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A COMPACT X-BAND LINAC FOR AN X-RAY FEL*

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Abstract

With the growing demand for FEL light sources, cost issues are being reevaluated. To make the machines more compact, higher frequency room temperature linacs are being considered, specifically ones using C-band (5.7 GHz) rf technology, for which 40 MV/m gradients are achievable. In this paper, we show that an X-band (11.4 GHz) linac using the technology developed for NLC/GLC can provide an even lower cost solution. In particular, stable operation is possible at gradients of 100 MV/m for single bunch operation and 70 MV/m for multibunch operation. The concern, of course, is whether the stronger wakefields will lead to unacceptable emittance dilution. However, we show that the small emittances produced in a 250 MeV, low bunch charge, LCLS-like S-band injector and bunch compressor can be preserved in a multi-GeV X-band linac with reasonable alignment tolerances.

INTRODUCTION

The successful lasing and operation of the LCLS [1] has generated world-wide interest in X-ray FELs. The demand for access to such a light source by researchers eager to harness the capabilities of this new tool far exceeds the numbers that can be accommodated, spurring plans for additional facilities. Along with cost, spatial considerations become increasingly important for a hard X-ray machine driven by a multi-GeV linac. The consequent need for high acceleration gradient focuses attention on higher frequency normal conducting accelerator technology, rather than the superconducting technology of a soft X-ray facility like FLASH.

C-band technology, such as used by Spring-8, is a popular option, capable of providing 40 MV/m. However, more than a decade of R&D toward an X-band linear collider, centered at SLAC and KEK, has demonstrated that this frequency option can extend the gradient reach to the 70-100 MV/m range. The following design and beam dynamics calculations show an X-band linac to be an attractive choice on which to base an X-ray FEL.

DESIGN EXAMPLE

We present here for consideration a design example of a compact X-ray FEL (CXFEL) driven by the X-band linear accelerator. A diagram of our layout is shown in Fig. 1. We assume an LCLS-like S-band injector up to 250 MeV and an initial bunch compressor, delivering a bunch of charge of 250 pC and a normalized emittance of 0.4-0.5 μm. After the injector, the beam is accelerated up to 6 GeV through a 150 m long X-band main linac, operating with single bunches at 70 MV/m. This includes a second-stage bunch compressor that reduces the rms bunch length from 56 μm to 7 μm. The resulting 3 kA peak current bunch is then sent to an undulator for the FEL interaction.

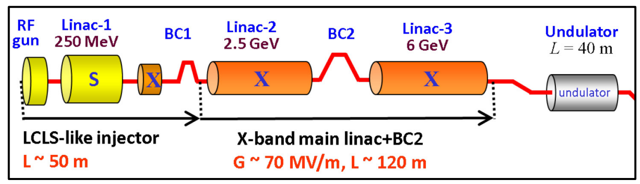

Figure 1: Schematic layout of a compact X-ray FEL driven by the X-band linear accelerator.

Selected beam, undulator and X-ray parameters for our FEL design are displayed in Table 1; those of LCLS are also included for comparison. We choose a radiation wavelength of λ_r=1.5 Å, the shortest wavelength in the LCLS design. Such X-rays could be generated by our beam in a 40 m in-vacuum type undulator with a period of 1.5 cm, half that at LCLS. Using analytical formulae from Ref. [2], we estimate that FEL saturation occurs at a length of about 30 m of undulator, with a saturation power of about 10 GW.

Table 1: FEL parameters of our CXFEL design compared to those of LCLS.

Parameter	symbol	LCLS	X-band FEL	unit
Bunch Charge	Q	250	250	pC
Electron Energy	E	14	6	GeV
Emittance	$\gamma\varepsilon_{x,y}$	0.4-0.6	0.4-0.5	μm
Peak Current	I_{pk}	3.0	3.0	kA
Energy Spread	σ_E/E	0.01	0.02	%
Undulator Period	λ_u	3	1.5	cm
Und. Parameter	K	3.5	1.9	
Mean Und. Beta	$\langle\beta\rangle$	30	8	m
FEL wavelength	λ_r	1.5	1.5	Å
Sat. Length	L_{sat}	60	30	m
Sat. Power	P_{sat}	30	10	GW
FWHM Pulse Length	ΔT	80	80	fs
Photons/Pulse	N_γ	2	0.7	10^{12}

As for the accelerator, it seemed reasonable to incorporate an LCLS-like injector, consisting of an S-band (2.856 GHz) rf gun followed by an S-band linac. A half meter X-band (11.424 GHz) section is then used

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prior to bunch compressor BC1 to compensate for the S-band rf curvature and linearize the bunch's longitudinal phase space. The transverse and longitudinal phase space controls are well-understood for this type of injector. Note, however, that SLAC and LLNL are in the process of designing an X-band photocathode rf gun and accelerators that should produce similar transverse emittances with half of the longitudinal emittance.

More pertinent to our purpose here, the bunch is shortened through BC1 so that the transverse wakefields are more tolerable in the physically smaller X-band structures of the main linac. Table 2 lists the main linac and bunch compressor parameters. RMS bunch length before and after compression are also indicated in the table.

Table 2: Main linac and bunch compressor parameters.

Parameter	symbol	value	unit
Linac-1 rms bunch length	σ_{z1}	650	µm
Linac-1S phase	ϕ_{1s}	-25	˚S
Linac-1X phase	ϕ_{1x}	-160	˚X
Linac-1 X voltage	V_{1x}	20	MV
BC1 energy	E_1	250	MeV
BC1 strength	R_{56}	-43	mm
Linc-2 rms bunch length	σ_{z2}	55	µm
Linac-2 phase	ϕ_2	-12	˚X
BC2 energy	E_2	2.5	GeV
BC2 strength	R_{56}	-20	mm
Linac-3 phase	ϕ_3	-2	˚S
Linac-3 rms bunch length	σ_{z3}	7	µm

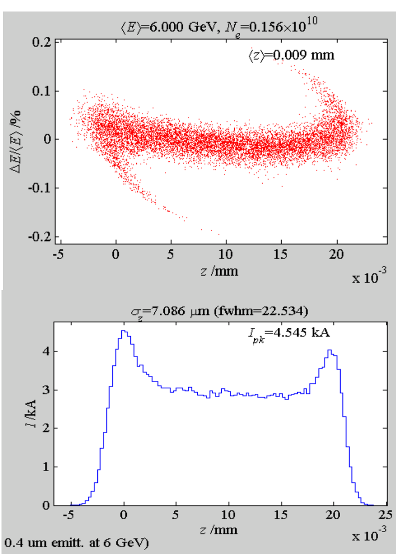

Figure 2: Litrack simulation results for longitudinal phase space and current profile after Linac-3 showing ~3 kA peak current in the bunch core and almost no energy-z correlation (bunch head is at $z < 0$).

Longitudinal phase space optimization was performed in Litrack [3]. We found that a shorter bunch length after BC1 is beneficial for the longitudinal phase space manipulation as well. In addition, due to the stronger rf chirp induced by the higher-frequency X-band linac, the Linac-2 phase is only off the acceleration crest by 12 X-band degrees. This makes the Linac-2 acceleration more effective and thus further decreases the total length required. The longitudinal wakefield in the X-band linac was incorporated in Litrack. We used the X-band structure H60, which has an average iris aperture radius equal to 18% of the X-band wavelength.

An optimized longitudinal phase space after Linac-3 is shown in Fig. 2. The core part of the bunch has a peak current of ~3 kA, while the head and tail parts have slightly higher peak currents. The energy-z correlation after BC2 is largely removed by the X-band wakefield in Linac-3. The normalized projected energy spread at 6 GeV is about 3×10^{-4}, while the slice energy spread is 2×10^{-4}.

X-BAND LINAC

The main linac, divided into Linac-2 and Linac-3 in Fig. 1, is composed of a series of X-band rf units. The layout of an rf unit might look like the one shown in Fig. 3, based on the X-band technology developed in the NLC/GLC linear collider programs from about 1992 to 2004. A 'two-pack' solid state induction modulator drives two XL4 klystrons whose combined 100 MW rf output pulse is then compressed by a factor of 10 in a SLED-II system. The resulting 480 MW pulse is then distributed to either six H60 structures or nine shorter T53 structures (see below) for an accelerating gradient of 70 MV/m.

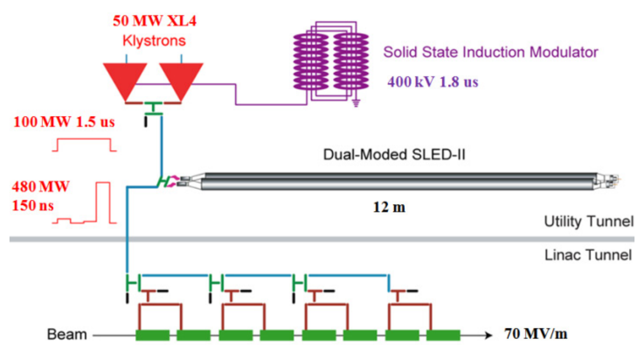

Figure 3: X-band rf unit layout. A pair of 50 MW klystrons sharing a modulator and an rf pulse compressor, powers several (6–9) traveling-wave accelerator structures.

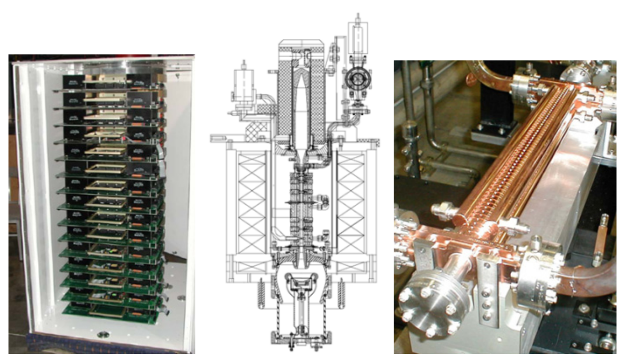

Figure 4: Solid state 400 kV modulator, SLAC XL4 50 MW 1.5 µs X-band klystron, and a T53 X-band accelerator structure.

Fig. 4 shows some of this technology, in particular (left) a stack of 15 induction cores and driver circuits for a hybrid two-pack modulator, (center) the cross section of an XL4 klystron with solenoidal focusing, and (right) a T53 accelerator structure. Fifteen XL4 klystrons have been built at SLAC and another two will be built in industry. Additionally, five 12 GHz versions (called XL5) have been built to accommodate linacs with 3 GHz injectors.

Two accelerator structures were developed for NLC/GLC: the T53 design for basic performance tests and a larger aperture H60 design for the linear collider (the "H" indicating higher phase advance per cell). A variation of the latter was developed in which the dipole mode wakes were 'damped and detuned' to allow multi-bunch operation. Details of the T53 and H60 designs are tabulated in Table 3. About 30 structures of these two types were built, and nearly all were high power tested. The expected rf breakdown rate per structure at 70 MV/m with 150 ns pulses is < 0.01 per hour at 120 Hz.

Table 3: Comparison of the T53 and H60 structure designs.

	Units	T53	H60
Structure Type		Constant Surface Field	Damped-Detuned
Total Cell Length	cm	53	60
Fill Time	ns	74	105
Phase Advance/ Cell	π	2/3	5/6
Average Iris Radius	% of λrf	13.4	17.9
Input Power for 70 MV/m Acceleration	MW	48	73

LINAC TOLERANCES AND COSTS

Tolerances in the X-band linac were examined using computed short-range transverse wakefield functions. The average along the bunch is shown in Fig. 5 as a function of rms bunch length. In both Linac-2 (before BC2) and Linac-3 (after BC2), the transverse wakefield in H60 was determined not to be a major issue in that:

- An injection jitter equal to the bunch size yields 1% emittance growth in Linac-2 and .003% growth in Linac-3
- Random misalignments of 1 mm rms, assuming 50 structures in each linac, yield an emittance growth of 1% in Linac-2 and 0.1% in Linac-3.

With the T53 structure, the jitter and misalignment tolerances for the same emittance growth are about a factor of three smaller, but still manageable.

For the purpose of doing X-band linac costing and optimization studies, the 2004 NLC linac cost estimates were scaled up by about a factor of four to account for the loss of economy of scale in going from 2,200 rf units to ~20 units needed for a 6 GeV linac. With tunnel and utility costs included, the relative linac cost versus acceleration gradient is plotted in Fig. 6 for the two structure designs, with the T53 minimum cost normalized to unity. At 70 MV/m, the cost is either at or near (within a few percent of) the minimum. The 'bare' cost (without engineering, management, contingency, escalation, etc.) for just the X-band linac with tunnel/utilities is approximately 60M$.

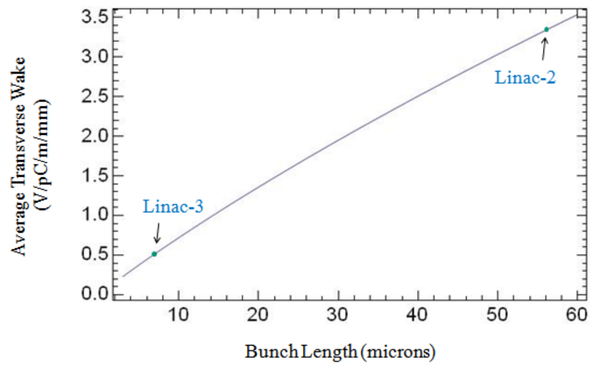

Figure 5: Transverse wakefield in the H60 structure averaged along the length of the bunch as a function of bunch length. The values for the design bunch lengths before and after the second bunch compressor are indicated.

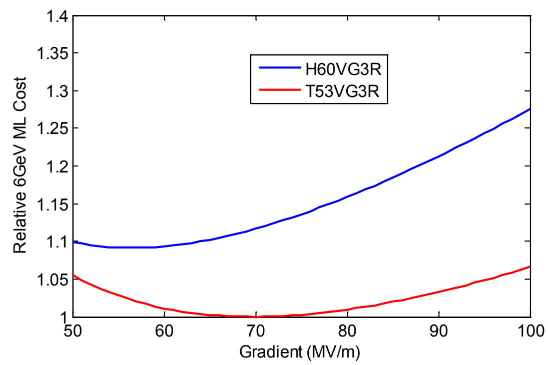

Figure 6: Dependence of the X-band 6 GeV main linac cost on acceleration gradient for the two structure types, normalized to the minimum for T53.

SUMMARY

In summary, an X-band linac driven XFEL appears feasible for low (250 pC) bunch charge and is appealing in terms of its compactness and low cost. Further studies to are underway to better optimize the linac design for this application and to more accurately estimate its cost. Several groups (MEGa-ray/LLNL, MaRIE/LANL, ELI/Romania, and University of Groningen/Netherlands) are interested in using this technology for X-ray or gamma-ray generation.

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