S-BAND HIGH GRADIENT LINAC FOR A COMPACT XFEL*

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Abstract

With the successful operation of LCLS, the first hard X-ray FEL (XFEL), other facilities are being proposed and developed world-wide. Due to limited site sizes, many proposed XFELs are based on C-band (5.712 GHz) and X-band (11.424 GHz) technology, which are capable of delivering acceleration gradients (> 35 MV/m), nearly double that of the SLAC S-band (2.856 GHz) linac. High gradient research at X-band shows that the operational gradient, for a fixed rf breakdown rate, scales as the -1/6 power of the rf pulse length. If such scaling holds at S-band as well, it should be possible to operate an S-band linac at a gradient higher than the 35 MV/m used in the SLC S-band positron capture accelerator by using shorter rf pulse lengths.

INTRODUCTION

There is growing demand for high gradient accelerators for future compact XFELs. Many proposed facilities are based either on C-band or X-band technology, which are capable of delivering a few times the operating gradient of traditional SLAC-type S-band structures. SCSS is driven by a C-band linac with a gradient over 35 MV/m [1], the Shanghai Hard XFEL and PAL are considering C-band linacs with over 35 MV/m acceleration [2, 3], and ZFEL is considering a 100 MV/m X-band linac [4].

However, with the few high power klystrons that have been produced at C-band and X-band, as indicated in Table 1 [5], building linacs based on these higher frequencies will unavoidably entail some technical risk. Considering long-term operation, maintenance, stability, and cost, higher frequency linacs may be considerably more expensive than ones using the much more mature S-band technology. Furthermore, there are limited numbers of suppliers of high peak power klystrons at these high frequencies. S-band technology has been serving the accelerator community for several decades and has spawned several commercial suppliers of high peak power klystrons.

Thus, it is instructive to explore the use of a high gradient S-band linac for a future compact XFEL. In this paper, we present design and cost considerations for a high gradient, single or double bunch-per-pulse S-band linac to drive an XFEL. As the operating gradient of an S-band, SLAC-type, 3 m accelerator structure is typically 20 MV/m, high gradient for S-band is taken to be 40 MV/m, a factor of two higher.

Table 1: Statistics of Available High Peak Power Klystrons at Different RF Frequencies

RF Frequency	**S (2.856 GHz)**	**C (5.712 GHz)**	**X (11.424 GHz)**
Basis	SLAC Linac	Spring-8 Test Linac	NLC Test Accelerator
Klystron	SLAC 5045	Toshiba E3746	SLAC XL4
	65 MW, 3.5 μs, 120 Hz	50 MW, 2.5 μs, 50 Hz	50 MW, 1.5 μs, 60 Hz
	46 % efficiency	47 % efficiency	41 % efficiency
	30 million hours of operation (since 1984)	Successfully operated in a test accelerator	23 XL4/5 klystrons produced
			Several have 10k hours but mostly below 35 MW
	More than 1,100 tubes	66 installed on Main 8 GeV linac	
	MTBF 75k ~ 100k hours	No MTBF Data	Life test starting on a new tube

ACCELERATOR STRUCTURE

In high gradient research conducted with X-band accelerator structures, a scaling of the practical operating gradient, for a fixed acceptable rf breakdown rate, as the -1/6 power of the rf pulse length has been observed. Though it may not hold exactly at S-band, this scaling is consistent with the general observation over a wide range of frequencies that higher gradients can be achieved with shorter rf pulse lengths.

While the typical acceleration gradient in an S-band accelerator is held around 20 MV/m to obtain good rf-to-beam power transfer efficiency, some S-band structures have been operated at higher gradients. A 5-cell S-band traveling-wave (TW) structure has supported over 100 MV/m after 500 hours of rf processing at a repetition rate of 20 Hz [6], an S-band 0.6 m TW structure has achieved a 57.1 MV/m gradient at a pulse width of 1 μs and a repetition rate of 25 Hz after 400 hours processing [7], and a 2 m TW S-band structure has achieved 40 MV/m with a pulse width of 4 μs and a repetition rate of 50 Hz [8]. The recent experience with X-band high gradient structures has led RadiaBeam Technologies to propose a prototype S-band standing wave (SW) structure with a gradient goal of 50 MV/m [9].

The most extensive experience with high gradient S-band operation comes from the SLC positron capture

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accelerator. It included a 1.5 m long structure with a 400 ns fill time that operated for more than a decade at 35 MV/m and higher. Given the shorter pulse length proposed below for the XFEL application, a gradient close to 40 MV/m should be achievable at an acceptable breakdown rate.

In a structure optimization study for low beam loaded linacs [10], a constant gradient S-band structure was proposed with a length of 2.4 m, a fill time of 265 ns, an average shunt-impedance of 58 MΩ/m and an input power of 56.9 MW for 20 MV/m acceleration. Fig. 1 shows the parameter profiles along the structure. Using S-band SLED cavities [11] to double the acceleration gradient would require a klystron output pulse of only 1.5 µs, as shown in Fig. 2, much shorter than the 3.5 µs klystron pulse length used in the SLAC linac to produce 800 ns “SLED’ed” pulses to power its structures.

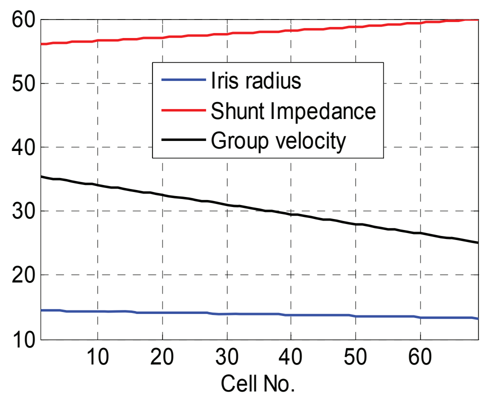

Figure 1: Optimized S-band TW structure design for high gradient operation. The units for iris radius, shunt impedance and group velocity are, respectively, mm, MΩ/m and c/1000.

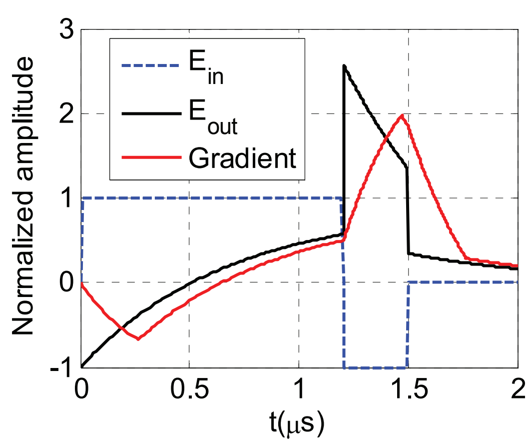

Figure 2: Normalized field amplitude waveforms of a SLED-driven linac. The dashed blue line and the solid black line represent the SLED system input and output, while the red line represents the relative acceleration gradient obtained in the structure. Negative values indicate a 180° difference from the accelerating phase.

LINAC COST STUDY

We now consider the relative cost of this approach using rough estimates of the component costs based on experience with high power rf systems and accelerators at SLAC. With a SLED system, one 5045 S-band klystron, of peak power 65 MW, can drive one optimized structure to the desired gradient of 40 MV/m. An rf station would thus consist of one klystron, one modulator, one accelerator structure and one LLRF system. The modulator and klystron efficiencies are taken to be 85% and 46%, respectively. The linac active accelerator fill factor is set to 0.95, with 5% of linac length alotted for non-accelerator elements. The beam pulse rate is assumed to be 60 Hz.

For a given beam energy, the relative linac cost versus acceleration gradient for this model is plotted in Fig. 3. The cost for a 40 MV/m linac is seen to be almost the same as that for a 20 MV/m linac. The cost breakdown for these two gradients is plotted in Fig. 4. A comparison of relative linac costs at three different rf frequencies is shown in Fig. 5, where the curves are based on the optimized structures and high power rf systems proposed in [10].

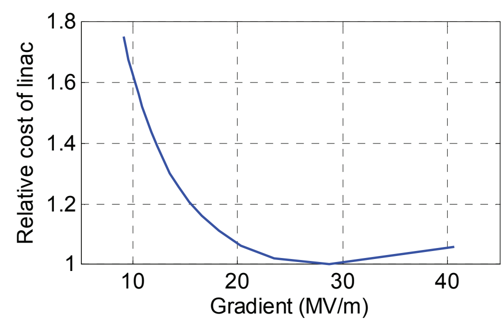

Figure 3: Relative S-band linac cost as a function of acceleration gradient. Due to the quantization of the number of accelerator structures per station, the curve is not smooth.

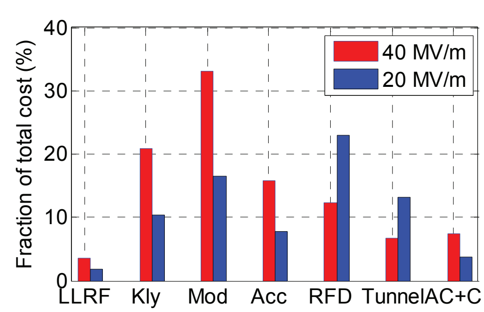

Figure 4: Breakdown of the S-band linac cost for the 40 MV/m (red) and 20 MV/m (blue) cases. LLRF, Kly, Mod, Acc, RFD, Tunnel and AC+C are, respectively, low level rf systems, klystrons, high voltage modulators, accelerator structures, rf distribution systems, linac tunnel, and AC site power and cooling.

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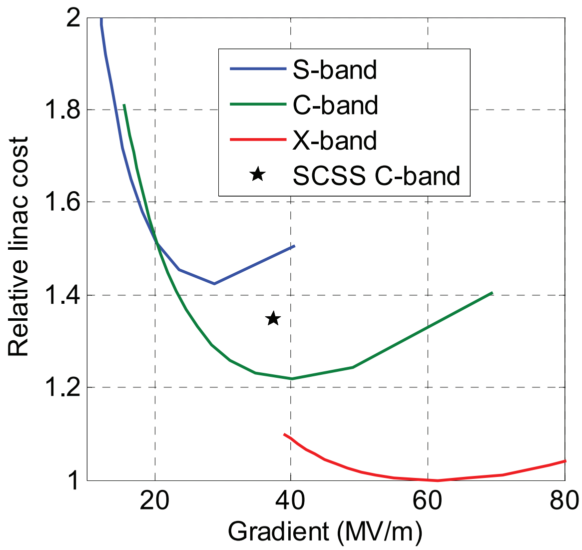

Figure 5: Relative linac cost vs. gradient for the same beam energy for different rf frequency choices. The black star represents the SCSS C-band linac cost without infrastructure [12].

SUMMARY AND DISCUSSION

Accelerator structure parameters are presented for a high gradient S-band linac optimized to drive an XFEL. Based on experience with high gradient X-band and S-band structures, the proposed short fill time S-band structure should operate stably at a gradient of about 40 MV/m. Either a single bunch or two bunches (< 50 ns spacing) per pulse could be accelerated in this scheme to drive an XFEL. With a 40 MV/m gradient, the cost of such a linac would likely be larger than that for C-band and X-band linac, but not prohibitively so.

Overall, considering the low wakefields, the maturity of the structure fabrication technology and the availability of commercial suppliers of high peak power klystrons, an S-band high gradient linac presents an attractive and practical option for driving future XFELs.

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