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OPTIMIZATION OF SUPERCONDUCTING UNDULATORS FOR LOW REPETITION RATE FELS

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Abstract

Superconducting undulators (SCUs) optimized for storage rings and MHz-level FELs require an intermediate beam screen to intercept the power deposited by the electron beam, due to resistive wall wakefields, to prevent magnet quenching. This beam screen increases the magnet gap by around 2 mm which is a significant increase when compared to the typical electron beam aperture of around 5 mm. However, lower repetition rate FELs only deposit of the order of tens of mW/m and so the beam screen is no longer needed resulting in a significant reduction in undulator magnet gap. We have investigated the impact of this reduced magnet gap and found that the magnetic field level increases greatly. For example, an SCU with a 15-mm period and 5-mm aperture optimized for a low repetition rate FEL instead of a storage ring will generate a field of 2.1 T compared to 1.4 T. Such a major increase in undulator performance could have a significant impact on the optimization of FELs. This paper describes how an SCU optimized for application in a FEL will be able to generate magnetic field levels far beyond those currently foreseen for any other magnet technology.

INTRODUCTION

Despite the ongoing improvements in permanent magnet undulators (PMUs), there is still a clear margin in performance advantage to be gained through the application of superconducting materials and it is for this reason that several groups around the world have been actively pursuing the detailed development of short period, high field SCUs for light source applications over the past ten years or more [1]. This research and development effort has led to the construction of a few SCUs which are now installed and in daily use on storage ring light sources in Germany [2] and USA [3]. These particular examples have exhibited very good operational performance in terms of reliability, stability, and user experience and this has increased confidence within the accelerator community that national FEL light source facilities, such as LCLS-II, should carefully assess employing SCUs rather than permanent magnet alternatives in their baseline configurations [4].

This paper explores how and when the engineering of SCUs can be significantly simplified for FELs compared to storage rings and the impact this will have on the available undulator parameters compared against the most advanced PMU options today.

SCU OPTIMIZATION FOR FELS

International efforts on SCU developments have primarily focussed upon storage ring applications which have different constraints to FELs. One clear difference is the accelerator vacuum requirement which is radically different between a stored beam facility and a single pass facility, with the former being far more demanding. Another difference is the relatively large good field region required in the storage ring undulators to maintain an adequate dynamic aperture and to enable efficient off-axis injection. Neither of these issues is of importance for single pass FELs, enabling narrower good field regions to be fit for purpose and potentially further simplifying the engineering.

However, the most significant difference between the two types of facility is the heating due to the electron beam in the SCU itself. In a storage ring care must be taken to ensure no synchrotron radiation from upstream dipoles can impinge on the SCU cold surface which is not an issue in FELs. More importantly though, in a storage ring there is significant beam heating due to resistive wall wakefields (RWW) within the SCU. This power level is too high for the 4K undulator magnet to handle without quenching and so all storage ring SCUs employ an intermediate beam screen between the magnet poles, held at between 10 and 20K, to absorb this power safely. This beam screen also acts as the beam vacuum chamber, which is essential to separate the machine vacuum from the magnet's thermal insulating vacuum. Significant engineering efforts are made to make this vacuum vessel have as little impact on the SCU magnet gap as possible but even with wall thicknesses of ~0.5mm and similar insulating spacing between this surface and the SCU coils and poles the magnet gap is increased by typically ~2.0mm compared to the aperture needs of the electron beam itself.

Since the power deposited by these wakefields scales linearly with the number of bunches passing through the SCU, it is clear that as the bunch repetition rate is reduced there will be a point at which the SCU will not suffer from significant beam heating and the internal vacuum chamber can be completely removed from the design and instead be replaced by a thin high conductivity copper liner similar to that employed by all permanent magnet in-vacuum undulators (IVU).

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Wakefield Calculations

We use the standard expression relating the longitudinal wakefield impedance of the beam pipe to the surface impedance of the beam pipe material at cryogenic temperatures [5]. The latter is a result of the anomalous skin effect (ASE) theory in metals [6, 7]. At room temperature, the classical skin depth is much larger than the mean free path of the conduction electrons in the metal and the ASE theory reproduces the surface impedance value obtained under normal skin effect assumptions. At cryogenic temperatures, however, the mean free path could greatly exceed the classical skin depth value. If, in addition, the bunch length is much greater than the critical length $\sigma_0 \approx 10$ fs (for copper) the ASE theory approaches the extreme anomalous skin effect regime (EASE) where the surface impedance only weakly depends on the temperature [8]. We consider an internal copper liner of circular cross-section with room temperature conductivity of 5.7×10^7 S/m, mean free path of 35.6 nm and relaxation time of 22.3 fs [5]. The residual resistance ratio (RRR) is set to 10, which is a conservative assumption. As the validity of the EASE approximation relies upon bunch lengths greatly exceeding σ_0, the longitudinal loss factor calculation is performed in the framework of the full ASE theory. Gaussian bunch profiles have been assumed.

From the calculated longitudinal loss factor the energy deposited within the SCU per bunch per meter has been calculated for two different representative FEL bunch charges and this is plotted in Fig. 1 for three alternative apertures. Note that we have also calculated the loss factors for two parallel plates, representing a flat copper liner mounted on the magnet pole surface, and found the results to be broadly similar to those of the circular aperture given here. The loss factor increases rapidly as the bunch length approaches 1 fs but we expect that this bunch length regime is only significant for low charge FEL operation (typically 20 pC) and so in fact the higher charge mode (assumed here to be 250 pC) has the highest energy loss per bunch at its shortest operational bunch length, presumed here to be 10 fs.

Figure 2 plots the power loss per meter within the SCU as a function of bunch repetition rate, or more strictly speaking the number of bunches per second, for two representative FEL bunches. Note that we have carried out similar calculations for the power loss per meter in the SCU designed for the Diamond Light Source and although the energy loss per bunch is orders of magnitude less due to the relatively long bunches (~15–20 ps depending upon the operating mode), the actual power loss per meter is ~1 W/m due to the high average beam current when compared to FELs. This storage ring SCU power level from RWW is similar to that calculated and observed at the APS [9]. We estimate, based upon our long experience of SCU development and cryogenic systems in general, that a cryocooler-based cooling system for the SCU will comfortably operate at 0.1 W/m. From this we see from Fig. 2 that even the extreme FEL bunch of 250 pC with an rms bunch length of 10 fs (~10 kA peak current) will comfortably sustain several hundred Hz repetition rate, at an aperture of only 3 mm. If longer bunches and/or lower bunch charges are acceptable then bunch repetition rates in excess of 10 kHz are feasible.

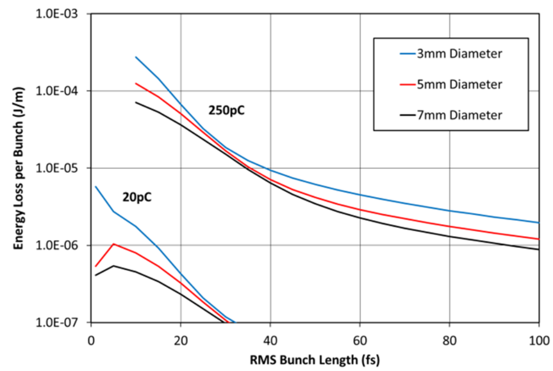

Figure 1: Energy deposited per bunch per meter, for two different bunch charges, in the SCU at 4K due to RWW as a function of electron bunch length and beam aperture.

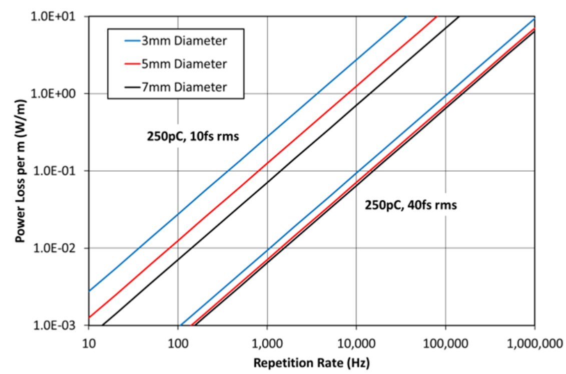

Figure 2: Power loss per meter, for two different bunch lengths, in the SCU at 4K due to RWW as a function of repetition rate and beam aperture.

SCU PARAMETERS

To compare the two types of SCU, one with the internal vacuum vessel and one with only a thin copper liner we have modelled the peak magnetic field in the undulator as a function of electron beam aperture and period using Opera 3D [10] for thirty separately optimized cases. The magnetic modelling assumes commercially available rectangular cross-section NbTi superconductor with a safety margin of 10%, operating at 1.8K. Each model has been individually optimized for the number of discrete windings per layer and for the number of layers. For models at 4K instead of 1.8K we typically observe a 10% reduction in peak field. For the case with the internal vacuum vessel (storage ring SCU) the magnet pole gap is 2.0 mm larger than the electron beam aperture (2 x 0.5 mm vacuum wall thickness plus 2 x 0.5 mm separation between the 20 K vessel and the 1.8 K magnet steel former and windings) and for the alternative case (FEL SCU) the magnet pole gap is only 0.2 mm larger than the electron beam aperture (2 x 0.1 mm copper liner mounted on the pole surface). A summary of the modelling results

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is given in Fig. 3 for an example 15 mm period device. Also included for comparison is a state of the art cryogenic permanent magnet undulator (CPMU) utilising $Pr_2Fe_{14}B$ with a remnant field of 1.57 T at 77 K [11] and the SwissFEL Aramis IVU [12], the most advanced undulator technology so far in an operating FEL. At a typical FEL beam aperture of 5 mm the Aramis IVU generates 0.8 T (K = 1.12), the CPMU will generate 1.1 T (K = 1.54), the storage ring SCU 1.4 T (K = 1.96) and the FEL SCU 2.1 T (K = 2.94).

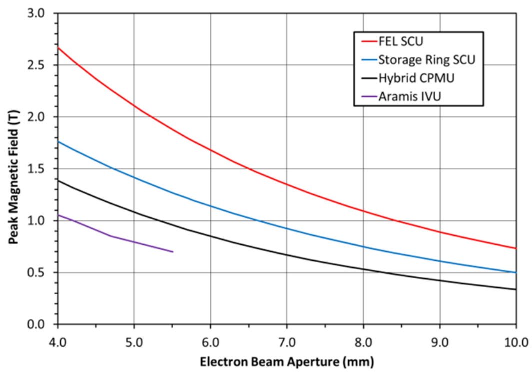

Figure 3: Peak magnetic field for a 15 mm period undulator as a function of electron beam aperture for both types of SCU, a state of the art hybrid CPMU and the Aramis IVU.

Fig. 4 shows how the peak field varies with period at a fixed electron beam aperture of 5 mm. Even at a period of 10 mm, the peak field is 1.2 T (K = 1.12) for the FEL SCU.

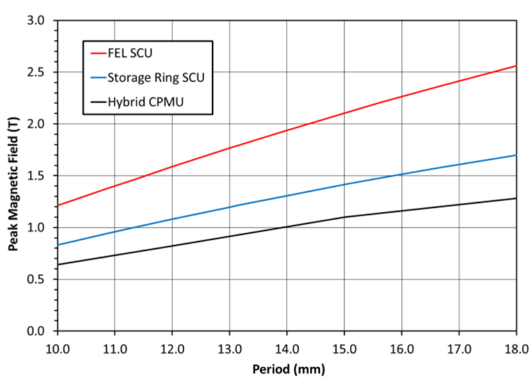

Figure 4: Peak magnetic field for a 5-mm electron beam aperture as a function of period for both types of SCU and a state of the art hybrid CPMU.

IMPACT OF ENHANCED SCU PERFORMANCE

In this section, we look at the impact of the enhanced performance offered by this new type of SCU on the fundamental parameters of an X-ray FEL. We take the SwissFEL Aramis hard X-ray FEL as an example. The Aramis FEL has an output wavelength range between 0.1 and 0.7 nm and this tuning range is enabled by adjusting the electron beam energy, not the undulator K value since it is assumed that K = 1.2 is a minimum value for sufficient FEL coupling. If we follow the same philosophy of optimization then the period of the undulator reduces to 10.3 mm from 15.0 mm and the maximum required electron beam energy is only 4.8 GeV cf 5.8 GeV, a saving of ~17% in beam energy, a key cost driver for all FEL user facilities. In addition, the saturation length of the FEL reduces by more than 20%. As an alternative optimization, we have maintained the period at 15.0 mm but now our maximum K value of 2.9 allows significant wavelength tuning at a fixed electron energy and the minimum energy required to reach the longest wavelengths is significantly higher meaning higher beam powers and so higher FEL output power. A summary of the two SCU options considered compared against the Aramis FEL is given in Table 1.

Table 1: Comparison of FEL performance for two FEL SCU optimizations (5.0 mm electron beam aperture) and the implemented IVU for the Aramis FEL (4.7 mm aperture). Assumes peak current = 3kA, emittance = 0.4 mm-mrad, absolute rms energy spread = 350keV.

	Aramis IVU	FEL SCU Option 1	FEL SCU Option 2	
Period (mm)	15.0	10.3	15.0	
K	1.2	1.2	1.2 to 2.9	
Energy (GeV)	5.8 2.2	4.8 1.8	5.8	3.8
Wavelength (nm)	0.1 - 0.7	0.1 - 0.7	0.1 - 0.3	0.23 - 0.7
L_{sat} (m)	27.9 - 15.5	22.0 - 12.3	27.9-17.2	24.4-13.4
P_{sat} (GW)	10.2 - 7.6	7.4 - 5.4	10.2-17.3	9.1-15.1

CONCLUSIONS AND FURTHER WORK

There are significantly different design constraints on an SCU when it is optimized for an FEL instead of a storage ring. The most important change is that no internal vacuum chamber is required when the power levels due to RWW heating fall below ~100 mW/m. This constraint holds for FELs operating in the kHz regime and below and so is generally applicable to all normal conducting RF and plasma driven FELs.

Without the internal vacuum chamber the SCU magnet gap reduces by ~1.8 mm, leading to magnetic field levels far beyond those currently foreseen for any other magnet technology and opening up new FEL facility optimization possibilities. Whilst this paper has been wholly focussed upon planar devices, the conclusions also hold for helical SCUs which can achieve similar field levels in each plane to those predicted for the planar option and also offer enhanced FEL coupling. Indeed, we have successfully constructed a short period, high field helical SCU for a different application in the past [13].

We are currently constructing a short planar FEL SCU prototype in the UK and plan to test it with beam on the CLARA FEL Test Facility [14] in 2018.

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