PRELIMINARY STUDIES OF A POSSIBLE NORMAL-CONDUCTING LINAC OPTION FOR THE UK'S NEW LIGHT SOURCE

R. P. Walker, R. Bartolini[1], C. Christou, J.-H. Han, Diamond Light Source, Oxfordshire, UK
[1]and John Adams Institute, University of Oxford, UK

Abstract

We report on recent studies of an X-band linac as a potential driver for a soft X-ray FEL facility, including cost optimization and beam dynamics issues.

INTRODUCTION

A Conceptual Design Report for a new soft-Xray light source facility, the New Light Source (NLS), was completed in May 2010 [1,2]. The NLS design was based on a number of free electron lasers covering the 50 eV to 1 keV range and operating at high repetition rate driven by a cw 2.25 GeV superconducting L-band linac. While the science case for the NLS was considered very strong, due to funding restrictions the project was put "on hold" after completion of the CDR. Since then we have been giving some consideration to a possible alternative option for the NLS which could provide similar performance but at reduced repetition rate, and potentially reduced cost, based on normal conducting technology. In particular, inspired by recent work at SLAC [3], we decided to investigate the application of X-band technology operating at lower gradient so as to achieve a 1 kHz operating frequency. We chose this repetition rate, and the same 2.25 GeV energy, as this was the baseline specification of the NLS for which there is already a robust science case.

Our initial considerations of an X-band linac driven soft X-ray FEL led to a design based on 1 kHz repetition rate at an accelerating gradient of 35 MV/m [4,5,6]. In this report we consider further the gradient/cost optimization, the impact on beam dynamics, and also compare costs with both an S-band design and the NLS superconducting linac.

X-BAND LINAC LAYOUT

A study of the issues arising when considering the design of an X-band linac at high repetition rate, including power dissipation issues and availability of RF power sources, was presented in [6]. The conclusion reached was that although suitable accelerating structures, klystrons and modulators do not currently exist, there is no fundamental obstacle to achieving 1 kHz operation with an accelerating gradient of around 35 MV/m, and the level of R&D and industrialization required should be relatively modest. A design based on these parameters was presented in [5], consisting of an S-band gun and a number of S-band accelerating sections, before the first bunch compressor (BC1) at 350 MeV. Following BC1, X-band accelerating sections take the beam up to 2.25 GeV (see Figure 1).

S-band Gun

Early work on an S-band injector resulted in a design capable of 400 Hz operation with a peak field at the cathode of 120 MV/m [7]. Subsequently the design was improved to reach 1 kHz operation with 100 MV/m at the cathode while still providing similar beam parameters [8]; further improvements on that design are reported in [9].

The gun includes optimised cooling water channels for high average RF power operation, for symmetric deformation by RF heating, and also for preserving the field balance between the first and second cells during RF operation. The coaxial RF coupler connected to the front opening of the gun allows cooling channels to be installed over the cavity cylinder body. The cathode installed at the centre of the rear wall is exchangeable and the size, 8 mm diameter, has been chosen for a minimum impact to the RF field as well as beam dynamics. According to ANSYS analysis, this gun can operate stably at an average RF power of 17 kW, which should allow 1 kHz operation with up to 3 μs RF pulse length at 100 MV/m peak field at the cathode. More information on the RF design, thermal analysis and vacuum performance for this gun were reported in [10].

X-BAND LINAC COST OPTIMIZATION

Table 1: Main Accelerating Structure Parameters

Parameter	X-band	S-band
Shunt impedance	100 MΩ/m	50 MΩ/m
Mode	2π/3	2π/3
Group velocity	2.44% c	2.08% c
Field attenuation	0.760 m^{-1}	0.113 m^{-1}
Filling time	136 ns/m	161 ns/m
Waveguide losses	5%/m	0.5%/m

For ease of comparison between schemes this analysis is based on a full 2.25 GeV energy linac i.e. ignoring any initial S-band sections. For simplicity of analysis a constant-impedance structure has been assumed with shunt impedance of 100 MΩ/m and iris radius $a/\lambda = 0.13$, a compromise between higher shunt impedance and higher wakefields [5]. Other main parameters are given in Table 1. In reality a constant gradient might be chosen to even out the power dissipation along the structure, however this is not expected to change the optimization. We assume no SLED system is used, both because a flat-top RF pulse of at least 200 ns is needed to accommodate multibunch operation (e.g. 5 pulses separated by 50 ns) and also because of the very high cost of the X-band

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Figure 1: Schematic layout of a generic X-band linac for a soft X-ray FEL. Gun indicates the Photocatode RF gun, S01 to S03 S-band accelerating structures, LH the laser heater, X4H the 4th harmonic (X-band) linearising RF cavity, BC1-BC2 the two bunch compressors, X01 to X07 various X-band accelerating structures, DL a dog-leg beam delivery system followed by one of several FEL undulator trains.

SLED system.

Figure 2 presents the results of a calculation in which both the length of accelerating structure and number of sections per klystron are varied The points in the figure correspond to integral numbers of sections per klystron (1 being the right-most, then 2,3,4,5,6,8,10) and these are joined by straight lines.

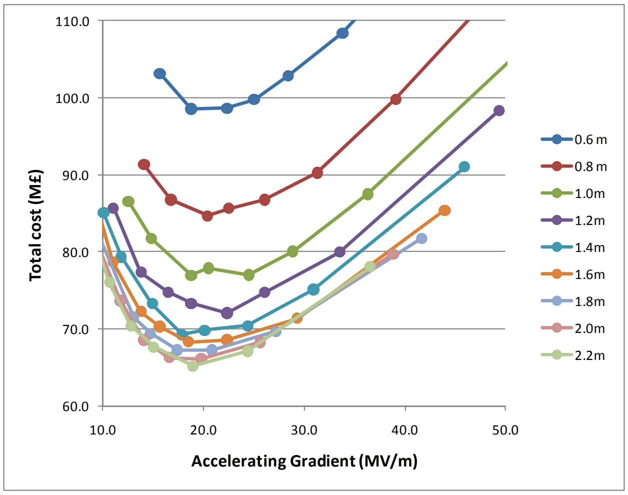

Figure 2: Cost optimization for the X-band linac.

The power source is assumed to be a 50 MW klystron, such as the XL-4 and other SLAC devices, up-rated to 1 kHz operation, with an assumed 50% efficiency. The modulator pulse is assumed to be limited to a minimum of 0.4 μs flat-top, with 1 μs rise and fall times, with an assumed 60% efficiency. For a 1.8 m structure for example, the filling time is 246 ns, and hence the required RF pulse is of the order 450 ns, corresponding to 22.5 kW average RF power. The average klystron beam power is then about 110 kW. Realistic losses of 5% per m for standard X-band waveguide are assumed, with 5 m minimum length for one section, plus appropriate additional length for connecting further sections to one klystron.

The assumed costs are given in Table 2. These are estimates based on the limited available information, and may have significant “error bars”. One should also note that these are “bare” costs of only the linac related parts, and exclude R&D, installation, commissioning, staff, contingency and VAT, and serve only for relative comparisons between schemes. The tunnel length assumes 0.2 m between every accelerating section, plus an additional 1 m every 15 m for quadrupole focusing etc. No allowance is made for bunch compressors as this is a constant additive factor. The tunnel + klystron hall cost is based on the estimates carried out for the NLS project. Operating costs, assuming 5,000 h of operation per year for 10 years, are based on today’s electricity cost of £0.07/kWh, with 33% overhead for the power needed to drive the associated cooling plant. Costs include replacement of klystrons on average after 20,000 h.

Table 2: Estimated X-band and S-band Linac Costs

Item	X-band	S-band
Klystron	£375k	£150k
Modulator	£300k	£300k
LLRF + drive amp.	£90k	£90k
Accelerating structure	£31k + £52k/m	£10k + £17.4k/m
Waveguide, per section	£80k	£80k
Tunnel + klystron hall	£69.1k/m	£69.1k/m

It is immediately apparent from Fig. 2 that the minimum cost drives one towards longer accelerating sections than are currently considered for high gradient X-band linacs (~0.6m), more similar in fact to the originally developed 1.8 m NLC structures, and secondly to lower average gradients, centred around 20 MV/m. It is clear that there is little to be gained in total cost from using structures longer than about 1.8 m. For this length the cost minimum of £67.2m occurs for 4 sections per klystron with a relatively low average accelerating gradient of 17.4 MV/m. Other parameters are summarised in Table 3.

Table 3: Results of Cost Optimization (2.25 GeV linac)

Item	X-band	S-band
Structure length	1.8 m	6 m
Structures/klystron	4	2
Average gradient (MV/m)	17.4	11.7
Linac length	154 m	212 m
No. of klystrons	18	16
Power consumption	4.2 MW	6.3 MW
Linac cost	£28.5m	£14.9m
Tunnel cost	£10.6m	£14.6m
Operating cost (10yr)	£28.1m	£27.0m
Total cost	£67.2m	£56.5m

Comparison with S-band Linac

For comparison we have also investigated the more conventional S-band technology, which previously formed the basis of the Sapphire facility concept [7]. The relevant parameters are given in Tables 1 and 2. A 50 MW

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klystron has been assumed in this case also. Because of the lower field attenuation the optimum structure length is greater than 6 m, however we have chosen to limit the length to this value for practical reasons. The cost minimum occurs for 2 sections/klystron. The average gradient for this case is only 11.7 MV/m, nevertheless the overall cost is still less than the X-band case. Table 3 gives the breakdown of costs. Comparing the two cases, the 1.8 m X-band solution is 32% more expensive as regards capital cost (with a different balance between linac and tunnel costs) but the operating cost is similar, the higher cost of replacing klystrons offsetting the lower power consumption.

It is clear that if X-band costs could be reduced to those of S-band components, then X-band would become the cheaper option. Other relevant factors in the analysis are the assumed shunt impedance and waveguide losses. An improvement in these parameters (e.g. shunt impedance of 140 MΩ/m), even with the higher unit costs, could also bring the X-band solution to a similar total cost.

Comparison with NLS Superconducting Linac

Table 4: NLS Linac Cost Estimates

Item	**Cost**
Linac	£68m
Cryoplant	£54.7m
Cryo building	£9.6m
Tunnel + RF Hall (220 m)	£15.2m
Operating cost (10yr)	£28.3m
Total cost	£175.8m

The equivalent cost of the 2.25 GeV NLS superconducting linac, which was based on 18 TESLA-like L-band cryomodules, adapted for cw operation at 15.05 MV/m [1], was £175.8m, including the cost of the refrigeration plant and associated building. Table 4 gives the cost breakdown. Clearly the cost exceeds significantly that of either normal conducting options – the price to pay for the benefit of high repetition rate operation.

X-BAND LINAC BEAM DYNAMICS OPTIMIZATION

Since the cost optimization now suggests using longer accelerating sections with lower gradient than we previously assumed, 0.53 m sections and 35 MV/m [4,5], we have investigated the impact of this on beam dynamics, choosing for convenience 2.1 m long sections (4x0.53) with nominal 20 MV/m gradient.

The electron beam parameters at the end of the injector (exit of S01 in Fig. 1) are given in Table 5, calculated using ASTRA [11]. These values are somewhat more conservative than those produced by the most recent injector optimization reported in ref. [9].

Table 5: Electron Beam Parameters at the Exit of the Injector Region (200 pC, 135 MeV)

Parameter	**Value**
Projected normalised emittance	0.21 μm
Slice normalised emittance	0.19 μm
Slice relative energy spread	4 10^{-6}
Bunch length, FWHM	7 ps
Peak current	30 A

The beam dynamics in the linac was calculated using elegant [12], including the effects of coherent synchrotron radiation, longitudinal space charge and cavity wakefields for two different modes of operation: short pulse SASE operation with 50 pC charge, and the more demanding 200 pC case for seeded FEL operation. This requires a bunch with constant parameters over a sufficient length to accommodate the seeding pulse and the relative timing jitter between the seed and electron pulses. A genetic algorithm was used to optimize average FEL gain length over the regions of interest of the bunch, and in the seeded case also the variation of gain length, as calculated using the Xie parameterization [13].

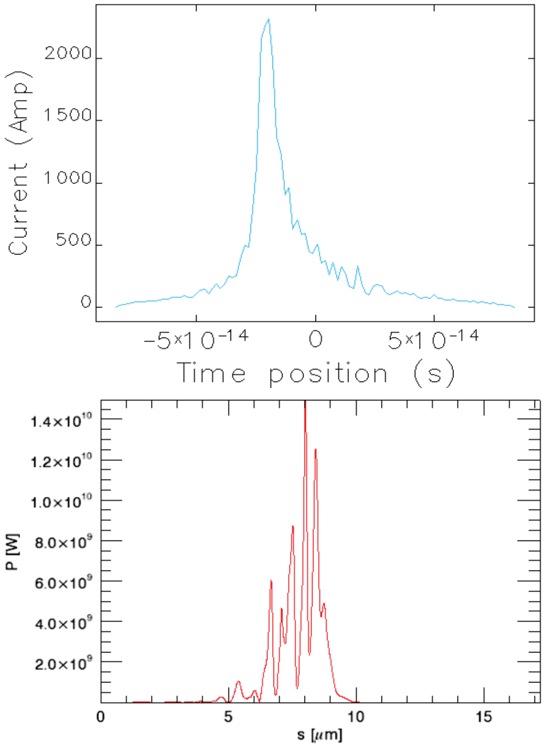

Figure 3: Electron beam current profile (upper) and FEL output pulse (lower) for the 50 pC case.

Figure 3 shows the result obtained in the 50 pC case. The electron bunch is highly compressed with a peak current in excess of 2 kA. FEL calculations using GENESIS [14] show that saturation is reached (at 1 keV) after ~ 30m. The resulting FEL pulse, shown in Fig. 3, has a width of ~ 5 fs FWHM.

Figure 4 shows the results for the seeded case. It can be seen that there is a “flat” region of approximately 100 fs in length with an average gain length of 1.3 m and with less than 10% variation in gain length.

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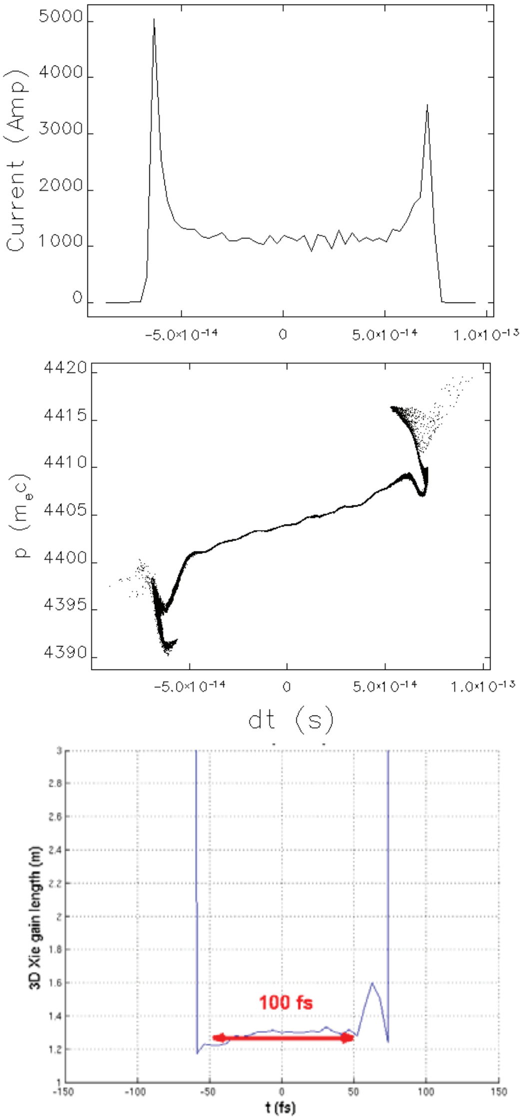

Figure 4: Current profile (upper), longitudinal phase space (middle) and estimated FEL gain length along the length of the bunch (lower) at the end of the X-band linac for the 200 pC case.

The results for both 50 pC and 200 pC cases are very similar to those obtained with a higher accelerating gradient [5], showing that the additional wakefields resulting from the longer linac do not have a dramatic effect. The results are also similar to those obtained previously for the NLS [1].

CONCLUSIONS

We have confirmed that as regards basic beam parameters, it appears feasible to use an X-band linac as a driver for a seeded soft X-ray free electron laser with a reduced accelerating gradient of ~20 MV/m that is consistent with operating at a repetition rate of up to 1 kHz. Such a solution would be significantly less expensive than a superconducting machine such as the NLS [1], but of course with the major drawback of not reaching the higher repetition rates that would be needed to meet the full science case.

Comparing S-band and X-band solutions for the particular choice of 1 kHz repetition rate, it appears that S-band would currently be a cheaper option. For X-band to be competitive with S-band, the currently estimated costs of X-band components, particularly the klystron, would have to come down significantly. A reduction in X-band waveguide losses would be of benefit, however the extra cost of waveguide components would need to be included in the analysis. An optimization of the accelerating structure parameters (as considered for example in ref. [15]) would also assist in making the X-band linac solution more cost effective, however if this is achieved by a reduction of iris radius then the impact on beam dynamics would need to be carefully assessed.

The use of C-band technology has not been considered here and would make an interesting comparison. Further work on normal conducting linac options should also asses the relative merits of the schemes in terms of beam stability, which is critical for seeded FEL operation.

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