Lasers for the New Light Source (NLS)

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Introduction

The New Light Source (NLS) is a proposed UK facility for the provision of highly coherent ultrashort light pulses from the terahertz to the soft X-ray[1]. It is based on a combination of technologies. High-energy photons (50 eV-1 keV plus harmonics) will be generated by free electron lasers (FELs). Low-energy ones (2.5-60 meV) will come from undulators and bending magnets. Conventional lasers will supply light from the infrared to the ultraviolet (60 meV-6 eV) and will also drive high harmonic generation (HHG) sources covering the VUV region (6-50 eV). Similar HHG systems will be used to seed the FELs.

The baseline parameters of the NLS include a pulse duration of ~20 fs FWHM (except in the THz region, where this is physically impossible) and a pulse rate of 1 kHz, with even spacing. The output beams are close to diffraction- and transform-limited. There is also a requirement for continuous wavelength tuneability. Potential upgrades include increases in the pulse rate, most probably in decade steps through 10 kHz and 100 kHz to 1 MHz.

Conventional lasers have been used alongside accelerator based light sources for many years, and as more FEL facilities come online their use is increasing further. The NLS takes this to a new level with lasers being completely integrated into the facility design from the very start. They can be divided into three groups: lasers which form part of the accelerator system, lasers to seed the FELs and lasers which deliver light directly to user experiments. These are discussed in more detail below.

Lasers for the accelerator

The NLS accelerator (see Figure 1) is a 2.25 GeV electron linac using superconducting RF modules. Lasers are used to generate the bunches of electrons in a "photoinjector", to increase their energy spread (in a "laser heater") and to diagnose their temporal properties at various points along the machine. The photoinjector and heater lasers must operate continuously for periods of months with very high reliability since the failure of either puts the whole NLS facility into immediate shutdown.

The NLS electron bunches, with a charge of 200 pC, come from a Cs_2Te photocathode illuminated by 260 nm laser pulses. With a minimum quantum efficiency of 1% the laser pulse energy at the cathode has to be at least 0.1 µJ. To avoid space charge degradation of the beam emittance while the electrons are still at low energy, they are produced in a relatively long bunch which is then compressed after it has been accelerated. The ideal bunch profile before compression is flat topped with a 12 ps FWHM and <2 ps rise and fall times. Since the electron photoemission simply reflects the laser intensity, this can be produced by passing a 1.5 ps laser pulse through an 8-fold optical stacker[2].

Given the reliability requirements, fibre laser technology has been chosen for the photoinjector.

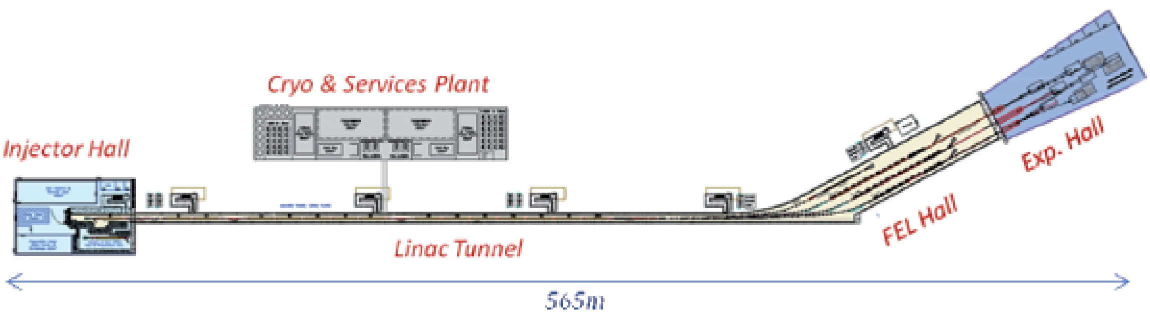

Figure 1. Overall layout, main components and scale of the NLS facility.

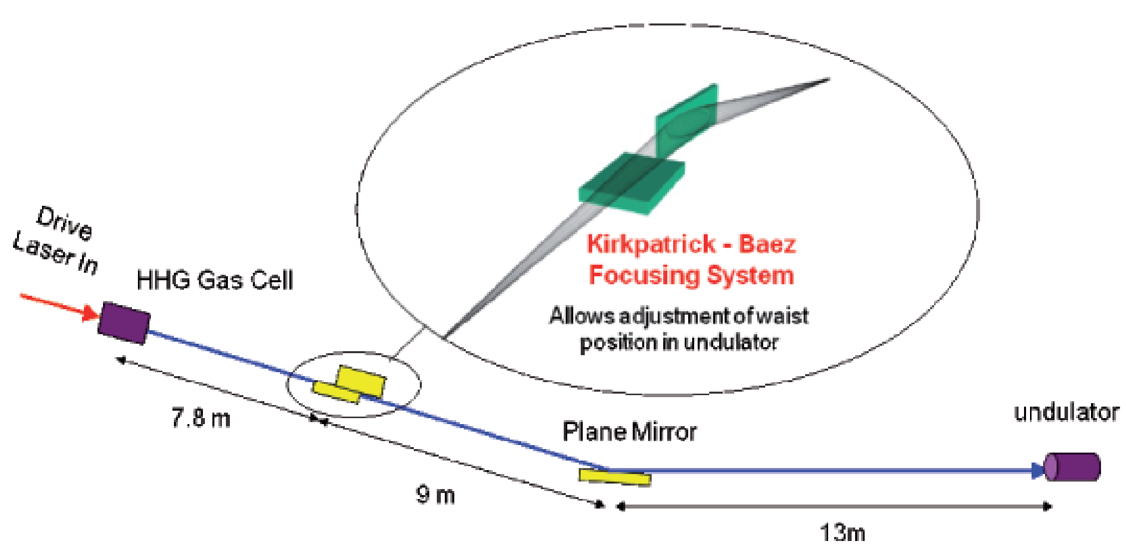

Figure 2. Layout of beam transport from HHG cell to FEL undulator.

Frequency quadrupled Yb:glass can deliver the required pulse length and wavelength. Unfortunately the quadrupling process is relatively inefficient and there are also losses in the spatial shaping of the beam (a near top-hat transverse profile is needed), the stacking and the transport to the cathode. The overall efficiency is budgeted at just 4.5% so the pulse energy at the laser output has to be 2.2 µJ. In recent years fibre lasers have been intensively developed and 1.5 ps pulses with at least this energy are already available at rates above 1 MHz from a commercial laser system [3].

Increasing the electrons' energy spread with a laser heater suppresses coherent effects which can otherwise degrade monochromatic electron bunches very seriously. It is achieved by co-propagating the electrons and the photons through an undulator at an early stage in the accelerator. Since the bunch is still long and not tightly collimated the pulse energy needed for complete overlap is quite high - ~150 µJ at the undulator. Once again the wavelength requirement (~1 µm) and the reliability aspects favour an Yb fibre laser but the energy is now close to the limit of what has been demonstrated. Assuming a suitable trade off between energy, spectrum and beam quality, a 100 kHz system has been reported [4] but extension to 1 MHz will need further development.

The temporal profile of the electron bunches strongly affects the performance of the NLS FELs. It is also very sensitive to the machine operating point. It needs to be monitored, therefore, both to ensure FEL stability and also to indicate conditions elsewhere in the accelerator.

The most direct way of measuring the bunch profile with the required resolution is with electro-optic (EO) sensing [5]. This uses the EO effect in a crystal, placed very close to the electron beam path, to sense the EM field of the bunch as it passes. The crystal is probed using a short laser pulse and the time-varying EM field (and hence the charge density) can be deduced by measuring the effects on the laser beam.

There are several schemes for EO sensing and the detailed laser specifications will depend on which one is eventually selected. However in general it is clear that:

a) the laser wavelength should be ~800 nm,

b) the laser pulses and electron bunches must be synchronized,

c) some schemes need a minimum spectral width (corresponding to the transform limit for a sub-100 fs pulse),

d) there may be a significant pulse energy requirement, particularly for schemes involving a nonlinear stage,

e) the measurement rate needs to be high enough for adequate sampling of the noise spectrum.

The simplest laser architecture uses the NLS clock signal, which is distributed as 1560 nm pulses on a fibre optic network, as the source for the EO laser. The pulse energy can be raised by a local Er doped fibre amplifier before frequency doubling to 780 nm. This meets all of the requirements except, perhaps, for the bandwidth and pulse rate (the pulse rate is subject to an average power limit if the pulse energy is high). If the bandwidth must be greater than the clock pulses can supply then a local oscillator, phase-locked to the clock, will be needed.

FEL seed lasers

Using HHG to seed the NLS FELs has at least three advantages: the output pulses can be made short, with relatively smooth, near transform-limited spectra; their timing jitter can be reduced; and the FEL undulators can be shorter, thereby reducing their cost. It is proposed to operate the FELs in harmonic mode which significantly relaxes the requirements on the seed tuning. The baseline specifications are that the seed pulses should cover the energy range from 50 to 100 eV with a peak power of 400 kW and 20 fs FWHM duration. They must be continuously and rapidly tuneable over the full energy range.

The required power and pulse duration amount to a pulse energy of 8 nJ at the undulator. The beam transport optics from the HHG cell have just three reflecting surfaces (see Figure 2) and even allowing for losses arising from removal of the pump radiation their throughput is expected to be 30-50%. So 16-24 nJ of harmonic light will be needed at the HHG cell. An

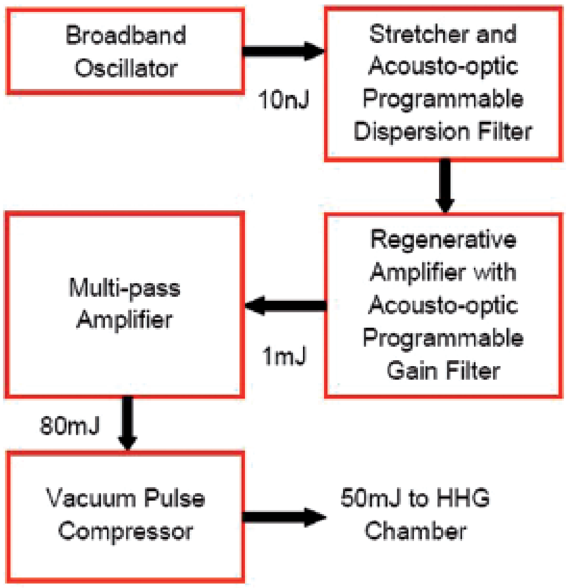

Figure 3. Architecture of the laser system used to generate the HHG seed pulses.

HHG system, based on loose focusing (f/250) into low pressure neon, has already produced comparable energies over a similar tuning range [6]. A 50 mJ, 30 fs pump laser was used there (the pulse shortens somewhat in the HHG process) and these parameters have been taken as the basis for the NLS design. The main differences will be that the NLS system will need to operate at 1 kHz and will also need to be tuneable.

One approach to achieving the required tuning range might have been to use optical parametric conversion in the pump system. However the inevitable efficiency losses present serious problems when average powers are high. Fortunately the tuning range does not need to be very large. A nominal 800 nm pump laser would only need to tune from 777 nm to 824 nm to allow the 33rd harmonic of the former wavelength to overlap the 35th of the latter. Tuning over this range has been demonstrated in a commercial Ti:S laser [7] and the technology of this system has been scaled for the NLS design. The architecture is shown in Figure 3. The light from an ultrashort pulse oscillator is amplified in a conventional regenerative/multipass system with the addition of two programmable filters. The first controls the spectral phase and is mounted with the stretcher i.e. outside the regenerative amplifier cavity. The second is an intracavity filter shaping the amplifier's spectral gain. It is this which tunes the laser's wavelength and the advantage of mounting it inside the cavity is that its single-pass profile can be relatively "soft". This improves the amplifier's output energy, stability and contrast.

A 1 kHz laser system delivering 50 mJ after compression needs a substantial pump laser array. With a conversion efficiency of 15-20%, 250-300 W of green pump light will be required. At present commercial pump lasers are limited to a single aperture power of 30-40 W so 6-10 such units will suffice. The increased pump power needed for 1 kHz operation also leads to increased heating of the power amplifiers' Ti:S crystals. Cryogenic cooling has become the standard approach to this problem and 150 W coolers are already in use.

Lasers for user experiments

The simultaneous availability of both accelerator based and conventional laser sources will allow NLS users to carry out sophisticated, multi-beam experiments. For this they will need the lasers to be continuously tuneable over a very broad range. The CLF already has experience of generating exactly this kind of light in its ULTRA [8] and Artemis [9] facilities. The tuning range and the techniques which will be used are indicated in Figure 4.

The most challenging spectral region is the one from 6 eV to 50 eV. This will be covered by extending the technique of tuneable HHG used for FEL seeding (see above). At high photon energies, which lie in the HHG plateau region, the major issue is generating sufficient pulse energy. The FEL seed laser aims to deliver, after transport, ~8 nJ or ~10^9 photons per pulse at 50 eV. This is well below the NLS target of 10^{11} photons per pulse. Developments will therefore be needed to raise the output energy. Optimising the focusing and gas conditions has recently resulted in the generation of 1 μJ pulses (1.6×10^{11} photons) at 39 eV using a 50 mJ, 50 fs drive laser [10]. In addition both quasi phase matching [11] and two colour pumping [12] have led to yield enhancements.

As the photon energy falls, HHG photon yield increases, both because the conversion efficiency climbs as the harmonic number falls and also because the number of photons per joule rises. At low photon energies the issue becomes the tuning range. Normal HHG only generates odd harmonics, so to deliver 6 eV this way using H5 would require tuning the drive laser to 1033 nm. It is impractical to do this using Ti:S without changing other pulse properties (duration, temporal shape etc.) significantly. In this case the solution may be to use two colour pumping [12], which generates a much more closely spaced manifold of "lines" or to drive the harmonics from an optical parametric amplifier (OPA) system which can reach the lower photon energies more easily. Such systems are already being developed [13].

Radiation in the infrared, visible and ultraviolet will be generated using nonlinear techniques driven by the short pulse Ti:S laser, which will be carrier-envelope phase stabilised. The coloured bars on the right hand side of the graph in Figure 4 reflect the energies available from a system driven by 6 mJ pulses. The black bars are the signal and idler outputs, and their second harmonics, from an optical parametric amplifier seeded by a femtosecond "white light" source. The blue bars are the results of sum frequency processes and their second harmonics. The brown bars extend the range into the mid infrared using difference frequency generation. With the increased energy available from the 50 mJ laser and using the most modern conversion techniques the tuning can be made continuous from 60 meV to 6 eV. The transition from one nonlinear scheme to another will need to be smooth from the users' point of view and, as far as possible, transparent. A high degree of automation will therefore be involved.

The NLS baseline specification does not include the delivery of pulses shorter than 20 fs. However the capability for this clearly exists and will be allowed for in the initial system design.

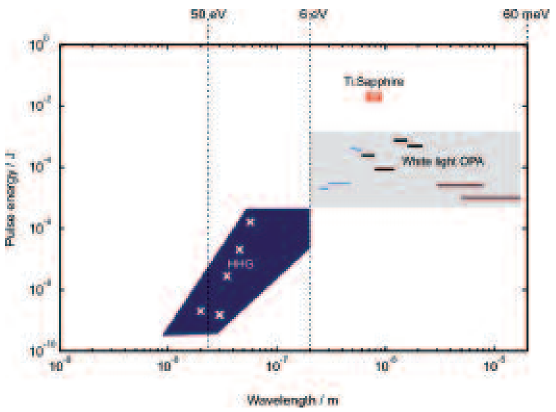

Figure 4. Output of broadly tuneable laser system based on tuneable Ti:Sapphire, OPA and HHG.

Conclusions

The New Light Source project is based heavily on the use of state of the art conventional lasers. Outline design work has confirmed that lasers for baseline (1 kHz) operation of the facility either exist already or are within plausible reach on the required timescale, given a realistic development programme.

Acknowledgements

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