OFF-AXIS UNDULATOR RADIATION FOR CLIC DRIVE BEAM DIAGNOSTICS

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Abstract

The Compact LInear Collider (CLIC) will use a novel acceleration scheme in which energy extracted from a very intense beam of relatively low-energy electrons (the Drive Beam) is used to accelerate a lower intensity Main Beam to very high energy. The high intensity of the Drive Beam, with pulses of more than 10^{15} electrons, poses a challenge for conventional profile measurements such as wire scanners. Thus, new non-invasive profile measurements are being investigated.

In this paper we propose the use of relatively inexpensive permanent-magnet undulators to generate off-axis visible Synchrotron Radiation from the CLIC Drive Beam. The field strength and period length of the undulator should be designed such that the on-axis undulator wavelength is in the ultra-violet. A smaller but still useable amount of visible light is then generated in a hollow cone. This light can be reflected out of the beam pipe by a ring-shaped mirror placed downstream and imaged on a camera. In this contribution, results of SRW and ZEMAX simulations using the CLIC Drive Beam parameters are shown.

INTRODUCTION

The CLIC Drive Beam (DB) accelerator will accelerate an intense electron beam up to 2.4 GeV [1]. The transverse beam profile should be measured at various points along the linac, and non-invasive profile monitors are being developed for this purpose. Parameters for the CLIC Drive Beam are shown in table 1. The profile monitors should have a resolution of 100 µm or better in order to measure the minimum beam size during quad scans. Intercepting devices e.g. OTR screens may be installed in parallel to provide cross-calibration, but could only be used during operation with reduced pulse length.

Table 1: Relevant Parameters for the CLIC Drive Beam Accelerator [1]

Bunch population	5×10^{10} e^-
Transverse Emittance	100 nm rad
Bunch length / spacing	13 ps / 2 ns
Pulse length	140 µs
Pulse Population	3×10^{15} e^-
Repetition Frequency	50 Hz

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A small permanent-magnet undulator can be used to generate synchrotron radiation (SR) from the CLIC drive beam, which can be used for transverse profile measurements. SR is an attractive option for beam diagnostics since it is non-destructive and carries both transverse and longitudinal beam information.

SR from an undulator [2] is emitted at a wavelength which is determined by the undulator coherence condition:

$$\lambda_{coh} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\varphi^2\right)$$

where λ_u is the undulator wavelength, K is the undulator parameter and φ is the angle of observation. Although most radiation is emitted in a narrow cone with an opening angle of $1/\gamma$ about the beam direction, some SR at longer wavelengths is emitted as a hollow cone with larger opening angle. Thus, it is possible to design an undulator which would emit visible light in a cone wide enough to be collected with a ring-shaped mirror a few metres downstream. The on-axis SR would be in the UV range. The ring mirror is in reality elliptical, so that when tilted at 45 degrees it appears circular when looking down the beam line.

The ring mirror would reflect the visible component of the SR perpendicularly out of the beam pipe through a transparent viewport, and it could then be imaged on a CCD camera. Longitudinal diagnostics using a streak camera would also be possible if required.

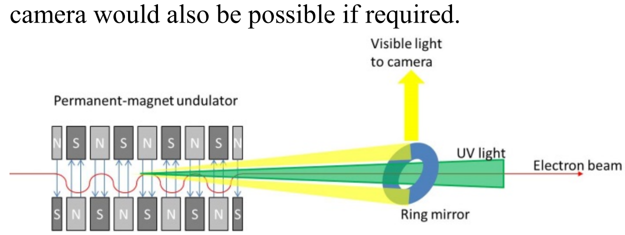

Figure 1: Schematic of off-axis SR observation.

MAGNET DESIGN

The period and peak field strength of the undulator must be tailored to the energy of the observed beam in order to generate visible light with a suitable opening angle.

A severe constraint is given by the large gap between the undulator poles. The current design of the CLIC DB accelerating structures foresees a beam pipe diameter of 98 mm [3], and local constrictions are to be avoided due to impedance effects.

The on-axis field strength of a pure permanent-magnet undulator [4] is given by

$$B_{peak} \approx 1.8\, B_r e^{-\pi g/\lambda_u}$$

where g is the gap height, λ_u the period and B_r is the magnetic field at the pole tips. Hybrid magnets do not increase the field strength when g/λ_u is large.

The remanent field for typical permanent magnet materials is 0.85-1.4 T. Larger fields can be achieved by using cryogenically cooled permanent magnets or superconducting electro-magnets, but this leads to a considerable cost increase.

In an ideal undulator, the horizontal components of the magnetic field should be zero, and the vertical field strength should be constant over the whole area of the beam. As g/λ_u is increased, the undulator tends to deviate from these conditions. The latter is particularly important since the emitted SR power scales with B^2. Thus, if electrons in different transverse positions see different field strengths, the image of the beam will be strongly distorted.

For this reason we set a limit of $g/\lambda_u \leq 1$ for the calculations below. This allows a satisfactory field quality to be produced. CST EM Studio [5] was used to investigate the field quality of a pure permanent magnet undulator with $g = \lambda_u = 10$ cm and the results are shown in fig. 2. Within a 1 cm^2 area in the centre of the beam pipe, the peak field varies by less than 5%.

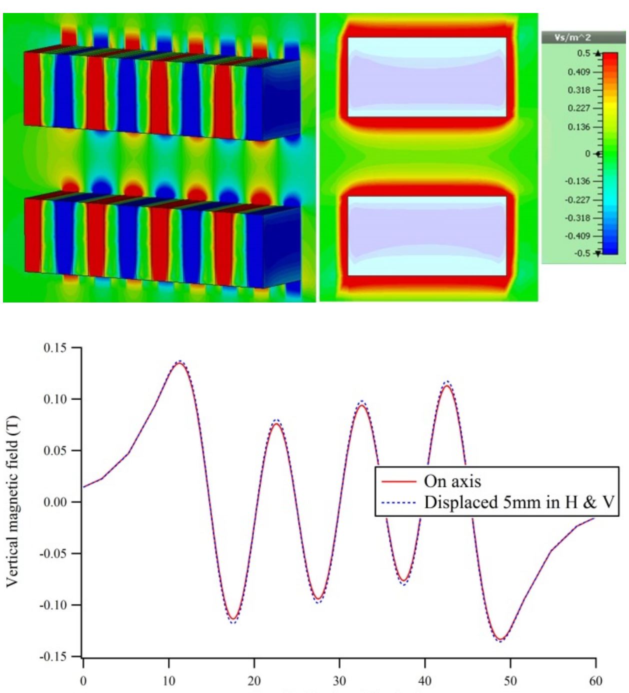

Figure 2: Field quality of an undulator with $g = \lambda_u$. Top left, vertical magnetic field B_y on centre plane of undulator. Top right, transverse map of B_y at longitudinal peak. Bottom, B_y along undulator axis (solid red line) and displaced by 5mm in H and V (dotted blue line).

Permanent magnets slowly demagnetise when exposed to radiation. A reduction of the field strength by roughly 1% can be expected after a dose of 20 kGy [6]. A reduction of a few percent could be acceptable for the diagnostic undulators. Larger reductions would need to be compensated by adjustment of the gap width, or eventually by replacement of the undulator. Further analysis would be needed to estimate the lifetime of the undulator magnets.

APPLICABLE BEAM ENERGIES

For an electron beam at a given energy, various combinations of undulator period and strength may produce visible light with the required opening angle. Fig. 3 shows the combinations which would produce 500 nm light with a 2.5 mrad opening angle using a pure permanent magnet undulator made of NdFeB (B_r=1.15 T) with $g \geq 10$ cm and $g/\lambda_u \leq 1$. It can be seen that the constraints can be fulfilled for all energies above 300 MeV.

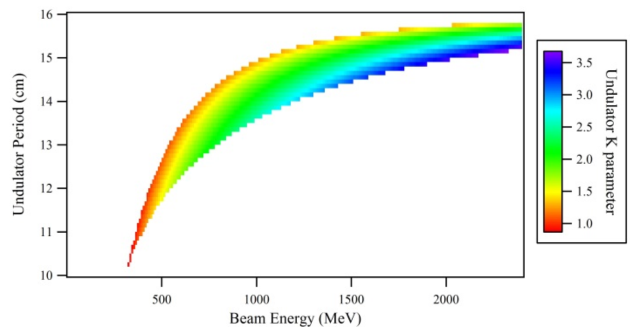

Figure 3: Undulator period and K parameter needed to produce 500 nm light at an opening angle of 2.5 mrad for different beam energies.

In order to determine the amount of light that could be gathered on the ring-shaped extraction mirror, simulations were performed with Synchrotron Radiation Workshop (SRW) [7]. As an example, Fig 4 shows the total SR and visible synchrotron light produced by a 500 MeV electron beam passing through an undulator with K=1.3 and 3 periods of 12 cm. If the ring mirror is located so as to capture light emitted with opening angle between 2 and 3 mrad, approximately 5% of the SR power will hit the mirror. The spectrum of SR on the mirror is very broad, as shown in figure 5.

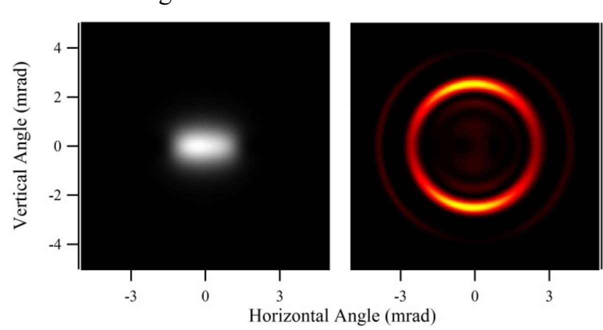

Figure 4: Total SR (left) and visible SR (right) from a 500 MeV electron beam crossing an undulator with 3 periods, K=1.3, λ_u=12 cm. Simulated with SRW.

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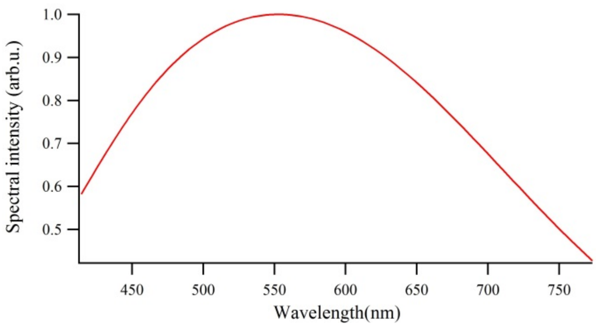

Figure 5: Spectrum of SR emitted with angle 2-3 mrad from a 500 MeV electron beam crossing an undulator with 3 periods, K=1.3, λ_u=12 cm. Simulated with SRW.

SRW simulations have been carried out for undulators suitable for other beam energies and the results are shown in table 2. The yield has been calculated for undulators with 3 periods, assuming the mirror captures all light with 400-750 nm wavelength and 2-3 mrad opening angle. For any beam energy, the light yield on the mirror can vary considerably for different K, λ_u combinations giving the same opening angle. Thus the undulators for which the yield has been calculated in table 2 are only examples.

The power radiated from an undulator scales with γ^2. However, most of the radiation is contained in a cone with half-angle 1/γ, so that as the beam energy increases, the fraction of SR reaching the ring mirror is reduced. These effects roughly cancel.

Table 2: Examples of K, λ_u combinations which fulfil the conditions for visible light at 2.5 mrad opening angle and $g/\lambda_u \leq 1$.

Beam Energy	Undulator Period (cm)	K	Light yield (photons / e^-)
300 MeV	10	0.7	2×10^{-3}
500 MeV	12	1.3	4.4×10^{-3}
1 GeV	14.5	1.6	2.8×10^{-3}
2.4 GeV	15.7	1.7	7×10^{-4}

The light yield can be increased by increasing the number of undulator periods. However, increasing the length of the undulator makes the resolution worse due to depth-of-field effect (see below) as well as increasing the cost and space requirement of the undulator.

At higher beam energies the power radiated on-axis can be considerable. Since it is emitted along the beam direction, however, it will be spread over a very large area of beam pipe, provided that no bending magnet is located close downstream. The frequency of on-axis radiation also increases strongly with beam energy. At 2.4 GeV beam energy, for the undulator shown in table 2 above, the on-axis radiation yield is 0.06 photons / electron, centred at 9.4 nm in the soft x-ray range. The average power emitted is 0.25 W for 50 Hz repetition rate, of which only 0.01% hits the ring mirror.

A magnetic chicane composed of separate dipoles could also be used to observe SR from the linac. However, the effect on the beam optics is considerably less when an undulator is used. The transverse movement of the electron beam inside the undulator is only 100 µm for the 300 MeV case above, and less at higher beam energies. The undulators can be matched so that the beam exits on the same line that it enters.

The use of off-axis undulator radiation could be extended to lower beam energies (100 – 300 MeV) by use of infra-red cameras or by accepting a constriction of the beam pipe to allow a smaller undulator gap.

EXPECTED RESOLUTION

A number of factors will affect the resolution of the profile monitor. The undulator represents an extended source so if the optical system is focused on the centre of the undulator, the entrance and exit will be slightly out of focus. Usually a narrow aperture is used to increase the depth of field of the optical system, but the large diameter of the ring-shaped extraction mirror makes this difficult.

In order to investigate the effect on the profile monitor resolution, a simple optical simulation was carried out in ZEMAX [8]. The SR wavefront calculated in SRW was written to a ZEMAX beam file (.zbf format). The ZEMAX Physical Optics mode was then used to propagate the wavefront through a simplified optical system with 1:1 imaging.

The undulator in this simulation had K=1.3, λ_u=12 cm as in figure 4 above. The 500 MeV electrons are defined as a filament beam i.e. a point source. Since ZEMAX physical optics only deals with one wavelength at a time, only SR at 500 nm was simulated.

The simulations were repeated for undulators with different numbers of periods, and the spot size of the beam waist is shown for each undulator in figure 6. As expected, the size of the focal spot depends on the number of undulator periods.

Thus, it is desirable to keep the undulator as short as possible. The improvement in signal-to-noise ratio brought about by the increased light yield of a longer undulator is unlikely to compensate the loss of resolution. In addition, cost and space constraints favour a shorter undulator.

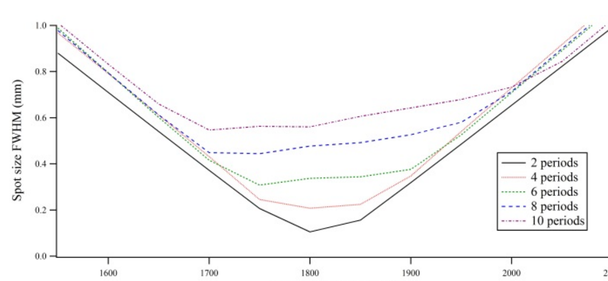

Figure 6: Focused beam waist of SR from undulators of different lengths. From ZEMAX simulation of a simple optical simple with 1:1 imaging.

The off-axis undulator radiation is split almost evenly between the horizontal and vertical polarisations (53:47 for the undulator investigated in fig 4 above) but the

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distribution is different as shown in figure 7. The point spread function of the two components is also different, and a small improvement in resolution can be achieved by observing through a horizontally polarised filter. The size of the focal spot for the above undulator is shown in figure 8 with and without the polarising filter.

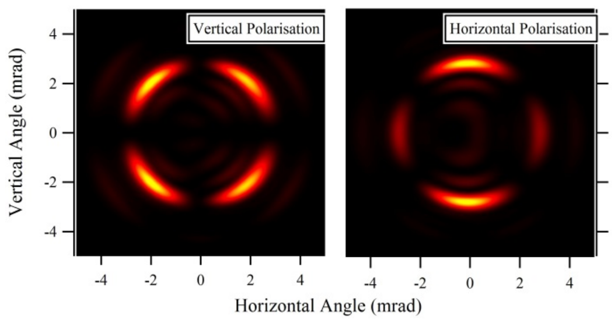

Figure 7: Vertically and Horizontally polarised components of visible SR from a 500 MeV electron beam crossing an undulator with 3 periods, K=1.3, λ_u=12 cm. Simulated with SRW.

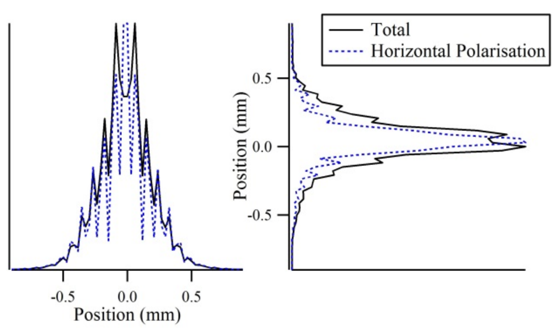

Figure 8: Horizontal and vertical size of the point spread function of visible SR from a 500 MeV electron beam crossing an undulator with 3 periods, K=1.3, λ_u=12 cm. Simulated with SRW and ZEMAX.

Clearly, other factors will affect the resolution of the final system, such as the camera pixel size and chromatic aberration. In addition, depending on the expected level of radiation at the monitor, it may be necessary to locate the camera at some distance from the beam. This is likely to adversely affect the resolution of the monitor, due to refraction in the long in-air light path.

The synchrotron light from the undulators could also be used for longitudinal measurements of bunch length and bunch purity. The bunch combination scheme for the CLIC DB requires tight limits on the population of satellite bunches. A fraction of the synchrotron light could be separated with a beam splitter or a flip-up mirror used to redirect light to a streak camera as required. The inherent time resolution of the undulator radiation is a few fs, due to the path difference of photons emitted at different locations in the undulator. Chromatic dispersion in the exit window is likely to be more important but could be eliminated by observing through a monochromatic filter.

CONCLUSION

A non-invasive method for measuring the beam profile in an electron linac by using off-axis undulator radiation has been described. The large diameter of the beam pipe in the CLIC Drive Beam constrains the undulator period and field strength. Nonetheless a suitable undulator could be designed for any beam energy over 300 MeV.

Both transverse and longitudinal profile measurements are possible. In the case of transverse profile, the resolution is limited by the depth of field, but it is acceptable for the CLIC DB case for undulators less than 50 cm in length.

ACKNOWLEDGEMENTS

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