Overview:
FCC Transverse Feedback Systems

Wolfgang Hofle
Outline

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

\[ T_{\text{signal}} = T_{\text{beam}} + n \ T_{\text{rev}} \]
LHC ADT Design Parameters

relative emittance increase at injection

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

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

blow-up factor

\[ \tau_{\text{dec}} = 68 \text{ ms} \]

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

<table>
<thead>
<tr>
<th>injection</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td>( E )</td>
</tr>
<tr>
<td>emittance (norm)</td>
<td>( \varepsilon )</td>
</tr>
<tr>
<td>injection error</td>
<td>( a_{\text{inj}} )</td>
</tr>
<tr>
<td>increase w/o FB</td>
<td>( a_{\text{inj}}^2/(2\sigma^2) )</td>
</tr>
<tr>
<td>max increase of ( \varepsilon )</td>
<td>( (\Delta \varepsilon/\varepsilon)_{\text{max}} )</td>
</tr>
<tr>
<td>Blow-up factor</td>
<td>( F_\varepsilon )</td>
</tr>
</tbody>
</table>

LHC Run 1 (50 ns): in practice smaller emittances available from injectors
LHC Run 2 (25 ns): nominal beam parameters with 4x72 bunches per injection
LHC transverse Feedback (ADT) kickers and amplifiers in tunnel point 4 of LHC, RB44 and RB46
Kickers and Power Amplifiers → JINR, Dubna Collaboration

- 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

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

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

Data from LHC run 1 (2012)
25 ns bunch spacing enhanced bandwidth
144 bunches (2x72)

damping at edges of batch slower
LHC run 2: enhanced bandwidth during injection and ramp
standard bandwidth in stable beams (lower noise)
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

injection kicker ripple $\rightarrow$ slower V-damping
FCC-hh TFB: 25 ns – 97.7 km

FCC tentative parameters

<table>
<thead>
<tr>
<th>Injection</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>emittance (norm)</td>
<td>$\varepsilon$</td>
</tr>
<tr>
<td>injection error</td>
<td>$a_{\text{inj}}$</td>
</tr>
<tr>
<td>increase w/o FB</td>
<td>$a_{\text{inj}}^2/(2\sigma^2)$</td>
</tr>
<tr>
<td>max increase of $\varepsilon$</td>
<td>$(\Delta \varepsilon/\varepsilon)_{\text{max}}$</td>
</tr>
</tbody>
</table>

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

$$\tau_{\text{dec}} = 100 \text{ ms} \quad (~3\times10^{-3} \text{ t.b.c.})$$

de-coherence time (needs determination)

FCC injection energy options

<table>
<thead>
<tr>
<th>Injection energy in GeV</th>
<th>Coupled bunch Instability rise times in turns (O. Boine-Frankenheim et al.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>8 … 16</td>
</tr>
<tr>
<td>1500</td>
<td>22 … 47</td>
</tr>
<tr>
<td>3300</td>
<td>43 … 91</td>
</tr>
</tbody>
</table>

fractional tunes: 0.72 or 0.32
impedance model being updated

Full simulation at injection in presence of:
- damping
- tune spread
- instabilities desirable
FCC injection damping (25 ns)

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

450 GeV case

blow-up factor limits

- 450 GeV
- 900 GeV
- 1.5 TeV
- 2 TeV
- 3.3 TeV (baseline)
- 5, 5.5 TeV

5% emittance blow-up and constant injection error (in mm)
## Parameters for injection damping

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

- 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.
also IPAC’17 TUPIK091
observed intra-bunch motion in LHC
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, 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 single bunch slow head-tail instability (2016)
- Targeted bandwidth in SPS → 1 GHz, needed BW scales with bunch length
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
FCC-ee
Impedance and Instability estimates done
M. Migliorati, E. Belli, Univ. Roma La Sapienza, IPAC’17

Strong coupled bunch feedback needed
- fast rise-times of 6 turns at operation on Z peak (45.5 GeV)
- extension of existing technology from B-factories
- Feedback design and technologies presented at last meeting in Rome
distributed kicker system (A. Drago, INFN, Frascati)

Impedance spectrum driving
resistive wall instability in FCCee
M. Migliorati et al. IPAC’17

Feedback methods with distributed
kickers could also be treated by
CERN developed framework
Summary
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

- GHz feedback can be an option to mitigate slow intra-bunch instabilities, kicker designs being proposed

- impact of feedback noise, suppression of emittance growth by ground motion and due to crab cavity noise needs consideration

- FCC-ee requires system with distributed kickers to be considered due to risetimes < 10 turns

- 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