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ACCELERATOR AND LIGHT SOURCE RESEARCH PROGRAM AT DUKE UNIVERSITY*

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Abstract

The accelerator and light source research program at Duke Free-Electron Laser Laboratory, TUNL, 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. With a maximum total flux of 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 highest-flux Compton gamma-ray source. Operated in the energy range from 1 to 120 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 work, we describe our recent light source development to enable the production of gamma rays in a new high-energy range: 100–120 MeV. We also summarize our recent research to develop new light source capabilities, including polarization control and orbital angular momentum beams.

INTRODUCTION

The accelerator-based light sources at the Duke Free-Electron Laser Laboratory (DFELL), Triangle Universities Nuclear Laboratory (TUNL) include a storage ring based free-electron laser FEL [1] and the FEL driven High Intensity Gamma-ray Source (HIGS) [2]. At the DFELL, we operate three accelerators: (1) a 0.16 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 the driver for both the Duke FEL and HIGS. The layout of the accelerator facility is shown in Fig. 1 and a list of key parameters of the booster injector and storage ring are summarized in Table 1.

The HIGS is a unique Compton gamma-ray source which employs a storage ring FEL as its photon drive (see Fig. 1). By colliding the electron beam and FEL beam inside a long optical resonator with high intracavity power, the HIGS can deliver a highly polarized gamma-ray beam (in either linear or circular polarization) while covering a wide range of energies from 1 to 120 MeV. The HIGS has demonstrated an unprecedented level of flux, with a maximum total flux of about 3×10^{10} γ/s around 10 MeV, making it the world's highest flux Compton gamma-ray source. The wide energy range combined with high flux performance makes the HIGS a unique and superior gamma-ray facility ideal for photonuclear physics research. Since 2008, the HIGS facility has been at the forefront of advancing low and medium energy nuclear physics using a real photon beam.

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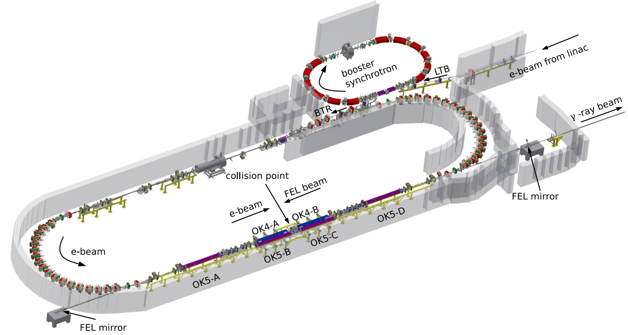

Figure 1: The layout of the HIGS accelerator facility with a linac pre-injector, a booster injector, and a storage ring. In the 34 m long FEL straight section, two helical OK-5 undulators are installed on the sides; in the middle section, an undulator switchyard system allows the use of either two planar OK-4 undulators or two helical OK-5 undulators. Compton gamma rays are produced in the center of the FEL cavity and transported in the electron beam's direction to the experimental areas.

Table 1: Parameters for Booster Injector and Storage Ring at HIGS

Parameter	Value
Booster Injector	(Main Injector)
Circumference [m]	31.902
RF frequency [MHz]	178.55
Number of RF buckets	19
Injection energy [GeV]	0.16
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 (≥ 0.6 GeV)
Two-bunch (HIGS)	~ 125 mA (≥ 0.5 GeV)
Duke FEL	(Undulator Switchyard)
Linear polarization	Two planar OK-4 undulators
Circular polarization	Four helical OK-5 undulators

STORAGE RING FEL DEVELOPMENT

At the HIGS, the new Compton gamma-ray beam capabilities are always derived from the new capabilities first developed for the FEL beam. For example, two-color FEL lasing [3, 4] has led to the development of two-color Comp-

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ton gamma-ray beam. In this section, we provide a summary of the most recent results from our storage ring FEL research and development program.

Precision Control of Linear Polarization

For precise control of photon beam's linear polarization, we have developed a novel method to produce the linearly polarized FEL beam using two helical OK-5 undulators operated with opposite helicities, but the same wavelength. By coherently mixing two circularly polarized undulator radiation components, a linearly polarized beam has been produced and amplified in the FEL cavity. The FEL beam's linear polarization can be precisely rotated to any desirable direction by tuning the buncher magnet sandwiched between the two OK-5 undulators [5, 6]. A critical instrument developed for this research is a dedicated FEL polarimeter without rotational optical elements to achieve high accuracy of about 10^{-3} for linear polarization measurements [6]. This has allowed us to explore a broad operational parameter space and achieve a very high degree of linear polarization, $P_{\text{lin}} = 0.997$, with a complete control of the direction of the linear polarization.

With this crossed helical undulator FEL, a linearly polarized Compton gamma-ray beam with a rotational polarization direction has been successfully generated. The gamma-beam polarization has been measured using a gamma-ray polarimeter. The measured degree of linear polarization of a 6 MeV beam is $P_\gamma = 0.971 \pm 0.015$ [5]. This novel polarization control technique will allow for not only the exploration of polarization-dependent nuclear observables but also a significant reduction of systematic errors in measurements.

Fast Helicity Switch

We have developed a new mode of the storage ring FEL operation with rapidly switchable circular polarization. In this mode, two OK-5 helical undulators in the middle of the FEL cavity (see Fig. 1) are powered with opposite helicities, with each of them capable of independently producing FEL lasing. By alternately setting the current of one undulator to produce FEL lasing while detuning slightly (typically by 6–8%) the current of the other undulator away from lasing, we can quickly switch the helicity of the FEL beam, up to about 10 Hz (as limited by the electron beam damping time). During the helicity switching, the FEL spectrum can be maintained with excellent consistency.

Using Compton scattering, we can also switch the helicity of the gamma-ray beam. The effort has been devoted to developing a set of operational procedures and control software tools to ensure the best consistency of the gamma-ray beam characteristics in two opposite helicities. Initial tests have demonstrated a high degree of consistency of the gamma-ray beam parameters during helicity switching, including its pointing direction, angular distribution, and energy spectral distribution. During the tests, an adjustment of the Compton collision angle is needed to compensate for a slight change in the electron beam orbit when the beam helicity is changed.

VUV Lasing Below 170 nm

The short wavelength operation of FEL oscillators is limited by the availability of high-reflectivity, thermally stable, and radiation-resistant FEL mirrors in the VUV wavelength. Fluoride-based multilayer coatings can be developed to have high reflectivity in the VUV region (200 to 150 nm). However, FEL mirrors with such coatings still suffer from thermal/mechanical instability and radiation damage due to intense synchrotron radiation. The main source of harmful radiation is the harmonic radiation from FEL undulators. With the OK-5 helical undulators, the harmonic radiation is emitted off-axis. To further limit this radiation incident on the downstream mirror, a water-cooled, in-cavity aperture system has been deployed to block the off-axis OK-5 radiation, typically in the UV to EUV region. This system is capable of reducing the amount of harmonic radiation incident on the front FEL mirror by as much as two orders of magnitude [7]. To further improve the thermal stability of the FEL cavity, sapphire is selected as the new substrate material for VUV mirrors because of its excellent thermal conductivity. The thermal contact between the FEL mirror and its holder has been improved by greatly increasing the contact areas on the side, front, and back of the mirror. The heat due to synchrotron radiation is then effectively conducted outside of the vacuum system using a holder made of a large copper (or aluminum) disk. The mirror mount assembly is actively cooled from outside using a compressed air vortex chiller.

Working with researchers from LZH [8], the Duke-LZH collaboration has developed and tested new fluoride-based, high-reflectivity 175 nm multilayer coatings. Using VUV FEL mirrors with a special evaporative fluoride multilayer coating LaF_3/MgF_2 protected by a SiO_2 top layer, we have achieved FEL lasing from 168.6 nm to 179.7 nm with excellent beam stability. This has set a new short-wavelength lasing record of 168.6 nm for oscillator FELs. Employing this VUV FEL in Compton scattering, we have produced the first 120 MeV gamma rays at the HIGS [9]. We have also tested the durability of these FEL mirrors by producing high-flux, circularly polarized gamma-ray beams at 86 MeV and 120 MeV for a nuclear physics experiment. This test has demonstrated that these 175 nm FEL mirrors are thermally stable and radiation robust with a useful life of more than 80 hours.

Orbital Angular Momentum Research Using FEL

In the recent decade, orbital angular momentum (OAM) beam research has flourished, benefiting from advances in laser and optics technologies. OAM beams have found a wide range of applications from atomic trapping to quantum information to lithography using conventional IR and visible lasers. The FEL can play a critical role to move OAM beam research into short wavelengths, from VUV to EUV to X-ray to gamma ray. Our research program has been focused on generating OAM beams using an FEL oscillator (Duke FEL). To generate OAM beams, the cylindrical symmetry

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of the FEL cavity transverse boundary is restored by using a spatial mask inside the cavity. This mask, comprised of a disk at the center and an annulus outside, is integrated with the downstream FEL mirror. Using carefully chosen disk sizes, we have produced coherently mixed OAM beams in the first few orders with the FEL lasing around 458 nm. The measured beam profiles have been carefully analyzed using a phase reconstruction method to reveal the complex optical phase front [10]. The measured beam intensity and reconstructed phase are found to be in good agreement with the corresponding calculated results. As part of this research project, we have developed a laser beam phase retrieval method which is suitable for short wavelengths [10] and a novel laser beam transverse mode analysis technique using Bayesian analysis [11, 12].

This research can lead to the generation of OAM gamma rays at the HIGS facility, which will open up new possibilities in photo-nuclear physics research.

STORAGE RING AND COMPTON GAMMA-RAY SOURCE DEVELOPMENT

For the storage ring research, we have focused on the study of intrabeam scattering, which can lead to a significant increase in the electron beam emittance and energy spread. We have developed a cost-effective, direct imaging transverse beam profile monitor for the Duke storage ring [13] with an excellent spatial resolution (about 30 μm). This system has been used to study the horizontal beam size growth over a wide range of electron beam energies and currents. A new beam profile monitor based on synchrotron radiation interferometry is being developed to measure the much smaller vertical beam size [14].

Since 2017, we have developed several new gamma-ray capabilities which are summarized in the following:

- Using high-reflectivity 190 nm oxide multilayer mirrors (sapphire substrates), we extended the HIGS operation into a new high-energy range of 100–110 MeV. Stable high-flux production was realized with active cooling of the FEL mirror from the outside;
- Using the aforementioned new fluoride multilayer mirrors, the HIGS operation was further extended to 120 MeV, with the expected highest energy reach of 130 MeV by using a new power supply configuration to raise the dc current of the OK-5 undulators;
- We developed a new mode of gamma-ray beam production with a low bremsstrahlung radiation background for a range of beam energies from 1.8 to 20 MeV; and
- We developed various techniques to control and manipulate the gamma-ray beam polarization; these new capabilities will be commissioned for user research.

The HIGS gamma-ray flux falls off steeply for gamma-ray energies below 10 MeV due to the scaling of FEL power with electron beam energy. To significantly boost the low-energy capabilities at the HIGS, we are working on a new Compton gamma-ray source concept, the HIGS2. With the HIGS2, the gamma-ray beam will be produced by colliding a high repetition-rate electron beam in the storage ring with a frequency matched laser beam inside a Fabry-Perot cavity, powered by an external laser. Compared to the HIGS, the HIGS2, a next-generation Compton gamma-ray source [15], is expected to substantially increase the gamma-ray flux by two to three orders of magnitude in 2–8 MeV, enable rapid polarization switch up to 100 Hz, and generate high-flux, high energy resolution gamma-ray beams (with the relative RMS resolution reaching 2×10^{-3}).

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