CONFIGURATION OF THE DIPOLE MAGNET POWER SUPPLIES FOR THE DIAMOND BOOSTER SYNCHROTRON

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Abstract

The synchrotron source, DIAMOND, requires a 3 GeV fast cycling booster synchrotron to inject beam into the main storage ring. A repetition rate of between 3 and 5 Hz is required for continuous filling, together with the need for discontinuous operation for 'top-up' injection. The paper presents the outline parameters for the booster dipole magnets and give details of the required power supply ratings. The suitability of present-day switch-mode circuit designs is examined; this assessment includes the results of a survey of the ratings of commercially available power switching solid-state devices. The proposed solution for the DIAMOND Booster magnets is presented, with details of how the power converter design influences the dipole coil configuration.

1 INTRODUCTION

The technical design for the new 3 GeV synchrotron radiation source DIAMOND has been developing for over a decade, culminating in the recent production of a full design report by the accelerator design team at the Daresbury Laboratory [1]. The large storage ring will be injected from a full energy (3 GeV) Booster Synchrotron. It is currently envisaged that the Booster will be capable of operating in a 'injection top-up' mode and this points to the choice of an 'switch mode' power supply solution, which will provide the required flexibility, together with other operational advantages. In previous proposals [2], two options for powering the Diamond Booster dipole circuit were considered: the traditional 'White Circuit' and a 'direct connection' option. Prompted by the successful introduction of a switch mode system at the Swiss Light Source [3], [4] and the further development of power semiconductors, the use of a switch-mode circuit with electrolytic capacitor energy storage system is now strongly favoured for the DIAMOND Booster dipole supply. The feasibility of this approach is dependant on a detailed assessment of the circuit requirements and the switch-mode system's capabilities.

2 THE BOOSTER DIPOLES

The booster design will be a 22 cell missing magnet lattice, containing 36 dipoles. The magnet and basic excitation parameters are shown in Table 1; these assume a biased sinewave field profile from injection to peak field, a configuration imposed by conventional circuits and available from a switch-mode system. The Table does not indicate the number of turns in the dipoles, as this parameter will be determined by the power supply design.

Table 1: Major Booster Dipole Parameters

Injection Energy	100 MeV
Extraction Energy	3 GeV
Number of dipoles	36
Magnetic length	2.17 m
Dipole field at 3GeV	0.8 T
Total good field aperture (h x v)	35 mm x 23 mm
Total gap	31 mm
Total Amp-turns at 3 GeV	20,330 At
RMS current density in coil	4 A/mm^2
Total conductor cross section	3122 mm^2
Total resistive loss-all dipoles	188 kW
Total stored energy at 3 GeV	73.3 kJ
Dipole configuration	'H' magnet, parallel ends

3 THE POWER SUPPLY DESIGN

3.1 Circuit Impedance and Excitation Levels

As indicated above, the magnet current and voltage levels must be adjusted to comply with the operational demands of the power supply. If a switch-mode system is to be used, the choice of the number of turns on the coil will be determined by the technical constraints of such a circuit. As an illustration, the power supply parameters for the complete dipole circuit are presented in Table 2 for possible alternative numbers of turns per magnet.

Table 2: Dipole power supply parameters for alternative number of turns per magnet

Number of turns/dipole	16	20	
Peak current	1271	1016	A
RMS current	778	622	A
Inductance (all dipoles)	0.091	0.142	H
Peak reactive voltage	1.81	2.26	kV
Peak V.A (peak I x peak V)	2.3	2.3	MVA

3.2 Benefits and Viability of the Switch-Mode Circuit

The traditional circuit used to power a fast-cycling synchrotron was known as the 'White Circuit'; this used an inductive/capacitative resonant circuit as the energy storage medium. Synchrotron projects using the White Circuit to power the booster include BESSY II, Berlin, DESY II, Hamburg, and ESRF, Grenoble.

An assessment of a switched-mode system, compared to the White Circuit, is given below:

- the switched circuit does not need a costly energy storage choke which increases circuit losses;
- the switch-mode circuit has, within the limits of rated current and voltage, flexibility of output waveform;
- after switch on, the switched system requires less than one second to stabilise;
- the technology of the switched systems is not yet fully established;
- the current and voltage levels possible in switched circuits are restricted by component ratings.

Switch mode circuits depend on the operation of high power solid state devices (Insulated Gate Bi-polar Transistors - IGBTs) which can switch current carry circuits at frequencies of many kHz. Such devices have recently become available and have now been utilised in the supply circuits of the Swiss (SLS) and Canadian (CLS) light sources. Table 3 shows the major electrical parameters for the booster dipole magnets in both these facilities. The figures for the Canadian Light Source relate to one quarter of the complete circuit, for the dipole chain is separated into four separate segments, each with its own power source. The requirements of the DIAMOND booster power converter with 16 turns per magnet are presented for comparison.

Table 3: Major electrical parameters of the bending magnets of recent booster synchrotrons

Facility	SLS	CLS	Diamond	
Number of circuits	1	4	1	
Inductance/circuit	80	72	91	mH
Max stored energy	36.1	42.1	73.5	kJ
Frequency	3	1	5	Hz
Max current	950	1082	1271	A
Max voltage	1,000	200	1,810	V

In can be seen from Table 3 that if a switch-mode system is to be used at 5 Hz in the DIAMOND Booster, it will need to operate at a significantly higher voltage compared to other contemporary facilities. The configuration and operation of the switch-mode system, together with the ratings of commercial power semi-conductor devices and other components, were therefore studied.

3.3 The Switched-Mode Circuit

A circuit diagram showing the basic switched mode module is given in Figure 1. A power supply may consist of several of these modules arranged with outputs connected in series or in parallel to obtain a range of output voltages and currents.

Depending upon the conducting state of the two IGBTs, (Q1 and Q2), the magnet load is either connected directly across the energy storage capacitors, connected in reverse across the energy storage capacitors, or is in freewheel mode. At any one time, the maximum voltage seen across an IGBT is the voltage across the capacitor. Hence, the maximum voltage across any one IGBT will be slightly greater than the peak voltage in the output. However, to minimise switching losses, current practice is to ensure that the operating currents and voltages are considerably lower than the IGBT ratings.

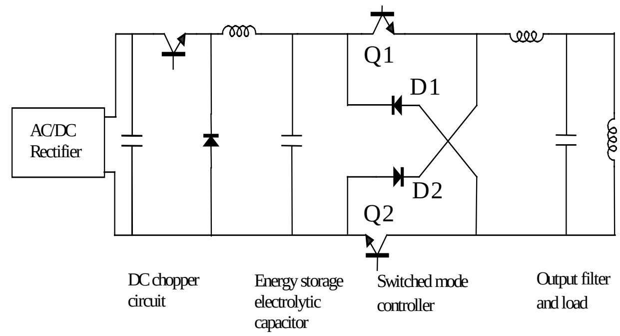

Figure 1: Basic arrangement of switched mode converter.

During normal operation of the circuit of Fig. 1, the voltage on the main energy storage capacitor does not reverse; furthermore, with the correct choice of component values, the voltage variation across this capacitor can be kept to a fraction of the total maximum circuit voltage. Hence, the use of a large bank of electrolytic units is technically feasible and commercially beneficial.

3.4 IGBT and capacitor ratings

One concern over the suitability of a switched mode solution is in regard to the voltage and current rating of the individual IGBTs and a study of commercially available devices was carried out. IGBTs produced by a number of manufacturers were included in the study. Typical data for maximum current and voltage rating are shown in Table 4.

Table 4: Achievable IGBT rating performance

Model	Forward Voltage	Direct current (at 25ºC)	Repetitive peak current
New device	6500 V	650 A	800 A
FZ1200R33	3300 V	2000 A	2400 A
FZ1500R25	2500 V	2600 A	3000 A

These ratings are plotted in Figure 2, which shows device peak voltage as a function of peak current; the Figure also shows the variation in peak current and voltage required for the DIAMOND Booster dipoles as the number of turns per magnet is varied.

The other significant issue is the voltage rating of the main electrolytic storage capacitor, a further critical parameter which will determine the maximum ratings available from a single power module. The capacitors used in the SLS and CLS circuits had maximum ratings of 500V. This is well below the maximum available IGBT voltage ratings shown in Table 4 and is low compared to the required DIAMOND Booster dipole ratings.

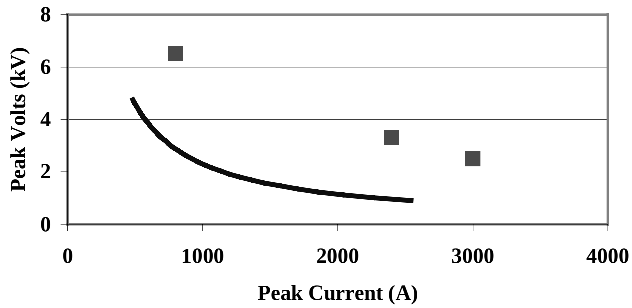

Figure 2: Variation in peak voltage and current for three commercial IGBTs (points); the continuous curve is the variation in peak current and voltage in the DIAMOND Booster dipole circuit as the number of turns is varied.

3.5 The Switch Mode Circuit for DIAMOND Booster

The data presented in Table 4 and Figure 2 indicate that solid state switches, which meet the requirements for a switch-mode circuit for the DIAMOND Booster dipole supply, are commercially available. However, the electrolytic capacitors used in other sources have an inadequate voltage rating. Discussions with commercial suppliers indicate that a variety of solutions to this problem are available:

i) the use of higher voltage electrolytic units, which are becoming commercially available as capacitor technology develops;

ii) the series connection of existing 500V capacitor units to increase the overall voltage rating of the bank;

iii) the combination of a number of individual supply modules into a single system, with current and voltage sharing networks to ensure satisfactory operation;

iv) the separation of the dipole magnets into four separate circuits which are independently powered (as employed at the CLS);

v) the division of the coils on each dipole magnet into four sub-units, with four separate power circuits, each including coils from every dipole.

The first three options involve significant development work, with consequential uncertainty and cost increase. The fourth option calls for very precise amplitude and phase control between the four circuits, which could be a source of operational unreliability. Hence, the final option, as described below, is now regarded as the favoured solution.

The proposed dipole power supply circuit is shown in Fig 3. Each dipole has four separate coil ‘bobbins’, which are mounted symmetrically above and below the gap. These are galvanically isolated from each other but, as they are mounted on the same yoke, their Ampere-turns add to produce the total excitation. The voltage across each bobbin is one quarter of the total magnet voltage. The bobbins are connected in series , with full transposition across the 36 dipoles. Each of the four circuits is then powered from a separate power converter, giving the power ratings shown in Table 5; the voltage is now reduced to a level consistent with present state-of-the-art technology. The total excitation current on each dipole is the sum of the currents generated by each power converter, so small imbalances between the circuits will not lead to discrepancies between the field in the dipole magnets.

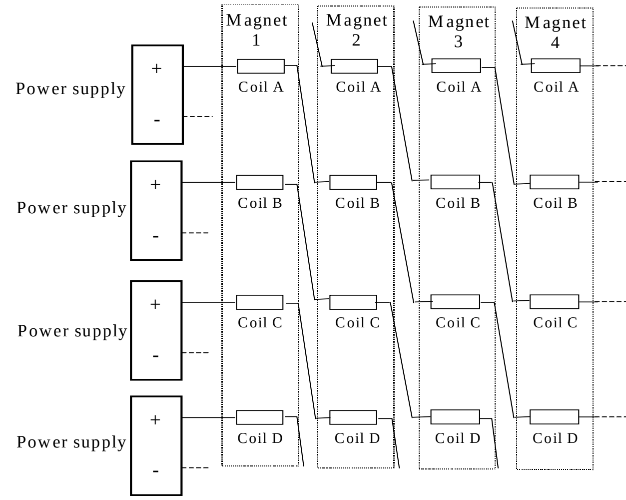

Figure 3: Proposed connection of four separate power converters to dipole coils divided each into four separate bobbins (described as Coils A, B, C and D).

Table 5: Parameters for the four dipole power converters when connected as per Figure 3.

Number of turns per dipole	16
Number of separate power circuits	4
Peak current per circuit	1271 A
Peak voltage per circuit	450 V

4 CONCLUSION

It is proposed to use a switch mode power supply system to excite the DIAMOND Booster dipoles at a repetition rate of 5 Hz. Existing switch mode circuit technology can be used, with little or no new development required, providing the dipole magnets are constructed with four separate coil bobbins which are then connected to four separate power converters with full circuit transposition.

5 REFERENCES

[1] DIAMOND Design Report, (Green Book), Daresbury Laboratory, 2002.

[2] Marks,N, Poole,D.E, “The Choice of Power Converter Systems for a 3 GeV Booster Synchrotron”, EPAC 1996.

[3] W.Joho et al, "The SLS Booster Synchrotron", Proc. 6th EPAC, Stockholm, June 1998.

[4] Irminger,G, Horvat,M, Jenni,F, Boksberger,H.U, “A 3 Hz, 1MW peak Bending Magnet Power Supply for the Swiss Light Source (SLS)”, Paul Scherrer Institut, November 1998.