VELOCITY BUNCHING SIMULATIONS FOR THE DESY VUV-FEL

J.-P. Carneiro*, B. Faatz, K. Floettmann
DESY, Hamburg, Germany

Abstract

The TESLA Test Facility is currently being upgraded to reach in its final stage as a user facility SASE radiation at a wavelength of 6 nm. After a brief description of the layout and status of the VUV-FEL, this paper presents start-to-end simulations studying velocity bunching as a scenario for the first operation of the accelerator.

INTRODUCTION

The injector of the VUV-FEL consists of a 1.5 cell RF gun operating at 1.3 GHz surrounded by 2 solenoids (a bucking and a main) and followed by a cryomodule (ACC1) containing eight TESLA type superconducting cavities. A high quantum efficiency Cs_2Te photo-cathode is inserted into the half-cell of the RF gun and allows the production of high charge bunches when illuminated by the UV light of a laser pulse (20 ps FWHM) with a wavelength of 262 nm. The optimal operation of the injector requires, for emittance compensation purposes, that the four first cavities of the cryomodule operate with a lower accelerating field (∼12.5 MV/m) than the four others (∼20 MV/m). The RF-induced curvature of the longitudinal phase space is corrected by the use of a third harmonic cavity installed at the exit of ACC1. Five cryomodules and two magnetic compressors will then accelerate the beam to 1 GeV and compress it down from $\sigma_z \simeq 2$ mm to $\sigma_z \simeq 62$ μm. Under optimal operation, the beam peak current at the entrance of the undulator is expected to be ∼2.5 kA, for a slice emittance <1.5 mm-mrad (in the radiation part) and a total energy spread of $\sigma_E \leq 1$ MeV. The radiation pulse is then expected to be in the order of ∼200 fs FWHM for a peak power in the GW level.

In the present status of the VUV-FEL, a shorter laser pulse length (∼10 ps FWHM measured with a streak camera) is available and the last cryomodules have not yet been installed. Furthermore, the third harmonic cavity is under development ([1]) and will not be available for use in the VUV-FEL within 2 to 3 years. Without this element, only a short part of the electron bunch can present at the undulator entrance the required beam properties (peak current, emittance and energy spread) to induce SASE radiation. Reference [2] indicates that a possible way to operate the VUV-FEL under these starting conditions is to use a low charge beam (0.5 nC) together with both magnetic compressors. At the entrance of the undulator, the bunch presents then a slice with a peak current of 1.3 kA, a normalized emittance <1.5 mm-mrad and a local energy spread of about 300 keV inducing a SASE radiation pulse of 15 to 50 fs at a wavelength of 30 nm. In this paper, we study an alternative option for the start-up of the VUV-FEL based on velocity bunching and on which no magnetic compression is used.

* Jean-Paul.Carneiro@desy.de

VELOCITY BUNCHING PRINCIPLE

The velocity bunching is based on the phase slippage between the electrons and the RF wave for a non-relativistic beam [3]. Reference [4] suggests, for the VUV-FEL, to use the first cavity of the first cryomodule (located ∼2.5 meters from the photo-cathode) to compress the bunch by velocity bunching.

This scenario, presented in Figure 1, shows ASTRA [5] simulations of the RMS bunch length as a function of the phase of the first cavity of ACC1 (relative to an acceleration on crest) keeping the phase of the other cavities to a maximum energy gain.

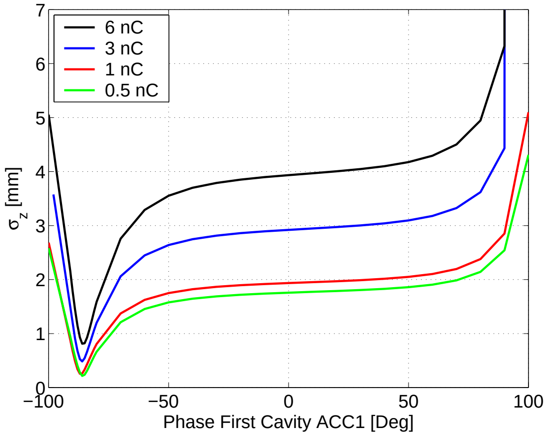

Figure 1: ASTRA [5] simulation of the RMS bunch length versus the phase of the first cavity of ACC1 (relative to acceleration on crest) for different charges. Outputs at the exit of ACC1 (z=13.6 m).

Four different bunch charges Q are studied and the outputs are taken at the exit of ACC1, at z=13.6 m. The main parameters of the injector used for these simulations were determined from measurements during the conditioning: field on the gun of 40 MV/m and accelerating field on the cavities of ACC1 of ∼12 MV/m. The beam enters

Q	Nominal			Velocity Bunching		
[nC]	I_n [kA]	ϵ_n [μrad]	ΔE_n [MeV]	I_n [kA]	ϵ_n [μrad]	ΔE_n [MeV]
0.5	0.03	1.3	0.13	0.65	3.2	0.58
1.0	0.05	2.0	0.15	1.2	5.1	0.72
3.0	0.10	5.3	0.33	1.8	8.6	0.91
6.0	0.16	9.9	0.57	2.1	15.6	1.35

Table 1: Main beam characteristics for nominal and velocity bunching operations and for different charges. From ASTRA [5]. Outputs at z=13.6 m.

the first cavity with a total energy of ~4.7 MeV and exits the cryomodule with an energy of ~107 MeV. Figure 1 indicates that a minimum bunch length is obtained for a phase of -86°. Table 1 presents the beam characteristics from ASTRA simulations at z=13.6 m for an optimized (laser diameter on the photo-cathode and solenoid field) operation of the injector under nominal (all cavities on crest) and velocity bunching (-86°) cases. The table shows that the use of velocity bunching enables a significant increase of the peak current (from 50 A to 1.2 kA for Q=1 nC) but it also degrades the projected emittance and the energy spread. The charge Q=6 nC corresponds to the maximum charge extractable from the RF gun using a laser diameter of 5 mm at 40 MV/m (maximum available, from [6]).

DISTRIBUTION AT Z=203 METERS

ELEGANT [7] has been used to track the compressed bunch obtained by velocity bunching from the exit of ACC1 to the entrance of the undulator (z=203 m). The four charges studied in the previous paragraph were transported along the VUV-FEL linac, taking both bunch compressors as drifts. The field on the cryomodules ACC2, ACC3 and ACC4 was ~14 MV/m in order to get a total energy of ~440 MeV. Figure 2 shows the beam current and slice emittance distributions at the entrance of the undulator for Q=0.5 nC, 1 nC and 3 nC. It is clear from these figures that first, the velocity bunching induces a sharp peak (~100 μm) at the head of the bunch and second, that the slice emittance in the peak keeps reasonable values (~5 mm-mrad for ~1 kA). The slice energy spread in the peak (which has not been plotted) stays below 200 keV.

SASE FEL OUTPUTS

The ELEGANT outputs were tracked in the undulator using the FEL code GENESIS [8]. The transverse distribution of the beam has been taken as gaussian with the appropriate emittance and the longitudinal one as given by ELEGANT. The peak of the current distribution has been matched into the undulator focusing structure.

The undulator of the VUV-FEL is made of six segments (of 4492 mm each) separated with doublet focusing and diagnostics blocks between. The undulator period is set at

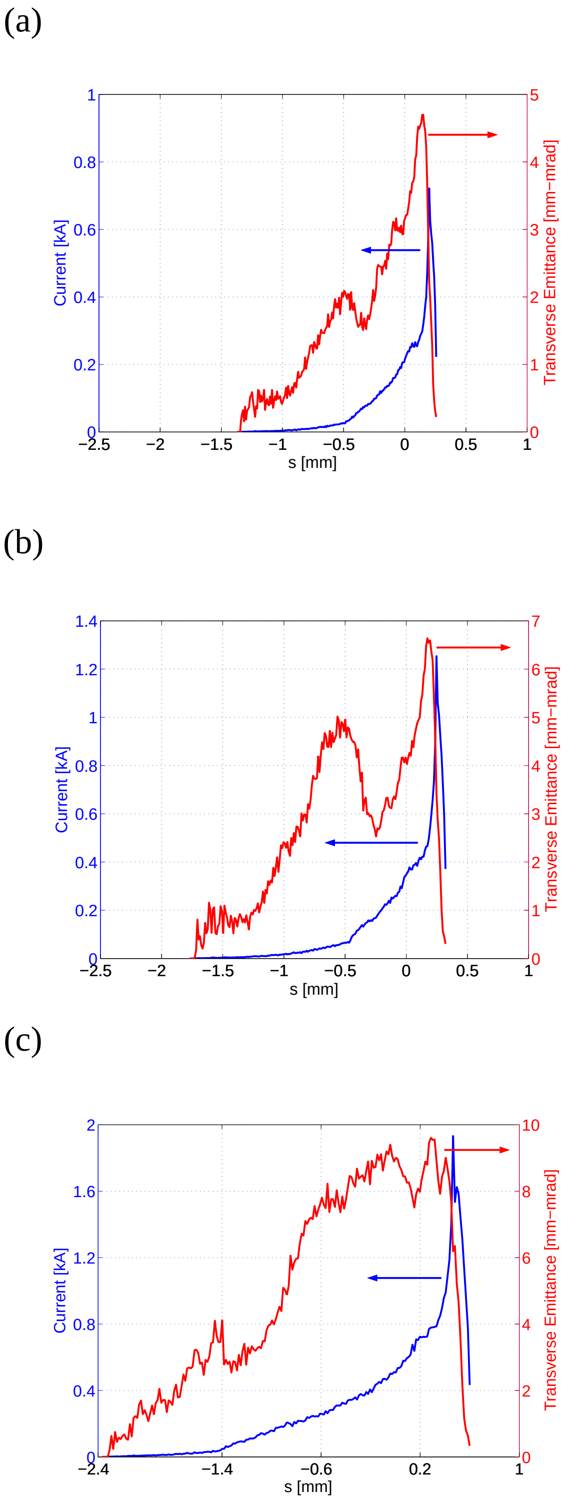

Figure 2: Current and slice emittance distributions at the entrance of the undulator (z=203 m) for bunch charges of (a) 0.5 nC, (b) 1.0 nC and (c) 3 nC. Bunch head for s>0. From ELEGANT [7].

(a)

(b)

(c)

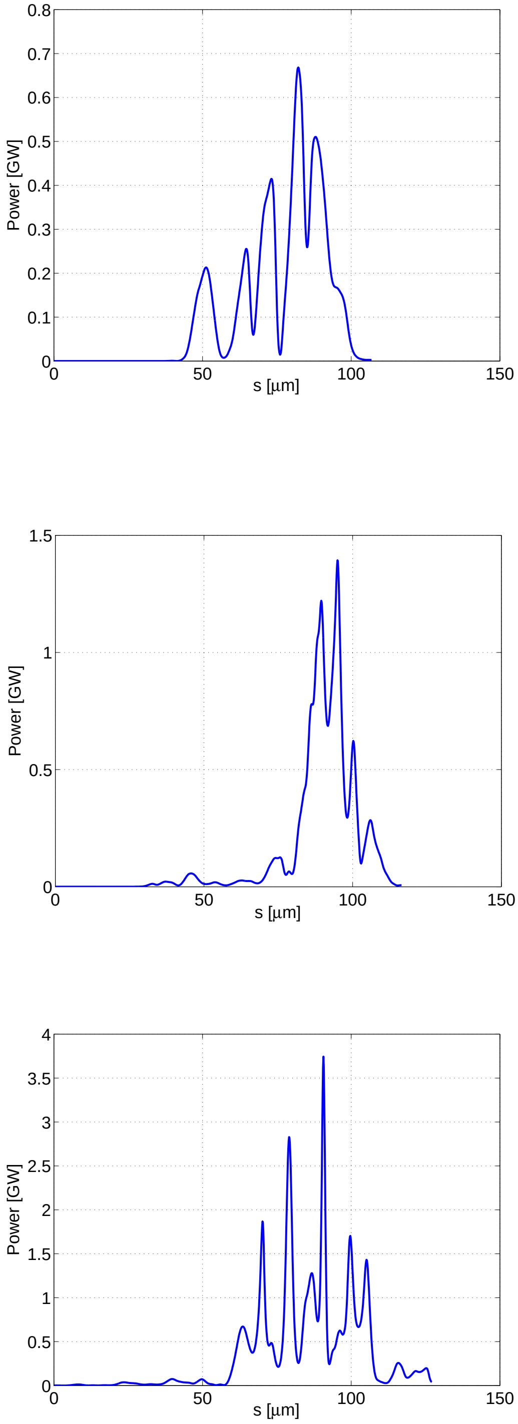

Figure 3: Radiation power at position of minimum spectral bandwidth for bunch charges of (a) 0.5 nC, (b) 1.0 nC and (c) 3 nC. From GENESIS [8].

Q [nC]	Saturation length [m]	Pulse duration FWHM [fs]	Mean power [GW]
0.5	15.233	80	0.2
1.0	13.268	65	0.5
3.0	15.233	100	1.0
6.0	19.165	500	1.0

Table 2: Main radiation power characteristics.

27.3 mm with an undulator parameter of K=1.23. GENESIS outputs of the radiating part of the distributions, corresponding to the peak in the current distribution shown in Figure 2, are shown in Figure 3 for the cases 0.5 nC, 1 nC and 3 nC. They show the power distributions at a position where the first peak reaches saturation, corresponding approximately to minimal spectral bandwidth. Table 2 shows the main characteristics of the radiation at the same positions, together with the 6 nC case.

CONCLUSION

The simulations presented in this paper show that the velocity bunching applied to the VUV-FEL produces bunches whose characteristics enable the SASE process in the undulator. However, it is important to notice that the space charge effects along the linac (mainly the longitudinal ones) have not been taken into consideration and can have a significant impact on the beam dynamics, especially for the high charge cases (3 nC and 6 nC). These effects should be studied in the future. First experimental studies of velocity bunching at the VUV-FEL began in June 2004 where the compression of the bunch has been observed with a pyrodetector located downstream of ACC1 for a phase of the first cavity of about -90°. More experiments on this subjects are foreseen in the VUV-FEL in the next months.

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