ACCELERATOR PHYSICS RESEARCH AND DEVELOPMENT PROGRAMS AT DUKE UNIVERSITY *

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Abstract

The light source research program at the Duke Free-Electron Laser Laboratory (DFELL) is focused on the development of accelerator-driven light sources, including storage ring based free-electron lasers (FELs) and Compton gamma-ray source, the High Intensity Gamma-ray Source (HIγS). The HIγS is the most intense Compton gamma-ray source currently available with an energy tuning range from 1 to 100 MeV. The accelerator physics program at the DFELL covers a wide range of activities, from nonlinear dynamics research, to the study of beam instability with advanced feedback systems, to FEL research and development. In this paper, we will report our recent progress in accelerator physics research and light source development to meet new challenges of today's and future accelerators.

INTRODUCTION

At the Duke Free-Electron Laser Laboratory (DFELL), the focus of accelerator research and development programs is the storage ring based free-electron lasers (FELs) [1] and Compton gamma-ray sources. The accelerators used to drive both the FEL and Compton gamma-ray source include (1) a 0.18 – 0.27 GeV linear accelerator pre-injector; (2) a 0.18 – 1.2 GeV full-energy, top-off booster injector; and (3) a 0.24 – 1.2 GeV electron storage ring. Since its commissioning in 2006 [2, 3], with a higher injection energy, the booster injector has greatly increased the beam current capability of the storage ring and substantially improved the reliability of the storage ring based light sources. The key parameters of the Duke booster injector and storage ring are summarized in Table 1.

In the 34 m long FEL straight section of the storage ring, four FEL wigglers are installed, including two planar OK-4 wigglers and two helical OK-5 wigglers (see Fig. 1). With these wigglers, we can configure several FELs to produce photon beams with different polarizations: (1) a linearly polarized OK-4 FEL with a one-wiggler configuration for higher power operation or a two-wiggler optical klystron FEL for higher gain operation; (2) a circularly polarized OK-5 FEL with one wiggler or two wigglers; and (3) a mixed-polarization high-gain distributed optical klystron FEL (DOK-1) with all four wigglers [1]. The OK-4 and OK-5 FELs are used as the photon source for the High Intensity Gamma-ray Source (HIγS) [4] by colliding the high power FEL beam inside the FEL resonator with an intense electron beam in the storage ring.

In 2008, the DFELL was merged with the Triangle Universities Nuclear Laboratory (TUNL) to become the largest on-campus accelerator facility of the TUNL. A variety of nuclear physics research programs have been developed to take advantage of the unprecedented gamma-ray beam performance of the HIγS. In the following sections, we describe the progress made since 2007 in the areas of accelerator physics research and light source development at the DFELL.

Table 1: Main accelerator and beam parameters for the Duke booster injector and storage ring (2009).

Parameter	Value	Comments
Booster Synchrotron		
Circumference [m]	31.902	
RF frequency [MHz]	178.55	
Number of RF bucket	19	
Injection energy [GeV]	0.18 – 0.27	
Extraction energy [GeV]	0.18 – 1.2	
One-bunch		
Cycle time [s]	1.8 – 2.0	
Extraction rate [nC/s]	0.05 – 0.06	
Six-bunch		
Cycle time [s]	3.5 – 5.5	
Extraction rate [nC/s]	0.20 – 0.35	
Storage Ring		
Operation energy	0.24–1.2 GeV	
Circumference	107.46 m	
RF frequency	178.547 MHz	
Number of RF buckets	64	
Max beam currents		
One-bunch (FEL)	95 mA	$\geq$ 0.6 GeV
Two-bunch (HIγS)	$>$ 80 mA	$\geq$ 0.3 GeV
Multi-bunch	$>$ 250 mA	60 bunches

ACCELERATOR PHYSICS RESEARCH

Our nonlinear dynamics research focuses on the study of the single particle dynamics in the storage ring using a single repetitive cell of a magnetic lattice. While not aimed at developing a specific lattice with a large dynamic aperture, this work allows us to take a fresh look at the issue of dynamic aperture optimization by studying a large number of magnetic lattices of different types and different numbers of repetitive cells. The relationship between the dynamic aperture of double-bend achromat and triple-bend achromat lattices and the number of repetitive cells has been explored using particle tracking simulation to reveal a simple scaling relationship [5]. This scaling is similar to the

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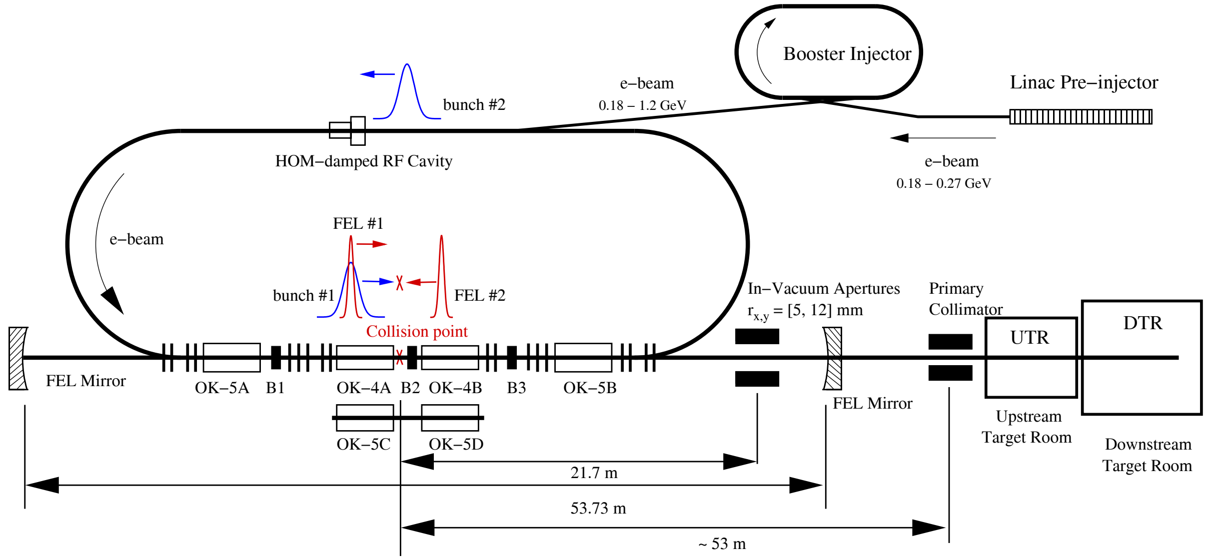

Figure 1: The schematic of the Duke storage ring light source facility in 2009. Since 2004, a number of major upgrades have been completed, including a new 0.18 to 1.2 GeV top-off booster synchrotron, a new 34 meter long storage ring straight section for hosting a higher order mode damped RF cavity and for a new injection scheme with the booster, and a new OK-5 FEL in the FEL straight section. The typical operation of the HIγS gamma-ray beam facility uses two electron beam bunches by colliding electrons in one bunch with FEL pulse generated by the other inside the FEL resonator. The new Upstream Target Room (UTR) will be constructed in fall 2009 as a second experimental area for research using the HIγS gamma-ray beam.

known sextupole strength scaling for a fixed lattice. The insight gained through this study motivates us to explore the change of beam dynamics for off-momentum particles with nominal sextupole settings, and for on-momentum particles with elevated sextupole strengths as the result of overcompensating the chromatic effects.

The performance of the storage ring FEL and HIγS critically depends on the ability of operating a highly stable electron beam with a large charge per bunch. To suppress the coupled bunch mode instabilities, a bunch-by-bunch longitudinal feedback (LFB) system has been developed using an integrated Gigasample processor and a broadband, waveguide over-loaded kicker cavity [6]. The LFB system is very effective in stabilizing the electron beam operation with a variety of bunch fill-patterns, including symmetric 2-, 4-, 8-, 16-, 32-bunch mode and a completely filled 64-bunch mode. The LFB system has been used to stabilize high bunch-current operation at various beam energies, resulting in a large improvement of the photon intensity of the Duke FEL and HIγS facility [7].

The Compton gamma-ray beam can be used as an advanced diagnostic tool to characterize the electron beam in the storage ring. At the DFELL, we have developed the capability to accurately determine the electron beam centroid energy with a relative uncertainty of a few times 10^{-5} for a relatively low energy electron beam at a few hundreds of MeV [8, 9]. This technique can also measure the energy spread of the electron beam, allowing us to study the relationship between the intracavity FEL power and the energy spread of the electron beam. In addition, we have developed an end-to-end gamma spectrum reconstruction method, a novel method based upon the Compton scattering model to uncover the true Compton gamma-ray beam energy distribution using the measured gamma spectrum from a high-purity Germanium detector [10, 11]. This technique is particularly important for gamma-ray beams between 10 and 15 MeV when the true gamma-beam spectra cannot be easily obtained with a good accuracy due to the complex detector response.

The energy of the electron beam in the storage ring can also be measured accurately using the electron beam depolarization technique by driving the spin resonance. This technique can be useful to predict the Compton gamma-ray beam energy for the above 100 MeV HIγS operation when the direct gamma-beam energy measurement becomes difficult. When operating at higher energies ($>$ 1 GeV), the electron beam will gradually become polarized in the storage ring due to synchrotron radiation in a reasonable amount of time. We have developed a simple technique to study the electron beam polarization build-up at 1.15 GeV using the measured decrease of the Touschek loss rate [12].

STORAGE RING FEL RESEARCH

At the DFELL, one of the main light source programs is the development of storage ring based oscillator free-electron lasers. The Duke storage ring FEL has been developed to operate in a wide wavelength range from infrared ($\lambda \sim$ 1 to 2 microns) to vacuum ultraviolet (VUV) ($\lambda \sim$ 190 nm). The Duke FELs, including OK-4 FEL, OK-5 FEL, and DOK-1 FEL, have been studied using both experimental and simulation techniques.

The increase of the electron beam energy spread can cause reduction of the FEL gain. The relationship between the FEL gain and beam energy spread has been experimentally studied for the OK-4 optical klystron FEL. As an experimental validation of the Madey theorem, we explored the degradation of the two-wiggler interference spectrum as the result of an increased energy spread of the electron beam. This study will be extended to a distributed optical klystron FEL with more than two wigglers.

An experimental study on FEL power scaling with the electron beam current and energy spread is being carried out for different FEL configurations [13]. In particular, we are interested in understanding the transition from the optical klystron mode operation when the electron beam energy spread is relative small to the conventional FEL operation at a large energy spread. A novel method to directly measure the electron beam energy spread simultaneously with the FEL operation has been developed.

A novel, pass-by-pass multi-stage FEL gain measurement system has been constructed to study the entire process of the storage ring FEL build-up [14]. This FEL gain measurement system uses fast photon detectors in four stages to record the growth of the FEL pulses from noise to saturation. With a large dynamic range, this system is particularly useful for studying the fast growth of the FEL power, critical for our FEL research with a long distributed optical klystron FEL.

Presently, for FEL operation with a higher energy beam ($>$ 600 MeV) and a shorter wavelength ($\lambda < 500$ nm), the Duke FEL power is limited not by the maximum beam current reachable in the storage ring, but by the thermal loading of the downstream FEL mirror due to intense wiggler harmonic radiation. For the helical FEL with wiggler higher harmonic radiation peaked off-axis, this problem can be effectively mitigated using an in-cavity, water-cooled, remotely controlled aperture system [15, 16]. The aperture system has been successfully used to facilitate higher power FEL operation. It has enabled stable UV OK-5 FEL operation with a substantial beam current. This in-cavity aperture system can also be used as an independent FEL gain control device, allowing the manipulation of the FEL gain without altering the electron beam parameters or operation conditions of the optical resonator [16].

A simulation study is being carried out using well-known FEL codes to study the storage ring FEL physics. The storage ring FEL model is being calibrated with experimental results by comparing the simulation results with the measured FEL build-up process for a variety of beam parameters. This model system will be fully developed to allow us to predict the performance of the Duke FEL when operated in new regions, in particular, in the VUV wavelengths (below 190 nm), and for high power FEL operation with a high beam current [13].

COMPTON GAMMA-RAY SOURCE

The Duke FELs are used as a photon source to drive the Compton gamma-ray source, the High Intensity Gamma-ray Source (HIγS), at Duke University [7, 4]. The HIγS facility is now capable of producing intense gamma-ray beams in a wide energy range (1 – 100 MeV) with a maximum flux performance on the order of 10^{10} γ/s total below 20 MeV. The HIγS produces almost 100% polarized gamma-rays, either linear or circular, with good energy resolution. Given these outstanding characteristics, the HIγS is a world-class Compton gamma-ray source for cutting-edge research in nuclear physics, astrophysics, medicine, and industrial applications.

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