THE 4TH GENERATION LIGHT SOURCE AT DARESBURY

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Abstract

4GLS is a next generation proposal for an advanced light source to be built at Daresbury Laboratory. The facility will consist of three integrated accelerator systems: a 25-60 MeV linear accelerator driving an Infra-Red Free-Electron Laser (FEL) at 13 MHz; a 750-950 MeV branch driving a 10-100 eV XUV-FEL at 1 kHz; a 600 MeV energy recovery linac carrying 100 mA current driving a suite of spontaneous sources at 1.3 GHz or a VUV-FEL (up to 10 eV) at 4 MHz. The latter two accelerator systems share a common superconducting linac based on 1.3 GHz TESLA technology, which will simultaneously accelerate the two bunch types (1 nC and 77 pC) whilst decelerating the returning 77 pC bunches. This paper will outline the project and its key features, including the 35 MeV ERL Prototype accelerator presently being commissioned, and will discuss the accelerator physics and technology challenges to be explored in the present Design Study.

INTRODUCTION

Daresbury Laboratory is proposing to construct a fourth-generation light source facility - 4GLS - delivering both free-electron laser and spontaneous synchrotron radiation output. 4GLS will enable the study of real-time molecular processes and reactions on timescales down to tens of femtoseconds in short-lived, nano-structured or ultra-dilute systems. Experimental focus will be on molecular and device function, rather than the largely structural focus of work presently performed at 3rd-generation synchrotron radiation sources and X-ray FELs. The scientific motivations are described more fully elsewhere [1].

4GLS will be a multi-source, multi-user facility, and will benefit from the use of superconducting radio-frequency technology and energy recovery, and will produce short pulse spontaneous radiation with pulse lengths from ~1 ps down to less than 100~fs. At longer wavelengths the short pulse lengths will produce coherence synchrotron radiation (CSR), so that 4GLS will also provide enormously bright THz radiation. The high-quality, low-emittance bunches generated in the linacs also provide an ideal source for the operation of 3 free-electron lasers (FELs): these FELs will generate short-pulse output in the IR, VUV, and XUV wavelength ranges. The combination of these output sources in a single complex provides a unique facility for a variety of user experiments [1,2]; many of the sources originate from the same electron bunch, offering potential levels of synchronisation down to the ~10 fs regime. Fig. 1 shows peak brightness values envisaged for the sources on 4GLS; there is typically an enhancement of eight orders of magnitude when compared to 3rd-generation facilities.

A conceptual design report outlining the present design has recently been published [2]. Significant aspects of this design have been informed by experience gained from the Energy Recovery Linac Prototype, which is presently being commissioned at Daresbury Laboratory [3,4].

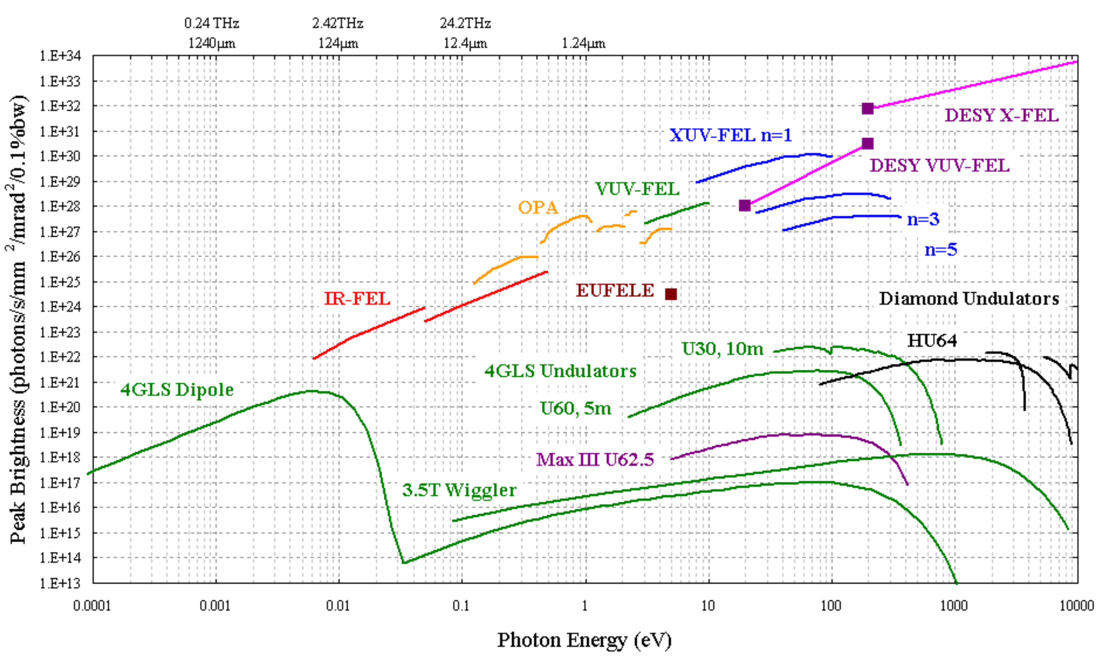

Figure 1: Peak brightness values for the 4GLS FELs, undulators, wiggler, OPA and dipoles compared with EUFELE, X-FEL, DIAMOND and Max III undulators.

FACILITY OVERVIEW

4GLS consists of three inter-related accelerator systems, shown in overview in Fig. 2. The first channel is a high-average-current loop (HACL) delivering 100~mA of current with a small transverse emittance and short bunch length (~1 ps) via a quasi-continuous bunch train from a 1.3 GHz frequency injector. The large beam power (60 MW at 600 MeV) necessitates the use of energy recovery by returning the electron bunches for deceleration in the same linac used for acceleration after their passage through the spontaneous devices and VUV-FEL [5]. VUV-FEL operation with bunch repetition rates above ~4 MHz presently feasible due to mirror power limitations, so a lower bunch repetition rate will be provided in the HACL for this mode. Typical beam parameters for the two modes are shown in Table 1, with those for the other parts of the facility.

The second major accelerator system is the XUV-FEL branch. The XUV-FEL requires a peak current of ~1.5 kA at beam energies from 750 to 950 MeV. This beam is derived from 1 nC bunches produced by a normal conducting RF photo injector operating at 1 kHz. At this repetition rate the 1 kW of beam can be safely dumped after traversing a final spontaneous undulator source.

Although the XUV-FEL beam and the high average-current beam discussed above are derived from separate electron sources, after suitable low energy acceleration they are merged and accelerated in a single superconducting linac. The 600 MeV HACL and 750 MeV XUV bunches are then separated using a spectrometer-based magnetic separator for delivery to their respective devices.

The third accelerator system is that required for the IR-FEL. The same linac technology is used to accelerate electrons to between 25 and 60 MeV to provide a fully integrated and synchronised IR-FEL facility (see Fig. 3). The main electron beam parameters for 4GLS are given in Table 1.

The 4GLS design utilises superconducting linacs to accelerate and manipulate the three beams required to drive the photon sources. The accelerating structures are all based on a fundamental RF frequency of 1.3 GHz and a modified TESLA-type cavity design operating at 2 K or below [6,7]. A prototype two-cavity cryomodule incorporating HOM-damped 7-cell cavities is currently being developed for the main linac in conjunction with a number of our collaborators [8], and is planned to be tested in ERLP in 2008 (see Fig. 4).

Table 1: The main electron beam parameters of 4GLS

Bunch Parameter	*XUV-FEL*	*HACL, 100 mA Operation*	*HACL, VUV-FEL Operation*	*IR-FEL*
Electron Energy	750 to 950 MeV	600 MeV	600 MeV	25 to 60 MeV
Normalised Emittance	2 mm mrad	2 mm mrad	2 mm mrad	10 mm mrad
RMS Projected Energy Spread	0.1 %	0.1 %	0.1 %	0.1 %
RMS Bunch Length	< 270 fs	100 to 900 fs	100 fs	1 to 10 ps
Bunch Charge	1 nC	77 pC	77 pC	200 pC
Bunch Repetition Rate	1 kHz	1.3 GHz	n x 4.33 MHz	13 MHz
Electron Beam Average Power	1 kW	60 MW	n x 200 kW	156 kW

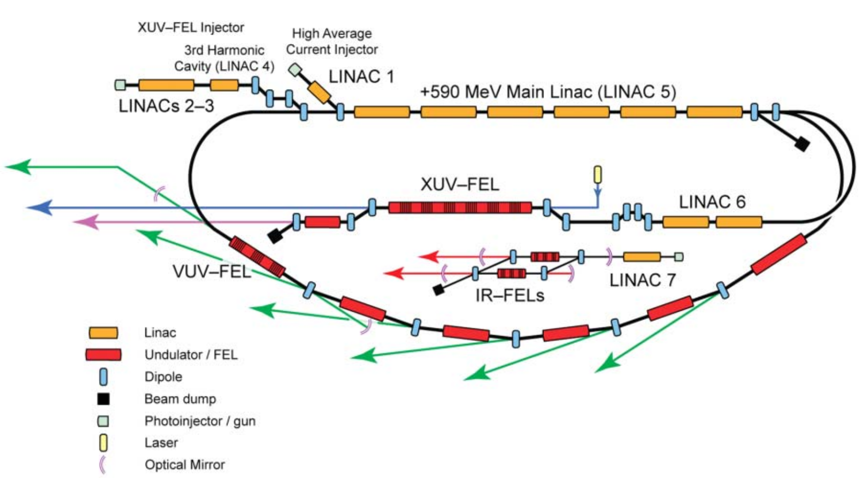

Figure 2: The conceptual layout of 4GLS.

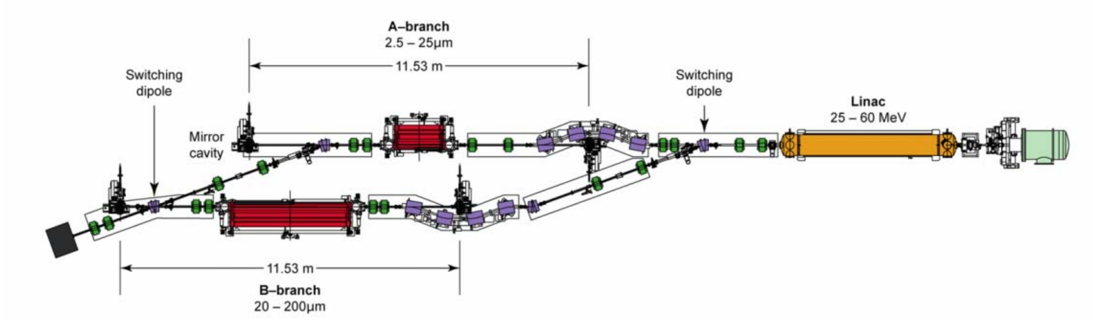

Figure 3: Schematic layout of the 4GLS IR-FEL. Two undulators give wavelength tuneability over 2.5 to 200 um.

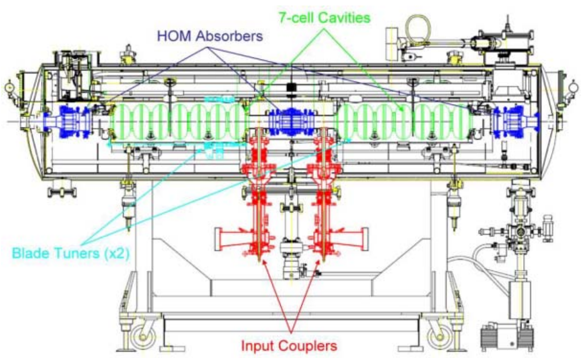

Figure 4: Prototype cryomodule incorporating two 7-cell modified TESLA-type cavities.

The most challenging area of accelerator design for 4GLS is in meeting the requirements of high peak current at the end the XUV-FEL branch whilst simultaneously transporting and accelerating a high quality high-average current (100 mA) beam to the energy recovery loop.

Both the HACL and XUV bunches must undergo a significant amount of compression to deliver the required peak currents to drive the XUV- and VUV-FELs, and to meet the requirements of the science case for different pulse lengths from undulators in the HACL. An innovative, integrated acceleration and compression scheme is proposed which meets the differing requirements for each bunch type whilst using the same main superconducting accelerator [7]. The HACL and XUV bunches are accelerated in the main linac with opposing phases (see Fig. 5): the high compression demands of the XUV-FEL are met using a two-stage compression scheme including 30 MV of 3rd-harmonic (3.9 GHz) correction of the RF curvature after pre-acceleration to 160 MeV, whilst in the HACL progressive compression through the undulator arc delivers the high peak current in the 77 pC bunches required to drive the VUV-FEL. Keeping the XUV and HACL bunches apart in RF phase by about 40 ps reduces the action of the longitudinal cavity wakefield from the 1 nC bunch on the following 77 pC bunch so that it may still be transported through the HACL (about 50 kV maximum energy shift). This also has the benefit of making the compression in both branches simpler, since the XUV bunch may be compressed by a chicane-like compressor, and the HACL bunches in the arcs.

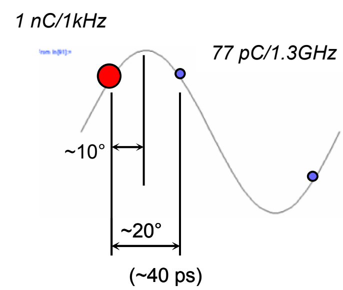

Figure 5: Principle of opposing-phase compression proposed for 4GLS.

Wakefield effects in both branches are minimised by performing the final compression stage at full energy, also keeping the bunches around the arcs are kept relatively long to control the disruptive effects of CSR emission [2]. Acceleration of a 100 mA beam is very challenging; to accelerate and decelerate such a beam requires that the linac transport design is tailored to give a high threshold for the disruptive beam break-up instability. This is achieved through a combination of techniques including substantial damping of HOMs in an advanced design of RF cavity, tight control of beam focussing throughout the linac and optimisation of coupling and overall transport properties in the energy recovery loop [9,10].

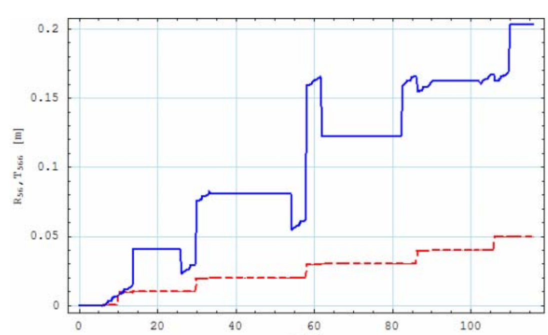

Figure 6: First (red/dashed) and second (blue/solid) order longitudinal dispersion values in the HACL insertion device arcs. An R_{56} of 1 cm/cell provided by each triple-bend achromat cell [2] gives progressive compression of the 77 pC bunches. The R_{56} is tuneable to zero to allow other modes of operation.

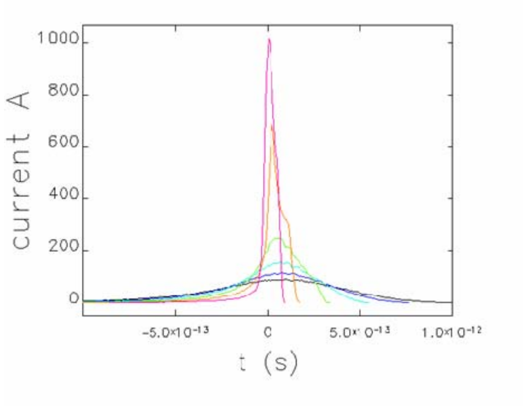

Figure 7: Progressive compression from HACL Straights 1 to 6 gives bunch lengths from ~900 fs (black) down to ~100 fs (pink).

A simple yet robust seeded design for the XUV-FEL is proposed [11] to ensure that ultra-high quality, reproducible, tunable radiation is available in the 8 to 100 eV photon range. The output pulses will have selectable polarisation, and a pulse repetition rate of 1 kHz set by the seed laser and by the photoinjector; upgrade paths to 10 kHz for both these items are likely. Established FEL theory and numerical simulation predict that this FEL will generate photon pulses with multi giga-watt power levels in pulses of duration ~50 fs FWHM. The pulses will have excellent temporal and spatial coherence with time-bandwidth products close to the Fourier transform limit for a Gaussian pulse. Unlike the self amplified spontaneous emission mode of operation, which self-starts from intrinsic noise, the FEL interaction here is acting as a true amplifier: the high quality spectral properties of the radiation input seed pulses are maintained by the amplified output radiation pulses. Recent advances in High Harmonic Generation sources mean that the seed requirements for the XUV-FEL already exist [2,11].

The VUV-FEL offers high repetition rates (at multiples of 4.33 MHz) with giga-watt peak power and >100 W average power [12]. Here advantage is taken of mirrors (with hole out-coupling) that are able to operate over the photon energy range of 3 to 10 eV. Photon pulse lengths of ~ 170 fs (FWHM) will be obtained in the standard operating mode and simulations suggest that pulses as short as ~ 25 fs may be possible in a super-radiant mode. The output pulses will have selectable polarisation and be fully tuneable. By using a pair of mirrors to reflect light emitted by the FEL back to the entrance of the device it becomes in effect self-seeding; no external conventional laser system is required and the output is stable. A particular feature of this FEL when compared with similar designs covering the same wavelength range is the tolerance to low mirror reflectivity. Extensive simulations have shown that mirror reflectivities in the range 40 to 60 % are acceptable for this design. Detailed modelling has been used to confirm excellent spatial and temporal coherence and a regime has been identified where the performance of the device is relatively insensitive to (and can even be enhanced by) degradation of mirror reflectivity [11].

The IR-FEL has been designed to produce high intensity, spatially and temporally coherent radiation with variable pulse lengths, flexible output pulse patterns and variable polarisation over the wavelength range 2.5 to 200 µm. The high-Q cavity-based design employs two undulators and hence offers the potential to satisfy user experiments at two different wavelengths simultaneously (see Fig. 3). The provision of short electron bunches offers the potential to operate the FEL in super-radiant mode to produce shorter pulses with higher peak intensities than available in normal operation: simulations predict FWHM pulse lengths of only a few optical cycles can be produced in this way. The implementation of a superconducting RF linac with the IR-FEL will offer highly stable operation and also high average powers (>100 W) though the option of running in modes that reduce the average power for sensitive samples will also be available.

There are six insertion device straights in the HACL, one of which is allocated to the VUV-FEL. The remaining five will be used to generate spontaneous radiation. To maximise the potential of the spontaneous sources three different undulator straight lengths have been chosen: two 14 m straights, two 10 m straights and two 8 m straights. Thus the total space available for undulators is ~64 m, which exceeds all other existing low-energy 3rd-generation light sources.

THE ERL PROTOTYPE PROJECT (ERLP)

ERLP is a precursor to 4GLS, and will develop and demonstrate the technologies and beam physics design to be used for 4GLS. The layout of ERLP is illustrated in Fig. 8 with results of start-to-end simulation, and shows how the existing building has in part determined the accelerator design. A 350 keV DC GaAs photocathode injector (closely based on the Jefferson Lab design [12]) delivers between 1 and 8125 80 pC bunches per train with 81.25 MHz spacing, from 1 to 20 Hz repetition rate; the cathode is driven by a mode-locked Nd:YVO_4 laser frequency-doubled to 532 nm. The two ACCEL-supplied cryomodules each contain two 9-cell TESLA-type 1.3 GHz cavities, and are based on the Stanford/FZ Rossendorf design [3]; these modules accelerate the beam to 35 MeV prior to compression to ~350 fs using a 4-dipole chicane with $R_{56} = 28$ cm. The IR-FEL is based on a 40x27 mm-period planar wiggler loaned from Jefferson Lab [4] and placed in a 9.224 m cavity. After passage through the FEL the spent electrons return to the 8.35/35 MeV cryomodule for energy recovery and are then dumped. Commissioning of the electron gun has begun and first electrons have been produced (see Fig. 9); the beam transport system has been procured and is presently being installed (see Fig. 10). Energy recovery and lasing are planned to be demonstrated during 2007.

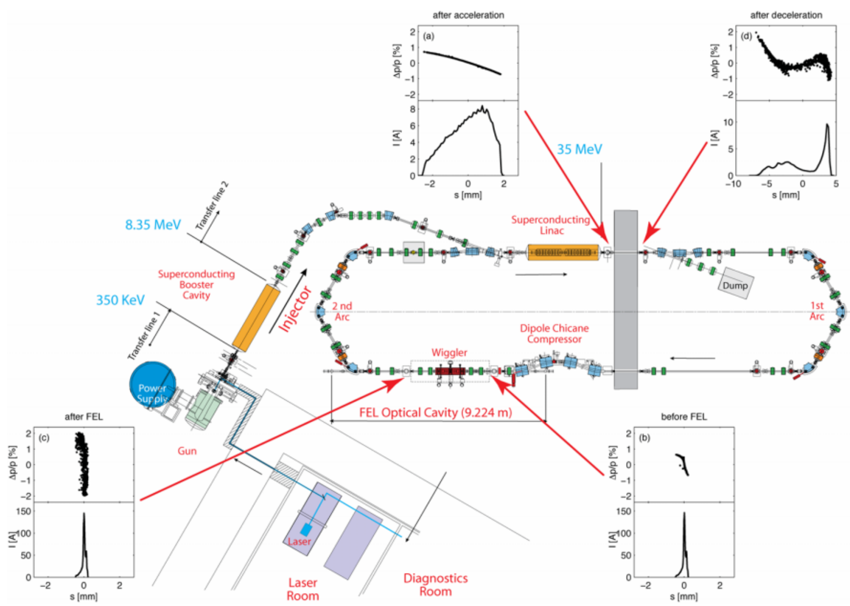

Figure 8: Layout of ERLP, showing typical beam distributions obtained from start-to-end simulation which include the effect of the IR-FEL lasing process [4]. The existing building shield wall is shown in grey.

Figure 9: First electrons from the 350 keV photoinjector, imaged onto a YAG screen.

Figure 10: Installation of the 8.35 MeV transfer line.

ACKNOWLEDGEMENTS

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