A SUPERCONDUCTING SYNCHROTRON DESIGN STUDY AT THE RUTHERFORD LABORATORY

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Summary

Design features of a superconducting synchrotron to replace Nimrod are outlined. Constraints imposed by existing accelerator buildings and plant determine many of the parameters. The separated-function doublet lattice has 20 focusing periods, with 4 long straight sections created by omitting bending magnets from the appropriate periods.

Introduction

A design study is in progress for a 22 GeV/c, 6.068 Tesla, superconducting synchrotron, (the 'SCS'), to replace Nimrod. The machine would use the existing accelerator building, experimental area, main power supply, and linac injector, but a 400 MeV fast-cycling booster synchrotron would be interposed between the linac and main ring. The proposed layout is shown in Fig. 2.

In this paper we list the machine parameters, and comment briefly on some features of the design [1].

Objectives

The study was initiated with the object of highlighting significant problems in superconducting synchrotron design, defining realistic parameters in good time, and guiding the experimental magnet development programme accordingly. Replacement of the existing machine, in the same building, is only one of several possible applications of pulsed superconducting magnets, but has the peculiar advantage of being the cheapest.

The earliest date by which the practicality of such a project might be established could well be 1975, in which case it would be about 1980 before a machine could be contemplated. There is a considerable body of opinion to predict that much interesting physics will remain to be explored at 22 GeV/c in the 1980's.

In the longer term, the SCS could become the booster for a much larger ring, a role for which the constant-gradient Nimrod is unsuitable.

A further incentive is that a superconducting synchrotron of this energy would provide an ideal pilot project for very large machines in the 1000 GeV range, allowing constructional and operational techniques to be optimized in a reasonably economic framework.

Apart from the constraints of existing buildings and plant, a number of firm design criteria were adopted at the outset of this study: they include a mean flux of more than 2×10^{12} protons per second, and an effective duty cycle in excess of 20%. Exploitation would be based on two ejected beams, going to Experimental Areas 1 and 3 of the present site.

Machine Parameters

Peak Momentum	22 GeV/c
Peak Bending Field	6.068 T
Circumference ($2\pi R_m$)	175m
Bending Radius (ρ)	12.095m
Circumference Ratio (R_m/ρ)	2.30
Injection Momentum (KE=400 MeV)	0.9543 GeV/c
Transition Momentum (γ_{tr} = 4.08)	3.71 GeV/c
Peak Quad. Gradient	g_F = 53.8 T/m
	g_D = 55.6 T/m

Lattice Data

No. of Focusing Periods	20
No. of Superperiods	4
No. of Quadrupoles	40
No. of Bending Magnets	80

Superperiod Structure	'ABCDA'
'A' Period	$O_4 \boxed{BBBB}\ O_4 \boxed{FBD}$
'B' Period	$O_1 \boxed{BBB}\ O_2 \boxed{FBD}$
'C' Period	LS $\boxed{FBD}$
'D' Period	$\boxed{B}\ O_3 \boxed{BBBFBD}$

(Boxes denote suggested cryostat arrangement. Each cryostat end subtracts 0.15m from free straight section lengths quoted below).

Length of Period	8.75m
Length of Long Straight, LS	6.05m
Medium Straight O_1	1.845m (IK_2; Fast EK)
Medium Straight O_2	1.175m (Ej. Septum 1)
Medium Straight O_3	1.8m (Inj. Kicker 1)
Medium Straight O_4	0.99m (Correction)
Eff. Length of Bender, B	0.95m
Eff. Length of Quad. F or D	0.5m

Beam Dynamics

Sagitta in Bending Unit 9.33mm

Normal Tuning: $Q_H = 4.80$; $\mu_H = 86.4°$
$Q_V = 4.85$; $\mu_V = 87.3°$

Maximum Betatron Functions: $(\beta_H)_{max}$ = 14.0m
$(\beta_V)_{max}$ = 13.6m

Max. Synch. Function $\alpha_p = \Delta x/(\Delta p/p)$ = 4.76m
(at beginning of 'ABCDA')

Min. Synch. Function $\alpha_p = \Delta x/(\Delta p/p)$ = -0.36m
(at end of period 'B')

Beam Emittance at Injection	ε_H	= 64mm x mrad
	ε_V	= 115mm x mrad
Momentum Spread:	$(\Delta p/p)_{inj}$	$= 3 \times 10^{-3}$
	$(\Delta p/p)_{tr}$	$= 5.3 \times 10^{-3}$
	$(\Delta p/p)_{ej}$	$= 0.93 \times 10^{-3}$

Machine Cycle & Flux

Cycle Time	6.75 s
Injection Platform	0.75 s
Field Rise (=Fall) time	2.0 s
Flat Top Time	2.0 s
Flux per Pulse	1.5×10^{13} protons
Average Flux	2.2×10^{13} protons/s
Eff. Duty Cycle (75% effic.)	22.2%

RF System

RF Frequency Range	7.32 MHz - 10.26 MHz
Harmonic Number	6
No. of Ferrite-Tuned RF Cavities	2 (in same LS)
Length of RF cavity	2.0m
Peak RF Volts (at γ_{tr})	54.6 kV
Av. Beam Power ($\beta \rightarrow 1$)	29.2 kW

Injection System (2 Turn Injection)

Booster Bunches/SCS Pulse		12
Vertical Inflector:	Septum	2 mm
	Field	3.09 kG
	Angle of Bend	17°

Vertical Fast Kickers: Filling Time 50 ns :-
Upstream, IK1 (in 0_3 of Period D):-
First bunch: (70cm x 224.6G)+(35cm x 219.2G)→7.36mrad
Second bunch: 70 cm x 224.6G → 4.94 mrad
Downstream, IK_2 (in 0_1 of Period B):-
First bunch: off
Second bunch: 35cm x 187.3G → 2.06 mrad

Ejection System

Resonant Q_H		4.66 (or 5.0)
Resonant Growth		10mm per 3 turns (or 1 turn)
Ejection Septa:		
S_1, in 0_2 of Period B:		1mm ; 0.8m x 0.27T
S_2 (in LS)	:	4mm ; 1.0m x 0.44T
S_3 (in LS)	:	7.5mm ; 0.7m x 0.84T
S_4 (in LS)	:	16mm ; 3.5m x 1.76T
Ejection Efficiency	:	90 - 95%

Max. Aperture Radius Data

H-plane (±mm):	Inj.	Trans'n
Betatron Ampl.	29.6	14.8
Synch. Ampl.	14.3	25.2
98% C.O. Deviation	14.6	14.5
Injection Errors	2.2	1.1
Ejection Allowance	3.4	3.4
Vac. Ch. + Cryostat	10.0	10.0
Less, C.O. Correction	- 9.1	- 9.1
∴ Inner Coil Radius(mm)	65.0	(59.9)

In bending units, the smaller β takes care of the ±4.65mm sagitta.

V-Plane at Injection (±mm)

Max. Betatron Ampl.	39.5
98% C.O. Deviation	9.4
Injection Errors	2.2
Vac. Ch. + Cryostat	10.0
Less, C.O. Correction	- 2.9
∴ Inner Coil Radius (mm)	(57.2)

As a result of this kind of arithmetic, we have taken an inner coil radius of 65 mm for the stored energy calculations.

Stored Energy

Benders	46.6 MJ
Quads.	3.2 MJ
Total	49.8 MJ

Booster Data

Max. Kinetic Energy		400 MeV
Inj. Kinetic Energy		15 MeV
(Transition Kin. En.)		(680 MeV)
Circumference		43.75m
SCS/Booster Circumf.		4
Bending Radius		3.361m
Cycling Rate		20 Hz
C.F. Lattice		FODo
No. of Periods		8
Magnet Lengths, F, D	:	1.32m
St.Section Lengths O, o	:	1.5m, 1.33m
Betatron Tunes, Q_H, Q_V	:	1.81, 1.77
Mag. Profile Params. F,D	:	$1.0m^{-1}$, $1.3m^{-1}$
Aperture (H x V)	:	17.0 cm x 8.89 cm
RF Frequency Range		1.21 - 4.89 MHz
RF Harmonic No.		1
Bucket Phase Space		0.1 eV.sec.
Beam Intensity		1.5×10^{12}ppp
Ej. Kicker Rise Time		127 ns

SCS Magnet Geometry

The need to minimise wasted space in the limited circumference has proved to be a vital design factor, and many features of the magnet geometry [2], sketched in Fig. 1, stem from this requirement. For example: a 'warm bore' is assumed, so as to dispense with special insulating sections: as far as possible, we envisage groups of magnets installed in a single cryostat in order to minimise the space taken up by cryostat ends. The coil ends are bent upwards so as to equate effective magnetic length with conductor length, leading to an outer cryostat radius of about 22 cm.

The laminated iron shield is located well outside the conductor, to avoid the non-scaling and non-linear effects of saturation, while protecting the aperture from external magnetic influences. The ejected beams are kicked outside the cryostat, but have to penetrate the iron through special channels.

From the outset, a circular aperture was chosen for constructional simplicity, ease of restraining the magnetic forces, and because there is likely to be no saving in stored energy by going to an elliptic aperture of the same major diameter. Similarly, the bending magnet boundaries are assumed to be rectangular: the relatively large sagitta then limits the unit length to about 0.95m.

The Lattice: Correction

The above magnet schematics lead to a maximum circumference of about 175m in the Nimrod building. Within this length, 4 long straights have to be accommodated, one for injection, one for RF, and 2 for ejection. Since special straight section insertions waste space, we have been led to choose a separated-function doublet lattice, where the 6m long straights are created simply by omitting benders from the longer inter-quadrupole regions of the appropriate periods. The fourfold superperiodicity, combined with aperture considerations, determines the choice N=20, $Q \approx 4.75$.

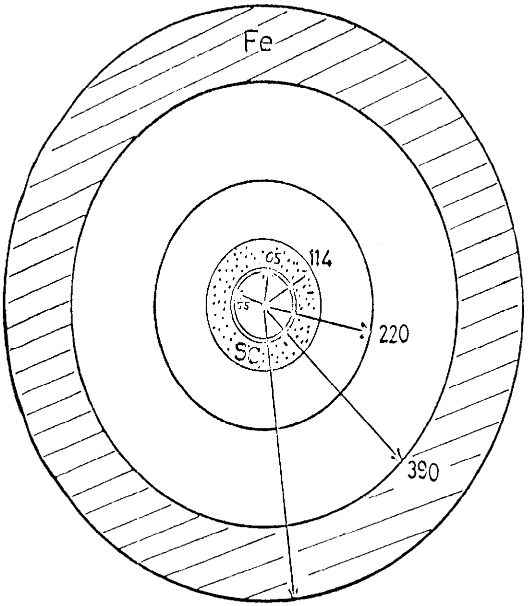

Fig. 1 - Schematic Magnet Geometry. Dimensions in mm.

Location of medium straights is determined by the demands of injection, ejection, and correction elements: all available spaces are used to accommodate such elements, as well as beam sensors, vacuum ports etc. As far as possible, it will be essential to incorporate correction windings and Q-shift windings in the main lattice magnets, but the detailed arrangement has yet to be resolved. Particularly in view of its possible importance as a pilot project, we have devoted considerable effort to the diagnostics, correction, and control aspects of the SCS. In computing closed orbit deviations, we have assumed field and misalignment errors comparable with those experienced with conventional magnets: correction is achieved by beam measurement in (at least) 20 sensors, followed by movement of the 40 quadrupole elements. Several computing techniques have been examined, with the result that a straightforward matrix inversion method is favoured.

Flux and Duty Cycle

The design criteria of 2×10^{12} protons/sec average flux and 20% effective duty cycle, combine to determine the flux per pulse (1.5×10^{13}) and the machine cycle (6.75s, 2s FT) within narrow limits.

RF and Injection

A further consequence of the limited circumference is that practical restrictions on injection kicker rise times severely limit the choice of RF. Thus, taking 50 ns rise time, the harmonic number cannot be greater than 6. Comparing the booster flux (1.5×10^{12}) with the required SCS flux (1.5×10^{13}), it is evident that 2-turn injection is required. Since the superconducting magnet aperture is circular, vertical injection of 2 booster bunches into each SCS bucket is an obvious choice. Two fast vertical kickers, one on either side of the inflector and spaced a betatron phase distance π apart, are then necessary.

The booster energy (400 MeV), and repetition rate (20 Hz) arise from the usual kind of compromise to be made between booster complexity and cost, and savings in main-ring aperture. At its present performance, the 15 MeV linac does not match the booster acceptance: a factor 1.5 increase in linac brightness is required; alternatively, we could accelerate negative ions in the linac and strip them in the booster to achieve the required flux.

An achromatic transfer system between the booster and the main ring has been specified in detail with accurate matching in all three phase planes. Synchronization between the two machines involves steering outside R_0 in the booster to provide phase slip between the RF buckets in the two machines.

Due to the relatively high flux in the small SCS circumference, the effects of longitudinal and transverse space charge forces are particularly severe at injection and at transition ($\gamma_{tr}=4.08$). A large part of our detailed design studies has been concerned with predicting and minimising these effects. In particular passage through transition demands a fast asymmetric Q-jump, about 4.9 to 4.6 in 0.4ns, and the maximum RF voltage required is approximately doubled, to 54.6kV. This voltage is provided by two 2.0m ferrite-tuned cavities in the same long straight: a drift-tube system cannot be contemplated due to its space requirement.

Ejection; Aperture

So far, ejection via the third integral ($Q_H=4\frac{2}{3}$) resonance has been studied, and is the primary factor determining the 6.05m long straight sections.

The $Q_H=5$ integral resonance is currently under investigation, and may have the advantage in efficiency and in the reduced number of elements required. The septum arrangement is the same in either case. In the SCS doublet lattice, ultra-fine electrostatic septa do not seem advantageous.

The effects of the large fringe-fields between the cryostat and the iron shield have not yet been assessed. It is worth remarking that iron close to the conductor would make ejection extremely difficult, in that a greater kick would be required to clear the magnet structure.

An aperture allowance of 3.4mm has been included for ejection, and may make the difference between 90% and 95% efficiency: detailed calculations are still in progress. In practice, it may prove worth while to tailor the magnet apertures through each superperiod, in order to reduce the stored energy. However, the total stored energy is less than 50MJ, within the capabilities of the Nimrod power supply, and we have taken the attitude that lack of standardization could be more costly than the extra power involved.

Costing

A preliminary costing of non-superconducting features of the project has been carried out, giving a figure in the region of £M4.5. Taking a rough estimate of about £M3.0 for the magnet system and refrigeration, the total SCS cost would be in the region of £M7.5. It should be emphasised that this is a very preliminary assessment, and may change significantly as detailed design proceeds.

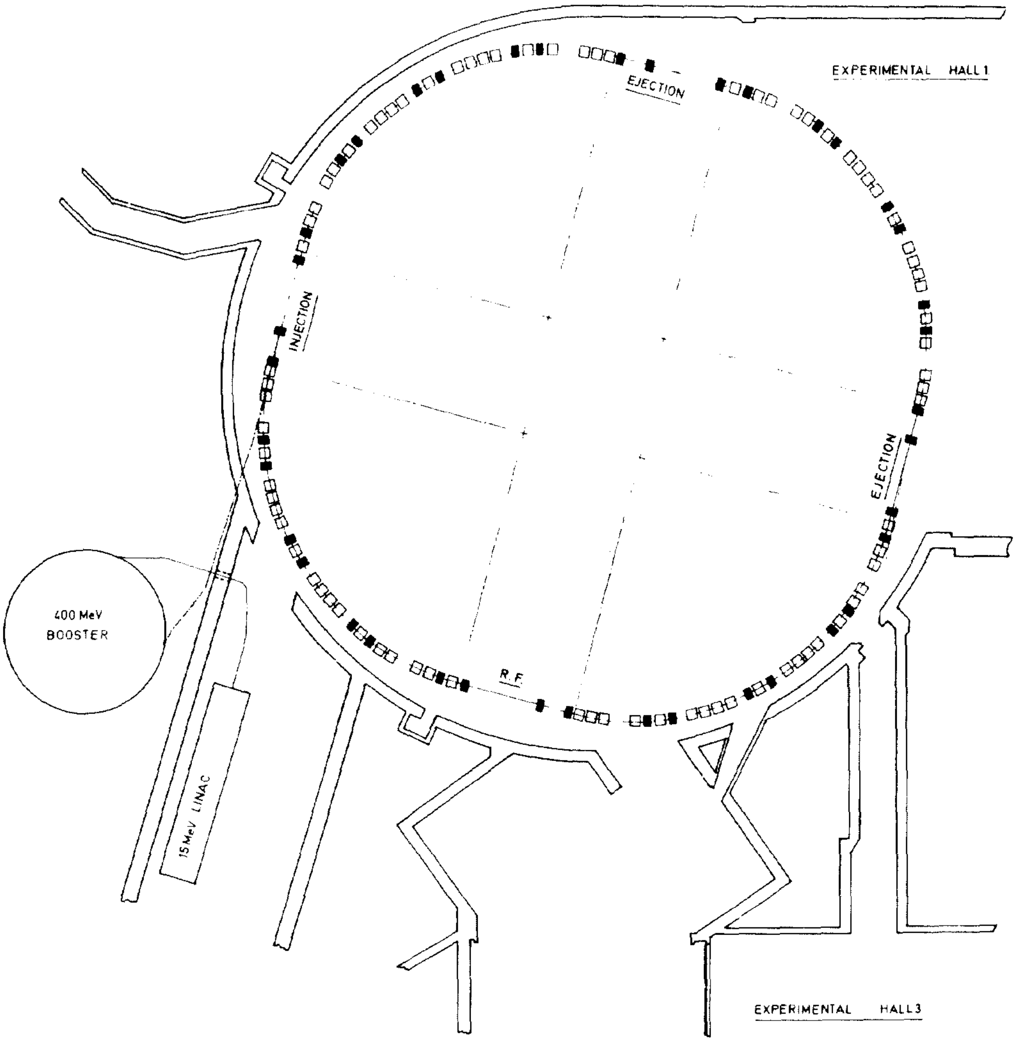

Fig. 2 - Layout of SCS and Booster in Nimrod Complex.

References

1. Various aspects of the machine design are detailed in a series of RHEL reports, SCS/MACHINE/1-33 by the authors of this paper.

2. Our ideas on magnet geometry are based principally on: 'Equations and Formulae for the Magnets with Air-cored Windings of Saddle Coil Type; RHEL/R203; J H Coupland (1970).