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A HIGH-REPETITION-RATE 15-BEV ALTERNATING-GRADIENT SYNCHROTRON

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ABSTRACT:

An AG synchrotron capable of accelerating time-average currents of order 3 microamperes is discussed. Descriptions of the magnets, magnetic excitation system, rf accelerating system, orbits and intensity considerations are given. The cost (at an existing laboratory) is estimated to be $45 million.

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INTRODUCTION

This report represents only a preliminary exploration into the feasibility and possible cost of constructing a high-repetition-rate alternating-gradient synchrotron. There was no time to optimize the various parameters and the study should not be taken as any very serious attempt to design such a machine. The main purpose of the study was to determine that there were no very serious obstacles in such a design. The choice of parameters, while admittedly arbitrary, was guided by the philosophy that the design of the various parts of the machine should lie within the "state of the art" at the present time, and that highly speculative ideas should not be involved in the initial operation. However, it was decided to leave room, if possible, for application of the more elegant injection techniques, which one expects to be perfected in the future, to increase the intensity.

CHOICE OF PARAMETERS

Energy: To be well above all known thresholds, the energy should be in the vicinity of 12 Bev, but to make the design more nearly comparable with the various FFAG proposals, we chose 15 Bev for this study.

Injection Energy: A high-repetition rate, high-energy synchrotron will obviously present a severe radio-frequency acceleration problem. This problem will be minimized by decreasing, as far as feasible, the range of frequency modulation required. This of course implies a relatively higher injection energy. A higher injection energy also increases the space charge limit and should provide an injected beam of higher quality, so that future

developments in injection technique would have room in which to make improvements in the intensity. Our guess at the injection energy which would minimize the total cost of the injection system and the radio-frequency acceleration system was 200 Mev, based on Brookhaven linear accelerator costs and Princeton radio-frequency system costs. Further study might show some better choice.

Magnet: The first choice of aperture was a linear scale-down of the Brookhaven AGS by a factor of two, based on the good experience at Brookhaven on magnet errors and a fear that the energy storage would make the cost of the power supply for a larger aperture prohibitive. After a few calculations, we realized that the cost of the power supply was not out of line with that of other components and we decided to base the design on the Brookhaven magnet cross section. One cannot readily further increase the aperture significantly because a high-repetition-rate magnet must be made of high silicon steel which is available in sheets with an absolute maximum width of 37 inches. The type of steel also limits the choice of maximum magnetic field, although both the space charge limit and the difficulty of the radio-frequency problem would favor higher values. We chose 10,000 gauss as the peak field at the central orbit, which gives a radius of curvature of about 50 meters.

Repetition Rate: We decided on 20 cycles per second for the repetition rate, in order to maximize the intensity, with the realization that the radio-frequency problem might force a reduction to 10 cycles per second. Calculations

on the acceleration problem indicate that 20 cycles per second is readily achievable. The type of excitation we chose is a biased sine-wave.

COMPONENT DESIGN

1. Magnet Structure

The number and length of magnets and straight sections was chosen so that a single unit cell would be about the same fraction of a betatron wave length as in the Brookhaven machine, namely 0.15. The straight sections have to be long and numerous enough to accommodate rf units capable of delivering a peak of about 3 megavolts per turn. It was assumed that 100 kilovolts could be obtained with a cavity requiring 150 centimeters of clear space; then about 30 cavities would be needed. Each straight section must be about 2 meters long (allowing 50 centimeters for coil ends). For reasons of orbit stability, the betatron wave length must be long compared to 2π times the length of the straight section.

All these requirements are met by the following structure: 40 unit cells containing 4 meters of magnet with positive gradient, 4 meters of magnet with negative gradient, and a 2-meter straight section. The 4-meter magnets could each be made of two 2-meter units to facilitate handling and to permit the individual magnet units to be straight rather than curved (the curvature of the orbit in a 2-meter magnet section consumes one centimeter of radial aperture compared with about 15 centimeters available in the Brookhaven aperture). These magnet sections would have to be separated by about 60 centimeters to allow for coil ends.

Some larger straight sections are desirable for injection and targeting. Therefore, we have lengthened five of the straight sections to 3 meters. This groups the 40 magnet periods into five "superperiods." The overall structure of a superperiod is shown in Fig. 1. The 3-meter straight sections permit access to secondary beams from internal targets at angles down to .02 radians ≈ 2 degrees, without deflection of the secondary beam by magnetic fields.

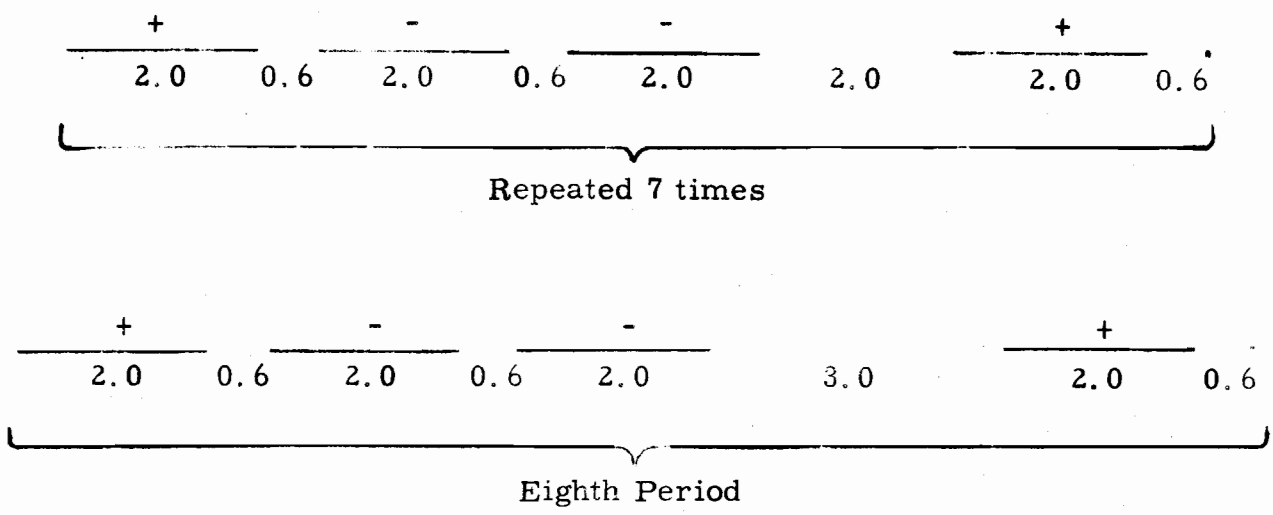


Fig. 1

Since there are five superperiods in the ring, the essential linear resonances occur at $\nu = 5/2,\ 5,\ 15/2$, etc. We must choose ν as far from these values as possible; the choice that corresponds most nearly to the Brookhaven criterion is $\nu = 6\frac{1}{4}$.

Calculations were carried out on the 704 using the "MESSY MESSY" program and show that this will be obtained with n = 156. The "beat factor" (ratio of the maximum value of the amplitude function β (s) to its average value R/ν, as defined in Courant and Snyder, Annals of Physics 3, 1 (1958)) is about 1.65.

This value of n corresponds to a somewhat "flatter" magnet pole than that used at Brookhaven. Therefore, if the overall magnet cross section is kept the same as at Brookhaven and, in particular if the gap at the aperture centerline is kept the same (3.5 inches = 8.9 cm), the available aperture will be somewhat greater than at Brookhaven, namely about 6 x 14 cm (after vacuum chamber wall and orbit curvature have been subtracted).

2. Magnet Design

For the purpose of the present study, we chose to use exactly the Brookhaven AGS magnet cross section, modified only by reducing the field gradient to give a suitable operating point with adequate straight-section space for radio-frequency acceleration. The other modifications of the Brookhaven design involve changes to allow the magnet to be cycled more rapidly, specifically, the type of iron, coil design, and some details of the support and clamp design.

In order to keep down the hysteresis losses in a rapidly cycled magnet, it is necessary to use a high-silicon transformer-type iron. The question is not so much that of power consumption, although this is not negligible, but the problem of cooling the magnet to avoid thermal distortion and changes in magnetic properties with temperature. The cooling can be readily accomplished by water-cooled plates cemented to the top and bottom of the magnet. (Princeton analysis and experience has shown that cooling the back of the magnet increases the thermal distortion.) These plates must be insulated from the magnet and made in fairly narrow strips--about 6" wide--to avoid

eddy-current losses, but this is simple and cheap and the scheme works well at Princton where the problem is very similar. Since the cooling required is less than 100 watts per square foot, forced air cooling also should work, but it would be noisy and more cumbersome.

The high-silicon iron, since it has a lower saturation value of B minus H, would not allow orbit fields as high as at Brookhaven, hence the choice of 10,000 gauss for calculating the orbit radii. There are other advantages to the use of high-silicon iron which in themselves would not justify its choice, but when that choice is forced by other considerations they simplify the overall magnet problem. The coercive force is about 0.2 oersted, or a factor of five lower than that of other magnetic materials which might be used; thus, at the 430 gauss injection field, remanent effects can be completely neglected. In addition, the permeability at low fields is high, about 2500 at 100 gauss. Although it appears that the injection field is so high that the permeability should be adequate anyway, one must remember that injection probably will take place only a few gauss above the minimum field, so that the incremental permeability is important.

The method of magnet fabrication might well be done more nearly like the Princeton magnet than that of Brookhaven, because the welding together of the laminations on the outside of the magnet could not be tolerated with the high-frequency operation. The consideration here is more one of power than of field characteristics, because the peak value of $\frac{1}{B}\frac{dB}{dt}$ is not much above that at Brookhaven. Since the Princeton magnet costs are higher than Brookhaven costs only because of the type of iron and a few provisions such

as separate pole tips and the necessity of curving the magnet because of the small radius, this type of fabrication should fit well within the magnet budget as outlined.

A calculation of the magnet coil dissipation shows that the Cambridge Electron Accelerator's coil design is applicable to this magnet. This design greatly reduces the eddy-current losses in the coils. Each of the four coils on one magnet would consist of 16 turns of twisted cable. The cable would consist of 7 strands, insulated from each other for low voltage, of 9/32"-diameter copper wire. The cooling would be accomplished by imbedding water-cooling tubes in the interstices between the approximately round cables. The power loss is only about 10 watts per foot of cable, which enables this elementary cooling system to work. The ground-wall insulation should be about 1/8" of micaglass high-voltage insulation, and the insulation between layers, where the voltage between adjacent conductors builds up, should consist of about 3/32" of the same material. There is evidence that this type of insulation will withstand radiation better than other types.

The energy storage of the magnet at 10,000 gauss peak field is known accurately by scaling Brookhaven data. The figure, which is surprisingly modest, is very nearly 5×10^6 joules.

The current required to reach 10,000 gauss with the 64-turn coil and a 3.5" gap is 1100 amperes peak. This is the sum of about 550 amperes direct current and about 390 amperes rms of 20-cycle alternating current. These figures would be changed slightly by detailed considerations of injection which would fix the minimum field, here assumed zero. The rms current (from which one computes heating) is 680 amperes. The coil losses

will be about 1200 kilowatts from the DC source, and 800 kilowatts from the AC source, of which 200 kilowatts are eddy-current losses.

The iron losses, principally hysteresis, will be below 500 kilowatts, probably closer to 300 kilowatts but, as these are difficult to estimate, the power supply calculations are based on the higher figure. There will be some stray eddy-current losses in the magnet core and clamps, mostly due to changes in flux distribution due to approach to saturation. An upper limit to these losses is estimated at 200 kilowatts.

3. Magnet Power Supply

To cycle a magnet with energy storage of 5×10^6 joules at 20 cycles per second involves a rate-of-energy transfer of several hundred megavolt amperes. This figure effectively rules out the use of rotating machinery for powering the magnet. Without unreasonable costs, the problem can be solved by resonating the magnet with condensers and providing the losses from a single-phase alternator. This sinusoidal excitation gives a favorable ejection duty cycle, but the rate of change of field at injection would be so high that high-current injection would be essentially impossible. In addition, the radio-frequency acceleration voltage required would be prohibitive, and eddy-current effects would be severe.

The solution to this problem was originally suggested by Westendorp and is in use at Cornell and Princeton. A direct current is superposed on the resonant alternating current such that the direction of the field never reverses. This system has many advantages: a) dB/dt at the injection field is independently adjustable; b) the maximum acceleration voltage re-

quired is halved; c) the radio-frequency voltage is low at the time when the frequency is changing; d) the rate-of-frequency modulation is considerably reduced; e) the maximum value of $(dB/dt)/B$ is comparable to a slowly cycled accelerator. In addition, the dissipation in the coils and especially in the magnet core is considerably reduced. This system requires a large choke, which is expensive, but its cost is partially offset by a reduction in the size of the condenser bank; the cost of the direct-current source is more than offset by the reduction in the size of the relatively expensive AC generator.

The basic circuit can be drawn as follows:

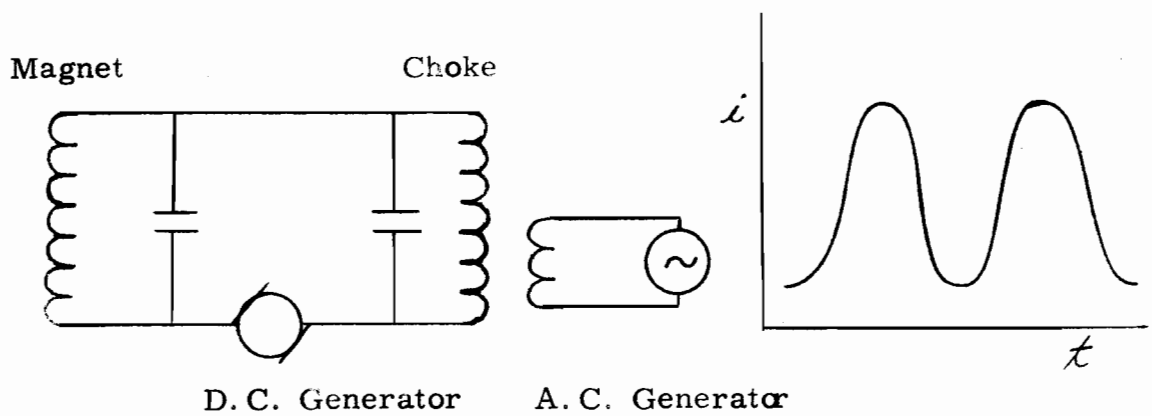


Fig. 2

Note that the choke is the primary energy storage element in the power supply system. When the energy in the magnet is minimum, dB/dt is zero so that there is no energy stored in the condensers. As drawn, the choke is also used as a transformer to isolate the AC generator from

direct currents. The cost of a choke is proportional to $(UL/R)^{3/5}$, where U is the peak energy storage and L/R is the time constant of the choke. Since the choke is the most expensive single item in the power supply system, its inductance is chosen to minimize the product of its energy storage and inductance, and its resistance is chosen as high as possible without unreasonable losses. An analysis of this system shows that the quantity UL is minimized by making the choke inductance equal to the magnet inductance. It would appear that a choke resistance equal to the magnet resistance would come close to the optimum. With this choice of choke inductance, the condenser bank must store at peak, one-half of the peak stored energy in the magnet.

It is obviously necessary to connect all of the accelerator magnets in series. Since the voltage across each magnet is 2400 volts rms, this cannot be done without making some change in the details of the power system connections to reduce the total voltage to ground. Except for the provision for inserting the DC generator, one notes that this circuit can be regarded as a series resonant circuit consisting of the magnets and its condensers, with a parallel resonant circuit consisting of the choke and its condensers acting as a direct-current bypass around the magnet condensers. The power system can then be connected as follows:

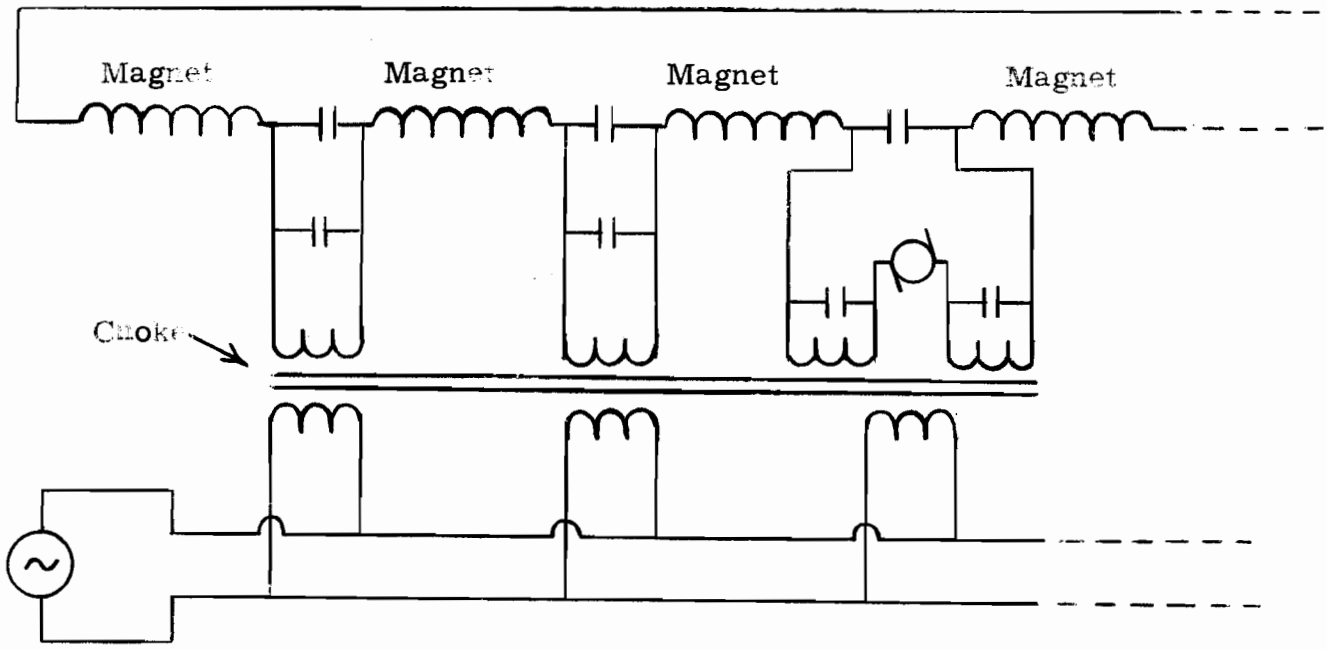


Fig. 3

It would appear that the magnets could be connected together in series in pairs to reduce the number of cables without excessive voltages. The choke for minimum weight should be a single unit, but this would be too large to manufacture and several would be required. One choke winding is shown split to provide the DC generator connections. The parallel connected primary winding on the choke serves as the AC feed as well as a method to increase the coefficient of coupling between the choke windings to move the many spurious modes of the system away from the operating frequency. The losses in the system (in kilowatts) are given in the following Table:

		AC	DC
Magnet Coils	(RI^2)	600	1200
Magnet Coils	(eddy)	200	
Magnet Iron		500	
Magnet Stray	(eddy)	200	
Condensers		900	
Choke		1000	1200
		3400	2400

A motor generator set with both DC and AC generators can provide this power. The speed can be controlled to keep the AC power source at the resonant frequency of the system.

4. Radio-Frequency System

Two rf systems were considered for this machine. The first system to be described is, essentially, the cavity system used in the Princeton machine, where the tuning of the system is done by saturating ferrite rings. The second system accomplishes the major portion of the FM cycle by mechanical tuning and trimming only was accomplished by ferrite.

The following Table contains the machine parameters that will define the rf system.

Table I

Injection	β =	0.567
Frequency at Injection	=	355 KC
Final Frequency	=	625 KC
Total Number of Straight Sections		40
Number Available for rf		35
Length of Straight Section		2 Meters, magnet to magnet 1.5 Meters clear
Max. Energy Gain per Turn		1.5 Mev/Turn

From a consideration of these parameters, the following were derived.

Table II

Harmonic Number	40
f_{inj}	14.2 mc
f_{final}	25.0 mc
Max. Volts/Turn	2.5 MV
Equilibrium Phase Angle	36°
Number of rf Stations	35
Max. Volts per Station	72 KV
Length of Cavity	1.5 Meters

(a) Cavity with Ferrite Tuning

The design of the cavity is then fixed by the properties of the ferrite. For Ferrite Type IVC, if one wants $\mu Qf = 2 \times 10^{10}$, the rf fields must be kept to less than 20 gauss. Princeton keeps the power dissipation in the ferrite to about 0.1 watt/cc. The initial $\mu = 150$ and final $\mu = 4$ at bias of $H = 100$ amps/cm.

These parameters lead to the following cavity design.

Table III

Inside Tube to Clear Beam	7.5 cm x 15 cm
Outside Radius	42 cm
Ferrite Size (Toroid)	$\ell = 1.5$ meters outside radius 42 cm thickness = 2.4 cm
Shunt Capacity	68 $\mu\mu$f
Weight of Ferrite per rf Station	460 Kg
Total Ferrite Weight	16.3 Tons
Average Power Dissipated/Cavity	$\sim$ 16 KW
Average Power in Ferrite	$\sim$ 3 KW
Total rf Power	$\sim$ 640 KW
Peak Bias Current	26,000 amps

The power as a function of magnet cycle phase is shown in the accompanying graph, Fig. 4.

It would seem from the above numbers that a somewhat better design would be to permit the rf fields to become greater than 20 gauss which would decrease the volume of the ferrite required at the expense of greater power dissipation in it. This would also decrease the bias current from the rather large value of 26 000 amps down to a smaller value. (The Princeton machine requires $\sim$ 15 000 amps.)

The above design represents only one "idiot-day" worth of design effort and a better system is clearly possible. However, within the scope of study for a high-repetition-rate AGS machine it is felt the above design does demonstrate that a suitable rf system should be realizable in practice at a reasonable cost.

(b) Variable Condenser Tuning with Ferrite Trimming

Calculations have been made for a drift-tube system because the geometry of drift tubes is especially suitable for condenser modulation. It was assumed that there are to be 35 drift tubes driven at the 40th harmonic of the cyclotron frequency of the beam.

The maximum energy gain of a proton traversing a drift-tube cavity is $E = 2 V_0 e \sin \frac{\varphi}{2}$, where V_0 is the peak voltage of the drift tube with respect to ground, and φ is the rf phase change during the time of traversal. For drift tubes 1.7 m long, $\varphi = 50.5^{\circ}$ so $V_0 = 86$ KV to give the required 2.5 Mev per turn assumed earlier. (This does not take into account the unequal spacing of the accelerating gaps in this magnet system, for which rf phase shift compensation can be used.)

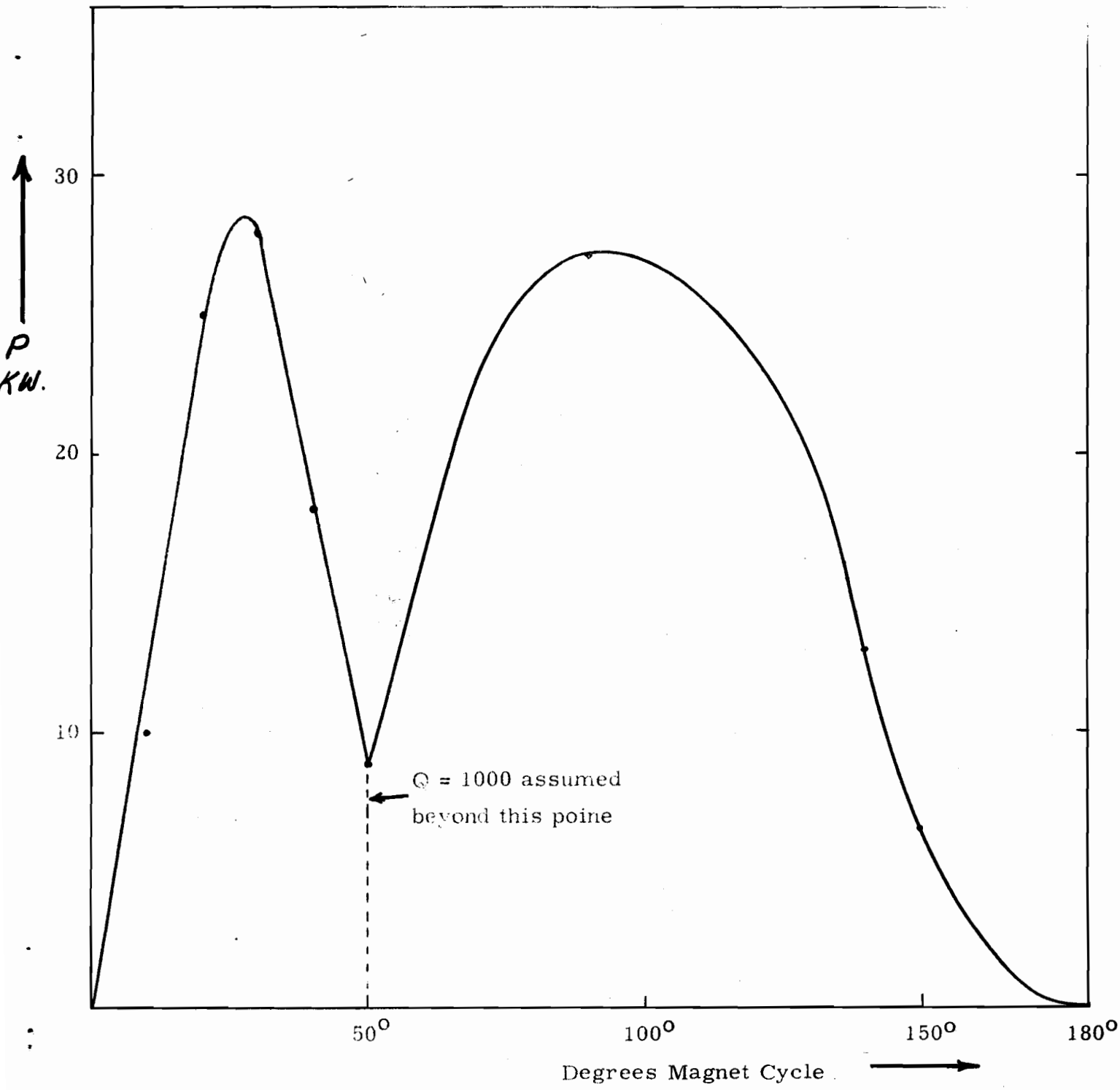
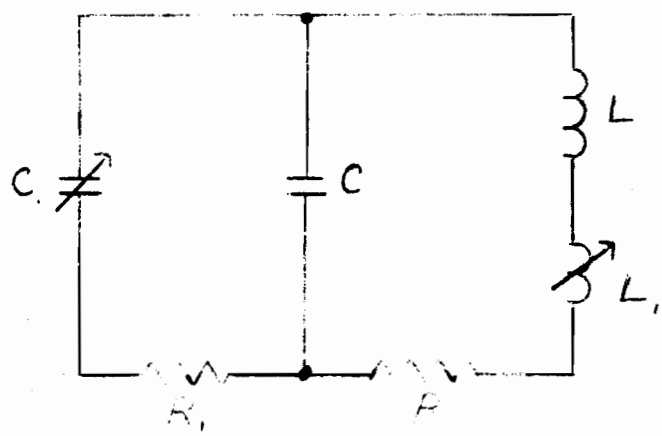


Fig. 4. RF Power vs. Magnet Cycle

It is assumed that each cavity consists of a drift tube attached to the end of a quarter-wave transmission line. The variable capacitor is assumed to consist of a rotor having a variable capacitance with respect to the drift tube and an approximately equal capacitance to ground. The effective variable capacitance between drift tube and ground will be denoted by C_1.

It is assumed that each transmission line is loaded with ferrite near the shorted end in such a way that the ferrite-tuned region acts as a small variable inductance in parallel with another fixed inductance.

The equivalent circuit of the cavity is:



C = drift tube capacitance to ground = 150×10^{-12} F

L_1 = effective inductance of ferrite-loaded and fixed inductances in parallel

Fig. 5. Equivalent Circuit of Drift Tube Accelerating Cavity

For the purpose of calculating resonance conditions on C_1-vs-time, L_1, R, and R_1 are neglected. Then $C_1 + C \simeq \frac{C}{\beta^2}$, so $C_1 = \frac{C}{1-\beta^2} - C$ γ. $C_1 + C$ is plotted against acceleration phase in Fig. 6. The interval of rapid variation extends only to 30 or 40 degrees; afterward the variation is quite slow. The most rapid variation is 11×10^{-12} F/degree, or 4.4% of $C_1 + C$ (taken as 250×10^{-12} F, the 20° value) per degree, corresponding to a frequency error of about 2.2% per degree. There seems to be no reason to doubt that a condenser can be built which would maintain the correct phase

relationship between magnet current at injection and the tuning cycle to within a tenth or even a hundredth of a degree throughout the cycle. This would seem to imply that a trimming correction of the order of $\frac{(C_1 + C)}{1000}$ would be adequate. However, in view of other uncertainties in the system, for example temperature-induced distortions changing C_1, or small variations in the amplitude of the AC component of magnet current, a larger amount of trimming must be provided. In the following discussion a tuning correction equivalent to $\pm$ 0.5% in $C_1 + C$ is assumed for the earlier part of the cycle.

The equivalent change in $L_1 + L$ is $\pm$ 0.5%. This can be provided by making L_1 variable by 1% of L. If L_1 consists of a ferrite-loaded inductance L_2 variable from 0.02 L to 0.75 L together with a fixed inductance L_3 = 0.02 L in parallel, L_1 ranges from 0.01 L to approximately 0.02 L. When L_2 = 0.02 L, the energy stored in L_2 is 1% of that stored in L. When L_2 = 0.75 L, its stored energy is quite small.

The rf power input to the ferrite in L_2 is given approximately by

$$P_2 = \frac{\omega W_2}{Q_f}, \text{ where } W_2 = \text{peak energy}$$

stored in L_2 during the rf cycle. Using W_2 = 0.01 W gives

$$P_2 = \frac{\omega}{100\, Q_f} \cdot \frac{1}{2} (C + C_1) V_o^2 = \frac{2 \pi \mu f^2}{(\mu Q_f f)} \cdot \frac{1}{2} C V_o^2$$

$$= 6.28 \times 10^{-36} f^2 C V_o^2 . \qquad \left(\begin{array}{l} \mu = 4 , \\ \mu Q f = 2 \times 10^{10} \end{array} \right)$$

Furthermore, if allowance is made arbitrarily for the reduction in anticipated tracking error by multiplying P by a factor $\frac{1 - \beta}{0.434}$ the power input to the ferrite through the acceleration cycle is as shown roughly

in Fig. 6.* The average rf power input is found to be about 245 watts per cavity; the total loss in ferrite is therefore 245 x 35 ≐ 8.6 KW.

For a loss density of 0.1 watts/cm^2 $\frac{8600}{0.1}$ = 86000 cm^3 of ferrite are needed, weighing 430 000 gms ≐ 0.5 tons.

To the rf losses in the ferrite must be added the losses in the copper. Assuming a Q of 1000 leads to an average loss of 21 KW per cavity, the total rf power required is thus approximately 735 + 9 ≐ 750 KW. This is to be compared with the figure of 640 KW for the all-ferrite tuned cavity system.

The power required for modulating the ferrite will of course be very much less in the drift-tube case.

Condenser-plus-ferrite tuning can also be applied to the simpler single-gap cavity, although the geometry is somewhat less favorable for the condenser.

It is concluded that the radio-frequency acceleration problem for the 15 Bev, 20-cps accelerator can be solved by either of the two approaches described above.

INTENSITY CONSIDERATIONS

The phase space acceptance of the accelerator in each mode is

$$A = \frac{\pi a^2 \beta}{RF}$$

where a is the semi-aperture of the mode and F the betatron oscillation beat factor. Allowing 1 cm for orbit error, and 1 cm (radial) for synchrotron

*The low dissipation is partly due to the use of the reduction factor $\frac{1 - \ldots}{0.434}$, which is only possible in an actual system if care is taken to avoid overloading the ferrite by use of a safetying device.

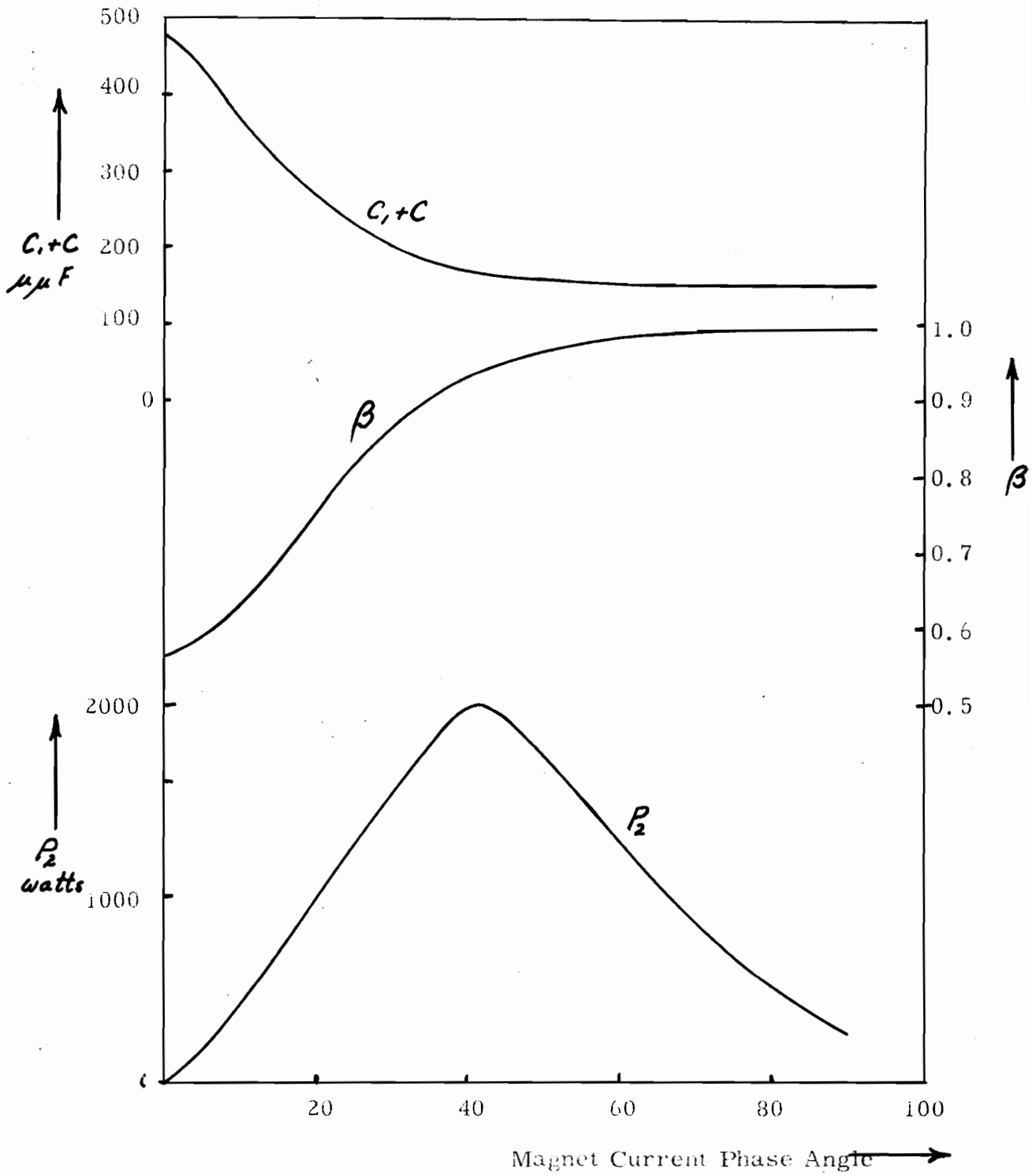

500
400
300
200
100
0
2000
1000
C₁+C
μμF
C₁+C
β
P₂
P₂
watts
1.0
0.9
0.8
0.7
0.6
0.5
β
20
40
60
80
100
Magnet Current Phase Angle

Fig. 6

oscillations at injection, we have a net aperture of 5 x 13 cm so that a = 2.5 for vertical, a = 6.5 for horizontal. With R = 7600 cm F = 1.6 ν = 6.25, we find

$$A_{vert} = 1.0 \times 10^{-2} \text{ cm-radian}$$

$$A_{hor} = 6.7 \times 10^{-2} \text{ cm-radian} .$$

Assuming an emittance of 2×10^{-3} cm-radian from the linac, there is room for 34 turns radially and 5 turns vertically, or altogether about 170 turns of injection if perfect optical procedures can be worked out.

The space charge limit is given by the MURA formula

$$I = 3 \times 10^{7} f \left(\frac{a}{R}\right)^{2} (\beta\gamma)^{3} \nu \Delta\nu$$

where β and γ are the values at injection, $\Delta\nu$ is the maximum detuning that can be tolerated, and f is the fraction of the circumference occupied by the injected bunch. An equivalent formula is

$$N = 10^{14} \times \frac{f \pi a^{2}}{R} T_i \frac{\gamma(\gamma+1)}{2} \nu \Delta\nu$$

where N is the number of particles per pulse, T_i is the injection kinetic energy in Mev, a and R are in cm, and γ is the value at injection.

Strictly speaking, a^2 in these formulas should be replaced by a b, the product for horizontal and vertical modes, since the charge density for a total number of particles is inversely proportional to a b R. Taking a = 2.5, b = 6.5, R = 7600, T_i = 200, γ = 1.21, f = 1/2, $\Delta\nu$ = 1/4, we obtain a space charge limit of

$$N = 1.4 \times 10^{14}, \qquad I = 2.1 \text{ amps}.$$

At 20 pulses per second, this is equivalent to a current of 460 microamperes.

Assuming the linac produces one milliampere, a single turn injected with f = 1 (assuming that bunching takes place just after injection, and that all particles are captured into buckets) corresponds to 0.06 microamperes time average. Thus 8000 milliampere turns must be injected to reach the space charge limit. If the emittance of the linac is 2×10^{-3} cm-radians as assumed, and we assume a maximum efficiency of 50% in filling phase space (80 turns injected), the linac would need 100 milliamperes. More realistically, we may hope for perhaps 5 milliamperes and 10 turns of injection, yielding a time-average current of 3 microamperes.

COST ESTIMATE

This estimate has been based chiefly on actual costs of the Brookhaven AGS, with appropriate scaling, together with figures from Princeton and Cambridge experience. However, certain costs have not been included.

If this machine were to be built as a single Laboratory (as in the MURA proposal) rather than as part of an existing Laboratory (such as Brookhaven) extra costs would be involved to provide for necessary auxiliary facilities such as a high-voltage substation, extra shops, steam plant, purchasing and general administrative personnel, etc.

This estimate, also, does not include any funds for experimental equipment for using the machine. Based on present experience, the annual running cost for operating large accelerators and providing experimental equipment

and facilities seems to be about 25 to 30 per cent of their construction cost. Omitted, also, are estimates for escalation and contingency funds.

1. Buildings

Costs for the tunnel housing the magnet ring have been taken to be 3/5 that of BNL, and include air conditioning and magnet foundations of the same simplicity. For the 200 Mev linac, the extra length of building has been scaled directly from Brookhaven costs--it is assumed that the rather crowded conditions there would be adequate. The experimental area has been increased to four times the Brookhaven Target Building to correspond to the area for single beams mentioned in the MURA proposal. This might be divided into two separate areas. Estimates for the shielding are based on an assumed wall thickness about 50 per cent greater than at BNL and the extra length needed for the larger experimental areas. It has also been compared with the Brobeck-MURA estimate. The office-labs-shops building has been increased to about 30 per cent greater than that at present in use at Brookhaven, since this has proved inadequate. The land improvements and utilities figure is taken directly from BNL and includes such items as grading, seeding, roads, sewer, electric, telephone, etc. This item would be considerably larger if the machine were not to be part of an already existing Laboratory.

Breakdown:

Ring Tunnel	$ 1.5 million
Linac Building	1.5
Experimental Areas	5.0
Shielding	2.5
Offices, Labs, Shops, Control Rooms	1.5
Water Cooling System	1.2
Land Improvement and Utilities	0.8
Architectural Engineering	1 to 2
Total for Buildings	$15 to 16 million

2. Linear Accelerator (200 Mev)

The cost of the preaccelerator part is assumed the same as Brookhaven. This includes an 800 kv Cockcroft-Walton set, requisite spare parts, ion source, vacuum and controls, viewing boxes, etc. The rf system will have to be different from that now installed at Brookhaven because of the larger average power requirements, but the price of such equipment is fairly well known. The tanks and drift-tubes prices are scaled directly from Brookhaven's as are the costs of vacuum pumps and their controls. It is assumed that the cost of the injection system connecting the linear accelerator to the synchrotron will be about the same as Brookhaven's.

Breakdown:

Preaccelerator	$0.2 million
RF System	2.0
Tanks and Drift Tubes	2.0
Vacuum System	1.0
Injection System Linac to Synchrotron	0.3
Total for Linear Accelerator	$5.5 million

3. Magnet

Although only about 2500 tons of steel will be used in this machine, the cost of the cores will be about the same as Brookhaven's (4000 tons). First, the steel must be a higher percentage of silicon and, using Princeton's cost figures, the price per pound of such sheet steel is about 50 per cent greater. The cost of the dies will be the same. The cost of fabrication has been scaled down as has that of the auxiliary hardware, such as jacks, clamps, trimming windings.

The coils of this machine can be made of stranded cable like those of the Cambridge Electron Accelerator. Similar stranded cable would be used to connect the power supply to the coils. It was felt that, in order not to be over-optimistic on prices, the same cost as Brookhaven's would be used.

Breakdown:

Magnet Cores and Auxiliary Hardware	$3.2 million
Coils and Connecting Cable	2.2
Magnet Testing Equipment	0.25
Surveying and Erection	0.15
Total for Magnets	$5.9 million

4. Magnet Power Supply

These estimates are based on Princeton experience. It is assumed that DC power costs about $100/KW and single phase 20 cycle AC power costs about $200/KW. The condensers, complete with racks, fuses and interconnecting busses cost about $0.50/joule at 20 cycles. The cost of the choke is estimated by noting that UL/R for our choice of parameters is 10.4×10^6 joule-seconds. Princeton has a firm quotation of about $700,000 for a choke with UL/R = 6.9×10^6 joule seconds. This Princeton choke is about as big as could be manufactured, so that several units would be required. Possibly, the best choice would be one choke per superperiod, but two or four chokes could be used. The estimate is based on a choice of four units.

Breakdown:

Chokes	$2.4 million
Condensers	1.25
Motor Generator Including Switchgear	1.0
Exciters for MG set	0.1
Substation for MG set	0.15
Total for Magnet Power Supply	$4.9 million

5. Radio-Frequency System

The cost of this component will depend on the type of system chosen. At Princeton, the first rf station plus development cost $0.75 million and the next three cost $0.1 million each. Thus it was estimated that 35 stations together with the necessary electronics might cost $3 to 4 million.

6. Vacuum System

The vacuum chamber is assumed to be similar to the Cambridge design. Pumps, gauges and controls have been scaled from Brookhaven costs.

Breakdown:

Vacuum Chambers	$0.4 million
Pumps and Gauges	0.2
Controls	0.1
Special Sections for Injection, Targets	0.1
Total for Vacuum System	$0.8 million

7. Controls

The general controls, including the main control room, should cost about the same as those at Brookhaven, namely, about $0.75 million.

8. Preliminary Design and Development

Although many of the components are based on items already fairly well designed, a certain amount of modeling would be necessary, particularly for the radio-frequency system. Thus about $1 million has been budgeted for this item.

9. Salaries and Administrative

It was assumed that about the same number of total staff would be necessary to build this machine as has been required for the Brookhaven AGS. These costs would then be about $6 million, for a six-year program.

10. Critique on Costs

The grand total of the above items is about $45 million. This is about 50 per cent higher than the cost of the Brookhaven AGS of twice the energy.

The difference in price can be broken down into three main items.

(a) Costs of larger buildings and shielding amounting to about $5-1/2 million. The greater part of this is for the fourfold increase in enclosed experimental space. Brookhaven is going to try out the use of large open paved areas, with underground power and water, and with cheap portable buildings. Experience will show whether this is feasible or whether some large extra cost will have to be added, in the future.

(b) Costs of raising injection from 50 Mev to 200 Mev, amounting to about $5 million. Further study might show that this could be cut down to 100 Mev without proportionately raising the cost of the radio-frequency system. One does gain in possible intensity by a factor that may be of the order of 10 (or higher with ideal injection techniques).

(c) Costs of 20-cycle operation, amounting to about $6 million. The Brookhaven AGS can be operated up to 10 or 12 Bev at one cycle per second without any change in design or cost. Thus this price can be equated, almost exactly, to a factor of 20 in intensity.