LOW ENERGY OPERATION OF THE DIAMOND LIGHT SOURCE

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Abstract

Within the last decade storage ring free-electron lasers (SRFELs) have reached UV output wavelengths and beyond: several facilities have achieved down to 250nm and quite recently below 200nm. The design of DIAMOND, the third-generation replacement for the existing SRS light source at Daresbury Laboratory, has been optimised at 3 GeV to provide high quality output for the scientific community, mainly from a range of insertion devices. In this paper we propose an additional DIAMOND regime at 1-1.5 GeV in an attempt also to include an SRFEL which would be of major benefit to users needing high quality, high brightness UV/VUV radiation. Such variable ring operating energy will have significant implications, not least in achieving acceptable beam lifetimes. In addition, enhanced beam coherent instabilities (notably microwave) at low energy will affect the single bunch length (peak current) and energy spread which will in turn limit the achievable FEL gain. All these factors will have to be assessed in the detailed design stages of DIAMOND.

1 DIAMOND LIGHT SOURCE

The recent successful demonstration of an SRFEL on the ELETTRA light source [1], together with earlier experience at LURE (Super-ACO) and elsewhere, has encouraged interest in the incorporation of such advanced facilities in all leading light sources.

The normal operating mode of DIAMOND at 3GeV is described in detail elsewhere [2]. No detailed FEL design has yet been undertaken or agreed, but it is likely to demand ring operation at much reduced energy. For the purposes of an initial feasibility study a comparison between 1.0 and 1.5 GeV has been assessed. At these energies the effects of Touschek scattering and intra-beam scattering (IBS) are significant in determining whether delivering peak currents in excess of ~10 A is possible with an acceptable lifetime. This paper gives only a first review of these issues but shows that operation even with the same low emittance optics as at 3 GeV is plausible for an FEL, given a few provisos; in fact an improved, dedicated optic would be selected for a funded project.

2 FEL OPERATING MODE

When operating in optimised FEL mode, the storage ring will be populated with bunches spaced apart in time by twice the round trip time in the FEL cavity, ensuring energy transfer occurs as frequently as possible; the cavity length is always chosen to be a sub-harmonic of the storage ring circumference, whilst satisfying other, practical constraints. The final circumference of the DIAMOND storage ring has not yet been fixed but may be finalised at 528 m (an increase on the present 489 m layout [2] to budget for additional elements), giving a harmonic number of 880 at 500 MHz RF frequency. With 8 equally spaced bunches this leads to a required cavity length of 33 m, which is reasonable (cf. the ELETTRA device which has a cavity length of 32.4 m [1]). Since a very small vertical emittance is not necessary for FEL operation, a conservative coupling value of 3% has been assumed for these calculations, which should both be readily achievable and provide a satisfactory Touschek lifetime; both greater coupling and larger emittance could be selected if necessary. The momentum acceptance will be the primary limit on the beam lifetime at low energies, via Touschek scattering and quantum lifetime; the 4% dynamic and physical acceptance limit specified for 3 GeV operation [2] has been assumed, the RF system being of course capable of supplying more than this at the lower beam energies.

3 BUNCH MODELLING

To provide peak currents of tens of Amperes, as will be needed for useful FEL gains, bunch currents of several milliamperes are required. At these currents the effects of bunch lengthening from potential well distortion (PWD) and from the microwave instability (MI) are large, but are beneficial in that they provide low enough number densities within the bunches to give an acceptable Touschek lifetime; however the issue is whether sufficient peak current can then be maintained, together with acceptable energy spread.

The ZAP code [3] was used to predict the effect on bunch parameters of PWD and MI (details are given in [4]); however, the implementation of Brück's approximation [5] for the Touschek lifetime which is used in ZAP is not valid in the strong-focusing regime characterised by most 3rd-generation light source lattices [6], and this includes the DIAMOND storage ring optics. This becomes even more true with bunches that have non-negligible vertical emittance; it is sobering to note that Brück's approximation can give a negative – i.e. non-physical – lifetime for particular sets of parameters. It is therefore necessary to use Piwinski's full three-dimensional relativistic formulation for the Touschek lifetime [7], and this has been implemented by the authors for the present calculation. ZAP is however still used to calculate the transverse emittance blow-up from IBS, using the Bjorken-Mtingwa formalism [8].

Quantum lifetime is given as

$$\tau_q = \frac{\tau_a}{2}\frac{e^{\xi}}{\xi}, \quad \xi \equiv \frac{a^2}{2\sigma_a^2},$$

where a, σ_a, τ_a are the acceptance, spread and damping time of the co-ordinate under consideration; this lifetime is a very strong function of the ratio a/σ_a, and for damping times between 1 and 100ms this ratio must be ~6 or greater to give lifetimes greater than a few hours. For an acceptance of 4% this sets an upper limit on the energy spread of around 0.67%; it is however likely that the FEL itself will set a limit on this parameter at a lower level.

4 LOW ENERGY LATTICE PROPERTIES

4.1 Single Particle Properties

The single-particle lattice properties of relevance for calculations here are given in Table 1. Optics properties are given in Table 2.

Table 1: Low Energy Operating Characteristics

	1.0 GeV	***1.5 GeV***
Mom^m Acceptance [%]	4.0	4.0
RF Voltage [MV]	0.436	0.738
Nat Bunch Length [mm]	1.49	2.11
Nat. Energy Spread	$3.2\ 10^{-4}$	$4.8\ 10^{-4}$
Nat. Emittance [nm-rad]	0.27	0.61
Assumed Coupling [%]	3	3
Trans. Damp. Time [ms]	264	78
Long. Damp. Time [ms]	131	39
Energy Loss/Turn [keV]	12.4	62.7

Table 2: General Storage Ring Characteristics

Circumference [m]	528
Betatron Tunes	28.9, 10.7
Average Betatron Functions [m]	8.46, 12.31
Momentum Compaction Factor	$1.6\ 10^{-4}$
Assumed Beam Pipe Radius [mm]	25
Assumed Broadband Impedance [Ω]	1.8

4.2 Bunch Current Variations

The effect of bunch current on the energy spread is shown in Figure 1. This shows that the maximum current that can be accumulated before the quantum lifetime significantly limits the beam lifetime is around 3-4 mA per bunch. The bunch lengthening – shown in Figure 2 – is significant even at these currents, so that the model used by ZAP may not be sufficient to correctly predict it. These results are based on an assumed ring broadband impedance of 1.8 Ω which is probably an over-estimate, and the real bunch lengthening and energy spread increase are likely to be much less than this, especially if the widely observed 'SPEAR scaling' applies [3]. The Touschek lifetime predicted from these parameters (Figure 3) - using the equilibrium emittance from IBS effects - is sufficiently long that even if the bunch length is appreciably shorter than predicted, operation at low energy should not be curtailed. The bunch lengthening effect would benefit from greater study and this will be undertaken during the planned DIAMOND Design Study, using both analytic and numerical approaches.

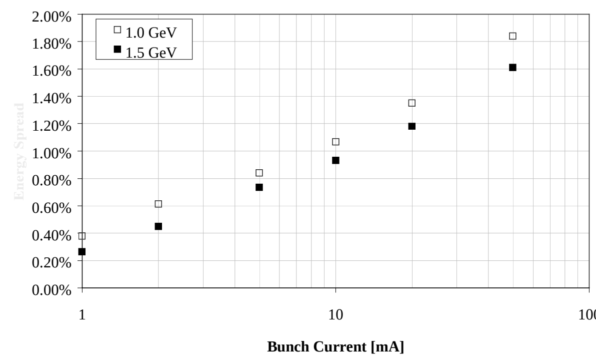

Figure 1: Variation of energy spread with bunch current, for 1.0 and 1.5 GeV operation.

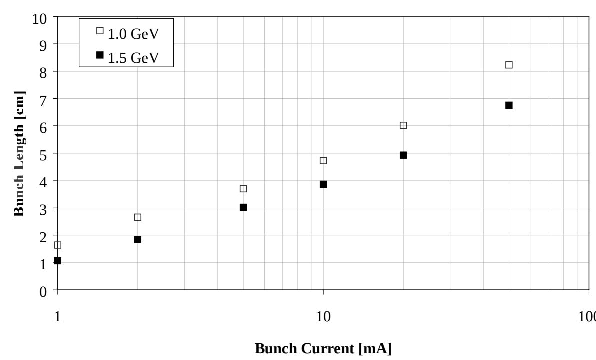

Figure 2: Variation of bunch length with bunch current, for 1.0 and 1.5 GeV operation, assuming PWD and MI effects are present.

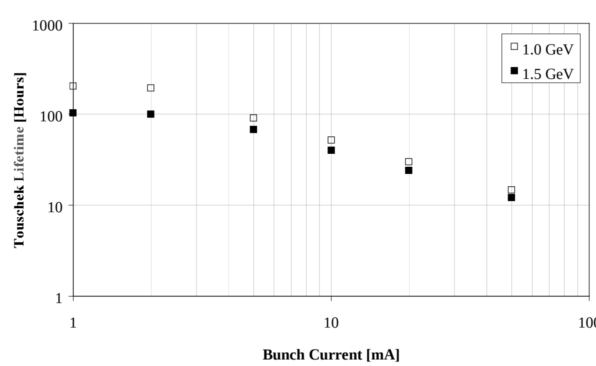

Figure 3: Variation of Touschek lifetime with bunch current, for 1.0 and 1.5 GeV operation. 3% coupling is assumed.

4.3 Predicted Peak Currents

Table 3 shows the peak currents which are predicted, given the bunch lengths modelled above. These show that even with a bunch current as low as 2mA to maintain the quantum lifetime, the peak currents are sufficiently high to allow for adequate gain per pass in an SRFEL, being about a factor 2 below the ELETTRA ones [1]. In practice peak currents several times higher would be targeted for a future experiment.

Table 3: Bunch density characteristics at 1.0 and 1.5 GeV. I_b is the bunch current.

I_b *[mA]*	N_b	I_{peak} *[A] (1.0 GeV)*	I_{peak} *[A] (1.5 GeV)*
1	$0.11\ 10^{11}$	12.9	19.8
2	$0.22\ 10^{11}$	15.8	23.0
5	$0.55\ 10^{11}$	28.6	34.9
10	$1.10\ 10^{11}$	44.6	54.6
20	$2.20\ 10^{11}$	70.1	85.6
50	$5.50\ 10^{11}$	128	156

5 FURTHER WORK

The results obtained so far, which use lattice properties which are similar to those likely to be adopted for the final DIAMOND design, show that the operation of an SRFEL at low energy is plausible. Because the bunch lengthening is significant the model used to calculate it may not be satisfactory and needs to be investigated further; the real bunch distribution may be both shortened and non-Gaussian, which will affect both the equilibrium emittance from IBS and the calculation and magnitude of the Touschek lifetime. Although SPEAR scaling may apply in the regime occupied by this lattice it is poorly understood, and a final estimate of bunch lengthening will require tracking studies with the proposed lattice. In addition, the assumed broadband impedance is an estimated upper limit, and a proper budget will be needed to predict lengthening effects more confidently. However, there is sufficient latitude in the optics to provide for increased emittance and coupling at low energy if it is required to offset a small lifetime.

Enhanced energy spread appears to be the main limiting factor in achieving high peak currents, so to maintain a high quantum lifetime with higher bunch currents either the increase in energy spread must be suppressed or the momentum acceptance must be increased. Increased momentum acceptance is in principle possible with a different lattice optics, since there is ample RF voltage at these energies. However, achieving an acceptance greater than 4% will require a well-optimised optics which is well-corrected in the real storage ring, and may well in practice be limited by the effect of small vertical apertures on the scattered particles, which can have couplings much higher than the core beam [9].

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