THE 500 MEV LINAC PROPOSED AS A NEW INJECTOR FOR THE AGS AT THE BROOKHAVEN NATIONAL LABORATORY

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The Brookhaven National Laboratory has proposed a conversion program* to increase the intensity of the AGS to about 2 x 10^{13} protons per second. A major feature of this program is a new linac injector to replace the present 50 MeV machine. This paper will describe the general features of the new linac. The work presented here represents the efforts of a large group of people from BNL and Yale.

The principal characteristics of the linac are shown in Table I. The initial design goal is for 50 mA of peak current at 500 MeV. However, it is important that the linac ultimately be capable of 100 mA peak current. Consequently, the accelerator is designed for a 100 mA beam and all of the necessary power equipment and other features are included. At full energy, the energy spread will be about 0.3% and the area in transverse will be about $5\pi \times 10^{-4}$ cm-rad. Both of these figures include the effects of the estimated errors in alignment and adjustment of the accelerator.

A maximum of approximately 10 pps will be needed for injection into the AGS when it is being operated at reduced output energy. The design pulse rate for the linac is set at 30 pps which increases the cost by about 1%. This means that there can be at least 20 pps of 500 MeV protons available for use as an independent research facility should this prove desirable. Although the duty cycle of such a facility would be low, it would still have an average current capability between 200 and 500 μ amp at 500 MeV which is adequate for the copious production of stopped mesons.

The preinjector will be a 750 kV Cockcroft-Walton generator. Existing proton linacs have used injection energies between 500 keV and 4 MeV. A lower limit is imposed by several considerations once the frequency of the drift tube linac is set. 1) The quadrupole field strength requirement increases and the cell length decreases as the injection energy is lowered, resulting in difficulty in installing the quadrupoles in the drift tubes. 2) As the drift tube gap decreases, the radial transit factor decreases, resulting in a worse radial distribution of field in the

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*A Proposal for Increasing the Intensity of the Alternating Gradient Synchrotron at the Brookhaven National Laboratory, May, 1964, BNL 7956.

TABLE I

Principal Characteristics of the Proton Linac

1. Beam Energy

   (a) Maximum energy: 503 MeV.
   (b) Energy variable in steps of 5-6 MeV from 187 MeV to 503 MeV.
   (c) Energy spread at full energy: approximately ± 0.3% or or ± 1500 keV.

2. Beam Intensity

   (a) Average current: 0.3 mA or 2 x 10^{15} protons/sec.
   (b) Peak pulse current: 50 mA (eventually 100 mA).
   (c) Pulse length and rate: 200 μ sec, 30 pps.
   (d) Beam duty cycle: 0.6%.
   (e) The rf microstructure of the beam will consist of 0.2 nsec pulses separated by 5 nsec.
   (f) Average beam power: 150 kW.
   (g) Beam quality, area in transverse phase space, 5 π x 10^{-4} cm-rad at 500 MeV.

3. Physical Characteristics

   (a) Total length: 1200 feet.
   (b) Total peak rf power: 77 MW (at 50 mA beam current).
   (c) Preinjector: 750 kV Cockcroft-Walton generator.
   (d) Drift tube accelerator: 0.75 to 187 MeV at 201.25 Mc/sec. One cavity ~ 8 m long followed by six cavities each ~ 21 m long.
   (e) Loaded waveguide accelerator: 187 to 503 MeV at 805 Mc/sec: 54 cavities each 3 m long, 54 rf amplifiers.
   (f) Transverse focusing by magnetic quadrupoles.

gap which in turn can adversely affect the quality of the beam. 3) At lower injection energies, space-charge blow-up of the beam will be more serious in the space between the preinjector and the linac. The upper limit on the injection energy is set by the dc generator. The maximum voltage for an air-insulated set is about 1.25 MV and about 12 MV for a pressurized machine. Furthermore, as the injection energy is increased, the amount of phase oscillation damping is decreased which could lead to serious difficulty at the transition in structures. For a linac frequency of 200 Mc/sec, there is little to be gained by going above 750 keV, at which energy the technology is well developed.

It is planned to install two completely independent preinjector systems with a switching magnet in the drift space so that either may be used to inject into the linac. The duplication of the preinjector is necessary to insure high reliability of the linac and also will provide facilities for a polarized ion source and for ion source development.

In order to achieve accelerated beams of 50 mA and eventually 100 mA from the linac, the ion source must be capable of delivering 200 and 400 mA, respectively, with sufficiently small emittances. The present choice is a modified duoplasmatron which should be capable of 200 mA output with a minimum of development. At present, no source is clearly capable of delivering 400 mA with a sufficiently small emittance to be injectable into the linac. Thus considerable design and development will be needed on the source before the linac can deliver 100 mA.

A buncher will be used to increase the capture efficiency and particularly to concentrate the particles near the synchronous phase. This latter function is particularly important because particles which are near the boundaries of the stable region at injection may be lost at higher energies, contributing to activation of the structure or at best will emerge from the linac with poor quality and hence be of little use. Several new designs for high efficiency bunchers are now being developed, and one of these will be used.

The drift tube section of the linac will operate at 201.25 Mc/sec and will accelerate the beam to 187 MeV. The general parameters of the drift tube section are shown in Table II. The possibility of operating the drift tube section at 400 Mc/sec has been considered but abandoned for the following reasons. A pressurized preinjector at about 3 MeV would be required which would greatly complicate the preinjector design. Even at this injection energy, the design of the first cavity of the linac would be very difficult. Furthermore, the loss of damping between 750 keV and 3 MeV would be serious. However, if the new high efficiency bunchers are successful, it may prove desirable to change from 200 Mc/sec

TABLE II

General Parameters of the Drift Tube Section

Input energy (MeV)	0.75	
Output energy (MeV)	187	
Energy gain (MeV)	186	
Peak beam current (mA)	50	(100)*
Beam duty cycle (%)	0.6	
Beam pulse length (μsec)	200	
Pulse repetition rate (pps)	30	
Rf pulse length (μsec)	400	
Rf duty cycle (%)	1.2	
Operating frequency (Mc/sec)	201.25	
Wavelength (cm)	148.97	
Number of cavities	7	
Peak excitation power (MW)	13.3	
Peak beam power (MW)	9.3	(18.7)
Total peak rf power (MW)	22.6	(32)
Average excitation power (kW)	160	
Average beam power (kW)	56	(112)
Total average power (kW)	271	(384)
Total length of cavities (m)	133.7	
Total intercavity drift space (m)	5.3	
Buncher space (m)	7	
Transition drift space (m)	10	
Total length (m)	156	

*Numbers in parentheses are for a peak beam current of 100 mA.

to 400 Mc/sec at an energy near 20 MeV which could lead to a reduction in the cost of the linac.

There will be seven independent cavities containing a total of 261 drift tubes. The cavities will be of conventional copper-clad steel construction. The first cavity will be about 8 m long and will operate at a reduced gradient (about 5 MV/m) to avoid the sparking problems which have been encountered at the low energy end of some linacs. The design of this cavity is intended primarily to assure good shaping of the beam in both transverse and longitudinal phase space. A very short drift space will be used between the first and second cavities. About 30 cm is the maximum allowable distance because of the debunching of the beam. It is planned to make the vacuum envelope continuous for the two cavities. The details of the drift tube cavities are given in Table III.

The second through seventh cavities will use shaped drift tubes, and the cost will be minimized with respect to shunt impedance and the sparking limit. It is expected that the MURA method of calculating cylindrical drift tubes will be used. The length of each cavity is so chosen that the peak power required per cavity will be about 5 Mw at 100 mA of beam current which will match the capability of one power amplifier. The lengths will vary from about 24 to 19 m which is short enough to assure reasonable ease in flattening the cavities.

The drift spaces between these cavities will be about 1 m long, and matching triplets may be required in the drift space, depending on the final choice of focusing arrangement. The details of the focusing system and of the particle motion will be treated in another paper.

The final rf amplifier stages will use the RCA 7835 triode which should be capable of delivering 5 MW peak power output in this service. Thus, there will be six final stages. The power to drive these six stages and the power for the first cavity will be obtained from another 7835 stage with power splitters and phase shifters in each drive line. Each 7835 will have its own hard tube modulator and power supply.

The vacuum system, cooling and other support systems will be generally conventional. Ion pumps will be used throughout. The rough tuning of each cavity to resonance will be accomplished by temperature control.

Following the drift tube section, there will be a drift space between 5 and 10 m long before the beam enters the loaded waveguide section. Because of the debunching of the beam, it is desirable to keep this distance as short as possible, but there is a considerable amount of equipment to be

TABLE III

Summary of Drift-Tube Tables

Cavity No.	1	2	3	4	5	6	7
β_{in}	0.040	0.140	0.294	0.383	0.443	0.487	0.522
β_{out}	0.140	0.294	0.383	0.443	0.487	0.522	0.552
Energy in (Mev)	0.75	9.33	43.34	77.35	108.07	135.79	162.01
Energy out (Mev)	9.33	43.34	77.35	108.07	135.79	162.01	187.09
Energy gain (Mev)	8.58	34.01	34.01	30.72	27.72	26.22	25.08
E_{gap} (Mv/m)	5.0	8.0	12.0	12.0	12.0	12.0	12.0
Range of R_s (MΩ/m)	41.0	50.0	56/40	40/31	31/25	25/21	21/18
Excitation power (Mw)	0.38	1.69	1.67	2.06	2.26	2.50	2.70
Beam power[1] (Mw)	0.43 (0.86)	1.70 (3.40)	1.70 (3.40)	1.54 (3.07)	1.38 (2.77)	1.31 (2.62)	1.26 (2.51)
Total power (Mw)	0.81 (1.24)	3.39 (5.09)	3.37 (5.07)	3.60 (5.13)	3.64 (5.03)	3.81 (5.12)	3.96 (5.21)
Accumulated power (Mw)	0.81 (1.24)	4.20 (6.33)	7.57 (11.40)	11.17 (16.53)	14.81 (21.56)	18.62 (26.68)	22.58 (31.89)
Cavity length (m)	7.78	21.81	23.66	21.51	20.06	19.53	19.19
Cavity diameter (cm)	94.8	95.0	89.4	87.9	86.4	84.9	84.0
Range of D.T. diameter (cm)	17.6	23.9/16.5	11.74/14.4	14.4/16.4	16.6/18.3	18.6/20.0	20.1/21.4
Range of D.T. length (cm)	4.65/13.9	16.3/32.9	33.7/38.0	38.6/41.0	41.8/43.3	44.1/45.2	45.7/46.6
Range of gap (cm)	1.50/6.97	4.93/10.9	10.1/18.7	18.3/24.7	24.2/30.0	28.4/32.4	32.1/35.5
Range of g/L ($\times 10^3$)	247/332	234/248	230/329	321/375	366/401	392/417	413/432
$\Delta W/L$ (Mev/m)	1.10	1.55	1.44	1.43	1.38	1.34	1.31
$\Delta W/P_{excit.}$ (Mev/Mw)	22.5	20.1	20.4	14.9	12.2	10.5	9.4
Bore diameter (cm)	2.0	2.0 & 2.5	3.0	3.5	4.0	4.5	4.5
No. of unit cells	59	67	47	35	29	26	24
Accum. No. of full D.T.[2]	58	124	170	204	232	257	280
Drift space length[3] (m)	7.0 + 0.3	1.0	1.0	1.0	1.0	1.0	10.0
Accumulated length[3] (m)	15.1	37.9	62.6	85.1	106.1	126.7	155.8
No. of quadrupole magnets	58	66	15	9	6	5	4
No. of magnets between cavities[4]	6 + 0	3	3	3	3	3	12
Accumulated No. of magnets[4]	64	133	151	163	172	180	196

(1) Numbers in parentheses are for a peak beam current of 100 ma.

(2) There are N_{cell}-1 full D.T.'s in each cavity plus 2 half D.T.'s

(3) The buncher space preceding Cavity No. 1 is 7.0 m and the space between Cavities No. 1 and No. 2 is 0.3 m. The accumulated length is measured from the start of the buncher space to the end of the transition section following Cavity No. 7.

(4) There are two triplet lenses in the buncher space, none between Cavities No. 1 and No. 2, one lens each between Cavities No. 2 - No. 7, and three lenses in the transition section.

installed in this space. There will be one or more quadrupole triplets for matching the beam emittance from the drift tube section into the transverse acceptance of the waveguide section. It seems clear that the analysis of the beam from the drift tube section can best be done here rather than drifting the low energy beam through the entire waveguide section. Consequently, a deflecting magnet must also be installed in the drift space. Complete beam analysis equipment and a small beam stop will be provided.

The choice of frequency for the loaded waveguide section is based primarily on the longitudinal dynamics of the particles at the transition. Extensive numerical calculations have been made and lead to the conclusion that 800 Mc/sec is the highest frequency which can be used safely when the drift tube section is operated at 200 Mc/sec. In the ideal case, it would be possible to transfer the beam from a 200 Mc/sec to a 1200 Mc/sec accelerator section at about 200 MeV, without loss of beam from the phase stable region. However, when the effects of improper adjustments and a reasonable safety factor are included, it becomes clear that 800 Mc/sec is a reasonable figure.

The conventional iris-loaded waveguide is clearly a usable structure in the standing wave mode for the acceleration of protons. However, better structures have been developed, as discussed in another paper. The slotted iris structure has been chosen for the high energy section of this linac because it gives the best compromise between bandwidth, shunt impedance, ease of fabrication and other factors. The operating frequency will be 805 Mc/sec, and there will be 54 independent standing wave cavities which will accelerate the beam from 187 to 503 MeV. The general parameters of the waveguide section are given in Table IV.

The cost minimization procedure has been applied to the design and results in a rather low acceleration rate which increases from 1.67 MeV/m to 2.06 MeV/m. This leads to a maximum value of E_0 of about 4.1 MV/m so that the peak fields on the surfaces should not exceed 10 MV/m which should be well below the sparking limit. Each cavity will be about 3 m or 8.5 λ long so that flattening should present no problem. The number of unit cells per cavity will vary from 30 to 22. The excitation power per cavity will be about 0.7 MW, and the total power per cavity at 100 mA will be about 1.25 MW. The energy gain per cavity varies from 5.1 to 6.4 MeV.

Each cavity will be powered by a single amplifier tube so that power splitting at high power levels will not be needed. The final amplifier tubes will be type RCA A15191 negative grid triode coaxitrons. It is believed that klystrons are not suitable for this application. Drive power for the 54 final amplifiers will be supplied by seven A15191's, each capable of driving eight finals through the appropriate power splitting networks.

TABLE IV

General Parameters of the Waveguide Section

Input energy (MeV)	187	
Output energy (MeV)	503	
Energy gain (MeV)	316	
Peak beam current (mA)	50	(100)*
Beam duty cycle (%)	0.6	
Beam pulse length (μsec)	200	
Pulse repetition rate (pps)	30	
Rf pulse length (μ sec)	250	
Rf duty cycle (%)	0.75	
Operating frequency (Mc/sec)	805.00	
Wavelength (cm)	37.241	
Number of cavities	54	
Peak excitation power (MW)	38.4	
Peak beam power (MW)	15.8	(31.6)
Total peak rf power (MW)	54.2	(70)
Average excitation power (kW)	288	
Average beam power (kW)	95	(190)
Total average power (kW)	406	(525)
Total length of cavities (m)	165	
Total intercavity drift space (m)	34	
Drift space at end of accelerator (m)	6	
Total length (m)	205	

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*Numbers in parentheses are for a peak beam current of 100 mA.

These seven drivers in turn will be driven by an intermediate power amplifier employing a single A15191. Thus, there will be 62 A15191's and a single low level drive chain. Each tube will have a separate hard tube plate modulator in order to allow individual control of the field amplitube in each cavity. Phase control between cavities will be accomplished by servo-controlled phase shifters in the drive lines to the final amplifiers. By including only the final amplifier in the servo-loop, the number of elements introducing phase noise is minimized.

The frequency of the accelerator is set by a highly stabilized 805 Mc/sec oscillator, and all of the cavities are tuned to this frequency. For the drift tube section, a 201 Mc/sec oscillator is phased locked by a signal taken from the first 805 Mc/sec cavity.

The cavities will be assembled in subsections consisting of two cavities separated by a 30 cm drift space which will be used as the vacuum pumping connection. The subsections are connected by a 1 m long drift space. Transverse focusing will be accomplished by quadrupole doublets placed in each 1 m drift space.

The vacuum system will employ ion pumps throughout and will operate at a pressure below 10^{-6} Torr. The cooling system and other accelerator support equipment will be generally conventional. Because the coaxitrons are fixed tuned and have no mechanical adjustments, they will be placed directly alongside the waveguide to minimize the length of waveguide. The accelerator will be located in a shielded tunnel, separated from the support equipment by a wall which varies from about 2 to 11 feet thick.

More detailed discussion of the design of this linac is included in several other papers presented at this Conference and in the Brookhaven Proposal BNL 7956.

WROE: I would like to know why you have so much more injected current than accelerated current. It seems to me that one should be able to accelerate more than half of the current from the injector.

VAN STEENBERGEN: In the conventional bunchers which are in use now, the effective capture in the linac is less than 50%. One wishes to operate the buncher to achieve good beam quality rather than for maximum capture. Hence, it seems that 400 mA from a source is not too much to assure 100 mA of accelerated beam at the end of the linac.

WHEELER: I think it is necessary to stress the importance of beam quality in these high intensity, high energy linacs. One must not lose many particles at energies above the neutron production threshold, so that particular care must be taken when the beam is transferred from the drift tube linac to the waveguide section at about 200 MeV. We have made estimates of the radiation background and activation of the accelerator. These will be very severe if more than about 0.1% of the beam is lost. Beam quality is also most important in an injector linac in order to assure good capture by the synchrotron.

CARNE: Why do you set a field strength of 10 MV/m at 800 Mc/sec?

WHEELER: That is an estimate (see text of paper). The cost minimization procedure indicates an average acceleration rate of about 1.75 MeV/m, and from this it is estimated that the peak surface fields should not exceed 10 MV/m. I think that this figure is conservatively below the sparking limit.

WROE: Are there any parts of the preinjectors which are more unreliable than the others?

WHEELER: Particularly at these high currents, the source itself is the biggest problem. However, since the source is in the high voltage terminal, you must shut off the Cockcroft-Walton set in order to get at the source. Hence, in order to allow rapid change over to a new source, two complete preinjectors are required. These can be switched by simply changing a magnet in the buncher space. The amount of money involved is small compared to the improved operating efficiency of the linac.