FEL RESEARCH AND DEVELOPMENT AT STFC DARESBURY LABORATORY

N.R. Thompson[1,3], J. A. Clarke[1], D. J. Dunning[1,3], G. M. Holder[2], S. Jamison[1], B. W. J. McNeil[3], M. D. Roper[1], M. R. F. Siggel-King[2,4], A. D. Smith[2], M. Surman[1], P. Weightman[2] and A. Wolski[2,4]
[1]Accelerator Science and Technology Centre (ASTeC), STFC Daresbury Laboratory, UK
[2]The University of Liverpool, Liverpool, UK
[3]University of Strathclyde (SUPA), Glasgow G4 0NG, UK
[4]Cockcroft Institute, Warrington, UK

Abstract

In this paper we present an overview of current and proposed FEL developments at STFC Daresbury Laboratory in the UK. We discuss progress on the ALICE IR-FEL since first lasing in October 2010, covering the optimisation of the FEL performance, progress on the demonstration of a single shot cross correlation experiment and the results obtained so far with a Scanning Near-Field Optical Microscopy beamline. We discuss a proposal for a 250 MeV single pass FEL test facility named CLARA to be built at Daresbury and dedicated to research for future light source applications. Finally we present a brief overview of other recent research highlights.

INTRODUCTION

In this paper we report on the progress in FEL research and development at STFC Daresbury Laboratory in the United Kingdom. We discuss progress on an operating IR-FEL which is part of the ALICE test facility, we report on design work for a proposed 250 MeV single-pass FEL test facility named CLARA (Compact Linear Accelerator for Research and Applications), and we summarise recent developments in theoretical work on novel FEL concepts.

ALICE

The ALICE facility at Daresbury Laboratory [1] has evolved from an ERL prototype for the 4GLS project [2] to a multi-functional facility hosting projects including the world's first non-scaling FFAG, EMMA [3], THz generation for use in a tissue culture facility and the UK's first FEL [4]. The FEL is an infra-red oscillator lasing over ∼5.5–9 μm. It is used for: developing experimental FEL expertise; benchmarking modelling; accelerator physics studies; a source for user experiments.

Figure 1 shows the ALICE layout including a view of the FEL line. A DC photoelectron gun (recently upgraded to a larger diameter gun ceramic to increase the operating voltage from 230 kV to 325 kV) with GaAs photocathode injects into the first superconducting module which accelerates to 6.5 MeV. For FEL operation the main linac operates in energy recovery mode and accelerates to typically 26 MeV. The nominal bunch charge is 60 pC, with bunches delivered at 16.25 MHz in trains of up to 100 μs with train repetition frequency up to 10 Hz. The variable gap undulator has 40 periods of length 2.7 cm. The optical cavity comprises two spherical gold-coated copper mirrors with hole-outcoupling in the downstream mirror. The FEL output is transported in-vacuo to a diagnostics room by a multi-optics beamline with a transmission efficiency of typically 35% for detailed characterisation and experimental use. The FEL delivers ∼3 μJ energy per micro-pulse, corresponding to ∼4 mJ per macro-pulse. Further details of the FEL operating parameters and performance are given in [4].

Calculations of the gain, from the exponential rise at the start of the train, have previously been made using a Mercury Cadmium Telluride (MCT) detector. The MCT detector does not fully resolve individual FEL pulses but exhibits a small modulation of the signal corresponding to the pulse train structure. Single-pass gain values of up to ∼25% have been measured using the MCT. Pre-amplification of the MCT signal slows the response, introducing an artificial limit to gain measurements. A new photoelectromagnetic IR detector, with sufficiently fast response to resolve individual FEL pulses, has recently been added. New software has been developed to continuously monitor the gain by fitting to the envelope of the exponential rise. This is proving valuable for more rapid optimisation.

The FEL pulse duration has thus far been inferred both from measurement of the output power and spectrum, and from direct measurements of the electron bunch length. Work has been done towards capturing the longitudinal profile of the FEL pulse in a single shot. This involves cross-correlating the FEL pulse and an external laser via co-propagation in a non-linear crystal. Preliminary experiments have demonstrated both spatial and temporal overlap in a co-linear arrangement and the next step is to move to a non-co-linear alignment to allow extraction of the FEL pulse profile.

The FEL output has also been integrated with a Scanning Near-field Optical Microscope (SNOM) [5] as part of a collaboration with the Universities of Liverpool and Rome. The motivation is sub-diffraction biochemical imaging of human tissue. The research programme aims to develop diagnostics and understand the mechanism and drug action in oesophageal cancer. The FEL tuning range of 5.5 – 9 μm is well matched to the molecular fingerprint region.

ISBN 978-3-95450-123-6

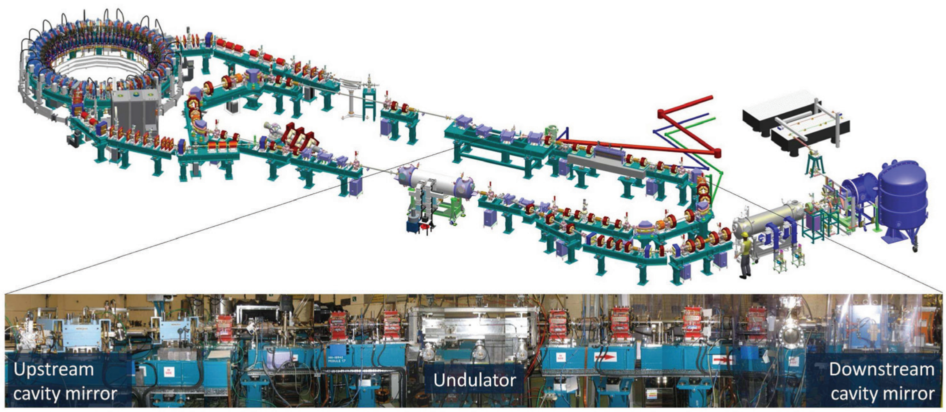

Figure 1: Layout of the ALICE facility and FEL line.

The IR beam in the diagnostics room is split with half sent to an Acton 0.5 m Czerny-Turner spectrometer (Princeton Instruments) with a pyro array detector (Delta Developments) providing single train spectral line measurements. The other beam is focussed onto an optics table on which the SNOM is located in air. Detection of the SNOM signal is by coupling the fibre to a cooled MCT detector. The ∼100 µs FEL pulse trains are ideally matched to the detector response and boxcar integration techniques. The SNOM data can be normalised to the intensity and spectrum from the array detector on a shot to shot basis. High quality SNOM images (an example is given in Figure 2) require good intensity and wavelength stability over the 1–2 hour scan times. The suite of on-line single shot beam quality diagnostics allows real time monitoring of the accelerator during these scans and offers the potential for feedback to the accelerator for maintaining optimum lasing in the future. With the FEL well set up, the variation of the power during scans is ∼3 % rms, and the wavelength fluctuation is <20 % of the bandwidth.

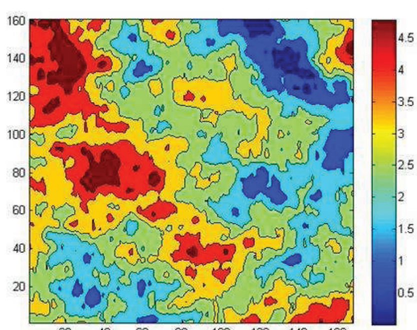

Figure 2: Nano-scale spatial resolution from tissue: 50×50 µm SNOM image showing variation of 8.05 µm light absorption. The DNA in the sample contributes strongly to this absorption.

Work has been initiated to extend the operating wavelength of the FEL to longer wavelengths, since 20 µm is of interest to potential users. Lasing has been established with a 23 MeV setup, generating 11 µm radiation at minimum undulator gap, and it is planned to develop a 17.5 MeV setup for 20 µm operation.

CLARA

It is proposed to build a dedicated FEL test facility, called CLARA, so that several of the most promising proposed schemes for enhancement of FEL output can be tested for subsequent implementation into a new UK national light source facility from conception. The primary aim of CLARA is 'to develop a normal-conducting test accelerator, able to generate longitudinally and transversely bright electron bunches, and to use these bunches in the experimental production of stable, synchronised, ultra-short photon pulses of coherent light from a single pass FEL using techniques directly applicable to the future generation of light source facilities'. In this context ultra-short means the photon pulse length should be shorter than, or of the order of, the FEL cooperation length. Further aims are to demonstrate high temporal coherence and wavelength stability of the FEL, for example through the use of external seeding or other methods and to develop the techniques for the generation of coherent higher harmonics of a seed source.

A new photoinjector test stand, the Electron Beam Test Facility (EBTF), is currently being assembled and this will act as the electron source for CLARA. The EBTF gun is a 2.5 cell S-Band cavity which will generate high brightness 6 MeV electron bunches. The electron bunches will be accelerated to nominal CLARA energy in normal conducting European S-Band linac sections. A number of operating regimes have been identified which have implications for the required hardware and layout of the accelerator. Parameters are given in Table 1. The Seeding mode is for schemes for harmonic generation and short pulse generation. In this mode the electron bunch will have a flat-top current distribution requiring the use of a 4th harmonic cavity operating at the EU X-Band frequency of 11.992 GHz. The Single Spike SASE mode will require a low charge bunch (estimated to be 20–100 pC) with a peak current of the order of 1500 A. Bunch compression will be achieved either via magnetic chicane or velocity bunching. The RAFEL mode is a future option which will require an upgrade to the photoinjector laser. Macropulses of up to 20 bunches at a repetition rate of 10 MHz will be used to drive a Regener-

ISBN 978-3-95450-123-6

ative Amplifier FEL (RAFEL) similar to that proposed for the 4GLS VUV-FEL [2]. Mirrors will be used to create an optical cavity around the radiator undulators to provide a small amount of feedback to self-seed the FEL and generate temporally coherent output. It is estimated that the system will reach saturation in around 10 round trips, allowing 10 pulses of saturation intensity for characterisation. The final operating mode is a lower energy (100 MeV) high repetition rate (400 Hz) mode for demonstration of hardware at these repetition rates and for the supply of electron beam for industrial applications.

Most of the seeding and harmonic generation schemes proposed follow a generic layout of one or two modulators where the electron bunch interacts with an external laser and then a long radiator section where the FEL reaches saturation. The approach with CLARA is to build a very flexible facility which will be able to switch between the different schemes relatively quickly. The long radiator section is common to almost all of the schemes and the area needing the most intervention will be the short modulator section so for greatest flexibility CLARA will be engineered so that the modulators are easy to exchange and align. The overall schematic layout of CLARA is shown in Figure 3.

The detailed parameters of the CLARA FEL are dictated by the requirement to interact with conventional laser seed sources. The primary external radiation source will be a Ti:Sa laser operating at 800nm. This can be used on its own, or to drive an Optical Parametric Amplifier (OPA) covering the range 2-20 µm (with extension to 100 µm via difference frequency mixing) or to drive a Higher Harmonic Generation (HHG) system giving output from the longest easily available wavelength of 100 nm. It is planned to operate over the range 400–266 nm for short pulse schemes, due to the availability of single shot pulse profile diagnostics over this range, whereas schemes requiring only spectral characterisation will operate at wavelengths as short as 100 nm. The FEL output wavelength range is thus 100–400 nm. The minimum undulator gap is expected to be 6 mm. It is then possible to tune over 400-100 nm range with a hybrid undulator with period of 27 mm and an electron beam energy of 250 MeV, while still allowing a sensible contingency. The modulator undulators, which in combination will tune from 800 nm to 100 µm, are not yet specified.

The CLARA design work is ongoing, with an Outline Design Report scheduled for publication in Spring 2013. A number of FEL schemes have been tested in initial simulations, with promising results previously published [6]. The intention is to include full start-to-end simulations of the most promising schemes in the ODR.

NEW CONCEPTS

Complementary to the development of the CLARA proposal, a programme of research with the University of Strathclyde is investigating new FEL methods and techniques. Some of these ideas are based upon the concept of creating coupled radiation modes by introducing of a series of relative radiation/electron beam shifts as the FEL interaction progresses along the undulator [7]. Such shifts may be achieved by introducing electron beam delay-lines composed of chicanes placed between successive undulator modules. To allow greater flexibility, research has also been conducted into novel isochronous delay lines that do not over-bunch electrons in transit through them [8]. For equal shifts, a series of equally spaced radiation modes develops which may become locked if there is a beam modulation at the radiation mode spacing. When starting from noise in SASE mode, these coupled modes create a high-power pulse-train structure in time with individual pulse lengths significantly less than that of the cooperation length, so that in the x-ray the pulse train forms a high power x-ray stroboscope with the spatio-temporal resolution of atomic processes. Modulation in both the electron beam energy [7] and current [9] have been shown to couple the modes in simulations and the process has been shown to be quite robust in 3D start-to-end simulations using realistic electron beams [10]. Simulations have shown that this method can be used to amplify an HH seed field in an FEL amplifier and retain the initial Attosecond Pulse Train (APT) temporal structure of the HHG seed [11]. By matching the modal properties of the undulator-chicane system to those of the HH seed field, the peak power of the seed may be amplified by a factor ∼300. Unlike the cases starting from noise [7, 9], no pre-conditioning of the electron beam (i.e. energy or current modulation) is required.

The Regenerative Amplifier FEL is a high-gain FEL which has a single pass gain below that required for SASE operation. The introduction of a very small cavity feedback (as little as $\sim 10^{-5}$ of the undulator power output) is predicted to generate radiation pulses of improved quality than possible using SASE [12]. With a power feedback of only approximately double the shot-noise power, the time bandwidth product is predicted to be more than five times better than the equivalent SASE result. These promising results have been extended to include electron pulses of RMS width of the cooperation length. In SASE mode of operation such pulses have been suggested as a source of single, attosecond, high-power x-ray pulses. However, the nature of SASE means that the pulses have a large temporal jitter making them more difficult to synchronise in pump-probe experiments. When such short electron pulses are employed in a RAFEL configuration however, this temporal jitter is stabilised to give stable 'single' Fourier transform limited, high-power x-ray pulses at Ångstrom wavelengths and of FWHM duration ~ 250 as [13].

The concepts developed for generating coupled frequency modes in a FEL amplifier [7, 9, 10] have been extended to FEL cavity oscillators operating in both the high-gain RAFEL mode and for lower-gain systems. When the frequency modes are coupled via a frequency modulation of the electron beam at the mode spacing, the modes lock in a similar way to that in a high-gain amplifier to generate a well defined pulse train. The example of a RAFEL

ISBN 978-3-95450-123-6

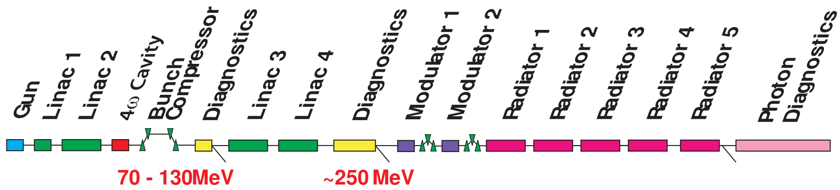

Figure 3: CLARA Schematic layout.

Table 1: Main Parameters for CLARA Operating Modes

	OPERATING MODES				
Parameter	Seeding	SASE	Single Spike SASE	RAFEL	Industrial
Max Energy (MeV)	250	250	250	250	100
Macropulse Rep Rate (Hz)	100	100	100	100	400
Bunches/macropulse	1	1	1	20	tbc
Bunch Charge (pC)	250	250	20–100	250	250
Peak Current (A)	125–400	400	1500	400	tbc
Bunch length (fs)	250–800 (flat)	250 (rms)	<30	250	tbc
Normalised Emittance (mm-mrad)	≤ 1	≤ 1	≤ 1	≤ 1	≤ 1
RMS Energy Spread (keV)	25	100	150	100	tbc
Radiator Period (mm)	27	27	27	27	-

operating in the soft-X-ray gave individual pulses conservatively estimated at 200 as duration at a wavelength of 3 nm. Scaled to the x-ray with wavelength $\lambda = 0.15$ Å, and for FEL parameter $\rho = 5 \times 10^{-4}$, such pulses are 24 as in duration.

In addition to in-house generated concepts, research is also being conducted into other methods for improving FEL output. In particular, the method of Echo Enabled Harmonic Generation [14] is being investigated, with some preliminary results presented in [15].

To facilitate the above and other research, a new 3D unaveraged FEL simulation code 'Puffin' has been developed by the University of Strathclyde. Puffin can model electron interactions with broad bandwidth radiation that include electron beam shot-noise and Coherent Spontaneous Emission (CSE) effects. Non-localised electron transport throughout the beam is modelled self-consistently allowing better modelling of systems where a larger electron energy range is required. Electrons are transported through a strong focussing channel with a fully variably polarised undulator. The code should prove to be a flexible research tool allowing exploration of new methods and ideas that cannot be modelled using other codes. Examples that will benefit from such studies include the variably polarised undulator [17] and where long-scale electron transport within the electron beam may generate significant CSE [18, 19].

REFERENCES

[1] Y. Saveliev, Proceedings of IPAC2012, New Orleans, **MOPPP022**, 613 (2012).

[2] 4GLS Conceptual Design Report, CCLRC, `http://www.4gls.ac.uk`, (2006).

[3] S. Machida et al., Nature Physics **8**, 243247 (2012).

[4] N.R. Thompson et al., NIM A **680**, 117-123 (2012).

[5] A. Cricenti et al., Appl. Phys. Lett. **71**, 151-153 (1998).

[6] J. A. Clarke et al, Proceedings of IPAC2012, New Orleans, **TUPPP066**, 1750 (2012).

[7] N.R. Thompson and B.W.J. M^cNeil, Phys. Rev. Lett. **100**, 203901 (2008).

[8] J.K. Jones, J.A. Clarke and N.R. Thompson, Proceedings of IPAC2012, New Orleans, **TUPPP069**, 1759 (2012).

[9] E. Kur, D.J. Dunning, B.W.J. M^cNeil, J. Wurtele and A.A. Zholents, New Journal of Physics **13**, 063012 (2011).

[10] D.J. Dunning, B.W.J. M^cNeil, N.R. Thompson and P.H. Williams, Physics of Plasmas **18**, 073104 (2011).

[11] B.W.J. M^cNeil, N.R. Thompson, D.J. Dunning and B. Sheehy, J. Phys. B: At. Mol. Opt. Phys. **44**, 065404 (2011).

[12] D.J. Dunning, B.W.J. M^cNeil and N.R. Thompson, Nucl. Inst. Meth. Phys. Res., A **593**, 116 (2008).

[13] B.W.J. M^cNeil and N.R. Thompson, Euro. Phys. Lett., **96**, 54004 (2011) and erratum **98**, 29901 (2012).

[14] G. Stupakov, Phys. Rev. Lett. **102**, 074801 (2009).

[15] J. Henderson, B.W.J. M^cNeil and D.J. Dunning, Proceedings of FEL2010, Malmo, Sweden, **MOPB32**, 99 (2010).

[16] L.T. Campbell and B. W. J. M^cNeil, 'Puffin: A three dimensional, unaveraged Free Electron Laser simulation code', Submitted (Accepted?) for publication in Physics of Plasmas also L.T. Campbell and B. W. J. M^cNeil, *ibid.*

[17] L.T. Campbell, B. Faatz and B.W.J. M^cNeil, Proceedings of FEL2010, Malmo, Sweden, **THPB15**, 622 (2010).

[18] D.J. Dunning, N. R. Thompson and B.W.J. M^cNeil, Proceedings of FEL2010, Malmo, Sweden, **THPB21**, 636 (2010).

[19] L. T. Campbell, B. W. J. M^cNeil, 'A Simple Model for the Generation of Ultra-Short Radiation Pulses', **THPD41**, *ibid.*

ISBN 978-3-95450-123-6