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Experimental Observations of Electron Beam
Instabilities in Storage Rings

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A B S T R A C T

The first electron storage rings were commissioned around 1962 and already beam instabilities were observed to limit their performance. Since then any new machine has revealed a new type of instability. A vast amount of knowledge, both experimental and theoretical, has been accumulated over the past 20 years on this subject, and this report gives a brief overview of the different phenomena encountered and of the understanding which has been developed in this domain. It appears that in order to optimize the performance of any new facility these phenomena must imperatively be taken into account at the design stage.

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I. Introduction

Around 1962 - 1964 the Princeton-Stanford electron-electron storage rings were being commissioned at the Mk III linear accelerator center at Stanford University. As soon as the stored current exceeded 5 mA, a vertical instability was noticed, with a resulting loss of part of the beam on the vacuum chamber. This phenomenon could be cured by powering octupoles or with a feedback system⁽¹⁾, and subsequently up to 500 mA of beam could be stored.

At about the same time a group at Novosibirsk in the USSR was working on the VEPP II e^+e^- storage ring. There phase instabilities of dense bunches were observed⁽²⁾. It had been predicted a few years earlier that in order to avoid this phenomenon the accelerating cavity should be tuned to a frequency somewhat lower than the RF generator frequency. However, the Novosibirsk team were able to show that even in this case the beam could be made unstable longitudinally by its interaction with a parasitic high frequency cavity. They also observed growth or damping of betatron injection oscillations depending on the tune of the machine⁽³⁾. This they similarly ascribed to the interaction of the beam with a high frequency transverse mode in a parasitic resonator. Phase instabilities were also observed in the Princeton-Stanford machine, as well as bunch-lengthening, for certain values of the RF frequency.

It was therefore made clear very early to the first experimenters who attempted to store high intensity beams in electron machines that these beams were fundamentally unstable. Powerful damping mechanisms had to be provided in the form of Landau damping or feedback systems to make these machines work. During the following 20 years, many electron storage rings were built, each of them revealing the existence of new types of instabilities. A considerable amount of work, both experimental and theoretical, has been necessary to understand and cure these effects. In this report we try to give an overview of the experimental observations of instabilities in electron storage rings. The aim is to cover all the relevant effects whose knowledge is necessary to any contemporary storage ring builder. Examples have been taken from as many machines as possible, to better convey an impression of universality, but even so it was impossible in a short report to do justice to all the work done in the field during 20 very productive years.

We will first introduce the "weak" instabilities due to long-range wake-fields (single bunch multiturn, or multibunch instabilities) or short-range wake-fields (head-tail effect) with a mention of an intermediate case when medium-range wake fields are involved. We will proceed by a survey of the important phenomenon of bunch lengthening, and then describe the "strong" instabilities generated by the "mode coupling" effects in both longitudinal and transverse phase planes*. This seems a natural way of classifying these phenomena and in addition it more or less corresponds to the historical order of appearance of these instabilities. The effect of trapped ions on the beam dynamics will be mentioned in the end.

II. Long-range weak instabilities

These are created by wake fields which do not decay too much during one revolution period, or, in the case of a machine with many bunches, which do not decay too much in between two bunch passages.

* In a "weak" instability the frequency shift generated by the wake-field is much smaller than the synchrotron frequency, whereas in a "strong" instability it is of the same order of magnitude or larger.

The two more important examples are the resistive-wall instability and the instability induced by high quality-factor cavity resonators.

The resistive wall instability was shown to affect the MURA FFAG accelerator continuous electron beam⁽⁴⁾, and a detailed theory was published by Laslett, Neil and Sessler in 1965⁽⁵⁾. In the absence of resistivity in the vacuum chamber walls, the electromagnetic force exerted by the image charges and currents are 90° out of phase with the transverse velocity of the beam and therefore merely change the betatron frequency. On the contrary in the presence of a resistive wall the wake-fields decay slowly after the beam passage and the force is phase shifted so that instability or damping can occur. The vertical instability observed in the Princeton-Stanford storage rings was ascribed to this phenomenon, although no proof was given that this was the real culprit. The transverse instability observed in VEPP II was clearly not due to the resistive wall, since its strong tune dependence can be explained only by invoking a narrow-band resonator. In fact the resistive wall instability, which is of extreme importance for high intensity proton accelerators and storage rings, does not seem to play a major role in electron machines, where it is overridden by other effects.

On the contrary, the powerful radio-frequency systems which are necessary to accelerate and hold the electron beams make use of high Q cavities, which are likely to generate long range wake fields when excited by dense bunches. The fundamental accelerating mode of these cavities is responsible for the longitudinal instabilities known as "Robinson instabilities" whereas higher modes can excite both transverse and longitudinal instabilities.

A crucial point for "weak" instabilities is the phase shift between the bunch displacement and the deflection given by the wake fields which are generated as a result of this displacement. For a given sign of this phase shift the oscillations are damped whereas they grow exponentially for the other sign. In the frequency domain we have the following picture: a collective mode of oscillation of the

bunches shows up as sidebands of certain harmonics of the revolution frequency. Above transition, a parasitic resonator straddling one of the upper sidebands gives rise to an instability whereas it stabilizes the corresponding mode if it sits on top of a lower sideband. In the case of longitudinal instabilities, we must examine the position of the synchrotron sidebands. Figure 1a displays the case of a machine with two bunches: the upper and lower sidebands of the revolution frequency harmonics pertain to the same collective mode, and therefore the effect of a resonator is proportional to the difference $R_+ - R_-$ of the impedance of the upper and lower sidebands. A strong effect can be induced only when a very sharp resonance curve is involved, as in the case of the fundamental accelerating mode of the RF cavities. Such an interaction results in the so-called "Robinson" instability, which can be observed in any electron machine. The cure is to detune the cavity with respect to the Rf so that the net effect $R_+ - R_-$ is damping. The case of one bunch is similar but with 3 bunches or more the picture is completely different, as shown in fig. 1.b. Now the two sidebands pertaining to certain collective modes appear at different harmonics of the revolution frequency. As a consequence, there is no cancellation between sidebands and strong effects can be induced by parasitic resonators of moderate impedance. In the case of betatron oscillations the sidebands are always separated because the tune value is at least of the order of one, and even a single bunch is potentially unstable.

The best illustration of all these long-range effects has been provided by the storage ring DORIS at the DESY Laboratory in Hamburg⁽⁶⁾. This machine was built to give a high luminosity by colliding two electron beams of high total intensity distributed over many bunches. It has been plagued by numerous instabilities of longitudinal and transverse multibunch modes due to the interaction of the beam with the high order resonances of the accelerating cavities. Figure 2 shows the field configuration of some of the resonances which couple to the beam. During the development of the instability, signals corresponding to the collective mode frequency can be detected by probes suitably placed inside the cavity.

The main characteristic of the multibunch instabilities is that their growth rates and thresholds depend on the total current and on the machine tune but only weakly on the chromaticity. They can be cured by feedback or Landau damping. In the transverse plane Landau damping is provided by octupoles which create a dispersion in betatron frequencies by giving different tunes to particles with different oscillation amplitudes. In the longitudinal plane, the natural dispersion of synchrotron frequencies near to the bucket separatrix can be exploited : it is sufficient to reduce the RF voltage until the bunch almost fills the bucket. This trick has been used at the C.E.A. in Cambridge⁽⁷⁾ and in the small machine SURF⁽⁸⁾ (National Bureau of Standards). Otherwise, a Landau cavity, working for instance on the third harmonic of the RF, can be used to create a large spread in synchrotron frequency. This has been used in the C.E.A. and at ADONE⁽⁹⁾ (Frascati).

Another way to increase the threshold of multibunch instabilities is to decouple the bunches by giving them different frequencies, so that only a small fraction of them can act coherently. At DORIS, an RF quadrupole powered on the 15th harmonic of the revolution frequency was used to decouple the bunches in the transverse plane. In the longitudinal plane, the RF system was decomposed into two subsystems, each tuned on a different harmonic number, so that individual bunches saw a varying RF voltage according to their azimuthal location around the ring. A similar method was used in ADONE.

However the best way to avoid these instabilities is to damp the unwanted modes in the cavities with the help of suitably placed loops and antennas, or to couple them out and damp them externally.

III. Short-range weak instabilities : the head-tail effect

This transverse instability was discovered in the second generation of storage rings ACO⁽¹⁰⁾ (in Orsay) and ADONE⁽⁹⁾. These machines were larger than the ones previously built, and operated with only a few bunches, so that effects due to short-range wake-fields acting within a bunch were likely to compete successfully with long range effects.

The new instability was clearly a single-bunch effect, and it was insensitive to the tune. On the contrary, it was very sensitive to the machine chromaticity and the bunch length. Pellegrini and Sands provided the theoretical explanation⁽¹¹⁾.

In this instability the regenerative action is not produced by the bunch going round the ring and experiencing the wake-field after one turn, but by the synchrotron movement of the particles within the bunch. The phase shift is produced by the chromaticity : for a bunch of length τ seconds, the betatron phase shift χ accumulated by a particle while going from the head to the tail amounts to

$$\chi = \omega_0 Q \frac{\xi}{\eta} \tau$$

where ω_0 is the revolution frequency, Q the tune, $\xi = \frac{dQ}{Q} / \frac{dP}{P}$ is the chromaticity and $\eta = \frac{d\omega_0}{\omega_0} / \frac{dP}{P}$.

It turns out that for strong-focusing machines as ACO, ADONE and all subsequently built storage rings, the parameter ξ/η is of the order 10 to 50, whereas it was only of order one in weak-focusing rings. As a consequence particles can experience large phase shifts χ in these machines even if the bunches are short. Now short, dense bunches are likely to leave strong short-range wake-fields in the high frequency parasitic cavities and cross-section variations of the vacuum chamber, and thus be prone to the head-tail instability.

A few head-tail modes are sketched in fig. 3. On the left modes $m = 0, 1$ and 2 are drawn in the case of a zero phase shift χ between head and tail (at zero chromaticity). Mode zero is the rigid dipole mode, mode 1 has a node in the center, mode 2 has two nodes, etc... On the right, modes 0 and 1 are drawn in the case of a phase shift π between head and tail : visibly now mode 1 shows a non-negligible centre of mass motion, whereas mode 0 is distorted and

has less center-of-mass motion than in the previous case. These considerations are important when one attempts to damp this instability with feed-back systems : a low frequency system may not be effective for certain machine parameters (at large x 's).

It is not easy to monitor the internal motion of the short bunches in electron machines. On the other hand in proton accelerators, the bunches are typically a few metres long, and internal modes can be seen. Figure 4 shows head-tail modes 0, 1 and 2 as seen on a transverse position pick-up electrode in the CERN-PS booster for a non zero phase shift between head and tail.

The head-tail instability can be cured by octupoles or when a large center of mass motion can be detected by feed-back systems. This was done in ACO and ADONE. However the best cure is to adjust the chromaticity to zero with sextupoles. In fact, if the chromaticity can be made positive (instead of the normal value around -1 for an uncorrected machine) one can profit from a strong damping due to the action of the short-range wake-fields above transition energy. This was put to good use in SPEAR 1 around 1973⁽¹²⁾, when it was found that a slightly positive chromaticity provided damping of the injection oscillations, thus increasing the stacking rate.

IV. Intermediate case: medium-range wake-fields

In the C.E.A. machine, the ring was partly filled by a long sausage of many bunches⁽⁷⁾. In the course of accumulation, a ragged pattern developed, a few consecutive bunches disappearing here and there. Although it looked like a collective bunch effect, this phenomenon disappeared for zero chromaticity, showing that it was in fact of head-tail type.

One can imagine that medium-range wake-fields produce mainly a head-tail single bunch instability, but are also able to weakly couple bunches together. In this case, the oscillation of a bunch is transmitted to the next one, helping to start its own head-tail

oscillation with a well defined phase shift with respect to the preceding bunch. This action can propagate along a few bunches, and stops when a bunch with a somewhat different frequency of oscillation is encountered.

There is no closed-loop around the ring, and this phenomenon is reminiscent of the beam-break-up instability in Linacs. It is not unusual to see patterns like this one in proton machines with a large number of bunches like the CERN SPS. In the C.E.A., these patterns were seen in the longitudinal plane as well as in the transverse plane.

V. Bunch lengthening:

Although this phenomenon does not usually produce beam loss, it is important because it can decrease the luminosity and lifetime of a collider and reduce the resolution in energy. On the other hand, it can also be a blessing in disguise when it helps avoid lethal instabilities. It was first noticed in the Princeton-Stanford e^-e^- storage rings; at certain RF frequencies the bunch length increased by up to a factor 2. This was attributed to the interaction of the beam with a parasitic resonator straddling a high harmonic of the revolution frequency, and producing a distortion of the potential well holding the bunch.

The idea of the potential well distortion was developed in the following years to explain this part of the bunch lengthening phenomenon which is not accompanied by a concomitant energy widening. The effect is easy to describe in the case where the coupling impedance is purely inductive. As shown in fig. 5 the effective slope of the Rf wave is reduced during the passage of the bunch. This leads to a bunch lengthening and a decrease in the single particle synchrotron tune. The dispersion in energy is not changed by this interaction; it is still determined entirely by the quantum emission of synchrotron light.

In the case of a capacitive coupling impedance, the interaction results in a bunch shortening. This phenomenon has indeed been recorded in a few machines.

Note that the coherent modes of the bunch undergo a smaller frequency shift than the single particles. This is easily demonstrated in the case of the rigid dipole mode: since the change of slope of the focusing RF wave moves with the bunch, it cannot be "seen" and therefore the frequency of this mode does not depend on the interaction. This has an important consequence, which is the loss of Landau damping. Landau damping is produced as a result of the coupling of the coherent mode with the single particles which have the same frequency. When the single particles frequency distribution ceases to overlap one coherent mode frequency, this mode may become unstable. Therefore potential well effects usually produce only a moderate change in bunch length, before instabilities appear and dominate the scene.

Bunch lengthening resulting from longitudinal instabilities is always accompanied by energy widening. This phenomenon is characterized by the existence of a threshold current as does any instability. Above the threshold at least one coherent mode grows until it is limited at large amplitude by the non-linearities of the bucket. At this point the bunch lengthens due to filamentation until it reaches stability, then it is slowly reduced to its original size by synchrotron damping, and the process starts again. This is shown in fig. 6 with an example taken from SURF at N.B.S.⁽⁸⁾. Well above threshold many modes usually become unstable, as can be seen on fig. 7 where many synchrotron sidebands appear on either side of a revolution frequency harmonic. The result is a "turbulent" motion of the bunch around a mean value which depends on intensity. This behaviour has been recorded on a large number of machines of different sizes and energies. Measurements done on the C.E.A. were published in 1971⁽⁷⁾. The existence of a threshold intensity was well established, and there was a good correspondence between the lengthening and the energy widening. During the same period measurements were made in

ACO⁽¹³⁾, ADONE^(9,14) and SPEAR I⁽¹⁵⁾ and a scaling law giving the relative bunch lengthening σ/σ_0 as a function of the intensity I and the energy E emerged:

$$\frac{\sigma}{\sigma_0} = k I^{1/2} E^{-5/3}$$

However, most of the time, it was not clear whether instabilities or potential well distortion were the dominant phenomenon, as theories in both domains were in competition to explain the measurements. In an attempt to clarify the subject, accurate measurements were made in 1976 - 77 both at SPEAR II in Stanford⁽¹⁶⁾ and at DORIS⁽¹⁷⁾ in Hamburg. These measurements were interpreted by taking both phenomena into account. In each machine a clear threshold was found, above which bunch lengthening was accompanied by energy widening. Below threshold, DORIS found a moderate (20%) bunch lengthening without energy widening which they attributed to an inductive type potential well distortion, (fig. 8), whereas in SPEAR II a small amount of bunch shortening was measured and explained by a capacitive potential well distortion (fig. 9). This is understandable because the bunches at SPEAR II were very small (a few cm) and could interact strongly with the high frequency part (above a few GHz) of the machine coupling impedance, likely to be capacitive in this frequency range. On the other hand, longer bunches interact more with the low-frequency part of the coupling impedance, which is inductive. In both machines the core of the bunch was found to widen more than the tails, giving a non-gaussian distribution. The threshold was marked by the sudden appearance of strong quadrupole sidebands on either side of revolution frequency harmonics, and higher order sidebands grew when the intensity was increased further.

Let us now examine in more detail the way in which the data was analysed in SPEAR II. By invoking basic theoretical considerations on longitudinal instabilities, it can be shown that the equilibrium bunch length above threshold must scale according to the parameter⁽¹⁸⁾

$$\xi = \frac{I\eta}{Q_s^2 E}$$

where I is the bunch intensity, $\eta = \frac{d\omega/dP}{\omega}$ has already been defined, Q_s is the synchrotron tune and E the energy. Moreover, if the coupling impedance $Z(\omega)$ can be approximated by a power law like $Z_0 \omega^a$ in the frequency domain of interest, the scaling law can be written:

$$\sigma_z = \text{Const.} (\xi R^3 Z_0)^{\frac{1}{2+a}}$$

where σ_z is the r.m.s. bunch length and R the machine radius.

Fig. 10 shows the SPEAR II data taken for different energies and different Q_s and intensities. The scaling is evident and from the slope of the line one can infer that $a = -.68$. Using this result the hypothetical shape of the SPEAR coupling impedance can be drawn as on fig. 11 for frequencies pertinent to very small bunches, that is a few GHz. Evidently, at low frequencies the same power law cannot be used. Fortunately SPEAR had worked with long bunches before its conversion from SPEAR I to SPEAR II. By plotting the old data on bunch lengthening in SPEAR I in the same way as for SPEAR II, a value of $a = 1$ valid for low frequencies was found. This allowed to complete the curve for the impedance as shown in Fig. 11. The free parameters Z_0 and ω_0 were subsequently determined by fitting the energy loss of the bunch calculated with this hypothetical impedance to the losses actually measured. This gave $\omega_0/2\pi = 1.3$ GHz and $Z_0 = 9\Omega$ (where as usual n is the frequency divided by the revolution frequency).

This was an important step towards the edification of the "Broad-band impedance model". Later on at the CERN ISR it was suggested to approximate the broad-band coupling impedance of storage rings by the impedance of a $Q = 1$ resonator peaked at around 1.3 GHz (fig. 12). This model is at the same time more physical and easier to

handle. Its remarkable success stems from its very good predictive power, which has now been verified in many machines, for protons as well as for electrons.

The scaling property discovered at SPEAR has been shown to describe as well the bunch lengthening measured in a small machine of the University of TOKYO, SOR⁽¹⁹⁾.

Bunch lengthening due to instabilities is easy to explain in multibunch machines: as we have seen, collective modes are easily excited by parasitic resonators in this case. But in single bunch machines like SPEAR, the coherent modes are strongly damped by the main accelerating cavity (Robinson damping) and another phenomenon must be invoked: the "mode-coupling" instability.

In a paper published in 1977 Sacherer⁽²⁰⁾ considers the case when a strong interaction with the surroundings produces frequency shifts of the normal modes of oscillation of a bunch as large as the synchrotron frequency ω_s . In this case two neighbouring modes which for low current are separated in frequency by ω_s , can overlap and become coupled. This results in a fast instability. It was already known experimentally that long proton bunches can become unstable at high frequency (the microwave instability) and that the thresholds for this instability can be predicted by applying the Keil-Schnell criterion for continuous beams to the local values of momentum-spread and intensity in the bunch⁽²¹⁾. Sacherer's theory showed that the same criterion can also be applied to the short electron bunches, for which the wavelength of the disturbance is not much smaller than the bunch length.

A theory by Pellegrini and Wang⁽²²⁾ gave another justification through a different approach.

In a machine with a longitudinal coupling impedance $\frac{Z}{n}$ the local Keil-Schnell criterion predicts instability if:

$$|\frac{Z}{n}| \geq \sqrt{2\pi} \frac{\sigma_l}{R} \frac{E\eta}{I} \left(\frac{\sigma_E}{E}\right)^2$$

σ_E is the energy width, and all other parameters have been defined before.

As σ_E/E is proportional to $Q_s \sigma_l/R\eta$ the formula can also be written:

$$\left(\frac{\sigma_l}{R}\right)^3 = \frac{1}{\sqrt{2\pi}} \xi \left|\frac{Z}{n}\right|$$

For an impedance $\frac{Z}{n}$ independent of frequency, this coincides with the SPEAR scaling law already mentioned ($a = 1$).

Recently accurate measurements of bunch lengthening and widening were done in DCI in Orsay⁽²³⁾. The results were interpreted using the above formulae. First they plotted the energy widening squared versus intensity divided by the bunch length. By doing so, they separated out the potential well bunch lengthening and by applying the first of the above formulae, could determine $|\frac{Z}{n}|$. The curve is a straight line which implies that $|\frac{Z}{n}|$ is constant over the frequency range of interest, and its slope indicates $|\frac{Z}{n}| = 7 \Omega$. Then they plotted the bunch length versus $\xi^{1/2}$ and found that the second of the above formulae now suggested $\frac{Z}{n} = 14 \Omega$. The explanation is that in this case the potential well effect is also taken into account. For the relatively long bunches of DCI, the broad-band impedance model predicts effective values of the coupling impedances about equal for potential well lengthening (proportional to the inductive part) and lengthening by instabilities (modulus). This is well borne out by these measurements.

The latest generation of large electron colliders (PETRA, PEP, CESR, LEP) has profited from the vast amount of knowledge which has been accumulated in the domain of beam-surrounding interactions.

Considerable effort has been made in these machines to control the coupling impedance of the vacuum chamber down to very low values of less than 1Ω , so that the major contribution is now localized in the accelerating cavities themselves. As a result, bunch lengthening phenomena are much less severe than in machines of the previous generation.

Before leaving the subject of bunch lengthening, it is worth mentioning an observation made on Tantalus I (University of Wisconsin)⁽²⁴⁾. In this machine the inflector system constitutes a resonating cavity which can be tuned by positioning the electrodes and happens to be strongly coupled to the beam. By acting on this system people are able to produce bunches longer or shorter than normal. They suggest the use of a similar device to passively control the bunch length in other machines whenever needed.

VI Transverse mode coupling instability

This is the latest instability discovered in electron storage rings. The first manifestation of this phenomenon has probably been seen around 1974 in SPEAR I. As already mentioned fast damping of betatron oscillations due to the head-tail effect at positive values of the chromaticity had been observed in this machine. In the same paper⁽¹²⁾ reference is made to a beating phenomenon involving more than one frequency and which appears at high values of the current, superimposed on the usual fast damping signals. Coupling between two head-tail modes (probably mode 0 and -1) pushed close to each other in frequency by their interaction with the vacuum chamber would explain this observation.

Some time later, in 1975, a mysterious vertical instability was noticed in SPEAR II⁽²⁵⁾. It was a single bunch phenomenon, which led to particle losses but was not accompanied by coherent signals large enough to explain the losses on the vacuum chamber. It was not strongly affected by changing the chromaticity, and was present for zero chromaticity, contrary to head-tail instabilities. The threshold

current showed a complicated behaviour with regions of stability appearing above the first threshold. This last point can certainly be explained by the bunch lengthening properties of the machine: just above the turbulent bunch lengthening threshold, the longitudinal density of the bunch does not increase with increasing current, and this may suppress the vertical instability. Probably for the same reason this vertical instability did not affect very much the performances of the machine.

Contrary to SPEAR, PETRA suffered very little bunch lengthening. In this machine a phenomenon with characteristics very similar to the SPEAR instability was observed to limit the performance of the collider well below the beam-beam limit⁽²⁶⁾. Eventually cures were found to circumvent this problem. The bunch was blown up as much as possible by a reduction of the longitudinal damping partition number obtained as a result of a change in RF frequency. In addition, the betatron functions were minimized in the RF cavities: this is equivalent to reducing the effective transverse coupling impedance, which mainly originates in the cavities for this kind of machine.

Dubbed for a while "vertical turbulence" by analogy to the turbulent bunch lengthening, this instability was interpreted by Kohaupt⁽²⁷⁾ as the result of coupling of the transverse head-tail modes. This is an extension of Sacherer's theory concerning the longitudinal modes: both longitudinal and transverse modes of a bunch are separated in frequency at small values of the current by multiples of the synchrotron frequency. Therefore wake-fields of the same order of magnitude of either longitudinal or transverse nature can produce mode coupling. One or the other phenomenon dominates depending on the relative magnitude of the longitudinal and transverse coupling impedances. Transverse effects are likely to dominate in the large machines with a small vacuum chamber inner radius.

The frequency shift of the fundamental head-tail mode $m = 0$ has been measured in many machines as a function of bunch intensity. In 1980, these measurements could be extended to mode 1 and 2 at CESR

(Cornell)⁽²⁸⁾. A fit to the broad band impedance model was able to explain the relative signs and magnitudes of the measured effects. The results are shown on fig. (13) for modes 0 and -1. Visibly these two modes converge as the bunch current is increased, although for the maximum current achievable in CESR they are far from crossing. Indeed, no instability was noticed in this machine.

Similar measurements on modes 0 and 1 were made in DCI⁽²⁹⁾. Again, a good fit could be made to the broad-band model. But it is in PEP that convergence of modes could be followed for the first time up to the instability threshold thus proving definitely the validity of the mode coupling theory.⁽³⁰⁾ Fig. 14a shows the evolution of the damped signal following a kicker excitation: as the intensity is increased, one observes a beating of lower and lower frequency. The signals are well reproduced by a simulation using a simple two-particle model (Fig. 14b).

To further illustrate this phenomenon, the result of another independent simulation⁽³¹⁾, using the best known approximation of the PEP coupling impedance is shown on fig. 15. When the current is increased, mode 1 does not move in frequency, whereas mode 0 plunges towards mode -1 until they attract each other and merge, giving rise to a fast instability.

To counteract this instability a number of measures can be taken. Lengthening the bunches and reducing the betatron functions in the cavities has already been mentioned. Bunch lengthening by the use of an octupole wiggler has been proposed for LEP⁽³²⁾. The transverse coupling impedance can be reduced in the RF cavities by choosing cavities with large bores and reducing the number of accelerating units: this is possible with the now available technology of superconducting cavities.

Outside the cavities, the vacuum chamber must be made as smooth as possible, a recipe already applied in modern machines.

In addition a suggestion has been made to hold constant the frequency of mode 0 with the help of a feedback system. Simulations have shown that the instability threshold could be raised this way by a factor two to four⁽³³⁾. Experiments are in progress.

VII. Effect of ions.

The effect on the beam dynamics of ions produced in the residual gas in the vacuum chamber has been recognized very early. This concerns only electrons because positive ions are repelled by positrons whereas they can be trapped by the negative potential well of the electron bunches. Under certain conditions they can accumulate in the beam which they tend to neutralize. As a consequence the almost perfect cancellation of electric and magnetic space-charge forces which prevails in high-energy electron machines is destroyed and a betatron tune shift proportional to the ion density is produced. Moreover, as the ion density is not constant over the beam cross-section, the tune shift depends on the particle amplitude, and this creates a tune spread in the beam. This effect has been measured recently in ADONE and compared to theoretical predictions (34).

As a result electron beams are usually much more stable against collective phenomena than positron beams due to the Landau-damping produced by the ion-induced tune spread. This fact was already noticed in the Princeton-Stanford rings⁽¹⁾ where beams of electrons ten times more intense than positrons could be stored when no counter measures were taken against instabilities. Trapped ions may also have unwanted effects, for instance decreasing the beam lifetime through scattering of the beam particles. For this reason machines of the first generations were equipped with clearing electrodes to eliminate them. Modern large storage rings with widely spaced bunches are less likely to trap ions than earlier machines.

VIII. Conclusions:

A large number of instabilities or other collective phenomena have been observed in electron storage rings. Every newly built machine has revealed an unexpected limitation following an increase in size, energy, and demanded performance. This feature will no doubt continue to characterise any similar enterprise in this domain.

Nevertheless, all phenomena already observed are reasonably well understood. It is therefore possible by a proper design to minimize their impact on the performance of the machine. As has been suggested at this workshop, a systems engineering approach involving all the knowledge accumulated in the domain of instabilities and other collective phenomena has to be used by those who contemplate building a new machine.

REFERENCES

1. Beam instabilities in the Princeton-Stanford storage rings
W.C. Barker, B. Gittelman, G.K. O'Neil, B. Richter
yth International Conference on High Energy Accelerators
Frascati 1965, p.330
2. Phase instability of intense electron beam in a storage ring
Auslander et al.
yth International Conference on High Energy Accelerators
Frascati 1965, p.339
3. Investigation of self excitation and a fast damping of coherent
transverse oscillations in VEPP-2
Auslander et al.
Symposium on electron storage rings,
Saclay 1966
4. Beam experiments with the MURA 50 MeV FFAG accelerator
C.D. Curtis et al
International Conference on High Energy Accelerators
Dubna, 1963
5. Transverse resistive instabilities of intense coasting beams in
particle accelerators
L.Jackson Laslett, V. Kelvin Neil, Andrew M. Sessler
Rev. Sci. Instr. V.36 N.4 p.436, 1965
6. DORIS present status and future plans
IX International Conference on High Energy Accelerators
Stanford, 1974, p.43
7. Synchrotron and betatron instabilities of stored beams in the
C.E.A.
R. Averill et al
8th International Conference on High Energy Accelerators
CERN 1971, p. 301

Dependance of phase instabilities on bunch length at the C.E.A.
R. Averill et al
US Particle Accelerators Conference
San Fransico, 1973, p.765
8. SURF's up at NBS : a progress report
G. Rabowsky, L.R. Hughey
US Particle Accelerator Conference
San Fransisco, 1979
IEEE trans. on Nucl. Sci. V.NS 26 N3, p. 3845

9. Single and two beam operation in ADONE
F. Amman et al
7th International Conference on High Energy Accelerators
Erevan 1969, V.2, p. 9

Electron positron storage rings: status and present limitations
F. Amman
US Particle Accelerator Conference
Washington, 1969
IEEE trans. on Nucl. Sci. V NS 16, N.3, p. 1073

Electron and positron storage rings: present situation and
future prospects.
F. Amman
8th International Conference on Particle Accelerators
CERN 1971, p. 63
10. Development and beam studies on ACO
J.E. Augustin et al
7th International Conference on high Energy Accelerators
Erevan, 1969
V.2, p.19

Beam dynamics on ACO
US particle Accelerators Conference
San Francisco 1973
p. 768
11. C. Pellegrini, Nuovo Cimento 64 A, 447, 1969

M. Sands SLAC-TN-69-8 and TN-69-10, 1969
(unpublished)
12. Fast damping of coherent dipole oscillations in SPEAR
IX International Conference on High Energy Accelerators
Stanford 1974, p. 338
13. Orsay Group, report ACO R.T. 34-69, 1969
(unpublished)
14. Status report on the electron-positron storage ring ADONE
US Particle Accelerator Conference
Chicago, 1971
IEEE transactions on Nuclear Science
V NS 18, N3, p.217
15. Some observations on bunch lengthening at SPEAR
M. Allen et al
IX International Conference on High Energy Accelerators
Stanford 1974, p. 352
16. Bunch lengthening and related effects in SPEAR II
P. Wilson et al
US Particle Accelerator Conference
Chicago, 1977
IEEE transactions on Nuclear Science
V NS 24, N3, p.1211

17. Bunch lengthening in DORIS
R.D. Kohaupt
X International Conference on High Energy Accelerators
Protvino 1977, V.2, p. 43
18. Scaling law for bunch lengthening in SPEAR II
A. Chao, J. Gareyte
SPEAR, 1971, PEP 224
(unpublished)
19. Bunch Lengthening in SOR
S. Asaoka et al
US Particle Accelerator Conference
Santa Fé, 1983
IEEE transactions on Nuclear Science
V NS 30, N4, p.2663
20. Bunch lengthening and microwave instability
F.J. Sacherer
US Particle Accelerator Conference
Chicago, 1977
IEEE transactions on Nuclear Science
V NS 24, N3, p.1393
21. Observation of microwave longitudinal instabilities
in the CERN PS
D. Boussard
CERN LAB II/RF/Int. 175-2

CERN-TH-RF/69-48, 1969
E. Keil, W. Schnell
22. On the condition for a single bunch high frequency fast blow-up
J.M. Wang, C. Pellegrini
International Conference on High Energy Accelerators
CERN, 1980, p. 554
23. Collective effects on D.C.I
J. Denard et al
US Particle Accelerator Conference
Washington 1981
IEEE transactions on Nuclear Science
V NS 28, N3, p.2474
24. Control of the bunch lengthening phenomenon in storage rings
E.M. Rowe, W.S. Trzeciak
IX International Conference on High Energy Accelerators
Stanford 1974, p. 365
25. SPEAR II performance
US Particle Accelerator Conference
Washington 1975
IEEE transactions on Nuclear Science
V NS 22, N3, p.1366

26. Single beam instabilities in PETRA
R.D. Kohaupt
US particle Accelerators Conference
San Fransico 1979
IEEE transactions on Nuclear Science
V NS 26, N3, p.3480
27. Transverse instabilities in PETRA
R.D. Kohaupt
XI International Conference on High Energy Accelerators
CERN 1980, p. 562
28. Single bunch current dependant phenomena in CESR
D. Rice et al
US Particle Accelerator Conference
Washington 1981
IEEE transactions on Nuclear Science
V NS 28, N3, p.2446
29. Single beam collective effects in DCI
J.Le Duff et al
XI International Conference on High Energy Accelerators
CERN 1980, p. 566
30. Comparison between experimental and theoretical results for the
fast head-tail instability in PEP
XII International Conference on High Energy Accelerators
Fermilab 1983, p. 209
31. Computer simulation of beams in high energy storage rings
R.h. Siemann
XII International Conference on High Energy Accelerators
Fermilab 1983, p. 271
32. Change of the energy distribution in an electron storage ring
by a dipole-octupole wiggler
A. Hofmann et al
US particle Accelerators Conference
Washington 1981
IEEE transactions on Nuclear Science
V NS 28, N3, p.2392
33. Transverse mode coupling with feedback
R. Ruth
XII International Conference on High Energy Accelerators
Fermilab 1983, p. 389
34. Observation of ion trapping at ADONE
Biagini et al
XI International Conference on High Energy Accelerators
CERN 1980, p. 687

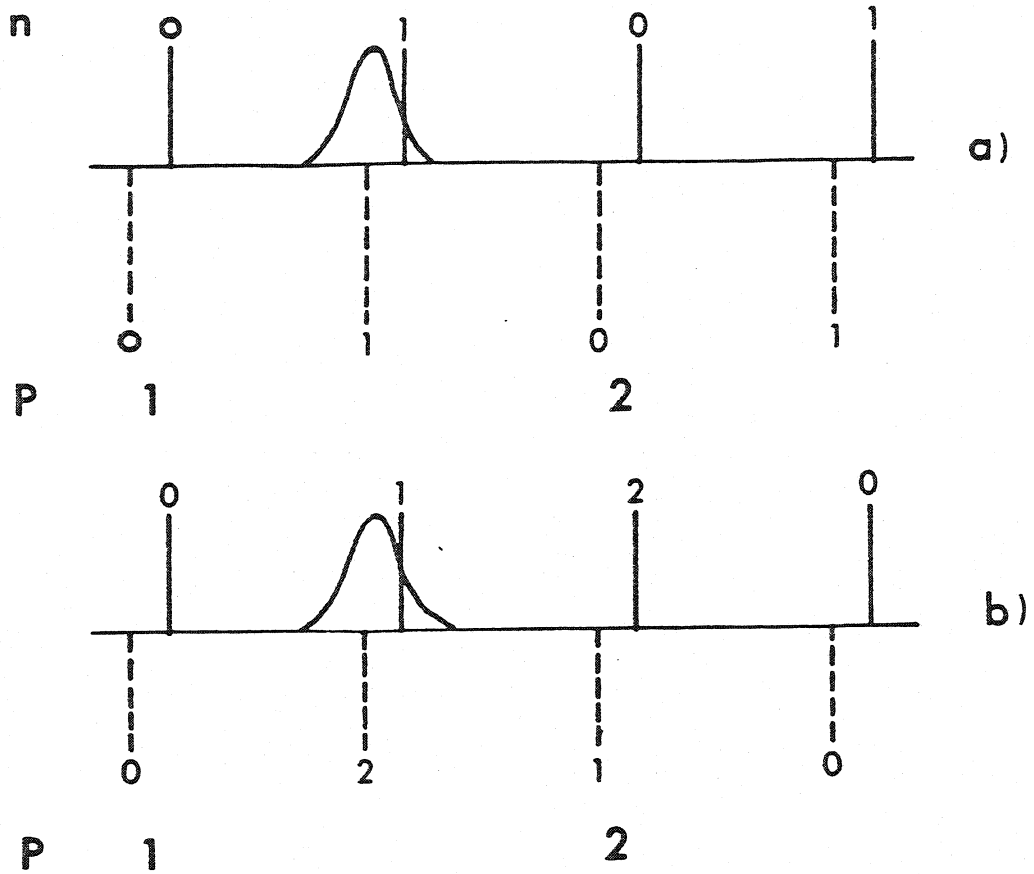
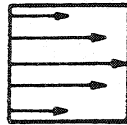
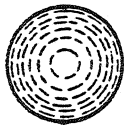


Fig. 1 Synchrotron sidebands relative to collective mode number n in the case of a machine with M bunches.
 a) $M=2$; b) $M=3$.
 Collective mode frequency:
 $\omega_p = \omega_0(pM + n \pm m\omega_s)$

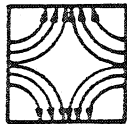
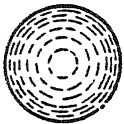
OBSERVED CAVITY MODES AT DORIS

FUNDAMENTAL MODE



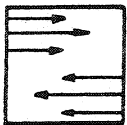
TM_{010} 500 MHz
($h=480$)

HARMONIC MODES



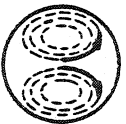
LONGITUDINAL INSTABILITY

TM_{011} 744 MHz
($h=715$)



TRANSVERSAL INSTABILITY

TM_{110} 779 MHz
($h=748$)



TRANSVERSAL INSTABILITY

TM_{111} 927 MHz
($h=890$)

Fig. 2 some of the RF cavity modes which induced instabilities of the multibunch beam in DORIS.

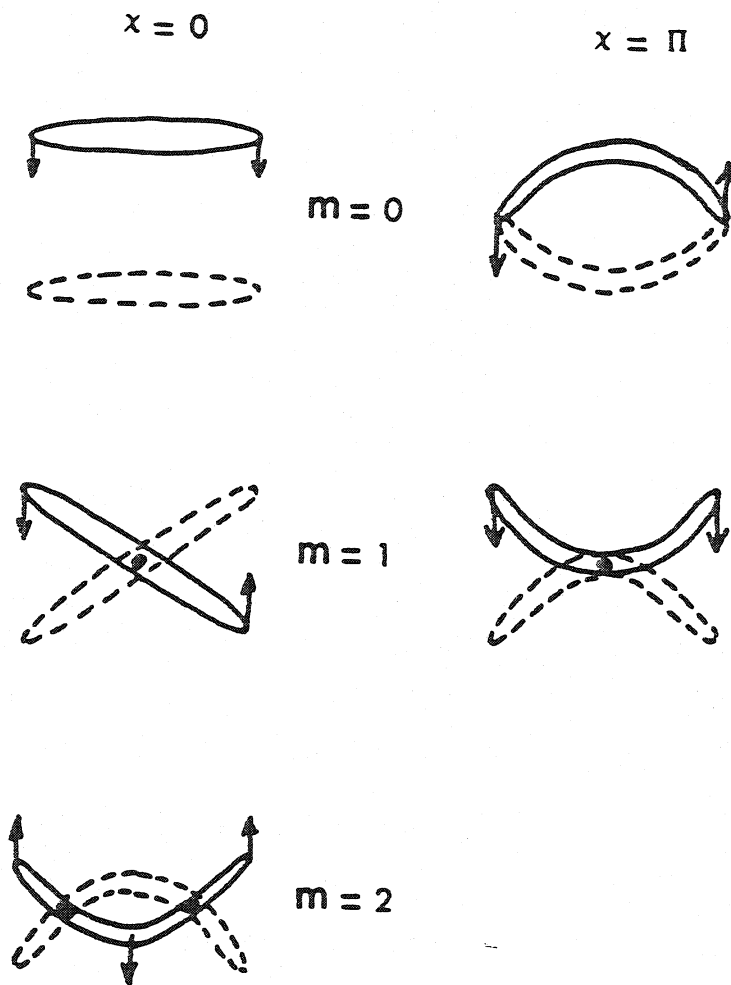
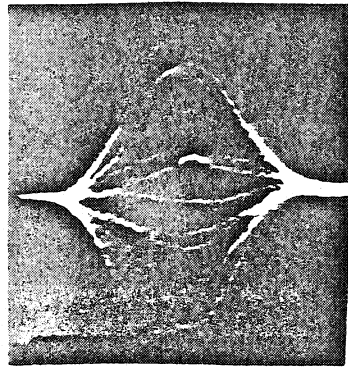
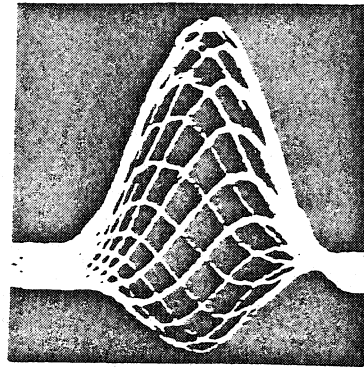


Fig. 3 Sketch of head-tail modes m for a phase shift $\chi = 0$ and $\chi = \pi$.



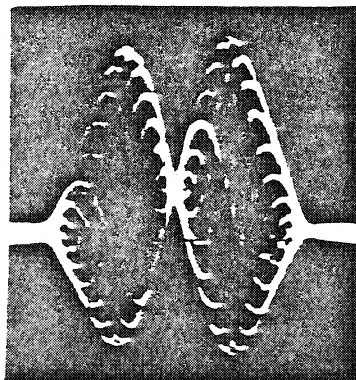
$\chi = 0$



62289

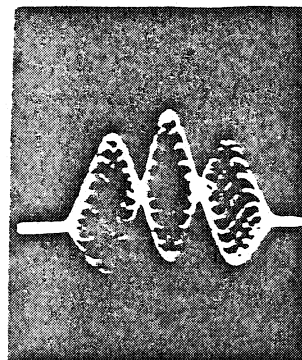
mode 0

$\chi = 2.3$ radians



$m = 1$

$\chi = 6.9$ radians



$m = 2$

$\chi = 6.9$ radians

62286

Fig. 4 Head-tail modes 0, 1 and 2 as observed in the CERN PS Booster on a position pick-up electrode.

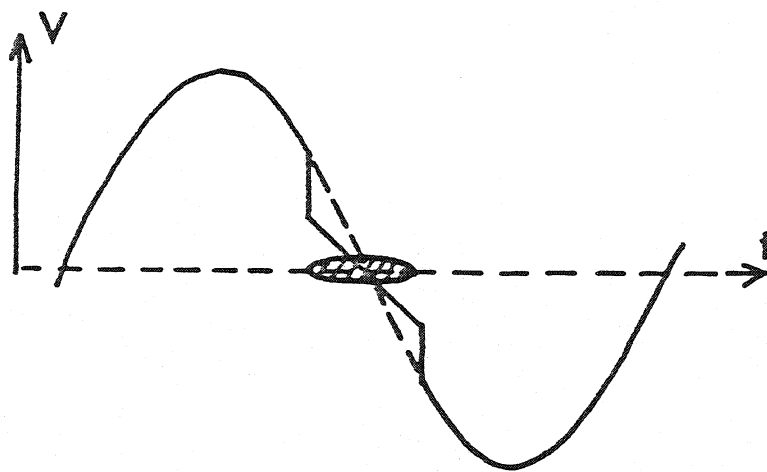


Fig. 5 Distortion of the RF waveform due to an inductive coupling impedance.

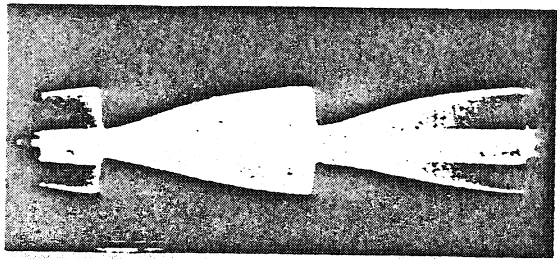


Fig. 6 Envelope of the signal from a capacitive beam monitoring electrode, showing the bursting oscillations leading to bunch lengthening in SURF.

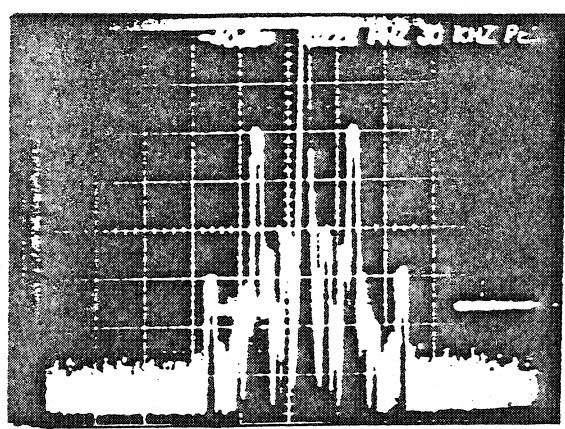


Fig. 7 Synchrotron sidebands around twice the RF frequency above the threshold for bunch lengthening in SURF. Modes up to octupole (at 4 times the synchrotron frequency) can be seen.

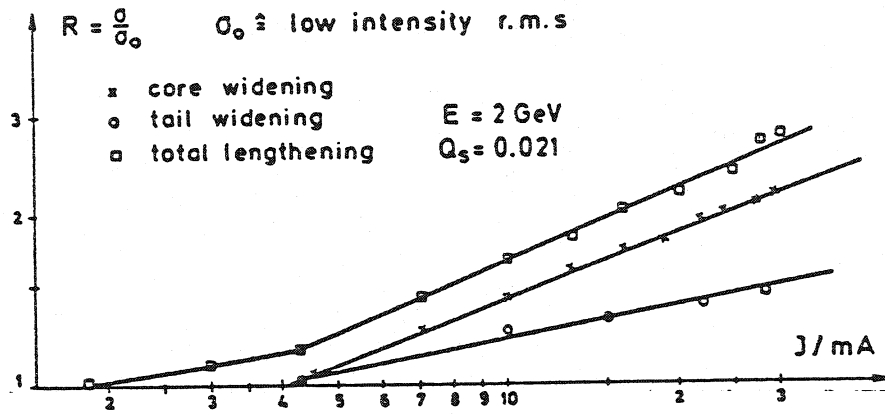


Fig. 8 Bunch lengthening and widening in DORIS

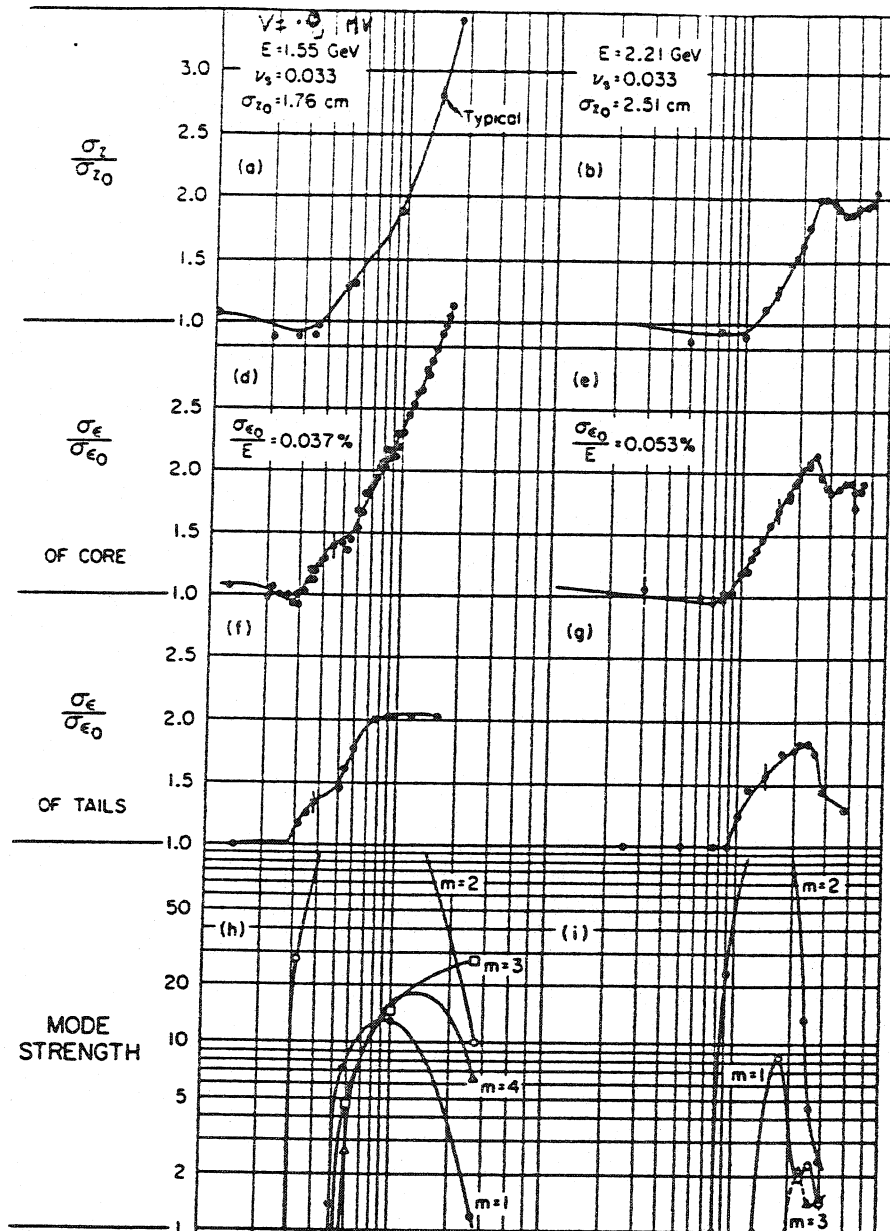


Fig. 9 Bunch lengthening in SPEAR II.

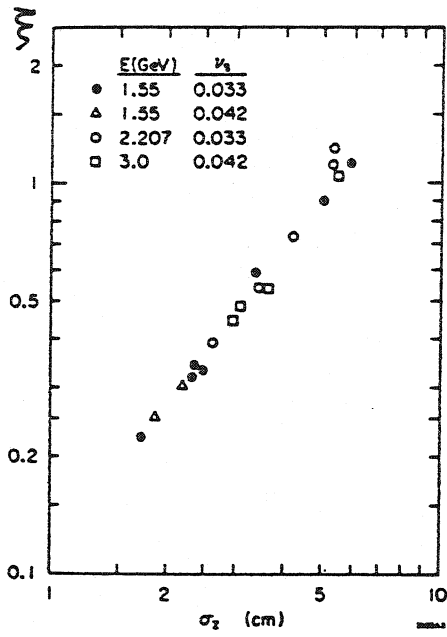


Fig. 10 Scaling parameter $\xi = \frac{I_n}{Q_s^2 E}$ as a function of σ_z in SPEAR II.

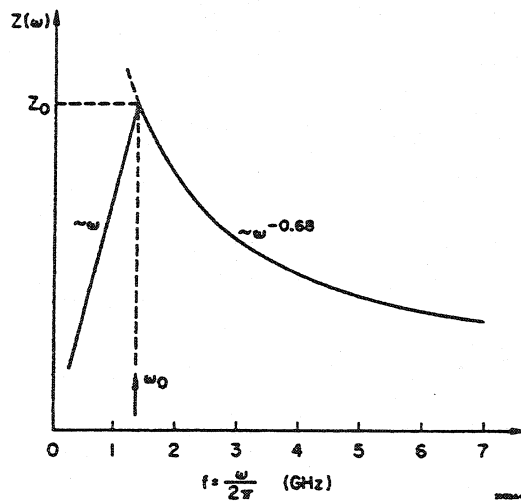


Fig. 11 Assumed form of the coupling impedance function $Z(\omega)$ versus ω in SPEAR II.

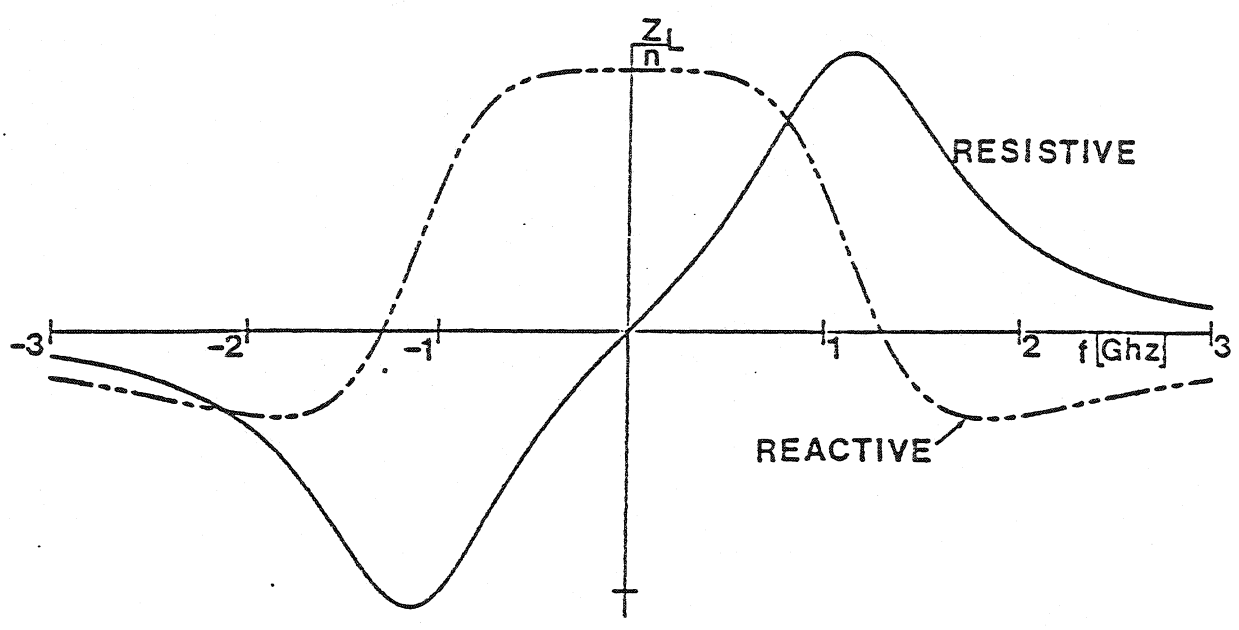


Fig. 12 The "Broadband" model of the coupling impedance. The real impedance is replaced by a low-Q resonator with resonant frequency F_r around the pipe cutoff.

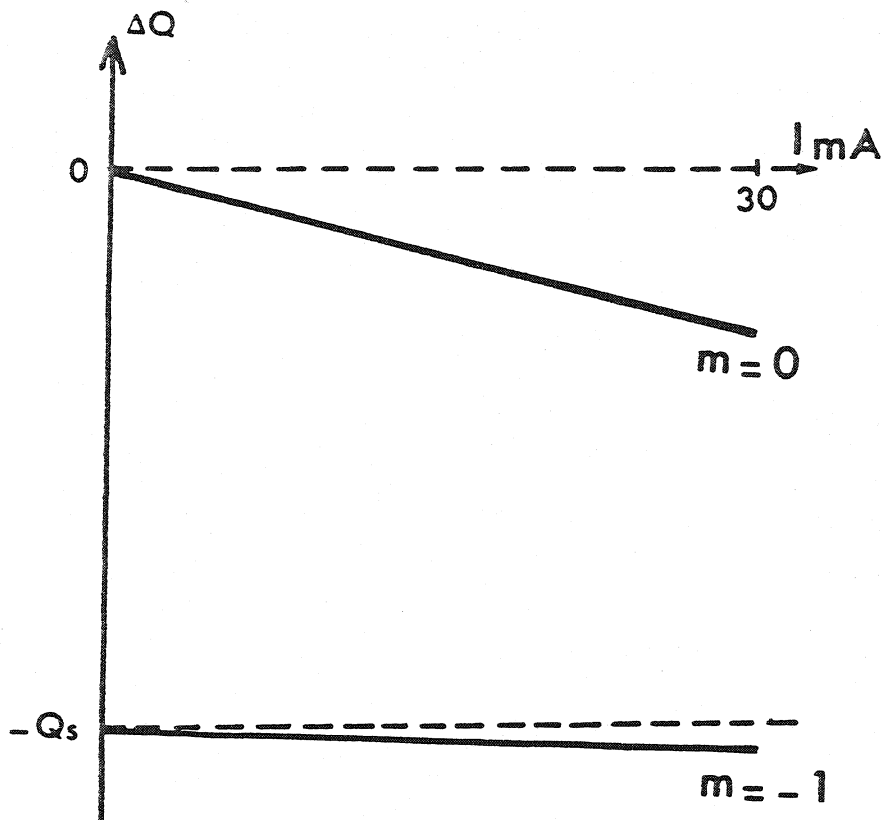


Fig. 13 Tune shift of head-tail modes 0 and -1 as a function of the bunch intensity in CESR.

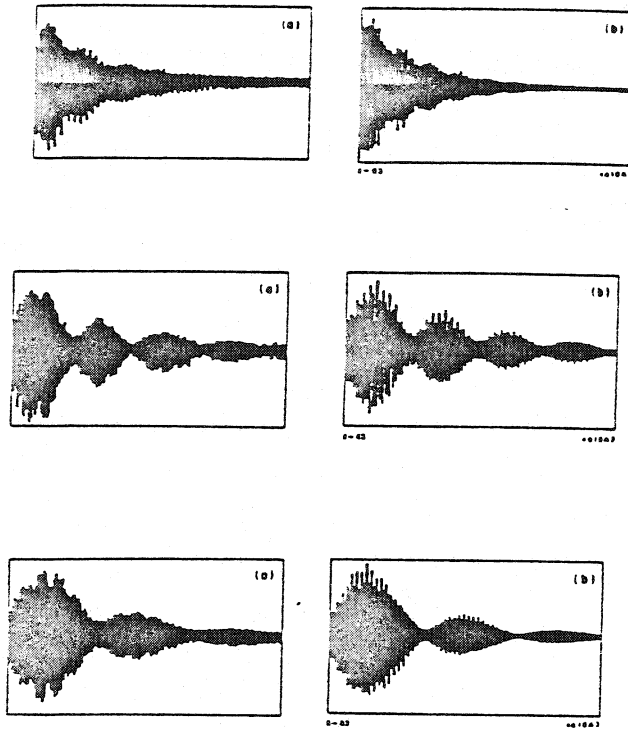


Fig. 14 Center of charge response to a kicker excitation as seen by an electrode pick-up in PEP just below the threshold of the mode coupling betatron instability. The intensity increases from top to bottom from I/I threshold = .77 to I/I threshold = .99
Left : response measured on a pick-up
Right: result of a simulation programme
This shows the beating of head-tail modes 0 and -1.

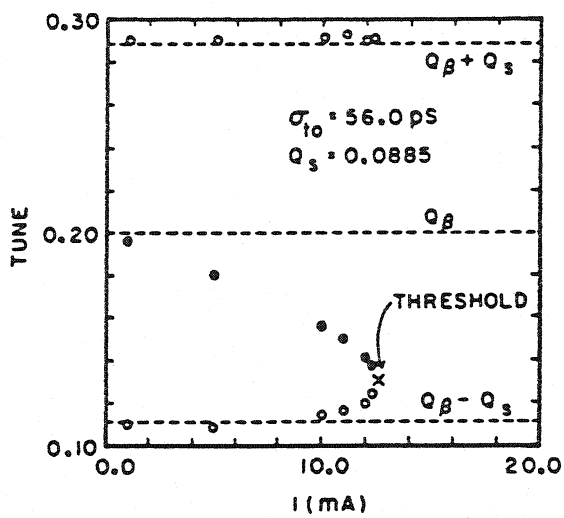


Fig. 15 Evolution of tunes for mode 0 (center) + 1 and -1 in PEP, obtained by a simulation programme, as a function of the bunch intensity.