ACCELERATOR PHYSICS RESEARCH AND LIGHT SOURCE DEVELOPMENT AT DUKE UNIVERSITY *

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Abstract

The accelerator physics and light source development programs at the Duke Free-Electron Laser Laboratory (DFELL) focus on beam dynamics research, beam instability studies, FEL research, and the development of storage ring based free-electron lasers (FELs) and Compton gamma-ray sources. The High Intensity Gamma-ray Source (HIγS) at Duke University is the highest flux Compton gamma-ray source currently available with an energy tuning range from 1 to 100 MeV. In this paper, we will report our recent progress in accelerator physics research and light source development to meet challenges of today's and future accelerators.

INTRODUCTION

At the Duke Free-Electron Laser Laboratory (DFELL), we focus on the research and development of the storage ring based free-electron lasers (FELs) [1] and Compton gamma-ray sources. The main accelerator facility at the DFELL is comprised of three accelerators: (1) a 0.18 – 0.27 GeV linac 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. Commissioning in 2006 [2, 3], the booster injector has significantly increased the performance of the storage ring and related light sources by substantially increasing the single-bunch and multi-bunch beam current capability. The key parameters of the Duke booster injector and storage ring are summarized in Table 1.

The Duke storage ring is designed as a dedicated accelerator driver for FELs with a long straight section (34 m). In this straight, four FEL wigglers are installed, including two planar OK-4 wigglers in the middle section and two helical OK-5 wigglers on the sides (see Fig. 1). The FEL wigglers can be configured in several ways to produce coherent radiation with different polarizations, and for either high-power or high-gain operation. Commonly used FEL configurations include (1) high-power FEL configurations with a single wiggler, either a planar OK-4 wiggler or a circular OK-5 wiggler; (2) high-gain FEL configurations with an optical klystron using either two OK-4 wigglers or two OK-5 wigglers; (3) the highest gain configuration with a distributed optical klystron FEL (DOK-1) with all four wigglers [1]. By colliding an intense electron beam inside the FEL cavity the FEL beam is used as the photon source to power the High Intensity Gamma-ray Source (HIγS) [4].

Since 2008, the DFELL has become a part of the Triangle Universities Nuclear Laboratory (TUNL) with the HIGS facility as the main on-site accelerator facility for TUNL's nuclear physics research programs.

Table 1: Main accelerator and beam parameters for the Duke booster injector and storage ring (2010).

Parameter	Value	Comments
Booster Synchrotron		
Circumference [m]	31.902	
RF frequency [MHz]	178.55	
Number of RF buckets	19	
Injection energy [GeV]	0.18 – 0.27	
Extraction energy [GeV]	0.18 – 1.2	
Storage Ring		
Operation energy [GeV]	0.24–1.2	
Circumference [m]	107.46	
RF frequency [MHz]	178.55	
Number of RF buckets	64	
Max beam currents		
One-bunch (FEL)	95 mA	$\geq$ 0.6 GeV
Two-bunch (HIγS)	110 mA	$\geq$ 0.5 GeV
Multi-bunch	$>$ 250 mA	60 bunches

ACCELERATOR PHYSICS RESEARCH

Nonlinear dynamics are a critical issue for the third-generation light source storage rings as well as future circular accelerators with strong nonlinear magnetic elements. Our recent work focuses on the study of the dynamic aperture of different types of storage ring lattices and with varying numbers of repetitive cells. The relationship between the dynamic aperture of a typical double-bend achromat or triple-bend achromat lattice and the number of repetitive cells has been explored using particle tracking simulation to reveal a simple scaling relationship [5]. This scaling is consistent with the known sextupole strength scaling for a fixed lattice type. The scaling relationship allows us to develop useful merits using the beam emittance and dynamic aperture to compare various types of storage ring lattices with different numbers of repetitive cells. By changing beam and lattice parameters around the scaled values, new insights have been gained by connecting dynamical behaviors of off-momentum particles with those of the on-momentum particle, and by visualizing changing dynamics as sextupole strengths are varied.

In the Duke storage ring, the maximum beam current in the multi-bunch mode is limited by longitudinal coupled

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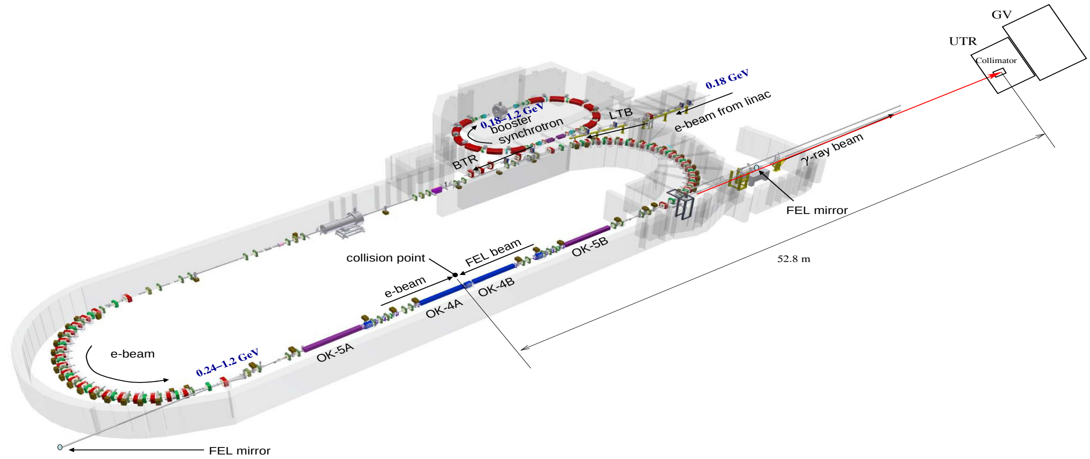

Figure 1: The schematic of the Duke storage ring accelerator facility including the linac pre-injector, full-energy top-off booster injector, and the storage ring. The Compton gamma-ray beam from the HIγS facility is sent to two experimental areas – the Upstream Target Room (UTR, completed in Jan. 2010) and the old target room, the Gamma Vault (GV).

bunch mode instabilities. To combat these instabilities, a bunch-by-bunch longitudinal feedback (LFB) system has been developed. This system employs an integrated Gigasample processor (iGp) [6], and a broadband, waveguide overloaded kicker cavity specially designed for the Duke storage ring [7]. The LFB system has been very effective in suppressing longitudinal instabilities with a number of commonly used bunch fill-patterns, including symmetric 2-, 4-, 8-, 16-, 32-bunch modes and the completely filled 64-bunch mode. The LFB system has played an important role in realizing stable high bunch-current operation of the Duke FEL and HIγS [8]. Using a similar iGp system, we have recently upgraded the transverse bunch-by-bunch feedback (TFB) system which was originally designed as an analog feedback system. The TFB is currently operational but further tuning and adjustment are being carried out to optimize the performance of the TFB.

The HIγS gamma-ray beam has been used as an advanced diagnostic tool to measure electron beam parameters. Recently, we have developed techniques to accurately measure the centroid energy of the electron beam in the storage ring with a relative uncertainty of a few times 10^{-5} for low energy beams at a few hundreds of MeV [9, 10]. In addition, we have developed a novel end-to-end gamma spectrum reconstruction method using a numerical model which simulates the entire process of gamma beam production (via Compton scattering), collimation, and detection. This method allows us to construct detailed energy distributions of Compton gamma-ray beams [10, 11, 12] at various energies, in particular between 10 and 15 MeV in which the conventional spectra reconstruction techniques have difficulties in producing a truthful gamma-ray energy distribution due to a complex detector response.

The electron beam in the storage ring can build up polarization due to the Sokolov-Ternov effect. The polarized electron beam will have a reduced Touschek loss rate. The beam lifetime measurement has been used to study the radiative polarization buildup process of a 1.15 GeV electron beam, by measuring the time constant of the process and equilibrium degree of the polarization [13, 14]. To make such an experiment successful, the critical step is to establish highly reproducible beam conditions to allow repeatable beam lifetime measurements as a function of beam currents. In addition, the accuracy of the beam lifetime measurement has to be improved to better than about 5%. We found that the 1.15 GeV electron beam could become highly polarized with a degree of polarization of 85%. This polarized beam can be used to accurately measure the beam energy using the resonant spin depolarization technique.

STORAGE RING FEL RESEARCH

The storage ring based oscillator FELs are the main light source at the DFELL. The Duke storage ring FEL has been operated in a wide wavelength range from infrared ($\lambda \sim 1$ to 2 microns) to vacuum ultraviolet (VUV) ($\lambda \sim 190$ nm). In the recent years, we have developed various experimental and simulation techniques to study the storage ring FEL.

The electron beam energy spread is a very important parameter for understanding the longitudinal beam dynamics and beam instabilities. For the storage ring FEL, the induced energy spread determines the FEL power. The electron beam energy spread also determines the minimal energy spread of a collimated HIγS gamma beam. We have recently developed a versatile method to accurately measure the electron beam relative energy spread from 10^{-4} to 10^{-2} using the optical klystron radiation. A novel numerical model based upon the Gauss-Hermite expansion has been developed to treat both spectral broadening and modulation on an equal footing. A large dynamic range of the measurement is realized by properly configuring the optical klystron. In addition, a model based scheme has been developed to compensate the beam emittance induced inhomogeneous spectral broadening effect. Using this technique, we have successfully measured the relative energy spread of the electron beam in the Duke storage ring from

6×10^{-4} to 6×10^{-3} with a high degree of accuracy.

Using the newly developed energy spread measurement technique, an experimental study on the FEL power scaling with the electron beam current, energy, and energy spread has being carried out. Measurements have been made to directly link the FEL power to the measured energy spread of the electron beam. The experimental results show that the relationship between the FEL power and induced energy spread holds well for different optical detuning conditions. A simulation model is being developed to study the FEL power scaling; this model will be calibrated with the experimental results. This work is expected to lead to a useful simulation model which can predict the FEL power and FEL induced energy spread for different levels of optical cavity loss as the FEL mirrors degrade.

The relationship between the FEL gain and electron beam energy spread has been experimentally studied using the OK-4 optical klystron FEL as a part of experimental validation of the Madey theorem [15]. Due to energy spread induced spectral broadening, a red-shift of the FEL lasing wavelength has been observed. This study will allow us to develop a new operational capability to fine tune the FEL lasing wavelength while maintaining the lasing power.

A novel, pass-by-pass multi-stage FEL gain measurement system has been developed to study the entire process of the storage ring FEL build-up from noise to saturation using fast photon detectors in several stages [16]. This system has also been used extensively to measure the FEL cavity loss in an ongoing study of FEL mirror degradation [17]. The continued FEL mirror reflectivity monitoring program has enabled us to predict the performance of the FEL beam and HIγS gamma-ray beam for user research programs with a number of FEL mirrors of various wavelengths.

The thermal loading of the downstream FEL mirror is the main limitation for high current, high power FEL operation. An in-vacuum, water-cooled aperture system has been developed to block off-axis wiggler radiation [18]. This system works effectively to enable higher current, highly stable operation of the helical OK-5 FEL in which much of the off-axis higher-harmonic radiation is blocked by the apertures. This system also helps to stabilize the FEL and HIγS operation with the planar OK-4 FEL. The in-cavity aperture system is also used to as an FEL gain control device, allowing the manipulation of the FEL gain without altering the electron beam parameters or operation conditions of the optical resonator [19].

COMPTON GAMMA-RAY SOURCE

The intracavity power of the FEL beam is used to drive the world's highest flux Compton gamma-ray source, the High Intensity Gamma-ray Source (HIγS) [4, 8]. The HIγS facility is capable of producing intense gamma-ray beams from 1 to 100 MeV with a maximum total flux exceeding 10^{10} γ/s around 10 MeV. The HIγS produces almost 100% polarized gamma-rays, either linear or circular, with excellent 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. The detailed description of HIγS is found in [20].

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