PROGRESS IN PROTON LINEAR ACCELERATORS

George W. Wheeler
Brookhaven National Laboratory
Upton, New York

Introduction

Two years ago at the second National Accelerator Conference, Nagle reviewed the advances in the design of proton linear accelerators. In this paper, I will report some of the progress which has occurred since then.

Two new proton linacs have recently come into operation; both are "conventional" drift tube types (they do not incorporate any of the recently devised field stabilization techniques). First is the 100 MeV linac injector for the 76 GeV synchrotron at Serpukhov in the USSR. This linac has been operating well for a year and a half and has achieved a peak current in excess of 100 mA. The other is the new 20 MeV injector for Saturne at Saclay. This linac, which incorporates a pressurized Cockcroft-Walton preaccelerator, has been operating for almost one year and produces a beam close to its design current of 20 mA. A number of refinements have been added to several existing linacs. In particular, at BNL the 50 MeV linac has been fitted with a high intensity duoplasmatron source and a high gradient column as well as a multiport RF system, and these modifications so far have raised the output current from 30 mA in 1.1 cm-mrad to 55 mA in 1.4 cm-mrad, an increase of about 50% in brightness.

At Karlsruhe, studies are continuing on the design of a 5-10 GeV superconducting linac, but it will probably be some time before any construction is undertaken. The ambitious ING project to build a 1 GeV, 65 mA CW linac at Chalk River has been temporarily suspended, but its proponents still hope to proceed with this or a similar project.

In the U.S., two new linacs are now under construction, the 200 MeV injector for the AGS (part of the AGS Conversion Project), and the 800 MeV linac for the Los Alamos Meson Facility. A third new linac, the 200 MeV injector for the 200 GeV synchrotron at NAL should be authorized for construction soon. In fact, NAL is building a 10 MeV prototype at this time. These linacs, all of which should produce their first beams in 1971 or '72, are a new generation of proton linac and will incorporate the latest developments. Much of this report will be concerned with these machines.

Table I lists their major parameters. The similarity between the BNL and NAL linacs is not coincidental as both are designed from the preliminary

<table>
<thead>
<tr>
<th>TYPE OF SERVICE</th>
<th>BNL INJECTOR</th>
<th>NAL INJECTOR</th>
<th>LASL MESON FACTORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>FINAL ENERGY (MeV)</td>
<td>200</td>
<td>200</td>
<td>800</td>
</tr>
<tr>
<td>PEAK CURRENT (mA)</td>
<td>100-200</td>
<td>100</td>
<td>17</td>
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<td>INJECTION ENERGY (keV)</td>
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<td>750</td>
<td>750</td>
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<tr>
<td>BEAM DUTY CYCLE (%)</td>
<td>0.2</td>
<td>0.15</td>
<td>6-12</td>
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<td>BEAM PULSE LENGTH (μsec)</td>
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<td>500-1000</td>
</tr>
<tr>
<td>PULSE RATE (pps)</td>
<td>10</td>
<td>15</td>
<td>120</td>
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<td>OPERATING FREQUENCY (MHz)</td>
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<td>201.25</td>
<td>805.00</td>
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<tr>
<td>LENGTH (ft)</td>
<td>460</td>
<td>460</td>
<td>2600</td>
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<tr>
<td>STRUCTURE</td>
<td>Multistem</td>
<td>Post Coupled</td>
<td>Post Coupled Drift Tube to 100 MeV then Side Coupled Waveguide to 800 MeV</td>
</tr>
</tbody>
</table>

* Work performed under the auspices of the U.S. Atomic Energy Commission.
BNL design with continuing close cooperation between the design groups.

The most recent intensive review of proton linear accelerators occurred during the sixth Conference on Proton Linear Accelerators held at BNL in May 1968. This report refers frequently to the Proceedings of that Conference.

Preaccelerators and Beam Transport

The combination of duoplasmatron source and high gradient (45 kV/cm) accelerating column has proven most successful for producing high brightness preaccelerator beams up to about 250 mA and is now in use at CERN and BNL. Much higher currents have been extracted and accelerated but phase space dilution in the process has limited accelerated linac currents to a maximum of 155 mA (at CERN). Considerably more development is needed on sources, column and beam transport before linac output currents of 200 mA or more are achieved. High duty cycle sources as needed by LASL also present some problems which are not yet completely solved although good progress is being made.

The air insulated Cockcroft-Walton operating at 750 kV is still generally favored as the high voltage dc generator. However, developments at Saclay and LNL indicate that much smaller units, either pressurized or in air, can be built with much saving in space compared to the massive Haefely units which will be used on the new linacs. The high peak currents and microdischarges associated with high gradient columns complicate the fast voltage control system (bouncer) requiring swings in excess of 100 kV.

Space charge effects in bright beams place severe requirements on the beam transport system between the preaccelerator and the linac and beyond the linac. Calculations indicate some emittance growth is unavoidable due to the nonlinear nature of the space charge forces. However, it appears that the beam may be sufficiently well controlled that the emittance can be matched from the source to the synchrotron inflector.

Considerable attention has been given to the design of bunchers including particularly the effect of longitudinal space charge. At the moment, the "double-drift" buncher, consisting of two separated cavities operating on the fundamental frequency, seems to be the most promising for high performance linacs. While the double drift buncher does not offer as high initial capture efficiency as the multiple harmonic bunchers, it should improve the quality of the captured beam thereby reducing the loss of protons at higher energies in the linac. However, Lapostolle has concluded that, whatever bunching device is used, it will be more effective at higher injection energies. Unfortunately, while the bunching will be better at 2 or 3 MeV, the initial phase damping in the linac will be noticeably reduced.

There has been little discussion of debunchers recently and in fact they have not been used on all existing injector linacs. However, it appears that a debuncher will be necessary for injection of an intense beam into a synchrotron, at least into the AGS. In the long drift space between the linac and the AGS, longitudinal space charge forces will introduce a large (2-3 MeV) energy spread which must be removed with a debuncher. A compromise approach, originally suggested by Teng and now being reinvestigated, is to operate the last one or two cavities of the linac on the unstable equilibrium phase thus producing a less tightly bunched beam at the linac exit and reducing the space charge effects in the drift space. Even so, a debuncher will still be required.

Beam Dynamics

The theory of beam dynamics in linear accelerators has long been well understood for low currents (beam power small compared to the cavity excitation power). The recent efforts have been directed to understanding the effects on intense beams produced by space charge forces and by the interaction of the beam with the accelerating fields (beam loading and breakup). Gluckstern has discussed linac beam dynamics in detail at this conference and so it will not be treated here except for a few comments.

Transverse beam breakup, which has been so troublesome in electron linacs, is not expected to appear in proton linacs operating in the peak current ranges presently planned. On the other hand, the effect of beam loading on the phase and amplitude of the accelerating fields is of great importance for achieving bright and stable beams. The new linacs will employ servo-control systems to maintain the phase and amplitude within design limits during acceleration; this requires a knowledge of the transient and steady state behavior of the cavities in the presence of an intense beam. Recent analyses of this behavior for drift tube cavities have been carried out by Lee and Nishikawa. Beam loading compensation by closed loop servos for the LASL side-coupled cavities has been studied extensively by Jameson. However, beam loading effects can never by completely compensated within a multiple cell cavity as long as the RF power is fed into the cavity at discrete points. As has been pointed out by Giordano and Nishikawa, there will always be a current-dependent phase shift between the drive point and the excitation of the cavity. Since the phase shift is proportional to the square of the distance between these points, considerable improvement can be obtained by shortening the length of the cavities (which is not practical for other reasons) or by increasing the number of points at which RF power is fed into the cavity. At BNL, a system using three or feed points has been fitted to the 110 ft long cavity of the 50 MeV linac and a two-point feed system will be employed on all cavities of the 200 MeV linac.

Accelerating Structures

One of the most important innovations in the linac field is the method of stabilizing the ac-
The accelerating field amplitude and phase by the introduction of resonant coupling devices between the accelerating cells of a cavity. While this idea is not new, it has not previously been applied to any proton linac. A number of coupling methods have been investigated and are capable of giving field stability which is of the order of ten times better than in the corresponding conventional structures. Since Knapp has just given a comprehensive review of resonantly coupled structures, I will only note a few of the proposed applications. For drift tube linacs, BNL favors the multistem arrangement while LASL and NAL plan on the post coupler. The multistem stem arrangement has the advantage of giving greater stabilization than the post couplers, but is more complex mechanically and absorbs more RF power, hence is better suited to very high current linacs. An alternating periodic structure is being considered for a superconducting, high energy particle separator at BNL. At Karlsruhe a superconducting slotted iris structure is being investigated for a 5-10 GeV proton linac.

RF Power Sources

Most drift tube linacs operate near 200 MHz except for the linacs in the USSR where 148 MHz is preferred. In the U.S., the RCA 7835 triode is the clear choice for the high power amplifiers (self-excited power oscillators are not practical on multicavities, and coaxitrons and amplitrons to date have failed to meet the severe requirements and it appears that the klystron has prevailed). Litton has developed for LASL a five-cavity klystron, with modulating anode, which delivers 1.25 MW at 6% duty and with about 50 dB gain and reasonable efficiency. The phase stability for the output has been demonstrated to be adequate for linac service.

Controls and Diagnostics

The control of long linacs has been receiving increased attention recently from proton linac designers although the subject is not new at SLAC and some other laboratories. The shift from relay to solid state logic is almost complete and solid state automatic control circuitry will be employed in the three new linacs.

The problems of computer control of an accelerator are still formidable but are being pursued at numerous laboratories. The LASL linac will have a computer as an integrated part of the control system and a somewhat similar arrangement is envisaged at NAL. The BNL linac will have an automatic control system which is readily adaptable to full computer control but will not be computerized during initial operation.

The beam diagnostic and monitoring techniques and equipment, which have been satisfactory on existing linacs, will no longer be adequate to achieve and maintain very bright beams and to strictly limit particle loss in the accelerator because this will require more detailed and rapid measurements of the beam characteristics. Especially for injector service, continuous, nondestructive beam observation is essential during the injected pulse. At BNL, in addition to monitoring the injected pulse, alternate pulses from the linac will be deflected into an analysis channel where fast emittance measurements will be made and the information used to stabilize the output on a pulse-to-pulse basis. Improvements are needed in beam position electrodes, nondestructive emittance devices and beam phase monitors, all of which are being investigated. Any device which intercepts any portion of the beam presents very serious design and operational problems because of the intense radiation it produces and therefore should be avoided wherever possible.

One particularly interesting device, not yet fully developed, is the beam density profile monitor. A prototype of such a device has been designed at ANL but is not yet operational. At BNL, a program is being set up to develop a method of fast density measurements by the direct interaction of the proton beam with a narrow transverse beam of microwaves or x rays or from a laser. This program is still in the most preliminary phase and no results are expected for a year or more.

Status of the BNL 200 MeV Injector Linac

The last part of this paper will be devoted to a brief report on the construction of the 200
MeV linac at BNL. The linac building complex is well advanced, see Fig. 1. All areas of the complex are closed in and installation of the electrical and mechanical services is progressing. Some preliminary installation of the preaccelerator components is expected to start by late April and the major installation effort should start in July.

The 750 kV Cockcroft-Walton generator is now in transit from Haefely, except for the bouncer which has not yet met the specifications. The ion source and high gradient column are being fabricated. The low energy beam transport equipment is mostly designed and being fabricated.

The two tank sections of linac Cavity $\#1$ have been delivered and are being prepared for drift tube installation (Fig. 2). A number of completed drift tubes are on hand and the fabrication is proceeding well. Figure 3 shows a view of the drift tube factory where the assembly of all drift tubes is being carried out. The technique of final drift tube closure by electron beam welding is proving most satisfactory. Installation of drift tubes in Cavity $\#1$ should begin late in March and the complete cavity be ready for installation in the linac tunnel in July. The fabrication of the other cavities and drift tubes is proceeding on a schedule which calls for the completion of Cavity $\#9$ by the middle of 1970.

The prototype 5 MW RF module has been operating for over a year and from the information gained, detailed designs and drawings have been prepared for each component in the system. These components are now being fabricated and will be housed in the enclosures shown in Fig. 4 which is a mockup arrangement of an RF module. Delivery of some of these units has commenced and the first complete module should be ready by July. Power from the final amplifier will be distributed to the two drive loops in each cavity by a system of 12 inch coaxial transmission line. Three hybrid junctions will be used in each system, one to split the power and one in each feed line to adjust phase. Figure 5 shows one of the hybrid phase shifters undergoing high power tests with the 7835.

Most of the other major components of the linac are on order although a few have been delayed. The first accelerated beam from the preaccelerator is expected in the fall of 1969 and acceleration to 10 MeV by the end of the year. This will allow a considerable period of time for tests and adjustment of Cavity $\#1$ while the rest of the linac is being installed. Acceleration of a beam to 200 MeV is hoped for during the first part of 1971.

References

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13. R. L. Gluckstern, Paper C-9, this Conference.
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Fig. 1. Aerial view of the AGS showing the 200 MeV complex in the right foreground.

Fig. 2. The two sections of linac cavity #1.
Fig. 3. The drift tube factory.

Fig. 4. A mockup of an RF module (without the 7835).

Fig. 5. A hybrid junction phase shifter and 7835 PA.