ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPMA016

LIGHT SOURCE AND ACCELERATOR PHYSICS RESEARCH PROGRAM AT DUKE UNIVERSITY*

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Abstract

The light source and accelerator physics research program at Duke Free-Electron Laser Laboratory (DFELL), Triangle Universities Nuclear Laboratory, is focused on the development of the storage ring based free-electron lasers (FELs), and an FEL driven state-of-the-art Compton gamma-ray source, the High Intensity Gamma-ray Source (HIGS). With a maximum total flux about 3×10^{10} γ/s and a spectral flux of more than 10^3 γ/s/eV around 10 MeV, the HIGS is the world's most intense Compton gamma-ray source. Operated in the energy range from 1 to 100 MeV, the HIGS is a premier Compton gamma-ray facility in the world for a variety of nuclear physics research programs, both fundamental and applied. In this paper, we will describe our ongoing accelerator physics and light source development program in the areas of the storage ring magnetic optics characterization and compensation, FEL physics, and development of gamma-ray beams in the higher energy range (100 to 158 MeV).

INTRODUCTION

The primary light 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]. At the DFELL, we operate 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 storage ring is a dedicated host for an oscillator FEL with several wiggler configurations. This FEL is the photon beam driver for the world's most intense Compton gamma-ray source, the HIGS which produces intense gamma-ray beams from 1 to 100 MeV with a maximum total flux about 3×10^{10} γ/s and a maximum spectral flux of more than 10^3 γ/s/eV around 10 MeV. The Compton gamma-ray beam at the HIGS is highly polarized (linear or circular), and has an excellent energy resolution. Since 2008, the accelerator facility has been operated mainly as the Compton gamma-ray source facility for routine user research in the area of nuclear physics and nuclear astrophysics. 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.

* Work supported in part by the US DOE grant no. DE-FG02-97ER41033.
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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)	~ 125 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

STORAGE RING LATTICE CHARACTERIZATION

Since 2013, we have devoted substantial time and effort to characterizing and compensating the magnetic optics of the Duke storage ring in order to optimize its operation. One of major challenges in this area stems from the use of all combined function quadru-sextupoles in the arcs in order to minimize the cross-talk between adjacent magnets of different types in the very compact arc lattice [3]. These magnets are standard quadrupoles but are powered by two different currents in the inner and outer coils. Consequently, the magnetic centers are separated from the geometric centers typically by more than 2 mm. The actual beam orbit in each magnet is not unknown in advance, and is subject to the change of the settings of quadrupole and sextupole components. In addition, the BPMs in the arc are instrumented relative to the geometric center of the quadru-sextupoles, making them much less reliable/accurate monitors for beam orbit measurements and lattice calibration.

Collectively, these issues present some significant difficulty to use the LOCO method [4] to calibrate the Duke storage ring lattice. Therefore, we worked to develop a direct beta-function measurement technique using the global tune changes caused by varying the strength of a quadrupole

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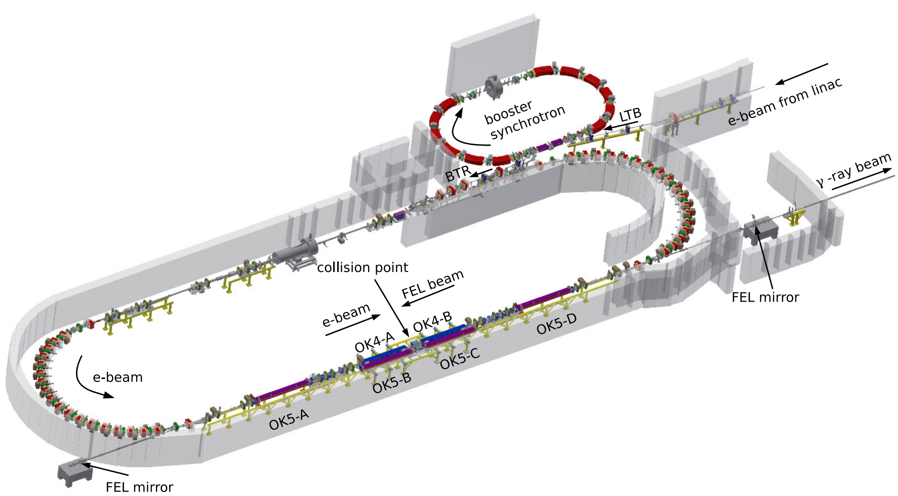

Figure 1: The recent configuration of the Duke storage ring accelerator facility. The HIGS accelerators include a 0.16 GeV linac pre-injector, a 0.16 – 1.2 GeV top-off booster synchrotron, and a 0.24 – 1.2 GeV storage ring. In the 34 m long FEL straight section, in addition to the two helical OK-5 wigglers on the sides, in the middle section, a wiggler switchyard system (since 2012) allows the use of either two planar OK-4 wigglers or two helical OK-5 wigglers. Compton gamma-rays are produced in the center of the FEL cavity and transported in the direction of the electron beam to the downstream experimental areas.

under study [5]. This method has been successful so far to allow us to simultaneously reconstruct a more realistic lattice model and to reduce the beta-function beating by almost a factor of three in the storage ring. Further improvement of this method will require us to have a better understanding of the quadrupole field hysteresis effect, and to obtain a better control of the measurement conditions and errors.

For the FEL operation, a total of six wigglers (2 linear OK-4 wigglers and 4 helical OK-5 wigglers) can be used in a number of combinations with the help of a wiggler switchyard system (see Figure 1). To preserve a large dynamic aperture, the focusing effect of the wiggler(s) needs to be compensated locally in the same FEL straight section without causing beta-beating in the rest of the lattice while preserving the global betatron tunes. For six commonly used FEL wiggler configurations, we developed a set of wiggler compensation schemes which are effective for the entire operational range of the wiggler field. These compensation schemes were implemented as a feedforward mechanism in the realtime accelerator controls system to allow transparent operation of the wigglers. In addition, we developed and implemented betatron tune knobs in the same straight section using 9 pairs of quadrupoles. These tune knobs with design/calculated parameters worked well and were critical for the initial commissioning and later routine operation of the Duke FEL and HIGS gamma-ray source. Recently, we performed careful calibrations of the tune knobs for several wiggler settings. The calibrated knobs can provide more accurate betatron tune control in a reasonably large range more than adequate for routine operation, with a maximum tune change discrepancy less than 3×10^{-3} (for $\nu_{x,y} = \pm 0.05$) [6]. The tune knob calibration work will continue for additional wiggler configurations, and for improved operational lattices as we continue to work on the lattice calibration.

STORAGE RING FEL DEVELOPMENT

2-Color FEL Lasing

Multi-color FEL lasing can provide new capabilities for application research. Among the storage ring FELs, the optical klystron (OK) FEL [7] in its early days was demonstrated to produce lasing at two adjacent wavelengths. However, their spectral separation is limited by the radiation bandwidth of a single wiggler. Using a set of specially developed dual-band, high-reflectivity mirrors, we developed and realized simultaneous two-color lasing of the Duke storage ring FEL in IR and UV with the same optical resonator. A special FEL configuration with three wigglers organized in two groups with two different wiggler settings was used to match the FEL gains at two wavelengths to the losses in the respective high reflectivity bands of the mirror. This is the first experimental demonstration of a tunable two-color harmonic FEL operation of a storage ring based FEL [8]. In this work, we demonstrated full control of the lasing wavelengths, one in the infrared region (around 720 nm) and the other in the ultraviolet region (around 360 nm)—the two lasing wavelengths can be harmonically related and tuned together in a range, and each of the lasing wavelengths (in IR or UV) can also be tuned independently. The total FEL power of 2-color lasing is similar to the single wavelength lasing for the same beam current. We also developed techniques to control the FEL power in each color. For example, we can operate 2-color lasing with good stability and roughly equal powers. Via Compton scattering, this 2-color FEL has recently been used to drive a 2-color gamma-ray beam. We

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plan to continue to develop the 2-color FEL and gamma-ray beams to make them suitable for application research.

Pulsed FEL Operation

The Duke storage ring FEL is routinely operated in the CW or quasi-CW mode with a single-bunch (2.8 MHz) or two-bunch (5.6 MHz) electron beam. Stable CW operation is typically realized by slightly detuning the electron beam revolution frequency to generate a small mismatch between the FEL's round-trip time in the laser cavity and electron beam's revolution time. If synchronization between the e-beam and FEL beam is realized perfectly, the FEL can be operated in the CW mode; but this synchronization condition can be difficult to achieve and maintain in many operation conditions. In this case, the FEL instability occurs, which leads to irregular (or chaotic) pulsing of the FEL beam due to the competition of slow synchrotron radiation damping and fast FEL gain process. To generate a regular pulsed FEL operation, a fast steering magnet was developed years ago to modulate the FEL gain [9]. This FEL gain modulator decouples the e-beam from the FEL beam in the interaction region for the most of time, but periodically allows a brief overlap of the electron and FEL beams. This enables the build-up of a high peak power FEL pulse using a well-damped electron beam. However, the use of this gain modulating device at low e-beam energies can cause beam losses and poor injection. Furthermore, the e-beam lifetime is significantly reduced due to the use of an energy damped e-beam without being able to take advantage of the bunch lengthening naturally associated with FEL operation.

To overcome these shortcomings, we developed and successfully tested an RF frequency modulation technique to pulse the FEL beam. The drive signal for the RF cavity is modulated to produce large enough FEL detuning to prevent FEL lasing for the most of time; the synchronization between the e-beam and FEL beam is then restored periodically for a short duration (typically a few milliseconds) to allow the FEL beam to build up. This process is repeated regularly in time with a time interval close to the natural (irregular) pulsing time intervals of FEL instability. In this process, the RF modulation (a longitudinal modulation) provides a regulation mechanism to stabilize the FEL pulsing (a form of chaos control). This new pulsed mode FEL operation (typically at tens of Hz, depending on e-beam energy) has been successfully used for certain nuclear physics experiments which demand a pulsed gamma-ray beam to achieve a significant reduction of the noise background [10].

GAMMA-RAY BEAM DEVELOPMENT

With newly realized electron beam and FEL beam capabilities, we were able to rapidly develop the corresponding new gamma-ray beam capabilities. For example, the 2-color FEL lasing has enabled us to produce a 2-color gamma-ray beam; and the pulsed FEL operation has led to a pulsed gamma-ray beam production. In the near future, we will focus on the development of high energy gamma-ray beams, first in the 100 to 120 MeV region, then toward 158 MeV for pion physics research. In this process, we need to push the accelerator hardware and equipment further into the region that these devices were not originally designed for. For example, we need to further increase the magnetic field of the OK-5 helical wigglers by operating them up to 4.0 kA beyond the already extended maximum operational current of 3.5 kA (the design specification was 3.0 kA). The preliminary test has been carried out successfully for this high current operation [11] with colder incoming cooling water. This new mode operation will become feasible with a planned cooling water system upgrade in the coming year.

The push toward the higher gamma-ray energies also requires us to reassess the possibility to extend the storage ring operation above 1.2 GeV (the original design energy was 1.0 GeV). While this energy extension remains very difficult without significant investment in hardware, even a small increase of the electron beam energy (5 to 10%) will be critical for the development of high-enemy gamma beams. We will also continue to develop durable, highly reflective FEL mirrors around 170 and 150 nm, but with a goal to produce next-generation FEL mirrors with substantially improved thermal conductivity to mitigate the heat loading problem when operating a large electron beam current in the VUV region. We expect to report progress at these fronts in the near future.

ACKNOWLEDGMENT

The author would like to thank the scientists, students, engineers and technical staff at the Duke FEL lab for their contribution to various research and development projects summarized in this paper.

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