ALTERNATIVE LINAC LAYOUT FOR EUROPEAN XFEL PROJECT

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Abstract

To control the microbunching instability at the European XFEL linac, we had optimized one linac layout with a double chicane. However, to relax jitter tolerance further, and to clean ignorable space charge force effects at the second bunch compressor, we have newly designed an alternative linac layout with two bunch compressor stages for the European XFEL project. In this paper, we describe design concepts, Start-to-End (S2E) simulations, and operational flexibility of our alternative linac layout for the European XFEL project.

INTRODUCTION

To supply coherent, ultra-fast, and ultra-bright SASE sources in hard X-ray region, DESY has a plan to construct the largest SASE FEL facility in the world, European XFEL [1]. Its main required parameters are summarized in Table 1. Recently, to control the microbunching instability at bunch compressors for the European XFEL project, we had optimized one linac layout (13JAN04 version) as shown in Fig. 1(top). Here only one bunch compressor (BC) stage with a double chicane is used to obtain a large slice energy spread before the second bunch compressor (BC2) [2], [3]. However it was reported that the jitter tolerance of an FEL driving linac with one BC stage is tighter than that of the other case with two BC stages [4]. Therefore we had investigated the impact of jitters on FEL performances for our current linac layout (13JAN04 version) [3]. According to our recent S2E simulations, rms bunch length, bunch arriving time, and saturation power of SASE source have somewhat large variations under jitters [3]. Since our current linac layout does not have any accelerating module between BCs, space charge force may be increased if bunch length is highly compressed at BC2. Therefore, to avoid any beam quality dilution due to space charge force, we put the double chicane at a somewhat higher beam energy of 510 MeV. According to our CSR-track simulation considering CSR and space charge force in BCs, the beam quality dilution due to space charge force is ignorable at 510 MeV [3]. By the help of well-damped CSR effects and microbunching instability, all projected and slice beam parameters of our current linac layout are much better than our requirements for the European XFEL project [3]. However, to relax jitter tolerance further, and to clean ignorable space charge force effects at the BC2, we have newly optimized an alternative linac layout (10AUG04 version) with two BC stages for the European XFEL project. In this paper, we describe design concepts, S2E simulations, and operational flexibility of our alternative linac layout for the European XFEL project.

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Table 1: Main parameters for XFEL project

Parameter	Unit	Value
beam energy E	GeV	20
single bunch charge Q	nC	1
slice normalized rms emittance ϵ_{ns}	μm	1.4
slice rms relative energy spread $\sigma_{\delta s}$	10^{-4}	1.25
peak current I_{pk}	A	5
maximum bunch train length	μs	650
bunch train repetition rate	Hz	10
minimum bunch spacing in a train	μs	0.2
wavelength of SASE source	nm	0.08-6.4
saturation length of SASE source	m	95-170
total undulator length	m	140.3-250.1

ALTERNATIVE LINAC LAYOUT

Generally, the minimum slice emittance is limited by thermal emittance, which is proportional to beamsize on the cathode [4], [5]. After considering two facts that decelerating electric field at the cathode due to space charge force is inversely proportional to the square of rms beamsize at the cathode, and the available maximum gradient of the L-band RF gun is around 60 MV/m at the cathode, we have reduced the rms beamsize on the cathode from 0.75 mm to 0.70 mm to reduce thermal emittance. Recently, by the help of a flat-top laser profile with about 21 ps (FWHM) length and about 7 ps rising and falling time, TTF2 gun (originally PITZ1 gun) had generated high quality electron beams with a projected normalized rms emittance of about 1.7 μm without any booster linac [6]. Therefore we expect that our XFEL injector can supply much higher quality electron beams by increasing the maximum gradient of gun, by improving uniformity of gun driving laser, by reducing rising and falling time of gun driving laser, and by accelerating beams quickly with a booster linac. According to our new ASTRA optimizations, XFEL injector can supply higher quality electron beams with a projected normalized rms emittance of around 0.88 μm by upgrading TTF2 gun. Detail injector re-optimizations for the European XFEL project are described in reference [7], and its optimized results are summarized in Table 2.

Basic bunch compressor design concepts are well described in reference [8], which is related with the SCSS bunch compressor, and detail bunch compressor design concepts of our current linac layout are described in ref-

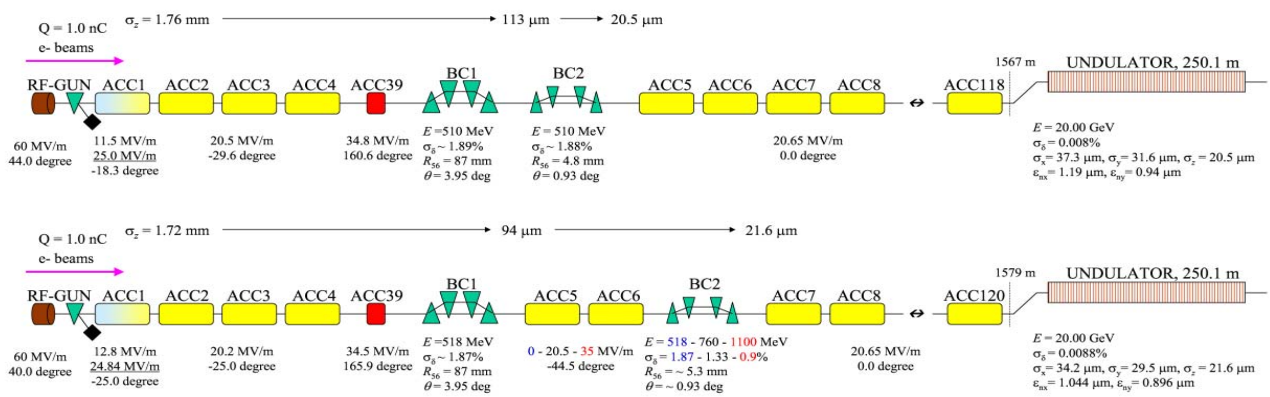

Figure 1: Current (top) and alternative (bottom) linac layout for XFEL project. Here all parameters are projected ones.

erence [3]. The same design concepts in references [3] and [8] are used in designing bunch compressors in our alternative linac layout.

To relax jitter tolerance, to clean ignorable space charge force effects at BC2, and to get operational flexibility, we have adopted followings in our alternative linac layout as shown in Fig. 1(bottom): First, after considering two facts that there is 30 m long drift space between the first bunch compressor (BC1) and BC2 in our current linac layout, and energy spread at BC2 should be high enough to control microbunching instability and CSR, we have added two TESLA modules with a high gradient of 35 MV/m between BCs. During the nominal operation, those modules will be operated with a middle accelerating gradient of 20.5 MV/m. In this case, beam energy at BC2 is about 760 MeV, which is good enough to clean ignorable space charge force effects at BC2. By operating those modules with the highest accelerating gradient of 35 MV/m, beam energy at BC2 can be increased up to 1.1 GeV. Note that our alternative linac layout can be returned to our current linac layout with a double chicane only by turning off those two modules and by rematching optics. In this case, microbunching instability will be effectively damped [3]. Second, generally, tight jitter tolerance can be improved by operating accelerating module with more klystrons. Therefore two klystrons will be dedicated to each module between BCs to relax the jitter tolerance further.

To avoid slice parameter dilution due to the microbunching instability in BCs, we have adopted followings in our alternative linac layout as shown in Fig. 1(bottom): First, to reduce overall CSR strength, we choose only two bunch compressors with the normal chicane instead of S-type chicane. Second, to keep the slice rms relative energy spread at the entrance of BC2 large, we put BC2 at a low beam energy of around 760 MeV. In this case, BC2 has still a large projected rms relative energy spread of around 1.33%. Third, during compression in BCs, slice energy spread generally becomes larger to conserve the normalized longitudinal emittance. Therefore slice rms relative energy spread

Table 2: S2E simulation results for XFEL project

Parameter	Unit	Value
RF frequency of gun and TESLA module	GHz	1.3
gun cell number	cell	1.5
laser spotsize at cathode σ_r	mm	0.70
laser pulse length (FWHM)	ps	20
laser pulse rising and falling time	ps	1.5
normalized thermal emittance	μm	0.60
maximum longitudinal solenoid field	T	0.198
maximum gradient at the cathode	MV/m	60
gun phase from zero crossing	deg	40
low / high accelerating gradient in ACC1	MV/m	12.8 / 24.8
ACC1 phase from on crest	deg	-25
projected emittance before BC1 / BC2	μm	0.88 / 1.00
slice emittance before BC1 / BC2	μm	0.75 / 0.75
bunch length before BC1 / BC2	mm	1.72 / 0.09
beam energy before BC1 / BC2	MeV	518 / 760
projected energy spread before BC1 / BC2	%	1.87 / 1.33
slice energy spread before BC1 / BC2	10^{-5}	0.86 / 3.8
projected emittance after BC2 / LINAC	μm	1.17 / 1.04
slice emittance after BC2 / LINAC	μm	0.75 / 0.75
bunch length after BC2 / LINAC	μm	21.6 / 21.6
beam energy after BC2 / LINAC	GeV	0.76 / 20.0
projected energy spread after BC2 / LINAC	%	1.3 / 0.009
slice energy spread after BC2 / LINAC	10^{-4}	1.17 / 0.05

before BC2 can be further increased up to 3.8×10^{-5} by compressing bunch length at BC1 strongly. Since the compression factor at BC1 is high, we put BC1 at 518 MeV to avoid any beam dilution due to space charge force.

To avoid projected emittance dilution due to CSR in BCs, we have adopted followings in our alternative linac layout as shown in Figs. 1(bottom) and 2: First, to reduce CSR, we should choose a smaller momentum compaction factor R_{56} of chicane. This is possible by choosing a somewhat larger projected rms relative energy spread σ_δ [8]. Af-

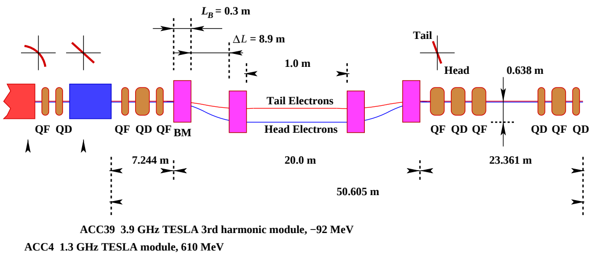

Figure 2: BC1 layout for XFEL project. BC2 chicane has the same layout except $\Delta L = 9.9$ m.

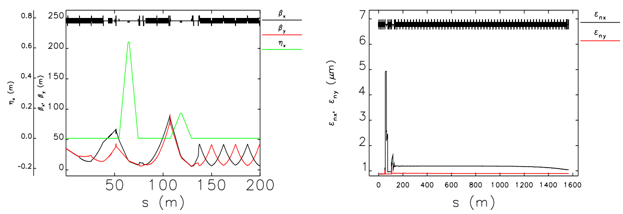

Figure 3: Twiss parameters around BCs (left) and projected emittances along XFEL linac (right).

ter considering the emittance growth due to chromatic effect, we choose $\sigma_\delta \simeq 1.87\%$ at BC1. Second, we choose short quadrupoles around BCs to reduce emittance growth due to chromatic effect. Third, for a required R_{56}, we can reduce dipole bending angle (hence, CSR) further by using a longer drift space ΔL between the first dipole and the second one as shown in Fig. 2 [8]. In case of BC2 which is located at a smaller σ_δ, we increase ΔL by 1.0 m to choose a smaller bending angle of 0.93 degree. Fourth, generally, CSR is weaker at BC1, and CSR becomes stronger at BC2 as bunch length is compressed. Hence, we choose a higher compression factor at BC1 and a lower compression factor at BC2 to reduce overall CSR effects in our two BCs. Fifth, we reduce CSR further by installing a 3rd harmonic module (ACC39) before BC1 to compensate nonlinearities in the longitudinal phase space as shown in Fig. 2 [8]. After considering about 92 MeV beam deceleration by ACC39 and difficulty in compensating of accumulated higher-order nonlinearities in longitudinal phase space due to geometric wakefields and RF curvature along TESLA superconducting modules (ACC1 to ACC4), ACC39 is moved from the downstream of ACC1 to the downstream of ACC4 in our alternative layout. Sixth, the projected emittance dilution due to CSR can be reduced further by forcing the beam waist close to the last dipole where α-functions are zero, and β-functions are their minimum as shown in Fig. 3 [8]. Since chromatic effects becomes smaller at BC2 due to smaller σ_δ, we choose much higher β-functions at the upstream of BC2 to give strong focusing in BC2 as shown in Fig. 3(left) [8]. In this case, the projected emittance growth due to CSR can be effectively reduced at BC2.

To check performance of our alternative linac layout, we have performed S2E simulations with ASTRA and ELEGANT codes as shown in Figs. 1(bottom) and 3(right), and as summarized in Table 2. Here emittance, energy spread, and bunch length are estimated in *normalized rms*, *rms relative*, and *rms*, respectively, and slice parameters before BC2 (after BC2) are estimated at ± 0.1 mm (± 0.02 mm) core region. In these simulations, we have included all important impedances such as space charge force in gun and ACC1, CSR and incoherent synchrotron radiation (ISR) in BCs, and short-range wakefields in all modules. According to our S2E simulations, all obtained slice parameters at the end of the XFEL linac are much better than our requirements as summarized in Table 2 and shown in Fig. 4.

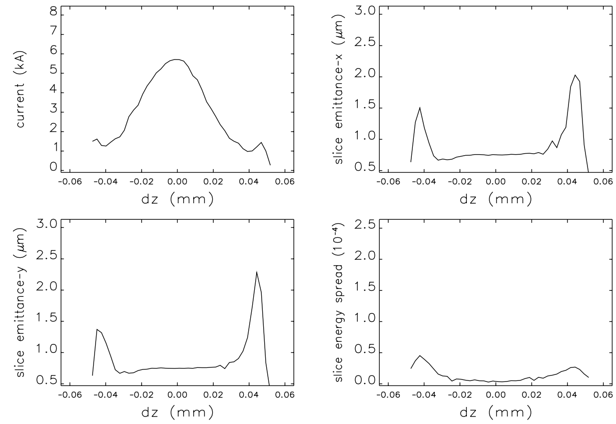

Figure 4: Slice parameters at the end of XFEL linac.

SUMMARY

Although two accelerating modules are added between BCs of our alternative linac layout, slice energy spread before BC2 is around 3.8×10^{-5}, which is about three times higher than that of TTF2. Since slice energy spread and beam energy at BC2 can be widely changeable by adjusting gradient of two modules between BCs, we expect that our alternative linac layout is safe from ignorable space charge force effects at BC2 and the strongest microbunching instability with 2.0 ps modulation period [2], [3]. We expect that jitter tolerance becomes looser by adding two modules between BCs and by dedicating total four klystrons to those two modules. Now, we are under investigating jitter tolerance in our alternative linac layout.

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