R&D OF X-BAND ACCELERATING STRUCTUREFOR COMPACT XFEL AT SINAP

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Abstract

One compact hard X-ray FEL facility is being planned at SINAP, and X-band high gradient accelerating structure is the most competitive scheme for this plan. X-band accelerating structure is designed to switch between 65MV/m and 80MV/m, and carries out 6.5GeV and 8GeV by 130 meters linac respectively. In this paper, brief layout and simulation of compact XFEL will be introduced, and in particular the prototype design of dedicated X-band acceleration RF system is also presented.

INTRODUCTION

Recently, FEL has been being developed to new era with great success, in particular LCLS[1], SACLA[2] were successful to carry out first lasing and user operation. Since further R&D of FEL technology, FEL facility is led to tendency of compact facility, and it makes it more feasible and acceptable.

Compact linac based on high gradient technology is one effective and crucial way to carry out compact FEL facility. Recently FEL facility are based on L-band (EuroXFEL), S-band (LCLS) and C-band (SACLA, SwissFEL), and the accelerating gradient is ranged from 20MV/m to 40MV/m [3], which also make facilities more compact step by step, however higher gradient is required for future compact facility, such as X-band high gradient technology. SLAC, CERN and KEK have developed X-band for several ten years, and have reached gradient higher than 100MV/m in the condition of experiment lab [4]. Based on present status of X-band accelerating structure, 80MV/m could be stable operation gradient, and it can make linac half scale of C-band linac, so that it's only about 200 meters required for 8 GeV linac for FEL facility.

Recently one hard X-ray FEL facility is being planned at SINAP, and one 6.5 GeV or 8GeV linac is required for FEL radiation. Since length of our campus is about 600 meters, and linac should be limited to be less 200 meters, so that the 65MV/m or 80MV/m gradient is required for 6.5 GeV or 8GeV respectively, and X-band high gradient technology is the first selection for hard X-ray FEL plan. In this paper, the brief layout and simulation of hard X-ray FEL is introduced, and prototype of X-band RF system is presented.

BRIEF LAYOUT OF FEL PLAN AT SINAP

Shanghai photon science centre is being planned, and there will be two FEL facilities built in the same campus of Shanghai Synchrotron Radiation Facility (SSRF) in future, which is shown in Figure 1.

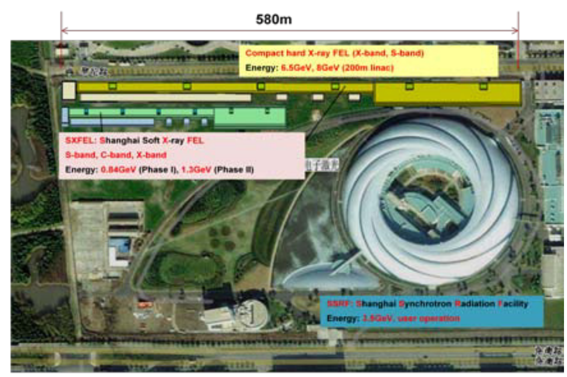

Figure 1: Layout of Shanghai photon science centre

Shanghai Soft X-ray FEL facility(SXFEL) is the test facility of future hard X-ray FEL facility, and its linac is composed of S-band and C-band accelerating structure in first step, and the total energy can reach 800MeV, as shown in Figure 2. In second step X-band RF system will replace C-band RF system for energy upgrading to 1.3MeV, and X-band accelerating structure will be operated at 80MV/m.

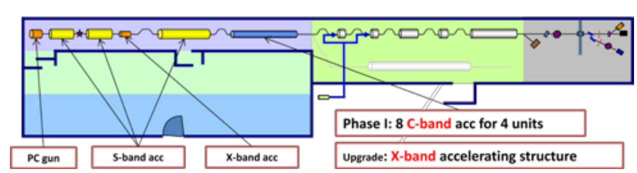

Figure 2: Layout of Shanghai Soft X-ray FEL

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Hard X-ray FEL has been proposed by SINAP, and it will be the facility for user operation, and it's brief layout is shown in Figure 3. This linac is planned to be composed of S-band injector and X-band main linac, and its total length is limited to be about 200 meters to match the 580 meters campus. This facility will be operated at two energy points of 6.5 GeV and 8GeV, which is related the 65MV/m and 80MV/m gradient respectively.

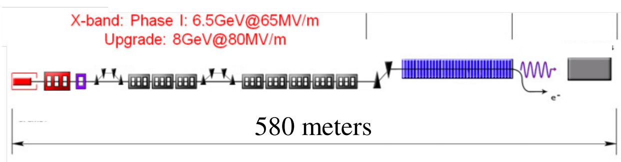

Figure 3: Layout of hard X-ray FEL at SINAP

BEAM DYNAMICS SIMULATION

Base on the prototype design of Hard X-ray FEL, Litrack code [5] is used for the 1-D beam dynamics simulation of linac, as shown in Figure 4. In Figure 4, these pictures are related to the start and end of linac in Figure 3, and the X-band RF system is operated on 65MV/m, so that the final energy of linac is 6.5GeV.

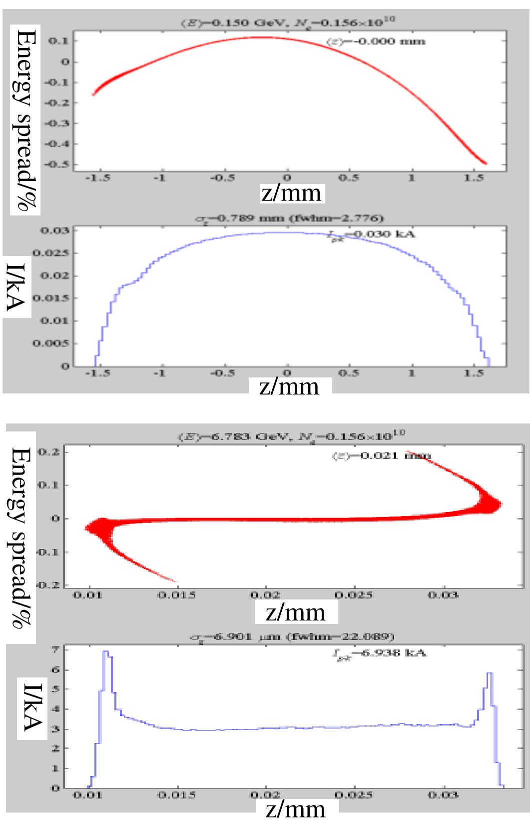

Figure 4: 1-D Beam dynamics simulation for hard X ray

As Fig. 4 shows, the injecting charge is 250pc, and the final energy is 6.5 GeV with 0.02% energy spread, and the peak current reaches 3000kA after two stage of beam compressor. All main parameters are presented in Table 1 below.

Table 1: Main Parameters of Hard X-ray FEL

Parameters	Value
Output Wavelength	0.07nm
Bunch charge	250pC
Energy	6.5GeV
Normalized emittance	0.4μm
Energy spread	0.02%
Pulse length (Full)	40fs
Peak current	3kA
Rep. rate	60Hz
Peak power	10GW
Peak brightness	$2*10^{33}$

PROTOTYPE DESIGN OF X-BAND ACCELERATING STRUCTURE

Based on the requirement of compact hard X-ray FEL, there are some considerations for the prototype of X-band accelerating structure, as listed below:

- Input power per each structure is less than 80MW.
- Maximum gradient: 80MV/m for 8GeV, and lower gradient 65MV/m for 6.5 GeV, so that total length of linac is less than 200 meters.
- Breakdown rate below 3e-7.
- Short range wakefield should be suppressed.

The breakdown rate is related to the gradient 80MV/m, and here is one parameter to represent the breakdown rate Sc [6], as shown in equation (1)

$$Sc = Re(S) + g_c \cdot Im(S) \quad (1)$$

where S is Poynting vector on the surface of structure, and normally gc is equal to 1/6. Sc should be less $4.2MV/mm^2$ for the required gradient and breakdown.

Short range wakefield is the crucial problem for FEL beam quality, and in particular size of X-band becomes extremely small, so the short range wakefield should be suppressed to acceptable level.

The effect on beam can be expressed by equation (2), and it shows that average aperture 'a' dominates the short range wakefield effect, when energy and gradient are fixed. [7]

$$A = \int_0^L \frac{\beta}{2E} ds < W_\perp > Ne^2 \approx 2.77 \frac{<\beta>}{m} \frac{N}{10^9} \frac{\sigma_z}{\mu m} \frac{mm^4}{a^4} \frac{MV/m}{G} \ln \frac{E_f}{E_0}$$

$$X'_{N.f} = AX_{N.0} + X'_{N.0}, \qquad X_{N.f} = X_{N.0} - AX'_{N.0} \quad (2)$$

where X represents transverse position and X' represents transverse angle. A is the important restriction to short range wakefield effect, and Figure 5 shows the relationship between 'a' and gradient for different A.

In order to keep good beam quality, A is limited below 0.3, so that average aperture 'a' is should be more than 3.8mm.

Based on considerations above, the target pre-design of prototype structure can be fixed, and CST and HFSS are used to analyze the 3-D simulation results, finally the Sc and field distribution are shown in Fig. 6, and other parameters are shown in Table 2.

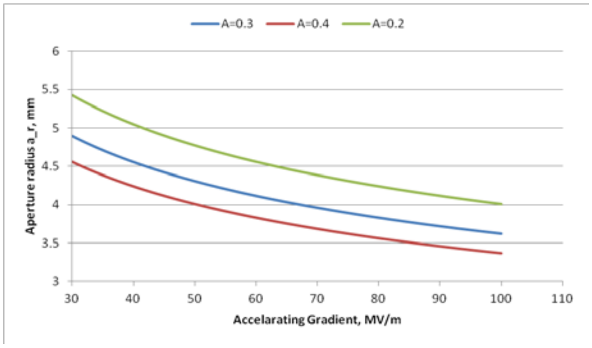

Figure 5: Aperture vs gradient as different A

As shown in Fig.6, all Sc is below 4.2 MW/mm^2, and the breakdown can be suppressed to acceptable level. Electrical field distribution is increased from start to end, so that input power can be reduced as small as possible, which is also better to suppress breakdown.

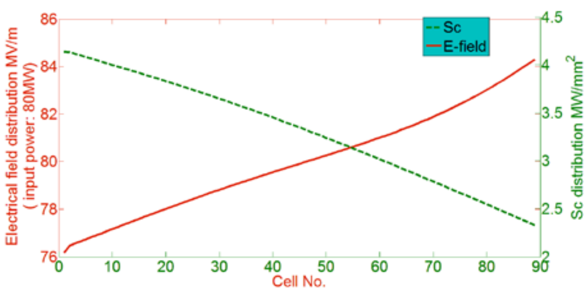

Figure 6: Sc and field distribution of prototype Structure

The 3-D prototype design is presented in Figure 7, and it composed of 89 regular cells and two dual-port coupler, and the couplers are required to eliminate both dipole and quadrupole field in the coupler.

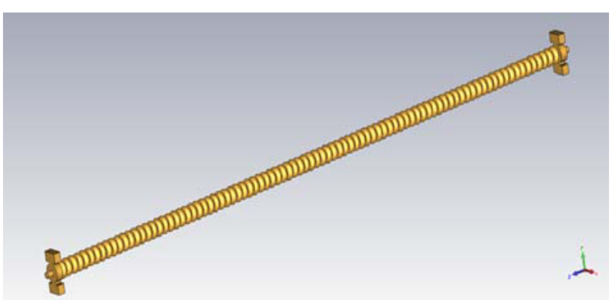

Figure 7: 3-D layout of prototype structure

X-BAND RF SYSTEM

Based on the requirement of XFEL and the pre-design of prototype, the X-band RF system is also designed for hard X-ray FEL, as shown in Fig. 8 below.

This X-band RF system is planned to use two 30MW klystrons, and then enhanced to 170MW by one pulse compressor. This power can feed two or three structures depending on energy option of FEL. If the 6.5 GeV is only required for FEL radiation, 170MW can drive three structures with 65MV/m; or 170MW also can drive two structures with 80MV/m for 8 GeV, and is easy provide 6.5 GeV by lowering klystron power to 22MW.

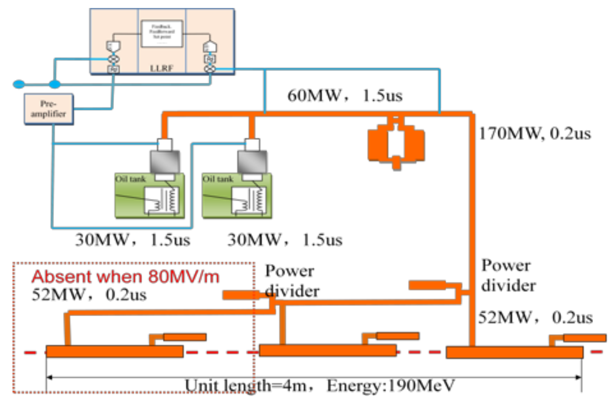

Figure 8: Layout of X-band RF microwave system

Based on requirement of FEL radiation, X-band accelerating structure design and X-band RF system design, main parameters of prototype design are presented in Table 2.

Table 2: Parameters of X-band RF System

Frequency	11424MHz
Phase advance	$4\pi/5$
Cell No.	89+2
Effective length	944.73mm
Cell length, d	10.497mm
Iris thickness, 2a	1.5 mm
Ratio of elliptic radius, b_a	1.8
Aperture, a_r	4.3~3.05.mm
Group velocity, Vg/c	3.45%~1.12%
Shunt impedance, R	86.7~108.7MΩ/m
Attenuation factor, τ	0.61
Filling time, t_f	150 ns
Sc	4.14~2.33 MW/mm^2
Emax/E0	2.68~2.02
Hmax/E0	2.68~2.39 mA/V
Input power, P_{in}	52MW @65MV/m 80MW @80MV/m
Two-Klystrons units	34 @65MV/m 51 @80MV/m

CONCLUSION

The long-term FEL R&D is being constructed and planned at SINAP, and X-band high gradient technology is one crucial technology for future development, and the draft beam dynamics, prototype of accelerating structure and relative RF system have been pre-designed. SINAP also participate the collaboration of XbFEL project in Europe, and will focus on and promote the X-band high gradient technology R&D in next step.

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