PLANS FOR H$^-$ ACCELERATION IN THE AGS LINAC*

D.S. Barton and R.L. Witkover
Brookhaven National Laboratory
Upton, New York 11973

Introduction

Since its commissioning in 1970, the 200 MeV Linac at the Brookhaven AGS has been capable of producing peak proton beam current of greater than 100 mA with pulse lengths up to 300 μsec at a repetition rate of 10 pulses/second. The linac typically runs at 5 pulses per second, providing a 60 mA pulse of 120 μsec duration every 1.6 - 2.4 seconds for conventional multiturn injection into the AGS. The intervening pulses of length up to 300 μsec are used by the radio-isotope production, chemistry and medical facilities. Preparations are now being made to inject and accelerate H$^-$ ions in order to implement charge exchange injection into the AGS. This paper describes the aspects of this work leading to an H$^-$ beam at 200 MeV.

The use of an H$^-$ beam for charge exchange injection is standard practice now at the Argonne ZGS[1] and in the Fermilab Booster.[2] In this method of injection, the H$^-$ beam trajectory is overlapped with the proton closed orbit in the circular machine. A thin stripper foil located at the overlap point removes the electrons yielding a source of protons on the closed orbit. This irreversible process allows multiturn injection into the same phase space (with some small dilution from multiple scattering in the foil) without violation of Liouville's Theorem. The use of charge exchange injection was first suggested for the AGS in 1972,[3] in particular, as a means to higher intensities. The successful implementation of the method at the Fermilab Booster has been a principal motivation for the renewal of interest in its use at the AGS. The use of an H$^-$ beam is expected to show advantages both for the linac operation and for the injection process. The lower beam current (20-30 mA) will give less loading of the rf cavities in the linac, which is expected to significantly increase the mean lifetime of the RCA 7835 triodes. The efficiency of charge exchange injection is very high (> 98%), in contrast to the low efficiency (20-30%) of conventional H$^+$ multiturn injection. Substantial reductions in radiation damage and activation of equipment are expected. Finally, improvements in injected beam quality and flexibility in the injection process are considered desirable in preparation for ISABELLE.

An H$^-$ source assembly and its associated instrumentation is now under construction and will be installed in the existing second 750 keV terminal at the AGS linac. A second low energy transport line (LEBT2) will be built and other minor modifications will be made to permit the acceleration of the H$^-$ beam. In the following sections, the motivation for the conversion to negative ions will be discussed in more detail and then the various development and conversion tasks will be described. Finally, a comment on the current status of the project and a summary of future plans will be given.

Motivation

The present system of H$^+$ injection into the AGS, which involves stacking multiple turns in transverse phase space, results in a circulating beam after injection with an emittance more than 5 times larger than the linac beam for 10^{13} protons accelerated. The use of charge exchange H$^-$ injection will allow more flexibility in the injection process by permitting the filling from a small fraction up to the full horizontal aperture of the machine. In principle, a considerably brighter beam is possible at injection. Whether increased brightness can be preserved through capture and acceleration depends on intensity related space charge tune shifts. At intensities of 3 x 10^{12} required for ISABELLE injection, a brighter beam with more flexible injection control is a reasonable expectation.

The use of highly reliable carbon stripper foils like those developed at Fermilab[4] should provide better than 98% injection efficiency. In contrast, the present system of H$^+$ injection is limited by injection losses of 70-80%. These losses occur in the straight section between the A and B superperiods on the inflector system and during the multiturn stacking process. Figure 1 shows the output of the AGS ring radiation monitor[5] during the injection period. A major goal of the conversion to charge exchange injection is to remedy this situation. A substantial reduction in personnel radiation exposure during maintenance

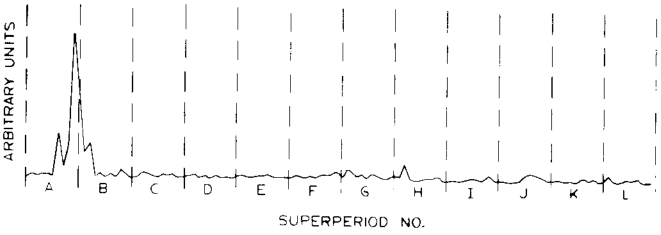

Fig. 1. Radiation monitor output during injection.

---

* Work done under the auspices of the U.S. Department of Energy.

and a decrease in the radiation damage to equipment in the injection area are anticipated.

While only minor adjustments to the linac rf will be required, the reduced beam loading is expected to be of significant benefit. At lower beam current it is possible to reduce the filament current of the RCA 7835 power amplifiers, which should significantly extend the tube lifetime. To obtain an estimate of this effect, tests using the H^+ beam were performed on Tank 2, a typical tank in terms of filament current. First, the filament current was adjusted to the minimum value which would sustain operation at 60 mA of beam current. Then, the current from the linac was reduced to 30 mA by adjusting the ion source and the filament current was again set at the minimum value for acceptable operation. The difference was only 2.25%, but when filament current is plotted versus emission lifetime[6] (Fig. 2), such a change is seen to correspond to a doubling of the tube life. Since lack of filament emission is the dominant mode of 7835 tube failure in the BNL linac, it is believed that the rate of tube replacement can be substantially reduced, resulting in direct cost savings and less downtime.

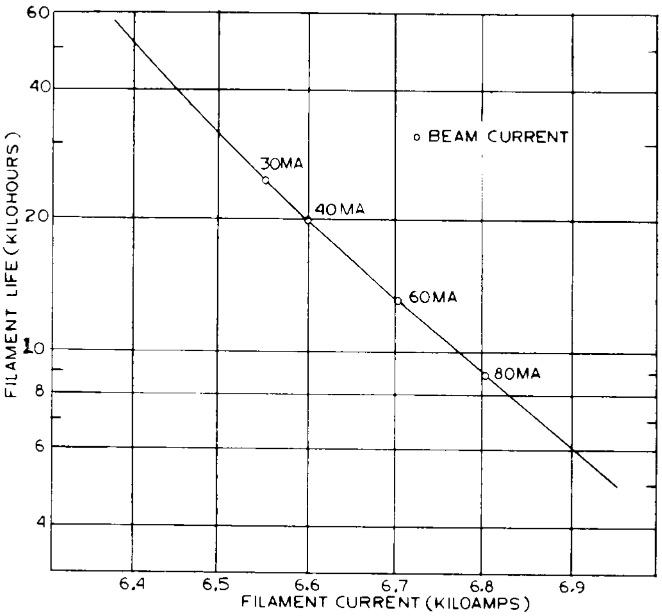

Fig. 2. RCA 7835 tube life vs filament current.

Preinjector

Extensive research and development of H^- ion sources has occurred during the last decade. Fermilab has developed and now routinely runs with a high current magnetron-type H^- source,[7] in an application essentially identical to that proposed for the AGS. The development of the Fermilab system benefited from related work at Novosibirsk,[8] Los Alamos,[9] Argonne[10] and by the Neutral Beams Group at Brookhaven.[11] Upon review of the requirements for the AGS preinjector, it was apparent that the Fermilab source design was well suited for the Brookhaven project. In addition to the advantage of commonality between the two laboratories with respect to comparisons of test and operation results, it has been possible to acquire two of several magnetron subassemblies recently fabricated at Fermilab.

The H^- source will be installed in the second preinjector pit which contains the Phillips Cockcroft-Walton generator from the original BNL 50 MeV linac. The Fermilab source design includes a 90° bending magnet to transport the extracted H^- beam away from the source and to prevent cesium from entering the transport system. To accommodate the rather large transverse dimension of this arrangement, it has been necessary to adapt the design to the BNL high gradient column,[12] which was designed with air insulation on the outside, requiring long support cones for the electrodes. The AGS H^- source will be mounted on the rear flange of the column as shown in Fig. 3; in this arrangement the 40-50 mA beam must be transported at 18-20 keV between the bending magnet and the first electrode of the column. The Fermilab design of the 90° combined-function bending magnet has a gradient index equal to 1.0 to focus the beam transverse to the bend plane. The BNL system includes, as shown, two pulsed quadrupole magnets which will contain the beam in the re-entrant portion of the column. The design of this system has been carried out using the program TRANSPORT, including linear space charge effects. Preliminary beam size measurements taken following the 90° magnet at Fermilab[13] have been used to constrain the output beam conditions in a calculation using the Fermilab geometry. It has been concluded that the beam inside the bending magnet is more than 90% space-charge neutralized by positive ions during normal operation. Initial beam parameters deduced from this study have been used in the design of the BNL transport system. The gradient index of the BNL bending magnet has been increased to 1.35 to provide the proper coupling to the quadrupole characteristics. Figure 4 shows the approximate beam size assuming substantial neutralization throughout the region.

Recent work by Sherman and Allison, at Los Alamos,[14] has shown that significant aberrations occur in a similar bending magnet geometry, especially in the transverse phase plane. The authors suggest that a non-zero sextupole term can reduce these aberrations which arise because of fringe field and finite pole effects. This technique has also been used in the design of the magnets for the National Synchrotron Light Source (NSLS) at Brookhaven.[15] A sextupole coefficient chosen to minimize the Y-Y' aberrations has been included in the BNL pole tip design for the H^- source bend magnet.

A pulsed quadrupole doublet has been acquired from the BNL Neutral Beams Group.[16] The pole-tip diameter is 7.6 cm, with a typical maximum field of 1.5 kG. To allow the power supplies to be referenced to ground, the beam is shielded from the magnet by a quartz sleeve and inner extraction tube, as shown in Fig. 3. The extraction tube,

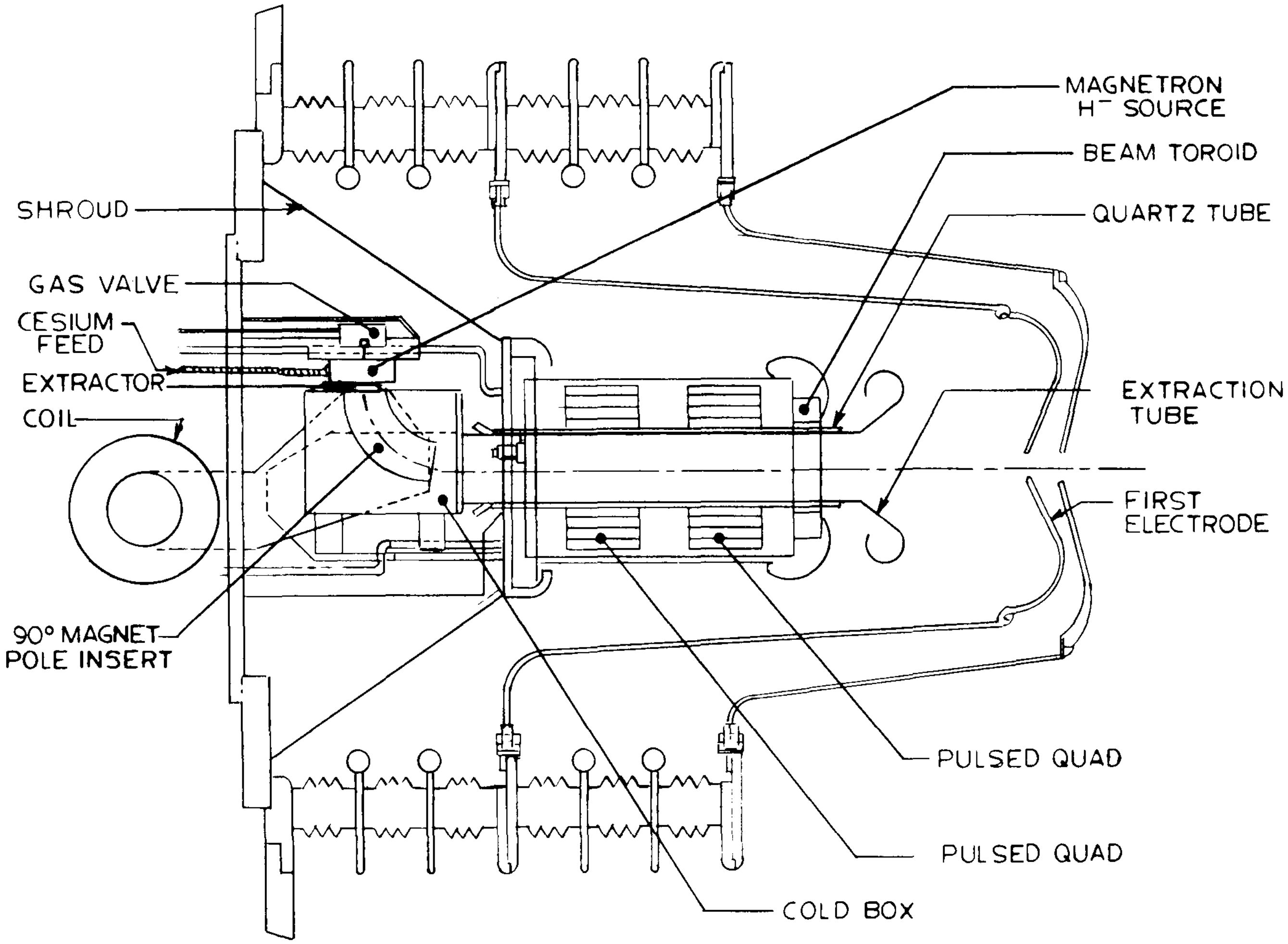

Fig. 3. Layout of H$^-$ source in BNL high gradient column.

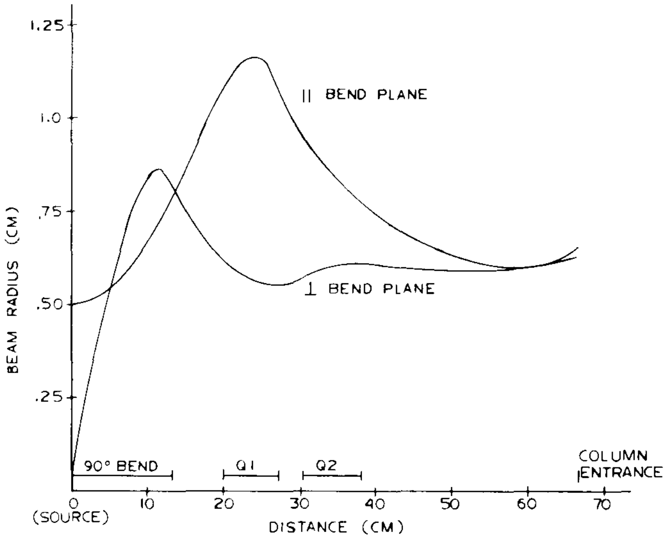

Fig. 4. 20 keV beam size profile in preinjector transport system (calculated).

along with the cold box and bend magnet pole-tips will follow the pulsed 18-20 kV extraction potential.

The Fermilab source operates with a beam pulse width of 60 μsec duration at repetition rate of 15 Hz. Since the source operation requires approximately the same duty factor, the BNL source which will run at 5 Hz needs a discharge pulse approximately 200 μsec long. The discharge pulser, with adjustable amplitude and timing characteristics, is an SCR switched pulse-forming network (PFN) of 1 Ω impedance and 300 V peak voltage. Modification of the Fermilab design has incorporated SCR's better suited to the BNL pulse width which has a maximum of 300 μsec.

A high voltage extractor electrode is used to pull the H$^-$ ions from the magnetron plasma. Tests at Fermilab have indicated that this electrode must be pulsed to avoid breakdown below the normal 18 kV operating level. The Fermilab design has again served as a starting point for the BNL extraction pulser. In particular, a thyratron has been added to the circuit to rapidly cut off the extraction pulse. This is triggered by the "stop" pulse and will be used in place of a chopper for fast beam turn-off. The extractor HV power supply must be remotely adjustable, as must the starting time and pulse width.

Two independently controllable pulsed power supplies are required for the quadrupole doublet. The standard linac quad pulser would have been electrically compatible with the quadrupole, but physical space requirements in the terminal made this impractical. A simple compact pulser has been built using a Darlington power transistor linearly discharging a capacitor bank of 139,200 μf. By using a feedback circuit the pulse has been kept constant to within 0.1% for more than 1 msec at 250 A. The risetime is determined by the L/R of the quad and pulser and is about 2 msec. The final unit housing two such pulsers has been built into a chassis 9 in. high which fits into a standard 19 in. relay rack. These units each have remotely adjustable amplitude and common start-trigger and pulse-width settings.

Locating the H^- source in Pit II requires a translating achromatic bend to transfer the beam into the input line to the linac. While the beam intensity is significantly lower for operation with an H^- source, it is still sufficient to cause a significant droop in dome potential during a long pulse. At the Pit II terminal a 50-mA beam experiences an 18.5-keV energy change over the course of a 200 μsec pulse. This corresponds to a momentum spread of 1.25% which would cause large beam excursions in the dispersive section of the beam line. Thus, a bouncer is required even for the relatively small extracted beam currents involved. For the recharge current required and the charging impedance available for Pit II, a bouncer of only 40-kV range will be sufficient. The extractor pulser for the H^+ duoplasmatron presently in use in Pit I can deliver the correct negative pulse with these characteristics. With this bouncer it should be possible to hold the momentum spread during the pulse to less than 0.1%.

Other required supporting subsystems include the 90° bending magnet power supply (remotely adjustable) and the -30° freon chiller for the cold box. Heaters are required for the cesium boiler, valve and transfer tube, of which only a fine adjustment of the boiler heater will be remotely controlled. In addition, there are several readbacks needed for thermocouples and vacuum gauges in the dome.

Controls

A total of 9 timing signals and 8 analog reference voltages must be sent to the dome controls from the ground station. Readback of 14 analog signals and approximately 16 digital status bits from hardware supporting the H^- source is also necessary. To handle this quantity of data it was clear that a multiplexing scheme was needed to keep the number of optical links reasonable.

Following the lead of Shea and Goodwin,[17] a control and communication system based upon a microprocessor has been developed. The hardware was chosen to be compatible with that of the National Synchrotron Light Source now under construction at BNL to make use of much of their system software.[18] This has allowed programs to be assembled on the AGS PDP-10 and directly downloaded into random access memory (RAM).

The system configuration is shown in Fig. 5. The processor is an 8080 packaged as an Intel/National 80/204 single board computer, utilizing the Multibus configuration and protocols. This board contains a UART (Universal Asynchronous Receiver/Transmitter) and 4 kilobytes of RAM. The Intel monitor, modified to permit communication through the 8080 to the PDP-10 and downloading of assembled programs, resides in 3K of the 4K Programmable Read Only Memory (PROM) on the board. The UART on this board is connected to a CRT terminal, in the case of the ground station, which serves as the normal operator interface. In the dome unit an optional terminal can be connected to this interface for local control.

An Intel/National 116 board is used to provide additional memory and the auxiliary UART. This UART may be connected to the PDP-10 for direct downloading of data or programs, or to the optical link for communication across the high voltage interface. This board is presently populated with only 4K of a possible 16K of RAM needed to store the control and display programs and data.

Analog reference voltages for control of the programmable power supplies are provided from commercial digital-to-analog (DAC) cards which are compatible with the Multibus. An 8-channel, 12-bit unit made by Data Translation Corporation is presently being used. Two such cards are required for the ground station.

The readback of analog data is also by means of a commercial multibus compatible card manufactured by Burr Brown Research Corporation. This unit handles 32 channels of 12-bit data as memory mapped I/O. Sample and hold circuits precede the inputs where needed.

A special card utilizing Intel 8253 counter/timer chips is being designed to provide the necessary triggers and pulses for both the dome and ground station hardware. Synchronization between the two stations will be provided by a separate optical link, which can also be used to reset the dome microprocessor.

Commercial receivers and transmitters are used for the optical links. These have been in service for some years on the existing ion source and will be continued for the H^- source. The units are connected via a 25-m quartz-fiber optic cable. This length allows the ground station units to be located outside the pit, providing greater safety against arcdown damage. The

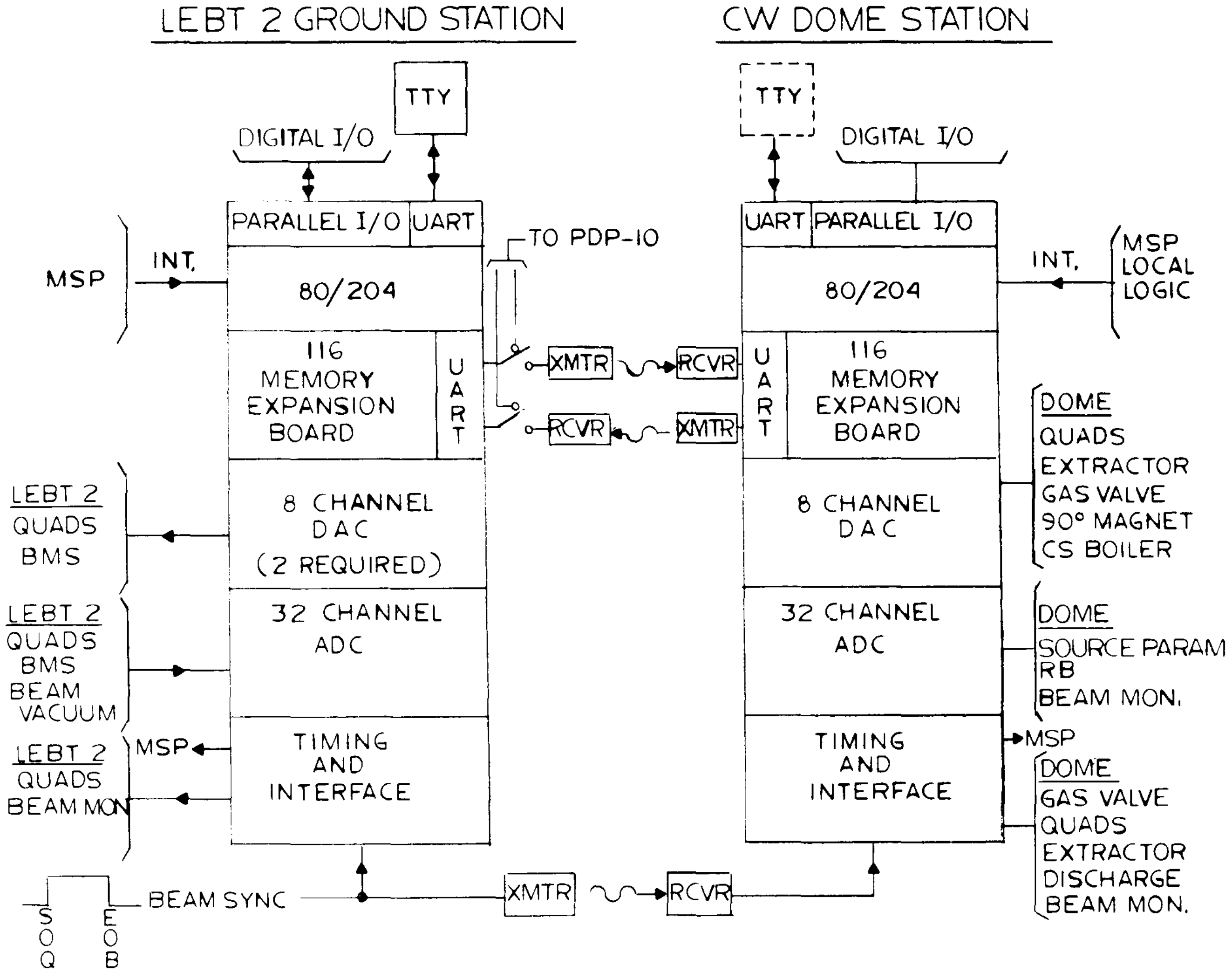

Fig. 5. Block diagram of H$^-$ preinjector control system.

data communication between the UART's will be as 7-bit ASCII code at a rate of 19.2 kilobaud. This should allow a complete refresh of data within the 200 msec inter-pulse period; however, this is not required. Data exchange between the two microprocessors will be as a character-by-character handshake of reference data from the ground station and readbacks from the dome station.

As can be seen, the two stations are similar in configuration with the ground station having a greater number of DAC cards to control the LEBT2 quadrupoles. The software will, however, be different. It will be possible to load the ground station programs into the dome when local control is required from that location.

The ground station software presents a multipage format to the operator. Input is by keyboard cursor control and numeric keys. The operator can make as many entries as desired before transmitting the input data as a group to the controlled elements.

Readback data is averaged over 8 beam pulses for display purposes. This is done local to the data-taking processor, with the display being updated upon data transmittal.

In addition to the computer-controlled hardware, local hard-wired logic will be utilized where system protection is required. This will typically be used during turn-on or turn-off sequences or when out-of-tolerance conditions indicate a danger to the hardware.

During the development and testing stages, this control system will be operated locally at the ground station. When actual acceleration in the linac begins, the ground station microprocessor will be interfaced to the PDP-10 so that it may be controlled from the AGS Control Room as a part of the accelerator system.

Low Energy Transport and Linac

After acceleration to 750 keV the H$^-$ beam must be transported into conjunction with the present Low Energy Beam Transport (LEBT) line before input to the linac. Floor pads for a second beam line were provided as part of the original building design. This line crosses from Pit II at 60° to intercept the beam line from Pit I just before the dual bunchers. A design study has been made, using the version of TRANSPORT which includes linearized space charge forces, for net un-neutralized beam currents up to 50 mA with a 60% filling factor. Immediately following the high gradient column are two pulsed quadrupole triplets of the BNL LEBT design.[19] These magnets will be used to match the beam from the column to the existing LEBT1 line. The 10 m section between the two 60° dc bending magnets is designed to be achromatic. Small air-cooled dc quadrupoles will be used in this section.

A destructive emittance measuring device is located just after the intersection of LEBT2 with LEBT1 to facilitate the matching. In this procedure the horizontal emittance of the H^- beam is made similar in orientation to the vertical emittance of the present H^+ beam so that polarity reversal of all quadrupoles downstream of the intersection is not necessary. It is expected, however, that some fine-tuning of the linac quadrupoles may be needed since the present tune was designed for a beam current of 100 mA. Readjustment of filament currents will be made on the rf amplifiers to optimize tube performance at the lower beam current. In addition to the standard beam transformers and emittance monitors, LEBT2 instrumentation must include means of measuring the beam profile or position because of the dispersive nature of the beam line. The choice of monitor for this purpose has not been made. Existing instrumentation in the linac will be upgraded and interfaced to the computer system where this has not yet been done. The beam transformers and low energy emittance monitors are already capable of bipolar operation, but the SEM profile monitors and the 200 MeV emittance devices will require modification in this respect.

Looking Ahead

The fabrication of the source assembly and instrumentation necessary to begin bench tests, including emittance measurements, is nearly complete. In early October, 1979, studies of source operation characteristics over as wide a range of parameters as possible will begin. Full computer-controlled emittance measurements will be made at the output of the subsystem consisting of source and 90° bending magnet in order to accurately determine the extent and importance of the space charge neutralization of the beam. The influence of variation of the gas flow and cesium supply will be made with both Fermilab and BNL bending-magnet pole-tip designs so that direct comparisons with the results of the TRANSPORT design study can be made. These tests should be invaluable, since the quadrupole doublet system can only be meaningfully tested in the full preinjector.

The full instrumentation of Pit II is expected to be completed by the beginning of 1980, so that complete preinjector tests can be carried out during the first quarter of the year. Much of the work on the LEBT2 construction will parallel that effort, with completion expected by early spring. No substantial impediment is then anticipated to achieving a 200 MeV H^- beam shortly thereafter.

Acknowledgments

The invaluable advice and assistance of C. Curtis and C. Schmidt of Fermilab is gratefully acknowledged. The encouragement of Y.Y. Lee and the support by J. Curtiss, N. Fewell, E. Grove, E. Jablonski, V. LoDestro and E. Rodger in the design and development are greatly appreciated. The authors also wish to thank K. Prelec, Th. Sluyters and P. Allison for helpful discussions.

References

1. E. Crosbie, et al., IEEE Trans. Nucl. Sci., NS-22, 1056 (1975).
2. C. Hojvat, et al., IEEE Trans. Nucl. Sci., NS-26, 3149 (1979).
3. A. Maschke, K. Prelec, Th. Sluyters, "Proposal for H^- Injection into the AGS", Nov. 10, 1972, unpublished.
4. C. Hojvat, M. Joy, R.C. Webber, IEEE Trans. Nucl. Sci., NS-26, 4009 (1979).
5. R.L. Witkover, IEEE Trans. Nucl. Sci., NS-26, 3133 (1979).
6. J.D. Stabley, Power Devices Application Engr., Solid State Div., RCA, Lancaster, PA, private communication.
7. C.W. Schmidt, C.D. Curtis, IEEE Trans. Nucl. Sci., NS-26, 4120 (1979).
8. Yu. I. Belchenko, G.I. Dimov, V.G. Dudnikov, Proc. 2nd Symp. on Ion Sources and Formation of Ion Beams, Berkeley, CA, VIII-1, LBL-3399 (1974).
9. P. Allison, IEEE Trans. Nucl. Sci., NS-24, 1594 (1977).
10. J.A. Fasolo, G.J. Marmer, J.S. Moenich, IEEE Trans. Nucl. Sci., NS-18, 94 (1971).
11. K. Prelec and Th. Sluyters, IEEE Trans. Nucl. Sci., NS-22, 1662 (1975).
12. Th. Sluyters, et al. Particle Accelerators, I, 15 (1970).
13. C. Schmidt, private communication.
14. J.D. Sherman and P.W. Allison, IEEE Trans. Nucl. Sci., NS-26, 3916 (1979).
15. J. Galayda, private communication.
16. R. Clipperton, K. Prelec, L. Sinsabaugh, "A Small Pulsed Quadrupole", AGS Div. H^- Tech. Note No. 3, BNL, Sept. 25, 1974.
17. R.W. Goodwin, R.F. Kocanda, M.F. Shea, Proc. 1976 Linear Accel. Conf., Chalk River Nuclear Lab., Ontario, Canada, AECL 6577 (1964) 264.
18. K. Batchelor, et al., IEEE Trans. Nucl. Sci., NS-26, 3387 (1979).
19. R. Damm, A. Otis, V. LoGrasso, Proc. 1970 Linear Accel. Conf., National Accel. Lab., Batavia, IL, 561 (1970).