BEAM TRANSFER CHALLENGES


31st May 2017, FCC week, Berlin
Outline

• Sources of emittance blow-up during beam transfer
  • Implications on hardware for low emittance 5 ns beams

• Machine protection limits
  • Injection protection and implications on injection kicker
  • Extraction protection and implications on dump kicker
  • Dump absorber and implications on dilution system
Error sources for delivery precision

• Correctable errors
  • Magnet misalignment
  • Magnet systematic (different laminations, steel,...) and random errors (different transfer function within a series)
  • Long term drifts due to temperature, humidity,...
  • All these errors lead to trajectory variations that can be corrected
  • Since the transfer function is considered correctable → ΔI/I = ΔB/B

• Uncorrectable (dynamic) errors
  • Random errors:
    Shot-to-shot stability
  • Systematic errors:
    Power converter ripple, kicker waveforms
Example for present PSB-PS transfer

- Extract, recombine four PSB rings and inject into PS via four kicker systems
- Can use TFB to counteract kicker waveform (systematic) and power converter ripple (random)
- No active handle on optics mismatch
- Reduction of \( dp/p \) with longitudinal damper helps to reduce dispersion and energy mismatch

Table 3: Emittance growth at PS injection due to different error sources in the PSB to PS transfer.

<table>
<thead>
<tr>
<th>Mismatch</th>
<th>Emittance growth [%], hor/vert</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pres. LHC</td>
</tr>
<tr>
<td>Steering</td>
<td>0.3/1.5</td>
</tr>
<tr>
<td>Betatron</td>
<td>4.6/6.8</td>
</tr>
<tr>
<td>Dispersion</td>
<td>4.4/8.8</td>
</tr>
<tr>
<td>Total</td>
<td>6.3/11.2</td>
</tr>
</tbody>
</table>

Vincenzo Forte
Example for present SPS-LHC transfer

Mismatch in roll angle at injection

Similar contributions from optics and steering errors as for lower energy transfer

Table 1: Estimated contributions to the emittance increase for transfer and injection into the LHC (TI 8 values).

<table>
<thead>
<tr>
<th>Error</th>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>(\Delta \epsilon / \epsilon_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steering (damped)</td>
<td>(\Delta \epsilon_{DC}/\tau_d)</td>
<td>\sigma</td>
<td>1.5</td>
<td>14</td>
</tr>
<tr>
<td>Betatron</td>
<td>(\lambda)</td>
<td></td>
<td>1.15</td>
<td>1.039</td>
</tr>
<tr>
<td>Dispersion</td>
<td>(\Delta D/\Delta D')</td>
<td>(m)</td>
<td>0.20</td>
<td>0.002</td>
</tr>
<tr>
<td>Energy</td>
<td>(\Delta p/p)</td>
<td></td>
<td>(5 \times 10^{-4})</td>
<td>1.002</td>
</tr>
<tr>
<td>Tilt</td>
<td>(\theta)</td>
<td>(rad)</td>
<td>0.052</td>
<td>1.013</td>
</tr>
<tr>
<td>Coupling</td>
<td>(\kappa)</td>
<td></td>
<td>0.03</td>
<td>1.001</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>1.048</strong></td>
</tr>
</tbody>
</table>
Error sources with Transverse Feedback as mitigation

• Kicker ripple, PC stability
• Presently contributes with 0.5% emittance growth assuming flattop ripple (the kicker rise fits well between bunches)
• In case of LIU rise time contributes and gives emittance growth of 2-3%

• Mitigations
  • Assuming extra effort in HW design (manpower and budget for R&D)
    • Faster systems – reduce rise time by ~10%
    • Factor ~5 reduction of waveform ripple
      • e.g. systems in PS complex with same B.dl requirement from +/-2% ripple → +/- 0.4%
      • e.g. systems in LHC from +/-0.5% → +/-0.1%
    • Aggressive damping times of 5-10 turns (instead of several 10s of turns) without injecting more noise into circulating beam
    • Build linear machines (e.g. scSPS) to keep detuning for higher amplitudes low

• Relative emittance growth can probably be controlled to ~1e-3 → most likely not even in FCC times measurable!
Error sources without active mitigation

- **Betatron mismatch**
  - No active handle, but independent of adiabatic shrinking
  - Presently have at least 20% error
  - Results in emittance growth of 1-3% per transfer
  - Very difficult to control since it relies on optics measurement with single passage of at least a factor 10 better or to control contribution from each magnet via HW specification

- **This could present the main issue concerning emittance growth**

- **Mitigations**
  - Huge improvement in optics measurement
  - Rebuild existing lines with HW much tighter specified, requires control of transfer functions within magnet series, heavy measurement campaign – time!
    - Same for power converters
Error sources without active mitigation

• Dispersion mismatch, energy error
• Dispersion relatively well measurable
• Mostly important for large dp/p – can be difficult if this is required for space charge mitigation

→ Could be issue for LIU/Hilumi

• Mitigations
  • Building new PSB recombination lines
  • Replacing PSB by Rapid cycling synchrotron
  • Replacing PSB by SPL
Error sources without active mitigation 2

- Energy mismatch
  - Can work on dp/p but might be needed for space charge forces

- Geometrical mismatch
  - Accounts for 1.3% emittance growth at LHC injection (B2)
  - Can be mitigated by skew compensation scheme or building a new TI 8 line

- Coupling
  - Considered to be in the noise of all the other errors

- Smaller contributors
Summary for errors from transfer systems I

• Present machines should operate in the range of 2-5% relative emittance growth per transfer from simulations
  • This includes damping from transverse feedback systems – otherwise emittance growth >50%
  • This does not account for emittance growth during cycle (e.g. transition crossing)

• However, in daily operation emittance growth of 20% can easily occur – without knowledge of the source

![Figure 2: Intensity along the batch in the SPS without transverse damper (top) and with transverse damper (bottom).](image)

![Emittance variation of 20% along the batch in LHC](image)

Figure 4: Vertical normalised emittance for several injections of bunch trains with 800 ns batch spacing.
Summary for errors from transfer systems II

• Compressable error sources (kicker with feedback systems) are not the big contributors

• Contribution from optics is important – and barely compressible when manpower, budget and schedule are of consideration...

• Assuming SPL as injector and 0.3 um at PS extraction (see Elena Chapochnikova’s presentation)

• 2 or 3 additional transfers – scSPS or LHC as injector
  • Transfer including errors from extraction kickers, TL hardware, injection kickers

• With aggressive improvements in the CERN injector chain, one can probably reach 1-2% emittance growth per transfer
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Machine protection during injection

• Injection protection elements for LHC will have to be upgraded for Hilumi era
  • Damage of collimators
  • Attenuation of beam

• Extensive studies for transfer line collimators and injection dump – profit for FCC
• Limit of around 5 MJ – depends on beam parameters, optics at injection

- Maximum # circulating bunches in FCC defined by synchrotron radiation impact
- Maximum # injected bunches defined by damage/attenuation limits of absorbers
- Definition of injection kicker rise time: 425 ns (see David Woog’s talk)
Machine protection during injection

- Damage limit of absorbers well studied

- Attenuation limit requires max allowed energy deposition on superconducting strands, worst case beam parameters

- Tracking studies to quantify shower impact will define
  - Conceptual design - phase space coverage by how many collimators in transfer line
  - Collimator settings – close collaboration with collimation team to preserve collimator hierarchy

- Particular importance of these studies due to unfortunate design of injecting into the experiment in FCC
Machine protection at extraction – dump kickers

• Extraction concept driven by machine protection
  • 8 GJ - correct functioning of beam dumping system is not a performance feature but imperative
  • See F. Burkart’s presentation

• Dump kickers
  • Reduction of kick strength to lower single switch voltage and reduce probability of self-trigger
  • Fast rise time for bunch separation on extraction absorbers – absorber survival
  • Investigation of switch architectures to avoid self-trigger (see P. van Trappen’s poster)
    • Detecting self trigger and short-circuiting charge to ground – crowbar
    • Series connection of two switches to inhibit current over magnet in case of single self-trigger
Machine protection at extraction – dilution system

- Dilution system vital if solid graphite dump block considered (see Anton Lechner’s talk)
- Alternative of water beam dump without dilution being investigated (see N. Tahir’s talk)

FIG. 1: Extraction layout scheme

F. Burkart, Anton Lechner
Dilution hardware

FIG. 3: a) The optimal pattern $R_i(t)$ eq. (3) (solid black line), a fitted exponential (dashed red line), and the optimal exponential (solid blue line) waveforms. b) The dump pattern with the fitted exponential time-dependence of the kickers.
Dilution hardware

- Damped LC circuit with 50 kHz frequency (see D. Barna, T. Kramer, FCC week 2016)
- Spiral from outside $\rightarrow$ max deflection reached after $\frac{1}{4} f = 5$ us
- Dump kicker has rise time of 1 us – immediate retrigger causes beam not sufficiently diluted
- Different rise times can be taken into account for programmed dump – not for async.
- $\rightarrow$ Adapt retriggering time to dilution kicker rise time in case of asynchronous beam dump
  - Single self-trigger with LHC retriggering time leads to ~30 bunches oscillating before clean extraction
  - Adapting the retrigger time causes ~145 bunches oscillating
Asynchronous dump

- Oscillation of a self-trigger 0.9 sig
  - Iterate on phase advance between extraction kickers and primary collimators
- With series-switch architecture down to 0.01 sig
- Retrigger asap ~several 100 ns
  - Dump block needs to be exchanged
  - 30 bunches oscillating
  - 6 bunches swept
- Retrigger after ~4 us
  - → dump block OK
  - 145 bunches oscillating
  - 6 bunches swept
- Re-trigger when next abort gap in sync
Beam impact on extraction equipment

- Self-trigger of kicker switches due to beam impact could trigger several modules at once
  - switches in gallery, dedicated shielding

- Beam rigidity requires most likely SC septum technology (see A. Sanz Ull’s talk)
  - Energy deposition studies on septum current leads
  - Design of passive septum protection
  - Combination of nc and sc septa technologies
Conclusions

• Emittance growth in the CERN injector chain
  • With a new dedicated low emittance injector chain, one can probably reduce the theoretical emittance growth from 2-5% to 1-2% emittance growth per transfer
  • Main limitation is the measurement and therefore operational control of these values

• Machine protection during beam transfer
  • Defines rise time and repetition rate of injection kicker
  • Careful study of injection protection since experiments will catch the shower of injection failures
  • Baseline design of extraction protection including dump absorber OK for programmed dump
  • Several scenarios studied for asynchronous dump – need to go into details of trigger delays between dump and dilution kickers
  • Switch architecture studies to limit impact of beam on machine in case of self-trigger
  • Alternative solutions (water beam dump, very low density graphite, powder) under consideration