VELOCITY BUNCHING AT FLASH

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Abstract

The vacuum-ultra-violet free electron laser in Hamburg (FLASH) is a linear accelerator driven SASE-FEL. In normal operation high peak currents are produced in magnetic bunch compression chicanes at beam energies above 120 MeV, where longitudinal dispersion allows path length changes of relativistic electrons. For low energy electron beams (≈ 5 MeV), the velocity dependence on the energy can be used to compress the bunch as well. Strong bunch compression at low beam energies gives rise to strong space charge interactions, moderate bunching, however, might be used to optimise the total bunch compression system of FLASH or the European XFEL. Experiments on the velocity bunching process at FLASH are presented here. Results on bunch length and transverse emittance measurements are discussed and compared with numerical tracking calculations.

INTRODUCTION

FLASH

The injector of FLASH consists of a 1.5 cell 1.3 GHz RF gun surrounded by two solenoid magnets and followed by a cryomodule (ACC1) containing eight TESLA type superconducting cavities (see Fig. 1). A high quantum efficiency Cs_2Te photo-cathode is located in the half-cell of the RF gun and allows the production of high charge bunches when illuminated by an UV laser pulse (about 4 ps long RMS) with a wavelength of 262 nm.

In the horizontal bunch compressor chicane following ACC1 (called BC2 for historical reasons) the bunch length is reduced by about a factor of 10 [1] in standard operation. Before the second compression step the electrons are accelerated in modules ACC2 and ACC3 to an energy of 380 MeV. In the second bunch compressor (BC3) the bunch length is further reduced by about a factor of 4. The designs of BC2 and BC3 are different. While BC2 is a simple four-bend-chicane, BC3 has an S-shape and consists of six dipoles of equal bending strength (see [2]). In total the electron bunches are compressed from a length of 2 mm RMS at the exit of the gun to approximately $50\ \mu$m RMS.

Velocity Bunching at FLASH

Velocity bunching (or ballistic bunching) for photo injector based linear accelerators was studied by Serafini et al.[3]. It is based on velocity differences along the bunch induced by a longitudinal correlated energy spread.

Numerical studies on velocity bunching were done in [4] or [5] using particle tracking codes like ASTRA[6].

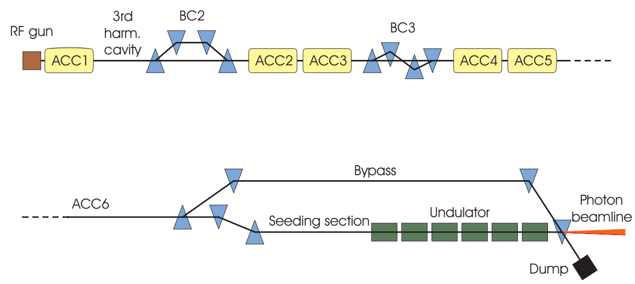

Figure 1: An overview of the FLASH free electron laser accelerator facility.

The electron beam produced by the RF-gun at FLASH has a typical beam energy of about $4-5$ MeV. The typical energy gain of a TESLA type cavity is about $10-20$ MeV. Therefore the first cavity of the first cryomodule ACC1 (located $\approx\ 2.8$ m from the photo-cathode) can be used to compress the beam, while further downstream relativistic velocities are reached.

Since a high peak current of the order of one kA ($I \approx \frac{q_{\mathrm{bunch}} c_0}{\sigma_z} = \frac{0.5\ \mathrm{nC}}{0.6\ \mathrm{ps}} \approx 800$ A) is reached at beam energies well below 50 MeV space charge forces are expected to play a dominant role. This can be observed as an increase in transverse emittance.

MEASUREMENTS

Experimental Outline

In order to perform measurements on velocity bunching the RF distribution of ACC1 has to be modified to allow different phase offsets in the first cavity ACC1.C1 with respect to the seven other cavities. This is done by manipulation of the standard 3-stab-tuners which are mounted in front of each cavity input coupler. One can find settings of these tuners that allow changes of the RF phase offset without changing the input power, from theory these are the symmetric settings were the stab one and three are set to the same position[7]. To make sure that the behaviour of the RF parameters fulfils the requirements the RF probe signals are checked and used for fine tuning of the tuner positions.

Bunch length is measured using the synchrotron light from the fourth dipole of the bunch compressor chicane BC2. The radiation is transported via an optical beam line consisting of parabolic mirrors outside the accelerator tunnel. In front of a streak camera a 540 ± 40 nm wavelength filter is used to mitigate longitudinal stretching of the light pulse by optical dispersion. From measurements

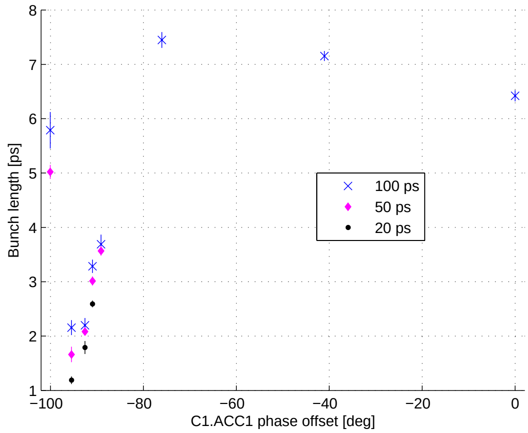

Figure 2: Bunch length measured with the streak camera at the synchrotron radiation port at the last dipole of BC2. For short bunch length higher voltages were used in the streak camera to optimise the resolution. For each data set the maximum screen range on the streak camera is given, smaller numbers thus correspond to higher streak voltages. Error bars show the standard error of the mean.

at full compression one can estimate that the overall resolution is approximately limited to about 1 ps (compare also with [8]). The bunch length is measured as a function of ACC1.C1 phase. For these measurements the phase offset of cavities ACC1.C2-C8 is chosen in a way that the correlated energy spread downstream the module is minimised. This reduces longitudinal effects of the magnetic chicane. Therefore bunch length changes are dominated by velocity bunching and not the bunch compressor chicane.

Transverse emittance is measured downstream of BC2 in a FODO section specifically designed for diagnostic purposes. Four OTR screens with a phase advance of $45°$ between them allow reconstruction of beam optics parameters and emittance[9]. Since the emittance matching and compensation scheme of the FLASH injector is perturbed by the RF manipulations in the first cavity, for each setting of the ACC1.C1 phase offset the main solenoid coil of the RF gun was scanned to find the minimal emittance. The minimal emittance for each phase setting is then used as the measured value.

Measurement Results

Measurements of the bunch length as a function of ACC1.C1 phase offset with respect to the beam (Fig. 2) confirms the expectation of a minimum bunch length for approximately -95 degrees off crest. The measured bunch length is here defined as the standard width of a Gaussian, which is fitted to the longitudinal intensity profile of the streak camera image.

The transverse emittance measured in the diagnostic FODO section downstream of BC2 is given in Fig. 3. The values are determined from the spot sizes on the OTR screens. In order to avoid overestimation of the emittance by the low intensity halo of the electron bunch, a lower intensity cut-off is introduced such that the integrated image intensity is 90% of the total one. The transverse emittances are given for 100% and 90% image intensies. A sigificant increase of emittance is observed towards large phase offsets in ACC1.C1 were the shortest bunch length is measured. High charge densities and therefore strong space charge forces result in an emittance increase.

One observes a stronger increase of the horizontal emittance compared to the vertical emittance. This is related to the fact that the magnetic chicane was not switched off during the emittance measurement. Emission of coherent synchrotron radiation, especially for compressed bunches, leads to an emittance increase due to energy changes within the dispersive section. This emittance increase is restricted to the bending plane of the dipoles. Vertical emittance is not affected by this effect and is therefore the figure which is related to the velocity bunching process.

Measurement errors of the emittance have two contributions. The statistical component derived from the image analysis of a series of beam images taking into account error propagation of the analysis procedure, and a systematic component related to beam energy errors. The emittance determination from the OTR beam images depends on an good knowledge of the transfer matrices between the different OTR stations, these matrices are determined from the quadrupole currents recorded during the emittance measurement. However, if the beam energy is not well known these matrices are inaccurate. If the beam is well matched in the FODO section, one can show that the dependence on energy error is small[9]. To achieve this matching five quadrupoles upstream of the FODO section are used in an iterative matching process.

The systematic error is determined by a Monte Carlo analysis. A random set of normal distributed beam energies around the nominal one assuming 5% peak to peak energy error is used for the emittance calculation. The RMS from the corresponding emittances is then added quadratically to the statistical error of the emittance measurement. For phase offsets in ACC1.C1 of $-96°$ no proper matching of the beam optics was possible due to the poor beam quality, which results in a high systematic contribution to the measurement error there (Fig. 3).

COMPARISON WITH SIMULATIONS

The FLASH machine settings during the measurements where used to set up the ASTRA tracking code[6]. ASTRA takes into account the photo cathode, the gun 1.5 cell cavity, the gun cavity as an aperture, the solenoid system of the RF gun, the eight cavities in ACC1, five quadrupole magnets, and the dipoles of BC2. 100.000 particles were used in these simulations, with a cylindrical grid for space charge calculations with 50 longitudinal slices and 12 radial elements each. Bunch length data are obtained in the

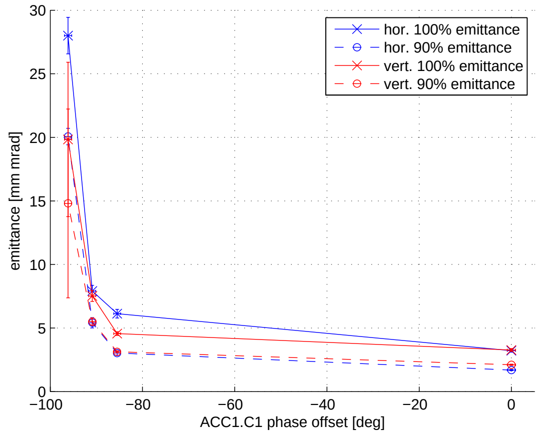

Figure 3: Emittance measured in the FODO section downstream of BC2. Data are given for 100% and 90% of beam intensity. In the 90% case a low intensity halo is subtrated. The increase of emittance towards high off crest phases is related to space charge forces.

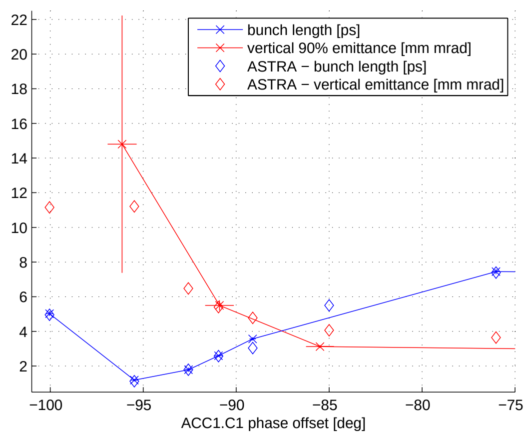

Figure 4: Comparison of measured values for beam emittance and bunch length and numerical simulations obtained from the ASTRA code. Vertical 90% emittance is given as in Fig. 3. Results from simualtions based on a numerical FLASH model agree with the measured data.

middle of the last dipole in BC2, which is the dipole used as a synchrotron radiator for the streak camera measurements. The emittance is taken before the first dipole, therefore no effects of coherent synchrotron radiation are included in these figures. In Fig. 4 the measured values of the vertical emittance and the bunch length are compared with ASTRA simulations.

SUMMARY AND CONCLUSIONS

It was demonstrated that velocity bunching at FLASH is possible. Indirect and direct experimental methods were used to confirm velocity bunching of the electron beam. Bunch length down to 1.2 ps were measured downstream of ACC1 with a streak camera. Emittance was measured and a strong growth of emittance toward short bunches was observed.

In order to prepare and understand the measurements different numerical tools were developed and used. A simple analytic model neglecting high order effects such as space charge forces was used for a fast approximation of expected results while ASTRA was used for detailed predictions as well as a *a posteriori* simulation of the measurement results. Measurements and simulations agree well so that one can conclude that the beam dynamics involved in the velocity bunching process are well understood.

The studies showed that velocity bunching is no suitable alternative to the standard compression scheme of FLASH using two magnetic bunch compressor chicanes since the emittance growth is not tolerable for SASE FEL operation. However one can think about intermediate pre-compression using velocity bunching as an additional 'knob' for optimisation of the total bunch compression system of FLASH and the forthcoming European XFEL.

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