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INJECTION AND ACCELERATION OF PROTONS IN THE ZERO GRADIENT SYNCHROTRON (ZGS) BY STRIPPING H^- IONS *

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Introduction

The booster injector program for the ZGS requires the stripping of H^- ions at 50 MeV as the source of protons in the booster accelerator.[1,2] Using the former Cornell 2.2 GeV electron synchrotron as a prototype booster, the injection of protons by stripping negative hydrogen ions in a poly-paraxylene thin film has already been demonstrated at the ZGS.[3] A brightness multiplication factor of 100 has been achieved. The limiting factor is the scattering of the circulating protons in the stripping foil.

Until now the booster injection and operation studies have been limited to ZGS off periods because the 50 MeV H^- ions are obtained by the same accelerating system that produces the 50 MeV protons required for injection into the ZGS. With the planned installation of Booster-II,[4] it will be desirable to use H^- ion stripping injection into the ZGS so that the booster tune up studies can be carried on during normal ZGS operation.

Two ZGS H^- injection trials have been performed during the past year. It has been demonstrated that H^- stripping injection into the ZGS is feasible and that only a small improvement in H^- current is required to make the process competitive with regular proton injection.

The ZGS H^- Injection System

Protons are normally injected into the ZGS at about 13 in radially out from the central orbit, after being deflected 3° by a thin septum magnet. As the protons are injected, the equilibrium orbit moves inward at about 0.1 in per turn and some injected particles are lost by hitting the injection magnet. During H^- injection, the inflector magnet is removed and the 3° bend accomplished by using about 2 ft of the magnetic octant downstream from the injection straight section. (Fig. 1) When the stripping foil is located at the correct radial position, an injection angle and ZGS injection field can be found such that the protons created by stripping are on an equilibruim orbit. In practice this condition is achieved by injecting a half turn of H^- ions and observing the radial oscillations using fast pickup position electrode signals. The radial position of the foil is adjusted so that a combination of injection angle and ZGS field can be found that produces nearly zero radial oscillation amplitude.

With the position of the foil correctly adjusted, a long H^- pulse (up to 600 μs) was injected while a relatively slow Ḃ (5.5 kG/s) moved the equilibrium orbit inward at the rate of about 0.017 in/μs (0.031 in/turn). The observed maximum coasting time for the early injected protons was found to be about 1.1 ms indicating a useful radial aperture of 18.7 in.

By varying the linac gradient during the pulse it was also possible to achieve a desired amount of energy ramp so that the instantaneous injection orbits could be made to move inward in the ZGS at a slower rate than the 0.031 in/turn for the already injected protons. In this way it was possible to trade off radial betatron oscillation amplitude for energy spread in the circulating beam.

After RF capture and acceleration to 200 MeV (magnetic field of 1 kG) the rate of rise of the magnetic field was increased from 5.5 kG/s to the normal 18 kG/s.

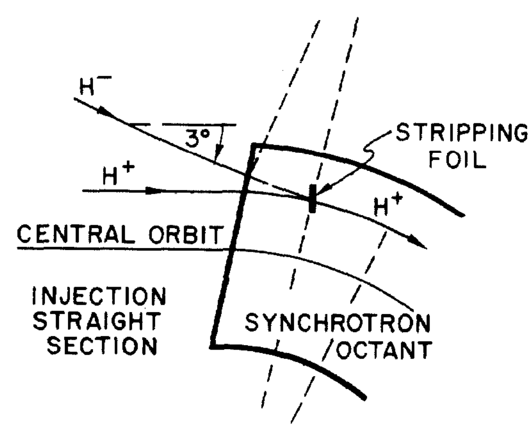

Fig. 1

H^- Stripping Injection into ZGS (Not to Scale)

ZGS H^- Stripper Foil Mechanism

The stripper foils were placed into Octant No. 1 of the ZGS with a swing arm mechanism (see Fig. 2). The foil was mounted on an aluminum frame which is shown in detail at the upper right hand corner of the figure. A 2 in wide 5500 Å poly-paraxylene foil was hung vertically between the tines of the frame.

Because the useful life of the foils has proved to be 4 or 5 h, automatic operation of foil changing to minimize the downtime of the accelerator is required. The foil holder is attached to an arm apparatus, which is swung into an automatic foil replacement magazine. The arm, upon reaching the magazine, is shed of its spent foil and a fresh frame with foil is attached. When

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this portion of the operation is completed the arm swings back into the stripping position while the magazine retracts to the corner of the L-1 straight section to prevent its structure from interfering with circulating beam.

The magazine contains about 40 frames. Thus with a 4 h life it contains enough foils for a week's continuous running before a fresh supply must be introduced.

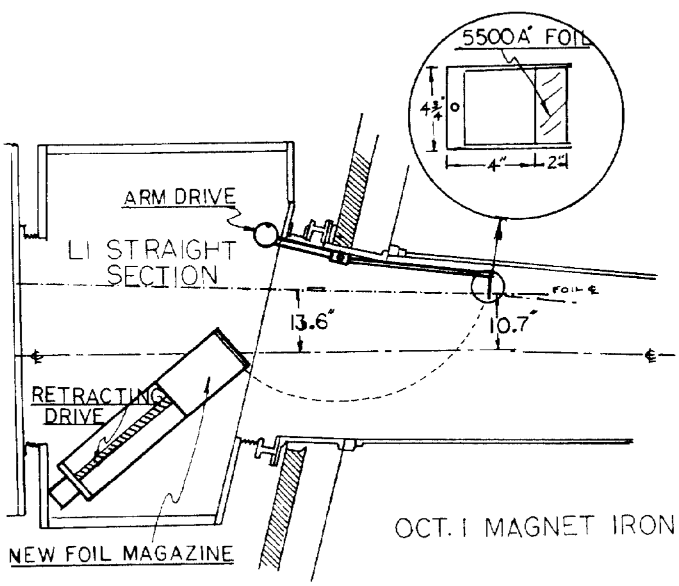

Fig. 2

Stripping Foil Holder and Automatic Changing System

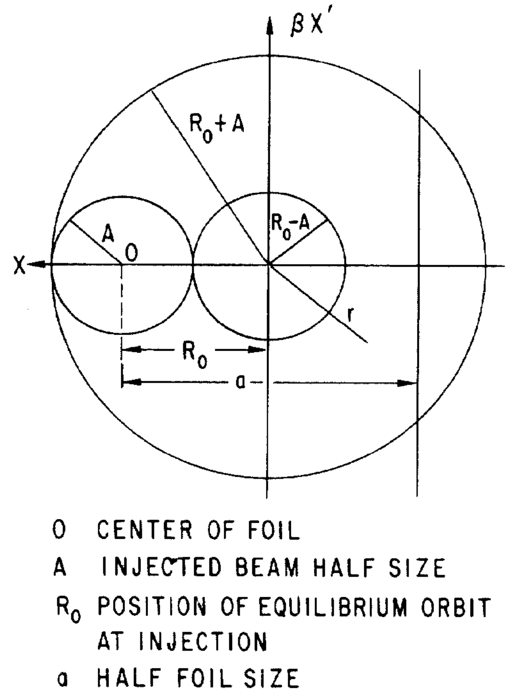

Fig. 3

Phase Space Diagram of Injected Beam

Stripper Scattering Effects

The stripping foils used so far have been about 5500 Å thick and have a density of about 1.1 g/cm^3. With a radiation length of 43.3 gm/cm^2 the root mean square scattering angle at 50 MeV is about 0.184 mrad for a single passage through the foil. This amounts to about a 0.235 in increase in oscillation amplitude in the ZGS. The total scattering angle produced by the foil is proportional to the square root of the average number of passes through the foil as the injected particles move slowly inward (0.031 in/turn) during the injection time.

The average number of passes through the foil may be derived using an adiabatic approximation as follows. In Fig. 3, consider all those particles on a circle of radius A injected at point 0 (center of the foil) with an equilibrium orbit position located a distance R_o radially inward. With very slow movement of the orbit those particles will occupy phase space

$$|R_o - A| \leq r \leq R_o + A \qquad (1)$$

with a density distribution

$$\rho(r, \theta) = \frac{1}{\pi^2 \sqrt{4 R_o^2 A^2 - (r^2 - R_o^2 - A^2)^2}} \qquad (2)$$

The normalization is

$$\int_0^{2\pi} d\theta \int_{|R_o - A|}^{R_o + A} \rho(r, \theta)\, r\, dr = 1 \qquad (3)$$

The average number of foil traversals can be obtained by finding the average value of the integral of ρ over the phase space determined by eq. (1) and being to the left of a as the equilibrium orbit moves to the right from R_o to $R_o + a + A$. The results for $2 R_o + A \leq a$ are given by

$$< n > = \frac{a - R_o}{a + A} \quad \frac{a + A}{\Delta R} \qquad (4)$$

where ΔR = orbit shift/turn = .031 in/turn. For $2 R_o + A > a$ the results are more complicated and require a double numerical integration. For A = 0 the correct equation for $2 R_o \geq a$ is

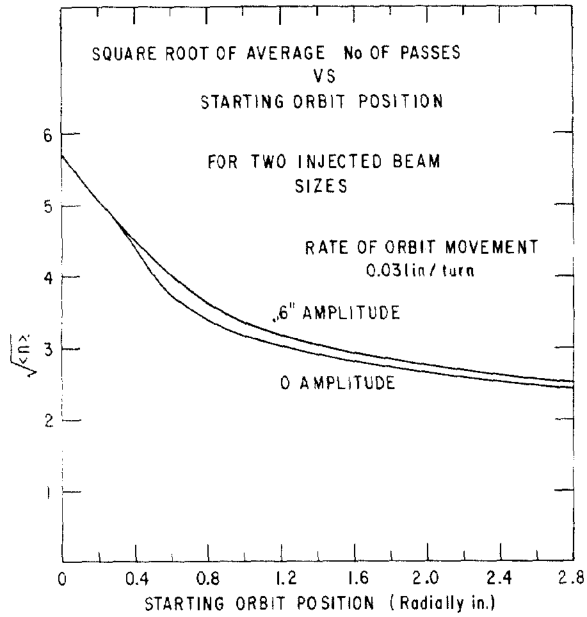

Fig. 4

Square root of No. of Passes Through Foil vs. Starting Orbit Position. 0 is Foil Center. 1 is Foil Edge.

$$<n> = \frac{1}{\pi a}\left[\sqrt{R_o^2 - (R_o - a)^2}\right.$$

$$\left. - (R_o - a)\cos^{-1}\frac{R_o - a}{R_o}\right]\frac{a}{\Delta R} \qquad (5)$$

The results for a = 1 in, and A = 0 and 0.6 in are shown in Fig. 4. It is seen that any amplitude beam injected with the equilibrium orbit passing through the foil will re-enter the foil an average of 32 times and suffer an rms scattering angle of

$$\sqrt{32}\ 0.184 \text{ mr} = 1.0 \text{ mr}. \qquad (6)$$

However, by injecting with the equilibrium orbit 1.7 in radially inward the scattering angle can be reduced by a factor of 2.

Coasting Beam Measurements

The total number of H^- ions injected onto the foil for a given pulse length was first determined by collecting all of the H^- ions in a Faraday cup at the end of the injection line. This number was compared with the total number of protons collected on a set of segmented detectors[5] located in a straight section 4 octants downstream from the injection section. (The beam was stopped downstream of these detectors to prohibit multiple turns for those protons passing through the segmented detectors.) Taking into account the transmission coefficient for the segmented detectors it was determined that almost all of the injected H^- ions were converted into protons and injected for 1/2 turn.

To determine the injection efficiency the segmented detectors were removed and the injected protons were allowed to coast across the chamber until they intercepted an inside Faraday cup. The circulating charge in the machine was monitored by observing an uncalibrated ion collecting system. Two typical results obtained in February, 1975 are shown in Figs. 5 and 6. The top signal on each trace is a toroid signal showing the shape and current for the H^- pulse. The center trace is the ion Q signal. The bottom trace shows the build up of charge on the inside cup. The calibration is 10^{12} protons/V.

One notes very little loss on the ion Q signal before charge starts appearing on the inside cup. The energy ramp on the linac had been adjusted so that the equilibrium orbit was constant for all injected particles.

A summary of the injection efficiencies measured in February, 1975 is shown in the following table.

Pulse Length μs	Injected 10^{12}	Coasting 10^{12}	Efficiency %
100	0.4	0.25	63
150	1.4	0.80	57
200	2.6	1.3	50
250	2.8	1.3	61
300	3.2	1.7	63
350	4.0	2.5	63
400	4.4	2.6	59
500	4.9	2.6	53

The injection efficiency appears to be no better than 60% for these injection conditions. It was observed that injection with the (constant) equilibrium orbit passing through the foil produced much worse

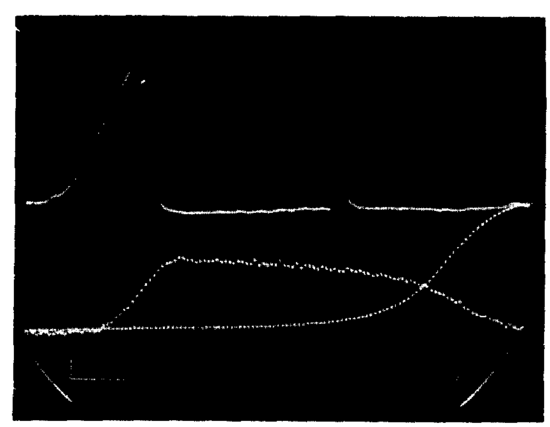

Fig. 5

160 μs Injected Beam
100 μs/div.
Top: H^- current 1mA/div.
Center: Ion Q Approx. 10^{12}/div.
Bottom: Inside Faraday cup 5×10^{11}/div.

results. The combination energy spread and betatron oscillation amplitudes size is about 8 in for the 500 μs injected pulse. The vertical size of the coasting beam determined by using stopping plates was almost 4 in. This agrees with the limiting vertical aperture of the stripping foil holder.

No different thickness foils were available to determine whether the injection was limited by foil scattering. However, booster studies have shown that thinner foils (3500 Å) yield the same stripping efficiency with less scattering.[3]

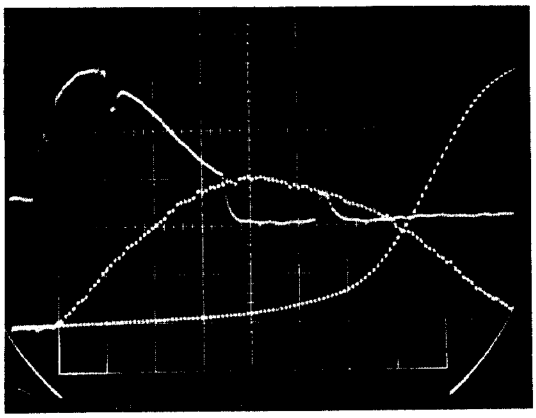

Fig. 6
400 μs Injected Beam Same Scales as Fig. 5.

Results

Peak currents of 3.5 mA of H^- ions have been achieved at 50 MeV. During August, 1974 an average current of 3.0 mA for 540 μs yielded 10^{13} H^- ions per pulse for stripping injection into the ZGS. Of this amount 2.9×10^{12} were accelerated for 40 ms from 480 G to 700 G. During the last attempt in February, 1975 (when the coasting measurements were performed) up to 6×10^{12} H^- ions yielded 1.5×10^{12} protons accelerated to 700 G. These results should be compared with normal proton injection at the ZGS where 35 mA for 200 μs (4.4×10^{13} protons) usually produce about 3.8×10^{12} protons at 700 G. Thus, the H^- strippping injection is about a factor of 2 better in overall efficiency. (Because of time limitations no attempt was made to accelerate the beam efficiently to full energy for the H^- runs. The acceleration of protons from 700 G to full energy at 19.8 kG in the ZGS is usually about 80% efficient).

A complete energy ramp, i.e. a constant injection orbit yielding a radial betatron oscillation amplitude of 1.5 in to 2 in was used to achieve the H^- run results quoted above. Using the measured 60% injected efficiency it is seen that the accelerations efficiency was about 45%. The large energy spread due to the energy ramp may have contributed to the acceleration loss. There was not sufficient time to determine whether a smaller energy ramp would have produced better results. A constant energy injection condition was tried and produced only half as many accelerated protons. This may have been due to increased foil scattering for those early injection orbits that must start near the center of the stripping foil (Fig. 4).

Conclusion

H^- stripping injection into the ZGS appears to be feasible and has demonstrated a factor of two improvements in efficiency over normally injected protons. It appears that foil scattering limits the total efficiency for H^- injection. It may turn out that thinner stripping foils and perhaps a somewhat faster increase of the magnetic field during injection will produce more accelerated beam. More intensive tuning of the injection, capture and acceleration will certainly lead to improvement. Lastly, an expected gain in source current leading to a factor of 2 increase in the H^- current to 5 or 6 mA will certainly make the H^- injection into the ZGS competitive with proton injection.

It should be noted that the beam loading of the ZGS linac limits the total current to the present value of 35-40 mA for proton injection. For this reason increased H^- currents can be expected to improve the beam delivered to the ZGS main ring while H^+ improvements cannot.

References

1 - R. L. Martin, Argonne National Laboratory, "The Argonne Zero Gradient Synchrotron Booster", IEEE Transactions on Nuclear Science, Vol. NS-18, No. 3 (June, 1971), pp 953-956.

2 - G. L. Dimov et al., USSR National Conference on Particle Accelerators, Moscow, USSR, October 9-16, 1968.

3 - J. D. Simpson, Argonne National Laboratory, "Operating Results from the ANL Booster", IEEE Transactions on Nuclear Science, Vol. NS-20, No. 3 (June, 1973), pp 198-201.

4 - E. A. Crosbie, M. H. Foss, T. K. Khoe, J. D. Simpson, "The Design of the Zero Gradient Synchrotron Booster-II Lattice", Submitted to IEEE Transactions on Nuclear Science.

5 - R. L. Kustom, E. F. Parker, C. W. Potts, R. B. Wehrle, F. R. Brumwell, "A New Diagnostic System for Studing the Injector and Injection at the Zero Gradient Sychrotron (ZGS)" IEEE Transactions on Nuclear Science, Vol. NS-20, 3, June, 1973, pp 518-522.