LHC Transverse Damper Expected Performance

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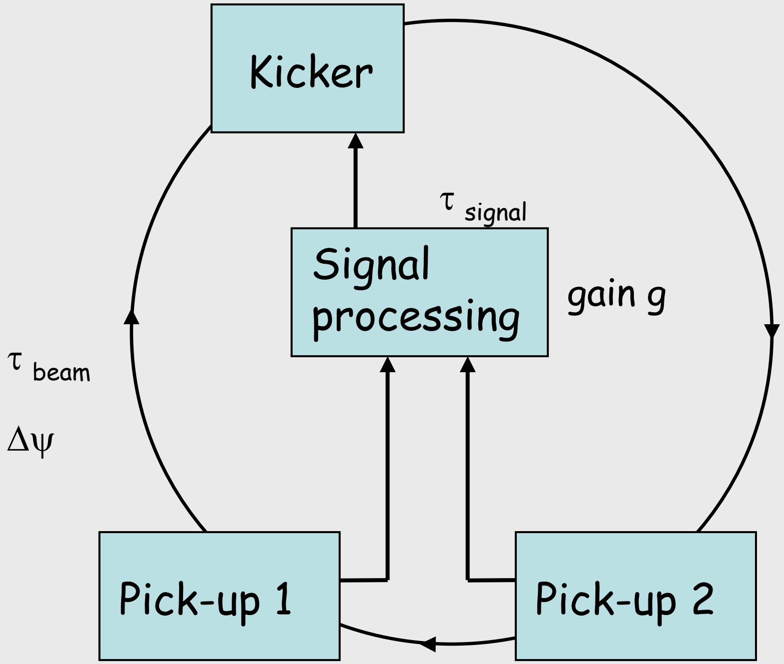
P. Baudrenghien, G. Kotzian, R. Louwerse, E. Montesinos (AB/RF/SR), V. Rossi, D. Valuch, V. Zhabitskiy (for JINR / Dubna collaboration)

Transverse multi bunch feedback principle



Need real-time digital signal processing

Match delays:
$t_{signal} = t_{beam} + MT_0$

T0 : beam revolution time

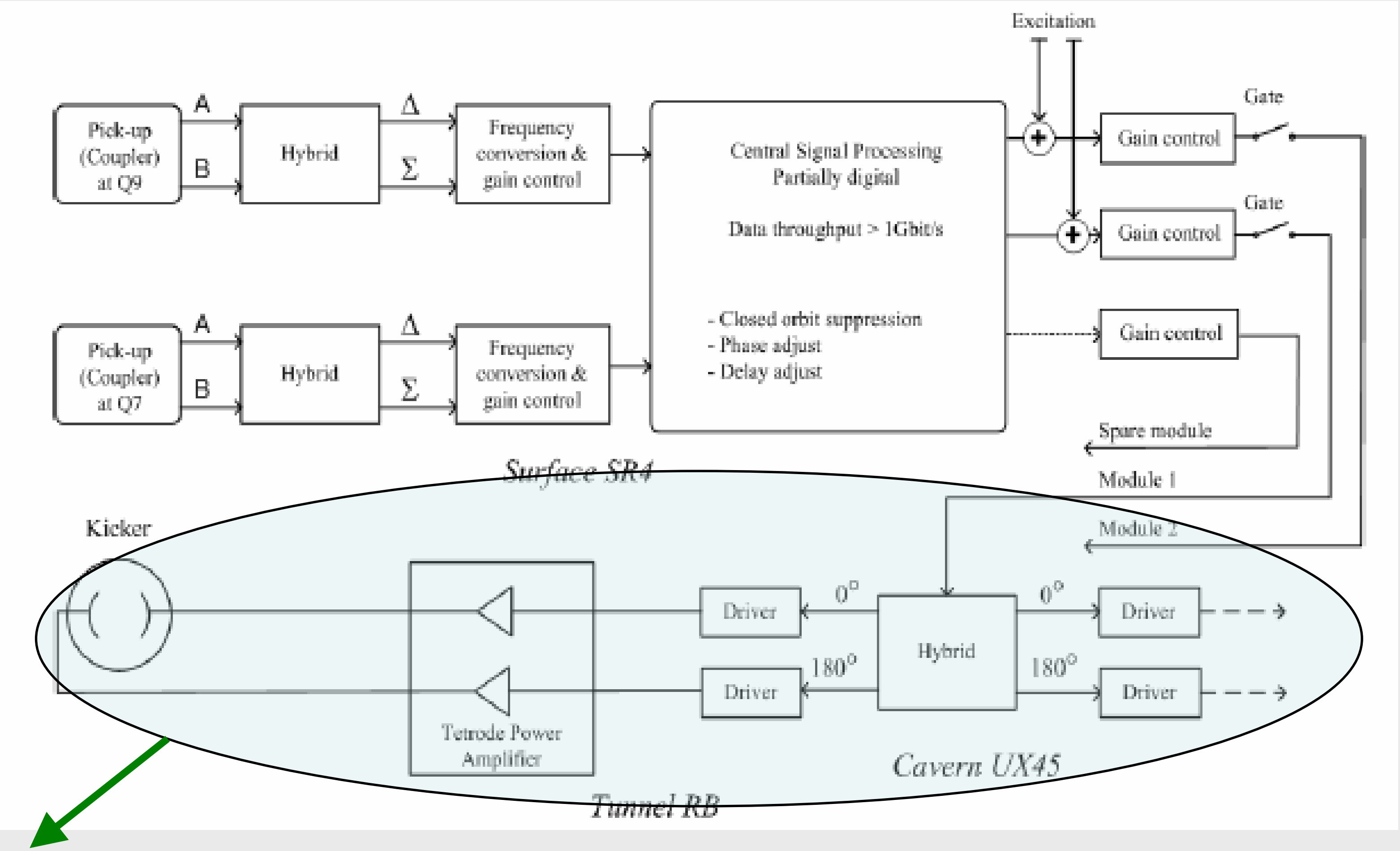
M=1: very common ->
“One -Turn-Delay” feedback
But M>1 also possible

phase *and* delay adjustments

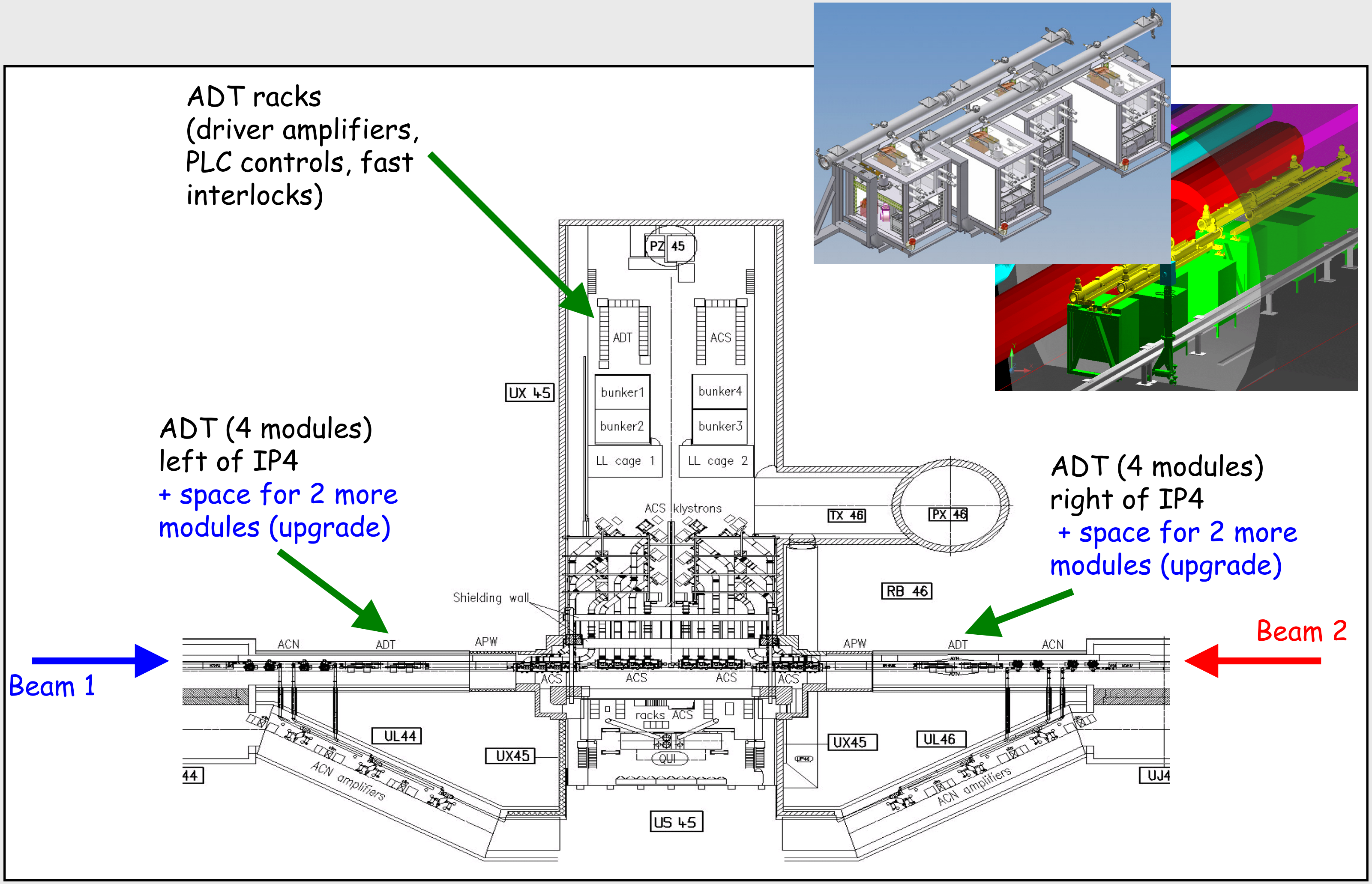
- damping: of transverse injection oscillations
- feedback: curing transverse coupled bunch instabilities
- excitation: of transverse oscillations for beam measurements & other applications

Overview of one ADT System

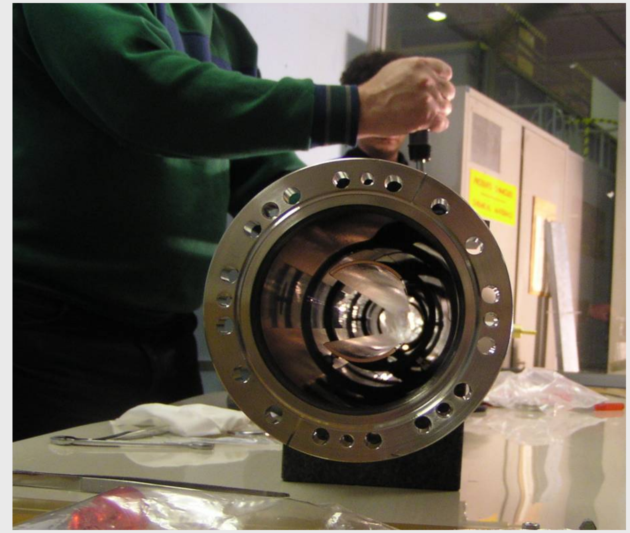
Choice: Digital electronics on surface -> easy access ! -> electronics under design and in production



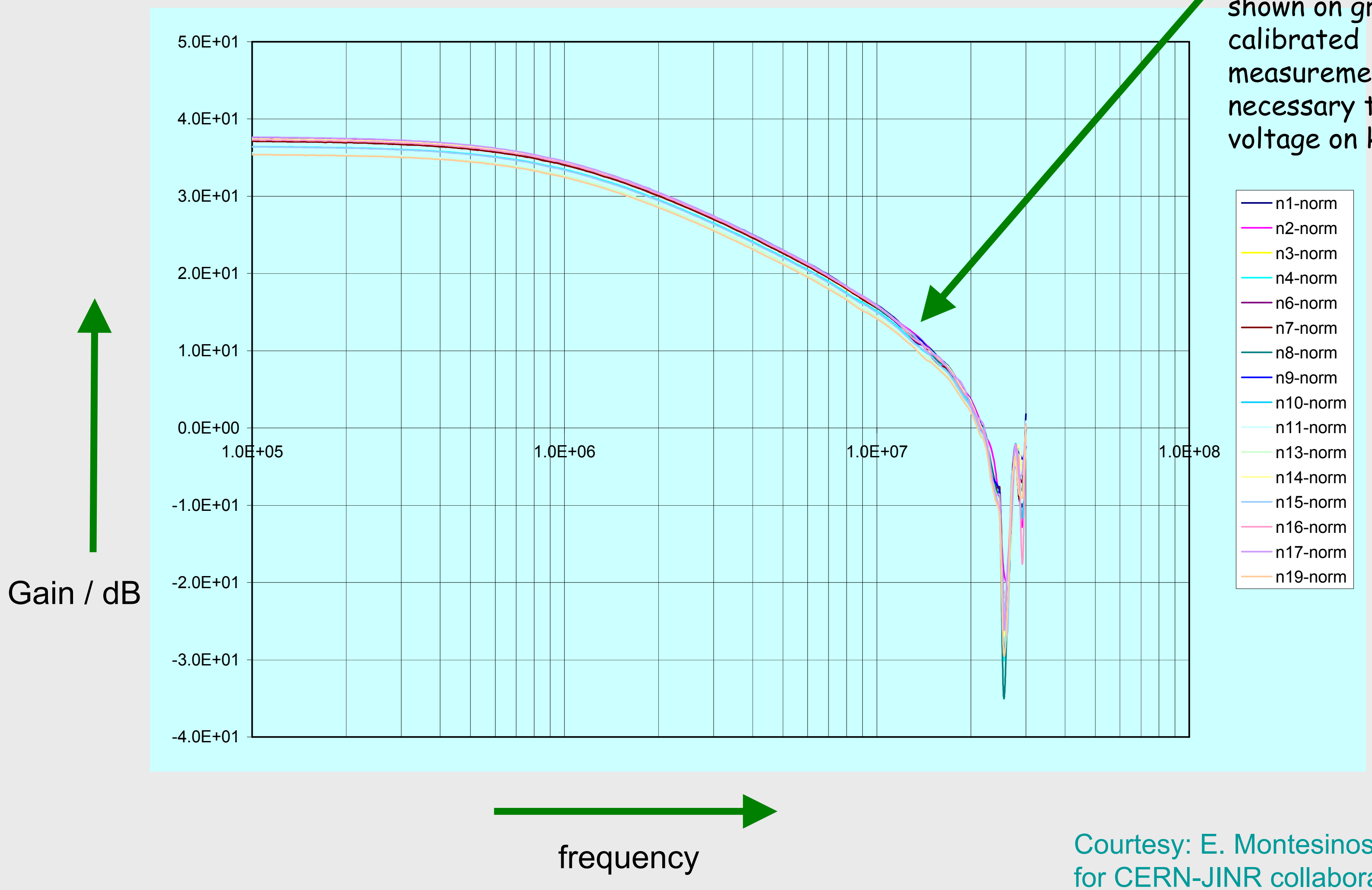
Kickers installed and baked-out, amplifiers under commissioning


ADT racks
(driver amplifiers, PLC controls, fast interlocks)
ADT (4 modules) left of IP4
+ space for 2 more modules (upgrade)
ADT (4 modules) right of IP4
+ space for 2 more modules (upgrade)
Beam 1
Beam 2
PZ 45
ADT
ACS
UX 45
bunker1
bunker2
bunker4
bunker3
LL cage 1
LL cage 2
ACS klystrons
TX 46
PX 46
RB 46
Shielding wall
ACN
ADT
APW
ACS
racks ACS
QUI
UL44
UX45
UL46
US 45
ACN amplifiers
44
UJ4

Assembly and Installation



Measured Characteristics of 16 Final Amplifiers



Actual performance between 10-20 MHz will be better than shown on graph -> calibrated measurements necessary to show real voltage on kickers

Courtesy: E. Montesinos (AB/RF/SR)
for CERN-JINR collaboration

Performance specification (1)
(LHC Design Report)

Beam parameters and requirements for nominal intensity:

Injection beam momentum	450 GeV/c
Static injection errors	2 mm (at β_{max}=183 m)
ripple (up to 1 MHz)	2 mm (at β_{max}=183 m)
resistive wall growth time	18.5 ms
assumed de-coherence time	68 ms
tolerable emittance growth	2.5 %
Overall damping time	4.1 ms (46 turns)
bunch spacing	25 ns
minimum gap between batches	995 ns
lowest betatron frequency	> 2 kHz
highest frequency to damp	20 MHz

Performance specification (2)

Equipment performance specification:

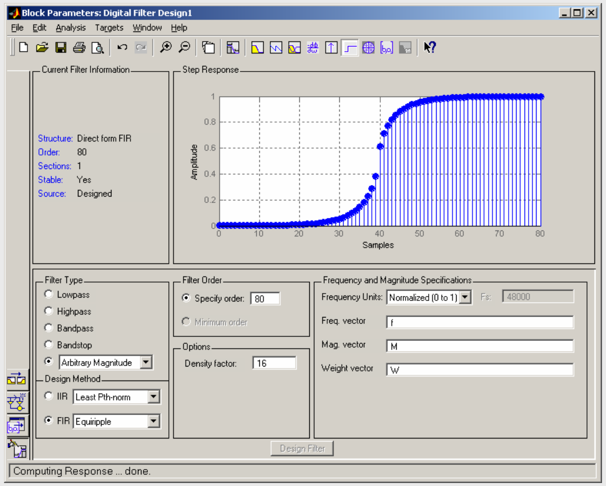
choice:	"electrostatic kickers" ("base-band")
aperture	52 mm
kickers per beam and plane	4
length per kicker	1.5 m
nominal voltage up to 1 MHz at b=100m	+/- 7.5 kV
kick per turn at 450 GeV/c	2 μrad

rise-time 10-90%, ΔV= +/- 7.5 kV 350 ns

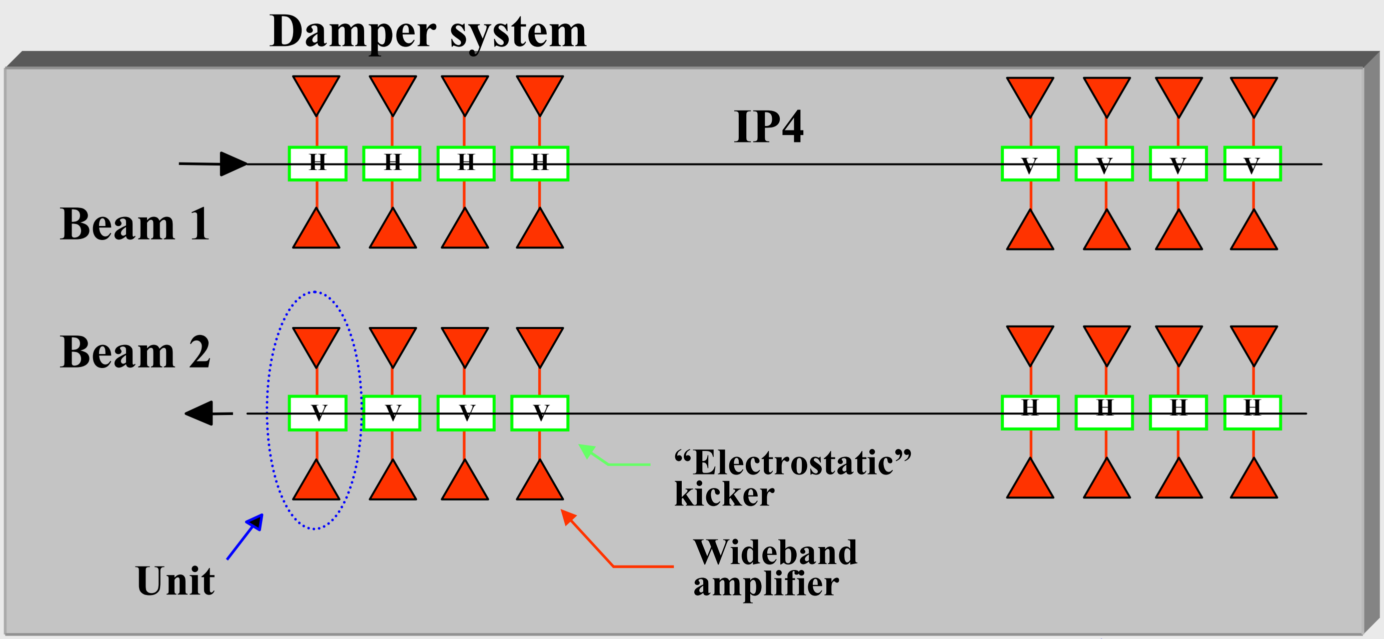
rise-time 1-99%, ΔV= +/- 7.5 kV 720 ns

must provide sufficient gain from 1 kHz to 20 MHz

noise must be less than quantization noise due to 10 bit / 2σ

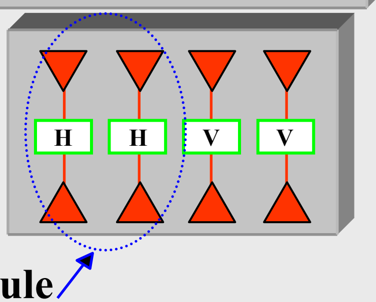


rise time fast enough for gap of 38 missing bunches



- 20 electrostatic kickers
- 40 wideband amplifiers, i.e. 40 tetrodes (RS2048 CJC, 30 kW)
  20 amplifier cases

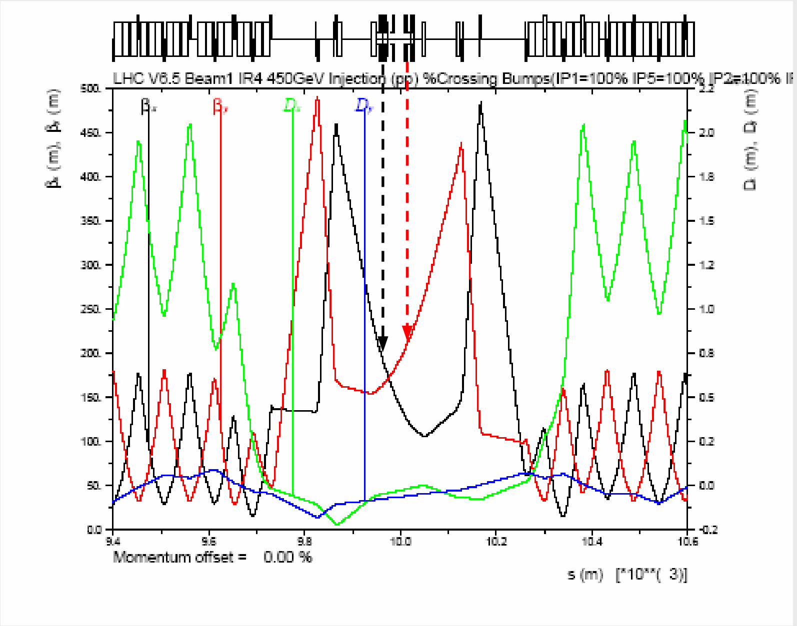
+ Spare units

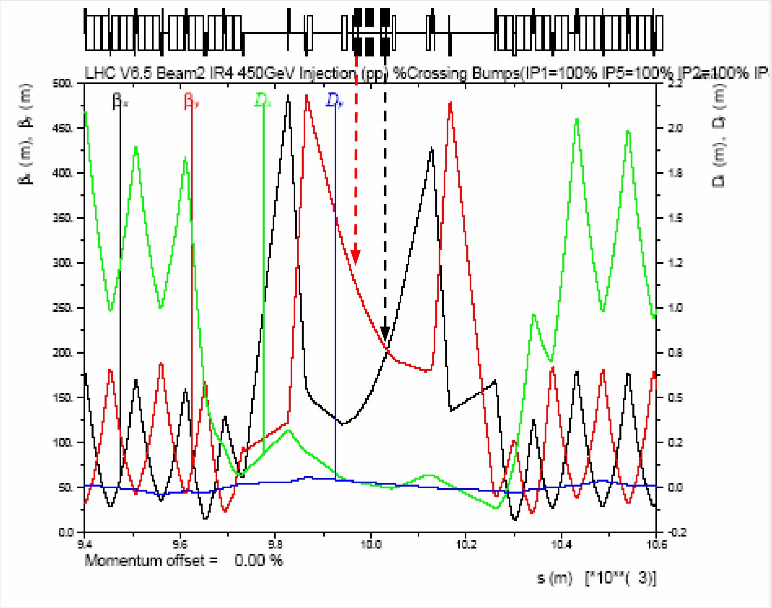


LHC optics at injection in IR4
(beams do not cross!)

Beam 1
high horizontal beta *left* of IP4
high vertical beta *right* of IP4

Beam 2
high horizontal beta *right* of IP4
high vertical beta *left* of IP4





Plots are Optics 6.4, sorry, 6.5 not very different for ADT)

Performance

LHCADT performance in **LHC optics version 6.500** compared to original assumptions (at **450 GeV/c**), assuming 7.5 kV maximum kick voltage, up to 1 MHz

	β=100 m performance	Optics 6.500 performance
	Kick per turn in σ	Kick per turn in σ @ β in m
ADTH beam 1	0.2 σ	0.271 σ at β=183 m
ADTH beam 2	0.2 σ	0.274 σ at β=189 m
ADTV beam 1	0.2 σ	0.301 σ at β=227 m
ADTV beam 2	0.2 σ	0.331 σ at β=275 m

Estimate of maximum capabilities (usage as beam exciter, abort gap cleaning etc.), assumes optics 6.5 as in table above, **450 GeV/c and 7 TeV** and running with up to ~15 kV DC for tetrode anode voltage (at 1 MHz 1.4x nominal)

	100 kHz	1 MHz	10 MHz	20 MHz
ADTH	0.42 σ / 0.11 σ	0.38 σ / 0.10 σ	0.12 σ / 0.03 σ	0.044 σ / 0.011 σ
ADTV	0.46 σ / 0.12 σ	0.42 σ / 0.12 σ	0.14 σ / 0.04 σ	0.049 σ / 0.012 σ

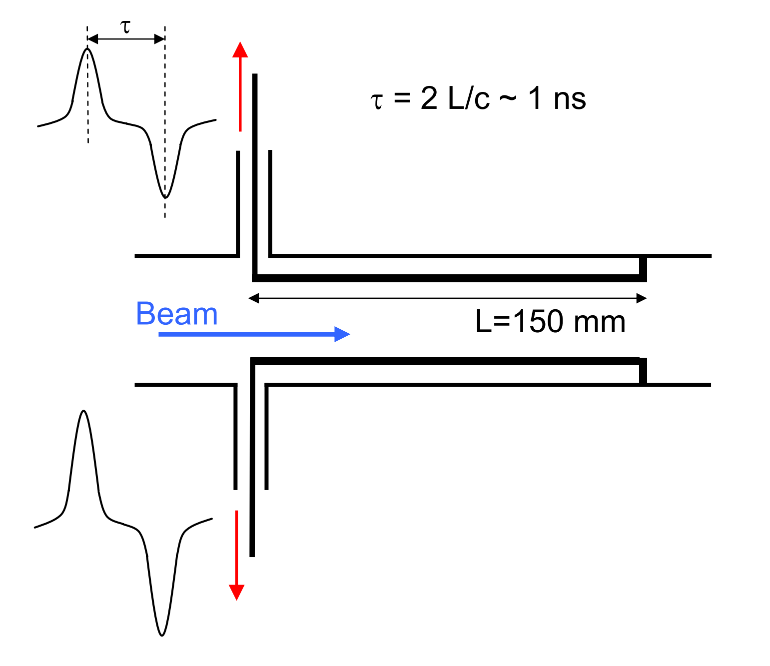
LHC ADT Low-level Electronics

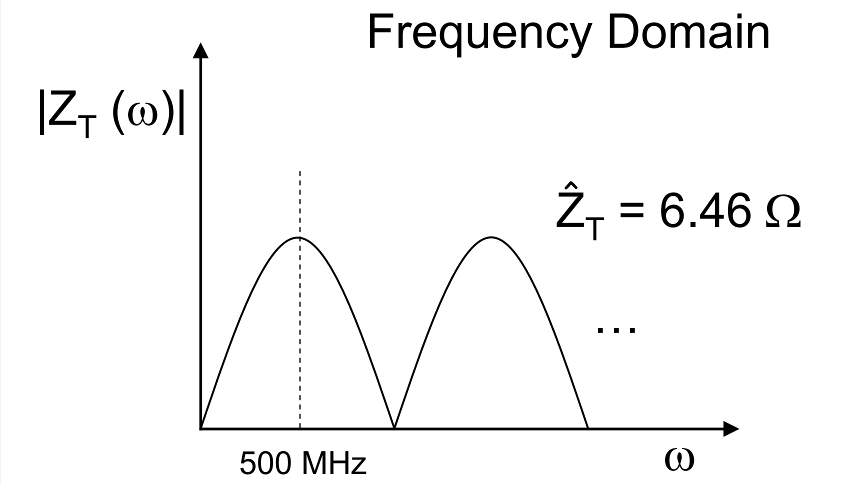
- System will be based on experience gained with SPS Damper
- Two coupler type pick-ups with betatron phase advance of ~90 degrees will be used (BPMC/BPMCA, provided by the BI group and integrated in quad)
- Spectrum repeats every 40 MHz (25 ns bunch spacing) -> analogue down conversion with a multiple of 40 MHz to base band , LO of 400 MHz chosen
- One of the horizontal pick-ups is installed at ~zero dispersion and it will be possible to use this pick-up and a Hilbert transformer (FIR filter) for the phase adjustment if wanted; Hilbert filter tested in SPS but not used in operation (reduced phase stability margin at very high gain)
- FPGA technology for implementing most of the functions digitally (notch filter, fine delay adjustment, betatron phase adjustment by two pick-ups or Hilbert filter and single pick-up use)

BPMC - Coupler type pick-ups

8 Dedicated Pick-ups BPMC @ Q7L, Q7R, Q9L, Q9R
50 Ω couplers of 150 mm length on one end short circuited

BPMC - Coupler type pick-ups

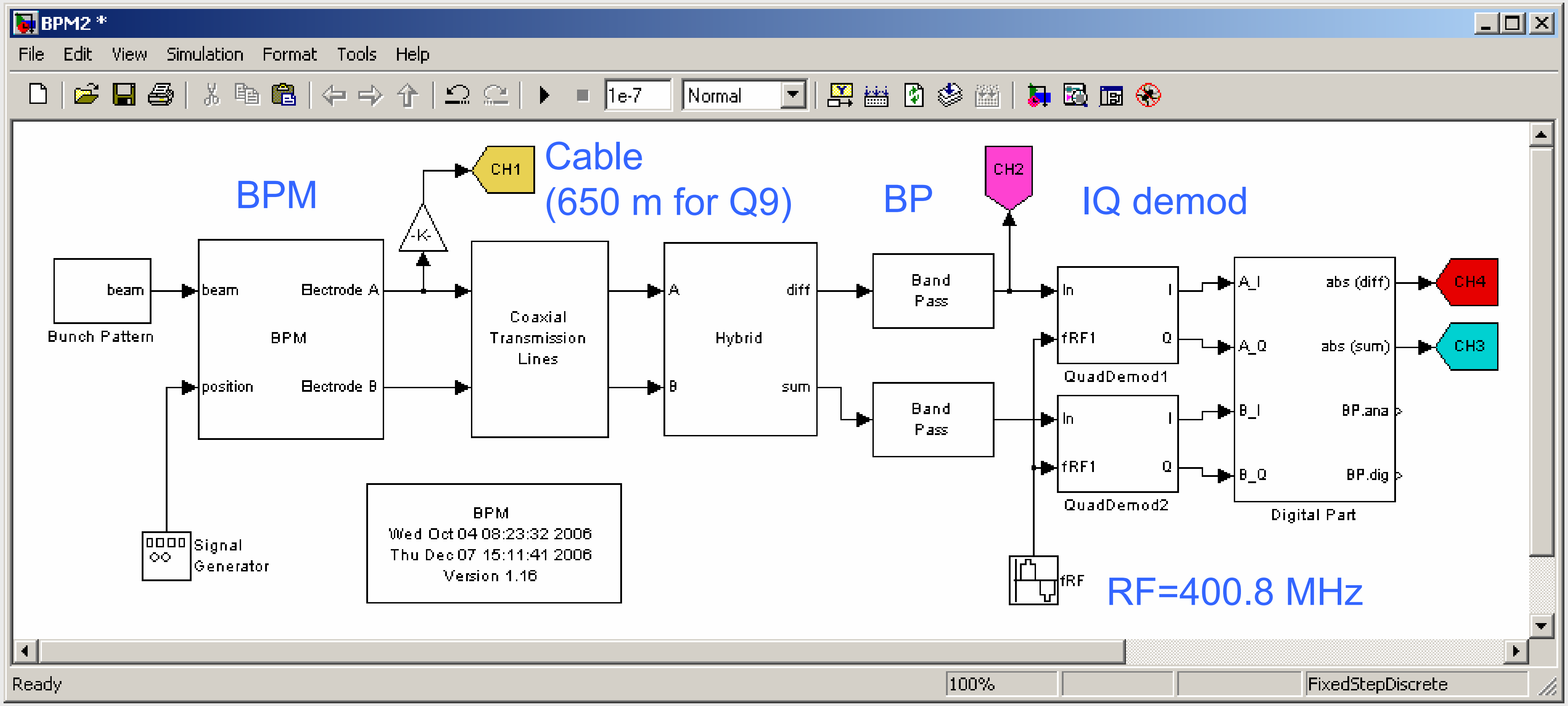




$$Z_T(\omega) = \hat{Z}_T \, j \sin(\omega\tau/2) \, e^{-j\omega\tau/2}$$

- Length of electrodes 150 mm
- Frequency domain: maximum of transfer impedance $\hat{Z}_T$ = 6.46 Ω @ 500 MHz
- Peak voltage (beam centered) for ultimate beam @ collision: ~140 V -> very large
- Peak sensitivity: 0.264 Ω / mm => 8.1 V/mm peak in time domain after ideal hybrid

Realistic simulation model is being developed
to include actual characteristics of hardware



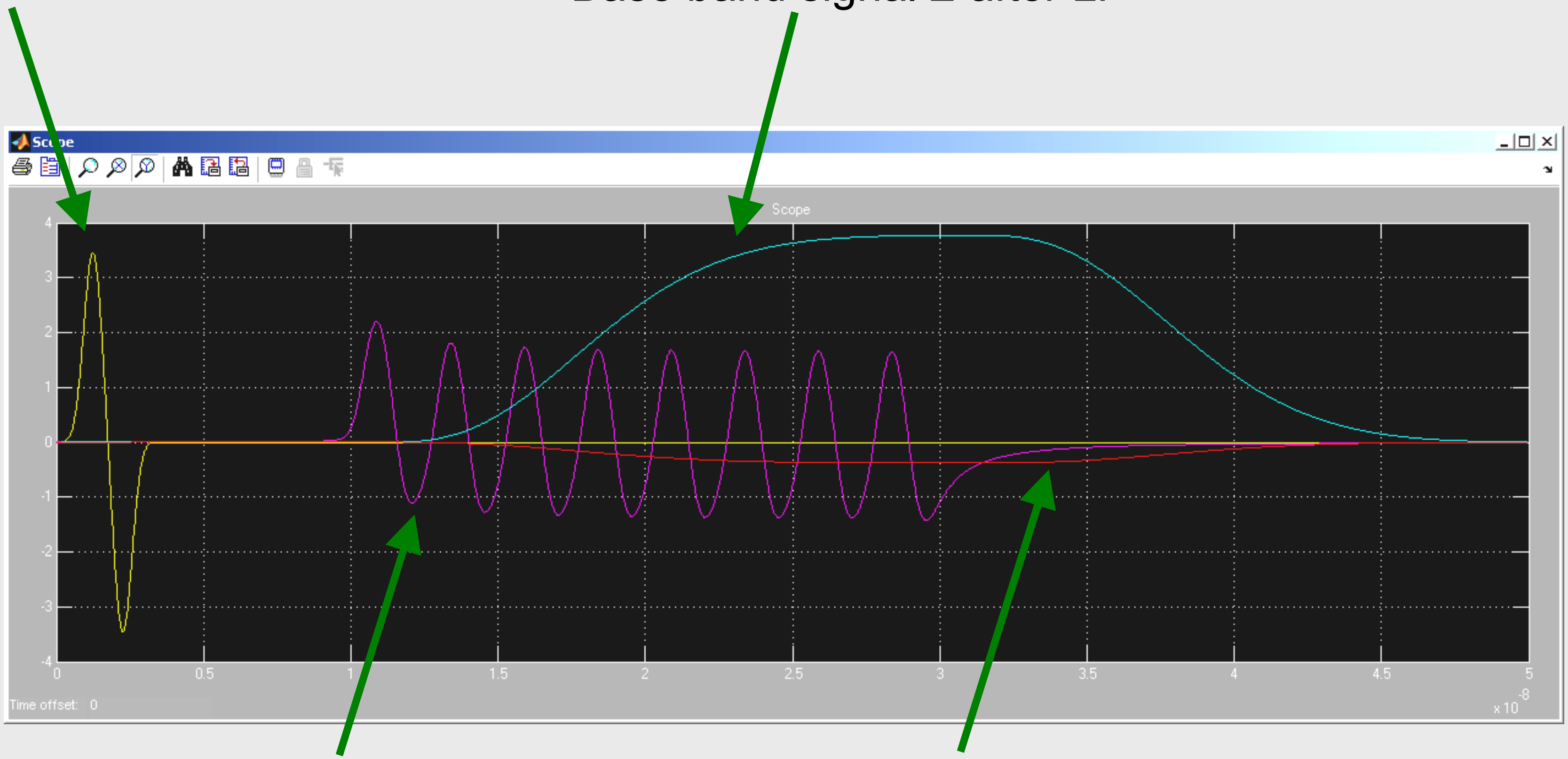
Bunch synchronous sampling @ 40 MHz and digitization with 16 bit
normalization (Δ/Σ) after calculation of sqrt(I*I+Q*Q) in digital part

G. Kotzian

Some simulation results, single bunch

Signal from pick-up

Base band signal Σ after LP

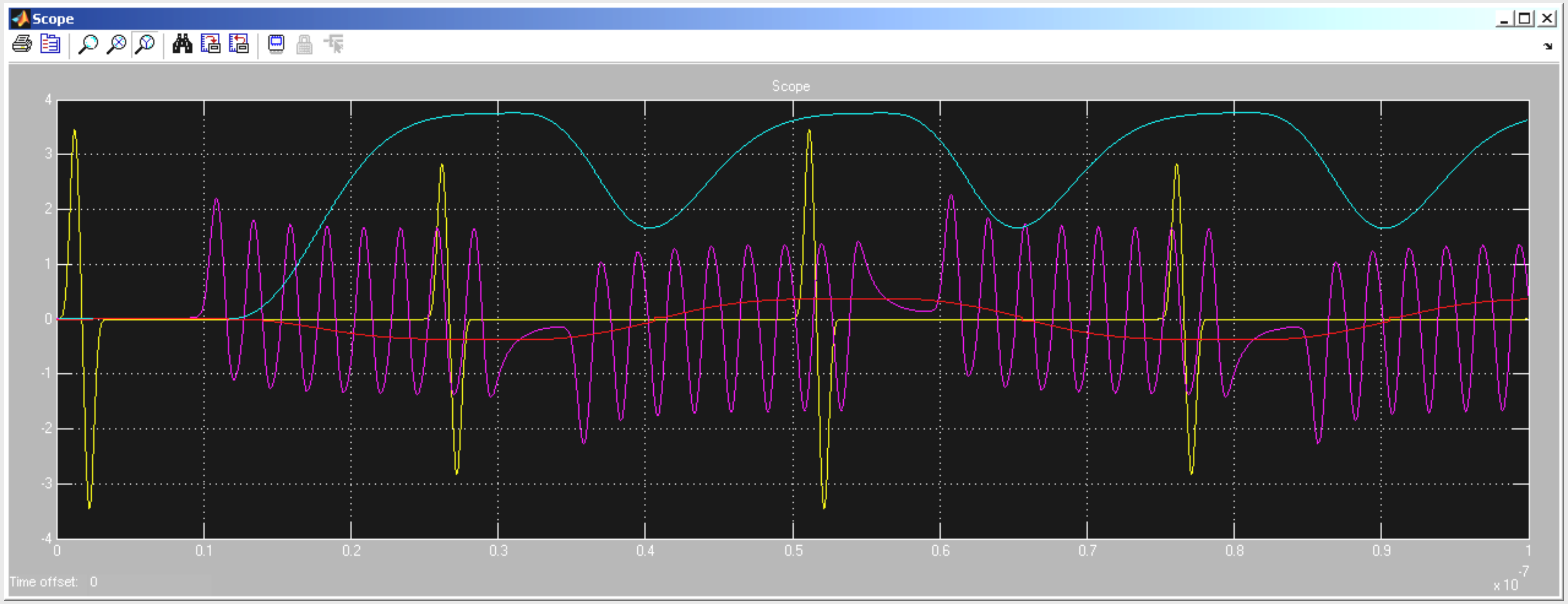


Response of BP filter to Δ signal from pick-up

Base band Δ signal after LP

G. Kotzian

Simulation results, bunch to bunch oscillations

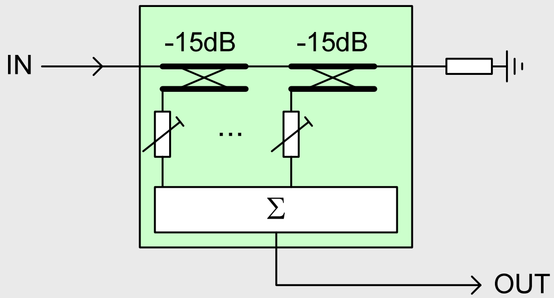


Simulation model enables us to study imperfections of hardware and also propagate noise or interferences through system and evaluate their impact

Bunch synchronous sampling with a 40 MHz clock rate

G. Kotzian

Band pass filter prototypes (1)



"Sampled line" type comb filter (8 sections):

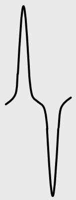
- uses series of directional couplers on a delay line plus n-way combiner

Advantages:

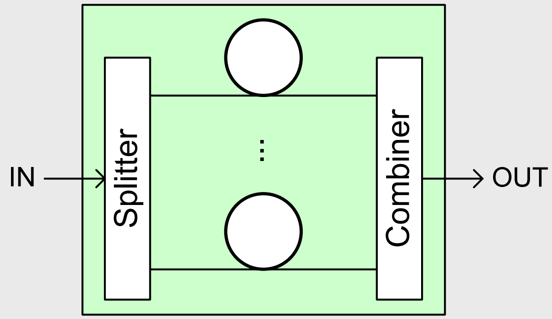
- Fully integrated on a single microwave substrate
- Easy to manufacture (standard PCB process)
- Excellent reproducibility of parameters

Disadvantages:

- Minimal insertion loss determined by couplers, in reality not better than -10 to -15dB (at f_c)



input



"Delay line" type comb filter:

- uses series of delay lines to form the impulse response, signals are combined at the end

Advantages:

- Very low insertion loss (**i**.e. only losses of the cables). Measured loss of prototype filter only 1dB

Disadvantages:

- Each delay line must have precise length
- Delay lines are rather long (e.g. up to 4.5m for 400MHz)
- Very manpower demanding for manufacturing
- Poor reproducibility of parameters when made of cables

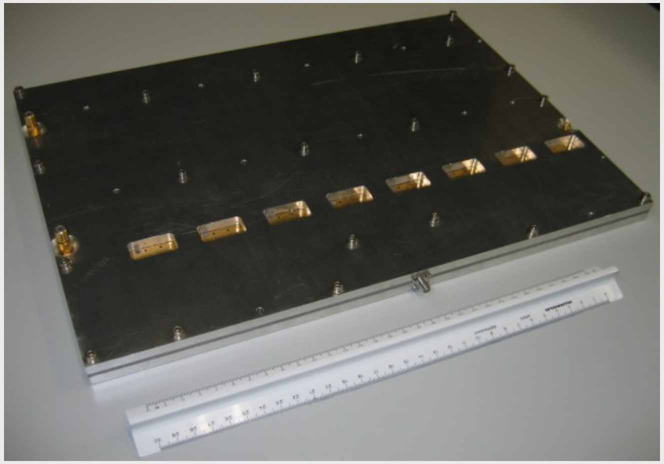
A printed version on high-epsilon microwave substrate is being studied right now (9 sections)

output

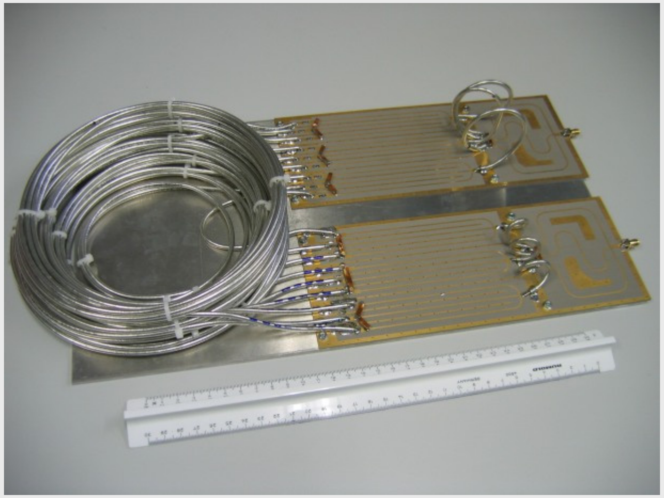
D. Valuch

400 MHz prototype band pass filters built

“Sampled line” type comb filter
8 dB attenuation @ 400 MHz achieved

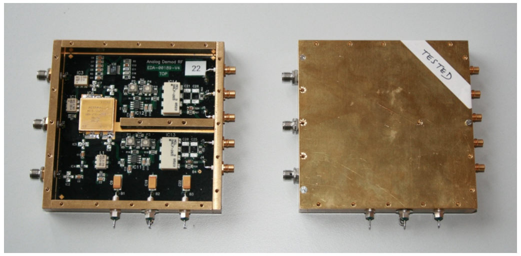


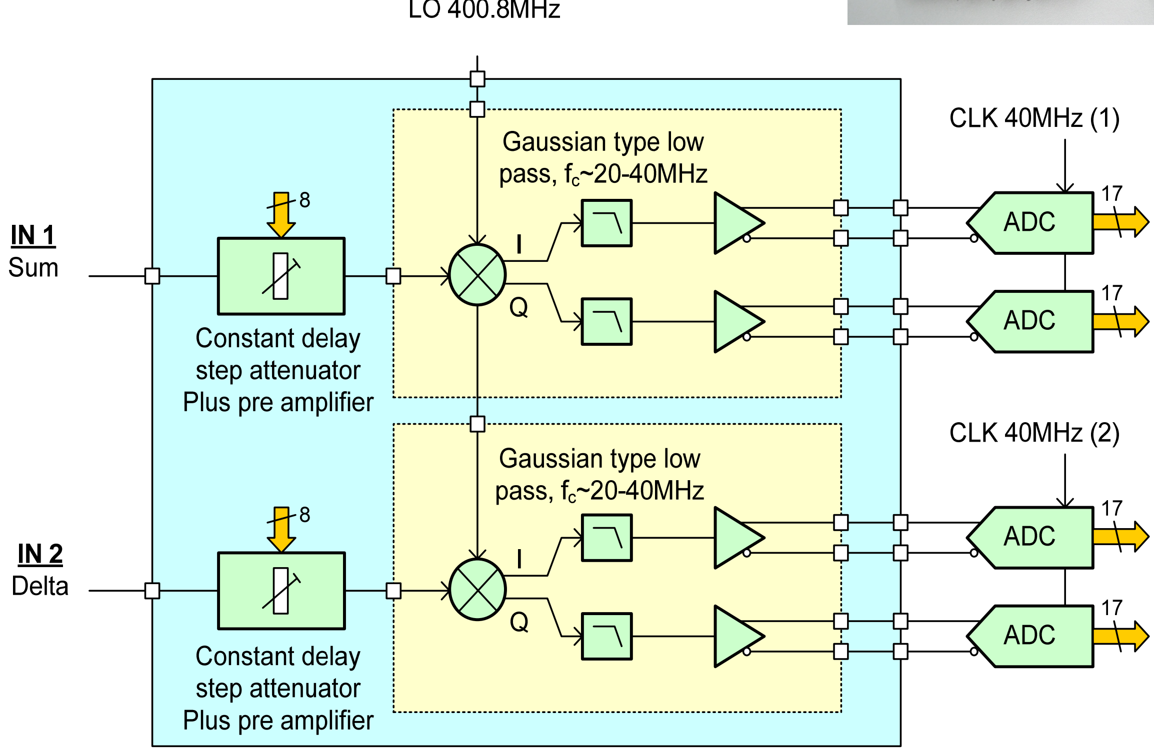
“Delay line” type comb filter
1 dB attenuation @ 400 MHz achieved



D. Valuch

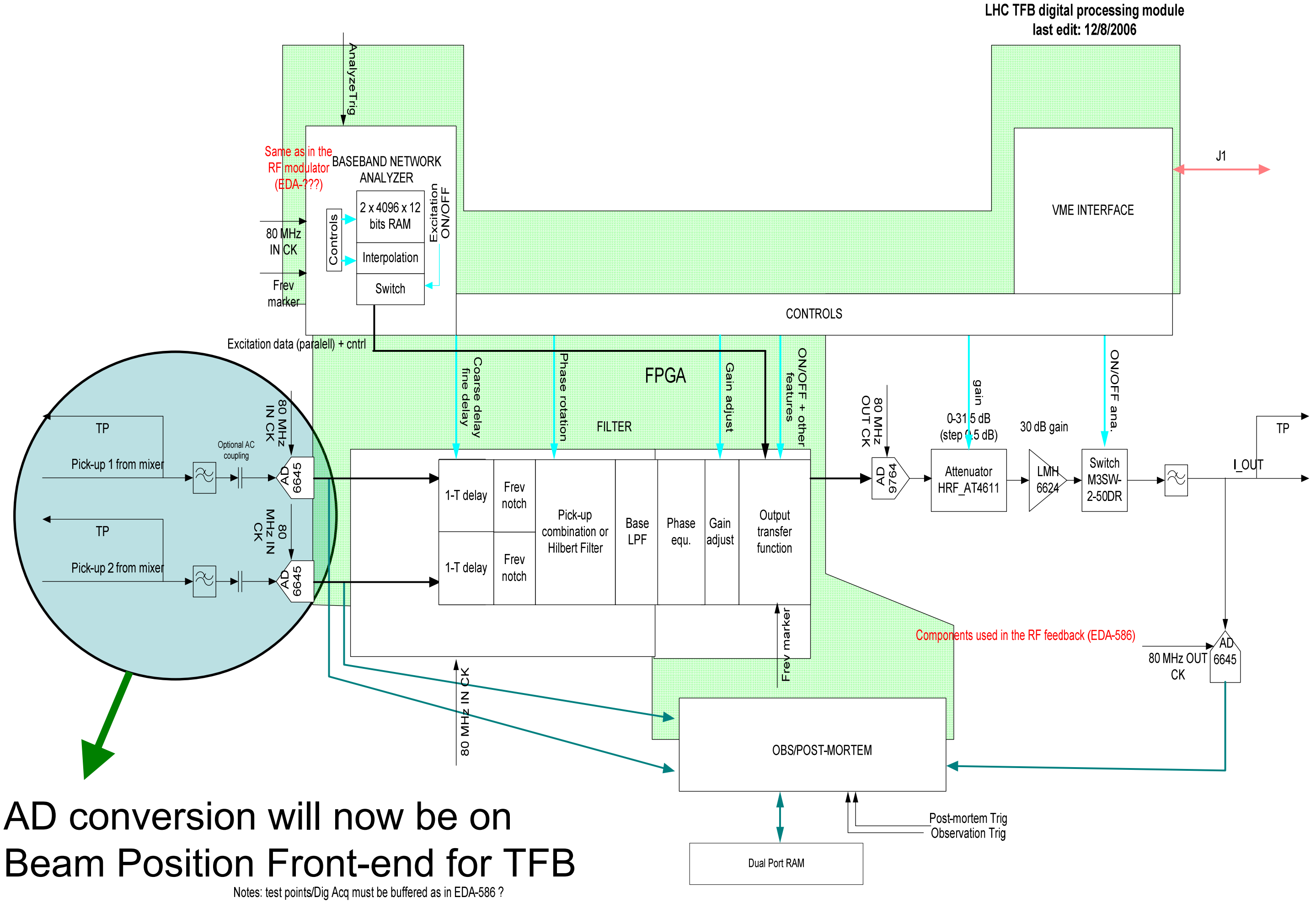
Beam position front-end
(two boards, analogue/ digital part)
prototypes in production





D. Valuch

Digital Processing Module, two 1T FB boards received under test
Reuse a modified version of this RF 1TF FB board for the TFB



AD conversion will now be on
Beam Position Front-end for TFB

Based on long. 1-TFB module (V. Rossi)

Signal levels from coupler type pick-ups

- Length of electrodes 150 mm
- Frequency domain: maximum of transfer impedance 6.46 Ω @ 500 MHz
- Peak voltage for ultimate beam @ collision: ~140 V -> very large
- Maximum of sensitivity at 500 MHz: 0.264 Ω/mm => 8.1 V/mm peak in time domain after ideal hybrid for ultimate beam [140 V x $2^{1/2}$ / 24.5 mm]

- install hybrid on surface (16.3 dB cable attenuation for Q9 will avoid saturation) -> peak voltage reduced from 140 V to ~21 V, OK for wideband hybrid H9 (25 W max)
- Hybrid: 2 dB (+3 dB -1 dB)
- after filtering: ultimate beam: ~0.38 V/mm @ 400 MHz; nominal **0.26 V/mm** (duty cycle 0.8), to be checked with simulations

Signal levels from pick-up

LHC Beam Parameters

	Injection	Collision
Beam Energy	450 GeV	7000 GeV
γ	479.6	7461
RMS bunch length in cm	11.24	7.55
F_{REV} in kHz	11.245	11.245
F_{RF} in MHz (h=35640)	400.789	400.790

Range of intensities for LHC beam and expected pick-up signal levels ($Z_T = 3.23\ \Omega$; $\hat{Z}_T(\omega) = 6.46\ \Omega$)

	Pilot	Nominal beam	Ultimate beam
Particles per bunch	5×10^9	1.15×10^{11}	1.7×10^{11}
Number of bunches	1	2808	2808
Circulating current (DC) in A	9×10^{-6}	0.582	0.860
Bunch peak current @ injection in A	0.9	19.6	29.0
Bunch peak current @ collision in A	1.3	29.2	43.1
Peak Voltage from PU @ inj. in V	**2.8**	63.4	93.6
Peak Voltage from PU @ coll. in V	4.1	94.3	**139.4**

Intensity range to be covered: factor 50

Aim at a better than 1 μm resolution

- Assume bunches oscillate with 1 μm rms (bunch-to-bunch)
- Power available from pick-up @400 MHz (+/- 20 MHz): **433 pW** (nominal beam) to be checked
- Thermal noise at 290 K: $k_B T = 4 \times 10^{-21}$ W/Hz; in 40 MHz BW: **0.16 pW**
- Digitization with effective 14 bit: 16384 discrete levels, assume 1 μm -> 4 steps then 14 bit are sufficient to cover +/- 2 mm
- Large margin with respect to thermal noise: To use this margin we should limit orbit variations at the pick-ups to less than +/- 2 mm.

LHC ADT upgrade possibilities to improve on S/N

- Digitization of pick-up signals underground -> save ~600 m of cable -> gain >12 dB (**factor 4**), but need to develop hybrids, filters and electronics to process large amplitude signals; alternatively use 1 5/8” cable: gain ~6 dB (factor 2)
- If limited by interference & noise on link from surface to tunnel (3 kHz- 20 MHz) -> built digital link and have Digital-to-Analogue conversion as close as possible to amplifiers (possibly find new space for driver amplifiers that are now in UX45)
- Increase beta functions at pick-ups (not very likely but worth a thought since otherwise no additional cost); in particular vertical beta function at BPMC.7L4.B2 for beam 2 somewhat low in optics version 6.5 (= 87 m)
- Average in the signal processing over several turns, i.e. 9 turns, gain of a **factor 3** in S/N if noise turn-by-turn uncorrelated - more turns not feasible due to limited signal processing power and sensitivity to tune.
- Use additional pick-ups; strip-line pick-ups at Q8 and Q10 may be available; gain in S/N **50%,** additional cables and electronics must be installed; further improvement by installing additional pick-ups, spread around the ring?