PERFORMANCE AND CAPABILITIES OF UPGRADED HIGH INTENSITY GAMMA-RAY SOURCE AT DUKE UNIVERSITY *

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Abstract

Since 2008, the upgraded High Intensity Gamma-ray Source (HIγS) at the Duke Free-Electron Laser Laboratory (DFELL) has provided users with gamma beams of unprecedented quality for scientific research. The recently completed accelerator upgrades include a higher-order mode damped RF cavity, a full-energy, top-off booster injector, redesigned storage ring straight sections, and a helical OK-5 FEL with two wigglers. The HIγS facility is now capable of producing high intensity gamma-ray beams in a wide energy range ($1 – 100$ MeV) using commercial optical resonator mirrors for a storage ring free-electron laser. It has achieved an exceptionally high flux, as high as 10^{10} γ/s total below 20 MeV, making it the most intensive Compton gamma-ray source available for scientific research. It produces almost 100% polarized gamma-rays, either linear or circular. Operated as the main accelerator facility by Triangle Universities Nuclear Laboratory (TUNL) since summer 2008, the HIγS is a dedicated Compton gamma source, capable of delivering more than $2,000$ hours of gamma-ray beam time per year with high reliability exceeding 95%. Future light source development at the HIγS focuses on extending the gamma-ray beam operation above the pion threshold energy and on realizing a fast switch of the gamma-ray beam helicity.

INTRODUCTION

The High Intensity Gamma-ray Source (HIγS) at Duke University is a new-generation accelerator-driven Compton gamma-ray source with a very high flux, a wide energy tuning range, and switchable polarizations. The high-intensity gamma-ray beam is produced at the HIγS by colliding an intense electron beam in the storage ring with a high power free-electron laser (FEL) beam inside an FEL resonator cavity. Since the first demonstration of the gamma-ray beam in 1996 [1], the HIγS facility has seen a large number of upgrades. In the recent years, the major accelerator upgrades included (1) the construction and operation of a $0.18 – 1.2$ GeV compact synchrotron as a full-energy, top-off booster injector for the storage ring; (2) the installation and operation of the helical OK-5 FEL with two wigglers [2]; (3) the development of new storage-ring straight section lattices, 34 m long each, to accommodate booster injection and to host the OK-5 FEL wigglers; (4) the installation and operation of the higher-order mode damped RF cavity system; and (5) the development of FEL beam and electron beam diagnostics and feedback systems, in particular, transverse and longitudinal bunch-by-bunch feedback systems [3]. In addition, major effort has been devoted to improving the performance of the FEL resonator by upgrading its mirror feedback system and by developing high-reflectivity FEL mirrors.

At the end of 2007, all major accelerator and FEL upgrades of the HIγS facility were completed. As the result of these upgrades, the HIγS reached an unprecedented level of performance, establishing itself as a premiere Compton gamma-ray research facility in the world [4, 5]. In the following sections, we will first describe the recent accelerator and FEL upgrades. We will then present the capabilities and performance parameters of the HIγS for the user research. Finally, we will outline our near-term development plan to increase the gamma-ray flux further at the lower energy end (< 20 MeV) and to extend the HIγS operation beyond the pion-threshold energy.

HIγS RELATED ACCELERATOR AND FEL DEVELOPMENT

Operation of the HIγS depends on a three-stage accelerator facility at Duke University. The first stage is a 0.18 GeV linac pre-injector with a photo-cathode RF electron gun for single-bunch injection into the booster synchrotron. As a second stage accelerator, the booster synchrotron is a $0.18 – 1.2$ GeV full energy, top-off injector, capable of single-bunch and multi-bunch operation. The third stage is a $0.24 – 1.2$ GeV storage ring which is used to power several storage ring based oscillator FELs.

One of the major accelerator upgrades was the development of a full-energy, top-off, booster injector [6]. The booster injector with a maximum extraction energy of 1.2 GeV is a very compact synchrotron with a circumference of 31.9 m. The booster synchrotron is operated as a full energy injector to the storage ring; its extraction energy can be chosen between its maximum value of 1.2 GeV and its minimum value of 0.18 GeV, the injection energy of the linac pre-injector. To minimize the injection loss induced radiation hazard, the booster was originally operated with a single-bunch injection scheme using a photo-cathode RF gun. In 2009, a multi-bunch booster injection was achieved with six bunches to increase the charge injection rate into the storage ring [6].

Since its initial operation in 2006, the booster has

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Table 1: . Parameters of the HIγS gamma-ray beam in the high-flux mode for user research (2009).

Parameter	Value	Comments
E-beam configuration	Symmetric two-bunch	
E-beam current [mA]	50 - 120	Total current
γ-ray energy, E_γ [MeV]		
With mirrors 1064 to 190 nm	1 – 100	With existing hardware
Total flux [γ/s]		
(a) No-loss mode ($\leq$ 20 MeV)		Both linear and circular
$E_\gamma = 1 - 2$ MeV	$1 \times 10^8 - 1 \times 10^{9(a)}$	
$E_\gamma = 2 - 20$ MeV	$1 \times 10^9 - 2 \times 10^9$	
(b) Loss mode (> 20 MeV)		Preferred Polarization
$E_\gamma = 21 - 100$ MeV	$1 \times 10^8 - 2 \times 10^{8(b)}$	Circular
Linear and Circular polarization	> 95%	Depending on collimator size

$^{(a)}$ The flux in horizontally polarization is higher with the OK-4 FEL than the flux in circular polarization due to the dynamic impact of OK-5 wigglers.
$^{(b)}$ The flux is currently limited by the capability of sustaining a high intracavity power by the FEL mirrors and electron injection rate.

played an essential role in enhancing the capabilities of the HIγS. In particular, the booster injector is critical for high gamma-ray flux operation in a so-call "electron-loss mode" above 20 MeV. In this mode, a substantial electron beam loss occurs due to a large energy loss of Compton scattered electrons. With the top-off injection, the booster periodically refills the storage ring to maintain a steady level of the electron beam current, hence the flux of the gamma-ray beam.

A high beam current per bunch is critical for the operation of the Duke storage ring FELs and HIγS. To increase the maximum single-bunch current, an advanced bunch-by-bunch longitudinal feedback system has been developed [3]. This system is particularly useful to maintain stable two-bunch HIγS operation with a high beam current (60 – 80 mA in two bunches) for low-energy electron beam operation ($<$ 350 MeV) and for higher cavity-loss, ultraviolet (UV) FEL operation in which substantial longitudinal motion can be excited by FEL power fluctuation.

The wide energy tuning of the HIγS gamma-ray beam, a factor of about 100, can be realized by changing the electron beam energy (a factor of about 4) and by changing the photon energy of the FEL (a factor of more than 5). The operation energy range of the storage ring has been extended from 0.27 – 1.0 GeV before upgrades, to 0.24 – 1.2 GeV after upgrades. The choice of polarization of the HIγS beam is realized by using either the planar OK-4 FEL or helical OK-5 FEL. Because two OK-4 wigglers and two OK-5 wigglers are installed in the same straight section, we can switch from linear polarization to helical polarization in minutes. In addition, a faster (tens of seconds) gamma-ray beam helicity switch system between left- and right-polarizations is being developed for user operation.

The OK-4 FEL and OK-5 FEL can be operated in two different configurations. The first one is a standard two-wiggler optical klystron aimed for a higher FEL gain. This configuration is useful for lasing at UV wavelengths with a relatively high FEL optical resonator loss. The second one is the one-wiggler conventional FEL configuration with a low-loss FEL resonator, typically at visible and infrared wavelengths. This configuration is particularly useful to increase the intracavity FEL power for high gamma-flux operation. We also choose this one-wiggler configuration to reduce the thermal power loading on, and radiation damage to the downstream FEL mirror caused by wiggler harmonic radiation.

Two additional developments are also critical for realizing high performance of the HIγS. The first one is the development of an in-cavity, water-cooled, remotely controlled aperture system with two independent apertures, one horizontal and the other vertical [7, 8]. The aperture system has been successfully used in a wide range of wavelengths (from 1064 to 265 nm) to reduce the thermal loading on the downstream FEL mirror by blocking much of off-axis higher harmonic radiation from helical wigglers. This has enabled us to operate the HIγS with a higher electron beam current. The second development is the high-reflectivity FEL mirrors. By reducing radiation damage to the downstream FEL mirror, a high-Q FEL resonator has been realized with a total round-trip loss about 0.1% for sustained gamma-ray beam operation.

HIγS OPERATION MODES AND CAPABILITIES

To support various research applications, several modes of operation have been developed for the HIγS. The HIγS can be operated to produce gamma-ray beams either in a quasi continuous-wave (CW) mode or in a pulsed mode; it can also be run in either a high-flux mode or in a high energy-resolution mode. With a total of four different operation modes, the HIγS has the flexibility to support a variety of user research programs which have different requirements for the pulse structure, flux, and energy-resolution. The quasi-CW, high-flux operation is the main operation mode for the majority of nuclear physics experiments conducted at the HIγS.

The fully upgraded HIγS facility was brought to user operation in 2007 with its performance exceeding the design specifications for the upgrades. The main operation parameters of the HIγS accelerators and FELs are found in Ref. [4]. Since 2007, the performance of the HIγS has been improved further in two areas. Below 20 MeV in the so-called "no-loss mode" in which the Compton scattered electrons are retained in the storage ring, the total gamma-beam flux has been further increased to about 1×10^{10} γ/s around 10 MeV. In the "electron-loss mode" above 20 MeV, highly stable high-flux gamma beam operation has been achieved. These successes can be attributed to the development of three new subsystems: the top-off booster injector, longitudinal feedback, and in-cavity aperture system. The HIγS gamma-ray beam performance parameters for user research in the CW, high-flux mode are summarized in Table 1. The listed gamma-flux performance for user operation is conservative; this allows us to continue the development of the higher flux operation to ensure sustained gamma-ray beam production with a reasonable FEL mirror lifetime. The gamma-beam flux on the experimental apparatus is a function of gamma-ray beam collimation. Typically, for a collimated gamma-ray beam with a 3% FWHM energy spread, the flux after the collimator is about 4.5% of the total flux given in Table 1. Currently, the maximum gamma-beam energy at the HIγS is limited to about 100 MeV due to the availability of high-reflectivity commercial FEL mirrors at the shortest wavelength of about 190 nm. The gamma-beam energy tuning range of the HIγS for several FEL wavelengths is shown in Fig. 1.

NEAR-TERM UPGRADES AND DEVELOPMENT

To extend the HIγS operation toward and beyond the pion-threshold energy of about 150 to 160 MeV, radiation-resistive 150 nm FEL mirrors with reasonably high reflectivity ($> 90\%$) should be developed. By closely collaborating with commercial optics companies, it is hopeful that durable 150 nm mirrors with a high reflectivity will become available in the next few years. Above 150 MeV gamma-ray operation with circular polarization will also require the installation of two additional OK-5 wigglers so that a long helical FEL with four OK-5 wigglers can be developed for a higher gain operation. To retain the linear polarization capability of the HIγS, a switch-yard system will be developed to mechanically switch between two planar OK-4 wigglers and two helical OK-5 wiggler in the middle of the FEL straight section.

SUMMARY

The HIγS facility is a new-generation, dedicated Compton gamma-ray facility with a wide energy range from 1 MeV to 100 MeV, switchable polarizations, and an unprecedented flux. The HIγS is capable of delivering more than $2,000$ hours of gamma-ray beam time per year with high reliability ($> 95\%$) using a five-day, two-shift operation schedule limited by the staffing level. Given these outstanding features, the HIγS is a world-class Compton gamma-ray source for a wide range of scientific research in nuclear physics, astrophysics, medicine, and industrial applications.

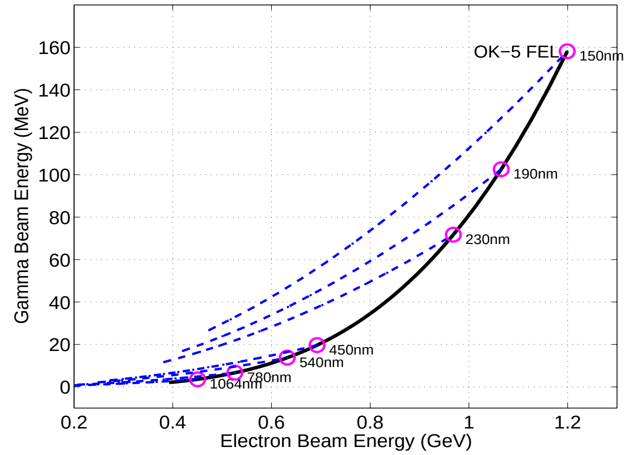

Figure 1: The energy tuning range of the circularly polarized γ-ray beam with the OK-5 FEL from 1064 nm down to 150 nm. A set of radiation resistive FEL mirrors with a high reflectivity at 150 nm are necessary to reach the highest gamma-beam energies – about 158 MeV with the existing 1.2 GeV storage ring. For a given FEL wavelength, the highest gamma energy is determined by the highest electron beam energy for FEL lasing as limited by the maximum magnetic field of the wigglers. The thick black curve shows the maximum gamma energy as a function of the electron beam energy. The blue dashed curves are the gamma energy tuning curves for a fixed FEL wavelength.

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