A 1 keV FEL DRIVEN BY A SUPERCONDUCTING LINAC AS A CANDIDATE FOR THE UK NEW LIGHT SOURCE

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Abstract

Several new light source projects aim to produce X-ray photons with high repetition rate (1kHz or above). We developed a conceptual design for a soft X-ray FEL driven by a superconducting LINAC based on L-band SC TESLA type RF cavities. We present here the results of the start-to-end simulations from the gun to the end of the undulators and the corresponding optimisation of the FEL performance at 1 keV photon energy.

INTRODUCTION

In the framework of the New Light Source (NLS) project [1] a science case [2] to support the construction of a new light source in UK has been recently produced. The users' requirements relevant for the machine design include the production of high brightness photons with energy up to 1 keV, with high repetition rate (1 kHz or above) in ultra short pulses (20 fs FWHM or less) containing at least 10^{11} photon per pulse at 1 keV, with a high degree of temporal and transverse coherence.

The NLS Physics and Parameters Working Group has considered two options for the accelerator design. In this paper we report the activity on the CW superconducting LINAC. A companion paper describes the study of a CW recirculating option [3].

The proposed LINAC consists of several key components. A low emittance electron beam is first generated by an L-band RF gun modified from the DESY design [4] and accelerated to 2.25GeV by fourteen TESLA type L-band superconducting accelerating modules [5]. Superconducting technology is chosen in order to meet the high repetition rate demanded by the science case. A maximum gradient of 20 MV/m is foreseen for the operation of such cavities at repetition rates higher than 1 kHz. The electron bunch is compressed in three stages using four-dipole magnetic chicanes, and longitudinal phase space linearization is carried out by a third harmonic cavity operating at 3.9GHz with a maximum gradient of 15 MV/m. Space has been allocated in the design for a laser heater before the first bunch compressor to suppress the micro-bunching instability. Following the LINAC is a collimation section for removal of the beam halo, a diagnostics section and a spreader section distributing the electron beam simultaneously to the three FEL lines. A schematic of the proposed facility layout is shown in Fig. 1 and a plot of the Twiss parameters is given in Fig. 2. The three FELs are based on a cascaded harmonic scheme with HHG seeding, however in this paper we base the gun and linac optimisation on the SASE operation of the 1 keV FEL.

Figure 1: Schematic layout of the proposed facility.

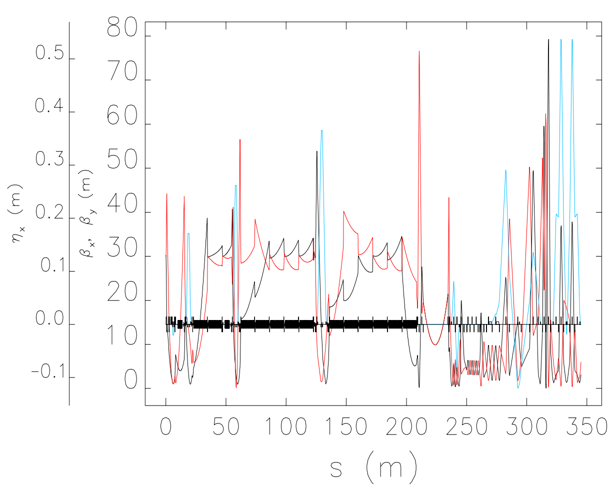

Figure 2: Twiss parameters for the LINAC, collimation, diagnostics and spreader sections.

LINAC OPTIMISATION

The goal of the LINAC optimisation process is to generate an electron beam suitable for seeded FEL operation with minimum gain length in order to reach saturation in an FEL of moderate length. This can be re-expressed as requiring an electron bunch with peak current above 1kA, normalised slice emittance below 1mm.mrad and slice energy spread below 2×10^{-4}. To guarantee the stable operation with the seeded schemes, the bunch substructure should ideally be uniform in a region long enough to accommodate the expected bunch arrival time jitter at the FEL, a 20fs seed pulse and pulse slippage along the FEL train of around 50fs, as required for the emission at 50 eV.

Design Considerations

The electron bunch generated by an optimised injector design is used as input for the elegant simualtions in the main LINAC. Tracking in elegant includes the effect of coherent synchrotron radiation (CSR), longitudinal space charge (LSC) and wakefields in the L-band accelerating structures. The optimisation work has considered the operation with different bunch charge. We report here the results of the operation with 500 pC.

For bunch compression an option consisting of three chicanes at energies of 100MeV, 400MeV and 1.2GeV has been selected. A third harmonic cavity is located upstream of the first bunch compressor at low energy in order to minimise the required gradient for phase space linearization. A modest compression factor of 1.8 is then carried out at the first compressor in order to give the best compromise between avoiding space charge effects and minimising further the curvature acquired from running off-crest with a long bunch in the subsequent RF cavities.

The lattice contains several quadrupole triplet matching sections to allow independent operation of the various LINAC components. For example, a change in the strength of one of the bunch compressors can be compensated locally without perturbing the rest of the machine. The optics matching has been carried out in such a way as to ensure minimum horizontal beta-function at the final dipoles in the bunch compressors to suppress coherent synchrotron radiation (CSR) blow-up of the slice emittance and energy spread. Beta-functions are constrained to moderate values elsewhere.

A key consideration for the LINAC optimisation was to reduce the final energy chirp on the electron bunch in the FEL train, ideally keeping it below the intrinsic SASE bandwidth (the Pierce parameter in the present case is of the order 1×10^{-3}). This requirement is particularly challenging for L-Band LINACs, where the wakefields are reduced compared to normal-conducting S-Band LINACs and cannot be used to remove the energy chirp. Attempts to operate the RF cavities beyond-crest after the final bunch compressor have also proved ineffective due to the short bunch length. As such, the optimisation has been carried out in such a way as to minimise the initial size of energy chirp imprinted on the beam by running the RF cavities close to on-crest, compensating for the reduced energy chirp with an increase in bunch compressor strength. However, in this scheme care has to be taken in order to avoid increasing the sensitivity of the LINAC to jitter.

Following the main LINAC, the collimation, diagnostics and spreader sections have all been designed to be transparent to the beam. The spreader sections consist of two TBA cells similar to the LBNL design [6], with the septum and kicker magnets for each FEL line replacing the first dipole of a TBA cell. The pulsed magnets are proposed to operate at a rate of up to 1kHz, offering a flexible bunch distribution structure of nominally 333Hz to each FEL line. An additional DC dipole magnet enclosing each kicker magnet will allow any one FEL to operate at 1 kHz at a time.

The LINAC optimisation process has been investigated using the SPEA2 genetic algorithm [7] linked to the elegant simulation program [8]. The genetic algorithm used here allows the simultaneous optimisation of several objective functions; in this case the 3D Xie gain length [9] and final energy chirp were minimised and the FEL power was maximised, averaged over a 250fs long section of the bunch. The parameters used for the optimisation are given by the RF cavity voltages, phases and the compressors strength. An example of the output from this optimisation scheme is shown in Fig. 3 and 4. Tracking performed through the collimation, diagnostics and spreader sections showed no further detrimental effects.

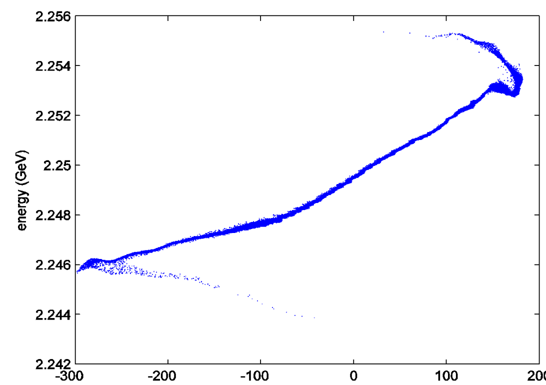

Figure 3: Typical longitudinal phase space plot of the electron beam at the exit of the LINAC.

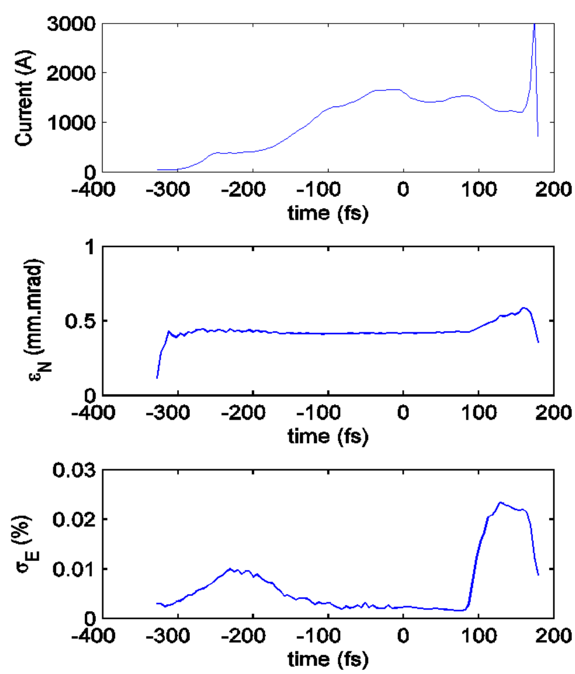

Figure 4: Typical electron beam slice parameters at the exit of the LINAC.

JITTER STUDIES

A realistic LINAC design must take into consideration the effects of realistic errors such as magnet field errors, alignment errors in the magnets, cavities and undulators, phase and voltage jitter in the RF cavities and fluctuations in output from the RF gun. To assess the consequences of such errors, extensive simulations have been carried out over many error seeds to determine the sensitivity of the bunch arrival time, energy, Xie gain length taking each error type individually and in combination. The errors investigated are summarised in Tab. 1, and the effects of the errors are given in Tab. 2.

Table 1: Summary of Error Magnitudes Used in Jitter Studies; all Values are r.m.s.

Parameter	Magnitude
Bunch charge	1%
RF gun cavity voltage	3×10^{-4}
RF gun cavity phase	0.3°
Solenoid field	1×10^{-5}
RF voltage	3×10^{-4}
RF phase	0.03°
Bunch compressor angle	1×10^{-4}
3rd Harmonic cavity voltage	9×10^{-4}
3rd Harmonic cavity phase	0.09°

Table 2: Summary of Bunch Error Sensitivity

Parameter	Magnitude
Arrival time	90 fs rms
Relative Xie gain length variation	1.5 % rms
Relative variation of the emittance	3% rms
Relative variation of central energy	0.01% rms

FEL OPERATION

The undulator channel considered was designed to guarantee a tunability of the FEL in the photon energy range from 430 eV to 1 keV by exclusively using the gap of the undulator train. The operation at lower photon energy is limited by the minimum gap allowed which was restricted to be 8 mm to avoid wakefield effects in the undulator. The operation at high photon energies is determined by the requirement to operate with a reasonable undulator parameter K which guarantees a sufficient FEL coupling. The choice of an undulator period of 32 mm with a gap of 14.6 mm for the operation at 1 keV generates a K~0.7 and a reasonably short 3D Xie gain length. Undulator sections of 3.5 m with breaks of 0.8 m for focussing and diagnostics were considered.

The slice emittance properties of the bunch generated at the end of the spreader are suffcient to drive a SASE FEL to saturation within 40 m with the undulator channel described, in good agreement with the 3D Xie length computation. In Fig. 5 we report the result of a time dependent GENESIS [10] which show that peak power in excess of 3 GW can be generated.

Preliminary studies on the operation of the injector and the LINAC with reduced charge of 2 pC have shown that a very aggressive compression of the electron bunch can generate ultra short electorn pulses with few fs FWHM and peak current of the order of 1 kA, even with such small charge. These type of bunches can then operate in the so called single spike regime [11] at 1 keV. In Fig. 6 we report the longitudinal profile of a single spike FEL pulse with 450 as FWHM and a product $\Delta f \Delta t$~0.62. The peak power is 200 MW corresponding to $6{\cdot}10^8$ photons per pulse.

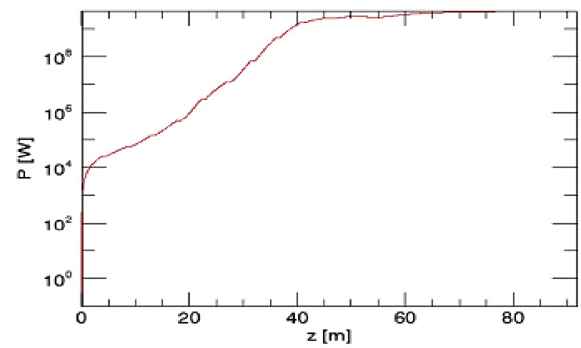

Figure 5: FEL power as a function of the distance travelled in the undulator train. GENESIS time dependent simulations.

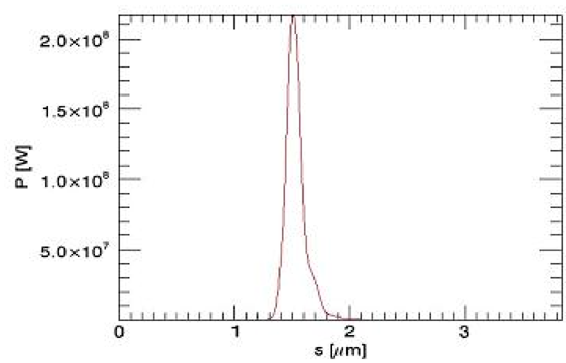

Figure 6: Longitudinal FEL pulse profile in the single spike regime.

CONCLUSIONS

We have presented the results of the optimisation of a 1 keV FEL driven by a single-pass superconducting L-band LINAC, which provides a promising option for the construction of a new light source in UK.

REFERENCES

[1] R. Walker et al., these proceedings.
[2] NLS Science Case, in www.newlightsource.org
[3] P. Williams et al., these proceedings.
[4] J-H Han, these proceedings.
[5] B. Aune et al., PRSTAB, **3**, 092001, (2000).
[6] A. Zholents et al., CBP Tech Note 401, (2009).
[7] E. Zitler et al., in Evolutionary Methods for Design, optimization and Control CIMNE, Spain, (2002)
[8] M. Borland, NIM A582, 54, (2007).
[9] M. Xie, PAC 1995, p. 183, (1995).
[10] S. Reiche, NIM A429, 243, (1999).
[11] R. Bonifacio, PRL 73, 70, (1994).