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Abstract

A coherent vertical oscillation occurs on the unbunched, coasting beam. At 5 GeV the threshold for observable vertical growth is about 1×10^{11} protons/pulse. The instability is suppressed by r.f. bunching. Oscillation frequencies observed are at $(n-\nu)$ times the circulation frequency with n having integral values of 3 through 10. Experimental data are presented. Analysis of the behavior as a coupled motion between the protons and neutralizing electrons is given.

Observations

A coherent vertical instability in the proton beam of the Bevatron is under investigation; the following is a progress report of that study. The axial oscillation develops whenever the beam is not bunched by the accelerating r.f. Most of the observations have been made while the beam is circulating on the flattop at 5 GeV, but coherent vertical motion has also been observed during injection at 19 MeV.

Axial oscillations are detected with capacitive pickup electrodes consisting of one plate above and one below the beam. A differential amplifier rejects the common mode signal from beam bunching and amplifies the signal from vertical coherent motions (Fig. 1).

The frequencies observed are of the class $f_n = (n-\nu_z)f_o$, where f_o is the revolution frequency of 2.455 MHz and n is the mode number, an integer. During flattop, frequencies corresponding to n = 10, 9, 8, 7, 6, 5, 4, and 3 occur. At any moment the motion is dominated by a single mode and the mode number changes toward lower values as the instability progresses. Figure 2 shows the sequence and duration of modes in an example case. The transition from one mode to the next lower occurs in less than a millisecond. Growth of beam height to full aperture and beam loss is caused by modes 6, 5, 4, and 3. Higher intensity increases the frequency of the initial mode and the duration of motion at the higher modes. At 4×10^{12} p/pulse, n = 10 is seen first, briefly, and beam loss will take place during n = 6; at 1×10^{12} protons f_6 is not strong. Threshold for the phenomenon is near 1×10^{11} protons when f_3 is seen.

A target flipping through the beam vertically in ~ 20 msec combined with a Cerenkov counter, measuring mostly fast π-mesons, gives a measure of the vertical beam height. In the range of 1×10^{12} protons/pulse the beam height doubles in 200 ms independent of intensity. The beam at higher intensity has a somewhat larger initial height.

The instability is not very sensitive to octupole component in the guide field. An added octupole that lowers ν by 0.001 for an increase in amplitude from 2 cm to 3 cm suppresses the vertical growth, but not the oscillation at 1.5×10^{11} protons.

The application of a local clearing field to sweep electrons out of the region within the pickup electrodes results in a decrease by a factor of about 2 in the coherent oscillation signal. Gas pressure in the aperture is 2×10^{-6} torr.

As indicated in Fig. 1 a power-amplifier has been installed. With a frequency synthesizer as source the beam can be driven open loop, or the pickup signal may be fed back for closed loop operation. By choosing the proper delay $\Delta\varphi$ at f_6 the growth can be arrested. It is not clear in detail how this suppressing operates, for even though the beam height increases only slightly during the time the loop is on, the signal on the pickup electrode is steady at f_6 and larger than in free oscillations.

The effect of the feedback is somewhat erratic, because occasionally the dominant mode of oscillation changes and the present closed loop has insufficient gain in other modes.

By driving with the loop open the frequency spread of the beam response can be measured.[1] The vector voltmeter in Fig. 1 measures the amplitude response and the phase relative to the frequency synthesizer. For the modes $f_n = (n-\nu_z)f_o$ a frequency spread of a few kHz can be measured. However, since these modes are not only driven by the power amplifier but also occur spontaneously, the measurement is difficult and interpretation uncertain. For the stable modes $f_m = (m+\nu_z)\ f_o$ (m=3,4,5) a frequency spread with corresponding phase shift has been measured as a function of intensity. An extrapolation to zero intensity gives a frequency spread of the unperturbed beam $\Delta S(m=4) = 2\pi \cdot 7$ kHz. This is the difference in the frequency of the applied voltage corresponding to the phase of the response lagging $\pi/4$ to leading $\pi/4$. At higher intensities the measured $\Delta S(m=4)$ increases.

From measured frequencies f_m and f_n at low intensities ν_z can be calculated to be

$$\nu_z = 0.9084 \pm .0004$$

The beam can also be driven at the frequencies f_n while the accelerating r.f. maintains bunching and the beam is stable against vertical coherent oscillations. The beam grows vertically to full aperture when driven with a deflecting field of 2100 V cm/cm. At n=6 the frequency range which produces this response is 12.492 to 12.502 MHz. These frequencies correspond to equivalent ν-values of 0.912 and 0.980 respectively.

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Interpretation

Attempts to fit this phenomenology within the usual framework of the transverse coherent beam instability[2] met with little success. The frequency spread within the protons is as stated above about 10^4 Hz. When this is compared with the calculated coherent frequency shift

$$U = \frac{N r_p c}{2\pi\nu\beta\gamma^3 (a+b)a}$$

of only 3×10^2 radians/sec for 10^{12} protons, it appears that the instability should be suppressed by the Landau damping.

The absence of instability in the r.f. bunched beam prompted Lloyd Smith to suggest[3] that we consider the beam neutralized by electrons. The bunched beam should be unneutralized and hence stable as observed. The gas pressure in the Bevatron leads to neutralization about 1 millisecond after debunching.

The instability behavior of a neutralized beam has been treated by Nielson[4] and most recently by Zenkevich and Koskarev[5]; this analysis appears to explain most of the observations. Electrons that oscillate in the electrostatic potential well of the protons will support an unstable, coherent motion of the two particle groups that may occur in frequency bands near the values $(n-\nu)\omega_o$. In first approximation, properties of the walls do not enter. The electron frequency $\nu_e\omega_o$ is given by

$$\nu_e = \left[\frac{2N_p r_e c}{\pi\omega_o (a+b)a}\right]$$

where,

$$r_e = 2.82 \times 10^{-13} \text{ cm}$$

$$c = 3 \times 10^{10} \text{ cm/sec}$$

and for the Bevatron,

$\omega_o = 1.54 \times 10^7 \text{ sec}^{-1}$ proton angular frequency

$a = 1$ cm, $b = 2$ cm initial beam radii.

This gives

$$\nu_e = 10.7 \text{ at } N_p = 4 \times 10^{12} \text{ protons}$$

$$\nu_e = 1.7 \text{ at } N_p = 1 \times 10^{11} \text{ protons}$$

These values predict closely the observed range of initial instability modes.

Unstable motion should arise when ν_e falls within the band

$$\nu_e = n-\nu \pm \frac{\nu_e \, \Delta\nu_p}{\sqrt{\nu(n-\nu)}}$$

where $\Delta\nu_p$ is the frequency of a proton in the electrostatic potential well of the electrons. [The total proton frequency is $(\nu^2 + \Delta\nu_p^{\,2})^{1/2}$.]

For the Bevatron

$$\nu = 0.91$$

$$\Delta\nu_p = 0.05$$

giving a band width of $\Delta\nu_e = \pm 0.12$ for $n = 6$.

We observe the oscillation initially at the frequency of the mode near ν_e, then the frequency shifts to progressively lower bands as the instability proceeds. It is reasonable to expect the value of ν_e to move lower as a result of vertical growth of the proton beam, loss of protons, and the growing electron amplitudes in a non-linear field. The rather small signal seen on a capacitive detector was seen to decrease upon removal of the local neutralizing electrons. This and the slowness of beam-width growth suggest that only a small fraction of the electrons present are involved in the out-of-phase two-bunch motion expected within the instability bands. We note that the population of electrons is constantly being renewed by continuing ionization of the gas and it is possible that only for a limited period in the lifetime of a free electron does its frequency fall in the band of instability. Transition to a lower band may occur when a sufficient population of electrons has accumulated in that band. We have made no analyses of such a highly non-linear process. While the degree to which we can explain the behavior of the instability is encouraging, that explanation is necessarily conjectural pending further analysis and experiments with clearing electrodes to alter the neutralization.

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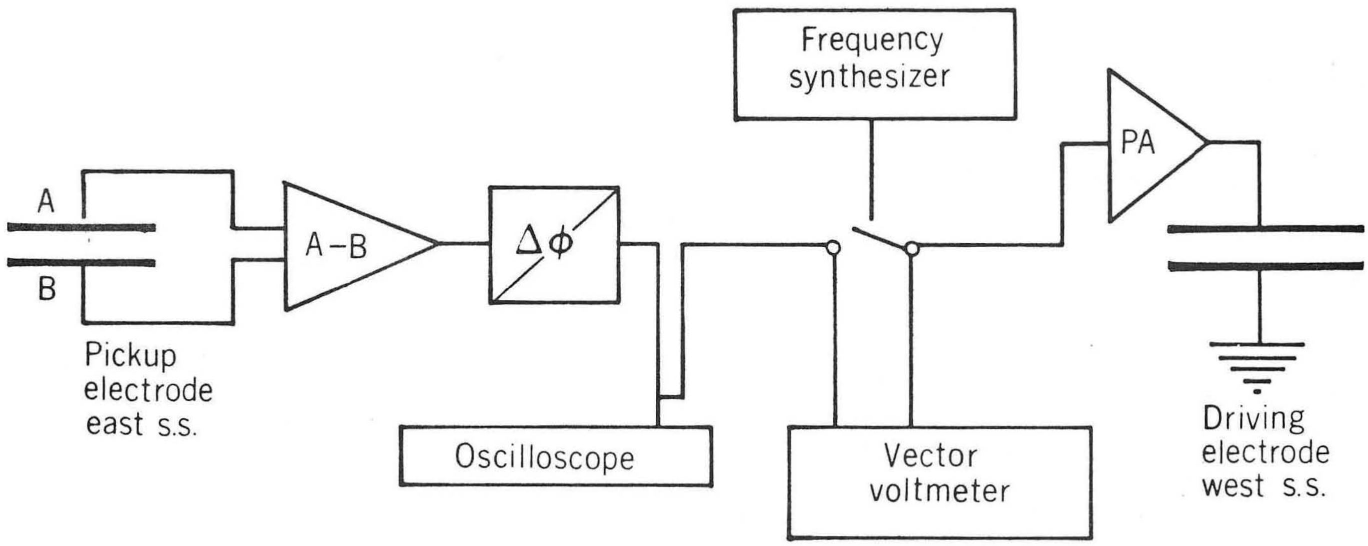

Detection and feedback diagram

Fig. 1

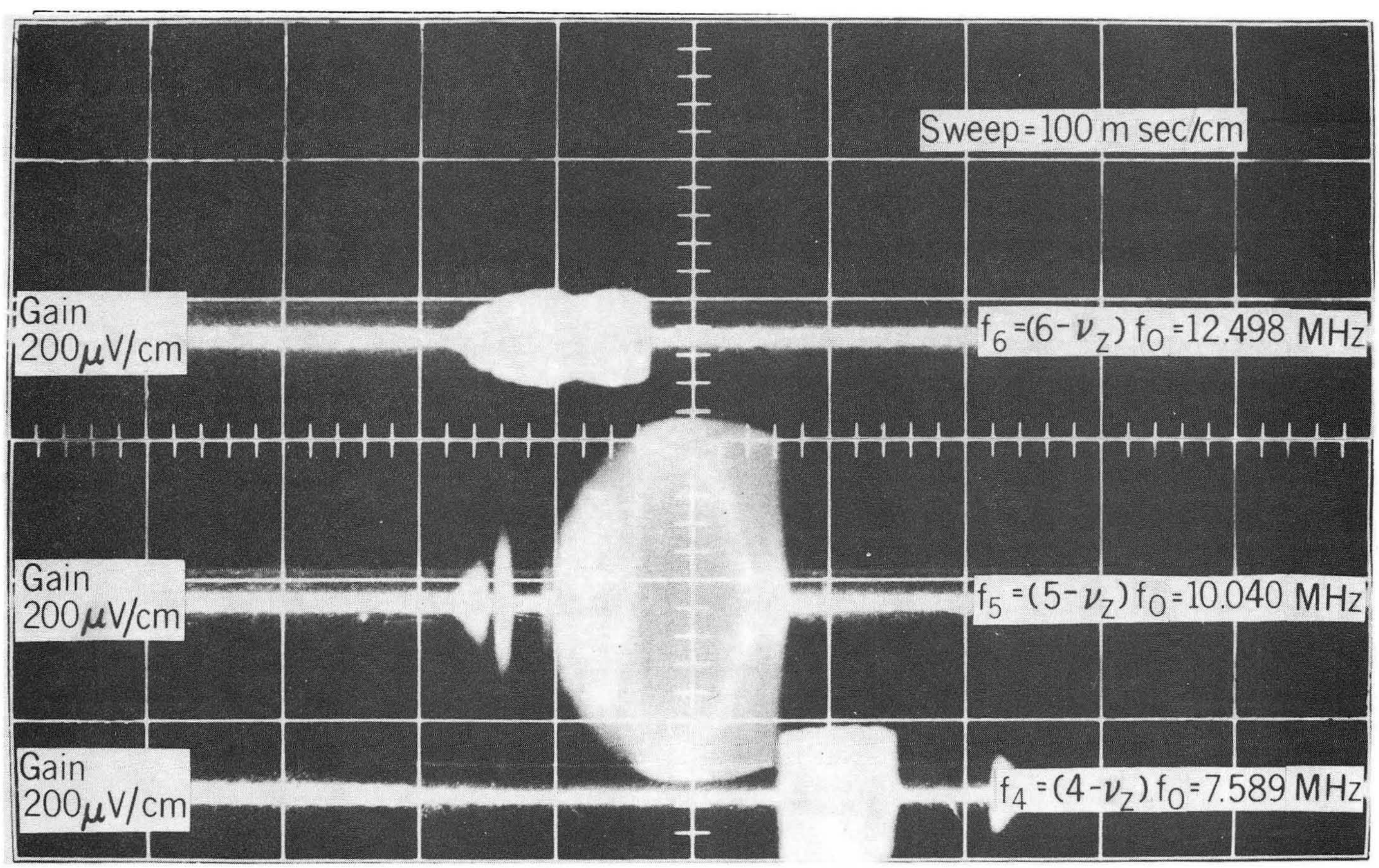

Fig. 2. Oscilloscope traces showing amplitudes of modes 6, 5, and 4.

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