A VUV FEL FOR PRODUCING CIRCULARLY POLARIZED COMPTON GAMMA-RAY BEAMS IN 70 TO 100 MEV REGION [*]

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Abstract

Recently, the Duke optical klystron FEL (OK-5 FEL) was commissioned to produce lasing in the VUV region (190 – 195 nm), overcoming substantial laser cavity loss due to low reflectivity of the VUV FEL mirrors. With two OK-5 FEL wigglers separated by more than 20 meters (a non-optimal configuration), adequate FEL gain was realized by operating the Duke storage ring with a high single-bunch current (30 to 50 mA). This VUV FEL has enabled us to produce circularly polarized Compton gamma-ray beams in the 70 to 100 MeV region at the High Intensity Gamma-ray Source (HIGS) at Duke University. This high energy gamma-ray beam capability will create new opportunities for both fundamental and applied research at HIGS. In this work, we report our preliminary results on VUV FEL lasing with a high single-bunch current and first production of gamma-ray beams in the 70 to 100 MeV region.

INTRODUCTION

The accelerator facility at the DFELL consists of three accelerators: (1) a linac pre-injection (0.18 – 0.27 GeV); (2) a full-energy, top-off booster injector (0.18 – 1.2 GeV); and, (3) an electron storage ring (0.24 – 1.2 GeV). The Duke storage ring is a dedicated accelerator driver for several different FEL oscillator configurations [1]. The Duke FEL (Fig. 1) has been used to power a world-class Compton gamma-ray source, the High Intensity Gamma-ray Source (HIGS) [2], with a maximum gamma-ray flux of more than 2×10^{10} gamma/s around 10 MeV.

The energy of the HIGS gamma-ray beam is changed by varying the energy of the electron beam and wavelength of the FEL beam. The maximum magnetic field of the FEL wiggler determines the highest possible energy for the gamma-ray beam which can be produced with a particular pair of narrow-band FEL mirrors. Using a set of high-reflectivity mirrors with wavelengths from 1060 nm to 240 nm, and with the help of a higher injection energy enabled by the full-energy, top-off injector, high intensity gamma-ray beams from 1 to 60 MeV have been produced for various research programs in recent years. To cover the next energy range of 70 to 100 MeV, the FEL needs to be operated in the VUV wavelength region around 190 nm. While lasing around 193.7 nm was first demonstrated with the OK-4 FEL in 1999 [3], at the time no attempt was made to produce high energy Compton gamma-ray beams due to rapid mirror degradation and lack of a full-energy injector.

In the recent years, three major developments have enabled the operation of the HIGS with a high beam current and at a high electron beam energy. The first one is the construction of a booster synchrotron as the full-energy injector to the storage ring. The second is the installation of two helical OK-5 FEL wigglers in the FEL straight section on the outside of the planar OK-4 wigglers (see Fig. 1). The third is the development of an in-cavity aperture system. Recognizing that high-harmonic radiation of a helical wiggler is off-axis, a laser aperture system has been developed with four independently controlled aperture poles to block most of off-axis radiation from helical wigglers [4]. Using these systems at a low electron beam energy (below 700 MeV), we have successfully run a very high electron beam current (90 – 110 mA in two bunches) to produce an unprecedented level of gamma-beam flux; at a high electron beam energy (above 700 MeV), we have been able to operate with a reasonably high beam current (50 – 80 mA in two bunches) to reach a maximum gamma-ray flux, which is limited by the electron beam injection rate of the top-off booster injector. With the early experience of 194 nm lasing (in 1999) with the OK-4 FEL, the capability of high flux gamma-ray beam operation in the 70 and 100 MeV region with the OK-5 FEL was projected. This was based on the assumption of the future availability of high reflectivity 190 nm FEL mirrors, as the OK-5 FEL in the present configuration has a much lower gain than the OK-4 FEL for a given electron beam current.

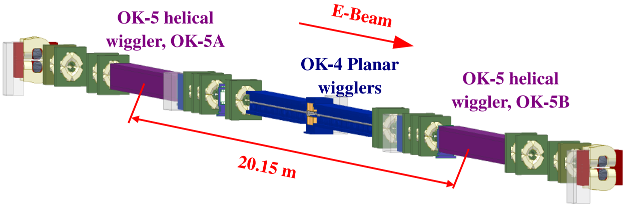

Figure 1: The existing layout of the four FEL wigglers in the straight section of the Duke storage ring. Two OK-4 planar wigglers are located in the middle of the section, and two OK-5 helical wigglers on the sides, separated by more than 20 meters.

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Table 1: OK-5 Wiggler Parameters. OK-5 wigglers are electromagnetic and the maximum field value shown is that at 3.5 kA of DC current.

Parameters	**OK-5**
Polarization	Circular
No. of wigglers	4 (2 installed)
No. of regular periods	30
Wiggler periods (cm)	12
Wiggler gap (mm)	40×40
Max. magnetic field (kG)	3.17
Max. wiggler K	3.53

VUV LASING AROUND 190 NM

The 190 nm high-reflectivity FEL mirrors are produced by a German vendor [5]. These are dielectric mirrors with an oxide multilayer coating applied using the ion-beam sputtering (IBS) technique. The mirror reflectivity around 190 nm is about 98% with a transmission of about 0.3%. To produce an optical beam with a small waste size for Compton scattering (and for enhanced FEL interaction in the OK-4 FEL configuration), a near concentric resonator is used. In addition to stringent specifications for surface quality, the the FEL mirrors have to be made with a precise radius of curvature slightly longer than the half length of the FEL cavity. For the FEL mirrors used in the recent 190 nm lasing test, the measured radius of curvature is about 27.4 m. To enhance the FEL gain, the OK-5 FEL is configured in the optical klystron mode with two OK-5 wigglers which are spatially separated by more than 20 m (see Fig. 1).

The study of the VUV FEL requires a set of designated optical diagnostics which need to be enclosed in a vacuum system or a nitrogen-purged system. To keep the cost down, we have developed a compact nitrogen-purged FEL diagnostic system which allows us to measure the FEL spectrum, extracted power, and beam image. This system is designed with flexibility; it can be extended to allow additional diagnostic substations to be attached.

The 190 nm lasing test was carried out in September, 2010 during a two-day window between user operations. The OK-5 FEL lasing was first achieved with a 750 MeV single-bunch electron beam around 191 and 192 nm. The threshold current for lasing was about 20 mA. By changing the wiggler magnetic field, FEL wavelength tuning was demonstrated from 190.2 nm to 194.3 nm (see Fig. 2). During 190 nm FEL operation, the horizontal and vertical apertures were closed to form a minimal opening of 10 mm (full gap) in order to block most of off-axis radiation from reaching the downstream FEL mirror.

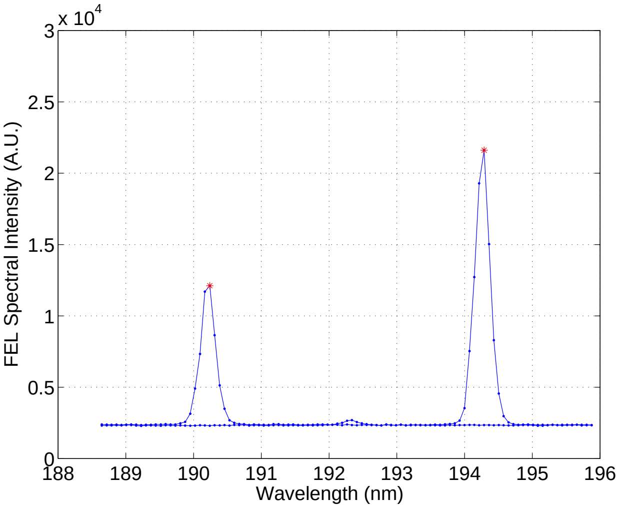

Figure 2: Two measured lasing spectra around 190 and 194 nm by tuning the magnetic field of the OK-5 FEL. The electron beam energy is 750 MeV. The range of the single-bunch beam current is from 35.5 mA to 31 mA during the search for the lasing wavelength tuning range.

During the two-day FEL lasing test around 190 nm, the OK-5 FEL was operated at three energies, 700 MeV with a single-bunch beam, and 900 and 1040 MeV with a two-bunch beam. At the end of the test, the cavity loss was measured using the turn-by-turn cavity power ring-down technique (see Fig. 3). The measurement showed that the one-turn cavity loss was about 5% after about 20 hours of FEL operation, or an integrated current-time of about 1.1 ampere-hours. The measured loss of 5% per pass is larger than the projected loss of about 4% with new mirrors using the data from the vendor. Furthermore, an increase of lasing threshold current was observed over the two-day period. However, there was no strong evidence for significant reflectivity degradation of these 190 nm mirrors after about 20 hours of FEL operation.

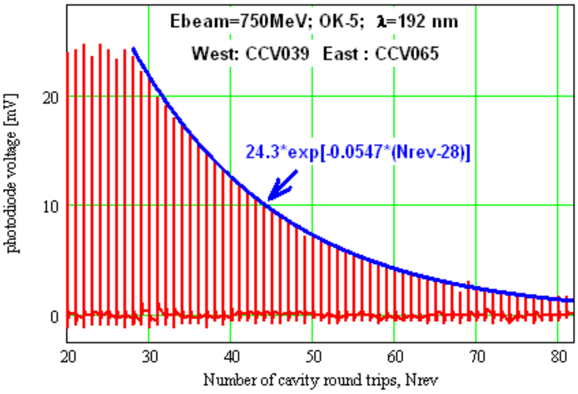

Figure 3: The measured turn-by-turn FEL power ring-down showing a one-turn cavity loss of about 5%. The electron beam energy is 750 MeV, and FEL wavelength is 192 nm.

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CIRCULARLY POLARIZED GAMMA-RAY BEAMS: 70 – 100MEV

By achieving lasing with the OK-5 FEL around 192 nm for the first time, a milestone in developing new gamma-ray beam capabilities at HIGS was reached. By changing the storage ring energy from 0.9 to 1.04 GeV, circularly polarized gamma-rays were produced in a range of energies from 70 MeV to 100 MeV. Operating the storage ring at 1.04 GeV and with a total stored electron beam current of 75 mA in two bunches, a gamma-ray beam with a total intensity of about 2×10^7 gammas/sec (in the 4π solid angle) was generated. This flux was produced with an uneven two-bunch beam; the lasing bunch had a higher bunch current of about 54 mA while a non-lasing bunch had a lower beam current of about 21 mA. Due to a very high lasing threshold current (> 21 mA), the FEL power was relatively low with an estimated average intracavity power of about three watts for Compton scattering.

Through a 12 mm diameter collimating aperture, the gamma-ray beam with a peak energy around 97 MeV was delivered to the HIGS target room with an intensity of 1.3×10^6 gammas/sec. After going through several copper attenuators, the gamma beam was sent to a large NaI detector for the spectral measurement. A measured gamma-ray beam spectrum around 100 MeV is shown in Fig. 4.

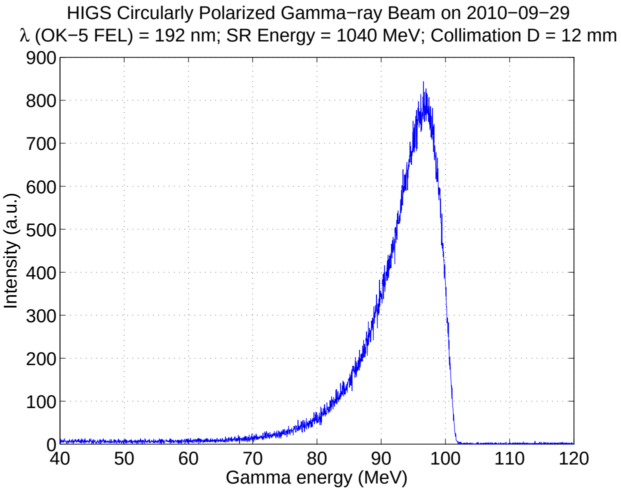

Figure 4: The measured Compton gamma-ray spectrum with a peak energy about 97 MeV. The electron beam energy is about 1.04 GeV and the FEL wavelength is 192 nm. The gamma-ray beam is collimated by using a lead collimator with a 12 mm diameter aperture.

SUMMARY

Presently, the OK-5 FEL configuration is not optimal with the two OK-5 wigglers separated by more than 20 meters in the straight section. This results in to a low FEL gain and a low intracavity optical power. This situation will be changed dramatically after we complete the FEL upgrade in 2012 with a wiggler switchyard system. The wiggler switchyard will preserve the linear polarization capability of photon beams (FEL beam and gamma-ray beam) produced by the OK-4 system. When the OK-4 system is not used, two additional OK-5 wigglers can be moved into the middle section of the FEL resonator to substantially increase the gain and power of the OK-5 FEL operation. With this configuration, a symmetric and even-charge two-bunch beam can be used to produce a higher average FEL power. With this optimal FEL wiggler configuration, an increase of the gamma-ray beam intensity by a factor of 5 or more is projected.

The successful production of circularly polarized gamma rays between 70 and 100 MeV at the HIGS facility has opened new opportunities for studies of the internal structure of nucleons. Important experiments involving Compton scattering on the proton, the deuteron and ^6Li, all designed to obtain precise measurements of the electric and magnetic polarizabilities of the nucleons, can now be performed at the HIGS facility. These programs and programs measuring spin polarizabilities of the nucleons will be greatly enhanced by our continued effort to develop gamma-ray beams above 100 MeV.

In the next two years, with the upgraded FEL system with two additional helical wigglers installed in the middle section of the FEL straight, we expect to extend gamma-ray beam production to 150 MeV (or higher), above the pion threshold energy. Such high energy gamma-ray beams will create new opportunities for scientists to study chiral dynamics via photo-pion production.

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