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DESIGN STUDY FOR A 1000-MEV BOOSTER SYNCHROTRON INJECTOR
FOR THE BROOKHAVEN AGS

MASTER

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I. Introduction

I-1. Background

In the May 1964 Proposal for the AGS Conversion program¹ a section (II-4) was devoted to the choice of the new injector whose higher energy was to make possible injection of larger numbers of protons than could be provided with the present 50-MeV linear accelerator. At that time, the proposed energy for the new injector was 500 MeV. Injector types considered were as follows:

- a) A 500-MeV linear accelerator.
- b) An isochronous cyclotron.
- c) An FFAG accelerator.
- d) A rapid cycling synchrotron.

The discussion of these injectors presented at that time can be summarized as follows:

a) The linear accelerator meets all of the performance criteria easily and appears technically to be preferable to the other possibilities. The only real basis on which it can be challenged is cost.

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

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b) The isochronous cyclotron has not been tested at such a high energy and it is not clear that a satisfactory beam can be extracted from it. Its cost is comparable with that of a linac.

c) The FFAG accelerator has been tested to 50 MeV (with electrons) but not above. It also appears to be as costly as a linac, if not more so.

d) The rapid cycling synchrotron involves less in the way of extrapolation of known techniques. It was the first choice as the injector for the American 200-BeV accelerator and the European 300-BeV machine. The 200-BeV injector (as described in the 1965 LRL "200-BeV Accelerator Design Study") is to be an 8-BeV synchrotron cycled at an 18 per second rate and requires 7 cycles (or 0.33 second) to fill the main ring. Its radius is one seventh of the radius of the 200-BeV ring. Its injector is a 200-MeV linac. The 300-BeV injector (as described in the 1964 CERN "Design Study of a 300-GeV Proton Synchrotron") is also an 8-BeV synchrotron cycled at 20 per second and requiring 12 cycles (or 0.6 second) to fill the main ring. Its radius is one twelfth that of the main ring. Its injector also is a 200-MeV linac. Although it appeared that such a synchrotron might be adapted to be useful as a new AGS injector, the necessity for rapid cycling would add drastically to its cost and complexity. Also the long period required for injection would slow down the ultimate cycling rate of the AGS and would introduce problems in maintaining the magnetic field of the AGS at a steady low value during the injection process.

In the light of these arguments (presented in more detail in the Proposal) it was decided that a 500-MeV linac was the appropriate choice for the new AGS injector.

In 1965 the AGS Conversion program was divided into two phases of which only Phase I was to be undertaken immediately. In Phase I the injector energy has been reduced to 200 MeV. The question of the appropriate choice of injector was reconsidered. Again the linac seemed to be the best choice.²

2. Alternating-Gradient Synchrotron Conversion Program, Scope of Phase I, September 1965 (BNL 9500).

At about this time some new considerations began to enter the field of injector design. At Brookhaven the rapid cycling injector was not regarded with favor and Brookhaven's Accelerator Department set about developing a more attractive alternate which had been under consideration for some time. Because space-charge limits for small synchrotron rings are not less, under appropriate circumstances, than those of larger rings for the same energy it seemed that all of the charge needed for injection into a super-energy ring could be stored in one pulse of an injector synchrotron and then transferred to fill the large ring by multiturn ejection. Ejection would take place over ten to twenty turns of the injector; this would be intermediate between rapid, single turn ejection and slow, several hundred turn ejection, both of which are presently in use. Although the intermediate technique had not been tested it was considered probably to be feasible and the new injection method was proposed by Brookhaven at the CERN-BNL-LRL super-energy coordination session held at CERN on April 6 and 7, 1965.

After the April, 1965 meeting the injector question was re-examined both at CERN and at LRL. At CERN several new injection systems were evolved including the interlaced ring system known as TART (invented by W. Hardt). Originally the TART scheme consisted of two interlaced rings but it was quickly shown that three or more interlaced rings were possible. At LRL a modification of the TART system using weak focusing magnets in four interlaced rings was proposed by A. Garren. This injector has been given the name QUART. In the meantime computer studies were undertaken at Brookhaven of the multiturn ejection process necessary for the "slow cycling booster synchrotron." The computer studies revealed three possible approaches:

a) Radiofrequency stimulation of betatron oscillations to amplitudes where they become unstable.³⁻⁵

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3. D.S. Robertson, "Multiturn Beam Extraction in AG Synchrotrons," BNL Accelerator Dept. Internal Report AADD-85, June 10, 1965.
 4. D.S. Robertson, "Stimulated Slow Extraction," BNL Accelerator Dept. Internal Report AADD-97, February 14, 1966.
 5. D.S. Robertson, "Bunched Beams from Resonant Slow Extraction Systems," BNL Accelerator Dept. Internal Report AADD-123, September 19, 1966.

b) Ordinary resonant extraction as used in the slow external beams of the CERN PS and to be installed at the AGS.⁶

c) The inverse of multiturn injection.⁶ In this method the equilibrium orbit is distorted locally until the beam is pushed across the septum of an extraction magnet.

Analysis of these various extraction methods indicates that all are possible. The extraction problem will receive further attention in the body of this report (Section III-10).

Two further CERN-BNL-LRL coordination sessions were held during 1966 on February 16-18 (at BNL) and on September 12-14 (at LRL). A large part of both meetings was devoted to injection questions. In addition, a two-week injection meeting was held from April 27 to May 10 partly at BNL and partly at LRL. During this session all facets of the injection problem were explored in detail.

The question of the appropriate injector for a super-energy accelerator is by no means resolved. Each laboratory has its own preferences and no general agreement exists. Probably this is due to insufficient study of the various alternates, and to the fact that, in all probability, the various injectors proposed will not differ importantly in performance or cost.

The disorderly situation described above has its implications for the various synchrotron improvement programs. New injectors are proposed for the CERN PS, for the AGS, and for the ZGS. At CERN another year of study is planned, but multiple ring injectors seem to be strongly favored. At Argonne, virtually all of the possibilities are still under study. At Brookhaven, work on the 200-MeV linac injector is far advanced; nevertheless it has been decided that a new look should be taken at booster synchrotrons. Consequently a study group was organized at the beginning of August, 1966, this group to submit, after a three or four month study, a report including a cost estimate

6. K.H. Reich, "Decaturn Beam Extraction from Synchrotrons," BNL Accelerator Dept. Internal Report AADD-100, April 6, 1966.

for an alternate synchrotron injector. The members of the study group are listed as the authors of this report.

The study group has undertaken a design study for an injector synchrotron having as its injector either a 50-MeV or a 200-MeV linac. It is hoped that, on the basis of this study, it will be possible to answer the following two questions:

- a) As part of Phase I of the AGS Conversion, is an injector synchrotron with 50-MeV injection preferable to the 200-MeV linac originally proposed?
- b) What are the relative advantages of 200-MeV injection over 50-MeV injection into a booster synchrotron? More generally, what is the optimum injection energy for a booster?

Since the answer to the first question is needed immediately, primary emphasis in this report is given to the design of a booster synchrotron with 50-MeV injection.

I-2. Choice of Injector Synchrotron

The injector study group decided almost immediately to concentrate on the slow cycling synchrotron that has continually been preferred at Brookhaven. The disadvantages of rapid cycling synchrotrons have already been outlined. The various interlaced ring schemes proposed at CERN and at LRL were felt to present too many untested features and were expected to be considerably more expensive and complex in their operation. Moreover the interlaced ring devices are in so early a stage of development that new variants are appearing continually. Since it is expected that construction of the new AGS injector can begin almost immediately it seemed that attention should be concentrated on the injector that seemed to the study group to promise the most satisfactory performance and the lowest construction cost.

I-3. Choice of Injector Energy

Since it appears desirable to use the same radiofrequency in the booster at full energy as is used in the AGS at the time of transfer from the booster into the AGS, and since the frequency of the accelerating field in the AGS is the twelfth harmonic of the frequency of revolution, the circumference of the booster cannot be reduced to less than one twelfth of the circumference of the

AGS. For most reasonable lattice configurations in the booster about half of the booster circumference will be occupied by magnets. A reasonable peak field for these magnets is about 10 kilogauss - a field at which saturation effects still are not troublesome. At this field the proton energy will be about 1000 MeV. Limitation of the field to lower values will result in very small savings - only minor savings in magnet cost and in magnet power supply cost will result and there will be no saving in cost of buildings, vacuum systems, control systems, etc. Hence a peak booster energy of 1000 MeV has been chosen.

At an injector energy of 1000 MeV it is, in principle, possible to inject into the AGS five times as many protons as can be injected at 200 MeV. Although many problems of transfer of charge into the booster and from the booster into the AGS remain to be solved, it seems reasonable to predict that with a 1000-MeV booster an improvement factor in intensity of at least three should be possible compared with a 200-MeV linac injector. Since 200-MeV injection is expected to raise the AGS intensity to about 10^{13} protons per pulse, an intensity of 3×10^{13} protons per pulse will be used in choosing the parameters of the booster synchrotron.

II. Basis for Booster Design

II-1. Basic Design Parameters

Before proceeding into the details of booster design, several design principles were established; these, in turn, fixed some of the basic parameters of the injector synchrotron. The choices are listed in the table below. The reasons for these choices are outlined in the sections that follow.

Final Booster Energy	1000 MeV (see Section I-3)
Intensity	3×10^{13} protons per pulse (see Section I-3)
Mean Radius	10.705 m (= 35.12 ft) (= 1/12 of mean radius of AGS)
Circumference	67.26 m (= 220.67 ft)
Rf Harmonic Number	First
Repetition Rate	2 per second
Rise Time to Full Energy	1/4 second
Transition Energy	1.1 to 1.2 BeV
Injection Energy	50 MeV (or possibly 200 MeV)
Horizontal Admittance	160π cm-mrad (or 32π cm-mrad for 200-MeV injection)
Vertical Admittance	64π cm-mrad (or 13π cm-mrad for 200-MeV injection)
$\beta_{\max}$	Less than 10 m

II-2. Mean Radius and Rf Harmonic Number

Since the rf accelerating system in the AGS operates on the twelfth harmonic, the booster radius has been chosen to be exactly one twelfth of the AGS radius. By use of the first harmonic in the booster, and by use of twelve turn extraction from the booster, the bunch pattern at transfer will be exactly that required in the AGS and no debunching and rebunching in the AGS will be required.

II-3. Booster Cycle

After the Conversion the AGS can be cycled to full energy once per second. It will then be possible to cycle the AGS to half energy twice per second. At present the AGS is never cycled to less than half energy; indeed most of its operation is at final energies near 30 BeV. Consequently it was decided that the maximum cycling rate necessary for the booster is twice per second. Rise time to full booster energy would be about 1/4 second.

II-4. Transition Energy

The energy corresponding to phase transition in the booster is to be set above its maximum energy so that it will not be necessary to include means for passing through this transition. In so small a ring it will be difficult to design for a phase transition very much higher than 1 BeV. There are,

however, advantages in setting the phase transition energy rather close to the final booster energy. As the phase transition is approached the amplitude of phase oscillations damps continually toward a very small value characteristic of the transition energy. The amplitude of radial oscillation (or the momentum spread), on the other hand, is initially damped, passes through a minimum, and then increases toward a rather large value characteristic of the transition. By choosing a transition energy not much higher than the final booster energy, it is possible to match the bunch shape extracted from the booster to the bucket shape in the AGS so that acceleration can proceed immediately in the AGS with no further matching procedures. Derivation of the appropriate booster transition energy is as follows:

The bunch shape in either the booster or the AGS can be described by the ratio of the momentum error Δp to the physical length L of the bunch. In terms of the relevant parameters this ratio is given by

$$\frac{\Delta p}{L} = (\text{a constant}) \sqrt{\frac{eV/R}{1/\gamma^2 - 1/\gamma_{Tr}^2}}$$

where eV is energy gain per revolution

R is machine radius

γ = (total proton energy) / (proton rest energy)

γ_{Tr} = value of γ at phase transition.

When the above ratio is matched between booster and AGS the value of γ_{Tr} for the booster proves to be 2.23, corresponding to a kinetic energy at transition of 1.15 BeV.

The transition energy derived above is such that the radial excursion (and hence the momentum error) at 1000 MeV is above the minimum. The radial excursion is given by

$$\Delta r \propto \gamma^{3/4} (\gamma_{Tr}^2 - \gamma^2)^{-1/4} (\gamma^2 - 1)^{-1/2}$$

whence the minimum radial excursion occurs at $\gamma = 1.73$ or a kinetic energy of 680 MeV. At 1000 MeV the radial excursion or the momentum error has increased to about 16 percent higher than the minimum value.

II-5. Booster Admittance

Although the achievable space-charge limit in a synchrotron is not yet well established, the basic phenomena involved are reasonably well understood and it is possible to state with some assurance that the number N of protons that can be injected into a synchrotron should obey the relation

$$N = (K \Delta v) \sqrt{A_V} (\sqrt{A_H} + \sqrt{A_V}) \beta^2 \gamma^3$$

where K is a constant independent of machine radius, aperture and v -value

A_V and A_H are the vertical and horizontal admittances of the synchrotron

β and γ are the usual parameters describing proton velocity and energy .

In the AGS, A_V and A_H are 4π and 12π cm-mrad, respectively.

The most conservative procedure would appear to be to assume that the AGS is space-charge limited at its present maximum of 2×10^{12} protons per pulse. If the booster synchrotron is to make possible acceleration of 3×10^{13} protons per pulse in the AGS its admittances must satisfy

$$\sqrt{A_V} (\sqrt{A_H} + \sqrt{A_V}) = \frac{3 \times 10^{13}}{2 \times 10^{12}} \sqrt{4\pi} (\sqrt{12\pi} + \sqrt{4\pi}) = 164 \pi .$$

Reasonable values that satisfy this relation are $A_V = 64\pi$ cm-mrad

$$A_H = 160\pi \text{ cm-mrad} .$$

If the admittance of the booster is filled at 50 MeV, the emittance of the beam in the booster after acceleration to 1000 MeV will be given by

$$E_V E_H = \frac{(\beta\gamma)_{50 \text{ MeV}}^2}{(\beta\gamma)_{1000 \text{ MeV}}^2} 64\pi \cdot 160\pi = 343 \pi^2 (\text{cm-mrad})^2 .$$

If a perfect extraction over twelve turns is achieved, the beam entering the AGS will have an emittance product of $343 \pi^2/12$ or $28 \pi^2$. The emittance can undergo a dilution during the extraction process by a factor of almost two and still will be able to fit into the AGS admittance of $4\pi \times 12\pi$.

The arguments presented above relate to injection into the booster at 50 MeV. If the booster injection energy is raised to 200 MeV its admittance (and hence its aperture) can be reduced. Since the product $\beta^2 \gamma^3$ at 200 MeV is

higher by a factor of about five than it is at 50 MeV, the booster admittances for 200-MeV injection must satisfy

$$\sqrt{A_V} (\sqrt{A_H} + \sqrt{A_V}) = 32.8 \pi .$$

Reasonable values to satisfy this relation are $A_V = 13 \pi \text{ cm-mrad}$

$$A_H = 32 \pi \text{ cm-mrad} .$$

The emittance product at 1000 MeV after perfect twelve turn extraction will be about $16 \pi^2$. In this case dilution in the extraction process by a factor of three will be tolerable and will still permit containment of the 1000-MeV beam in the AGS aperture.

If the AGS aperture is filled at 1000 MeV, the emittance product at 30 BeV will be

$$E_V E_H = \frac{(\beta\gamma)_{1000 \text{ MeV}}^2}{(\beta\gamma)_{30 \text{ BeV}}^2} 4\pi \cdot 12\pi = 0.14 \pi^2 (\text{cm-mrad})^2 .$$

This product is higher by a factor of about 30 than the emittance product when, as at present, the AGS aperture is filled at 50 MeV. The dimensions of the 30-BeV beam will be $30^{1/4}$ or about 2.4 times those of the present accelerated beam.

II-6. Limitation on $\beta_{\max}$ and Choice of Booster Aperture

When the required admittance for a synchrotron has been fixed the size of the aperture required is given by

$$a^2 = A \beta_{\max} / \pi (\text{meters})^2$$

where a is the semi-aperture (in meters)

A is the admittance in meter-radians

$\beta_{\max}$ is the maximum value of the Courant-Snyder β function (in meters).

After some preliminary exploration of possible lattices for the booster synchrotron it became evident that an upper limit of about 10 m could be assigned to $\beta_{\max}$. Lattices which required larger excursions of β were excluded from consideration. In the lattice finally chosen (see Section III-2

below) $\beta_{\max}$ has a value of 8.35. Using this value together with the admittance figures derived in the preceding section the following aperture figures have been derived. The figures tabulated are full aperture (not the half aperture given by the formula at the beginning of this section). These figures represent aperture inside of the vacuum chamber. Magnet gaps will be somewhat larger because of finite thickness and deflection of vacuum chamber walls and because space must be left for poleface windings.

	<u>50-MeV Injection</u>	<u>200-MeV Injection</u>
Vertical aperture	6.0"	2.7"
Horizontal aperture	9.5"	4.2"

Evidently, for 200-MeV injection the booster magnets will be somewhat smaller in cross section than the AGS magnets. For 50-MeV injection the booster magnets will be about twice as large in cross-sectional dimensions as the AGS magnets.

Because of the low ν -value and because of the relatively large aperture, aperture requirements for magnetic field errors and magnet misalignments will be very small. For the purposes of this study they will be neglected. Horizontal aperture required for phase oscillations also is small (less than 2 cm).

II-7. Choice of Injection Energy

The process of 50-MeV injection into the booster will be treated in more detail in Section III-9 below. Here only a brief comparison between 50-MeV and 200-MeV injection will be presented.

The emittance of the injected beam at 200 MeV will be about a factor of two lower than the beam emittance at 50 MeV. Hence the decreased admittance of the booster with 200-MeV injection will be matched by the smaller emittance of the beam to be injected. But at 200 MeV almost twice as many turns must be injected for the same final intensity since the velocity of a 200-MeV proton is about twice that of a 50-MeV proton. For a 100 mA, 50-MeV injected beam about 67 turns must be injected to reach a total charge of 3×10^{13} protons (cf. Section III-9). At 200 MeV about 120-turn injection will be required.

At 50-MeV injection it seems possible to inject a complete charge into radial phase space only. At 200 MeV it will probably be necessary to inject also into vertical phase space. Although such injection is quite possible in principle, it has not yet been tried in any AG synchrotron.

III. Booster Synchrotron Design

III-1. Injector

As was noted in the introductory section, primary emphasis in this study is on an injector synchrotron with 50-MeV linac injection. Some consequences of raising the linac energy to 200 MeV already have been noted. In this section, however, design efforts have been directed exclusively to boosters with 50-MeV injection.

Intensive study has been given to the question as to whether the 50-MeV injector should be the present AGS injector with suitable modifications. Section IV below will be devoted to answering this question.

III-2. Lattice Structure for Injector Synchrotron

A number of possible lattices for the injector synchrotron have been explored and, in the course of the exploration, a set of criteria for choice of lattice evolved. These were as follows:

- a) The transition energy should be between 1.1 and 1.2 BeV (cf. Section II-4).
- b) $\beta_{\max}$ should be less than 10 m (cf. Section II-6).
- c) Straight sections of 1.5 meter length or more should be available for injection and ejection gear.
- d) If possible all magnet back legs should be inside of the ring, keeping as much external space as possible clear for injected beams and particularly for ejected beams.
- e) The lattice should, if possible, be conventional in design and not use extreme or untested components.
- f) The ν -value should be chosen, consistent with the lattice symmetry, to make possible inclusion of orbit distorting magnets at distances one quarter wavelength upstream and downstream from injection and ejection points.

- g) Super-stopbands corresponding to low order symmetries should be avoided.

The lattice finally chosen involves a simple FODO sequence repeated twelve times. In its first version all magnets were 1.275 m long and all straight sections were 1.48 m long. Two possible combinations of K-values ($K = \frac{1}{B} \frac{dB}{dr}$) were evaluated with the following results:

K in D magnets (m^{-1})	-1.95	-1.55
K in F magnets (m^{-1})	2.10	1.75
Horizontal ν -value	2.71	2.28
Horizontal β_{max} (m)	8.46	8.36
Horizontal β_{min} (m)	2.1	2.9
Vertical ν -value	2.8	2.3
Vertical β_{max} (m)	8.0	8.1
Vertical β_{min} (m)	2.0	2.9
Transition energy (BeV)	1.42	1.10

This lattice satisfies all of the important criteria and has the advantages of simplicity and accessibility since all back legs can be kept inside of the orbit ring.

A number of modifications to this lattice have been studied. In its final form the straight section downstream from the F magnet has been lengthened to 1.9 m to allow more space for extraction systems. Final parameters of the lattice are:

K (m^{-1}) in both F and D magnets	1.75
Length of F magnets (m)	1.42
Length of D magnets (m)	1.28
Length of F-D straight section (m)	1.905
Length of D-F straight section (m)	1.00
Horizontal ν -value	2.331
Vertical ν -value	2.373
Horizontal β_{max} (m)	8.35
Vertical β_{max} (m)	8.35
Transition energy (BeV)	1.125

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The configuration of the injector ring using this lattice is shown in Fig. 1. Also shown in this figure are possible locations for injection and ejection gear and rf accelerating stations.

Other lattices studied included the following:

a) A hybrid lattice shown in Fig. 2a. One of the twelve superperiods of this lattice includes a focusing magnet of length 2.445 m, a short straight section 0.60 m long for coil ends, a defocusing quadrupole 0.40 m long, and a long straight section 2.155 m long. This lattice has the advantage of providing twelve rather long straight sections and of using rather low K-values (possibly as low as 1.0) in the F magnet. It has the disadvantage of requiring quadrupole back legs outside of the ring. This lattice was the second choice but finally was rather arbitrarily rejected in favor of the FODO lattice.

b) A separated function lattice, one of whose eight superperiods is shown in Fig. 2b. The superperiod consists of a horizontally defocusing quadrupole, a 1.2 m bending magnet, a focusing quadrupole, a bending magnet, a defocusing quadrupole, a 1.8 m straight section, a focusing quadrupole, and a second 1.8 m straight section. All quadrupoles are 0.30 m long and all short straight sections are 0.30 m. This lattice has the advantage of two contiguous long straight sections but was rejected because of the presence of magnet and quadrupole back legs outside of the orbit.

c) A spiral edge lattice consisting of 18 superperiods like the one shown in Fig. 2c. It consists of one zero gradient magnet with rather extreme wedge focusing at its ends, and a 2.45 m straight section. This lattice, though intriguing, was rejected as involving an untested and probably troublesome magnet design.

d) A lattice with four π -phase-shift straight sections, one superperiod of which is shown in Fig. 2d. Quite low K-values are required in the bending magnets in this lattice. It was rejected as being too great a departure from standard practice.

$D = 70'$
 $F = 1.4M$
 $D = 1.25M$
 $A_1 = 1.9M$
 $A_2 = 1.0M$

Fig. 1. FODO lattice showing injection, ejection, rf stations and betatron acceleration stations.

(a)

(b)

(c)

(d)

Fig. 2. Other lattices considered.

III-3. Magnet Design

The total magnet length shown in the lattice of Fig. 1 is 32.4 m, whence the peak field at the equilibrium orbit for 1000-MeV protons should be 11 kG. In practice, however, it is found that the effective bending length of a magnet is longer by about one gap width than the physical magnet length. If the physical magnet lengths are those listed in the preceding section, the total bending length will be more than 10 percent greater than the length shown and the orbit field will be reduced to about 10 kG. This approach has been chosen and magnet design is for a peak orbit field of 10 kG.

The K-value of 1.75 m^{-1} will also be affected by end effects. This effect, however, is much smaller than the effect on the bending field and, for the purposes of this study, it has been neglected.

As shown in Section II-6, a vertical aperture of 6.0 inches is required inside of the vacuum chamber. It is assumed that the wall thickness of the vacuum chamber (including its deflection under evacuation) will be 1/4 inch and that pole face windings 1/4 inch thick will be required on both poles. Hence the magnet gap at the equilibrium orbit will be 7.0 inches.

The radial aperture over which good field is required was shown in Section II-6 to be 9.5 inches. At least two extra inches are desirable to accommodate sagitta, phase oscillations, and the distorted orbits required at ejection. Hence it would seem desirable to provide about 12 inches of good field at full energy.

Since the aperture dimensions are almost exactly twice those provided in the AGS magnet, the first approach to magnet design was a direct scaling of the AGS magnet by a factor of two except that it seemed reasonable to increase somewhat the current density in the coils and hold their dimensions to less than twice those of the AGS magnet coils. Using computer procedures developed during our magnet studies for super-energy accelerators, the pole contour was modified to give a field having a K-value of 1.75 m^{-1} . It was found that the final magnet gave a radial field distribution whose gradient up to 10 kG was correct to within 1.5 percent over a radial extent of 12 inches. The shape of the pole is shown in Fig. 3. Steel permeabilities used were those of the steel in the AGS magnets.

Fig. 3.. Magnet pole shape.

Attempts were now made to take advantage of the fact that the peak field in the booster will be less than that in the AGS (13 kG). It did not seem possible to make major cuts in the magnet pole width on the low field side without introducing bad field distortions, so cuts were made on the high field side until bad saturation effects began to appear on that side. Figure 4 shows the variation in high field K-value as a function of the cut made. On the basis of this curve the pole width was cut from the 25-inch width of the scaled AGS magnet to 23 inches. The effect of cutting the thickness of the return leg was then studied. The disturbance of K-values as a function of back-leg width was studied, as was the dependence of ampere-turn requirements. The latter appears to set the cogent limit. As can be seen from Fig. 5, not only do the required ampere turns rise rapidly as the back-leg thickness is decreased below about 20 inches, but also differences begin to appear between the field vs. ampere-turn characteristics of open and closed magnets. Since it is planned to run all magnets in series no significant difference in this characteristic can be tolerated. Hence a back-leg thickness of 20 inches has been chosen. The final magnet shape incorporating these changes is shown in Fig. 6.

Although it might appear that magnet dimensions have been reduced until the high field performance of the magnet has become marginal, an additional safety factor exists. Since low field performance is not required of the booster magnets (injection is at about 1800 gauss) a better high field steel can be used in the booster than was used in the AGS. Low carbon steels can be expected to retain good permeability to fields about one kilogauss higher than does the silicon steel used in the AGS.

The flux density at several points in the booster magnet is shown in Fig. 7. The back-leg flux has an average value of about 15 kG for 10 kG at the orbit. The permeability of AGS steel drops from about 1000 at 15 kG to about 500 at 16 kG. Hence it is to be expected that the performance of this magnet will begin to deteriorate at this point.

If the magnets are made as straight blocks a rather large allowance must be included for sagitta. In the 1.42 m magnets the total sagitta allowance is 2 inches; in the 1.28 m magnets the allowance is about 1.5 inches. If, on the other hand, the magnets are made in two blocks each to reduce the

Back-leg width = Pole width

$\Delta K/K_0$ = Percent gradient change over 12 inches

Fig. 4. High field variation of K as a function of pole width.

Fig. 5. Effect of back-leg thickness on
ampere turns required (for 23 inch
pole).

Fig. 6. Cross section of magnet.

Fig. 7. Flux density at various points in magnet (in kilogauss).

sagitta by a factor of four, a V-shaped space will exist between the blocks having a maximum block separation of about 7 inches and presenting rather unpredictable field patterns. In view of this point, and because mechanical supports, vacuum chambers and coils become much more complicated for the split magnet, it has been decided that the extra aperture should be provided and the magnet should be made as a single straight block. This will have the additional consequence that the beam will enter and leave the magnet at an angle as great as 8° to the normal to the magnet end. Analysis of the effect of this end focusing on the beam is difficult and it seems probable that the correct field patterns should be derived from a full-scale magnet model.

In summary, the characteristics of the booster magnet are:

Peak field on orbit	10 kilogauss
K	1.75 m^{-1}
Gap at equilibrium orbit	7 inches
Radial extent of good field	12 inches
Over-all width	52 inches
Over-all height	58.5 inches
Peak ampere turns (total)	144,000
Peak stored energy	1.8 megajoules
Magnet weight	510 tons
Current density in coil	3000 amp/sq.in.
Number of turns per magnet	48 (four 12-turn pancakes)
Size of individual conductors	27/32 in. $\times$ 1-5/16 in. (with 3/8 in. hole for cooling water)
Size of individual pancakes	2 in. $\times$ 8½ in.
Total coil resistance (including bus)	0.20 ohm
Coil inductance	0.39 henry
Coil weight	37 tons
Coil voltage (for two parallel paths)	2400 volts inductive + 300 volts resistive

Cost studies on smaller and larger coil cross sections than those given above indicate that, when the cost of 15 years of operation is included, the above coil design probably involves current densities that are higher than

those that give an over-all cost minimum. Further detailed studies of magnet design are required to arrive at the optimum coil size, shape and location. It is not expected that these studies will result in any important reduction in the over-all cost estimate for the booster.

III-4. Magnet Power Supply

From the figures presented in the preceding section the following figures can be derived, assuming that the magnet coils are connected to present two parallel paths to the power supply:

Peak current	6000 amperes
Peak voltage at peak current	2700 volts
Stored energy	1.8 megajoules
Energy dissipated per cycle	0.3 megajoule
Power supply rating	16 MVA

These parameters are appropriate for a motor-flywheel-alternator power supply similar in character to those used for the AGS and the Cosmotron. The generator should be rated at about 16 MVA, the motor at about 1000 hp, and the flywheel should be capable of storing about 20 megajoules.

These requirements are all met by the present Cosmotron power supply. Hence estimates have been made of the cost of restoring that machine to "like new" condition and moving it to the new injector.

III-5. Poleface Windings

Poleface windings will be required for beam diagnostics and for correction of the magnetic field at injection and ejection. They should be capable of modifying the field gradient without introducing other field components and of introducing a sextupole component as desired. Gradient corrections should be of a form such as to change a field pattern given by

$$B_x = - B_o K y$$

$$B_y = B_o (1 - K x)$$

to a new pattern given by

$$\begin{aligned} B_x &= - B_0 (K + \delta) y \\ B_y &= B_0 [1 - (K + \delta) x] \end{aligned}$$

In a magnet with hyperbolic poles with the geometry shown in Fig. 8 the current density on the pole faces can be shown to be given by

$$I = - \frac{B_0 \delta x_0^2 y_0}{4\pi \mu_0} \frac{1}{(x_0 - x) r} \text{ amperes per meter}$$

For the magnet geometry under consideration here

$$B_0 = 10 \text{ kilogauss} = 1 \text{ tesla (or } 0.2 \text{ T at injection)}$$

$$K (= 1/x_0) = 1.75 \text{ m}^{-1} \text{ (or } x_0 = 0.592 \text{ m)}$$

$$y_0 = 3.5 \text{ inches} = 0.0889 \text{ m}$$

$$\mu_0 = 10^{-7} \text{ henries per meter}$$

If the ν -value is to be changed by one half unit at injection (or by one tenth unit at full field), δ must be about 0.35 m^{-1} for $B_0 = 0.2 \text{ T}$. At the point on the magnet pole above the orbit ($x = 0, y = y_0$) the current density given by the above equation is 49 amperes per centimeter. The current density required on the high field side of the orbit drops to 24 amperes per centimeter at a distance of 25 cm from the orbit; that on the low field side rises to reach a value of 136 amperes per centimeter at a distance of 25 cm from the orbit.

To introduce a sextupole field component of the form

$$\begin{aligned} B_x &= 2 B_1 xy \\ B_y &= B_1 (x^2 - y^2) \end{aligned}$$

the current density on the pole face must be given by

$$I_s = \frac{B_1}{4\pi \mu_0} \frac{y (r^2 - x_0^2)}{r} \text{ amperes per meter}$$

Fig. 8. Geometry for analysis of current density in poleface windings.

This current has opposite signs at the radial extremities of the aperture and passes through zero a short distance to the low field side of the equilibrium orbit. For a choice of B_1 of 0.16, a value which leads to sextupole fields of 100 gauss at a distance of 25 cm from the orbit, the necessary poleface current densities 25 cm from the orbit are 34 amperes per centimeter on the high field side and 110 amperes per centimeter on the low field side.

The windings to perform these two functions should be independent and should have their returns distributed between the regions inside and outside the magnet pole in such a way that as low a voltage as possible is induced by the changing flux in the magnet gap. It is proposed that the windings should be fabricated of porcelainized copper bars.

III-6. Vacuum Chamber

Probably the most troublesome factors in vacuum chamber design are associated with eddy currents. In the AGS, eddy current effects are almost negligible but in the booster here in question the magnetic field rises about 3 times as fast as does the AGS field, and the chamber dimensions are almost double those of the AGS vacuum chamber. If, for example, a 6 x 12 inch chamber is constructed of Inconel 3 mm thick, the total eddy current induced in the chamber will be about 200 amperes. Losses will be over 200 watts per chamber and the magnetic field at the center of the chamber will be depressed below the desired value by about 15 gauss. Inward and outward forces of the order of 60 pounds per chamber will be exerted on the chamber walls because of the interaction between the eddy currents and the main field.

These figures are uncomfortably high and it seems desirable to modify the chamber design to reduce them. Ceramic or glass chambers are possible but, to withstand atmospheric pressure it seems probable that thicknesses greater than 1/4 inch will be necessary. Also, dimensional tolerances cannot be maintained in ceramic chambers with the same precision as is possible in metal chambers; this will result in a further reduction of the useful aperture.

The most satisfactory chamber design studied uses corrugated Inconel. The dimensions of the corrugations are indicated in the cross section shown in Fig. 9. With these dimensions, eddy currents will be reduced by a factor

Fig. 9. Wall of corrugated vacuum chamber.

of $3\pi/2$ or 4.7. Eddy current fields will be reduced by the same factor and power dissipated will drop by 4.7^2 or 22.

In the AGS vacuum chamber the maximum stress under evacuation occurs at the intersection of the wall with the major diameter. In this chamber, which has major and minor axes of 7 inches and 3.12 inches and a wall thickness of 0.078 inches, the maximum stress is 43,500 psi. Under this stress the chamber has top and bottom deflections of about 0.1 inch. If the same stress is to be allowed to develop in a booster chamber having a solid wall it can be shown (cf. "Design of Glass Vacuum Chambers of Elliptical Cross Section," S.J. Morrison, The Engineer, March 28, 1952) that the necessary wall thickness is 0.128 inch or about 3 mm. The relative strength of the corrugated chamber can be compared in terms of the moment of inertia of its cross section. This moment for the chamber shown in Fig. 9 is about 33 percent higher than that of a solid wall with a thickness of 0.128 inch. Hence it can be concluded that the corrugated chamber has adequate strength.

Adopting the assumptions that there is to be one pump per superperiod and that a pressure of 10^{-7} mm Hg is to be maintained at the pumps, the computed pumping speed per pump is 600 ℓ /sec. The maximum pressure midway between pumps will be only a few percent higher than that at the pump. If one pump per two superperiods is used, the necessary pumping speed is 1200 ℓ /sec and the maximum pressure midway between pumps is about 1.1×10^{-7} mm Hg. Under the latter conditions, if one pump failed the maximum pressure at that pump would be about 2×10^{-7} mm Hg.

III-7. Radiofrequency System

In the approximately 0.2 second period of acceleration, the protons will make about 650,000 revolutions. Accordingly, the energy gain per turn must be about 1500 volts. If a stable phase angle of 30° is chosen as in the AGS, peak volts available must be 3000 per turn.

The radiofrequency must have the same starting value of 1.4 MHz as is now used in the AGS. At 1000 MeV the frequency has risen to 3.9 MHz.

The design of the rf system is complicated by the relatively large amount of beam power required. During the acceleration cycle, for 3×10^{13} protons

accelerated, the average power supplied to the beam is about 25 kW. The circulating current at injection is 7.0 amperes. At 1000 MeV the circulating current will be 19.5 amperes.

The reaction of this beam on the field in the accelerating cavity will be serious and must be taken into account in designing the accelerating system. An approximate analysis can be made using the equivalent circuit shown in Fig. 10. Here R is the power supply impedance assumed to be resistive, L is the cavity inductance, C is the capacity of the accelerating gap including any additional loading capacity, and i_4 represents the current in the beam. While the beam bunch is passing the gap, i_4 has the value I , otherwise i_4 is zero. The frequency of the driving signal is the resonant frequency of the unloaded cavity.

We now investigate the behavior of the circuit when the first beam bunch arrives. Prior to this time the gap voltage is the same as that of the power supply; the gap voltage and the various currents are

$$V = V_o \sin \omega_o t$$

$$i_1 = 0$$

$$i_2 = - \frac{V_o}{\omega_o L} \cos \omega_o t$$

$$i_3 = \omega_o C V_o \cos \omega_o t = - i_2 \quad \text{since } \omega_o^2 = 1/(LC)$$

$$i_4 = 0$$

At time t_o , i_4 increases to the value I ; it continues at this value until time $(t_o + \delta)$ at which time it returns to zero. During the beam pulse the gap voltage and the various currents can be determined in the usual way subject to the conditions that neither the current in L nor the voltage on C can change discontinuously. It is evident that, initially, the current that cancels the beam current must come entirely from the capacitor C . Later in the pulse the gap voltage and the various currents are as follows:

$$V = V_o \left\{ \sin \omega_o t - \frac{I}{\omega_o C V_o} e^{-k(t-t_o)} \sin \omega(t - t_o) \right\}$$

Fig. 10. Equivalent circuit for accelerating cavity.

where $k = 1/(2RC)$ and $\omega^2 = 1/(LC) - 1/(2RC)^2 = \omega_0^2 - k^2$

$$i_1 = - (2Ik/\omega) e^{-k(t-t_0)} \sin \omega(t - t_0)$$

$$i_2 = - \frac{V_0}{\omega_0 L} \cos \omega_0 t + (I/\omega) e^{-k(t-t_0)} \left\{ k \sin \omega(t - t_0) + \omega \cos \omega(t - t_0) \right\} - I$$

$$i_3 = \omega_0 C V_0 \cos \omega_0 t + (I/\omega) e^{-k(t-t_0)} \left\{ k \sin \omega(t - t_0) - \omega \cos \omega(t - t_0) \right\}$$

$$i_4 = I$$

Immediately after the beginning of the pulse the rate of change of voltage is:

$$V' = \omega_0 V_0 \cos \omega_0 t_0 - I/C$$

If $I = \omega_0 C V_0 \cos \omega_0 t_0$ the slope of the voltage wave will be reduced to zero and phase stability will be lost. But $\omega_0 C V_0 \cos \omega_0 t_0$ is exactly the value of the current that was circulating in the cavity just before the arrival of the pulse. Hence the cavity must be designed in such a way that the circulating current just before the arrival of the beam bunch is much larger than the instantaneous current in the beam.

The gap voltage during the pulse can be expressed also in terms of the ratio of the total energy ϵ extracted during the pulse by the beam to the total stored energy E in the cavity. This ratio is:

$$\frac{\epsilon}{E} = \frac{I \delta V_0 \sin \varphi_0}{(1/2) C V_0^2}$$

where φ_0 is the equilibrium phase. In terms of this ratio the gap voltage during the pulse is given by:

$$V = V_0 \left\{ \sin \omega_0 t - \frac{\epsilon}{E} \frac{1}{2\omega \delta \sin \varphi_0} e^{-k(t-t_0)} \sin \omega(t - t_0) \right\}$$

$$\approx V_0 \left\{ \sin \omega_0 t - \frac{\epsilon}{E} \frac{1}{2 \sin \varphi_0} \frac{t - t_0}{\delta} \right\}$$

Evidently for minimum distortion of the wave the ratio of energy abstracted to energy stored should be kept as small as possible.

After the beam pulse has passed the gap, the gap voltage is given by:

$$V = V_0 \left\{ \sin \omega_0 t + \frac{I}{\omega C V_0} e^{-k\tau} \left[(1 - e^{-k\delta} \cos \omega\delta) \sin \omega\tau - e^{-k\delta} \sin \omega\delta \cos \omega\tau \right] \right\}$$

where $\tau = t - t_0 - \delta$ and so represents time measured from the end of the beam pulse.

The wave distortion will be worst at the end of the acceleration period since at this point the beam bunch will have its shortest length and I will have its greatest value. In Fig. 11 the wave shape is plotted for three cases where the capacity across the gap is varied by a factor of ten. The total number of protons in the pulse is assumed to be 3×10^{13} in all cases. The pertinent parameters for the three cases are summarized in the following table:

	<u>Case 1</u>	<u>Case 2</u>	<u>Case 3</u>	
Frequency	3.97	3.97	3.97	MHz
ω_0	2.4933	2.4933	2.4933	$\times 10^7 \text{ sec}^{-1}$
C	16,000	3,200	1,600	μF
L	0.1	0.5	1.0	μH
R	10	10	10	ohms
$k [= 1/(2RC)]$	3.125	15.625	31.25	$\times 10^6 \text{ sec}^{-1}$
$\omega = (\omega_0^2 - k^2)^{1/2}$	2.4736	1.9430	1.8839j	$\times 10^7 \text{ sec}^{-1}$
δ	4.20	4.20	4.20	$\times 10^{-8} \text{ sec}$
$\omega_0 \delta$	$\pi/3$	$\pi/3$	$\pi/3$	
I	120	120	120	amperes
$I/(\omega C V_0)$	0.1011	0.6433	1.3270/j	

As expected, the distortion of the wave shape during the pulse becomes rather extreme when the gap capacity is reduced. In all cases, however, the recovery after the pulse is very rapid. In all cases the phase shift at the end of the wave is less than three degrees.

The above treatment is, of course, only approximate. The steady state situation can be derived by tracing a number of waves as outlined above or by a Fourier analysis of the steady-state situation. Qualitatively, however,

Fig. 11. Distortion of accelerating wave by beam loading.

the behavior of the system can be estimated from the above treatment. It would appear that, using reasonable values for system parameters, beam loading should not present insuperable problems.

The beam bunch will, of course, not appear as a square pulse as assumed above but will probably have a form better approximated by a half sine wave. This will result in slightly less drastic deformation of the voltage wave than that indicated in the figure.

The accelerating cavity design can now proceed subject to the requirement that the stored energy in the cavity should be considerably greater than the energy abstracted in one passage of the beam bunch. As will now be demonstrated, this can be accomplished with a cavity loaded with ferrites similar in properties to those already in use or with ferrites which have been tested as samples.

It will be assumed that all of the acceleration takes place in a single cavity. The following design relations will be used:

$$\text{Stored energy in cavity: } E = \frac{1}{2} \frac{B_{\max}^2 A \ell}{\mu} \text{ joules}$$

where $B_{\max}$ is peak rf flux density (tesla)

A is ferrite area (m^2)

ℓ is magnetic path length (m)

μ is ferrite permeability (henry/m)

$$\text{Energy abstracted by beam: } \epsilon = I \delta V_0 \sin \varphi_0 = N e \omega_0 B_{\max} A \sin \varphi_0 \text{ joules}$$

where I is instantaneous beam current (amperes)

δ is length of beam pulse (seconds)

V_0 is peak gap voltage (volts)

φ_0 is stable phase angle

N is number of protons in beam bunch

e is the electronic charge ($= 1.6 \times 10^{-19}$ coulombs)

ω_0 is the angular frequency of the rf system

Cavity inductance: $L = \mu A / \ell$ henries

Cavity impedance at resonance: $Z = \omega_o L Q$ ohms

where Q is the figure of merit of the ferrite .

Power dissipated in ferrite: $P = \frac{V_o^2}{2Z} = \frac{\omega_o B_{\max}^2 A \ell}{2\mu Q}$ watts

Power density in ferrite: $p = \frac{\omega_o B_{\max}^2}{2\mu Q}$ watts/m³ .

The following design parameters are assumed:

$V_o = 3000$ volts

Energy gain per turn = 1500 volts, whence $\phi_o = 30^\circ$

$N = 3 \times 10^{13}$ protons per pulse, whence $\epsilon = 0.0072$ joules

$\epsilon/E = 0.1$, whence $E = 0.072$ joules

$\ell = 1.5$ m

$p = 5 \times 10^5$ watts/m³ = 0.5 watts/cm³

Frequency range = 1.4 to 3.9 MHz

$B_{\max} = 0.025$ tesla (250 gauss) at 1.4 MHz

= 0.009 tesla (90 gauss) at 3.9 MHz .

From the design relations the following quantities can now be derived:

μ at 1.4 MHz = $70 \mu_o$ ($\mu_o = 4\pi \times 10^{-7}$ H/m)

μ at 3.9 MHz = $9 \mu_o$

Circulating current $i_{\max}$ at 1.4 MHz = 426 amperes

$i_{\max}$ at 3.9 MHz = 1190 amperes

Ferrite area $A = 0.0136$ m² = 136 cm²

Ferrite volume = 0.0204 m³

Total dissipated power $P = 10,200$ watts

$Q = 62.5$

Capacity across gap $C = 1/(\omega_o^2 L) = 16,000 \mu\mu F$.

The ferrite requirements are thus a μQ product of 70×62.5 or 4370 at a maximum flux density of 250 gauss. This μQ product is well within the characteristics of available ferrites. The ferrite weight is about 210 pounds. In a single cavity the rather high power density assumed would require rather

efficient cooling. This should, however, be relatively easy in view of the small ferrite cross section. The cavity could be made in two halves, each 4×17 cm in cross section and laminated for efficient circulation of a coolant. The bias winding for tuning by ferrite saturation could then be wound as a figure eight to cancel coupling between rf and tuning power sources.

The effect on the cavity design of a reduction in the specified power density can be shown by a second design example in which the following parameters are specified:

$$p = 4 \times 10^5 \text{ watts/m}^3 = 0.4 \text{ watts/cm}^3$$

$$\ell = 2.0 \text{ m}$$

$$B_{\max} = 0.020 \text{ tesla (200 gauss) at 1.4 MHz (72 gauss at 3.9 MHz) .}$$

All other parameters are to remain the same as in the previous example. The derived parameters are now as follows:

$$\mu \text{ at 1.4 MHz} = 75 \mu_0$$

$$\mu \text{ at 3.9 MHz} = 10 \mu_0$$

$$i_{\max} \text{ at 1.4 MHz} = 426 \text{ amperes as before}$$

$$i_{\max} \text{ at 3.9 MHz} = 1190 \text{ amperes as before}$$

$$\text{Ferrite area } A = 0.0171 \text{ m}^2 = 171 \text{ cm}^2$$

$$\text{Ferrite volume} = 0.0342 \text{ m}^3$$

$$\text{Ferrite weight} = 350 \text{ pounds}$$

$$\text{Power } P = 13,700 \text{ watts}$$

$$Q = 47$$

$$\text{Capacity across gap} = 16,000 \mu\mu\text{F as before .}$$

These are equally satisfactory design parameters and result in a slightly easier cooling problem.

If it is desired, the accelerating system can be subdivided into two accelerating stations located at diametrically opposite straight sections as shown in Fig. 1.

III-8. Initial Betatron Acceleration

Since the space-charge limit of the booster at injection is reduced by a factor greater than two by the initial bunching it is of interest to consider initial acceleration by the mechanism used in the betatron. This provides an additional advantage in that, during the transition from betatron to rf acceleration the bunching process can be carried out with 100 percent efficiency.

Betatron acceleration requires the presence of a changing magnetic flux linking the particle orbit. To this end the beam passes through one or more laminated magnetic cores. These cores are magnetized before injection to a flux density of 15 kilogauss then, during a few milliseconds after injection, the flux is reversed. Rf acceleration is then applied and during rf acceleration the flux density is restored rather slowly to zero. This flux restoration will introduce decelerating fields but these can be compensated by a small increase in either the peak rf field or of the stable phase angle.

Initially two betatron cores are to be included in the system. Each is to have a cross-sectional area of one square meter; hence the total flux change linking the orbit will be 6 webers. The momentum change, Δp , due to this flux is given by

$$\frac{c}{e} \frac{\Delta p}{r} = \frac{c}{2\pi r} (\text{flux change}) \text{ eV/c}$$

$$= 26.76 \text{ MeV/c}$$

Thus the momentum is changed from its 50-MeV injection value of 310.36 MeV/c to 337.12 MeV/c. This corresponds to a kinetic energy of 55 MeV.

At the normal rate of acceleration the proton energy would be increased from 50 to 55 MeV in about 4 milliseconds. Unless the magnet cycle is modified, 4 milliseconds would hence be the time in which the betatron flux is reversed.

The total weight of each core would be about 80,000 pounds. Each would be located in one of the 1.9 meter straight sections. The core length along the orbit would be about one meter.

Using only two cores the space-charge limit will be raised by about ten percent. At some later date, when the booster has been driven to its

space-charge limit, another factor of about two could be gained by the addition of eight more cores of one square meter cross section. This would permit betatron acceleration to about 100 MeV.

III-9. Injection

At 50 MeV the revolution period in the booster will be 0.714 micro-second. With a 100 milliamperere injected beam supplying charge at the rate of 6.24×10^{17} protons per second the total charge injected per revolution will be 4.46×10^{11} protons. Hence to supply a total charge of 3×10^{13} protons, injection must persist over about 67 turns or about 48 microseconds.

It is expected that the 50-MeV injected beam will have an emittance in either plane of about π cm-mrad. Since the horizontal admittance provided in the booster is 160π cm-mrad, injection could, in principle, be accomplished by stacking only in the horizontal plane. The density of the injected beam will, however, be well above the density of a space-charge-limited beam in the booster and the consequences of injecting only in the median plane are somewhat unpredictable. Hence it may be preferable to dilute the emittance of the injected beam during the injection process. This can be accomplished, for example, by injecting off the median plane.

Computer studies of the injection process using 50-turn injection have given the figures in the following table for the ratios of the captured beam to the total number of protons injected. In all cases the injector septum was 10 cm removed from the center of the chamber in the radial direction.

	<u>Injector on median plane</u>	<u>Injector 4 cm above median plane</u>
Septum 1 mm thick	78 percent	89 percent
Septum 2 mm thick	74 percent	87 percent

These figures are improved by a few percent if the first five and the last five turns are excluded from the evaluation.

Much more extensive studies of the injection process are needed before an injection procedure can be chosen. The possibility of more use of vertical phase space should be explored. Also the effects of the residual 200 Mc bunching from the linac must be explored.

III-10. Beam Extraction at 1000 MeV

The process of extraction of the 1000-MeV beam during twelve revolutions is critical in the choice of a booster of the type considered in this report. Unless each turn has the same intensity and approximately the same emittance, and unless each turn has little more than one-twelfth of the emittance of the 1000-MeV beam before extraction, the booster will not yield the more intense beam in the AGS to be expected from its higher energy. Analytical and computer studies indicate that the necessary specifications can be met; but so far this type of extraction has not been attempted on any large synchrotron. If the decision is made to proceed with the booster an attempt should be made on the AGS to verify the theoretical predictions and to extract a beam during a few AGS revolutions.

Two types of extraction have been studied for the booster. They are nonresonant extraction where, by magnetic bumps, the beam is moved into an extraction septum magnet, and resonant extraction on a half-integral resonance.

a) Nonresonant extraction. Studies of this process have involved a conventional orbit bump produced by two magnets one half betatron wavelength apart. Starting with an accelerated beam of uniform density it has been shown that twelve turns of equal intensity and approximately equal emittance can be extracted. The shape of the emittance patterns obtained is shown in Fig. 12.

In the calculation of these patterns it is assumed that each of the bumps is independently adjusted for each turn of the extraction process. The computer program adjusts these two parameters to satisfy two conditions. These are (i) the correct area of phase space is moved past the septum, and (ii) the height of the center of gravity of the area is constant. In practice it might be desirable to add one or more additional bumps to permit simultaneous control of the oscillation outside the half wavelength between bumps. It is, however, unnecessary to include them in this feasibility computation. The parameters used in these computations to describe the particle trajectories were derived from actual lattice structure computations with physically realizable positions of the bump magnets and septum. Since no resonance properties are used for this type of ejection, the dependence of details of the

process on v -value is small. There should be no difficulty in accommodating the v -values associated with the momentum spread in the beam. Some of these details are still under study and will be the subject of a later report by M.Q. Barton.

At the left side of Fig. 12 the emittance patterns of the twelve extracted turns are shown superposed. The area of each emittance pattern is 2π cm-mrad. The ellipse which encloses most of these areas has an area of 4π cm-mrad corresponding to the vertical admittance of the AGS. (As will be presented in the next section, a 90° rotation of phase space is to be included between the booster and the AGS.) It is evident from Fig. 12 that the emittance patterns of the extracted turns cannot be completely fitted into the vertical admittance of the AGS. The loss of particles would be only about ten percent, however, and could be much smaller if the ellipse parameters can be adjusted separately for each turn.

A more complete study of the ejection process should include a more realistic distribution of charge density. Measurements made on the AGS and on the CERN PS indicate that the charge distribution is Gaussian. Also the effect has been neglected of the momentum distribution in the beam. This momentum distribution will result in a radial spread of the order of one centimeter and will cause a time distribution of the momentum of the extracted beam. This may require an appropriate variation in time of the beam transport system carrying the extracted beam to the AGS.

b) Resonant extraction. To accomplish resonant extraction the accelerator is tuned slowly toward the half integral stopband after which that stopband is widened by exciting a perturbing quadrupole. That quadrupole is azimuthally so located with respect to the septum magnet and the two with respect to the accelerator lattice, that the radial emittance ellipse of the circulating beam at septum azimuth has its major axis coinciding with the displacement axis and its minor axis parallel to the radial momentum axis. Due to the resonant blow-up the ellipticity of the emittance ellipse increases exponentially with time as long as the betatron tune and the quadrupole strength are preserved. Eventually part of the ellipse will jump the septum and extraction begins.

The mechanism is attractive because it minimizes the amount of beam intercepted by the septum and also because it yields convenient shapes for the emittance of the external beam.

Considering small departures from the assumed tune and quadrupole strength values one finds that the system can be arranged so that the growth rate is affected only by the quadrupole strength and not by the tune. However, the direction of the external beam centerline is highly sensitive to variations in the tune in addition to being moderately affected by the quadrupole strength. For the present booster one calculates the relation

$$\frac{\Delta x'}{X'} \approx \frac{\Delta \nu}{\nu}$$

where $\Delta x'$ represents the variation in direction,
 X' the angular spread of the external beam at the septum magnet entrance,
 $\Delta \nu / \nu$ the relative change in tune.

Assuming that $\Delta x' / X' = 0.1$ is tolerable one has to require $\Delta \nu / \nu \leq 10^{-4}$.

In view of the extreme stability of the guiding field magnet structure it seems probable that this condition can be met. The field gradients are affected by eddy currents and saturation effects. However, the extraction energy is well defined and with it the extraction field strength. By synchronizing the magnet with the power supply ripple one can arrange the extraction to occur at or near a specified phase of the ripple and eddy current field.

The tune should be a sufficiently flat function of the radial beam position so that variations in tune due to noise and errors in the beam positioning system remain within tolerance. Flatness of tune is also desirable in order to prevent dispersion of the external beam due to momentum spread.

It has been suggested that variations in the space charge in the circulating beam might cause unacceptably large fluctuations in tune. That charge can be measured during the accelerating cycle which precedes the extraction period and the result may be used to change the setting of the tuning elements accordingly. Even after compensation this effect may still cause structure in the external beam as the circulating beam is bunched. The synchrotron

oscillation period being much longer than the extraction period, particles at different azimuths see different space-charge forces and therefore different tunes. It is believed that this effect is sufficiently small.

With the system as described so far the instantaneous current in the external beam is determined only by the brightness distribution in the unperturbed emittance ellipse and by the instant of observation. The current exhibits a maximum and approaches the value zero asymptotically with time. It is proposed to introduce a suitably programmable closed orbit bump to obtain better control. If the bump excursion at septum azimuth can be continuously controlled during the extraction period and if the maximum excursion is big enough to push the closed orbit across the septum, one can achieve the desirable square waveform of the external beam current.

Generation of the bump requires at least two bending magnets but in general four, in order to control both the excursion and the direction of the beam axis at septum azimuth while preventing any closed orbit distortion outside the bump area. The perturbing quadrupole must be located outside the bump area. The closed orbit motion in the bump is decidedly nonadiabatic so that coherent betatron oscillations (with growing amplitudes) would be set up if the bump encompassed the perturbation.

The actual bump program is completely determined by the original brightness distribution and will come out rather oddly in general. One may decide, however, to sacrifice a small fraction of the circulating beam by shaping it so that it will suit a more convenient program. This possibility may be exploited still better if the tolerance on the height of the external beam pulse is not too small.

As particles at a given longitudinal position in the bunch sample the bunch excursion once each revolution they see a step-like program, even though the excursion may be a continuous function of time.

It is important to make the bump program as simple and smooth as possible in order to reduce the investment in the power supplies for the bending magnets.

Figures 13 and 14 demonstrate what bump programs are obtained in the case of a uniform brightness distribution and for accepted losses of 5% and 10%. The program for 10% is simpler than the one for 5% as the required

Emittance, external beam

Shift program

Loss = 5%

Fig. 13. Bump program for resonant extraction, and output emittance for 5% accepted loss.

Fig. 14. Bump program for resonant extraction, and output emittance for 10% accepted loss.

Shift program

Loss = 10%

excursion increases at each step, while the 5% curve requires decreasing excursions as well during the first few revolutions.

In both cases one may approximate the program with a monotonically increasing curve and still have the external beam current within reasonable tolerances.

Figures 13 and 14 also give the emittance diagrams at the septum magnet entrance for the external beam after each revolution. As the vertical boundaries to the left always coincide with the septum position, it is obvious that the beam centerline moves parallel to itself to the right as extraction progresses. In addition, the aspect ratio changes.

In order to have the external beam fit the AGS acceptance as well as possible it is desirable to shift its axis parallel to itself, to a standard position which requires two bending magnets, one of which may be the septum magnet itself, and to transform its emittances (horizontal and vertical) as well as possible to standard shapes. This requires at least four quadrupoles of adjustable strength in the external beam channel.

Comparing this resonant extraction method with nonresonant extraction one may conclude that the former requires a slightly larger aperture and therefore slightly stronger bending magnets than the latter. Resonant extraction offers primarily a better behavior of the external beam emittance, which may lead to reduced dilution of phase space, a slightly smaller loss on the septum and, at the possible cost of some small loss of beam intensity, a more convenient bump program.

III-11. Phase-Space Rotation

If an interchange between the horizontal and vertical emittances is not made between the booster and the AGS very different dimensions are required for the booster aperture. If the booster aperture is filled at 50 MeV and the vertical aperture is to have a value such that the beam's vertical emittance at 1000 MeV is 4π to match the vertical admittance of the AGS, the vertical admittance of the booster must be 22π . If the horizontal admittance of the booster must now be such as to give a space-charge limit in the booster at injection of 3×10^{13} protons, it can be shown from the formulae

in Section II-5 that the horizontal admittance must be 917π . These figures correspond to an aperture about 3.5 in. $\times$ 22.5 in. The cross-sectional area of this aperture is 38 percent greater than the area of the aperture derived above and the vacuum chamber and magnet dimensions become quite unreasonable. Also, the horizontal beam emittance of the extracted 1000-MeV beam is 12.5π , slightly greater than the horizontal admittance of the AGS and leaving no allowance for phase-space dilution.

Another advantage of phase-space interchange is that the inhomogeneity between extracted turns is transferred from the horizontal plane to the vertical plane where it will not affect resonant extraction from the AGS since the resonant extraction is carried out in the horizontal plane.

An interchange between horizontal and vertical emittance can be accomplished by passing the beam through the field of a solenoid, or by transformation of beam characteristics through a series of quadrupole lenses.

The rotation angle for a solenoid with field B_0 and length ℓ is

$$\theta = \frac{B_0 \ell}{2B\rho}$$

where $B\rho$ is the magnetic rigidity.

For 1-BeV protons, $B\rho = 5.66 \times 10^4$ gauss-meters. To obtain a rotation of 90° ($\theta = \pi/2$) we therefore need

$$\begin{aligned} \ell &= 17.8 \text{ meters for } B_0 = 10 \text{ kilogauss} \\ \ell &= 3.56 \text{ meters for } B_0 = 50 \text{ kilogauss} \end{aligned}$$

This is a formidable device.

An alternative is to use a set of quadrupoles rotated around the usual axis.

The 4×4 matrix for a system of rotated quadrupoles may be written

$$\begin{aligned} & \begin{bmatrix} I \cos \alpha & I \sin \alpha \\ -I \sin \alpha & I \cos \alpha \end{bmatrix} \begin{bmatrix} H & 0 \\ 0 & V \end{bmatrix} \begin{bmatrix} I \cos \alpha & -I \sin \alpha \\ I \sin \alpha & I \cos \alpha \end{bmatrix} \\ &= \begin{bmatrix} H \cos^2 \alpha + V \sin^2 \alpha & (V - H) \cos \alpha \sin \alpha \\ (V - H) \cos \alpha \sin \alpha & H \sin^2 \alpha + V \cos^2 \alpha \end{bmatrix} \end{aligned}$$

where H and V are the 2×2 matrices for horizontal and vertical motion in the quadrupole system and I is the 2×2 unit matrix. In order to produce an interchange of phase spaces the diagonal submatrices above must vanish:

$$H \cos^2 \alpha + V \sin^2 \alpha = H \sin^2 \alpha + V \cos^2 \alpha = 0 .$$

This is possible only if $\cos^2 \alpha = \sin^2 \alpha$, i.e., $\alpha = 45^\circ$, and $H = -V$ (the horizontal and vertical matrices must be negatives of each other).

The latter condition can be satisfied by a sequence of six alternating quadrupoles. Suppose these are equally spaced, and have strength F and D. In the thin lens approximation the matrices for one doublet are

$$\begin{bmatrix} 1 & L \\ \pm 1/D & 1 \pm L/D \end{bmatrix} \begin{bmatrix} 1 & L \\ \mp 1/F & 1 \mp L/F \end{bmatrix}$$

The matrix for three doublets is the unit matrix for horizontal motion, and its negative for vertical motion, if for one doublet

$$\cos \mu_H = 1 - \frac{L}{F} + \frac{L}{D} - \frac{L^2}{2FD} = \cos \frac{2\pi}{3} = -\frac{1}{2}$$

and

$$\cos \mu_V = 1 + \frac{L}{F} - \frac{L}{D} - \frac{L^2}{2FD} = \cos \frac{\pi}{3} = \frac{1}{2} .$$

This is satisfied by

$$\frac{L}{F} = \frac{\sqrt{17} + 1}{4} = 1.28 , \quad \frac{L}{D} = \frac{\sqrt{17} - 1}{4} = 0.78 .$$

Take $L = 1$ meter; aperture 4 inches; pole tip field 10 kG. We find for the lengths, for 1-BeV protons ($\rho = 5.66$ m)

$$\ell_F = 0.36 \text{ m} ; \quad \ell_D = 0.22 \text{ m} .$$

Thus six 4-inch quadrupoles, three of them 36 cm long, three of them 22 cm long, will do the job. This alternative appears preferable to the solenoid.

III-12. Instrumentation and Controls

For the initial start-up, operation and shakedown of the Cockcroft-Walton preinjector, the linac and the booster ring, a single control room located within the linac/booster ring building would be provided. This control room would be equipped and instrumented as necessary first to operate these accelerators on an individual subsystem basis, and finally as a composite injector complex. At the time when this complex actually became the injector for the main AGS ring, its operation would shift to the main AGS control room with particular emphasis on all the various injection, acceleration and extraction processes involved. From this point on, the control room in the linac/booster ring building would normally be unattended and yet would serve as the local diagnostic center for equipment in this complex.

If the project were to consist of the linac and booster ring only, the use of relay logic for the various on-off sequences and interlocking functions would seem proper. However, considering the distances involved from this complex to the main ring control center as well as the complexity of the overall operation, detailed study would be given to the possibilities of using solid-state logic and, further, arranging this logic to be compatible with one or another high speed, large capacity data processing systems. In addition, such systems, perhaps with certain computational facilities, would be considered and evaluated as a means of gaining more effective and efficient proton injection, acceleration and extraction in the various subaccelerators comprising the AGS complex.

A complete complement of diagnostic equipment is essential to the reliable operation of the booster and its injector and preinjector. This will include devices for measuring beam emittance before and after the linac, for measuring and displaying beam energy and energy spread after the linac and as many pick-up electrode stations as possible in the booster ring. Probably a small computer will be a useful component of the diagnostic system for the booster.

III-13. Shielding

Shielding requirements for the booster were established by measurements made on the Cosmotron which, for this purpose, was operated at a peak energy of 1000 MeV. The circulating beam intensity was 1.1×10^{11} protons per second;

after acceleration this beam was brought onto a fixed copper target 1 in. x 1 in. x 3 in. located in the south straight section of the machine.

Radiation measurements were made above the target but inside the Cosmotron shielding using plastic scintillators (C^{11} activation) film and pocket dosimeters. Also, to establish the rate of attenuation in the Ilmenite-loaded concrete of the Cosmotron shield, the same detectors were located between beam port plugs in the 45° beam from the target.

The fast flux attenuates exponentially at 45° to the circulating beam with a decay length of 115 g/cm^2 .

Measurements as a function of azimuth around the accelerator show maxima both inside and outside the shielding. These maxima lie on a straight line passing through the target and inclined about 60° to the circulating beam direction. The roof shield over the south straight section is 6 ft of Ilmenite-loaded concrete or an attenuation distance corresponding to 823 g/cm^2 . At 60° this corresponds to about 950 g/cm^2 . The relative sizes of the inside and outside maxima indicate a decay length of 117 g/cm^2 in good agreement with the 45° figure of 115 g/cm^2 .

The target length and the density of copper are consistent with the conclusion that about half of the particles interacted in the target. If it is assumed that in the booster 10 percent of the 3×10^{13} protons are lost in the extraction process, the radiation levels will be $3 \times 10^{12} / 0.5 \times 10^{11}$ or about 60 times as high as those in the Cosmotron experiment. Using the measured decay lengths and assuming that the radiation maximum will be at about 60° to the circulating beam it can now be demonstrated from the Cosmotron measurements that the maximum radiation level inside the shield will correspond to about 1.4×10^7 particles per cm^2 per second. A shield wall or roof of 9 ft of Ilmenite-loaded concrete will attenuate this radiation to about 80 per cm^2 per second or to about 20 mrem/hr, which is regarded as a reasonable and safe value.

This shield should cover the ring for a distance of about one half of a betatron wavelength downstream from the extraction point. It is proposed that the 9 ft shield should cover one quarter of the ring. The other three quarters of the ring include no devices that will induce beam loss and so

should be relatively free from radiation. Over this part of the ring about 6 ft of heavy concrete should be adequate.

The shielding configuration around the booster is shown in Fig. 15.

III-14. Buildings

As will be presented in Section IV, the decision has been made that the present 50-MeV linac should not be used as the injector for the booster but that a new 50-MeV linac should be constructed for this purpose. The new linac and the booster would be housed in the same building, which would contain also a control room, experimental areas, offices, laboratory, and work space comparable with those proposed for inclusion with the 200-MeV linac.

As shown in Fig. 15, the injected beam from the linac and the beam ejected from the booster will be 60° apart at the booster ring. The ejected beam will be carried to the A-20 straight section of the AGS in a tunnel about 150 ft long.

The building plan is shown in Fig. 16. The building is rectangular, 120 ft x 520 ft. The greater part of the building, 420 ft long, will be a high-bay area with crane coverage. Space in the proposed building is subdivided as follows:

High-Bay Area		50,500 SF
Booster Ring	13,000 SF	
Booster Service Equipment	10,200 SF	
Linac	16,500 SF	
Heavy Assembly	10,800 SF	
Low-Bay Area		12,000 SF
Light Assembly	4,200 SF	
Lab - Office	7,800 SF	
Total Building Area		62,500 SF

The building would be located as shown in Fig. 17 to the west of the AGS in an area where it would not interfere with any experimental facilities.

Fig. 15. Shield for booster synchrotron.

1" = 20'

• FIRST FLOOR PLAN •
1" = 60'

Fig. 16. Building plan.

Fig. 17. Site plan.

IV. Possible Use of the Present AGS Linac as Injector for the Booster

IV-1. Linac Specifications

The injection energy for the booster synchrotron has been set at 50 MeV. This immediately raises the question of the possibility of using the existing 50-MeV linac as the injector to the booster. In this section, the following items are considered:

- a) Requirements and specifications for the injector linac.
- b) Modifications which would be required in order that the existing linac meet the specifications.
- c) The general design of a new 50-MeV linac.
- d) Comparative cost estimates and time schedules.
- e) Interference with AGS operations.

In the over-all context of the AGS Conversion project, the injection system up to 50 MeV represents a fairly small portion of the cost but has a very profound effect on the quality and reliability of the operation of the entire AGS complex. Thus it is axiomatic that the injection system be of the highest quality and technical compromises in the interest of economy only should be minimized.

Because of some remaining uncertainties in the multiturn injection process in synchrotrons, it is difficult to state exactly the most desirable characteristics of the beam to be injected into the booster. Also, there is some uncertainty in the relation between peak beam current and brightness of the beam to be expected from the linac. Thus it is not clear whether one desires a linac peak beam current of 50, 100 or 200 mA with the correspondingly smaller number of injected turns required for the higher currents. Consequently, the linac parameters are specified to cover as wide a range of operating conditions as seems practical at this time. The general parameters are listed in the table below.

Output energy	50 MeV
Peak beam current	200 mA, maximum
Beam pulse length	200 μ sec, maximum
Pulse repetition rate	4 pulses/sec
Beam quality	$\sim \pi$ cm-mrad at 50 MeV and 100 mA

It is believed that these parameters can be achieved readily if a new linac is built. If the existing linac were to be used, extensive modifications would be required. The ultimate performance capabilities of the existing linac when fitted with the new short C-W column are not known but it is impossible with present knowledge to guarantee that it would meet the above parameters. It must be remembered that many significant advances in linac technology have occurred since the existing linac was designed.

The general layout of the 50-MeV linac is outlined below. The differences between a new linac and the modified existing linac are pointed out.

a) Preaccelerator. Two complete units would be provided in adjacent but separate pits. In either case (new or modified linac), one new unit would be purchased and the second would be the present unit.

b) Accelerating structures. There would be three independent cavities having energy gains of about 10, 20 and 20 MeV, respectively. In the modified linac, the first two 10 ft sections of the existing linac would be discarded and replaced by a completely new first 10-MeV cavity. The remaining nine sections of the existing cavity would be regrouped into two independent cavities. For these two cavities, the existing drift tubes would be reused.* Additional rf ports would have to be added to these cavities. In the case of a new linac, multistem drift tubes would be used in the second and third cavities. This new technique cannot be employed with the modified linac and thus it is expected that the beam quality from the modified linac would suffer somewhat as compared to a new linac.

* Drift tube quadrupoles of the existing linac have been tested to determine their thermal limitation in power dissipation. Spare quadrupoles under test show that they can dissipate 120 watts average with $30^{\circ}\text{C } \Delta T$, which is more than sufficient for the proposed increase required in the magnetic field gradient for magnets above 10 MeV. However, the first few magnets in the existing linac could not achieve the required fields.

7

c) Rf system. It is proposed to use CFTH-515 triodes as the final amplifiers in either case. One tube would be used on the first cavity and two each on the other cavities. The drivers would also be 515's, so that a total of 8 units is required. New modulators and phase control equipment would be supplied in either case. A proposed layout of the rf system is shown in Fig. 18.

d) Quadrupole pulsed and power supplies. New units would be required in either case as the existing units cannot supply the 200 μ sec pulse length with adequate regulation.

e) Vacuum system. In the modified linac the existing evapor-ion pumps would be retained. In the new linac sputter-ion pumps would be used in order to take advantage of the latest technology. In the modified linac, changes would be required in the roughing system to accommodate the three cavities.

f) Cooling system and services. In the modified linac, some parts could be retained but major modifications would be required.

g) Controls. In the modified linac a completely new control system and control room would be required. The new control system must be compatible with remote operation, and furthermore, to minimize the AGS downtime during the modification a new system would be required.

h) Beam transport system. In either case, a beam transport system to the booster would be required as well as a sophisticated beam analysis system. In the modified linac, a beam transport system directly to the AGS would have to be retained at least until the end of the Conversion project.

i) Buildings. The present linac building is inadequate even for the existing linac and extensive modifications would be required. Additions, shown in Fig. 19, would be made to the existing building to accommodate the modified linac and its services and to add desperately needed service space. The proposed layout of the modified linac in its building is discussed below (Section IV-2). In this case a separate building, shown in Fig. 20, would be required for the booster ring and a beam transport tunnel from the existing linac building to the booster would have to be installed (see Fig. 21). In the case of the new linac, it is proposed to locate the linac and the booster

Fig. 18. Linac rf system.

NOTE: NEW ADDITION SHOWN HATCHED...

NOTE:
SEE PLAN @ LEFT
FOR 2ND FLOOR
HERE

Fig. 19. Modifications required in existing linac building.

Fig. 20. Separate booster building for use if existing linac is injector.

AADD-127

Fig. 21. Site plan if existing linac is used.

in a single new building. Cost estimates for the two alternatives are given in Section IV-3 below. It will be observed that use of the modified linac building and a separate building for the booster is considerably more expensive than a combined building for the booster and a new linac. This arises from the fact that it is impossible to organize the modifications to the existing linac building in a rational fashion; this leads to rather inefficient use of the space. Furthermore, making major modifications and additions to an existing building, which is in use, is usually more expensive than building on a new site.

In neither of the layouts shown is provision made for a possible future extension of the linac to about 200 MeV. With the modified linac building, it is impossible even to consider this possibility. With the new linac, a change in the proposed layout could accommodate this possibility.

IV-2. Schedules

The construction schedule for a new linac is straightforward in that it does not interact with any other part of the program except through its completion date. It is clear, however, that the completion date should be as early as possible to allow for shakedown before the linac is needed to start tests on the booster. A construction schedule for a new 50-MeV linac is included elsewhere in this report.

The schedule for modifying the existing linac is much more complicated. During any time that modification or relocation of any existing part of the linac is being carried out, the entire AGS complex is shut down. The need to minimize this downtime has dictated the general procedure which would be followed.

The new preinjector, with its beam transport and the new first 10-MeV cavity would be installed behind the existing preinjector pit (cf. Fig. 19). These new units would be installed and operationally tested before the existing machine was shut down. The new additions to the building would also be completed prior to this date. As much as possible of the new control room and rf system would also be installed and tested. The proposed schedule for the modification when the existing linac is shut down is shown in Fig. 22.

SCHEDULE FOR 50 MEV LINAC CONVERSION

TIME IN MONTHS

— SINGLE SHIFT OPERATION
 █ DOUBLE SHIFT OPERATION

8 MONTH
 LINAC
 SHUTDOWN

Fig. 22. Schedule using existing linac.

The following operations would have to be carried out during the shutdown:

- a) Tear down the existing linac and preinjector.
- b) Deck over the existing preinjector pit and refurbish the building where the linac now is located.
- c) Rework the cavity sections which are to be reused.
Add the new rf ports.
- d) Install mechanical and electrical services and relocate those parts of the rf system which are presently in use.
- e) Assemble cavities #2 and #3 in their new location, install and align drift tubes.
- f) Connect up and test complete rf system, condition the cavities.
- g) Complete control wiring from new control room.
- h) Install new beam transport system to booster and extend transport system direct to AGS.
- i) Run beam tests.

If sufficient manpower is available, it might be possible to do this in a period of 8 months. It seems impossible as well as impractical to schedule this shutdown at the same time as the four-month shutdown which is proposed for installation of the new motor-generator set, which should be accomplished as early as possible in the Conversion project. Thus, this 8-month shutdown for the linac modification would have to coincide with the major shutdown for the modification of the AGS ring. This could lead to serious manpower shortages. Furthermore, if the booster were ready for testing prior to this time, it would be necessary to use a beam from the existing linac to test the booster, using alternate pulses from the linac during AGS operation. This, at best, would be a poor test, since the character of the linac beam would differ from that of the modified linac. On the other hand, if the booster were not ready at the time of the major AGS shutdown, it would be necessary to operate the AGS with the beam from the modified linac while the testing of the booster was being carried out. This would result in lengthening the total time of the Conversion project.

IV-3. Cost Comparison

The table below gives a summary cost comparison between a new linac and the modified existing linac and then presents the details of the estimate for the linac equipment. The building cost shown includes the costs associated with the booster building as well as the linac building because in the case of the new linac a single building is proposed and it is not feasible to separate out those costs associated only with the linac.

These tables show that there is some saving associated with the modification of the existing linac in terms of the accelerator components alone. The saving is small because those parts of the existing linac which are reused must all be reworked and moved. As stated earlier, the building complex for the modified linac is more expensive and this essentially offsets the saving in the accelerator components. Contingency, EDI&A and escalation are not included in these tables.

Summary Cost Comparison (Amounts in Thousands of Dollars)

	<u>New Linac</u>	<u>Modified Linac</u>
Accelerator Components		
Preinjector	446	446
Accelerator cavities	1,120	563
Rf system	1,153	898
Control and transport	460	500
Mechanical and electrical services	<u>432</u>	<u>432</u>
Subtotal	3,611	2,839
Buildings		
Linac	{	1,921
Booster		1,365
Radiation Shielding	<u>425</u>	<u>429</u>
Total	<u>6,963</u>	<u>6,554</u>

BUILDING COST ESTIMATE

Combination New Linac - Booster Scheme
(Amounts in Thousands of Dollars)

Modifications to Existing Structure		0
New Structures		2,690
High-Bay	50,500 SF @ \$45/SF	2,270
Office-Lab	12,000 SF @ \$35/SF	420
Special Foundations		50
Cranes		100
General Excavation		42
Connecting Tunnels		45
Site Work, Utilities, AGS Conjunction		*
Subtotal, Buildings		2,927
Radiation Shielding**		425
Total		3,352

* Included in AGS Conversion budget.

** Net cost after deduction for 6500 tons of Cosmotron shielding.

BUILDING COST ESTIMATE

Modified Existing Linac - Booster Scheme
(Amounts in Thousands of Dollars)

	<u>Linac</u>	<u>Booster</u>
Modifications to Existing Structure, 5,000 SF @ \$40/SF	200	-
New Structures		
High-Bay 24,300 SF @ \$55/SF	1,340	24,000 SF @ \$45/SF 1,080
Office-Lab 5,600 SF @ \$45/SF	253	
Special Foundations	10	36
Cranes	100	90
General Excavation	18	9
Connecting Tunnels	-	150
Site Work, Utilities, AGS Conjunction	<u>*</u>	<u>*</u>
Subtotal, Buildings	1,921	1,365
Radiation Shielding**	<u>240</u>	<u>189</u>
Subtotals	2,161	1,554
TOTAL		<u>3,715</u>

* Included in AGS Conversion budget.

** Net cost after deduction for 6500 tons of Cosmotron shielding.

Details of the Estimate of Accelerator Components
(Amounts in Thousands of Dollars)

	<u>New Linac</u>	<u>Modified Linac</u>
Cockcroft-Walton (1)	157	157
Ion Source (1)	10	10
Accelerating Column (1)	67	67
Beam Transport to Linac	60	60
Preinjector Vacuum System	37	37
Preinjector Cooling System	3	3
Preinjector Controls	12	12
Preinjector Labor & Miscellaneous	<u>100</u>	<u>100</u>
Total, Preinjector	446	446
Accelerator Cavity #1	55	55
Drift Tubes for #1 (58)	127	127
Tuners (40)	16	16
Quadrupoles (60)	30	30
Accelerator Cavities #2 and #3 (new)	176	-
Accelerator Cavities #2 and #3 (rework existing)	-	27
New Drift Tubes (70)	154	-
New Tuners (50)	20	-
New Quadrupoles (70)	35	-
New Tank Supports (6)	6	-
Quadrupole Power Supplies	45	45
Intertank Equipment (3)	45	45
Vacuum System	201	28
Cooling System	30	20
Assembly Labor & Miscellaneous	180	150
Labor to Strip Existing Linac	<u>-</u>	<u>20</u>
Total, Accelerator Cavities	1,120	563

		<u>New Linac</u>	<u>Modified Linac</u>
Low Level Rf		40	40
Pulsed Power Supply		120	60
4616 Driver		64	64
CFTH-515 Systems (@ \$33,000)	(8)	264	(3) 99
Modulators		175	175
Phase Shifters		50	50
Transmission Lines		120	150
Capacitor Banks		60	30
Rf Cooling System		10	10
Controls		100	100
Labor & Miscellaneous		<u>150</u>	<u>120</u>
Total, Rf System		1,153	898 .
Control Room		300	300
Beam Transport to AGS		-	30
Beam Analyzing System		40	-
Beam Transport to Booster		75	130
Labor & Miscellaneous		<u>45</u>	<u>40</u>
Total, Control & Beam Transport		460	500
Mechanical & Electrical Services, Total		<u>432</u>	<u>432</u>
TOTALS		3,611	2,839

IV-4. Conclusion and Recommendation

It is recommended that a completely new 50-MeV linac be built as an injector for the booster. This recommendation is based on the conclusions to be drawn from the preceding paragraphs:

- a) A new linac can be built and operationally tested without interference with AGS operations and probably can be ready before the modified linac could be. Modification of the existing linac will cause serious interference with AGS operations.

- b) A new linac will employ all of the latest technology and can be expected to give somewhat better performance than the modification of the existing linac.
- c) The freedom to choose the linac location will simplify the building design and add flexibility in the site, including space for possible future expansion.
- d) The cost of a new linac is essentially the same as that of modifying the existing machine. The difference indicated by these estimates is within the accuracy of the estimates.

V. Summary of Time Schedules, Manpower and Costs

V-1. Engineering and Construction Schedules

Figure 23 presents a construction schedule for the 50-MeV linac-booster synchrotron combination and its building. It is believed that design and construction can be completed in a period of three and one half years. Six months in the latter half of the fourth year is included for system test before the AGS is shut down for the change to the new injection system.

It will be noted that in some cases installation of components is shown to begin before the building is completed. In these cases it is assumed that some beneficial occupancy of the building will be possible before its final completion.

V-2. Manpower Estimates

In the tables that follow, man years are tabulated year by year for the various activities involved in design and construction of the booster synchrotron and its injector. Total man years chargeable to pre-construction and pre-operation R&D, administration and construction are 428.

FIG. 23. CONSTRUCTION SCHEDULE FOR 1000-MEV BOOSTER SYNCHROTRON

Manpower Estimate for 50-MeV Linac Injector
(Man Years)

	Year												Total		
	<u>S</u>	<u>1st</u> <u>P</u>	<u>O</u>	<u>S</u>	<u>2nd</u> <u>P</u>	<u>O</u>	<u>S</u>	<u>3rd</u> <u>P</u>	<u>O</u>	<u>S</u>	<u>4th (half)</u> <u>P</u>	<u>O</u>	<u>S</u>	<u>P</u>	<u>O</u>
Preinjector and Beam Transport	1	1	1	1	1	3	1	1	3	$\frac{1}{2}$	$\frac{1}{2}$	$1\frac{1}{2}$	$3\frac{1}{2}$	$3\frac{1}{2}$	$8\frac{1}{2}$
Radiofrequency	0	4	6	0	4	6	0	4	6	0	2	3	0	14	21
Tanks and Drift Tubes	0	3	4	0	3	6	0	3	10	0	$1\frac{1}{2}$	3	0	$10\frac{1}{2}$	23
Vacuum	0	1	1	0	1	1	0	1	3	0	$\frac{1}{2}$	$1\frac{1}{2}$	0	$3\frac{1}{2}$	$6\frac{1}{2}$
Controls	0	2	1	0	2	3	0	2	3	0	1	$1\frac{1}{2}$	0	7	$8\frac{1}{2}$
Water	0	$\frac{1}{2}$	0	0	$\frac{1}{2}$	0	0	$\frac{1}{2}$	0	0	0	0	0	$1\frac{1}{2}$	0
Power	0	$\frac{1}{2}$	0	0	$\frac{1}{2}$	0	0	$\frac{1}{2}$	0	0	$\frac{1}{2}$	0	0	2	0
ME, EE Drafting	0	1	10	0	1	10	0	1	8	0	$\frac{1}{2}$	3	0	$3\frac{1}{2}$	31
Physics, General	3	2	0	3	2	0	3	2	0	$1\frac{1}{2}$	1	0	$10\frac{1}{2}$	7	0
Administration	<u>0</u>	<u>0</u>	<u>6</u>	<u>0</u>	<u>0</u>	<u>6</u>	<u>0</u>	<u>0</u>	<u>6</u>	<u>0</u>	<u>0</u>	<u>3</u>	<u>0</u>	<u>0</u>	<u>21</u>
Total	4	15	29	4	15	35	4	15	39	2	7	17	14	52	120
R&D included	<u>2</u>	<u>4</u>	<u>4</u>	<u>2</u>	<u>4</u>	<u>4</u>	<u>2</u>	<u>4</u>	<u>4</u>	<u>1</u>	<u>2</u>	<u>2</u>	<u>7</u>	<u>14</u>	<u>14</u>
Total less R&D	2	11	25	2	11	31	2	11	35	1	5	15	7	38	106

S - Scientific (Physicists)

P - Professional (Electrical and Mechanical Engineers)

O - Other (Engineer Aides, Technicians, Machinists, etc.)

Manpower Estimate for 1000-MeV Booster Synchrotron
(Man Years)

	Year												Total		
	1st			2nd			3rd			4th(half)					
	S	P	O	S	P	O	S	P	O	S	P	O	S	P	O
Magnet	1	2	2	1	3	3	1	3	6	½	1½	3	3½	9½	14
Vacuum	0	1	1	0	1	2	0	1	4	0	½	2	0	3½	9
Water	0	½	0	0	½	1	0	1	3	0	½	1½	0	2½	4½
Controls	0	1	0	0	2	2	0	2	3	0	1	1½	0	6	6½
Rf	0	2	2	0	2	3	0	2	4	0	1	2	0	7	11
Power and MG Set	0	½	0	0	1	1	0	1	2	0	½	1	0	3	4
ME Gen. & Drafting	0	2	4	0	3	8	0	3	8	0	1½	4	0	9½	24
EE Gen. & Shop	0	3	3	0	3	7	0	3	8	0	1½	4	0	10½	22
Physics Gen.	2	0	0	2	0	0	2	0	0	1	0	0	7	0	0
Site and Buildings	0	1	1	0	1	1	0	1	1	0	½	½	0	3½	3½
Survey	0	0	0	0	0	0	0	½	2	0	½	1	0	1	3
Machine shop	0	0	3	0	0	5	0	0	5	0	0	2½	0	0	15½
Injection and Ejection	2	2	0	2	4	4	2	4	6	1	2	3	7	12	13
Administration	<u>0</u>	<u>0</u>	<u>2</u>	<u>0</u>	<u>0</u>	<u>8</u>	<u>0</u>	<u>0</u>	<u>10</u>	<u>0</u>	<u>0</u>	<u>5</u>	<u>0</u>	<u>0</u>	<u>25</u>
Total	5	15	18	5	20½	45	5	21½	62	2½	11	31	18	68	156
R&D included	<u>4</u>	<u>6</u>	<u>6</u>	<u>3</u>	<u>5</u>	<u>5</u>	<u>3</u>	<u>5</u>	<u>5</u>	<u>1</u>	<u>2</u>	<u>2</u>	<u>11</u>	<u>18</u>	<u>18</u>
Total less R&D	1	9	12	2	15	40	2	17	57	2	9	29	7	50	138

In summary, the total manpower requirements for the booster and the linac are:

	S	P	O	Total
Including R&D and Administration	32	120	276	428
Including only Administration	14	88	244	346
Excluding R&D and Administration	14	88	198	300

V-3. Cost Estimate

The cost estimate for the booster is presented in the following schedules:

Schedule A - Site, Utilities, Buildings and Structures

These estimates have been prepared by the Civil Engineering group in Brookhaven's Accelerator Department. The details of these estimates have been presented in Section IV-3 of this report.

Schedule B - Accelerator Systems

The linac estimate is based on the latest revision of the estimate presented in detail in the Phase I Scope Report (BNL 9500). The booster estimates are based on Brookhaven experience in the various special fields involved.

Schedule C - Research and Operating Equipment

No items have been included under this category.

Schedule D - Engineering, Design, Inspection and Administration

Architect-Engineering costs are estimated at 12.5 percent of Schedule A. Brookhaven engineering costs are based on the manpower tables given in Section V-2 and on the FY 1966 average operating budget dollars per man year as follows:

Scientific and Professional	16,520 per man year
Other technical personnel	10,720 per man year

General and Administrative costs are derived from the personnel tables in Section V-2 and on a figure of \$11,500 per man year.

Schedule E - Escalation and Contingency

The bases for these estimates are the same as those used in the estimates in the Scope Report (BNL 9500).

SUMMARY COST ESTIMATE
(Amounts in Thousands of Dollars)

SCHEDULE A - SITE, UTILITIES, BUILDINGS AND STRUCTURES		3,352
Buildings	2,927	
Shielding	425	
 SCHEDULE B - ACCELERATOR SYSTEMS		 9,021
Linear Accelerator	4,061	
Booster Synchrotron	4,960	
 SCHEDULE C - RESEARCH AND OPERATING EQUIPMENT		 0
 SCHEDULE D - ENGINEERING, DESIGN, INSPECTION AND ADMINISTRATION		 3,919
 SCHEDULE E - CONTINGENCY AND ESCALATION		 3,581
Contingency	2,604	
Escalation	977	
 TOTAL		 <u>19,873</u>

SCHEDULE A - SITE, UTILITIES, BUILDINGS AND STRUCTURES
(Amounts in Thousands of Dollars)

Structures	2,690
High-Bay (50,500 SF @ \$45/SF)	2,270
Office-Lab (12,000 SF @ \$35/SF)	420
Special Foundations	50
Cranes	100
General Excavation	42
Connecting Tunnels	45
Site Work, Utilities, AGS Conjunction (these are included elsewhere in the Conversion estimate)	0
Subtotal, Buildings	2,927
Radiation Shielding (net cost after deduction for 6500 tons of Cosmotron shielding)	425
Total, Schedule A	3,352

SCHEDULE B - ACCELERATOR SYSTEMS
(Amounts in Thousands of Dollars)

Linear Accelerator (for details refer to BNL 9500):

Preinjector	446
Accelerator cavities	1,120
Rf system	1,153
Control and transport	460
Mechanical and electrical services	432
Labor	<u>450</u>
Subtotal, Linear Accelerator	4,061

Booster Synchrotron:

Magnet core (1,023,000 lb @ \$1.075/lb)	1,100
Magnet coil (75,000 lb @ \$4/lb)	300
Magnet power supply (16,000 kVA @ \$42/kVA)	672
Poleface windings (17,200 lb @ \$5/lb) (including returns and supports)	86
Poleface winding power supplies (4 @ \$12,500 each)	50
Vacuum system, including pumps and controls	170
Rf system	650
Phase-space rotation	68
Betatron acceleration	150
Beam transport	400
Controls	245
Injection	75
Ejection	378
Pickup electrodes and beam monitoring	66
Labor	<u>550</u>
Subtotal, Booster Synchrotron	<u>4,960</u>

Total, Schedule B 9,021

SCHEDULE D - ENGINEERING, DESIGN, INSPECTION AND ADMINISTRATION
(Amounts in Thousands of Dollars)

Architect-Engineer (12.5 percent of Schedule A)	419
Engineering - BNL	2,811
S and P - 102 man years × \$16,520	1,685
Other - 105 man years × \$10,720	1,126
General and Administrative - BNL	529
46 man years × \$11,500	
Travel, communications, supplies and equipment	120
Computer time	40
	<hr/>
Total, Schedule D	3,919
	<hr/>

SCHEDULE E - CONTINGENCY AND ESCALATION
(Amounts in Thousands of Dollars)

Contingency on Schedule A at 15 percent	503
Contingency on Schedule B at 17 percent	1,364
Contingency on Schedule D at 15 percent	<u>737</u>
Subtotal, Contingency	2,604
Escalation (6 percent of Schedules A, B, and D)	<u>977</u>
	<hr/>
Total, Schedule E	3,581
	<hr/>

A 1000-MeV booster with 200-MeV injection would be somewhat less costly since its magnet would have cross-sectional dimensions reduced by about a factor of two below the booster magnet for 50-MeV injection. Costs of the magnet power supply, the poleface windings, the rf system and the vacuum chamber would all be materially reduced. On the other hand, to achieve the same total charge in the booster about twice as many turns must be injected for the same injector current.

Whether or not the booster is chosen as the new AGS injector, it would appear that studies of booster design should be continued. There seems to be little doubt that a booster synchrotron of some variety will be included in the injection systems of the 200-BeV and the 300-BeV accelerators.

VII. Acknowledgements

The injector study committee is indebted to a large number of members of the Accelerator Department for much generous assistance. Major contributions to the study have been made by

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V-4. Comments on Cost Estimate

The magnet power supply estimate in Schedule B could be reduced by about \$340,000 if the motor-generator set from the Cosmotron were used for the booster. A new ignitron rectifier bank would still be necessary since it is planned to use the Cosmotron's rectifier bank as part of the new power supply for the AGS magnet. The new rectifier bank is estimated to cost \$250,000. An additional \$70,000 would be required to move the Cosmotron's motor-generator system and to refurbish it to a "like new" condition.

Schedule D is about 33 percent of the sum of Schedule A and Schedule B. This percentage is somewhat higher than that ordinarily derived in estimates for accelerator projects. The reason for this is the materially larger staff required for the design and construction of two accelerators. The 300 man years total quoted in Section V-2 is to be compared with a total of about 230 man years for design and construction of a 200-MeV linear accelerator.

The total estimate of slightly less than \$20 million is to be compared with a figure of about \$18 million for a 200-MeV linear accelerator. Since the booster estimate has been prepared rather hastily, the difference between the two figures cannot be regarded as significant. The booster estimate cannot be regarded as accurate to better than ten or fifteen percent.

VI. Conclusions

As has been indicated throughout the body of this report, a number of design problems remain to be solved. The study group has, however, convinced itself that the problems which remain are soluble. The group believes, although it cannot promise, that the remaining problems can be solved in times consistent with the schedule presented in Section V-1.

Use of a 1000-MeV booster synchrotron injector rather than a 200-MeV linac injector gives promise of a higher final AGS intensity by a factor between three and five. The cost of the booster is comparable with that of the linac. On the other hand, a number of uncertainties still remain in the booster design and its design and construction would require a materially larger staff than would be necessary for the linac.