PLANNED DETECTION AND AMPLIFICATION OF INFRARED SYNCHROTRON RADIATION FOR ELECTRON-BEAM DIAGNOSTICS AND MANIPULATIONS*

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Abstract

Amplification of beam-induced radiation (e.g. synchrotron or undulator radiation) is a necessary component of optical stochastic cooling of hadrons or heavy ions. We discuss a proposal to measure and amplify synchrotron radiation from a bending magnet of the Advanced Photon Source. The measurements will be in the short-wavelength infrared region (SWIR) and amplification will be accomplished using a pumped Chromium:Zinc Selenide (Cr:ZnSe) crystal with maximum gain at $\lambda \simeq 2.2$ µm.

INTRODUCTION

The amplification of Synchrotron Radiation (SR) is a critical component of a proposed beam cooling technique known as Optical Stochastic Cooling. In OSC damping of a particles phase-space amplitude is achieved by feeding back on the particle beam, inside an undulator (the ’kicker’), SR that was generated upstream in an identical undulator (the pickup). Amplification of this radiation increases the effectiveness of the this technique. More information on the theory behind the OSC can be found in [1] [2] [3]. Here we discuss a proposed experiment to measure and amplify SR at one of the bend magnets (beamline 35-BM) of the Advanced Photon Source (APS). In particular we focus on the Short-Wavelength Infared Region SWIR $\lambda \in [2.0, 3.0]$ µm. This wavelength regime is the most suitable for a planned proof-of-principle OSC experiment at the IOTA ring at Fermilab [4].

The 35BM beamline is already equipped with an optics transport line that has been successfully used for beam diagnostics in the visible range [5]. The transport line incorporate reflective optics and can be used in the SWIR wihtout loss of performance. A beam splitter will be placed at the virtual source (see Fig. 1) to direct the SR toward our experimental setup. A unique advantage of working at 35-BM is the availability of an experimental hutch which can be accessed during APS standard operation. Such an accessibility will ease difficulties associated with alignment in the SWIR region as the main beam can directly be used to align the setup. The measurements will be done in two phases. In phase I the SR is simply detected and characterized while in a subsequent Phase II it will be amplify. Our measurements do not require any particular APS setting and so can be performed parasitically during nominal operation.

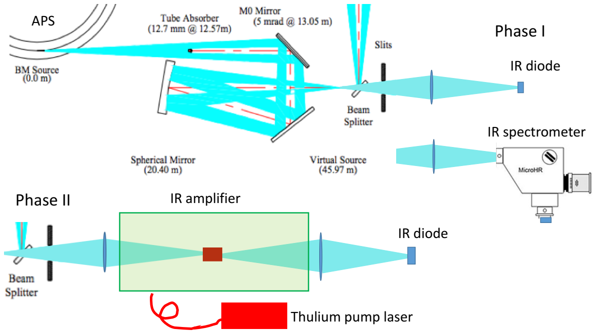

Figure 1: Overview of the two phases of the proposed experiment. Phase I consists of measuring the SR with a diode and spectrometer. Phase II would demonstrate amplification of SR with a Cr:ZnSe amplifier. Figure adopted from [5].

DETECTION OF SYNCHROTRON RADIATION

The IR detector to be used is a thermoelectrically-cooled InAs diode from HAMAMTSU (model C12492-210). It has a good spectral response over a broad wavelength range $\lambda \in [1, 3.4]$ µm and a 1-mm diameter photosensitive area. The total flux expected from the dipole magnet was calculated using the SYNCHROTRON RADIATION WORKSHOP (SRW) software [6]. An angular acceptance of 5 mrad was used and the critical element of the transport beamline were included. The beamline especially incorporates a 12.7-mm diameter water-cooled copper tube used to intercept the central part of the SR before the first mirror. Such a mask was implemented to reduce heating. The solid angle of the tube ($\approx$ 1mrad) is considerably larger than the opening light cone typical ascribed to SR ($\approx 2/\gamma = 0.15$ mrad for a 7 GeV electron). However the critical wavelength of 35BM is 0.6 which is by more than 4 orders of magnitude shorter than the IR wavelengths we are interested. Therefore from diffraction effects, we expect the radiation pattern in the SWIR to be significantly larger than $2/\gamma$. The expected brightness is plotted in Fig. 2. Computation yielded an average power of 100 µW over the wavelength

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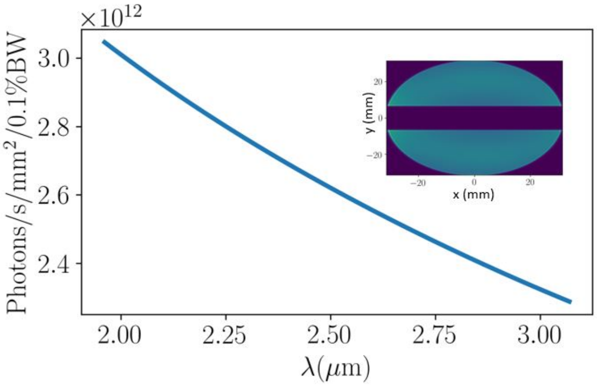

Figure 2: Expected brightness coming from 35BM computed using SRW. The inset shows the transverse distribution of SR integrated over the measurement band.

$\lambda \in [2.0, 3.0]$ μm and considering a 100-mA average beam current. Assuming negligible losses in the beamline neutral density filters will be utilized to prevent saturation of the diode.

Our initial detection of the SR will aim at characterizing the sensitivity and response time of the diode. In addition to being a necessary firs step in our experiment these measurements serve a duel purpose for also determining the viability of this particular diode being used for downstream diagnostics in the OSC experiment in IOTA. The diode signal will recorded with a laptop-controlled (RedPitaya) digital oscilloscope.

In a second step of the detection of the SR the spectrum will be measured using a high-resolution grating spectrometer from horiba (model Micro-HR). The spectrometer can be set to scan automatically over the wavelength range of the diodes detectability. The signal from the diode is digitized in concert with the scan via software provided by the manufacture. The SR average power is many orders of magnitude larger than the diodes NEP ($\approx$ 10 pW/$\sqrt{Hz}$). Therefore, even with large losses in the spectrometer through spectral filtering the signal integration time can be set so that the entire scan takes at most of few minutes. We anticipate the required integration time will be much longer than any time structure of the APS beam and so the spectrometer will essentially be a stand-alone device.

AMPLIFICATION OF SYNCHROTRON RADIATION

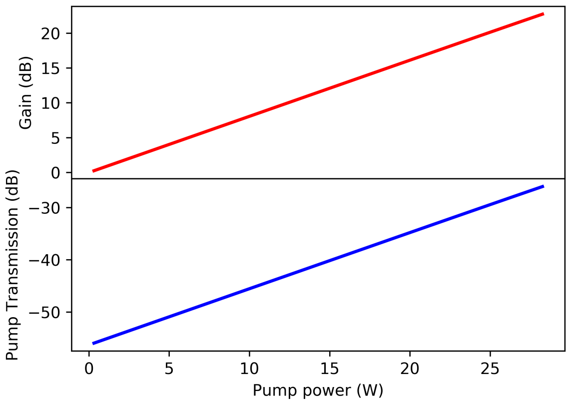

Figure 3: Computed gain and pump transmission as a function of pumping laser power assuming a 100 μm pump radius.

Amplification will be done in a single-pass through a highly doped ($N_t = 1.35 \times 10^{19}$ions/cm^3) Cr:ZnSe crystal. Pumping is done with a solid-state Thulium Fiber laser from IPG photonics at $\lambda_p = 1908$ nm. The gain is found by first computing the attenuation of the pump beam intensity, I_p, propagating through the crystal by numerically integrating [7].

$$\frac{I_p}{dz} = -I_p N_t \left(\frac{(1 + I_p \sigma_p e A)(\sigma_{pa} + 2\sigma_{pe})}{I_p A(\sigma_{pa} + 2\sigma_{pe}) + 1} \right) \tag{1}$$

where σ_{pe} and σ_{pa} are the emission and absorption cross-sections at the pump laser wavelength and $A \equiv \tau / h\nu_p$. Here τ is the fluorescence decay time and $\nu_p = c/\lambda_p$. The absorbed pump intensity is related to the gain (in power) by

$$G = \exp\left(\frac{\sigma_s \tau}{h\nu_p} \Delta I_p\right) \tag{2}$$

where σ_s is the emission-cross section at the amplification wavelength and $\Delta I_p = I_p(z = 0) - I_p(z = L)$. The expected gain at the emission peak is plotted in the top pane of Fig. 3.

A diagram of the amplifier appears in Fig, 4. In order to overlap the pump and SR paths a dichroic mirror will be used to reflect at the pump wavelength and transmit the SR light. Amplifier gain is determined by pump intensity and so to keep the required pump laser power reasonable a focusing lens is needed to reduce the pump laser spot radius to 100 μm. An iris can be used to reject SR light outside of the pump spot.

A second dichroic mirror after the amplifier is used to separate out pump and SR. Additionally we note that, at the intensities needed for this test pump absorption saturation effects are small and so the crystal will absorb most of the pump power. The pumps transmission it plotted in the bottom pane of Fig. 3.

SUMMARY & STATUS

We have presented details related to a planned experiment to measure and amplify SR radiation from a bending magnet at the APS in Argonne. Calculations of the brightness in the SWIR regime indicate it is well above the detectors noise-equivalent power. Amplification of SR using a single-pass

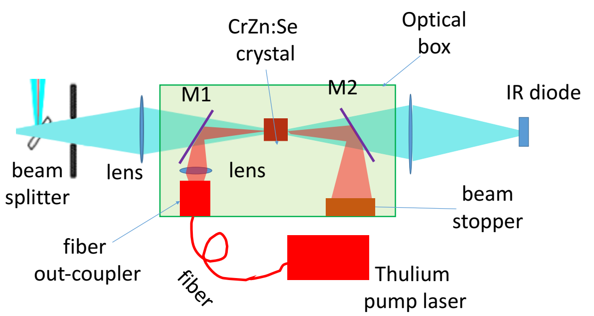

Figure 4: Schematics of the single-pass amplifier. M1 and M2 are dichroic mirror reflecting the thulium-pump laser.

amplifier based on a Cr:ZnSe crystal should be capable of increasing the SR radiation by almost two order of magnitudes. The amplifier is in its final tests and will be moved to APS in the summer 2018. The successful completion of the proposed experiment will test a critical component of the optical stochastic technique schemes but also provide impetus for research related to the possible use of amplified beam-induced radiation. Such a capability could have application in the development of beam diagnostics and advanced beam-manipulation techniques.

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