EXTERNAL BEAM PERFORMANCE AT P.P.A.*

J. Kirchgessner
Princeton-Pennsylvania Accelerator
Princeton, New Jersey

Summary

The proton beam extraction system which is now operational at the Princeton-Pennsylvania Accelerator is a resonant system operating on the $\nu=2/3$ radial betatron resonance. This method of extracting from a weak focusing synchrotron was first proposed and shown to work by Turrin et. al. at Frascati, Italy.[1,2,3]

The system requires that the synchrotron magnet be tuned to $\nu_r=2/3$ with a quadrupole magnetic field component and that an azimuthally varying second harmonic hexapole field be applied to drive the oscillations.[4]

When the oscillations have reached sufficient amplitude the particles enter the aperture of a septum magnet which bends them clear of the synchrotron. The beam is then steered and focused to the first target point in the External Beam building.

Excitation Magnets

Placed in four short straight sections symetrically disposed around the synchrotron are four "Excitation" magnets. These magnets produce simultaneously, independently controllable quadrupole and hexapole field components. Figure 1 shows the current flow and the resulting field components in the two cases. These magnets have previously been described in greater detail.[5]

There is also a dipole winding on each of these magnets which is useful in producing a first harmonic closed orbit distortion which shifts the beam closer to the extraction magnet aperture.

Figure 2 shows a plan view of the synchrotron with the placement of the various extraction components and the polarity of the field components in the synchrotron magnets, the excitation magnets, and the extraction magnet.

The sequence of operation consists in establishing a fixed second harmonic hexapole field component proportional to B which establishes a fixed oscillation growth rate. The quadrupole component is then increased toward that value which corresponds to the $\nu_r=2/3$ resonance. As the resonance is approached, the protons with the greater initial betatron amplitudes will become unstable and be extracted first. In this manner the extraction rate is controlled by controlling the rate at which the $\nu_r=2/3$ resonance is approached.

Figure 3 shows the orbits of particles with respect to the central orbit. At $\nu_r=2/3$ there are 2 radial betatron oscillations per 3 revolutions around the synchrotron. The placement and phase of the hexapole magnets are shown. The location of the extraction magnet is shown with it's septum. The placement of a "shadow target" is shown in the normal target straight section. This target intercepts that beam which would strike the septum. This prevents radiation damage to the septum magnet and secondary beams from this target are available to the primary experimental area.

The behavior of the system is observed with a phosphor coated flag at a position corresponding to the entrance of the extraction, septum magnet. The effects of the quadrupole and hexapole field components can be observed and set to the correct value.

Extraction Magnet

The purpose of the extraction magnet is to intercept the proton beam when the betatron oscillations have reached sufficient amplitude and to bend the particles clear of the synchrotron magnet. It is desired that the current septum be as narrow as possible in order to have a high extraction efficiency. The extraction magnet used in this system operates at a peak field of 14 kilogauss, the septum conductor thickness is 1/8 inch and the overall septum thickness is 3/16 inch. The magnet is 57 inches long and the aperture is 1/2 inch high by 1 inch wide.

This magnet which has a peak power dissipation of 250kW is water cooled and is powered with a transistor modulator which is able to precisely program the current to 0.01% accuracy.[6]

The septum of the extraction magnet is at a radius 3 inches greater than the central equilibrium particle orbit. Previous plans included the plunging of this magnet at a 20Hz rate with a peak to peak excursion of 2 inches. Tests however have indicated that the system performs satisfactorily with the magnet fixed at a radius outside the injection aperture. There are no plans now to plunge this magnet.

Figure 4 shows a photograph of the extraction magnet presently being used. The magnetic shielding fastened to the magnet coil clamps reduces the external stray magnetic field to less than one gauss.

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External Beam Line

After the beam is bent by approximately 9 degrees by the extraction magnet the beam must be steered and focused to the first target point some 80 feet away.

The synchrotron vacuum system extends to within 5 feet of the first target point.

The first element in the transport line is 3 feet of laminated shielding which protects the beam from the very strong divergent field of the synchrotron magnet in this region.

The next element is a vertical steering dipole, the purpose of which is to vertically center the beam through the later elements.

In order to pass through the tunnel to the external beam building the beam must be bent horizontally by 1 degree. As the momentum of the beam is changing by 10% during the desired extraction time, the dipole consists of a dc dipole and a laminated ac dipole of 1/10 the bending power. This ac dipole is 100% modulated during the spill time.

Along the line are two monitor boxes which contain remotely movable X and Y scanning scintillation fingers. These monitors are used to set the proper current programs on the extraction magnet, the vertical dipole and the horizontal ac and dc dipoles.

Approximately 35 feet from the extraction magnet is a quadrupole doublet. Here again the dc quadrupoles are aided by adjacent ac quadrupoles in order to track the 10% momentum variation during the extraction time.

Figure 5 is a plan view of the beam line from the synchrotron to the first target point.

One experiment is presently using a $\frac{2\text{GeV}}{c}$ secondary π beam from the first target position. A second experiment is using a zero degree K+ beam from a second target point 48 feet downstream with a focusing doublet in between. These experiments will not run simultaneously. When the second is operating the first target will be removed and the ac quadrupoles will be overdriven in order to compensate for the second dc doublet as well as the first. This will move the first focus but the second focus remains fixed as the momentum varies.

Performance of the System

The excitation magnet system was operating in July, 1965. The beam was made to blow up radially and the particles were observed at the entrance to the extraction magnet. A long spill (5 msec) was acheived and the spill was relatively devoid of synchrotron oscillation structure.

The only difficulty encountered was that we discovered that the equilibrium orbit had to be centered to 0.1 inch in order to avoid a vertical blow up on the ν_V=1 resonance. This feature was predicted by earlier digital calculations.

In September, 1966, the extraction magnet was installed and powered. At that time the vacuum beam line was not complete nor were the ac magnets in the beam line operating.

A short (200 μsec) spill was achieved and with a dc quadrupole doublet the beam was focused to a 3/4 inch diameter spot at a distance of 85 feet from the synchrotron. The large spot was due to the air scattering and exit window scattering of the proton beam.

The extraction efficiency was measured to be 74%. This measurement was made by radioactivitation of a gold foil in the external beam and comparing the activity with a similar gold foil activation on the internal target with the same amount of circulating beam striking the target via RF steering.

Assuming that oscillation growth rate is exponential and therefore the particle distribution falls off as $\frac{1}{R}$, the maximum extraction efficiency would be 81%. This is simply due to the ratio of the septum width to the extraction aperture width.

In December, 1966, the vacuum beam line was completed and the system again operated. Figure 6 is a radioautograph made at the first focus point showing the beam spot size and distribution. This shows that 75% of the proton beam lies within a 1/8 inch diameter circle at this point. Other measurements have shown the beam intensity to be less than 1% at 1/4 inches from the center of the spot.

Digital calculations performed earlier indicated a vertical emittance of .16 mrad.cm. and a radial emittance of .37 mrad.cm. With the focusing system we are using this would yield a spot size of .18 inches high by .16 inches wide which is consistant with our measured results.

Immediate plans include two modes of operation of the extraction system:

1) For four machine cycles the beam is RF steered to an internal target. Every fifth machine cycle part of the beam is spilled internally and then after a 2 to 3 msec. delay during which time the beam is steered back to a central orbit, the remaining beam is extracted in about 100 μsec.

2) Each machine cycle the beam is extracted over a 10 msec. period with the beam shared approximately half and half between the external target and the

2) internal target which is operating in a shadow target mode.

At the Princeton-Pennsylvania Accelerator most experiments make use of the very tight RF bunching of the beam. When the beam is RF steered to an internal target, the secondary particle bunch width is measured to be less than the extent in time of the beam bunch in synchrotron phase space. The proton beam bunch time spread in about 2.5 nsec. but the secondary particle bunch time spread (full width at half maximum) has been measured to be not greater than 1.1 nsec. This is due to the fact that the synchrotron phase space is peeled sequentially and we observe only the time spread in betatron phase space. When the beam is resonantly extracted, the betatron phase space is sequentially peeled and particles are taken indiscriminately from all parts of synchrotron phase space. The measured beam bunch time spread of the extracted (or resonantly targeted) beam is 2 nsec. (full width at half maximum).

Some difficulty has been encountered in shadowing the extraction magnet septum. Due to the fact that the shadow target is 1/2 betatron wave length before the septum, the system is not achromatic with respect to the energy spread of the beam. Thus, the septum can be completely protected only by using a shadow target that is wider than the septum by an amount equal to twice the width of the beam in synchrotron phase space. This has the effect of lowering the extraction efficiency, probably to less than 50%. A shadow target 1 betatron wave length before the septum adequately shadows the septum in an achromatic way, but the secondary particles from this target are not experimentally useful. A solution is being tested which consists of a shadow target λ before the septum. This target serves as an energy loss jump target for the particles striking it which then feed the $\frac{\lambda}{2}$ target where the secondary particles are experimentally useful. This system has been tested and seems to perform satisfactorily.

Another difficulty has arisen with the shadowing of the septum. Due to reasons which are not fully understood there is a twist in the mapping from a vertical shadow target to the vertical septum. There also seem to be present large coherent vertical oscillations or displacements. Detailed median plane measurements of the beam at high energy have been made and it has been determined that a small first harmonic in the median plane location has a large effect on these phenomenon and indeed the twist can be removed with the proper location of the median plane.

References

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6. D.E. Huttar, Proc. 1966, National Electronics Conf., Vol. 22, p. 950.

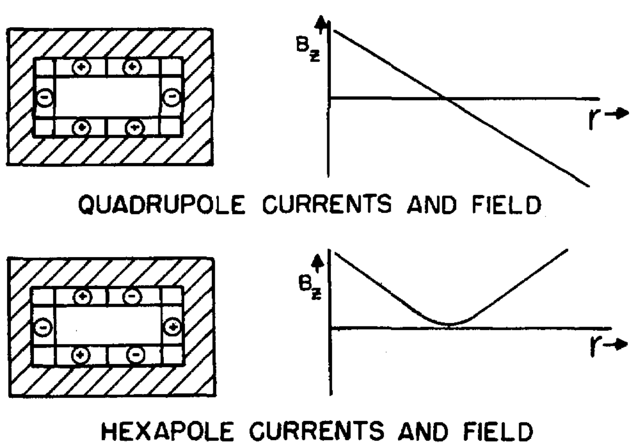

Fig. 1. Section through an excitation magnet showing directions of current flow and resultant fields on the median plane. In actual use these currents are superposed to give a combined but separately controllable field.

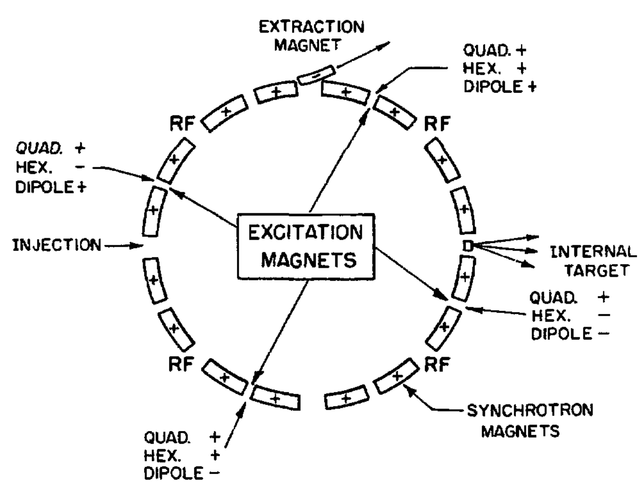

Fig. 2. Plan view of the synchrotron showing location of system components and polarity of fields used.

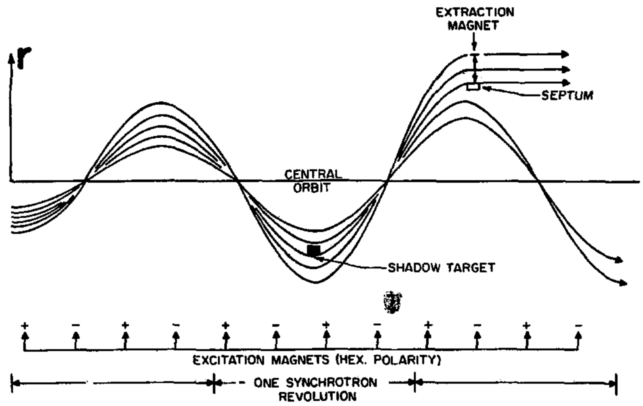

Fig. 3. Plot of particle trajectories with respect to central orbit followed 3 turns around the synchrotron. The location of the shadow target, the extraction magnet and septum and the excitation magnets are shown. The polarity of the hexapole field component is shown.

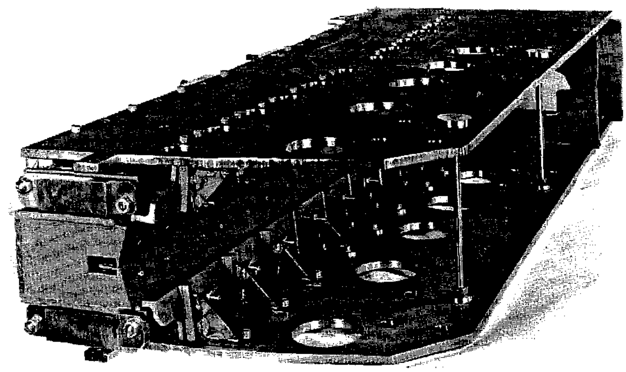

Fig. 4. Photograph of the extraction magnet from upstream end showing aperture and septum. The magnet is constructed of 14 mil grain oriented silicon steel. The conductor is 1/8 inch square copper with a 0.075 inch diameter water passage.

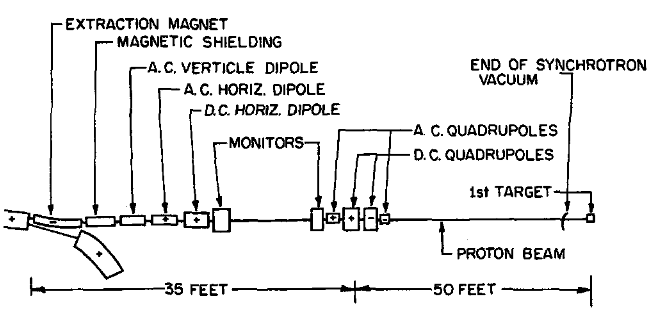

Fig. 5. Plan view of the external beam line to the first target. The various magnets and monitor boxes are shown.

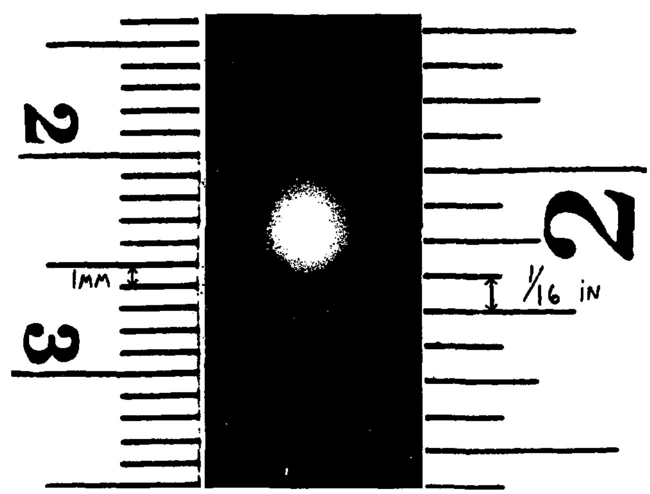

Fig. 6. Radioautograph made from a 0.010 inch Cu. foil placed at the first target point. Target exposure time 10 minutes at fixed momentum.