SEPARATED FUNCTION SYNCHROTRONS*

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I. Introduction

The development of strong focusing was the most significant modern discovery for high energy synchrotrons, and perhaps the most significant also in high energy physics.

The machine with which we have experience, the Brookhaven AGS, is an extremely productive and powerful device, and is a great credit to the people who created it. Yet in operation it does show properties one would wish to improve upon in the next generation. For example, work of G.T. Danby and E.C. Raka on the fast external beam a few years ago revealed subtleties of behavior which would not have been important for internal targeting. Not only sensitivity to crossing half-integral resonances, but also third-integral nonlinear resonance behavior was encountered, such as $2\nu_x + \nu_y = 26$. The possibilities for encountering one or another of such affects as a function of radius and momentum are considerable.

On one occasion the presence, by error, of a small remanent sextupole perturbation due to previous testing of the slow external beam system caused the beam to grow by about a factor of three in one dimension and then rotate by coupling through large angles so that it could not traverse a septum extraction magnet.

The variation of ν_x and ν_y with excitation and radius is appreciable with such a machine,both due to the internal properties of the magnets and also due to end effects. These combine in different ways with the variation of ν due to momentum, making correction more difficult for both ν_x and ν_y.

For fast external beams such problems are largely overcome by producing less marginal systems. Resonant slow extraction, which will be almost certainly the normal mode of operation for a very high energy machine, is in a real sense always marginal. Much greater control of ν values with a high multiplicity of correcting quadrupole and sextupole fields will be necessary for straightforward routine operation and flexibility.

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In addition, it is very probable that many of the complex injection properties of the 30 BeV machines are affected or certainly at least confused by the presence of ν couplings and by twists of the resonant planes (although for very large machine projects these comments will be more appropriate to boosters).

Now the development of beam transport elements of high optical quality has advanced at a rapid rate in the past decade. Having been involved in this development produced a conviction that single multi-polarity elements could provide excellent optical properties more simply over a wider range of excitation.

Detailed separated function machine properties were investigated[1]. To crystallize the work, a comparison was first made with a highly developed combined function design, the Lawrence Radiation Laboratory 200 BeV Design Study[2].

Apart from a brief discussion of the practicality of separated function, we will attempt to mention only a few features here, concentrating on some which are real or apparent problems. It is a large subject and the matter is developed in more detail in the references[1,3,4]. Figure 1 illustrates a typical lattice period of a 200 BeV separated function design.

II. Stored Energy and Power Consumption

Even for an ideal system which had magnetic field only inside the vacuum chamber, the separated function case with equivalent lattice properties would have about half the quadrupole strength and stored energy. This is because a localized quadrupole is stronger acting than a distributed one. Only about 1/10 the lattice space required for dipoles is used for quadrupoles. For practical magnets, a reasonable design of separated function dipole has less wasted stored energy outside the vacuum chamber.

Incidentally, as can be seen in Fig. 2,combined function proton machine magnets are also excited to high peak fields of approximately 20 kG, although this does not occur at the aperture centerline. For a given practical length of magnet of either type at maximum practical excitation, typically about 20 ft, one needs for equivalent machines about 25% fewer pure dipoles and deflection azimuthal circumference. In addition a good combined function machine design will require high multiplicity of correction quadrupoles in the lattice. These are of course weaker, but space-wise they take a good fraction of the space required for a separated function quadrupole lens. Also one ends up,after looking at lattice parameters,with fewer periods for the separated function design, so that the equivalent space increase required for separate focusing quadrupoles is effectively less than 10% of the deflection circumference.

The magnet cost and stored energy are almost entirely determined by the dipoles. On balance, because of the greater compactness of the window frame dipole, the stored energy can be somewhat smaller. The total magnet cost is also appreciably lower, and the circumference smaller. It should be emphasized that this is not an automatic endorsement of exciting any type of lattice to the highest possible fields. We are stating here only comparisons of both lattices at the same maximum fields inside the magnets. Except for the possible conversion of existing machine rings with high field magnets, such as superconducting elements, it is not clear that any system is automatically optimum in cost and utility at the highest possible magnet fields.

The actual comparison of the two lattice types is predicated on the current density in the dipole coils, which is an important design assumption. We used, for example, current densities of about 6000 amps/in^2 in the copper which are quite reasonable from a thermal stressing and cooling point of view. C-type combined function magnets have generally used quite low current density,since there is very little magnet cost savings in increasing it. With a window frame design, as the apertures get smaller horizontally current density must be considerably higher to be practical. As a result, the dissipation in the ring is greater. Considering this increased resistance and a less favorable time constant, one requires for moderately uniform rate of rise a somewhat larger power supply, even with the lower inductance.

The cost of power supplies is considerably smaller than that of magnets. Brookhaven is in the process of doubling the AGS pulsing rate with a new power supply at a cost which is small compared to the present day magnet costs. Three times the new AGS power supply could power a separated function 200 BeV lattice quite handily.

Power costs will be higher as well. Considering shutdowns, maintenance, machine studies, etc., if one uses present figures of the AGS, a separated function 200 BeV machine might use roughly $500,000 per year more power. This is completely in the noise of overall operating expenses.

Very important for a very high energy facility is the fact that it is much more likely to run more of the time at reduced energies than the 30 BeV machines[1].

These figures are included simply to show the disadvantages in power requirements are minor compared to the cost savings and other advantages of the separated function design.

III. Tolerances on Coil Locational Errors and Eddy Currents

A disadvantage often raised against window frame magnets is that eddy currents in the coils and tolerances on coil locational errors are serious problems. This is not the case. Window frame dipole coils are only in a very weak sense "pole face windings" in that in the aperture region one has parallel dipole equipotentials coincident with the iron surfaces. Aberrations produced are completely negligible as a result of quite conservative insulation spaces between turns[4]. Only transverse misalignment of the inner turns is critical and normal good tolerances will give errors up to a few parts in 10^4 at maximum horizontal aperture, and falling off very rapidly[4]. A small model was constructed to test for eddy currents, high field properties, etc., (Fig. 3). Eddy currents are important primarily for high repetition rate boosters, but even there they will appear mainly as a power supply load factor. Eddy currents superimpose current distributions which behave like a series of current septa. Eddy current repression fields can be quite large inside the turns, but return through the yoke, producing only a very small shunting affect in the aperture region. This produces a dipole field rise rather than the usual eddy current depression, but with very small aberrations. Such affects are easily measured to good accuracy by observing the out of phase component of the field after nulling out the major component proportional to H. Results of such measurements are given in Ref. 4. Detailed features of magnet errors in general and orbit distortions have also been considered[1].

IV. Radiation Damage

Radiation damage to coils in window frame magnets is an objection legitimately raised against the separated function design. However, for very high energy machines almost all of the primary beam striking the vacuum chamber will interact in the chamber. Coil life in the high radiation areas, which are a small part of the machine, will be determined by maximum exposure to any part thereof. For any magnet type, efficient coil location will expose some part of the coil to very intense cascades of ionizing particles and neutrons developing in the chamber, clamps, the magnet core, etc.

In the case of dismantled AGS magnets from high radiation areas, residual radiation levels in the poles and coils are quite isotropic. Detailed investigation of this matter has been made for the CERN I.S.R. project[5]. They estimate after ten years of running using 1/5 of the 10^{13} protons per pulse of the P.S. that the C-type magnet coils will accumulate 1×10^9 rads of exposure, and the pole face windings 2×10^9 rads.

For particles lost from an rf bucket the median plane is more directly exposed than pole face windings. However, for beam loss through scattering from extraction septa, etc., the situation is reversed to a considerable extent.

In summary, particularly at very high energies where cascades will develop further, there appears to be no appreciable difference between the two magnet types in high radiation areas and high exposure must be lived with, unless special very large aperture magnets are used.

V. Tracking, ν Control and Aberrations

The basic premise to this work is that one can produce operationally simpler and more precise optical properties with a separated function lattice. The ideal location for high multiplicity ν control is in auxiliary windings in the quadrupoles themselves. This supposes very superior tracking of the focusing strength with deflection.

A combined function magnet has typically 3 or 4% change in k value at peak fields, and even at fields of about 12 kG about 1% tracking error in k value ($k = G/B$).

A dipole of 20 ft length will show a decrease in effective length of about 1/500 at peak field. A quadrupole of 60-in. length with a 5-in. aperture will show about 1% decrease of effective length at 16 kG pole tip field, and a two dimensional saturation of about 3 or 4%. For such small changes, the optical effects of change of internal strength versus change of effective length are minute, and only their sum is relevant. The dipole saturation is almost completely a two dimensional problem. One can then easily arrange the tracking of k to be within $\sim$ 1% with the help of a two dimensional magnet computing program. For all magnets in series the applied voltage (and stored energy) across the quadrupoles in the lattice for 100% excitation is less than 10% of the total. A comparatively very small power supply can be used with auxiliary windings to provide a few percent change of ν value. This supply can have a low mutually induced voltage to overcome and can be servoed to high accuracy. This could be done by sampling the field of a dipole and quadrupole in series with the ring. Alternatively, the quadrupole circuit can be independently excited and servoed to track the dipole. One then has ideally located ν control of high precision with the ability to vary ν values to avoid higher order resonances, etc.

The separated function design is superior from the point of view of aberrations[1,3,4]. Except at the highest fields the dipole has extremely small aberrations internally. Its ends contribute only a very small vertical focus term, or ν split. This is very insensitive to location in the aperture and to excitation. At 22 kG, end effects at full horizontal aperture cause about 1/1000 equivalent gradient error due to sextupole. Other end effects are even smaller. Above 20 kG appreciable sextupole appears internally, but even at 22 kG about a one foot long sextupole per half cell would give good compensation. One wants widely distributed sextupole in any event for "chromatic" correction of ν and general ν control with radius.

Quadrupoles can be made with no aberrations of practical importance over the range of excitation[1,3,4].

VI. Conclusions

The separated function lattice gives a machine in our opinion which is superior, and also can be considerably cheaper. However, it has additional advantages both in the design stage and finally as an operating machine. The decoupling of functions means that flexibility is inherent to a much greater degree. Many of these magnet and lattice parameters cannot be considered here. However, Figs. 4 and 5 illustrate required quadrupole strengths for lattices with 20, 30, 40 and 60 ft respectively of dipole per half cell. For separated function lattices $\sim$ 60 degrees phase advance per period is favorable. The capacity for change to an existing lattice based on operating experience, or the replacement or addition of components is much more practical[1,3,4]

All machines today should be designed with the capacity for future changes in their magnet structure built in. For example, increasing the current density of window frame dipoles a factor of ten with cryogenic excitation coils will permit at least 50% increase in energy[1,3,4]. The advantages in very low stored energy and precision optical properties of iron are retained.

Eventually air core magnets may be inserted into an existing lattice. This could be done also for a combined function lattice, but the effects of mechanical deformations due to the high forces, end effects, etc., favor single multipolarity elements[1,3,4] for the air core case as well.

Acknowledgements

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References

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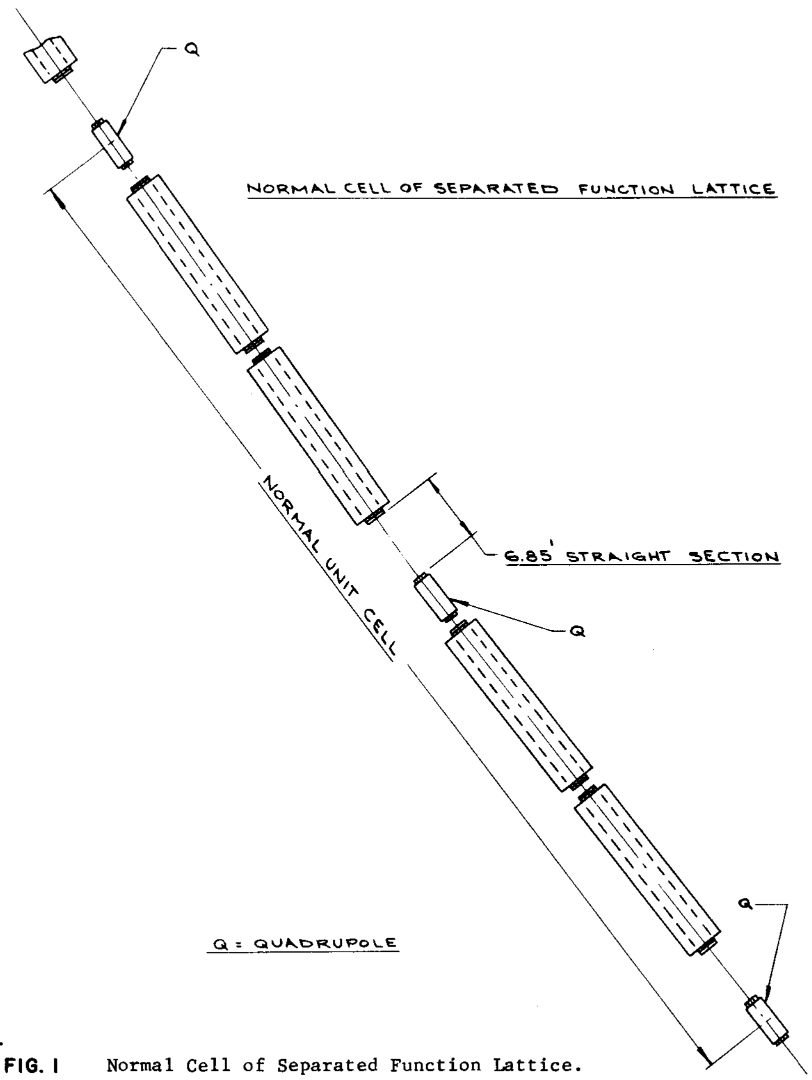

FIG. 1 Normal Cell of Separated Function Lattice.

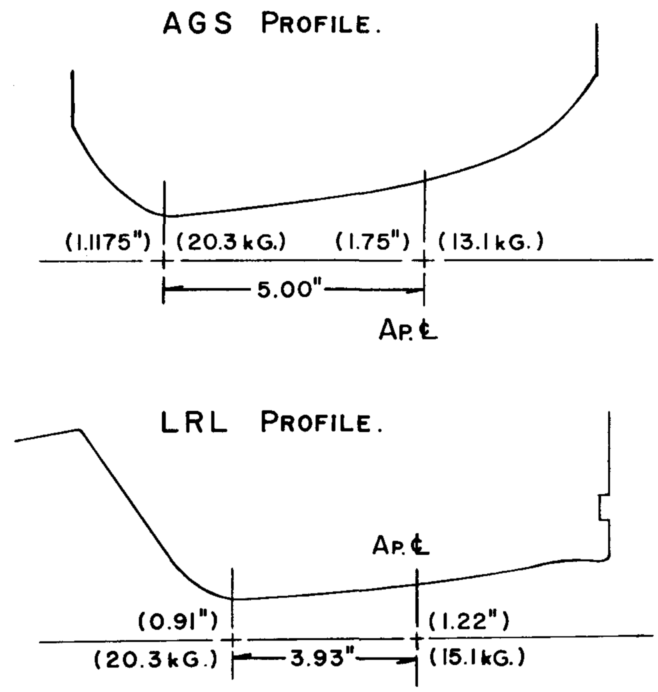

FIG. 2 Comparison of AGS and Proposed LRL Magnet Profiles.

FIG. 3 Scaling Magnet Model.

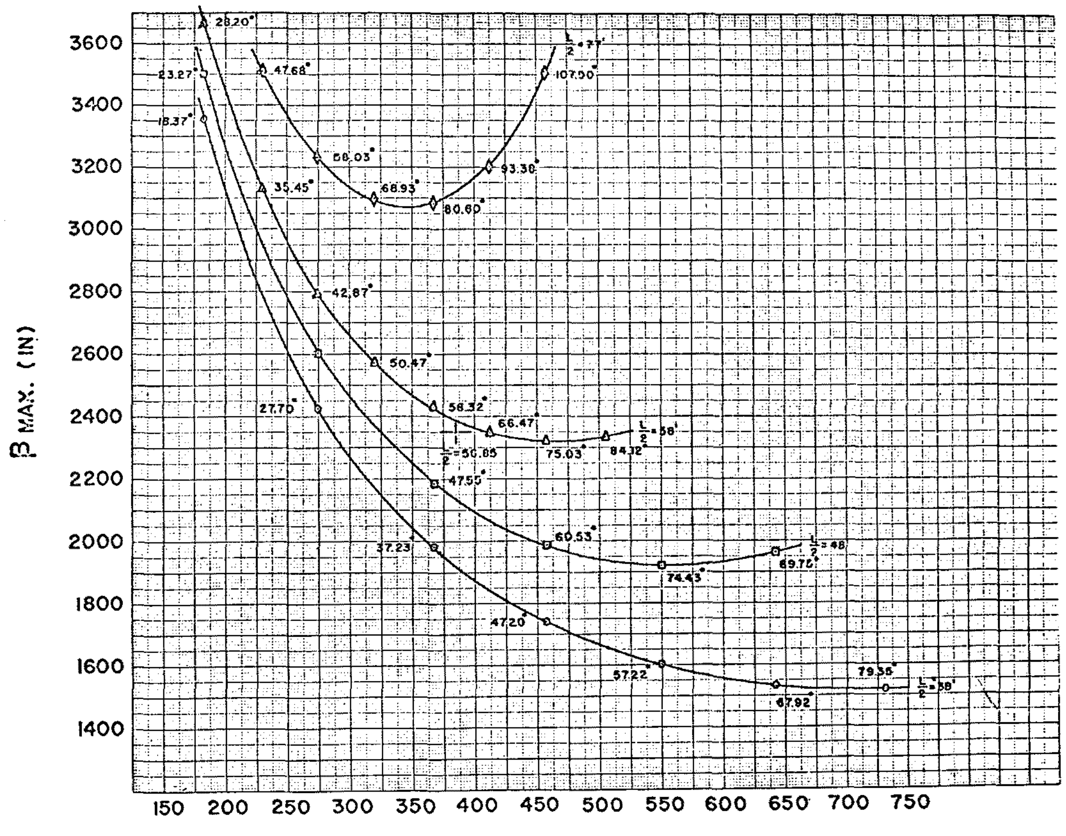

FIG.4 (Curve of β_{max} Versus GL_Q for p = 200 BeV/c).

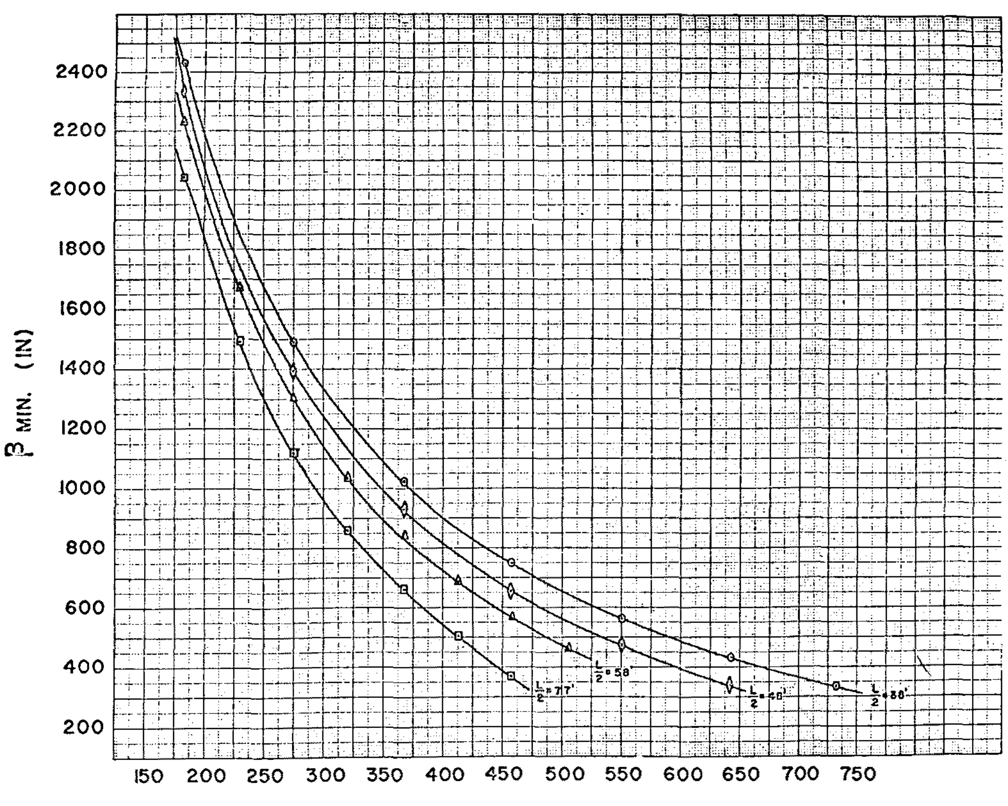

FIG.5 (Curve of β_{min} Versus GL_Q for p = 200 BeV/c).