SHORT PULSE SYNCHROTRON LIGHT FROM JEFFERSON LAB'S NUCLEAR PHYSICS ACCELERATOR *

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Abstract

There has been recent interest in developing sources of X-rays, both coherent and incoherent, for advanced materials science and other scientific studies. In particular, there is interest in developing so-called fourth generation light sources, which are driven by electron linacs. One distinguishing feature of the fourth generation sources is the very short pulse length, usually under 1 psec rms, that is possible from a linac driven source. Because of recent successes in achieving very short bunches out of its injector, it is natural to investigate whether the Jefferson Lab nuclear physics accelerator might be used as a copious source of incoherent short-pulse synchrotron light. In this note we present the results of calculations of the expected synchrotron radiation spectrum from bend magnets at four locations in the CEBAF accelerator. The results show that substantial numbers of short pulse X-rays are produced.

1 INTRODUCTION

Thomson scatter events in the Jefferson Lab FEL will produce X-rays of energy up to about 15 keV, with photon brightnesses at the level of 10^6 photons/mm^{2}mrad^{2}sec in a 1% bandwidth [1]. Because of our recent success in achieving very short bunches out of the Jefferson Lab main injector [2], it is natural to investigate whether the CEBAF accelerator might be used as a copious source of X-rays. In this note we present the results of calculations of the expected synchrotron radiation spectrum from bend magnets at four locations in the Jefferson Lab nuclear physics accelerator. The results show that substantial numbers of X-rays are produced. The fluxes are interesting enough that preliminary fourth generation X-ray experiments could be performed at Jefferson Lab, prior to installation in a beamline at the TESLA light source at DESY or the Linac Coherent Light Source (LCLS) proposed for Stanford. This is especially true given that all necessary X-ray producing equipment is already installed and "available". The precision timing in the accelerator allows one to time the X-rays at the 100 fsec level. It bears worth emphasizing that the repetition time in a typical experiment would be at the repetition rate of the accelerator, i. e., 500 MHz presently, and 31 MHz in about a year's time. This time structure is changed by a suitable change to the laser pulse structure on the source. In contrast, present day rings have pulse durations of order 30 psec, making them unsuitable as sources for studies involving ultrafast phenomena.

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2 X-RAY BRIGHTNESS

The standard synchrotron radiation formulas were used to estimate the brightness (for 100 μA beam at 500 MHz) of the synchrotron radiation emerging from the nuclear physics machine at Jefferson Lab. Begin with Jackson's Eqn. 14.83 [3],

$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{3\pi^2 c}\Big(\frac{\omega\rho}{c}\Big)^2\Big(\frac{1}{\gamma^2}+\theta^2\Big)^2$$

$$\times\big[K_{2/3}^2(\xi) + \frac{\theta^2}{(1/\gamma^2)+\theta^2}K_{1/3}^2(\xi)\big], \qquad (1)$$

for the emission spectrum (energy radiated per unit frequency interval per unit solid angle) of a single electron. Because the beam emittance is so small ($\epsilon_{rms}^n \approx 1.0$ mm mrad), a typical electron angle is of order 0.01 mrad or smaller at 4 GeV. As this angle is smaller than the $1/\gamma$ radiation emission angle, the brightness is not much changed due to the effects of finite electron beam emittance. Eq. 1 is used to estimate the photon brightness (at θ=0) as

$$B \approx \frac{\gamma^2}{2\pi\sigma_x\sigma_y}\frac{3\alpha}{\pi^2}\frac{\Delta\omega}{\omega}\xi^2 K_{2/3}^2(\xi)\frac{I}{e}, \qquad (2)$$

where α is the fine structure constant, $\xi = \lambda_{cr}/\lambda$, and $\Delta\omega/\omega$ is the bandwidth. Jackson's definition (Eqn. 14.85) of the critical wavelength $\lambda_{cr} \approx 2.09\rho/\gamma^3$, is used in the tabulation. The average current I_{ave}/e is used to compute the average brightness, and the peak brightness is estimated using $I/e \approx q/\sqrt{2\pi}e\sigma_t$ where q is the charge per bunch and σ_t is the measured rms bunch duration of 85 fsec.

As results, the radiation spectrum into a 0.1% bandwidth is displayed for four possible magnets in the CEBAF accelerator. The first magnet is a first pass bend magnet at the end of linac 1 (445 MeV). The second magnet is a first pass bend magnet at the end of linac 2 (845 MeV). The third magnet is an arc nine bending magnet, before the final pass through the south linac (3645 MeV). The final magnet is a high energy bending magnet right before the Hall C entrance, where the beam energy is 4.045 GeV. Table 1 summarizes some of the properties of the synchrotron emission from these bend magnets. The beam sizes are assumed to be 100 μm by 100 μm at 4 GeV, scaled by $\gamma^{-1/2}$ for the lower energies, i. e., the beam optics β is assumed to be independent of energy. The brightness as a function of wavelength is shown in the Figures 1 and 2, which give the peak and average brightness of the synchrotron emission from each magnet.

Compared to, for example, an APS bend, the main difference in the average brightness of magnet 4 arises from

Table 1: Electron beam and synchrotron radiation parameters for various magnets in the Jefferson Lab Nuclear Physics Accelerator

Magnet	E (MeV)	ρ (m)	λ_{cr} (Å)	E_{cr} (keV)
1	445	5	159	0.078
2	845	10	46.3	0.268
3	3645	30	1.73	7.16
4	4045	46	1.94	6.38

the reduced average current at the Jefferson Lab accelerator. On the other hand, the peak brightness from this magnet exceeds that of other bend magnet sources, because the pulse length is so short. Obviously, installing an undulator at Jefferson Lab could increase these brightnesses farther, as in the transition between 2nd generation and 3rd generation synchrotron sources. Such a brightness is already competitive with a proposed alternative storage-ring based source of short pulse radiation [4], as the average current producing the short-pulse radiation is comparable.

From the figure, it appears that either high energy magnet gives good X-ray brightness. The X-ray production rate is between 10^{11} and 10^{12} photons/sec mm^2 mrad^2 in a 0.1% bandwidth in the range of 1-10 angstroms. These X-rays will be distributed in a pulse that mirrors the e-beam pulse in time. Therefore, because it is possible to preserve the short bunch out of the injector, an X-ray pulse length of under 100 fsec should be possible.

3 LONGITUDINAL BEAM DYNAMICS

So far, it has been demonstrated experimentally only that short electron pulses emerge from the injector. No beam bunch length experiments have been performed at higher energies. On the other hand, there is high confidence, based on beam longitudinal dynamics measurements, that the short bunch length will be retained at high energies. Because the bunch is relativistic, and the accelerator recirculation arcs are designed to be isochronous, bunch lengthening can arise only from incorrect linac phasing coupled to residual uncorrected M_{56} in the arcs. Two pieces of experimental data indicate that this is not a problem. Typically, the bunch runs on crest in the accelerator within 0.5° of the phase of maximum energy gain. The cresting is continuously monitorred by observing synchrotron light at a high dispersion point of the arc, and by phase modulation measurements [5].

As part of the present arc setup procedure, the M_{56} is adjusted to under 10 cm, and the path lengths are adjusted so that the phase error in higher passes is a few tenths of a degree. The instrumental limit of the currently installed measuring devices is 1 mm for M_{56} and 50 μm for the path length [6]. Even with worst-case assumptions about how potential errors add, a bunch length change under 10% during acceleration to high energy is indicated.

4 CONCLUSIONS

In this note it is shown that potentially interesting numbers of short-pulse X-rays are currently being produced at the CEBAF accelerator. It "only" remains to provide some access to these X-rays to allow experiments to proceed.

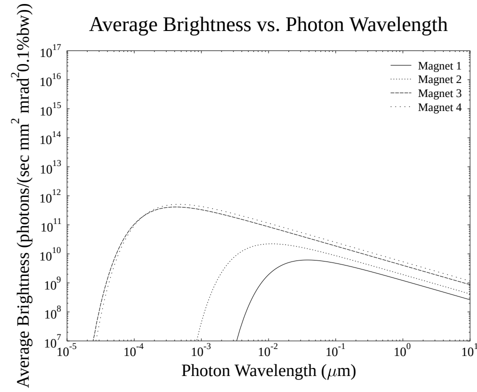

Figure 1: Average Brightness vs. Wavelength

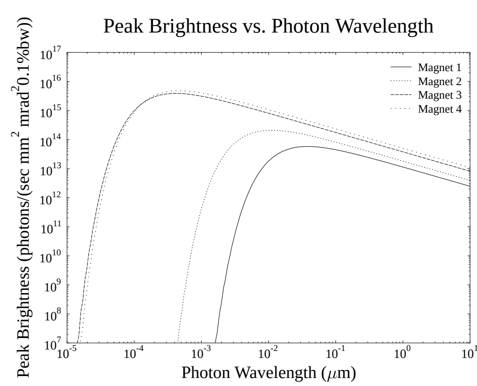

Figure 2: Peak Brightness vs. Wavelength

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