LHC Injectors Upgrade

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Transverse Feedback Systems along the Injectors Chain and Outlook for Post-LS2 Performance

W. Hofle

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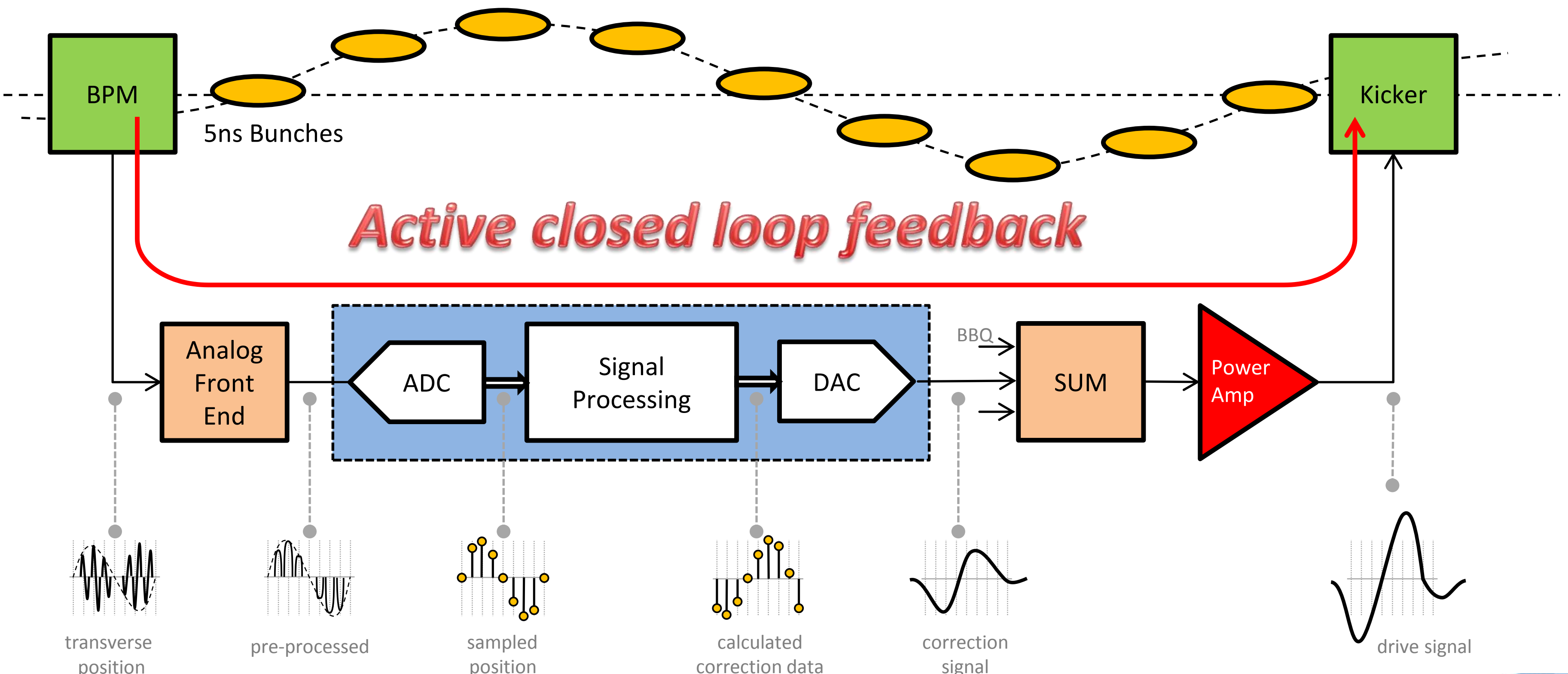
Transverse Feedback (TFB, "Damper")

- Purpose of these feedbacks:
  - Injection oscillation damping (preservation of emittance)
  - Transverse instability damping → simply cannot operate without feedback (PSB H-plane, PS without coupling, SPS, LEIR)
  - Manipulations on bunches (excitation, blow-up and blow-out)



Digital or analog signal processing system, one or more pick-ups and kickers
Coupled bunch or intra-bunch

Current – and LIU upgrade – scope of TFBs

	PSB	PS	LEIR	SPS
Injection Oscillation Damping	multi-turn, p^+ → H- injection 50 MeV → 160 MeV	yes, bunch to bucket transfer 1.4 GeV → 2 GeV (possible larger injection oscillations)		yes, bunch to bucket transfer, injection kicker ripple key in LIU to decrease batch spacing (in particular for ions)
Instability Damping	Horizontal instability → Feedback essential for operation	mitigated also by coupling and chromaticity → LIU relies on mitigation by feedback instead; eCloud CB instability at 26 GeV, flat-top	Instability damping during beam capture after cooling and in ramp optimization	Horizontal and vertical coupled bunch instability (resistive wall impedance and ecloud) → FB essential ecloud intra-bunch instability, scrubbing
Beam manipulations, measurements	Exciter for optics measurements	Blow-up to shape emittance; Bunch knock-out for 80 b scheme		blow-up to shape emittance, cleaning beam gaps, crystal collimation studies

Changes with LIU upgrades highlighted + Exciter for tune measurement (all machines)

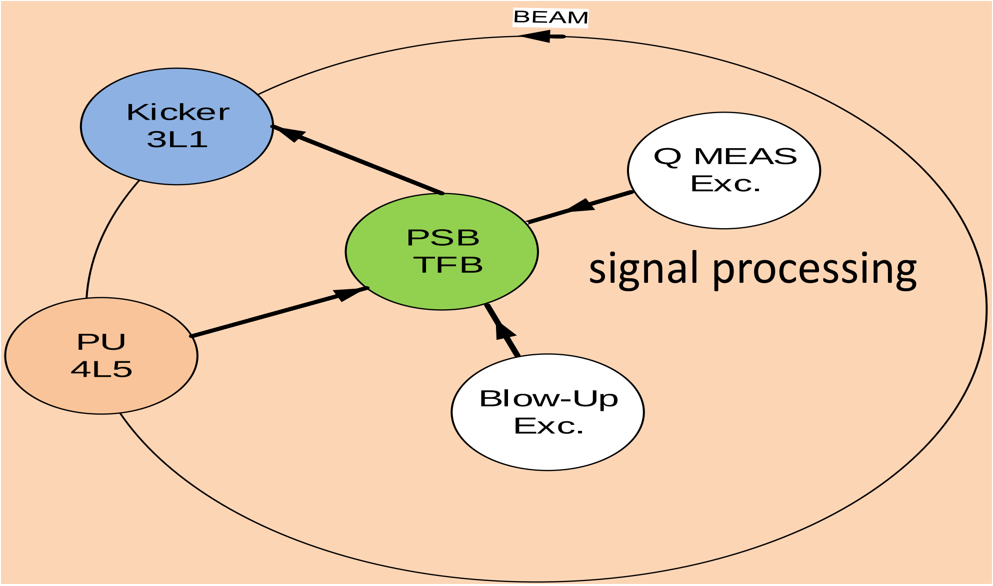
Scope of technology and LIU upgrades

Machine	Frequency	Technology and LIU upgrade path	Scope of LIU upgrade	Status of LIU upgrade
PSB 50 MeV (160 MeV) to 1.4 GeV (→ 2 GeV)	13 MHz H-plane most important	electrostatic PU solid state amplifiers strip-line kicker 100 W → 800 W	new head PU amplifier new digital electronics new power amplifiers consolidation (cooling etc.)	under design firmware→ to do under design mostly completed
PS 1.4 GeV (2 GeV) to 26 GeV/c	<< 50 kHz to 23 MHz	electrostatic PU solid state amplifiers strip-line kicker 800 W → 5 kW	new digital electronics new power amplifiers consolidation (cooling etc.)	done under design mostly completed
LEIR (Pb) (4.2 -72) Me V/u	up to 100 MHz	currently a copy of the original PSB system	needs for upgrade are under definition	part of 2015 LEIR studies
SPS 14 GeV/c to 450 GeV/c	10 kHz to 20 MHz	strip-line PU for 25 ns digital processing tetrode amplifiers	new PUs (LHC/FT beams) new digital processing consolidation (cabling + power system)	largely done except for ions, improvements and "tuning" + instrumentation !
SPS	wideband → ~ 1 GHz	vertical, strip-line and slot line kickers digital processing (US LARP / SLAC)	only prototype & proof of principle in LIU baseline (US LARP supported: leading lab: SLAC)	MD use ongoing strip-lines done slot-line under design

PSB and PS

A. Blas and team

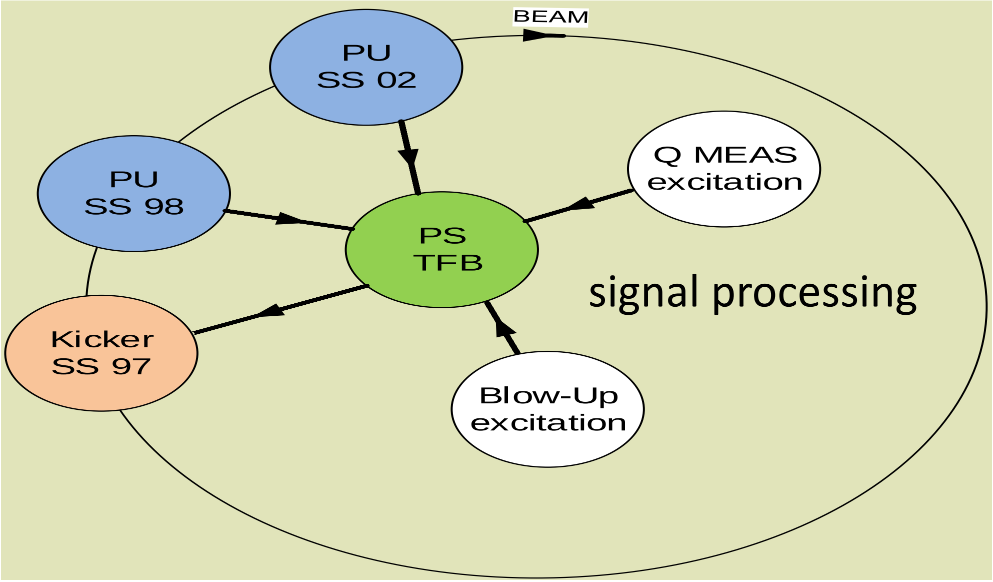
PSB and PS dampers LIU Upgrades



PSB
4 rings
two planes

Motivation for upgrades:

- Increased kick strength
- Replacement of obsolete hardware

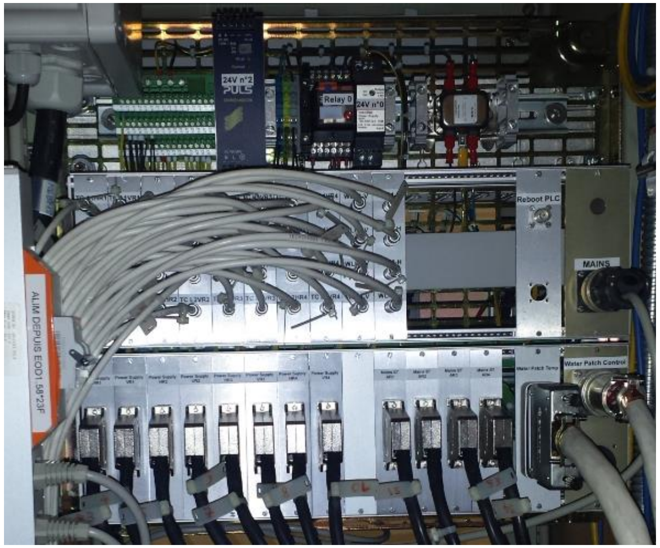


PS
two planes

Consolidation and infrastructure PSB and PS dampers, and LEIR

- Completed → improved reliability, increased availability
  - New PLC power control in all machines
  - New water distribution in all machines
  - New power supplies for solid state amplifiers in all machines
  - New Oasis monitoring systems (digitizers + software)
  - New and additional racks and cabling renovation (PSB / PS)

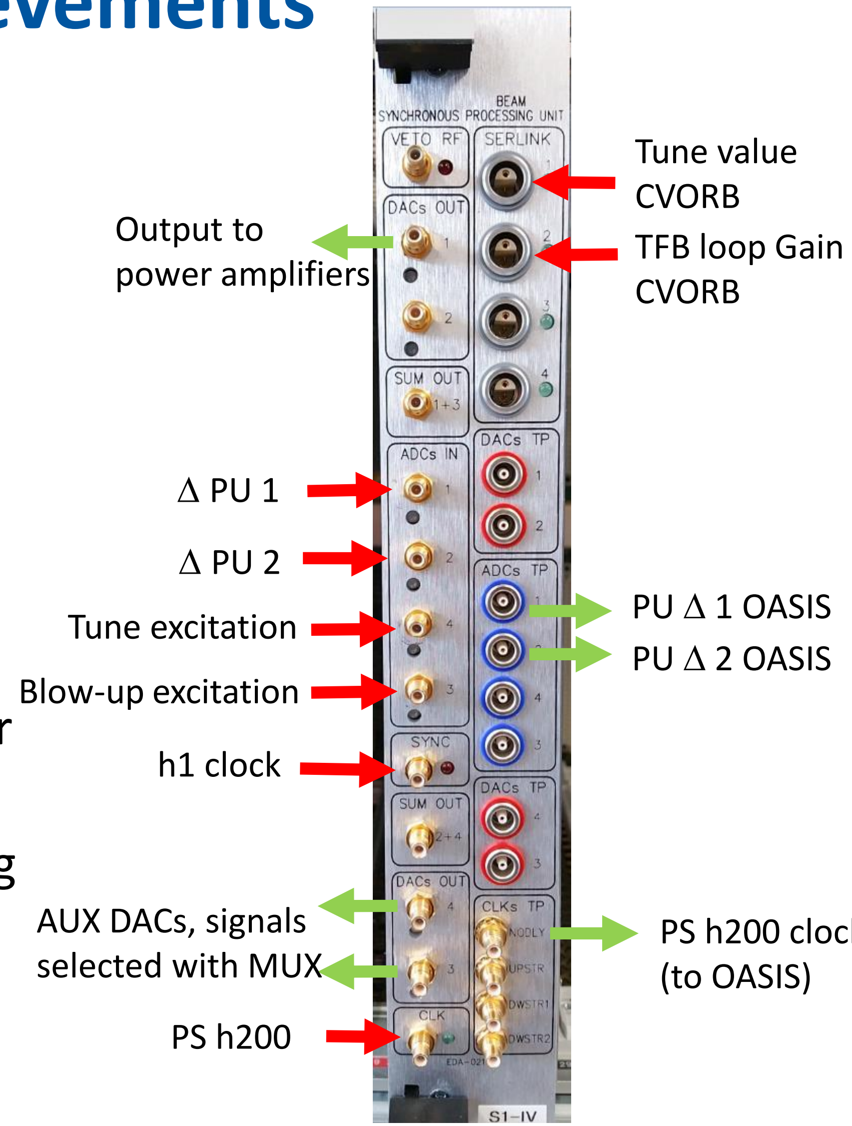
PSB Water Cooling System



PSB PLC Power System Control

PSB & PS damper signal processing
2015 Hardware - Achievements

- Development for PSB and PS dampers
  - Based on longitudinal PS 1TFB electronics
  - LHC RF VME standard
- Features
  - Fully digital processing with analog input/output
  - FPGA based with custom firmware for PSB and PS dampers
  - Automatic delay compensation during acceleration



Hardware completed in 2015

Digital Signal Processing Board

PS (PSB) Damper Signal Processing
- Firmware -

Features

- PU selection
- Loop betatron phase setting from the tune value as a function of time (1 degree precision)
- Removal of revolution line (closed orbit variation)
- Automatic delay adjustment to the particle time of flight (1 ns precision and jitter free)
- Blow-up signal generation with:
  - 9 individual excitation vectors
  - 3 possible excitation gaps programmed in revolution angles (bunch suppression for 80 bunch scheme)
  - Fractional harmonic of the excitation selected with a function generator
- Digital summation of tune measurement and external blow-up signals

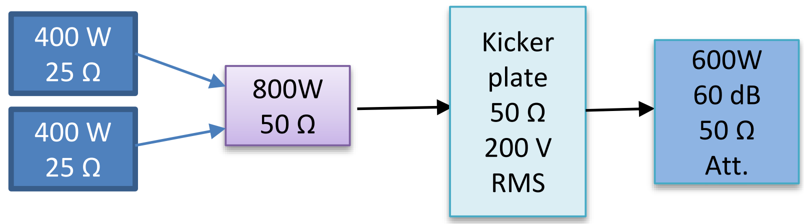
LEIR, PSB, PS Dampers “To Do’s”

- New power amplifiers for the PS and PSB
  - 136 RF power units of 400 W are required
- New power impedance matching transformers for the PS kickers
- Fesa Class for the PSB new electronics
- Working set and synoptic for the new PSB and PS damper electronics
- Upgrade of the control crates in PSB
- New head amplifiers for the pick-ups in the PSB (R2E !)

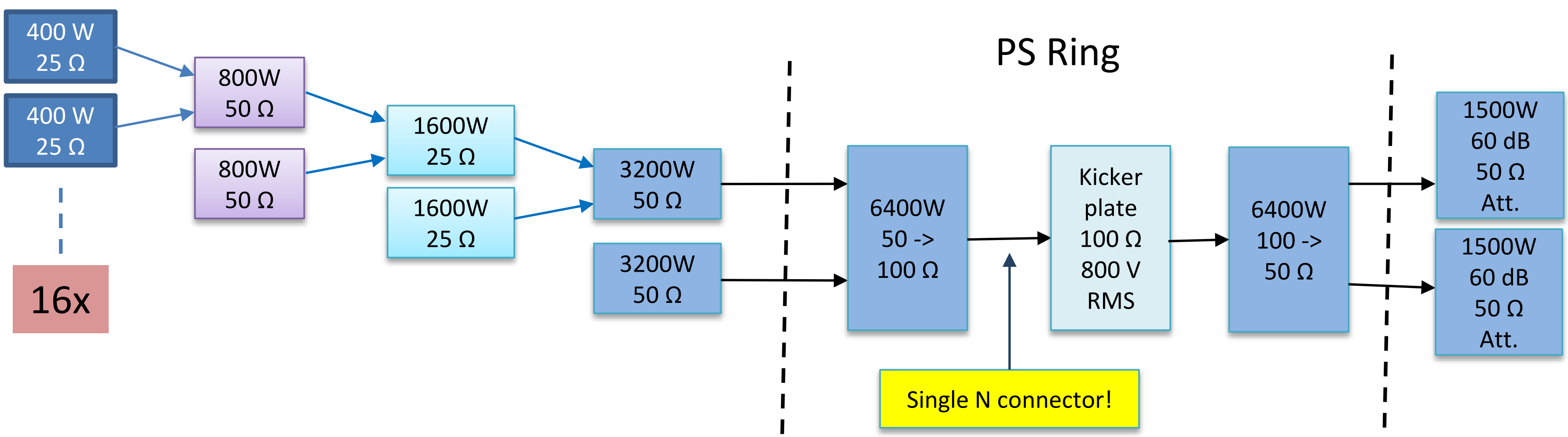
Critical Path:
Manpower available for amplifier development and production follow-up shared between several projects within the RF group

Path for PSB-PS amplifier development

PSB



PS



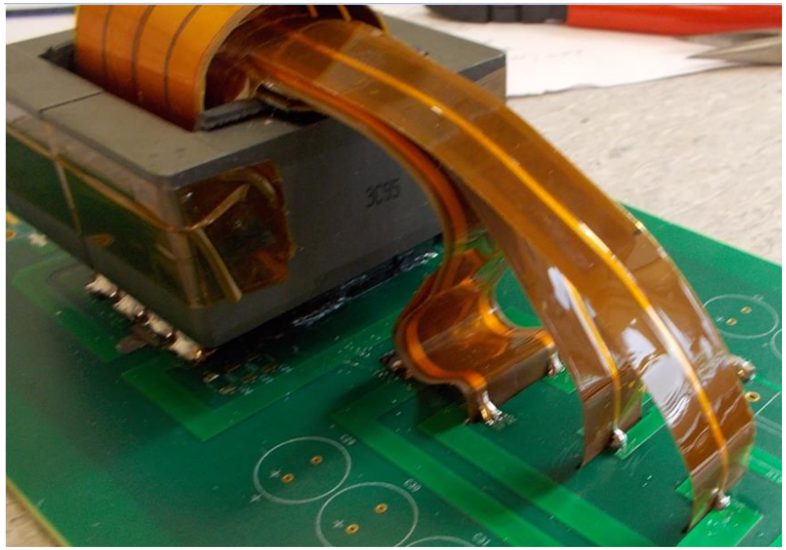
Status of amplifier development

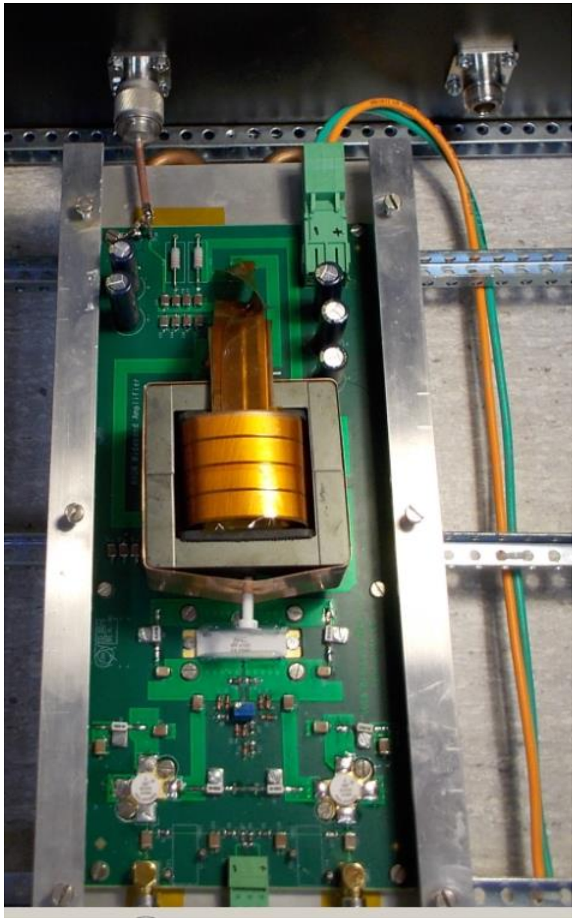
- Development of 400 W RF amplifier basic building block is advancing
  - in-house development
  - support structure for the manufacturing and assembly of the many units required and being put in-place, critical for completion
  - alternative solutions reviewed within BE-RF in December 2015, retained in-house development (performance, cost & schedule); back-up plan for PSB amplifiers identified based on another development

	PS amplifiers	PSB amplifiers
Quantity	6 x 5 kW = 96 x 400 W units + kicker matching	20 x 800 W = 40 x 400W blocks

Status of amplifier development

- Basic building block, 400 W, 25 Ohm output impedance
  - Development advancing, prototype performance ok
  - Based on LDMOS transistor BLF574
  - Innovative matching transformers
  - 3C95 ferrite core
  - Transformer ratio: 1.5625 : 6.25 : 25





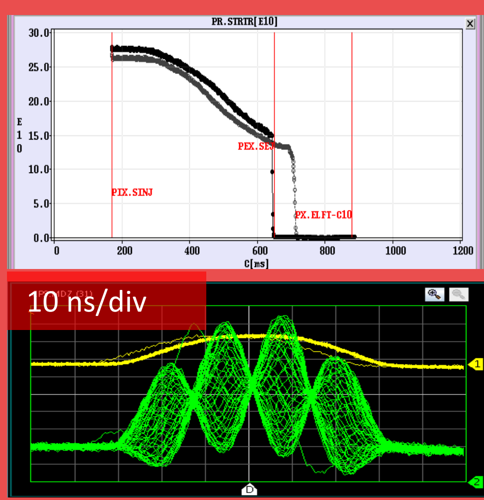
R. Louwerse

Performance of upgraded PSB Damper

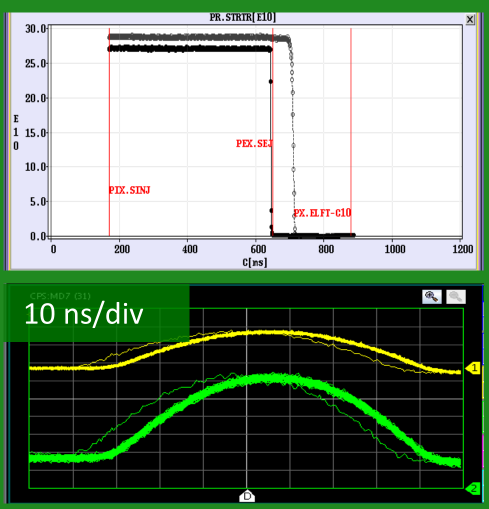
- 800 W power requirement per kicker plate requested for optics measurements
  - nota bene: scaling today's kick strength with 100 W per kicker plate from 1.4 GeV to 2 GeV requires less than 800 W
- injection of H- from LINAC4 at 2 GeV completely different than current transverse phase space painting at 1.4 GeV → learning curve after LS2 to be expected
  - main improvements for injection damping and instability damping from new digital signal processing and new head amplifiers
- Bandwidth
  - power amplifiers: aim for highest bandwidth achievable (above current 13 MHz used) compatible with 800 W requirement
  - Signal processing bandwidth: defined by clock frequency chosen (64 x f_{rev}, frequency swing during acceleration)

Towards performance of upgraded PS Damper: Achievements

- 5 kW per kicker plate expected to damp +/-3 mm error at 2 GeV in less than 30 turns → improvement to the current 800 W
- 5 kHz lower cut-off frequency for injection damping for optimal performance desired
- 23 MHz for damping injection kicker ripple
- 20 MHz for coupled bunch instability damping (half bunch repetition frequency for 25 ns bunch spacing); also intra-bunch damping



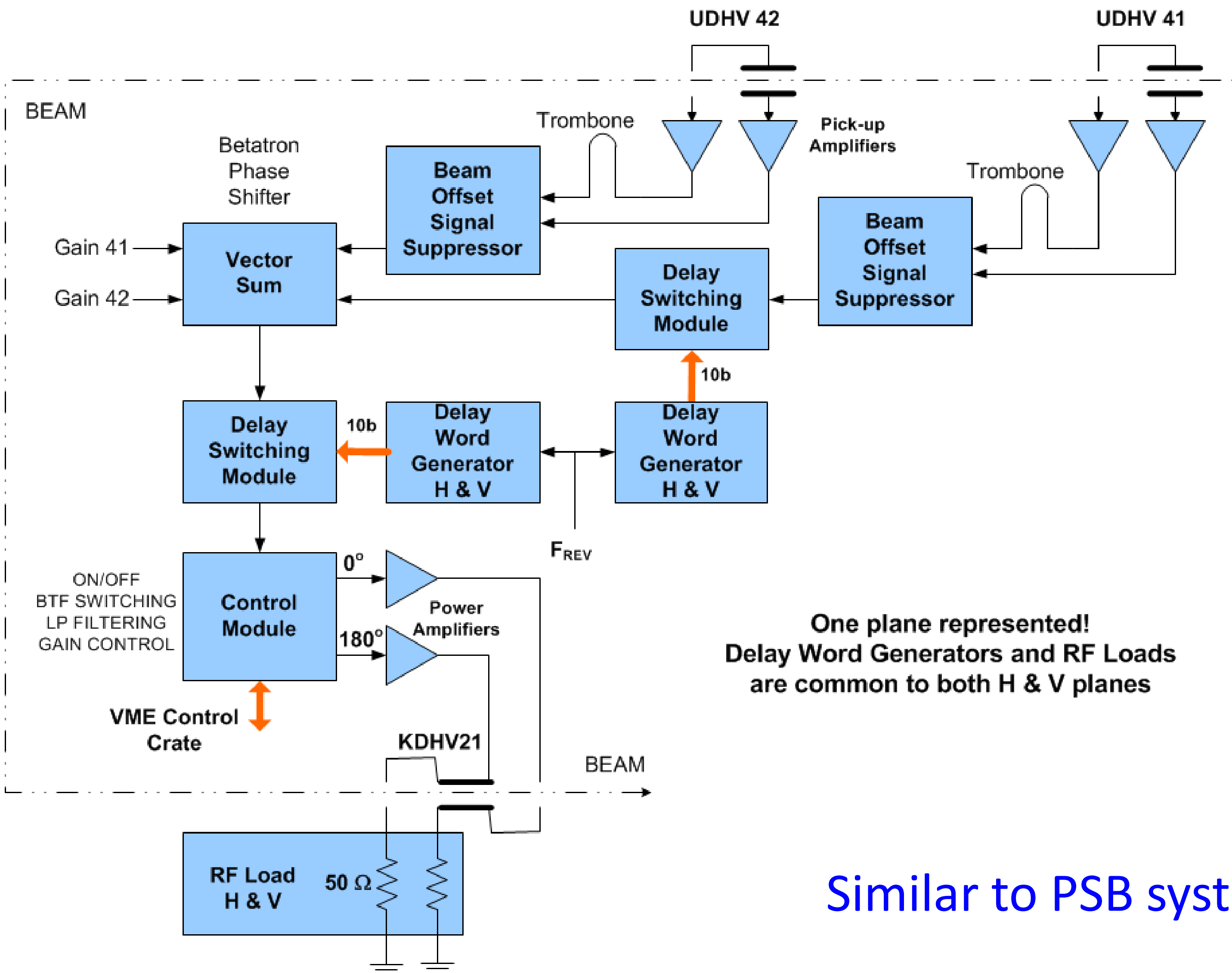
PS TFB OFF



PS TFB ON

LEIR

LEIR: Overview of current TFB system



One plane represented!
Delay Word Generators and RF Loads are common to both H & V planes

Similar to PSB system

Summary of 2015 LEIR damper study

LEIR TFB essentially a copy of the original system deployed in PSB

Generally satisfactory performance with bunched and un-bunched beam

Improvements requested

- Programmable phase and gain settings along cycle
- FFT diagnostics of loop signals
- Monitoring point between pick-up and the critical Beam-Orbit-Suppression System (BOSS) in the signal chain
- Replacement of the BOSS (Beam Orbit Suppression System) if needed
  - leverage on development for SPS wideband feedback
  - feasibility of a digital system to be studied

Based on 2015 observations, further studies to be carried out in 2016:

- on reduced stability margin at extraction (possible source: delay error)
- monitoring signals before BOSS unit (to track down spurious signals observed)

SPS

Coupled bunch feedback → 20 MHz

G. Kotzian, W. Hofle,
D. Valuch and team

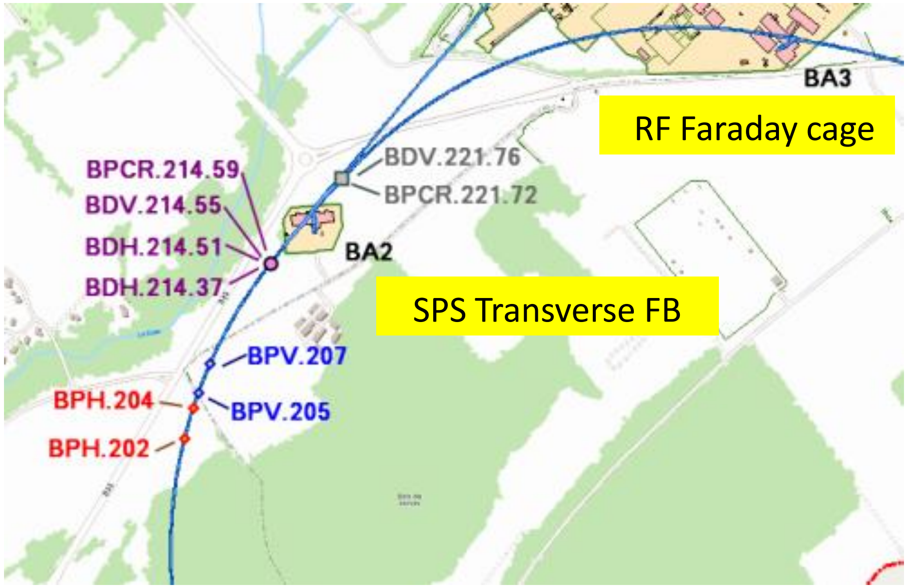
Motivation for SPS damper LIU upgrade

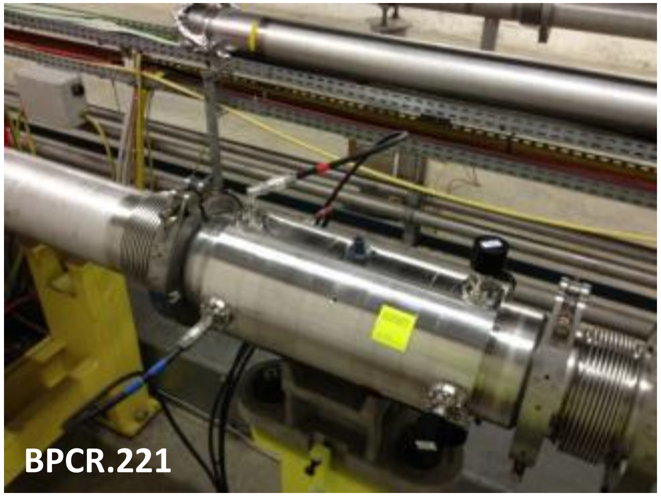
- Incompatibility of sharing pick-ups with beam instrumentation orbit system after LS2 BI upgrades
- Obsolete hardware with limited observation capabilities for instabilities → bring system up to LHC ADT standards
- Obsolete controls (G64) hardware and MIL 1553 phasing out in LS1
- Incompatibility of hardware with requirement to damp scrubbing doublet beam → defined urgency of upgrade in 2014
- Requirement to damp single bunches in view of crab cavity tests with good efficiency and a low noise system
- Requirement to provide damping for ions and improved damping for protons for injection damping at short batch spacings
- Possibility to adapt frequency response to needs by using a digital system

Priority established: FT & LHC p beams, then ions;
progress limited by available man power
(same team also working on LHC ADT)

SPS damper hardware in tunnel (point 2)

- 2 BPCR (H/V) for LHC type beams (couplers maximum ZT @ 200 MHz)
- 2 BPH electrostatic PU (pFT)
- 2 BPV electrostatic PU (pFT)
- 2 kickers for each plane (BDH, BDV)

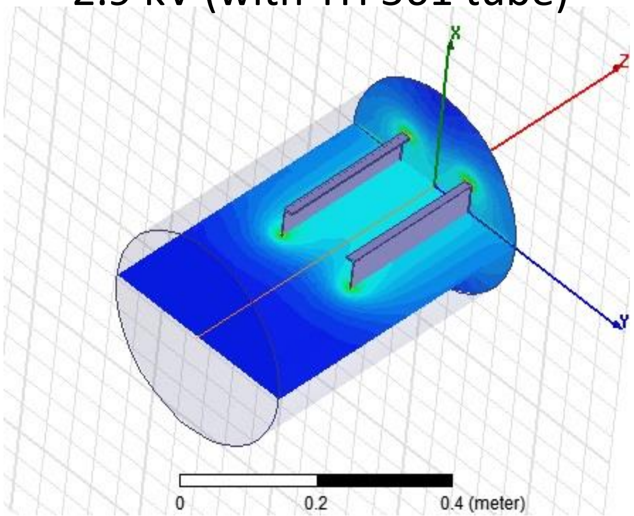




- new dedicated BPMs installed in LS1 (BI group)
- re-cabled with 7/8-inch smooth wall coaxial cables during LS1; cabling clean-up in BA2
- BDH / BDV kickers unchanged

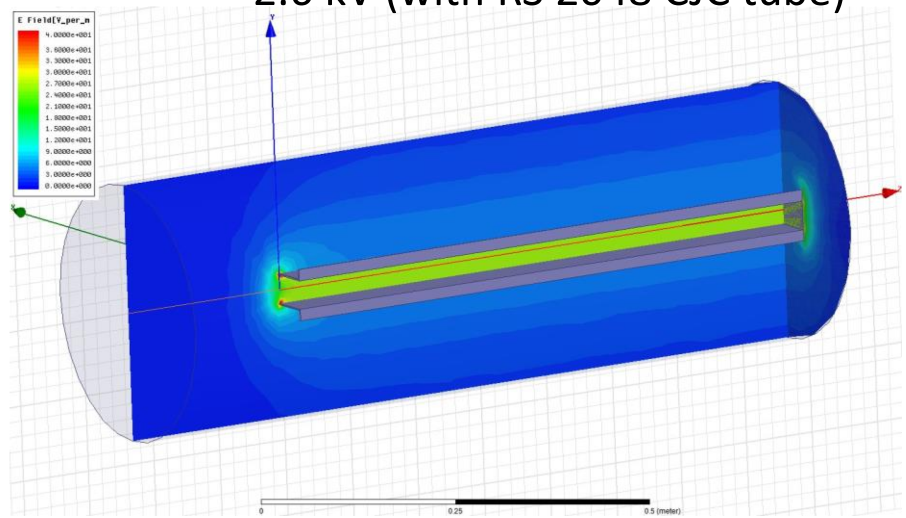
SPS Feedback kickers: Kick Strength

2.9 kV (with TH 561 tube)



Horizontal kicker (BDH)

2.6 kV (with RS 2048 CJC tube)



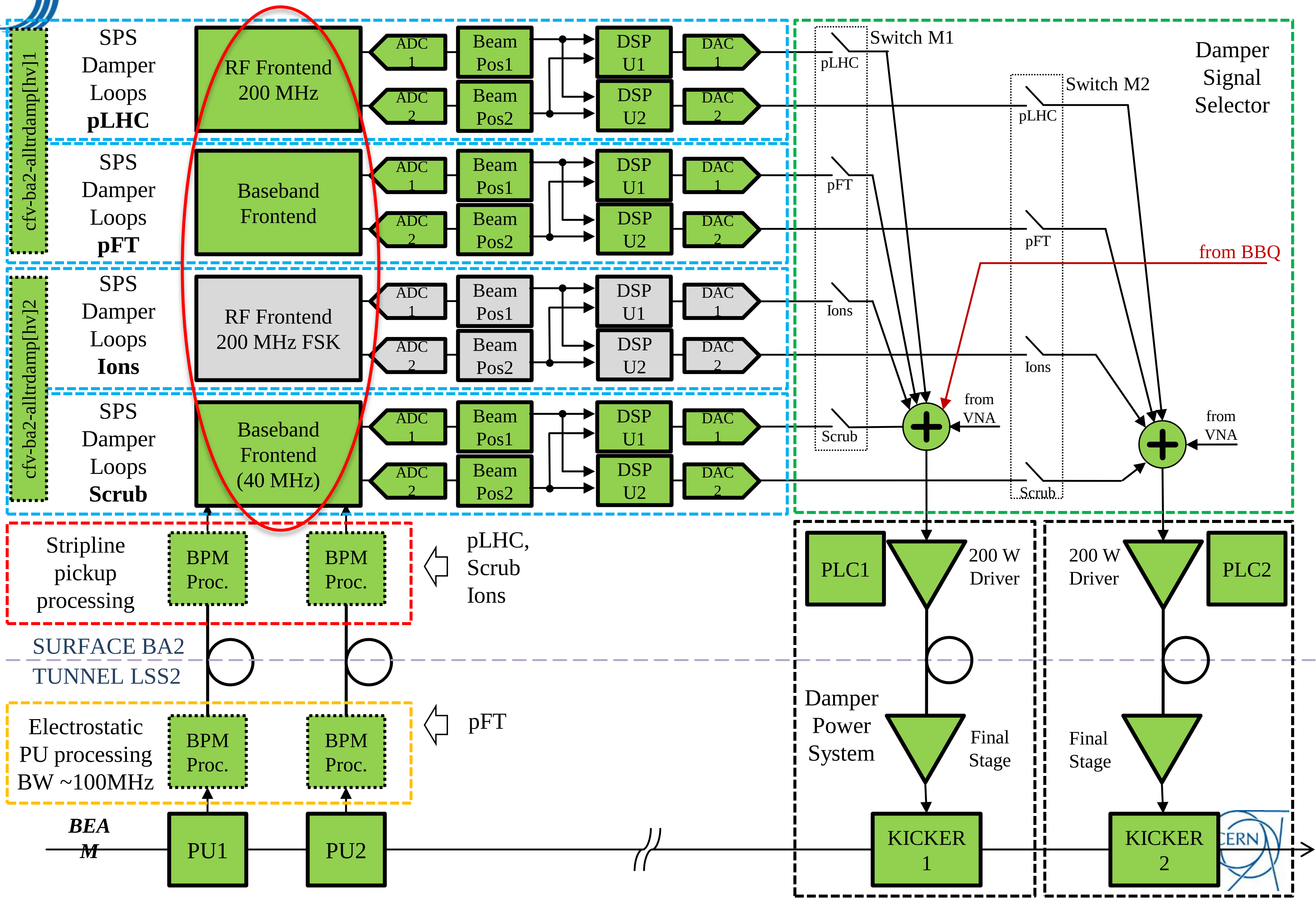
Vertical kicker (BDV)

plane	Length/gap mm/mm	Δp eVs/m	kV transverse	µrad at 26 GeV/c
H	2x 2396/142	3.3×10^{-4}	98	3.8
V	2x 1536/38	7.2×10^{-4}	215	8.3

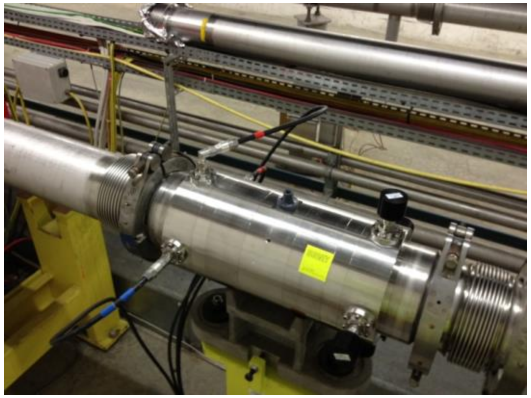
damps ~5 mm injection error (β=100 m) at 26 GeV/c in 20 turns (gain=0.1) in V-plane

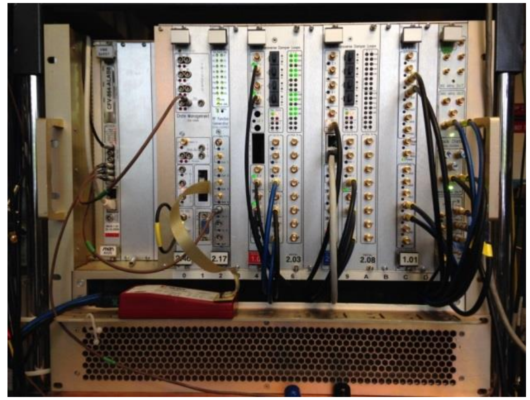
- 26 GeV/c: kick per turn 8.3 mrad (→ 0.54 mm at b=100 m) in V-plane
- regularly running at 0.5 ms damping time (20 turns)
- resistive wall growth rate for lowest mode: 0.5 ms to 1 ms

SPS damper overview (one plane of two)



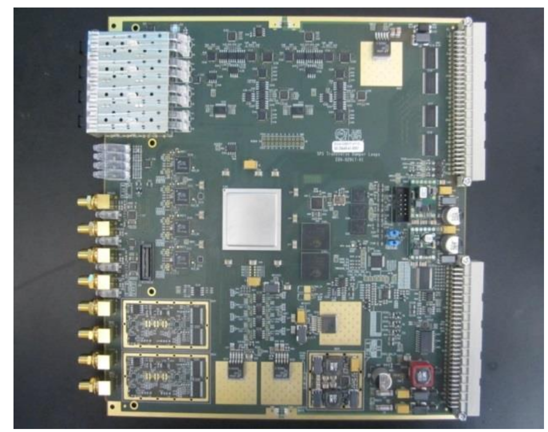
SPS Transverse damper LIU Upgrade: Achievements 2014/2015 and plans





2014 commission start after LS1

- 6 new pick-ups
- new electronics
- new controls
- p-FT, pLHC, p-scrub damped

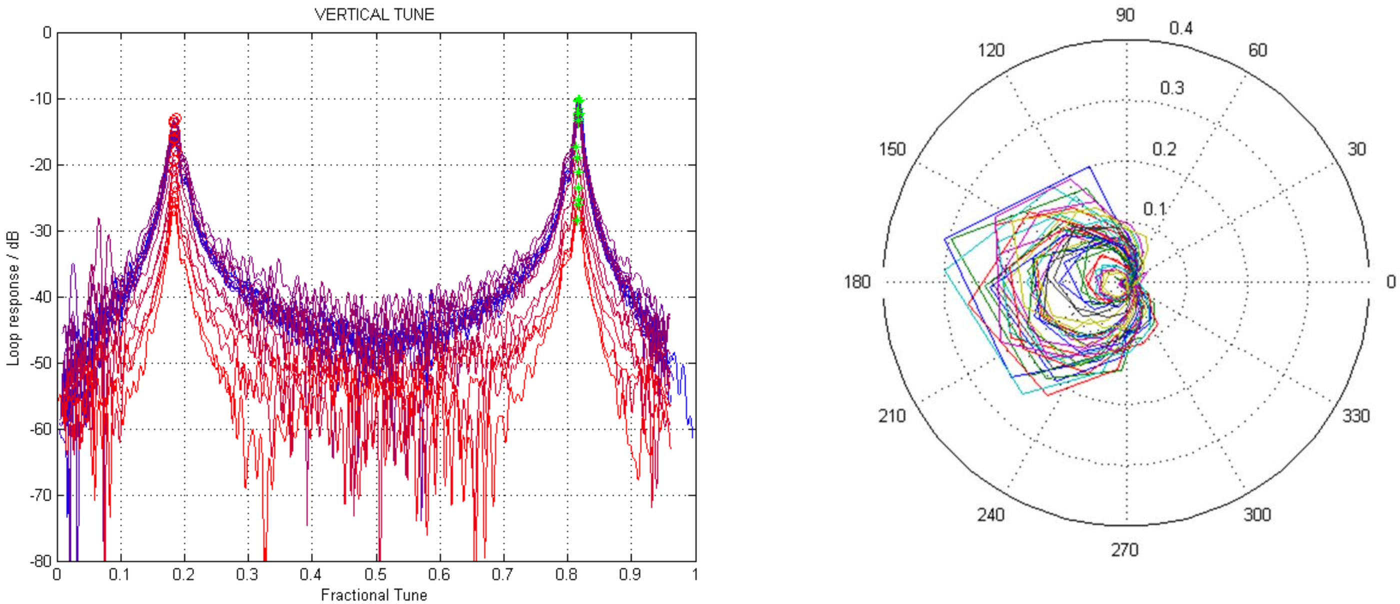


2015 and 2016

- complete electronics and commission for ions
- understand instabilities observed (scrubbing beam), increase to full bandwidth of 20 MHz for scrubbing beam
- optimize gain, delay
- software interfaces (GUI)
- observation box for signal acquisition

SPS damper after LS1 - commissioning

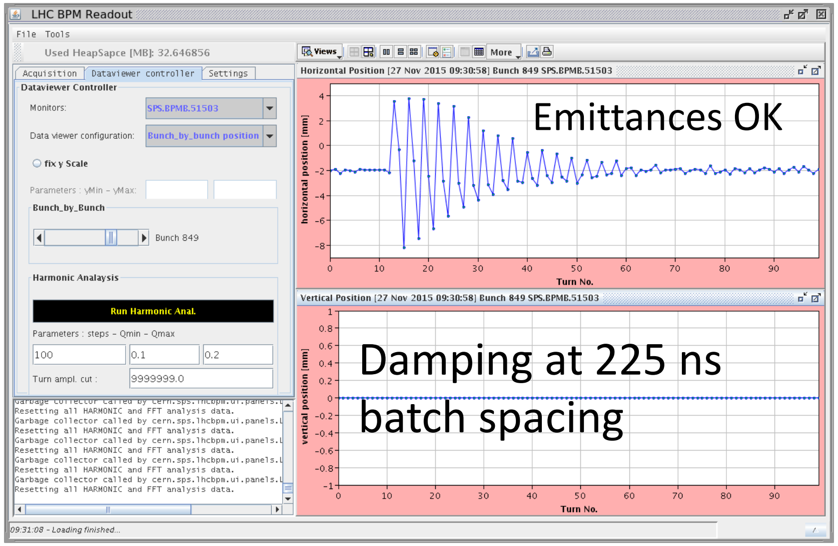
- Successful setting-up for p-FT, LHC type beams and scrubbing doublets after LS1 with new digital hardware
- Ion injection damping using hardware for protons
    - Limitations due to frequency modulation scheme for ions
- Improvements in hardware and tuning as well as instrumentation ongoing
- User interface development ongoing

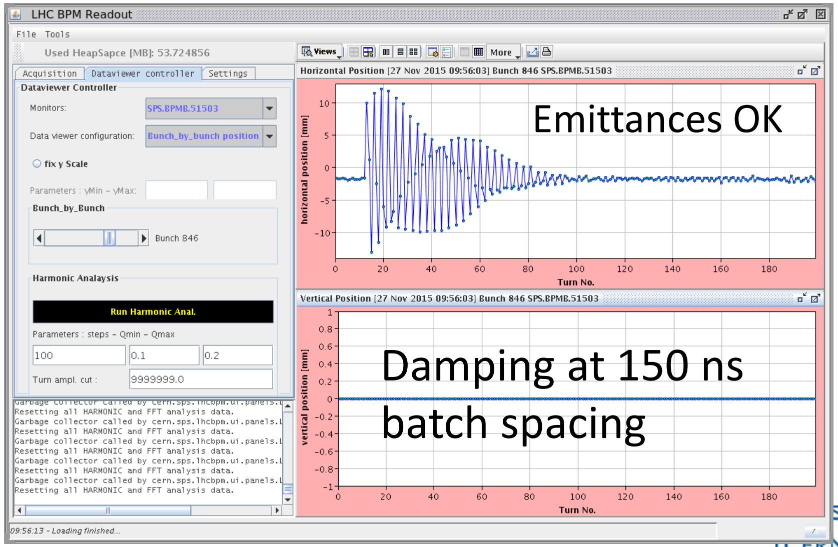


BTF measurements (open loop) as part of setting-up

SPS Ions damping: 1st tests in 2015

- Special requirement for ions: Frequency Shift Keying (FSK) for ion operation
  - Delay error up to 166 ns
  - Planned compensation by delaying RF clock from BA3 to align in time the RF clock and beam signals from pick-ups, and for the kickers → under development
  - Operation in 2015 without clock compensation allowed already improvements in the batch spacing





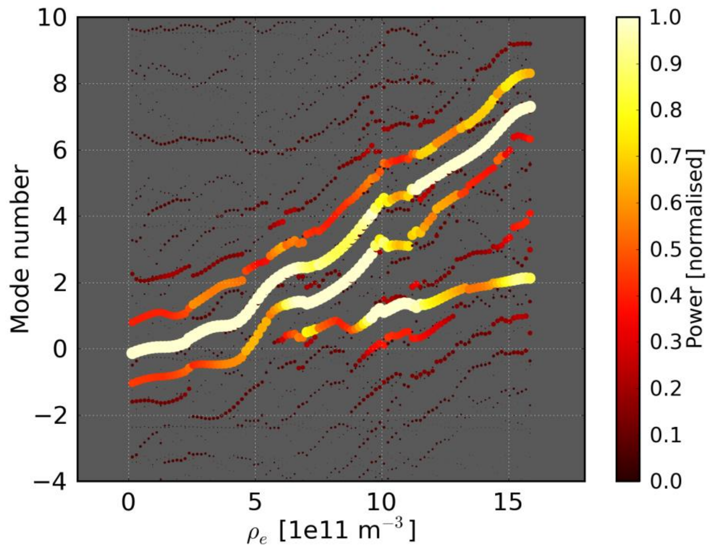
SPS
High Bandwidth Transverse Feedback

(aka Wideband Feedback)
few MHz to 1 GHz

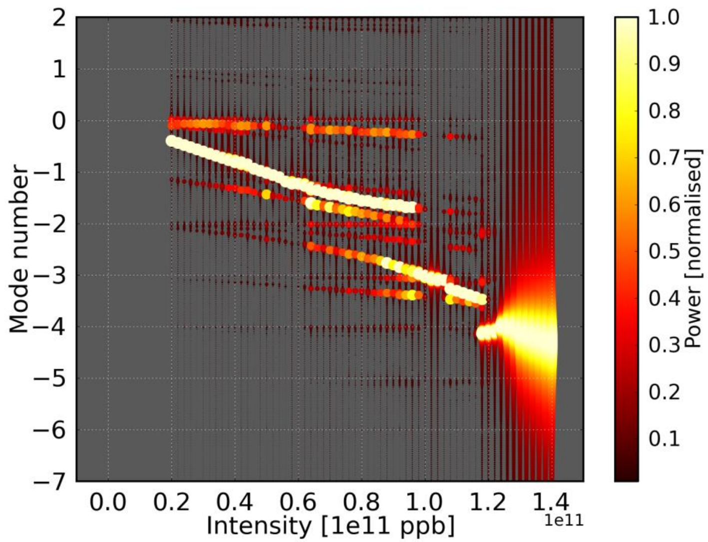
High Bandwidth Transverse Feedback

- Intra bunch feedback on short bunches
  - Damping of impedance driven (TMCI) and ecloud instabilities shown in simulation
  - Motivated by ecloud instability, LIU and US LARP support a prototype proof-of principle development for a vertical system for the SPS with a target bandwidth of 1 GHz

ECI (limitation at 25 ns spacing)



TMCI (single bunch intensity limitation)

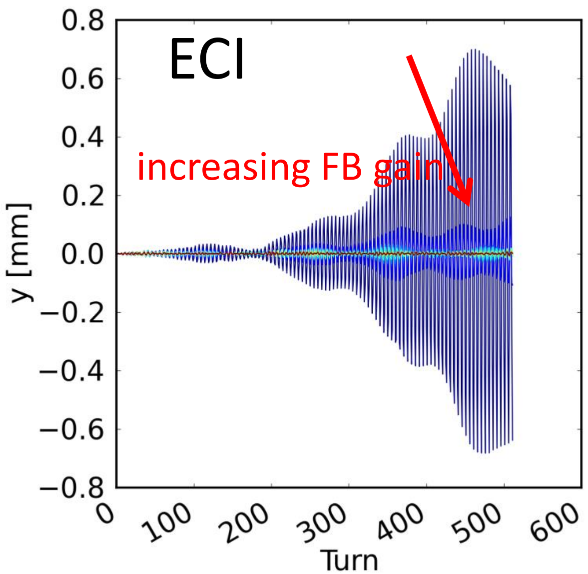


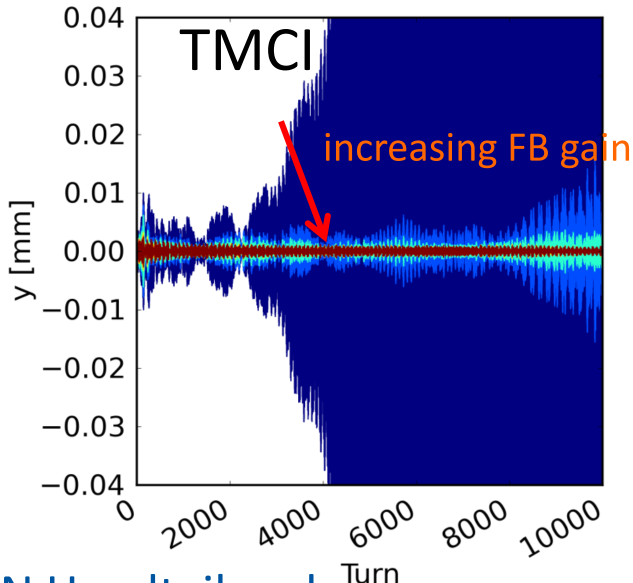
Mode Spectra without feedback

High Bandwidth Transverse Feedback Hardware & Simulation of performance

- Digital hardware for 4 GS/s supplied by SLAC
  - Commissioned in single bunch MDs
  - Planned for experiments with 25 ns trains for 2016

- Kickers
  - Initially used exponential pick-up (BPW) from 1970's with 4x100 W
  - Two new kicker designs launched
  - Short strip-lines (3 dB @ 700 MHz) developed, built and installed
  - Slotted line kicker design ongoing (higher frequency reach beyond 1 GHz)





Simulation with CERN Headtail code

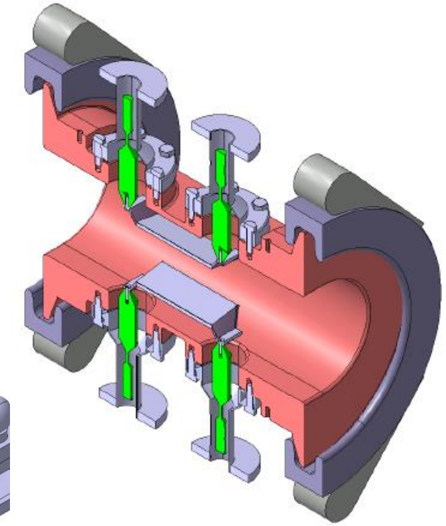
Kicker designs

Short strip-line kicker

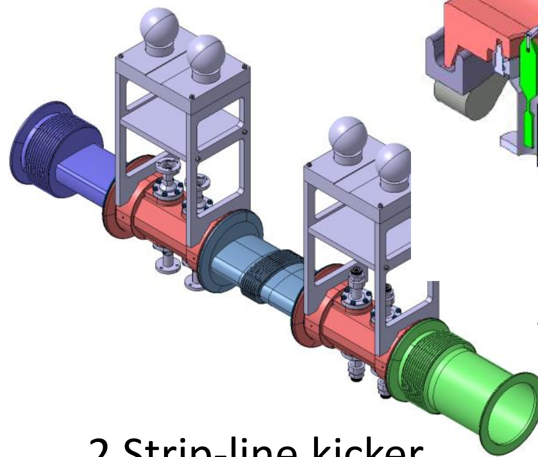
- Two kickers installed in the SPS with four 250 W solid state power amplifiers for 2016 operation
- First kicker used in 2015 machine development experiments
- One spare available

Slotted line kicker

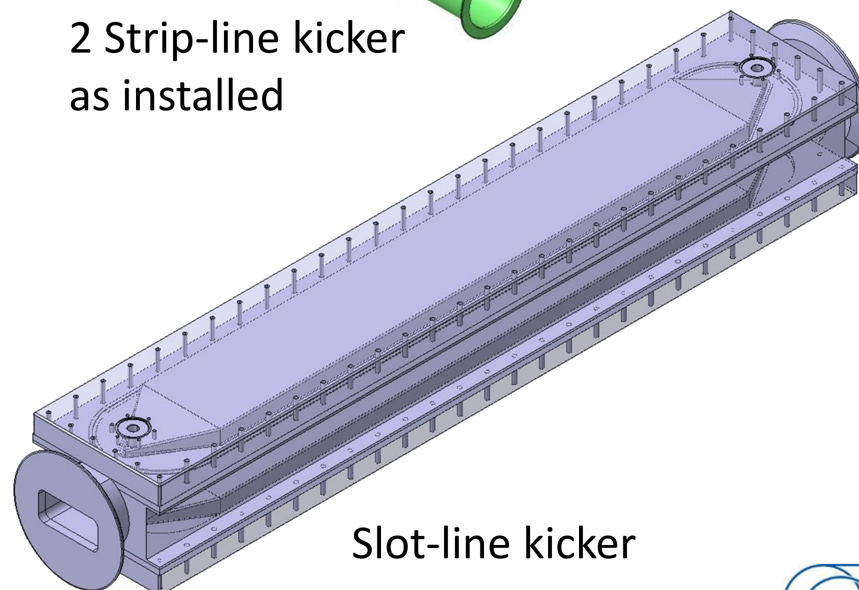
- Design to be completed
- Construction of prototype
- Experimental evaluation of shunt impedance in lab in 2016
- Decision on installation at Project Review in 2016



Strip-line kicker

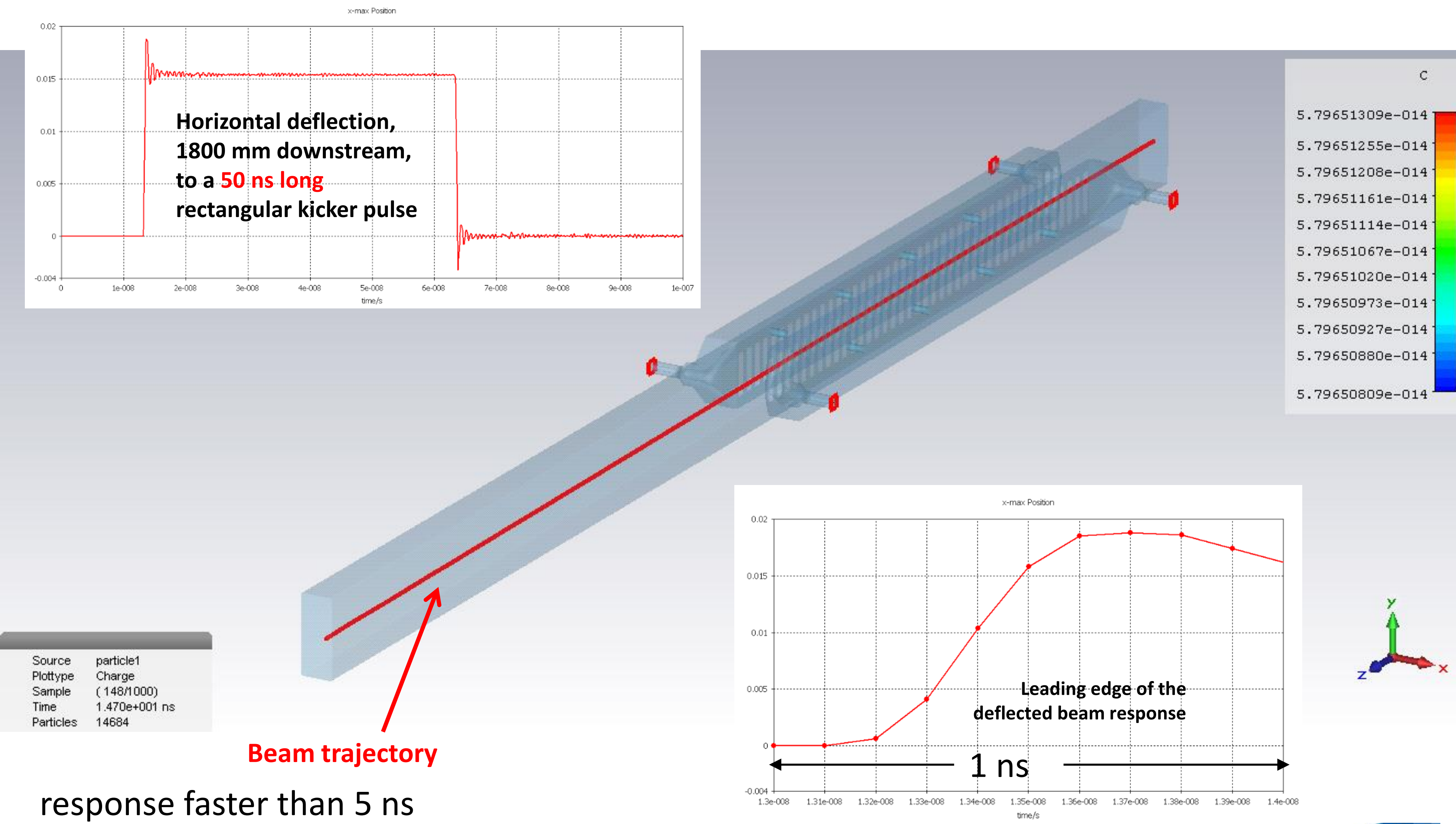


2 Strip-line kicker as installed



Slot-line kicker

Proposed slotted kicker: action on beam



response faster than 5 ns

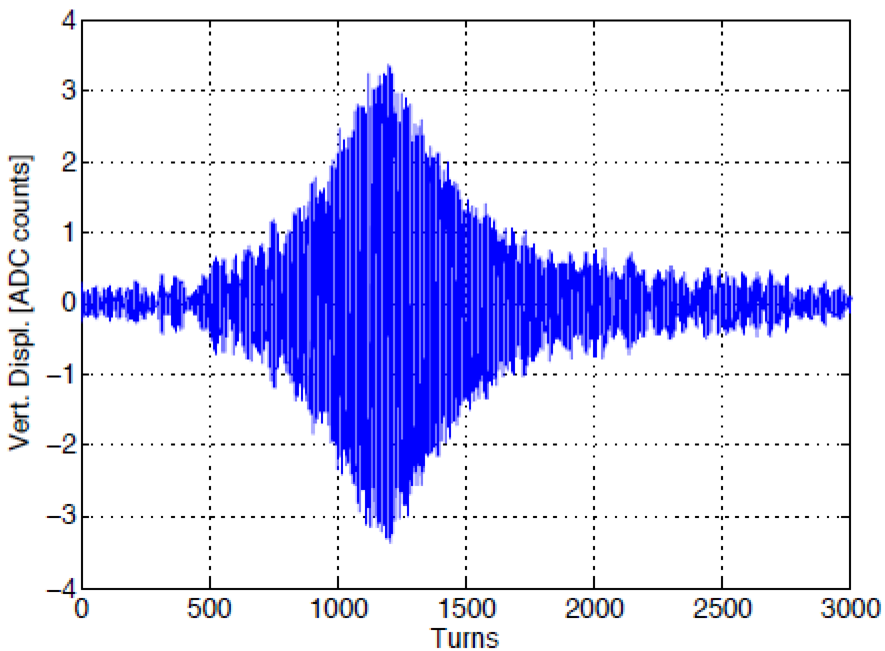
kicker can target individual bunches @ 5 ns spacing !

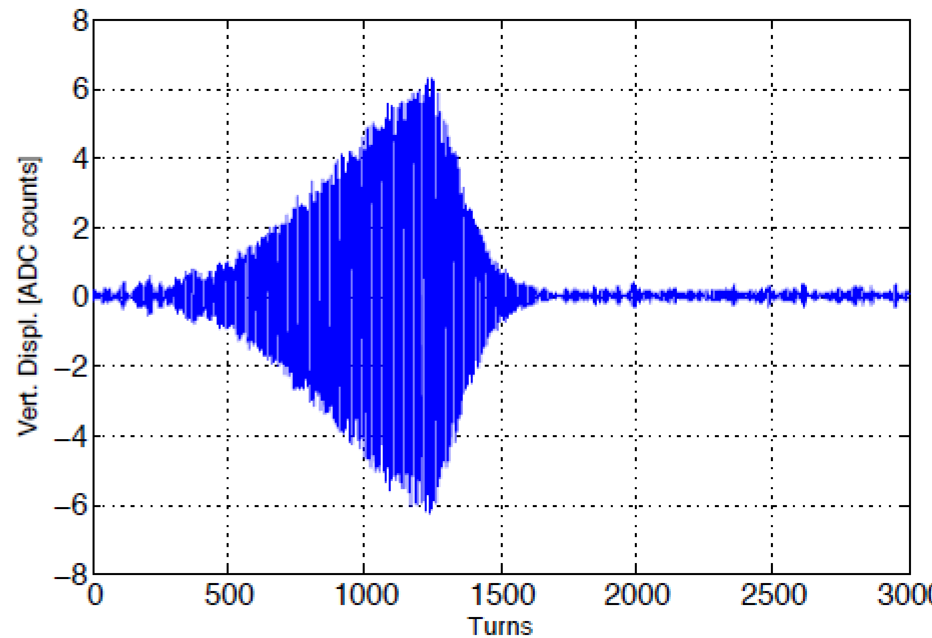
enormous value beyond high bandwidth feedback

Simulation: M. Wendt

MD results with new kicker in 2015

April 2015 SPS MD - Grow/Damp measurements





- Grow/damp SPS Measurement - Damping G=4 (left) G=16 (right)
- Intensity $2x10^{11}$ with low chromaticity Q26 lattice (special beam)
- $\nu_y = 0.185$ $\nu_s = 0.006$
- Feedback gain is switched to promote instability, then damp it
- Quantifies damping from increased gain of system, compare to models

High Bandwidth Transverse Feedback
- Priorities for 2016 -

- Full use of installed new strip-line kickers
  - Tackle challenge of Q20 optics (controller design)
  - Demonstrate experimentally intra-bunch motion damping (4 GS/s) – on a bunch train with new SLAC supplied firmware (USLARP support)
  - Demonstrate damping on a bunch train with new SLAC supplied firmware
  - Possibility to drive kickers with existing SPS coupled bunch damper hardware being considered with tests in 2016
- Kicker Design
  - Advance slot-line kicker design and manufacturing
- Review in autumn 2016
  - Performance of the prototype system with beam
  - Future use of the installed system
  - Possible extensions (full fledged system) in SPS adapted to LIU needs
  - Explore the possible continuation of R&D for other accelerators and studies (PS, LHC, FCC) based on experience gain with the SPS system

Conclusions: Transverse Feedbacks

- LEIR:
  - MD effort needed to define final scope of a possible upgrade
  - Control of parameters and closed orbit suppression identified as most critical items and being addressed
- PSB:
  - Infrastructure consolidation well advanced or completed
  - New digital processing hardware built, firmware under design, pick-up head amplifiers under design
  - New 800 W power amplifiers on critical path
- PS:
  - Consolidation and new electronics completed, software to complete
  - New power amplifiers on critical path (5 kW)
- SPS
  - Coupled bunch feedback upgrade essentially completed; ions damping and some rebuilding of hardware (spares, performance improvement) under way
  - High bandwidth damper: critical tests and review planned for 2016