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DEVELOPMENT OF SHORT UNDULATORS FOR ELECTRON-BEAM-RADIATION INTERACTION STUDIES *

P. Piot[1,2], M. B. Andorf[1], G. Fagerberg[3], M. Figora[4], A. Sturtz[4]
[1] Department of Physics and Northern Illinois Center for Accelerator & Detector Development, Northern Illinois University DeKalb, IL 60115, USA
[2] Fermi National Accelerator Laboratory, Batavia IL 60510, USA
[3] Department of Physics, Northern Illinois University DeKalb, IL 60115, USA
[4] College of Liberal Art & Science, Northern Illinois University DeKalb, IL 60115, USA

Abstract

Interaction of an electron beam with external field or its own radiation has widespread applications ranging from coherent-radiation generation, phase space cooling or formation of temporally-structured beams. An efficient coupling mechanism between an electron beam and radiation field relies on the use of a magnetic undulator. In this contribution we detail our plans to build short (11-period) undulators with $\sim$ 7-cm period refurbishing parts of the ALADDIN U3 undulator [1]. Possible use of these undulators at available test facilities to support experiments relevant to cooling techniques and radiation sources are outlined.

INTRODUCTION

Over the recent years there have been a wide interest in laser-photon interaction. The motivations for such explorations include the manipulation of electron bunches [2], the generation of coherent radiation [3] along with the possible phase-space cooling based on optical-stochastic cooling [4, 5] (OSC) or on chromatic coupling [6]. Additionally, undulator radiation enables the indirect measurement of the electron-beam parameter [7].

Motivated by such opportunities along with developing an experimental program centered on the optical control and phase-space cooling of electron beams, we recently acquired an undulator magnet which is being reconfigured as three short undulator magnets (henceforth dubbed as "micro-undulators"). One of the magnets is foreseen to be installed at the Fermilab Accelerator Science & Technology (FAST) facility to initiate tests of subsystem relevant to a planned proof-of-principle experiment at the Integrable-Optics Test Accelerator (IOTA) ring [8].

UNDULATOR DESIGN & STATUS

Our group has recently acquired an undulator available as surplus from the decommissioned ALADDIN storage ring at University of Wisconsin, Madison. This magnet dubbed as undulator U3 is a current-sheet-equivalent-material (CSEM) undulator composed of Nd-B-Fe permanent magnets [1]. The U3 undulator was nominally configured as a variable-gap undulator and the peak magnetic field is parametrized as a function of the gap g with the formula $B(g) = B_0 \exp\left[-g\left(\frac{\pi}{\lambda_u} + \frac{1}{d}\right)\right]$ where the coefficients $B_0 = 2.2692298$ T and $d = 2453.705 \times 10^{-3}$ m were obtained from a fit to the measurements carried by the ALADDIN team [9]. The latter parameterization is valid for gap $g \in [10, 150]$ mm corresponding to undulator parameters $K \equiv \frac{eB\lambda_u}{2\pi mc}$ field in the range $K \in [0.02, 9.60]$ (here e and m are the electronic charge and mass and c the velocity of light). The expected radiation-wavelength range for energy available at several Midwestern accelerator facilities is shown in Fig. 1. The wavelength spans the near infrared to ultraviolet wavelengths. For reference Fig. 1 also displays the wavelengths associated to several laser media available at some of the considered accelerator facilities. The U3 undulator was delivered to NIU in May 2016 and disassembled during the Summer. A new frame is currently being designed and we expect the first micro-undulator to be undergoing magnetic measurement before the end of 2016. We eventually will build three micro-undulators from U3 each

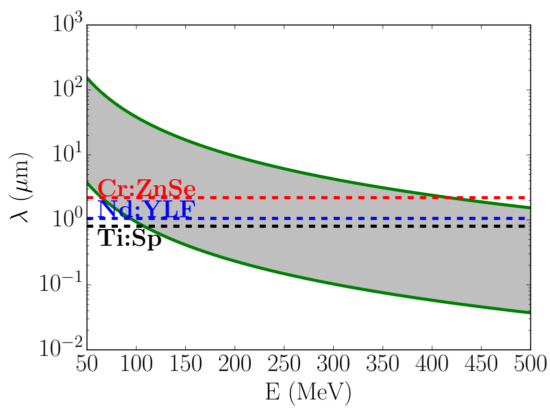

Figure 1: Range of wavelengths (shaded area) attainable with various electron-beam energies available at Midwestern accelerator facilities using the U3 undulator. The horizontal dashed lines with associated labels represents the wavelength of lasers available at FAST and illustrate that optical pulses formed by these laser media could be coupled to the electron beam in the U3 undulator.

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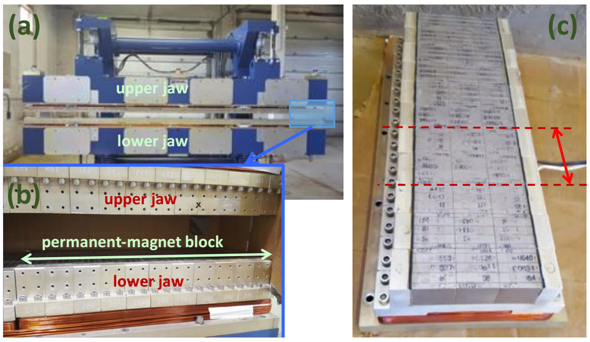

Figure 2: Photographs of the U3 undulator upon receiving at NIU (a), close-up on the 11-half-period blocks (b) and example of salvaged block consisting of $5\frac{1}{2}$ periods (c). A total of 18 blocks were retrieved. The red double arrow in (c) indicates the period.

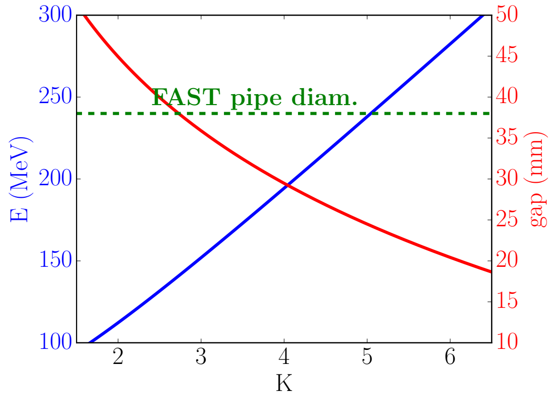

Figure 3: Required beam energy as a function of undulator's strength parameter K for a resonant wavelength of 2.2 μm.

consisting of 11 periods (with same period and parameter as U3. The number of periods was selected to minimize the work required during the undulator reconfiguration phase (the permanent-magnet blocks are mounted on "unit block" consisting of 11 half-period; see photographs in Fig. 2). The main parameters of the micro-undulators are summarized in Table 1.

Table 1: Main parameters of the micro-undulator magnet in construction at NIU.

parameter	nominal value	range
undulator type	pure CSEM	$--$
period, λ_u	70.7	mm
number of period	11	$--$
length	778	mm
gap	$g \in [10, 100]$	mm
peak B field (for $g = 24$ mm)	0.7	T

APPLICATIONS

Optical stochastic cooling

In short OSC is an undemonstrated cooling technique capable of increasing charged-particle beams brightness [4, 5]. It consists in (i) detecting electromagnetic radiation produced by the beam while passing in a "pick-up" undulator magnet, (ii) amplifying the radiation signal, and (iii) interacting the amplified signal with the same beam at a later stage in a "kicker" undulator magnet.

Based on various beam-dynamics consideration for IOTA, the a near-infrared laser wavelength is required ($\lambda \geq 2$ μm); see details in Ref. [10]. We have identified Cr:ZnSe as a possible gain medium for the needed single-pass amplifier. Cr:ZnSe lases within $\sim [2.2, 2.9]$ μm (with peak gain centered at 2.46 μm) and is an appealing medium given its large amplification bandwidth and its capability to support high gains in a single-pass operation. In the planned proof-of-principle experiment in IOTA, the permissible optical delay is limited: the magnetic chicane, used to delay the charged-particle beam, can only introduce a 2-mm delay (the limitation comes from impact on the IOTA dynamics aperture). Such a small delay requires the use of a thin crystal and associated focusing lenses. Additionally, the small circumference (40 m) of IOTA requires the amplifier to operate at a $\sim$ 7.5-MHz in order to ensure the OSC correction is applied at each turn. For this reason we envision CW pumping as the best option as it will enable the laser to operate in a steady-state mode (which also simplifies thermal management). The micro-undulators under construction will produce radiation with minimum wavelength ~ 2.2 μm for a large range of energy available at the FAST facility [11] with proper adjustment of the gap; see Fig. 3. At the nominal 100-MeV energy (IOTA injection energy), the required undulator gap will be > 50 mm corresponding to $K \sim 1$. The

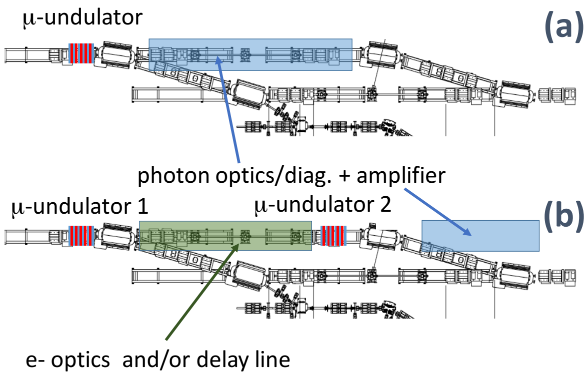

Figure 4: Possible undulator configurations in support to various experiments. In (a) one micro-undulator is used to produce radiation while (b) incorporates two micro-undulators separated by the appropriate magnetic lattice.

first micro-undulator is foreseen to be located in the FAST linac as diagrammed in Fig. 4(a) to support the development of components critical to the OSC proof-of-principle experiment before its realization in IOTA. Specifically, the proposed configuration will enable the characterization of undulator radiation at $\sim 2\ \mu$m along with investigating the effect of focusing optics on bandwidth and wavefront distortions. In a subsequent stage the undulator radiation will be focused on a Cr:ZnSe crystal pumped with a CW thulium laser to demonstrate active amplification of the undulator radiation. We plan on exploring the amplification process for various configurations and crystal thickness and verify the expected gain for the limited crystal thickness ($\sim$ 1-mm) permitted in the IOTA experiment.

Energy modulation

The micro-undulators in construction will also enable the coupling of laser pulse to the electron beam. At FAST an available amplified Nd:YLF ($\lambda = 1054$ nm) is under development to support a gamma-ray inverse-Compton-scattering source [12]. The mJ-level infrared pulse will be transported at the end of the FAST linac close to the foreseen location of the micro-undulator. The expected maximum energy modulation will be on the order of $\Delta E \sim 5$ MeV (assuming a 1-mJ, 3-ps laser pulse at $\lambda = 1054$ nm with a 100 μm waist and considering $K = 4.3$ consistent with a 300-MeV electron beam). Such an energy modulation is much larger than the anticipated slice energy spread (< 100 keV at 300 MeV) and support microbunching studies (using a subsequent chicane). Applications of energy-modulated beam include researches on coherent radiation and the development of novel beam diagnostics, e.g., based on the optical-replica technique [13].

Optical beam control & information preservation

In a later stage two micro-undulators could be installed in a beamline as diagrammed in Fig. 4(b) (here taking the FAST facility as an example). Such a configuration will enable the optical control of beams and the investigation of information preservations. Specifically when combined with a laser, the undulators separated by a strong-focusing channel could be used to support laser-assisted conditioning techniques discussed in Ref. [6]. An important aspect of such a conditioner is the ability to impress an energy modulation at the optical scale and remove it within the downstream undulator after the beam has been transported through a strong-focussing channel. The setup could support investigation of the energy-modulation and -demodulation scheme and its sensitivity to laser parameters and beamline tolerances. Alternatively, the two undulators, separated by a chicane, could provide a platform to investigate further topics associated to OSC and in particular the development of relevant diagnostics based on the interference of radiation pulses emitted from the two undulators [14, 15].

Radiation sources

A 300 MeV beam passing through a micro-undulator tuned for $K \simeq 1.4$ would generate 1.054 μm radiation. Such a radiation could be back scattered against a next bunch to produce, via inverse Compton scattering (ICS), γ rays with peak energy close to 1.2 MeV. Such a scheme is synergistic with on-going work at Fermilab to develop a high-repetition-rate γ-ray source based on ICS [12]. An increase of the 1.054-μm-radiation intensity could be accomplished using a coherent stacking cavity, a free-electron laser process [16], or possibly amplified with an amplifier similarly to the one under investigation for OSC.

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