Ensuring bunch stability in multi-MW beams

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As present and future machines look to provide multi-MW beams for probing the high intensity frontier, hadron bunches will need to remain stable while experiencing large wake-driven coherent tune shifts (ΔQ_{coh}) as well as large space charge (SC) tune shifts (ΔQ_{sc}.)

For a single bunch at zero chromaticity without multi-turn wakes, electron clouds or additional beams, there exists only one transverse collective instability known as the transverse mode coupling instability or TMCI. This instability occurs when a wake causes the coherent tune of two bunch modes to merge resulting in the imaginary part of the tune (growth rate) to increase rapidly.

It is important to understand how this instability is affected by space charge. According to [1, 2, 3, 4, 5, 6], the TMCI intensity threshold increases with the space charge tune shift and at a sufficiently strong SC, the threshold of the wake-driven coherent tune shift is proportional to the SC tune shift. This statement suggests that bunches will remain stable for any number of particles, given that the wake-driven tune shift and the space charge tune shift both depend on this. Thus, if a beam is stable at a certain number of particles, it will continue to be stable as the number of particles are increased. This in itself is odd and also seems to be in disagreement with measurements at the CERN SPS[7]. A resolution to this issue was suggested in [8] arguing that SC does indeed raise the TMCI threshold however, in its place, brings a different class of instabilities known as *convective instabilities.*

Convective instabilities are not true instabilities in the the sense that, the bunch modes are still stable but there is spacial amplification. However, they do make the bunch more prone to instability. If a convective instability occurs, the bunch could see huge head-to-tail amplification. The use of a traditional damper system would only feed these head-to-tail oscillations leading to the bunch becoming unstable.

Figure 1 shows a general sketch of the instabilities areas on the SC-wake plane. There, w and q represent the wake and space charge parameter which are defined as $w = \Delta Q_{coh}/Q_s$ and $q = \Delta Q_{sc}/Q_s$. The TMCI threshold is represented by the line $w_{th} \simeq a + b\,q$. Above this threshold, the colour gradient represents the growth rate for the TMCI and below the threshold, convective instabilities can develop where the colour gradient represents the amplification factor.

I propose to explore the SC-wake plane in order to understand single bunch stability for strong space charge and arbitrary coherent tune shifts. The Fermilab Recycler already operates in the strong space charge regime. Re-bunching to longer 2.5 MHz bunches, which are already used for the Muon program, will allow us to enter the convective instability region. With the addition of a 'waker', a dedicated wake-building feedback system, the SC-wake plane can be extensively explored.

The 'waker' will be similar in design to a traditional damper system, except it will run with arbitrary phase such that it excites coherent growth rather than damps it. A dedicated diagnostic will also be developed which is capable of measuring the intra-bunch motion. This will be needed to properly identify modes within the bunch along with growth rates for TMCI and amplification factors for convective instabilities.

In addition to the Recycler, the Fermilab Main Injector can also be used in a different way. Both the wake and the space charge parameter are inversely proportional to the synchrotron tune. Thus, the high wake and space charge region can be explored near transition crossing when $Q_s \to 0$.

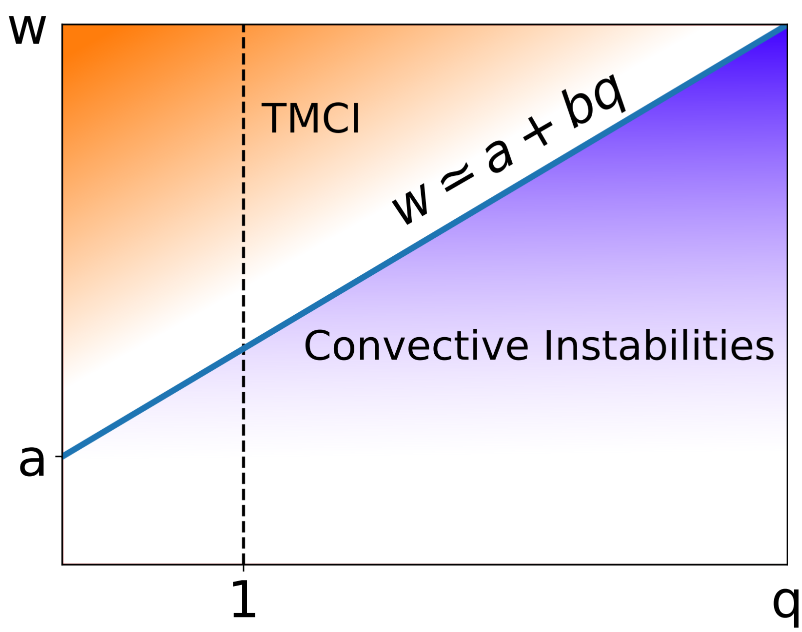

Figure 1. General sketch of the instability areas on the SC-wake plane. The color gradients represent the growth rate for the TMCI and the amplification for the convective instability. The white area at $w \leq a$ corresponds to stability with insignificant amplification. The convective amplification grows exponentially with the wake amplitude; the TMCI threshold $w \simeq a + b\,q$ does not prevent the convective amplification to grow this way in the TMCI area as well. The coefficients $a = w^0_{th}$ and b depend on the shape of the wake function

Even with a waker, there are some limitations to using the Recycler as it already has some impedance which cannot be removed. Moving the waker to the Integrable Optics Test Accelerator (IOTA) once it is ready to store protons would allow the implementation of practically any impedance due to the low velocity and long bunches inside the ring.

The ultimate aim is to fully explore the SC-wake plane in order to understand the different instabilities. A 'waker' and IBM (intra-bunch motion) monitor will be developed and installed in the Recycler and eventually moved to IOTA to facilitate this. Additional studies such as transition crossing in the Main Injector, how Landau damping effects the instabilities and multi-bunch effects will also be investigated. With this understanding, limitations for multi-MW proton beams, as well as possible methods for overcoming them, would be determined.

References

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