MAGNET DESIGN FOR A VERY HIGH ENERGY SYNCHROTRON EMPLOYING A SEPARATED FUNCTION MAGNET LATTICE*

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Summary. The authors conclude from an investigation that for a very high energy proton synchrotron a separated function magnet lattice is superior to the conventional combined function lattice. In addition, the direct and indirect effects of the resultant smaller radius make it an economically attractive alternative. With long straight sections employed, there is no fundamental objection to a closed magnet structure. Indeed the shielding automatically provided appears to outweigh any disadvantages. The expected almost total dependence on high intensity external beams of primary protons requires a very high degree of beam optical excellence. A lattice utilizing quadrupoles and "window frame" dipoles can be constructed with very small aberrations in the azimuthal integrals of their fields. The optical properties can be very accurately controlled for a range of dipole fields extending from lower values than practical with combined function magnets up to considerably higher values. Quadrupole aberrations allowed by symmetry are of high multipole order and can be made extremely small. Only even order dipole aberrations are allowed. However, these are very small from very low fields up to values approaching 20 kG. For higher excitations appreciable sextupole appears, followed by 10-pole. However, since widely distributed sextupole lenses are desirable for parameter control, there is no strong argument against exciting the dipoles to fields with moderate sextupole aberration. In contrast to the end effects of combined function magnets, there is no significant variation of beam resonant frequency with radius, other than the "chromatic" variation with momentum. This variation is easily and accurately compensated for with sextupoles. Dipoles and quadrupoles powered in series can be designed to track better, considering the range of excitation as a whole than the inherent tracking of gradient to dipole field in a combined function magnet. Servo-controlled auxiliary windings can easily hold very constant the resonant frequencies. Dipole and quadrupole high field "bumps" incorporated in these elements will retain only minute remanent perturbations at injection. The closed structures shield the beam from stray fields at injection and also greatly reduce the possibilities of twist of the median plane. The effects on the beam of coupling of the modes of oscillation during acceleration and of nonlinear resonance phenomena are much more critical for efficient external beam operation than for internal target use. These effects can be avoided with a separated function lattice. In addition to providing a better and more flexible operating machine, the ability to vary widely and control accurately over the whole aperture the resonant frequencies and other parameters will greatly aid in understanding space charge and other injection phenomena. This flexibility is also a great asset to a two stage development of a large and costly machine. For example, the excellent low field optical properties would permit good operation at the proton intensity level of present machines without the complexity of a final large booster stage. Furthermore, the complete independence of the functions lends itself easily to building into the ring the capacity for future addition or rearrangement of components for higher energy operation. Going even further, the separated function lattice is most suitable for possible ultimate replacement of the magnet units by air core superconducting elements. As an intermediate superconducting step, the magnet system proposed can be modified to give fifty percent increase in peak machine energy, using superconducting windings only as excitation coils for the iron magnets.

Introduction

The idea of a separated function magnet lattice for a very high energy synchrotron is obvious in itself. It was not our purpose to show that the same job can be done with different hardware. The motivation for this work came from experience in helping to build and operate the Brookhaven AGS and from participating in the recent development of magnetic elements of high beam optical purity.

The AGS is a magnificent machine and is certainly a triumph to the people who conceived it and to those mainly responsible for having brought it to its high level of achievement. (Remarks concerning the AGS in this paper apply by and large to the CERN PS as well.)

The strong focusing machines do require close tolerances to avoid destructive resonant effects and excessive equilibrium orbit distortions, but there is another side to this. The very large radius of curvature compared to the cross-section, which will be even more true for higher energy machines, leads to appreciable simplifications. The lattice consists of many magnet modules with two dimensional mechanical and magnetic properties, apart from small end effects. An illustration of the benefits is the fact that even severe magnet shorts in high radiation areas have been corrected in a matter of days.

Work of G.T. Danby and E.C. Raka (unpublished) on the dynamic properties of the AGS fast external beam has revealed, on many occasions, subtleties of behaviour which normally would not be important for internal targeting. For example, beam size increase, which is disastrous for extraction, occurred due to a very small remanent history in sextupoles previously used to excite a 2/3 horiz-

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ontal resonance for tests of the slow external beam. By means of a method devised to photograph one traversal of the beam through a fluorescent screen inside the machine, it was observed that the beam was tripling in size horizontally. Later in the cycle it was rotating through large angles because of horizontal to vertical ν coupling. In addition a small perturbation due to a septum fringing field can cause trouble not only on the half integral resonance but nonlinear resonance losses also have been encountered. With radius and momentum as variables the possibilities for $3\nu_x=26$, $2\nu_x + \nu_y = 26$, and $3\nu_y = 26$ occurring in the AGS are considerable. At high intensities the beam size appears more sensitive to small disturbances, gas pressure, etc. Coherence was found to have some association with troublesome beam size changes, but did not appear to be the primary factor.

All the above problems can be overcome, or avoided, in one manner or another to give reliable and efficient fast external beam operation at high intensities, but clearly it would be better to minimize disturbances. Operational dependence on efficient extraction of slow external beams with reproducible spill rates is very sensitive to machine subtleties and requires excellent control of parameters. Similarly sophisticated injection schemes for optimum acceptance are affected by injection field orbit "bumps", distortions of the β factors, ν variation with radius, horizontal and vertical coupling, and twist of the median planes due to stray fields. The combined function magnet system is prone to all these disturbances (although they can largely be avoided by injection at quite high fields).

Since a thorough and excellent design for a 200 BeV combined function machine had been made by the Lawrence Radiation Laboratory Design Study Group,[1] we proceeded to investigate an equivalent machine with a separated function lattice.[2]

Our interest in cost is secondary. However, accelerators being very expensive tools it was first important to establish, at the very least, that cost was reasonably competitive. Table I shows lattice parameters, and Fig. 1 illustrates a normal period of the separated function lattice.

Comparison of the Magnetic Properties of the Two Types of Components

The combined function magnet can be designed to have excellent magnetic properties at intermediate fields where the permeability, μ, is high. It is, however, really a deformed dipole, and as μ decreases the field configuration deteriorates. The maximum field allowable on the aperture centerline is basically set by saturation of the minimum gap. Above this point the ratio of the gradient to the dipole component ($k = G/B_o$) changes more than is acceptable, and higher field multipolarities are just within controllable bounds. B_o max is therefore a function of the k value and of the horizontal and vertical aperture dimensions desired (Fig. 2).

At low fields, where window frame dipoles and quadrupoles still have good properties, distortions occur in the combined function magnet due to low permeability. Eddy currents in the vacuum chamber, the remanent field pattern, and penetration of stray fields all tend to distort field configurations. Eddy currents in the iron, if present in appreciable magnitude, also distort since they tend to produce a less deformed dipole.

Dipole magnets having an aperture of 2.4 inches vertically by 5 inches horizontally and approximately 20 ft. long were chosen for this investigation (Fig. 3). Peak fields of 20 and 22kG were considered. Magnet yoke thickness was chosen to give negligible contribution to saturation so that any decrease of incremental B with I represents saturation in the pole surfaces. The window frame dipole has plane parallel pole surfaces which are dipole equipotentials. As a result decreasing permeability tends, to first approximation, to add reluctance without distorting the equipotential planes. As a result it retains good field properties over a greater range of μ. The left-right symmetry represses the orders of multipolarities allowed and also tends to repress their amplitudes.

Internal two dimensional aberrations were computed using the SIBYL[3] program and compared with experimental data on existing window frame dipoles in excess of 20 kG. Calculations with permeability data of a silicon steel shows that at 20 kG with a 95% packing factor 3.75% additional excitation current is required due to saturation and aberrations are just appearing, which are predominantly sextupole. At 22 kG the current increase due to saturation is 9% and the sextupole aberration is about 5 kG-feet per dipole at maximum horizontal displacement ($X_{max} = 2.5$ in.). The 10-pole aberration was about 10% of this value at X_{max} so its effect is very small. For intermediate fields very low aberrations will be present.

The remanence is much lower for the window frame dipole than for a C-type magnet of the same steel, since without external magnetomotive force spontaneous reorientation within the closed core results. What remanence remains exhibits low aberrations which are constrained to be sextupole, 10-pole, etc. Excitation fields as low as a few gauss contain very little aberration. Eddy currents in the core and in the vacuum chamber, to good approximation, produce a dipole field and only affect the magnitude: their aberrations are less than in a combined function equivalent.

Eddy currents in the exciting coils are in closer proximity to the aperture with the window frame design. However, the modification to the distribution of current density is still one dimensional and, to good approximation, has very minor influence on the field in the aperture. Only assymetrical eddy currents in the two turns immediately adjacent to the vacuum chamber are important. Aberrations will result if the top turn is shifted horizontally with respect to the bottom turn. However, since the inner turns in each layer of the two layer coil are wound first, this tolerance can be held sufficiently close with good fabrication procedures. This condition has been simulated experimentally and appears to present no problem at injection fields lower than practical with a combined function lattice.

The use of split window frame dipoles eliminates the need for all external coil clamps except on the ends. No coil wedging devices and vacuum tube clamps would be required since both the coil and the vacuum chamber would be completely contained within the magnet aperture along its length. Split dipoles also simplify the assembly and disassembly of the vacuum chamber and coils. Horizontal accuracy of alignment of the top and bottom half magnet cores need not be precise since only the average gap separation has a tight tolerance.

Quadrupoles of a type developed at the AGS[4] which can be driven to high pole tip fields with moderate power consumption and with high quadrupole field purity were considered (Fig. 4). These can be assembled with no yokes on the sides, where necessary, without any optical deterioration. The lowest order internal aberration is 12-pole ($6\theta, r^5$). It can be made arbitrarily zero in design; the next order ($10\theta, r^9$) is about 0.2% at maximum aperture. The next order ($14\theta, r^{13}$) is about 1% in amplitude at full aperture, but falls as r^{13} and is academic for practical orbits. These aberrations are slowly varying and are quite small over the complete range of excitation to fields higher than used in this investigation. Remanence again is small and predominantly quadrupole due to the four-fold symmetry. Eddy currents in the cylindrical vacuum chamber sections are also quadrupole to very good approximation.

The only significant end effect in the quadrupoles ($r^5, 6\theta$) is only about 1/200 in gradient (1/1000 in field) at full aperture and slowly varying with excitation. However, the integral gradient length can be made completely linear in design, even cancelling this small effect by an equal and opposite internal one. For the (twenty foot long) dipoles the end effects still have left-right symmetry and at 22 kG and X_{max} the sextupole term in the ends contributes a gradient error about 1×10^{-3} of the quadrupole gradient. The 10-pole is about five times smaller. (Note: Fig. 5 shows a suitable 6 module power supply arrangement identical to the 2 module connection for the converted AGS).

Beam Optics and Tolerances

Apart from sextupole aberrations in the dipoles above 20 kG, magnet aberrations in the separated function lattice are extremely small in their effect. End effects will produce a small vertical focus term. This will be very linear and no problem since larger built in ν-splitting will be desirable. The effect of higher order end effects will be microscopic. The left-right and up-down symmetry of the elements eliminates twist of the planes of oscillation or field bumps due to interactions of auxiliary stray fields and of the earth's field with the magnets. One has dipole, quadrupole and sextupole fields of high multiplicity and the capacity to precisely control them. Some distributed octupole field may be useful, although no octupole aberration is present. Auxiliary control of the quadrupole field is ideally located in the quadrupoles themselves.

These arguments assume excellent tracking of the series powered dipole and quadrupole fields. The combined function magnet gives this property automatically, but in practice k varies 3 to 4% over the range of excitation. Well designed dipoles and quadrupoles in series will track better than this without correction. However, field monitors in units in series with the ring can servo control auxiliary windings to hold the tracking easily to within 1×10^{-3} parts.

In a combined function machine the variation of integral gradient length with radius has an appreciable effect on ν values as a function of radius. For ν_y this effect partially cancels the "chromatic" variation. For ν_x the two terms add. The gradient variation is due to end effects and varies with excitation making accurate control difficult. For the separated function lattice only chromatic variation is present and is easily and accurately compensated with sextupole.

For a strong focusing accelerator magnet errors and equilibrium orbit distortions are absolutely vital factors[5]. For the combined function case one effectively "shims" the magnet by defining a magnetic centerline approximately coincident with the aperture centerline where the integral field through the magnet is the desired value. This magnetic centerline is located on the prescribed lattice.

However, in practice, with mechanical and optical errors, one has random errors up to 0.05% of the dipole field B_o in both the horizontal and vertical planes. On both the present machines and on higher energy versions this is, in practice, quite tolerable and gives a low probability of excessive distortion.

For the separated function dipole the position on the lattice is not critical; only accurate leveling is necessary. The one tight tolerance is the average gap separation. A change of 1.5 mils gives 1×10^{-3} parts error. However, this is a known error and can be easily measured to 1×10^{-4} parts. Such errors can be coped with by stacking around the lattice. If desired at the time of measurement they could be removed with simple end shims (12 mils = 1×10^{-4} parts). A single quadrupole error in position is more sensitive than the same error on a combined function magnet. However, there are about 1/3 as many units to have these statistical errors so the effective positioning tolerances would be about the same.

The effective centers of the quadrupoles and dipoles do not shift at low and high fields. With the combined function magnet such effects occur although this can be partially compensated by stacking order on the ring.

Comparison of the Two Lattices

The vacuum chamber accessibility within a C-magnet is lost with closed dipoles, but has very limited use. The separated function design has twice as many short straight sections per period. The quadrupoles are accessible for insertions such as pickup electrodes, and they have excess vertical aperture which is very important. Since no auxiliary quadrupoles are necessary, and horizontal orbit deflectors may be incorporated into the dipoles more useful straight section space becomes available.

From a shielding point of view, inaccessibility seems to be a great advantage. The coils appear at first sight to be subject to more radiation in the separated function case. In a very high energy machine almost all the primary protons which strike the vacuum chamber will interact in the chamber because of the very small incident angle. Regardless of the magnet design, efficient coil location would expose some portion of the coil to the cascades of ionizing particles and neutrons which will fan out from the vacuum chamber, magnet core, etc. Coil life will be determined by the maximum exposure of any part of the coil. Coil life could be expected, therefore, to be about the same for both designs. Coil replacement, when necessary, is easier on a split dipole magnet. Better radiation shielding is provided by the closed structure which also lends itself more to servicing from one side of the ring. The lattice is also more compact and takes less space.

For injection and extraction of primary protons there is no practical disadvantage to the separated function design.

Present thinking places internal target operation on the low key because of the very sharply peaked forward production and severe radiation problems to the machine. For a very high energy machine multiple traversal targets are less efficient than at 30 BeV. Secondary beams will require septum magnets against the vacuum chamber in the downstream end of long straight sections to sweep the beam away from the ring. It appears that just about any practical layout would work equally well on either lattice.

It should be noted that the degree of saturation at 22 kG in the window frame dipole is about the same as at the design peak field of combined function magnets. The separated function design is not predicated on pushing to limiting fields: a 20 kG version is only slightly more expensive than a 22 kG design, but uses about 20% less power.[2]

Either lattice can have good beam optical properties, but the separated function design will have better and operationally simpler control of both ν_x and ν_y over the entire useful aperture. For equivalent machines with the same betatron phase space acceptance, the separated function version, has about 30% smaller radius. This reduces rf power gain per turn, for example, increases the incoherent space charge limit and has other practical advantages.

Additional Advantage of the Separated Function Lattice

The greater flexibility of the separated function system will be a great aid to the study and understanding of space charge and other injection phenomena. At injection the magnetic parameters can be varied widely and precisely. With excellent control and perhaps, precisely controlled nonlinearity, considerable intensity gains may be made.

This flexibility leaves one free to make changes to the lattice of an existing machine much more easily than with a combined function machine. The knowledge acquired in both particle and accelerator physics after operating at very high energies could then interact in future modifications. For example, the beam transport type of quadrupole elements can be strengthened for either higher ν or higher energy operation, or replaced by different ones. Similarly, additional dipole deflection can be added for higher energies.

Considerations of injection energy were beyond the scope of this work. This is a complex subject involving sufficient acceptance of betatron and synchrotron phase space for some injection scheme at the intensities desired, and adequate space charge limits. Injection schemes contemplated are expensive and operationally very complex. Various possibilities arise, for example, the final stage of the injector system might be eliminated or temporarily left out for a later modification. With excellent optics at lower fields, as well as flexibility, a more modest injector could well fulfill the desired goals.

Any contemplated very high energy machine should have capacity for conversion to superconducting magnets. Some of the associated hardware of the two magnet lattices is not interchangeable making conversion from one system to the other unlikely. Therefore, the use of a separated function lattice, which is superior for air core magnets, is more desirable.[2]

A modest modification to the dipoles proposed can give a 50% increase in peak energy by using superconducting windings only as cryogenic exciting coils.[2] The shielding, stored energy, and precision advantages of iron cores are retained. Aberrations are about double the 22 kG values and controllable. This is speculative, although technically sound, and illustrates the adaptability of such components.

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References

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Table I Machine Lattice Parameters or Function of Quadrupole Strength.

L/2 (ft.)	GL_B (kG/in. × in.)	$\Delta\mu$ (deg.)	β_{max} (in.)	β_{min} (in.)	ν_1 N = 72	ν_2 N = 84	.01 α_{max} (in.)	.01 α_{min} (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 kG/in. × in. is the quadrupole design strength used in the cost comparisons.

(b) More accurately, this design strength gives a half period length L/2 = 56.85 ft. This produces β_{max} = 2350 in. compared with 2300 in the LRL design.

(c) .01 α_{max} for LRL = 2.36 in. (including appreciable increase due to the Collins straight sections).

(d) ν for LRL is ~ 13.75 in the normal periods (plus about 3 units due to Collins straight sections).

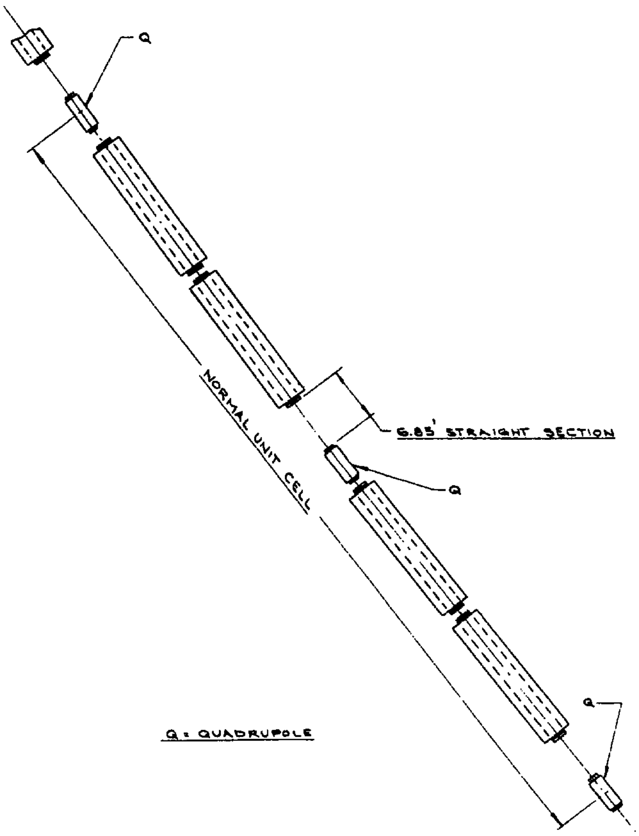

Fig. 1. Normal Cell of Separated Function Lattice.

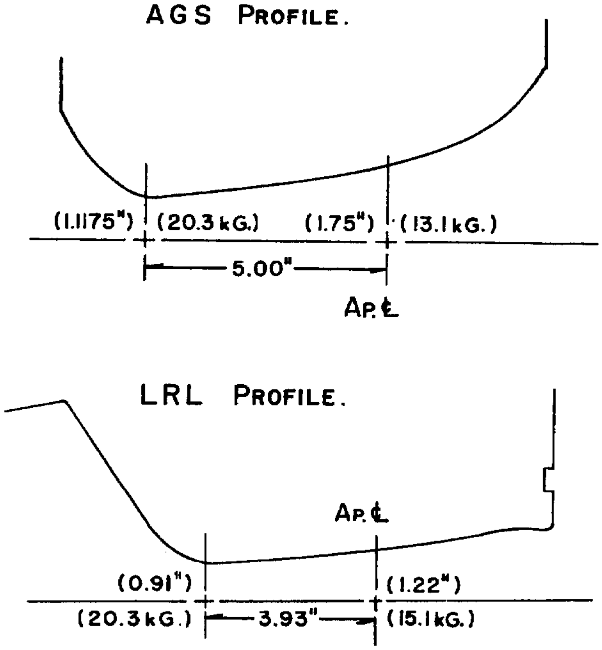

Fig. 2. Comparison of AGS and Proposed LRL Magnet Profiles.

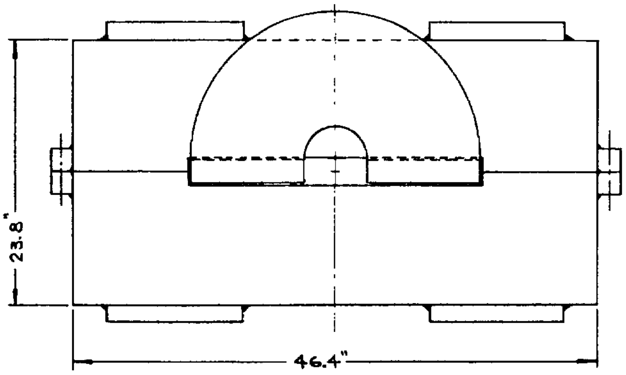

Fig. 3. Typical End View of a Dipole Magnet with a 2.4" × 5" Aperture.

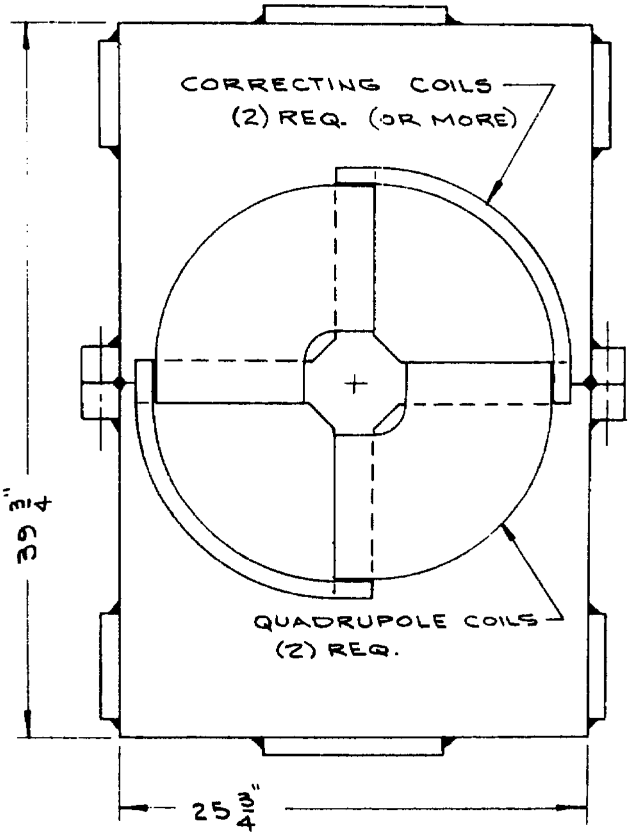

Fig. 4. Typical End View of a 5" × 58.5" Quadrupole Magnet.

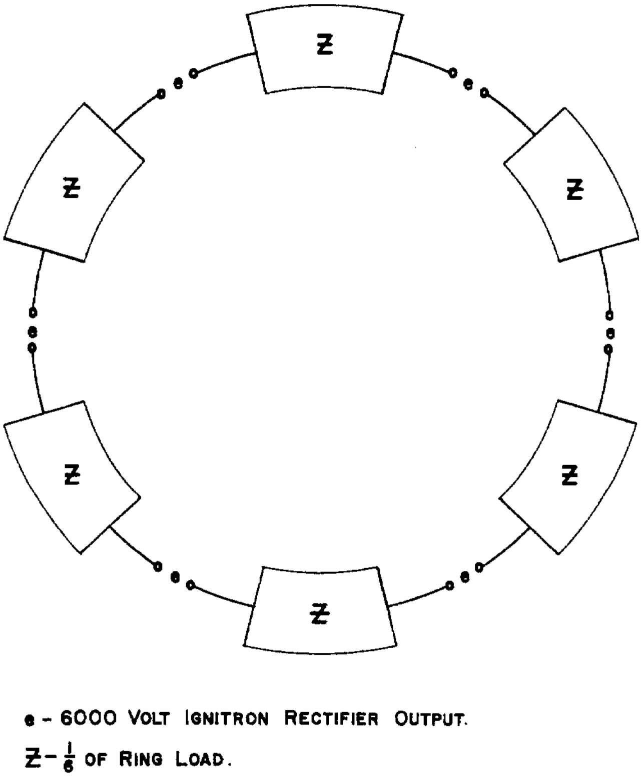

Fig. 5. Possible Configuration for Powering 200 BeV Ring.