LHC Injectors Upgrade Workshop

Montreux, 13 - 15 February 2019
Transverse effects with twice brighter beams in the PS

Matthew Fraser

S. Albright, F. Antoniou, H. Bartosik, H. Damerau, V. Forte, A. Huschauer, A. Lasheen, H. Rafique, E. Senes
Contents

• What will change after LIU?
  • Overview of hardware upgrades, target beam parameters, upgraded injection scheme and recent MD’s (low chromaticity and high intensity)

• Sources of emittance growth during transfer and on injection plateau:
  • Catalogue of (known) contributors and their weighting, with latest MD results
  • Brightness measurements and BT-BTP transfer line re-matching
  • The challenge of systematic errors, deconvolution and present uncertainties

• Conclusion and outlook:
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  • Large momentum spread coupled with dispersion is a challenge for accurate betatronic emittance measurements (especially for bright beams!)
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## Beam parameters

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*Latest MD data taken in 2018 (F. Antoniou and A. Huschauer et al.)*

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Known issue with H dispersion mismatch

- Dispersion function is mismatched on transfer to PS causing blow-up:
  - Long-standing BT-BTP design issue
  - MD’s last year quantified mismatch empirically with PS BPM’s, fast turn-by-turn SEM electronics delivered in 2018
  - Dispersion reproduced with MADX and re-matched optics on R3 used for MD’s

\[
\sigma_x^2 / \beta_{x,\text{fit}} [\mu m] = 0.48 \mu m \quad (\sigma_x = 0.907 \mu m) \\
M_{r,x} = 0.99 \quad (M_{\text{ref},x} = 1.01) \\
\beta_{x,\text{fit}} = 0.795 \text{ rad} \\
q_x = 0.185 \\
d\psi/d\phi = 0.013 \mu m \\
d\sigma_x/d\phi = 0.00 \times 10^{-4} \\
\Delta M_{r,x} = 0.89 \% \\
\phi_{r,x} = 1.48 \text{ rad} \\
\beta_{x,\text{fit}} = 12.65 \text{ m}
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\[Q_x = 6.21\]

Turn-by-turn profile measurements:

Dispersion mismatch confirmed as the dominant source of beam envelope oscillations in first turns
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- Mitigation under LIU project is the upgrade of BT-BTP transfer line

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BCMS cycle with low chromaticity

• Important step was made last year deploying the TFB on operational LHC and MD beams:
  • PFW used to correct chromaticity at low energy
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• Next steps:
  • Upgraded TFB system in LS2
  • Further approach zero chromaticity (and vertical)
  • Implementation also on standard production beams
High intensity MD’s

- Successful set-up and optimisation of HI beams:
  - Intensity of $2.6 \times 10^{11}$ ppb at PS extraction seems within reach using presently available RF upgrades
High intensity MD’s

• Successful set-up and optimisation of HI beams:
  • Intensity of $2.6 \times 10^{11}$ ppb at PS extraction seems within reach using presently available RF upgrades
  • Transverse tune optimization along the flat bottom:
    – Adjustment of the TFB gain settings according to increased intensity
    – Vertical chromaticity increased by $\Delta Q'_y \approx 1$ during the ramp

After optimisation: close to $2.5 \times 10^{11}$ ppb (LHC standard – 72b)
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*For input emittance of 1 mm mrad (rms, norm) at 1.4 GeV and 75e10 p

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KFA45 ripple + post-pulse

TFB should be effective to compensate ripple ($< 30$ MHz), effectiveness of damping to be computed

KFA45 field measurements now available: to be analysed
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BT-BTP optics for brightness studies

- Re-matched optics was provided to study sensitivity of blow-up at injection to dispersion mismatch [ref6]:
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    - Deconvolution of $\Delta p/p$ introduces errors on measured Twiss ($\alpha, \beta$)
    - PSB Twiss parameters not measured accurately (yet!)

LIU Workshop, 13-15 February 2019
BT-BTP optics for brightness studies

- Re-matched optics was provided to study sensitivity of blow-up at injection to dispersion mismatch [ref6]:
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  - MADX model compared to betatronic mismatch measured on the PS injection BSG’s:
    - Deconvolution of $\Delta p/p$ introduces errors on measured Twiss ($\alpha, \beta$)
    - PSB Twiss parameters not measured accurately (yet!)
    - MADX model good enough to significantly reduce mismatch

![Operational optics](image1.png)

![Re-matched optics](image2.png)
BT-BTP optics for brightness studies

• Re-matched optics was provided to study sensitivity of blow-up at injection to dispersion mismatch [ref6]:

Dispersion function [m]

LIU Workshop, 13-15 February 2019
Matthew Fraser
Dispersion mismatch at injection

• Blow-up independent of initial emittance, proportional to $\left(\frac{\Delta p}{p}\right)^2$

• i.e. a constant offset as $f(\text{intensity})$ on brightness curves:

$$\Delta \varepsilon = \frac{1}{2} M_D^2 \left(\frac{\Delta p}{p}\right)^2 \text{ where } M_D^2 = \left(\frac{\Delta D^2 + (\beta \Delta D' + \alpha \Delta D)^2}{\beta}\right)$$

$\varepsilon_n = (\beta \gamma)_{\text{rel}} \varepsilon_g$ is not forgotten!
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<td>Operational T-by-turn BPM response</td>
<td>0.40 ± 0.04</td>
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Operational optics

$\varepsilon_n = (\beta \gamma)_{rel} \varepsilon_g$ is not forgotten!
Dispersion mismatch at injection

- Blow-up independent of initial emittance, proportional to \( \left( \frac{\Delta p}{p} \right)^2 \)

- i.e. a constant offset as \( f(\text{intensity}) \) on brightness curves:

\[
\Delta \varepsilon = \frac{1}{2} M_D^2 \left( \frac{\Delta p}{p} \right)^2 \quad \text{where} \quad M_D^2 = \left( \frac{\Delta D^2 + (\beta \Delta D' + \alpha \Delta D)^2}{\beta} \right)
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<td>T-by-turn SEM envelope beating (fitted D mismatch)*</td>
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</tr>
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</table>

*error analysis to be completed

$\varepsilon_n = (\beta \gamma)_{rel} \varepsilon_g$ is not forgotten!
Dispersion mismatch at injection

• Blow-up independent of initial emittance, proportional to \( \left( \frac{\Delta p}{p} \right)^2 \)

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<td>0.40 ± 0.04 0.14 ± 0.02</td>
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<td></td>
</tr>
<tr>
<td>(fitted D mismatch)*</td>
<td>0.397 0.110</td>
<td></td>
</tr>
</tbody>
</table>

*error analysis to be completed

\( \Delta \varepsilon \text{ BCMS OP abs. [mm mrad]} \)

0.15 0.011 – 1.8

\( \varepsilon_n = (\beta \gamma)_{\text{rel }} \varepsilon_g \)

is not forgotten!
Betatronic mismatch at injection

- Blow-up dependent on initial emittance, expected to be negligible:
  - i.e. a linear $f(\text{intensity})$ on brightness curves:
    \[
    \Delta \varepsilon = \frac{\varepsilon_0}{2} \left( M_g + \frac{1}{M_g} - 2 \right) \text{ where } M_g + \frac{1}{M_g} = \beta \gamma_0 + \gamma \beta_0 - 2 \alpha \alpha_0
    \]

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    where $M_g + \frac{1}{M_g} = \beta \gamma_0 + \gamma \beta_0 - 2 \alpha \alpha_0$

• Envelope would beat twice as fast ($2q_H$) if betatronic mismatch was dominant

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*error analysis to be completed

$\varepsilon_n = (\beta \gamma)_{\text{rel}} \varepsilon_g$
is not forgotten!

$\beta$ - mismatched
$\beta_0$ - matched

Technique

- **T-by-turn SEM**
  - envelope beating (fitted mismatch)*

*Operational optics – H plane*

*Re-matched optics – H plane*
Betatronic mismatch at injection

• Blow-up dependent on initial emittance, expected to be negligible:
  • i.e. a linear $f(\text{intensity})$ on brightness curves:
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| $\Delta \varepsilon$ BCMS OP abs. [mm mrad] | 0.007  
|---------------------------------------------|--------|

$\varepsilon_n = (\beta \gamma)_{\text{rel}} \varepsilon_g$ is not forgotten!

$\beta$- mismatched
$\beta_0$ - matched

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$\sigma_{x,\text{fit}}^2 / \beta x_{\text{fit}}$ [µm]

Operational optics – H plane

Re-matched optics – H plane
Space-charge in PS

- Sensitivity of blow-up after injection to WP:
  - BCMS OP on Ring 3: low Q’ cycle, 72e10 p
  - WP shows little sensitivity over range of 0.02
  - “Fast” blow-up appears only close to integer
  - No significant impact on blow-up from the space-charge induced tune spread at timescales > 2 ms
• Sensitivity of blow-up after injection to WP:
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  • WP shows little sensitivity over range of 0.02
  • “Fast” blow-up appears only close to integer
  • No significant impact on blow-up from the space-charge induced tune spread at timescales > 2 ms

• Next steps:
  • Simulations with space-charge to be carried out and benchmarked with measurements
Measured H blow-up: BCMS 0.9 eVs

- Re-matching BT-BTP has only a small impact on filamented horizontal emittance measured 15 ms after injection using the wire-scanner:

![Graphs showing measured and modeled blow-up](image-url)
Measured H blow-up: BCMS 1.5 eVs

- Re-matching BT-BTP has only a small impact on filamented horizontal emittance measured 15 ms after injection using the wire-scanner:

![Graphs showing emittance blow-up measurements with dates and model details]
Measured H blow-up: re-matching BT-BTP

- Re-matching BT-BTP has only a small impact on filamented horizontal emittance measured 15 ms after injection using the wire-scanner:

![Graph 1: 0.9 eVs - BT-BTP re-matching - abs blow-up](image1)

- 26th September & 11th November 2018

![Graph 2: 1.5 eVs - BT-BTP re-matching - abs blow-up](image2)

- 6th November 2018
Measured H blow-up: BCMS from R3

- Re-matching BT-BTP has only a small impact on filamented horizontal emittance measured 15 ms after injection using the wire-scanner:

<table>
<thead>
<tr>
<th>Beam type</th>
<th>Relative momentum spread [1e-3]</th>
<th>OP optics $\Delta \varepsilon$ abs. [mm mrad] @ $I = 75e10$ p</th>
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<tbody>
<tr>
<td>Measured by TOMO</td>
<td>Expected</td>
<td>Measured</td>
</tr>
<tr>
<td>BCMS OP</td>
<td>0.9</td>
<td>0.15</td>
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<tr>
<td>BCMS 1.5 eVs</td>
<td>1.4</td>
<td>0.36</td>
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<tr>
<td>Ratio (1.5 eVs/OP)</td>
<td>$2.4 = (1.4/0.9)^2$</td>
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*Dominant blow-up only from dispersion included in expected blow-up (other sources only few %)
• Re-matching BT-BTP has only a small impact on filamented **horizontal emittance** measured 15 ms after injection using the wire-scanner:

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<td><strong>BCMS OP</strong></td>
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<td>0.36</td>
<td>0.027</td>
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• A large, missing systematic contribution to the emittance growth is observed
• Difficult to explain entirely with the expected sources of blow-up
Impact of deconvolution algorithms

- Observed systematics in the measured data, see “Impact of deconvolution algorithms” in F. Antoniou’s presentation, but also numerically:

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<th>Distributions</th>
<th>Quadrature (Gauss. fit) Emittance Error [%]</th>
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<td>6D Gaussian</td>
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<td>( \varepsilon_T = 2.5 \text{ um} ), ( \varepsilon_L = 0.5 \text{ eVs} )</td>
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<tr>
<td>4D Gaussian + 2D Parabolic</td>
<td>+ 4.4</td>
<td>+ 2.7</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>4D Gaussian + 2D Parabolic</td>
<td>+ 14.9</td>
<td>+ 7.5</td>
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<tr>
<td>$\varepsilon_T = 2.5 \text{ um}, \varepsilon_L = 1.4 \text{ eVs}$</td>
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Contents

• What will change after LIU?
  • Overview of hardware upgrades, target beam parameters, upgraded injection scheme and recent MD’s (low chromaticity and high intensity)

• Sources of emittance growth during transfer:
  • Catalogue of (known) contributors and their weighting, with latest MD results
  • Brightness measurements and BT-BTP transfer line re-matching
  • The challenge of systematic errors, deconvolution and present uncertainties

• Conclusion and outlook:
  • Looking to the future at 2 GeV and operation with large longitudinal emittance
Conclusion

- Turn-by-turn measurements after injection have confirmed and quantified the dispersion dominated mismatch

- Significant H (rms) blow-up in PS of ~ 0.33 mm mrad measured on BCMS OP 0.9 eVs compared to an expected blow-up of ~ 0.15 mm mrad:
  - No known physical source can explain the relatively large blow-up observed

- Re-matching BT-BTP TL made no significant impact on filamented emittance:
  - Same conclusion was reached after T-by-T SEM MD’s in early 2000’s [Ref7]

- Systematic errors play an important role in emittance measured from profiles:
  - Uncertainty in the optics parameters (e.g. $\beta$ in PSB) and systematic errors in the momentum deconvolution algorithm (distribution dependent) are likely culprits

- No evidence yet that space-charge is driving the apparent blow-up
Outlook

• Too early to state firmly the expected blow-up during transfer at 2 GeV with the apparent role played by systematic errors:
  • Bright beams with large D make absolute emittance measurements challenging

• Lack of sensitivity to re-matching of the transfer line is concerning…
  • Further studies are planned in 2019 to check impact of systematic errors: from changing (filamented) distributions, including simulations with space-charge
  • Single coherent report to be published with full analysis of BGI and WS data

• Improved tools are needed to effectively de-convolute beam profiles
  • Will need to use lessons learnt in LS2 and apply them in operation in Run 3
Acknowledgement

• Thanks to the PSB and PS OP crews for putting up with us on very busy MD days and helping taking the data presented

• Thanks to BE-BI for the provision of the turn-by-turn SEM grid electronics and acquisition in 2018
References

• [Ref1] Studies by E. Senes, presented by M.A. Fraser at LIU Beam Performance Meeting, Emittance growth at PS injection for different longitudinal emittances, CERN, Geneva, 5 July 2018

• [Ref2] M. Serluca et al., Optics Studies and Space Charge Effects during the Injection Process at the CERN PS, Space charge meeting, CERN, Geneva, 6 April 2017

• [Ref3] M.A. Fraser, KFA14 flat-top ripple measurements, ABT-TCM meeting, CERN, Geneva, 1 October 2018


• [Ref6] V. Forte et al., Overview of the CERN PSB-to-PS Transfer Line Optics Matching Studies in View of the LHC Injectors Upgrade Project, WEP2PO006, HB 2018, Daejeon, Korea, 18 -22 June 2018

Blow up from KFA14

- PSB extraction kicker waveforms measured for all rings [ref3]:
  - Beam-based measurements using short ($\sigma = 10$ ns) INDIV bunch
  - Ripple < $\pm1.5\%$
Blow up from KFA14

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  - Ripple < ±1.5%
  - Blow-up depends on bunch length and estimated at <1% for LIU BCMS
Blow up from KFA14

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  - Beam-based measurements using short ($\sigma = 10$ ns) INDIV bunch
  - Ripple $< \pm 1.5\%$
  - Blow-up depends on bunch length and estimated at $<1\%$ for LIU BCMS

- Beam-kicker synchronisation is an important commissioning step

\[\text{LIU STD = 205 ns (4$\sigma$)}\]
\[\text{LIU BCMS = 135 ns (4$\sigma$)}\]
Blow up from KFA10 and KFA20

- Recombination kicker waveforms measured and emittance growth assessed [refX]:
  - Beam-based measurements carried out using long bunches
  - Rise-times limit length of bunches
  - **Vertical** blow-up depends on bunch length
  - Estimated blow-up depends on ring, worst-case < 3%
  - Worst-case LIU standard beam at 2 GeV (205 ns) from 2 – 3% shown in table:

<table>
<thead>
<tr>
<th>KFA</th>
<th>Vertical blow-up [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R1</td>
</tr>
<tr>
<td>BT1.KFA10</td>
<td>1.9</td>
</tr>
<tr>
<td>BT4.KFA10</td>
<td>0</td>
</tr>
<tr>
<td>BT2.KFA20</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.1</strong></td>
</tr>
</tbody>
</table>
Blow up from KFA45

- Beam based measurements combined with PSpice model current to estimate emittance blow-up [ref5]:
  - Measurements resolution limited (~5%)

![Graph showing beam current and emittance blow-up analysis](image.png)

Post-pulse

Matthew Fraser
Blow up from KFA45

• Beam based measurements combined with PSpice model current to estimate emittance blow-up [ref5]:
  • Measurements resolution limited (~5%)
  • Blow-up at 3.5% for certain bunches

• Post-pulse ripple shown to be constant and does not scale with voltage

• Next steps:
  • Magnetic measurements made in tunnel at start of LS2 available, blow-up estimates to be reviewed
*Measured H blow-up: $\Delta \varepsilon$ unaccounted for?*

- To elucidate the challenge we face with systematics, let’s consider what effective emittance blow-up is missing to give the measured values
  - Assuming independent error sources, adding linearly:
    \[
    \Delta \varepsilon_{\text{missing}} = \varepsilon_{\text{PS,meas}} - \left( \varepsilon_{\text{PSB,meas}} + \frac{1}{2} M_B^2 \left( \frac{\Delta p}{p} \right)^2 \right)
    \]

<table>
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<tr>
<th>Beam type</th>
<th>$\Delta \varepsilon_{\text{missing}}$ for OP optics [mm mrad]</th>
<th>$\Delta \varepsilon_{\text{missing}}$ for Re-matched optics [mm mrad]</th>
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<td>BCMS 1.5 eVs</td>
<td>0.07 ± 0.06</td>
<td>0.32 ± 0.09</td>
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- A large, missing systematic contribution to the emittance growth is observed
- Difficult to explain entirely with the expected sources of blow-up
Dispersion mismatch vs. DP/P

• Study of blow-up measured with wire-scanners using standard LHC25 beam as function of longitudinal emittance:
  
  - $\Delta \varepsilon \propto \left(\frac{\Delta p}{p}\right)^2$ for large $\Delta p$
  - Factor two larger mismatch observed
  - Deconvolution/systematics in both machines play a role

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<td>$I = 1.6e12 \ p$</td>
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<tr>
<td>Wire-scanner profile $\Delta \varepsilon$ (Deconvolution of dispersive component needed)</td>
<td>$0.77 \pm 0.003$</td>
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<tr>
<td>T-by-turn data (BPM/SEM)</td>
<td>$0.40 \pm 0.04$</td>
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Introducing significant betatronic mismatch

- Deliberate mismatch to excite betatronic mismatch:
Sensitivity studies with mismatch of BT-QNO10

- Systematic emittance blow-up studies
Measured V blow-up: BCMS 1.5 eVs

- Re-matching BT-BTP has no impact on filamented vertical emittance measured 15 ms after injection using the wire-scanner:
Summary of blow-up studies

- Emittance blow-up measurements are sensitive to systematic errors and appear unreliable
  - Important to better understand role played by errors on optics functions, changing distributions with filamentation and deconvolution etc.

- Horizontal blow-up measured after filamentation is larger than expected from the observed envelope oscillations at injection:
  - In other words, re-matching TL (validated by T-by-T measurements) has very little impact
  - Same conclusion was reached after T-by-T SEM MD’s in early 2000’s
  - Difficult to attribute the unknown blow-up source to imperfections (e.g. steering, kicker ripple, injection energy error, etc.)
  - No blow-up seen in ~ms after injection on WS measurements: indicates fast effects (<2 ms, comparable to profile measurement integration time) or systematic error