BEAM EXTRACTION FROM THE PROTON SYNCHROTRON[*]

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The importance attached to external beams for proton synchrotrons is dramatically illustrated by the history of the late Cosmotron. This pioneer accelerator was in operation about one year when plans were started for an external beam. The scheme devised by O. Piccioni[1] was first tested in 1955 and was used extensively throughout the remaining life of the machine. This extraction scheme has been copied in most other weak focusing proton synchrotrons. The essential features of this scheme are illustrated in Fig. 1. The beam passes through a jump target where the particles lose enough energy so that the equilibrium orbit is suddenly shifted to the position shown by the dashed line. The particles execute an oscillation about this new closed orbit having a maximum inward excursion one half horizontal betatron oscillation wavelength downstream from the jump target. A magnet placed at this position deflects the particle out of the accelerator. Because of the half wavelength relation between jump target and ejection magnet, a horizontal image of the jump target is formed at the ejection magnet so the aperture requirements of this device are minimized. In the Cosmotron, it is possible with the pole face windings to adjust the field index of the accelerator so that 1/2 wavelength is just one revolution. Then with that adjustment, the vertical oscillations are tuned so that one revolution is a full wavelength and the jump target is imaged in both planes in the ejector. Ejection efficiencies of 40% were available at the Cosmotron. Both fast and slow spill rates are possible with the Piccioni scheme.

Variations of this scheme are in use at the Bevatron in Berkeley, at ZGS in Argonne, at Saturne in France and at Nimrod in England. Most of these improved versions use two or more magnets or lenses instead of the single ejector of the Cosmotron. These are arranged to reduce the deflection of the first magnet so that a thinner septum coil and hence a thinner jump target is possible, and to improve the focusing either at the final ejection magnet or in the fringing field where the beam emerges from the accelerator. These improvements enhance the optical quality and efficiency of the beam. Efficiencies as high as 65% have been reported.

In the early days of the AGS machines, plans were advanced for incorporating a version of this type of extraction. It is clear, however, that there are two fundamental difficulties. The first problem is that because of the momentum compaction in the AGS, a large energy loss is necessary to shift the orbit. The second problem is that multiple scattering and energy spread induced by the jump target are disastrous to the optics of the emergent beam. Fortunately, alternative extraction schemes have been developed to obviate these difficulties.

The first extraction systems developed for the Brookhaven and CERN machines were the single turn fast extraction schemes. The Brookhaven system, described in some detail at the Conference two years ago,[2] is illustrated in Fig. 2. Here a "fast kicker" magnet is switched on in the 200 ns interval between accelerated bunches. The particles are deflected sufficiently to fall behind the thin septum of the next magnet which is $3/4\ \lambda$ downstream. This magnet deflects the particles further to the inside. Then $3/4\ \lambda$ further downstream the deflection is sufficient to deflect the particles clear of the machine. The septum and ejector magnets are rammed as close as possible to the accelerated beam. The fast kicker is a picture frame magnet enclosing the entire aperture. Some important parameters of the magnets are listed in Table I.

Table I

Magnet	Aperture (in)	Length (in)	Field (gauss)	Comments
Kicker	2 x 5	60	500	200 MW pulse power
Septum	½ x 1¼	84	2000	0.060 in septum
Ejector	0.8 x 2	84	15000	

The AGS has conveniently $3/4\ \lambda$ per superperiod so the simplest array consists of kicker, septum and ejector in the middle ten foot straight sections in successive superperiods. Any spacing of an odd number of quarter wavelengths can be used between these components. Our current beam for the RF separated beam to the 80 inch bubble chamber has $5\ {}^3/_4\ \lambda$ between septum and ejector.

The fast beams at CERN[3] are similar in principle but considerably different in engineering details. The CERN staff has also developed two important conceptual design improvements. The first improvement stems from their beautiful work on septum technology. By achieving fields of the same order as that of the Brookhaven ejector in a magnet with a septum coil of only three millimeters, the septum-ejector functions can be combined into a single magnet. The second improvement consists of eliminating the ramming of this magnet. This is achieved by distorting locally the equilibrium orbit to bring the beam to the fixed septum which is located at the outside

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edge of the aperture. This technique is relatively easy in the AG synchrotron and is useful for targeting as well as beam extraction. Fig. 3 shows a sketch of such a "bump" which is to be used for a beam at Brookhaven. Backleg windings are powered on the magnets whose names and focusing action are given in the figure. By choosing the magnets with careful attention to the spacing and symmetries, little perturbation in the operation of the accelerator results. Actually, the ultimate system would use both ramming and orbit bumps. The septum magnet inevitably encroaches somewhat on the injection aperture unless it is placed so far outside that good optics is impossible. Thus, it should be rammed, but the orbit bump technique works very well and it probably is much simpler to combine a short stroke ram and orbit bump than to construct a really satisfactory long stroke ram. The orbit bump also permits a rapid switch from external beams to internal targets or the reverse.

Ejection efficiencies with fast beams of this type are commonly 95%. The beam emittance is virtually the same as that of the accelerated beam so that spot sizes possible are frequently more limited by the transport optics than by the properties of the beam. Spot sizes as small as 2 mm diameter have been reported by CERN. Because fast kicker magnets can be turned off with the same speed as they are switched on, it is possible to eject cleanly some of the bunches and accelerate the remainder undisturbed for use of some other experiment.

For counter and spark chamber experiments, it is desirable to extract the beam over hundreds of milliseconds instead of over a single revolution. This is achieved by the use of non-linear resonances. We recall that instabilities occur in the equations of motion of betatron oscillation when perturbations are present in accordance with Table II. The third integral resonances are immediately useable for resonance extraction. The slow ejection system being developed at the Brookhaven AGS will use such a resonance. The ν value will be tuned to near $8\ {}^2/_3$ and the resonance will be excited by a configuration of sextupoles with the 26th azimuthal harmonic. The properties of this type of resonance are summarized by looking at the phase space plot shown in Fig. 4. This shows the position and slope of particles on successive revolutions at a single azimuth of the accelerator. The dominant feature of this diagram is the trio of fixed points. These are connected by smooth curves which reduce to straight lines if the perturbation is purely that given in the table. The area enclosed by these curves corresponds to bounded or stable motion. Outside this area the particles spiral out of the accelerator as indicated by the arrows. Because of the third-integral nature of the motion, a particle appears on successive branches on successive revolutions. Spiral pitches of nearly an inch per three turns can be achieved so the efficiency for missing a thin septum magnet can be quite high. The area of the stable region is dependent on the strength of the perturbation and the separation of ν from an exact third integer. Thus the beam spill is controlled by tuning the machine slowly towards the resonance or gradually increasing the excitation of the perturbation. The particles are thus squeezed out of the separatrix and spiral out to the septum.

Table II

Equation of Motion	Resonance	Growth
$x'' + \nu^2 x = A \cos n\theta$	$\nu = n$	Linear
$x'' + \nu^2 x = Ax \cos n\theta$	$\nu = n/2$	Exponential
$x'' + \nu^2 x = Ax^2 \cos n\theta$	$\nu = n/3$	Faster than Exponential

Computations necessary to construct Fig. 4 are done as follows. We assume that one has access to a computer program which can trace a ray around the accelerator starting with given initial conditions. Now in the vicinity of a fixed point (ξ, ξ') there exists a matrix M such that

$$M \begin{pmatrix} x_1 - \xi \\ x_1' - \xi' \end{pmatrix} = \begin{pmatrix} X_1 - \xi \\ X_1' - \xi' \end{pmatrix}$$

where (x_1, x_1') are the initial conditions and (X_1, X_1') are the coordinates after three revolutions. Solving this matrix equation for (ξ, ξ') we get

$$\begin{pmatrix} \xi \\ \xi' \end{pmatrix} = \begin{pmatrix} I - M \end{pmatrix}^{-1} \left[\begin{pmatrix} X_1 \\ X_1' \end{pmatrix} - M \begin{pmatrix} x_1 \\ x_1' \end{pmatrix} \right]$$

The matrix M is computed by actually tracing three rays instead of just one. It is simple to use the sets $[x_1, x_1']$, $[x_1 (1 + \epsilon), x_1']$, and $[x_1, x_1' (1 + \epsilon)]$ which become after three revolutions, (X_1, X_1'), (X_2, X_2'), and (X_3, X_3'), respectively.

Then with some algebra we get

$$M_{11} = \frac{1}{\epsilon x_1} (X_2 - X_1) \qquad M_{12} = \frac{1}{\epsilon x'} (X_3 - X_1)$$

$$M_{21} = \frac{1}{\epsilon x_1} (X_2' - X_1') \qquad M_{22} = \frac{1}{\epsilon x'} (X_3' - X_1')$$

Since the equations of motion are actually non-linear, this procedure is not exact but simply generates an approximation to (ξ, ξ') and M. Using the (ξ, ξ') so computed as a new (x, x') we can iterate until the fixed points are determined with arbitrary accuracy. The eigenvectors of the matrix M represent the asymptotes of the hyperbolic trajectories near the fixed point. The slopes of the asymptotes are then given by

$$\frac{\Delta x'}{\Delta x} = \frac{- M_{11} + M_{22} \pm \sqrt{(M_{11} + M_{22})^2 - 4}}{2 M_{12}}$$

where the minus sign is identified with the outgoing trajectories. We can now launch a particle on this asymptote slightly removed from the fixed point and compute its trajectory until it spirals out to where the septum is located. The computer program used for the AGS traces rays by numerically integrating the equations of motion through tables of measured magnetic fields, and all quadrupoles, sextupoles and orbit bumps are correctly included. The same program carries the rays after deflection by the septum and ejector through the fringing fields and to the entrance of the external beam transport system.

The hardware for the beam to be tested this summer at the AGS consists of:

a) Four of the ring sextupoles spaced 90° with alternating polarities.

b) A thin septum magnet in a five foot straight section.

c) An ejector magnet in a ten foot straight section about one quarter wavelength downstream from the septum.

d) An orbit bump to make the septum much closer to the equilibrium orbit than other aperture limits in the machine so that the beam will spiral into the septum rather than spraying uniformly about the whole circumference.

e) The usual transport equipment, instrumentation, shielding, etc.

The use of the third integral resonance is certainly not unique to the AGS. Application of this technique to the Princeton-Penn weak focusing synchrotron[4] is described in another paper at this session. It is also used at the electron synchrotron at Frascati, Italy.[5] An interesting feature of the Frascati system is that the sextupole perturbation is generated with poleface windings.

The CERN slow extraction system uses an integral resonance combined with sextupole nonlinearities.[6] It is an interesting question in semantics whether this is a $\nu = 6$ integral resonance or a $\nu = {}^{18}/_{3}$ integral resonance. In any case the principles are the same except that the three fixed points degenerate to a single point giving rise to the phase space diagram shown in Fig. 5. The hardware at CERN uses a single quadrupole to shift the ν-value from 6.25 down to near $\nu = 6$. Six ring sextupoles are connected to synthesize the sixth harmonic of the sextupole moment. In the original scheme tested about two years ago, a single septum-ejector was used and an orbit bump similar to the one described above was included. The septum ejector magnet is an impressive technological development. The coil is 20 mm high and only 3 mm thick, and has a current pulse of 16,000 A for 200 ms. The fringing field is less than 0.1%. In a later development for a new beam extracted in their straight section 62 a thin septum lens is included. Efficiencies of 95% are theoretically possible with this scheme. The CERN group has added two very important improvements to the resonant ejection scheme. The first consists of using the beam output to servo the quadrupole to produce a very constant spill rate during the ejection. The second improvement is the development of "fast-slow" ejection for bubble chambers. Here the resonant extraction scheme is used but parameters are so operated that the beam is spilled in a spike of about 1 ms duration. This is fast enough for good pictures but slow enough for stepping magnets to be used to distribute the events more uniformly over the chamber's volume.

Resonant extraction is also possible using the half integral resonances. Such a scheme is in use at the Cambridge Electron Synchrotron.[7] A unique feature of this installation is that a single septum current strip has a nonlinear fringe field which excites the resonance as well as acting as septum magnet. Half-integral resonant extraction has also been proposed by the Berkeley design study for the 200 GeV machine.[8] With all of these possibilities for choice of resonance to be used, the question is frequently raised as to which resonance is best. There are some fundamental differences in the properties. For example, it has been shown theoretically that the CERN scheme has potentially a smaller emittance than the third integral scheme used at BNL. The actual choice, however, is dominated by practical considerations such as the natural ν-value of the machine, ease of introducing appropriate perturbations, and the matching of the large amplitude motion to the lattice.

The future of external beams for AG proton synchrotrons is very clear. The ever-increasing intensity of these machines is creating an untenable radiation problem for the components of the accelerator and for maintenance personnel. It is therefore mandatory that the internally targeted beam should not be increased. Removal of the beam to an external target is the obvious solution; but this is also demanded by the experiments. The evolution of the experimental program at each energy range follows a familiar pattern. At first the experiments are of an exploratory nature and the equipment is very simple. Then more severe requirements are put on the data and the setups are more complex. Soon it becomes impossible to erect these experiments about the internal targets of the accelerator and the usage of external beams increases. This is particularly true in high energy physics where the production cross section of interesting secondary particles is so strongly enhanced in the forward direction. These considerations are so compelling for the 200 GeV machine that the beam extraction systems must be incorporated into the machine from the start.

At Brookhaven, we have also considered the possibility of extracting the beam in exactly n turns where n is some integer of order 10. This scheme would be required if one wished to use an ordinary synchrotron for an injector to a larger synchrotron. For example, the AGS might be used as an injector for a 200 GeV machine. The 200 GeV machine would be constructed with a circumference exactly seven times that of the AGS and seven turn extraction would be required from the AGS. Recently we have also examined the possibility of using a 1 GeV booster synchrotron instead of the 200 MeV linac as part of the current AGS improvement program.^{9} In this case the booster would be built with a circumference one twelfth that of the AGS and twelve turn extraction would be required. This might be accomplished by a variation of the half-integral resonance technique as studied by Reich and Claus^{10} or by a reversal of the scheme used for multiturn injection. An orbit bump of about $^1/_2\ \lambda$ is created by two bump magnets. The strength of these magnets is programmed in discrete steps by switching the current between bunches and with the level of each step adjusted to push an appropriate fraction of the beam past the septum which is located at the center of the bump. Fig. 6 shows the emittance of the successive revolutions at the septum for a typical case. In the calculation of these patterns the computer adjusts for each revolution the bump magnet strength just upstream of the septum so that the area of the pattern is one twelfth the area of the initial ellipse. Simultaneously, the other bump magnet is adjusted to make the average slope $(\bar{x}')$ the same for all revolutions. This is accomplished by a simple two parameter linear programming iteration. We visualize that the real machine might run with a similar scheme. The bump magnets would be switched between RF bunches in the booster to the value for the next revolution. An on line computer could look at the intensity and slope of the beam ejected on each revolution and correct the twelve steps for the next booster pulse. In Fig. 6 we see that nearly all the beam can be accommodated in an ellipse of twice the area of the individual patterns. This dilution of a factor of two in phase space density could be tolerated in most injection situations.

In summary, the AGS type machine is capable of generating beams of good efficiency and optical quality over an enormous range of duty cycles.^{11}

References

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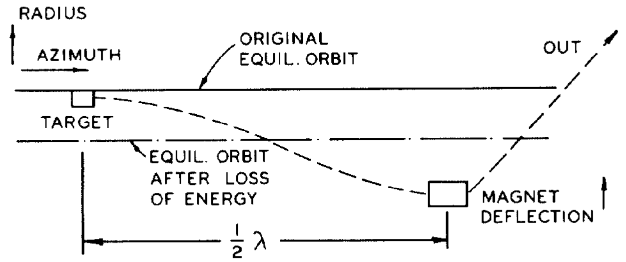

Fig. 1. Diagram of Piccioni scheme.

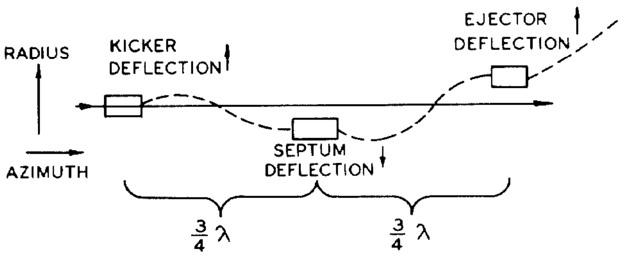

Fig. 2. Schematic of fast beam at the AGS.

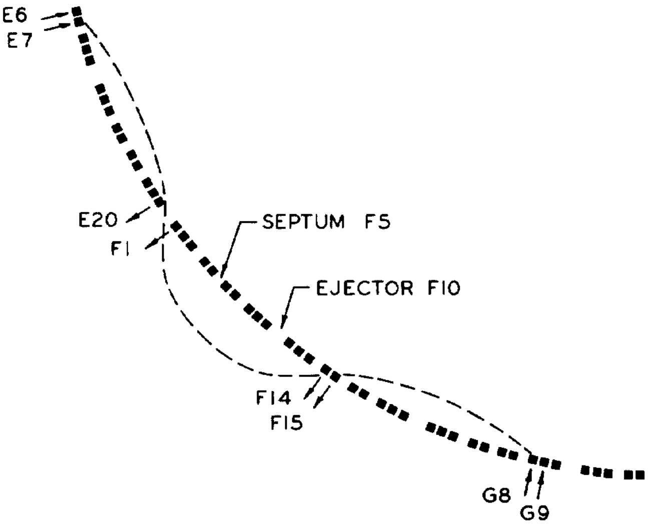

Fig. 3. Orbit bump at AGS. Magnets E6, F1, F14 and G9 are horizontally focusing, E7, E20, F15 and G8 are defocusing.

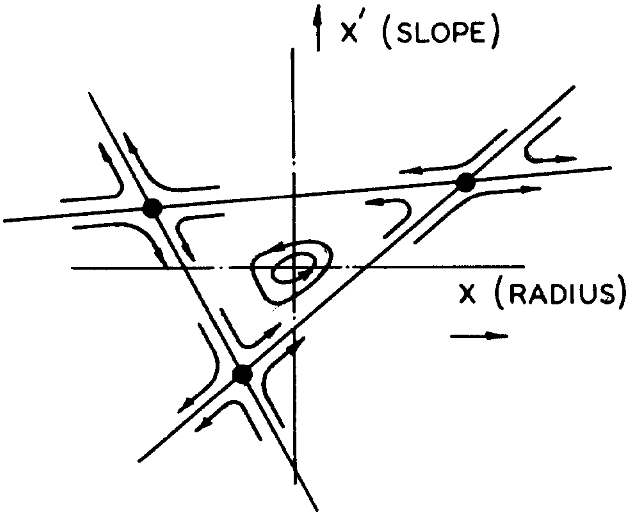

Fig. 4. Phase space motion near 1/3 integral resonance.

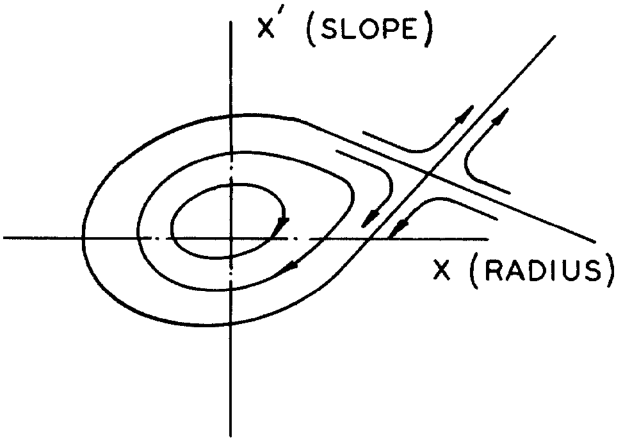

Fig. 5. Phase space plot for integral resonance as used by CERN.

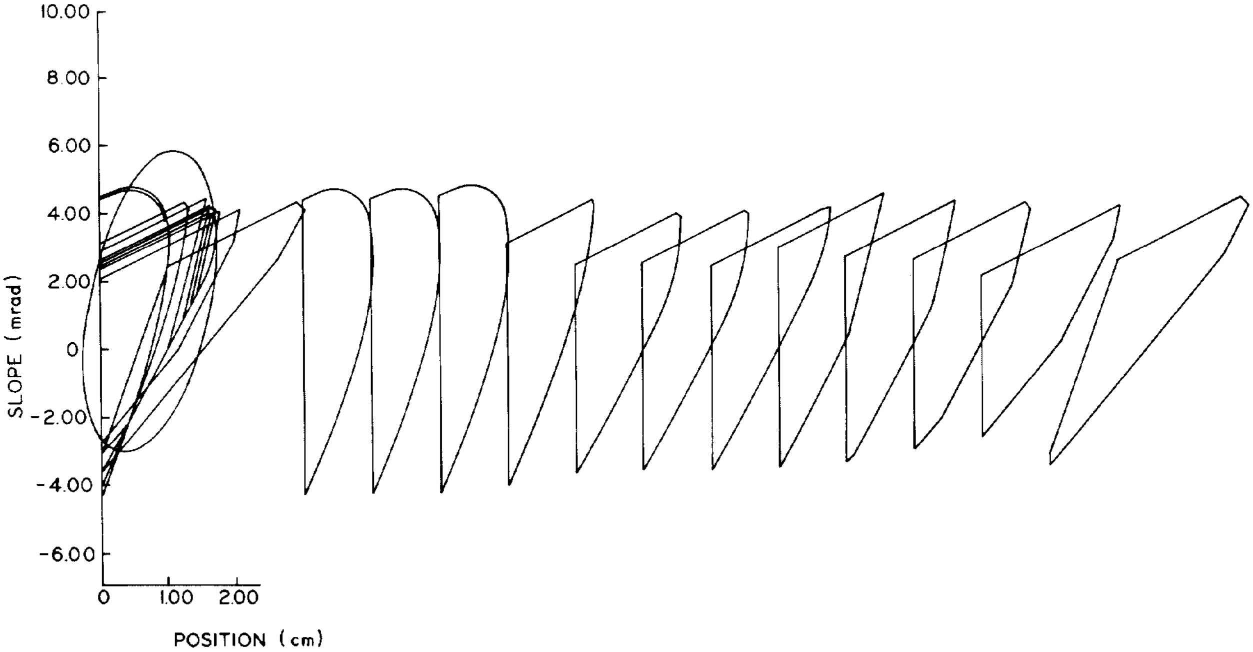

Fig. 6. The emittance limits for individual turns of 12-turn extraction. On the left the individual patterns are superimposed for comparison with a constant ellipse of twice the area of the individual turns representing the acceptance of the large accelerator. The individual patterns are also shown separately to permit examination of the variation in shape.