TWO-BUNCH OPERATION AT THE FERMI FEL FACILITY

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Abstract

FERMI [1] is a linac-driven free electron laser (FEL) based upon the High Gain Harmonic Generation (HGHG) scheme [2]. In standard conditions a bunch of 700 pC of charge with sub mm-mrad emittances [3] is accelerated to 1.2-1.5 GeV in a normal conducting S-band linac [4] and drives FEL-1 [5] or FEL-2 [6] undulator line, which lase respectively in the range 100-20 nm or 20-4 nm. A number of two-color schemes have been implemented at FERMI for pump/probe experiments, all consisting in making two portions of the same electron bunch lase at two different wavelengths, with a time-separation from 0 to few hundreds of fs [7-9].

In order to increase the time separation to ns and tens of ns we have explored the acceleration of two independent electron bunches separated by multiple of the linac main radio-frequency period, i.e. 333 ps. Measurements and characterization of this two-bunch mode operation are presented, including trajectory control, impact of longitudinal and transverse wakefields on the trailing bunch and manipulation of the longitudinal phase space.

INTRODUCTION

The idea of producing two electron bunches separated by tens of ns have been successfully demonstrated in the LCLS linac [10] and is an option taken into serious consideration in the future operation of the SwissFEL [11]. However, the generation and propagation of a two-bunch system presents a series of criticisms. The most important concerns the wakefields excited in the linac sections by the drive bunch that affect the energy and the trajectory of the trailing bunch. Furthermore, it is critical to control and steer the beam trajectory by looking at the beam position monitors (BPM) because the latter considers the two bunches as a whole system. Moreover the BPM signal of two bunches get added like vectors with a response that is null for some time-delay (ΔT). Another issue regards the photoinjector two-pulse laser alignment that in case of large ΔT (~10 ns or more) becomes critical.

In order to test and verify the feasibility of the two-bunch operation at FERMI, we have carried out an experimental study producing two identical bunches with a ΔT from 0.66 ns to 2.33 ns. The following sections present the measurements and characterization of this two-bunch mode operation, including trajectory control, impact of longitudinal and transverse wakefields on the trailing bunch and the possibility to manipulate the second bunch longitudinal phase space by acting on the time-delay and on the charge of the drive bunch.

PHOTOINJECTOR SETUP

The FERMI photo-injector laser (PIL) system is based on Ti:Sapphire as an active material and regenerative amplifier/multipass chirped-pulse amplifier design [12]. For the two-bunch experiment, the PIL system has been modified after the UV shaping and a schematic layout is reported in Fig. 1. The UV pulse is split according to the polarization and the second pulse is driven through a delay-line able to introduce a temporal shift from 600 ps to 2.5 ns with respect to the first pulse. A rotating half-wave plate, placed before the splitting, is used to distribute the total laser energy between the two pulses. Finally each UV pulse has an independent shutter.

Also the laser heater pulse that is directly generated from the PIL pulse, has been split in order to be able to heat both electron bunches.

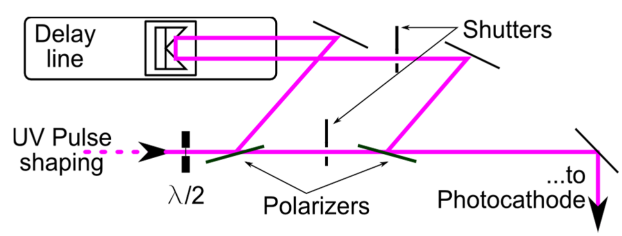

Figure 1: PIL system modified for the two-bunch operation.

The first goal of the two-bunch mode operation consists in generating two bunches as much as possible identical, since they have to share the same linac setting parameters. Therefore, they need to have the same charge and being separated exactly by multiple of the main rf period, so that $\Delta T = N \times 333.5$ ps.

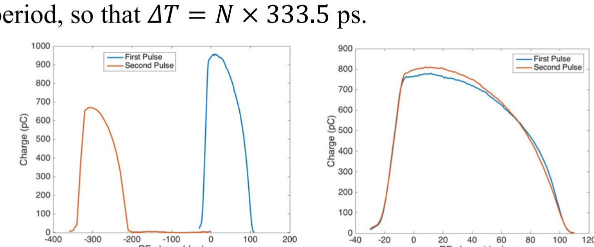

Figure 2: Schottky scan performed sending in turn only one laser pulse on the cathode. The measurement was made before (a) and after (b) the fine tuning of the temporal delay ΔT and of the half-wave plate rotating angle.

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We have carried out a Schottky-scan, i.e. a measurement of the extracted charge versus the gun rf phase, sending in turn only one PIL pulse on the cathode (results plotted in Fig. 2). We have tuned the temporal delay between the two pulses in order to have the same zero-charge extraction phase. Adjusting then the half-wave plate rotating angle in order to have the same laser intensity on the cathode allows to obtain two Schottky scans overlapping in time with the same shape (Fig. 2b).

TWO-BUNCH TRAJECTORY CONTROL

PIL Pulses Alignment

We have firstly explored the minimum available ΔT=0.66 ns. It is mandatory to align both PIL pulses transversally on the cathode in order to make them coincident. Otherwise, a misalignment as small as ~10 μm over a laser spot size of 0.65 mm (radius) would lead to have ~100 μm differences in the trajectories, as depicted in Figure 3. After a rough alignment of the second PIL pulse on the cathode, we proceed as follows: we propagate only the drive bunch, steering its trajectory on the reference one. Then we disable the trajectory feedback and we propagate only the second bunch, which usually undergoes through a different trajectory (see Fig. 3 on the left). Finally we move the transverse position of the second PIL pulse in order to steer the second bunch on the reference trajectory (see Fig. 3 on the right).

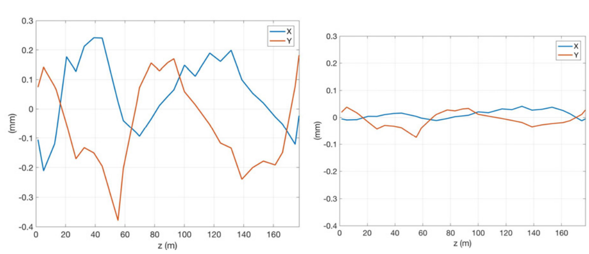

Figure 3: Second bunch (alone) trajectory along the linac before (on the left) and after (on the right) fine tuning the transverse position of the second PIL on the cathode. The reference trajectory (all reading at zero) corresponds to the first bunch trajectory obtained by sending only the first PIL pulse.

At this stage, operating with only the first bunch or only the second bunch is equivalent: the measured optics and emittance along the linac of both bunches transported alone are very similar. However when both bunches are propagated, several issues have to be faced, concerning the BPMs response and the wakefields effects.

Beam Position Monitor

In the FERMI linac, stripline BPMs have been adopted to improve the response of the system for short electron bunches. The electronic signal generated by the bunch takes 1 ns to reach the short-circuit on a BPM edge and be reflected back. As a consequence a second bunch with a ΔT=1 ns perfectly cancels the electronic signal of the first one. The BPM signal excites a band-pass filter at 500 MHz with a resulting output oscillating pulse of about 1μs. Thus, an almost complete cancellation of the response signal occurs every 2 ns, defining the sequence of forbidden delay, that are ΔT=1ns-3ns-5ns-7ns, …

Long Range Wakefields

FERMI linac is comprised of two kinds of rf accelerating sections: SLAC-type travelling wave sections in the first part and Backward Travelling Wave (BTW) sections in the second part [4]. When the beam passes through the latter, strong geometrical wakefields are excited due to their small iris [13] and during the trajectory optimization it is mandatory to minimize their effects. However, the transverse wakefields induced by the drive bunch and acting on the bunch itself (short range) differ from those one acting on the trailing bunch (long range). Thus, minimizing the former by steering the first bunch trajectory when it is propagated alone does not imply an optimization of the second bunch trajectory. In addition, the longitudinal wakefields excited by the first bunch change the energy of the trailing bunch. The latter will radiate in the undulator line at a slightly different frequency, allowing having two-color FEL mode[10].

Figure 4 shows the long-range wake potential in the BTW sections calculated by using ECHO code and MAFIA solver [13].

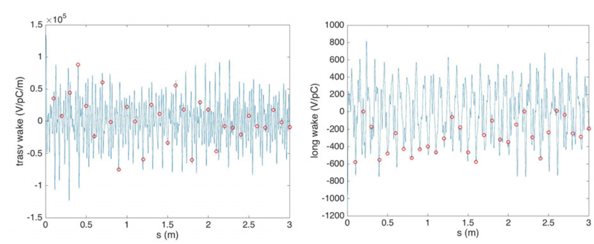

Figure 4: Simulated long-range transverse (on the left) and longitudinal (on the right) wake potential in the BTW sections. Red circles correspond to the wake potential sampled by bunches in subsequent rf buckets.

TWO-BUNCH MODE EXPERIMENT

After defining the best trajectory of the first electron bunch, we turned off the trajectory feedback because the BPMs are not able to distinguish between the two bunches. Then we opened the second PIL shutter and the BPMs read the trajectory of the two-bunch system. An example is reported in Figure 5.

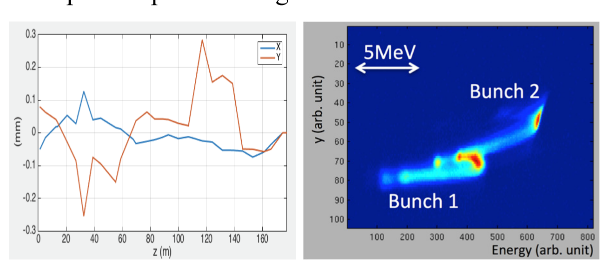

Figure 5: BPMs trajectory reading (on the left) and YAG screen image collected in the diagnostic beam dump (on the right) in two-bunch mode, when ΔT=1.66 ns.

As already mentioned, the transverse wakefields induced by the drive bunch in the linac sections affect the trajectory of the trailing bunch. It is therefore necessary to slightly adjust the first bunch trajectory to minimize the effect of the long-range transverse wakefields. By the other hand, as said above, the effect of the long-range longitudinal wakefields excited by the drive bunch is unavoidable and strongly depends upon the temporal separation ΔT. Figure 6 shows the energy distribution of both bunches measured in the diagnostic beam dump (DBD) at the end of the linac versus ΔT. Comparing the plot on the top with the others, one can observe that the rf structures beam loading affects also the energy of the drive bunch.

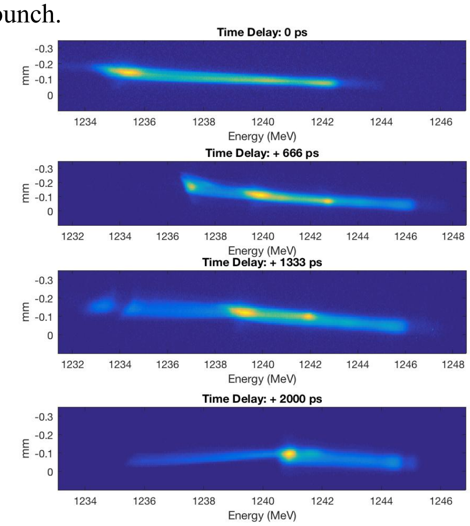

Figure 6: Energy distribution of the two bunches measured in DBD versus ΔT. The drive bunch is on the right and the trailing one is on the left.

If the time-delay is slightly changed by few ps around an integer number of rf period, the trailing bunch samples a slightly different rf phase in the linac before the bunch compressor, resulting over or under compressed with respect to the drive pulse.

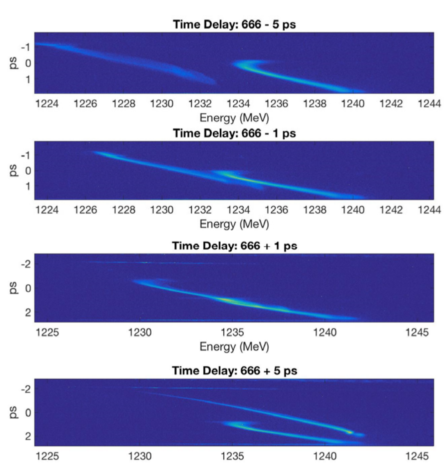

Figure 7: Longitudinal phase space of the two bunches when ΔT is changed by few ps around 666 ps. Second bunch on the left.

Figure 7 shows the longitudinal phase space measured with the rf deflector [14] in DBD when ΔT is varied around 666 ps.

Finally we changed the drive bunch charge and we measured the longitudinal phase space (see Fig. 8)

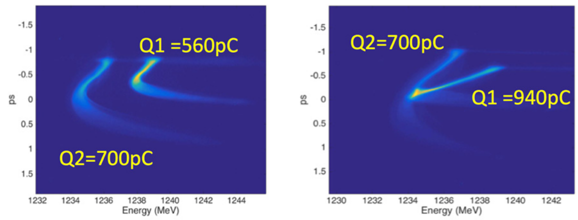

Figure 8: Longitudinal phase space of the two bunches with ΔT=666ps, when the leader bunch has 560 pC (on the left) or 940 pC (on the right). The trailer bunch has a charge of 700 pC.

CONCLUSION

At FERMI, we have successfully generated two bunches, with a time-delay from 0.66 ns to 2.3 ns, that have been transported through the linac and the undulators up to the main beam dump, with an acceptable optics and trajectory control. The long-range wakefields induced in the linac sections by the drive bunch and affecting the trajectory and energy of the trailing bunch have been studied. Fine tuning the drive bunch charge and/or the time-delay has allowed to change the peak current of the trailing bunch and its longitudinal phase space in a control way, opening the door to novel machine configurations.

We have finally lased on the FEL-1 line at 16nm in the two-bunch mode by placing the seed laser on the drive or on the trailing bunch with not relevant differences between the two cases. In future we are going to use two seed laser pulses and produce two-color FEL beams separated by few ns.

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