SIMULTANEOUS RESONANCE EXTRACTION*

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Introduction

As reported in the 1971 National Accelerator Conference proceedings,[1] beam can be extracted from the Zero Gradient Synchrotron (ZGS) using the integral resonance $3\nu_x = 3$. A full sextupole magnet,[2] consisting of two windings (sextupole and dipole) and located in the L1 straight section, is used together with an inside thin septum (0.06-in) magnet[3] for the extraction process (Fig. 1). The septum magnet in S2 drives the beam into the aperture of a thick septum magnet[4] located in S3, which in turn drives the beam radially outward into the extraction chain for External Proton Beam II (EPB-II) starting in the L4 straight section. A fast dipole bumper magnet located in L3 has been used to reduce the stable phase space region to provide short spills (50 µs) for bubble chamber experiments. Slow extraction using rf drive with feedback to decrease the stable region is possible but has not been utilized for experiments. Slow extraction using a rising field on flattop with no rf is also possible but must wait for active ripple suppression to be practical.

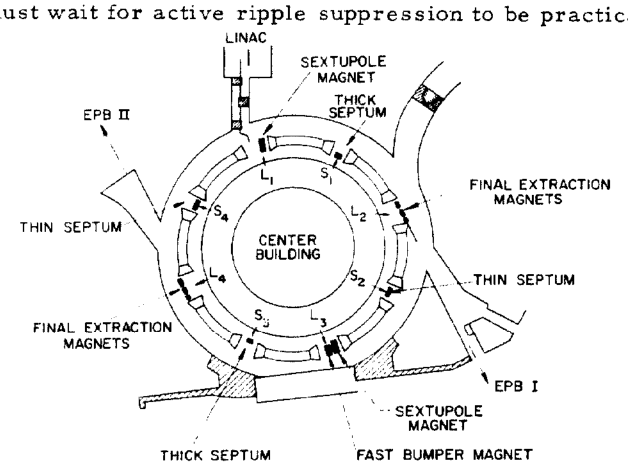

Fig. 1 ZGS Extraction System

Thin and thick septum magnets, similar to the magnets in S2 and S3, are located in straight sections S4 and S1, respectively, and have been used with an energy loss target to provide long spills into the EPB-I extraction chain starting in L2. With the recent addition of a full sextupole magnet in the L3 straight section, integral resonance extraction has been accomplished using the S4, S1, L2, EPB-I system in the same way as the S2, S3, L4, EPB-II system.

The normal radial betatron tune for the ZGS on flattop is about .84. This tune condition is quite far removed from the $\nu_x = 1$ integral resonance condition and results in the stable phase space region not being well formed during the extraction process.[5] In addition, computer calculations have shown and experience has confirmed an undesirable vertical growth of the extracted beam for the larger radial betatron oscillations. The overall efficiency of this extraction system, including the external chain, has been limited to about 65%.

When the new vacuum chambers were installed in the ZGS in 1972, pole face windings were included and it is now possible to change the radial tune on flattop to ~.71 so that $3\nu_x = 2$ extraction is possible using both sextupole magnets in L1 and L3. In addition, this extracted beam can be shared in both septum magnets in S2 and S4 so that the beam can be spilled simultaneously into EPB-I and EPB-II with the $3\nu_x = 2$ resonance. During a short experimental run in February of this year, simultaneous resonance extraction was verified and it proved to be possible to control the ratio of the amount of beam into the two proton areas by adjusting the dipole fields of the two magnets in L1 and L3. On this first attempt, the total efficiency of the beam extracted was 45% for small beams.

Description of $3\nu_x = 2$ Simultaneous Extraction

With the two sextupole magnets located in straight sections L1 and L3 (Fig. 1) connected to produce inward angular kicks, the locations of the unstable fixed points are illustrated by the phase diagram in Fig. 2. The unstable fixed point at any azimuthal position is defined as that phase point which is repeated after three complete revolutions around the machine and two complete circuits of the phase diagram. If phase point 0 at an azimuthal position just upstream of the sextupole magnet in L1, say, is an unstable fixed point, its phase position must be such that after receiving an inward angular bump in the sextupole field it will rotate through straight sections S1, L2, S2, and L3 (phase advance $\pi\nu_x/2$), receive an inward bump in L3, rotate through S3, L4, S4, to L1, receive an inward bump in L1, rotate to L3 (same phase point as 0, 1.5 revolutions around the ZGS), and repeat the circuit of the phase diagram to arrive back at point 0 in L1 after three revolutions around the ZGS. It is apparent that, with identical fields in the two sextupole magnets, each straight section in the ZGS shares the same three fixed points with the straight section 180° removed in azimuth. In particular, L1 and L3 share the same fixed points as do S2 and S4.

The separatrices joining the unstable fixed points (shown somewhat incorrectly as straight lines in Fig. 2) are also shared by the radially opposite straight sections. Thus, protons with phase points just inside the unstable fixed points will, as viewed once every revolution in S2 and S4, move along the lines c in Fig. 2. Those protons having phase points just outside the separatrices will move toward the unstable fixed points and then move radially outward on the phase diagram along the extensions of the separatrices (illustrated by arrows in Fig. 2 for S2 and S4). The area of the stable phase space region inside the separatrices depends on the sextupole field strengths,

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the radial betatron tune, the amount of dipole field (separately controllable in L1 and L3), and the equilibrium orbit position (x_p in the following figures). Figure 3 shows the computed area of the stable phase space region for a tune of $\nu_x = .73$ for various sextupole fields and a linear combination of the dipole field strength and equilibrium orbit position.

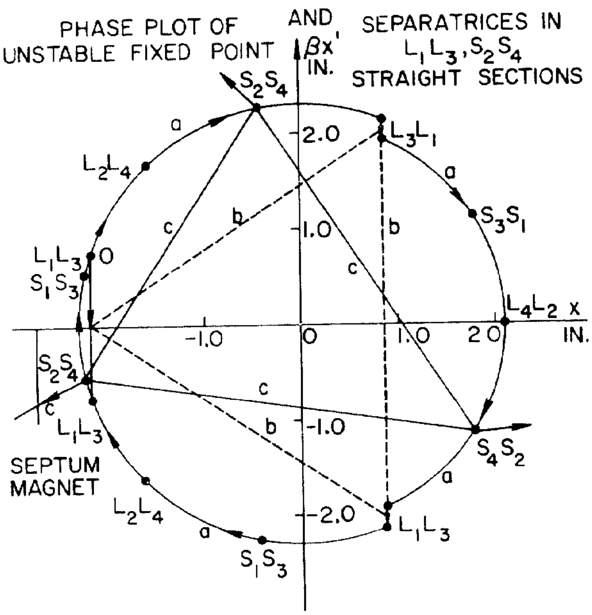

Fig. 2 Details of $\nu_x = 2/3$ Unstable Fixed Points Around the ZGS

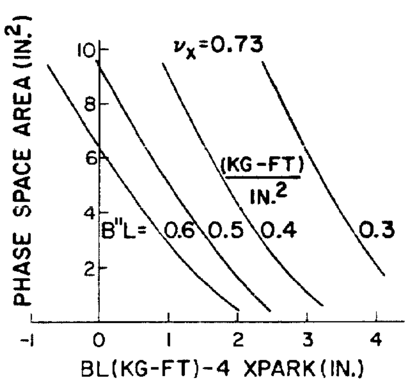

Fig. 3 Stable Phase Space Area as a Function of Sextupole Field, Dipole Field, and Equilibrium Orbit Position

The extraction process for the ZGS occurs in the following manner. First, the proton beam is parked at a given position near the beginning of the flattop of the main magnet pulse. The sextupole and dipole fields in L1 and L3 are then turned on to a strength such that the stable phase space area is somewhat larger than that of the circulating beam. The equilibrium orbit position, the sextupole field strengths, the dipole field strengths, or any combination of these, is then changed in such a way as to decrease the stable phase space area to zero. At any given time during this process, those protons occupying phase points outside the stable region move away from the stable region along the extensions of the separatrices until they arrive inside the septum magnets located in S2 and S4. For equal sharing, the amount of beam lost on the septum of each magnet at any time during this process is proportional to the ratio of the septum thickness to the inward movement of the phase point at the septum position in S2 or S4 sfter completing 1.5 revolutions of the ZGS and arriving within the aperture of S4 or S2.

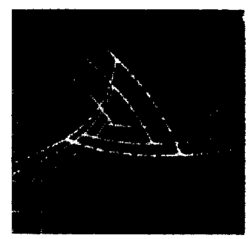

Fig. 4

$B''L = 0.6$ kG-ft/in^2

$BL = 0.0$

$x_p = 0, -0.3, -0.6$ in

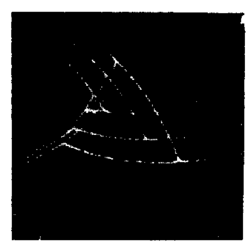

Fig. 5

$B''L = 0.6$ kG-ft/in^2

$BL = 0, 1.2, 2.4$ kG-ft

$x_p = 0.0$ in

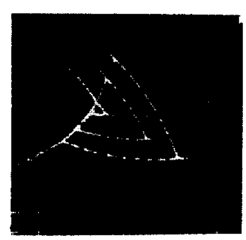

Fig. 6

$B''L = 0.6$ kG-ft/in^2

$(x_p, BL) = (0.0, 0.0)$

$(-0.1, 0.8)$

$(-0.2, 1.6)$

(in, kG-ft)

Figures 4, 5, and 6 show computer calculations of the stable region and the separatrices for various methods of decreasing the stable phase space area. In Fig. 4, the area has been decreased by moving the equilibrium orbit position inward. Figure 5 shows the result of accomplishing the same thing by increasing the dipole fields in L1 and L3. In Fig. 6, a combination of equilibrium orbit position and dipole field changes have been used to keep the inward arm of the separatrix at a fixed angular position as the stable area is decreased.

Details of a typical equal sharing extraction calculation are shown in Fig. 7. With the fields on the magnets in L1 and L3 at the indicated values, the stable phase space area is decreased by moving the equilibrium orbit from .06 inches to -.50 inches with respect to the centers of the sextupole fields. During this time, the unstable protons penetrate into the septum magnets in S2 and S4 and sweep out a phase space area A, as shown. Line a is the position of the septum S2, S4 and line b is the shadow of the S2, S4 septum in S4, S2. After receiving a given change in angle in the septum magnets, the area A is transformed into the area B at the exit of the magnets. At the entrance to the sextupole magnets in L3, L1, the extracted beam occupies area C, which is transformed to area D by the L3, L1 magnets. From this region, the extracted beam rotates to area E within the apertures of the first pair of extraction magnets in S3, S1, where it receives a large positive angular change for exit into the outside extraction magnets located in L4 and L2.

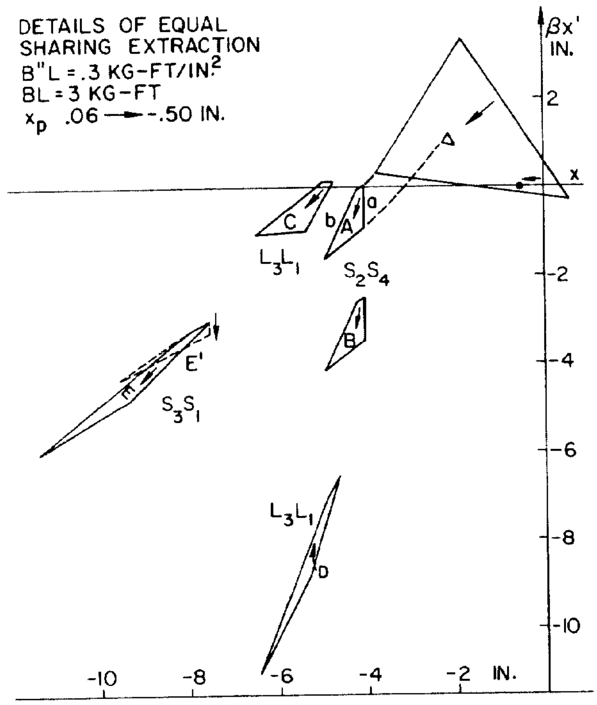

Fig. 7

In Fig. 7, the fields at the septum magnets have been adjusted so that the area E is at least 7.5 in radially inward from the sextupole centers. The radial defocussing of the extracted beam in going through the sextupoles in L3, L1 (area C to D) is an undesirable feature of the present location of the sextupoles and will be discussed later. Some of this defocussing effect can be eliminated by decreasing the septum magnet field during the extraction process so that the phase space in S3, S1 can be made to occupy E'. This improvement of the phase space size by changing the septum magnet fields during extraction was verified during the initial trials mentioned in the Introduction. Similar ramping of the septum fields to improve the quality of the extracted beam is assumed for the remaining illustrations in this paper.

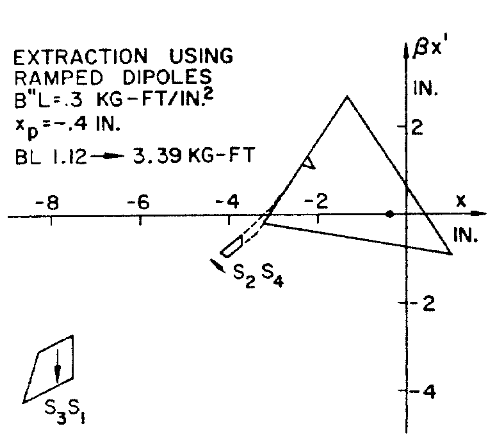

Fig. 8

Figure 8 shows the extracted beam area at the entrance of the S2, S4 thin septum magnets and within the apertures of the S3, S1 extraction magnets for a stable phase space area decrease caused by increasing the dipole fields in L1 and L3. The increase in angular spread in S3, S1 over that at S2, S4 is caused by the increasing dipole fields experienced by the extracted beam in going through L3, L1. The space magnification is due to the sextupole fields in L3, L1.

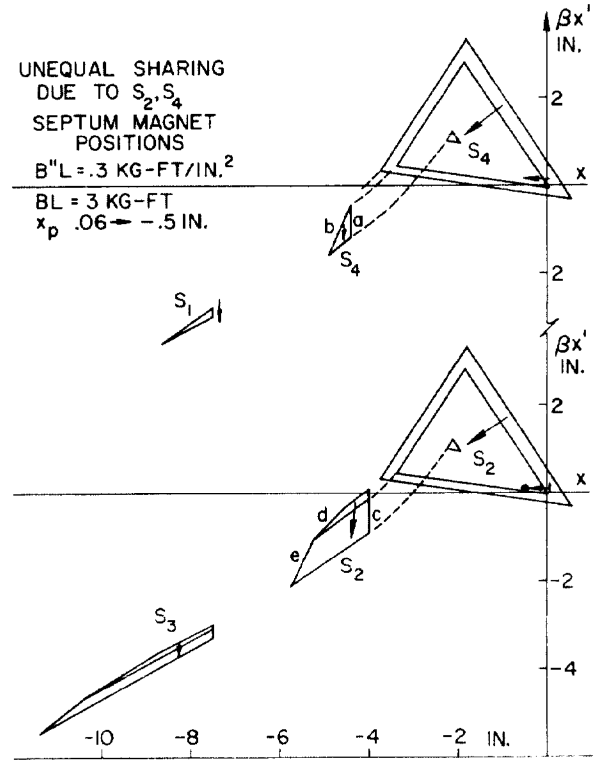

Fig. 9

Unequal sharing of the extracted beam due to unequal positioning of the septum magnets in S2 and S4 is shown in Fig. 9. During the early part of the extraction, the beam arrives first at theseptum in S2 and does not see the septum in S4 before it arrives within the aperture of S2 after three revolutions around the ZGS. Line d in the figure is the shadow of the S2 septum position in the S2 aperture for this early portion of the extraction process. Eventually, the extracted beam begins to penetrate the aperture of the magnet in S4. For the remainder of the extraction time, line e is the shadow of the S4 septum in S2 and line b is the shadow of the S2 septum in S4. The relative efficiencies for any time during this period are approximately (c-e-t)/(a-b-t) where a, b, c, and e are the corresponding space positions on the indicated phase space lines in Fig. 9, and t is the thickness of each septum magnet (assumed equal).

A relatively easy method of controlling the sharing of the beam to the two proton areas by controlling the relative dipole fields is illustrated in Fig. 10. The effect of using a larger dipole field strength in L3 than in L1 is to displace the stable phase space area in S4 inward relative to that in S2. As a consequence, the extracted beam enters the septum magnet in S4 earlier than it does in S2 and penetrates further during the whole extraction time. In Fig. 10, line d is the shadow in S4 of the S4 septum after three revolutions line e is the shadow in S4 of the S2 septum after 1.5 revolutions, and line b is the corresponding shadow in S2 of the S4 septum. During the initial trial of the system, it proved to be possible to adjust the relative dipole fields for any desired ratio of the amount of extracted beam to the two external beam lines.

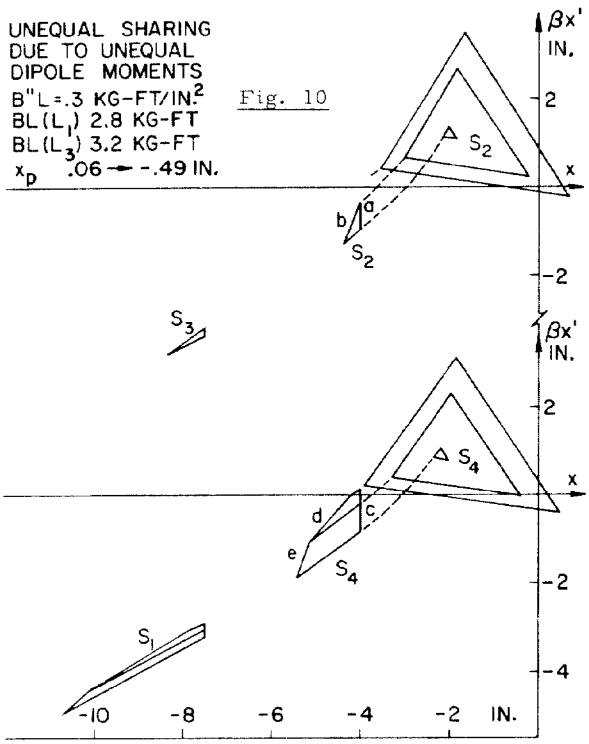

Fig. 10

Preliminary Conclusions

Simultaneous $\nu_x = 2/3$ resonance extraction into the two ZGS proton areas appears to be feasible and attractive. Slow spills (with rf structure) should be possible using a sum signal from the proton areas to control the rate of spill and a difference signal (applied say to one of the dipole coils in the L1 or L3 magnets) to control the sharing. Slow spills without rf structure will be possible after active ripple suppression on flattop for the ZGS is accomplished (in perhaps six months). Fast spills ($\sim$ 50 μs) to either proton area using a fast bumper magnet in L3 and $2\nu_x = 3$ resonance has also been demonstrated, but more study is necessary to determine whether the quality of the extracted beam can be made sufficiently small to permit reasonable extraction efficiency with the sextupole magnets in their present locations.

The location of the sextupole magnets in L1 and L3 between the thin septum magnets in S2 and S4 and the extraction magnets in S3 and S1 causes an undesirable radial defocussing (and an equally harmful vertical overfocussing) of the extracted beam. The sextupole magnets have been placed in these straight sections initially because of the necessity of maintaining an operational integral resonance extraction system to EPB-II during the early attempts at $2\nu_x = 3$ extraction. Equally satisfactory $2\nu_x = 3$ inwardly directed separatrices exist in S2 and S4 if the sextupole magnets are moved to the L2 and L4 straight sections. Larger, but still available, septum magnet fields would be required and the defocussing of the extracted beam would not be present. However, the integral resonance mode of the extraction would no longer be possible.

The harmful effects of the interference of the extracted beam by the sextupole magnets in their present locations can be reduced somewhat by controlling the fields of the septum magnets during the extraction time. However, this is not practical for the very fast spills. The feasibility of adding thin septum quadrupoles in the region of the thin septum magnets is being considered. During the next few months of tuning and measurement, a decision will be made whether to leave the sextupole magnets in L1 and L3 or to move them to L2 and L4 and to rely entirely on the $2\nu_x = 3$ extraction.

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