TIMING JITTER STUDIES FOR SUB-FS ELECTRON BUNCH GENERATION AT SINBAD

J. Zhu[#1,2], R. Assmann[1], U. Dorda[1], J. Grebenyuk[1], B. Marchetti[1]

[1] Deutsches Elektronen-Synchrotron, DESY, Hamburg, Germany
[2] Universität Hamburg, Hamburg, Germany

Abstract

Generation of ultra-short electron bunches with a few femtoseconds arrival-time jitter is the major challenge in plasma acceleration with external injection. Meanwhile, peak current stability is also one of the crucial factors for user experiments when the electron bunch is used for free-electron laser (FEL) generation. ARES (Accelerator Research Experiment at SINBAD) will consist of a compact S-band normal-conducting photo-injector providing ultra-short electron bunches of 100 MeV. We present bunch arrival-time jitter studies for two different compression schemes, velocity bunching and magnetic compression with a slit, at ARES with start-to-end simulations. Contributions from various jitter sources are quantified.

INTRODUCTION

External injection of electron bunches into laser-driven wakefield acceleration (LWFA) allows precise manipulation of the phasespace of the electron bunches and thereby provides possibilities to optimise the following acceleration and transport inside the plasma. However, the requirement on the synchronization of the electron bunch to the drive laser is rather stringent [1]. SINBAD (Short Innovative Bunches and Accelerators at DESY) is a proposed dedicated accelerator research and development facility [2]. One of the baseline experiments at SINBAD is LWFA with electron bunches generated by ARES (Accelerator Research Experiment at Sinbad) [3], which will allow the production of ultra-short bunches by velocity bunching (VB) [4] or by magnetic bunch compression (BC) with a slit [5].

In LWFA experiments, considering the general case that the cathode laser and the drive laser are different, the total timing jitter between the electron bunch and the drive laser is given by

$$\sigma_{t_{total}} \approx \sqrt{\sigma_{t_b}^2 + \sigma_{t_o}^2 + \sigma_{t_a}^2} , \qquad (1)$$

where σ_{t_b} is the bunch arrival-time jitter (ATJ) relative to the reference, σ_{t_o} is the contribution from synchronization of the drive-laser oscillator and σ_{t_a} is the jitter of the drive-laser amplifier. The aim of this study is to quantify the term σ_{t_b} in equation (1) with different compression schemes at ARES and to identify the major jitter sources.

ANALYTICAL MODEL OF ATJ WITH MAGNETIC COMPRESSION

Considering a general case of a linac consisting of a gun and a couple of cavities powered by a single klystron, the ATJ of the electron bunch downstream of the chicane is well-known as [6]:

$$\sigma_{t_b} \approx \sqrt{\frac{R_{56}^2}{c^2}\left(\sigma_{\delta_V}^2 + \frac{h^2}{k_{rf}^2}\sigma_\phi^2 + \sigma_{\delta_B}^2\right) + \frac{\sigma_{t_0}^2}{C^2}} , \quad (2)$$

where R_{56} is the longitudinal dispersion of the chicane, c is the velocity of light, h is the chirp of the bunch, k_{rf} is the rf wave number, $C=1/(1+hR_{56})$ is the compression factor and σ_{δ_V}, σ_ϕ, σ_{δ_B} and σ_{t_0} are the cavity voltage jitter, the cavity phase jitter, the magnetic field jitter of the chicane and the ATJ at the gun exit respectively. However, in order to directly compress the pulse duration of the electron bunch generated at a photo-injector to sub-fs with only one compression stage, a sub-mm wide slit will be placed in the middle of the chicane at ARES. Since the slit only allows electrons with certain energies to go through, the energy jitter upstream of the chicane will almost *not* be converted into the ATJ downstream of the chicane. In this case, the bunch arrival time downstream of the chicane is given by

$$t_b \approx t_0 + t_c + \frac{s}{c} , \qquad (3)$$

where t_0 is the arrival time of the bunch at the gun exit, t_c is the timing offset of the "collimated" bunch relative to the centroid of the whole bunch at the entrance of the chicane and s is the path length of the "collimated" bunch in the chicane. In this case, one can derive that the ATJ downstream of the chicane is given by

$$\sigma_{t_b} \approx \sqrt{\left(\frac{1}{hc}\right)^2 \sigma_{\delta_V}^2 + \left(\frac{1}{ck_{rf}}\right)^2 \sigma_\phi^2 + \left(\frac{R_{56}}{c}\right)^2 \sigma_{\delta_B}^2} . \quad (4)$$

It is obvious that equation (2) and (4) are the same in the case of full compression $(1+hR_{56}\approx0)$. Note that the ATJ at the gun exit will anyhow be fully compressed regardless of the compression factor in the case with a slit. In the meanwhile, however, the cavity phase jitter will be totally converted into the ATJ downstream of the chicane.

At ARES, two identical S-band travelling-wave structures (TWS) will be powered by their individual klystrons. In this case, one can prove that the minimum ATJ will be achieved when both TWSs are operated with the same voltage and phase, and is given by

$$\sigma_{t_b,\min} \approx \sqrt{\left(\frac{R_{56}}{c}\right)^2 \left(\sigma_{\delta_B}^2 + \frac{1}{2}\sigma_{\delta_V}^2\right) + \frac{1}{2}\left(\frac{1}{ck_{rf}}\right)^2 \sigma_\phi^2} .$$

$$(5)$$

Table 1: Summary of the Sensitivity, Jitter and Tolerance Studies

Jitter Source	Unit	Sensitivity		RMS Jitter set 1		RMS Jitter set 2		RMS Tolerance	
		VB	BC	VB	BC	VB	BC	VB	BC
Laser-to-RF	fs	126.5	-*	100		80		50	
Gun Charge	%	-	6.6	4		2		2	
Gun Phase	deg	0.49	1.8	0.10		0.02		0.06	
Gun Voltage	%	0.40	0.60	0.10		0.02		0.05	
TWS1 Phase	deg	0.0098	0.021	0.06		0.02		0.008	
TWS2 Phase	deg	-	0.022	0.06		0.02		0.015	
TWS1 Voltage	%	0.10	0.055	0.05		0.02		0.008	
TWS2 Voltage	%	1.2	0.064	0.05		0.02		0.015	
BC B-field	%	-	0.030	0.02	\	0.02	\	0.01	\
ATJ	fs			62.0	42.3	21.5	15.8	9.3	9.5

* The jitter contribution from this source is negligible.

Note that the contributions from the cavity voltage jitter and the magnetic field jitter can be reduced by using a weak chicane.

START-TO-END SIMULATION

The start-to-end (S2E) simulation was carried out with ASTRA [7] and ELEGANT [8]. ASTRA was used to track the bunch up to the end of the linac with 10,000 macro particles in the VB case and 100,000 macro particles in the BC case (the number of particles after the slit is about 3,800). The photocathode laser was assumed to follow a Gaussian longitudinal distribution with rms duration of 3 ps and 125 fs for the BC case and the VB case respectively. A uniform transverse laser intensity distribution was assumed at the photocathode surface for both cases. Main parameters used in both simulations are summarized in table 2. For the BC case, ELEGANT was then used to simulate the bunch transport in the chicane ($R_{56} \approx$ -10 mm) with CSR effect included. The longitudinal phase-spaces (LPS) of the reference bunches after compression for the above two cases are shown in Fig. 1. It is noted that, in the BC case, the LPS with only CSR effect included is quite different from the LPS simulated with IMPACT-T [5], where both space charge effects and CSR effect were included. The reason is that the LPS will be smoothed out by the longitudinal space charge effect if the peak current is too high during compression. As a comparison, the peak current shown in Fig. 1 is around 3 kA, which is about twice as high as the peak current given in [5].
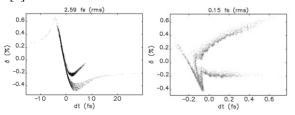

Figure 1: Final LPS of the reference run for the VB case.

(left) and the BC case (right).

Table 2: Summary of Parameters Used in Simulation

Parameter	Unit	VB	BC
Initial Bunch Charge	pC	0.5	10
Gun Phase	deg	0.0	0.0
Gun Gradient	MV/m	110	110
TWS1 Phase	deg	-90.3	-59.2
TWS2 Phase	deg	0.0	-59.2
TWS1 Gradient	MV/m	23.0	23.9
TWS2 Gradient	MV/m	23.0	23.9

The jitter sources used in S2E simulation and the sensitivities of these jitter sources are summarized in Table 1. Here the sensitivity $j_{sen,i}$ refers to the amplitude of the jitter corresponding to 10-fs ATJ. It is obvious that the contribution from the phase jitter of TWS dominates in both cases. Based on the sensitivity studies, the expected bunch ATJ performance of the acceleration can be estimated by

$$\sigma_{t_b} \approx 10 \sqrt{\sum_{i=1}^{n} \left(\frac{j_{\mathrm{tol},i}}{j_{\mathrm{sen},i}} \right)^2} \, (fs), \qquad (6)$$

where $j_{\mathrm{tol},i}$ is the jitter (or tolerance) of the ith jitter source. There are two jitter sets list in table 2. The 1st set is conservative [6], and the total ATJ was calculated to be 62.0 fs for the VB case and 41.9 fs for the BC case. The second one is much more challenging [9], but the total ATJs for the both cases are still larger than 10 fs. In order to suppress the ATJs of the both cases to less than 10 fs, a tolerance budget was derived, which is shown in table 2. In this tolerance budget, the phase jitter of the first TWS is required to be less than 0.008 deg.

The stability of the bunch peak current is another crucial parameter for applications like free-electron laser

(FEL). However, the number of macro particles of the final bunch in the BC case is small because of the slit, which will cause large error in peak current calculation. Therefore, we present the results of the bunch length jitter here, which is a good approximation to the peak current jitter. The results show that the response of the bunch length is generally not a linear function of the amplitude of the individual jitter source, as illustrated in Fig. 2. Within the ranges of various jitter sources shown in Fig. 2, the contributions from the laser-to-rf jitter, the gun voltage jitter and the TWS1 phase jitter dominate in the VB case, while the contributions from the voltage jitters of the gun and the two TWSs dominate in the BC case.
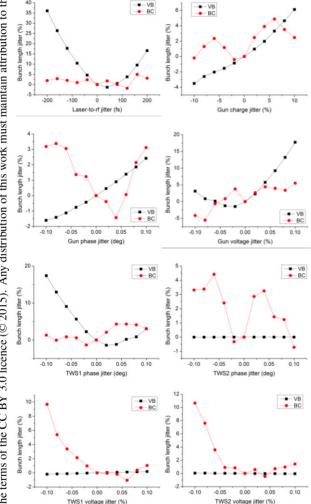

Figure 2: Bunch length jitter as a function of jitters from different individual jitter sources.

We performed 250 randomized S2E simulations with errors generated from 3-sigma Gaussian distribution using the 1st set of jitters given in table 1 for each case, and the statistic results are shown in Fig. 3 and Fig. 4 respectively. It is found that the simulation results of ATJ match very well with the results given by equation (6).
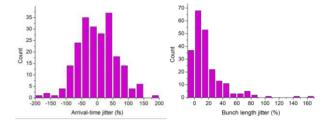

Figure 3: Statistic results of ATJ (left) and bunch length jitter (right) for the VB case. RMS ATJ is about 60.9 fs and rms bunch length jitter is about 23.6%.
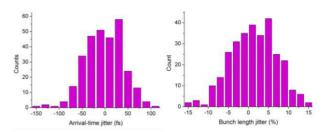

Figure 4: Statistic results of ATJ (left) and bunch length jitter (right) for the BC case. RMS ATJ is about 41.5 fs and rms bunch length jitter is about 3.2%.

CONCLUSION

Start-to-end simulations have shown that the contribution of the phase jitter of the S-band traveling-wave structure dominates the bunch arrival-time jitter at ARES for both velocity bunching and magnetic compression with a slit. A challenging tolerance budget was formed which can reduce the bunch arrival-time jitters of both cases to less than 10 fs.

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