Collective Effects in a Short-Pulse FEL Driver

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Abstract

We explore a design for a linac driver which utilises 1.3 GHz CW accelerating structures to deliver short electron bunches with repetition rates potentially up to 1 MHz. A 200 pC bunch is compressed to deliver significant charge into a time width less than 10 fs, delivering a peak current in excess of 10 kA with a reasonable energy spread. We discuss start-to-end modelling of this system, including the limitations from coherent radiation emission.

INTRODUCTION

The UK New Light Source [1] is a project to deliver world class photon output to users across a wide range of wavelengths using a combination of advanced conventional lasers and accelerator-based sources, in particular to drive one or more free-electron lasers. One option is a high-repetition-rate source based on TESLA-type superconducting L-band accelerating modules, and is described further in a separate paper [3]; such an approach is also being considered elsewhere [2, 4]. We propose a scaleable design which allows staged construction from an initial electron energy of 735 MeV, and which provides flexible compression to deliver a variety of bunch lengths for different types of photon output sources. In this paper we consider a short-bunch configuration delivering significant charge into a $\sim$ 10 fs time width, suitable for weak superradiant output. The design assumes an adapted XFEL injector operating at 1 kHz repetition rate [6], but eventual operation up to 1 MHz may be possible with an alternative injector design [3, 2, 5].

SHORT-BUNCH CONFIGURATION

The short bunch configuration is shown in Figure 1. A PITZ-type photocathode gun [7] is followed by two eight-cavity cryomodules operated at 17 MV/m, and a third-harmonic (3.9 GHz) module for linearisation of the longitudinal phase space, which delivers a mean energy of 220 MeV. In short bunch mode, the generated electron bunch has a FWHM length of 10 fs, a slice energy spread of 0.25 % and a transverse slice emittance of 1.33 mm mrad in the central 5 fs slice. By utilising a lower bunch charge of 200 pC, and by allowing a slightly larger transverse emittance and energy spread, a relatively high peak current can be delivered, with half (100 pC) of the charge delivered within a 10 fs central slice, corresponding to an effective

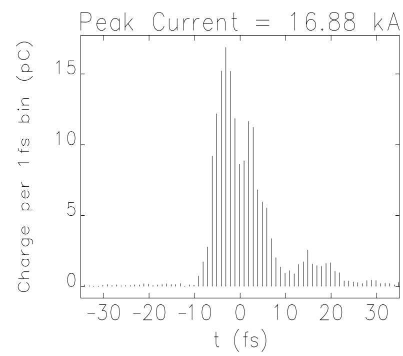

Figure 2: Current profile after BC2 at 735 MeV.

peak current of over 10 kA (see Figure 2). The full electron beam parameters are summarised in Table 1. Higher electron energies will be obtained by adding cryomodules [3].

Table 1: PULSE short bunch mode accelerator parameters.

Parameter	Value
Bunch charge	200 pC
Average bunch rate	1 kHz $\rightarrow$ 1 MHz
1.3 GHz gradient	17 MV/m
3.9 GHz total voltage	20 MV
Linac 1 phase	$-26.0°$
Energy at BC1	220 MeV
BC1 R_{56}	58.98 mm
Linac 2 phase	$-20.0°$
Final energy	735 MeV
BC2 R_{56}	11.90 mm
Bunch length (FWHM)	10 fs
Projected energy spread	0.56 %
Slice energy spread (5 fs)	0.29 %
Slice emittance (5 fs norm.)	1.43 mm mrad
Peak current (5 fs)	11.5 kA
Accelerator length	110 m

START-TO-END MODELLING

The space-charge tracking code, ASTRA [8, 9] has been used to model the bunch from the photocathode to the end of the second cryomodule. It is then tracked through the third-harmonic and following accelerator elements with ELEGANT [10]. One dimensional coherent synchrotron radiation (CSR), longitudinal space-charge (LSC) and linac wakefield effects are included.

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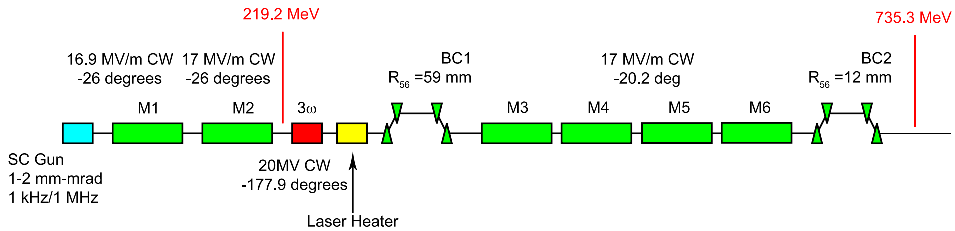

Figure 1: Layout of the first stage, showing the two-stage compression configuration for short bunch operation.

These programs are enclosed inside wrapper scripts written in Python that automate the process of matching the optics, generating the various inputs required, submitting batch jobs to serial or parallel machines and processing and analysing the results. Parameter tuning is performed over runs with 1×10^4 macroparticles. 2×10^5 macroparticles are used to verify results

We choose to optimise our system for large peak currents at the expense of small energy spread. Figures 3 and 4 show the longitudinal phase space of the bunch after the first and second compressors respectively. At the exit of BC2 we obtain a projected emittance of 2.84 mm mrad and an RMS energy spread of 4.1 MeV. Long tails contribute to these values, which it may be possible to reduce through optimisation of the injector. However, it is the characteristics of the central, lasing, slice that are more important. Table 2 shows the emittance, charge and energy spread over a central slice as a function of its width. It can be seen that over half the charge lies in the central 10 fs.

Table 2: Peak (lasing) slice analysis after BC2.

Bin	**Emittance**	**Charge**	$\Delta E/E$	I_{peak}
1 fs	1.32 mm mrad	16.9 pC	0.21%	16.9 kA
5 fs	1.43 mm mrad	57.5 pC	0.27%	11.5 kA
10 fs	1.91 mm mrad	104 pC	0.29%	10.4 kA

THREE-DIMENSIONAL CSR CALCULATIONS

A 3D CSRtrack [11] calculation was performed in the important BC2 compressor, and compared with one-dimensional projected methods provided by ELEGANT and CSRtrack. Fig 5 compares the longitudinal phase space of the bunch after BC2 and in Fig 6 we compare the current profile. We summarise the differences in Table 3. The tails of the bunch contribute to an RMS projected emittance growth, but the emittance degradation of the central slice is acceptable.

MICROBUNCHING

Typically, the uncorrelated slice energy spread in a bunch generated by a photocathode RF gun is very small. Therefore any modulations or shot-noise fluctuations are

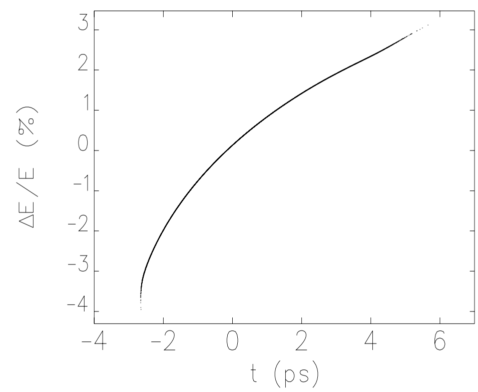

Figure 3: Longitudinal phase space after BC1 at 220 MeV.

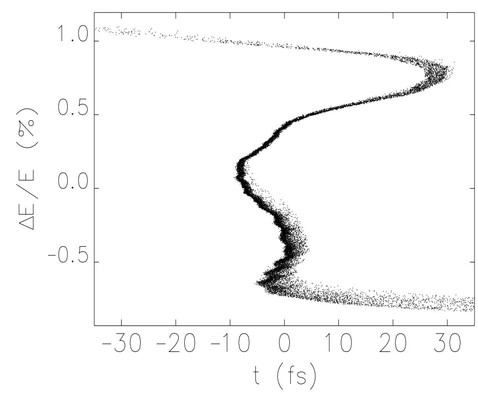

Figure 4: Longitudinal phase space after BC2 at 735 MeV.

well-defined in the current profile. Theoretical and numerical studies of the evolution of these density modulations have shown that they become amplified during this compression process. Sources of impedance such as coherent synchrotron radiation (CSR) in the chicanes [12, 13, 14],

Table 3: Comparison of emittance and energy spread after BC2, as calculated using projected (Elegant) and 3-D (CSRtrack); the slice with most charge is compared.

Parameter	**Projected**	**3-D CSRtrack**
Projected ε	2.84 mm mrad	4.95 mm mrad
Slice ε (5 fs)	1.43 mm mrad	1.85 mm mrad
Slice $\Delta E/E$ (5 fs)	0.29 %	0.27 %
I_{peak} (1 fs)	16.9 kA	14.5 kA

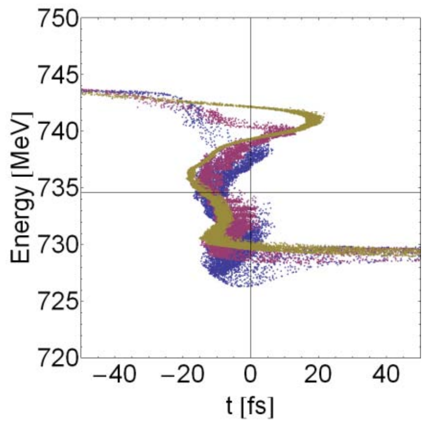

Figure 5: Longitudinal phase space after BC2 at 735 MeV. Compared are the 1-D projected method in ELEGANT (orange), the 1-D projected method in CSRtrack (pink) and the 3-D CSRtrack method (blue).

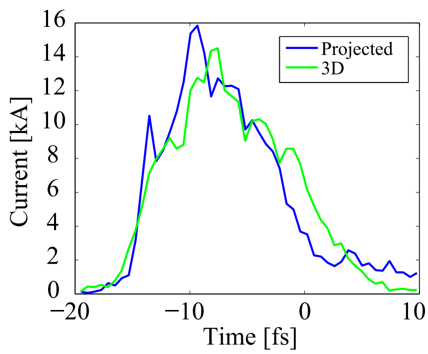

Figure 6: Current profile after BC2 at 735 MeV using CSRtrack. Compared are two CSRtrack mathods: projected (blue) and 3-D (green).

longitudinal space-charge (LSC) and linac wakefields [15] lead to energy modulation which is then converted to additional density modulation by the compression chicanes. This microbunching instability has been observed at the TESLA Test Facility (TTF) [16], the BNL deep ultraviolet FEL (DUVFEL) [17] and may have been seen recently in the LCLS injector.

We are currently undertaking a study of this microbunching gain utilising a 2-D Vlasov-Maxwell solver which has been successfully tested against the Zeuthen benchmark bunch compressors [18, 19] and applied to study the microbunching instability in the first bunch compressor system of FERMI@ELETTRA [20]. We anticipate that this instability can be controlled via the introduction of uncorrelated energy spread before the first bunch compressor at 220 MeV using a laser modulator. However, it is a matter of active study how important the microbunching instability is to an upright bunch configuration such as the one we have shown.

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