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Generation of coherent far infra-red radiation utilising a planar undulator at the 4GLS prototype

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Abstract

An Energy Recovery Linac (ERL) Prototype facility to be built at Daresbury Laboratory serves as a testbed for the study of beam dynamics and accelerator technology important for the design and construction of the 4th Generation Light Source (4GLS). This paper describes the possibility of utilising a planar undulator at the 4GLS prototype facility for the generation of coherent synchrotron radiation in the far infra-red region.

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1. Introduction

Recent advances in accelerator technology have led to steady progress in the generation of high-brightness electron bunches (short bunch length, high peak-current, small transverse emittance) much sought after for driving free-electron lasers (FELs). During circular motion, an electron bunch starts to emit Coherent Synchrotron Radiation (CSR) at wavelengths equal to or longer than the bunch length. The emission of CSR can lead to severe degradation of the beam quality and much effort has been devoted to mitigating the CSR effects for transport of electron beams in accelerators [1].

CSR is emitted in the far-infrared (FIR) spectral range, i.e. terahertz (THz) region. This region is also referred to as the “THz gap” since it is not directly accessible with both electronic and photonic devices, and thermal sources are very weak. Accelerator-based facilities are promising sources to overcome this limitation. The first evidence of CSR was reported in 1989 [2]. CSR emission has also been observed at several electron storage rings (Refs. [3,4] and references therein). Recently, broadband high-average power CSR from sub-picosecond electron bunches has been measured at the last dipole magnet of the magnetic bunch compressor of the Jefferson Laboratory FEL [5].

Coherent, high-power, narrow-band FIR radiation can be produced by passing sub-picosecond

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electron bunches through an undulator [6,7]. In this report, we discuss the predicted performance of a planar wiggler proposed as part of the Energy Recovery Linac Prototype (ERLP) facility at Daresbury Laboratory.

2. Undulator parameters

Daresbury Laboratory has been given funding for the construction of an Energy Recovery Linac Prototype (ERLP) facility [8] that operates at a target electron beam energy of 30–50 MeV. The injector comprises a DC photocathode gun and a super-conducting booster cavity for high repetition rates. The ERLP serves as a testbed for the R&D neeeded for the design study of the 4th Generation Light Source (4GLS) [9].

The main objectives for the ERLP are the demonstration of energy recovery from an electron bunch with an energy spread induced by a radiation source and the development of expertise in such technology. Another aim is the simultaneous operation and synchronisation of multiple radiation sources. To achieve this it is proposed to pass the electron beam through both an IR oscillator FEL [10] (based on a wiggler on loan from Jefferson Laboratory which has previously been used in the IR Demo FEL [11]) and a planar undulator [12] for the generation of CSR which will be de-commissioned from the SRS soon. The latter undulator is a pure-permanent magnet undulator with a variable gap. For a gap of 20–80 mm, the on-axis magnetic peak field $\hat{B}$ and the undulator parameter K can be calculated from Eq. (4) given in Ref. [12]. The wavelength of the fundamental radiated on-axis is then given by the resonance condition:

$$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \tag{1}$$

where λ_w is the period length and $\gamma = E/(m_e c^2)$ the electron beam energy in units of the electron rest mass. For the given parameters, the wavelength range 10–300 μm would be covered. The main parameters of the undulator and the proposed ERLP design are listed in Table 1.

Table 1
Main parameters of the ERL prototype design and undulator

Parameter	
Electron beam	
Beam energy E	30–50 MeV
Bunch charge Q	>80 pC
Bunch length (FWHM)	<0.5 ps
Undulator	
Period length λ_w	100 mm
Number of periods N_w	10
Length	1.0 m
Gap	20–80 mm
Peak magnetic field $\hat{B}$	0.7–0.1 T
Undulator parameter K	6.4–1.0
Wavelength range at 30 MeV	300–16 μm
Wavelength range at 40 MeV	175–12 μm
Wavelength range at 50 MeV	113–10 μm

3. Undulator output

The total power P radiated at a frequency ω by an electron bunch moving through an undulator in the absence of any FEL interaction is given by [7,13]

$$P(\omega) = p(\omega)[N_e + N_e(N_e - 1)|\bar{F}(\omega)|^2] \tag{2}$$

where $p(\omega)$ is the radiation power emitted by one electron and N_e the number of electrons in the bunch. The form factor $\bar{F}(\omega)$ is the Fourier transform of the longitudinal charge distribution of the electron bunch and describes the effects of CSR. The emitted spectrum depends on the form factor $\bar{F}(\omega)$ and, hence, on the particular charge distribution in the electron bunch.

For simplicity we assume a Gaussian charge distribution. This approximation is not strictly valid in practice but is useful for estimating the total power and spectral distribution. The Fourier transform then takes the form

$$\bar{F}(\omega) = e^{-(1/2)\omega^2\sigma^2} \tag{3}$$

where σ is the rms electron bunch length in the time domain. The form factor has been calculated for the wavelength range that is spanned by the undulator at a beam energy of 40 MeV. The results are shown in Fig. 1 for four different bunch lengths (0.1, 0.2, 0.3 and 0.4 ps (FWHM)). For the radiation emitted into the cone of half angle $\theta_{\mathrm{cen}} = \sqrt{1+K^2/2}/\sqrt{\gamma^2 N_w}$ the relative spectral bandwidth (FWHM) is given by $\Delta\lambda/\lambda = 0.89/N_w = 0.089$ [13]. The normalized spectral distribution for a fixed gap of 27 mm is also given in Fig. 1. The energy radiated into the central cone θ_{cen} by a single electron passing through a planar undulator is given, in SI units, by [7,13]

$$E_{\mathrm{cen}} \simeq \frac{2\pi e^2 f_{\mathrm{B}}^2 \xi}{\varepsilon_0 \lambda_0} \qquad (4)$$

where λ_0 is the resonance wavelength (Eq. (1)) and $f_{\mathrm{B}} = J_0(\xi) - J_1(\xi)$ a parameter that accounts for the additional axial electron motion in a planar undulator with J_n the Bessel function of nth order and $\xi = K^2/(4+2K^2)$. The pulse energy (radiation energy per electron bunch) radiated at each resonance wavelength over the entire wavelength range of the undulator can then be calculated from Eq. (2). The result is shown in Fig. 2 for a beam energy of 40 MeV, a bunch charge of 80 pC and four different electron bunch lengths which are in accordance with the form factor calculations in Fig. 1. The strong effect of the form factor on the radiated pulse energy can clearly be seen. The pulse energies vary by several order of magnitude over the accessible wavelength range of the undulator. At a given wavelength, i.e. for a fixed gap, the pulse energy is very sensitive to the bunch length and, hence, the undulator may be able to be utilised for the measurement of ultra-short bunch lengths [13,14].

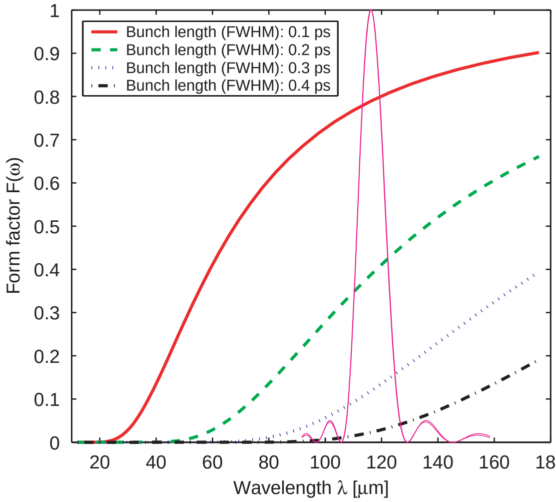

Fig. 1. Variation of the form factor $\bar{F}(\omega)$ over the wavelength range covered by the undulator at a beam energy of 40 MeV. A Gaussian longitudinal bunch profile was assumed. In addition, the normalized spectral distribution for a fixed gap of 27 mm is shown.

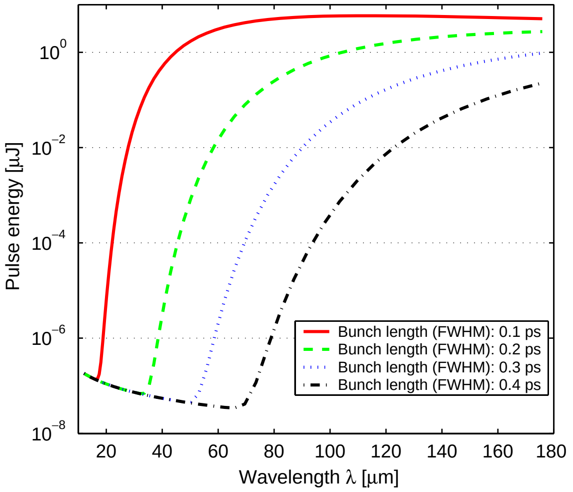

Fig. 2. Variation of the pulse energy over the wavelength range of the undulator calculated for four different electron bunch lengths (bunch charge: 80 pC; beam energy $E = 40$ MeV).

Due to slippage in the undulator—the radiation advances by one wavelength per undulator period—the pulse duration in the CSR regime is $\approx N_w \lambda_0 / c$ and the resulting pulse duration is about 1–10 ps.

The radiated pulse energy depends strongly on the bunch charge. This is demonstrated in Fig. 3 for four different bunch charges and a bunch length (FWHM) of 0.2 ps. For bunch charges over 200 pC and wavelengths longer than 120 µm the pulse energy surpasses the 10 µJ level.

4. 1-D time-dependent studies

The previous analysis neglects the effects of any collective FEL interaction that may occur between the emitted radiation and the electrons. Such interaction may effect the charge distribution

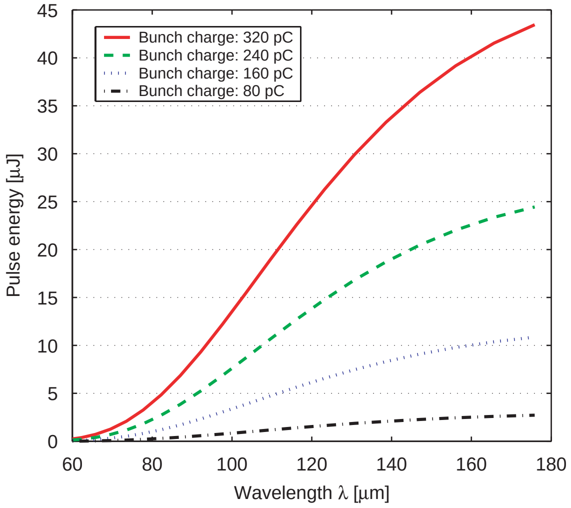

Fig. 3. Variation of the pulse energy over the wavelength range of the undulator calculated for four different electron bunch charges (bunch length (FWHM): 0.2 ps; beam energy $E = 40\,\mathrm{MeV}$).

within the electron pulse and so alter the characteristics of the radiation emission. In an attempt to model such effects the various parameters used to characterise the FEL interaction were calculated and the 1-D numerical model of Ref. [15] was employed to give estimates of the emitted radiation energy. This model uses unaveraged equations of motion for the electrons and is able, under the 1-D assumption validity, to describe radiation evolution at the sub-wavelength scale so enabling modelling of CSR effects in ultrashort electron pulses.

We assumed an 80 pC Gaussian electron pulse of duration 0.2 ps FWHM with beam energy 40 MeV, and tuned the undulator to give a resonant wavelength of ~175 μm. Assuming the undulator has natural focussing in both planes and a normalised beam emittance of 10 mm mrad, the matched beam radius is ~223 μm. The 1-D FEL parameter of Ref. [15] is then $\rho \approx 0.11$ and the gain length is $l_g \approx 0.075\,\mathrm{m}$. It is immediately apparent from the relatively large value of ρ that the 1-D model of Ref. [15] is close, if not beyond, the Compton limit of validity in which space charge effects may be neglected [16]. Furthermore, the gain length is significantly longer than the Rayleigh range $Z_r \approx 894\,\mu\mathrm{m}$ and it would be expected that radiation diffraction effects would dominate any longitudinal FEL interaction. The model of Ref. [15] could not therefore be expected to model in any meaningful way the emission of radiation from the short electron pulse as described. This has been confirmed in simulations which yield a radiation pulse energy of approximately two orders of magnitude above that of the analysis of the previous section.

It would be of interest to extend the model of Ref. [15] to include transverse effects and so be able to model any collective FEL effects in systems such as that described in this paper. Work is currently underway to develop such a model.

5. Conclusions

An existing planar undulator could be employed at the ERL Prototype facility for the generation of coherent FIR radiation in the spectral range 50–300 μm. For bunch charges above 80 pC and electron bunch lengths shorter than 0.4 ps (FWHM), this undulator will emit 1–10 ps long pulses with energies of up to several μJ with a relative spectral bandwidth of ≃9% (FWHM). As the requirements on the beam quality in terms of energy spread and emittance are not stringent for the generation of CSR, it may be possible to operate the undulator following the exit of an IR oscillator FEL and use the radiation of both devices for synchronisation or pump–probe experiments. The undulator could also be used for electron pulse shape/length measurements. Further work is required to describe the CSR emission in time dependent models.

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