Laser-Seeded Free-Electron Lasers at the NSLS

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The National Synchrotron Light Source (NSLS) has a long tradition of research and development in accelerator physics and light source technologies. Over the past two decades, the NSLS has made many pioneering contributions to the development of storage-ring-based light sources, such as the Chasman-Green lattice, global orbit feedback systems, and in-vacuum insertion devices. Even from the earliest days of the NSLS, the staff also had started to explore the potential of free-electron-laser (FEL)-based light sources, leading to some seminal work on the theory of self amplified spontaneous emission (SASE) FELs [1,2].

In the late 1980s, Brookhaven National Laboratory (BNL), together with the NSLS, established the Accelerator Test Facility (ATF) to advance the basic technologies for future light sources, which led to the development of today's most widely used radio frequency (RF) photoinjector (1.6 cell, 2856 MHz BNL gun). The high-brightness electron beams produced by the photoinjector made possible the experimental demonstration of both a SASE FEL and a high-gain harmonic-generation (HGHG) FEL [3,4].

The Source Development Lab (SDL) at the NSLS was developed during the last decade into a state-of-the-art, fully operational ultraviolet FEL and high-brightness electron beam laboratory. The SDL is the world leader in the development of laser-seeded and HGHG FELs [5,6], which provide fully coherent ultrashort pulse radiation in the IR and VUV regimes. The SDL is an ideal platform to explore new cutting-edge ideas in FEL

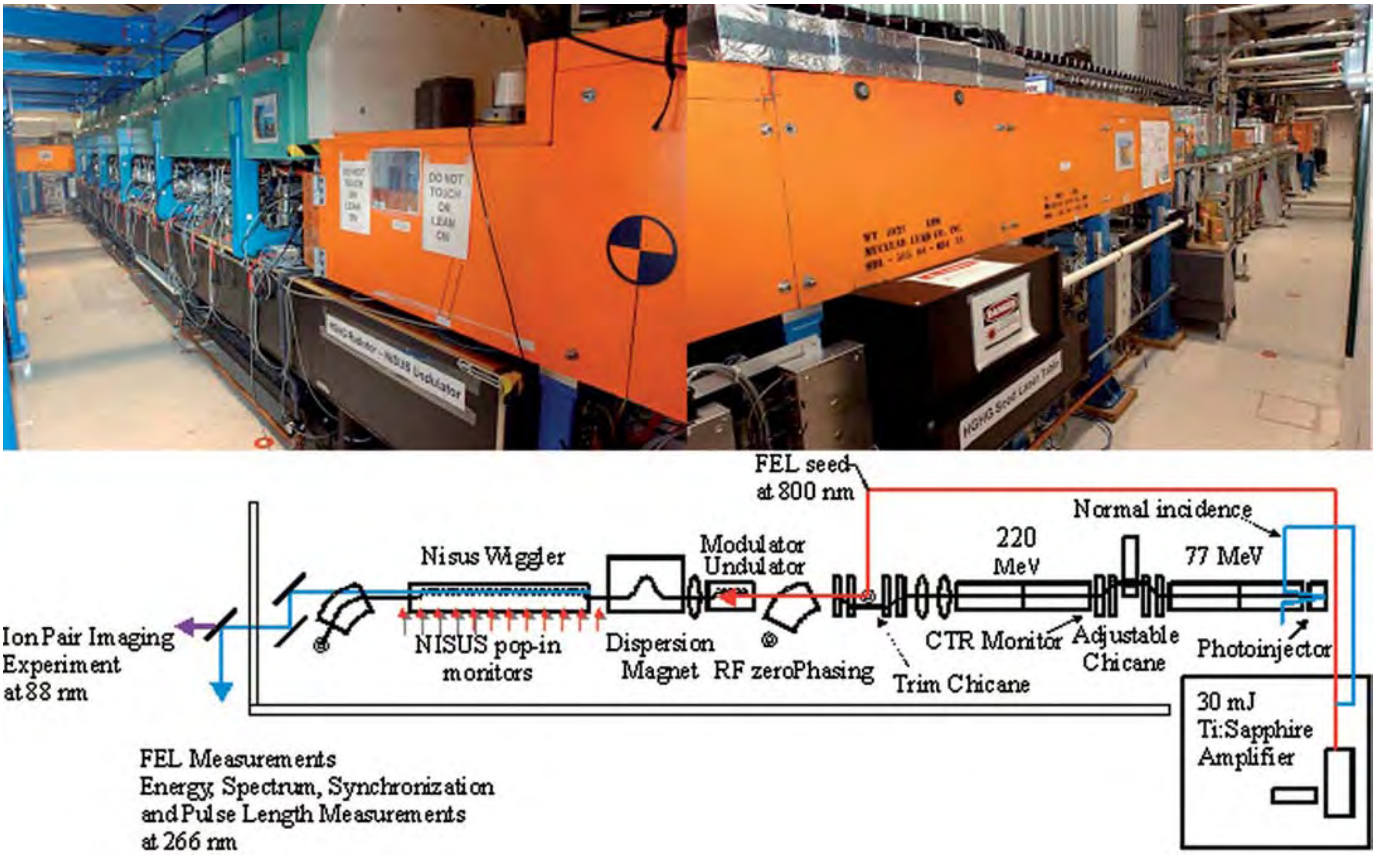

Figure 1: NSLS Source Development Laboratory layout.

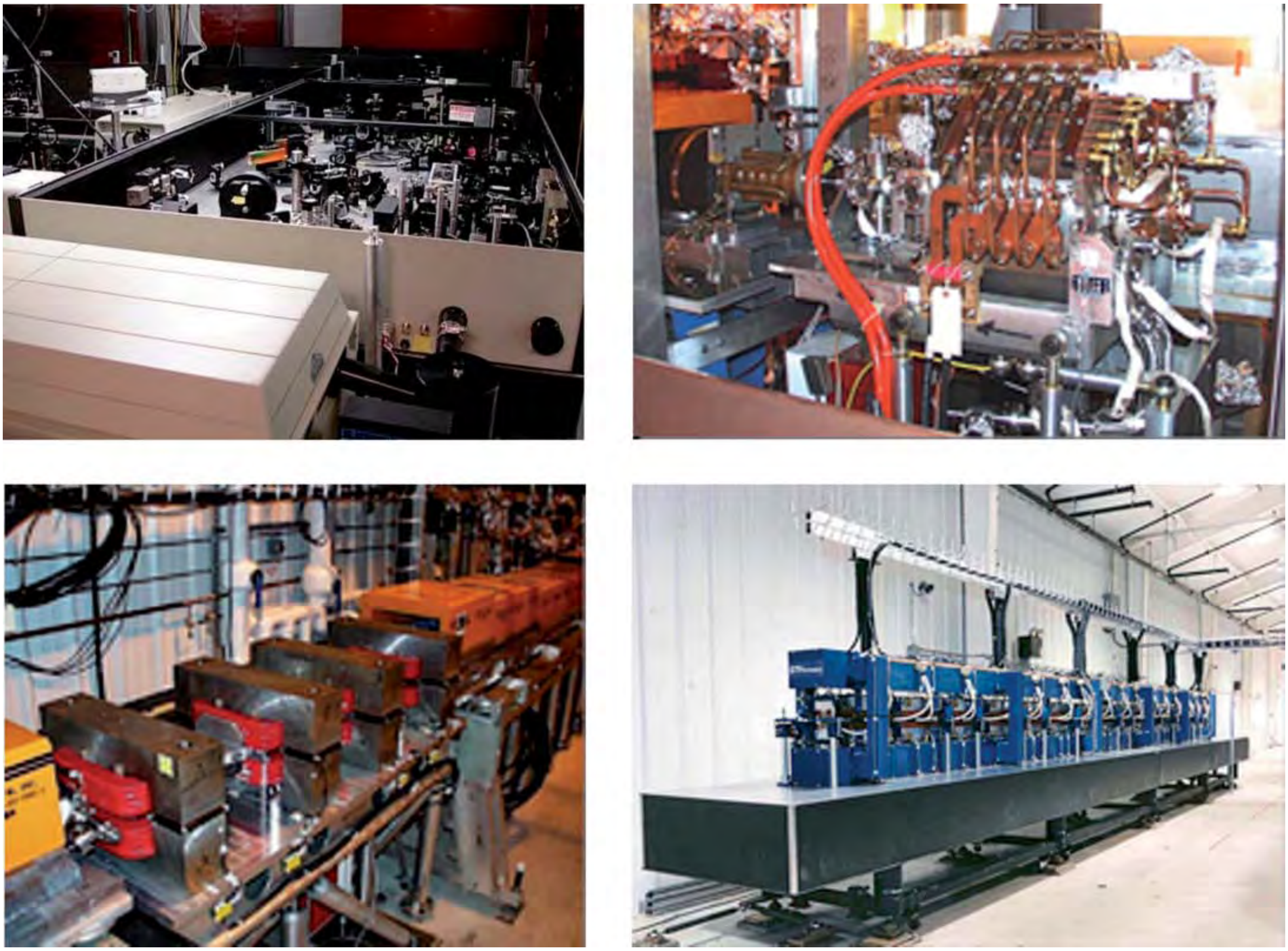

Figure 2: Key hardware elements of the SDL. Clockwise from upper left: 50 mJ, 100 fs CPA titanium-sapphire laser; 1.6 cell S-band photoinjector; four-magnet chicane bunch compressor; 10 m taperable NISUS undulator.

development that will help chart the course for future FEL development. The third harmonic radiation (89 nm) from an HGHG FEL at the SDL has also enabled novel chemical dynamics experiments on ion pair imaging [7].

Overview of the NSLS source development lab (SDL)

At the heart of the SDL lies a high-brightness electron beam obtained from an RF photoinjector driven by a titanium sapphire laser. The electron beam energy is variable from 2–5 MeV in the photoinjector and up to 300 MeV in the succeeding S-band linac. One of the unique features of the SDL laser system is that it was designed in such a way that a single laser system is used to drive both the RF photoinjector and to provide a seed laser pulse for the FEL. This set-up makes it possible to achieve sub-ps timing jitter between the seed laser and the electron beam. The SDL titanium sapphire laser system consists of an RF-synchronized 100 fs oscillator and a chirped-pulse amplifier (CPA) system. The 100 fs pulse generated by the titanium sapphire oscillator is stretched before being sent to the amplifiers. The SDL laser amplifier system is made up of a regenerative amplifier and two two-pass amplifiers and is capable of generating 50 mJ output. The amplified pulse is divided into two pulses before the final compression. One pulse is compressed down to 4-10 ps (full width at half maximum) and frequency tripled to 266 nm for driving the photoinjector. The other can be stretched from 100 fs to 6 ps (FWHM) for the laser-seeded FEL and other applications.

The high-brightness electron beam has been used for both coherent THz generation [8] and FEL applications. The SDL FEL system consists of three magnets: a modulator, a dispersion magnet and a radiator undulator. The modulator is a variable-gap undulator where the electron beam

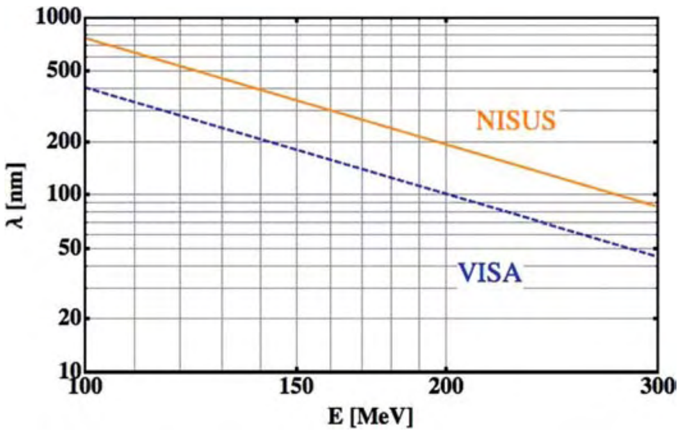

Figure 3: Calculated fundamental FEL output wavelength versus electron beam energy for both the NISUS and VISA undulators at the SDL.

interacts with the seed laser to produce an energy modulation; the dispersion magnet converts the energy modulation into a spatial modulation on the electron beam. The radiator is the 10-m-long near infrared scalable undulator system (NISUS) undulator, which is made up of 16 sections, where the gap of each individual section is adjustable. There is a beam profile monitor (BPM) and a steering magnet for each undulator section that can be used for both the electron beam and seed laser alignment. A 2-m-long strong-focusing visible-infrared SASE amplifier (VISA) undulator is also available at the SDL. The SDL facility can be used for both SASE and laser-seeded FELs; however, SASE is primarily used for electron beam optimization and trajectory correction.

Key hardware elements of the SDL include:

- 50 mJ, 100 fs titanium-sapphire chirped pulse amplification laser system;
- 1.6 cell S-band RF photoinjector;
- 300 MeV S-band (2856 MHz) linear accelerator;
- 4 magnet chicane bunch compressor;
- 1 m modulator undulator ($K = 2.5$, $\lambda_M = 8$ cm);
- electromagnetic dispersion magnet ($B = 1$ T);
- 10 m taperable NISUS undulator ($K = 1.1$, $\lambda_N = 3.89$ cm);
- 2 m strong focusing VISA undulator ($K = 1.2$, $\lambda_V = 1.8$ cm).

The SDL is housed in a 50 m × 15 m building located across the street from the NSLS. The layout of the SDL is shown in Figure 1 Figure 2 displays the key hardware systems at the SDL, all of which are fully operational.

Recent SDL FEL experiments

SASE and laser-seeded FELs

While in principle FELs can operate in either an oscillator or an amplifier configuration, the present lack of suitable mirrors makes the amplifier the only candidate for short wavelength FELs as evidenced by the choices at the Linear Coherent Light Source (LCLS) in the USA, the SPring-8 Compact SASE Source (SCSS) in Japan and the X-ray Free Electron Laser (XFEL) in Europe. Though SASE FELs can provide light with nearly full transverse coherence, the fact that they start from noise results in a photon beam that lacks longitudinal coherence [9].

To improve the longitudinal coherence of an FEL, several seeding schemes are now being explored around the world. In the X-ray regime, self-seeding employing two undulators was proposed at DESY in Germany [10], and recent progress in High Harmonic Generation (HHG) using a high-power laser made it feasible to explore direct seeding in the XUV regime [11–13]. All these seeding schemes involve an FEL amplifier with a coherent seed. A longitudinally coherent seed pulse is required to generate FEL light with both longitudinal and transverse coherence.

For the wavelength regime accessible at the SDL (see Figure 3), the fundamental of a titanium sapphire laser (800 nm) or its harmonics obtained using well-established crystal doubling (400 nm) or tripling (266 nm) methods can be used for coherent seeding. Most aspects of seeded FELs can be explored on the SDL platform: coherence, nonlinear harmonics, tapered

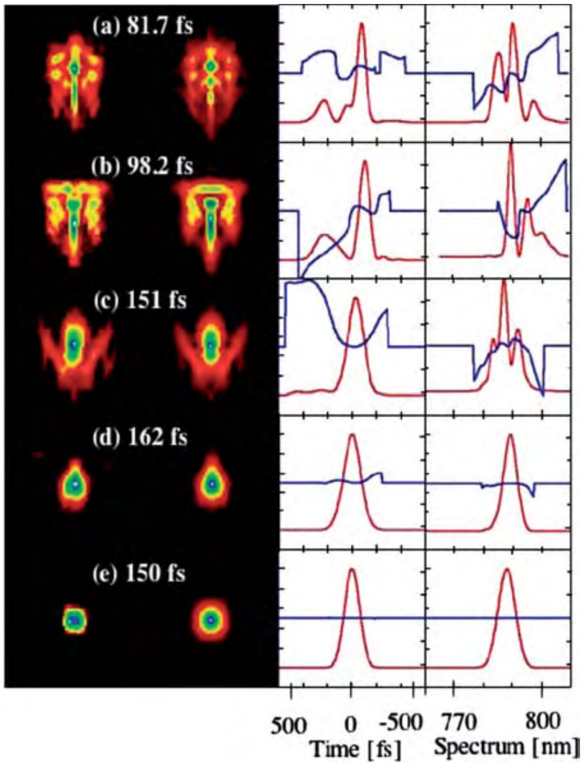

Figure 4: Each FROG result is a row in the figure labeled by the FWHM of the main temporal peak. Starting from the left, the four columns are: raw and retrieved FROG images, temporal and spectral distributions including phase. Amplitudes (red) are normalized and phase (blue) are plotted from −6 to +6 radians. The 150 fs seed laser is the last row in the figure [18]. Reprinted figure with permission from Phys. Rev. Lett.: T. Watanabe, X.J. Wang, J.B. Murphy et al., Physical Review Letters 98, 034802, 2007. ©2007 by the American Physical Society.

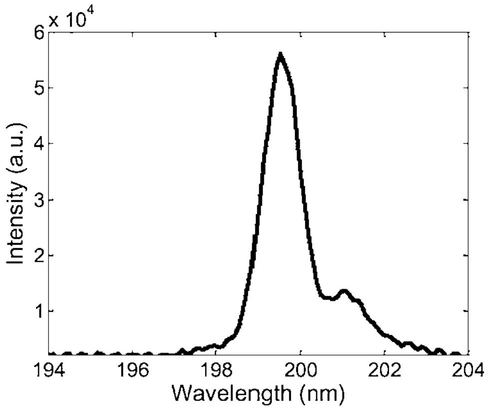

Figure 5: The measured spectrum of 4th harmonic HGHG light at the SDL.

undulators, HGHG, superradiance, etc. In the following, we present some of the recent laser-seeded FEL amplifier experimental results obtained at the SDL, and indicate future directions for research.

Laser-seeded FEL amplifier and detuning

After the first FEL amplifier experiment at 10 µm in the 1970s [14], nearly all of the FEL amplifier experiments performed during the last three decades were in the millimeter wavelength regime [15,16]. The SDL laser-seeded FEL amplifier experiment program was initiated to investigate the basic FEL amplification process with a coherent laser seed and to demonstrate efficiency enhancement. With the 800 nm titanium-sapphire laser directly injected into the 10-m-long NISUS undulator, along with the resonant electron beam, more than four orders of magnitude gain over the input seed was observed.

While an SASE FEL always adjusts itself to operate on resonance, a seeded FEL can be detuned off resonance by adjusting the electron beam energy for a fixed seed wavelength. Recently, we successfully demonstrated the FEL detuning technique at the SDL [17]. The output energy and spectrum were measured as the electron energy was scanned. The FEL energy along the undulator was also measured for the resonant and detuned cases, and the FEL efficiency was doubled with the detuned electron beam energy. We also observed the increase in the FEL gain length with energy detuning.

FEL pulse evolution in the exponential gain and superradiance regimes

One of the exciting recent experimental results from the SDL is the first experimental characterization of an FEL pulse evolving in both the exponential gain and the superradiance regimes [18]. Pulse lengthening of a 150 fs (FWHM) seed laser was observed in the exponential gain regime followed by pulse shortening in the superradiance regime. Using a frequency-resolved optical gating (FROG) diagnostic technique, both temporal and spectral information could be extracted simultaneously and pulses as short as 82 fs (FWHM) were measured (Figure 4). By adjusting the input seed laser power, the saturation point for the exponential gain regime could be positioned along the 10 m NISUS undulator so the growth of the FEL energy beyond saturation was also measured.

High-Gain Harmonic-Generation (HGHG) FELs

An HGHG FEL makes use of two undulators (modulator and radiator) separated by a dispersive section to generate higher harmonics of a coherent seed laser [3] (see Figure 1). An energy modulation is imparted to the electron beam in the modulator by the resonant seed laser (λ_s), which is then converted to a density modulation in the dispersive section where the path length depends on energy. The radiator undulator is tuned to be resonant with a higher harmonic of the seed laser, $\lambda_r=\lambda_s/n$, so the bunched electron beam can radiate at this higher harmonic. Both second and third harmonic (n=2, 3) HGHG FELs have previously been demonstrated at the NSLS [3,5] and recently, operation at the fourth harmonic, (n=4) with $\lambda_r=199$ nm, was obtained (see Figure 5) [6]. The modulator undulator together with the 300 MeV electron beam make it possible to explore HGHG at harmonic numbers as high as seven in the future.

Future experiments at the SDL

The near-term focus at the SDL is to continue the laser seeded FEL amplifier program at 800 nm with further studies of tapering for efficiency enhancement and high-charge operation with 1 nC/bunch. We will also continue to push the frontier of HGHG FELs by exploring higher harmonics (n = 5, 7) and a cascaded HGHG FEL (two-stage), both of which are critical for the realization of an HGHG FEL in the X-ray regime. The SDL is also well positioned to explore various ideas of generating ultrashort SASE FEL pulses, such as the use of an emittance spoiler [19], and to study the amelioration of space charge or coherent-synchrotron-radiation-induced microbunching with a laser heater [20].

Acknowledgements

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