ACCELERATOR PHYSICS RESEARCH AND LIGHT SOURCE DEVELOPMENT PROGRAMS AT DUKE UNIVERSITY *

Y. K. Wu†
Department of Physics, Duke University, Durham, NC 27708-0319, USA

Abstract

The Duke Free-Electron Laser Laboratory (DFELL) has recently completed two major accelerator/light source development projects — we successfully commissioned the world's first distributed optical klystron FEL (DOK-1 FEL) and a new 0.24 – 1.2 GeV booster synchrotron. The DOK-1 FEL has a much improved FEL gain compared with two-wiggler optical klystrons. This allows the DOK-1 FEL to become a versatile light source for UV-VUV operation and as a driver for a high-flux Compton gamma-source. The top-off booster injector for the Duke storage ring is part of the upgrade project of High Intensity Gamma-ray Source (HIGS), a facility jointly developed by the DFELL and Triangle Universities Nuclear Laboratory. The accelerator and light source development has created new opportunities for accelerator physics research. In this paper, we will report our recent progress in accelerator and light source development as well as the ongoing accelerator physics research programs at the DFELL.

INTRODUCTION

The light source research and development program at the Duke Free-Electron Laser Laboratory (DFELL) focuses on the UV-VUV FEL research and the development of a unique Compton gamma-ray source, the High Intensity Gamma-ray Source (HIGS). The main driver for these light sources is a 0.24 to 1.2 GeV electron storage ring which was first brought into operation in 1994. The recent light source development and upgrade projects include (1) the development and commissioning of world's first distributed optical klystron FEL, the DOK-1 FEL; (2) the development and commissioning of a very compact a 0.24–1.2 GeV booster synchrotron for top-off injection into the storage ring. Employing four wigglers, two circular and two planar, the DOK-1 FEL has achieved the highest gain operation among all storage ring based FELs and demonstrated controlled polarization switches of the FEL beam by a nonoptical means through the manipulation of a buncher magnet [1]. Commissioned in 2006 [2], the new booster synchrotron has greatly increased the beam performance of the storage ring, resulting in much increased single-bunch current and steady beam current operation in the continuous injection mode. These two major accelerator projects have led to several notable developments at the DFELL including (a) new and more reliable techniques to measure the storage ring FEL gain and FEL optical cavity loss [1]; (b) a versatile physics-based EPICS control system and a robust beam diagnostics system for the booster synchrotron [3, 4, 5]; and (c) the development of transverse and longitudinal coupled-bunch feedback systems [6, 7]. The ongoing accelerator physics research and development programs are in the areas of (a) FEL physics research; (b) beam instability research; (c) polarized electron beam research; and (d) the development of a longitudinal feedback system for the storage ring. As of spring 2007, the upgraded Duke storage ring light source facility (see Fig. 1), including the new booster synchrotron, several configurations of FELs (OK-4 FEL, OK-5 FEL, and DOK-1 FEL), and the upgraded HIGS, were operational for the user programs.

* Supported by US AFOSR MFEL grant FA9550-04-01-0086, U.S. DOE grant DE-FG02-01ER41175, and U.S. DoE grant DE-FG05-91ER40665.
† wu@fel.duke.edu

FEL DEVELOPMENT AND RESEARCH

Recent FEL research program at the DFELL has been focused on developing the storage ring based high gain distributed optical-klystron FEL. In 2005, we commissioned the DOK-1 FEL, a hybrid distributed optical-klystron, with two horizontally polarized wigglers and two circularly polarized wigglers [1, 8]. The horizontally polarized wigglers, two older OK-4 wigglers, are located in the middle of the 34 m long straight section; the circularly polarized wigglers, two newly developed OK-5 wigglers, are located either upstream or downstream from the OK-4 wigglers (see Fig. 1). In 2005, with the DOK-1 FEL, we realized the highest FEL gain among all storage ring FEL oscillators at about 47% per pass at 450 nm [1]. The much improved FEL gain will allow us to push the wavelength limit of the Duke FEL below 190 nm, deep into the VUV regime. This is critical for both the FEL application research programs and for certain nuclear physics programs which require high energy gamma-ray beams above 90 MeV. The DOK-1 FEL is also a very versatile coherent light source. In 2005, by changing the electron beam pathlength between two sets of wiggles with different polarizations using a buncher magnet, we demonstrated the polarization switch of the FEL beam [1]. Further development is needed in this area to achieve a better control of polarization manipulation at a higher repetition rate (1s to 100s Hz). An FEL with rapidly switchable polarizations is expected to have important applications in materials science and biophysics.

With the new booster injector, the electron beam can now be injected into the storage ring at any energy between 0.24 and 1.2 GeV. A higher injection energy has allowed us to significantly improve the single-bunch capabilities (see the section below). A higher single bunch current creates new opportunities to operate Duke FEL in many different con-

1-4244-0917-9/07/$25.00

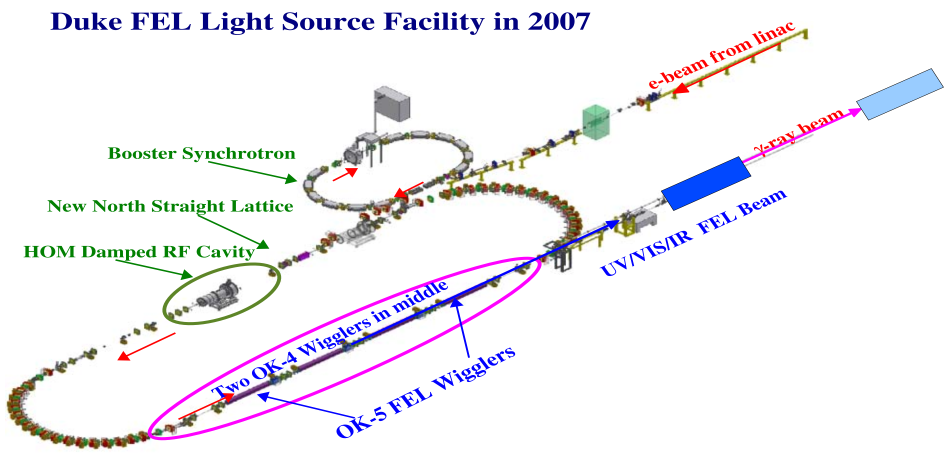

Figure 1: The fully operational Duke light source facility in 2007. The upgrades since 2005 include a newly commissioned 0.24 to 1.2 GeV booster synchrotron for top-off injection, a new 34 meter long storage ring straight section in the north, and a newly commissioned OK-5 FEL and DOK-1 FEL in the south straight section.

figurations, including: (1) the OK-4 optical-klystron FEL with two horizontally polarized OK-4 wigglers in the center of the FEL cavity; (2) the OK-5 optical-klystron FEL with two circularly polarized OK-5 wigglers separated by more than 20 m; (3) a conventional planar FEL with one OK-4 wiggler; and (4) a conventional circular FEL with one OK-5 wiggler. With the newly gain freedom of FEL configurations, we have proposed to develop a novel multicolor FEL at Duke [9]. This new light source will open doors to many applications research programs from chemistry to biology to nuclear physics.

TOP-OFF BOOSTER SYNCHROTRON

The High Intensity Gamma-ray Source is a facility jointly developed by the DFELL and Triangle Universities Nuclear Laboratory (TUNL). The corner-stone of the recent HIGS upgrade is the development of a new 0.24–1.2 GeV top-off booster synchrotron for the Duke storage ring. Before this upgrade, the Duke storage ring utilized a low energy linac injector at 0.27 GeV. For user operations above this energy, the electron beam energy was slowly ramped up in the storage ring, which reduced the operation efficiency. Without a full energy injector, the HIGS was not able to be operated with a sustained high gamma flux in the electron-loss mode with the gamma-ray energy above 20 MeV. In this mode, the Compton scattered electrons are lost after losing a large amount of energy, more than what is sustainable by the available energy aperture of the storage ring. Furthermore, due to long damping times (on the order of a second at the linac energy of 0.27 GeV), the single-bunch current was typically limited to less than 20 mA due to a variety of beam instabilities. The low single-bunch current had prevented high gain and high power operation of the FEL and limited the flux performance of the HIGS. The main goals of the recent HIGS upgrade are: (1) to enable high energy gamma operation in the loss mode by replenishing the lost electrons using a top-off booster injector; (2) to improve the FEL and HIGS performance with a higher single-bunch current.

This new booster is a very compact synchrotron with a circumference of 31.9 m and a maximum dipole field of 1.76 Tesla at 1.2 GeV. Because of its compact size, the effect of magnetic saturation is rather significant at higher beam energies. Elaborate orbit, tune, and chromaticity compensations are necessary to enable this booster to operate over a wide energy range. The booster is also designed to allow beam extraction at any energy between 0.24 and 1.2 GeV with a fast kicker (25 Hz) for extracting electron bunches individually. In addition, the booster injection (or extraction) scheme utilizes one vertical kicker, which requires certain complex injection (or extraction) orbit bump arrangements due to a very limited vertical aperture. Because of these unusual requirements which pushes several technical limits, the development of this booster injector has been a challenge.

To meet this challenge, we used several novel approaches. First, we developed this booster as an accelerator with dual operation modes: (1) as a storage ring; (2) as an energy ramping synchrotron. This allowed us to commission the booster as a storage ring at a given energy, perform lattice compensations, and project the lattices at higher energies. By repeating this process for a number of energies, slices of the commissioned lattices were used to build up energy ramping tables for all power supplies. These tables were then successfully used for booster ramping. Second, the field compensation scheme for magnets was developed and then implemented in the low level controls of the EPICS based control system [3, 11, 12]. This allowed the magnet saturation effects to be taken care of at the appropriate level while presenting to the user a higher level control which is independent of the beam energy. Third, power supplies were developed and tuned to allow smooth energy ramping [10, 11] in the booster. Fourth, a set of well thought-out beam diagnostics systems were developed

 1-4244-0917-9/07/$25.00

for the booster and related beam transport lines [4, 5]. The above measures were critical for successful commissioning of the booster synchrotron in 2006.

The booster has been used successfully in the top-off operation. Fig. 2 shows a period of top-off injection in the two-bunch operation mode for gamma-ray production with a 459 MeV electron beam. The peak-to-peak variation of the storage ring beam current is kept to about 0.4 mA or 0.6% of the stored beam current of 65 mA. The top-off injection has also been used to demonstrate the sustained operation of 40 MeV gamma-ray beams with a high flux in the electron loss mode with a 790 MeV electron beam.

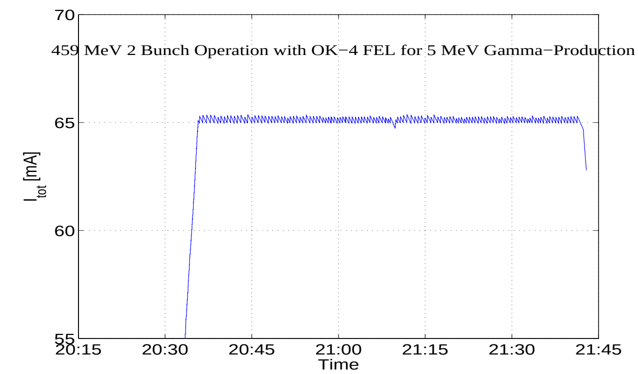

Figure 2: Measured electron beam current in the storage ring with top-off injection. The beam current at 459 MeV was recorded during the production of 5 MeV gamma-ray beams in the two-bunch operation.

The FEL research and user operation have also been significantly benefited from this full energy booster injector. The single-bunch current is significantly increased; with the booster we have demonstrated a maximum single-bunch current of about 70 mA with the help of FEL lasing. An even higher current is possible but is hardware limited — the BPM pickup voltage need to be reduced to avoid damage to the BPM electronics modules at very high single-bunch current [13].

ACCELERATOR PHYSICS PROGRAMS: PRESENT AND NEAR FUTURE

In addition to the light source development programs, we have carried out and will continue to carry out a number of accelerator physics research programs in the near future. In the area of beam instability research, we have developed systems to study the onset of microwave instability by directly measuring the changes of the beam energy spread in the storage ring [14]. These measurements will be compared with direct bunch-length measurements. In addition, a longitudinal couple-bunch feedback system is under development which will enable us to operate a high multi-bunch current at low beam energies [6, 7]. On the FEL research, we are developing various optical diagnostics system to better understand the startup process and power scaling of various forms of the storage ring FEL oscillators, from conventional FEL, to optical-klystron, to distributed optical-klystron. We are also in the process of developing a multi-color FEL which will have many novel applications. We also have an on-going research program to study the polarized electron beam in the storage ring. This program aims at measuring the degree of the electron beam polarization with a novel optical detection system [15] and at measuring the absolute energy of the electron beam in the storage ring using the resonant spin-depolarization process.

We would like to thank all DFELL scientific, engineering, and operation staff for their contributions to the very successful accelerator research and development programs in the last two years.

REFERENCES

[1] Y. K. Wu *et al.*, Phys. Rev. Lett., 224801 (2006).

[2] S. F. Mikhailov *et al.*, “Commissioning of the Booster Injector Synchrotron for the HIGS Facility at Duke University,” these proceedings, PAC2007.

[3] S. Hartman *et al.*, “A Physics Based Approach for Ramping Magnet Control in a Compact Booster,” these proceedings, PAC2007.

[4] V. Popov *et al.*, “Electron Beam Diagnostics for a 270 MeV Linac and a Compact 1.2 GeV Booster Synchrotron,” these proceedings, PAC2007.

[5] Y. K. Wu *et al.*, “A tune measurement system for low current and energy ramping operation of a booster synchrotron,” these proceedings, PAC2007.

[6] Y. K. Kim *et al.*, “New Generation Digital Longitudinal Feedback System for Duke FEL and HIGS Facilities,” these proceedings, PAC2007.

[7] Y. K. Kim *et al.*, “Growth Time of Longitudinal Coupled Bunch Mode Instability in the Duke FEL Facility,” these proceedings, PAC2007.

[8] Y. K. Wu *et al.*, Proceedings of 2005 FEL Conference, p. 407 (2005).

[9] Y. K. Wu, first presented in an invited talk at Center for Advanced Studies of Accelerators (CASA), Jefferson Lab, Aug, 2006.

[10] V. Popov *et al.*, “Power Supply System for a Compact 1.2 GeV Booster Synchrotron,” these proceedings, PAC2007.

[11] S. F. Mikhailov *et al.*, “Challenges for the Energy Ramping in a Compact Booster Synchrotron,” these proceedings, PAC2007.

[12] J. Li *et al.*, “Compensation of the Beam Dynamics Effects Caused by the Extraction Lambertson Septum of the HIGS Booster,” these proceedings, PAC2007.

[13] J. Li, P. Wang, Y. K. Wu, “BPM signal conditioning for a wide range of single bunch current operation in Duke storage ring,” these proceedings, PAC2007.

[14] S. Huang, J. Li, Y. K. Wu, “A direct electron beam energy spread measurement system for Free-Electron Laser and beam instability research,” these proceedings, PAC2007.

[15] C. Sun and Y. K. Wu, “The Feasibility Study of Measuring the Polarization of a Relativistic Electron Beam using a Compton Scattering Gamma-Ray Source,” these proceedings, PAC2007.

1-4244-0917-9/07/$25.00