OPTICAL SYSTEMS FOR THE FOURTH GENERATION LIGHT SOURCE, 4GLS

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Abstract

4GLS is a multi-user, multi-source facility proposed for construction at Daresbury Laboratory in the UK. By exploiting super-conducting linac technology with energy recovery, it will combine three free electron lasers and a range of conventional synchrotron radiation sources covering the THz to SXR region. The facility will provide femtosecond pulses at high repetition rate, with the FELs delivering GW peak power in the VUV and XUV region. This paper discusses the options and challenges for the optical systems associated with the suite of photon sources. The beamlines will need to operate both independently and in flexible, synchronised combinations. Together with the requirements for preserving the ultra-bright, fast pulse properties, this places unique demands on the design, layout and operational modes. The paper summarises current technical achievements and identifies the research and development necessary before detailed design of the 4GLS optical systems.

INTRODUCTION

The Fourth Generation Light Source, 4GLS, was conceived as an optimal solution to the needs of the low energy photon-based research community in the UK [1]. Funding for a research and development phase was awarded in 2003; this includes production of a conceptual design and the construction of an ERL-prototype.

The 4GLS suite of light sources

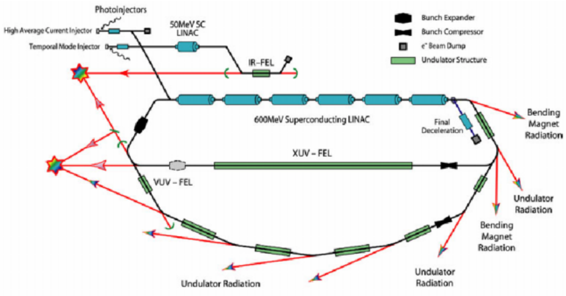

Figure 1. A scheme for the layout of 4GLS and its proposed FEL and spontaneous sources.

The uniqueness of 4GLS is due to combining superconducting energy recovery linac technology for production of high quality electron beams with a variety of free electron lasers, undulators and bending magnet sources.

Figure 1 shows a scheme for the layout of the suite of sources. A driver for this layout is the aim to direct multiple sources onto a user experiment; this is constrained to varying degrees by the usable optical deflection angle. Hence the XUV FEL is shown on a bypass arm of the electron beam transport system. This layout will evolve during the conceptual design process.

Table 1: 4GLS sources and existing relevant systems

4GLS source	Examples of relevant existing systems
XUV FEL 10-100eV	One user facility in second phase commissioning: Tesla Test Facility, 10-200eV[2] phase 2 due October '04
VUV FEL 3-10eV	Several experiment projects: EUFELE, 3.5-6.5eV [3] DUV-FEL BNL [4] NIJI IV [5]
IR FEL 0.02-0.4eV	Several user facilities: FELIX [6] 0.25-0.005 eV Jefferson Lab [7] CLIO 0.012 - 0.4[8]
CBS KeV-Mev	Purpose built facility for medical applications: Vanderbilt FEL Centre [9] Several FEL based experiments [10]
THz CSR <0.01eV	Demonstration experiments: For example, BESSY II [11], Jefferson lab [12], ALS [13]
Undulators 1-400eV	examples on 3rd generation storage rings with longer pulse lengths
Bending magnets <3000eV	examples on 2nd and 3rd generation storage rings with longer pulse lengths

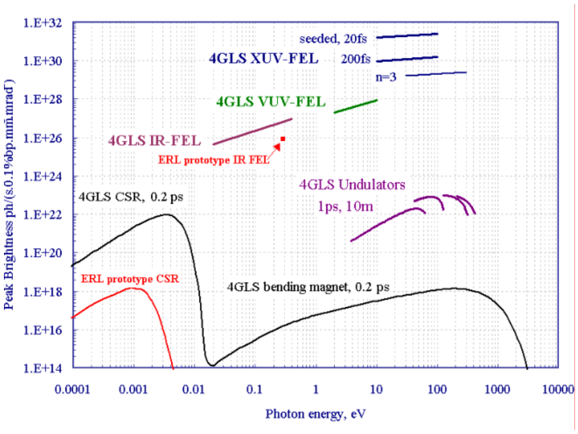

Figure 2. Estimated peak brightness for the 4GLS suite of photon sources. Also shown are the calculations for the ERL prototype currently under construction

Determination of required research and development during the design phase depends on the current operational experience with sources similar to those proposed for 4GLS. Table 1 lists the 4GLS suite of FELs and other sources and identifies the most comparable, existing facilities; the calculated peak brightness is shown in Figure 2. While the potential of FEL sources is being explored in several projects, only IR FELs have significant operational experience as user facilities.

ISSUES AND OPTIONS FOR THE PHOTON BEAMLINES

The optical systems for 4GLS need to match the proposed science programme and to preserve the unique properties of the source. As the conceptual design phase starts, it is important to understand the current state of the art and to highlight key technological challenges.

XUV FEL

The XUV FEL will operate in single pass mode with no constraints due to cavity optics. The design parameters are still to be determined, but pre-design goals are shown in Table 2.

Table 2. Goals for XUV FEL performance.

parameter	**Pre-design values**
range	10-100eV
energy/pulse	2mJ
Pulse length	20-100fs
Micro-pulse	Repetition rate 65Mhz, 650 pulses
Macro-pulse	Repetition rate 60Hz
Average power	80W
bandwidth	3-6 x 10^{-4}
divergence	30 – 150 μrad

The proposed experimental programme will require both monochromated and direct FEL beams with micro-focussing options, covering the first and higher harmonics of the radiating undulator.

The most challenging source parameters for the XUV FEL beamline design are the energy per pulse which is sufficient to cause component damage and the ultrashort pulse length goal which will place optical path difference and stability constraints on the mechanical design.

No operational experience is available for pulse energies at this photon energy or pulse length; the only similar source is the Tesla Test Facility VUV FEL, currently in phase 2 commissioning and due to take beam in October 2004. Significant research has been done on laser ablation and damage thresholds, mostly driven by micromachining requirements [14]. These show that several damage mechanisms exist such as ablation, lattice damage, and photoemissive stress [e.g. 15] which depend on the energy deposited per unit area, the surface condition, absorption efficiency in the material, the pulse length and the photon energy. Schemes to mitigate the effects are proposed in design studies for Tesla X-FEL [16], LCLS X-ray FEL [17] and TTF VUV FEL [18]. These are based on using grazing incidence geometries and low Z materials to reduce flux density and absorption. More exotic schemes such as multifaceted reflectors, gas optics, and renewable mirrors have also been proposed [15, 19].

The most relevant values for laser damage thresholds (LDT) come from research carried out at TTF phase 1 showing that LDT ranges from 0.03 J/cm^2 for bulk Si to 0.06 J/cm^2 for bulk carbon [20]. Using the LDT for carbon and the estimated energy density per pulse for the 4GLS XUV FEL, a grazing incidence optic would need to be at a minimum distance of 30m to give a safety margin of 1/10 of the LDT. While this has been accommodated easily in the layout of TTF phase 2 which is a single source entering an experiment building via a long tunnel, it could have a significant impact on the layout of 4GLS. The use of low Z materials will also affect the output spectrum of the optical system, giving undesirable absorption edges in the XUV and SXR range; for example, carbon mirrors would affect the exploitation of higher harmonics.

However, the available data are very limited as they only give values for ablation from a few bulk materials whereas SR optics traditionally exploit thin coatings on substrates (frequently dielectrics). Also, the accumulated effects during long term exposure at different repetition rates are not known. Gratings may have specific issues due to the surface profile. More measurements are required to ensure appropriate optical engineering designs.

It is expected that apart from the instantaneous heat load considerations, designs similar to existing 3rd generation SR beamlines can be adapted for use on 4GLS [21]. Ultrafast pulse length and stability preservation will demand isochronous photon beam design; optical path differences experienced by a 200 fs pulse as it transits a beamline will need to be less than 10 microns (compared to several mm for 3rd generation storage ring pulses of ~10 ps). Vibration and thermal drift also need to be considered at this level.

A schematic layout is shown in Figure 3 which incorporates an expansion space to reduce the power density on the beamline optics and a pair of deflection mirrors to select use of either the direct or monchromated beam. To cover the full harmonic photon energy range of 10 to 500 eV with a higher resolving power than the FEL bandwidth may need two optimised monochromator modules. The expansion space could usefully contain gas phase filtering, intensity attenuation and photon diagnostics similar to the systems developed for TTF phase 2 [22].

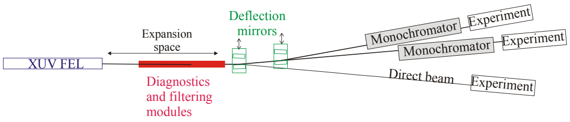

Figure 3. Schematic layout for XUV FEL beamline.

VUV FEL

The proposal for the VUV FEL is based on an optical klystron; the pre-design goals are shown in Table 3. Such systems have operated successfully on storage ring facilities [23] with the highest energy so far, 6.5 eV, 190 nm, demonstrated by EUFELE at Elettra [24].

Table 3. Goals for VUV FEL performance.

parameter	Pre-design values
range	2-10eV
energy/pulse	15 μJ
Pulse length	200-1000 fs
repetition	Repetition rate 6.25 MHz
Average power	100W
bandwidth	$<4 \times 10^{-4}$
divergence	150-400 μrad

Again, both monochromated and direct FEL beam will be required with a range of post focussing options. Designs evolved for 3rd generation storage ring sources utilising near normal incidence optics can be used. While the average power loading is non-trivial, it is within current experience. The instantaneous power loading is much reduced from the XUV FEL case but may yet restrict the acceptable mirror incidence angles.

The most critical issue is that of cavity optics receiving the full radiation load at normal incidence from the laser cavity while needing to maintain very high reflectivity to sustain lasing. Outcoupling this power also requires either significant transmission or a holed resonator. These technical issues are currently limiting the lasing and tuning range of cavity FELs to less than 6.5eV[25]. In order to reach the pre-design goal of 10 eV, 4GLS will exploit the enhanced gain due to higher bunch charge and shorter electron bunches. This reduces the requirement for cavity mirror reflectivity from the extremely high value of >95% required for storage ring FELs. Even with this relaxed criterion, cavity mirror technology working over long periods above 6.5 eV still needs to be proven. Recent experimental results for capped aluminium mirrors give a best reflectivity of 75% at 10eV [26]. Damage thresholds for these are now needed.

An alternative scheme would exploit high gain harmonic generation and remove the need for an optical cavity. Lasing has been achieved at 4.6 eV (266nm) at the Brookhaven DUV FEL with 80-100 μJ per pulse [27]. The third harmonic has been used for experiments at 13.9 eV (88 nm) with measured power of 0.3 μJ per pulse [28].

IR FEL

The IR FEL is based on an optical cavity design; the pre-design goals are given in Table 4. In the infra-red, a wide variety of optical systems is possible and a significant operational experience is available from IR FELs and dedicated laser facilities [29].

Table 4. Goals for IR FEL performance

parameter	Pre-design values
range	0.4 – 0. 017 eV
energy/pulse	75 μJ
Pulse length	100 fs – few ps
repetition	10 MHz
Average power	900 W
divergence	0.4 – 7 mrads

Compton Backscattering source

Recent assessment has shown the potential of using Compton backscattering on 4GLS to generate ultra-short X-ray pulses. Existing projects cover the use of CBS in medical imaging and extending the applications of IR FEL facilities [9, 10]. The average flux ranges from 10^9 to 10^{12} ph/sec thus the primary optical difference from 3rd generation storage ring sources is mainly in the pulse duration. Pulse lengths below 300fs become shorter in physical length than the extinction lengths of Bragg crystals affecting the diffraction process. This problem is being addressed by the research and development activities for LCLS and TESLA X-FEL[16, 17].

Coherent Synchrotron Emission (THz)

Coherent radiation is produced in accelerators when the electron bunch length is becomes less than the wavelength of the radiation [12], giving flux enhancements of the order of 10^9. Emitted power levels up to 1 Wcm^{-1} have been measured [30]. As with the IR FEL, there are no specific challenges for optics in this region.

Spontaneous sources

4GLS will also provide a suite of undulator and bending magnet sources; the primary operational mode may need to have pulse lengths of ~1 ps to reduce the likelihood of SASE and CSR emission. The proposed devices will be high flux and brightness sources covering IR to SXR with variable polarisation and the flexible pulse characteristics of the ERL. The absorbed heat load on the undulator beamlines will be substantially reduced from devices on existing 3rd generation machines, while providing a peak brightness two orders of magnitude higher. As with the FEL beamlines, existing optical concepts will be transferable to 4GLS, requiring only the additional consideration given to preserving the fast timing characteristics of the emitted photon pulses. The exploitation of IR and visible light will be simplified by the ease of extracting large apertures from the smaller, more flexible ERL ring architecture.

CONCLUSIONS

In summary, the progress from 3rd generation storage ring to 4th generation ERL and FEL photon sources both brings new optical challenges and removes others.

The greatest challenge will be finding suitable optical materials which can withstand the instantaneous heat load, particularly from the XUV FEL, reducing the constraints on the optical design to more optimal levels.

A further need is to find cavity mirror optics which deliver the desired tuning range for the VUV FEL.

General optical systems mechanical design has to preserve the fast pulse properties for all the 4GLS sources. This is likely to be most acute for large optical systems (high performance XUV monochromator and beamline can extend over 30m) or for optics requiring significant cooling.

The ease of extracting large apertures will remove difficulties experienced by IR and visible beamlines on storage ring sources. The low electron beam energy also removes the average power load issue for low energy undulators sources.

Research into optics resilient to high instantaneous and average heat load will be part of the next stage of the 4GLS project.

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