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DOUBLE-BUNCHES FOR TWO-COLOR SOFT X-RAY FREE-ELECTRON LASER AT THE MAX IV LABORATORY

J. Björklund Svensson*, O. Lundh, Department of Physics, Lund University, Sweden
J. Andersson, F. Curbis, M. Kotur, F. Lindau, E. Mansten,
S. Thorin, S. Werin, MAX IV Laboratory, Lund, Sweden

Abstract

The ability to generate two-color free-electron laser (FEL) radiation enables a wider range of user experiments than just single-color FEL radiation. There are different schemes for generating the two colors, the original being to use a single bunch and two sets of undulators with different K-parameters. An alternative scheme was recently shown, where two separate bunches in the same RF bucket are used for lasing at different wavelengths in a single set of undulators. We here investigate the feasibility of accelerating and compressing a double-bunch time structure generated in the photocathode electron gun for subsequent use in a soft X-ray FEL at the MAX IV Laboratory.

INTRODUCTION

The MAX IV Linear Accelerator Ţ is a warm S-band electron accelerator serving as full-energy injector for the 1.5 and 3 GeV storage rings [2] as well as the Short Pulse Facility (SPF) [3], where the electron bunches are compressed to 100 fs at an emittance of ≲1 mm mrad and a bunch charge of 100 pC. A compact overview of the linac is shown in Fig. 1. The layout of the MAX IV facility is such that the SPF houses three available slots, located downstream of the transfer line to the 3 GeV storage ring. The end of the linac, from the second bunch compressor and downstream, is shown in Fig. 2, with the existing sections and possible extensions on white and orange background, respectively. Simulations indicate that it is possible to compress the bunches to well below 100 fs and still keep the emittance low [4].

The Soft X-ray Laser (SXL) project, currently in the early conceptual design phase, is a collaboration between many Swedish research groups with experience from both user and accelerator sides [5]. The idea is to use one of the SPF beamlines to house a soft X-ray free-electron laser (FEL) operating in the 0.25-1 keV energy range at pulse lengths below 100 fs, paired with unique pumping, detection and imaging schemes. Strong scientific interest has also been expressed towards a two-color radiation operation mode.

Two-color FEL radiation pulses are a way of extending the experimental range at an FEL by producing two radiation pulses with a certain variable separation in energy and time. The original implementation [6] of the concept for X-rays used a single electron bunch and two differently tuned undulator sections to achieve lasing at two different wavelengths, while a more recent development [7, 8] uses two electron bunches, accelerated in the same RF period, and only one undulator section. Benefits of using the double-bunch technique include allowing both colors to reach saturation intensity and a simpler undulator setup. Double electron bunches can be obtained in a few different ways, but we will focus on generation by tailored laser pulses in the photo-cathode electron gun.

Generating the double-bunch time structure in the photocathode gun at MAX IV would require some additional work on the laser system [9, 10], but no further addition to the accelerator or lattice seems necessary, potentially making this technique a cost-effective extension of the operational capabilities of the SPF. Because of the layout of the facility, see Fig. 2, this could synergetically enable experiments on beam-driven plasma-wakefield acceleration (PWFA) [11]. We have used the particle tracking code `elegant` [12] to simulate the acceleration and compression of a double-bunch beam in the MAX IV Linear Accelerator.

BUNCH COMPRESSION

Compression and Linearization

To compress the bunches longitudinally, the MAX IV linac employs two double achromat compressors, see e.g. [4], which have a positive first-order momentum compaction, R_{56}. This means that a positive chirp, with respect to longitudinal coordinate z, is required for compression. This is achieved with a positive off-crest phase in the RF voltage. The naturally positive second-order momentum compaction, T_{566}, has been optimized with sextupoles in such a way that it cancels out the longitudinal phase-space curvature imposed by the RF field. This means that the phase space linearization is done using the optics alone; no higher-order harmonic cavity is employed. This compressor scheme is simple, reliable and economical.

One effect of this compression scheme is that the first bunch, which arrives closer to the peak of the RF voltage, will in many cases obtain a smaller (and less linear) chirp than the second bunch, particularly in the first linac section, L0-L1b (see Figure 1). This can lead to weaker compression of the first bunch, yielding a beam where the second bunch is shorter than the first. The second bunch curvature can also become over-compensated, leading to asymmetric compression. Part of the tuning process involves minimizing these effects.

Wakefields and Coherent Synchrotron Radiation

Short-range geometric longitudinal wakefields can influence the bunch chirp in the linac [13]. The effects of these wakefields increase with both bunch charge and degree of

* jonas.bjorklund@fysik.lth.se

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Figure 1: Compact layout of the MAX IV Linac. Yellow denotes radiofrequency (RF) structures, red/green are focusing/defocusing quadrupole magnets, purple are dipole magnets, orange are sextupole magnets and blue are special magnets. PG and TG are photo-cathode and thermionic RF guns, respectively, L are the linac sections and BC1 is the first bunch compressor. This view is cut right before BC2, which is shown in Fig. 2.

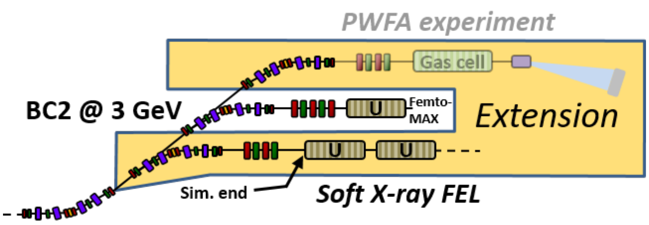

Figure 2: End of the linac and SPF (see Fig. 1) with the 3 possible beamlines, of which FemtoMAX is the only existing to date. U denotes undulator. Possible extensions are within the orange field.

compression. Since the energy chirp is positive with respect to z, and the wakefields cause a progressive decrease in particle energy going backwards in the bunch, the total energy chirp of the bunches increases, which leads to a stronger compression. This was studied in Refs. [14, 15] for single bunches in the MAX IV linac.

Also of concern is coherent synchrotron radiation (CSR), where the bunch irradiates itself with coherent low-frequency radiation, leading to an emittance growth in the compressors. Typically, the tail of the bunch irradiates the head of the bunch, but in the case of two bunches with short length and separation, there is also a risk that the second bunch could irradiate the first bunch.

SIMULATION RESULTS

Tracking of the particles is done from after the pre-injector [16], see Fig. 1, to after a preliminary matching section constructed with 4 quadrupoles, see Fig. 2, using `elegant`, with both wakefields and CSR enabled and 250k particles per bunch. A preliminary double-bunch structure is created using Gaussian distributions for the transverse sizes and divergences, while it is parabolic in time (Beta distribution with shape parameters $\alpha = \beta = 2$) with longitudinal momentum coordinates accounting for different longitudinal phase space curvature of the bunches. The results presented here are found with initial bunch lengths of 2.7 ps full width at half-maximum (FWHM), separation of 4 ps peak-to-peak and with the first bunch 10 degrees off-crest out from the pre-injector, see Fig. 3a. The normalized emittance is 0.3 mm mrad in both directions and for both bunches and they are set to contain 50 pC each.

The main variables for controlling the final time structure are the RF phases in the linac. The phase in the first linac section is mainly used to control the energy separation of the bunches, since the degree of compression in BC1 determines how far apart the bunches sit in the RF wave in the second linac section (L2-L19). The second linac phase is then used to get the peak current sufficiently high without sacrificing too much emittance. Both must be varied together to achive a certain end result, as the variables are not completely independent.

An example is shown in Fig. 3b, which displays the longitudinal phase space and current of the beam at the end of the preliminary matching stage. The first (second) bunch horizontal normalized emittance, $\varepsilon_{n,x}$, is 0.5 (0.5) mm mrad, the bunch length, τ, is 10.1 (13.5) fs fwhm with a peak current, I_p, of 4.7 (3.4) kA, and the bunch separation, Δt, is 80 fs. This is achieved by placing the centroid RF phases in L1 and L2-L19 (see Fig. 1) at 29.75 and 6 degrees off-crest, respectively. As a result, the final energy spread is $\lesssim$0.05 % rms around each current peak and the energy separation is ~0.35 % between the average energy of each bunch.

CONCLUSIONS AND OUTLOOK

Firstly, because of the fact that the wakefields increase the bunch chirp imposed by the RF, it is at present not possible to simultaneously have a short pulse and a very narrow energy spread of the individual bunches. This problem is exacerbated greatly by inclusion of CSR effects, which spoil the electron beam spectrum in BC2, as seen in Fig. 3b. In the figure, it also appears that the first bunch exhibits larger CSR modulations than the second, possibly meaning that the second bunch has irradiated both itself and the first bunch. It is also evident that the second bunch, unlike the first, is not compressed symmetrically, which is due to over-compensation of the phase space curvature in the compressors. This lowers the peak current somewhat, compared to a symmetric compression.

The nearest future step in this investigation include simulating the pre-injector with ASTRA [17], to use more realistic beams as input for the tracking simulations. Simulations of the FEL dynamics using Genesis [18] will also be performed. A parameter space for varying the time and energy separation, while keeping the peak current constant, also needs to be mapped out. For this at least a third variable is needed, besides the two linac phases. Since parameters such as laser pulse separation at the cathode and bunch charge will affect the beam emittance out from the pre-injector, it might be more practical to change e.g. R_{56} and/or T_{566} in BC2, as suggested in [8]. As there are currently no linac sections after BC2, the beam energy at BC2 is the final beam energy, which disables the beam energy at BC2 as a tuning param-

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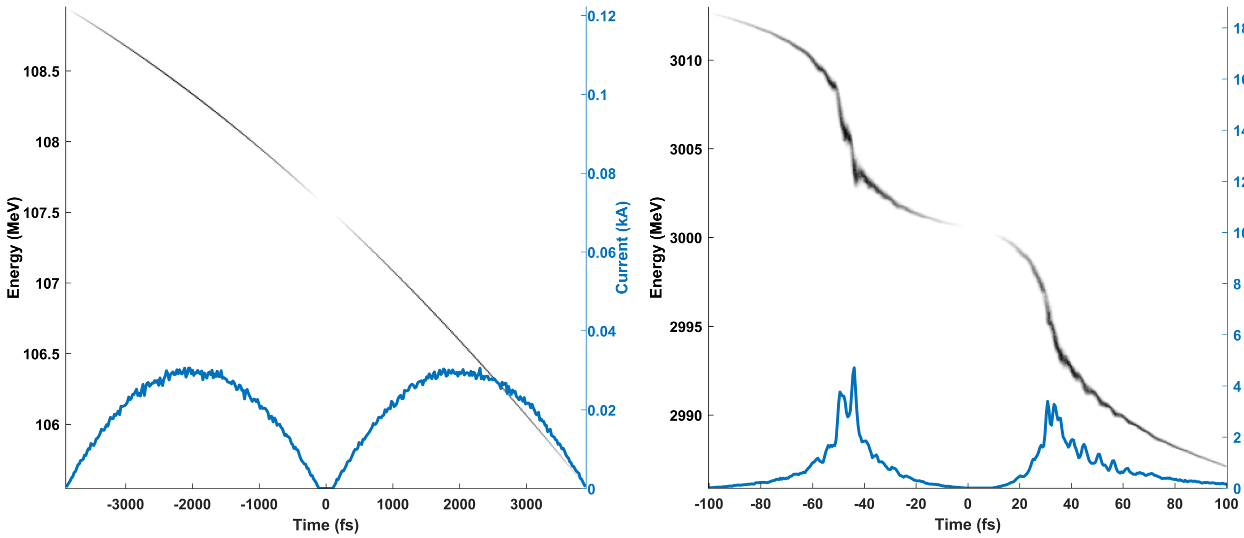

(a) Simulation start (b) Simulation end

Figure 3: 2D histograms of the longitudinal phase spaces (greyscale) and the corresponding currents (blue) at the start and end of the simulation. The histogram density ranges from white (minimum) to black (maximum). The first bunch is to the left in the figures. Parameters from this particular simulation are given in the text.

eter even if the linac is capable of reaching up to 3.6 GeV. A passive (de-)chirper placed before BC2 could, however, provide practical tuning of the individual bunch chirps using the wakefields, particularly for low-charge bunches.

Better control of the slice Twiss parameters is also needed. At present, the Twiss paramteters vary over the bunch lengths and between the bunches, something that causes a slight mismatch throughout the linac. As the total beam energy spread at BC1 is $\gtrsim$1.7 % rms, some higher-order dispersion is also transmitted through the compressors, which needs to be addressed. Also making the compression of the second bunch more symmetric would equalize the peak currents.

However, the results from these early simulations are very similar to the results presented in [8], with a ~4 kA peak current and $\lesssim$100 fs time separation at 3 GeV and ~0.35 % energy separation, even when including CSR in the simulations. With the presented values for peak currents and emittances, it is not unreasonable to assume that these two bunches can achieve lasing. Thus, we conclude that it appears feasible to accelerate and compress a double-bunch beam with FEL quality in the MAX IV Linear Accelerator.

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