For precision beams one pushes the techniques of component and beam design to practical limits and uses precision measurements and perhaps auxiliary corrections for the best performance. Since compensation has its limits, well constructed magnets with large ratios of length to aperture and small aberrations are attractive. The quantitative effects on beam quality depend on the actual optics of the beam. As the optics get more complex the effect is generally worse, for example, the focusing of a compact triplet is weaker than that of a doublet with elements of the same strength, although more symmetrical in both planes; the relatively weak difference between the strong focal components does the net focusing. As a result the impact of aberration can be magnified.

II. Cost and Performance Criteria Used

a. Quadrupoles

It should be emphasized that the cost analysis strictly reflects local conditions and parameters related to the 30 GeV facility. The conclusions drawn here have relevance to other facilities. Quadrupole costs and design estimates have been made in this report to cover the range from 2-in. to 8-in. diameters. This was done for various lengths and fields using reasonable design assumptions. For the most part capital costs plus five years (at 4000 hrs) of maximum power were used to optimize coil area. This is equivalent to 10 years operation at a mean field of 70% maximum. The power cost for both quadrupoles and dipoles assumes 1c per kW-hr and 4000 hrs operation/year at full field and a conversion efficiency of 80%. This results in $500/yr - 10 kW dissipation.

The total capital cost is an attempt to estimate the total cost to the laboratory of a functioning magnet - this includes total magnet assembly cost, power supply cost, cost of a single electrical hookup assembly (labor plus materials), and prorated cooling cost.

All quadrupoles discussed are of the BNL narrow type, with rectangular coil sections. Except for the circular aperture region, the entire space is essentially occupied by either coils or iron. Such magnets have the potential for high field excitation even if they are connected for lower field use, for system economy.

The magnet optimization was of necessity done early in the study. In principle it should be based on total capital costs and total operating costs rather than on magnet costs and power costs alone. Clearly the power supply should be included. Other cost factors, such as the number of times a beam is torn down and reconstructed, maintenance costs, etc., are determined by other system parameters and are harder to estimate.

In practice further optimization is not necessary for the purpose of these comparisons. For all quadrupole costs, further optimization would push towards larger coils to reduce power at the highest fields. These coils are already almost as large as practical for reasons of iron return path length and various indirect factors. In summation, the costs are believed to be as close to optimization as is needed for a comparative study. Detailed specific improvement is unlikely to affect the apparent conclusions.

† All costs in this study are 1970 dollars.
b. Dipoles

The window-frame dipole, like the quadrupole, is a magnet where essentially the entire space not occupied by coils or iron can be used in the design of itself, but strongly retaining this capability for the quadrupole has only a weak effect on total costs. In contrast, for dipoles the vertical aperture, or gap, has a strong influence on power consumption and costs. This occurs because the coil area is much more weakly coupled to the aperture. A 2-in. gap, for example, requires 9 times less power than a 6-in. gap at the same field with the same coil area. Indeed, in various applications the AGS standard 18D72 window frame magnets are shimmed down from 6-in. by inserting two iron plates as poles. One has then a low power H-type magnet with poles and a large coil area, although far from optimum.

Compact H-type dipoles with poles can be constructed with a rectangular opening inside the iron yoke identical to a window frame. Rectangular iron slabs are inserted as poles so that they can be shimmed to any aperture. This is not only a flexible, but also an economical structure.

Estimates were made for a variety of compact H-magnets with poles, for 2-in., 4-in., and 6-in. vertical gaps and with lengths from 6-ft to 12-ft. Coil cross sections were chosen by optimizing capital and operating costs on the same basis as for quadrupoles. The calculations show very large potential savings in operating and capital costs by using small vertical aperture, pole-type dipoles. It is necessary however, to include consideration of pole-edge aberrations in the design and calculations, and the fact that saturation occurs at somewhat lower fields than with window frame designs.

Computer calculations using the TRIM program were made for a variety of geometries and fields. As is well known, pole edge shimming can considerably increase the working horizontal aperture for high precision requirements. Figure 1 shows the effect of a simple rectangular shim on the pole edge for high μ correction. Pole face windings can also be used if desired and can be tuned. This is sometimes done for precision beams even with window frames at higher field levels.

The computer calculations in Fig. 1 were performed for M36 silicon steel permeability for convenience. For actual hardware we would use low-carbon steel plate. The effect, however, is essentially the same for both steels at 5 KG. The saturation properties of low carbon steel permits ~ 15 KG operation for typical pole widths.

The aberrations are almost entirely determined by the iron contours. The details of the exact location and of the area of the exciting coils are very weak perturbations for the range of coil cross sections studied in this report. These observations were confirmed by TRIM.

c. Impact of Power Supply and of Facility Factors

The implications of the economic comparisons made in this report would apply even for the magnets alone. However, the interaction with power supply and facility costs pushes in the same directions and strengthens the case. Indirect results of using smaller and lighter elements such as relative ease of handling, spatial compatibility, interaction with shielding, impact on maintenance of smaller power supplies, etc., are not included in this report.

III. Power Supply and Facility Costs

Figure 2 shows power supply rating in kW vs power supply cost in dollars. These curves clearly show that large supplies are expensive and the cost per kW is very sensitive to current. The 120V curve was chosen in Fig. 2 for use in the cost estimates for two reasons:

1. this is a reasonable design voltage to attempt to match the magnet at full rating.
2. this curve is about the mean of the various voltage curves.

The dashed line is an extrapolation from 60 kW to meet the power supply curve for small electronic SCR power supplies.

The beam transport magnets proposed with relatively modest power requirements, i.e., under 60 kW, could use small electronic SCR power supplies. These supplies are relatively cheap and provide good regulation and very low ripple. For example, prices for SCR current power supplies from 5 to 20 kW range from $1500 to $3500 each, which makes them economically attractive. These small supplies have the further advantage of being relatively light and portable permitting the supply to be located close to the magnet so that the heavier dc cable run is relatively short and the ac cable run to the power supply is the longer line. This type of supply provides potential savings in both material and labor.

In practice there will always be some power supply mismatch, so the 120V power supply curve may be somewhat low. The error due to mismatch both of kW and of volts is greater for large power supplies. In addition, the relative impact of power supplies on total costs is greater for higher dissipations. Thus a correction to our results for mismatch would only strengthen further the case for lower dissipation.

IV. Quadrupole Magnet Costs

Figure 3 shows the ac power costs for the various apertures and fields for a 5-ft quadrupole. To determine power costs the following assumptions were made:

a. the magnets would operate 4000 hrs/year at full field.

b. a conversion efficiency of 0.8 was used for the power supplies.

c. a cost of 15/kW-hr was used.

This family of curves clearly shows the effect of aperture size and field on magnet power costs. It is also apparent that the curves for high field values have steeper slopes than those for the lower fields. The reason for this is that the ratio of coil area to aperture decreases with increasing aperture sizes in order to keep the magnet core size within reasonable limits. Increasing aperture size for magnets operating at low pole-tip fields does not affect the magnet power requirements markedly, but for high fields the power requirements increase more rapidly with increasing aperture.

Figure 4 shows the total magnet system installed cost (the cost of the magnet, power supply, cooling water supply, and installation) for a 5-ft long quadrupole. It is quite clear that increasing either aperture size or pole-tip field results in large increases in total magnet installed cost. Unfortunately, large aperture quadrupole magnets generally require high pole-tip fields to provide a reasonable field gradient in the energy range at the AGS.

In summary, smaller aperture quadrupoles, with a given B_T, are also considerably cheaper. This is not only true for the magnet cost itself, but strongly reflects the fact that a narrow version small quadrupole can have appreciably larger relative coil area, when systems optimized, and still have a good ratio of aperture to total width. Even though the 8-in. aperture quadrupoles in this paper are much more costly than the smaller versions, it should be borne in mind that these 8-in. magnet designs are themselves a lower power design than the 3-in. 6-in. quadrupoles in use at BNL and 4-in. and 6-in. versions are planned. These designs have not been published, although preliminary work on narrow quadrupoles has been reported.
V. Dipole Magnet Costs

Figure 5 shows the total dipole magnet installed cost vs magnet length for magnets with aperture heights of 2-in., 4-in., and 6-in., and with aperture widths of 6-in., 10-in., 14-in., and 18-in. Total magnet installed costs increase sharply with increasing aperture height. It is worthy of note that the dipole aperture width has a weak effect on total magnet installed cost. This is a bonus to the beam designer since a low field, relatively long dipole magnet requires more aperture width to provide the same sagitta as a relatively short, high-field magnet.

Figure 6 shows power costs vs dipole magnet gap and length. If the coil area remained constant, the 6-in. gap curves would be 6 times higher than the 2-in. curve. The intermediate value reflects the fact that practical coil areas are strongly systems dependent involving both capital and operating costs.

Examination of Fig. 6 indicates that doubling the magnet length from 6-ft to 12-ft increases the power cost by only 65% for the 6-in gap since the end section of the coil remains constant regardless of length. Note the point at the top showing the operating cost of one of our existing 18D72 magnets operating at 15 kG. These magnets were originally designed for operation at 22 kG.

In summary, by using dipoles with small gaps but relatively wide poles in conjunction with smaller quadrupoles, one can save factors of 2 to 3 in capital costs and even more in power costs.

With gaps of ≥ 6-in. or greater, the window frame circuit is preferable since it still retains its original advantages over the poled H-magnet, i.e., higher field capability, and good field properties over the entire aperture. In addition it compares favorably with the H-magnet from an overall size and cost viewpoint. The square aperture in the H-magnet due to pole edges results in very wide poles being required to provide a reasonable good field aperture when the gap is large. The greater freedom in choosing coil dimensions of the poled magnet is not particularly useful for large gaps, and the advantage of reduced magnet size and power consumption obtained from small vertical aperture poled magnets when compared to window frame versions is markedly decreased with larger vertical apertures.

VI. Conclusions

It has been demonstrated that beam transport apparatus costing much less to purchase and operate than current practice can be built. This study has been made using direct costs relating to manufacture, installation, and operation. It is believed that further savings due to detailed design of specific components would compensate for loss due to practical mismatch of components. Furthermore, inevitably, this mismatch error will increase the spread strengthening the case for the proposed approach.

A basic feature underlying this new approach results from the possibilities inherent with target stations remote from the machine, plus higher primary beam intensities. Technical innovation in quadrupole design permits quadrupoles of small aperture with field capabilities up to 15 kG, but sufficiently narrow in physical extent that the ratio of the acceptance to the solid angle blocked out for other beams is high.

Employment where feasible of quadrupoles in a manner to deliberately reduce dipole vertical gaps to ≥ 3-in., even at the expense of horizontal aperture, can lead to very large reductions in cost. The use of lower magnets operating at lower fields results in large power reductions which in itself is not surprising, but the total capital cost is also somewhat less.

Although not considered in this report, exceptionally narrow quadrupoles of any of the apertures considered can be constructed for special, extremely narrow front ends locations, at the cost of increased power dissipation.

The state of the art of computer programs for magnetic circuit analysis permits complete confidence in the design and correction of a greater variety of components for flexible and economical usage without the necessity of modeling.

Reduction in power to the levels proposed also allows economical semi-portable power supplies to be used. A wide variety of supply parameters could be provided for efficiency. The supply could be located near its magnet and maintenance done elsewhere in an electronic repair shop. Such supplies have excellent regulation and could easily be controlled from a central location.

VII. Discussion

For a thin lens with constant pole-tip field and length, the acceptance is independent of aperture. In practice a quadrupole doublet is not a thin lens. As apertures get smaller there is also a limit on how close one can approach a target. There is therefore some loss of acceptance due to these factors. Conversely, large aperture iron quadrupoles are often gradient limited in our momentum range for efficient optics, and beam design can also be modified to more effectively use smaller elements so that acceptance loss can be minimized.

A central question is to what extent are the findings of this study applicable?

1. Even direct substitution of lower field versions of larger aperture magnets in existing beam designs, where feasible, is itself a significant improvement in cost reduction.

2. Assuming one were to substitute smaller elements in existing beam designs with a reduction in acceptance, the result of the very large economies incurred in both capital and operating costs allow many more beams. With higher primary intensity and longer running periods the integrated physics output can be substantially increased.

3. Finally, by scaling quadrupole distances closer to targets, and by redesigning the beam the acceptance sacrifice of Item (ii) need not occur and solid angles will not suffer appreciably.

Even with direct substitution, lower field and/or smaller apertures will often result in systems economics sufficiently large to outweigh disadvantages. It is also strongly believed that re-evaluation based on Item (iii) would provide an even greater number of satisfactory beams for a given amount of money.

References:


Figure 1 Effect of a simple rectangular shim on the pole edge for high μ correction.

Figure 2 Power supply rating in kilowatts vs power supply cost in dollars. All power supply curves except the curve for small electronic SCR power supplies are based on: 1) 440V ac, 60 Hz, 6-phase or 12-phase rectification; 2) complete regulation of current; 3) reversing switches built in.

Figure 3 AC power cost per 4000 hour-year in 10^5 dollars vs quadrupole pole tip aperture in inches for a 5 ft long magnet.
Figure 4 Total installed cost of a quadrupole magnet 3 ft long in 10^3 dollars vs pole tip aperture in inches.

Figure 5 Total magnet installed cost in dollars vs dipole magnet length in feet for B_o = 15 kG.

Figure 6 Power cost in dollars per year vs magnet length in feet for dipoles with B_o = 15 kG.