OBSERVATION OF TRANSVERSE QUADRUPOLE MODE INSTABILITIES IN INTENSE COOLED ANTIPROTON BEAMS IN THE AA

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Abstract

In the CERN Antiproton Accumulator (AA) a breathing mode type of instability has been identified as an intensity limiting mechanism in cooled stacks. The more well-known dipole mode instabilities are adequately controlled by the existing damper system. With the aid of a quadrupole pick-up it was possible to observe transverse modes in the beam at frequencies (n-2Q). The instabilities occur only at certain emittance and intensity thresholds and are believed to be caused by uncleared pockets of ions trapped in the beam potential. A quadrupole kicker was added to the machine so that these modes could be excited and Beam Transfer Functions were measured for each of the possible modes. Feedback may be applied to actively damp the quadrupole modes.

Introduction

Transverse coherent quadrupole instabilities are a special case of intensity limiting mechanisms, not normally harmful in circular machines with positive particles. In the quadrupole mode the beam size oscillates, in contrast to the well-known dipole mode instabilities where the position of the beam oscillates. Instabilities are an important issue in the AA where high-current beams coast for many hours and are cooled to very low emittances.

The stability threshold for transverse dipole modes is quite low due to a combination of Lasslett space-charge tune shifts, low emittances, the resistive wall impedance, and almost zero chromaticities. Active damping[1] has therefore been used for many years to suppress dipole mode instabilities occurring at frequencies $(n-Q)*f_0$, where Q is the tune and f_0 the revolution frequency. The very small chromaticities are necessary to avoid nonlinear resonances while accepting a large momentum spread. Very high-order (up to 20-30) nonlinear resonances are known to be excited by residual pockets of uncleared ions[2] in the ring when the negative antiprotons are stored.

In spite of the damper, coherent ion-antiproton instabilities[2] have been observed for many years with cool $\bar{p}$ stacks above a few 10^{11} $\bar{p}$. These instabilities used to limit the minimum transverse emittances at high stack intensities, but never caused any loss of antiprotons.

Surprisingly, and in spite of substantial effort put into improving the ion clearing[3], this coherent instability became a severe limitation to $\bar{p}$ stack intensity (few 10^{11} $\bar{p}$) in June 1988 when increased $\bar{p}$ stacking rates thanks to the ACOL project[3] became available. The instability manifests itself as periodic "hiccups" where the emittance increases rapidly and a beam loss equivalent to several hours of $\bar{p}$ stacking occurs. The recent lower intensity threshold for the instability is probably due to a higher beam density, while the resulting loss is caused by the reduced transverse acceptances; both resulting from the ACOL conversion of the AA core cooling systems.

Experimental evidence forced us to abandon the hypothesis of a transverse dipole mode. An improvised quadrupole resonant pick-up was quickly hooked up, and strong coherent signals were immediately observed for the two lowest frequency unstable quadrupole modes $(5-2Q_H)$ and $(6-2Q_H)$.

The theory[4] confirms that while a quadrupole mode is only weakly driven by beam pipe impedances, this is not the case for coherent interaction with an ion cloud.

History of Observation of Ion Induced Coherent Effects

Bursts of coherent ion-antiproton instabilities were first observed using an electrostatic closed orbit pick-up. The mode first observed was the lowest frequency dipole mode $(3-Q_V)*f_0$, where $Q_V \approx 2.26$, at a frequency of 1370 kHz. The instability occurs at certain emittance and intensity thresholds, at which the transverse ion frequency resonates with the lowest frequency transverse n-Q mode in the beam.

The coherent signal barely exceeded the noise floor of the pick-up when using a 3 kHz observation bandwidth. Initially it was believed that this was due to amplitude limitation arising from nonlinearities in the ion motion rather than nonlinearities in the beam motion, so that beam-ion instabilities are limited to a smaller maximum amplitude than beam-wall instabilities.

To improve the sensitivity, a pair of more sensitive transverse pick-ups were installed during the ACOL conversion by using longer plates (540 mm) closer to the beam (gap = 46 mm), and resonating these plates in differential mode at 1350 kHz (3-Q mode) (Fig. 1). This resonant circuit is tapped to obtain optimum noise match into a head amplifier which uses a pair of dual gate MOSFETS.

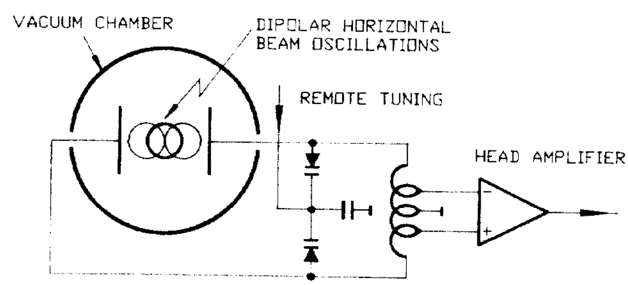

Fig. 1 Resonant dipolar pick-up.

The sensitivity was thus increased by about 3 orders of magnitude. This made it possible to observe unstable, exponential growth of the 3-Q modes over several orders of magnitude, the footprint of an unstable linear system. Also the transverse Schottky noise can be observed at this very low frequency making very precise incoherent tune measurements possible (few 10^{-5}), although at present this signal is perturbed by another noise source when the damper is on, namely the white noise of the damper pick-up filtered through the Beam Transfer Function (BTF), which reflects the coherent tune.

Two mysteries remained however. Firstly the maximum amplitude of the dipole motion was not large

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enough to explain the observed emittance blow-up. Secondly an experiment was done to increase the damping rate of the $3-Q_H$ by injecting the signal from the very sensitive resonant pick-up into the horizontal damper with the proper phase. The experiment was successful in completely suppressing the coherent signal of the $3-Q_H$ mode, but unsuccessful in suppressing the emittance blow-up associated with the instability.

And yet it was still evident that we had a coherent instability since filamentation noise appeared at many $(n \pm Q_H)*f_0$ lines in the spectrum. By filamentation noise we mean a noise power level of a transverse sideband temporarily increased above the Schottky noise power level expected from the known intensity and emittance. This noise is due to lumpiness in the phase plane, and usually observed after a coherent instability has reached its maximum amplitude.

This led us to suspect a mode not observable so far by our pick-ups: the transverse quadrupole mode.

Observing Transverse Coherent Quadrupolar Instabilities

An improvised quadrupole pick-up was quickly made by connecting the plates of the existing resonant vertical pick-up in common mode (Fig. 2). Due to the gaps between the plates only a fraction of the total induced charge is induced on the plates, and this fraction depends on both vertical and horizontal beam size. The sum signal will therefore be sensitive to both horizontal and vertical quadrupole modes.

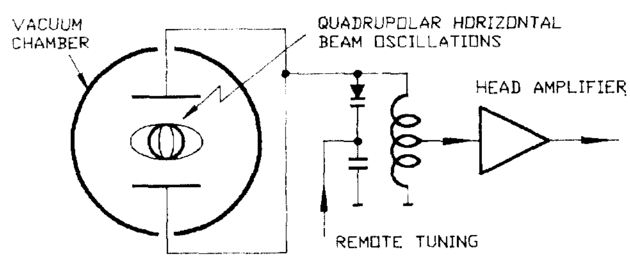

Fig. 2 *Improvised quadrupole pick-up.*

With horizontal tunes just above 2.25 the possibly unstable quadrupole mode of lowest frequency occurs at a frequency $(5-2Q_H)*f_0$. To ensure adequate sensitivity the pick-up was made resonant at this frequency ($f \approx 850$ kHz, $Q \approx 20$). The quadrupole mode signal was then observed versus time with a spectrum analyser set up as a fixed tuned receiver.

When the instability threshold was approached with a stack of 3×10^{11} $\bar{p}$, a fast rising and very strong coherent signal was observed at a frequency corresponding to the $5-2Q_H$ mode, rising by as much as 80 dB during the hiccup (Fig. 3). As usual, emittances were blown up sufficiently to cause loss of antiprotons. The initial rise time is difficult to measure due to the slow time base (5 s/div), but an e-folding time of about 100 ms or less is indicated. Even far away from the pick-up resonance strong $6-2Q_H$ and $6-2Q_V$ mode signals have been observed ($f \approx 2.7$ MHz). Potentially stable modes such as $-3+2Q_V$ and $-3+2Q_H$ have much smaller amplitudes as expected from theory. The quadrupole mode stability could be influenced by changing the clearing voltage. The threshold can also be substantially raised by applying a small positive chromaticity, which obviously increases the Landau damping for these low frequency modes, but unfortunately also increases the area the stack occupies in the tune diagram, which results in high-loss rate due to ion-induced nonlinear resonances.

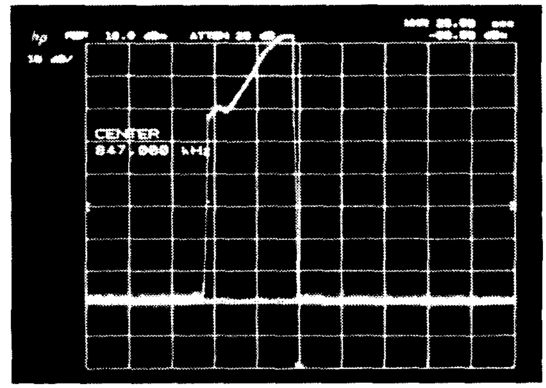

Fig. 3 *Example of the evolution of a hiccup.*

A more useful cure was to move the tune closer to the diagonal, where no coherent instabilities have been observed up to 8.5×10^{11} $\bar{p}$, even with low chromaticities. This intensity was, however, only reached after having cured high stack loss rates due to ion induced nonlinear resonances. The cure consists of shaking the ions by applying a transverse sine-wave excitation to the beam. This technique may also have beneficial effects on the coherent quadrupole instabilities.

Any quadrupole pick-up, which evaluates the second-order moment of the transverse charge distribution, will inevitably also be sensitive to the square of any dipole oscillation. A dipole mode, like $(3-Q_H)*f_0$, will therefore also be observed by a quadrupolar pick-up, but due to the squaring action of this pick-up it will appear at twice the frequency: $(6-2Q_H)*f_0$, which is the same frequency as a quadrupole mode.

Any *even* quadrupole mode signal (like $6-2Q_H$) is therefore caused only by a true quadrupole motion of the beam if no significant dipole motion is observed by a dipole pick-up at half the frequency. This ambiguity does not apply to *odd* quadrupole mode numbers (like $5-2Q_H$), where no half-frequency dipole mode exists.

Beam Transfer Functions

Beam Transfer Functions (BTF) for the transverse dipole modes have proven to be a powerful tool for analysing the influence of chromaticity, emittances, and space charge on Landau damping, as well as confirming the stabilizing effect of the transverse damper.

With the aid of an rf quadrupole kicker and the previously described quadrupole pick-up, quadrupole mode BTF's can be measured (Fig. 4). The HP 3582 performs two-port network analysis by noise excitation and dual channel FFT in the frequency range 0-100 kHz. Frequency translation to the desired mode frequency is done by a local oscillator and mixers. The response of the lower LO sideband is rejected by an image rejection mixer in the beam response branch. The noise excitation used by the FFT analyzer is less likely to modify the beam distributions than a swept oscillator. In addition the FFT measurement is much faster than a conventional network analyser.

By keeping the excitation power level sufficiently low blow-up of stack emittances is avoided. In Fig. 5 the amplitude and phase response for the mode $6-2Q_H$ is shown. The stability diagram is more useful to analyze the stability of a mode, and is obtained by making a polar plot of the inverse of the complex beam transfer function as a function of frequency (Nyquist diagram) (Fig. 6). This representation of the BTF for the $6-2Q_H$ mode shows that for the large beam emittance during the measurement there is adequate Landau damping to ensure stability.

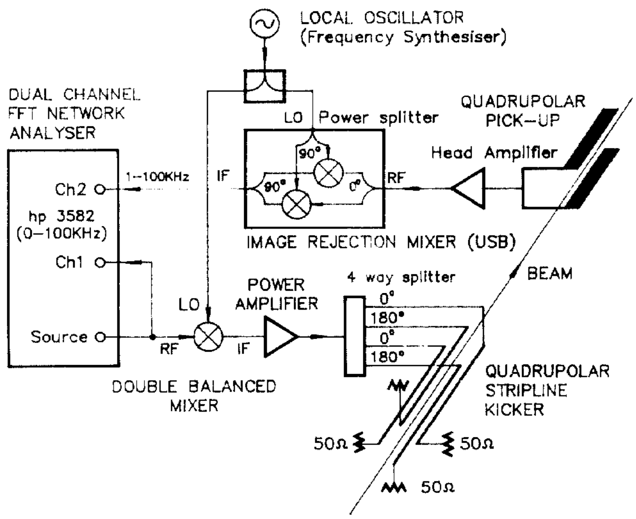

Fig. 4 Quadrupole mode BTF set-up.

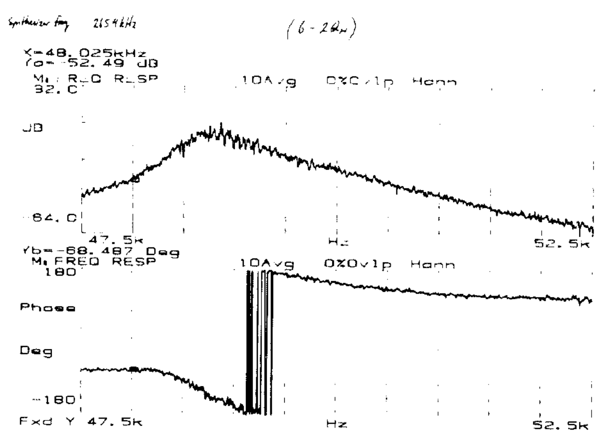

Fig. 5 Amplitude and phase response for $6-2Q_H$ mode.

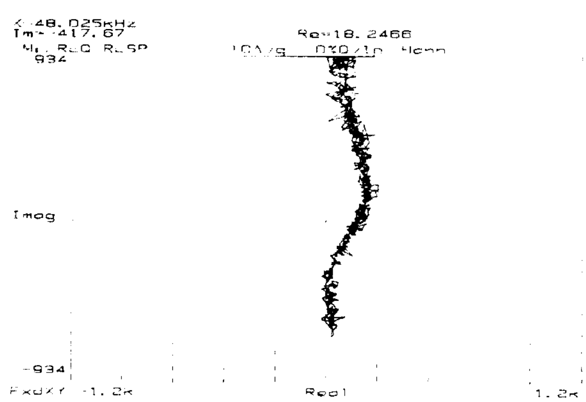

Fig. 6 Inverse of complex BTF as function of frequency ($6-2Q_H$ mode).

The studies made with the BTF measurement were, for example, to see if the stability changed noticeably as the emittances were cooled to low values where hiccups were known to occur. No correlation could be found though with the BTF at different emittances. In addition, we also sought, and failed, to find a correlation between stability of a mode and change in chromaticity. Limited control of the chromaticity is achieved by exploiting the dependence of chromaticity on stack momentum. However, the vertical modes ($n\pm2Q_V$) do exhibit far greater stability which can be attributed to the significantly higher chromaticity in the vertical plane.

It appears that for the quadrupole mode there is no significant loss of Landau damping due to space charge as is the case for dipole modes. Nevertheless sufficient residual neutralization is apparently present in a $\bar{p}$ stack to shift the coherent quadrupole mode frequency to its stability limit.

A further application of the BTF measurement is to assess the possibilities of damping the quadrupole modes by closing a feedback loop between the pick-up and kicker. The BTF permits verification of correct phase advance from pick-up to kicker for all vertical and horizontal quadrupole modes, as well as absence of dipole and longitudinal response. The major difficulty in implementing such a quadrupole mode damper seems to be to obtain adequate sensitivity of the quadrupole pick-up while rejecting the very high common mode signals present during rf unstacking.

The largest reproducible changes in the measured stability diagrams of the quadrupole modes of a $\bar{p}$ stack occurred with changes in the ion clearing voltage. An optimum voltage could be found which gave maximum stability according to the BTF, but this voltage would not necessarily be the same for different stack intensities or emittances.

Clearing Current Signature of Ion Induced Dipole and Quadrupole Instabilities

When the condition for an ion-beam coherent instability is fulfilled, namely for sufficiently populated ion pockets having ion transverse bounce frequencies close to a beam dipolar or quadrupolar unstable modes, ions gain large amplitudes and may be lost to the chamber wall before having a chance to reach the nearby electrode. The resulting effect can be seen as a dip in the continuous recording of the current, and this may help in locating the culprit pocket.

Conclusion

The unique configuration of the AA has allowed us to study this intensity limiting quadrupole instability mode in isolation from other instabilities. With the measured BTF and Stability diagrams we have been able to study the contributing factors to beam stability under different beam conditions. The BTF diagnosis also confirmed the feasibility of damping these unwelcome modes. The best solution, though, has been to gradually rid the machine of remaining ion pockets by improving the clearing, careful choice of tunes, and even shaking the beam.

References

[1] F. Pedersen, W. Pirkl, K.H. Schindl, IEEE Trans. on Nucl. Sci., Vol. NS-30 (1983) p. 2343.

[2] E. Jones et al., IEEE Trans. on Nucl. Sci., Vol. NS-32 (1985) p. 2218.

[3] F. Pedersen et al., this conference.

[4] R. Alves Pires et al., this conference.