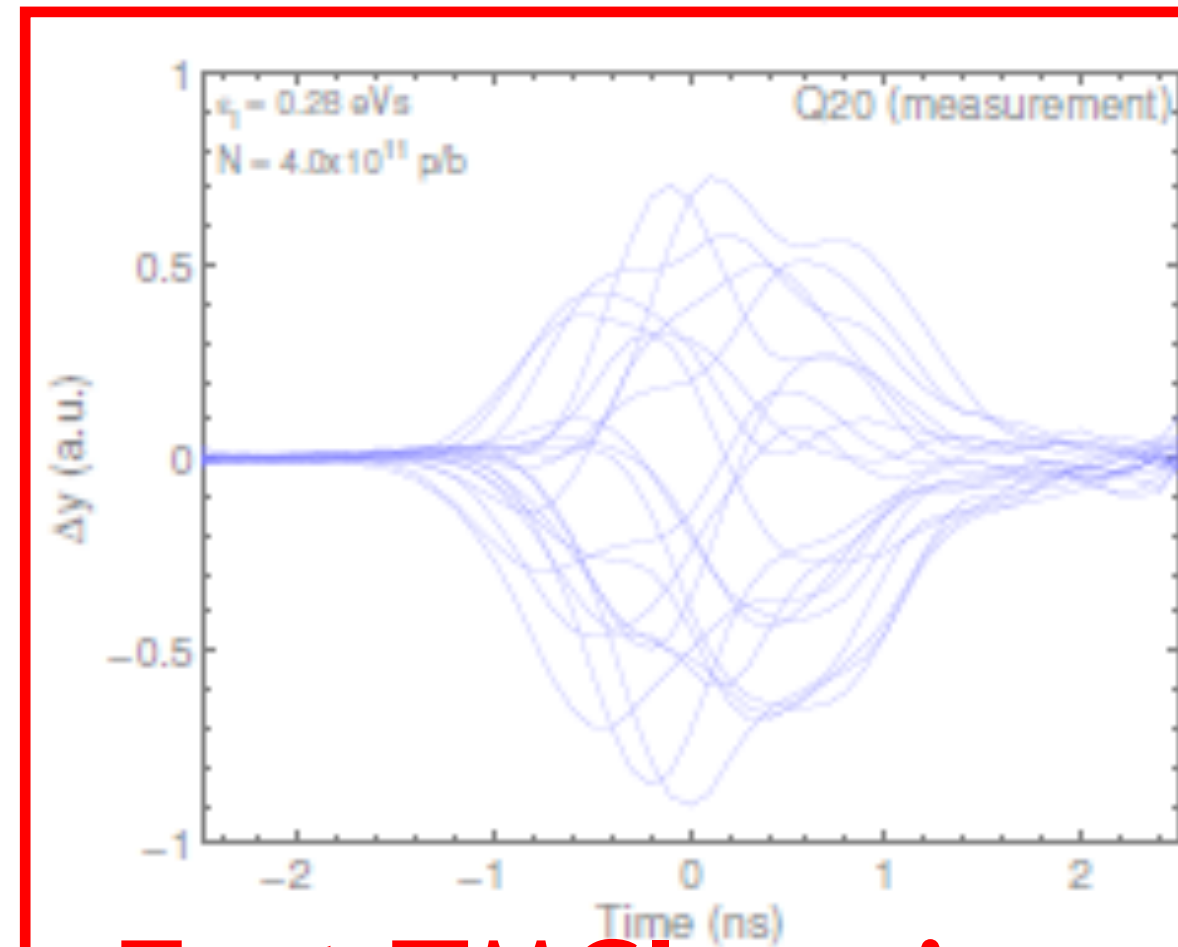
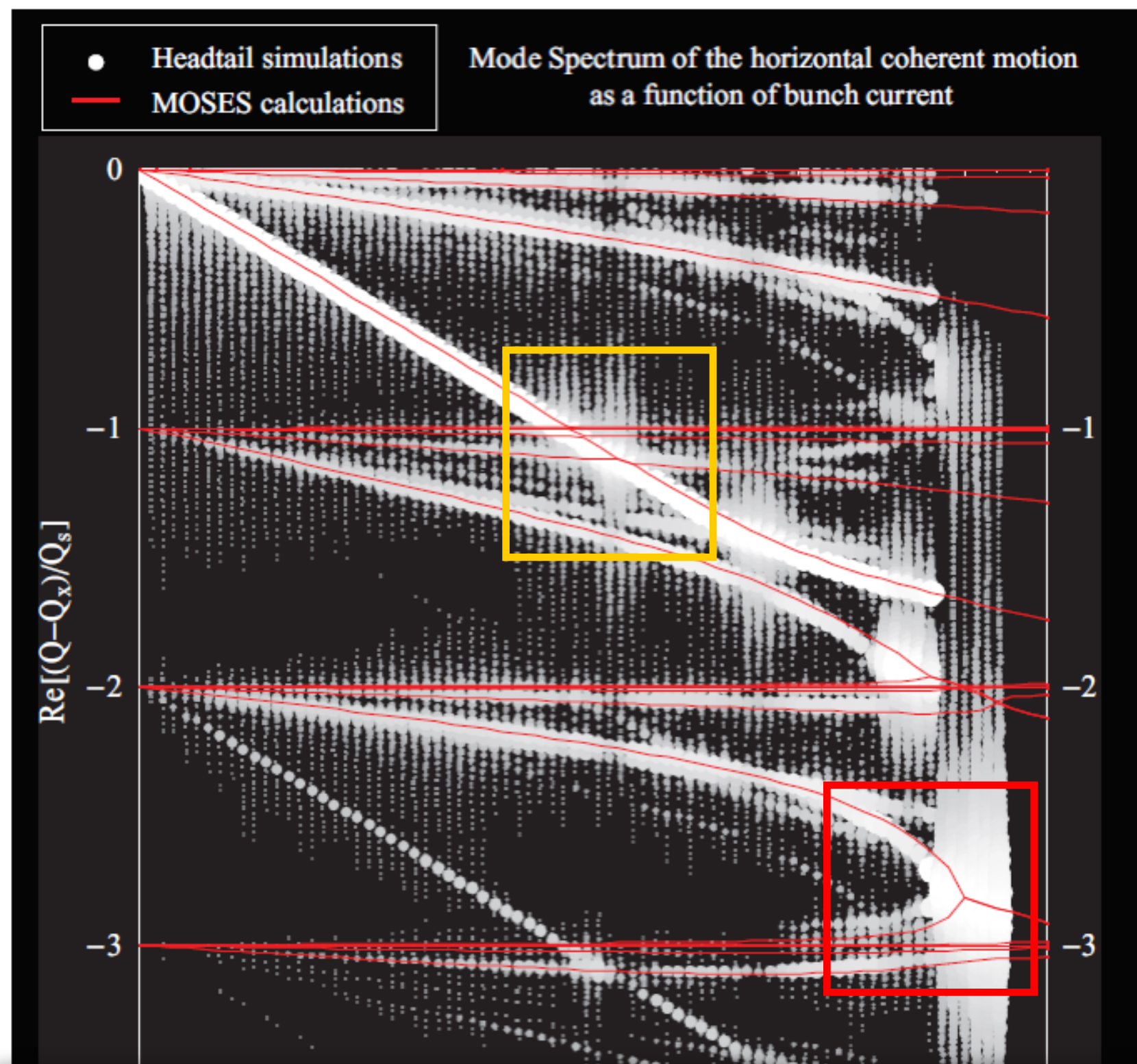
# LHC Injectors Upgrade



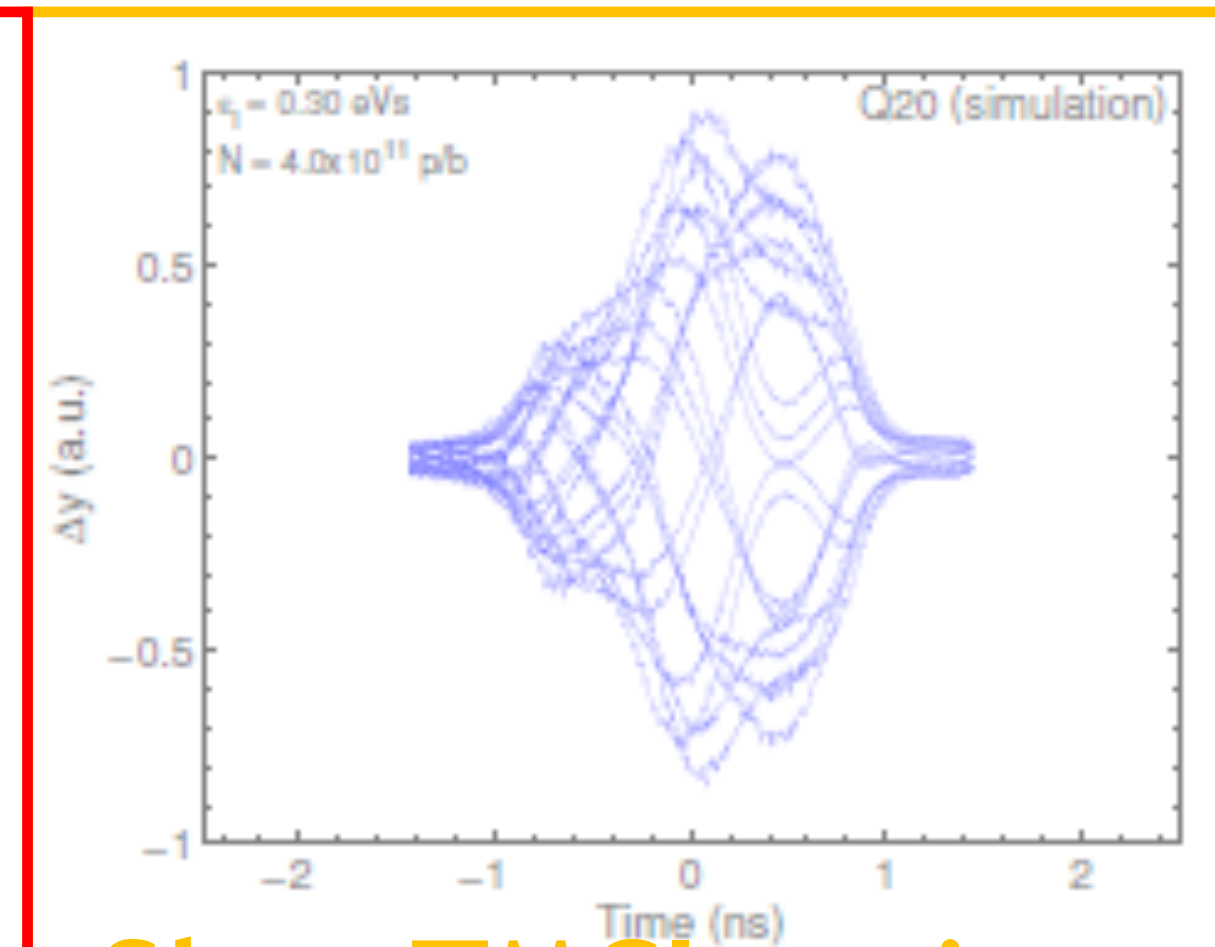
# The Transverse mode coupling instability

- SPS TMCI has a long history of studies...
- It can be reasonably well reproduced using a broadband resonator impedance model at around 1.3GHz

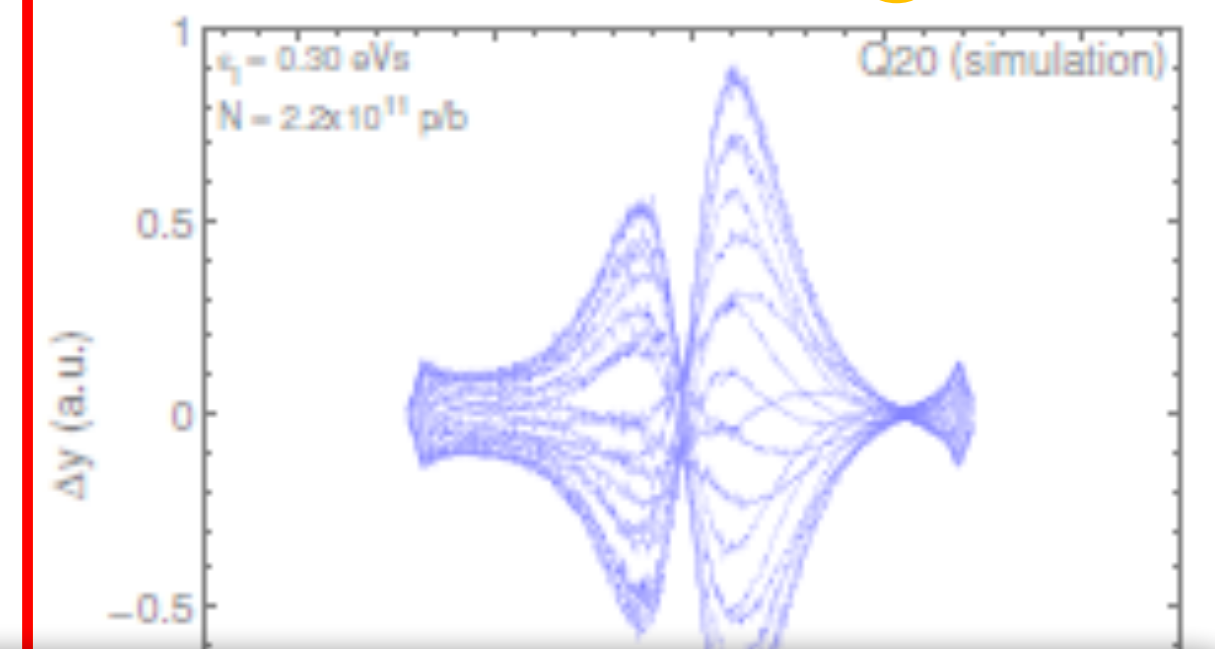
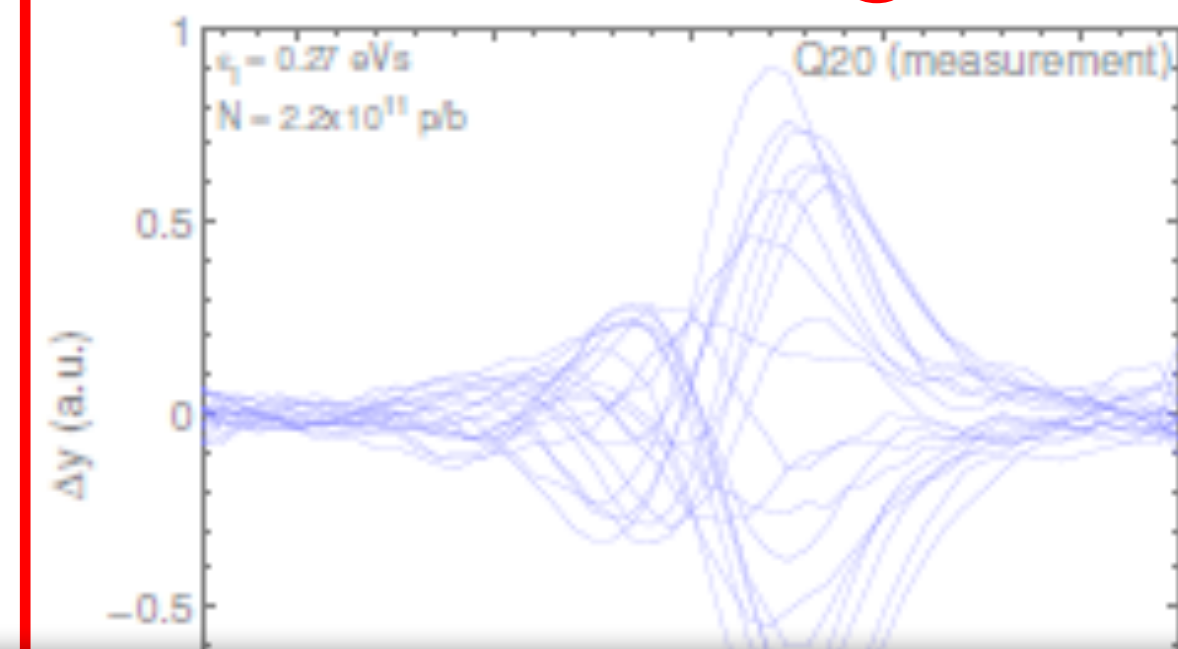
H. Bartosik



**Fast TMCI regime**



**Slow TMCI regime**



The Q20 TMCI threshold is out of the reach of the LIU parameters - the Q22 TMCI threshold, however, **dangerously approaches this.**