LHC injection system along run II

F. M. Velotti, M. Barnes, W. Bartmann, C. Bracco, B. Goddard, V. Kain, A. Lechner, G. Trad, V. Vlachodimitropoulos, J. Wenninger

…and thanks a lot to T. Argyropoulos, M. Pojer, B. Salvachua and the whole SPS and LHC shift crews
Outline

→ LHC injection system availability 2018

→ Evolution of injection system over run II
  ↦ MKI run II evolution
  ↦ TDI run II evolution

→ SPS-to-LHC transfer line: steering and losses
  ↦ Steering frequency in 2017/18
  ↦ Steering analysis
  ↦ Injection losses in 2017/18
  ↦ Transverse losses - TI2 and TI8
  ↦ Expected injection losses for run III

→ Commissioning: from run II to run III

→ Limitations from injection devices post-LS2
  ↦ Can we reach 1.8e11 ppb in 1.8 um?

→ Conclusions
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LHC injection system availability 2018

→ 99.3% availability (48h on average) of the LHC injection system in 2018

↓ Slightly worse than 2017, which was the best year in terms of availability for run II

- Main faults were related to the MKI
  - Faulty delay board caused about 7h downtime
  - Electrical breakdown in MKI2B and consequent suspicious vacuum activity

- The MKI2B will be replaced during LS2 with the so-called “MKI-cool” (see later in this talk)
LHC injection system availability 2018

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- Main faults where related to the MKI
  - Faulty delay board caused about 7h downtime
    - Problem understood and countermeasures being put in place during LS2
  - Electrical breakdown in MKI2B and consequent suspicious vacuum activity
    - The MKI2B will be replaced during LS2 with the so-called “MKI-cool” (see later in this talk)
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MKI run II evolution

→ During LS1, substantial upgrade of the MKIs performed:
  ↓ Upgrade of MKI beam screens adding screen conductors to reduce beam induced heating => this removed max number of bunches limits from run I (post-LS1 design)
  ↓ Upgrade of the vacuum systems on the interconnections between Q5 and MKIs (EYETS16/17)
    ‣ Interconnects NEG coated and NEG cartridge integrated => During the rest of run II, no issues seen with MKI vacuum interlocks

→ MKI2D exchanged during 2016-TS3
  ↓ Following the deteriorating situation of the high-impedance contact within the MKI2D magnet, it was decided to replace the magnet (same design as post-LS1 version)

→ MKI8D replaced during 17/18 YETS with upgraded version
  ↓ Cr$_2$O$_3$ coating on the inner part of the alumina tube
    ‣ Rapid reduction of dynamic vacuum during scrubbing
    ‣ Conditioned dynamic vacuum a factor 3 better than previous MKI8D
  ↓ Modified beam screen design (part of HL-LHC baseline design)
    ‣ Aim to reduce beam induced heating in the ferrite yoke and re-direct it to easier-to-cool areas (rings)
  ↓ Significant improvements observed during 2018 run
→ MKI post-LS1 design defines the present limitations!
TDI run II evolution [1, 2]

→ The TDI suffered several issues during run I and posed operational limitations

→ Starting from LS1, two major stages of upgrades took place: during LS1 itself and during YETS 15/16

→ Modifications during LS1:

→ NEG cartridges, Ti coating on Aluminium, reinforced beam screen, temperature probes

→ At restart in 2015, the TDI.4R8 was the one suffered the most:

  ‣ Large vacuum spikes during injection and pressure build up (=> dumps)
  ‣ Beam-based measurements (impedance team) shown significant discrepancies between the TDI in IP2 and IP8 => Ti coating in TDI.4R8 found severely degraded

→ During 2015, the spare hBN blocks of the TDIs were treated in vacuum at high temperatures => 20% of the blocks cracked after 800°C and 50% after 1000°C

  ‣ Limits put on operation to prevent failure of the TDIs (details in LMC 215/217)

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[1] A. Lechner, “Summary of issues with the present TDI – the TDI history in a nutshell”
Modification during 2015/16 YETS:

- Replacement of hBN blocks with R4550 graphite, copper coating on graphite blocks, modified clamping of cooling pipes, added an interferometric system, replacement of CuBe blocks with CuCrZr

- Operational limits from TDI removed for the rest of run II
  - Beam-based measurements (impedance team) showed the expected improvement coming from the replacement of hBN blocks with R4550 and their coating

- Main issue observed during 2016: strong pressure increase in the TDI.4R8 during jaw movement. This showed conditioning effects

Very smooth operation from 2016!

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SPS-to-LHC TL: steering and losses

→ SPS-to-LHC transfer line trajectory stability has been a topic of studies since run I (L. Drosdal, V. Kain, C. Bracco, W. Bartmann, etc.)

- Two source of horizontal trajectory variations were identified: shot-to-shot variations and long term drifts (vertically, both lines are very stable)

- Shot-to-shot variations:
  - For TI2, the main source was identified to be the MSE in LSS6
    - In the winter stop 2011/12 the MSE power supply was improved and the current jitter halved => the factor 2 improvement was also measured as trajectory jitter during 2012 start up
  - For TI8, 2 main sources of trajectory instability were isolated as the MKE and MSE in LSS4

- Trajectory slow drifts:
  - For TI2, the main sources were identified as the SPS orbit and the MSE
  - For TI8, the main source was identified as the SPS orbit

→ Necessary to re-steer the line
  - Beginning of run: ~ twice a week
  - End of run: every second day
  - Frequently the same corrector proposed (TI 2: RCIBH.20804, in phase with MSE/MST)
  - Offsets drifting back and forth
  - Dependence on SPS supercycle

TL Stabilit
L. Drosdal, Evian 2011

→ Dumps due to injection losses end of 2011
  - Number of dumps due to injection losses since middle of July
  - Try to avoid dumps, start steering before we reach dump level

→ Large shot-by-shot variations are observed for both lines in the horizontal plane – sources identified as the MSE and possibly MKE4

→ Bunch-by-bunch variations on beam 2 in horizontal plane - caused by a ripple on MKE4

→ MSE stability under improvement

→ MKE4 needs further investigation

→ Drifts still to be investigated

Estimate 2012 if stability is not improved: 1h steering x 0.5/days x 120 days = 60h!

5 h later - same super cycle composition → Trajectory has changed

LHC Performance Workshop - Chamonix 2012
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    - For TI8, the main source was identified as the SPS orbit
Steering frequency in 2017/18

→ How much TI2 and TI8 have been steered?

- Comparing 2017 and 2018, it seems that this year the total number of steering iterations was almost doubled for both lines.

- There is also a trend in number of steering iterations per month building up in 2018, instead almost constant in 2017.

- Also in 2012, though, there was an increase in steering frequency during the last part of the year. That also corresponded with the change from Q26 to Q20.

→ Comparing this with the SPS injection:

- 2017: SPS injection was treated without the concept of golden trajectory and golden orbit at injection.

- 2018: Introducing golden orbit and trajectory halved the steering iterations in TT10.

- Hence the most fair comparison between TT10 and TI2/8 is in 2018, where we had about 25% more steering interactions in TI2/8 than TT10 => including also TT2 there is very little difference between them!
→ Jorg’s TL steering analysis for TI2:

 ↩ The final trajectory rms of TI2 is rather stable along the year => variation in 0.4 mm range

 ↩ De-convoluting all corrections:

 ‣ A large variation in V (almost twice than in H) observed during the middle of the year, but then it drifted back…

 ‣ Instead the amplitude of the change keeps growing in the H plane

 ↩ If the TT60 correctors (larger strengths) are left out, the changes in rms are much smaller => this indicates that the changes are dominated by the SPS orbit (H, V)/ extraction elements (H)
Steering analysis in 2018 - TI8

→ Jorg’s TL steering analysis for TI8:

- The final trajectory rms of TI8 is rather stable along the year => variation in 0.4 mm range

- De-convoluting all corrections:
  - A large variation in V (almost twice than in H) observed during the middle of the year, but then it drifted back…as for TI2
  - Instead the amplitude of the change keeps growing in the H plane

- If the TT40 correctors (larger strengths) are left out, the changes in rms are much smaller mainly in V => this indicates that the changes are dominated by the SPS orbit (H, V)/extraction elements (H)
Possible to correct back to May multi-bunch trajectory with many SVD eigenvalues

- Better for TI2 as it seems that for TI8 there is an energy error like where its amplitude varies in time…to be investigated further

TI2 and TI8 correction and steering strategy:

- Proposed to take a clean reference with multi-bunch beam ASAP and use it as golden for steering
  - Perform some SVD cleaning with many eigenvalues after TS (or when time allocated)

- Place 2 (or better 3) x12 bunches in every filling schemes to allow, or better encourage, for possible steering at every fill
  - Even better, have two compatible filling schemes ready, one with 3x12 bunches and one with single 12 bunches for a dynamic switch in case steering not necessary…
Injection losses

→ Why we are that sensitive to trajectory drifts and jitters (transverse losses, Q7, Q8, BOT)?

懂事 The TL collimators, TCDI, in order to protect the LHC aperture are sitting at 5 sigma from the defined trajectory
懂事 Losses at some TCDIs are seen (showers) at LHC BLMs in IP2 and IP8
懂事 Some locations are much more sensitive to this issue => for example in TI2, which is the most sensitive, the TCDIH.29205 is very close to the Q8 BLM and to the interconnection between MBB-MBA (BOT)
懂事 Steering clearly helps!

懂事 Another source of losses at injection is the presence of satellites at both extremities of the injected beam (longitudinal losses TDI)
懂事 This manifests itself still with injection losses (mainly at the TDI!)
懂事 Steering is useless in this case!
Injection losses - B1 transverse

→ BLMQI.08L2.B1E30_MQML:LOSS_RS01 (Q8)

→ BLMBI.08L2.B0T10_MBB-MBA_07L2:LOSS_RS01 (BOT)
Injection losses in 2017/18

→ Losses at injection of B1 are slightly different between 2017 and 2018

Insensitive injection quality BLMs - losses dominated by the TDI (longitudinal) => better in 2018!

Insensitive injection quality BLMs - losses dominated by the interconnection BLM (transverse)

Comparing the readings at the Q8, in 2017 basically all (>99%) events were below 10% of dump threshold, instead in 2018 this was for 95% of the injections
Transverse losses 2017/18

→ Normalised transverse losses at the TCDIs comparable between 2017 and 2018

↓ In 2018 clear increase in spread - it seems more severe in TI2 than TI8

↓ MSE.6?
→ Trajectory jitter at the TCDIH.29205 and TCDIH.87441 over a week seems larger in 2018 than 2017

⇒ Reasons still to be investigated

→ Worth it to re-check stability and compare to numbers obtained in the past years
Correlation between losses at the 3 critical BLMs and all TCDI BLMs

There are correlation paths, as expected

First 2 TCDIH seems to be the first to be hit (showering on the downstream ones)

This is also in agreement with Lene's conclusions about being the MSE and MKE the sources of jitter

Completely uncorrelated losses at the TCDIs with TDI!
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Completely uncorrelated losses at the TCDIs with TDI!
→ TCDIH.29050 is the one with usually the highest losses readings

↳ TCDIH.29205 is the first (longitudinally) exhibiting the most clear correlation pattern with the “injection quality” LHC BLMs

→ Correlation plots between all TCDI BLMs and the TCDIH.29205:

↳ Linear correlation between the 29050 and 29205, although not so good

↳ “Thanks” to the larger amount of data at higher losses in 2018, clearer correlation plots => all losses recorded at the TCDIs after the 29205 seem to be dominated by losses/showers from TCDIH.29205 => very “good” phase with MSE.6
Using the correlation pattern shown between TCDIH.29205 losses and Q8 and BOT BLM readings, data can be fit and make an empirical model.

Using a simple polynomial + exponential fit the data in 2017 can be reconstructed using the model obtained from 2018 data.

Still some systematics…

This may be useful to evaluate and optimise BLM shielding for the new TCDILs and to extrapolate expected injection losses for run III.
Expected losses at injection run III

→ Using what was just discussed, we can try to extrapolate the expected losses at injection over run III

倮 Proposal to re-introduce filter on BOT BLM as in Q8 => factor 20 reduction

倮 The we can look at both 2017-like year or 2018-like, i.e. in terms of stability

倮 Assumptions:
  › BCMS: \( I_0 = 1.4 \times 10^{11} \) p/b, same emittance as 2018, 240 bunches
  › Standard: \( I_0 = 1.8 \times 10^{11} \) p/b, 20% larger emittance than 2018, 288 bunches

**BCMS - based on 2017**

**BCMS - based on 2018**

**Predictions for run III**

<table>
<thead>
<tr>
<th></th>
<th>Q8 &lt; 20%</th>
<th>BOT &lt; 20%</th>
</tr>
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<tbody>
<tr>
<td>2017</td>
<td>&gt; 99%</td>
<td>98%</td>
</tr>
<tr>
<td>2018</td>
<td>&gt; 99%</td>
<td>87%</td>
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</tbody>
</table>

Run III (BCMS) 86-95% 92-98% (WF) Run III (Std) 65-70% 75-85% (WF)

Please note that these predictions do NOT consider longer TCDIs nor changes in shielding!
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→ Commissioning of transfer lines and LHC injections been improved over the run II

→ Main changes in the alignment and validation of TCDI/TDI:

↳ TCDI validation procedure completely automatised and simulations available for online benchmark
  ‣ Script/application maintained and upgraded over the years, e.g. tentative to use it for validation with ions…this will become an operational GUI

↳ TCDI automatic alignment using both jaws separately
  ‣ First version of script ready, tested (also in HiRadMat) and used for optics change with ions last year
  ‣ It will become a GUI soon

↳ Plan to investigate and implement automatic injection protection system validation, MKI waveform scan, etc.
What will change after LS2?

→ New transfer line collimators to cope with the increased beam brightness towards HL-LHC
  ↳ TCDI from 1.2 m to 2.1 m graphite (and/or 3DCC)
  ↳ Designed to withstand 288 bunches of 2.0e11 p/b in 1.3 um emittance
  ↳ Re-matched optics in TI2 and TI8 to satisfy beam size requirements at $\beta_x \times \beta_y > 3600m^2$

→ New LHC injection protection/dump - TDIS (segmented)
  ↳ From 4.185 m single-block device to 3-block device of 1.6 m length each - individually movable
    ‣ Design to withstand all LIU/HL-LHC baseline beams up to 2.0e11 p/b in 1.37 um emittance

→ Replacement of MKI2B with “MKI Cool” to complete new MKI design validation
  ↳ Water cooling of surface in contact with ferrite rings
  ↳ It will give even better thermal performance than MKI8D
  ↳ Limits for run III still dictated by post-LS1 design (6 of 8 magnets)
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Limitations from injection devices post-LS2

→ Limit to LIU/HL-LHC baseline parameters for transported/injected beam from the SPS to the LHC
  ↳ New TCDIL and new TDIS

→ MKI limits for injected beam:
  ↳ Up to 7.8 us pulse length operated so far - OK for 240 bunches per train (8.2 us might be in reach, if needed, but to be evaluated in MD first)

→ MKI limits to max number of storable bunches given by post-LS1 magnets installed
  ↳ Details in: V. Vlachodimitropoulos, “Hardware limitations at injection” (https://indico.cern.ch/event/663598/) and “Update on MKI impedance studies” (https://indico.cern.ch/event/734086/)
Can we reach $1.8 \times 10^{11}$ p/b in 1.8 $\mu$m?

→ OK for TCDIL and TDIS

→ MKI:
  
  - Steady state approach used
  
  - Assuming 2808b with $1.8 \times 10^{11}$ p/b, equidistant and equi-populated bunches with Gaussian longitudinal profile

  - Assuming $1.8 \times 10^{11}$ p/b, $t_{bl} = 1.2$ ns, equidistant and equi-populated bunches with Gaussian longitudinal profile

→ These limits are intended for normal operation. In case of usage for specific tests, depending on the operational conditions foreseen (previous cool down, time at flat top, etc.), allowed parameters (N of bunches and bunch length) to be evaluated

⇒ $1.8 \times 10^{11}$ p/b not excluded and OK for normal operation with limitations as indicated in the plots!
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Conclusions

→ Significant changes over run II for both MKI and TDI
   ↳ These changes permitted to achieve the last year performances maintaining the expected availability from the systems and machine protection

→ The TL steering frequency topic came back this year due to losses at injection, mainly for B1
   ↳ Indeed the steering frequency increased towards the end of the year, as already observed during last year of run I
   ↳ TL steering analysis (Jorg) shown slow drifts, mainly in the H plane, increasing until the end of the year and pointing towards SPS orbit/extraction elements
     ↳ In agreement with 2012 studies
       ✓ Proposed “TL steering cleaning” campaign after TS to restore initial multi-bunch trajectory (reference)
       ✓ Proposed to include 2 (or 3) x 12bunches in every filling scheme to allow/encourage steering at every injection ⇒ possibly with the possibility to dynamically change filling scheme
   ↳ Steering directly linked to injection losses
     ↳ In 2018, better longitudinal losses performance than 2017. In 2018, worse transverse losses, especially B1, as expected
     ↳ One of the main issues was the lack of filter on interconnection BLM MBB-MBA - very close to TCDIH.29205:
       ✓ Propose to implement filter on this BLM - discussion already started with threshold WG. Details to be evaluated also accounting for new TCDIL and shielding
       ✓ Trajectory jitter at the TCDIs seems to have gotten worse and this seems to point towards the MSE in LSS6 - more analysis needed - model of the whole SPS extraction in TLs too. Constant follow up

→ For run III, new TCDIL and TDIS will make the LHC injection protection system ready for LIU beams
   ↳ For 1.8e11 p/b in 1.8 um:
     ✓ No limits for TDIS and TCDIL
     ✓ Heating of the MKI with post-LS1 design define the normal operational limitations on max number of bunches storable and bunch length or cool-down. Details of operation at this intensity to be discussed but not showstoppers
Thank you!
Zoom in

2017

2018
TDI VS TCDI losses 17/18

The image contains multiple scatter plots showing the relationship between TDI and TCDI losses. Each subplot represents a different set of data points, with the x-axis and y-axis scales varying across the plots. The plots appear to be comparing TDI (Total Dosimeter Integration) and TCDI (Total Charged Dosimeter Integration) losses across different conditions or measurements.
Mean trajectory evolution TCDIH

TCDIH.29205

\[ \langle x \rangle_{1W} \text{ / mm} \]

2017-06, 2017-08, 2017-10, 2017-12, 2018-02, 2018-04, 2018-06, 2018-08, 2018-10

Mean 1W 2017
Mean 1W 2018
Injection losses VS TCDI_pos
Injection losses VS TCDI_pos
Source of TI2 drifts

L. Drosdal, “ANALYSIS OF LHC TRANSFER LINE TRAJECTORY DRIFTS:

CM$_2$O$_3$ coating $\Rightarrow$ faster beam conditioning

Normalized pressure for MKI interconnects

MKI2D-Q5 @2017 & MKI8D-Q5 @2018

The alumina tube of the upgraded MKI8D, coated with 50nm of Cr$_2$O$_3$, shows faster conditioning with beam than the uncoated (MKI2D) tube.

Upgraded MKI

LMC 01/08/2018
MKI2/8D-Q5 normalized pressures after YETS 2016-17

MKI*D-Q5, 2017: Normalized pressure for interconnects vs Beam Integral (“old” MKI8D, “new” MKI2D)

Q5-MKI8D interconnect retained its beam conditioning during EYETS 16/17. Historically, 8D-Q5 normalized pressure has generally been ~3-12 times higher than 2D-Q5 (with 25ns beam): the reason isn’t understood.
Correlation between losses at the 2 critical BLMs and all TCDI BLMs

First 2 TCDIHs show non-random patterns with the Q7 BLMs

Completely uncorrelated losses at the TCDIs with TDI!

As losses were very well under control, main focus on B1/TI2
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