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Jacques.Gareyte@cern.ch

Does LHC need Landau damping Octupoles?

Jacque Gareyte, SL Division, AP Group

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Summary

Octupoles have been used in many accelerators or storage rings to Landau damp collective instabilities, from 1962 until now. In view of the present knowledge on LHC coupling impedance and instability theory, we recommend that the LHC be equipped with Landau damping octupoles at each available place close to Q_F and Q_D quadrupoles, so as to produce a tune shift of about 1 10^{-4} at 1 R.M.S. beam size.

1 INTRODUCTION

The very intense LHC beams will be subject to severe transverse collective instabilities. The most violent ones will be damped by an active feedback operating up to 20 MHz, that is capable of treating each bunch separately, on its fundamental dipole mode. High order modes have to be stabilized by Landau damping. For this mechanism to be effective, the tune of the individual particles in the beam must be spread over a sufficiently large range so as to render coherent excitation of the beam by the wakefields impossible. Such a tune spread can exist naturally in a particle collider owing to its inherent non linearities, or it can be introduced intentionally with octupoles. My considered opinion is that we should provide the LHC with an effective system of Landau damping octupoles. However, the cost of such a system is not negligible, and good arguments must be found to justify this request.

I will start with a short historical account to show that octupoles are widely used in accelerators. Then I will examine the case of the LHC. Finally I will make recommendations.

2 HISTORY OF OCTUPOLES IN ACCELERATORS

The first preoccupation of accelerator or storage ring pioneers was probably not collective instabilities. Their concern was more to make sure that “some” particles would accept to circulate for a while. The case of the CERN PS, which was the first large machine to use strong focusing and which started operating in 1959, is well documented. The major concern of the PS builders was non-linear resonances. Octupoles were introduced to detune large amplitude particles out of resonance, thereby providing a “closed” phase space and avoiding particle losses. As we will see in a moment, these octupoles turned out to be very precious, but for a completely different purpose.

The Princeton-Stanford ring

The first report on the use of Landau damping octupoles I found in the literature concerns the Princeton-Stanford electron-electron storage rings which started operation at the MkIII linear accelerator center at Stanford University in 1962. In this machine the current was limited to 5 mA by a vertical collective instability (probably due to the resistive wall). Using an octupole they could push the threshold up to 500 mA. Later on, a feedback system was developed to better control this instability. This is a typical scenario that has been experienced in many other machines.

The CERN PS

As already mentioned, the PS was equipped from the start (1959) with 10 octupoles. For many years, these were not used and some of them disappeared to make room for more useful equipment. However, in 1968, the beam intensity had been raised to about 10^{12} protons per pulse. At this level it became very difficult to adjust the different internal targets and beam lines, and this was shown to result from a vertical instability occurring after transition. Subsequent studies showed this to be the first observation in proton machines of the newly discovered head-tail instability. The existing octupoles were invaluable in helping to diagnose the problem. However, they were not strong enough to suppress the instability in all conditions, and more powerful magnets were built. Once understood in detail, the head-tail instability was finally suppressed by careful adjustment of chromaticity, including a jump from negative to positive value at transition. However, further increase in beam density revealed other types of collective instabilities which were in turn damped by the octupoles. Now the PS accelerates routinely 3 10^{13} protons per cycle. It uses feeback systems but octupoles are still essential for operation and machine studies.

The CERN SPS

The well known resistive wall instability was expected to be a problem in the SPS, and an active feedback was foreseen from the beginning (in 1976) together with a few octupoles. Thanks to these wise measures the SPS started in earnest. However, as beam intensity increased towards the design value of 10^{13} protons per cycle, it became clear that both the feedback and the octupole systems were insufficient. The power and bandwidth of the feedback were increased, and a new set of 48 more powerful octupoles were constructed. With these improvements the beam intensity went up progressively to 4.8 10^{13} protons per cycle. The feedback damps the more dangerous modes at low frequency. These cannot be damped by octupoles since the tune spread needed is too large and would send particles onto dangerous 3rd and 4th order resonances, creating in turn beam losses. Octupoles are used to damp high frequency modes, which are difficult to damp by feedback.

The KEK Photon Factory

The KEK Photon Factory is a 2.5 GeV electron or positron storage ring used as a synchrotron light source. A new transverse instability was recently discovered in this machine when it is operated with positrons. This was explained by an accumulation of photo-electrons in the potential well of the positively charged beam. It is currently controlled by exciting octupoles, thereby inducing in the beam a tune spread as large as 0.02 [2].

These four examples cover the whole era of high performance accelerators from 1962 to 1998. They demonstrate that octupoles are invaluable tools because they provide an easy, universal, efficient handle to manipulate instabilities. They are not only an immediate cure, they are part of the diagnostic equipment. In addition, I see them as an insurance against the occurrence of unforeseen, new phenomena which always show up in a new machine.

There are probably many other examples of the same kind. However, there are also examples of machines which operated without octupoles. This was the case of LEP and HERA, which were not equipped with octupoles.

LEP

LEP used positive chromaticity to damp head-tail mode m=0, as is usual. The novelty was that mode m=1 grew in this case with a rise time shorter than the synchrotron damping time, and very often destroyed the beam. This had been predicted by Pellegrini and Sands in 1967, but had never been observed before. The cure is to use active feedback to damp mode m=0 and slightly negative chromaticity to damp mode m=1. However, it took years to have a sufficiently reliable feedback. It would have been wiser to foresee a few octupoles in LEP (some octupoles recuperated from the ISR were installed a few years after the start up, but they were much too weak). Octupoles could have been used also recently to reduce the large detuning with amplitude at high energy in the high tune lattices

HERA

During its first years of operation HERA had problems of single particle dynamic aperture, and was not confronted to collective instabilities. After a while the beam density increased and a new, collective phenomenon perturbed operation during the ramp (it was dubbed the “Batman” effect). Since they had no octupoles, they tried to create Landau damping with sextupoles, which are not appropriate for this purpose since they produce tune spread only to second order. Finally the phenomenon was recognised as being a plain head-tail effect, and was eliminated by chromaticity adjustment. But it has created a lot of confusion for some time. Again, I believe that octupoles would have been very useful.

3 THE CASE OF LHC

In the LHC Project Note 163[3] J.P. Koutchouk and F. Ruggiero make a detailed review of different cases requiring Landau damping octupoles. Including a safety margin of about 2 to cope with unknown coupling impedances and theoretical uncertainty, they conclude that a tune shift of 10^{-4} at 1σ is necessary. This corresponds to $3.6\ 10^{-3}$ at 6σ, a value which is known to reduce the dynamic aperture, but which is still compatible with operation of the LHC.

4 RECOMMENDATIONS

There are good scientific arguments based on our present knowledge of LHC coupling impedance and on the most refined instability theory to justify the need for Landau damping octupoles in the LHC. The necessary tune spread is of the order of 10^{-4} at 1σ.

The spool pieces which correct the magnet b4 at injection are too weak. Their strength should be increased by about a factor 10 to be effective for Landau damping.

The 88 octupoles foreseen to be installed close to the Q_F and Q_D's at places which are still available would provide 70% of the required detuning. This is probably acceptable although we would favour some increase in strength.

Considering the arguments developed in this note, I would not take the risk of not providing the LHC with Landau damping octupoles. Especially because it will be impossible to install them later in case of proven need.

References

[1] W.C. Barker et al, 1965, 5th Conf. On High Energy Accelerators, Frascati, Italy

[2] K.Ohmi, 1998, KEK preprint 98-17

[3] J.P. Koutchouk, F. Ruggiero, LHC Project Note 163