STABILIZATION OF THE FAST HEAD-TAIL INSTABILITY BY FEEDBACK

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Abstract

The fast head-tail[1,2,3] (or transverse mode coupling) instability occurs in most recent electron-positron accelerators when the frequency of the mode 0 (the transverse coherent dipole motion) becomes equal to the frequency of mode -1. In the absence of feedback these modes approach each other as a function of beam intensity. When the modes couple at the threshold current the transverse emittance of the bunch becomes 'blown up' and a strong coherent dipole oscillation is usually observed. A transverse 'reactive' feedback system can control the frequency of the coherent dipole moment (mode 0) by employing a beam pick-up/kicker arrangement with a multiple of 0.5 tune shift between them. This system can be used to shift the mode 0 away from the mode -1 and thereby allow the accumulation of higher intensities before the onset of instability. The effect of reactive feedback on the instability has been studied using analytical techniques with various combinations of localized/distributed wake fields and localized/distributed feedback systems. In addition a 'few-particles' model has been used to study the case of localized wakes and feedback with betatron phase advance between the two. Finally a multi-particle simulation code has been written and used to investigate the instability in the presence of feedback under the most realistic conditions. A dedicated machine experiment has been performed on the PEP storage ring using a modified version of the existing feedback system. This experiment clearly demonstrated that the use of a strong feedback system can greatly increase the threshold for the transverse mode coupling instability.

Introduction

The approximate parameter dependence of the threshold intensity for the transverse mode coupling instability[4,5,6] is given by[7]

$$I_{th} \simeq \frac{2\pi\ f_s\ E/e\ F(\sigma_s)}{\sum_i \beta_i\ f_i\ \frac{R_\perp}{Q}_i} \simeq \frac{8\ f_s\ E/e}{\sum_i \beta_i\ k_{\perp i}(\sigma_s)} \qquad (1)$$

where f_s is the synchrotron frequency, β_i, $k_{\perp i}$ are the amplitude function and the loss factor of the impedances: the sum is performed over the transverse impedance and the form factor $F(\sigma_s)$ has a minimum of around unity when the beam pipe diameter is of the order of the full bunch length ($\sim 4\sigma_s$).

For the LEP collider the design intensity is dictated by the threshold for this instability. The estimated threshold current of 0.75 mA/bunch has been obtained only after optimization of the parameters of equation (1). This optimization involved:

(i) reduction of the β values at the RF cavities,
(ii) design of new bellows so as to reduce their contribution to the total transverse impedance,
(iii) use of wiggler magnets at injection so as to increase the natural bunch length and hence increase $F(\sigma_s)$, and
(iv) increase of the synchrotron frequency.

In addition to these measures a transverse feedback system has been proposed[8] to combat this instability. Such a system should ensure that the design current is not limited by the TMCI provided the transverse impedance of the 'rest' of the ring (i.e. excluding the copper cavities) is within approximately a factor of four of its presently estimated value. In the event that the estimated impedance is correct the maximum intensity will be limited at a level above the design intensity, possibly by phenomena other than the TMCI.

Many different approaches have been used to study this type of instability, ranging from the use of simplified two[9] (or more) particle models to the solution of the Vlasov equations[10,11] and later computer simulations[12,13,14]. Experimentally the symptoms of the instability were first measured in SPEAR[15] and later at PETRA[16] where in fact the first successful attempt was made to explain its nature[4]. Since then systematic measurements have been made at PEP[17], CESR[18] and DCI[19] to establish and improve the theory.

Principle of Reactive Feedback

The onset of the TMCI occurs when the frequency of head-tail mode 0 (i.e. the coherent or centre of gravity betatron motion) decreases with increasing beam current and finally couples to mode -1. Clearly this situation may be avoided by controlling the coherent betatron frequency (without changing the incoherent one) so as to prevent coupling to mode -1. The coherent betatron frequency may be controlled by a feedback system (gain = g) which has an even multiple of $\pi/2$ betatron phase advance between the pick-up and the kicker (reactive feedback), i.e.

$$\overline{\Delta y'_k} = g\overline{y}_{pu} = g\sqrt{\frac{\beta_{pu}}{\beta_k}}\ \overline{y}_k \ \ (\text{for } \Delta\mu_{pk} = 2\pi) \qquad (2)$$

and hence the approximate coherent tune shift is

$$\Delta Q_{FB} \simeq \frac{-\beta_k}{4\pi}\frac{\overline{\Delta y'_k}}{\overline{y_k}} = -g\sqrt{\beta_k\beta_{pu}} \qquad (3)$$

Usually, for technical convenience, the pick-up and kicker are located physically close to one another, and the correcting kick is applied after one (or more) turns. Consequently the phase advance between the pick-up and kicker depends on the machine tune. This dependence is easily avoided by using two separate pick-ups, spaced by approximately $\pi/2$ in betatron phase. In this case the feedback damping coefficient ($\alpha_{FB} = 1/\tau_{Fb}$) as well as the coherent tune shift ($\Delta\mu_{FB}/2\pi$) can be independently controlled by adjusting the gains in the loops containing each pick-up, i.e.

$$-\frac{2\ t_{rev}}{\tau_{FB}} = g_1\sqrt{\beta_1\beta_k}\ \sin\mu_{1k} + g_2\sqrt{\beta_1\beta_k}\ \sin\mu_{2k} \qquad (4)$$

$$2\{\cos(\mu_0+\mu_{FB})-\cos\mu_0\} = g_1\sqrt{\beta_1\beta_k}\sin\mu_{k1} + g_2\sqrt{\beta_2\beta_k}\sin\mu_{k2} \qquad (5)$$

The design parameters for the LEP feedback system are described in an accompanying paper[20] to this conference.

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Effect of Reactive Feedback on the TMCI

The first analysis of the effect of the proposed reactive feedback on the TMCI was performed using a two-particle model[21], distributed wake fields and distributed feedback, and a step function wake field. This analysis concluded that a factor of two enhancement in threshold current would be expected for a reactive feedback system capable of providing a coherent tune shift of the same magnitude as Q_S. The model was later improved[22] by going to an infinite number of particles (Vlasov equation) and using a realistic wake field calculated for the LEP RF cavities. The improved model gave essentially the same results as the simpler model. Some doubts about the validity of the assumption concerning distributed wake fields and feedback motivated the development of another simple model which allowed study of the effect of a single localised wake field and a localised feedback system[23]. This model indicated the existence of 'coherent' synchro-betatron resonances, but also showed that feedback would enhance the threshold current provided the betatron tune value was properly chosen. This model was later extended to allow[24]

i) more particles; up to five were studied

ii) variation of the phase advance between the kicker and the wake field

and

iii) many wake fields per turn.

This model clearly demonstrated that (at least for high Q_S values of the order of > 0.1) the enhancement of the threshold current is a strong function of the betatron phase advance from the localised kicker to the localised wake field.

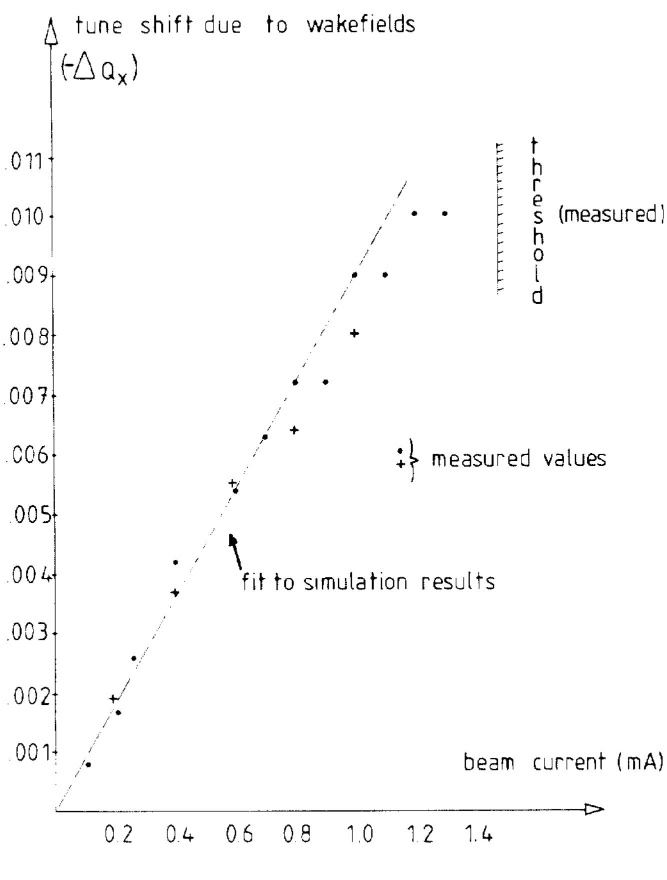

Fig. 1 Measured and simulated tune shift as a function of bunch current.

In parallel with the analytical studies, a computer simulation[14] was developed which allowed study of feedback under more realistic conditions (e.g. nonzero chromaticity, higher harmonic cavities etc.) and permitted many localised wake fields separated in betatron phase space as well as many feedback systems. A comparison[25] between the simulation model and the few-particles model showed that, under identical and necessarily simplified input conditions (imposed by the simpler model), both techniques produced approximately the same results. In addition the simulation code clearly confirmed the importance of the betatron phase advance between the kicker and the localised wake field.

Feedback Experiment at PEP

In view of the fact that the performance of the LEP collider is dictated by the TMCI it was considered crucial that the effect of feedback on this instability be studied not only theoretically but also experimentally. Consequently a proposal[26] was made to perform a dedicated machine experiment on the PEP collider. For this experiment[27] the PEP storage ring was operated at low energy (4.5 GeV), with modified optics and modifications to the existing[28] PEP feedback system. The PEP storage ring was chosen for the following reasons.

(i) It is likely that the impedance produced by the PEP accelerating structure is very similar to that of the LEP structure since both structures resonate at ~ 350 MHz and are similar in construction.

(ii) Previous experimental observations had shown (unlike the PETRA storage ring) that the onset of the instability was accompanied by coherent signals at the betatron frequency of the beam. This suggests that the mode coupling takes place between the dipole mode ($m = 0$) and the quadrupole mode ($m = -1$). This is a necessary condition for feedback to have a significant effect.

A special configuration was chosen so as to ensure that the TMCI would occur predominantly in a single transverse plane (horizontal). In order to convert the existing feedback from resistive to reactive a time delay was incorporated so as to apply the feedback kick on the second turn.

The coherent horizontal tune shift produced by the wake fields was measured as a function of beam current in the absence of feedback (ref. Fig. 1). One set of these results (marked x) was taken by accumulating current to near the threshold current and then removing particles with a scraper and measuring tune as a function of current; the other set (marked o) was measured during accumulation. From these results it can be seen that the tune shift increases linearly for currents up to ~ 0.8 mA. Above this intensity the increase becomes less steep. Above 0.8 mA it was also observed that the beam became longitudinally excited, indicating longitudinal turbulence and bunch lengthening (see later). Also shown in Fig. 1 are the results of the simulation program. The agreement is very good for both the tune shift and the threshold current (see later Figs. 2 and 3).

The simulation tune shifts were obtained by performing FFTs on the centre of gravity motion of the beam. The computed FFTs are shown as a function of current in Fig. 2 and Fig. 3 shows the frequency shift of the lower modes as a function of beam current.

The gain of the feedback system was calibrated by measuring (at low current) the coherent tune shift as a function of the gain setting. The threshold

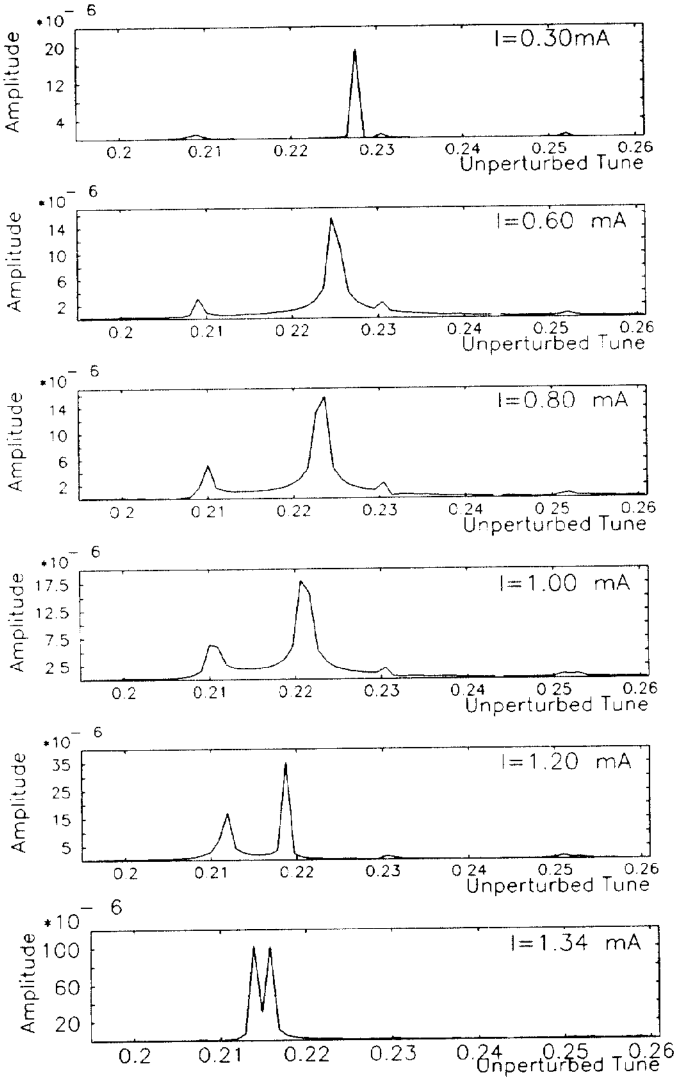

Fig. 2 FFTs of centre of gravity motion as a function of bunch current (simulation).

current was measured as a function of the gain of the reactive feedback by setting the gain at the beginning of accumulation and then accumulating current until a fast loss occurred. The results (shown in Fig. 4) show that the enhancement of the threshold current increases fairly linearly with the feedback gain. At gain values equivalent to a feedback tune shift of greater than $2Q_s$ the instability in fact completely disappeared.

The measured increase in the threshold current agrees well with simulation results up to a feedback gain of around Q_s. However at feedback gains greater than Q_s, theory shows that with small currents mode 0 should couple to mode +1 thereby decreasing the threshold. It is not yet fully understood why in practice this does not actually happen.

In order to compare resistive and reactive feedback an experiment was performed where all conditions were identical except the phase advance between the pick-up and the kicker. Figure 5 shows the results of this test. Unexpectedly, at high gain the resistive feedback produced a larger enhancement of the threshold current than the reactive feedback. This is in contradiction to the results obtained from theory and is not fully understood. It is worthwhile

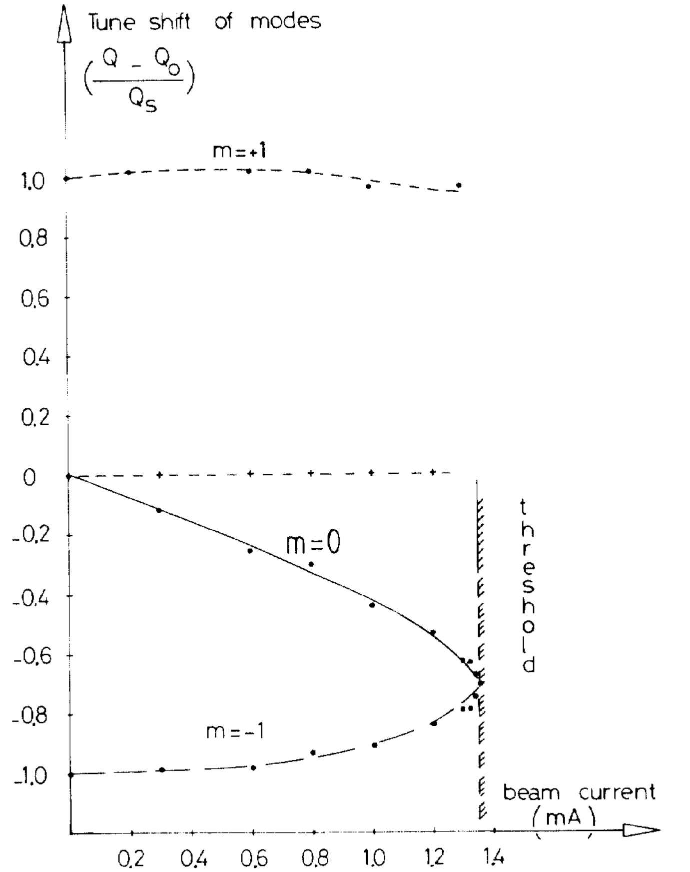

Fig. 3 Tune shift of lower modes as a function of bunch current.

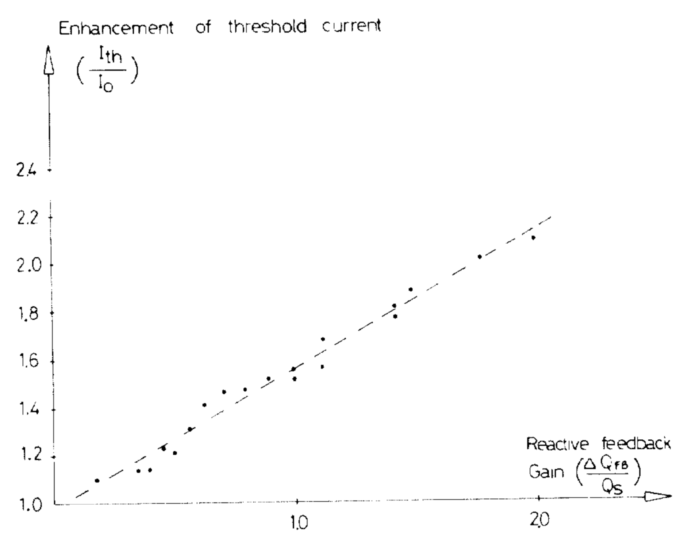

Fig. 4 Measured enhancement of threshold current as a function of the reactive gain.

to emphasize the fact that the maximum gain shown on the plot is indeed strong damping; a value of 1.0 for the normalized gain corresponds to a damping rate of ~ 7 turns when $Q_s \approx 0.022$.

As previously pointed out, longitudinal turbulence was suspected at currents above ~ 0.8 mA. For

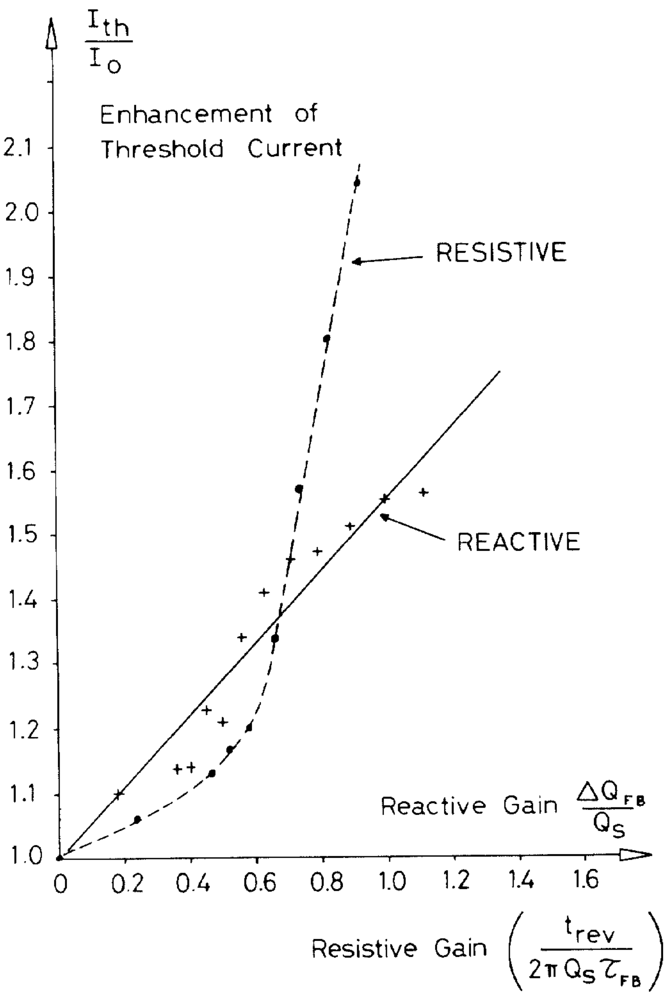

Fig. 5 Comparison of effect of reactive and resistive feedback.

this reason the bunch length was measured as a function of current; the highest currents being obtained with the use of feedback. Figure 6 shows indeed strong bunch lengthening at currents above around 0.5 mA. Such bunch lengthening may easily accentuate the improvement measured and attributed to the feedback system in the following way. The feedback system allows an increase in the threshold current which in turn causes bunch lengthening and therefore increases the threshold even more. The bunch lengthening was included in the simulation program by simply imposing the measured dependence of bunch length on current in the search routine for the threshold current.

Figure 7 shows the simulation results of threshold current against bunch length for three values of reactive gain. Also included in the plot is the measured bunch length as a function of current. Clearly the point at which a threshold current curve intersects with the bunch lengthening curve gives the threshold current (and bunch length) for a given feedback gain. It can also be seen that the threshold current is significantly increased by increasing the gain to ~ 0.8 Q_s and that the threshold current is never reached with a gain of $2.2Q_s$. This is in agreement with the experimental observations at high gain; however the simulation code has not been successful in reproducing the experimental results in the gain region from 1.0 Q_s to ~ 2.0 Q_s.

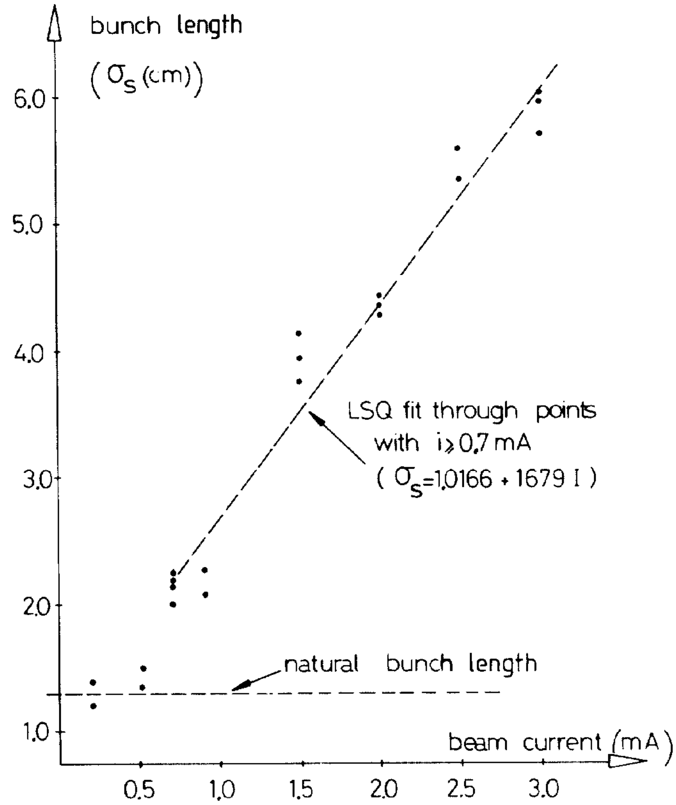

Fig. 6 Bunch lengthening as a function of bunch current.

LEP Hardware Requirements

A detailed description of the LEP feedback hardware is given in an accompanying paper to this conference; however for completeness a short description of the main components is given here. The feedback system is comprised of the following principal components per transverse plane:

(i) two 1.5 m kicker magnets
(ii) one 'pulser' amplifier
(iii) fast digital processing electronics
(iv) two standard LEP beam position monitors plus detection electronics.

The bandwidth of the system allows each counter-rotating bunch to be treated independently.

The inductance of the 'vacuum' cored kicker magnet is incorporated in a resonant circuit as has been previously done in PEP[28] and PETRA[29]. The current pulser is triggered once per bunch passage and produces a full sine wave current pulse in the kicker magnet. The trigger time of this current pulse is modulated so as to provide the computed kick at the time of arrival of the bunch. The computed kick is evaluated in a fast digital processor from input values of the required damping coefficient, the feedback tune shift and from the digitized measured betatron amplitudes at the two beam monitors. The analogue signals from the beam monitors are digitized using fast analogue to digital converters (FADC). The closed orbit contribution (common mode signal) is suppressed by averaging the digitized signal over previous turns.

The kicker magnets are made from stainless steel and are comprised of a cylindrical tank and a pair of

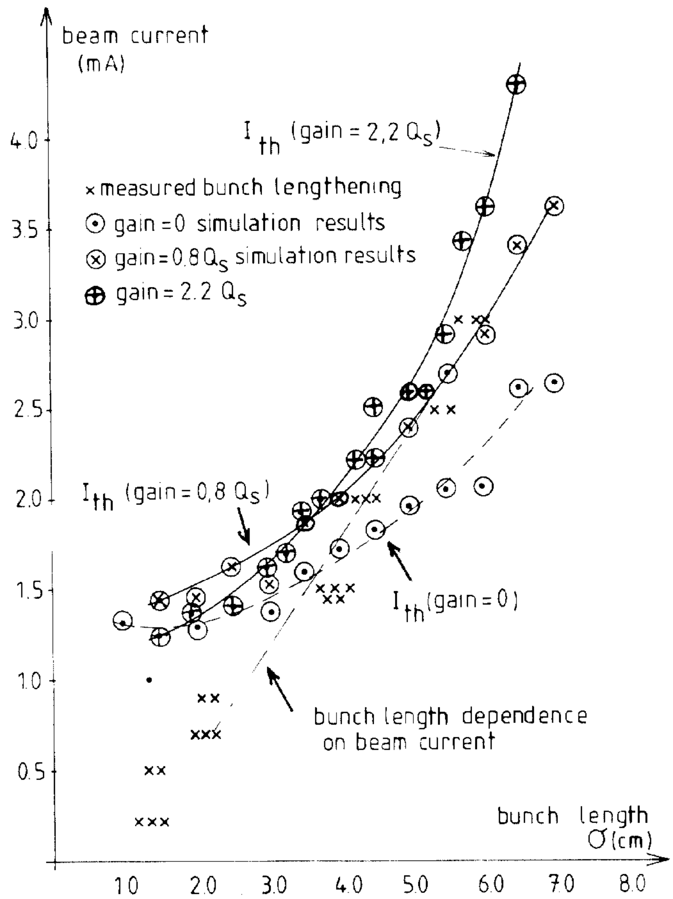

Fig. 7 (Simulation results) Threshold current as a function of bunch length for various reactive gain values. (Also plotted is the measured dependence of bunch length on bunch current.)

water-cooled electrodes. The field quality in the gap is much improved by shaping the edges of the electrodes (lips). The fields and the distribution have been computed and measured[20].

For a maximum estimated coherent betatron oscillation of 1 mm peak-to-peak the system must be capable of providing an integrated field of around 4 Gauss-m, requiring a peak current from the pulser of around 30 A.

Conclusions

It has been shown, both theoretically and experimentally, that a strong feedback system can considerably enhance the threshold current for the Transverse Mode Coupling Instability. In the case of Reactive feedback the experimental behaviour has been predicted fairly accurately by a simulation code up to feedback gains of the order of the synchrotron tune. For gains between one and two Qs the simulation (and theoretical) results predict a reduction in the threshold current whereas in practice a linear increase with gain was measured. The effect of bunch lengthening has been shown to be capable of exaggerating the benefical effects of feedback. Unexpectedly it has been shown experimentally that strong resistive (damping) feedback greatly increases the threshold. This behaviour is currently being investigated.

A strong feedback system (one per transverse plane) has been designed and is currently being built, for the LEP collider. This system is capable of being totally reactive or resistive or a mixture of the two. The reactive system is capable of tune shifts greater than Qs, and the equivalent resistive system capable of damping times of the order of two machine revolutions.

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