SAPPHIRE – A HIGH PEAK BRIGHTNESS X-RAY SOURCE AS A POSSIBLE OPTION FOR A NEXT GENERATION UK LIGHT SOURCE

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Abstract

We present the results of initial studies of one option for a possible new UK light source, based on a normal conducting S-band linac and photocathode gun.

INTRODUCTION

A New Light Source (NLS) project [1] has been recently launched in the UK 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 accelerator-based sources. While the key science drivers that will determine the specification of the new facility are still under active discussion by a number of science working groups, a number of options are being considered for the accelerator source, one of which is a free-electron laser (FEL) based on a normal conducting S-band linac and photocathode gun. A companion paper from our collaborators within the NLS project considers an alternative scheme, based on a superconducting linac [2].

The main aim of the scheme outlined in this paper is to produce ultra-short, high peak brightness radiation pulses in the X-ray region of the spectrum, employing available technology that minimises cost, timescales and risk. An energy of 3 GeV was chosen to allow 2 keV to be reached in the fundamental, and 5-12 keV using the 3rd and 5th harmonics. A possible extension of the linac to higher energy (~6 GeV) in a second stage, to allow this region to be accessed in the fundamental, is taken into account in our initial considerations of layout of the facility.

In this report we present some details of the design, including a new design of RF gun, and initial results of S2E simulations from the gun to the FEL output. The baseline design is based on a repetition frequency of 100 Hz, however we are investigating the possibilities of increasing the repetition rate of the various critical components into the few 100 Hz region and we report our preliminary conclusions.

RF GUN AND INJECTOR OPTIMISATION

A new design of S-band photocathode gun has been made, downscaled from the PITZ/FLASH L-band gun [3] to 2998 MHz, see Fig. 1. This geometry was chosen because of its coaxial input coupler which allows for flexibility of the gun solenoid position and very efficient cooling, and its coaxial symmetry which eliminates asymmetries in the RF field and thermal deformation. It is also a well proven technology at L-band [4].

The PITZ gun currently operates with a mean RF power of up to 50 kW [5]. Scaling as $(1/f)^2$ would suggest 9.4 kW is possible at S-band which should allow operation up to 420 Hz at 120 MV/m (requiring 7.4 MW peak power) and 3 μs pulse length.

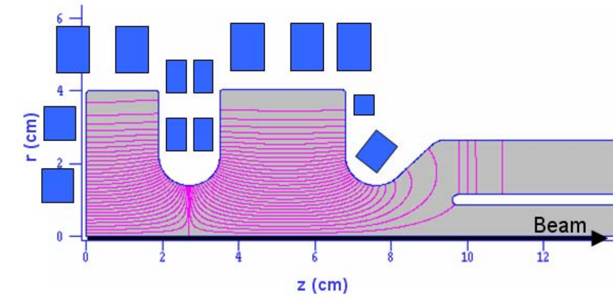

Figure 1: Geometry of the Sapphire S-band gun with co-axial coupler. Blue squares indicate the possible location of cooling channels.

The injector has been optimised using the SUPERFISH (cavity), POISSON (solenoid), and ASTRA (beam dynamics) codes for the relevant simulations. The latter were carried out up to an energy of 328 MeV. During this process the first half-cell length has been optimised for lower transverse emittance and shorter bunch length, the geometry and position of the gun solenoid has been optimised for lower transverse emittance and the position and gradient of the first accelerating section has been optimised. A photocathode drive laser operating at 263 nm was assumed with optimum 6 (10) ps flat-top pulse length, 0.7 ps rise/fall time, and uniform intensity within a 0.5 (0.9) mm radius spot size, for the 0.2 (1) nC cases respectively. We assumed a thermal emittance of 0.2 (0.36) mm mrad for a 0.5 (0.9) mm radius spot size. Figure 2 shows the resulting beam size and emittance in the injector region for the 0.2 nC case.

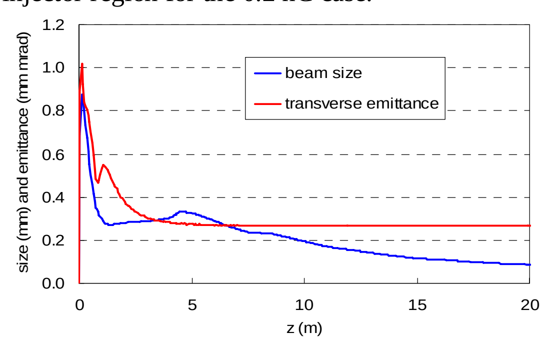

Figure 2: Evolution of beam size and emittance as a function of distance from the cathode for the 0.2 nC case.

Table 1 summarises the final beam parameters for 0.2 nC and 1 nC operation for various percentages of the beam distribution, as well as the slice emittance. We conclude that the new design of gun looks promising for both high repetition rate and good beam parameters.

Table 1: Calculated transverse (normalised) and longitudinal emittances for various beam fractions, for the 0.2 nC and 1 nC cases

Charge - Beam fraction	Transverse emittance (mm mrad)	Longitudinal emittance (keV mm)
0.2 nC -100%	0.27	134.0
0.2 nC - 95%	0.21	101.1
0.2 nC - 90%	0.18	81.1
0.2 nC - 80%	0.13	56.8
0.2 nC - Slice (95%)	0.23	-
1 nC - 100%	0.50	624
1 nC - 95%	0.38	472
1 nC - 90%	0.33	378
1 nC - 80%	0.24	264
1 nC - Slice (95%)	0.43	-

LINAC AND RF

S-band was chosen as the waveband for the main acceleration because accelerating structures, modulators and klystrons are well developed and proven over several decades at 2856 MHz or 2998 MHz. The two main types of accelerating structure that are readily available are the DESY type II and SLAC 3 m ones; these structures are compared in Table 2.

Table 2: Comparison of the DESY type II linac and SLAC 3 m accelerating structures available at 2998 MHz.

Property	DESY structure	SLAC structure
Length	5.2 m	3.0 m
Shunt impedance	51.5 MΩ/m	52 MΩ/m
Attenuation	0.5 Neper	0.49 Neper
Mode	$2\pi/3$	$2\pi/3$
Q	14000	12500
Filling time	740 ns	690 ns
Number of cells	156	89

Performance of SLAC and DESY structures are similar, and the 3 GeV Sapphire requirements can be met with either 16 RF stations, each driving two DESY structures, or 12 RF stations, each driving four SLAC structures, excluding any additional requirements for redundancy.

The accelerating gradient can be generated with a 35 MW klystron pulse with a flat-top of at least 5 µs suitable for compression in a SLED cavity. Modulator pulse stability targets are < 0.1% flat-top reproducibility and < 0.01% ripple, with pulse rise and fall times of less than 1 µs. These targets can be met by a new generation of modulator based on solid-state switching of modular amplifier units rather than the traditional thyratron-switched line-type pulser. Several manufacturers and laboratories are developing modulators of this type, offering increased efficiency and reliability and an ability to operate at higher repetition rates than ever before, possibly up to 1 kHz.

As the repetition rate of the linac is no longer limited by the modulator, care must be taken in handling the increased levels of average dissipated power available to the klystrons, SLED cavities and accelerating structures. S-band klystrons already exist that separately satisfy high average and high peak power demands. The enhanced collector cooling that is provided in the high average power klystrons needs to be combined with a high peak power klystron, and manufacturers have indicated their readiness to supply this, allowing repetition rates of up to 400 Hz. A redesign of the klystron gun to reduce the arcing rate is also being discussed.

Average output power at 400 Hz, 20 MV/m operation is 70 kW per klystron, well above the normal operating rate of the two structure designs. SLAC routinely operates at 120 Hz repetition rate, and the DESY type II linac has been operated at 50 Hz. Unfortunately the average power dissipation limits have not been explored for either SLAC or DESY structures or for SLED cavities, and further work is required to determine what maximum repetition rate is achievable. The main design difference between the two structures is the use of a collinear load in the DESY structure and an external load in the SLAC structures. While the DESY approach preserves the symmetry of the structure, it may prove to be more difficult to adapt the cooling circuit to cope with the high average power dissipated in the collinear load than the external load. We have therefore provisionally selected the SLAC structure for beam dynamics simulations and layout considerations.

BEAM DYNAMICS AND FEL OPTIMISATION

The 3 GeV linac consists of 12 SLAC accelerating sections (scaled to 2998 MHz), one X-band linearising cavity, two bunch compressors (at 460 MeV and 1.2 GeV) and one dog-leg before entering the undulator section. The linac sections (each consisting of 4 tubes) are separated by quadrupole doublets. The beam dynamics in the linac and bunch compressors has been calculated using the ELEGANT code, taking CSR in the compressors and wakefields in the linac (based on SLAC data) into account. The program takes as input the output beam distributions of the new S-band gun calculated using ASTRA.

The optimisation of the accelerator section amplitudes and phase, and bunch compression factors, has been carried out in two different ways, to achieve two separate objectives:

i/ the shortest bunch length, for use as a possible spontaneous radiation source in an initial stage

ii/ a short bunch length, with high beam quality suitable for driving a FEL

Initial simulations have been carried out with a charge of 0.2 nC. The result of the first optimisation produces a very narrow pulse of 4.2 fs FWHM, shown in Fig. 3. The emittance in this case is increased significantly due to CSR effects to 3.6 mm mrad (normalised), however this is still sufficient (0.6 nm rad at 3 GeV) for a spontaneous radiation source. The energy spread is 0.25%.

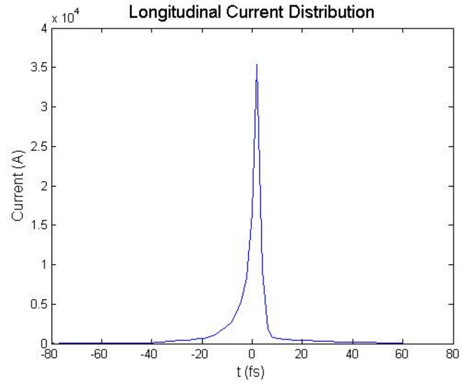

Figure 3: Longitudinal pulse profile distribution optimised for minimum bunch length.

The second optimisation produces a somewhat longer pulse, 40 fs FWHM, with peak current of 7 kA, but with better emittance of 0.7 mm mrad, and 0.2% energy spread (projected). The ELEGANT output has been fed into a time dependent GENESIS simulation to calculate the radiation power development at the fundamental photon energy of 2 keV (Figure 4). The FEL is based on a train of in-vacuum undulators with 21 mm period (K = 1.44) in sections of 4.5 m separated by 0.7 m. The focussing along the undulator train is based on a FODO lattice with one quadrupole in each drift section between undulators. In this preliminary simulation the average power saturates at around 2.5 GW after 62 m. The radiation output in this case has the characteristic spiked structure of a SASE-FEL with many spikes of pulse length approximately equal to a cooperation length of about 0.5 fs FWHM. Over the full 83 fs pulse the total energy is 208 μJ/pulse, corresponding to 6.5 10^{11} photons/pulse.

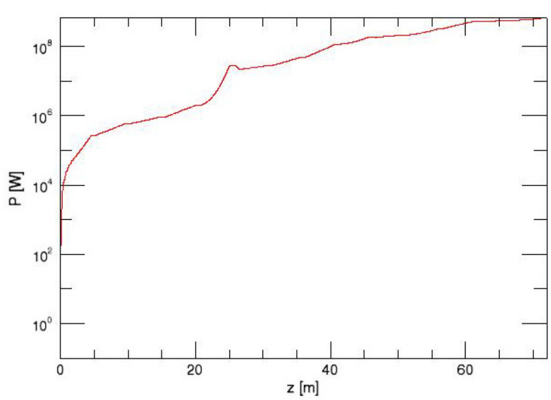

Figure 4: FEL power evolution along the undulator.

BUILDINGS AND SERVICES

A detailed architectural scheme has been developed considering the plan and cross-sections at various points along the linac tunnel, undulator and beamline halls. This has informed a detailed cost study for the buildings and services and allowed some cost optimisation to be carried out. The main options that have been considered include:

- Placing of the klystron hall above, or to the side, of the surface built linac tunnel;
- Surface built linac tunnel, or a cut-and-fill buried tunnel using either in-situ cast concrete, pre-cast concrete box sections, or pre-cast circular sections;
- Continuous or segmented service building.
- Building options to allow later extension of the linac to higher energy.

Our conclusions so far suggest that a design with the klystron hall above the linac tunnel is cheaper as the built footprint is much reduced. Also, a cast in-situ buried tunnel appears the cheaper option over the surface built. Whether or not piling is required under the surface built thick tunnel walls will depend on a final detailed foundation design. A risk of the buried tunnel is of course the possibility of flooding or leaks and avoiding this could easily offset any marginal cost savings. For either tunnel option a careful assessment of stability requirements for the linac itself is needed before progressing the design in detail. The linac tunnel is likely to have a lower stability requirement than the undulator hall where electron and photon beams must be kept in close alignment. Although even here, if motorised undulator supports are adopted with active feedback to continually align them, the requirements for the floor could be relaxed, as for example at the LCLS [6].

Regarding services, the best solution appears at present to be a main 1200 m^2 primary service building with main transformers, boilers, chillers and air-blast coolers serving two 200 m^2 secondary services buildings containing local heat exchangers and electrical distribution (with further buildings added later for the second stage linac extension). In this way cooling pipework circuits and power distribution cable runs can be kept much shorter supplying a local section of linac with consequent savings on pressure and voltage drops.

ACKNOWLEDGEMENTS

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