CERN-ACC-NOTE-2018-0057
01-02-2018
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The impact of the use of alternative RF frequencies on the TMCI thresholds for HL-LHC

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Abstract

Alternative scenarios for using different configurations of RF frequencies exist and are under study for the HL-LHC. One particular scenario considers the use of a 200 MHz fundamental system which may have advantages over the standard 400 MHz used in the LHC today. In particular, in terms of heat load generated by electron clouds, this approach appears to provide significant advantages with relaxed requirements on the necessary cooling capacity. One of the main concerns with this scenario, on the other hand, is the lowering of the transverse mode coupling instability (TMCI) which puts a hard limit on the reachable intensity. In this note we focus on the evaluation of the TMCI thresholds for the different scenarios and give some guidelines on what configurations are tolerable from a transverse stability point of view. We also briefly address the impact of an idealized transverse damper on the TMCI thresholds.

Keywords: 200 MHz, HL-LHC, electron cloud, TMCI, transverse damper.

Contents

1 Introduction

The LHC has been designed with a 400 MHz fundamental superconducting RF system. This is twice the frequency of the SPS and close to the frequency of LEP, which was 352 MHz, allowing the same proven technology of niobium sputtered cavities to be applied. After several machine studies and upgrade programs in the SPS, short bunches compatible to this RF frequency could be delivered to the LHC [1]. The short bunches are important to maximize the obtainable peak luminosity which in absence of crab cavities is penalized due to the geometric luminosity reduction factor originating from the crossing angle at the IP. Yet higher frequencies, while better for producing the short bunches required in store, could not accommodate the injected bunch lengths from the SPS.

A capture system at 200 MHz to reduce injection loss and ease operation had been proposed and designed but never actually installed. For HL-LHC, the use of a 200 MHz fundamental RF system complementary to the 400 MHz RF system has been proposed as an alternative scenario in ref. [2]. It has the same potential advantages over the pure 400 MHz scheme used for the LHC today due to the larger acceptance and consequently larger bunch lengths. Among these are a reduction of intra-beam scattering, reduced RF heating and the possibility of luminosity leveling with bunch length. One of the biggest advantages are the reduction of the heat load generated by electron clouds in the dipoles, this having proven to be one of the currently most hazardous limitations for high intensity operation in the HL-LHC.

However, there are also some drawbacks associated to this scenario, among one of the most worrisome being the lowering of the transverse mode coupling instability (TMCI) threshold. The TMCI thresholds for this scenario have been investigated for the first time in ref. [3], where it was found, that the TMCI thresholds dangerously approach the nominal intensity values for HL-LHC. Since then, there have been some adaptations in the machine optics and in the impedance model both of which have a beneficial impact on the TMCI threshold. For this reason, these studies were repeated taking into account the recent changes as well as a more detailed modeling of the longitudinal motion to also consider the synchrotron tune spread resulting from the non-linear motion in the relatively full RF buckets in the HL-LHC.

We focus in this report on the potentially detrimental effects of the lowering of the TMCI threshold. The beneficial effect for electron cloud build-up and heat load generation has been presented in [4]. After briefly reviewing the results obtained earlier, we will first describe the assumptions and the simulation model and then present the new results where we compare the TMCI thresholds for operation at 200 MHz against operation at 400 MHz. We will add the results obtained when combining multiple harmonic RF systems to extrapolate a model that allows to estimate the TMCI thresholds for a given synchrotron frequency and bunch length. Finally, we will include a transverse damper to the simulation model and assess its impact on the TMCI thresholds.

2 Scaling of the transverse mode coupling instability threshold

With the potentially beneficial impact of a 200 MHz RF system on the e-cloud generated heat loads which has been shown in [4, 5] the question arises whether there are any important caveats to take into account. As pointed out already in the past, a severe limitation may arise from a lowering of the TMCI thresholds. We will now investigate these thresholds further. We will show estimated threshold values for operation with a 200 MHz system and compare these thresholds with other scenarios such as the classical 400 MHz case as well as different combinations of multi-harmonic RF systems. We will also asses the impact of an idealised transverse damper on the TMCI thresholds.

2.1 Previous results and main changes

Table 1 summarizes some of the parameters used in ref. [3] and compares them with the parameters used for the present studies and specified in ref. [6]. One of the main changes is the slight decrease of the transition gamma, which leads to an increase in both the bunch length and the synchrotron tune.

For the LHC and also for the HL-LHC at top energy the impedance is driven mainly by the colli-

Table 1: Parameters used for the different scenarios in 2013 and in 2016.

Parameter	*Units*	*2013 baseline*	*2013 200 MHz*	*2016 baseline*	*2016 200 MHz*
Energy	[TeV]	7	7	7	7
Voltage	[MV]	16	6	16	6
$\gamma_{\text{transition}}$		55.68	55.68	53.86	53.86
ε_z	[eVs]	2.5	3.5	2.5	3.8
σ_z	[cm]	7.55	12.6	8.1	15
Q_s	$[1 \times 10^{-3}]$	2.0	0.88	2.11	0.92

mators and a rough estimate for the TMCI thresholds can be made as in ref. [7]

$$\operatorname{Im}(\mathfrak{Z}_{\text{eff}}) = \frac{4\pi}{e^2} \frac{E}{N_b\, \beta_{\text{avg}}} \tau_b\, Q_s\,, \tag{1}$$

with $\mathfrak{Z}_{\text{eff}}$ the effective impedance(which implicitly also depends on τ_b), E the beam energy, N_b the number of particle per bunch, τ_b the bunch length in units of time ad Q_s the synchrotron tune. In particular, it becomes evident that in first approximation, the TMCI threshold scales with the product of the bunch length and the synchrotron tune (for constant $\mathfrak{Z}_{\text{eff}}$), which is why an increase in either one helps to raise the TMCI threshold and relax the limits on the maximum reachable bunch intensity.

Using just the changes in bunch length and synchrotron frequency one can then already infer to what extent the TMCI threshold will be relaxed in comparison to the first study. With

$$N_{\text{th}}^{2016} \approx \frac{\sigma_z^{2016}\, Q_s^{2016}}{\sigma_z^{2013}\, Q_s^{2013}} \times N_{\text{th}}^{2013} \approx 15\%\,, \tag{2}$$

that is, and increase of 15% is expected, raising the TMCI threshold from what was found to be around 2.6×10^{11} to about 3×10^{11} particles per bunch. In addition, there have been some further refinements in the impedance model which now takes into account the Mo- and MoGr-coating for further impedance reduction of the collimators as well as in the tracking model which includes the synchrotron tune spread as a result of the non-linear motion in the RF bucket. We will see that this further increases the TMCI thresholds to very acceptable values.

2.2 Simulation model

The simulation model includes the wake fields as obtained from the most recent impedance model detailed in ref. [8]. It employs tracking in the transverse plane via transfer matrices parameterized via the Twiss parameters in smooth approximation. The impedances are weighted by the beta functions at their respective locations in the ring and are then lumped into a single interaction point. The interaction of the beam with the machine impedance is thus computed and applied once per turn. The synchrotron motion is implemented by integrating the longitudinal equations of motion imposed by the RF bucket in a leap-frog scheme. This leads to a more detailed modeling of the synchrotron motion compared to describing the motion using a linear bucket. In particular, one obtains a broader synchrotron tune spectrum instead of just a single distinct value for the synchrotron tune. This can help stabilizing against TMCI as the coupling tends to get washed out.

Figure 1 shows an example of the obtained synchrotron tune spectra from a tracking simulation and compares tracking in a single harmonic RF bucket with tracking in a double harmonic bucket[1] superposed in phase (bunch shortening mode) and in counter phase (bunch lengthening mode). It can be seen that operating in a double harmonic system can significantly increase the synchrotron tune spread. This is typically used in the longitudinal plane to enhance Landau damping. It can also help in the transverse plane against TMCI, in which the dominant quantity, however, is the average synchrotron tune. For this reason, operation in a double harmonic system in bunch shortening mode is most favourable to increase the TMCI threshold.

[1] fundamental and double harmonic superposed

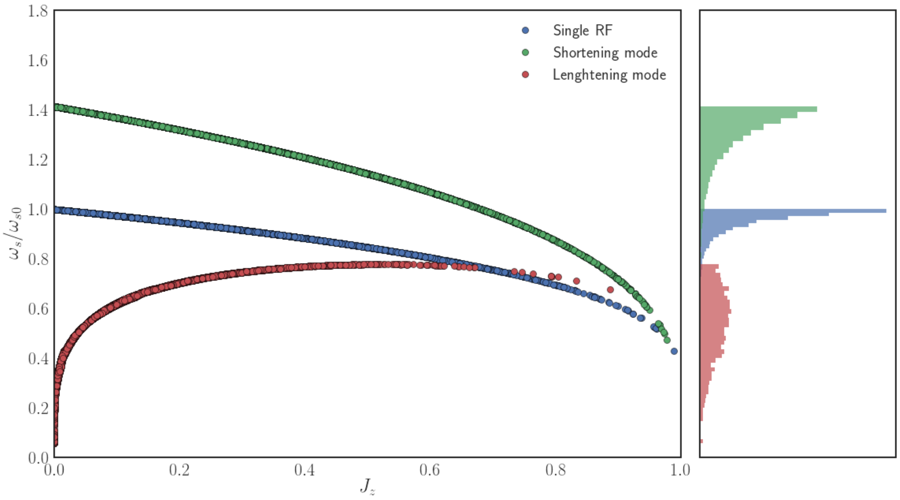

Fig. 1: Synchrotron tune spectra obtained from a tracking simulation comparing single harmonic as well as double harmonic RF systems. Clearly, there is no single distinct value of synchrotron tune in a realistic RF bucket.

To then obtain the TMCI thresholds, we perform an intensity scan where we track a bunch over 20'000 turns in the presence of the HL-LHC impedance for different intensities. The coherent betatron tune is extracted along with the rise times. One can plot the obtained betatron tune spectra and growth rates for the different intensities to identify the onset of the TMCI.

2.3 Results

Using the HL-LHC impedance model at 7 TeV, scans were made in bunch intensity to obtain and to compare the TMCI thresholds in the different scenarios. The plots in fig. 2 compare the pure 400 MHz scenario (left) to the pure 200 MHz scenario (right). The onset of the TMCI is clearly visible.

A fist observation is that the TMCI thresholds are considerably higher than what was found in the past, which was expected, as mentioned earlier, due to the refinement of the impedance model as well as the more accurate treatment of the synchrotron motion. Second, it can be seen that the 400 MHz option exhibits higher TMCI thresholds compared to the 200 MHz option. This is a result mainly due to the synchrotron frequency which for the 200 MHz case is lower and where the impact of this is not compensated by the increase in bunch length.

Another scan was made, this time comparing TMCI thresholds for the pure 200 MHz single harmonic RF case with the situation of a double harmonic RF system comprising of the fundamental 200 MHz with a 400 MHz system superposed at half the voltage of the fundamental one, once in phase (bunch shortening) and once in counter phase (bunch lengthening). As seen already from the synchrotron tune spectra in fig. 1, this has an impact on the average synchrotron tune which is higher in bunch shortening mode and significantly lower in bunch lengthening mode. It also has an impact on the the bunch length. The two effects combined, together with the modification in the synchrotron tune spread, change the behaviour and onset of the TMCI as can be seen from the simulation results plotted in fig. 3. Compared to the single harmonic RF case, the situation improves somewhat in bunch shortening mode as the synchrotron tune on average increases more rapidly than the bunch length shrinks. The situation is the opposite for bunch lengthening mode.

Further studies were made with different combination of the different RF systems also using the 400 MHz as the fundamental system. Collecting all the results with the obtained TMCI thresholds one can apply a regression to extrapolate to some extent the expected TMCI thresholds for different combinations of bunch lengths and average synchrotron frequencies as depicted in fig. 4.

In the HL-LHC, while the beams are in collision, bunches will loose intensity through various effects, the dominating one being burn-off. At the same time the bunch length shrinks. One can see then from fig. 4 that if the bunch length shrinks fast enough, one may still hit the TMCI threshold. This can be particularly threatening for the 200 MHz case if the bunch length shrinking below 8 cm due to radiation

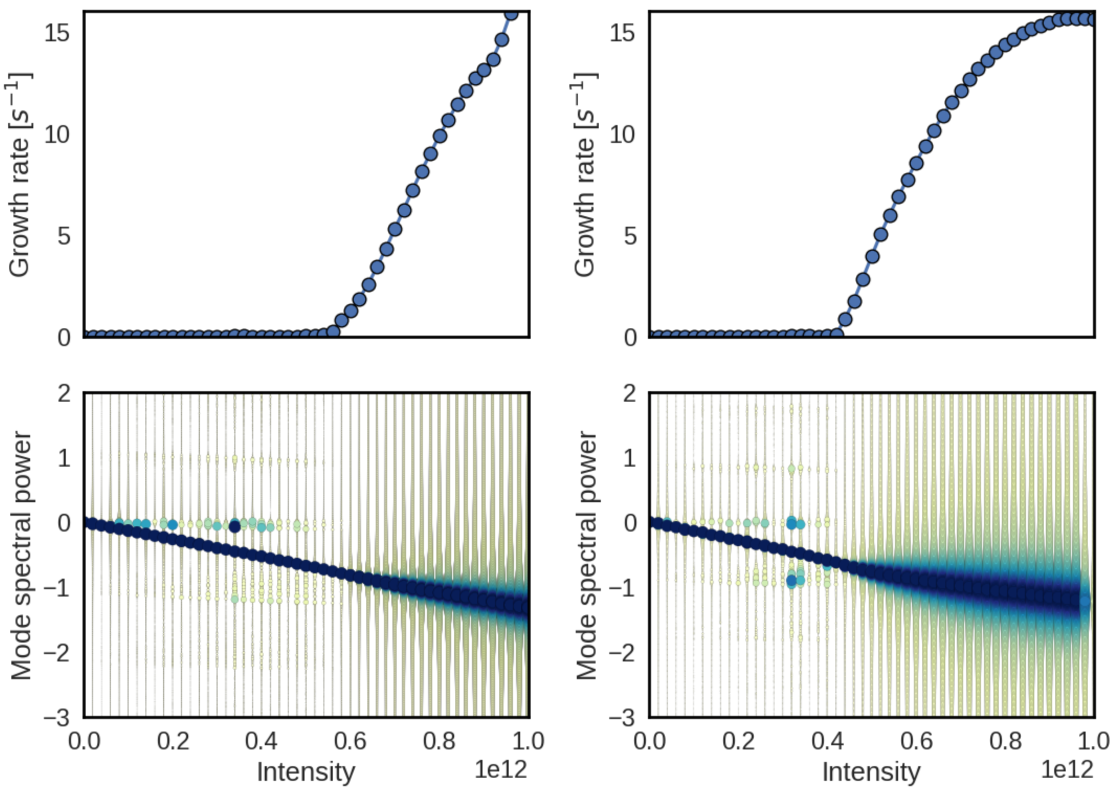

Fig. 2: Intensity scan in presence of the HL-LHC impedance at flat-top using a pure 400 MHz RF system (left) vs. a pure 200 MHz RF system (right) – the top plot shows the instability growth rates, the bottom plot shows the coherent mode power spectrum for different intensities. The TMCI can be clearly detected when modes 0 and -1 couple.

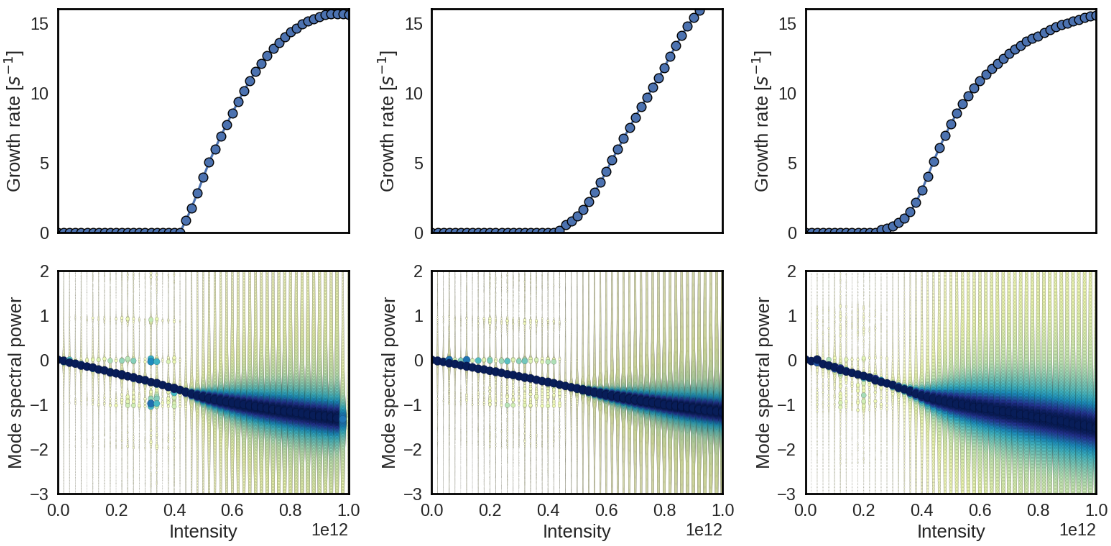

Fig. 3: Intensity scan in presence of the HL-LHC impedance at flat-top comparing a pure 200 MHz system (left) with a 200 MHz system operated in conjunction with a second harmonic system at 400 MHz at half the voltage of the fundamental system. The harmonic system is added once in phase (center) for bunch shortening and once in counter phase (right) for bunch lengthening. The top plot shows the instability rise times, the bottom plot shows the coherent mode power spectrum for different intensities.

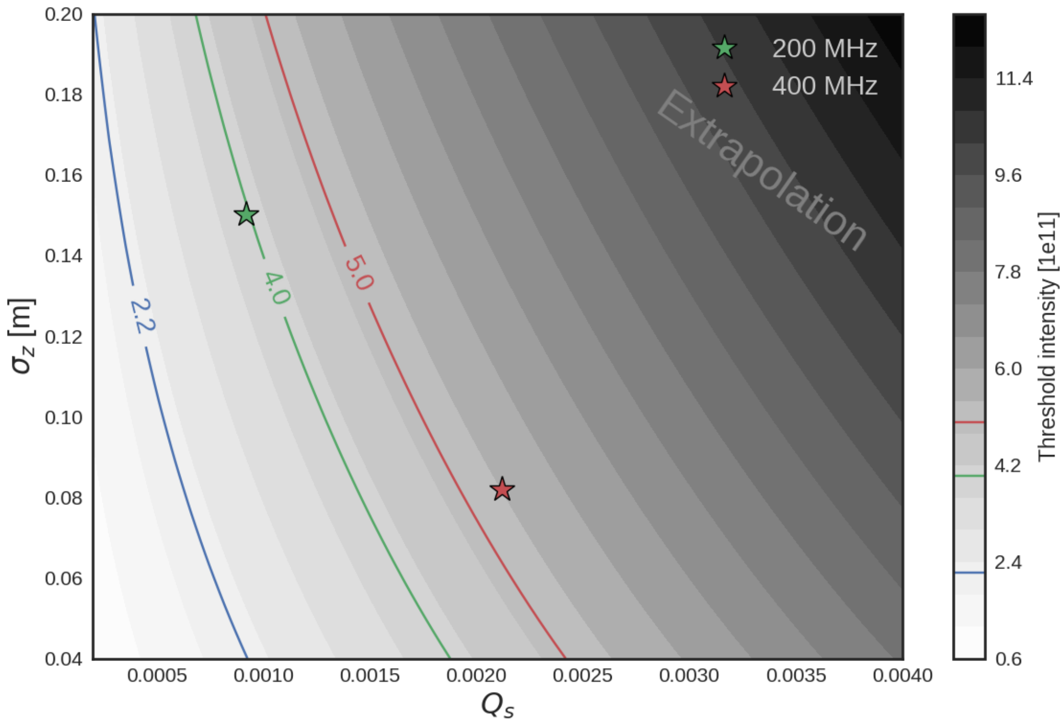

Fig. 4: A regression on TMCI thresholds for different combinations of RF systems allows to give estimates on the TMCI thresholds for different bunch lengths and average synchrotron frequencies. The two working points for the 400 MHz and the 200 MHz single RF are indicated.

damping. One can counteract this by a recapture with the 400 MHz system once bunches have reached a compatible bunch length to boost up the synchrotron frequency and increase the margins on the TMCI thresholds.

Moreover, limitations would first come from the longitudinal plane where beam stability is much more of an issue for the 200 MHz case and one would heavily depend on a higher harmonic system (i.e. 400 MHz) to ensure beam stability as is discussed in detail in [9].

2.4 The impact of the transverse damper

An idealized transverse damper as described in sec. 2.2 was added to the simulations to assess its impact on the TMCI threshold. We learned from the sections above that the TMCI in the HL-LHC is a result from a coupling of modes 0 and -1. A transverse damper acts efficiently on mode 0, hence, one may expect with mode 0 mitigated by the transverse damper, the coupling between modes 0 and -1 is impacted. Simulations reveal that this is, in fact, the case. Figure 5 shows an intensity scan done for the case of the 200 MHz system, with a TMCI threshold at 4×10^{11} particles per bunch, first without a transverse damper (left) and then comparing this to the case including a transverse damper (right). The spectrum on the right side displays how mode 0 is indeed suppressed by the transverse damper.

It is, however, remarkably observable that with the suppression of the TMCI, the rise time is not vanishing, but instead shows characteristics similar to a classical headtail mode. One of the features of these modes is that it they do not exhibit a distinct threshold value after which they grow unstable but they instantaneously have a finite growth rate for finite intensities. This can be seen when looking at the growth rates shown on the right side of fig. 5.

Figure 6 shows a full comparison of growth rates between the 200 MHz and the 400 MHz cases with and without a transverse damper. The behavior observed above is confirmed, where a clear threshold behavior can be seen for the two cases without a transverse damper. With the inclusion of a transverse damper, the trend instead exhibits a slow constant rise in growth rate with intensity. This can be understood when realizing that the transverse damper can be seen as yet another type of impedance which

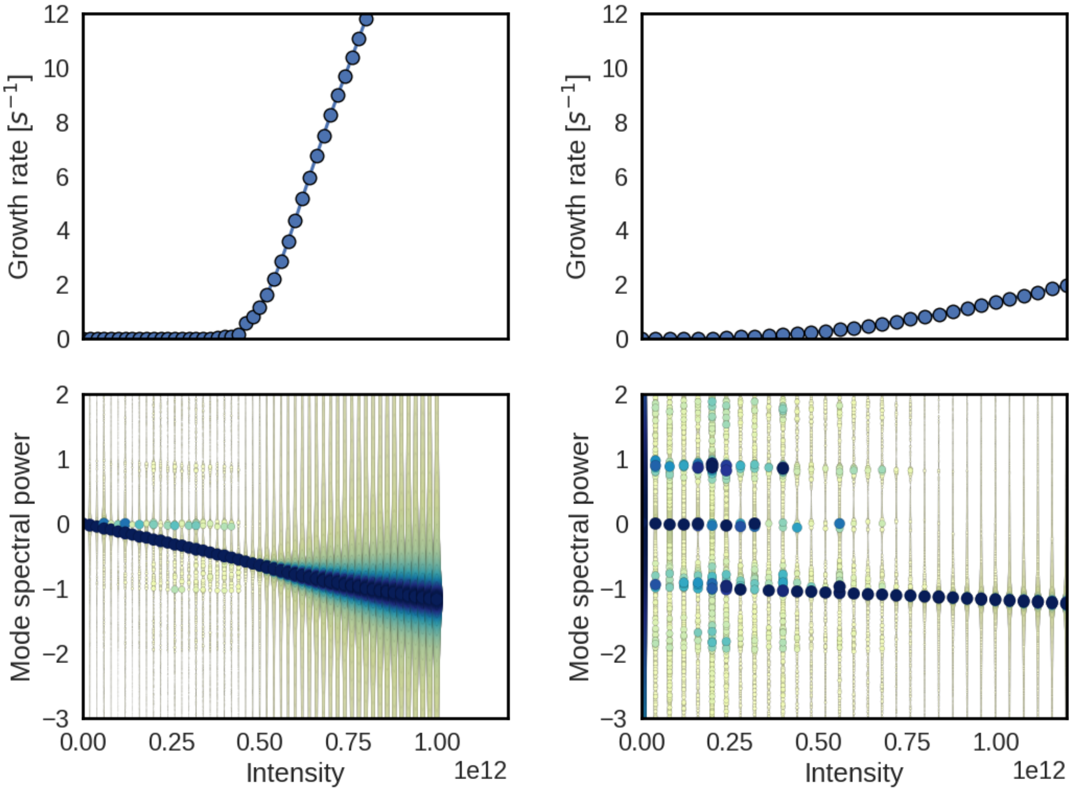

Fig. 5: Intensity scan in presence of the HL-LHC impedance at flat-top. The plots above show the case of 200 MHz operating in combination with a 400 MHz system in bunch shorting mode. The plots on the left hand side are without a transverse damper while the ones on the right hand side include a transverse damper. The top plot shows the instability growth rates, the bottom plot shows the coherent mode power spectrum for different intensities.

modifies the machine impedance. The interaction of the beam with this new global impedance consequentially changes the dynamics of the system.

One may ask now, whether it is beneficial to combat TMCI using a transverse damper. Clearly, a TMCI induced by a coupling with mode 0 is affected by a transverse damper. What happens then, is that the transverse damper modifies the impedance and a TMCI is no longer present in its original form. This comes at the expense of a newly rising headtail-like mode.

To assess whether or not the addition of the transverse damper is desirable, a comparison must be made on a case by case basis. For example, it may be desirable for the case where one would like to considerably exceed the TMCI threshold. The newly arising mode will be present for low intensities but will also have significantly lower rise times compared to the TMCI at large intensities such that it may be possible to damp this mode by other means such as Landau damping, for example. However, there are indications that this new mode is not a headtail mode in the typical sense and the effectiveness of Landau damping to combat this mode is still under investigation [10].

3 Conclusion

In this note, the impact of the use of alternative RF systems for HL-LHC i.e., a 200 MHz fundamental system on the transverse stability, in particular, the TMCI threshold has been revisited. The threshold has been estimated in the past to dangerously approach the nominal intensity values being around 2.6×10^{11} ppb. Including recent modification in the optics, leading to a slightly lower transition energy, as well as the most recent impedance model, which takes into account coated collimators, together with a slightly larger nominal bunch length and a detailed modeling of the longitudinal dynamics these results could now be rendered more precisely. The new TMCI threshold was found to be around 4×10^{11} ppb for operation in a single harmonic system. The threshold increases when combined with a second harmonic system in

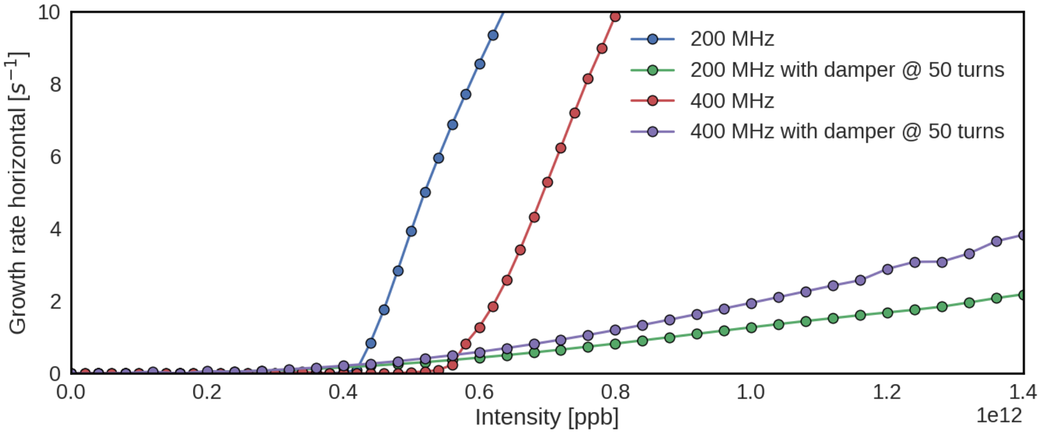

Fig. 6: A comparison of growth rates featuring the use of a pure 200 MHz and a pure 400 MHz RF system for which simulations were run both without a transverse damper and by including a transverse damper. Several of the features mentioned above are manifestly visible in this plot. The TMCI thresholds are lower for the 200 MHz case which exhibits a smaller synchrotron tune. The cases including a transverse damper show finite growth rates also below the TMCI thresholds. The growth rates remain lower above the TMCI thresholds.

bunch lengthening mode. Further simulations were carried out comparing 200 MHz and 400 MHz fundamental systems as well as a combined double harmonic system made of a 200 MHz and a 400 MHz system operated in bunch shortening or in bunch lengthening mode. This allowed also to roughly extrapolate the TMCI thresholds for different combinations of synchrotron frequency and bunch length which can become important when considering different operational scenarios where bunch lengths may shrink during a fill as presented in Ref. [5].

Finally, the impact of a transverse damper on the TMCI threshold was investigated. It was found that the TMCI threshold can be attenuated. However, a new type of instability arises instead, which does not seem to feature a distinct threshold. It also exhibits lower growth rates. In this sense it is similar to a classical headtail mode. However, the effectiveness of Landau damping against this potentially novel type of instability is still under investigation.

4 Acknowledgements

We wish to thank R. Calaga, J. Esteban Muller and E. Shaposhnikova for valuable input. Research supported by the HL-LHC project.

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