A FULL-ENERGY BOOSTER FOR DIAMOND

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Abstract

A compact, rapid cycling 3GeV booster synchrotron has been designed for the proposed UK national 3rd generation light source DIAMOND. A FODO lattice with 24 bending magnets has been selected, offering low circumference and a high degree of flexibility in terms of lattice functions and working point. The large number of bending magnets provides a low beam emittance, appropriate to injection into the storage ring, and furthermore reduces the maximum required field of the cycled dipole bending magnets. The beam properties of the chosen solution allow RF power to be supplied using only two cavities, and relatively long free straights are available to accommodate the large septum demanded by 3GeV beam extraction. Alternative "missing dipole" schemes to provide space for extraction have also been assessed; these do not provide a superior or more economical solution and lack the operating flexibility of the preferred design.

1 INTRODUCTION

The proposed new UK national synchrotron light source, DIAMOND [1], includes the provision of a rapid cycling, full energy booster synchrotron. It is intended that the booster will cycle at up to 10Hz with a beam current of up to 20mA, providing around 5mA per cycle in the storage ring. Options for the booster lattice design, and the resulting beam properties, as well as a full energy extraction scheme, have been modelled and a 24 dipole FODO lattice selected.

2 THE LATTICE DESIGN

Constraints on beam properties within the booster ring are fairly relaxed; clearly, excessive beam sizes are undesirable due to the resulting increased magnet apertures and beam stay clear requirements. The storage ring injection scheme however places severe conditions on the extracted booster beam. On the other hand, properties within the booster lattice (such as dispersion or chromaticity) are not in general of high importance, since the booster is not itself a light source.

A highly compact booster, with a circumference small enough to fit inside the storage ring, can be provided by a FODO-based lattice design. Options with specific optical functions, such as achromat cells, are not required. The electron beam extraction energy of 3GeV is challenging for any compact booster, particularly at a cycling frequency of 10Hz. Magnet design considerations [2] lead to an upper limit on bending dipole field of around 1.2T; at the same time, injection energy is determined by available output of pre-injector schemes, and at injection energy (presently 50MeV) magnet strengths should not be so low that remanence and external fields become non-negligible. Initial studies of storage ring injection schemes [3] have suggested that the extracted emittance should be reasonably low, preferably well below 150nm.rad. Both of these requirements imply that the number of bending dipoles should be at least 20 with dipole fields in the region 1.1-1.2T. A suitable solution which does not impose unreasonable demands on magnet and power supply [4] design can be obtained for a compact double-FODO lattice with 12 repeating supercells, each containing 2 dipole magnets. The high extraction energy and the relatively high repetition rate lead to a required minimum of around 50-60m of dipole magnetic length.

For low emittance, a phase advance of around 1/4 betatron wavelengths per FODO unit will be optimal. This requires only moderate quadrupole field strengths, and is comfortably achieved by the allocation of one quadrupole magnet of each type (F/D) per dipole. Such a design has relatively low natural chromaticity which can be corrected with low integrated sextupole strength, and therefore sextupole magnets have been restricted to only half of the inter-dipole straights. This means that alternate straights provide an increased free space for injection into the booster, extraction, and provision of RF power; in particular, the proposed extraction scheme (see below) requires at least two closely spaced long straights of around 1.8m length.

A lattice supercell which satisfies the above conditions has been designed and modelled, and optimal component sizes deduced. The layout is shown in Figure 1 (all lengths in m). A suitable working point with a phase advance of around $\pi/2$ per FODO (for low beam emittance) has been chosen, avoiding resonance lines. The resultant calculated lattice functions are shown in figure 2.

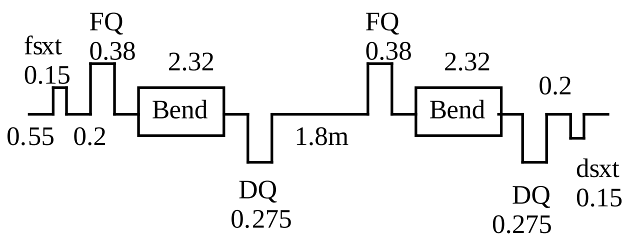

Figure 1: The Booster Lattice Supercell (lengths in m). The straight sections on each side of the bending magnets are of length 0.25m.

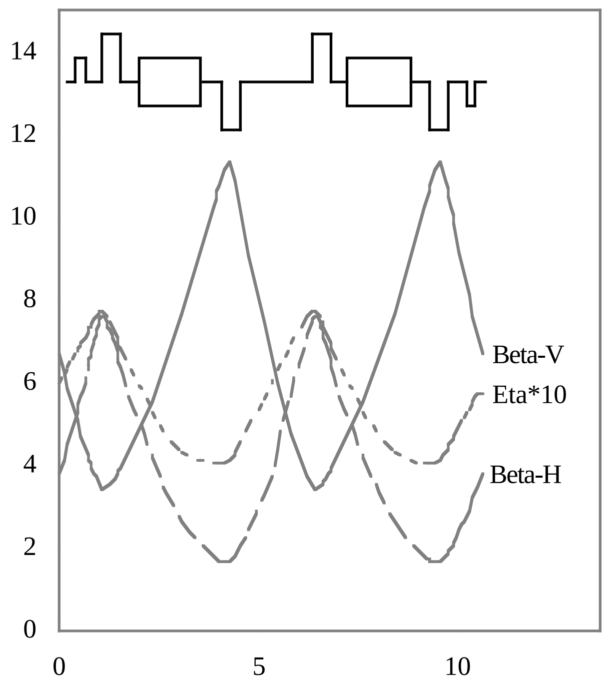

Figure 2: Horizontal and vertical β-functions and dispersion η (×10) plotted through the lattice (all in m)

The machine parameters for the chosen operating point are given in Table 1. Higher tune values reduce beam emittance only negligibly; lower values do however lead to a significant degradation without any major benefit in terms of quadrupole design. The design of the RF power system is reported separately [5]. The present lattice also offers a relatively low momentum compaction factor, leading to a requirement for only 2 RF cavities which can be accommodated in 2 of the long straights.

Table 1: Machine Parameters

No. of supercells (each 2 dipoles)	12
Supercell length	10.55m
Machine circumference	126.6m
Extraction energy	3.0GeV
Injection energy	50MeV
Harmonic number	211
RF Frequency	499.65MHz
Dipole bending radius	8.862m
Length of long straights	1.80m
Tunes (Radial, Vertical)	6.37, 3.38
Natural Chromaticities (R, V)	-6.43, -5.47
Momentum Compaction Factor	0.02455

The properties of the present lattice have been modelled to derive the beam characteristics (such as energy loss per turn, damping times, energy spread and emittance) at energies from injection (50MeV) up to full energy (3GeV). These quantities are given, together with the corresponding fields for all magnet families, at injection and at full energy, in Table 2 below. It should be noted that, until short damping times are attained at around 1.5GeV, the beam emittance is dominated by the adiabatically damped residual injection emittance.

Table 2: Energy dependent parameters at injection (50MeV) and full energy (3GeV)

	50MeV	3GeV
Dipole Field (T)	0.019	1.13
FQUD Gradient (T/m)	0.248	14.89
DQUD Gradient (T/m)	0.246	14.75
FSXT field (T/m^2)	2.60	155.9
DSXT field (T/m^2)	-3.20	-191.77
Energy loss / turn (keV)	6.24×10^{-5}	808.5
Radial damping time (s)	673	3.12×10^{-3}
Vertical damping time (s)	677	3.13×10^{-3}
Longitudinal damping time (s)	339	1.57×10^{-3}
σ_E/E_0	1.44×10^{-5}	8.64×10^{-4}
Radial emittance (nm.rad)	0.033	117.9

A number of alternative layouts and lattice types have been studied. An extremely compact synchrotron could be achieved by essentially eliminating all free space in the ring other than 4 "missing dipole" cells to accommodate injection, extraction and RF cavities, although in this case extraction schemes are more demanding. The reduced symmetry does however lead to less regular lattice functions. Furthermore, it is difficult to achieve low emittances without increasing the number of dipole magnets. In order to achieve an emittance of 150nm.rad at 3GeV, such a design requires 36 dipole bending magnets (with a further 4 "missing dipole" cells) giving a circumference of 118m [6]. Not only is this little improvement on the circumference of the preferred lattice, but a far greater proportion of the ring is now filled by magnet elements leading to a less cost efficient solution.

3 APERTURE REQUIREMENTS

The design specifications of magnet elements and vacuum systems are critically dependent on the aperture required by the beam size and orbit position errors. The sensitivity of the lattice to closed orbit errors has been estimated for rms quadrupole position errors of 0.1mm and for fractional dipole field and roll angle errors of 5×10^{-4}. Beam size contribution from the effects of energy spread has also been calculated using the computed dispersion function (see figure 2) and the damped energy spread at 3GeV (see table 2). The same calculation has been made at 50MeV using the assumed energy spread of the injected beam (0.3%). The beamsize due to emittance has been determined as a function of energy from 50MeV up to 3GeV, taking account of both the adiabatically damped residual emittance of the injected beam and the equilibrium beam emittance arising from radiation excitation and damping. The ratio of required physical aperture compared to beam size (σ) increases with energy due to the more rapid redistribution of particles in the beam as synchrotron radiation increases; at 3GeV, an aperture in excess of 4σ is required to achieve 1s beam lifetime, while at 50MeV 1σ is adequate. Longer lifetimes are unnecessary in a 10Hz booster synchrotron. However, injection imposes a minimum 3σ aperture; the calculations show that this is a tighter constraint that 6σ at 3GeV. On-axis single-turn injection requiring no additional aperture allowance is feasible in such a large circumference ring. The beam stay clear allowance, based on 3σ at 50MeV and including closed orbit errors, is plotted in both planes in figure 3.

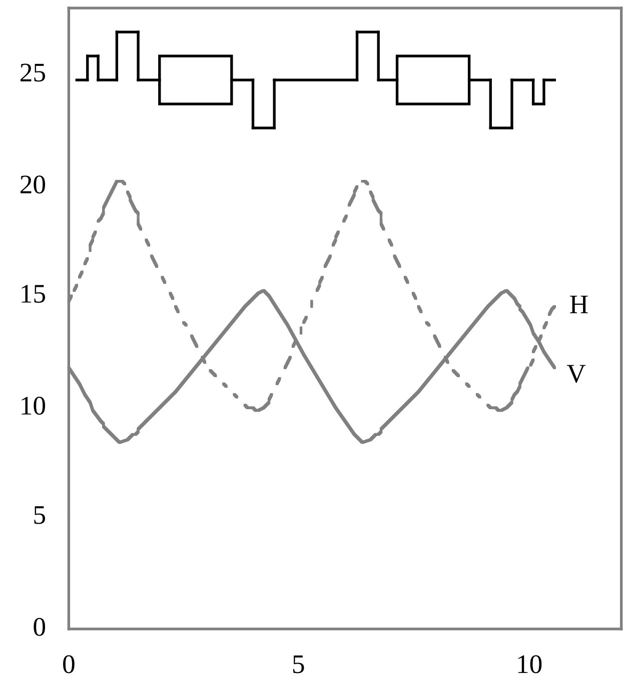

Figure 3: Horizontal (dashed line) and vertical (solid line) beam stay clear allowances (mm) as a function of distance through the booster lattice (m)

4 EXTRACTION

The extraction scheme developed for the booster has been chosen to exploit deflections in existing magnet elements where possible. A slow closed extraction bump is applied using bump elements B1, B2 and B3. In fact, all of these introduce beam kicks in the same (outward) direction; because of the large bump amplitude, the focussing power of the F-quadrupole at the peak of the bump (see Figure 4) is so great that B2 acts to moderate this, returning the bump trajectory more gradually to the unperturbed closed orbit. The first D-quadrupoles before and after the bump peak also help to generate the large displacement. At the moment of extraction, a fast extraction kicker KE deflects the beam into the pre-septum PS, which further deflects the beam to enter the main extraction septum MS. For the extraction path shown, the clearance through the main septum is 25mm from the undisturbed closed orbit, which is ample in the light of the calculated beam stay clear; the 0.5m long bump magnets apply kicks of up to 6.25mrad, the fast extraction kicker (0.7m) applies 1.4mrad, and the pre-septum (0.3m) 8.7mrad. All of these can be comfortably achieved for a 3GeV beam with component lengths which fit within the available free space.

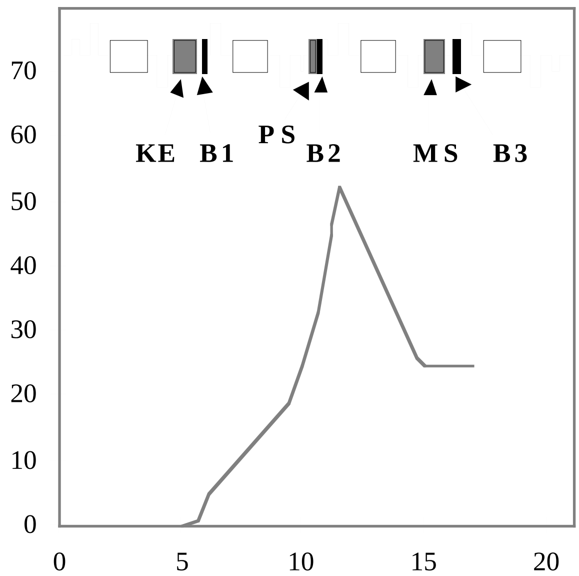

Figure 4: The booster extraction scheme: extracted beam path (mm from closed orbit) against distance through extraction region (m); see text for key to components

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