TIMING AND SYNCHRONISATION CONSIDERATIONS FOR THE NLS PROJECT

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Abstract

The NLS project team is designing a UK-based ultrashort light pulse facility covering the whole spectrum from the terahertz to the soft X-ray. It will be based on a suite of sources including seeded FELs, conventional lasers and undulators. Experiments will frequently be multi-beam and will often depend on precise management of the pulse timings. With pulse durations of ~20fs or less the aim will be to reduce timing jitter to the 10-20fs level. In addition to the needs of the NLS's users, stable operation of the machine itself will also require adequate timing control. In particular reproducible FEL operation will depend on good temporal overlap between the seed photons and the electron bunches. This paper covers both the underlying issues, (e.g. choice of pulse rates, passive and active timing management, requirements specification) and also the approaches taken in specific NLS areas (e.g. choice of clock and distribution system, management of electron bunch timing, management of fluctuations in beam transport paths). Subsystem jitter budgets are presented.

INTRODUCTION

The New Light Source (NLS) is a proposed facility for the provision of ultrashort, widely tuneable light pulses to the UK and international research community. Its specifications are science-driven and they have been presented, along with an outline machine design, in a recently-published report [1]. The proposal is under continuous development and the latest plans for the NLS's timing and synchronisation are presented below. In the case of timing they cover basic principles but do not describe the implementation since this is not expected to be technically challenging. The synchronisation requirements, on the other hand, are easy to define but will be extremely challenging to deliver. Possible solutions are therefore discussed in some detail.

TIMING

The time structure of the NLS electron bunches is very simple. They are equally spaced with a ~1 kHz baseline rate. This is expected to rise, as the source is developed, in approximately decade steps to an eventual target of ~1 MHz. The individual FELs will be fed with bunches kicked from the train, allowing simultaneous multi-user operation of the facility.

The precise pulse rates, both for the electron bunches and for other machine subsystems, are set by a number of operational considerations:

- The timing will be controlled by an ultra-low noise clock signal and all of the rates will need to be easily derivable from this. Unless there is an overriding reason to the contrary they will all be integer fractions of it.
- The 10 kHz-1 MHz bunch rates will be integer multiples of one another. This will allow baseline subsystems to be installed with a built-in capacity to handle upgrades and will also allow legacy systems to remain operable following those upgrades.
- There will be a strong preference for the integers to be the products of small primes and, ideally, for them to be of the form $2^n \times 3^m$. This ensures compatibility with a wide range of resonant subsystems and also allows the simplest types of multiplier and divider to be used. Simple devices tend to have the lowest phase noise which is important for low timing jitter. (However if the noise levels of so-called "synchronous" dividers can be tolerated then the jitter becomes independent of division ratio.)
- The NLS is being developed in the context of the EuroFEL programme [2] and the aim is, if possible, to agree common component specifications with our EuroFEL partners. This will encourage commercial manufacture with its associated benefits. Pulse rates are among the parameters which might be agreed.

Figure 1 shows a scheme for generating electron bunch rates which meet the first three criteria and which are close to the nominal 1 kHz - 1 MHz values. It is based on a 216.67 MHz clock. The rationale for choosing this rate is a good example of the degree of detail needed to achieve the very lowest levels of noise.

216.67 MHz is convenient since it is close to optimum for the type of fibre laser which will form part of the clockwork (see below). It is also an integer fraction of the 1.3 GHz machine RF. However a complication arises with the other part of the clockwork - a low-noise RF source used to provide long-term timing stability. Such sources have been commercially available for many years and standard frequencies have evolved for them, including 5 MHz and 10 MHz. The need for the clock frequency to be integer-related both to the machine RF and to one of the standard source frequencies inevitably involves some difficulty since the ratio of the two has 5 and 13 as factors.

On the left hand side of figure 1 is a scheme for locking the clock to the reference source at their lowest common multiple frequency – 650 MHz. The use of high ratio

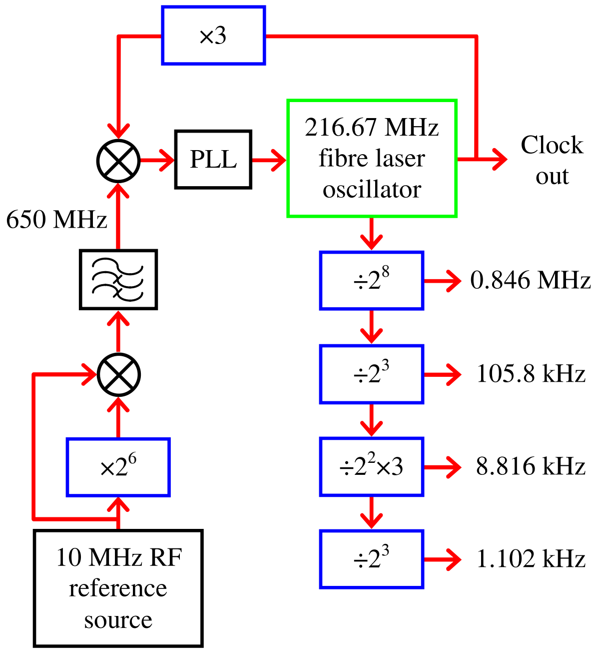

Figure 1: Possible clock architecture for the NLS.

multipliers (×5, ×13) for the reference is avoided by generating 65 as $2^6 + 1$. This has the disadvantage that the mixer also produces a relatively close output at 63 MHz which would ideally be filtered out. The final choice of the mix-and-filter approach or the high ratio multipliers will depend on the performance of available components.

SYNCHRONISATION

A schematic NLS layout is shown in figure 2. From the users' viewpoint there is only one explicit synchronisation requirement which is that the light pulses from the various sources should arrive at the experiment with a relative time jitter of no more than 10 fs rms. There are, however, several additional implicit requirements which must be met for stable operation of the machine. The most demanding of these is that the photon pulses from the HHG seed system and the electron bunches must arrive at the FEL undulator with a relative time jitter of no more than 20 fs rms. Otherwise the shot-to-shot fluctuations in the FEL output pulses' properties will become too large.

Light Pulses at the User Experiments

Figure 3 shows the hardware used to deliver the light pulses to the user experiments. The beam from a high-power, short-pulse tuneable Ti:Sapphire laser system is focused into an HHG chamber where 50-100 eV seed pulses for the FEL are produced. These modulate the electron bunches in the first of a series of undulators [3]. The bunches pass, via a chicane, to one or two "radiator" undulators which generate the FEL light itself. This then travels to the experiment via the beamline optics. The pulse train is sampled as close to the experiment as possible and its timing is compared with the signal from the master clock. The phase sensor feeds a PLL controller which acts on the seed laser oscillator to suppress the FEL output timing jitter. The endstation laser is very similar to the seed laser, so it has not been shown in detail. In addition to an HHG chamber, which provides light from 6-50 eV, it also feeds a suite of nonlinear optical conversion stages with an output spanning 0.06-6 eV. It has a similar timing controller fed by sensors at its output.

The synchronisation system can be broken down into three: a) the master clock and its distribution fibres, b) the phase-locked laser and frequency conversion systems and c) the light transport paths after the timing sensors.

Two schemes for clock generation and distribution have already been developed. Both have demonstrated jitter levels which would meet the NLS's needs. One is based on a cw laser, modulated with an RF clock signal. The distribution fibres are, essentially, interferometrically monitored and the architecture allows the timing to be corrected using relatively inexpensive programmable controllers [4]. The alternative scheme is based on a modelocked femtosecond laser pulsing at the clock rate (as shown in figure 1). In this case the fibre lengths are stabilised by measuring the timing of pulses retroreflected

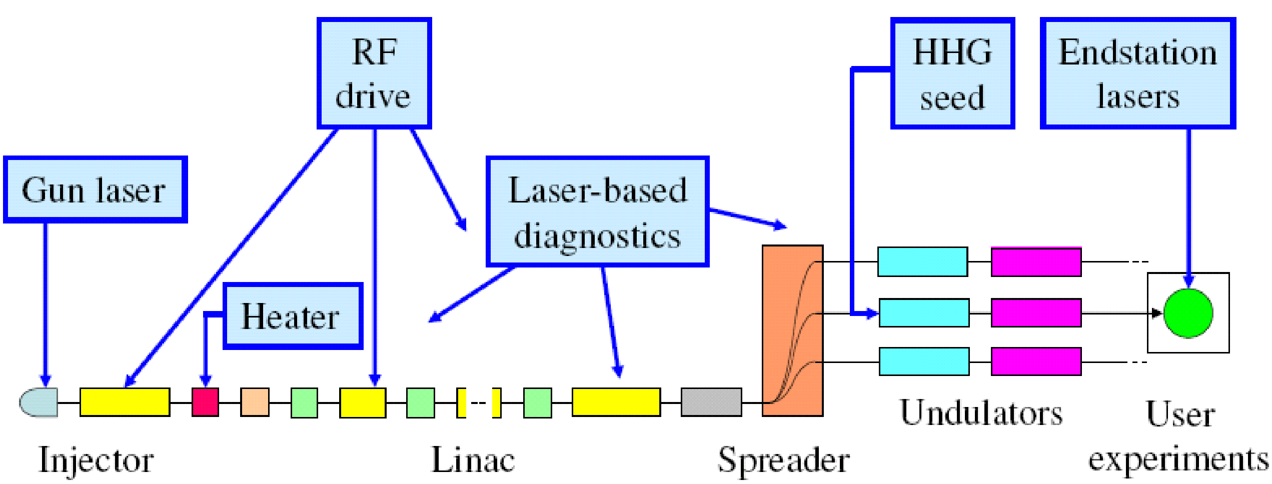

Figure 2: Schematic layout of the NLS including (blue boxes) subsystems which need to be synchronised.

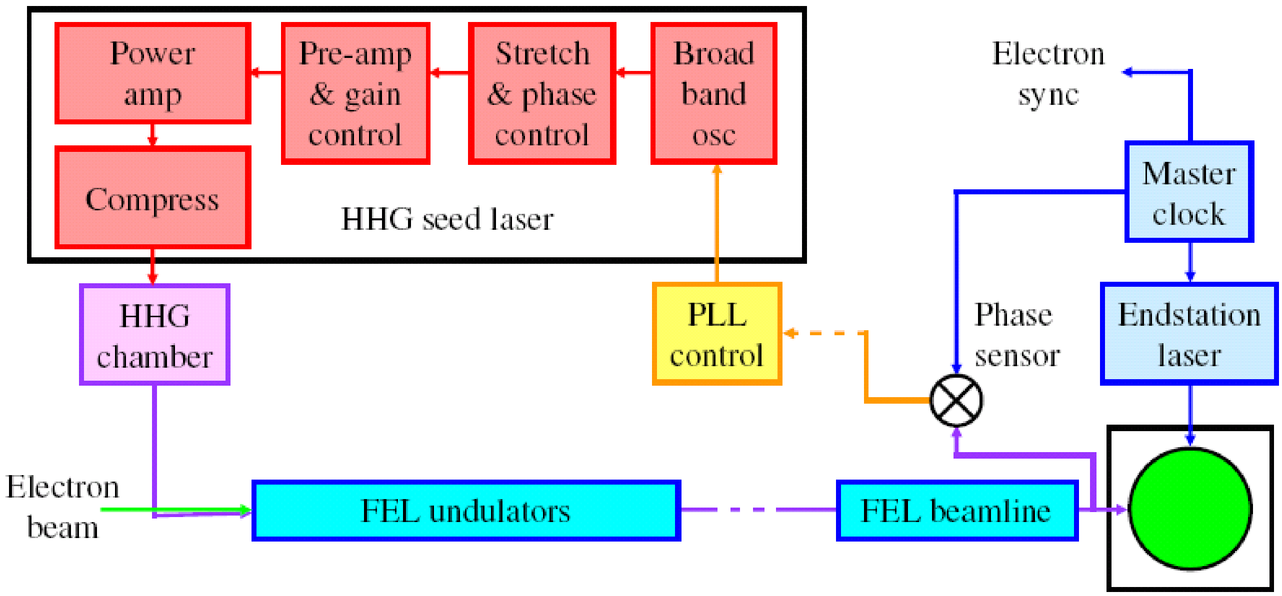

Figure 3: Components which determine the timing of light pulses at the user experiment.

from the remote end, using outgoing pulses as the reference. At this stage of the NLS project it is only necessary to show that at least one of the schemes will suffice. In this paper the second one is discussed.

The jitter of the clock signals in the pulsed scheme, measured at the far end of the distribution fibre relative to the clock, has been reduced over a period of years by a succession of design improvements. It was reported in [5] as 4.4 fs rms, superimposed on a slow drift (25 fs over 12 hrs). More recently it has been lowered to less than 2 fs rms, and with improved thermal and mechanical stabilisation and careful selection of individual components the drift has been eliminated [6].

The phase-locking of laser systems in general is a broad subject area with a long history. The resulting timing stability depends strongly on many factors, including:

- The phase noise present before locking is attempted,
- The intrinsic properties of the laser medium,
- The laser cavity design,
- Noise on the reference (clock) signal,
- The performance of available phase sensors,
- The choice of the timing (or frequency) actuators,
- The phase-locked loop (PLL) controller design.

For the NLS PLLs a number of design principles will, as far as possible, be followed. In summary:

- Sensors will be sited close to the point where the signal is used,
- Actuators will be sited close to the noise source(s),
- Sensors will measure the parameter of interest rather than a proxy,
- The burden on the feedback control system (FCS) will be minimised by, for example, minimising the intrinsic noise in the system and transferring deterministic changes from the FCS into dedicated feedforward circuitry,
- The paths of fast/low-level signals will be kept short.

For Ti:Sapphire laser oscillators a timing jitter of ~1 fs was achieved several years ago [7]. However the NLS laser systems include an extended chirped-pulse amplifier chain with tuning elements, frequency changers (HHG, optical parametric etc) and, in the case of the seed laser, an FEL and a set of beamline optics, all inside the PLL. The tuning elements will add timing variations albeit, in principle, deterministic ones. There may also be noise contributions from, for example, cooling plant. The final laser amplifiers will operate at restricted pulse rates which will introduce a Nyquist sampling limit on the maximum offset frequency at which phase noise can be detected. When the laser pulse rate is as low as 1 kHz this limit will be a few hundred hertz. Noise above this will either have to be measured using a proxy probe (e.g. a separate high pulse rate laser co-aligned with the main beam) or will have to be eliminated at source by passive stabilisation. A further complication will be that in the case of the endstation laser carrier-enevelope phase (CEP) stabilisation will be implemented. This will act by changing the oscillator cavity length in the same way that the synchronisation system does. Any conflict between these two systems will need to be resolved.

In addition to the phase noise arising in the extended laser amplifier system, there are at least two jitter issues associated with the FEL. Firstly, since this is an HGHG design, the seed timing is impressed on the electron bunch in the modulator and is than carried forward into the radiator by the electrons. So any variation of the B-field strength in the intermediate chicane will lead to a change in the FEL output timing. Secondly the radiation leaving the FEL will consist of the short seeded pulse on top of a SASE background, whose timing will follow the envelope of the electron bunch. If the phase sensor is to detect only the timing of the seeded pulse then it must operate as a threshold detector with sufficient temporal resolution to distinguish the pulse from the background. An integrating or centroiding detector will not work. At present the authors know of no suitable sensor operating over the required range of X-ray photon energies. Developing such a sensor will a high priority for the NLS programme.

Given the range of issues which remain to be resolved it is not currently possible to calculate a laser/FEL system timing jitter based on past experience. Instead budget figures have been specified and an R&D programme will be put in place to produce a design which meets these. For the endstation laser a target of 5 fs rms has been set. For the seed system, which includes the FEL and its long transport path, this has been raised to 7 fs.

The third components of the light pulse system are the beam paths after the final timing sensors. These (or, more exactly, the difference between them) must be inherently stable since they cannot be actively controlled except, perhaps, by a proxy sensing system. Achieving stability will be complicated by the redesigns which inevitably occur when user experiments change. These will need to be subject to tight engineering control, and individual designs will be verified off-line before experiments begin. However the requirements are well below those needed for optical interferometry which demands tenth-wave (sub-fs) stability and which is routinely delivered over distances of several metres. On this basis a design target of 3 fs (one optical wave) per path, or 4 fs for the pair of paths, has been set. This target should be relatively easy to deliver provided the path lengths can be kept short. Problems may, however, appear if the final X-ray timing sensor has to be substituted by a more conventional optical sensor at the HHG chamber. This has the advantage that it is proven technology but it will extend the unstabilised path to include the seed beam transport, the FEL itself and the beamline optics. Designing these for intrinsic stability on the 3 fs timescale for extended periods would be a serious challenge.

Table 1 summarises the jitter contributions from the subsystems which deliver light to the user experiments. With the above targets the overall figure of 10 fs is met.

Electron Bunches and HHG Seed Pulses

Synchronising the electron bunches and the HHG seed pulses at the entrance to the undulator involves some of the subsystems described above. The seed pulse jitter relative to the master clock should be a little over 5 fs rms, made up of 2 fs from the clock distribution and 5 fs from the laser itself. The electron bunch jitter also has a clock distribution element. Additional contributions arise in the opto-electronics which recover the RF signal from the (optical) clock and in the electron generation, acceleration and transport hardware. NLS acceleration and transport have been modelled and with careful design and state-of-the-art control of RF and magnetic fields it appears that their net jitter can be as low as 14 fs [8]. The electron generation time is set by the gun laser timing which can, in principle, have just a few femtoseconds jitter. In the current design this will be reduced by a further factor of ~60 in the bunch compression process, so in this paper it has been neglected. However certain types of energy stabilisation scheme can undo this reduction [9] and if one of these is eventually used then the gun laser timing will need to be revisited. An RF recovery system compatible with the pulsed clock and based on a balanced optical-microwave phase sensor has demonstrated a timing jitter of 7 fs rms [10]. The clock distribution will add a further 2 fs making a total for the electrons of just under 16 fs rms. The overall figure for the electrons and the seed laser combined is 17 fs rms.

Table 1: Summary of Light Pulse Timing Jitter

Subsystem	RMS jitter
Clock distribution (2 channels)	3 fs
Endstation laser	5 fs
HHG seeded FEL	7 fs
Optical transport (2 channels)	4 fs
QUADRATURE SUM	10 fs

CONCLUSIONS

Timing and synchronisation will be vital to the success of the NLS. A timing scheme has been developed which meets the current requirements. Issues associated with synchronising photon pulses and electron bunches have been identified and plausible jitter budgets have been set.

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