# VERTICAL INSTABILITIES IN ELECTRON STORAGE RINGS

## Part I - COHERENT VERTICAL INSTABILITIES IN THE MURA 50-MEV ELECTRON ACCELERATOR*

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Investigations have been made of vertical instabilities of the circulating beam in the MURA electron accelerator. This accelerator is of the radial-sector FFAG type. The magnetic field increases as the radius to the 9.3 power. The direction of magnetic field is reversed in adjacent magnets. This leads to focusing for the vertical motion in the machine. The beam is injected at an energy of 100 kev onto an orbit whose radius is approximately 120 cm. Particles are accelerated by a betatron core to 2 Mev and then by a radiofrequency system to energies up to 51 Mev. This accelerator is a model whose purpose is to investigate beam stacking and high-intensity effects in accelerators.

Investigations of beam stacking have been performed for various energies from 15 Mev to 45 Mev. Approximately one year ago we achieved stacked-beam intensities which could not be improved by any means at our disposal. This limit corresponds very closely to what one calculates for the neutralized space-charge limit. That is to say, this is the llmit one calculates

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*Work carried out by C.H. Pruett, C.D. Curtis, F.E. Mills, R.A. Otte, D.A. Swenson and D.E. Young.

when one assumes that trapped ions in the beam shift the betatron oscillation frequencies to the nearest resonance. It was then decided to attempt to sweep out these ions by means of a vertical electric field.

These clearing electrodes were installed in early December. These electrodes reduce the available vertical aperture to the beam in the machine and thus limit the final achievable stacked beam. One interesting result with the clearing electrodes was that, even though the electrodes were made of titanium and the polarity of the electric field was such as to drive the ions in the electrodes, no pumping by these electrodes has been observed. After the electrodes were sufficiently outgassed by ion bombardment it was possible to operate with a satisfactory pressure for stacking. It was found that, without the clearing electrodes, currents were limited to about 3 amperes, the same current density as before. When the electrodes were energized sufficiently to sweep out the ions, the stacked beam increased to approximately 7 amperes.

When this current was reached, instabilities of the stacked beam were observed whereby approximately 80 to 90% of the stacked beam was lost over a period of several hundred microseconds. Further investigation showed that this instability was a coherent motion of the whole stacked beam in the vertical direction. Similar instabilities have been observed with the Stanford electron storage rings. It is found that the instability can be characterized by the number of waves, m, which are present in the whole circumference of the electron beam. The naturally-occurring instability appears to take place with m = 3 or m = 4. The vertical position of the beam can be measured by a pair of electrodes above and below the beam. The frequency observed with these electrodes is of the form $(m + \nu_y)\omega_o$ or $(m - \nu_y)\omega_o$. It was further observed that no azimuthal bunching of the beam took place during the instability.

To interpret this vertical motion we can consider that the motion of each particle is described by betatron oscillation and that there is an initial condition which leads to m waves in the circumference of the beam. This is possible in many ways by various combinations of amplitude and phase of the electron beam but there appear to be two distinct choices which might be of interest:

a) Assume an amplitude distribution $a(\phi)$ which is constant and a phase distribution $\gamma(\phi)$ which varies linearly around the circumference of the ring.

$$a(\phi) = \text{const.}$$

$$\gamma(\phi) = m\phi \quad ,$$

where $\phi$ is a coordinate moving with the beam. In this case one observes the frequencies $(m - \nu_y)$ or $(m + \nu_y)$ depending upon the direction of the wave.

b) Assume that the phase of the betatron oscillations is constant around the ring and that there is an amplitude distribution given by

$$a(\phi) = \text{const.} \cos (m\phi) \; .$$

In this case, frequencies $(m - \nu_y)$ and $(m + \nu_y)$ are obtained simultaneously. Experimentally, only $(m - \nu_y)$ frequencies were observed, so that it seems that the oscillations can be interpreted by assumption (a) and that they move in only one direction with respect to the electron direction.

L.W. Jones (Michigan): At any one moment of time, is there an integral number of oscillations?

F.E. Mills: Yes, this is required by the uniqueness of the description of the beam. However, it is possible that different m values would be present at the same time.

J.P. Blewett (BNL): Did you measure at more than one place?

F.E. Mills: Yes, the phase was checked at several places in the machine to make sure that the above description was adequate.

Since the reason for the threshold current at which the instability occurred was not understood, an attempt was made to excite the vertical instabilities by means of transverse electric fields. It was found that the instability could be initiated by a very short pulse of transverse electric field at the frequencies $(m - \nu_y)$. The instability for m = 3, 4 and 5, but not for m = 0, 1, 2 or 6, could be initiated. Further, the instability for all of the m values mentioned could be excited, except m = 2, by a continuous radiofrequency field. This, however, is probably just the ordinary radiofrequency "knockout" that one would expect.

A further experiment was attempted to excite the beam in its neutralized condition. With beam neutralization, it was found that it was never possible to excite the instability. A further attempt was made to quench the instability once it had started by turning off the clearing electrodes. In fact, the instability was not quenched, but this result was not very meaningful because the ionization time of the beam is longer than the growth rate of the instability.

## Interpretation

Having understood the form of the growing waves in the electron beam, the nature of the force which drives the instability was investigated. One is tempted to consider hydromagnetic-type instabilities such as the classic hose instability. However, this instability depends upon the reaction of two groups of particles upon each other, say the electron versus the trapped ions. Since the instability is not observed when ions are present, this cannot be the source. One might also expect some sort of a machine-resonance phenomenon. However, the motion is coherent but is not tied to the structure so this must be excluded too. The clue to the character of the force is given by the exceedingly slow growth rate observed, i.e., the time to double the amplitude is approximately 100 microseconds. This corresponds to many thousands of revolutions of the electrons so the force must be very weak compared to the magnetic-guide-field restoring forces. One is then tempted to consider the classic instability of a beam inside a tube; the forces, then, are due to image charges in the walls of the tube. Order-of-magnitude estimates indicate that the image charges could produce an effect of this size. However, it is necessary that there be an appreciable retardation of the force. In this case, the phase shifts are such as to cause some waves to grow. This sort of phenomenon has been investigated by D.C. de Packh at the Naval Research Laboratory and he has calculated growth rates. He has recently applied his results to the MURA stacked beam and estimates growth rates which are close to those observed.

A more difficult question to answer comes from the observation that a coherent mode cannot persist for a very long time in a beam which has a large frequency spread.

## Discussion

J.P. Blewett (BNL): It might be possible, if the beam itself is providing the energy to feed the instability, to use a signal from a set of pickup electrodes and feed this to the vertical electrodes to quench the vertical instability.

F.E. Mills: We intend to try that this summer. de Packh has described a means of doing this.

E.D. Courant (BNL): How many gaps are present in the clearing electrodes, and could their arrangement be such that this could induce a large fourth harmonic?

F.E. Mills: This question has been looked at and seems not to bear any direct relationship to the observed frequencies.

J.P. Blewett: How closely have you approached theoretical current limits on stacking?

F.E. Mills: The neutralized space-charge limit has been reached. Experimentally, several things were tried in an attempt to increase the current, such as higher injected currents and more efficient rf. However, the stacked-beam intensity remained the same.

G. Parzen (MURA): It seems that several aspects are not yet completely understood. For example, when the beam is completely neutralized, it does not behave like a neutralized beam is expected to behave; it does not blow up. The simple picture for a neutralized beam suggests that the beam should disappear, because when losing particles it feeds the resonance and starts losing particles faster.

L.W. Jones (Michigan): A simplification in the model is certainly that a uniform ion density is assumed; in any real situation a nonhomogeneous distribution can be expected to lead to nonlinear terms due to the space-charge forces. This might provide a mechanism for losing, say, the peripheral particles.

F.E. Mills: To what extent these particular results from electron beam stacking are relative to proton beam stacking remains to be studied. It might not be important for proton beam stacking, because of parametric dependences.

L.W. Jones: What is the un-neutralized space-charge limit?

F.E. Mills: The un-neutralized limit is determined by the static image forces exerted by the walls on the beam. The increase of the neutralized phase is not as large as one might expect, perhaps a factor of 20.

L.W. Jones: So it would be from 3 amperes to, say, 60 amperes?

F.E. Mills: It would be of that order of magnitude. Let me point out, however, that we did not expect to obtain this limit because we are limited by other considerations. Our injected beam is space-charge limited at 100 kv. This beam then undergoes the negative-mass instability as it crosses transition energy. This, then, determines the current-per-unit energy spread, which is the phase-space density, and determines the maximum beam we can stack. We could hope to go as high as 15 amperes but in order to do this we shall have to increase our aperture.