BEAM DIAGNOSTICS ON THE ZGS

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Abstract

The detection equipment installed in the Zero Gradient Synchrotron (ZGS) is described. Most measurement techniques and equipment are similar to those of other synchrotrons with the possible exception of fluorescent screens of high transmission viewed by storage TV systems. We find these useful for a variety of diagnostic techniques at injection, such as measurement of equilibrium orbits, median plane, injection angles, and angular spreads. The value of these techniques, which depend upon the focussing properties of the synchrotron, lies in their ability to separate magnet effects from injection effects. These techniques are described in some detail. Also discussed briefly are some of the problems that we have encountered, such as unbalanced ground currents, tune variation during the accelerating cycle, and a vertical instability with a sharp intensity threshold.

Beam Diagnostics on the ZGS

The ZGS is a weak-focussing synchrotron with no field gradients in the octants except for eddy current and residual field effects. The effective gradient is achieved by end focussing (Fig. 1). Each of the four short straight sections contains a dc magnet with coils for producing various types of fields, most important of which are a homogeneous field, a linear gradient field, and a parabolic field. These are used for precise tuning at injection and thus take the place of pole face windings common in most weak-focussing synchrotrons. The dc magnets also allow nearly circular injection orbits, while the high energy orbits are far from circular. The latter are much further inside in the short straight sections which facilitates beam extraction without plunging magnets.

The induced current in a single turn around each octant can be controlled by a series rheostat to adjust the injection equilibrium orbits. This correction was found necessary in the initial operation of the ZGS. The difficulty was found to be due to unbalanced octant currents from low leakage resistances-to-ground of the raw-water cooling lines to the cathodes of the rectifiers in the ring magnet power supply. The leakage resistances were balanced and very little correction of this type is presently needed.

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Most of the detection equipment presently installed in the ring is shown schematically in Fig. 1. Of the six induction electrodes, two are required for the radial position indication and feedback, one measures the charge in the machine, one the phase of the beam with respect to the rf voltage to provide phase feedback correction, and the remaining two are used for indicating and damping vertical oscillations which we have encountered. The position electrodes are also used in the usual way for measuring radial and vertical tune at injection. Radial and vertical tune measurements during the acceleration cycle are made by exciting betatron oscillations with the driven electrode to destroy the beam.

Measurement of the vertical tune throughout the acceleration cycle indicated a dip in the vertical tune wave number early in the cycle due to the build up of eddy currents in the magnet. This dip was sufficient to cause $\gamma_y = \gamma_x$ at two points in the cycle and significant beam losses were observed at one of these two points. Retuning was required to make $\gamma_x > \gamma_y$ throughout the cycle.

Flip and slit mechanisms are contained in four straight sections. The slit mechanism is a stopping plate extending the radial width of the aperture. It can be adjusted to any vertical height from either above or below the beam aperture. The flip mechanism is an aluminum target 1/2" wide and 1/2" thick attached to this same plate. It can be swung into the beam at any radial position and to any desired vertical height from above or below. These devices are useful for measuring beam size, equilibrium orbits and median plane at any time in the cycle.

Various kinds of detectors or beam stops can be mounted on the probe shafts in each of the straight sections and inserted to any radial position. Presently we have stopping plates on all the probes in the short straight sections and vertical segmented detectors on each of the probes in the long straight sections. These are obviously useful for a variety of purposes.

The detection equipment at the output of the inflector includes Faraday cups, slits, and vertical segmented detectors which can be swept radially. These are used for lineup of the beam from the Linac.

Perhaps the only equipment we have which is not more or less common with other accelerators are the fluorescent screens in the ring. They exist in all long straight sections and consist of a series of thin vertical bars coated with fluorescent material. These screens can be rotated into the beam for injection studies and removed for acceleration. They are viewed by a storage TV system with the monitors located in the control room. The screens have a transmission of 90% so that many individual turns can be seen. The transmission can be cut down to see more detail of the first few turns by inserting more than one screen at the same time. In addition, a stopping plate can be rotated into the beam in the L-1 straight section to observe the first turn only.

We have found these scintillation screens most helpful for a variety of diagnostic techniques which I would like to describe. The technique depends upon the focussing properties of the synchrotron and the fact that the tunes can be varied over relatively wide ranges. Figure 2 shows a radial phase space plot of the injected beam. Protons will have a variety of equilibrium orbits due either to their energy spread or injection at different fields. In spite of these differences, they will focus on the outside of the machine each time they have completed one betatron oscillation. The tune can be adjusted so that any particular turn focusses on a screen in one of the long straight sections. The radial position of these foci, corrected for the shrinkage of the orbit per turn, is a measure of the relative equilibrium orbit radii. The correction, of course, is known quite well as a function of the tune. This technique thus permits the very rapid measurement of the equilibrium orbit radii with reasonable accuracy in the long straight sections. Figures 3 and 4 show the beam on the L-1 screen for a variety of radial tunes. The L-1 screen contains a solid plate which shadows the inflector in the lower left-hand corner. It is connected as a Faraday cup and thus reads the beam which would normally strike the inflector. One can see that the 5th turn is focussed at this position in the upper right-hand picture of Fig. 3. In the upper left-hand picture the focussed turn is the 11th or 12th, whereas the focussed turn in the lower right-hand picture is the 6th and in the lower left possibly the 13th. In Fig. 4 the 7th turn is shown focussed in the lower right-hand picture, the 8th turn in the lower left, and the 9th in the upper left. The upper right-hand picture was included because it shows 8 or 9 clearly distinct turns. It is unusual to see all of the turns so clearly separated. In all of these pictures, of course, the injection field is higher than normal in order to separate the turns of interest on the screen.

We presently have no means for measuring radial foci on the outside in all of the short straight sections. We have therefore developed another technique for short straight section measurements with the screens. The phase space plot of Fig. 5 explains this technique. The tune is adjusted such that the S-3 straight section, 5/8 of the way around the machine, is 1/2 betatron wave length from the inflector. A 7" stopping plate is inserted into the aperture from the inside and stops all of the injected beam with the exception of that penetrating a 3/8" slit at its center. Beam penetrating this slit will then miss the stopping plate in S-3 for four additional turns around the ring and will be focussed on the Faraday cup shadowing the inflector on the L-1 screen. This beam will also focus successively in each of the other short straight sections and will be the furthest inside beam at these positions. By inserting stopping plates from the inside in each of the short straight sections until the reading on the L-1 Faraday cup disappears, one can measure the position of this beam in each of the short straight sections and thereby the relative equilibrium orbit radii. The relationship between relative measurements in the short straight sections compared to those of the long straight sections is made by observing an outside focus in the S-4 straight section by means of the flip target at that location.

This technique is also useful for measuring the radial angle between the injected beam and the equilibrium orbit in addition to the angular width of radial injection. It can be seen from Fig. 5 that the 3/4 and 1-3/4 turns in L-4 should overlap radially, as well as the 1st and 4th turns in L-1, if the injection angles are centered parallel to the equilibrium orbit. They will not overlap radially if the injection angle is wrong. Figure 6 shows this effect. The upper right-hand picture shows the 3/4 turn only on the L-4 screen, while the upper left-hand picture shows this turn clearly separated from the 1-3/4 turn nearby. The injection angle error in this case is 0.8 mrad and can be observed also on the L-1 screen on the lower right-hand picture. When the injection angle is corrected, all of these turns do overlap radially. It is possible to find various conditions of tune for which turns should overlap radially at the proper injection angle, but to find them clearly distinct vertically so that the condition can be recognized is pure chance. One such case is shown in the lower left-hand picture of Fig. 6 in which the 2nd and 4th turns on the L-1 screen overlap radially and are separated vertically.

Vertical foci should also occur in somewhat the same way as for radial foci. Since the vertical aperture of the synchrotron is much less than the radial aperture, it is more important to form a narrow vertical image at the output of the inflector in order to see the foci distinctly. A vertical phase space plot similar to Fig. 2 would show the center (the median plane) identical for all particles. Therefore a second vertical focus should occur at each odd half wave length of the vertical betatron oscillation. In principle, by observing the vertical foci for a number of different turns at different radii, one can observe directly the median plane since the foci should occur at equal distances above and below the median plane. We have not yet been particularly successful with this technique, but some vertical foci are shown in Fig. 7.

Perhaps the most imporant use of the focal conditions observed on the screens is in diagnosing difficulties. The value of these techniques lies in the ability to separate effects due to magnet irregularities from those due to injection irregularities and in further narrowing the search to smaller areas of individual components. As an example, we recently observed a jitter of one inch from one pulse to the next in the radial position of the 2-1/2 turn focus in L-3. The radial position will be independent of jitter in timing, injection energy, or injection angles. It could depend upon radial position of injection, but this cause was eliminated by observing that the 5th turn focus in L-1, the injection straight section, was steady. The fact that the spot remained in focus eliminated the gradient and parabolic coils of the dc magnets from consideration because they effect the tune of the synchrotron. The difficulty was located, before it led to more serious troubles, by observing that the firing angles of one group of rectifiers was varying with respect to those of the other group by a few degrees in a random way from pulse to pulse. A small silicon rectifier in the bias supply was breaking down at a voltage level which happened to occur near injection.

A vertical instability in the beam at intensities greater than 3 to 6 x 10^{11} protons per pulse has been encountered. For intensities above this threshold, 80 to 90% of the beam is lost rather suddenly at approximately 100 msec after injection. The precise time of the loss varies somewhat with intensity and the threshold varies with radius, being highest on the inside of the synchrotron. Vertical electrodes indicate a build up time of the vertical oscillation of about 20 msec before the sharp loss occurs. Initial attempts to damp these oscillations with a vertical driving signal operating at the betatron frequency were only partially successful since the eight rf bunches around the ring (the ZGS operates on the eighth harmonic) sometimes behave independently. A 50 Mc/sec system is presently being built in collaboration with the MURA group. It consists of a detection electrode and a driven electrode in the S-3 straight section, appropriate amplifiers, and a programmed variable delay line. It will detect the vertical position of each beam bunch, amplify the signal and apply it to the driven electrode when the given beam bunch arrives back at the S-3 section one turn (~3/4 betatron wave length) later. It thus should damp the oscillation of each beam bunch separately.

We have made attempts to correlate the limited data obtained to date, with the theory of Laslett, et al,[1] on transverse resistive instabilities of intense coasting beams. The radial dependence of the threshold does not seem to fit the theory if one includes the damping due to energy spread. However, the theory deals with coasting, rather than bunched beams, so that no definitive statement about the cause of our instability can be made at this time.

We presently accelerate to full energy about 8% of the injected beam with 4 mA injected for 100 μ sec. At higher injection currents (15 mA to 20 mA is common) we obtain somewhat reduced efficiencies. Aside from the vertical instability problem at higher intensities, the difference could be due to a large number of effects including the variation of the Linac emittance with intensity. This question is not yet resolved. The overall efficiency of 8% is broken down as follows: coasting beam efficiency 90%, initial rf pickup 30%, rf acceleration 30%. We expect to be able to improve these efficiencies and to increase the operating intensity of the ZGS.

Acknowledgements

A great many members of the Particle Accelerator Division have contributed to beam diagnostics and related components in the ZGS. To name them all would be impractical. I would, however, like to acknowledge the active collaboration of L. Teng; and R. Daniels, L. Klaisner, D. Nordby, R. Trendler, and A. Hemel of the Operations Group; J. Martin, R. Winje, J. McDonnell, and J. Dinkel of the RF Group; L. Ratner, T. Khoe and

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Reference

(1) L. Jackson Laslett, V. Kelvin Neil, A. M. Sessler, UCRL No. 11090, November 9, 1964.

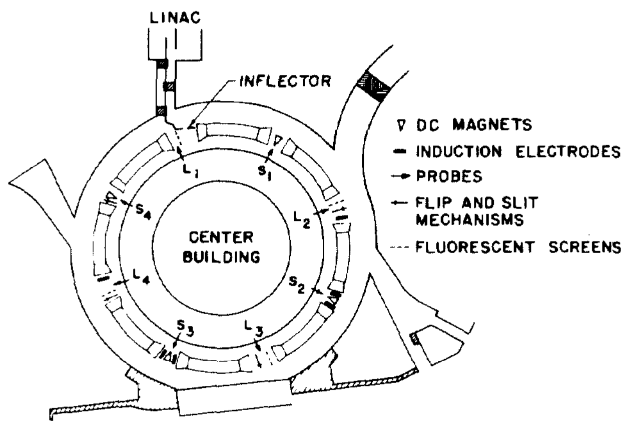

Fig. 1. Detection Equipment of the ZGS.

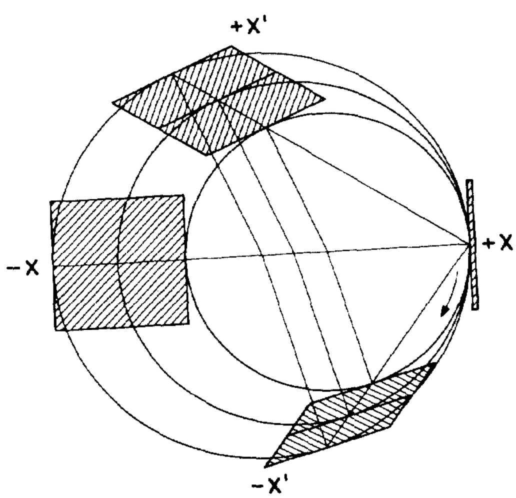

Fig. 2. Radial Phase Space Plot.

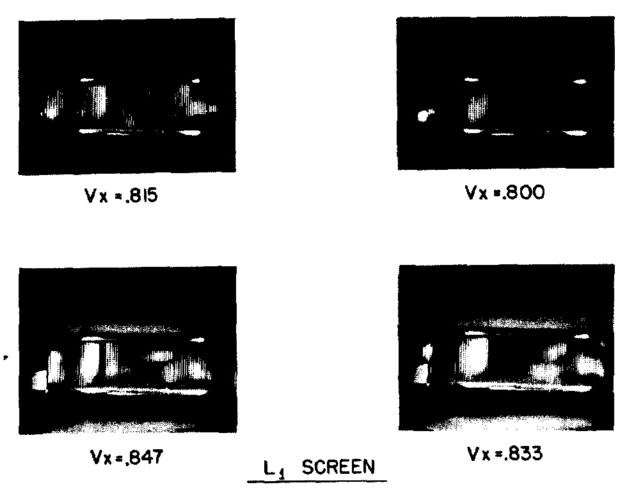

Fig. 3. Beam on the L-I Screen for Various Values of Tune.

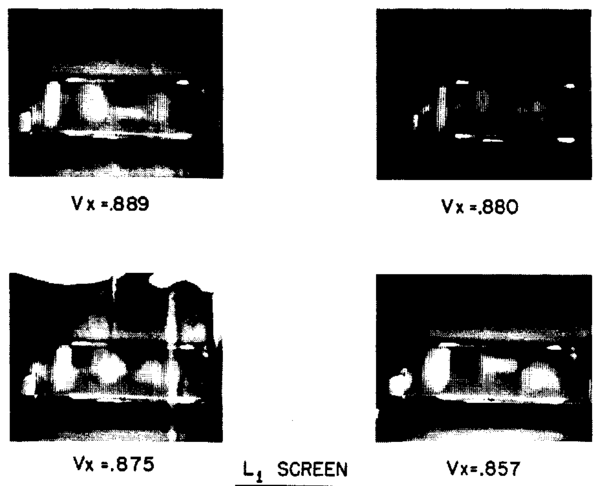

Fig. 4. Beam on the L-I Screen for Various Values of Tune.

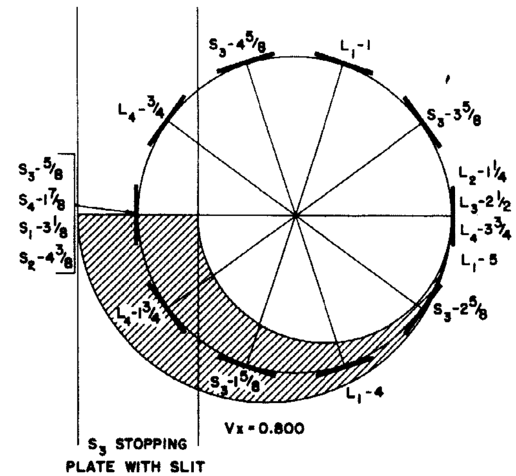

Fig. 5. Radial Phase Space Plot with Slit.

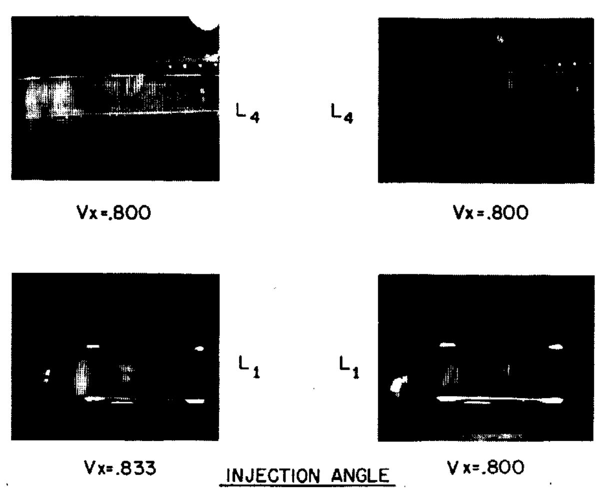

Fig. 6. Beam Through Slit on Screens.

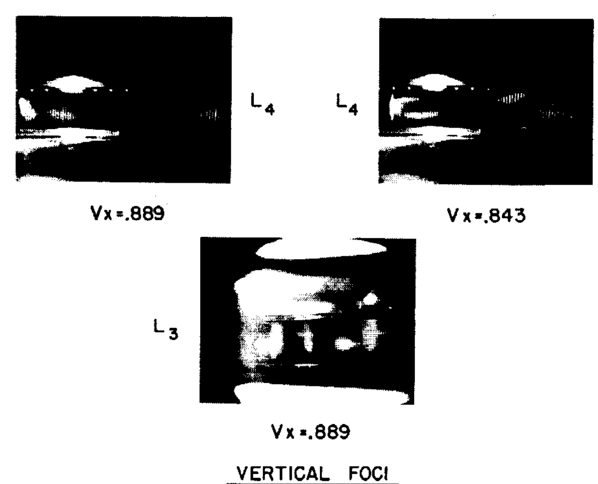

Fig. 7. Example of Vertically Focussed Beam.