ACCELERATOR PHYSICS AND LIGHT SOURCE RESEARCH PROGRAM AT DUKE UNIVERSITY*

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Abstract

The accelerator physics and light source research program at the Duke Free-Electron Laser Laboratory, Triangle Universities Nuclear Laboratory, is focused on the development of the storage ring based free-electron lasers (FELs), and a state-of-the-art Compton gamma-ray source, the High Intensity Gamma-ray Source (HIGS). Driven by the storage ring FEL, the HIGS is the world's most intense Compton gamma-ray source with a maximum total flux of a few 10^{10} γ/s (around 10 MeV). Operated in the energy range from 1 to 100 MeV, the HIGS is a premier nuclear physics research facility in the world. In 2012, we completed a major accelerator upgrade project with the installation of a wiggler switchyard system which allows changeovers between two planar and two helical FEL wigglers in the middle of the FEL section. In this paper, we report the light source R&D activities related to the wiggler switchyard project and VUV FEL lasing, and provide a summary of the accelerator physics research program at the laboratory.

INTRODUCTION

The main photon sources at the Duke Free-Electron Laser Laboratory (DFELL), Triangle Universities Nuclear Laboratory (TUNL), are storage ring based free-electron lasers (FELs) [1] and the FEL driven High Intensity Gamma-ray Source (HIGS) [2]. The facility operates three accelerators: (1) a 0.16 – 0.27 GeV linac pre-injector; (2) a 0.16 – 1.2 GeV full-energy, top-off booster injector; and (3) a 0.24 – 1.2 GeV electron storage ring. The Duke electron storage ring is a dedicated driver for the storage ring based FELs. The FEL is the photon source for the HIGS, the world's most intense Compton gamma-ray source. The HIGS facility is capable of producing intense gamma-ray beams from 1 to 100 MeV with a maximum total flux exceeding 10^{10} γ/s around 10 MeV. The HIGS produces highly polarized gamma-rays, either linear or circular, with excellent energy resolution for nuclear physics research.

Since 2008, the accelerator facility has been operated mainly as the Compton gamma-ray source for nuclear physics experiments. The layout of the accelerator facility is shown in Figure 1 and a list of key parameters of the Duke booster injector and storage ring are summarized in Table 1.

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Table 1: Parameters for the Duke Booster Injector and Storage Ring. The storage ring FELs can be operated using two different sets of wigglers with the wiggler switchyard.

Parameter	Value
Booster Synchrotron	(Main Injector)
Circumference [m]	31.902
RF frequency [MHz]	178.55
Number of RF buckets	19
Injection energy [GeV]	0.16 – 0.27
Extraction energy [GeV]	0.16 – 1.2
Storage Ring	
Operation energy	0.24–1.2 GeV
Circumference	107.46 m
RF frequency	178.55 MHz
Number of RF buckets	64
Max beam currents	
One-bunch (FEL)	95 mA ($\geq$ 0.6 GeV)
Two-bunch (HIGS)	$\sim$ 120 mA ($\geq$ 0.5 GeV)
Multi-bunch (60)	$>$ 300 mA ($\geq$ 0.5 GeV)
Duke FELs	(Wiggler Switchyard)
Linear and circular pol.	Two planar OK-4 wigglers plus two helical OK-5 wigglers
Circular polarization	Four helical OK-5 wigglers

ACCELERATOR PHYSICS RESEARCH

In the Duke storage ring, the maximum beam current in the multi-bunch mode is limited by longitudinal and transverse coupled bunch mode instabilities. To combat these instabilities, state-of-the-art FPGA based bunch-by-bunch longitudinal and transverse feedback (LFB and TFB) systems have been developed in the recent years. A high-performance, broadband waveguide overloaded LFB kicker was developed for the Duke storage ring [4]. The LFB system has been very effective in suppressing longitudinal instabilities, resulting in stable beam current operation with a number of bunch fill-patterns, including symmetric 2-, 4-, 8-, 16-, 32-bunch modes and the completely filled 64-bunch mode. The symmetric two-bunch operation is the bunch pattern used for Compton gamma-ray production with a two-bunch beam current ranging from 80 to 120 mA. The TFB system has been found to be important for high current operation with more than two symmetric bunches. In particular, we are in the process of developing a high current, symmetric 4-bunch mode of operation as a possible means to further increase the gamma-ray flux for the HIGS operation.

Using the TFB, we have developed two different ways to measure the betatron tunes – a slow one by scanning the drive frequency in a preset region and recording the

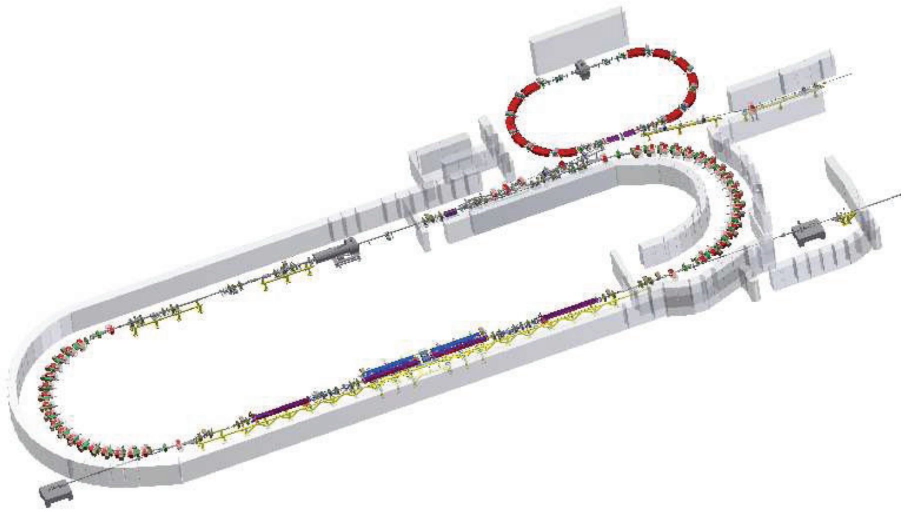

Figure 1: The schematic of the Duke storage ring accelerator facility, showing the full-energy top-off booster injector, storage ring, and FEL laser cavity. In the middle of the FEL straight section, a wiggler switchyard is shown to allow the switching between two planar and two helical wigglers. The collision point for gamma-ray production is located in the center of the FEL cavity and the Compton gamma-rays are sent to experimental areas along the direction of the electron beam in the FEL straight section.

beam response at each frequency, and a fast one by driving the electron beam using a broadband signal. The TFB based tune measurement system has been used as an important beam diagnostic for a number of studies [3], including (1) calibrating tune and chromaticity knobs ; (2) measuring the betatron tune shift with the single-bunch current to study beam impedance; (3) studying tune stability; and (4) measuring betatron tunes of individual bunches in a multi-bunch beam. We found that the Duke storage ring has excellent tune stability, with a peak-to-peak vertical tune variation of about 0.0002 (or a relative tune variation of 5×10^{-5}) during typical 30-minute measurement periods [3]. The impedance study using the bunch-current dependent tune shift is in the preliminary stage, and additional measurements will be performed in the near future.

Using the transverse feedback, we have also developed a new way to remove parasitic electron bunches in the storage ring [5]. Small electron bunches can form when the HIGS is operated to produce high energy gamma-rays ($>$ 20 MeV) as electrons scattered by FEL photons are recaptured in the adjacent RF buckets in the storage ring. These small, parasitic electron bunches can collide with the FEL beam to produce gamma-rays, which are considered to be a form of signal background for nuclear physics experiments. The transverse feedback system can be switched to operate in the positive feedback to drive the parasitic bunches in a phase-locked mode. The main bunches are not affected as a proper bunch pattern is selected digitally to ensure a “zero” drive signal for the main bunches. Using the TFB based electron bunch cleaning method, this gamma-ray beam background can be reduced by a factor of 30 to 50, practically eliminating this type of signal background for nuclear physics experiments.

In the area of magnetic optics, we are developing new storage ring lattices with a lower emittance to help increase the gain of the FEL operating in VUV, and new lattices with low beta-functions for a future Compton gamma-ray source. These developments are in the preliminary stage and will be reported in the future.

STORAGE RING FEL DEVELOPMENT

FEL Wiggler Switchyard

VUV FEL lasing in an oscillator FEL is difficult to realize due to increased cavity mirror losses below 200 nm. Operation of a VUV FEL requires a high gain system with a long section of wigglers. Before 2012, in the 34 m long FEL straight section of the Duke storage ring, a set of four mixed polarization wigglers were installed, including two planar OK-4 wigglers in the middle and two helical OK-5 wigglers on the sides. To increase the FEL gain, two more helical OK-5 wigglers could to be installed in the middle section to replace the planar OK-4 wigglers. However, the user program has a continuing need to use the linear polarization capabilities made possible with the OK-4. To resolve this conflict, a wiggler switchyard system was developed to allow the use of either two OK-4 wigglers or two helical OK-5 wigglers into the middle of the FEL section.

After several years of delay, the installation of the wiggler switchyard was carried out in early 2012, followed by a smooth commissioning of the storage ring and operation of the Duke FEL in June, 2012. Since Summer 2012, the wiggler switchyard system has been exercised three times, with a reduced downtime in each subsequent changeover. At the present time, FEL wigglers can be changed out in about a week, followed by the resumption of the FEL operation for user experiments. More details about the wiggler

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switchyard project, and its commissioning and initial operation can be found in [6].

The magnetic field compensation for wigglers is very important for FEL operation in order to reduce the impact of uncompensated magnetic field on the electron beam orbit. After the installation of the wiggler switchyard, we developed compensation schemes for all six wigglers (two planar OK-4 and four helical OK-5 wigglers). For the OK-5 wigglers, a pair of horizontal and a pair of vertical correctors built into the ends of the wigglers were used. For the OK-4 wigglers, a pair of adjacent horizontal orbit correctors were used. The field compensation schemes were experimentally determined using a beam based technique by monitoring the leakage orbit around the storage ring and effectiveness of the orbit correction using the designated correctors. The wiggler field compensation can significantly reduce the leakage orbit in the FEL straight section (for example, a factor of ~5 at a high wiggler current for OK-4), compared with the uncompensated case [7]. In addition, magnetic field compensation was also performed for four FEL buncher magnets, including three regular bunchers and a pseudo-buncher constructed using four horizontal correctors. To enable a transparent operation of wigglers and bunchers, all measured compensation schemes were implemented in the feed-forward controls [8]. The wiggler field compensation has been found to be critical for the stable, high quality operation of the Duke FEL and HIGS.

Soft Orbit Bump

At the HIGS, production of the high-energy, high-intensity gamma-ray beams above 70 MeV requires the use VUV mirrors below 200 nm, and a high-current electron beam above 0.9 GeV. At these high e-beam energies, the EUV and soft x-ray radiation from the end-of-arc dipole magnet is one of the dominant causes for rapid degradation of the downstream FEL mirror. Since 2011, we have worked to develop a "soft" orbit bump using designated orbit correctors at the end of the straight section to steer the electron beam away from the FEL mirror using a weak magnetic field. The magnetic field in this bump is designed to be much weaker compared with that in the arc dipoles to ensure that the critical energy of radiation in the bump field is similar to or lower than the FEL photon energy. This "soft" orbit bump also significantly reduces the total amount of radiation on the FEL mirror from orbit steering.

The "soft" orbit bump project has been carried out in two phases. In Phase I, a total of four orbit correctors (including two individual and two built-in correctors) are used to realize a maximum horizontal orbit steering of 1.2 mrad. This bump was successfully used in the 87 MeV gamma-ray beam production runs with the FEL lasing at 192 nm (Spring 2013), and it helped to extend the FEL mirror lifetime to more than 160 hr [9]. In Phase II, a total of eight correctors were used (including three newly installed individual correctors) to increase the total steering angle before the dipole to about 2 mrad. The orbit bump was further extended into the arc section to include the first three dipole magnets. This new bump has been designed, installed, and commissioned recently [9][10]. The impact of the upgraded "soft" orbit bump will be evaluated with future VUV FEL operations.

DEVELOPING NEW GAMMA-RAY CAPABILITIES

With the wiggler switchyard, we have gained substantial flexibility in operating the Duke FEL system in a variety of wiggler configurations (or different FELs). This has afforded us an opportunity to develop new gamma-ray capabilities in parallel to providing gamma-ray beams (both linear and helical) to the user program. In the near term, we have two main development projects for the HIGS: (1) to develop high-energy gamma-ray beam capabilities between 100 MeV and 158 MeV; (2) to further increase the gamma-ray flux in the energy range of 6 to 12 MeV by developing a new HIGS operation mode with a high-current, symmetric 4-bunch beam. The push toward the higher gamma-ray energies requires the development of durable, highly reflective FEL mirrors around 170 and 150 nm. It also requires us to solve the instability problem of the FEL cavity under substantial thermal loading when operating a large electron beam current. Progress in these areas will be reported at a future conference.

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