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A 200 BEV ACCELERATOR EMPLOYING A SEPARATED FUNCTION MAGNET LATTICE

G.T. Danby, J.E. Allinger and J.W. Jackson

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PURPOSE

The purpose of this report is to show that a separated function 200 BeV proton synchrotron is inherently a better and more flexible machine than the conventional combined function design. Additional advantages will be discussed which may well be of great importance. Furthermore, it is a very practical machine. A cost estimate shows that it can be constructed for considerably less money.

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INTRODUCTION

The idea of either separated function or combined function magnet systems for a strong focusing accelerator is obvious in itself. However, both the AGS and CERN PS and several smaller accelerators were constructed using combined function C-magnets with a shaped pole profile.

To consider this question now is not to question the correctness of the choice made at that time. Conversely, because the AGS and P.S. have been very successful accelerators does not preclude the possibility that changing circumstances could lead to a different magnet lattice being a better choice.

Several obvious factors enter into re-considering this question. New aspects of magnet design and fabrication have been highly developed in recent years.

Quadrupoles providing high gradients with good linearity are necessary for a practical separated function machine. Otherwise, any reduction in circumference obtained by using higher deflecting fields will be more than lost when one inserts the necessary quadrupoles into the lattice. Knowledge of quadrupoles was fairly primitive at the inception of the AGS, since after all strong focusing was a new concept.

Secondly, the window frame dipole has become very common at high energy establishments. It has much lower aberrations at high fields than the C-magnet, and even the somewhat more symmetrical H-magnet, but requires coils fabricated with the coil ends bent through 90° with respect to the central region of the coil. This is now a routine fabrication technique which is not a source of serious worry.

A third and very important factor of change is in the area of accessibility to the vacuum chamber within the magnets. The 30 BeV machines utilized the open side of the magnets for injection and for primary proton beam and, in some cases, secondary beam extraction. The development of very long straight sections, as pioneered by T.L. Collins, and the need to run more and more with external beams for very high energy interactions results in the situation where in the LRL 200 BeV Study⁽¹⁾ this accessibility is practically not used at all, except for small vacuum connections. The trend to external beams is dictated both by the sharp forward production of secondaries and the radiation problems within the accelerators resulting from internal targeting with very high energy high intensity beams.

As a result, in principle, the LRL magnet structure could be replaced by a separated function lattice, still keeping the straight sections to provide accessibility for components, injection, extraction, etc.

Experience with the magnet system of the AGS, both during construction and as a research tool, plus direct experience in the recent evolution of beam transport magnets of high optical purity created a strong conviction that a separated function lattice would produce a superior machine. It is the detailed considerations of beam optical properties, including aberrations, of the two magnet systems that reveals much of their respective merits. Otherwise there is no great incentive.

Cost analysis must be considered in this study since the accelerator is a tool (and a very expensive one). If this report concluded with the opinion that the proposed system is better, although the combined function system will work quite well, and that, incidently, the proposed system would probably cost fifty million dollars more, there would not be many readers. However, beyond knowing that costs were competitive as the study advanced, the primary motive was, and is, to make if possible, a better functioning accelerator.

The new knowledge available on magnet components, greatly aided by the new computational methods available, obviously helps the theoretical aspects of machine design. In addition these factors are very important in the practical matter of costs.

In summary, the detailed magnetic knowledge which was the incentive for this study also is responsible for the practical benefits which make it economically competitive.

Part I is devoted to a general comparison of the machine described in the 200 BeV LRL Design Study, with a separated function equivalent.

Part II describes specific components to match properties, and the interrelated cost analysis which shows it is economically a very attractive alternative.

Having established a specific, and practical, alternative in Part II, further specific comparison of performance is described in Part III.

The final section, Part IV, outlines further inherent possibilities of the flexible separated function design.

I. COMPARISON OF THE TWO TYPES OF MAGNET COMPONENTS

A. Combined Function Magnet

The obvious attraction of a combined function magnet is that one gets the focusing gradient "for nothing." The iron and copper profile can be designed to give very linear gradient across the aperture, that is a quite constant k factor, (the ratio of gradient to dipole strength), as long as the permeability is very high. Its weakness is that it is really a highly deformed dipole, so that as soon as the permeability drops, the spatial distribution of the field deteriorates rapidly. Thus, both its low field and high field properties are poor.

Consider, for example, the AGS magnet profile scaled exactly to smaller cross section, for the purpose of designing a component for a larger machine. Both horizontal and vertical dimensions scale down by the scaling factor, but the slope of the iron pole surface would not be changed at a given (scaled) value of x . The result would be an increase in $k = \frac{G}{B}$ proportional to the inverse of the scaling factor. However, if one wants^o to maintain the original value of k , the slope will then be reduced by the scaling factor.

In addition, for a 200 BeV machine, to keep the ν value from increasing greatly, one makes a weaker focusing machine. This also reduces the slope of the pole profile. Both these factors are inherent in the lattice parameters desired and produce a less "deformed" dipole. This means the minimum gap field is lower for a given aperture centerline field B_0 , and the magnet does not saturate until higher values of B_0 are reached. Another way of saying the same thing is that the component of field in the iron which flows towards the minimum gap, rather than out of the surface, is reduced. In the LRL Study Group proposal, the magnet design, as worked out with the Sibyl Program for computing magnetic profiles, results in a usable field shape up to 15.1 kG, which is about 2 kG greater than the usable peak dipole field on the aperture centerline in the AGS magnets.

In Figure 1 is shown a cross section of the AGS and proposed LRL magnet profiles. This shows that both give the same ideal minimum gap fields at the operating maximum fields of $B_0 = 13.1$ kG and 15.1 kG respectively. (Due to the 95% packing factor these fields are actually ~ 21.4 kG).

Furthermore, the derivative of the field has dropped off about the same amount in both these cases. This is true both at the aperture centerline and also at 5 cm to the high field side in the LRL magnet, and the equivalent position of $5 \times 3.5/2.44$ cm in the AGS magnet. This comparison presupposes, as is true, that current conductor locations and yoke and pole thickness are sufficient in both cases so that excitation is effectively limited only by minimum gap saturation. For example, in the LRL 200 BeV Design Study, a comparison of the gradient drop due to saturation at the aperture centerline at 15 kG is shown for a slanted vs. a straight edged pole. The former is shown to be a better magnet, equivalent to about 1 kG more usable dipole field at saturation. However, the straight edged pole shown is clearly inadequate, and the thickness increase in the yoke on the inside is clearly more important than the detailed shape. The AGS magnets curve away for a bit and then indeed are straight edged, but have adequate yoke to provide flux to the minimum gap side. It should also be noted that as the slope of the profile decreases, and less flux is funneling into the minimum gap from the direction of the aperture centerline the yoke should be thicker on the minimum gap side.

It should be stressed that the above is not to criticize the LRL Study Group for its elaborate Sibyl calculations⁽²⁾ on the magnet profile and properties. (Sibyl has been used extensively in this report as well.) Clearly in a detailed design study, everything reasonable should be done, and even modest gains are well worth the effort. However, great improvements were not made over the AGS and PS magnets. The unlimited "modelling" available on the computer does allow one to optimize the use of materials, for example, but the performance improvements are almost all inherent in modifying the magnet for the desired 200 BeV lattice. This is said to emphasize the starting point of this report, that high field limitations of the combined function magnet are inherent in the fact that it is a deformed dipole.

This discussion bears out also that, for a combined function magnet, varying either the vertical aperture or the usable horizontal aperture alone, and independently, has severe limitations. If the vertical aperture is changed, as we have seen, for a given k the peak dipole field attainable changes. This interacts also with the horizontal pole widths. However, as the vertical aperture is increased the poles should be wider to retain good properties over the full horizontal aperture. For horizontal increase with a constant aper-

ture centerline gap height, the minimum gap gets smaller, and peak fields will fall. In summary, the smaller the vertical and horizontal apertures possible for a given k , the higher the saturation field. When these dimensions are increased, the peak dipole field will fall, and hence the whole machine has to be increased in radius.

The LRL 200 BeV Study Group, also looked in to a symmetrical yoke version. This is basically an H-magnet with hyperbolic gradient poles inserted. This did not result in any appreciable improvement as far as magnetic properties are concerned. This is not surprising, since the symmetry was imposed in a location where it has no benefit. The properties of the iron, plus the profile of the iron and of the current elements in the region of the aperture almost entirely determine the field properties, for a reasonably designed magnet. In other words, the location of the yoke, provided it has a reasonably low reluctance, is largely irrelevant.

The situation then is that combined function magnets can be used up to about 15 kG peak field, in the 200 BeV lattice proposed, by employing many quadrupole and sextupole correction lenses in the lattice. This is for a gradient of $\sim 8\%/in$. For higher gradient magnets or a larger aperture, the peak dipole field would be lower.

B. Separate Function Magnets

Let us consider this in two parts:

1) Dipole.

This discussion is restricted entirely to the choice of window frame dipoles, because they have a very basic dipole symmetry, so that a practical real magnet satisfies very exactly simple boundary conditions. For infinite permeability this results in a dipole field occupying a rectangular aperture with a linearly rising field in the region occupied by the coil. The fact that the pole surfaces are plane and parallel and are dipole equipotentials in the region of the aperture results in a very high degree of natural symmetry, so that aberrations are small even for fairly low permeability. This also means that conductor location is not too critical and in practice a coil designed to good, but common, tolerances gives no aberrations of any consequence.

One could still keep these features with H-magnet poles, for example. This would easily allow more vertical space for coils but unless the poles are very wide the edge effects introduce large aberrations, even with wedged sides on the poles. Dipole magnets which must have pole regions considerably

wider than the desired horizontal aperture, to keep aberrations small, are not practical for our purpose.

In general, one can consider any combination of current elements and iron profile which produces a dipole potential with low aberrations present in the region of the aperture. However, since dipole equipotentials are by definition plane parallel surfaces, any other iron profile shape will not be an equipotential surface. In such a case, only the interplay of current elements and the profile produce the dipole field, and any errors in conductor geometry distort the field. Also, the varying potential on the iron surface makes the aberrations very sensitive to permeability. Considering that one needs compact magnets and very precise magnetic fields for accelerator components, the window frame seems to be the best choice of dipole.

As stated before, because the symmetry is indeed that of two equipotential parallel surfaces, even for permeability considerably lower than would be tolerable in a combined function magnet the amount of aberration is still very low. This results in purer dipole fields over a wide range of excitation from low to very high values of the field. Furthermore, the aberrations that do arise are constrained by the transverse symmetry to be even powers of the displacement. ie. X^2 , X^4 , etc. This means, as will be shown later, that dipole fields well in excess of 20 kG can be produced which have negligible aberration in the aperture, except for a moderate sextupole term. The benefits of symmetry also apply to low field distortions due to eddy currents in the magnet cores, coils, and (rectangular) vacuum chambers. These result in a reduction in the field which is itself mainly of a dipole nature, so that small aberrations are produced. The remanent field is lower for the window frame geometry than for a C shaped yoke magnet of the same steel. This is due to the fact that any spontaneous reorientation of the domains to produce a closed magnet circuit entirely within the core results in a lower energy state. In summary, the remanence is low, and what exists still exhibits low aberrations which are also constrained by the symmetry to be sextupole, 10 pole, etc. Similarly, eddy currents produce low aberrations so that in principle a ring could be constructed using window frame magnets with injection at lower dipole fields than in the AGS or PS. (It will be shown later that similar symmetry arguments applied to the quadrupole do not change this conclusion.) With respect to stray fields, the situation is also better for a separated function system. The earth's field will be excluded from the dipoles and quadrupoles. For the very small residual interaction of the earth's

field near the ends of the magnet blocks, the earth's field will be rotated to give up-down symmetry and therefore produce no coupling. Any auxiliary fringing fields due to extraction magnets, etc., will be completely shielded inside magnet cores, and so the situation is better in this respect also. The only stray field of any consequence, which is due to the earth's field, would be in the long straight sections, and very long superperiod straight sections.

2) Quadrupoles.

To compete economically with combined function magnets quadrupoles with very high gradients and minimum lengths are required.

Quadrupoles of very high quadrupole field purity, capable of being driven to high pole tip fields, and having quite modest power consumption, have been developed at the AGS (G. Danby and J. Jackson, unpublished manuscript). These quadrupoles have an additional feature that they can be assembled as top and bottom halves only, so that there is complete radial access from the vacuum chamber out.

The quadrupoles proposed in the LRL study for the Collins straight⁽³⁾ sections, for example, also have this feature. However, they are constructed from the point of view that two combined function C-magnets can be made to face each other and produce a resulting quadrupole field. This is matched to the elliptical vacuum chamber. However, such quadrupole magnets will produce octupole and other aberrations if driven to high fields.

Our split quadrupole was based on the recognition that if the four fold symmetry of the poles and coils is maintained until one enters a region of low reluctance (the base of the poles), the symmetry advantages remain completely, as far as field properties are concerned, and it is irrelevant whether there are two or four yoke plates. This magnet design has been in use here for a few years and is widely copied at other laboratories.

To date these have been used either as "normal" quadrupoles, or as "narrow" ones with no side plates, but with coils occupying the full coil slot width. For special locations one could use special thin coils and leave a free radial aperture for beam everywhere beyond the vacuum chamber. It is a flexible design and overall dimensions can be changed to accommodate such special requirements. Neither of these operations affect aberrations and such special quadrupoles could easily be made to "track" their normal counterparts, since

only yoke reluctance is a factor of any consequence.

The four fold symmetry of quadrupoles constructed with four identical poles and with four identical conductor packages in the slots results in a situation where only field components varying with radius as r , r^5 , r^9 , etc. can be produced. The design mentioned above is such that the integral of gradient length can be made completely linear with radius. That is, the first harmonic (r^5 , 6θ) can be varied at will, in design, so the small contribution due to end effects, which will be about 1/200 in gradient (1/1000 in field) at full aperture, will be cancelled by an equal and opposite deviation from zero amplitude in the two dimensional part of the field. The coefficient of the next aberration is $\sim 0.1\%$ in field at full aperture, but varies as r^9 . The r^{13} term is large, but also academic, even for a completely filled aperture. It is $\sim 1\%$ in field, at full aperture, but falling as r^{13} . Since a particle almost touching the vacuum chamber in practice spends very little of its time there, such a high power aberration is not relevant.

C. Tracking

In a separated function machine, the dipoles and quadrupoles must track so that v remains constant as the momentum increases. For a v of about 16, a tracking error of $\pm 0.1\%$ gives a Δv of $\sim .017$, which is better than necessary. The symmetry arguments which made the magnet aberrations less sensitive to permeability changes, also make for less sensitivity to variations in excitation properties. Tracking reduces to designing the quadrupole yoke thickness to show the same nonlinearity of gradient with excitation as the dipole ratio of field to excitation. This can be designed to good accuracy by relatively simple calculations. In addition, any accelerator will incorporate correction quadrupoles so the gradient can be dynamically corrected. For example, in the LRL 200 BeV Study at maximum field of 15.1 kG; the ratio of gradient to dipole drops almost 4% below the intermediate field value. Correction is necessary at injection, as well as at saturation (the LRL design has 120 correcting quadrupoles for its 480 gradient C-magnets).

The ideal distribution for this correction is in the quadrupole fields themselves. In the separated function lattice this is the obvious location for quadrupole correction. An auxiliary winding with an excitation capacity of a few percent of the primary winding can be servoed to keep constant the ratio of G/B by means of two Hall probes or such field monitors in spare units in series with the ring of dipoles and quadrupoles. An accuracy of considerably

better than 0.1% can be easily obtainable. (Ripple is no problem in this auxiliary (presumably SCR) supply, since 100% correction should correspond to only $\sim 1\%$ of the gradient.)

In summary, the separated function magnet system has the added problem of making the quadrupoles track with the dipoles. On the surface, the combined function magnet appears to achieve this automatically. However, at both high and low fields correction is necessary. This is costly in space, extra components, and complexity, since for good correction many compensation quadrupoles must be distributed around. Well designed dipoles and quadrupoles powered, in series, will track better over the whole acceleration cycle than the combined function magnet used to its saturation field. Compensating coils in the quadrupoles can be servoed to hold very close tolerances in a simple and practical way. This is also the ideal optical location.

D. Comparison of the Two Lattices

The conventional combined function lattice is a tested highly successful system. It also provides accessibility on the open side, but as mentioned earlier, this has ceased to be as important a factor in the super energy machines.

The separated function lattice can be shown to have extremely pure field components and can be made to give any desired magnetic properties. The beam optical knowledge and experience of the accelerator community is such that one does not have to doubt the capacity to compute and predict with certainty the optical properties of a lattice of magnets of known field properties. For this reason one does not have to fear building a machine "differently". In the separated function machine we have a very variable lattice and there is no problem of flexible machine design.

Before considering any detailed comparison it should be stated that this study relies very heavily on the LRL 200 BeV Study as a basis for comparison. By and large we rely on its conclusions and costs, as assembled by a large and competent group. Their report describes an excellent second generation version of the 30 BeV machines.

Our study, by comparison, represents a few man-months of actual work (based, of course, on the accumulation of ideas over a period of years). We attempt only to study the questions related to the basic differences of the separated function approach. However, to discuss the practicality of the

separated function lattice we must discuss cost comparisons. The power supply and power dissipation and cooling are naturally intermeshed with magnet lattice, as well as the tunnel, and so must also be considered. Most other aspects are not touched, as being common to either machine. This is not only practical for a modest study, but also completely fair to a cost comparison between the two magnet lattices, since we have carefully matched characteristics to the LRL values.

However, having stated the limited scope of the study, and our indebtedness to the LRL Group results, it should also be stated that within the area of comparison this is a quite detailed study. We believe the magnet concepts developed are inherently superior and the magnetic properties and cost figures to be very thoroughly studied. The field properties and engineering problems exploited in this report are the result of considerable immediate theoretical and practical experience with just such components.

The ideas for applying their superior optical properties to an accelerator lattice have been accumulating for some time. As to whether the result would be a practical alternative, considering cost, and other complexities and requirements for an accelerator, was something we did not know at all until a few weeks ago. The results appear to indicate that the matter should be seriously considered by the accelerator community as a whole prior to starting on the next generation of accelerator.

For our lattice a simple method of machine parameter design was devised which gives the basic machine parameters $\beta_{\max}$, $\beta_{\min}$, the momentum compaction $\alpha_{\max}$, the phase advance $\Delta\mu$ per period, and, of course, the v of the ring. This gives the parameters required for a design comparison and is adequate for the purposes of this report. No straight section design is included, but clearly this can be incorporated since it is a flexible machine. For purposes of comparison of properties and costs the 12 LRL straight sections have been arbitrarily incorporated, as is, both as to number and to length.

The lack of accessibility of closed magnets as far as beam injection and extraction are concerned is not serious. The quadrupoles which we have designed could easily be made completely open on the horizontal symmetry plane, in any event, with no change in field properties, so the only problem is the dipole side yokes.

For injection this is absolutely no problem. For extraction of high energy external beams, the channel can be quite small (as a result, the LRL

final ejection magnets have an aperture cross section of 0.4" vertically x 1" horizontally). Channels of this size could be provided, for example, at the rear of the dipole coils, or even as "holes" in the coils or cores. Certainly, some such channels can be provided in the few dipoles necessary. Also, if desired there is no doubt that special C-type dipoles could be made for special locations, like deflection inside straight sections. The LRL machine would have special short gradient magnets in its straight sections. The problem of aberrations at high fields in a C structure could be taken care of by making them about 30% longer and running them at a proportionally lower field. The saturation tracking properties could be easily arranged to be the same. This would be done independent of aberrations by controlling yoke thickness well removed from the poles.

For secondary beams, the dipoles would not be significantly worse. Present thinking places consideration of internal targets on a low key, because of the very sharply peaked forward production and severe radiation problem in the machine. Apart from the disadvantage to the machine, experimentally it is very hard to get at these very small production angles and collect a large solid angle of secondaries. With the smaller aperture machines and much larger β values at 200 BeV, the advantages of multiple traversal over external targets are less also due to an appreciable fraction of the primary protons being scattered into the vacuum chamber.

Still, a machine must be flexible to meet all developments, and it is conceivable that unknown factors could make a great deal of internal targeting vital. In any case, septum magnets against the vacuum pipe in the downstream end of the straight section will be used to sweep the secondary beam away from the ring. The LRL design has two open magnets immediately downstream of the straight section, followed by two magnets with the back legs on the side of an outside beam. (On the inside of the ring, the situation is reversed.) In our lattice if the first dipole after the end of the long straight section was of the ordinary type described in this report, we would be somewhat worse off for a magnetically swept beam of very high momentum drifting past it on the outside of the ring. This does not seem to be too serious considering the other advantages to be described, and can no doubt be designed out. Certainly special dipole magnets at the end of the straight section could be made either as C magnets to provide large interior channels, or else by making cores wider or coils thinner in the window frames. That is, large windows could be

provided between a coil and an expanded core for special sections. (If all "clever" solutions were disregarded, appropriately longer straight sections could be considered for on the order of one million dollars, with many other fringe benefits.)

E. Radiation

There are two main factors to consider. Our magnets shield the exterior parts of the ring much better than combined function magnets. On the other hand, our coils get more exposure. (The LRL coils on the inside are also quite exposed, so this difference may not be too significant to coil fabrication problems.) In balance, the separated function machine is much better from the radiation point of view, because current thinking on coils is geared to large radiation exposure, and the shielding advantage of the completely enclosed vacuum chamber in the major part of the circumference will be very large. This is considered in more detail later.

F. Beam Optics

All magnets under discussion have no curvature, so that their fields are two dimensional except for the end effects. (x is the horizontal and y the vertical axis in this report.) At the magnet ends azimuthally varying field components are present with the same multipolarities as allowed by the boundary conditions in the two dimensional part of the field. This is usually approximated for a given field component to a step function of amplitude equal to the internal two dimensional amplitude, and of azimuthal length such that the product of the field and this length equals the actual azimuthal integral through the entire magnet.

Weaker properties, such as vertical focusing in the end fields, are approximated quite well with this step function model. Because the magnets are long compared to their apertures, and the radius of curvature of the protons is very great, optical deviations from the predictions of this model are very small. (Other field components are present in the ends involving higher derivatives of the two dimensional multipolarities which are not so well approximated by the step function model. These are small and the two ends are almost self-cancelling. They have a completely negligible affect.)

The optical properties at high and low fields are better for the separated function lattice. The combined function magnet can be designed for very good two dimensional properties at intermediate fields. The end effects, principally the change of integral gradient with radius, are certainly small

enough so that they can either be corrected with compensating magnets or even over large ranges ignored, as in the AGS. (In the LRL Study it is planned to compensate both for the effect of gradient length variation with radius, plus the change of ψ with radius due to momentum change, by varying the profile of the magnets. This requires two different profiles for F and D magnets.) At low fields and high fields, the field properties vary dynamically quite severely, compared with the separated function machine. This is not to say that with adequate correcting lenses, properly varying as a function of main magnet excitation, one cannot produce good optical properties and make the machine function well, but certainly the separated function machine can excel in this respect with much simpler compensations. In addition to the earlier arguments, the integral dipole fields still have symmetry in their ends and for the lengths required here they deviate only negligibly from the properties of an infinitely long dipole magnet. That is, the two dimensional properties apply. The contribution of the ends to $\Delta G/G$ at 22 kG, and 2.5" radius, will be about 1×10^{-3} parts due to sextupole, and about 5 times smaller for 10 pole.

The computations gave 3.75% saturation at 20 kG, and 9% saturation at 22 kG. For this reason fields above 22 kG are not considered. As will be discussed later, we deliberately used conservative saturation permeability estimates, and a conservative M-43 steel. Using experimental permeability data, and M-45 steel, or low carbon steel as proposed by LRL, should reduce this saturation.

At 22 kG, the amount of sextupole field component at 2.5 inches was about 5 kG - feet per dipole. The 10 pole is roughly 10% as large, so that uncorrected it will cause no difficulty over most of the aperture. Two sextupoles per period, or roughly 150 in all, each about the same strength as the 120 LRL proposed sextupoles (i.e. approximately 15 kG-feet integral pole tip field at 2.5") will provide well distributed sextupole component at all fields, as well as taking care of dipole saturation up to 22 kG.

An alternative possibility for dipole correction is pole face windings. These are conceptually simple for the window frame dipole. However, it appears that the increased vertical aperture requirements would increase cost and complexity more than widely distributed sextupoles in straight sections.

As shown previously, the quadrupoles are designed to have no integral aberrations to high order.

In the combined function machine, the change of ν values caused by the variation of integral gradient lengths with radius is comparable in magnitude to the variation due to momentum change with radius. However, the two terms partially cancel for the change of ν_y with radius, and add for the variation of ν_x with radius. For the separated function lattice, with only the momentum variation present, good optical compensation with sextupoles is considerably easier. The major additional effect present should be the very weak wedge focusing (vertical focusing), assuming the two ends of the dipoles were parallel surfaces. This could be easily changed to give equal focusing in both planes by slightly wedging the magnet ends, but there seems to be no point in doing this. In fact, some built in ν splitting may be advantageous, to ease the work of correction devices. Slight wedging of end angles could be a useful parameter.

G. Affects of Magnet Errors

There are advantages to the magnet units being less sensitive to permeability decrease, apart from the question of not having to provide as many programmed corrections. According to the LRL 200 BeV Design Study, a variation of 1% in a defined saturation induction or in the stacking factor for the CERN PS magnet at 14.4 kG resulted in a gradient change of 1/3% at the aperture centerline and of 1.5% at 6 cm into the narrow gap. While slightly smaller numbers should occur for the LRL magnet at 15.1 kG, the fact that the ν of the machine is twice as large means that this effect must be controlled more closely or considerable reduction of aperture, plus stop-band widening, will result.

Consider the separated function quadrupoles with 1% deviation in packing factor, for example. The quadrupoles can be made extremely linear to peak gradients higher than planned here and will be insensitive to steel and packing factor fluctuations unless designed to saturate. However, for tracking purposes, one may choose to deliberately introduce saturation in the yoke to compare approximately with the dipole saturation at peak field. (This must be weighed against making the auxiliary windings do the compensation.) In this case, 1% variations could give a gradient bump of a few tenths of a percent at peak gradient. This means that care should be taken on the quadrupoles to make them as uniform as possible, if saturation is deliberately built in. They are relatively minor in total cost ($\sim \$2.5$ million) compared to the dipoles. (i.e. $\sim 10\%$).

Dipole field errors limit strong focusing ⁽⁴⁾accelerator design, producing distortions in the ideal equilibrium orbit. In the combined function machine this results predominantly from errors in locating the magnets correctly, or due to variations in the magnets themselves. Ignoring nonlinearities, an error in horizontal position results in no change of gradient, but a different "dipole" field. Similarly, vertical errors result in a "dipole" bump producing a vertical impulse.

For the AGS (or the LRL Design) one defines the magnetic aperture centerline of each magnet as a line through the magnet, approximately coincident with the defined mechanical aperture centerline, which gives the desired identical vertical component of field at some excitation. It must also give no horizontal field component, after the magnet is level with respect to rotation about the aperture centerline. For intermediate fields, variations in this location from unit to unit are due to mechanical imperfections in assembly and welding. At high and low fields, additional changes due to packing factor and steel property fluctuations occur.

Integral magnetic field measurements not only allow one to check for gross imperfections, such as excessive core shorts, etc., but they also provide a location for the magnetic centerline with respect to mechanical fiducial locations and leveling pads. This centerline is itself a function of excitation. In practice one effectively "shims" the magnets to get greater identity of units by finding the magnetic centerline. To first order, this procedure compensates for individual variations. The sensitivity of good magnetic field measurements is very great, and the limit on locating the centerline is set by the ability to transfer this location back to fiducials, and then later to reverse the procedure when locating the magnetic centerline on the ring.

The affect of statistically distributed dipole bumps around the ring is an absolutely vital parameter for a strong focusing machine. One may choose to locate the magnets on their intermediate field centerlines, for example. At injection field and peak field the effect of changes in the centerline location with excitation enter the picture, in addition to the errors in positioning. The effect of this can be controlled somewhat by deliberately arranging the magnet order on the ring.

For the combined function machine the limiting factor on minimizing equilibrium orbit distortions is the ability to translate magnetic centerlines into the lattice by using fiducial locations and leveling. Fortunately, what is attainable with good surveying techniques causes only modest orbit distortions in the present machines.

The situation does not change greatly for the LRL design. The bigger machine makes things somewhat worse, but an error of 7 mils for the LRL design would be roughly equivalent to 10 mils, in its statistical weight, on the AGS lattice. Practically speaking this does not represent any appreciable change between the LRL and AGS lattice.

For a separated function design, calculations should be carried out for statistically distributed dipole bumps. However, the affect will be roughly the same as for the combined function machines. It will be shown in the following discussion that statistical errors will be very small due to dipole components. Quadrupole location, however, like that of the combined function magnet, should be as precise as possible: the overall affect on the orbit bumps with a given statistically distributed positional error will be about the same for both lattices. However, the number of elements to be positioned is much less in the separated function design. This is sufficient for the purpose of this report.

Consider, vertical orbit bumps due to dipole magnets. There will be no horizontal field component due to errors in positioning the dipole. Only rotation around the centerline can cause a horizontal field component. During magnetic measurements on the individual magnets, the plane of the leveling pads can be accurately established. The geometry of the dipole is favorable to precision leveling (see Fig. 4). In the ring, leveling is much easier than locating a position to a few mils. The dipoles will have very small vertical orbit distortions.

For errors in the vertical component of field, the situations are quite different. The combined function magnet has the advantage that its magnetic centerline can be defined at the location which gives no dipole error. However, an error of about 5 mils in getting this magnetic centerline located in the lattice gives an effective dipole error of one part in two thousand. Additional errors enter, as discussed earlier, at peak fields and also at low fields. The latter is made worse by remanent fluctuations, but at the high injection

field planned by LRL the low field effects should be considerably smaller than in the 30 BeV accelerators. Furthermore, as mentioned before, these effects can be considerably reduced by deliberate distribution on the ring.

The dipole magnet has the advantage that positioning errors have negligible affect on the vertical dipole component. Conversely, one cannot use the transverse location of the magnets to compensate for component error. However, one has the great advantage that the 10-foot magnet blocks (there are two to a magnet) can be combined into magnets and these magnets distributed around the ring in a manner to reduce bumps. We are not dealing now with a statistical limiting error in locating the magnets, but with components of precisely known dipole error. Magnetic measurements are very easy on dipoles. (Positioning accuracy takes most of the work, and time, on combined function magnets.) The error can easily be measured to better than 1 part in 10^4 .

The one tight tolerance of the split dipole design is on the average gap separation. A change of 1.5 mil in average separation between the top and bottom halves gives about 1 part in 10^3 dipole error. Dipole geometry lends itself to precision registry between the two halves, and, combined with planned location around the ring, should compensate for deviations which contribute to orbit bumps.

There is a further very attractive possibility. In the combined function case, one effectively "shims" the magnet by adjusting its location. For the dipole, there is no reason why permanent shimming to 1×10^{-4} parts, for example, could not be done during magnetic measurements. Some control on separation might be used, but simple rectangular sheets fitting pre-drilled holes on end plates could be used for a very fine adjustment. (12 mils in length represents 1 part in 10^4). This is a matter for further consideration, but there is no reason to believe that the dipoles could not be effectively made a minor source of orbit bumps at intermediate fields.

For low fields, variations due to steel properties affect either magnet system. However, for various reasons discussed earlier in this report, the window frame dipole will be less sensitive to this error, and furthermore, will not produce a gradient bump.

For the dipoles at peak field a change of field in the laminations in the vicinity of the pole surface would result in a dipole bump only. The sextupole present at 22 kG would be affected negligibly by small changes of exci-

tation. A plot of the saturation as a function of excitation will give the sensitivity to variations in field in the laminations. For the AGS magnets, the aperture centerline field divided by the excitation current, and plotted versus current, shows about the same percentage slope at 13 kG as the present dipole at 22 kG. The LRL Design magnet will be about the same at 15 kG, which means that all three designs, when used to saturations of a few percent, are comparable for dipole bumps due to magnet steel and packing factor fluctuations. However, the dipole produces no quadrupole bump as in the case of the combined function magnet. Modest orbit distortion at peak field is less serious than at injection field.

For the quadrupoles in the separated function lattice, the affect of position error is similar to the combined function magnet case. By magnetic measurements, one locates the centerline of the quadrupole (defined in a similar manner to the combined function centerline), except that the magnitude of the "dipole" field is zero. Again, any error in transferring this center to the lattice can result in horizontal and vertical orbit bumps. Surveying accuracies comparable to those for combined function magnets will be required. Any affects due to high or low fields are not only small in magnitude, but also do not cause the center to move, so orbit changes are not produced.

II. DESCRIPTION OF PROPOSED MACHINE

A. Detailed Design

The first design choice is the vacuum chamber dimensions; then a window frame dipole can be designed around it.

The aperture of the LRL Study was chosen; 2.4 in. vertically by 5 in. horizontally. Strictly speaking, the 5" width is easily adequate for the LRL 12 cm width inside the vacuum chamber, but the LRL aperture centerline gap is 2.44 inches. However, this gap decreases to 2.4 inches, about $\frac{1}{4}$ " to the inside. Depending on vacuum chamber design, it is probable that the rectangular aperture gives more effective vertical aperture. In any case an increase to 2.44" would cost 0.6 million dollars more. A roughly optimum length of 20 feet was chosen for the dipoles, considering magnet cost, tunnel costs and sagitta. For a peak field of 20 kG at 200 BeV this requires 340 dipole units for the entire ring deflection of 360° . For a peak field of 22 kG, 309 dipole units are required. (Clearly these numbers must be varied a few percent by changing unit lengths so that proper period numbers result, but this will have no appreciable effect on the total cost). The 20 kG number differs by only 4 dipoles (or 2 quadrupoles) from a suitable number of 336. The number 309 (310 was used in the cost estimates) is roughly half way between 336 ($N = 84$) and 288 ($N = 72$) dipoles. If the dipole lengths were increased or decreased by $\sim 7\%$ either 288 or 336 dipoles would be used. This would affect the final cost by $\sim \pm \$0.6$ million depending on which was chosen.

The yoke and coil cross sections were varied over reasonable limits and preliminary cost functions established. With the help of the Sibyl program for computing magnetic properties, aberrations and saturation decrease of the B vs I function were studied for various cases. A 95% packing factor, and conservative extrapolation of steel permeability data were used. The thickness of the yoke was chosen to give negligible contribution to saturation, so the decrease of incremental B with I represents saturation in the pole surfaces themselves.

Cost studies quickly showed that the best choice would be in the region of 20 to 22 kG based on M-43 steel and conservative high field permeability extrapolations. At higher fields the power supply and dissipation become excessive. Again it should be noted that the symmetry of the potential surfaces is such that considerable saturation can result without producing

appreciable aberration of the dipole field, so that considerably higher field values are limited only by the power aspects.

Having established a reasonable design, the vertical and horizontal apertures and coil sizes were varied to give differential cost functions.

Next, knowing reasonable lengths for periods employing these dipoles, the machine parameters were calculated by means of some simple machine design functions which were derived. (This method was checked by calculating the properties of the storage ring proposed by Tinlot et.al.⁽⁵⁾ for the SLAC facility). Very good agreement was found for $\beta_{\max}$, $\beta_{\min}$, and the momentum compaction, versus $\Delta\mu$, the phase advance per period, with the properties of that ring as calculated on the Synch program.⁽⁶⁾ (This was a much more severe test of the approximations than a 200 BeV ring, since this storage ring was designed for a very large momentum acceptance).

The machine parameters required in turn gave the range of quadrupole strength required. Then quadrupoles of both 5 inch and 7 inch

aperture were designed to give some idea of differential cost.

Two strengths, 15 kG and 18 kG, respectively, at the pole tip, were considered to get rough cost differentials as a function of magnet cross section, and power, as well as length. (The latter variable also affects tunnel circumference as well as period length).

With reasonably optimum figures on quadrupoles and better optimum figures on dipoles we can now design a period quite accurately.

In the LRL 200 BeV design, besides the gradient magnets there are 240 nominally 10 foot straight sections, and 12 long Collins straight sections of 166.3 feet each. These "10 foot" straight sections are really 7.8 feet long.

The 10 foot straight sections contain 120 quadrupoles and 120 sextupoles, for saturation correction of the main magnets. In addition, for injection corrections, there are quadrupoles, skew quadrupoles, sextupoles and deflection coils. Also included are high field bump magnets, and other apparatus.

1) Available Short Straight Section Space

It will now be shown that, as far as apparatus inserted into the aperture, and vacuum connections to the chamber are concerned, the present configuration will allow more access:

The only obvious use of the open C for access in the LRL study is for high vacuum coupling to the chamber, in every other magnet. This is naturally done through an oval port of about the vertical aperture in height and several times this dimension in width.

Consider the short straight sections. LRL has 240 of these, allowing 6 in. clearance, all around, between the magnet over-all lengths, for vacuum pipe connection.

In the present design, this 6 in. all round clearance is maintained. However, since only single coils are used which immediately curve upward, an over-all accessible region of 2 ft. is available on the bottom. Also the chamber, if desired, can be extended vertically on the top since the coil ends are several inches above the top of the apertures.

With a quadrupole immediately following two dipoles, a second short straight section is also available. We thus have twice as many short straight sections per period (assuming four dipoles per period.) Furthermore, devices such as pick up electrodes, shields, targets, etc, which can be inserted in the C magnet can be easily located in the quadrupoles of the lattice. This space will be readily accessible. The vertical aperture is always limited in the C magnet; but in the quadrupole there is always an excess of vertical space, even at a vertical β maximum. Thus pick-up electrodes, for example, can be readily designed to go in locations of horizontal minimums.

Considering the last fact, plus twice as many short straight sections, which are accessible from the bottom, there is much more available space in this design since most of the miles of accessibility in the "C" magnet design is irrelevant.

2) Ten Foot Straight Sections

The LRL design, quite wisely, has included appreciable space in 10 ft. (actually 7.8 ft. available clear length) straight sections. Two per period are provided. Each of the 240 spaces contains either one of 120 correcting quadrupoles or one of 120 correcting sextupoles. In addition there are two skew quadrupoles, five low field horizontal closed orbit deflectors, and five low field vertical closed orbit deflectors per super-period. (The 120 correcting quadrupoles are not necessary in the present proposed case. Auxiliary quadrupole windings provide easier, and better, correction. Similarly

the horizontal orbit correctors could be incorporated into the main dipoles.)

Even in the cases where two of these devices are in the same straight section, the space used is only about 3 ft. The reason for the additional 5 ft. of straight section is that in four of the superperiods the orbit bump and extraction magnets for targeting and external beams must also be inserted. Clearly then, the LRL design allows in other locations plenty of spare straight section, which is certainly a good thing.

To compare the two lattices, since we remove the correcting quadrupoles plus some more elements in the separated function case, we can easily remove one foot from the straight sections and still be comparing very fairly the two proposals. This will still leave more useful space free than in the LRL case. In the five locations at which high field steering pairs are present in the four superperiods required, only 1.5 ft. of this is vertical steering; the rest is used for horizontal steering, and this can easily be incorporated into the main dipoles. This is an inherent advantage of the separated function lattice. (The horizontal low field orbit deflectors can also be so included if desired). If one were to go to a slightly more complex superperiod structure like the AGS, with greater variety of straight sections, one might end up with perhaps four quite long straight sections per superperiod, with the others considerably shorter. While this argument could be applied to both machines, the savings would be much greater in the separated function because of the fewer correcting elements required. (For weighing this, the total cost of the 240 x 8 ft. of straight section is roughly \$5 million for the tunnel costs alone). However, to be fair to the present comparison, we will use 7.8 ft., minus 1 ft., noting that this gives more useful free space, and allows for more distributed sextupole strength if desired.

It should be noted that the separated function lattice saves not only 1 ft. per "10 ft" straight section, but also that their total number decreases. This is not an unfair comparison, but simply part of the gain of the lattice proposed. The fact that we have fewer periods and, therefore, fewer "10 ft." straight sections does not decrease the useful space. We have as much space, for rf, external beams etc., in the 12 very long straight sections, and the slightly shorter 10 ft. straight sections contain actually as much or more free space, in the necessary locations.

3) Very Long Straight Sections

No long straight section design was done, but given the flexibility of this lattice one can easily incorporate such sections. For purposes of comparisons we use the length and cost of the 12 LRL design straight sections.

In summary, the lattice described is made up of the required main dipoles and quadrupoles, plus "10 ft." straight sections which are one foot shorter than the LRL proposed length.

4) Basis for Cost Estimates

The LRL tunnel cost figures are used. Changes in tunnel cost were made by scaling linearly the part of this cost which is directly related to tunnel length.

Our tunnel lengths are obtained by adding the 12 Collins straight sections, plus the "9 foot" straight sections, to the total length of dipoles and quadrupoles.

A lattice with two 20 foot long dipoles per half period gives comparable properties to the LRL lattice. Table 1 lists parameters as a function of quadrupole strength for a half period length $\frac{L}{2}$ of 58 feet. The two dipoles are 44 feet overall, and the remaining 14 feet contains the quadrupole plus the actual 6.8 feet of straight section. (A total of 56.85 ft. would be more correct, but the change is small in the parameters.) The cost analysis was arbitrarily worked out for 340 dipoles and 170 quadrupoles in the case of 20 kG. This is simply because 340 dipoles of the given length bend 200 BeV through 2π radians.

Actually, as already mentioned 336 dipoles and 168 quadrupoles would be a good number from the point of view of machine design ($N=84$). If four fewer dipoles were used with their lengths proportionally increased, there would be no change in dipole cost. We would simply save two quadrupoles plus two straight sections, and for the purposes of studying costs, this is negligible.

For 22 kG peak field, 10 percent fewer dipoles were used, which is 310. This results in 155 quadrupoles. In this case, we are roughly half way between an N of 84 and an N value of 72 (i.e., 144 quadrupoles).

In this case the 22 kG figures would be about \$0.6 million more or less, depending on which way one chooses to go. This is not important for the purpose of this report, and one is not tied to a super-periodicity of 12, so we have left the figures as is. The point is that since our core blocks are made in two halves of about 10 feet each, we are free to make them somewhat longer if desired.

The cost analysis was done using a quadrupole strength $GLB=385 \text{ kg/in.} \times \text{in.}$. This gives $\sim 62^\circ$ phase advance per period, and is indicated in Table I. The values of β_{max} and ν are about the same as for the LRL design. The momentum compaction is stronger i.e., α_{max} is smaller; even allowing for some increase due to the long straight sections between superperiods, this lattice should still have a better momentum compaction figure than the comparable combined function lattice.

Detailed design was worked out for a 2.4" x 5" aperture for four different dipoles; 10" wide coils and 12" wide coils at both 20 kG and 22 kG peak excitation. Table II shows these parameters. Dipoles with a 7" aperture and also various cases with 2" vertical aperture, were calculated to give differential cost data.

Quadrupoles were designed with a 5" aperture and with a 7" aperture. Since these are a minor item compared to the dipoles, only rough attempts at optimization were made. Examples with 15 kG and 18 kG peak field were worked out, to give some idea of the cost of excitation versus length. The former was used for the cost study, and parameters are listed in Table II.

Figures 2 and 3 show the lattice structure. Fig. 4 shows an end view of the dipole magnet. The single coil bends up on the ends, producing a weak up-down asymmetry. Pairs of dipoles should have their coil ends alternate from top to bottom in different cells, but this may not be necessary since the perturbation will be very small.

Fig. 5 shows an end view of a quadrupole with a 5" aperture. Again, for simplicity only 2 coil packages are used for the main excitation in series with the dipoles. The auxiliary compensating coils are also shown. Again, the asymmetry is very small in its effects, but will produce a very weak octupole moment. These coil ends could be staggered.

The LRL maximum power cycle and yearly usage were used exactly in the cost estimate. The power supply was rated for the constant voltage required to give peak current in 0.8 seconds, plus the 0.6 sec flat top.

Table III gives the cost comparison to the appropriate LRL components for the four different dipole cases mentioned above. The last row gives the cost savings. Again, let it be said that other costs should be about the same for either lattice, since this separated function lattice is matched to the overall LRL parameters.

B. Explanation of Cost Data in Table III

1) Dipoles

To derive reasonably accurate cost estimates for the magnets required in the proposed 200 BeV accelerator the costs of magnets having a cross-section very closely approaching that of the proposed bending magnets were used to calculate the estimated costs. The magnets used for a cost comparison with the dipoles were the original AGS main magnets. The material cost for AGS magnets has not increased appreciably since their procurement but the labor costs were adjusted upwards by three percent a year to determine present day costs. A split dipole also is somewhat more expensive than a solid "C" magnet since additional machining and care is required to finish the partings and to drill and dowel the half magnets together. This is much easier than with a split H magnet with gradient poles, since only one dimension needs high precision. The total estimated cost of this additional machining was divided by the calculated weight of the dipole and the resulting machining cost in cents per pound was added to the escalated labor cost and original material cost of the AGS magnets in cents per pound to give a cost per pound for split dipole magnets, fabricated in quantity at today's material and labor prices.

In comparing magnet systems with different cross-sections the total weight of the magnet was calculated. The cost of the particular magnet under consideration was then determined by using as a base price the cost of AGS magnets at current costs and adjusting this cost upward or downward by the difference in weight between the AGS and dipole magnets of equivalent length times the material cost if the magnets vary slightly in weight. If the magnets vary considerably in weight, the cost adjustment is made by using the product of the weight differential and the sum of the material cost and handling cost to account for the increased difficulty encountered in handling a heavier magnet.

One saddle bent coil is required per magnet in the split dipole magnet system. The cost for these coils was determined by escalating the initial cost of the AGS magnet coils to current prices and increasing this escalated price further to compensate for the additional labor required to wind and form a saddle bent coil. The price so determined compared quite favorably with prices we are currently paying for saddle bent magnet coils.

To determine the savings resulting from the proposed magnet system, the costs of the split dipole magnets and quadrupole magnets were compared to the costs of LRL's "C" magnets. Since the split dipole magnets were estimated using the original AGS core and coil prices as a base, the LRL magnets were estimated using the same base so that an equitable comparison of cost could be made. On this basis, the cost of the LRL "C" magnets was estimated at \$30,232,000.00 instead of \$25,000,000.00 as originally noted in the LRL report. The principal factor affecting the increased estimate of the LRL magnets was the higher cost of the coils. A price of \$3.00 per pound was used to estimate the cost of the LRL coils as compared to \$3.50 per pound for the coils in this report. The reason for the differential in unit cost is that the saddle bent coil proposed in this report would be slightly more expensive to make than the flat bending magnet coil used on a "C" magnet.

Although several magnet apertures in combination with different coil cross sections were investigated, no real attempt was made to optimize the magnet system, which means that additional savings will probably result from further investigation leading to an optimum magnet system.

The total savings resulting from this proposal were adjusted by the same factors as in the LRL report.

2) Quadrupoles

The correcting quadrupoles required in a 200 BeV accelerator using split dipoles are almost equal in cross section to the eight inch laminated quadrupoles used in the BNL beam transport system. The cost of the existing 8 in. quadrupole magnets was adjusted for quantity and was used as a base for determining quadrupole costs. Slight variations in cross section were accounted for in the same manner as those in the main magnet cost analysis.

3) Tunnel

To determine the tunnel savings resulting from this design, it is necessary to examine only the costs which are directly affected by tunnel length since all other costs will remain the same regardless of which system is used. For this reason only \$31.095 million of the total LRL estimate of \$44.36 million was used to determine the savings which could be obtained by the use of a separated function magnet system. The actual savings were

determined by multiplying the ratio of the two tunnel lengths by \$31.095 million. This saving was then adjusted by the factors used in the LRL study.

4) Cooling Water System

The ratio of LRL's estimate for the cost of a LCW water supply system to the total dissipated power in the main ring results in a unit cost of \$51 per kilowatt of dissipated power. This unit cost was used in this report to determine the cost of an equivalent cooling water system to dissipate the heat in the main ring magnets. The total cooling water required in this design is greater than that in the LRL study by a factor of ~ 3.5 , but the increase in the cost of a cooling water system does not vary directly with its capacity. For this reason a factor of 0.75, which we consider conservative, was used as a multiplier to determine the increase in cost of the cooling water system in this design.

5) Vacuum System

The portion of LRL's estimated vacuum system costs which is affected by tunnel length was separated and used to determine the savings resulting from the shorter tunnel required in this proposal.

6) Power Supplies

In the case of the power supply, we have chosen to consider a different system, after discussions with the power engineers at BNL. In this case, we are comparing two different types of supply. The system proposed in this report is the scheme used on the AGS and which will also be used on the converted AGS.

While it is not unreasonable, if so stated, to compare different power supply systems as well as different magnets, the prime purpose of this report is only to compare the two magnet systems. If we were to use our power supply estimate for the LRL lattice, the cost differential would be smaller between the two machines. However, we have allowed them the benefit of better steel and thus better saturation properties of the magnets. Awaiting more accurate power supply costs, and a better optimization of our magnet lattice cost on a more equitable basis, it appears that the cost differential will not change appreciably. This matter will be treated in detail in the Discussion of Costs.

7) Power Cost

Local or state agencies will provide utilities to a facility such as a 200 BeV accelerator at very nominal cost no matter where it is located due to the economic impact a facility such as this can have on any area. A cost of one half cent per kilowatt hour can therefore be used to determine power costs wherever the accelerator is located. In comparing power costs, LRL's original power cost figures were used. (They have revised their coils to somewhat higher resistance).

Although the operating cost of the accelerator in this report will be appreciably greater than that in LRL's proposed accelerator, this disadvantage is more than offset by the initial savings in construction, better magnet system, easier maintenance and other factors noted in this report.

8) R.F. Costs

The voltage per turn required scales with tunnel length for constant rate of change of momentum. For the same number of particles the current varies as the inverse of the voltage so that beam power is unchanged. The R.F. system is inherently inefficient and, furthermore, almost all of the cost is associated with the high power components. For small variations, the R.F. costs should, therefore, be almost proportional to the volts per turn. For this reason we used the ratio of tunnel length multiplied by LRL's R.F. costs and decreased this by 15% to provide a correction factor for beam loading.

Although our power cost would be almost \$1 million more per year than for the LRL machine, this figure is definitely not optimized from a design point of view; and furthermore, considerable doubt can be raised as to whether the power usage is not unrealistically high. Further discussion of this subject will be found in the Discussion of Costs.

9) Summary

In making an economic evaluation of the two proposed magnet systems, the same base was used not only to determine the cost of the system described in this report but also to re-estimate the cost of the system in the LRL study. The merit of this procedure is that any differences of opinion on estimated costs will affect both systems by the same amount and the total savings, therefore, will not be changed.

The dipole system proposed in this report has additional merit because the cores can be made in two blocks butted together to provide a core of the proper length since the required alignment of these sections will not be difficult. This permits a choice of core length to provide ease of fabrication and also to provide further freedom in optimizing the design of the machine lattice.

Although each magnet block is composed of top and bottom half sections bolted together, this type of construction presents no great problems either from a magnetic or fabrication point of view. The parting flanges will be machined in a plane several mils above the lamination plane so that a very small air gap will exist between the top and bottom core laminations when the two half magnets are assembled together. (We have been using laminated quadrupoles for years which are also fabricated with small air gaps at the parting centerline). The only tight tolerance will be on the average value of the assembled vertical gap height.

The use of dipole magnets, as described in this report, eliminates the need for practically all the external coil clamps; all of the coil wedging devices and all of the vacuum tube retaining units which are required in a "C" magnet. The coil and vacuum chamber are completely contained in the dipole magnet except at the coil ends where a coil clamp is required.

The width of the magnets in this proposal is greater than that of the LRL magnets, but the overall width of the LRL magnet assemblies in the tunnel is greater since the "C" type magnets are staggered on each side of the beam orbit.

It is readily apparent that the magnet support system for the staggered "C" magnet assembly in the LRL design would be more expensive than the in-line magnet support system required for the dipole magnets.

Any coil replacement in the magnet system due to radiation damage would be considerably cheaper in the dipole magnet system since the total coil cost for a dipole magnet is less than half the cost of the "C" magnet coils.

In addition, it appears to be a simpler job. Although the top half of a dipole magnet must be lifted to remove either a coil or vacuum chamber

section, this operation is quite simple as it simply entails the removal of two coil clamps, a few dowels and parting bolts and the lifting of the top half magnet by means of a lifting device and crane. In order to remove a coil from a "C" magnet, however, thirteen coil clamping sections must be removed, about the same number of coil wedging devices must be removed, and the vacuum system must be disconnected and the vacuum tube removed. The coil must then be removed horizontally through the gap which is not a simple procedure. From the foregoing discussion, it is apparent that maintenance of the magnets will be considerably more difficult and expensive for a C magnet than for a dipole magnet. Even though a "C" magnet were removed from the tunnel and replaced with a spare magnet assembly, the labor and time required to break the vacuum, replace the magnet and re-evacuate would be greater than to replace a coil in the dipole in position.

The magnets in this study have yokes on both sides of the vacuum chamber. As a result radiation exposure outside the magnets is much less than for the open side of a "C" magnet. Maintenance of the ring components therefore, could be performed from one side of the machine. For this reason it may be possible to eliminate one of the two tracks tentatively proposed by LRL. Any resulting reduction in tunnel width would reduce the cost of the tunnel considerably. This is a complex subject, and it is not obvious what is best. For this reason we do not pursue it, other than to comment that the present compact closed magnets are advantageous in tunnel design.

A further comment in this respect is that the work space around the present AGS is obstructed in quite a few areas by experimental equipment. It is quite likely, therefore, that similar areas around the proposed 200 BeV machine would be obstructed so that transportation of magnet assemblies around the ring in either the outside or inside work areas may be a problem. For this reason it may be desirable to provide room for transporting magnet assemblies over the beam magnets rather than beside them. Which from an economic viewpoint would also seem more desirable, since reasonably small increments in tunnel height are cheaper than increases in tunnel width.

In summary, the closed magnets do have significant advantages, because of the much better shielding over most of the ring. Not only is this an advantage in protecting components from radiation damage, but the situation is much better also from the standpoint of protecting maintenance personnel. Although appreciable savings will result from the above benefits, none of these savings are used in the cost comparison.

C. Discussion of Costs

The pattern of the cost difference is clear. There are large savings on the magnets, and on the tunnel because of the smaller circumference. There is a loss on the power supply, and on energy dissipation.

1) Power Supply Costs

The power supply costs are certainly the most questionable item in this comparison. For the magnets we have used our cost criteria to estimate both magnet systems and, because we have extensive experience in estimating costs on magnet systems we felt confident in doing this.

When we started to make comparisons, we first attempted to use the LRL power supply estimates for our requirements as well. However, it is immediately apparent that whereas in general the LRL estimates are quite detailed, when it comes to the major power supply item, the rectifier system, the estimates are more vague.

The reason for this is quite clear. The LRL group has decided to depend on the possible evolution of higher voltage SCR's. They have outlined a system using many 1300 volt SCR modules. While this still requires many modules distributed around the load, it is still a factor of about 4 or 5 higher in voltage than can be achieved with common present day solid state rectifiers.

Estimating costs versus power output for SCR supplies, if one increases the current output while maintaining constant voltage, the cost goes up considerably less than linearly. While questioning our power engineers at BNL on this question of scaling costs it became clear that they still favor the AGS rectifier system. This employs banks of common 3000 volt ignitrons (which have been running more than satisfactorily for years with little trouble). The AGS power supply provides 6000 V and about 7000 amps of output. For the AGS conversion, this system will be duplicated and the two outputs distributed so half the load lies on either side of each supply. The voltage to ground will still never be more than 6000 volts anywhere.

Since this could be expanded to the approximately 6 modules which would be required for the machine under study here, it was decided to consider such a power supply system. Fig. 6 illustrates the distribution of 6000V modules around the ring load.

The cost of the 40 MVA power supply in 1957 was about \$1 million. In duplicating this at today's prices for the AGS Conversion, the Power Group finds that costs have increased about 57%. This figure is very close to the normal escalation figures used for equipment.

This would indicate a present day cost of roughly \$1 million for each 30 MVA of peak power. We have used a figure of 20 MVA per million dollars, which would appear to be conservative.

This should be more than enough to cover the additional costs of providing for long flat tops. Also, since our time constants are shorter, our peak droop is about 50% more than that of the AGS. While we have included in the ratings the additional voltage required to overcome this, flexible operation with constant $\dot{B}$ might make it desirable in a detailed study to overrate the supply a little more. On the other side of the picture, buying a large number of identical modules at the same time should result in substantial cost reduction on the overall supply. On balance, it would appear that our power supply cost estimate is probably high.

The next question would be how to scale to the LRL requirements of a peak of about 160 MVA.

Based on our cost estimate, to build the LRL machine with our power supply scheme would cost \$8 million instead of the LRL figure of \$11 million for the power supply. (See Table III for our MVA requirements.)

Thus, if one takes the point of view of comparing the two machine lattice types, both with our proposed Power Supply, the cost savings of the separated function would decrease by about \$3 million before escalation. It is clear that the separated function lattice, while cheaper in all other respects, costs more for power supply and for power dissipation, if one wants to use the ability to go to high peak fields. It then becomes more important than with a combined function lattice to consider power supply costs in great detail in optimizing machine parameters.

Fortunately, for the window frame dipole there is less wasted stored energy outside the region of the aperture. For the same number of turns, the inductance of the separated function ring is 3.2 henries versus 5.2 henries for LRL. This is for the case of 10 inch coils, and 22 kG peak fields. Although the separate quadrupoles do increase inductance, the decrease in dipole stored energy per unit length, plus the reduction of total dipole magnet length around the ring, results in a lower ring inductance.

As a result even with excitation to 50% higher dipole fields, the ring voltage (33 kV) is about the same as the LRL figure, even allowing for the higher resistance. As a result the 50% higher peak power enters quite easily as higher current, and for a larger supply the differential cost for current should scale with a figure cheaper than 20 MVA per million dollars.

Even allowing for some reduction of the \$3 million, including the fact that a better optimum could be arrived at for our lattice with accurate power supply figures, it is still clear that if one compares only magnet lattices alone, using our proposed supply in both cases, an appreciable reduction in the savings would result. However, as will be seen in the following section, the cost comparisons contain magnetic factors unfair to the separated function estimates. These should result in savings that will compensate for this difference. This fact, coupled with the fact that the power supply estimates are not very good to begin with, has caused us to leave these figures unchanged.

2) Magnet Costs

A most important factor relates to magnet steel. We chose to use a common M-43 sheet steel in the price estimates for both magnet systems. We also chose conservative values for B saturation for our magnet calculations using Sibyl. Preliminary checks with steel companies confirm the fact that our high field permeabilities are indeed low, and we are waiting for experimental data.

However, the LRL magnet design and machine cost estimates are based on the use of a special low carbon steel giving 1 kG higher field than the steel we used for the same degree of saturation.

Although the base cost of low carbon steel is less than the cost of silicon modified steel the additional cost of heat treating the low carbon steel, to prevent carbon precipitation and magnetic aging may well boost the unit cost as high as M45 silicon steel for example. M45 will be better and cheaper than M43 for our purposes. The quality of a finished punching made from low carbon steel is also poorer than one made from silicon steel because of the greater burr and shear angle obtained during the punching operation. Handling of dead soft steel laminations would also be somewhat more difficult and magnetic properties would vary more between heats.

In summary, it doesn't make any difference which material is used in making a cost comparison as long as the same material is used in both systems. For this reason M43 steel was used to determine our cost for both the LRL magnets and the magnets proposed in this report. Any change in price resulting from the use of low carbon steel would affect both magnet systems by the same amount.

As it stands in this report, LRL has the benefit of better steel and this gives higher saturation field.

We deliberately chose to be conservative since this is a preliminary study. With one kilogauss higher saturation field due to the type of steel, plus more realistic permeability results, our current requirements and dissipation would drop. This would reduce power supply costs, but instead one would reoptimize the machine design, possibly to a higher peak field.

In the LRL study, it is stated that about 10% of the core fabrication effort can be charged to the shuffling. In the separated function case, the dipoles do not need as elaborate shuffling, for reasons discussed earlier. As a result, only sizable groups of laminations need be shuffled. For example, modules of laminations could be shuffled for magnetic uniformity, and rotated for left-right symmetry, and the result would be completely satisfactory provided the physical length and packing factors were precisely controlled. This would save considerable money.

The quadrupoles, if the cores are made to deliberately track the dipole saturation, which seems sensible, should be carefully shuffled. If this yoke saturation is not built in, no elaborate shuffling is necessary. In any case, quadrupoles are only about 10% of magnet costs.

The fact that considerably less precision surveying is required must have some cost advantages. The only tight tolerance on dipole location required is on rotation about the beam axis. This is much easier than the tolerances of a few mils on translation necessary with combined function magnets. We have approximately 150 quadrupoles to be surveyed and held to a few mils in displacement for the separated function case, versus 480 main magnets, and 120 saturation correction quadrupoles. Tolerances on quadrupole location will probably be slightly tighter than on combined function magnets.

Depending on how high a peak field is chosen, there could be fewer, or more sextupoles. However, even in the latter case, the fact that fewer other correction and deflection devices are required, and can be incorporated to an appreciable degree into auxiliary windings in the main components, should result in appreciable savings.

Finally, a second stage study on all the magnetic parameters to result in a better optimum should increase the cost differential.

It seems that the above factors would more than compensate for the difference between the two power supply estimates, if one wanted to compare only differences due to the magnet schemes. A comparison between a separated function and a combined function machine, with a more detailed study of power supplies and with an optimized magnet lattice for each with the same steel (or if with different steels, this fact being reflected in the magnet costs) would still appear to give a cost differential of about \$25 million.

3) Power Costs

It is clear that the separated function lattice under discussion has appreciably higher power consumption than the magnet system in the LRL design. The vertical space available for the coils in the dipoles is limited to the aperture, and there are practical and cost limits on extending the coil widths. The higher peak fields also contribute significantly to the differential. For the same coil cross section, a 22kG ring has a power dissipation 50% higher than a 15kG ring.

In the four examples in table III, we are consuming, on peak energy and flattop, about 45 megawatts, which is about three times the LRL dissipation.

The LRL yearly power usage is based on continuous running except for 16 hours a week, plus 6 weeks of shut down per year. It was also assumed that 3/4 of the time will be at full power, and 1/4 of the time at half power. This is equivalent to 6125 hours per year at full power. At this rate, our power bill would be almost 1 million dollars more per year. Even this is only modest interest on the \$25 million savings.

This power estimate is, in our opinion, much too high. First, experimental power requirements are considerably larger in any case than the

machine requirements, so it is not a question of a modest A-C. power grid versus a large one. The incremental power facility cost is in this case small, since we are not discussing a major power facility change. (Admittedly, predominant use of superconductivity for experimental beam magnets could reduce experimental power loads, but certainly for a machine built in the near future, great amounts of A-C. power will be provided.)

From a physics program point of view, the ~ 30 BeV machines do not run 6100 hours per year at maximum energy and maximum flat-top.

More use of slow external beams will increase flat-top usage somewhat, but considering that power consumption varies as the square of proton momentum, to consider a power cost for 6100 hours per year at maximum power seems unrealistic.

Further, in using the 30 BeV machines, a large part of the time one is straining to produce interactions at good rates with energy transfers somewhat above the roughly 1BeV mass range of present particles. With a 200 BeV machine, the energy transfers get much larger than these rest energies. If the machine is working a good part of the time with resonant states of presently known particle systems, the argument that maximum power will not be used most of the time becomes stronger.

If, on the other hand, a new physics of particles an order of magnitude heavier appears, in accordance with some of the present predictions, then we are back to the situation with the present high energy machines. However, the present 30 BeV machines were known, a priori, to have to strain to produce energy transfers in the nucleon rest energy range, and they do not consume maximum power most of the time.

For the 200 BeV case, the more complete decoupling of experiments from the machine should help to shorten shutdowns compared to the present machines. Also, removing from the ring more devices which require routine maintenance should help. Conversely, new problems of more remote operation and of maintenance and repairs in high radiation areas will certainly hurt.

There is no doubt that a considerable amount of AGS maintenance could be designed out in the light of experience. A considerable amount of this is planned for the conversion. For example, vacuum troubles due to radiation damage is now a major source of downtime. Much of the experience gained at

the AGS and PS can be applied to the 200 BeV machine, and this would support a better prospective running record. However, the problems of multistage injection with complex schemes for injecting, stacking, and ejecting are going to cause considerable downtime. External beams also require more sophisticated operation. Prevention of severe radiation to the machine is another example of a prospective problem.

There seems no reason to believe the running time will be much different than with present machines. In addition to shutdowns, one has maintenance and repairs and appreciable machine studies especially on a ground-breaking new accelerator. Only a small fraction of machine study time is at maximum power. Machines on the frontier of the accelerator and particle physics art are subject to continuing pressures for change and adaptation. As machines get larger and more expensive, many things have to be lived with longer because of the logistics involved.

The method of billing by the power company is a complicated factor. However, the above discussion indicates that the 200 BeV machine power consumption will be much less than allowed for in the cost comparisons.

It seems more likely that one half million dollars per year for excess power for the separated function lattices shown would be reasonable. This discussion was pursued at length, not because the increased power bill matters much, but out of conviction that higher current density coils will produce a more optimum design in any case.

4.) Summary

While no claim is made that costs have been optimized, the general pattern of the comparison is clear and is not likely to shift much with optimization. Significant savings have been made from several sources, all resulting from the reduction in circumference. Losses, although much smaller, result from the increased stored energy and power dissipation.

The lattice proposed has a dipole coil cross section smaller and therefore cheaper than the LRL coils. This means the LRL design machine could be made cheaper also, with increased power dissipation. To be fair in considering this question, we cut their coil area in half so that it was the same as ours. The magnet core width and cost were also reduced. Dissipation is double, and power supply cost was increased on the same basis as our power supply costs. The result was about \$4 million savings,

and with the difference in annual power bill between the two machines cut in half. (Since our power costs are three times theirs.)

It is a matter of judgment, as discussed earlier, what is optimum current density. However, this exercise shows that the difference of ~\$25 million between the two lattices proposed is not strongly dependent on this factor. As a result the savings appear to be inherent between the two systems when both are well designed.

III. CONCLUSIONS ON THE COMPARISON OF THE TWO LATTICES

This report is not intended to detract from the LRL 200 BeV Study.

It is gladly conceded that if the LRL machine were built as proposed, it would be a good second generation strong focusing accelerator. At the 667 gauss injection field for 8 BeV protons, good control of the beam optical properties will be possible with the components included in the LRL report. However, this study shows that even if we compare the separated function design, proposed herein, on the combined function designs' own terms; that is, with the same aperture, the same injection energy, and the same $\beta_{\max}$ and ν values, it appears to have many advantages, apart from the fact that the cost should be considerably less. The only disadvantage of the separated function lattice, in accessibility, proves to be largely a phantom. As far as useful space within the cells is concerned for inserting apparatus, it was shown that there are considerably more useful short straight sections available. This more than makes up for the theoretical, but almost entirely unused miles of accessibility within the open sides of the C magnets. Furthermore, the quadrupoles are accessible for insertions which do not interact with magnetic fields, such as pickup electrodes, and have excess vertical aperture which is very important.

From a shielding point of view, "inaccessibility" appears to be a great advantage. The small percentage of coils around the ring which are subject to extreme irradiation from internal targeting, etc. may be somewhat more exposed than in the LRL magnets, but it is not obvious how much worse off, considering ends of coils, etc. The determining factor will be maximum exposure of any part of the coil, and the ends are turned away from the vacuum chamber. Also, secondary fluxes grow and fan out from very energetic particles striking either the coil or the core. Our coils are considerably cheaper, furthermore, and it is not obvious that we are any worse off at all.

With good operation, most magnet exposure in high radiation areas will be due to secondaries from targets and aperture stops.

Since more or less routine replacement of coils at certain locations is accepted as a future fact of life, the much better shielding for personnel and apparatus of the separated function machine would appear to far outweigh any possible coil disadvantage.

For injection and extraction of primary protons there is no practical disadvantage to the lattice proposed here. Only for very small angle, very high energy, secondary particles is there some disadvantage to the present proposed schemes. Most secondaries will be scooped up by septum magnets against the long superperiod straight section vacuum chambers, and this can obviously be done for either machine.

Only in the case of such small angles that small cross section septum magnets were used inside the open C's immediately downstream of the long straight section would the separated function be appreciably worse off. However, it is doubtful that one would want to try injecting into an accelerator with such a perturbation allowed. Another more likely case is for very high energy secondaries drifting through the two open C magnets, and being scooped out in the 8 ft. of available "10 ft." straight section before coming to the back of the following magnets. This situation is greatly helped on the outside by the ring curving away, but even so, this appears to be a rather limited possibility unless very high field superconducting magnets are used. Furthermore, in the future if such high energy small angle internal targeting became vital, which seems unlikely, large holes could be allowed between the exciting coils and the back leg yoke of special window frame dipoles. This could be done with little beam optical deterioration.

For the separated function lattice compared, the betatron phase space acceptance is the same, and the momentum compaction and theoretical space charge limit slightly better. The radius is about 30% smaller, and for the same v value the space charge limit is commensurately higher.

The separate function lattice has the best of beam optical comparisons, even though the LRL machine certainly includes the elements for good control of optical parameters. Incidentally, utilizing only the simple basic design of dipoles and quadrupoles used in this report insures the best optics at all excitations. It would have been somewhat cheaper in stored energy and could have reduced the dissipation if we had considered "modified" window frame dipoles and elliptical quadrupoles. For example, somewhat more vertical space might be used in the dipoles for coils in the regions farthest from the aperture. The usable peak field would be lower, but power supply costs would also be lower. Elliptical quadrupoles could be shaped around the vacuum pipe, and narrower poles provide more space for coils. However, the quadrupole field would be more permeability sensitive, and octupole moment aberration would appear at high and low fields. This may be bad for space charge and other injection problems. It is not clear that a cost optimization would result in higher or lower costs, but the optical superiority of not "cutting corners" seems sufficient to stick to the best elements one can make.

An example of the increasing importance of excellent optics is in the work of Danby and Raka (unpublished) on the AGS fast external beam. At one point great difficulty was encountered in extracting the beam. Previous tests of high field nonlinear resonance excitation for the slow external beam left a small remanent field distribution in the machine. By error this perturbation was not properly demagnetized and near injection caused appropriate hori-

zontal beam growth. By using a scheme devised for photographing only one revolution of the beam; the beam (really the superposition of 11 individual beam bunches) could be seen. This revealed a beam about three times normal size in one dimension and sometimes tilted through very large angles at high energies. Hollow "smoke ring" beams also were observed! (Probably a superposition of individual bunch shape and coherent displacement of the bunches.) Clearly the beam was blowing up, and then was rotating due to v coupling. The remedy was the removal of the remanent aberration.

This example illustrates the importance both of excellent control at injection of optical properties, and also at high fields. As injection gets more complex and attempts are made to fill all of the available phase space, any horizontal and vertical coupling at any excitation becomes more serious. Also care must be taken that any high field aberration or orbit bump deliberately introduced does not leave a similar remanent perturbation large enough to affect injection. Clearly the remanence must be very small, particularly for resonant bumps, or else must be accurately cancelled with a compensating current. (Demagnetization is not practical for a cycling accelerator.) This is an argument that deliberate high field orbit displacement bumps or resonant bumps can most safely be put in as small perturbations on very strong elements normally used during the acceleration cycle rather than as high excitations of an element used for this purpose alone. The small perturbation leaves no remanent history, while a highly excited exclusively perturbation element will. In the latter case, the bump must be physically removed at injection, or else accurately compensated, which can be operationally complicated. In the separated function lattice, dipole and gradient high field bumps can best be incorporated into the strong basic dipoles and quadrupoles. For sextupole bumps (if desired) both lattices are equivalent.

At 8 BeV injection energy (about 972 gauss for the 22 kG peak field case) the optics of the separated function lattice will be excellent, with very little compensation required. (Again, let it be stressed that while this lattice is better, injection into the LRL ring at 667 gauss will be quite good.) For the elements used, no octupole fields can occur, unless deliberately introduced by auxiliary magnets, and this should help with injection and space charge problems. Also, the left-right and up-down symmetry of the separated function lattice eliminates any twist of the planes of oscillation or bumps due to interaction with the earth's field and other stray fields. This is very important at injection, because large accelerators will continue to have smaller vertical than horizontal apertures as long as they are excited with coils of copper or aluminum. All this points to optics which are ideal to very high accuracy. As one makes very sophisticated attempts to inject in a complex manner more and more intensity, the ability to have v_x and v_y controlled to high accuracy in both planes, and to eliminate coupling, and to introduce precisely controlled perturbations, becomes vital. In this capacity the lattice components proposed in this report are far superior; this fact would justify building this machine, even if it had turned out to be more expensive.

One related comment is that one could probably make about a 20 kG peak field lattice which would require no sextupoles at saturation, but the above arguments support going to higher peak dipole fields and including many sextupoles, since they are desirable in any event as part of the control of the field properties. Considered as an expansion about the orbit center, one then has dipole, quadrupole, and widely distributed sextupole field components under control. Octupole fields are not present, the 10-pole field

is very small and could even be easily corrected if desired. Twelve pole field is also not present because of the quadrupole design, and all higher multipolarities are very small and of academic interest because of their very strong radial dependence.

The above is based on the assertion that very linear quadrupoles and dipoles can be made to track to high accuracy in a simple manner, by servoing the ratio of the gradient to the dipole field to make the quadrupoles track. This is a straightforward problem; in practice to get tracking far better than the "built-in" tracking in combined function elements is easy. The flexibility inherent in the separated function design is very valuable. One is free to vary parameters within the excitation limits of the components. At injection, where it is most valuable for machine study purposes, the parameters could be varied over quite wide limits. Precise control of nonlinearities and ability to make changes in v would be priceless in studying and understanding space charge and other injection phenomena. For example, if in the future one wishes considerably stronger quadrupoles, the straight sections and quadrupole excitation is conservative enough that the quadrupoles could be replaced, and about \$2.5 million worth of very respectable experimental beam transport quadrupoles would be available.

The other direction where the flexibility may result in great benefits is in choosing the aperture. This can only be discussed in relation to costs and judgment of operational effectiveness. Part of the LRL costs optimization, which is not within the scope of this report, is the choice of aperture and injection energy. For a separated function lattice the major component cost, the dipole, can have arbitrary horizontal and vertical apertures since the potentials are orthogonal and the two components completely de-coupled. Size is only a question of ring component cost and

power supply requirements. LRL in revisions to their design do give differential costs for horizontal and vertical aperture changes. However, this is a complex matter since both planes are interrelated. For the hyperbolic pole face, the peak field attainable will decrease as horizontal size increases, for a given k value, unless one tolerates more field deterioration. A decrease in peak dipole field will have an appreciable cost affect.

An optimization for injection into the separated function lattice would in all probability end up with different final parameters. However, the purpose of this report was a comparison of the two designs by matching closely the parameters of the LRL main ring. It appears that the proposed lattice compares very well even with this restriction.

IV. ADDITIONAL ADVANTAGES OF THE SEPARATED FUNCTION DESIGN

It is clear that the design that has evolved for the 200 BeV combined function machine is intimately connected with the lattice itself. A detailed optimization of the separated function design would in all probability lead to a different set of machine parameters.

As stated earlier, the combined function lattice, with corrections for end effects and for momentum change with radius, can be made to have excellent properties at intermediate fields. At low fields and high fields the complexity and number of compensations required become greater.

The separated function lattice, because of the symmetry of its components, can be easily maintained in a condition of arbitrarily good optics over a range from lower dipole fields to considerably higher fields. The latter property has of course been partially exploited in this study. However, as was noted, the limit of ~ 22 kG was set on the basis of power consumption; not because it would be impractical to provide correction fields for the X^2 , and eventually X^4 dependent aberrations which are slowly growing.

At low fields, the optics of this lattice can, practically speaking, be held to excellent tolerances for injection. This, however, gets intermeshed with other conditions for good high intensity injection and will be considered later.

Another property besides the above obvious extrapolations which follows inherently from the advantages of this lattice is the ability to make a stronger focusing machine. This property is also intimately tied into injection at low fields, and will also be discussed later.

A. High Field Use of the Separated Function Lattice

Let us consider the stage beyond the presently contemplated generation of accelerators. The possible use of superconducting magnets enters everyone's

mind. Good reliable wire for winding superconducting magnets has begun to appear in the last year or so, and the price is arbitrary, so that the economics of large scale use in the future seems to be no problem. In the next few years, more and more apparatus for experimental facilities will be built using superconducting magnets. The use of such magnets in a synchrotron assumes pulsing at the low frequencies involved. This will be assumed in the following, since otherwise all discussion of other than dc accelerator magnets is academic.

Almost no one at this stage would seriously propose a superconducting accelerator for the immediate future, but it would seem wise to incorporate into the 200 BeV machine, if possible, the potential for conversion after a few years. Leaving aside all of the engineering problems of superconducting magnets, one is still left with the problems of providing fields of high optical purity, and of the power supply.

It would seem that if pulsed superconducting accelerators are ever built, the real ingenuity will be not in winding the coils but in the power supply.

For an accelerator magnetic field, the stored energy is essentially proportional to the circumference, minus straight sections, times the usual integral of the field squared over the cross section in air. (This ignores the energy in the iron.) This integral can be equated to B_o^2 , the aperture centerline field squared, times an arbitrary cross section A. Since the momentum is proportional to the circumference and to B_o , the maximum stored energy is proportional to the maximum values of momentum and B_o , and to A.

Practical problems of very small apertures make it difficult to make great reductions in A. For superconducting high energy accelerators, the stored energy will be proportional to the product of the momentum and field.

As an example, a 1000 BeV machine, with a peak dipole field of 60 kG,

would have a stored energy approaching twenty times as large as the LRL 200 BeV machine, apart from reduction due to A. Clearly one must pump this energy in and out of the synchrotron by some cheaper method than at present, or much of the savings of the high fields will go into the power supply. Alternatively, one can slow the whole time scale down, since there is negligible dissipation. As an example, if one accelerated at one-tenth the rate, held the flat top for ten times longer (or more) and inverted for ten times longer, the power supply would only have to be rated for one-tenth the value. However, to get the same amount of physics done, the time average beam intensity must be constant. (Also, ring radiation exposure is constant.) Obviously, the protons captured and accelerated would have to be ten times more per pulse. (This example points out that very high intensity capabilities, beyond what one can afford for radiation reasons at current repetition rates, may be a great advantage in future superconducting accelerators. The possibility adds another incentive to the study of injection problems at high intensity.)

Consider the optical problems. Air core magnets are easier to design theoretically, since one can in a straightforward manner create the magnetic potentials desired in two dimensions. End effects are comparable to those of present accelerator magnets, and so can be coped with. However, even with normal copper conductors, the problem is one of locating and maintaining the current in the desired position. In practice most present precision magnets have tolerances of a few mils on their iron profiles and of about 100 mils on their conductor profile. For a good design, the iron tolerances almost entirely determine the optical precision. In addition, a temperature dependent or field dependent motion due to changing stress in the coils can be very serious in an air core magnet. Clearly a superconducting accelerator magnet will have to locate and hold its current distribution to very

high precision.

It would be reasonable to consider for the 200 BeV accelerator the capacity for a future switch to superconducting magnets. While a combined function lattice can be made also with air core magnets, it seems preferable to use a separated function lattice. The peak fields are lower, since the gradient field is not added to the dipole. Therefore, a higher dipole field magnet system could be made with the same materials. The higher symmetry of the separated function magnets would appear again to be important, now for mechanical reasons, different from those for iron magnets. The very strong forces will be distributed with the correct symmetry also for separated function magnets. This means that most mechanical distortions will be restricted by symmetry, so the field aberrations resulting will be smaller in amplitude and restricted to the usual multipolarities characteristics of the magnet. Also, it would seem that if the original 30 BeV machines had been made with air core magnets instead of the existing iron core magnets that the lattice proposed in this study would probably have been used.

In summary, it appears worthwhile to consider for the 200 BeV machine the possibility of eventual conversion to air core superconducting magnets and thus to considerably higher energies. While this is still in the crystal ball stage, some detailed consideration might lead to modest changes in design which would perhaps make this possibility easier if it ever does come to fruition. Furthermore, this is an additional reason for the more flexible separated function design proposed.

We now go even further and state that if one were to consider a practical design for a superconducting synchrotron, a modest modification of the proposed 200 BeV design appears the most attractive. Consider the dipole coils being replaced with a superconducting coil package. We arbitrarily consider

a package one inch wide, and of course, having the same vertical height as the copper coils. We increase its width somewhat, to reduce aberrations in the aperture. We are simply using this coil for a zero resistance excitation coil, and still retain the high optical symmetry of the iron dipole. The locational tolerances for the excitation coils are now loose; clearly they can be as great as for large copper coils. Further, a rectangular iron bar can be inserted in the extra space beyond the coil to provide a very thick yoke. This results in a low value of the field everywhere except near the aperture. Preliminary calculations for about 30 kG show this is indeed feasible. Saturation increases peak currents about 50%, but the impedance drops by even a larger figure due to width reduction. The sextupole field component was about double that provided for in the main body of this report. It could be compensated for within straight sections slightly longer than the ones proposed.

For very high fields one could consider opening the gap by spreading apart the top and bottom halves and inserting iron shims between the magnet halves. These shims (which could be laminated lengthwise to simplify fabrication) can be made to liberal tolerances since a solid steel shim will be placed between the magnet parting flanges to maintain precise alignment.

This would allow space for pole face windings to correct to very high fields. Alternatively, increased vertical aperture could be attained (at the expense of more stored energy). Combined with the already larger horizontal aperture, this could significantly increase the intensity capabilities.

While this is speculative, it is technically sound and again points to the future possibilities of the flexible separated function design.

The quadrupoles are capable of being used to the 50% higher gradient required. Alternatively, their coils could be replaced by superconducting

coils, or the quadrupoles could be replaced by new iron or superconducting ones. They are, after all, \$2.5 million of good experimental beam apparatus.

The tracking of dipole to gradient fields is still no problem since the thickness of the yoke inserts in both dipoles and quadrupoles can be controlled in a manner to give the same saturation characteristics.

The inductance, and thus the stored energy, will be much lower than in a pure air core field, or in the usual iron core case with large area copper coils. Furthermore, present thinking would not seriously extrapolate much beyond 30 kG for the peak dipole field even for an air core superconducting machine.

One would have the tremendous advantage of first trying superconductivity on a functioning machine. It appears both from an optical and stored energy point of view that you could not make a better choice if you started from the beginning than with this modest modification. Note that the significant reduction in the cross section occupied by flux more than compensates for saturation and combined with the elimination of the coil resistance, the same rise rate could be attained with the same power supply. The same rf system could be used to accelerate to 300 BeV. Very long flat tops with negligible power usage would be feasible.

As a third stage (looking through two crystal balls) one might in the future use pure air core magnets in the lattice and get to even higher energies. The above arguments, while speculative, appear to be a strong inducement to using the separated function lattice proposed. It should be borne in mind that the speculative parts are not too relevant to this design. If it is never possible to build superconducting synchrotrons from the point of view of the physics or engineering of superconductivity (which seems unreasonably pessimistic) the whole question is academic. However, in the proposed de-

sign nothing is lost in that case either, other than aspirations. But given the existence of practical superconducting magnets, the construction of a synchrotron with them is well within the realm of practicability.

No doubt some things would have been done differently starting fresh on a superconducting design, but also some important unpredicted lessons would be learned cheaply on a conversion. As was shown, the use of superconductivity for producing precision field properties, with plenty of space available for ease of packaging, makes the problem much easier from a practical coil design viewpoint as well.

In summary, one would get about 100 BeV of additional energy almost for the price of the superconducting coils alone.

B. Low Field Possibilities

Injection of high intensity beams with high reliability for minimum cost into a 200 BeV accelerator is a complex subject, and is the major focus of attention for the accelerator community. Amongst the many requirements of the main ring itself at injection are good beam optical properties, sufficient acceptance of betatron and synchrotron phase space for some injection scheme at the intensities desired, and a space charge limit adequate for these intensities. In addition, general thinking runs toward a linear accelerator as the initial stage, followed by at least one stage of circular booster accelerator. Systems with a small rapid cycling booster (with concomitant complexity of design of power supply, vacuum chamber, etc.) followed by a large slow ring are contemplated. In addition, complex multiple orbit rings have been proposed at CERN⁽⁷⁾ and LRL. All of this will cost about \$40 to \$50 million by present estimates. The juggling of the energies of various stages (including the injection energy of the main ring), physical apertures, ν values, etc. is complex and involves emittance estimates for

preinjectors, space charge limit estimates, etc.

The machine lattice proposed in this report has some interesting possibilities in this direction also.

Let us commence this discussion by consideration of the AGS at injection. (The remarks in general also apply equally to the CERN/PS.) The situation is that the beam optical properties of the AGS at the injection field of about 120 gauss are poor. (Let me hasten to add for the benefit of non-AGS people that the writer of this statement has a proprietary interest in this machine, and is very proud of its many achievements. The AGS and PS are probably the most precise, beautiful, and productive accelerators ever built.)

The asymmetry inherent in the combined function magnet results in appreciable low field distortion due to asymmetrical remanence, eddy currents, and interaction with the earth's field in a manner to produce severe coupling from the horizontal to vertical plane. The horizontal and vertical v values change with position and excitation. Only by delicate balancing of skew quadrupoles, normally oriented correcting quadrupoles, sextupoles, radius, orbit deflections, etc., can the machine be made to operate well at all. Yet with all of this, plus the added time dependent complexity of multiple-turn injection, the machine works very well and exceeds some of the estimates of the space charge limit!

The conversion of the AGS to injection at higher energy has a multifold but inter-related purpose. The theoretical space charge limit at 200 MeV is 4.5 times higher than at 50 MeV and increases with higher energies. The phase space acceptance is effectively larger because of the adiabatic damping with higher momentum, and the beam optical properties of the synchrotron will have lower aberrations.

Suppose the situation were unchanged from the present AGS at 50 MeV

injector energy, except that the beam optical properties were essentially ideal. By this we mean that ν was constant to high accuracy for all usable equilibrium orbits (including both monochromatic non-linear effects, and the momentum affect). By this we imply accurate control of parameters. It is not obvious that one does not want to deliberately introduce controlled aberrations. Clearly one wants controlled bumps, skew quadrupoles, etc. even with superior optics.

What would be the difference in the two situations? With better optics, the acceptance would be effectively greater, since orbit excursions, and $\beta_{\max}$ distortions effectively reduce the aperture. Distortions of ν due to space charge and image forces could be larger since ν would not wander about the resonance "necktie" except under deliberate manipulation. (Since we are implying comparison with a separated function lattice, it should be said that the space charge limit difference due to the parabolic vs parallel pole profiles are expected to be very small. This is reasonable, since the slope of the profile in the hyperbolic case is only a few percent per inch and image forces should be roughly the same.) It is hard to believe that with these improvements, plus the broader plateaus for tuning of the many injection parameters which would result, that a significant intensity improvement would not be obtained.

Admittedly, one could be a pessimist and say that while all this would make operation easier, significant improvement would not result because of the space charge limit. Apart from functional variations, the absolute numbers of space charge limits are questionable. This is an extremely difficult problem, and great ingenuity has gone into getting the best answers possible, since these questions are absolutely vital. The relevance of the results to decisions is re-enforced by the higher probability that relative

intensity would vary in the predicted manner. The results would still be useful, unless the space charge limit exceeded the desired intensity.

A further possibility which could be better studied with superior injection optics would be the effect on space charge distortion of v , due to deliberately introducing non-linear terms into the field, or due to introduction of time dependent gradient modulations to destroy a persistent resonant mode. The latter has been shown by Courant⁽⁸⁾ to produce diffusion of the beam, but perhaps for the short times required this could be accepted, in some combination with non-linear restoring forces.

The above is clearly speculative, but it would be foolish to ignore possibilities of controlling the space charge distortion. (It would be roughly analogous to accepting the fact, after the Tacoma Bridge disaster, that suspension bridges were hopelessly subject to resonant destruction.) It is relevant to the present discussion in that superior optics of injection increase the possibilities for study and control.

It is clear that the above is really directed at the two possibilities for the 200 BeV magnetic lattice. However, by discussing the present machines it was hoped to make the discussion more related to experience.

However, the proposed LRL machine has two advantages in this direction over the AGS or PS. Mainly because of the space charge considerations and phase space acceptance at injection, it is proposed to inject at 667 gauss. At this higher field, coupling and other aberrations should be much lower. The AGS and PS were a revolutionary departure in accelerators. By contrast, the 200 BeV designs tend to be direct extrapolations, which is quite reasonable. The LRL design has incorporated sufficient correcting lenses so that better beam optics should be expected with proper programming of these devices.

Injection at high momentum to overcome space charge effects and to increase the phase space acceptance for a given aperture tends greatly to ease the beam optical problems because the injection field has increased by ~ 6 times. These advantages over the present machines certainly have been well thought out, but the separated function lattice does open the door to considering other directions. The practical capacity to consider high v values, the fact that good optical properties can be obtained at lower injection fields, and the fact that the major magnetic component, the dipole can have the vertical and horizontal apertures varied independently appears to point to other possibilities.

It can be argued that the cost of injectors, regardless of the method used, is small compared to the main synchrotron and experimental facilities. However, they still represent a great deal of money (\$50 million) and, operational research on cost aside, the complexity of booster schemes equals or exceeds that of the converted AGS. Even on the AGS at present, the linac and synchrotron tend each to be "organic" entities and the "marriage" between the two has to be watched more closely than most interactions. If one now adds two more entities in between, the operational problems and personnel will increase considerably. There is no doubt that it can be done, but to maintain at a high level of efficiency the various stages, with the extractions and injections, will be the chief new operational aspect of this next generation of accelerators.

Returning to comparison with the AGS, even with the first stage of conversion, with its expected space charge limit increase of about 4.5, and the phase space shrinking with momentum, the present intensity of 2×10^{12} protons per pulse can be expected to reach 10^{13} . Linac emittances in the near future are expected to shrink considerably, and allowing for the fact

that the coupling and other optical problems found at 120 gauss will be considerably reduced, it seems probable that the intensity goals of the LRL study will be reached on the AGS. An additional stage of conversion should certainly more than insure this.

One possibility which could be considered is that, for about the cost of an 8 BeV booster ring, the aperture of the separated function lattice can be increased to be about the same as the AGS. The optical properties at 200 MeV (78 gauss injection field) could be made quite good, but probably a smaller linac followed by a modest booster would be wiser. In any event, the injection system could be a modest one, more or less identical to that of the converted AGS. The only disadvantage would be that the theoretical incoherent space charge limit for a v of ~ 16.75 would be about one half as great as for the AGS, since the radius is about four times as large. This may or may not be important, but no great loss would result from betting that it didn't matter. During machine studies v could be varied at will and this question investigated experimentally. Then, if necessary, the quadrupole strength could be increased to give a ratio of R/v for the 200 BeV machine which is perhaps $3/4$ as large as the AGS, by increasing quadrupole excitation one third.

With the advantages resulting from a larger aperture, and injecting at perhaps 500 MeV, we could in all probability reach the desired intensity goals of 3×10^{13} particles utilizing the advantages of excellent optics, including no coupling, and the capacity to vary v at will for injection studies. If desired in the future, for even higher intensities or other reasons, a large booster could be inserted as a "conversion" project.

One could consider different lattices, involving either more or less periods. We are free to make dipoles either shorter, or longer, because of using two core blocks. The length is limited by practical coil lengths.

Clearly, the number of quadrupoles can then be changed, so that the N value, $\beta_{\max}$, etc., are varied. The lattice described was chosen to match the LRL design study parameters. By using more and stronger quadrupoles, with accompanying increase in cost, $\beta_{\max}$ will clearly get smaller, and ν higher. This seems like a fruitful area for further study.

In this vein it is quite possible that the separated function lattice might be useful for boosters as well. It is not obvious that this is so, since the higher field possibilities are not important for a booster. However, large apertures, with equal horizontal and vertical dimensions, for example, can easily be made and also have good optical properties, including the effects of eddy currents. The latter can be a problem, with rapid cycling, for large apertures, but again for separated function magnets and rectangular vacuum chambers, the symmetry restricts the effect mainly to a reduction in field. The capacity for very high ν 's in a booster, with resulting space charge limit increases and greater momentum compaction, might prove useful. After all, schemes such as TART⁽⁷⁾ seem to be devised to give small R while still having strong focusing within the lattice. That is, as accelerators get larger, they tend to get weaker focusing, to keep the ν value down. If one is prepared to use a higher ν than is practical in a combined function lattice, study might show some appreciable advantages in boosters as well as in the main ring.

In summary, further study, using the greater freedom to vary lattice parameters and physical aperture parameters with the magnet elements proposed for the separated function lattice, could result in a simpler method of providing injection at high intensities into a 200 BeV accelerator. In addition, the ability to vary focusing parameters accurately over wide ranges at injection would permit much better study and understanding of this complex subject.

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REFERENCES

1. 200 BeV Accelerator Design Study, Lawrence Radiation Laboratory Report, UCRL - 16000, June 1965.
2. SIBYL was first written by R. S. Christian, then of MURA and now at Purdue University.
3. T. L. Collins, Long Straight Sections for AG Synchrotrons, Cambridge Electron Accelerator Report CEA-86, July 10, 1961.
4. E. D. Courant and H. S. Snyder, Annual Physics (New York) 3, 1 (1958).
5. D. Greene, F. Lobkowicz and J. Tinlot, Muon and Antiproton Trap at SLAC, University of Rochester Report UR-875-98, September 28, 1965.
6. A. A. Garren and J. W. Eusebio, A Computer System for Synchrotron Design and Orbit Analysis, Lawrence Radiation Laboratory Report UCID-10-10153, April 10, 1965.
7. W. Hardt, A Slow Cycling Injection Method for Intensity Improvements of the CERN-PS (Twin Accelerator Transfer Scheme), Proceedings Accelerator Conference, Frascati, Italy, May and August 1965.
8. E. D. Courant, Brookhaven National Laboratory, private communication.

TABLE I

MACHINE LATTICE PARAMETERS AS FUNCTION OF QUADRUPOLE STRENGTH

L/2 (FT)	G_{LB} ($\frac{KG}{IN} \times IN$)	$\Delta\mu$ (DEG.)	B_{MAX} (IN)	B_{MIN} (IN)	v_1 N = 72	v_2 N = 84	$\alpha_{MAX}^{.01}$ (IN)	$\alpha_{MIN}^{.01}$ (IN)
58.0	458.6	75.0	2318.0	563.0	15.00	17.51	0.94	0.52
	412.7	66.5	2350.0	686.0	13.30	15.52	1.11	0.64
	385.5				~12.4 ~	14.6		
	366.9	58.3	2433.0	839.0	11.66	13.61	1.37	0.89
	321.0	50.5	2574.0	1035.0	10.10	11.79	1.75	1.14
	275.2	42.9	2794.0	1299.0	8.58	10.01	2.32	1.61

(a) *385.5 $\frac{KG}{IN} \times IN$ is strength

calculated in cost comparisons.

(b) This would give for L/2 = 56.85 ft. $B_{MAX} = 2350$ in.
compared with 2300 in for LRL.

(c) $\alpha_{MAX}^{.01}$ for LRL = 1.53 in. (including some increase due to
Collins straight sections)

(d) v for LRL is ~ 13.75 (plus about 3 due to straight sections)

TABLE II

DIPOLE MAGNET PARAMETERS

	2.4"x 5"Aperture 10" Coil	2.4"x 5"Aperture 12" Coil	2.4"x 5"Aperture 10" Coil	2.4"x 5"Aperture 12" Coil	Units
Peak Flux Density at Orbit	20	20	22	22	kG
Gap	2.4	2.4	2.4	2.4	Inches
Useful Horizontal Aperture	5	5	5	5	Inches
Effective Length	242.4	242.4	242.4	242.4	Inches
Peak Excitation	97,200	97,200	107,000	107,000	A-Turns
No. of Turns	16	16	16	16	-----
Peak Current	6070 *	6070 *	6680 *	6680 *	Amps
Coil Resistance $\times 10^3$	6.02	5.11	6.02	5.11	Ohms
Heat Dissipation $I^2_{rms} R$	99.0	81.8	131.5	110.8	kW
Core Length	20	20	20	20	Feet
Core Weight	70,300	90,600	82,800	103,200	Lbs.
Coil Weight	3050	3660	3050	3660	Lbs.
Assy. Weight	73,350	94,260	85,850	106,860	Lbs.

* Current does not include saturation effect but in power supply and power consumption calculations the saturation effect was included.

QUADRUPOLE MAGNET PARAMETERS

	5" Quadrupole	7" Quadrupole	Units
Pole Tip Field	15.8	15	kG
Aperture	5	7	Inches
Effective Length	61	90	Inches
Core Length	58.5	86.5	Inches
Peak Excitation	152,000	213,000	A-Turns
Heat Dissipation $I^2_{rms} R$	45.6	96.2	kW
Core Weight	14,950	21,000	Lbs.
Total Coil Weight	1192	2300	Lbs.
Est. Assembly Weight	16,500	23,750	Lbs.

TABLE III

	2.4" x 5" Aperture 10" Coil - 20 kG	2.4 x 5" Aperture 12" Coil - 20 kG	2.4 x 5" Aperture 10" Coil - 22 kG	2.4 x 5" Aperture 12" Coil - 22 kG	Units
Dipole I ² R (Peak)	80.8	68.6	97.8	82.8	MW
Quadrupole I ² R (Peak)	18.57	18.57	18.6	18.6	MW
Peak I ² R	99.37	87.17	116.4	101.4	MW
Dipole VI	148.9	165.9	171.2	190.6	MW
Quadrupole VI	13.39	13.39	12.76	12.76	MVI
Total VI	162.29	179.29	183.96	203.36	MVI
Power Supply Required	211.0	222	237.5	250.0	MVI
Dipole Costs	19.2×10^6	20.3×10^6	17.97×10^6	19.35×10^6	Dollars
Quadrupole Costs	2.55×10^6	2.55×10^6	2.32×10^6	2.32×10^6	Dollars
Total Magnet Cost	21.75×10^6	22.85×10^6	20.29×10^6	21.67×10^6	Dollars
Quad. Power Cost Per Yr.	0.237×10^6	0.237×10^6	0.237×10^6	0.237×10^6	Dollars
Dipole Power Cost Per Yr.	1.030×10^6	0.876×10^6	1.250×10^6	1.058×10^6	Dollars
Total Power Cost Per Yr.	1.267×10^6	1.113×10^6	1.487×10^6	1.295×10^6	Dollars
Rf Cost	7.565×10^6	7.565×10^6	6.80×10^6	6.80×10^6	Dollars
Cooling Cost	1.583×10^6	1.392×10^6	1.858×10^6	1.603×10^6	Dollars
Power Supply Cost	10.55×10^6	11.10×10^6	11.880×10^6	12.50×10^6	Dollars
Tunnel Length	11,622	11,622	10,770	10,770	Feet
Tunnel Cost	25.4×10^6	25.4×10^6	23.5×10^6	23.5×10^6	Dollars
Vacuum Cost	2.11×10^6	2.11×10^6	1.96×10^6	1.96×10^6	Dollars
Magnet Savings	8.99×10^6	7.89×10^6	10.45×10^6	9.07×10^6	Dollars
Rf Savings	1.395×10^6	1.395×10^6	2.16×10^6	2.16×10^6	Dollars
Tunnel Savings	5.695×10^6	5.695×10^6	7.595×10^6	7.595×10^6	Dollars
Vacuum Savings	0.480×10^6	0.480×10^6	0.630×10^6	0.630×10^6	Dollars
Power Supply Saving or Loss	Saving 0.650×10^6	Saving 0.100×10^6	Loss 0.680×10^6	Loss 1.30×10^6	Dollars
Cooling Loss	0.944×10^6	0.753×10^6	1.219×10^6	0.964×10^6	Dollars
Magnet Savings Adjusted	14.01×10^6	12.32×10^6	16.30×10^6	14.15×10^6	Dollars
Rf Savings Adjusted	2.18×10^6	2.18×10^6	3.37×10^6	3.37×10^6	Dollars
Tunnel Savings Adjusted	7.42×10^6	7.42×10^6	9.88×10^6	9.88×10^6	Dollars
Vacuum Savings Adjusted	0.749×10^6	0.749×10^6	0.983×10^6	0.983×10^6	Dollars
Power Supply Savings or Loss Adjusted	Saving 1.013×10^6	Saving 0.156×10^6	Loss 1.060×10^6	Loss 2.03×10^6	Dollars
Cooling Loss Adjusted	1.228×10^6	0.980×10^6	1.583×10^6	1.253×10^6	Dollars
Total Savings Without Adjustment	16.266×10^6	14.807×10^6	18.936×10^6	17.461×10^6	Dollars
Total Savings Adjusted	24.144×10^6	21.845×10^6	27.890×10^6	25.10×10^6	Dollars

EXPLANATION OF COSTS

1. A duty factor of 0.417 (also used by LRL) was used to determine dissipated power.
2. Power costs were calculated on the same basis as for the LRL Study. (6130 hrs. of operation per year at 0.5 cents per kW-hr.)
3. Rf costs were determined by reducing the LRL rf cost estimate by the ratio of the tunnel lengths in the two design studies, and increasing this cost by 15% to compensate for beam loading.
4. The cooling load in this report is 3.5 times greater than the load in the LRL Study. Cooling costs were, therefore, determined by multiplying the product of the cooling load in kW and LRL's cooling cost per kW by 0.75 since the cost of a cooling system does not increase in proportion with capacity.
5. Power supply costs were determined at the rate of 1×10^8 dollars per 20 MVA power required.
6. Tunnel costs were determined by multiplying the ratio of tunnel lengths by 31.095×10^6 dollars which is the portion of total tunnel cost in the LRL Study that is affected by length.
7. Vacuum savings were also determined by the product of the tunnel length ratio and the vacuum costs recorded in the LRL Study.
8. The adjustment factor used in this tabulation is the same as in the LRL Study, which is 25% for EDIA and 25% for contingency on manufactured components; 12.5% for AE and 15% for contingency on general construction.
9. An estimated cost of 30.742×10^6 dollars for the LRL "C" magnets plus trimming quadrupoles was used in this study for cost comparison with the dipole and quadrupole magnets.

FIG 1
AGS PROFILE.

LRL PROFILE.

COMPARISON OF AGS AND PROPOSED LRL MAGNET PROFILES.

NORMAL UNIT CELL

6.85 STRAIGHT SECTION

Q = QUADRUPOLE

FIG. 3
SUGGESTED LAYOUT OF SEPARATED FUNCTION MACHINE

FIG. No. 4

TYPICAL END VIEW OF A DIPOLE MAGNET.
WITH A 2.4" x 5" APERTURE.

FIG. NO. 5

TYPICAL END VIEW OF 5" x 58.5"
QUADRUPOLE MAGNET.

POSSIBLE CONFIGURATION FOR POWERING 200 BEV RING.

e - 6000 VOLT IGNITRON RECTIFIER OUTPUT.

$Z - \frac{1}{6}$ OF RING LOAD.