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TRANSVERSE BEAM STABILITY OPTIMIZATION BASED ON BEAM TRANSFER FUNCTION MEASUREMENT

by

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ABSTRACT

Previously stabilization of large beams against the transverse resistive wall instability was achieved in the ISR by active damping and by imposing a constant chromaticity over the energy aperture. The introduction of the beam transfer function set-up has opened up the possibility of measuring the actual beam stability diagram. Based upon it, the stability margin is estimated. The influence of the complex wall impedance and of the betatron distribution is compensated by modulation of the chromaticity. A 55 A stack has been accumulated under such conditions.

INTRODUCTION

The vertical transverse resistive wall instability is one of the most severe limitations to increasing the beam intensity in the ISR; as a consequence, the machine is operated close to the instability threshold, requiring an ever refined control of the transverse beam dynamics.

The theory of transverse instabilities is well established, eg.1),2),3); it relies however on parameters that, until recently, were hardly measurable to the accuracy required by the ISR control (the coupling impedance, the betatron distribution).

A simplified stability criterion was thus derived⁴⁾, which, for the low frequency modes, may be written as:

$$\frac{I}{\Delta Q} \leq k \frac{F\gamma}{|Z_T|} ; \quad Q' = \frac{\partial Q}{\partial \Delta p/p} = \text{constant}$$

with I: beam current; ΔQ : betatron spread; Z_T : coupling impedance; F: form factor depending on the betatron distribution and coupling impedance phase angle.

I and ΔQ may be measured accurately, whilst their threshold values and the condition $Q'=\text{constant}$ are difficult to establish.

The stability criterion has been successfully used up to an intensity of 35 A ($7 \cdot 10^{14}$ p); beyond this limit, the stability of operation decreased.

Although beam response to sinusoidal excitation had already been studied^{5),6)}, it is only with the introduction of the beam transfer function set-up⁷⁾ that the beam stability diagram could be exploited to control the stability margin.

INFLUENCE OF THE BETATRON DISTRIBUTION AND WALL IMPEDANCE ON THE BEAM TRANSFER FUNCTION

The beam response to an RF excitation at frequency ω is given by:

$$r(\omega) = \left[\left\{ \frac{I}{\Delta Q} \int \frac{f(\omega_\beta) d\omega_\beta}{\omega - \omega_\beta} \right\}^{-1} - Z'_T \right]^{-1} \quad 8)$$

where $f(\omega_\beta)$ and Z'_T are the normalized betatron frequency distribution and coupling impedance; the beam transfer function is the beam response for a wide band exciter covering the frequencies of a fast or a slow wave, expressed as a set of amplitude and phase pairs $A(\omega)$, $\phi(\omega)$; the function $[1/A(\omega), -\phi(\omega)]$ is known as the stability diagram, where the origin is the unstable point.

Whilst the influence of I and ΔQ is clear, it is interesting to expand on the influence of $f(\omega_\beta)$ and Z'_T for a given $I/\Delta Q$ (Figure 1):

Fig. 1

- Ideally (Fig. 1a), the stability diagram is a semi-circle; the stability margin is constant whatever the frequency of the perturbation; the beam transfer function presents a constant amplitude and a linear phase rotation.
- For a realistic betatron distribution (Fig. 1b), the stability margin is reduced; the transfer function amplitude and phase rotation are larger near to the extreme beam frequencies.
- The coupling wall impedance shifts the unstable point by $-Z_T$ (Fig. 1c); the transfer function becomes asymmetric and exhibits a large spike corresponding to the stack bottom frequencies for an inductive impedance.

THE NEW TRANSVERSE STABILITY CRITERION

The amplitude and phase of the transfer function reveal mechanisms that may lead to an instability; its peak amplitude is a direct measurement of the Landau damping; a high level not only expresses a small stability margin, but equally a possible premature saturation of the active feedback system. It is thus natural to use it as a stability criterion. The maximum allowed amplitude was established experimentally by reducing ΔQ and measuring the amplitude; it was set to correspond to the minimum ΔQ below which the beam is lost, increased by 50% to allow for transient stability reduction during phase displacement acceleration, tune and chromaticity correction, etc.

TRANSVERSE STABILITY OPTIMIZATION

Means to increase the transverse stability are required when the stability criterion is not satisfied.

No consideration is given to the resistive wall impedance, which is compensated by an active system; Figure 2(a) shows an actual beam transfer function, where the influence of the reactive wall impedance is clearly preponderant over the influence of the "natural" betatron distribution. Transverse stability optimization will thus be achieved by compensation of the inductive wall impedance.

The frequency spectrum of the disturbances being a priori unknown, the best stability diagram that can be aimed at is a semi-circle, i.e. a constant amplitude transfer function. To meet this criterion, two possibilities are open:

- either to provide a reactive feedback system,⁹⁾ which, within its frequency range, compensates Z_T ,
- or to choose a betatron distribution such that the stability diagram will be as close as possible to a semi-circle; such a compensation is valid for all collective modes.

The modification of the betatron distribution for a given longitudinal distribution may be performed by controlling the variation of the chromaticity over the energy aperture (Fig. 3): $f(\omega_\beta) \sim 1/Q'(\Delta p/p)$.

A simple approach

The chromaticity at the bottom of the stack is increased in steps whilst the tune and chromaticity over the rest of the stack is modified to keep the tune and tune spread constant; the process is repeated until the optimum stability criterion is fulfilled.

A more systematic approach

A specific skew trapezoidal betatron distribution was found to compensate almost ideally the effect of the reactive wall impedance (Fig. 4); for an initially linear $(Q, \Delta p/p)$ relationship, the ratio of this ideal betatron distribution to the measured one gives simply the correction factor to be applied to $Q'(\Delta p/p)$, and, by integration, the ideal tune diagram.

Fig. 2 Beam transfer function of an ISR beam

Fig. 3 Tune diagram

Fig. 4

Implementation

Chromaticity control at the stack bottom is realized by using a single pole face winding (PFW) of the main magnet; the complete 24 PFW's are used to improve its selectivity as well as to keep the tune and tune-spread constant. Modulation of the vertical chromaticity requires either a corresponding modulation of the horizontal chromaticity or a fine betatron coupling compensation to avoid the effect of the linear coupling resonance $Q_H - Q_V = 0$.

APPLICATION

Stability optimization has been used both for peak performance experiments and physics running:

Stability tests: for a given ΔQ , the maximum stable current without active damping is 30 A ($6 \cdot 10^{14}$ p) for the ideal betatron distribution whilst it is 15 A under normal conditions.

Peak performance tests: reliable stacking above 50 A is realized, compared to 40 A under normal conditions.

Physics running: stability optimization has permitted a reliable operation at a 25% higher current level.

CONCLUSION

Visual inspection and optimization of the Landau damping has proven to be a very powerful tool.

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