TIME JITTER MEASUREMENTS IN PRESENCE OF A MAGNETIC CHICANE IN THE FERMI@ELETTRA LINAC

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Abstract

Accurate and highly stable temporal synchronization between an electron bunch and a pulse from an external seed laser is one of the key requirements for successful operation of a seeded FEL in the XUV and soft x-ray regime. These requirements become more stringent when the electron bunch is longitudinally compressed to sub-ps durations in order to increase the current for more efficient FEL action. In this paper we present experimental measurements of the electron bunch arrival time jitter after the first magnetic compressor of FERMI@Elettra seeded FEL as a function of the compression factor. The experimental behavior of the pulse-to-pulse time jitter agrees both with results from tracking code simulations and with predictions from an analytical approach that takes into account the different sources of time jitter in FERMI, namely the photoinjector drive laser, the RF accelerating cavity phases and voltages, and fluctuations in the chicane bending magnet currents.

INTRODUCTION

The FERMI@Elettra free electron laser (FEL) at the Elettra Laboratory of Sincrotrone Trieste [1] is a major European FEL project. FERMI is a single-pass, S-band linac-based externally seeded FEL implementing high gain harmonic generation in the 65-4 nm fundamental output wavelength range. Commissioning started in September 2009, the first FEL output with seeded operation was produced in December 2010, and first light was provided to users in April 2011 [2]. One of the key requirement for guaranteeing a successful operation of this seeded FEL facility has been the stability of the temporal overlapping between the electron bunch and the seed laser. A shot-to-shot time jitter of the seed laser of about 50 fs (rms) has been measured, while the electrons arrival time jitter (ATJ) is strongly dependent on the longitudinal compression factor implemented. Although the nominal configuration includes two stages of magnetic bunch length compression, only the first one, called BC1, was installed at the time of the measurements reported in this paper. BC1 is a movable chicane that allows a continuously tunable bending angle in the range 0-122 $mrad$. The maximum R_{56} term provided by the system is 96 mm. In the next section of this paper we present an analytical model for describing the behavior of the electrons ATJ after activating the magnetic longitudinal compression, which takes into account the fluctuations of the chicane bending currents, of the upstream RF sections (phases and voltage) used for inducing the linear chirp and the time jitter of the injector drive laser. Comparison between the analytical model and tracking code results is presented in the third section. Measurements of the electrons ATJ versus the compression factor are reported in the forth section.

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ANALYTICAL MODEL FOR ARRIVAL TIME JITTER

The electron bunch ATJ is defined as the short-term (up to few tens' of seconds) time-of-flight variation of its center-of-mass relative to the time-of-flight of a (virtual) reference particle. The reference time-of-flight is determined by the nominal setting of the accelerator and magnetic lattice as well as by specific initial conditions in the longitudinal phase space for the reference particle. We assume pure longitudinal acceleration in the RF sections so that the energy gain of each electron is a function of the sampled RF phase ϕ and could be written as $E = E_i + eV \sin\phi$, with E_i representing the electrons energy at the injector exit and considering the maximum energy gain for $\phi = \pi/2$. Only linear dispersive motion with no energy change is considered in the chicanes, which are characterized by a R_{56} linear transport matrix element. Chicane is assumed to be achromatic, symmetric and made of four identical dipole magnets. For such a geometry and small bending angle, $\theta \ll 1$, $R_{56} = -2\theta^2\left(l_1 + \frac{2}{3}l_2\right)$, where l_1 is the dipole rectilinear magnetic length and l_2 is the distance between the first (third) and second (fourth) dipole magnet edge. As well known, the bending angle depends linearly from the magnetic field (B) and, for a given field, from the beam energy E: $\theta = \frac{eBl_1}{E}$. The electron beam is assumed to be ultra–relativistic ($\beta \sim 1$), thus the longitudinal charge distribution is frozen in the straight sections. Our analysis excludes any considerations about the particle transverse phase space and frictional forces.
The ATJ of the center-of-mass dt is given by

$$dt = \frac{1}{c}\left(d(R_{56}\delta) - \frac{1}{2}dR_{56}\right) \tag{1}$$

We remind that $R_{56} = R_{56}(\theta)$ and the relative energy deviation $\delta = \delta(V,\phi) = (E - E_0)/E0$, with E_0 the reference energy of the center of mass.

Developing the differential terms in equation (1) and assuming $\theta \ll 1$ we have:

$$\begin{aligned} dR_{56} &= \frac{\partial R_{56}}{\partial\theta}\left(\frac{\partial\theta}{\partial B}\right)\delta B = -4\theta\left(\tfrac{2}{3}l_1 + l_2\right)\frac{\tan\theta}{B}\delta B \\ &\cong_{\theta\ll 1} -4\theta^2\frac{\left(\frac{2}{3}l_1 + l_2\right)}{B}\delta B = 2\frac{R_{56}}{B}\delta B \end{aligned} \tag{2}$$

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and

$$d\delta = \left(\frac{\partial\delta}{\partial V}\right)_\phi \delta V + \left(\frac{\partial\delta}{\partial\phi}\right)_V \delta\phi = \\ = \frac{e\sin\phi\delta V + eV\delta\phi\cos\phi}{E} \quad (3)$$

Inserting equations (2) and (3) in equation (1) we obtain:

$$dt \approx dt_0 + \frac{R_{56}}{c}\left[\frac{dV}{V}\frac{eV\sin\phi}{E} + d\phi\frac{eV\cos\phi}{E} - \frac{dB}{B}\right] \quad (4)$$

We have neglected the term δdR_{56} since the relative energy deviation δ is usually less than 1%.

The initial bunch time jitter at the injector exit dt_0 is essentially induced by the driven laser time jitter relative to the RF gun phase. In absence of any jitter sources after the injector, dt_0 is compressed from a negative R_{56} because earlier (later) arrival at the RF field of the bunch centroid, that translates into an earlier (later) arrival at the finish point, means a lower (higher) energy at the chicane, therefore a longer (shorter) path length with respect to the reference trajectory. This way, the initial timing jitter is exactly reduced by the compression factor CF at the end of the beam line: $dt_{0,f} = dt_0/CF$. The one-stage bunch length compression factor in the linear approximation is defined as follows:

$$CF = \frac{1}{1+hR_{56}} \quad (5)$$

and the linear energy chirp h is:

$$h = \frac{1}{E}\frac{dE}{dz} = \frac{2\pi}{\lambda_{RF}}\frac{eV\cos\phi}{E_0 + eV\sin\phi} \quad (6)$$

Considering all jitter sources described above as small and independent perturbations to the particle motion, the electron bunch ATJ after the chicane is obtained by summing all the jitters in quadruture as follows:

$$dt^2 \approx \left(\frac{dt_0}{CF}\right)^2 + \left(\frac{dB}{B}\right)^2\left(\frac{R_{56}}{c}\right)^2 + \\ + \left(\frac{dV}{V}\right)^2\left(\frac{R_{56}}{cE}\right)^2(eV\sin\phi)^2 + \\ + (d\phi)^2\left(\frac{R_{56}}{cE}\right)^2(eV\cos\phi)^2 \quad (7)$$

The last term of equation (7) plays the crucial role during the longitudinal bunch compression and it is interesting to plot ATJ as a function of the RF phase in different configurations.

Figure 1 shows the ATJ behaviour versus the upstream linac L01 RF phase (i.e. versus CF) for several RF phase jitter values in two particular cases of initial time jitter: 80 fs and 150 fs . In this example we have assumed a linac voltage jitter of 0.2% and a chicane magnets current jitter of 0.01%. For small values of RF phase jitter, ATJ decreases during the longitudinal bunch compression. On the contrary if the RF phase jitter is not so small, a local minimum of the ATJ versus the RF phase is observable and for larger values of phase jitter and at high compression factor this minimum approaches to $\pi/2$ (CF=1) and ATJ is increased very much. This effect is stronger in case of small initial time jitter so that the requirement on the RF phase stability becomes more stringent.

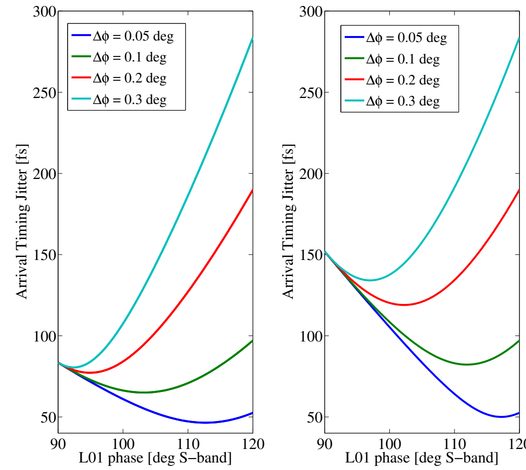

Figure 1: $dV/V = 0.2\%$, $dB/B = 0.01\%$, $R_{56} = -41mm$. Initial time jitter $80fs$ (left) and $150fs$ (right).

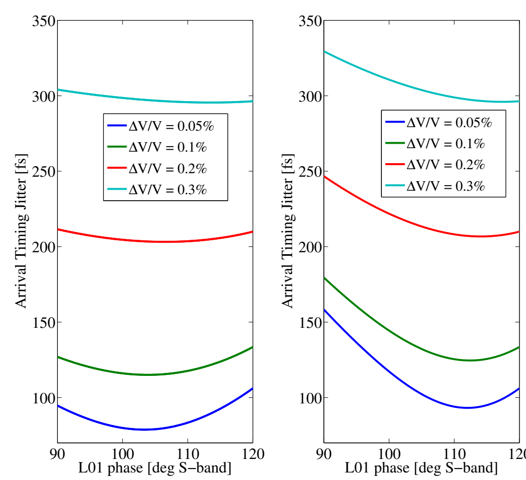

Figure 2: $d\phi = 0.1deg$, $dB/B = 0.01\%$, $R_{56} = -41mm$. Initial time jitter $80fs$ (left) and $150fs$ (right).

Figure 2 shows ATJ versus the RF phase for several upstream linac voltage jitter in the same two previous cases of initial time jitter (80 fs and 150 fs), assuming a fix RF phase jitter of 0.1deg and a magnets current jitter of 0.01%. When increasing the linac voltage jitter, all curves are shifted towards higher values of ATJ and progressively "squeezed ", even if the local minimum is yet observable.

COMPARISON WITH TRACKING RESULTS

In this section we present a comparison between ATJ estimated from analytical model and the LiTrack [3] tracking results for two RF phase jitter cases $0.1deg$ and $0.3deg$ respectively. The rms jitters for the phases and voltages of the accelerators and for the R56 compression parameter of the chicane are applied to a statistical study that uses the technique of Latin Hypercube Sampling (LHS) [4]. A number of configurations having randomly picked RF voltages, phases and compression parameter within the specified jitters are the input to LiTrack [3]. A statistical analysis of global output parameters like arrival timing provided an estimation of the ATJ. Figure 3 shows the statistical results over 400 different configurations of the acceleration, compression and photoinjector parameters, at constant bunch charge and assuming $dt_0 = 150fs$ and $\Delta V/V = 0.1\%$. Litrack results are in good agreement with the analytical approach described above.

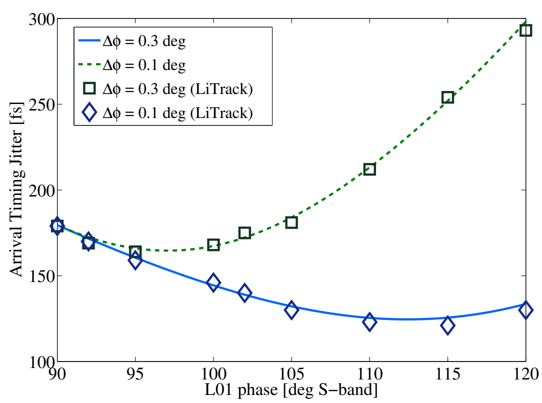

Figure 3: $dV/V = 0.1\%$, $dB/B = 0.01\%$, $R_{56} = -41mm$. Initial time jitter: $150fs$.

EXPERIMENTAL RESULTS

In order to experimentally investigate the ATJ behavior as a function of the compression factor, we have systematically added an artificial noise in the Low Level RF system involved directly in the upstream linac to increase the RF phase jitter in a controlled way. The upstream linac voltage and chicane magnets current jitters have been measured, obtaining respectively 0.2% and 0.01%. The nominal RF phase jitter is 0.06 deg and we have enhanced it to 0.15 deg, 0.3 deg and 0.7 deg. Figure 4 and 5 show a very good matching between the experimental results and the expected analytical behavior of ATJ versus the upstream linac RF phase. A local minimum of ATJ occurs for a RF phase of 102 deg ($CF \sim 1.8$) when the RF phase jitter is 0.15 deg.

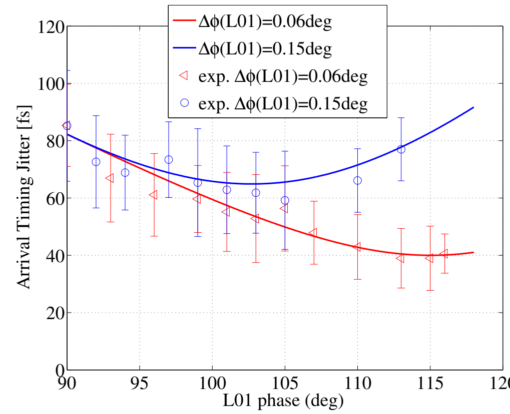

Figure 4: Measurements and theoretical expectation of the ATJ versus linac phase for a RF phase jitter of 0.06 and 0.15 deg S-band. R_{56}=-41 mm, dt_0 from the injector is 80 fs.

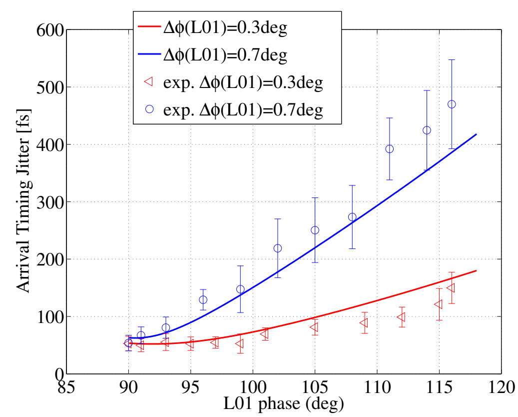

Figure 5: Measurements and theoretical expectation of the ATJ versus linac phase for a RF phase jitter of 0.3 and 0.7 deg S-band. R_{56}=-41mm, dt_0 from the injector is 60 fs.

CONCLUSION

An analytical approach to estimate the ATJ after magnetic chicane compression has been presented and compared successfully with tracking code expectations and experimental measurements results.

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