FEL PROPOSAL BASED ON CLIC X-BAND STRUCTURE

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Abstract

A linear accelerating structure with an average loaded gradient of 100 MV/m at X-Band frequencies has been demonstrated in the CLIC study. Recently, it has been proposed to use this structure to drive an FEL linac. In contrast to CLIC the linac would be powered by klystrons not by an RF source created by a drive beam. The main advantage of this proposal is achieving the required energies in a very short distance, thus the facility would be rather compact. In this study, we present the structure choice and conceptual design parameters of a facility which could generate laser photon pulses below Angstrom. Shorter wavelengths can also be reached with slightly increasing the energy.

INTRODUCTION

X-band accelerator development has gained improvement within last ten years, motivated by the need for high-gradient accelerators for the future linear colliders in high-energy physics research [1]. Studies on accelerating structures operating at 11.4 GHz were made at SLAC and KEK, in the last two decades of the nineteen (up to 2004), for the development of a TeV-scale high energy Linear Collider, and led to achieve 65-70 MV/m accelerating gradients [2]. Design of accelerator cells [3], manufacturing [4], and characterization technique [5] have been developed. Later, significant progress have been achieved by the CERN CLIC (Compact Linear Collider) Collaboration, that has recently demonstrated the possibility to operate 12 GHz accelerating structures with an average loaded gradient higher than 100 MV/m [6], values far beyond those reached with the present S and C band technology. The development of power sources for x-band structures [7] gives opportunity this technology may represent an useful solution to get very compact and cost effective linacs for multi-GeV electron beams. More recently, after the successful operation of the new FEL light sources like LCLS, SACLA, FERMI, a stronger and more vigorous interest in X-band technology has arose. The demand for new FEL facilities is worldwide continuously increasing, spurring plans for new dedicated machines. This led to a general reconsideration of costs and spatial issues, particularly for the hard X-ray sources, driven by long and expensive multi-GeV NC linacs. For these machines the use of X-band technology can greatly reduce costs and capital investment, reducing the linac lengths and the size of buildings. To pursue this objectives, a scientific collaboration has recently been established among several laboratories, interested in FEL developments, aimed at validating the use of X-band technology for FEL based light sources [8]. The specific objectives of the collaboration will include the design, assembly and high power tests of an X-band accelerating module for FEL applications, made up of two accelerating structures, RF pulse compression and a waveguide distribution systems. Special care will be given to the operating gradients, RF breakdown fault rate, alignment issues, wake fields, and operating stabilities. The overall objective of the collaboration is to support the feasibility studies of new research infrastructures and/or the major upgrading of existing ones, using X-band technology. The work program foresees a strong interaction between FEL scientists, FEL designers and accelerator experts. Starting from the FEL output specification, a fully self consistent FEL facility design will be established (in terms of accelerator layout, major hardware choices, and FEL

MACHINE DESCRIPTION

The proposed facility is a two-stage 6 GeV linac, consisting of an S-Band injector and high-gradient X-band linac which can deliver a high-repetition rate low-emittance beam, one or several undulator sections and photon beam lines with a user facility. The proposed layout is given with Fig. 1. Expected facility length is about 550 m and basic parameters of facility is given in Table 1.

Injector

The injector is proposed to be similar to the injector at SwissFEL [9] . It is based on S-band RF gun operating at about 100 MV/m gradient and standard S-band structures operating at about 20 MV/ gradient.

Main Accelerator

The X-band accelerating structures developed for CLIC project [10] are planned to be used in main accelerating sec-

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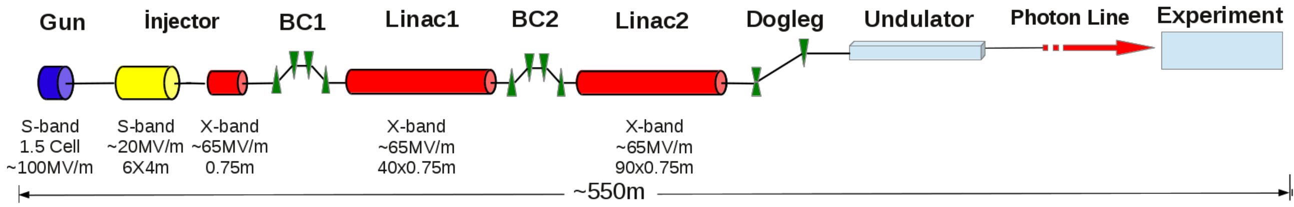

Figure 1: Layout of proposed facility.

Table 1: Basic Parameters of an X-FEL Facility Based on X-band Linac

	Parameter	Unit	Value
Main Linac	Energy	GeV	6
	Bunch Charge	pC	250
	Normalized emittance	μmrad	<0.5
	RF pulse length at structure	ns	150
	Pulse repetition rate	Hz	50-100
	Number of bunches per pulse	#	1-3
	Linac frequency	GHz	12
	No of structures per RF module	#	10
	Total (effective) module length	m	10 (7.5)
	Number of RF modules needed	#	12
	Linac gradient	MV/m	65
	No of klystrons per RF module	#	2
	Klystron output power	MW	50
	Klystron output pulse length	μ	1.5
	Total (effective) linac length	m	150 (100)
Injector	Energy	MeV	300
	Linac frequency	GHz	3
	Linac gradient	MV/m	20
	Number of klystrons	#	5
	Klystron output Power	MW	50
	Total (effective) injector length	m	50 (25)

tion. In order to define structure parameters initially we have the impact of single bunch wake field along the main linac. As the beam traverses down along the linac, the head of a single bunch undergoes an unperturbed transverse motion. On the other hand the tail, experiences deflection due to the wake excited by the preceding particles. The amplitude of the deflection in normalized transverse coordinates so called amplification factor will be

$$A = \frac{Ne^2}{2}\int_0^L \frac{\beta(s)}{E(s)} W_\perp(s)ds \qquad (1)$$

where N is number of particles per bunch, β is beta function along the linac, E is energy and $W_\perp$ is the transverse wake potential of the structures [11]. Figure 2 shows the curves of maximum amplifications of $\max[\frac{A_x}{A_{x0}}] = 0.1$ and 0.4 versus gradient of two different CLIC structure (CLIC-502 [10], CLIC-G [12]). As it can be seen on the figure in order to get $\max[\frac{A_x}{A_{x0}}] = 0.4$ the gradient of CLIC-G structure must be more than 110 MV/m while the gradient above 35 MV/m is acceptable for CLIC-502 type of structure. Both structure do not allow to get $\max[\frac{A_x}{A_{x0}}] = 0.1$ amplification.

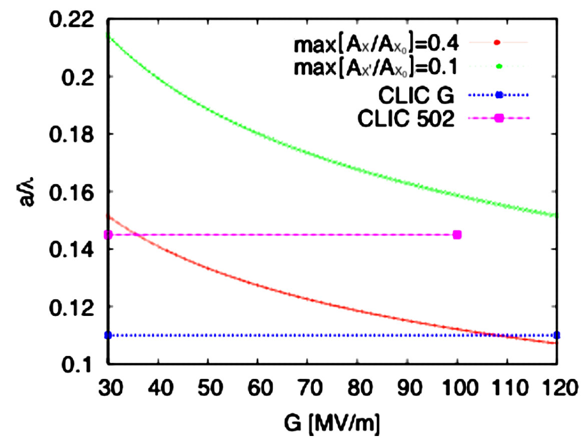

Figure 2: Amplification factor of a single bunch versus gradient and a/λ of structures.

Figure 3 shows the amplification of slices along a Gaussian bunch using CLIC-502 structure with structure parameter of $a/\lambda = 0.15$ and gradient of $G = 65$ MV/m. In the calculation simplified wake model for CLIC structure has been used. As it can be on the figure the amplification of tail in real coordinates is below 0.2 but the angle reaches 1.6.

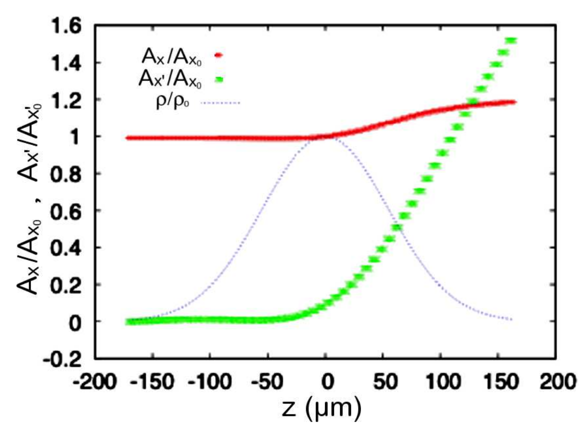

Figure 3: Deflection of slices along Gaussian bunch.

Cost estimation has been done using the structure database of CLIC taking into account wake field effect and

- Structure; a/λ, gradient, length, input power
- Module; pulse compressor, number of structure per module

and the cost has been compared between each other. The summary of cost estimation is given with Table 2

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Table 2: Summary of Basic Parameters of Cost Optimization

Parameter	CLIC-502		Optimum
Structures per RF unit	12	16	10
Klystrons per RF unit	2	2	2
Structure length (m)	0.23	0.23	0.75
a/λ	0.145	0.145	0.125
Allowed gradient (MV/m)	100	100	>80
Operating gradient (MV/m)	77	67.5	65
Energy gain per RF unit (MeV)	213	248	488
RF units needed	27	23	12
Total klystrons	54	46	24
Linac active length (m)	74	84	88
Cost estimate (a.u.)	76.2	71.5	51.7

Pulse Compressor and RF Module Layout

Using the results given in Table 2, 10 structures will be installed on one RF module and fed by one RF station which is essentially is combination two klystrons. Schematic view of the module and power combination/distribution system is given with Fig. 4.

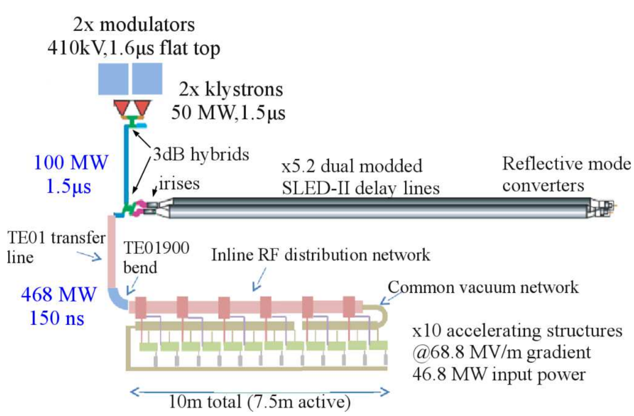

Figure 4: Layout of proposed facility.

Two klystron that each has power of 50 MW and pulse length of 1.5 µs will be driven by two individual modulator. The RF pulses will be combined with hybrids combiners. Single RF pulse that has 100 MW power and 1.5 µs length will be compressed to 150 ns by SLED-II delay lines [13]. After compression expected RF power is 468 MW. The compressed power will be distributed by an RF network to each structure evenly which means each structure will be fed by 46.8 MW power yielding 68.8 MV/m gradient.

SIMULATIONS

Preliminary simulations has been performed for the injector, main accelerating section and FEL generation.

Injector

Similar to LCLS [14] a 1.5 cell photo cathode RF gun operating 100 MV/m gradient at 3 GHz is proposed for the electron source. The cathode of the gun is assumed to deliver 250 pC bunch charge and 9 ps full width half maximum bunch length. Travelling wave accelerating structures that are operating with 20 MV/m gradient at 3 GHz are fallowed the RF gun similar to SwissFEL. Astra code [15] has been used for simulations and optimization injector section. The beam size and emittance along the RF gun and two RF structures of injector is given with Figs. 5. As it can be seen the projected normalized emittance ε_x is below 0.5 mm.mrad.

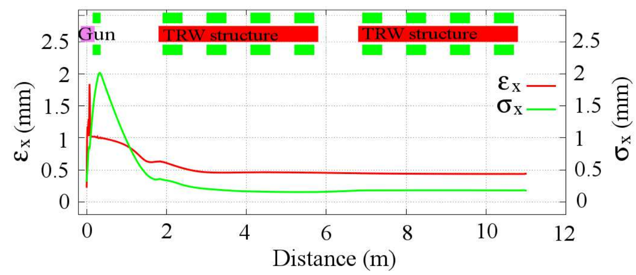

Figure 5: Emittance and horizontal beam size through the injector.

Main Accelerating Section

The injector is followed by an X-Band structure as a chirp linearizer in order to perform better bunch compression. A bunch compressor is located after the linearizer structure afterward two stage main accelerating section separated with bunch compressor is proposed for the main accelerating section (see Fig. 1). FODO type of lattice is proposed for beam transport and Elegant code [16] has been used for tracking.

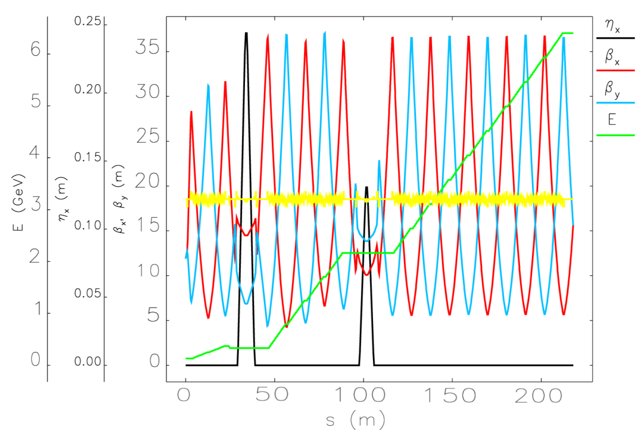

Figure 6: Beam energy, and Twiss functions along the main linac.

Figures 6 and 7 show the beam energy and Twiss functions along the linac and final longitudinal phase space of the bunch. As it can be seen on Fig. 7 the bunches are compressed down to $\sigma_t = 26$ fs ($\sigma_z = 8\,\mu$m) and RMS energy spread at the end of linac is $\sigma_E/E = 0.06\%$

Lasing Section

For the lasing section it is proposed that planar undulators each has about 4.2 m length are located on FODO type of

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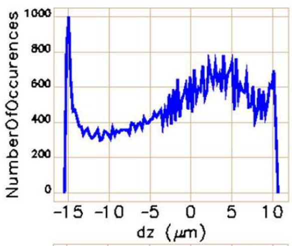

Parameter	Unit	Value
E	GeV	6.120
$\varepsilon_{n,x}$	μmμrad	476.056
$\varepsilon_{n,y}$	μmμrad	468.766
ε_z	MeV.μm	11.870
σ_x	μm	23.540
σ_y	μm	22.760
σ_z	μm	7.465
σ_E	MeV	2.359
$\Delta E/E$	%	0.039

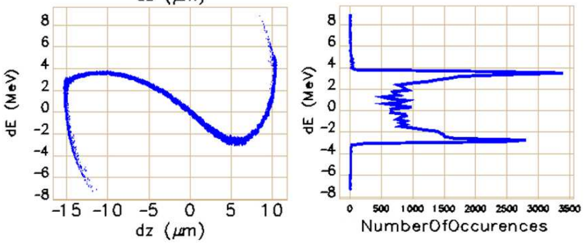

Figure 7: Longitudinal phase space of bunch at the end of linac.

lattice. Free electron laser (FEL) at very small wavelength range can be produced with a single-pass devices in the Self Amplified Spontaneus Emission (SASE) mode. The resonant wavelength of radiation produced from a undulator is given by

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + K_{\mathrm{RMS}}^2\right), \tag{2}$$

where λ_u is the undulator period, K_{RMS} is the RMS undulator strength and γ is the relativistic factor. Figure 8 shows saturation process of FEL at 1 Å resonant wavelength for beam energy of 6 GeV and undulator period of $\lambda_u = 15$ mm and undulator strength of $K_{\mathrm{RMS}} = 1$. As it can be seen the power saturates around 50 m.

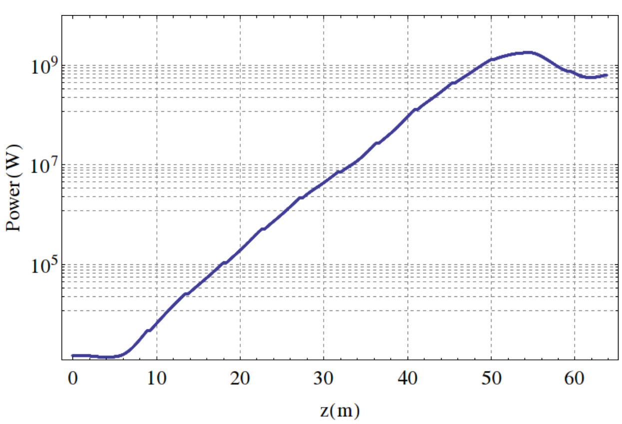

Figure 8: Power growth along the lasing section.

CONCLUSION

In this paper we focused on feasibility of usage of CLIC X-Band structures driving an FEL facility. We described preliminary simulations. It is shown that the radiation below 1 A can be produced in SASE mode. The self seeding and tapered undulator options should be studied in future work.

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