RF System and Transverse Feedback

FCC-hh

Wolfgang Hofle

BE-RF-FB

Start with where we stand → LHC

- ✓ Key FCC-hh parameters very similar to LHC
- ✓ 25 ns and 5 ns bunch spacing options
- ✓ Beam current similar to LHC, 1×10^{11} protons per bunch for 25 ns

FCC-hh RF system and transverse feedback design follow same design path as for the LHC Design:

- → LHC: Super conducting RF cavities with low R/Q to mitigate impact of transient beam loading, half detuning used, strong RF feedback
- → moderate RF voltage requirements, power requirements dominated by power needed for beam loading compensation
- → strong transverse feedback for coupled bunch instability mitigation driven by resistive wall impedance of beam screen and machine elements
- → knowledge of impedance key to define parameter space for RF system and transverse feedback
- → FCC-hh will have significant synchrotron radiation damping; emittance control important both longitudinal and transverse (blow-up may be needed)

FCC-hh RF Design Considerations

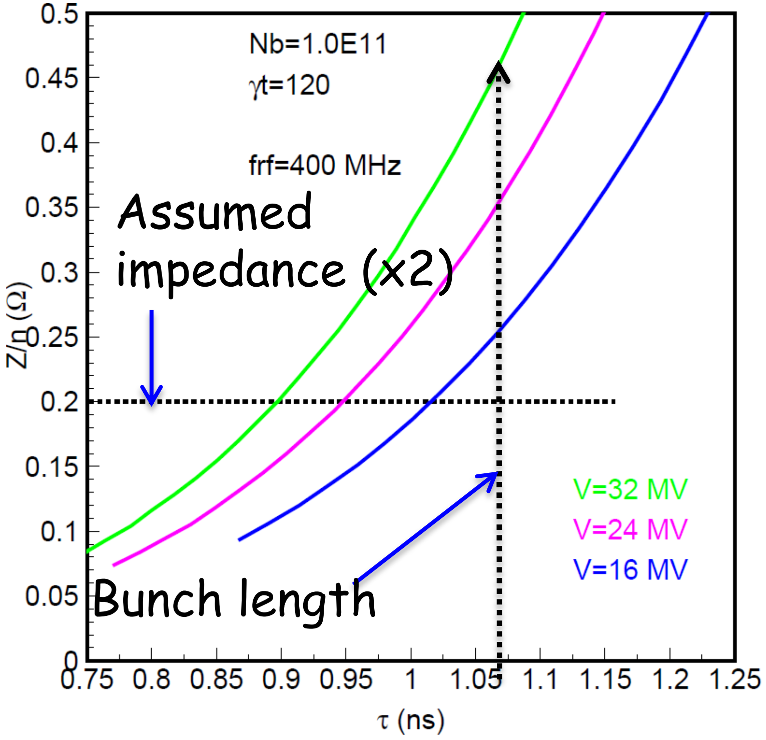
400.8 MHz seems a good baseline
- ❑ 16 MV minimum with no margin
- ❑ 32 MV seems fine

200 MHz appear somewhat low
- ❑ Needs higher voltage (>100MV)
- ❑ Or longer bunches (12cm)

800 MHz appears too high for main system perhaps needed as higher harmonic system as being considered for LHC

Combination of 200 and 400 MHz also an option ?

E. Shaposhnikova



RF system will look very similar to LHC RF system at 400.8 MHz

Transverse Feedback: LHC

ADT - LHC Transverse Feedback (Damper)

- ✓ Injection damping → high gain, low bandwidth, large kick strength
- ✓ Instability damping → gain adapted to instabilities, bandwidth can be tailored by signal processing
- ✓ Preservation of emittance → low noise, detection of μm oscillation
- ✓ Tool for transverse blow-up → loss maps, quench tests, aperture measurements
- ✓ LHC Transverse Feedback → operation with colliding beams well established using a digital system, a first in a Hadron Collider
- ✓ Full exploitation of ADT data for beam diagnostics and tune measurement being prepared for Run 2
- ✓ Improvements prepared in LS1 (number of pick-ups, electronics, software upgrade), reduction of noise, to come on gradually in run 2

FCC-hh Requirements

- ✓ Injection damping → high gain, low bandwidth, large kick strength
- ✓ Instability damping → coupled bunch instabilities driven by resistive wall impedance of beam screen / beam pipe
- ✓ Preservation of emittance → low noise, detection of μm oscillation
- ✓ Maintaining emittance → noise injection to counteract emittance shrinking by radiation damping at top energy and during ramp ?
- ✓ Advanced diagnostics potential and compatibility with tune measurement needs to be given attention from the beginning → learn from LHC and High Lumi LHC experience

- ❑ Do we require to damp single bunch instabilities ?
- ❑ Do we require to damp internal bunch motion (TMCI like) ?
- ❑ Are there narrow band transverse impedances that require damping with high gain up to half the bunch repetition frequency (see for example the issue with HOMs of High Lumi LHC crab cavities) ?

LHC ADT Design parameters

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

relative emittance increase at injection

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

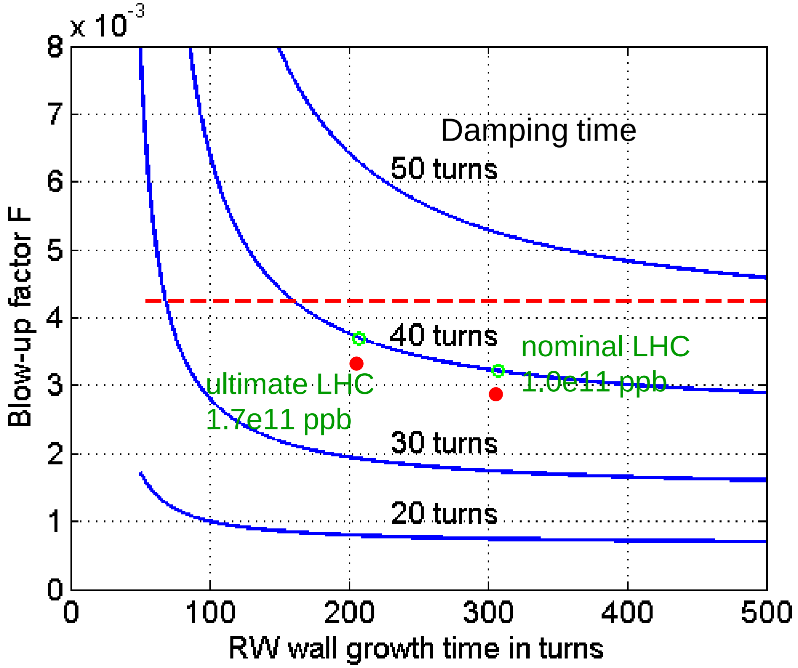
blow-up factor

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

de-coherence time
(in design report due to Q')
Full tune spread 1.3x10^{-3}

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

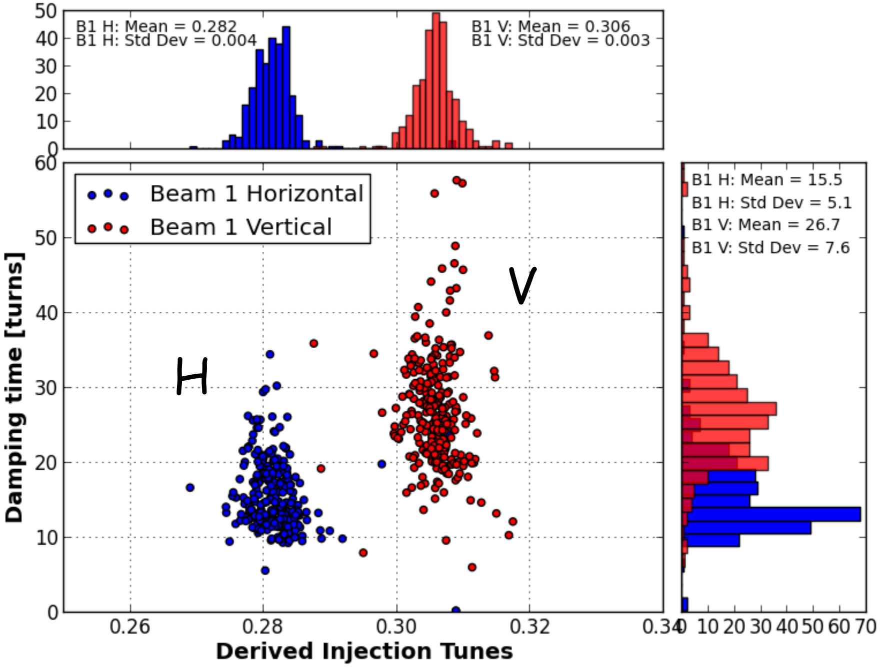
injection		value
energy	E	450 GeV
emittance (norm)	ε	3.5 µm
injection error	a_{inj}	4 mm @ β=185 m
increase w/o FB	$a_{\mathrm{inj}}^2/(2\sigma^2)$	(5.92)
max increase of ε	$(\Delta\varepsilon/\varepsilon)_{\max}$	0.025
blowup factor	F_ε	< 4.22 x10^{-3}



LHC Run 1: in practice smaller emittances available from injectors

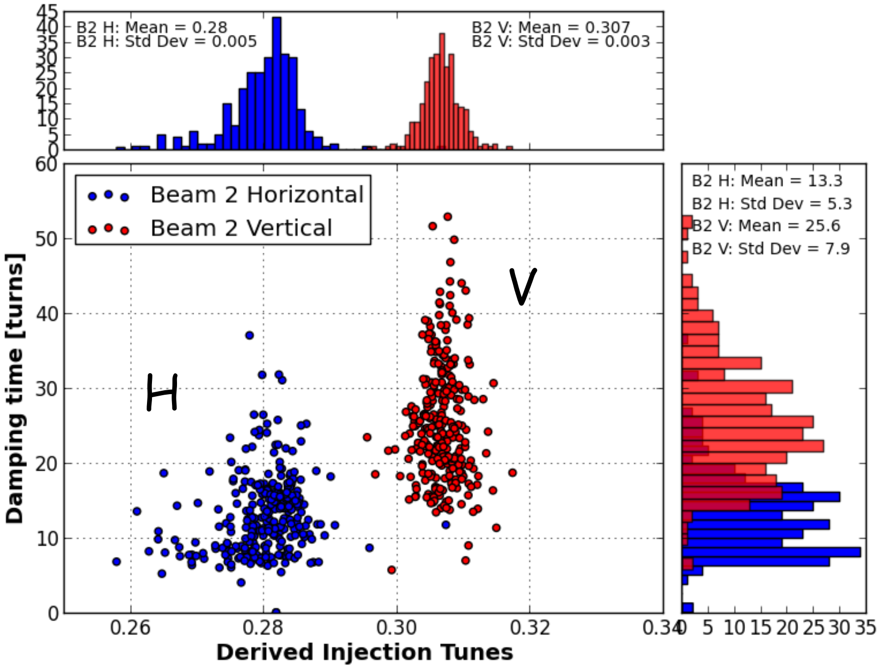
LHC 2012 Run achievements

Damping times as measured on first bunch of batch



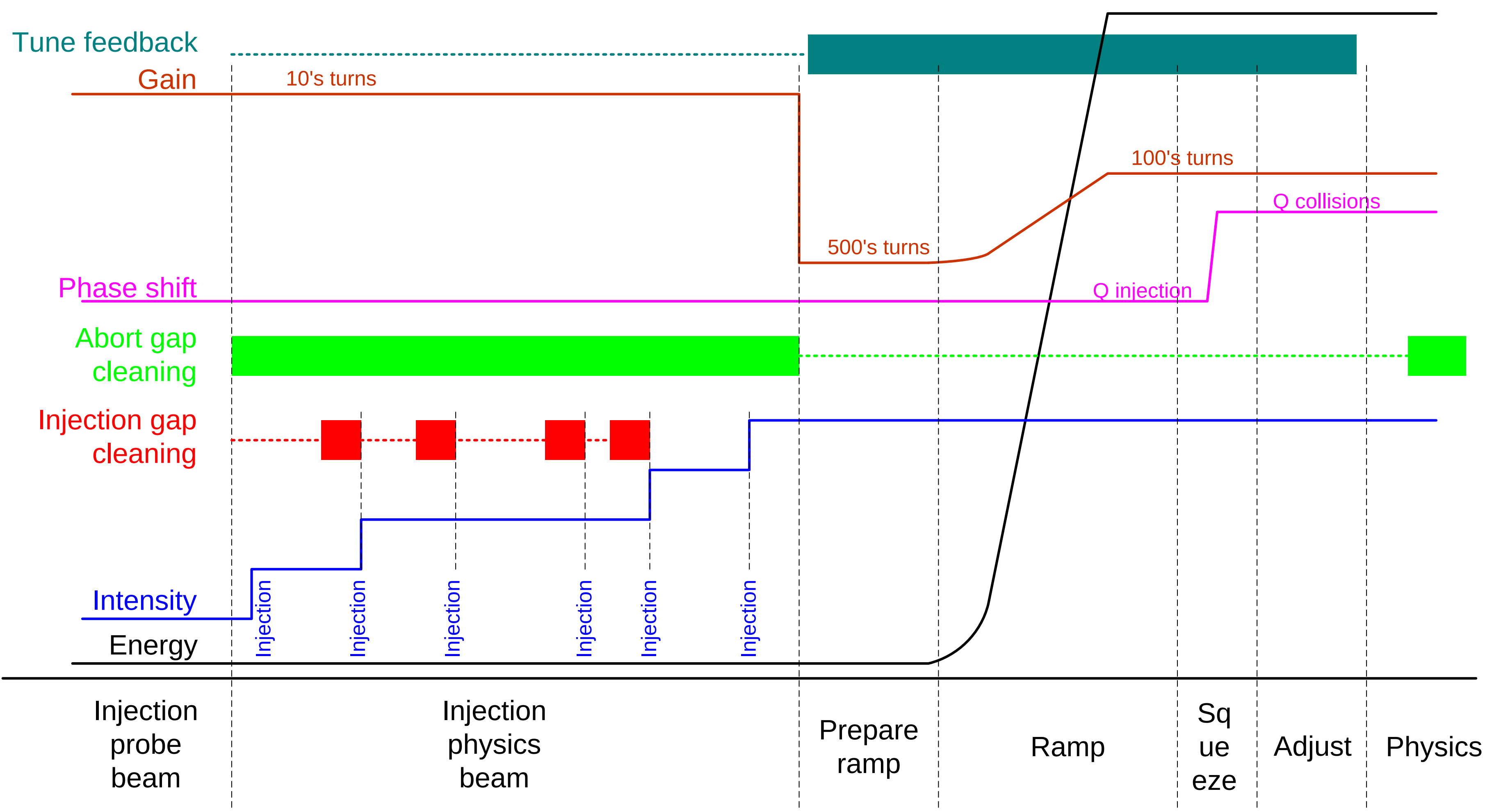
Beam 1
H: 16 turns
V: 27 turns

Beam 2
H: 13 turns
V: 26 turns



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

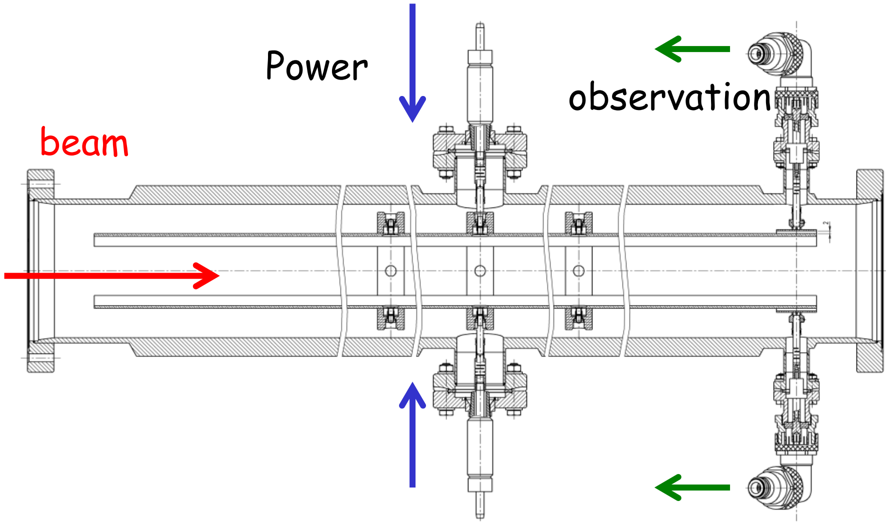
LHC ADT within Operational Cycle



curtesy D. Valuch

needed to lower gain in ramp for FB-tune measurement compatibility

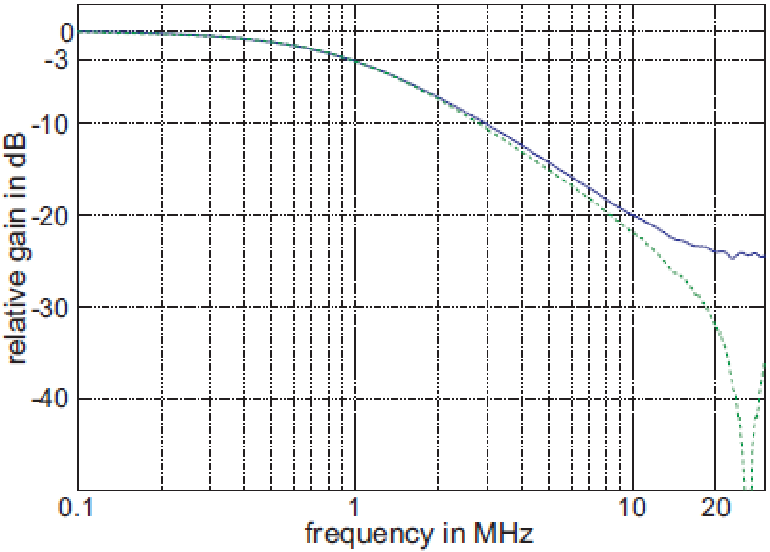
LHCADT Power and Kicker System



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

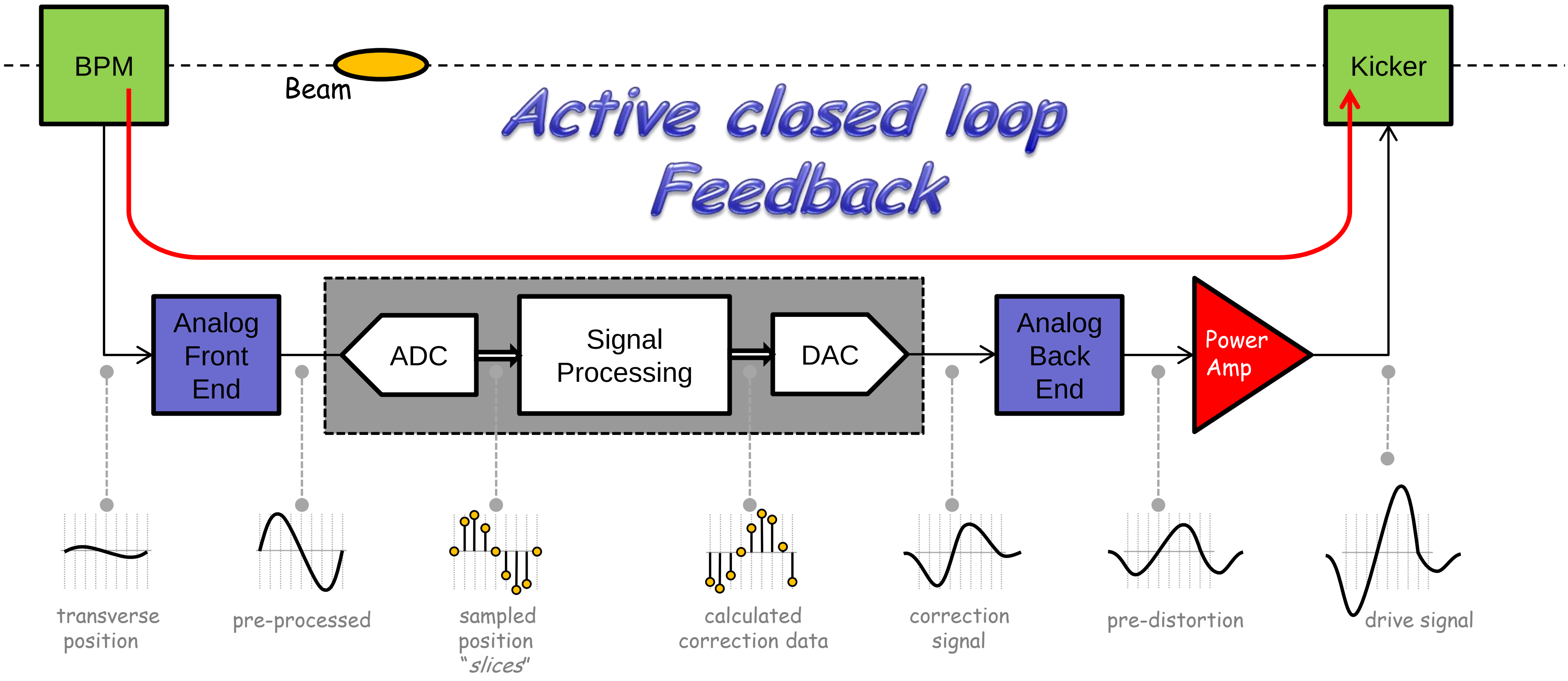
LHC transverse Feedback (ADT) kickers and amplifiers in tunnel point 4 of LHC, RB44 and RB46



Measured ADT frequency response. Green: bare power amplifier, blue: power amp + kicker.

FCC-hh requires more bandwidth (5 ns option bunch spacing option)

R&D: intra-bunch feedback (SPS)



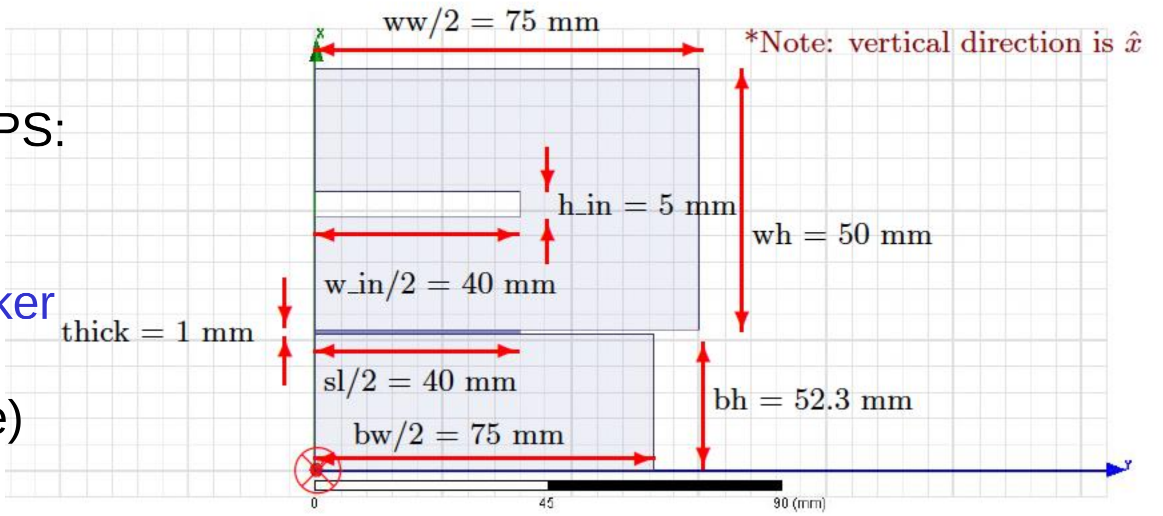
- ❑ capacity to damp intra-bunch instabilities, 4-8 GS/s digital feedback
- ❑ originally started as e-cloud instability
- ❑ also shown to damp TMCI in simulation if synchrotron tune low
- ❑ closed loop experiments in SPS started
- ❑ milestone to demonstrate feasibility: mid 2016
- ❑ targeted bandwidth → 1 GHz
- ❑ good to cover large range of bandwidth

supported by US-LARP
and SPS-LIU
J.D. Fox et. al

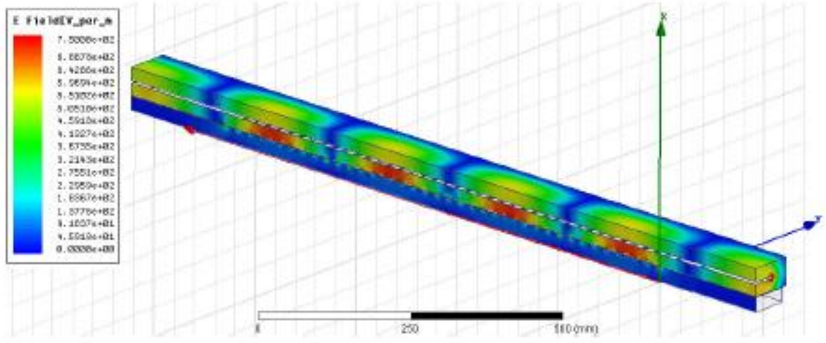
US LARP Feedback Kicker Design

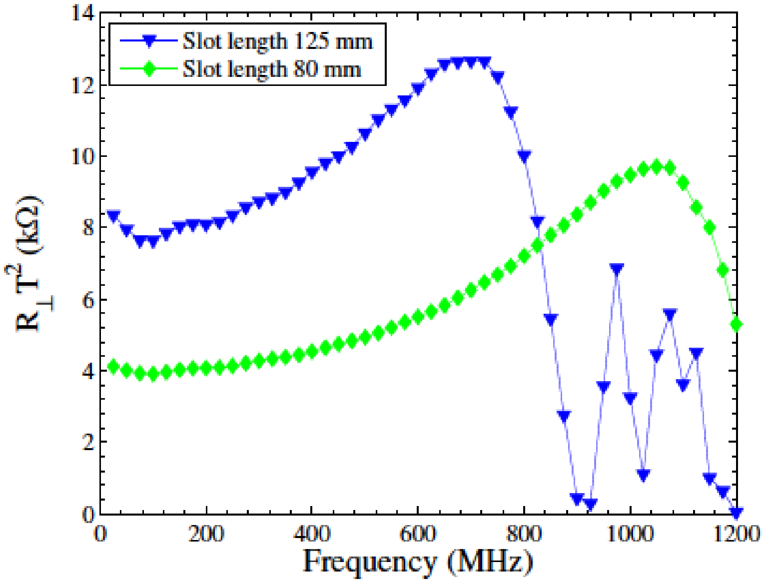
Need for high Bandwidth requires new kicker for the SPS:

- Inspired by Stochastic Cooling Systems → Faltin type kicker considered (strip-line with slotted shield to beam pipe)



Develop for test of prototype in SPS





J. Cesaratto et al. (SLAC)
WEPME061, IPAC'2013

FCC-hh TFB: 25 ns -100 km option

injection		value
energy	E	3300 GeV
emittance (norm)	ε	2.2 μm
injection error	a_{inj}	1 mm @ β=185 m ?
increase w/o FB	$a_{\text{inj}}^2/(2\sigma^2)$	(4.32)
max increase of ε	$(\Delta\varepsilon/\varepsilon)_{\max}$	0.05
blowup factor	F_ε	< 11.6 x10^{-3}

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

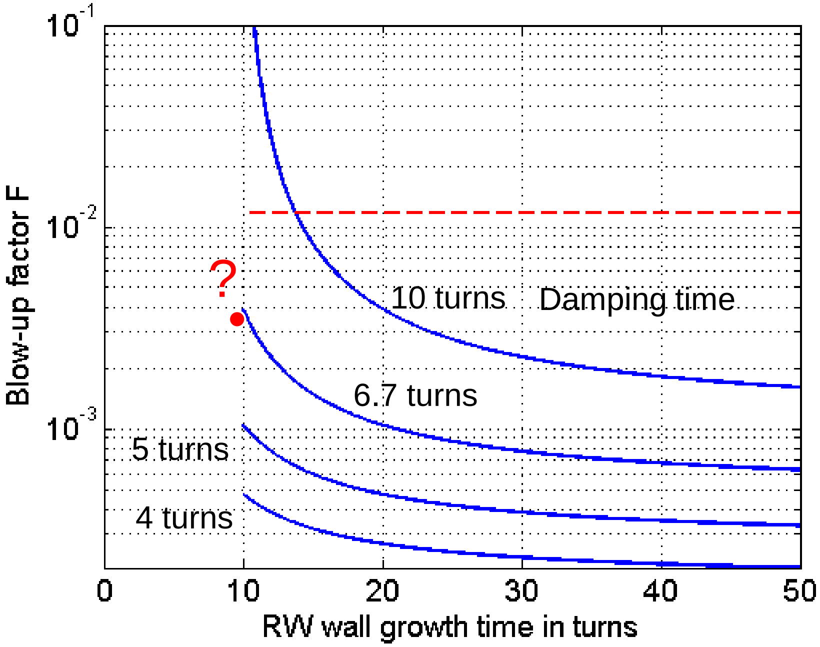
relative emittance
increase at injection

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

blow-up factor

$$\tau_{\text{dec}} = 100\,\text{ms} \quad ?$$

de-coherence time
(needs determination)



FCC versus LHC:

- smaller injection error
- slower de-coherence ?
- but faster instability

→ develop feedback algorithms for fast damping

Summary FCC-hh RF & TFB

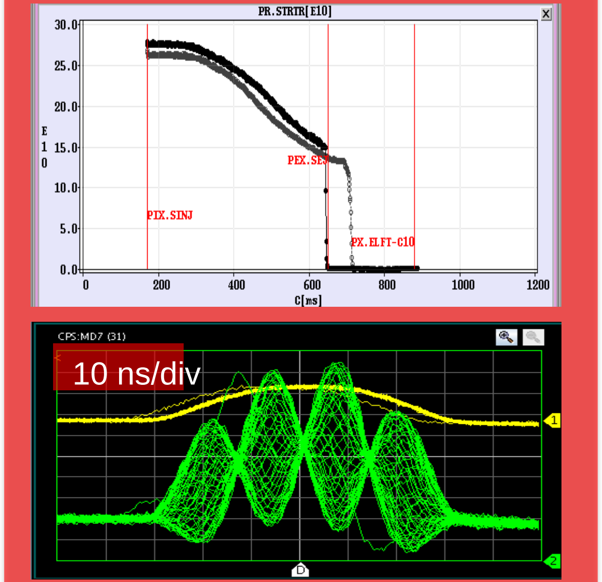
- RF system: 400.8 MHz, up to 32 MV, similar in scale and scope to LHC
- Impedance estimates key to RF and TFB design
- TFB design:
  - coupled bunch feedback with options for 5 ns and 25 ns bunch spacing (driven by resistive wall instability → fast instability rise times)
  - bandwidth up to 100 MHz for 5 ns option to cover all CBMs
  - injection damping → kicker waveform a challenge (ripple)
  - TMCI instability: Potential of intra-bunch GHz feedback is being investigated with US-LARP supported work for the SPS
  - needed R&D for FCC covers the technology of kicker, power systems, signal processing electronics and algorithms
    - Leverage on US LARP work for SPS Feedback !

Spare Slides

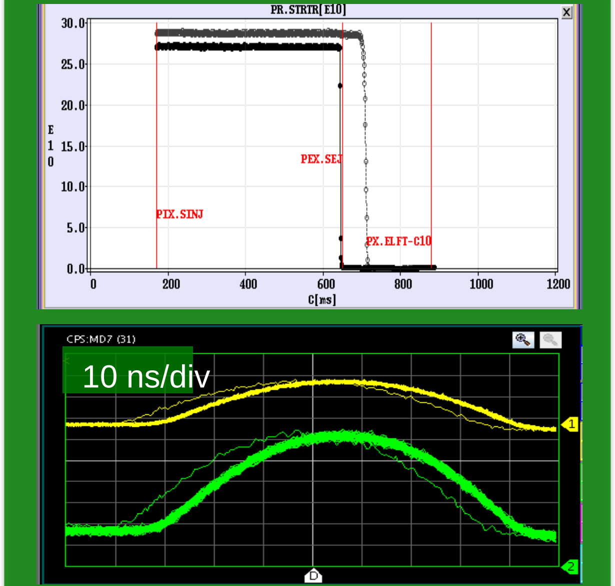
FCC-hh versus FCC-ee TFB

- Requirements for FCC-hh and FCC-ee are different with respect to
  - bunch spacings, 25 ns or 5 ns (hh) versus 20 ns (ee@Z) and more (ee)
  - bunch length → choice of frequency band for feedback (low hh, high ee), i.e. short bunches in ee
  - impact of synchrotron radiation damping
  - TMCI: Intra-bunch feedback feasible for hh, not feasible for ee, revisit “reactive feedback” (tests in LEP), covered by ABP ?
- separate topics but some overlaps between hh and ee for technology part, some synergy
- options for 100 km and 93 km only marginally different for TFBs
  - focus on 100 km (3.75x LHC) option for parameters and design
  - treat 93 km (3.5x LHC) option as fully equivalent ?
- Need more work on impedance budget, instability thresholds, risetime calculations and beam transfer estimates

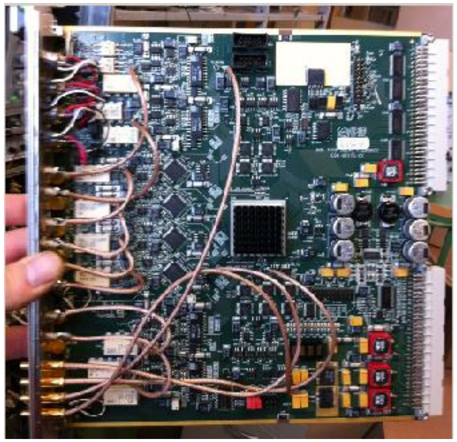
CERN PS intra-bunch FB

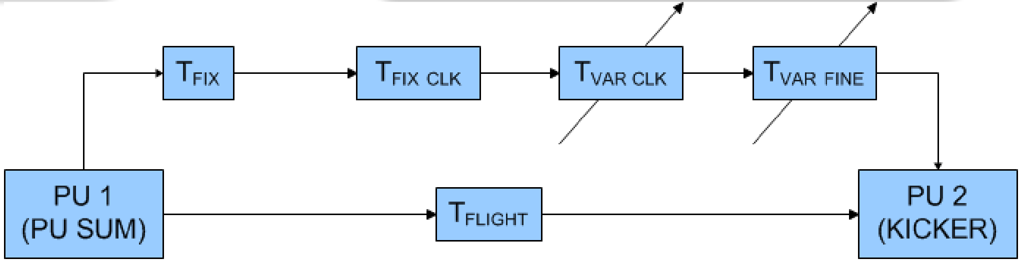


PS TFB OFF



PS TFB ON





T_{FIX}

$T_{FIX\ CLK}$

$T_{VAR\ CLK}$

$T_{VAR\ FINE}$

PU 1
(PU SUM)

T_{FLIGHT}

PU 2
(KICKER)

1.4 GeV → 26 GeV

Challenge:

Time of Flight Compensation

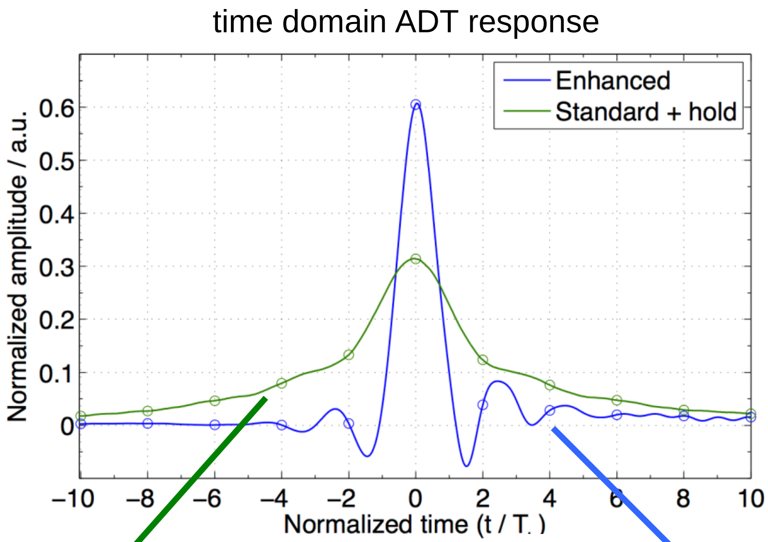
Fully digital implementation

A. Blas et al. IPAC’13, WEPME011

D. Perrelet (CERN BE-RF)

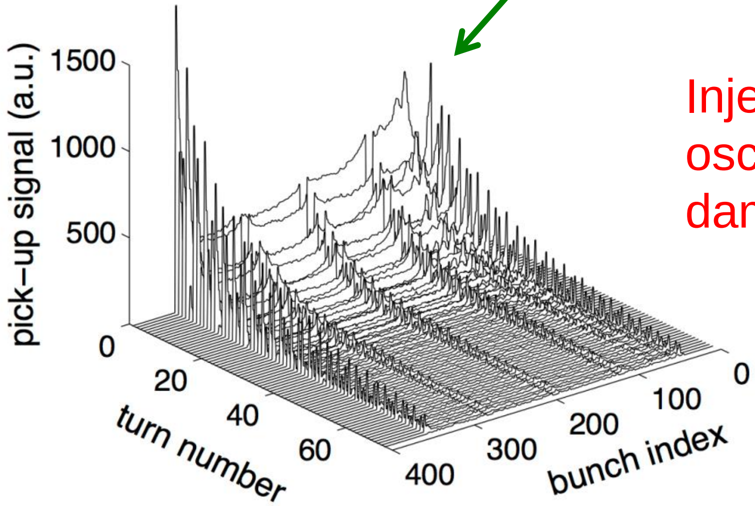
Injection Oscillations – Batch View

LHC

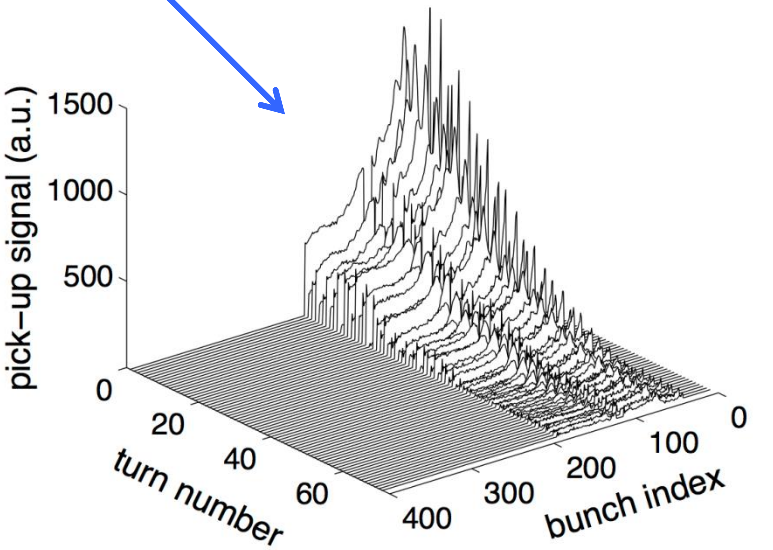


50 ns bunch spacing
standard + hold
144 bunches (4x36)

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



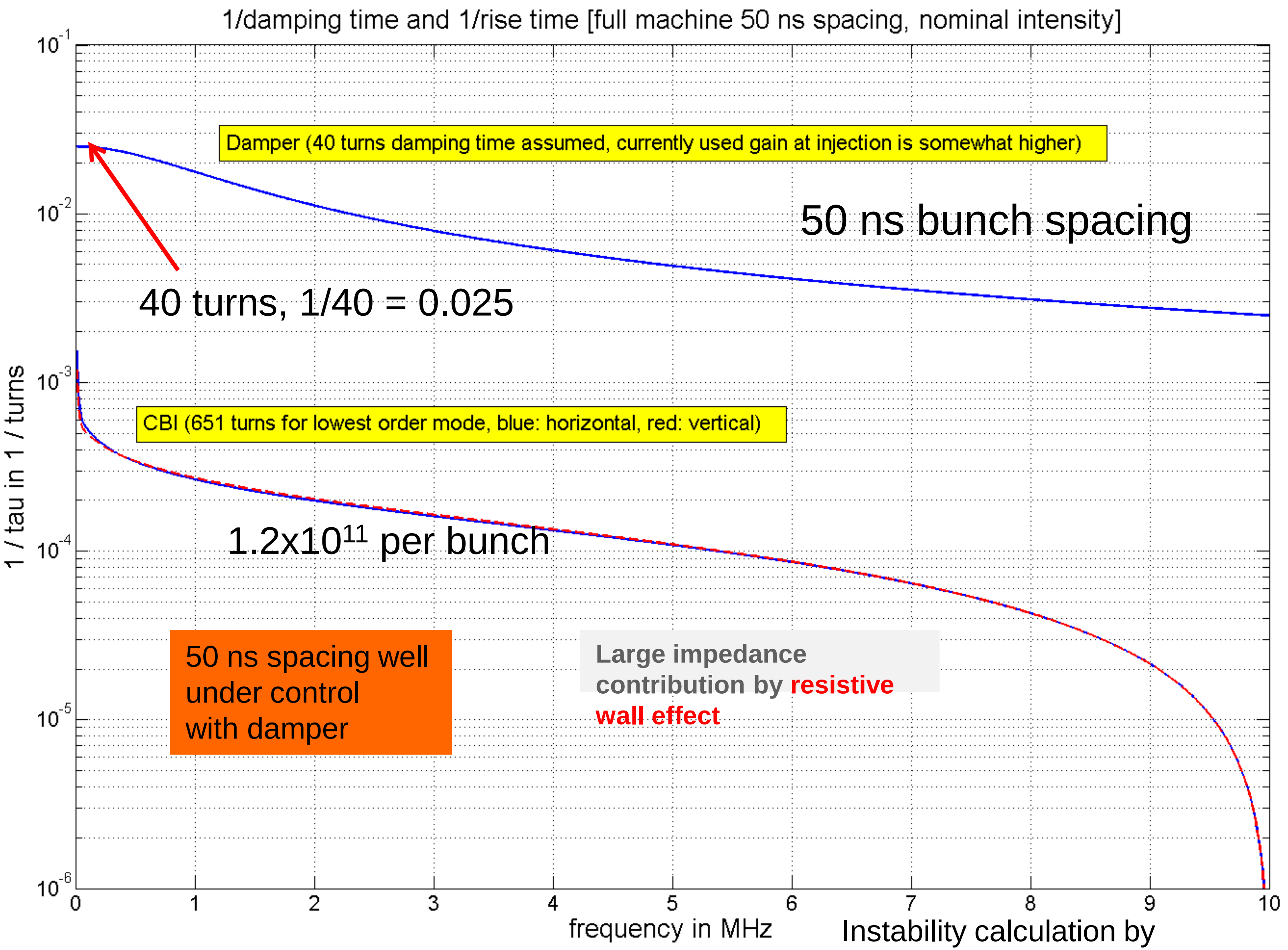
Injection
oscillation
damping



damping at edges of batch slower

IPAC’13, WEPME43

LHC Run 1: 50 ns spacing



Damper (40 turns damping time assumed, currently used gain at injection is somewhat higher)

50 ns bunch spacing

40 turns, 1/40 = 0.025

CBI (651 turns for lowest order mode, blue: horizontal, red: vertical)

1.2×10^{11} per bunch

50 ns spacing well under control with damper

Large impedance contribution by resistive wall effect

Instability calculation by
N. Mounet (CERN BE-ABP)