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600 MHz RF SYSTEM FOR 200 BeV ACCELERATOR

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I. Introduction

In this report a discussion of an rf system which combines the advantages of both linear and circular accelerators will be presented. This is achieved by employing five iris-loaded structures which are grouped together in one long straight section (34 m) forming a traveling wave linac. The whole accelerating system is confined to one location only, thus eliminating long cable runs, and the rf control station can be located directly above the iris-loaded structures. Mechanical dimensions of the magnet ring, as well as the magnet parameters, are assumed to be the same as those for the 200-BeV machine studied by the Berkeley group.¹

A frequency of 600 MHz is selected as it approaches the upper limit dictated by several requirements inherent in the synchrotron. The justification for such a high frequency becomes apparent from the following sections, in view of the high shunt impedance, R_0 , low power loss in the structure, and wide bandwidth. Traveling wave operation is preferred over standing wave for the following reasons:

- a) Twice the acceleration for the same field strength.
- b) The guide is matched to the power source and a very low VSWR can be achieved throughout the bandpass by broadbanding the couplers.
- c) Better behavior under beam loading conditions.²

1. 200-BeV Accelerator Design Study, UCRL 16000, Vol. 1 (1965).
2. "Design Study of a 300 GeV Proton Synchrotron", CERN Report AR/Int, SG/64-15, Vol. I, p. 113 (1964); also, W. Schnell, Report CERN 64-10 (1964).

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Before proceeding with a detailed description of the design philosophy adopted for various parts of the accelerating system, it should be mentioned that the CERN group² have considered a 180 MHz traveling wave system for their proposed 300-BeV machine. Their report contains also a survey of several design approaches.

II. General Considerations

The most important part of the accelerating system is the selection of the parameters for the iris-loaded waveguide. High frequencies are favored for some outstanding features discussed later and, therefore, the choice of the operating frequency should be an important factor in an optimum design. Primary limitations appear to be the size of the iris hole $2a$ (Fig. 1) through which the proton beam passes and the phase oscillation frequency Ω . Extrapolating to 600 MHz from data available at 3 GHz, $2a \approx 12$ cm represents a group velocity $v_g \approx c/25$. But v_g increases with increasing diameter $2a$, resulting in the decrease of the shunt impedance R_0 and the attenuation parameter αl . Both effects are undesirable in producing an efficient accelerating structure (section III). Unless a different slow wave structure is used or the aperture of the synchrotron can be decreased, 600 MHz appears to be the upper frequency limit for the chosen length of the accelerating guides.

Next, let us turn our attention to the phase oscillation frequency Ω given by³

$$\Omega = (-\eta h eV \cos \theta_0 / 2\pi E)^{\frac{1}{2}} \omega_0 \quad (1)$$

where

$$\eta = \left(\frac{E_0^2}{E_1^2} - \frac{E_0^2}{E^2} \right) = \alpha - \gamma^{-2} \approx 2 \times 10^{-3} \quad (2)$$

3. E.D. Courant and H.S. Snyder, "Theory of Alternating-Gradient Synchrotron", Ann. Phys. 3, 1-48 (1958).

$$\alpha = \text{momentum compaction factor} \approx 4 \times 10^{-3}$$

$$\gamma = E/E_0 \text{ for injection at } 20 \text{ BeV} \approx 21$$

$$h = \text{harmonic number} \frac{600 \text{ MHz}}{\omega_0} \approx \frac{6 \times 10^8}{7 \times 10^4} \approx 8.6 \times 10^3$$

$$eV = \text{energy gain per turn} \approx 3.0 \text{ MeV}$$

$$\theta_0 = \text{stable phase angle} = 45^\circ$$

$$E = \text{injection energy} \approx 20 \text{ BeV}.$$

For the above conditions resulting $\Omega \approx (2 \times 10^{-2}) \omega_0$, which is well within the permissible range² even if the acceleration takes place at one point only. Since $\Omega \propto \sqrt{f}$, higher rf frequency is, in principle, possible.

The total voltage per turn, V , which the rf system has to supply to the beam equals $V_0 \sin \theta_0$. Due to the high energy of the protons, $> 20 \text{ BeV}$, a phase angle $\theta_0 = 45^\circ$ is selected rather than 30° as used in the existing proton synchrotrons. From previous considerations, $V \approx 3.0 \text{ MV}$ and $V_0 \approx 4.3 \text{ MV}$ per turn. An iris-loaded structure could impart this voltage with a modest power if it were not for the heavy beam loading expected. In fact, if pulses of 3×10^{13} protons are to be accelerated to 200 BeV , the total beam power will equal $\sim 1 \text{ MW}$. It is due to the heavy beam loading, for which the system has to be designed, that a rather low attenuation parameter $\alpha \ell$ is preferred resulting in high power dissipated in the load in the absence of the beam. In electron linacs, for example, $\alpha \ell$ lies between 0.5 to 1.2 as compared to $\alpha \ell \approx 5 \times 10^{-2}$ in this case. However, as the beam enters the structure and receives acceleration from the energy in rf fields, the attenuation parameter effectively increases, thus increasing the efficiency of the structure. A large fraction of the rf power dissipated in the load is thus converted into the beam power. Nevertheless, the accelerating guide stays matched to the driver for any intensity with the exception of the reactive component. The reactive component can be controlled to a certain degree by a phase servo within the radial control loop.

Since the whole rf system is designed to fit into one long straight section (34 m), the length of the structure $\ell = 5 \text{ m}$ was primarily determined by the maximum feasible power output from a microwave tube. As will be seen

from the reasoning in the subsequent sections, five structures, each driven from a 200 kW amplifier, could provide 1.0 MW of rf which is more than adequate to accelerate 2×10^{13} protons per pulse; 200 kW microwave tubes are well within the present state of the art.

The performance of an untuned system which employs resonant cavities depends largely on the prescribed bandwidth, Δf . Very efficient structures can be designed due to a narrow $\Delta f/f$ determined by high injection energy, from which follows

$$\frac{\Delta f}{f} = 1 - \beta_{20} \approx 10^{-3}, \quad (3)$$

where $\beta_{20} = v/c$ for a 20-BeV proton. One should add that a much higher bandwidth can be achieved in a loaded structure.

Finally, the table below gives the parameters of the accelerating structure for which the design is developed in the next section and a sketch of which appears in Fig. 1.

Number of structures	5
Length of structure, l	5 m
Inside diameter, $2b$	~ 40 cm
Beam hole diameter, $2a$	12 cm
αl	$\approx 5 \times 10^{-2}$
v_g/c	$\approx 4 \times 10^{-2}$
R_o	$\approx 22 \times 10^6$ MV/m
Q	$\approx 15 \times 10^3$
Total power required for 200 BeV without beam loading	≈ 350 kW
<u>Power dissipated in the walls</u> Input power	$< 10^{-1}$
Beam loading for 2×10^{13} protons/pulse	~ 600 kW

Fig. 1. Iris-loaded accelerating structure.

III. Accelerating Structure

As there are no linear accelerators operating in the 600 MHz range, most of the parameters must be extrapolated from data available at 2.856 GHz. In particular, extensive use is made of the information obtained at SLAC⁴ and at BNL^{5,6} in connection with the existing electron linac and the particle separator. Let us, therefore, briefly review the scaling factors for the more useful parameters and figures of merit as a function of operating frequency. We obtain:

Dimensions	$\propto f^{-1}$
Shunt impedance	$R_o \propto f^{\frac{1}{2}}$
Rf loss factor	$Q \propto f^{-\frac{1}{2}}$
	$R/Q \propto f$
Maximum permissible electric field strength	$\propto f^{\frac{1}{2}}$

Furthermore, let us write down a few equations necessary for the design of the structure, namely

$$\text{Phase velocity } v_p = \frac{\omega}{\beta}, \quad (4)$$

with $\beta = 2\pi/\lambda_g$

$$\text{Group velocity } v_g = \frac{\partial \omega}{\partial \beta}, \quad (5)$$

$$\text{Attenuation parameter } \alpha = \omega/2Q v_g, \quad (6)$$

$$\text{Energy gain with no beam } q V = \sqrt{2} q \frac{1 - e^{-\alpha l}}{\alpha} \sqrt{P R_o} \sin \theta, \quad (7)$$

where P = input power, and θ = phase angle of the rf voltage.

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4. A.L. Eldredge, G.A. Loew and R.B. Neal, "Design and Fabrication of the Accelerating Structure for the Stanford Two-Mile Accelerator", SLAC Report No. 7, 1962.
 5. H. Hahn, H.J. Halama, Rev. Sci. Instr. 36, 1788 (1965).
 6. H. Hahn, H.J. Halama, Nucl. Instr. Methods (to be published).

Phase slip φ of protons traversing a structure due to a frequency change Δf resulting from the change in particle velocity during acceleration:

$$\varphi = k\ell \frac{c}{v_g} \frac{\Delta f}{f}, \quad (8)$$

where $k = 2\pi/\lambda_0$.

The results from the measurements performed both at SLAC and at BNL lead to the selection of a circular iris-loaded waveguide (Fig. 1) operating with three irises per wavelength ($2\pi/3$ mode). This mode gives the maximum value of R_0 at a given frequency.⁴ Furthermore, the traveling wave regime is chosen and the phase velocity, v_p , of the rf wave is matched to the velocity of protons, which can be done, of course, only at one energy.

Having selected the above parameters, the next important consideration is the bandwidth of the structure. It is obvious from the dispersion diagram (Fig. 2), that $\Delta f/f \gg 10^{-3}$ can be obtained in a loaded waveguide. In fact, since $v_g = \partial\omega/\partial\beta$, the group velocity represents the slope of the dispersion curve and, as such, indicates the amount of phase shift per given frequency change. A higher v_g is clearly desirable if we wish to keep φ in Eq. (8) to a minimum. On the other hand, the shunt impedance R_0 and $\alpha\ell$ decrease with an increase in group velocity and a compromise must be made. Since the group velocity is primarily determined by the diameter of the iris hole, $2a = 12$ cm (section II), the resulting $v_g/c \approx 0.04$. By adjusting the inside diameter $2b$ of the structure so that v_p equals velocity of protons in the middle of the bandwidth and letting $\ell = 5$ m, Eq. (8) yields an acceptable phase slip $\varphi \approx \pm 45^\circ$ at either end of the rf bandwidth. The acceleration is reduced to

$$\frac{\sin \varphi/2}{\varphi/2} \approx 1 - \frac{1}{24} \varphi^2$$

resulting in a negligible loss of 2.5% only. This high value of v_g also entails a loss of approximately 15% in R_0 , some of which can be gained back by making the irises thinner.

Fig. 2. Typical dispersion diagram.

Let us next apply the scaling factor and extrapolate from tables and curves in Ref. 4 to obtain

$$R_0 \approx 22 \text{ M}\Omega/\text{m}$$

and

$$Q \approx 1.5 \times 10^4 .$$

From Eq. (6) it follows that

$$\alpha \approx 1 \times 10^{-2} \text{ nepers/m}$$

which gives a power loss $P_L \approx 0.43 \text{ dB}$ in each 5 m accelerating structure, corresponding to $P_L/P < 10\%$.

Finally, by solving Eq. (7) for the total energy gain per turn (3.0 MeV) and by assuming a stable phase angle $\theta = 45^\circ$, we find that an input power of $< 70 \text{ kW}$ is required for each structure under no beam loading condition. From this, only $< 7 \text{ kW}$ will be dissipated in the walls and the remaining 63 kW will be transmitted to the load at the end of the iris-loaded guide. The above figure represents only a fraction compared to the power in the beam. In fact, for a pulse of 2×10^{13} protons accelerated to 200 BeV in 1 sec, the beam power $\approx 640 \text{ kW}$. Such severe beam loading will change the field configuration within the loaded structure and a great deal of study remains to be done in this region. It is anticipated that the problem will be studied on an actual model in the AGS, as outlined in section VI.⁷ Moreover, it is clear that if a circulating beam of 2×10^{13} protons per pulse is suddenly lost and $\sim 200 \text{ kW}$ are fed into the structure, the electric field will increase and a check must be made that no breakdown occurs. Using an equation derived for the BNL deflector in Ref. 5,

$$E_{\text{peak}} = \rho [k P (c/v_g)(R_0/Q)]^{\frac{1}{2}} \leq 5 \times 10^5 \text{ V/m} , \quad (9)$$

where an estimated value $\rho = E_{\text{peak}}/E_{\text{average}} \approx 1.5$.

7. G.K. Green, private discussion.

Extrapolating to the case of 600 MHz, the maximum permissible electric field $E_{\max} \approx 10$ MV/m. The resulting factor $E_{\max}/E_{\text{peak}} \leq 20$ assures arc-free operation; 180 kW must, of course, be dissipated in the load until the rf power is turned off. By selecting a readily available high power load, no difficulty is anticipated if the beam is suddenly lost.

Due to low dissipation in the accelerating structure, only a relatively simple water cooling equipment will be required. It is, however, advisable to employ a separate closed loop cooling system for each structure as there exists the possibility of bringing them to the same frequency by operating them at different temperatures if the stringent mechanical tolerances are not adhered to. This method is, in fact, used in the BNL rf separator and replaces other means of tuning. Incidentally, one could intentionally operate the accelerators at different temperatures in a scheme to locate them at different points of the passband for better results. The necessary accuracy for the water cooling system can be found from

$$\frac{\Delta\phi}{\Delta T} = 2\pi \frac{\ell}{\lambda} \delta \frac{c}{v_g} \approx 1.5^\circ/1^\circ\text{C} \quad , \quad (10)$$

where δ = temperature coefficient for copper = 1.7×10^{-5} . Consequently, a system which can hold the temperature of coolant within $\pm 1^\circ\text{C}$ around a preset point results in a phase change of $\pm 1.5^\circ$ and is quite sufficient.

IV. High Level

The high level system supplies ~ 200 kW of rf power to the beam in each of five identical stages which are located about 15 m directly above the accelerator, similar to the method used at SLAC. Since the couplers of the traveling wave structure are carefully matched to the resistive load throughout the bandwidth, no serious limitation is imposed upon the output port of the power source. The operating frequency, however, restricts the selection of the driver to either a klystron or an amplatron.

Klystrons are characterized by high gain (up to 60 dB) and rather low efficiency (30 to 50%). Amplitrons, on the other hand, are low gain devices (~ 10 dB) with high efficiencies. Figures as high as 80% are quoted in

Raytheon data sheets. For a system where ~ 1 MW of cw power is needed, high efficiency is of paramount importance. Furthermore, several tube types do not require any filament power as their platinum cathodes are heated by electron bombardment and consequently have a very long life. At present, a tube with 72 kW of average power is available in our bandwidth, but higher powers have been achieved at other frequencies. In view of the two features discussed above, the development of a 200 to 300 kW amplatron might well be worth consideration. Incidentally, the Los Alamos group are testing an 805 MHz 400 kW amplatron⁸ for their proton linac.

Both klystrons and amplatrons have acceptable phase characteristics and units of power comparable to that required for our application have been built and operated at various frequencies. It should be pointed out that, by the time a driver for the accelerator is required, the microwave tube picture might look quite different. At the present time, however, the unavailability of a suitable 200 kW tube operating at 600 MHz, even though it is well within the present state of the art, is a drawback of this accelerating system.

For the sake of discussion, let us select a klystron similar to Eimac 5K210000LQ or 4KM170000LA, with output of 100 kW, gain 45 dB, and anode voltage of 35 kV at 10 A. The combined output of two klystrons (200 kW) is fed through a standard rectangular waveguide (11.750 in. $\times$ 6.000 in.) to the input coupler of each structure. A similar waveguide connected to the output coupler carries the rf power to the waster load, such as Eimac WL150, capable of dissipating up to 300 kW. The load is also located above the accelerator as is the rest of the high level equipment. The low attenuation of the feeding waveguides < 0.005 dB/m results only in a modest water cooling system, but the input feeding line must be temperature controlled to $\pm 2^\circ\text{C}$ to keep the phase variation with temperature to within 0.7° for all five stages.

Each pair of klystrons is powered by a separate power supply of conventional design and will not be covered in this discussion. Suffice it to say that the only requirement is good short-term dc stability, as this determines

8. B. Silberman of Raytheon, private communication.

the magnitude of the phase drift in each high level stage. To implement the phase stability, high level stages are equipped with separate servos which maintain the phase across each stage constant. These closed loops are described, together with low level circuits, in the next section. No great demands are imposed on the amplitude stability as $V \propto \sqrt{P}$, and a 5% change in power causes only $\sim 2.5\%$ change in accelerating voltage, which is certainly negligible.

Finally, the high level system must contain some provisions to ensure continuous operation of the accelerator if a power tube fails and has to be replaced. It is not advisable to put idle accelerating structures into the ring as they will absorb energy ΔV from the beam according to⁴

$$\Delta V = \frac{I R_o \ell}{2} \left(1 - \frac{2 \alpha \ell e^{-2\alpha \ell}}{1 - e^{-2\alpha \ell}} \right) . \quad (11)$$

Energy loss ΔV increases with peak current I and represents a large value at the maximum currents proposed, especially if R_o is high. Besides, the idle structures would require tunnel space, and therefore this solution is considered to be unattractive. Instead, a system employing two independent drivers for each 5 m section is selected and both outputs are connected to a high power waveguide switch. The nonoperating driver is in a standby position and, in case of failure, can be substituted simply by actuating the switch and changing the input coax cables.

V. Low Level

A phase lock system is used similar in principle to that employed at the AGS, and most of its components are also located directly above the accelerator. In practice the circuits are simpler than those of the AGS due to a much narrower bandwidth (~ 3000 X) as well as to the absence of long cable runs. A major difference, however, lies in the higher operating frequency. Another factor influencing the complexity of low level circuits depends on the method of injection and bunching. The system described must either do the bunching at $\dot{B} \rightarrow 0$ or a buncher must be used in the injection line-up to achieve a highly efficient capture.

As seen from a schematic of the over-all system in Fig. 3, the circulating beam, bunched either by a starting oscillator, O, or a prebuncher, induces a voltage in pillbox cavity C. The coupling coefficient and the loading are adjusted for an output of ~ 1 W at 2×10^{13} protons and $Q \approx 300$. Standard coaxial cables with a total attenuation of 0.5 dB transmit the signal to an AGC'd amplifier, A_1 , which establishes an output of 3 W. The signal then passes through a fast microwave switch, S, and two phase shifters which will be discussed later. The fast diode switch switches the signal from a phase lock oscillator (O in Fig. 3) to the beam control operation, as in the low frequency version at AGS.

It remains now to amplify the rf signal to a suitable level for driving the selected 45 dB klystrons. Allowing for 3 dB loss in associated cables, an amplifier, A_2 , with maximum gain ≈ 20 dB and output power of 100 W is more than adequate. The gain of A_2 is varied by a signal derived from one of the five final drivers through a directional coupler, DC_4 , to keep the power to the beam at a constant level.

Let us now turn our attention to phasing problems by dividing them into three groups for better understanding.

1. Synchronization of accelerating voltage phase at the input to each structure

As mentioned before, the waveguides which feed the accelerators are temperature controlled and permit only a relative phase variation of 0.7° , which is negligible. A far more severe problem lies, however, in the dc stability of the high voltage power supplies where a 1% change in the voltage causes a phase change of $\sim 10^\circ$ across the klystron. On the other hand, from the standpoint of amplitude as much as a 5% change in power (section IV) influences the operation of the machine very little. It is clear that a closed loop circuit maintaining the phase across the drivers constant should be incorporated. To this end, directional couplers DC_2 and DC_3 , as shown in Fig. 3, couple out a small fraction of rf signal which is compared in phase bridge P.⁹ As long as the two

9. H. Hahn, H.J. Halama, and H.W.J. Foelsche, BNL Accelerator Department Internal Report AADD-91 (1965).

Fig. 3. Schematic diagram of over-all accelerating system.

Legend: PE - split position electrodes, CH - chopper, F - difference amplifier, D - synchronous detector, V - varactor phase shifter, C - pickup cavity, DC - directional coupler, A₁ - constant output amplifier, S - switch, O - starting oscillator, LS - variable phase shifter, A₂ - final amplifier, P - phase servo, B - phase shifter, K - driver, W - accelerating structure, L - load.

signals are in a prescribed phase relationship to each other, no error voltage is produced. In case of phase drift, the resulting output of phase bridge P is amplified and transmitted to a ferrite phase shifter to restore the desired relationship. Furthermore, due to the frequency change during the acceleration cycle, the circuits of the phase servo require a high degree of symmetry. Each driver must, of course, have its own servo system,

2. Phase change due to frequency variation

The electrical length, L , of the cables, the amplifiers, and the waveguides connecting the cavity C and the iris-loaded structure will introduce a variation in the phase shift $\Delta\phi$ depending on $\Delta f/f$ as

$$\Delta\phi = \frac{2\pi}{\lambda_0} L \frac{\Delta f}{f} \quad (12)$$

Assuming $L < 100$ m, $\Delta\phi < .72^\circ$ is obtained. This small phase shift could probably be handled by the circuit treated in the next paragraph but in view of the stringent requirements which beam loading will impose on those circuits, a simple open loop system (LS) is also included. Briefly, it measures the frequency deviation Δf and produces a correction to keep $\Delta\phi \approx 0$.

3. Radius lock

The radius lock adjusts the average phase of the accelerating voltage by looking at the average position of the circulating beam. The low frequency analog of this system which controls the position of the AGS beam is described in Ref. 10. The beam position can be determined either by using a microwave cavity resonated in a mode with dipole symmetry¹¹ or by a split electrode acting as two plates of a condenser. The latter method is selected in conjunction with two chopper circuits, CH, which discharge the electrodes at $f \approx 400$ kHz $> 5 \omega_0$. Two coax cables (Fig. 3) transmit the chopped signals

10. H.J. Halama, BNL Accelerator Department Internal Report HJH-5 (1961).

11. O.H. Altenmueller, R.R. Larsen, G.A. Loew, 1964 PTGMTT Intern. Symp. Digest, p. 38 (1964).

to an AGC'd difference amplifier F. The AGC signal is derived from the directional coupler DC_1 and is proportional to the total circulating beam. The output of F is demodulated in a synchronous detector, D, driven from the same source as the choppers, and a dc signal proportional to the average position of the beam is obtained. This signal now controls a fast varactor phase shifter, VS, and thus maintains the average energy gain per turn as prescribed by $\dot{B}$.

Before leaving this section let us briefly mention an additional task imposed on the above circuits by heavy beam loading. The beam loading effects depend primarily on the intensity and on the phase angle of the bunches with respect to the rf wave. The fact that φ [in Eq. (8)] $\neq 0$ through the accelerating cycle introduces further complications. However, as φ varies rather slowly with time, the radius lock can be expected to control this effect. On the other hand, it would not be difficult to design a corrective servo if it should be required.

VI. Test Model

From the above discussion it appears advisable to perform an actual test on an existing accelerator to study various features of this high frequency system. In particular, very little is known about beam loading in circular machines and the use of the proposed high R_0 structure could provide a unique opportunity for such a study with very modest expenditure.

It is suggested, therefore, to install a 1 m long accelerator (section III), operating at 600 MHz, into the AGS magnet ring. Due to a rather small beam hole (12 cm), the structure must be placed in a location of minimum horizontal betatron oscillation,¹² although an oval-shaped hole¹³ could be used since only five irises and two end plates are required. In fact, it is desirable to increase v_g , due to the small αl (1×10^{-2}) of the 1 m structure, from the standpoint of beam loading study, and $v_g \approx 2 \times 10^{-2}$ will be assumed. A ten foot straight

12. E.C. Raka, private communication.

13. H. Hahn, private communication.

section appears to be an ideal choice as it could accommodate all the necessary components. Unfortunately, none is available and so the iris-loaded guide must be installed into one five foot straight section and the pickup cavity with position electrodes into another. The beam is accelerated by the existing AGS rf system to 20 BeV, whereupon the flat-top is initiated and the beam is debunched. The B is then adjusted to match an rf system with the following characteristics:

Total energy gain	$\sim 3 \text{ BeV}$
Accelerating time	0.27 sec
Energy gain per turn	$\sim 30 \text{ keV}$

From Eqs. (3) and (7) it follows that the bandwidth $\Delta f/f$ is $\sim 2 \times 10^{-4}$ and the power, P, required without beam loading at $\sin \theta = 0.7$ is $\sim 1.5 \text{ kW}$. The attenuation ($\sim 0.15 \text{ dB}$) and phase slip ($< \pm 10^\circ$) are negligible. Since the intensity of 2×10^{12} protons per pulse implies $\sim 3.6 \text{ kW}$ in the beam, it is clear that by varying the injection intensity, a wide range of beam loading can be studied.

The beam will be bunched and controlled by essentially the same circuits that are described in section V. The radius lock might be the only auxiliary phase servo necessary in view of $\Delta f/f \approx 2 \times 10^{-4}$. This will depend primarily on the electrical length of the equipment and the cables between the pickup cavity and the accelerating structure. A klystron capable of delivering $\sim 5 \text{ kW}$ is preferable and would permit the testing of beam loading up to the maximum AGS capacity. A good choice appears to be an Eimac klystron type 4KM50000 LA5 with the following characteristics:

Output	$\sim 10 \text{ kW}$
Gain	$\sim 54 \text{ dB}$
Input	$\sim 50 \text{ mW}$
Dc requirements	17 kV at 1.8 A .

Practically no other amplification is required with the exception of the initial AGC'd amplifier. In addition to the beam loading, various schemes of bunching could be studied and an optimum method developed.

VII. Conclusion

This paper has attempted to point out the more significant advantages of the proposed high frequency accelerating system. These are high energy gain per unit length, low power dissipation, and an elegant simplicity. The only components located in the tunnel are the iris-loaded waveguides, electrodes, and two choppers using conventional low power tubes which require no maintenance. Only one straight section is utilized for the total rf system, resulting in a shortening of the ring and tunnel. The selected frequency represents also an important advantage for high energy physics experiments as it simplifies considerably the design of the rf beam separators which will be necessary at these energies. Furthermore, with only a modest effort, the system can be evaluated under true operating conditions at the AGS and appropriate modifications suggested.

Among the disadvantages are the rather high injection energy and a greater cost of rf power at higher frequencies. Moreover, desirable drivers, namely 200 to 300 kW microwave tubes, although well within the state of the art, are at present unavailable, at least in the unclassified market.

In conclusion, it should be stressed that no optimization of various parameters was attempted and the final structure may differ from the proposed one. Here, however, the results from model measurements and the information on the behavior under heavy beam loading gained from the suggested tests must assist. In addition, many significant details were omitted for the sake of greater clarity.

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