THE ARGONNE ZERO GRADIENT SYNCHROTRON (ZGS) BOOSTER*

R. L. Martin
Argonne National Laboratory
Argonne, Illinois

Summary

The former Cornell 2.2-GeV electron synchrotron operating at 30 Hz will be used as a rapid-cycling booster for injecting protons at 200 MeV into the ZGS to increase the space charge limited intensity of the ZGS. Negative hydrogen ions of 50 MeV will be injected into the booster with the electrons stripped at injection for acceleration of protons. The reasons for using this type of injection along with the history and status of the program are discussed.

Introduction

The concept of the ZGS booster to substantially increase the circulating intensity of the ZGS is a small rapid-cycling synchrotron inserted between the 50-MeV linac and the ZGS. The booster would operate at 30 Hz and inject up to 16 pulses at 500 MeV in 1/2 s into the ZGS for acceleration to 12 GeV once every 3 s. In order to achieve the desired high intensities in the booster each cycle, negative hydrogen ions would be produced in the source, accelerated to 750 keV in the existing Cockroft-Walton preaccelerator, and to 50 MeV in the linac. These ions would then be injected into the booster with stripping of both electrons to produce protons on the central orbit of the booster for acceleration to 500 MeV. With this technique a factor of 18 in circulating intensity of the ZGS appears feasible. The physical arrangement, dictated by the existing layout, is shown in Fig. 1.

It has long been known that the limiting intensities of synchrotrons due to space charge defocusing is a strong function of injection energy, varying as $\beta^2\gamma^3$ where β is the proton velocity at injection relative to the velocity of light, and γ the ratio of its total energy to the proton rest mass. The advantage of higher injection energy for any machine is shown in Table 1.

Table 1. Dependence of Space Charge Limit on Injection Energy

Injection Energy	$\beta^2\gamma^3$	Ratio
50 MeV	0.115	1.0
200 MeV	0.572	4.8
500 MeV	2.069	18.0

A study of possible improved injectors for the ZGS was carried out in 1966.[1] Although many injector ideas existing at the time were included in the study, the conclusion was reached that a 200-MeV proton linac, although expensive, was the most straightforward and had the highest probability of success. It is worthy of note that both the National Accelerator Laboratory and Brookhaven National Laboratory have constructed proton linacs of 200 MeV. Also included in this study was the possibility of a rapid-cycling booster.

It had been recognized for some time that the space charge limited intensity of most accelerators with the same injection energy is relatively independent of radius. This is shown by the formula

$$N_{sc} \sim \frac{B\, b\, (a+b)\, \nu\, \Delta\nu}{R}\, \beta^2\gamma^3 \qquad (1)$$

where B is the bunching factor, a and b the radial and vertical apertures, respectively, ν the number of betatron oscillations per revolution (also called Q value), and R the radius of the machine. The factor $\Delta\nu$, the allowable change in betatron frequency due to space charge effects, is usually taken as 0.2 although it might be made somewhat larger by appropriate design. The factor ν/R does not vary significantly for any alternating gradient synchrotron since the focusing forces are kept more or less optimum so that ν increases approximately as R. For weak-focusing synchrotrons, such as the ZGS, the low value of ν/R is compensated by the larger aperture. As a result of Eq. (1), it appears quite feasible to design a small synchrotron for 50-MeV injection with the same space charge limit as any of the operating high energy proton synchrotrons. The advantage of using such a booster for injecting many such pulses at higher energy into a larger machine is quite obvious.

The major problem with a rapid-cycling booster for the ZGS, however, was injection of protons into a small synchrotron. There is a fundamental impossibility of injecting protons up to the space charge limit in any of the normal ways when the radius is sufficiently small that the space charge limit implies a higher density of protons in phase space than exists in the injected beam. This fact relates to the second law of thermodynamics which states that one cannot achieve a brightness of the image (here circulating beam) greater than the brightness of the source in any reversible process. Normal multiturn injection does not circumvent this principle in that successive turns are injected into different areas of the acceptance phase space, hence brightness is not increased.

For the ZGS booster the injection problem has been overcome, at least in principle, by the recognition that the above restriction does not apply to injection of negative hydrogen ions with stripping of both electrons to form protons directly on the central orbit of the synchrotron. One can view this process in several equivalent ways. It would be correct to say that one is defeating the second law of thermodynamics by introducing an irreversible process (stripping) between the source and the image. Alternatively, one might justifiably claim that the source of protons for acceleration was the stripper foil itself on the central orbit

---

*Work performed under the auspices of the U.S. Atomic Energy Commission.

of the synchrotron and that no injection process is involved. However, the most straightforward viewpoint is to look at the particle dynamics. One can continuously inject into the same phase space area thereby increasing the brightness of the circulating beam. The protons must traverse the stripper media on each turn however. The multiple scattering in the stripper will enlarge the phase space area of the circulating beam and would eventually cause beam loss. Whether multiple scattering effects dominate before the space charge limit is reached depends upon the emittance of the injected beam compared to the acceptance phase space, the thickness of the required stripping media, the injection energy, and other factors, so that a specific set of parameters must be considered. A schematic comparison of this method of injection with normal proton injection is shown in Fig. 2.

The concept of H^- injection with stripping is rather old.[2] The practical feasibility of this technique for use with the ZGS booster, however, was stimulated by the work of Dimov[3] who achieved a relatively intense pulsed H^- source (16 mA) and demonstrated injection of > 1000 turns of 1.5 MeV H^- with gas stripping into a very small machine. Thus with 1.5 -MeV injection the feasibility of the injection process has been demonstrated and the space charge limit reached before multiple scattering became a serious problem.

The stripping cross sections vary inversely with kinetic energy so that at 50 MeV about 30 times as many atoms/cm^2 are required as were used by Dimov. While gas jet strippers still appear feasible at 50 MeV, the gas pumping load, especially for 30 Hz operation, presents a formidable problem. Fortunately, the required number of atoms/cm^2 ($\sim 3\times10^{18}$ of carbon) is within the range of the thinnest foils of adequate strength that can be produced. Tests made on a 0.5μ plastic foil have confirmed these views. In such a foil the rms scattering angle at 50 MeV is calculated to be 0.5 mrad for 50 traversals through the foil and 1.0 mrad for 200 traversals. With reasonable aperture of the booster and 50-MeV emittances equivalent to present values, the larger number of traversals can be accommodated.

An initial design of a booster synchrotron with a circumference 1/4 that of the ZGS was carried out in 1969.[4] It would have had a useful aperture of 2" vertically by 4.5" radially, a vertical tune of 1.77, radial tune of 1.68, and accelerate protons to 500 MeV at a repetition rate of 60 Hz for injection of perhaps 20 pulses into the ZGS. The calculated space charge limit of this booster was 5×10^{12} protons/pulse for an ultimate potential of 10^{14} protons/pulse in the ZGS.

Economic factors have dictated, however, that we carry out this program in a number of independent phases. We were indeed fortunate to obtain the former Cornell 2.2-GeV electron synchrotron, complete with vacuum system, ac generator, resonating capacitors, and dc filter (the former 300-MeV synchrotron), when its operation was discontinued in November, 1969. Its properties appear adequate to fulfill the early phases of the ZGS booster program.

Properties of the Former Cornell Synchrotron

The layout of the synchrotron at Argonne is shown in Fig. 3. It has a radius of curvature of 20' in the 12 magnet sections, and two long straight sections, of which one is used for injection and one for extraction as shown. The circumference factor compared to the ZGS is 1-3.3, which will present some interesting but solvable problems of synchronized fast injection into circulating buckets of the ZGS RF system. It is a strong-focusing synchrotron with tune value of 3-3/8, both vertically and radially, and a usable aperture of 7/8" vertically by 2-1/2" horizontally. It is this small aperture, together with the β function which contribute to the calculated space charge limit of 10^{12} protons/pulse. The synchrotron is resonated at 30 Hz with a dc bias such that the minimum field, at injection for 50 MeV, is 1710 G. For acceleration of protons to 200 MeV the peak field required is 3520 G, and for 500 MeV, 6000 G. Both of these peak field values are considerably less than used in operation as an electron synchrotron at Cornell.

The Booster Program

A development program has been initiated to prove many of the ideas presented above. The goals of this program are to study injection of negative hydrogen ions of 50 MeV into a small, rapid-cycling booster, to study the stripping and efficient RF capture processes, confirm the space charge calculations, and study any emittance growth during acceleration and fast extraction. For this purpose the former Cornell synchrotron has been installed as shown in Fig. 3 and is essentially operative along with the beam transport line to the Booster Building. To date, 50-MeV protons have been transported successfully through the line and matching studies in the transport line are presently being carried out. Negative hydrogen ions may be available for injection studies in the near future.

The H^- source will be of the proton duoplasmatron-type with a hydrogen charge exchange cell. Such a source has been tested and has delivered in excess of 10 mA of H^- ions. Details of the source are published in another paper of this Conference.[5] Assuming 50% transmission through the column, 750-keV beam transport, present 50-MeV linac, and 50-MeV beam transport, 5 mA of H^- will be available for injection into the booster. Possibilities of increasing this current by higher source brightness and addition of a second harmonic buncher in the 750-keV line for higher transmission through the linact exist. The emittance of the 50-MeV H^- beam is assumed to be π mrad-inches in both planes, equivalent to that of our present 50-MeV proton beam. The small aperture of the development booster, however, may require limiting the vertical emittance to half of this value, which emittance contains > 70% of the beam.

Present plans for the stripper involve a foil of 0.5μ thick plastic[6] rotated through the beam during injection in synchronization with the 30-cycle magnetic field of the resonant booster magnet. The foil will be totally in the path of the injected beam during the injection time and the area presented to the circulating beam will decrease linearly to zero in a time comparable to the injection time once injection is completed. Foils of this type have been tested for stripping efficiency for H^- ions at 50 MeV and for lifetime when exposed to irradiation of 50-MeV protons. Stripping efficiency was $> 95\%$ and the foils survived irradiation by 3×10^{18} protons of 50 MeV over 1 in^2 area. Many such foils will be attached to the rotating wheel in a manner that will allow releasing one when it is damaged and inserting a new one automatically in order to insure adequate lifetime of the stripper.

Because only about 5.5-keV/turn acceleration is required for a peak energy of 200 MeV, a straightforward single-tap ferrite cavity has been constructed using surplus ferrite rings available from Argonne and Brookhaven National Laboratory. Low power tests of this cavity indicate no serious problems. The RF amplifiers, master oscillator, and feedback circuits are in construction at the present time. The ZGS injection scheme requires single-turn extraction from the booster. This will be accomplished by the indicated (Fig. 3) kickers and septum magnets. K1 and K2 are single-turn magnets with a 100-ns rise time. These kickers cause the beam to pass through the outer gap of a radially defocusing quadrupole at the beginning of the long straight section and then into the septum magnet. This fast extraction system is still being designed.

An independent, though related, program to inject 50-MeV H^- ions directly into the ZGS with foil stripping is also being carried out. An initial test of this type of injection with very low H^- intensity was carried out in 1969 with very encouraging results. With a minimum of 3 mA of H^- injected into the ZGS for 400 μs we believe we can match the normal operating intensity of the ZGS and we hope to improve on this performance. The booster development program would then be carried out during normal operation of the ZGS for high energy physics by delivering one injection pulse of 50-MeV H^- to the ZGS and one to the booster ever 3 s.

During the development phase, it is very desirable to study the phase space characteristics of the fast extracted beam. For this purpose the transport into the earth mound surrounding the ZGS will be carried to the point indicated in Fig. 3 and diagnostic tools for extracted beam studies will be provided.

The first phase of the booster injector program, the goal of which is to make the former Cornell synchrotron an operational injector for the ZGS at 200 MeV, will then be carried out by extending the beam transport to the ZGS itself and providing conventional fast kicker and bumper magnets for injection into the ZGS. Eight injection pulses will be delivered to the ZGS in 1 s (one every four cycles of the booster). A second phase of this program will provide for modification of the source and 50-MeV linac to match the 30-Hz repetition rate of the booster.

The present program schedule calls for initial beam bunching in the Cornell ring in late calendar 1971 with extraction studies continuing through spring of 1972. By summer of 1972 beam will be injected into the ZGS from the development booster.

The program outlined above is considerably short of our initial goals for a booster injector. Nevertheless, it permits a great amount of accelerator technology development with an operating booster to increase the intensity of the ZGS at a very reasonable cost. The ultimate booster would be another step from this and would include new booster magnets and ring with larger aperture, modifications to the booster RF and extraction systems for 500 MeV, modifications to the ZGS RF system to accelerate 10^{14} protons/pulse, and replacement of the present dc magnets in the ZGS. Use of systems designed for the Cornell machine would be made when possible, such as the RF amplifiers and related circuitry, the ac power supply, and even the Cornell magnets, which would be used as a new choke in the power system. Extension of the program beyond that outlined, however, is conjecture at this time.

Acknowledgments

I am happy to acknowledge the large contribution to the development of these ideas by many members of the Accelerator Division, with particular thanks to E. Crosbie and T. Khoe. D. Nordby and R. Bertermann were instrumental in moving the former Cornell synchrotron and associated systems to Argonne.

I would like to express by appreciation to B. MacDaniel and associates at Cornell University for their very fine cooperation and to Brookhaven National Laboratory for the loan of surplus equipment. The Booster Group at Argonne, under the leadership of J. Simpson, is actively working on the project.

References

[1] S. C. Snowden, Editor, Midwest High Energy Study Group, "Study of High Intensity Injectors for the ZGS," MHESG 12.10.1, (November, 1966).

[2] G. I. Budker, G. I. Dimov, On the Charge Exchange Injection of Protons into Ring Accelerators, International Conference on High Energy Accelerators, Dubna, USSR, August 21-27, 1963, Published by the U.S. Atomic Energy Commission's Division of Technical Information, CONF-114, Book 2, pp. 1372-7.

[3] G. I. Dimov, et al, USSR National Conference on Particle Accelerators, Moscow, USSR, October 9-16, 1968.

[4] "Proposal for a 500-MeV Booster Injector for the Zero Gradient Synchrotron," (June, 1969), Argonne National Laboratory, Accelerator Division, Argonne, Illinois.

[5] J. Fasolo, G. Marmer, J. Moenich, Argonne National Laboratory, Design and Performance Characteristics of the Zero Gradient Synchrotron H^- Ion Source and Related Systems, 1971 Particle Accelerator Conference, Chicago, Illinois, March 1-3, 1971, To be Published in IEEE Transactions on Nuclear Science

[6] Poly-para-xylylene film developed by Carbide Chemicals and Plastics, Research and Development Department, Bound Brook, New Jersey.

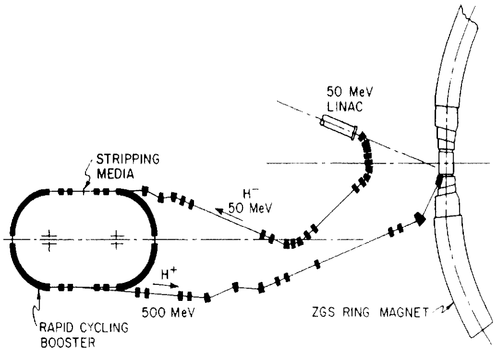

Fig. 1 Initial ZGS Booster Arrangement

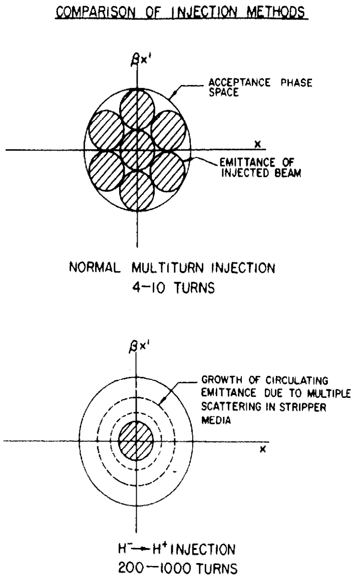

Fig. 2 Schematic Comparison of H^- Injection Principle with that of Normal Proton Injection

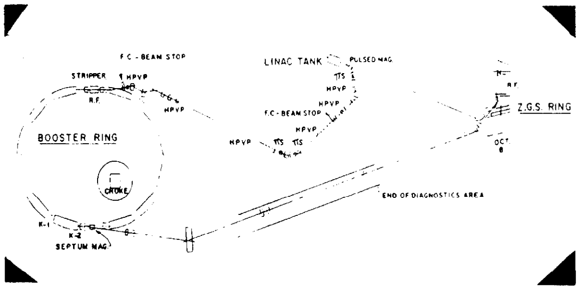

Fig. 3 Layout of Former Cornell Synchrotron at Argonne