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ABSTRACT

The NSLS has a long-standing interest in providing the best possible synchrotron radiation sources for its user community, and hence, has recently established the Source Development Laboratory (SDL) to pursue research into fourth generation synchrotron radiation sources. A major element of the program includes development of a high peak power FEL meant to operate in the vacuum ultraviolet. The objective of the program is to develop the source, and experimental technology together to provide the greatest impact on UV science. The accelerator under construction for the SDL consists of a high brightness RF photocathode electron gun followed by a 230 MeV short pulse linac incorporating a magnetic chicane for pulse compression. The gun drive laser is a wide bandwidth Ti:Sapphire regenerative amplifier capable of pulse shaping which will be used to study non-linear emittance compensation. Using the compressor, 1 nC bunches with a length as small as 50μm sigma (2 kA peak current) are available for experiments. In this paper we briefly describe the facility and detail our plans for utilizing the 10 m long NISUS wiggler to carry out single pass FEL experiments. These include a 1 μm SASE demonstration, a seeded beam demonstration at 300 nm, and a High Gain Harmonic Generation experiment at 200 nm. The application of chirped pulse amplification to this type of FEL will also be discussed.

Keywords: UV Laser, FEL, RF photocathode gun, pulse compression, SASE, high gain harmonic generation, CPA

1. INTRODUCTION

The National Synchrotron Light Source (NSLS) has for several years been engaged in various activities aimed at advanced source development. These include upgrades and enhancements of the existing storage rings, and pursuit of advanced source technologies for coherent synchrotron radiation both in storage rings, and in FELs. Some of these programs require a dedicated machine which would not impact on the operation of the active user program on the NSLS storage rings. Building on technological developments at the BNL Accelerator Test Facility (ATF), and taking advantage of resources recovered from curtailed programs, the NSLS established the Source Development Laboratory (SDL) as the home for these projects. The function of the SDL is to facilitate *coordinated development* of sources and experiments to *produce and utilize* coherent sub-picosecond synchrotron radiation. To achieve these objectives, the SDL machine development plans fall roughly into three areas; electron beam development, coherent synchrotron radiation experiments, and the Ultraviolet Project FEL.

With respect to the program, the design and structure of the facility is largely dictated by the approach we have taken for the production of short wavelength FEL radiation: high gain single pass operation. This strategy has the benefit that it eliminates many of the optical limitations of oscillator configurations and allows for a much broader range of possible pulse formats. It does however shift the technological burden to the electron beam and wiggler. For the FEL to succeed, we need to produce a high peak current, high brightness electron beam, and accelerate it to high energy without emittance dilution. Also, the field quality of the long wiggler must satisfy very tight tolerances on trajectory errors. These requirements have played a significant role in shaping the facility and the research program. The stability requirements for our users have also dictated the development of the seeded beam FEL. At the time of writing, we are focusing our attention on the assembly and commissioning of our electron linac, and the installation of our gun laser system. In the following sections, the machine components and their parameters are described, followed by an outline of the anticipated research program.

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2. ACCELERATOR DESCRIPTION

2.1 Laser Driven RF Photocathode

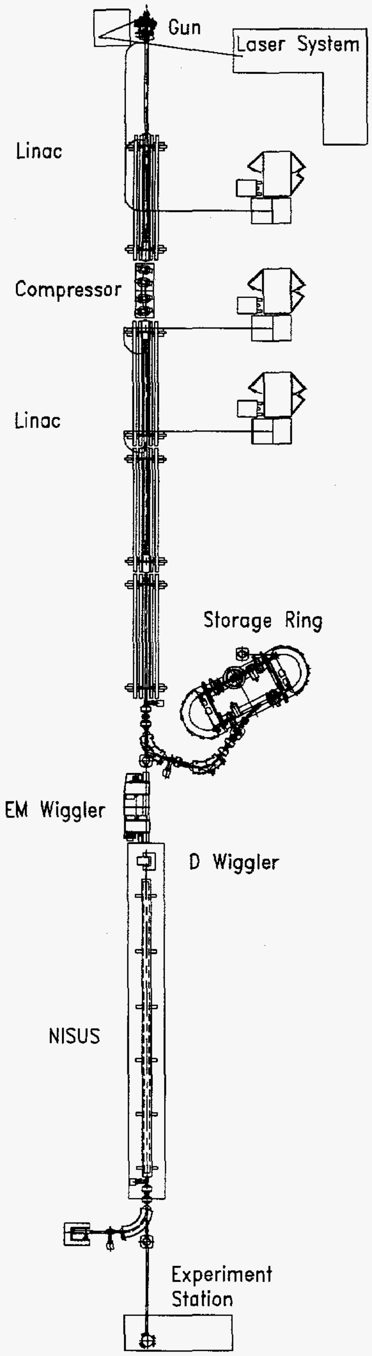

Fig. 1. Schematic layout of the SDL accelerator. Energy Modulation (EM) Wiggler; Dispersive (D) wiggler. Other labels defined in text.

The electron source for the SDL accelerator is a radio-frequency photocathode gun developed as part of a collaboration between BNL, SLAC, and UCLA[1]. It is a 1.6 cell S-band (2856 MHz) structure, with a measured maximum gradient of 140 MV/m, yielding an exit energy of approximately 8 MeV. Improvements over the original BNL design [2] include elimination of the side coupling into the half-cell to reduce emittance growth due to the TM_{110} mode, installation of a removable cathode allowing different cathode materials (e.g. magnesium) to be used, and increasing the half-cell length to increase RF focusing and decrease the peak field on the cell-to-cell iris. The emittance correction solenoid has also been improved with the addition of a re-entrant iron flux return to produce a more uniform magnetic field with little fringing. PARMELA runs [3,4] indicate that this RF gun is capable of producing electron bunches with 7 ps flat top, 1 nC charge, and normalized RMS emittance of 1.3π mm-mrad. The laser system used to excite the RF photocathode is based on a wide-band Ti:Sapp oscillator [5] mode-locked to the 35th subharmonic of the RF frequency. Phase jitter is less than 1 ps. The light output from the oscillator enters a multipass amplifier that stretches the pulse, amplifies it, and recompresses to produce 10 mJ in a final pulse length of 150 fs. Up to 0.4 mJ of the 266 nm third harmonic of the amplified pulse is then stretched to a final pulse length adjustable from 300 fs to 20 ps. An aberrated telescope is used to produce an elliptical beam for a square transverse intensity profile and 65 degree wavefront tilt to match the incidence angle on the RF photocathode. The square intensity profile is optimal for emittance correction. The wide bandwidth of the Ti:Sapp laser allows for longitudinal pulse shaping so that nonlinear emittance correction may be investigated.

2.2 Linac and Magnetic Bunch Compressor

The linac (Figure 1) currently consists of four SLAC-type constant-gradient linac tanks operating at 2856 MHz, with provision for installation of a fifth section. The first two linac tanks and the gun are driven by an RF system which can produce up to 45 MW of peak output power. These sections accelerate the electron beam to approximately 84 MeV. They also produce an energy chirp on the electron beam in preparation for bunch compression in a magnetic chicane. The compressor consists of four identical electromagnets 190 mm long operating at fields up to 0.4T. The compressor may be operated at any value from zero field to full strength. A phosphor flag and collimator are installed at the point of maximum dispersion for use as energy-spread diagnostics, and for slice emittance[6] studies. Tracking studies with MAD[7] indicate the bunch should compress by a factor of 12, from an RMS length of 600 μm to 50 μm. Following the chicane the beam is accelerated through two more linac tanks, each powered by its own RF system, to provide a maximum energy of 230 MeV. Space is available for a fifth linac tank, which could in principle bring the total energy of the linac to 310 MeV. Immediately following the linac is the first dipole magnet for a transport achromat. Initially these optics will be used for characterizing the electron beam, and studying emittance growth due to coherent synchrotron radiation and centrifugal space charge forces. Ultimately this transport line may be used for injection into a small storage ring for the generation of coherent synchrotron radiation in the far infra-red[8]. Of course, the electron beam can pass directly through to the FEL experiments when the first dipole magnet is unpowered.

2.3 Wiggler

The FEL experiments are located in the 'straight ahead' beamline following the linac. For the harmonic generation experiments, an energy modulation wiggler and dispersive section are required[9]. These devices will be configured to allow exchange of energy between the electron beam and a seed laser beam. The energy modulation will then be converted to spatial modulation by the dispersive section. The prebunched beam will then be used to produce and amplify radiation in a long wiggler. In the initial experiments however, we will use only the existing 10 m long NISUS wiggler[10] (originally built by STI, Inc. for Boeing Aerospace) for SASE and seeded amplifier studies. The properties of the electron beam and the wiggler are summarized in table 1. The NISUS wiggler is constructed of vanadium-permendur poles and samarium-cobalt magnets, with iron shims added for error reduction. The gap is remotely adjustable and has a maximum field strength of 0.56 T. There are 256 periods, each of length 38.9 mm.

The magnet is constructed in 16 segments which are coupled by flexural hinges allowing the device to be configured with a compound taper. The taper prescription can be adjusted for different machine conditions to provide the maximum possible energy extraction from the electron beam. Within each magnet section, six of the sixteen poles are canted to provide strong natural focusing. Additional focusing and steering correction is provided by 'four wire' correction stations imbedded into the vacuum chamber. These wires are located around the electron beam duct inside the magnet gap, and are oriented parallel to the path of the electron beam. Dipole steering corrections or additional quadrupole focusing can be provided by applying appropriate currents to each wire. To make this possible each wire has its own independent power supply. There are 17 of these correction stations equally distributed over the length of the wiggler. Between these sections, the vacuum chamber has provision for pumping, and the installation of pop-in beam monitors. These monitors will be used to verify the proper location and focusing of the beam by the correction magnets.

Electron Beam	
Max. Energy	230 MeV
Peak Current	2 kA
Bunch Length	200 fs $< \sigma_z <$ 20 ps
RMS Emittance	$< 2\ \pi$ mm-mrad
$\Delta E/E$	0.5%
Wiggler	
Length	10 m
Period	38.9 mm
Peak Field	0.56 T
Num. Poles	256
a_w	1.44 max
Min. Gap	14.4 mm
Energy Taper	< 20%
FEL	
Wavelength	80 nm $< \lambda <$ 1000 nm

Table 1: SDL Accelerator parameters.

3. ELECTRON BEAM EXPERIMENTS

Several of the important beam parameters for the FEL experiments have an unusually large range of adjustment. The pulse length and energy spread can be varied and optimized with both the drive laser and the magnetic chicane. The initial pulse length may be varied by nearly two orders of magnitude via the Ti:Sapp laser alone. Recent magnetic compression studies[11] have shown that increasing the initial pulse length can lead to shorter final pulses. This is because the more intense wakefields and higher space charge of an initially short bunch increase the nonlinear distortion in the energy-phase correlation used for compression[12]. Finally, one can optimize the bend angle in the compressor so that the nonlinear effects of the longitudinal wakefield and RF are partially canceled by the effect of the nonlinear dependence of path length on the energy deviation.

Very short, high current bunches propagating through bends can experience significant transverse emittance growth through two distinct effects, the longitudinal centrifugal space charge force (CSCF)[13], and coherent synchrotron radiation (CSR)[14]. Emittance growth due to CSCF scales as Q $(a/\delta)^2$ where Q is the bunch charge, a is the bunch radius, and δ is the bunch length. Similarly, CSR scales as $Q(a/\delta)^{4/3}$. Simulations including the effects of CSR indicate that the emittance grows from 1.2π mm-mrad to 2.0π mm-mrad in the final bend of the compressor when compressed to a final bunch length of 0.6 ps. Greater compression is possible, but results in larger emittance. The bunch length, transverse size, and charge will all be varied in order to study the magnitude and scaling of these effects. The compressor vacuum pipe has a radiation port for synchrotron radiation which will be used as a diagnostic for bunch length and beam size. The emittance may be measured immediately before and after the compressor to isolate the effects of CSR and CSCF.

At high energy, the bunch length will be verified through two methods. By passing the beam through a foil, coherent optical transition radiation (OTR) will be generated at wavelengths comparable to the bunch length. An experiment is planned following the linac which measures the coherent OTR spectrum. Additionally, the final linac section and bend may be used to produce an energy chirp which can then be "streaked" on a phosphor screen to measure bunch length. This profile measurement combined with charge measurements in the Faraday cup or BPMs will give the bunch charge profile. The drive laser pulse is approximately 1mm long by 1mm in radius. The very short longitudinal profile significantly affects the minimum emittance achievable via solenoidal emittance correction[15]. By varying this profile, we will study the relative strength of the nonlinear terms in the emittance correction. Measurements of the slice emittance as developed at BNL's Accelerator Test Facility will be used in these studies.

4. FEL Experiments

The FEL development program for the SDL will take place in stages based on machine requirements and modifications. In the first stage, a normalized emittance of 6.5π mm-mrad at a beam energy of 130 MeV is required. The electron beam will be used directly in self-amplified spontaneous emission (SASE) experiments. The output wavelength will be roughly 1μm with an anticipated peak power of 70 MW. Since conventional laser sources operate well at this wavelength, the principle purpose of this part of the program will be comissioning of the machine, and investigation of the FEL physics associated with start-up from noise. The effects of tapering for energy extraction and the harmonic content of the output radiation will also be investigated. Thus far, it has been suggested that the stability of a SASE based source, from the view point of a user, may be problematic. The radiation wavelength, pulse energy, duration, and bandwidth will all depend on variables associated with the electron accelerator. Tracking all of these parameters for short pulses in real time may represent too great a challenge for many classes of experiments. One way to reduce these problems is to use the radiation from a seed laser to produce the energy modulation. In this scheme it has been shown theoretically[9] that the central wavelength and bandwidth will depend only on the seed laser properties, and that only the pulse energy will be influenced by the accelerator. To explore this experimentally, the first seeded beam operation at the SDL will be at the Ti:Sapp fundamental (900 nm) using just the NISUS wiggler which will provide both the energy modulation and the required dispersion for spatial bunching. It should also be possible to conduct Chirped Pulse Amplification (CPA)[16] experiments at this wavelength, which could yield photon pulses as short as 10 fs.

For CPA operation, the electron pulse will be made as long as 20 ps to provide an energy chirp on the electron beam. The seed laser, which for the early experiments, will also be the gun laser, will provide a chirped optical pulse with an energy slew that is matched to the electron beam chirp. Essentially this introduces a correlated chirp to the FEL so that using optical techniques, the resulting FEL radiation can be compressed to produce the short radiation pulse. After the addition of an energy modulation wiggler and dispersive section to the accelerator at a later date, the FEL output wavelength will be pushed to 200 nm using harmonic generation. A 400 kW beam from the Ti:Sapp at 400 nm will bunch the electron beam, which will then lase on the 2nd harmonic, producing 70 MW at 200 nm. With the addition of a 5th linac section increasing the beam energy to 310 MeV and improvement of emittance to 1π mm-mrad, FEL operation below 100 nm should be possible, including the demonstration of CPA at 80 nm with a 5 fs pulse duration.

The utilization of the FEL radiation produced by these experiments will very much depend on the results of the FEL development and characterization program. It is our expectation that this laboratory will provide a unique capability for sub-picosecond synchrotron radiation research[17], and we have arranged the facility so that multi-color experiments combining FEL radiation, and radiation from the seed laser or auxiliary lasers will be possible. The specific experiments will depend on prevailing conditions, but programs in chemical and atomic physics have been outlined which take advantage of the short pulses at vacuum UV wavelengths. These include a variety of problems such as threshold photofragmentation studies of a number of currently inaccessible species (including many important in atmospheric photochemistry such as CH_4, CO_2, H_2O, and most of the chloro-fluorohydrocarbons). The source properties are in principle well suited for performing photoelectron spectroscopy on radicals, complexes and clusters due to the accessible energy range, pulse energy, and laser bandwidth. The SDL FEL will be amenable to experiments involving the photoionization of vibrationally excited ground states, photofragment translational spectroscopy, and the state selective detection of dilute species in the gas phase and at surfaces. One could also extend the investigation of above threshold atomic stabilization into the deep ultraviolet, thus exploring experimentally the stabilization of light atoms which has, up to now, only been theoretically predicted, as well as a whole range of super-intense Laser-Atom physics.

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