MD 751: Train Instability Threshold

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Summary

The purpose of this MD is to measure the octupole current thresholds for stability for a single bunch, and then make an immediate comparison (with the same operational settings) for a train of 72 bunches separated by 25ns. From theory, the expected thresholds should be similar. Any discrepancy between the two cases will be of great interest as it could indicate the presence of additional mechanisms that contribute to the instability threshold, for example electron cloud.

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1 Introduction

Throughout run I, several instabilities occurred whose origin could not be explained [1, 2]. In run II a study of the octupole current threshold for stability for a range of different chromaticities is underway. This allows a direct comparison between the predicted instability thresholds (simulated in DELPHI [3]) and measurements, which can indicate possible sources of impedance that have not been taken into account yet. The current status of these measurements can be found in Fig. 1.
The current stability model can be used to consider both single bunch and coupled bunch motion. However, for the damping times considered, the results of single and multi-bunch should be the same (as a perfect damper will damp the coupled bunch motion). It is believed that this assumption is true in the LHC for a train of 72 bunches with 25 ns bunch spacing. This MD aims to compare the instability thresholds for a single bunch with a train of bunches to determine if this is the case.

Initially, a single bunch will be accelerated to 6.5 TeV (end of squeeze optics) and some single bunch instability measurements will be performed, starting first with $Q’ \approx 7$ in both planes before moving to $Q’ \approx -5$. Then, a train of 72 bunches with 25 ns spacing will be accelerated to 6.5 TeV (end of squeeze optics), where for B1, $Q’ \approx 7$ and B2, $Q’ \approx 15$. The instability threshold will then be determined. A final ramp will then be performed that exchanges the roles for each beam, and uses B1, $Q’ \approx 15$ and B2, $Q’ \approx 7$ (flat top optics).

## 2 MD Procedure

### 2.1 Ramp with single bunch

The fill number for the initial ramp with a single bunch per beam was 4284 which occurred between 09:20 and 14:26 local time on 28-08-15.

An overview for the first ramp can be found in Fig. 2. One single bunch and two probes were accelerated to 6.5 TeV and moved to end of squeeze optics. It was observed later that while the intensity of the probes was lower, so too were the emittances. This meant that each of the bunches had approximately similar brightnesses, causing the probes to also become unstable during the instability analysis. A summary for each of the instabilities observed during the fill can be found in Tab. 1. The key result in this case is that the single nominal bunch became unstable at approximately 70 A for $Q’ \approx 7$. 

![Image of graph showing status of single bunch measurements at the end of MD1 for various damping times, d. Shown is the octupole current threshold vs chromaticity at flat top for measurements (points) and predictions (red, green and blue lines). Each point has been normalised to the nominal bunch parameters.](image-url)
Figure 2: Overview of the first ramp for single bunch instability threshold measurements. Three different chromaticities were able to be probed, due to some instabilities occurring without increasing the emittance or intensity of the bunches.

Table 1: Summary of relevant parameters observed for the single bunches during the first ramp.

| Beam/Plane | Time   | $4\sigma_t$[ns] | $\epsilon_H$[µm] | $\epsilon_V$[µm] | $N_b[10^{11}]$ | $J_{oct}$[A] | $Q'H$ | $Q'V$ | $m$ | $|l|$ | $M$ | $\tau$[s] |
|------------|--------|----------------|-----------------|-----------------|----------------|-------------|-------|-------|-----|------|-----|--------|
| B2V        | 12:40  | 1.03           | 3               | 2.1             | 1.1            | 66          | 6.6   | 6.4   | 0   | -    | 1   | 83     |
| B2V        | 12:59  | 1.03           | 3               | 2.1             | 0.86           | 66          | 6.6   | 6.4   | 0   | -    | 1   | ?      |
| B2V        | 12:59  | 1.03           | 1.6             | 1.2             | 1.1            | 66          | 6.6   | 6.4   | 0   | -    | 1   | 74     |
| B2V        | 13:30  | 1.03           | 3               | 3.1             | 1.05           | 81          | -5.7  | -3.4  | 0   | -    | 1   | 0.3    |
| B2V        | 13:49  | 1.03           | 1.8             | 2.6             | 0.8            | 488         | 0.9   | 0.1   | 0   | 1    | 1   | 10     |
| B2V        | 13:52  | 1.03           | 1               | 1.6             | 0.6            | 429         | 0.9   | 0.1   | 0   | 1    | 1   | 21     |
| B2V        | 14:10  | 1.03           | 1.7             | 10              | 0.75           | 150         | 0.9   | 0.1   | 0   | 1    | 1   | 13     |
| B2H        | 13:30  | 1.03           | 3.1             | 3.4             | 1.05           | 82          | -5.7  | -3.4  | 0   | -    | 1   | 0.4    |
| B1V        | 13:30  | 1.05           | 2               | 4.6             | 1.1            | 81          | -8    | -3.7  | 0   | 2    | 1   | 47     |
| B1H        | 12:40  | 1.05           | 2               | 3.7             | 1.1            | 66          | 7.2   | 7.3   | 0   | -    | 1   | 43     |
| B1H        | 12:59  | 1.04           | 2               | 3.7             | 1.1            | 66          | 7.2   | 7.3   | 0   | -    | 1   | ?      |
| B1H        | 14:00  | 1.05           | 5               | 3               | 1.0            | 263         | 0.7   | 0.1   | 0   | 1    | 1   | 20     |
| B1H        | 14:10  | 1.05           | 25              | 3               | 0.93           | 95          | 0.7   | 0.1   | 0   | 1    | 1   | 26     |
Figure 3: Status of all single bunch measurements. Shown is the octupole current threshold vs chromaticity at 6.5 TeV for measured (points) and DELPHI predictions (red, green and blue lines). Each point has been normalised to the nominal bunch parameters.
2.2 First ramp with 72 bunches

The fill number for the first ramp with 72 bunches with 25 ns spacing was 4287 which occurred between 06:19 and 18:06 local time on 28-08-15.

For machine protection reasons, a nominal bunch had to be injected first, followed by a train of 12 bunches (to verify the transfer line optics). These were then dumped and followed by the injection of a single nominal bunch and 72 bunches with 25ns spacing. The chromaticity was set to $Q' \approx 15/10$ in H/V at injection (to mitigate blowup from injection instabilities), which increases during the ramp until 15/15 at flat top at which point the chromaticity in B1 was reduced to 7/7, while B2 remains at 15/15. When moving to end of squeeze optics, activity in the BBQ for B2V was seen for $\beta^* \approx 9m$. This type of activity had been observed for physics fills throughout run II and resulted in blowup along the train, which is shown in Fig. 4.

![Figure 4: Vertical beam size of the 72 bunch train as measured from the BSRT at flat top before the squeeze (black) and after the squeeze (red).](image)

The octupole current was reduced in steps of 37.5 A (as it was anticipated that the train would become unstable at octupole currents similar to that measured for single bunches, around 70 A). Activity was first observed in B1H for currents of 366 A, which began oscillating with an approximately constant amplitude. This incurred losses in B1, and blowup towards the end of the train. While observing this activity, a rapid instability in B1V triggered a dump of both beams. An overview of this behaviour can be seen in Fig. 5. The Headtail monitor was triggered, which allowed a clear inter-bunch pattern to be observed corresponding to radial mode $|l| = 1$. This is seen in Fig. 6.

After the dump, it was observed that there was a synchronous phase shift along the train, which is shown in Fig. 7. This is typically used as an indicator for the presence of e-cloud (in presence of pure impedance effects it would show a constant phase offset along the train). The synchronous phase shift, coupled with the pattern of blowup observed from the BSRT during the squeeze, gives a strong indication of the presence of more e-cloud than originally thought.
Figure 5: Activity in B1H caused losses, but the rapid growth seen for B1V is what triggered the dump of both beams. Shown here is the octupole currents, the intensities of each beam and the BBQ data for both beams and planes.

Figure 6: Inter-bunch oscillation for bunch 1418 in B1H. A clear $|l| = 1$ can be observed.

Figure 7: Synchronous phase shift along the 72 bunch train for B1 (left) and B2 (right). This is typically indicative of e-cloud.
2.3 Second ramp with 72 bunches

The fill number for the second ramp with 72 bunches with 25 ns spacing was 4288 which occurred between 18:06 and 20:08 local time on 28-08-15.

Due to time constraints, the final ramp that was performed still contained the original 12 bunch train (for transfer line validation), with a large gap between the 12 bunches and the 72 bunches. For this ramp, flat top optics were used for the threshold measurement. The same parameters as for the previous ramp were used at injection, except that at flat top the chromaticity in B2 was now reduced to $Q' \simeq 7$ in both planes, while B1 remains at $Q' \simeq 15$ (role reversal from previous ramp). At octupole currents of approximately 350 A (very close to what was observed in the previous ramp), a rapid instability in B2V was observed that triggered a dump in both beams. This is shown in Fig. 8.

![Figure 8: A rapid instability in B2V triggered the dump of both beams. Shown here is the octupole currents, the intensities of each beam and the BBQ data for both beams and planes.](image)

As before, synchronous phase shifts were observed in both beams along the train of 72 bunches. This is shown in Fig. 9.

![Figure 9: Synchronous phase shift for 72 bunch train at flat top for B1 (left) and B2 (right).](image)

In both cases, the beam that became unstable was the beam with the lower chromaticity ($Q' \simeq 7/7$ vs $Q' \simeq 15/15$). Each of the train instabilities observed and one of the single bunch instabilities are shown in Tab. 2. It is clear that for trains of 72 bunches the instability threshold is greater by approximately a factor of 5 than for single bunches, while, from DELPHI computations, we would expect a similar
octupole threshold. It is not currently clear whether this factor of 5 arises directly as a result from an interplay between e-cloud and impedance at flat top. This will be examined in future MD’s by measuring the instability thresholds of trains of bunches in the presence and absence of e-cloud.

Table 2: Summary of relevant parameters observed for the first single bunch instability (first entry) to be compared with the results of the train instabilities (bottom three entries).

| Beam/Plane | $4\sigma_t$[ns] | $\epsilon_H$ [$\mu$m] | $\epsilon_V$ [$\mu$m] | $N_b$ [$10^{11}$] | $J_{oct}$[A] | $Q'H$ | $Q'V$ | m | $|l|$ | M | $\tau$[s] |
|------------|-----------------|----------------------|----------------------|------------------|--------------|-------|-------|----|-------|----|---------|
| B2V        | 1.03            | 3                    | 2.1                  | 1.1              | 66           | 6.6   | 6.4   | 0  | -     | 1  | -       |
| B1H        | 1.06            | 2.5                  | 4                    | 1.1              | 356          | 7     | 7     | 1  | 1     | 72 | 3.5     |
| B1V        | 1.06            | 2.5                  | 4                    | 1.1              | 356          | 7     | 7     | -1 | -     | 72 | 1       |
| B2V        | 1.06            | 4                    | 2.8                  | 1.1              | 350          | 7     | 7     | 0  | -     | 72 | 0.5     |

The current status of instability threshold measurements for single bunches and trains can be found in Fig. 10.

3 Conclusions

While there are disagreements between the threshold values predicted in DELPHI and measurements (with each regime being explored in its own right), it is clear to see that for 72 bunches with 25 ns spacing there is an additional mechanism that provides a large increase in the required stabilising octupoles (70 A vs 350 A). Future MD’s are planned that will attempt to disentangle between e-cloud and impedance based effects, in order to provide a level of certainty that e-cloud is increasing the stability threshold at flat top.
4 Acknowledgments

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References

