CONSIDERATIONS FOR A NEW LIGHT SOURCE FOR THE UK

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Abstract

The current status of the definition of the scientific requirements for a New UK Light Source, and how these might be met by a new facility incorporating advanced laser and FEL sources, is presented.

INTRODUCTION

The New Light Source (NLS) project [1] was launched in April 2008 by the UK Science and Technology Facilities Council (STFC) to consider the scientific case and develop a conceptual design for a possible next generation light source based on a combination of advanced conventional laser and free-electron laser sources. Work on NLS draws on expertise from STFC Daresbury and Rutherford Laboratories - which includes the Accelerator Science and Technology Centre (ASTeC) and Central Laser Facility (CLF) - Diamond Light Source, the John Adams and Cockcroft accelerator institutes, and various Universities.

NLS is a "science driven" project. The aim is *firstly* to define the key science drivers that are likely to be relevant for many decades to come, *secondly* to define the technical solution, and *thirdly* to assess funding and location.

The NLS project has two distinct phases. In the current first phase the primary activity is the development of the science case through a process of consultation with the UK scientific community. In parallel, various physics and technological issues related to lasers and FELs are being addressed to assess the current state-of-the-art as well as the developments that are likely to occur within the timescales of construction of NLS. Phase 2 will commence following approval of the broad facility specification by STFC in November. The outline facility design will be agreed by January 2009 after which a design report and proposal for funding will be prepared for submission in October 2009.

SCIENCE CASE

As part of the scientific consultation, various workshops have been held in 2008:

- Ultra-fast Electron Dynamics & Attosecond Science, 13th May
- High Energy Density Science, 20th May
- Condensed Matter, 21st May
- Chemical Science, 22nd-23rd May
- Life Sciences, 19th June

A Workshop on Advanced Photon Sources was also held (June 3rd-4th) which provided useful information about the state-of-the-art of both laser and FEL sources. Information about the workshops and copies of presentations are available on the project website [1]. Science coordinators were appointed and working groups were set up for each of the areas listed above, reports from which fed into a draft science case, which will soon be available on the project web site [1] and open for consultation, before a final version is presented via various committees to the STFC Council in November 2008.

The main emerging science themes are as follows:

♦ Imaging Nanoscale Structures: enabling the making of instantaneous images of nanoscale objects that show the full microscopic structure pictured at any desired instant which could allow, for example, the internal motions of sub-cellular structures in living systems to be followed.

♦ Capturing Fluctuating and Rapidly Evolving Systems: characterising the rapid intrinsic evolution and fluctuations in the positions of the constituents within matter by the use of coherent soft X-ray scattering.

♦ Structural Dynamics Underlying Physical and Chemical Changes: revealing the underlying structural dynamics governing condensed matter changes and chemical and biochemical processes by using laser pump-X-ray probe techniques.

♦ Ultra-Fast Dynamics in Multi-Electron Systems: providing the capability for measuring the multi-electron quantum dynamics that are present in all complex matter by using attosecond pump-attosecond probe techniques.

DESIRED SOURCE PARAMETERS

The source parameters that have emerged so far as being desired by the scientific community to optimally match to the above themes are as follows:

- High brightness radiation (up to 10^{12} photons/pulse) covering a broad spectral range, ideally from THz to photon energies of ~1.5 keV in the fundamental, with harmonics up to 7.5 keV
- High repetition rate, ideally 1-10kHz (or higher) with even pulse spacing for optimized data collection and for efficient synchronization to external lasers, including for seeding and slicing
- Capable of easy wavelength tuning
- High degree of transverse coherence, with temporal coherence close to the Fourier transform limit
- Pulse durations down to ~20fs for soft X-ray applications, with sub-femtosecond capability required for attosecond science
- Spectral linewidths of ~0.1% in the soft X-ray region, with the possibility of reducing this in the future
- Two-colour capability for pump probe experiments with synchronisation jitter better than 10fs. e.g. THz-UV (pump), VUV-Soft Xray (probe)
- Synchronised auxiliary devices i.e. high power lasers, pulsed electron beam, high magnetic field facilities

Such a combination of capabilities would form a unique facility enabling groundbreaking new science. While the source parameters are achievable, through a combination of linac-based FEL and advanced conventional laser technology, some compromise in performance, or staging of the project, might be necessary in order to stay within likely funding levels. For this reason, at the current stage a number of technical options are being considered which will only be narrowed down following discussion and approval of the science case. In this report we concentrate mainly on the aspects related to the FEL source(s) rather than the laser sources.

SOURCE CONSIDERATIONS

Choice of Linac Technology

An important issue facing NLS is the choice of linac technology, which has a strong impact on the pulse repetition rate as well as on the photon energy reach, for a given cost. A high (> ~400 Hz) repetition rate of single pulses demands superconducting (SC) linac technology operating in continuous-wave (cw). Normal conducting (NC) linac technology is however significantly cheaper, allowing a higher energy to be reached for a given cost. The higher cost for SC technology is made up of the higher machine cost per MeV (partly because of the lower gradient, but mainly the higher intrinsic production cost), the cost of the cryogenic plant, and increased building costs (because of the longer linac length, and the extra space required for cryogenic plant). Our initial estimates show that the total cost of a new facility (including two FELs, buildings, services, salaries and overheads etc.) based on a SC linac is of the order of 60% more expensive than one employing a NC linac of the same energy in the range of 1-3 GeV.

The intermediate case of a pulsed SC linac, with a low repetition rate of macro-pulses, such as FLASH and the future EU-XFEL, allows a higher energy to be reached than a cw SC linac however is less favoured because of the associated difficulties of signal detection and also synchronisation with seed or pump-probe lasers and so has not been considered for NLS.

The significant difference in cost between normal and superconducting technology means that the requirements for any new facility which are not pre-determined by, for example, the availability of an existing linac, or other site constraints, must have a clear justification. At the current stage both linac options are still being considered as part of the current generic studies for NLS, continuing earlier work on particular NC [2] and SC [3] machine designs.

A cw linac in principle opens up the possibility of another option, that of a recirculating linac. At first sight this is an attractive option both in terms of capital cost as well as operating costs. Significant difficulties have to solved however in terms of maintaining the required beam quality in the return loop(s) as well in providing the necessary bunch compression. The cost benefit however appears to be so significant that this option will certainly be considered further in the coming months.

Temporal Coherence.

To overcome the fluctuations in the temporal and spectral profiles of individual pulses which are inherent in the SASE mode of operation, seeding the FEL process with coherent laser radiation is now being considered by many FEL projects. Similarly for NLS, a strong desire has been expressed for pulses with good temporal coherence near the Fourier transform limit. The common approach to seeding at short wavelengths is to use laser sources based on HHG (High Harmonic Generation) in gases, for which there has recently been a successful demonstration at 160 nm [4]. Table 1 shows our current estimates of the required seed laser power to overcome shot-noise by a factor of 10^3. Simulations show that a factor of 10^2 is required for good temporal coherence and for a good ratio between the peak intensity from the seeded portion and the SASE background from the rest of the pulse; a further factor of 10 has been included to account for losses, imperfect focusing etc., of the seed radiation.

Table 1: Estimated power, and pulse energy (based on 20 fs pulse length), required from a seed laser at various wavelengths.

Wavelength	Peak power	Pulse energy
100 nm	10 kW	0.2 nJ
10 nm	100 kW	2 nJ
1 nm	1 MW	20 nJ
0.1 nm	10 MW	200 nJ

Comparing Table 1 to the capabilities of current laser sources shows that seeding should be possible using HHG in gases down to wavelengths of approximately 7 nm using commercial mJ-level, multi-kHz drive lasers. There is however a great deal of activity directed to increasing HHG conversion efficiency, as well as drive laser power, so that on a scale of ~ 5 years there are good prospects of reaching the levels required for seeding at 1 nm. Use of solid target HHG provides a possible route for reaching the few keV range over the next 5-10 years, however there are significant scientific and technical challenges to be overcome which would require a substantial R&D programme. We are therefore also considering FEL high gain harmonic schemes as a way of extending the photon energy range over which longitudinally coherent radiation can be produced.

Short Pulses

A key feature of NLS will be the provision of short, femtosecond, and if possible sub-femtosecond, pulses. The requirement will be met in the first instance either by seeding with a short ~20 fs laser pulse, where such a source exists, or in the SASE mode by compressing the electron pulse. Studies have confirmed that for both NC S-band and SC L-band designs electron pulses of the order of 10 fs can be produced with a charge of 0.2 nC [2,3]. Note that here and in the following discussion all pulse lengths refer to FWHM values.

For shorter pulses a number of options are being studied. Various “slicing schemes” have been put forward, see for example ref. [5] and references therein, which employ a few-cycle IR laser to energy modulate a slice of the electron bunch, so that only those electrons in less than one optical period length of the bunch are matched to the subsequent SASE FEL. Most of these schemes have been studied for 1.5 Å wavelength and promise pulses of ~250 as. It is important to note however that under normal circumstances the minimum pulse length is limited to a value of the order of the co-operation length $L_c = \lambda/4\sqrt{3}\pi\rho$, and hence the minimum number of optical cycles is given by $N_c = 1/4\sqrt{3}\pi\rho$. For a typical value of $\rho \approx 10^{-3}, N_c \approx 46$ and hence of the order 150 as at 1 nm, and 1.5 fs at 10 nm. Simulations for one such scheme in the soft X-ray region by Fawley [6] give results which are consistent with this: 1.5 fs at 8 nm and 2.3 fs at 32 nm. We conclude therefore that slicing techniques should be capable of delivering few-fs pulses in the few-nm to 100 nm region, and potentially sub-fs at wavelengths less than a few nm; in all cases pulses are many tens, or hundreds, of optical cycles long.

Another possibility for generating short pulses is the so-called "single spike" mode of operation [7]. This requires a short electron pulse length of the order of the FEL co-operation length, which can be achieved by operating a photocathode gun with very low charge (~ pC) [8]. Simulations show that ~ 250 as pulses are possible in the LCLS at 1.5 Å [9], increasing to 2.7 fs at 3 nm in SPARX [8]. These are no shorter therefore than the slicing schemes, and generally with lower peak power. Furthermore the scheme suffers from the disadvantage of large shot-to-shot intensity variations, as well as not being synchronised to an external reference (other than the photocathode laser). The advantages however are the simplicity - a standard injector may be able to be operated at low charge without hardware modification – and the low background as compared to a "sliced" pulse which sits on top of a significant SASE background.

The only method to date that is not constrained to the generation of radiation pulses of length the order of the cooperation length is that of the mode-coupled and mode-locked methods of [10]. Recent work shows that it should be possible to amplify an HHG seed to saturation while retaining its attosecond structure [11].

Two-colour capability

An important requirement for NLS is the ability to carry out various kinds of pump-probe experiments, for example with a THz-UV pump, VUV-Soft X-ray probe. THz radiation can be provided relatively easily using a second source following the main FEL, similar to the Infra-red undulator at FLASH [12]. The advantage of this arrangement is that the radiation is synchronised with high precision to the main FEL pulse. Assuming suitable undulator parameters, if the electron pulse length is of the order of 10 fs then intense coherent spontaneous radiation is emitted for wavelengths greater than approximately 10 μm. At shorter wavelengths, down to about 150 nm, conventional lasers are competitive and more likely to be used than an accelerator based source, provided the required synchronisation can be achieved.

CONCLUSION

A "snap-shot" of the status of the NLS Project as of end of August 2008 has been presented, including some of our initial considerations for meeting the desired source parameters. A period of consultation on the draft science case is about to be begin, eventually leading to an outline facility design, which will then be worked on in detail before submission for funding in Autumn 2009.

ACKNOWLEDGEMENTS

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REFERENCES

[1] http://www.newlightsource.org/
[2] R.P. Walker et al., "Sapphire – A High Peak Brightness X-ray Source as a Possible Option for a Next Generation Light Source", Proc. EPAC 2008, p. 142.
[3] P. Williams et al., "PULSE - A High Repetition Rate Linac Driver for X-ray FELs", Proc. EPAC 2008, p. 148.
[4] G. Lambert et al., "Seeding the FEL of the SCSS Test Accelerator with the 5th Harmonic of a Ti: Sa Laser Produced in Gas", Proc. EPAC 2008, p. 109.
[5] E.L. Saldin et al., "Attosecond Pulses from X-ray FEL with an Energy-chirped Electron Beam and a Tapered Undulator", Proc. FEL 2006, p. 202.
[6] W.M. Fawley, Proc. International Workshop on Frontiers in FEL Physics and Related Topics, Elba, Italy, Sep. 2007, NIM A 593 (2008) p. 111.
[7] R. Bonifacio et al., "Spectrum, Temporal Structure and Fluctuations in a high gain Free Electron Laser starting from Noise", Phys. Rev. Lett. 73, 70, (1994).
[8] J.B. Rosenzweig et al., "Generation of Ultra-short, High Brightness Electron Beams for Single-Spike SASE FEL Operation", NIM A 593 (2008), p. 39.
[9] S. Reiche et al., "Development of Ultra-short Pulse, Single Coherent Spike for SASE X-Ray FELs", NIM A 593 (2008), p. 45.
[10] N.R. Thompson and B.W.J. McNeil, "Model-Locking in a Free Electron Laser Amplifier", Phys. Rev. Lett., **100**, 203901, (2008).
[11] B.W.J. McNeil et al., "Retention of Attosecond Pulse Structure in an HHG Seeded FEL Amplifier", Proc. FEL 2008, to be published.
[12] M. Gensch et al., "New Infrared Undulator Beamline at FLASH", Infrared Physics & Technology 51 (2008) p. 423.