SUPERCONDUCTING SYNCHROTRON DEVELOPMENT AT BNL†

A. van Steenbergen, BNL Advanced Synchrotron Study Group
Brookhaven National Laboratory, Upton, New York, USA
(presented by G.K. Green)

Abstract

A few aspects of a design study of a superconducting synchrotron of nominally 100 GeV proton energy are presented, related to basic parameters, magnet-dewar system, resonant extraction with "imperfect" superconducting dipoles, and the possibility of partial corrections for magnet component errors in a synchrotron lattice. In a separate Appendix a progress report on the superconducting magnet work being carried out at BNL, is given, dealing with the state of development of conductors and magnet circuit design, and further summarizing the performance data of test solenoids and model synchrotron magnets. In conclusion, plans for the design of superconducting storage rings and specific superconducting component development will be indicated.

Introduction

With the rapid progress being made in superconducting magnet development the construction of a high field synchrotron magnet system has become possible. It became therefore of interest to investigate if an acceptable guide field structure could be designed, making use of superconducting high field magnets, but with manageable construction tolerances; and if these techniques would result in cost reductions for a high energy proton synchrotron (or storage ring), when compared with a room temperature magnet system. At Brookhaven, studies along these lines have been carried out.[1] Until recently, the main effort has been concerned with the design of a 100 GeV proton synchrotron, concentric with the AGS and located within its tunnel, making use of the AGS as the injector synchrotron. Its main purpose would have been to upgrade the proton energy range of the Brookhaven facility and to serve as a "pilot plant" project of a superconducting accelerator. Subsequently, BNL plans have further crystallized and presently the design work for a set of 216 GeV superconducting storage[2] rings is in progress. The 100 GeV synchrotron ring has served, however, as a realistic model for evaluation of certain beam dynamical problems, such as resonant extraction from a small aperture synchrotron with "imperfect" magnets, and several of its subsystems designs (magnet system, refrigeration system, resonant extraction, etc.) continue to be relevant to the present storage ring study.

100 GeV Synchrotron Parameters

The general design of the 100 GeV superconducting ring was guided by the desire to locate the device in the existing free space around the AGS, in the same tunnel. The basic parameters are summarized in Table I. Beam transfer between the AGS and the CMS* would be done by means of synchronous bunched beam transfer, making use of horizontal-vertical transverse phase space interchange in the 30 GeV transfer line for more optimized matching to the circular aperture of the ring. No internal targeting would be used. Vertical fast beam extraction and also vertical resonant slow beam extraction modes have been designed for the synchrotron. The stated full aperture value of 1.5 in. (with a "good field" value of ≅ 0.8 in.) is satisfactory for beam injection, and adequate (not generous) for vertical resonant beam extraction. Several faster magnet cycles have been used, the present repetition rate was somewhat guided by the criterion to make the magnet system dynamic losses small compared with the overall magnet dewar system static losses (< 25%).

TABLE I. CMS PARAMETERS

CMS structure	Separated function, FoDo
Ring circumference	$C_{CMS} \cong C_{AGS}$
Maximum dipole field	40 kG
Maximum proton energy	112 GeV
Injection energy	30 GeV (AGS as injector)
Beam intensity	10^{13} protons per pulse
Magnet aperture	1.5 in. ("full" aperture)
Repetition period	8 s (2.4 s acceleration, 3.2 s "flat top", 2.4 s de-excitation and dwell)

Magnet System

The magnet structure has been subdivided into 48 magnet-dewar system modules, each containing a single magnet cell, with the required long straight sections being provided for by leaving out specific dipoles in a regular cell unit. Further details of the dipole magnet units are given in a separate Appendix, here only the overall magnet system parameters for ≅ 100 GeV superconducting ring are summarized. The magnet ("dynamic") dissipation values, for a single coil layer, cos θ current distribution, dipole magnet are given in Table II. These values apply to the 1.5 in. aperture diameter dipole unit using braided NbTi composite wires with 7 μm diameter superconducting filaments.

The value for the coil hysteresis loss is based on a calculated value, using the Bean model approach and multiplying the resultant hysteretic loss by a factor of 2, this factor being based on extensive comparisons of calculated values and experimental results obtained with model dipoles and solenoids, up to degraded performance levels. The magnet excitation parameters are given in Table III, where, for the sake of comparison, also some stored energy values are presented for a 60 kG peak field, 1.5 in. full aperture magnet system.

---

† Work done under the auspices of the U.S. Atomic Energy Commission.

* Cold Magnet Synchrotron, "cold" referring to 4.5°K (superconductors) or, in an earlier design stage, also 12°K (pure aluminum conductor).

TABLE II. MAGNET SYSTEM DISSIPATION

per cycle, per unit length of magnet	Coil hysteresis	7.2 J/m
	Resistive	≅ 0 J/m
	Iron shield†	3.0 J/m
	Eddy current,vac.ch.	2.1 J/m
	Total	12.3 J/m
Average magnet cycle, per unit length		1.54 W/m
Magnet system dissipation, aver.		1.0 kW

†Essentially hysteresis only. Based on 0.018 J/lbs/ cycle, as a result of low temperature measurements.

TABLE III. MAGNET EXCITATION PARAMETERS

Maximum field	40 kG	(60 kG)
Current density	30 kA/cm^2	
Conductor current	2000A (braid conductor)	
Number of A-turns	0.19 10^6 A-t	(0.57 10^6A-t)
Stored energy per Unit length	7.2 kJ/m, aperture	(16.2 kJ/m)
	5.9 kJ/m, in coils	(47.9 kJ/m)
	1.0 kJ/m,iron shield	(26.2 kJ/m)
Total, per m of dipole	14.1 kJ/m	(90.3 kJ/m)
Total in magnet system‡	8.6 MJ	(54.4 MJ)

‡Including quadrupoles and correcting sextupoles.

Based on the foregoing parameters, magnet subsystem designs have been carried out!

Two possible modes of cooling the magnet system, operating in the 4.5°K-5°K region have been studied in some detail. These are nucleate boiling liquid helium immersion and forced convection with supercritical helium flow. The attraction of the latter approach is its well defined heat transfer properties associated with single phase flow and the possibility of using long, narrow channels in the magnet system.

In the earlier design concept of the overall refrigeration system, dewar feed through current lead losses were not sufficiently taken into account and a two loop supercritical He flow system was favored.[3] Subsequent studies, taking heat leak losses of 1 W per 1000 A plus 0.046 g/s of He at 4.5°K per 1000 A lead current, into account led to improved design concepts.[4,5] The refrigeration system parameters are presented in Table IV.

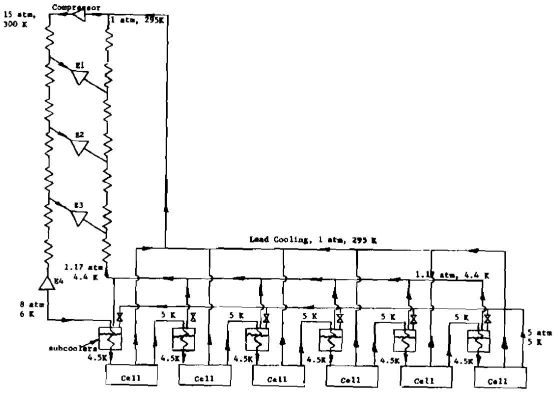

Fig. 1. Magnet system refrigeration cycle, refrigerant supercritical helium.

Presently for a long magnet dewar system, as for the 100 GeV CMS, a refrigeration system utilizing nucleate boiling heat transfer is favored although studies of both modes of cooling are being continued, also in connection with a possible design option of operating at lower temperature (1.4°K) in order to obtain 30% higher dipole fields. The improved conceptual design for the supercritical He flow refrigeration loop system is shown in Fig. 1.

TABLE IV. REFRIGERATOR PARAMETERS

Static load magnet-dewar and distribution		2.25 kW
Current leads		0.75 kW
Magnet system "dynamic load"		1.0 kW
Refrigerator rating:	40 kW at 4.4°K plus 33 gr/s He mass flow	
Mode of cooling	liquid He immersion	forced convection cooling using supercritical He
Total He flow	570 gr/s	860 gr/s
Compressors	1820 hp(1.4MW)	2760 hp(2.1MW)
	(in, 1atm,295°K;out,15atm,300°K)	

Beam Ejection

Two modes of beam extraction have been studied for the CMS, i.e., the resonant, third integral, extraction method and the fast "shaved" beam extraction method.[1,6] Only that aspect of the slow resonant extraction will be mentioned associated with the tolerable magnitude of the dipole magnet sextupole component, either due to iron shield saturation or construction errors of the coil block locations of the magnets. (It is assumed here that all dipoles are identical, the random variation from magnet to magnet will be dealt with below.) As indicated in the foregoing, vertical resonant extraction is being contemplated for the CMS.[7]

With a sextupole component in the dipole magnets, associated with the vertical-horizontal coupling of the particle betatron oscillations, a vertical (resonant) amplitude growth results in a shift of the horizontal equilibrium orbit, which in turn causes a ν_y shift ($\Delta\nu_y$), which affects the vertical resonant extraction. Numerical results obtained for the CMS indicate that for a dipole magnet sextupole component value of $b_2 = \frac{1}{2}$ (B''/B$_0$) = 0.4%/in.^{2}, a vertical amplitude growth of 1 cm results in an equilibrium orbit shift of 0.02 cm, which in turn causes a $\Delta\nu_y$ value of -0.02 ν units. As a consequence the "amplitude" of the unstable fixed points would change by 1.3 cm, larger than the basic amplitude growth; this is inherently impossible, i.e., the particles are prevented from becoming (fully) unstable as a result of their own amplitude growth. In transverse phase space this manifests itself as a distortion of the separatrix branches.

The detailed study of the resonant extraction process with the "imperfect" CMS dipoles provide for criteria of the tolerable sextupole and higher pole field components and for possible modes of compensation. The simplest method, of course, is the complete (dynamic) compensation in the dipoles with correcting windings. In order to gain understanding, and also because of possible magnet construction difficulties, the alternative method, that of a "point", high multiplicity, dynamic sextupole compensation in the CMS lattice, has been studied. By using 48 correcting sextupoles, it is possible to correct for the $\Delta\upsilon_y$ value, mentioned above, proportional with the vertical betatron amplitude; but not simultaneously for the $(\partial\upsilon_y/\partial R)$ behavior; also caused by the distributed sextupole components. (For good resonant beam optics[8] and avoidance of a dynamic aperture limitation $\partial\upsilon_y/\partial R$ should be $\cong 0$.) By adopting now also a set of 4 octupole correcting magnets in the CMS lattice, it is possible to maintain $(\partial\upsilon_y/\partial R) = 0$ and correct also the distortions of the separatrix branches associated with resonant extraction, up to values of the sextupole component in the CMS dipoles of $b_2 = 0.75\%/\text{in.}^2$. The case[9] for resonant extraction with CMS dipoles with sextupole field components of $b_2 = 0.5\%/\text{in.}^2$ is shown in Fig, 2, where it is evident that the use of the correcting octupole magnets, in addition to the correcting sextupole magnets, is essential in order to achieve resonant beam extraction.

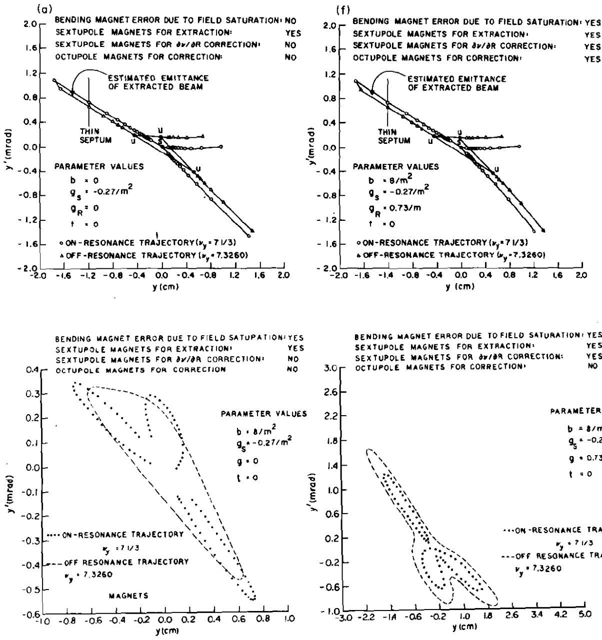

Fig. 2. Vertical resonant extraction effect of bending magnet saturation.

Magnet Component Tolerances

Above, the tolerable magnitude of the sextupole components in the CMS dipoles, equal from magnet to magnet, but not necessarily constant during the magnet cycle, is indicated. In reality, of course, random variation from magnet to magnet do occur.

As part of the magnet computation program, the sextupole component contribution to the median plane field as a result of the "symmetric" motion (typically as a result of the force field) of the dipole current blocks and as a result of random placement errors of all current blocks in a single dipole, varying randomly from dipole to dipole (construction tolerances) has been determined. Denoting ϵ as the radial or azimuthal positioning error of a single current block in a cos θ current distribution dipole magnet, then the rms sextupole component is given by[10] $\langle b_2\rangle_{rms} = 3\,(2/N_b)^{\frac{1}{2}}\,R^{-3}\,\langle\epsilon\rangle_{rms}$ where N_b is the number of current blocks and R is the radius of the "current sheet" location. Typically, for a value of $\langle\epsilon\rangle_{rms} = 0.004$ in. for the single layer dipole magnet, $\langle b_2\rangle_{rms} = 0.2\%/\text{in.}^2$. Because of the random distribution from magnet to magnet, azimuthal field perturbation harmonics are introduced, the most serious of which is the 22nd harmonic, which is the driving term for resonant extraction. Actually the magnitude of this term, as a result of the indicated field errors, is comparable with the resonant extraction driving term magnitude, in addition to which the other azimuthal harmonics generated cause major distortions of the extraction separatrix branches (see above), making beam extraction for the indicated tolerances impossible.

A study of this problem done by M. Month and others[9] indicated that by adopting a second set of resonant extraction sextupoles, in order to control independently phase of the extraction harmonic and rate of resonant extraction, in addition to the use of the correcting octupoles, as indicated above, acceptable resonant extraction is possible with a random dipole magnet sextupole component magnitude of $0.4\%/\text{in.}^2$, corresponding to rms placement errors of the individual current blocks of 0.008 in. Evidently, the use of correcting lattice elements leads to such magnet constructional tolerances, as may actually be achievable in the construction and operation of the low temperature dipole magnets.

Acknowledgments

The CMS studies reported here are but a brief summary of extensive work carried out by many in the Accelerator Department, principally coordinated by ED Courant, MQ Barton, GT Danby, I Polk, WB Sampson, and the author. Constant encouragement and support by FE Mills, GK Green and JP Blewett were essential to the completion of the study.

References

1. "Design Study of a Cold Magnet Synchrotron (CMS)" BNL 15430, A. van Steenbergen, Editor, 1970.
2. "200 GeV Intersecting Storage Accelerators", J.P. Blewett, these Proceedings.
3. "Refrigeration and Distribution System", Section 4.5 of Ref. 1, R. Gibbs, J. Jensen, A. Raag, A. Schlafke.
4. "Refrigeration Systems For Large Magnet Dewar Systems", J.E. Jensen, BNL Accel. Dept. Int. Rep. CRISP 71-4.
5. "Cryogenic Engineering Aspects of Pulsed and Steady State Superconducting Magnet Systems", J.E. Jensen, BNL 16002, 1971.
6. L.N. Blumberg, J.G. Cottingham, J.W. Glenn, J.J. Grisoli, M. Month, A. van Steenbergen, IEEE Trans. Nucl. Sci. NS-18, No. 3, 1009, 1971.
7. E.D. Courant, R.W. Chasman, A. van Steenbergen, IEEE Trans. Nucl. Sci. NS-18, No. 3, 707, 1971.
8. "Beam Ejection", Section 7 of Ref. 1, L. Blumberg, R. Chasman, M. Month, A. van Steenbergen.
9. M. Month, R. Chasman, G. Parzen, IEEE Trans. Nucl. Sci. NS-18, No. 3, 966, 1971.
10. M. Month, G. Parzen, Particle Accelerators, 2, 227, 1971.