FIRST ESTIMATE OF THE OVERALL HERA-P TRANSVERSE IMPEDANCE BY MEANS OF GROWTH RATE MEASUREMENTS

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Abstract

A transverse coherent amplitude growth is occasionally detected in the HERA proton ring for small negative values of the chromaticities. This phenomenon has been carefully studied, and the characteristic behaviour of an head-tail instability has been evidenced. The overall transverse impedance of the machine is now under investigation. Systematic growth rate measurements were performed during the machine studies of November 1994; they were repeated in December 1995 also in the presence of controlled linear coupling which, in the mean time, had shown to be a crucial ingredient for the instability to occur. The results of these measurements will be shown: they were found reasonably consistent among each other, therefore allowing us to give an estimate of the effective transverse impedance of HERA-p.

1 INTRODUCTION

In the HERA (Hadron Electron Ring Anlage) electron-proton collider a transverse coherent excitation of the proton beam was observed at the injection energy of 40 GeV shortly after the first start up of the machine in 1992. Since then, this instability, affecting the motion in both the horizontal and the vertical plane in the same way, has appeared from time to time, saturating the electronics of the betatron tune measurement pick-ups, and leading to partial or complete beam loss.

After careful investigations from different points of view it is now clear that, although extra multi-bunch effects can also be present, it is mainly a single bunch effect. Soon it was known that the excitation can be sometimes stimulated artificially by decreasing the Landau damping in the machine, either by scraping the beam transversely by means of collimators, or compressing it longitudinally by means of extra RF voltage. Recently it has been found that, on top of this, some coupling between the transverse planes is necessary for the instability to start.

A clear chromaticity dependence, the instability appearing for negative ξ values, suggested that it could be the case of an head-tail instability, but the fact that its strength was decreasing when moving towards larger negative values ($\xi = \Delta Q / \frac{\Delta p}{p} < -6$) is not observed usually in other machines, therefore numerical simulations were performed in order to check the consistency of the observations.

By means of multi-particle tracking simulations[1] with the realistic wake-field of an HERA-p 208 MHz RF cavity, it was definitely possible to identify the phenomenon with an instability of the head-tail kind, the simulation results being in quite remarkable agreement with the predictions of the theory of transverse bunched-beam instabilities[2] in the presence of the corresponding transverse impedance. Also the weakening of the instability at large negative ξ, was shown to be fully consistent with this kind of instability, the difference with other particle accelerators being in the particular HERA-p optics parameters that allow to reach rather large values of the chromaticity without spoiling the dynamic aperture, and in the typical chromatic frequency shift involved.

2 HEAD-TAIL INSTABILITY

When a charged-particle bunch interacts with the transverse impedance $Z_\perp(\omega)$ of an accelerator the oscillation frequencies of its l azimuthal modes are shifted by the complex quantity:

$$\Delta\omega_l = -i \, \frac{1}{1+l} \, \frac{\beta_o c^2 I_o}{4\pi f_{\rm rev} Q \frac{E}{e} L} \, Z_{\perp\,\rm eff}(\omega_\xi) \qquad (1)$$

where $\beta_o = v/c$, $f_{\rm rev}$ is the revolution frequency, $I_o = N_{\rm b} e f_{\rm rev}$ is the bunch current, Q is the betatron tune, E is the beam energy, L is the bunch full length, $\omega_\xi = \omega_{\rm rev}\xi/\eta$ is the so-called chromatic frequency, ξ and η being the machine chromaticity and dispersion respectively, and $Z_{\perp\,\rm eff}(\omega_\xi)$ is the effective transverse impedance:

$$Z_{\perp\,\rm eff}(\omega_\xi) = \frac{\int_{-\infty}^{+\infty} h_l(\omega-\omega_\xi)\; Z_\perp(\omega)\; d\omega}{\int_{-\infty}^{+\infty} h_l(\omega)\; d\omega} \qquad (2)$$

where $h_l(\omega)$ is the bunch power spectrum for mode l.

If we consider only the $0^{\rm th}$ mode, the real part of this frequency shift, which is proportional to the imaginary part of the impedance, corresponds to a coherent betatron tune-shift, whilst its imaginary part corresponds to either an amplitude growth or damping depending on the sign of the real part of the impedance. When this amplitude growth occurs an instability develops which, due to the typical motion of the particles within the bunch, is commonly called head-tail instability.

3 IMPEDANCE MEASUREMENT

The measurements with beam of the coherent tune-shift and of the amplitude growth rate can provide valuable information about the machine transverse impedance. In particular, the measurement of the local coherent tune-shift all around the machine can help identifying those elements in the machine whose contribution to the global impedance is larger [3].

In the HERA proton ring the possibility of performing this kind of measurement was analyzed, but it was found that the machine parameters involved are such that, with the expected effective impedance, tune-shifts to be measured would be very small, smaller than the resolution of the instrumentation, or, at most, of the same order.

By means of growth-rate measurements at different chromaticities, instead, because of the definition of the chromatic frequency ω_ξ, it is possible to obtain information on magnitude and frequency dependance of the real part of the global effective transverse impedance of the machine.

3.1 *Growth Rate Measurement*

Measurements of instability growth times as a function of the chromaticity have been performed in order to characterize the real transverse impedance of the HERA proton machine.

From Eq. 1 it follows that for the parameters of HERA-p at injection energy, a growth rate

$$\begin{aligned} \frac{1}{\tau_{\rm g}} &= -\frac{\beta_o c^2}{4\pi f_{\rm rev} Q \frac{E}{e} L}\, I_o \Re[Z_{\perp \rm eff}(\omega_\xi)] \qquad (3) \\ &= -\frac{1{\times}(2.998{\times}10^8)^2}{4\pi{\times}47304{\times}32.28{\times}(40{\times}10^9){\times}0.6}\, I_o\, \Re[Z_{\perp \rm eff}] \\ &= -\,0.195\, I_o\, \Re[Z_{\perp \rm eff}] \end{aligned}$$

can be expected for the $0^{\rm th}$ mode, which means that, with currents of a few hundred μA, negative effective transverse impedances of the order of a few hundred kΩ/m would induce instabilities with growth times $\tau_{\rm g}$ of the order of some fractions of second, which are reasonably easy to detect.

It should be noted here that the proton bunch is quite short in HERA, and the corresponding bunch power spectrum is rather wide, with $\sigma_{h(f)}$ of the order of 90÷130 MHz. This implies that, due to the convolution of the impedance with the bunch spectrum, Eq. 2, it will only be possible to see broad-band-like behaviours of the impedance, all resonant effects with width smaller than the bunch spectrum remaining hidden in the effective impedance $Z_{\perp \rm eff}$.

All measurements were performed at the injection energy of 40 GeV. In order not to mix with multi-bunch effects, a single bunch from PETRA was injected for each measurement at the maximum achievable current of about 200÷300 μA. The standard operational injection procedure with bunch rotation in the transfer from PETRA and 2 RF systems in HERA-p was used. Although avoiding bunch rotation would have left the bunch a little bit longer, increasing the resolving power of the bunch spectrum, it was not possible to get the instability started without it. Also the standard operational values of betatron tunes were kept, but it was necessary to exchange their fractional parts in order to be able to excite the beam. Injection errors and closed orbit were checked from time to time and reoptimized when necessary.

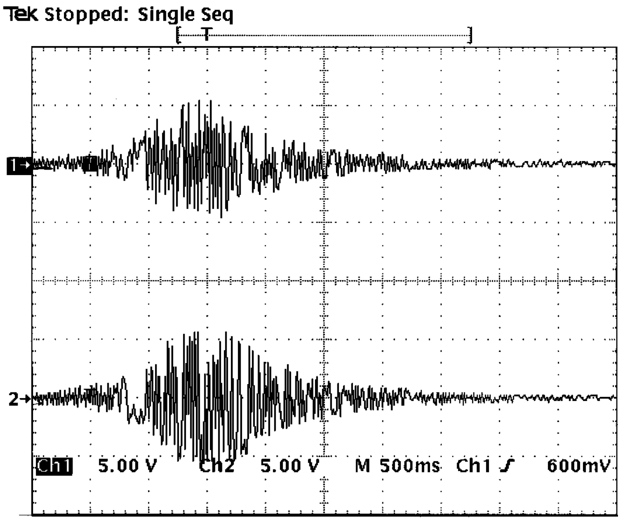

Figure 1: Growth time acquisition: the transverse position of the bunch center of charge as signal from horizontal and vertical pick-ups is displayed as a function of time

The measurement of chromaticities was running continuously and the values were recorded as soon as the instability would start, together with the bunch current and the bunch length. The beam signal was taken from the very sensitive betatron-tune measurement pick-ups and acquired by means of a sampling oscilloscope; its growth was evaluated graphically.

Growth times of the order of 100 to 700 ms were measured. A typical example of data acquisition is shown in Fig. 1. In this case the instability develops with a growth time of 440 ms for a few seconds, then, after quite large amplitudes are reached and a large fraction of the bunch particles has been lost, some Landau damping effect like amplitude-dependent tune-shift prevails, and in another few seconds the instability is damped down. Both transverse planes are affected, due to coupling.

Two sets of data were taken in 1994 and 1995. In both cases the horizontal chromaticity was kept at a safe positive value around 2 or 3, while the vertical one was varied within the range $-10 \div 0$ in a controlled way.

Different procedures were used in the two sets of measurements in order to stimulate the instability: in 1994 some Landau damping suppression was introduced cutting away the particles at large amplitudes by injecting the beam in HERA with collimators partially closed onto the beam. Shortly after the 1994 data taking, in the attempt of reproducing those measurements, it was discovered that if the

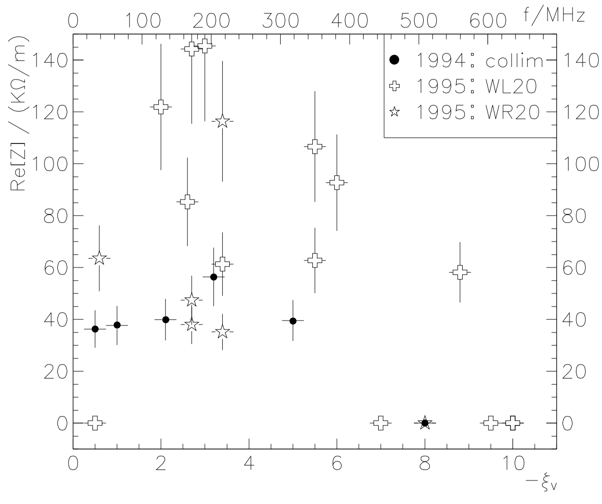

Figure 2: HERA-p effective transverse impedance as a function of chromaticity (frequency), computed from measured growth times

machine tuning is very good and, in particular, linear coupling is very well compensated it is almost impossible to drive an instability; it was therefore supposed that some residual coupling should have been present also during the former measurements.

In 1995 growth time measurements were repeated with the same setup of 1994. The dependence on coupling was investigated and it was confirmed that, with the appropriate chromaticities, it was enough to move from its optimized value the excitation current in one of the two skew quadrupoles available in the machine to make the beam unstable. Thus, both vertical chromaticity and coupling were scanned changing also one skew quadrupole at a time and recording its current.

3.2 Results

Eq. 3 has been used to compute the real part of the HERA-p effective impedance. The latter would coincide with the true impedance only in the case of constant $Z(\omega)$ over the whole bunch spectrum for each value of chromaticity/frequency considered; as already said, this can only be satisfied for a broad-band impedance, which is not necessarily the case. However, the knowledge of the effective transverse impedance at injection, when the bunch spectrum is the narrowest allowed, is more than sufficient to estimate the electromagnetic interaction of the machine components with the beam also at higher energy, as the corresponding transverse impedance will result even more smoothed out in the convolution with a wider bunch frequency spectrum.

The measurement results are summarized in Fig. 2 where the three groups of data are shown: 1994 data, where the instability was induced by means of collimators, 1995 data, with the instability driven by changes in skew quadrupole WL20, and 1995 data, with the instability driven by changes in skew quadrupole WR20. The computed effective impedance is displayed as function of both chromaticity (lower axis) and frequency (upper axis).

A broad-band or broad-band-like effective transverse impedance of the order of 100 KΩ/m can be identified, peaked between 150 and 350 MHz; this means that the source of this impedance will have to be looked for amongst the machine components with full transverse dimension between 40 cm and 1 m.

The computed impedance values are affected by a relative error of the order of 15÷20% due to the error in the measurements of beam current, bunch length and growth time, whilst the indetermination in the chromaticity value is roughly 0.25. On top of this, one should also consider the indetermination due to either known or unknown fluctuations of other machine parameters.

One known parameter is linear coupling which was varied on purpose during the 1995 measurements. Its effect can be recognized in the larger spread amongst the 1995 data, whilst the data from 1994, indicated with filled dots, seem to be more concentrated around a smooth curve. Unfortunately, no simple correlation between coupling, measured growth times and chromaticity has been found until now. Further investigation is needed, maybe with the help of particle tracking simulations.

The four 208 MHz Radio-Frequency cavities have been candidate as one of the possible causes of the head-tail instability in HERA-p, but it has already been shown [1] by numerical particle tracking that the expected growth time of the instability for these cavities is of the order of some seconds, or even more, due to the presence in the machine of sources of Landau damping, therefore they are to be excluded.

4 CONCLUSION

Although coupling was recognized as essential for the head-tail instability to occur, the driving mechanism has not been clarified yet. Nevertheless it was possible to employ it to provoke the instability artificially in order to measure growth times, keeping reasonable consistency with the measurements made at constant coupling, and allowing an estimate of the HERA-p transverse impedance.

5 REFERENCES

[1] F. Galluccio, *Numerical Simulations of Head-Tail Instabilities in the HERA Proton Ring*, in Proc. of Workshop on Collective Effects in Large Hadron Colliders, Montreux (CH), 17–22 October 1994, Particle Accelerators Vol. 50, 1995, pp. 141-151 (also DESY-M 95-03, INFN/TC-95-14, March 1995).

[2] F.J. Sacherer, *Transverse Bunched Beam Instabilities — Theory*, Proc. 9th Int. Conf. on High Energy Accelerators, Stanford, CA, USA, 1974, p. 347.

[3] D. Brandt, P. Castro, K. Cornelis, A. Hofmann, G. Morpurgo, G.L. Sabbi, J. Wenninger, B. Zotter, *Measurement of Impedance Distributions and Instability Thresholds in LEP*, Proc. 16th Particle Accelerator Conference, Dallas, TX, USA, 1995 (also CERN-SL-95-34-AP, Jun 1995).