FCC-hh Transverse Feedback Systems

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Acknowledgements: K. Li, J. Komppula

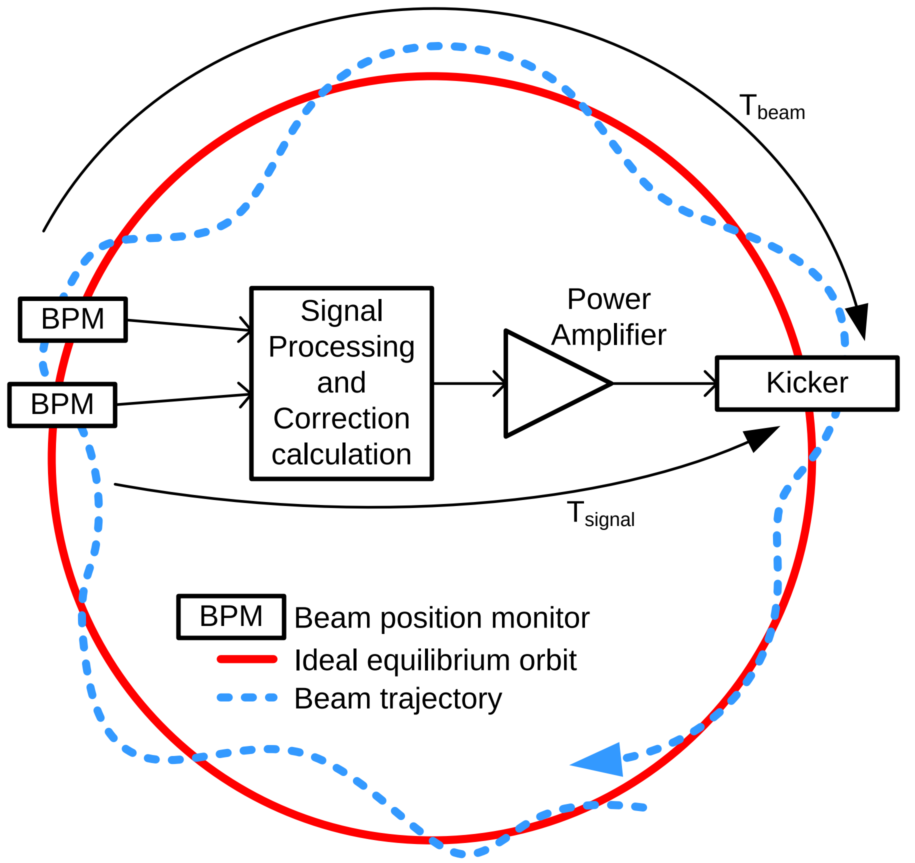
Outline

- FCC-hh transverse feedback system
  - recap of LHC transverse feedback system (ADT)
  - design considerations for FCC-hh from injection damping and simulations
  - intra-bunch feedback and simulation environment
- Conclusions

Principle of Transverse Feedback

LHC

- two pick-ups per beam and plane used (H and V)
- extension to four pick-ups under way for LHC Run 2
- feedback with FIR filters for phase adjustment – multiple turns of delay
- gain limited by type of feedback filter used
- vector sum for more robust phase adjustment possible



$$T_{signal} = T_{beam} + n\, T_{rev}$$

LHC ADT Design Parameters

$$\frac{\Delta\varepsilon}{\varepsilon} = F_\varepsilon \cdot \frac{a_{\mathrm{inj}}^2}{2\sigma^2}$$

relative emittance
increase at injection

$$F_\varepsilon = \left(1 + \frac{\tau_{\mathrm{dec}}}{t_{\mathrm{d}}} - \frac{\tau_{\mathrm{dec}}}{t_{\mathrm{inst}}}\right)^{-2}$$

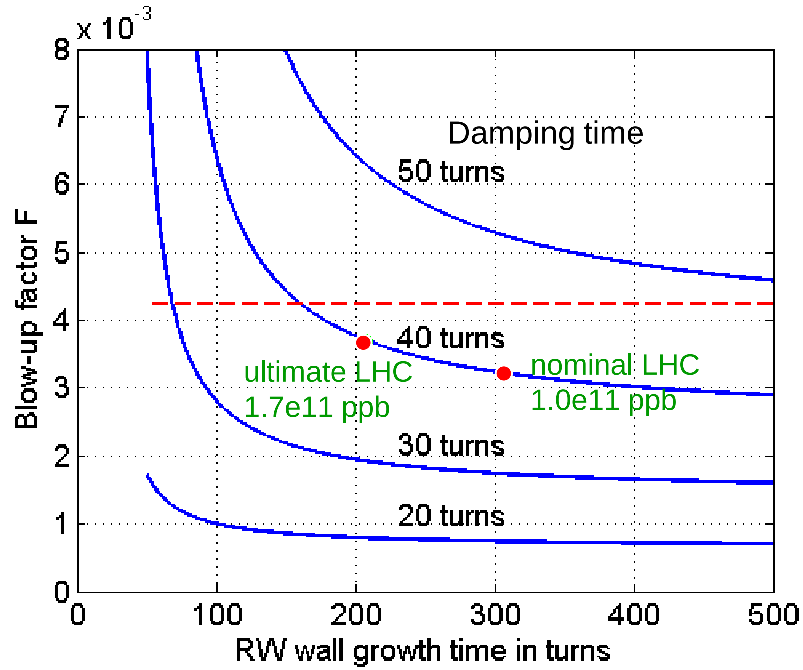
blow-up factor

$$\tau_{\mathrm{dec}} = 68\,\mathrm{ms}$$

de-coherence time
(in design report due to Q')
Full tune spread 1.3×10^{-3}

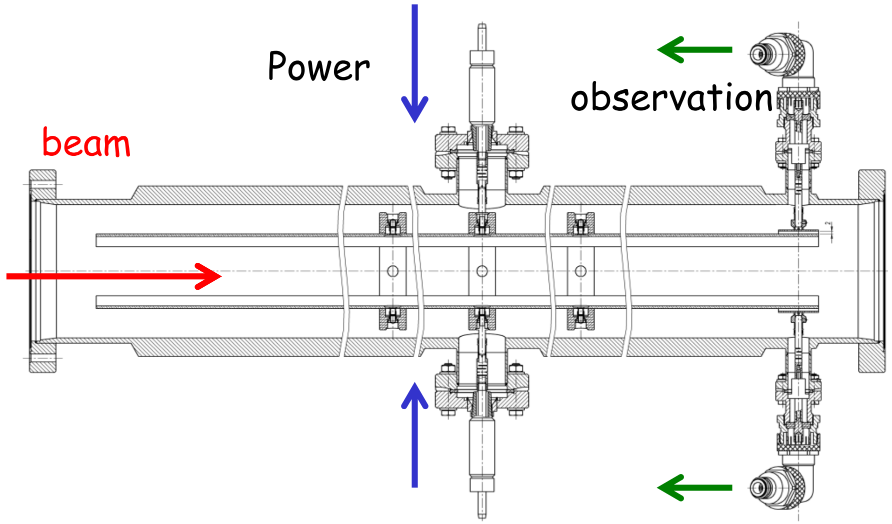
EPAC'08, THPC121
LHC Design Report CERN-2004-003

injection		value
energy	E	450 GeV
emittance (norm)	ε	3.5 μm
injection error	a_{inj}	4 mm @ β=185 m
increase w/o FB	$a_{inj}^2/(2\sigma^2)$	(5.92)
max increase of ε	$(\Delta\varepsilon/\varepsilon)_{max}$	0.025
Blow-up factor	F_ε	$< 4.22 \times 10^{-3}$



LHC Run 1 (50 ns): in practice smaller emittances available from injectors (BCMS)
LHC Run 2 (25 ns): aimed for nominal, in practice BC(M)S type beams (3x48 and 8b4e)

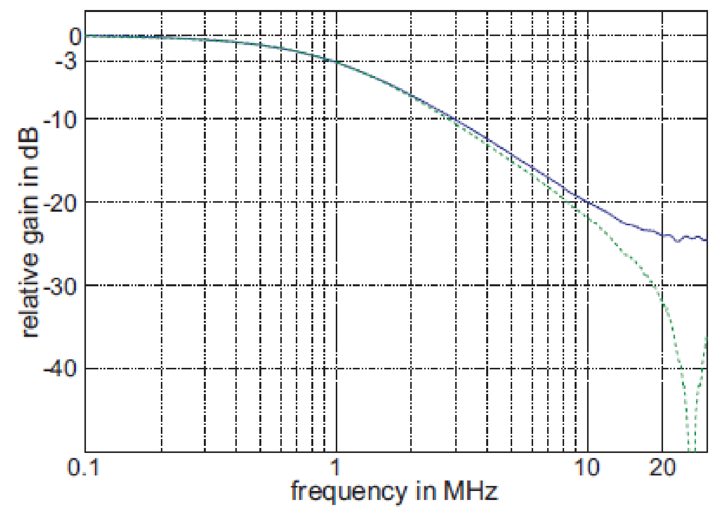
LHCADT Power and Kicker System



ADT kicker. The beam is kicked by electric field

- kicker length: each kicker 1.5 m
- max voltage: 10.5 kV
- 2 μrad kick to 450 GeV beam
- gain up to beyond 20 MHz
- 16 kickers,
- 32x30 kW tetrode amplifiers
- bandwidth up to 20 MHz
- scaled from SPS system

LHC transverse Feedback (ADT) kickers and amplifiers in tunnel point 4 of LHC, RB44 and RB46
Kickers and Power Amplifiers → JINR, Dubna Collaboration



Measured ADT frequency response. Green: bare power amplifier, blue: power amp + kicker
Batch spacing (injection: 925 ns - 975 ns) matched to 1 MHz “power bandwidth”

LHC TFB – Use Cases

- Initially designed for
  - injection damping
  - feedback during ramp (coupled bunch instabilities)
- LHC Physics Run 1 (2010-2013)
  - providing stability at all times in the cycle
    (including with colliding beams !)
  - diagnostics tool to record bunch-by-bunch oscillations
  - abort gap and injection gap cleaning
  - blow-up for loss maps and aperture studies
  - tool to produce losses for quench tests
  - tune measurement and online damping time measurement (from Run 2 onwards)

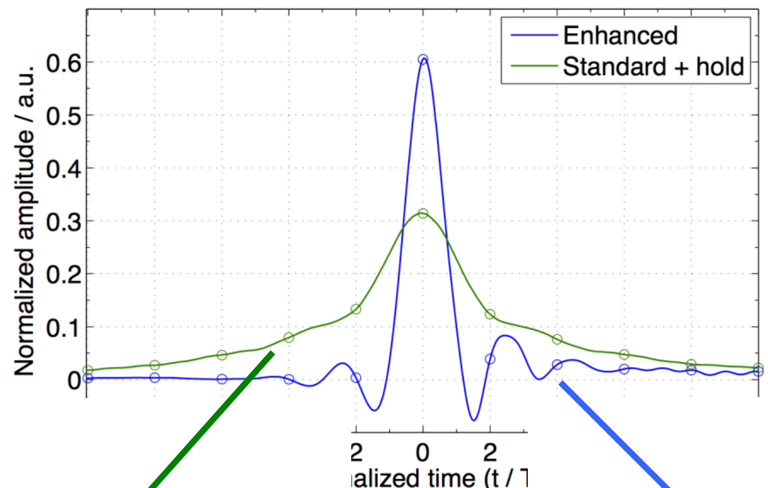
Injection oscillations – batch View

LHC

V-plane

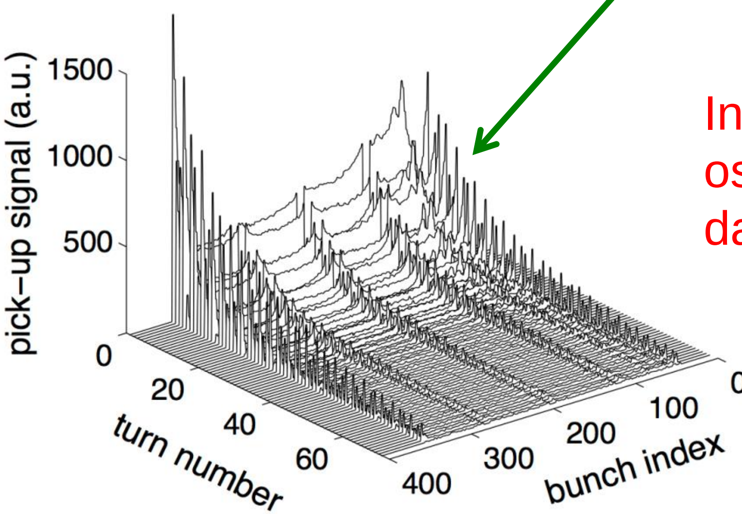
Data from

LHC run 1 (2012)

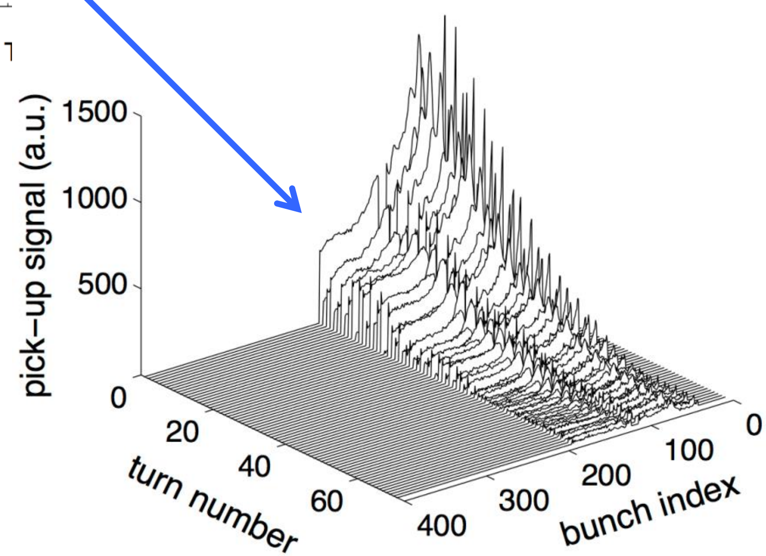


50 ns bunch spacing
standard + hold
144 bunches (4x36)

25 ns bunch spacing
enhanced bandwidth
144 bunches (2x72)



Injection
oscillation
damping



damping at edges of batch slower

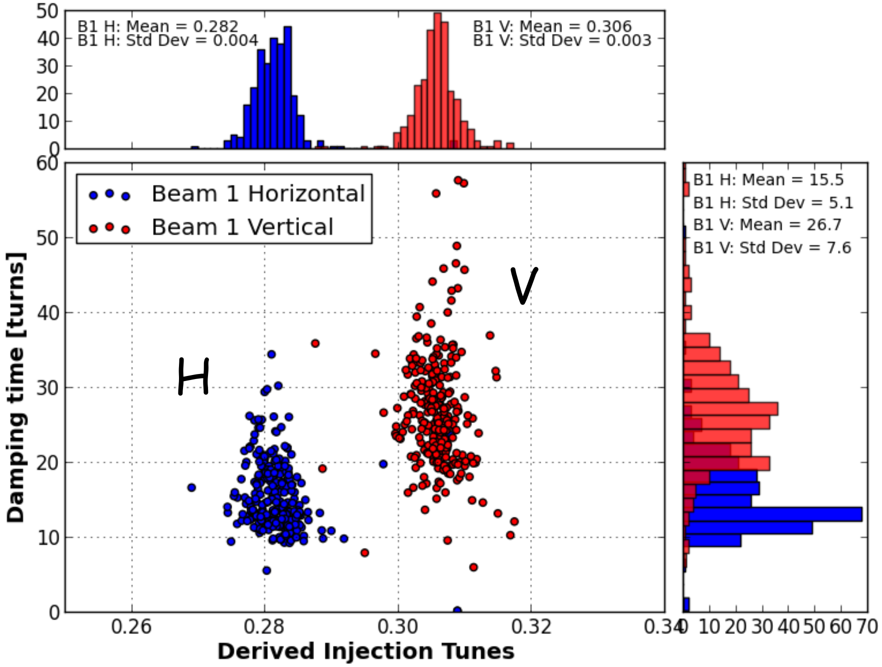
LHC rum 2: enhanced bandwidth during injection and ramp

standard bandwidth in stable beams (lower noise)

IPAC’13, WEPME43

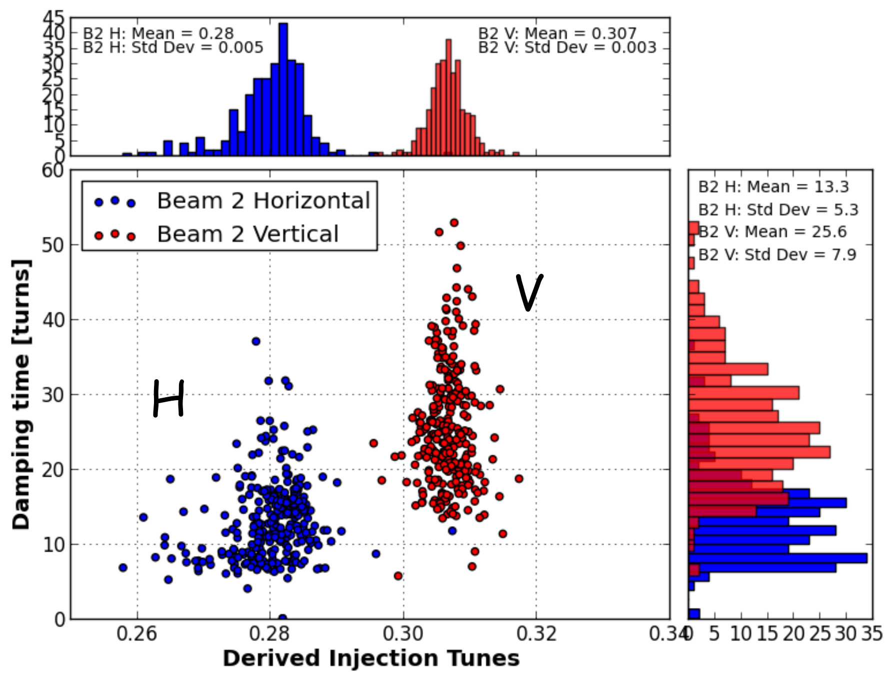
LHC 2012 Run 1 achievements

Damping times as measured on first bunch of batch



Beam 1
H: 16 turns
V: 27 turns

Beam 2
H: 13 turns
V: 26 turns



LHC, curtesy A. Macpherson
See also IPAC'13, FRXCA01

injection kicker ripple → slower V-damping

FCC-hh TFB: 25 ns – 97.7 km

FCC tentative parameters

injection		value
emittance (norm)	ε	2.2 μm
injection error	a_{inj}	1 mm @ β = 200 m
increase w/o FB	$a_{inj}^2/(2\sigma^2)$	depends on energy
max increase of ε	$(\Delta\varepsilon/\varepsilon)_{max}$	0.05

FCC versus LHC assumption:
- smaller design injection error
- 0.5 mm + 0.5 mm ripple
- de-coherence different
- faster instability

FCC injection energy options

Injection energy in GeV	Coupled bunch Instability rise times in turns (O. Boine-Frankenheim et al.)
450	8 … 16
1500	22 … 47
3300	43 … 91

fractional tunes: 0.72 or 0.32

impedance model being updated

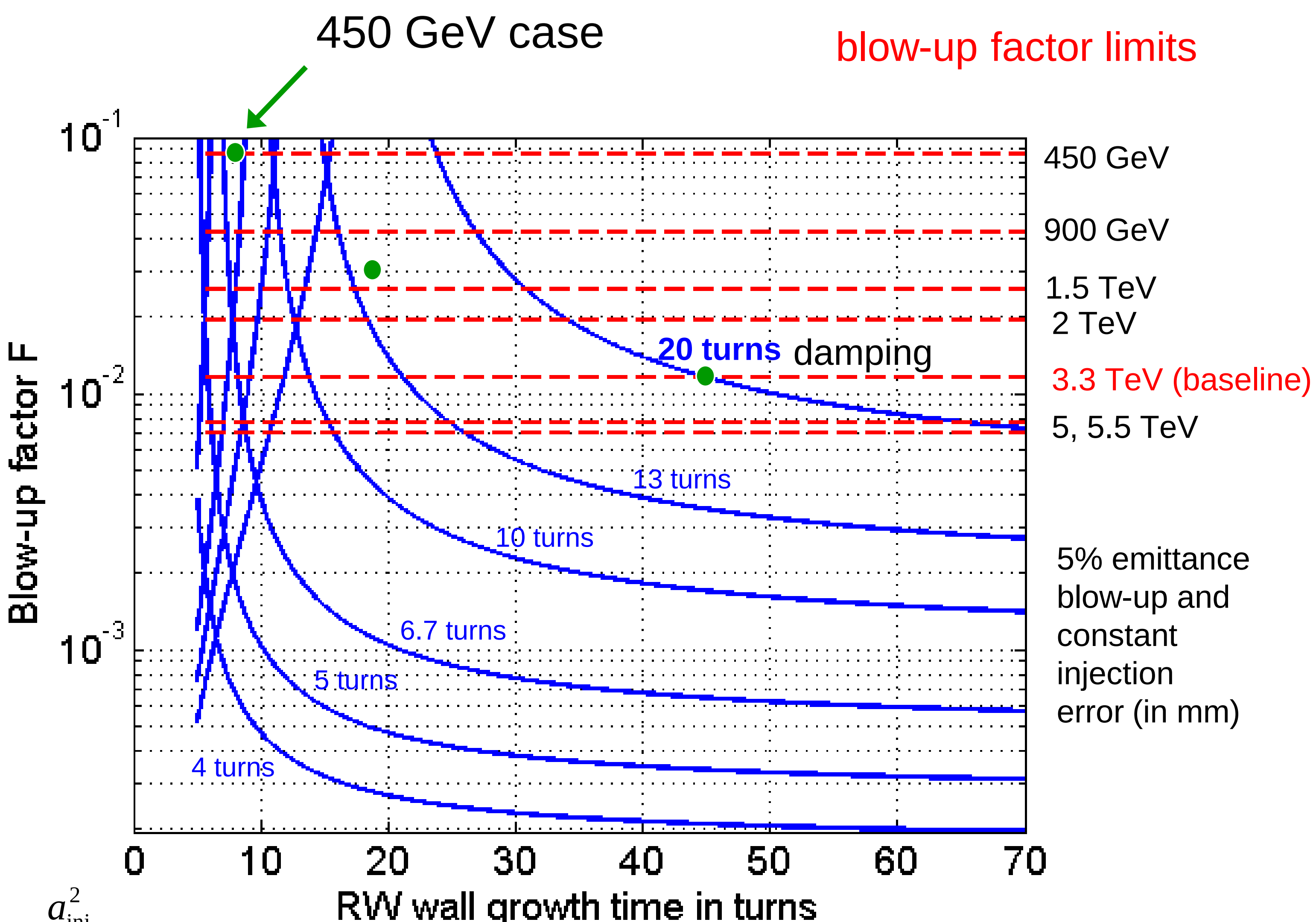
$\tau_{dec} = 100\,\mathrm{ms}$ (~3×10^{-3} t.b.c.)

de-coherence time
(needs determination)

Full simulation at injection
In presence of
- damping
- tune spread
- instabilities

desirable

FCC injection damping (25 ns)



$$\frac{\Delta\varepsilon}{\varepsilon} = F_{\varepsilon} \cdot \frac{a_{\text{inj}}^2}{2\sigma^2}$$

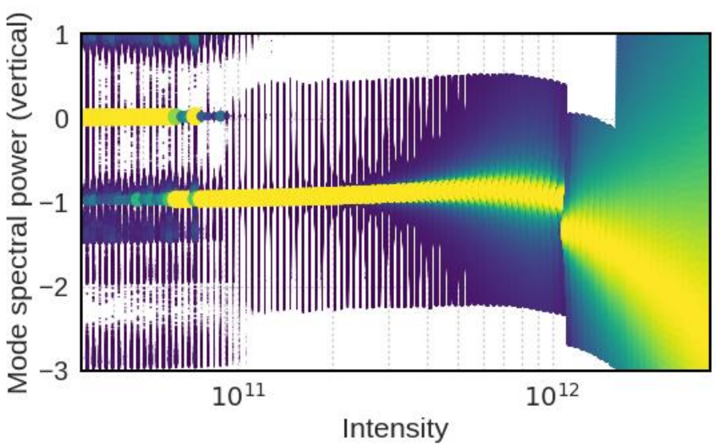
Parameters for injection damping

Parameter	LHC	FCC-hh (25 ns)	FCC-hh (5 ns)	
energy (inj.)	0.45	3.3	3.3	TeV
emittance (norm) ε injected	3.5	2.2	0.44	μm
bunch spacing	25	25	5	ns
batch spacing	925	300	300	ns
max FB frequency	20	20	20 (100)	MHz
Power bandwidth FB	1	3	3	MHz
injection errorr a_{inj}	4 (1)	1	1	mm
max increase of ε with FB	2.5	5		%
res. wall instability growth	310	80 (43)	80 (43)	turns
damping time FB	40 (13)	20	20	turns
deflection (total)	2	0.5	0.5	μrad
voltage per kicker (1.5 m)	7.5	2.5	2.5	kV
# kickers per plane/beam	4	22	22	

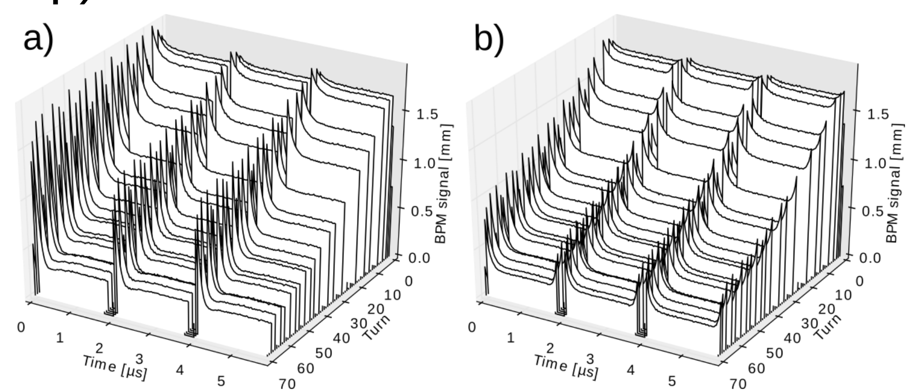
- 5 ns option requires additional (e.g. strip-line kickers) to cover 20 -100 MHz
- LHC damping is as achieved in regular operation () limited by feedback stability
- ref. beta for kickers / injection errors: ~200 m
- 100 m – 150 m needed (staggered installation)
- for CDR optimization possible, propose consistent set of parameters for baseline

Simulation – damping-instability

- simulation environment developed to cover coupled bunch and intra-bunch feedback (macro-particle code)
- integrated with CERN head tail code
- objective: refined quantitative results for CDR for coupled bunch and intra-bunch feedback using full impedance model, injection error, and de-coherence by non-linearities
- injection damping (determine blow-up)
- instability mitigation by feedback



study of influence of dipolar feedback on TMCI (64 turns damping time)



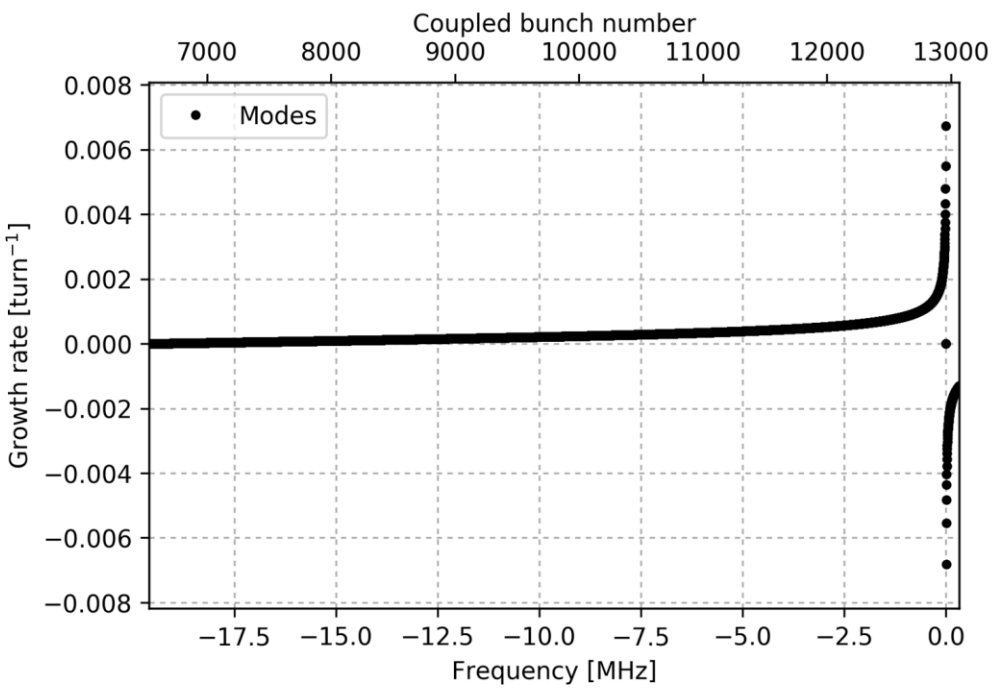
injection damping

(different signal processing can be evaluated)

see poster J. Komppula et al. at FCC week in Berlin (2017)

also IPAC'17 TUPIK091

Results with Head-tail for CBI

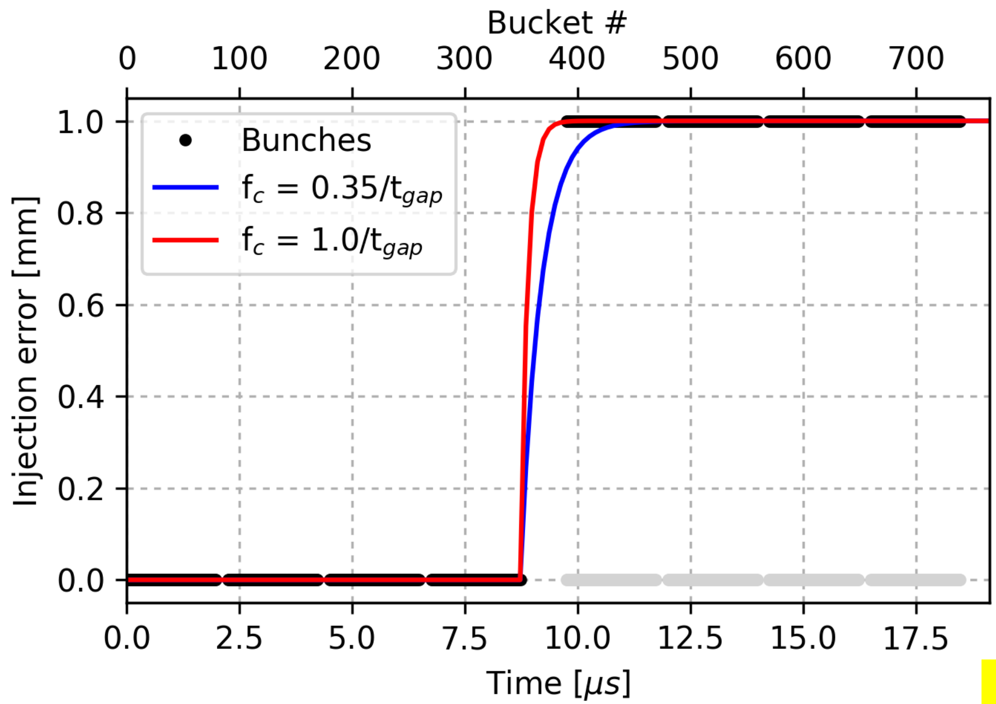


25 ns bunch spacing

- Full number of bunches
- Wakefield from impedance model
- Bench marking ongoing

J. Komppula et al.

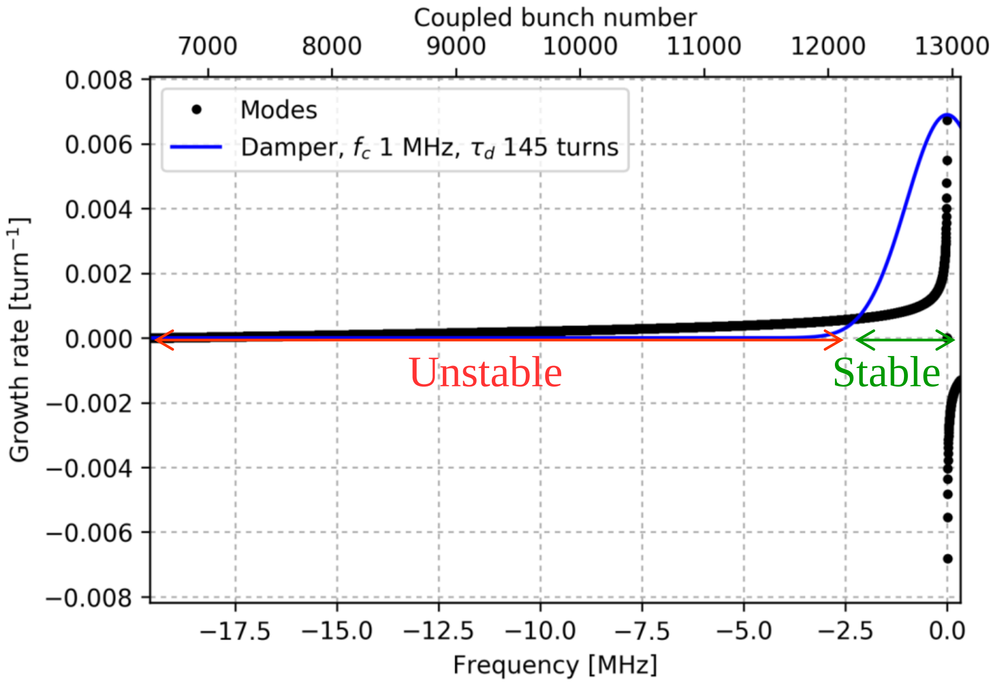
Bandwidth – step response



J. Komppula et al.

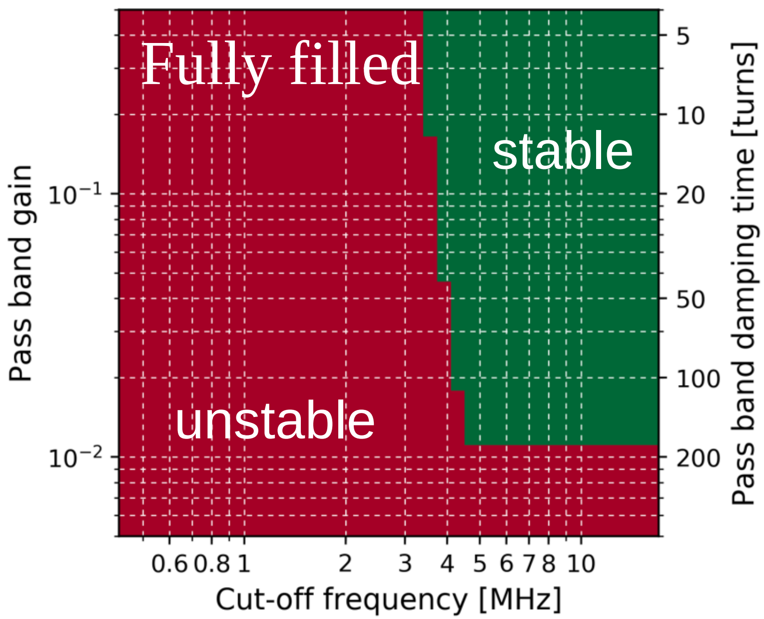
- Frequency up to which full kick strength must be available given by gap length between injected batches and acceptable tolerances
- Modelling with low pass (e.g. gaussian)

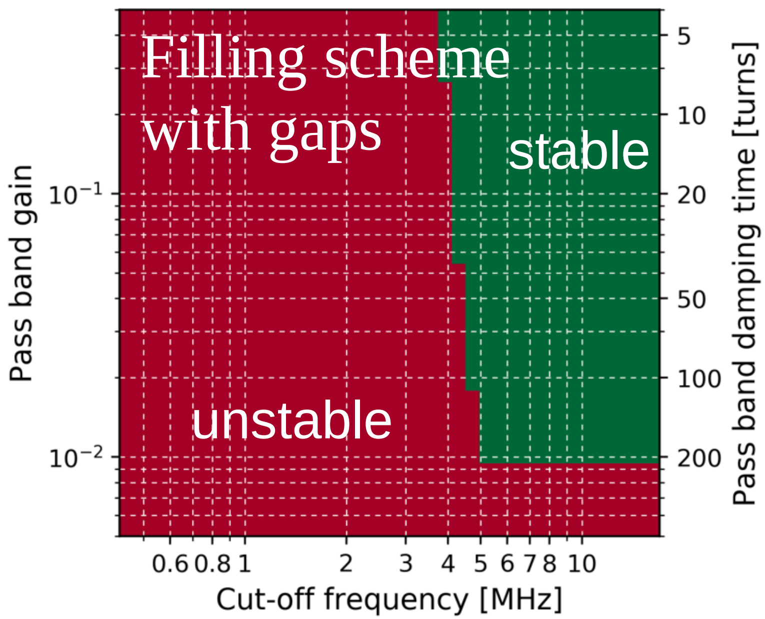
Inclusion of damper



- Inclusion of damper with its frequency response

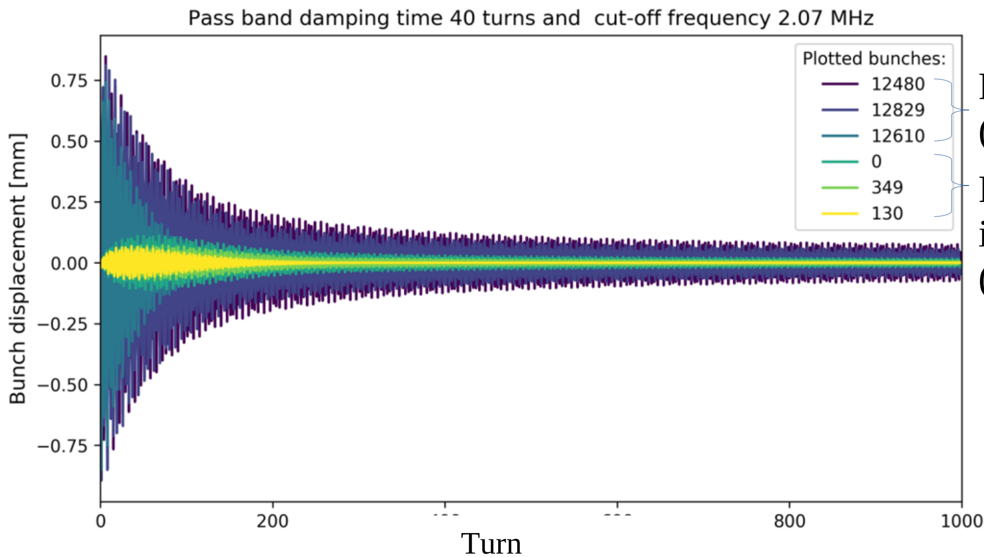
damper – numerical results





J. Komppula et al.

Injection damping



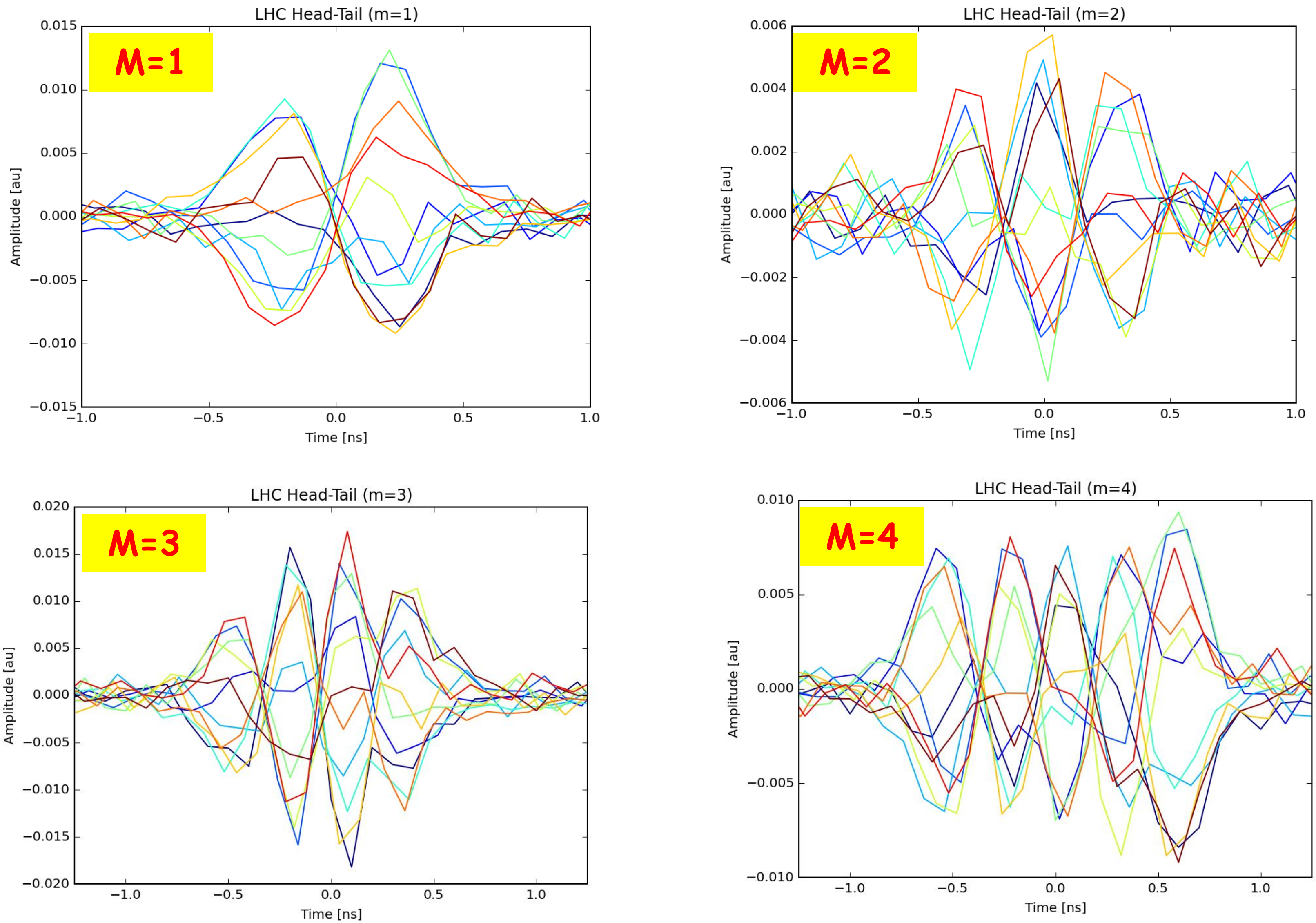
Significantly longer damping times on the edge of the injected batch (damper model sensitive)

Wakes induce small oscillations to the previously injected bunches

Next step:

- Improve model for the damper
- Numbers for the emittance growth from multibunch PyHEADTAIL simulations
- Taking into account chromticity, octupoles and injection kicker ripple

Intra-bunch motion at LHC



observed intra-bunch motion in LHC

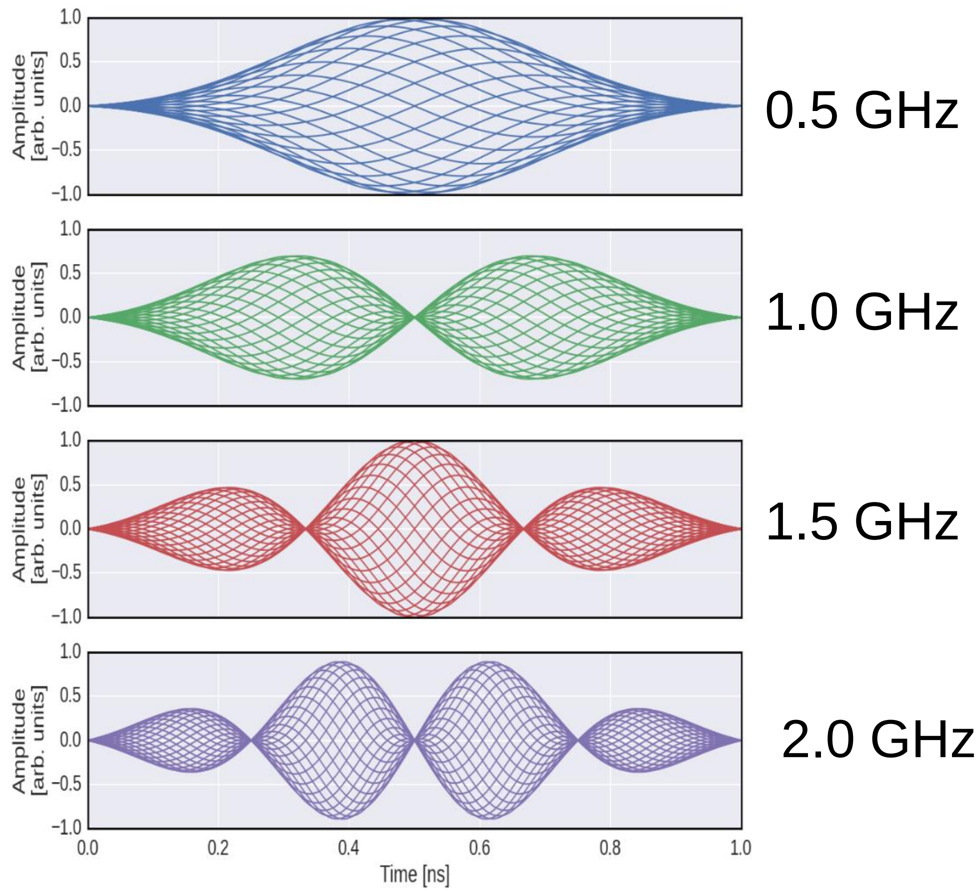
T. Levens

Mitigation of intra-bunch motion

upgrade options for
LHC Transverse Feedback
(under study)

options:

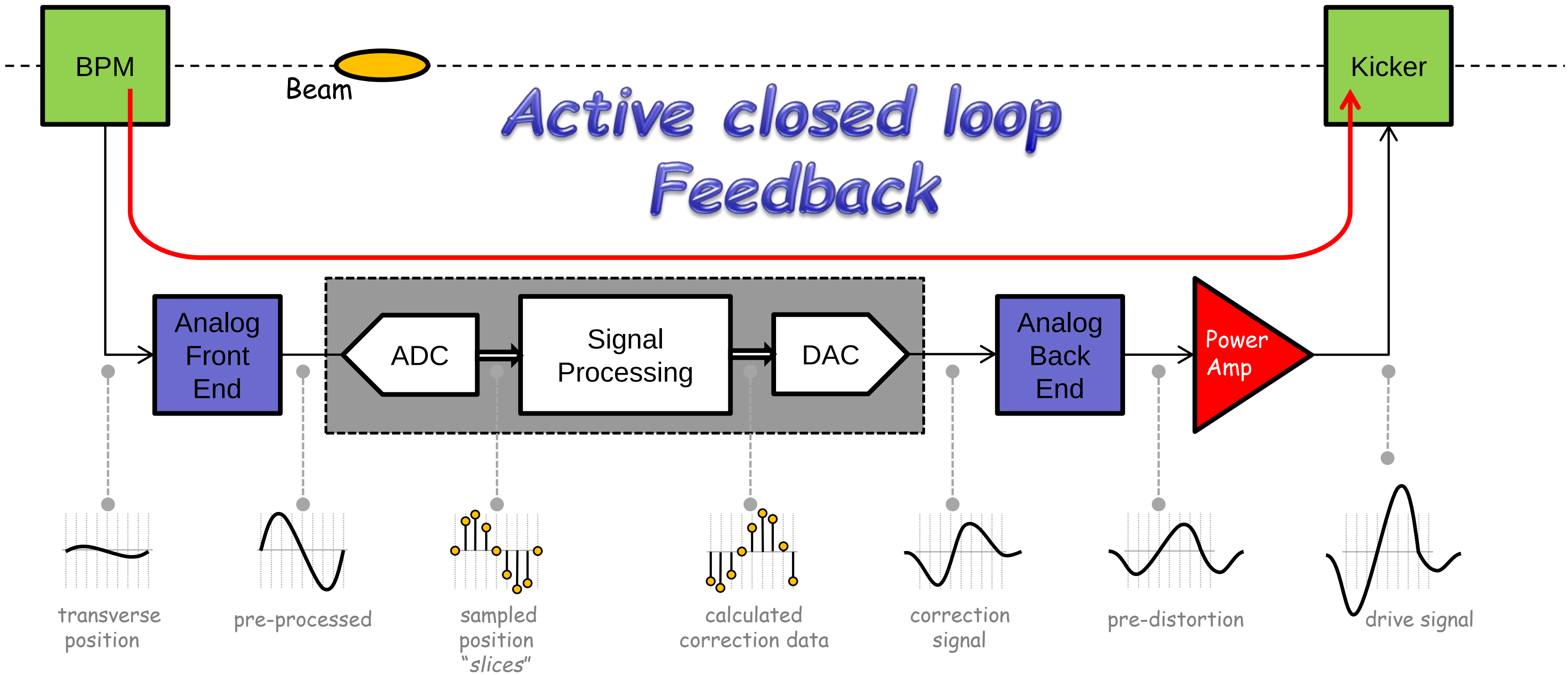
1. Extension of current system:
   long strip-line at 40 MHz for true bunch-by-bunch damping
2. Band-by-band approach:
   strip-line at 400 MHz in combination with slot-lines at 800, 1200, 1600, 2000, 2400,… MHz



under study for FCC, based on LIU SPS developments
mitigation of e-cloud and TMC instability

SPS LIU demonstrator results:
J.Fox, K. Li, e. Bjorsvik,
IPAC’17, TUPIK119

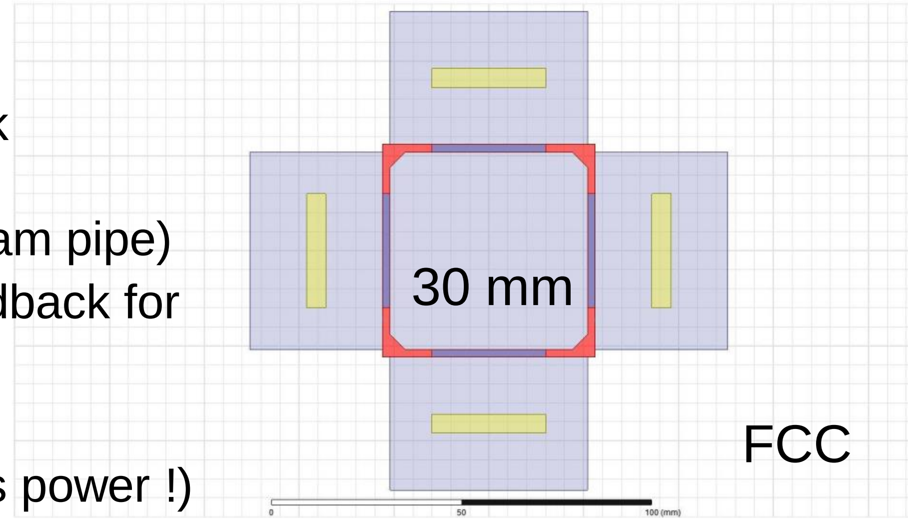
R&D: intra-bunch feedback (SPS)

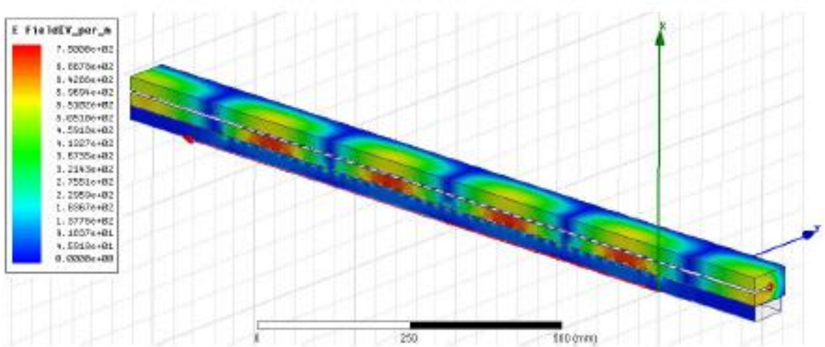


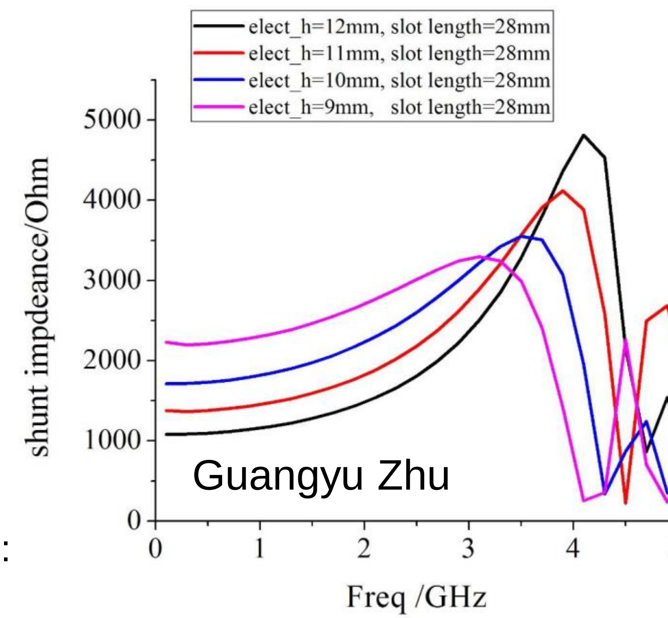
- capacity to damp intra-bunch instabilities, 4-8 GS/s digital feedback
- started as e-cloud instability feedback in SPS
- also shown to damp TMCI in simulation if synchrotron tune low
- closed loop experiments in SPS started
- Feasibility at 450 GeV demonstrated on slingle bunch slow head-tail instability (2016)
- targeted bandwidth in SPS → 1 GHz, needed BW scales with bunch length

Perspectives: Kicker Design

- ❑ R&D for SPS intra-bunch feedback
  → Faltin type kicker being built
  (strip-line with slotted shield to beam pipe)
- ❑ applicable to FCC intra-bunch feedback for up to 4 GHz
- ❑ optimization of shunt impedance
- ❑ caution: TeV beam energy (→ kWs power !)







SPS prototyping (installation foreseen in 2017/2018 YETS):
J. Cesaratto et al. (SLAC), IPAC’2013
M. Wendt (CERN), IPAC’2017

Conclusions and outlook

- need a coupled bunch feedback with options for 5 ns and 25 ns bunch spacing (driven by resistive wall instability → fast instability rise times at low frequency)
- LHC type transverse feedback system proposed as baseline for 25 ns option, 22 kickers per plane and beam with adaptation of power bandwidth to FCC needs
- 5 ns option requires additional kickers to cover higher frequencies (strip-lines)
- GHz feedback can be an option to mitigate slow intra-bunch instabilities, kicker designs being proposed based on SPS-LIU R&D
- impact of feedback noise, suppression of emittance growth by ground motion and due to crab cavity noise needs consideration
- simulation environment developed, integrated with head-tail code to refine in simulation the specifications and evaluate the performance for the CDR treating coupled bunch and intra-bunch instabilities as well as injection errors and filamentation