JITTER AND TOLERANCE STUDY OF L-BAND FEL INJECTOR

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Abstract

Linac-based Free Electron Lasers (FELs) require very high quality and stable electron beams from their injectors both for the lasing process and for use of the FEL beams in experiments. Various kinds of jitter in the injector may sensitively affect the FEL operation. In this paper, we study the jitter sources in the injector designed for the proposed UK's New Light Source project and simulate how much they impact on the beam dynamics. Then, we discuss the required jitter tolerance to maintain good machine performance. Preliminary studies of a velocity bunching scheme to improve performance and to reduce sensitivity to jitter are also presented.

INTRODUCTION

The proposed UK's New Light Source (NLS) will be a linac-based Free Electron Laser (FEL) covering a wide energy range of photon radiation up to 1 keV [1]. The baseline design of the NLS facility aims at operation with 1.1 kHz. L-band (1.3 GHz) superconducting cavities will be used as the main linac while an L-band (1.3 GHz) normal conducting photocathode gun will be used for the production of high quality beams. The first design of the NLS injector consisting of a gun and a linac module with 8 TESLA type superconducting cavities has been reported [2]. In the first injector design, velocity bunching was not applied because the most conservative approach was pursued. A start-to-end simulation was successfully done with the injector design [3]. However, some improvement was sought to reduce the energy chirp after the injector in order to improve operation of the laser heater and partly to reduce the beam energy fluctuations caused by gun RF amplitude and phase errors which produce beam arrival time jitter at the end of the linac. The latter issue is important because NLS will use seeding for the FEL process by means of an external laser and therefore synchronisation between the electron beam and seed laser pulse is crucial.

The gun uses a laser pulse for beam generation at the cathode, RF field for beam acceleration in the gun cavity, and solenoid field for beam focusing. Therefore, jitter of the laser energy and arrival time at the cathode, RF phase and amplitude, and the solenoid field may affect the beam properties such as beam emittance, bunch length, beam energy and arrival time. Jitter can be reduced to some extent by using improved hardware (RF, laser and water cooling systems) and feedback systems; however, there will always be a limit on what can be achieved. On the other hand, a more relaxed tolerance is useful to simplify the hardware and feedback requirements and make the operation more reliable. In this article, we firstly study beam parameter jitter resulting from gun parameter variations, including cathode laser, focusing solenoid and gun RF. Then, we define the dominant jitter sources determining electron beam quality and find a possible way for increasing the injector tolerance.

JITTER SOURCES IN THE INJECTOR

Given the injector layout, beam dynamics simulations were carried out using ASTRA [4] for various errors in the input parameters. Some of the errors such as laser pulse length, laser position, laser beam size, bunch charge, solenoid field, gun phase and gun RF amplitude are jitter, which can vary from electron bunch to bunch. On the other hand, errors like beam thermal emittance and solenoid position do not change within a short time scale. For this study, the input values for ASTRA simulations were chosen by considering the reported or measured ones at FLASH [5], which is a running machine for user service and has a similar layout to the proposed NLS injector. At FLASH, the cathode laser position jitter was measured to be about 30 µm rms, the bunch charge jitter about 1%, the solenoid field jitter about 0.02 mT. The FLASH gun shows 0.1% rms jitter in RF amplitude and 0.1 degree rms in phase [6]. According to beam tracking simulations for the NLS injector jitters of this level does not affect the beam quality (Table 1). These numbers may become even smaller with improved hardware and regulation systems. However, the presently achievable stability in the FLASH gun may be good enough in terms of beam emittance and bunch length.

The thermal emittance may be the most dominant contribution to emittance increase. After optimisation of the injector beam dynamics with the high RF gradient gun, the thermal emittance remains as one of the biggest emittance sources in addition to space charge. Therefore, thermal emittance increase has a significant effect on the final emittance. For the no error case, a kinetic energy of 0.7 eV for electrons emitted from the cathode was assumed for the calculation of the thermal emittance in the beam dynamics simulations. The thermal emittance may be changed depending on the wavelength of the cathode laser and the surface condition of the photocathode, which are however not quickly varying parameters.

The rise/fall time of the cathode laser temporal distribution can be another important factor in determining the beam quality. However, a rise/fall time of about 2 ps has been achieved at PITZ [7], which is sufficiently small that it no longer influences the beam quality.

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Table 1: Beam transverse emittance and bunch length changes at the end of injector (15 m) due to different input parameters in ASTRA simulations. For comparison, the beam parameters without error are shown.

Error source	Error range	ε_x (rms), mm mrad	z (rms), mm
No error		0.3045	1.336
Laser			
length (12 ps)	11	0.3166 (4.0%↑)	1.298 (2.8%↓)
	13	0.2966 (2.6%↓)	1.376 (3.0%↑)
rise/fall time (2 ps)	1	0.2933 (3.7%↓)	1.321 (1.1%↓)
	2.5	0.3119 (2.4%↑)	1.346 (0.8%↑)
	3	0.3208 (5.4%↑)	1.357 (1.6%↑)
	4	0.3420 (12.3%↑)	1.385 (3.7%↑)
position, Δx (μm)	50	0.3049 (0.1%↑)	1.336
	100	0.3062 (0.6%↑)	1.336
beam size (0.48 mm)	0.46	0.3019 (0.9%↓)	1.336
	0.50	0.3111 (2.2%↑)	1.336
thermal emittnace	10%↑	0.3265 (7.2%↑)	1.362 (2.0%↑)
	20%↑	0.3492 (14.7%↑)	1.314 (1.7%↓)
bunch charge (200 pC), ΔQ	−4 pC	0.3021 (0.8%↓)	1.327 (0.7%↓)
	−2 pC	0.3033 (0.4%↓)	1.331 (0.4%↓)
	2 pC	0.3057 (0.4%↑)	1.341 (0.4%↑)
	4 pC	0.3070 (0.8%↑)	1.346 (0.8%↑)
Solenoid			
position, Δx (μm)	25	0.3046	1.336
	50	0.3049 (0.1%↑)	1.336
	100	0.3062 (0.6%↑)	1.336
angle, Δθ (mrad)	0.2	0.3048 (0.1%↑)	1.336
	0.5	0.3066 (0.7%↑)	1.336
position, Δz (mm)	−1	0.3054 (0.3%↑)	1.336
	1	0.3079 (1.1%↑)	1.336
max field, ΔB (mT)	− 0.02	0.3044	1.336
	+ 0.02	0.3045	1.336
Gun			
phase	−0.6°	0.3071 (0.9%↑)	1.329 (0.5%↓)
	−0.3°	0.3054 (0.3%↑)	1.333 (0.2%↓)
	0.3°	0.3042 (0.1%↓)	1.340 (0.3%↑)
	0.6°	0.3044	1.343 (0.5%↑)
amplitude, ΔE (MV/m)	+0.1	0.3082 (1.2%↑)	1.333 (0.2%↓)
	+0.05	0.3051 (0.2%↑)	1.335 (0.1%↓)
	−0.05	0.3064 (0.6%↑)	1.338 (0.2%↑)
	−0.1	0.3111 (2.2%↑)	1.339 (0.2%↑)

In addition to the beam quality, the electron beam position jitter at the end of the injector was studied (Table 2). Laser position jitter at the level expected (about 30 μm rms) should therefore not significantly affect the beam position. The solenoid position and angle errors have large effect; however, these are not quickly varying jitter sources. At PITZ the solenoid transverse position (Δx) could be aligned within tens of μm [8] by using a beam-based alignment and such position misalignments did not significantly degrade the beam quality. The solenoid angle (Δθ) could be aligned within hundreds of μrad [8] by using the same method and such solenoid angle misalignments did not affect the beam quality either. The simulations for NLS show that such misalignments do not give rise to excessive beam position errors; however this will be confirmed by tracking these cases through the entire linac.

Table 2: Beam position variations at the end of the injector (15 m) due to different input parameters in ASTRA simulations.

Error source	Error range	x position, Δx (μm)	y position, Δy (μm)
Laser			
position, Δx (μm)	25	0.007	0.026
	50	0.013	0.046
	100	25.0	95.5
Solenoid			
position, Δx (μm)	25	−48.7	−66.7
	50	−97.3	−133.4
	100	−195	−269
angle, Δθ (mrad)	0.2	−134	184
	0.5	−335	459

During the start-to-end simulations of the NLS machine, it turned out that the most serious issue was the beam arrival time jitter at the end of linac, which was caused by the beam energy jitter in the injector. The beam energy jitter mainly resulted from the RF phase and amplitude of the gun. In the next section, we examine these effects.

HIGH TOLERANCE INJECTOR DESIGN

A new injector design is ongoing with the aim of making the arrival time at the end of the linac less sensitive to gun jitter. In this design, the first cavity of the first module has a larger negative off-phase from the on-crest condition. When the gun RF amplitude is lower, the beam energy after the gun is lower and the arrival time at the first linac cavity increases. If the first cavity operates at a negative off-crest phase, a beam arriving later acquires more energy from the RF field in the cavity. In this way, the jitter caused by the gun amplitude error can be compensated by properly setting the first linac cavity phase and amplitude. Here, we report the first result of this ongoing study.

In the first injector design [2], the phase of the first linac cavity was −12° from on-crest and the RF amplitude was 22 MV/m. Such phase and amplitude were insufficient to compensate for beam jitter. For the compensation the linac phase should go towards −90° from on-crest, which is the condition of velocity bunching [9]. When full velocity bunching was applied with a first linac cavity phase of −90°, the electron bunch length was decreased by about a half. However, the temporal beam distribution was changed from symmetric to tilted to the beam head direction. The tilt of the distribution was amplified when the beam propagates though the linacs and the bunch compressors downstream [10]. We therefore moved the phase to −82° in order to eliminate the tilt. With that phase, a symmetric bunch distribution could be obtained (Fig. 1), with the velocity bunching decreased by about 25% instead of 50%. To achieve this good shape of beam at the end of injector, the cathode laser pulse shape should be manipulated to be inclined rather than uniform, which would be done during the cathode laser pulse shaping. After optimisation of the beam parameters and the longitudinal phase space distribution, the RF phases were set as −2° for the gun, −82° for the first cavity of the first module, −10° for the second, third and fourth cavities, and 5° for the last four cavities. The focusing solenoid field was adjusted for smallest transverse emittance. The transverse projected and slice emittances were close to the values (0.3 mm mrad for 0.2 nC) obtained with the original injector design without velocity bunching.

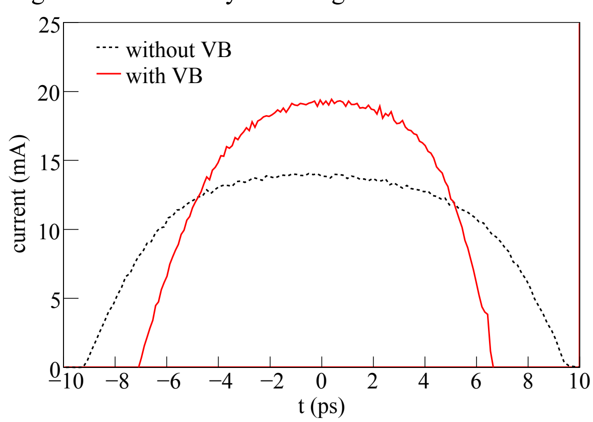

Figure 1: Temporal distribution of beams at the end of the injector with velocity bunching (solid red) and without velocity bunching (dotted black) [2]. The peak current increases from 14 mA to 19 mA by velocity bunching.

Beam arrival time and energy jitter at the end of the injector were studied with varying gun RF phase and amplitude. The gun phase is the RF phase when an electron beam is emitted from the cathode by the laser pulse. The gun phase error has two contributions: the laser arrival time jitter at the cathode and the RF phase jitter. The laser arrival time jitter may result from the laser oscillator or the laser transportation. The gun phase jitter does not significantly change the beam emittance and pulse length as shown in the previous section but does affect the beam arrival time and beam energy at the end of the injector. The variation of beam arrival time at the end of the injector as a function of gun phase relative to the nominal phase for both injector designs (without and with velocity bunching) is shown in Fig. 2. When velocity bunching is applied, the arrival time jitter is reduced by 19% compared to the case without velocity bunching. For example, when the gun phase has 0.1° error, the arrival time changes by about 30 fs in the case with velocity bunching.

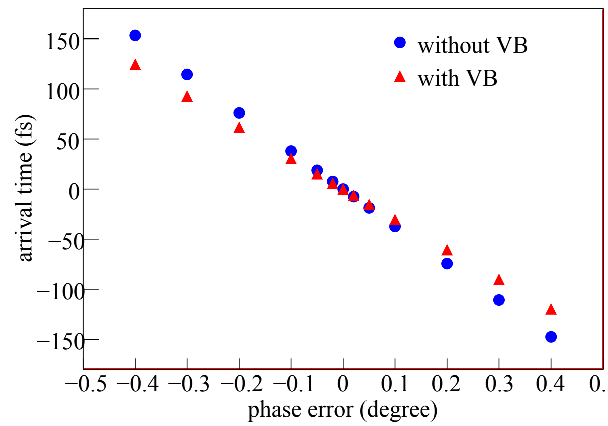

Figure 2: Variations of beam arrival time at the end of the injector with gun phase. When velocity bunching (VB) is adopted, arrival time error is reduced by 19% compared to the case without velocity bunching.

The variation of beam energy at the end of the injector as a function of gun phase is shown in Fig. 3. When velocity bunching is applied, the arrival time jitter is reduced by 77%. When the gun phase has 0.1° error, the energy changes by about 3 keV in the case with velocity bunching. When we tracked the beam with a gun phase error of 0.1° through the NLS linac, the beam arrival time at the end of the NLS linac (that is, at the entrance of the undulator) was changed by 0.5 fs compared to the case without gun phase error.

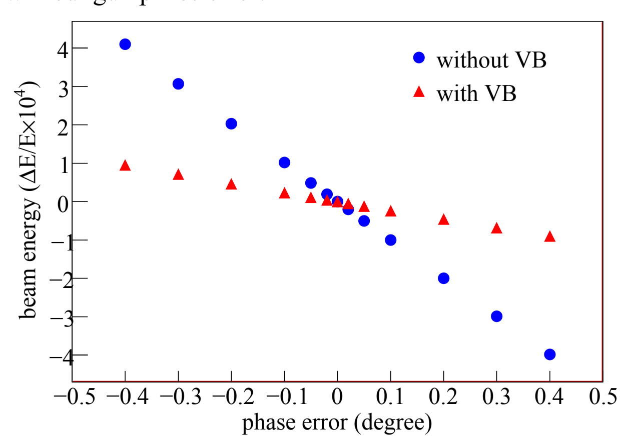

Figure 3: Variation of beam arrival time at the end of the injector with gun phase. When velocity bunching (VB) is adopted, arrival time error is reduced by 19%.

When the gun RF amplitude is different from the designed value, 50 MV/m, the beam energy after the gun is changed. This beam energy jitter at the gun changes the beam flight time to the first linac and causes beam energy jitter at the end of the injector. The flight time difference for beams with different beam energy is large because beams are not fully relativistic before the first linac module. The variation of beam arrival time at the end of the injector as a function of gun RF amplitude is shown in Fig. 4. When velocity bunching is applied, the arrival time jitter is reduced by 12%. When the gun amplitude has 0.05 MV/m error, the arrival time changes by about 110 fs in the case with velocity bunching.

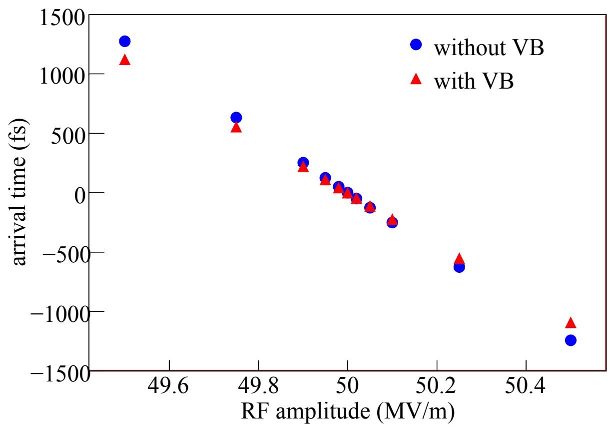

Figure 4: Variation of beam arrival time at the end of the injector with gun RF amplitude. When velocity bunching is adopted, arrival time error is reduced by 12%.

The variation of beam energy at the end of the injector as a function of gun RF amplitude is shown in Fig. 5. When velocity bunching is applied, the arrival time jitter is reduced by 91%. When the gun amplitude has 0.05 MV/m error, the energy changes by about 3 keV in the case with velocity bunching. When we tracked the beam with a gun amplitude error of 0.05 MV/m through the NLS linac, the beam arrival time at the end of the linac was changed by 7 fs compared to the case without gun RF amplitude error.

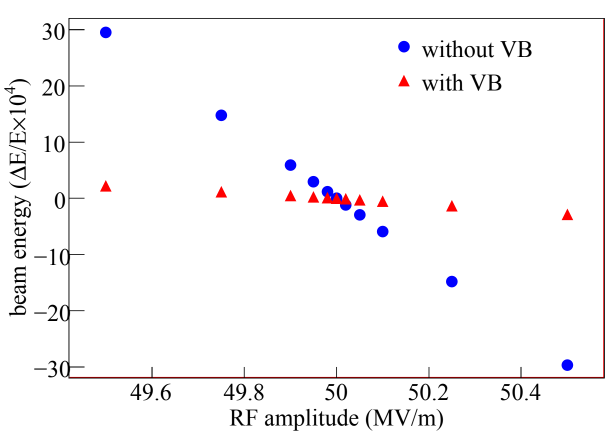

Figure 5: Variation of beam energy at the end of the injector with gun RF amplitude. When velocity bunching is adopted, beam energy error is reduced by 91%.

Since at the end of the injector shorter (longer) beam arrival time is correlated with lower (higher) beam energy for both phase and amplitude errors in the RF, the effect of the bunch compressors in the linac on the off-energy particles is to produce a compensating time shift, reducing the arrival time jitter at the end of the linac considerably compared to the value at the end of the injector. With 0.05 MV/m rms gun RF amplitude and 0.1° rms gun phase errors, the beam arrival time jitter at the end of the linac was about 8 fs rms. The beam arrival time jitter at the end of the linac increased to 10 fs rms when first linac module jitter (RF amplitude by 0.01% rms and phase by 0.01° rms) was included and to 12 fs when other linac module jitter and magnetic bunch compressor jitter (magnet power supply by 0.001% rms) were also included. For the case without velocity bunching, the beam arrival time jitter at the end of the linac was 14 fs rms when all of the jitter contributions discussed above were included. The beam energy jitter at the end of the linac was 0.0038% rms and 0.0054% rms for the cases with and without velocity bunching, respectively.

DISCUSSION

We have found that jitter in various gun systems, laser, RF and solenoid, within the range of stability achieved at FLASH and PITZ, did not affect the beam emittance and bunch length. However, beam arrival time jitter at the end of the linac caused by the injector jitter is a potential problem for seeded FEL operation.

In the case of velocity bunching, beam energy jitter at the end of the injector caused by gun RF amplitude and phase jitter was considerably reduced because the jitter in the gun could be compensated by the RF field at the first cavity of the first linac module. As a consequence the jitter in both arrival time and energy at the end of the linac are reduced using this scheme. We are investigating further improvements by adjusting the phase and amplitude of the cavities in the first linac module in order to find a complete jitter compensation condition.

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