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BEAM DYNAMICS STUDIES IN A STANDING WAVE Ka-BAND LINEARIZER

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Abstract

Next generation FEL user facilities require high quality electron beams with kA peak current. The combination of a high brightness RF injector and a magnetic compression stage represents a very performant solution in terms of electron beam emittance and peak current. One of the important issues is the design of a proper device that acts as linearizer for the beam longitudinal phase space at the magnetic compression entrance. Recently, the design of a SW Ka band RF accelerating structure has been proposed with promising results. The paper reports on electron beam dynamics studies in the described RF structure.

INTRODUCTION

The XLS-CompactLight collaboration is studying a X-band linac based FEL source in the range from infrared to X-ray (i.e., with wavelengths of the order of microns to Angstroms). The X-band linac is driven by a C-band RF injector (Fig. 1). Two operation have been considered for the photo-injector, on crest and RF compression, to obtain the beam parameters reported in Table 1 at the RF photo-injector exit (laser heather entrance). In on-crest RF injector operation case and in RF compression operation the beam exits the photo-injector with about 400 µm length [1] and 110 µm length respectively.

Table 1: Electron Beam Parameters at the RF Photo-Injector Exit

Parameters	RF Photo-Injector Exit	Units
Q	75	pC
Rep.Rate	0.1 – 1	kHz
Energy	125	MeV
$\frac{\sigma_E}{E}$	0.5	%
$\epsilon_{n,rms}$	0.15	µmrad
σ_z	380	µm
I_{peak}	20	A

Beam length in the gun area are usually of the order of mm so to have bunch long enough to reduce the emittance degradation due to the transverse space charge forces before the beam became ultra-relativistic. This process naturally leads the beam assumes a non-linear longitudinal phase space (LPS) because of the RF field curvature. In this work, we have reported the beam dynamics study when Higher Harmonic Cavity (HHC), acting as LPS linearizer after the RF gun, is employed.

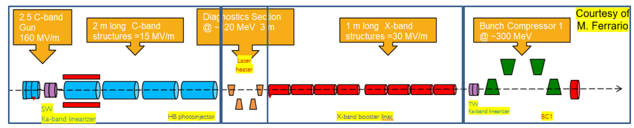

Figure 1: The XLS final layout, that has been optimised after a deep investigation of all possible alternatives.

THE Ka-BAND STRUCTURE

A SW Ka-band linearizer has been designed in the framework of the XLS collaboration and is detailed described in [2]. The RF design of the Ka-band linearizer was carried out with HFSS. The choice of a short SW cavity option, which is 8cm long, is due to avoid modes overlapping and the corresponding total number of cells is 19. This is also the result of taking advantage of our decade-long experience with the design, fabrication, tuning and high-power testing of structures with similar geometries [3–5]. The 3D model used for the RF simulations and the colour plot of the electric field distribution inside the linearizer is given in Fig. 2.

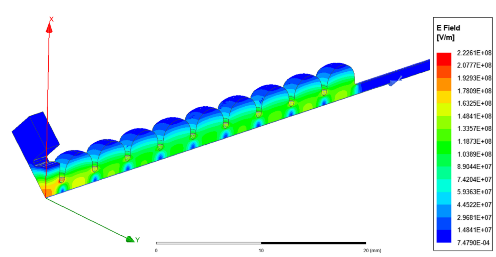

Figure 2: 3D model of one-eighth of half a SW structure simulated with the HFSS software. The surface electric field is shown for a 125 MV/m on-axis accelerating gradient.

From analytical calculations the integrated voltage we should use for the LPS linearization at the photo-injector exit is of about 2.5−3.0 MV that corresponds to an maximum applied electric field E_{max} = 10 − 15 MV/m on average [6]. Anyhow we can't use higher voltages without dumping the beam or disrupt its phase space quality. The equation for space phase linearization is [7]:

$$V_{HHC} = \frac{k^2}{k_{HHC}^2} V \cos\phi \qquad (1)$$

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where V_{HHC} and V are the amplitudes of HHC and accelerating voltages respectively, k_{HHC} and k are RF wave number and cos ϕ is the phase of accelerating voltage.

SIMULATIONS

To better comprehend the Ka-band structure effects we have simulated by using ASTRA simulation code [8], two XLS working point: on-crest RF injector and RF compression operation. Following the electron rms parameters evolution, electron beam phase space and slice analysis are reported in detail.

Reference XLS Working Point: On-Crest RF Injector Operation

The reference XLS working point assumes a 75 pC electron beam and the parameters, without the Ka-band structure, that are listed in Table 2.

Table 2: On Crest Working Point: Comparison between Simulated and Target Main Electron Beam Parameters at the RF Photo-Injector Exit

Parameters	Sim. Result	Target
Q (pC)	75	75
Rep.Rate (Hz)	1000	1000
Energy (MeV)	**126**	125
$\frac{\sigma_E}{E}$ (%)	**0.11**	0.5
$\epsilon_{n,rms}$(μmrad)	**0.12**	0.2
σ_z(μm)	380	380
I_{peak}(A)	20	20

Figure 3 reports the rms transverse normalized emittance, the transverse spot size and the bunch length evolution respectively, without linearizer, along the machine until the photo-injector exit. On the left of Fig. 4 the electron beam slice emittance is shown. As it is possible to note on the right of Fig. 4, the Ka-band linearizer leads to a peaked, but asymmetric current distribution. From Fig. 5 (on the right) we note that the longitudinal phase space (red line) is represented by a line, indeed the Ka-band linearizer has been inserted after the gun to linearize the longitudinal phase space itself.

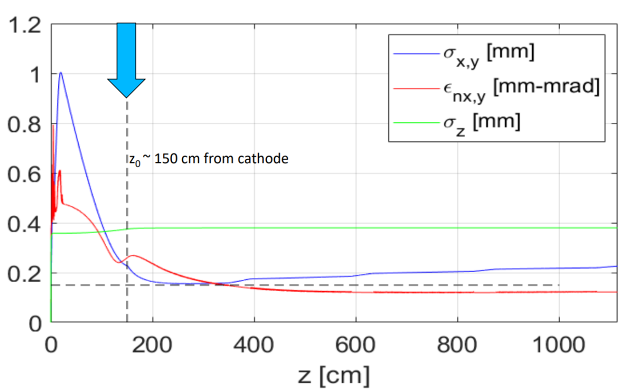

Figure 3: Evolution of the electron beam transverse normalized emittance (red line), transverse spot size (blue line) and bunch length (green line) without linearizer until the photo-injector exit.

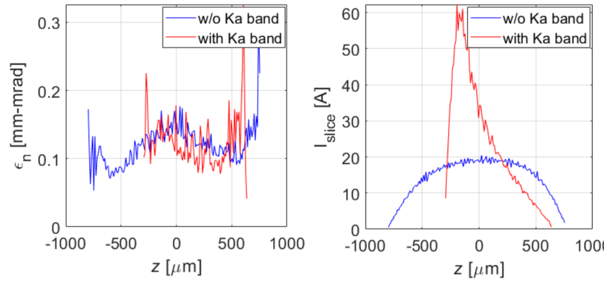

Figure 4: Electron beam slice analysis in terms of emittance (left) and peak current (right) at the photo-injector exit spaces with (red line) and without (blue line) the Ka-band linearizer.

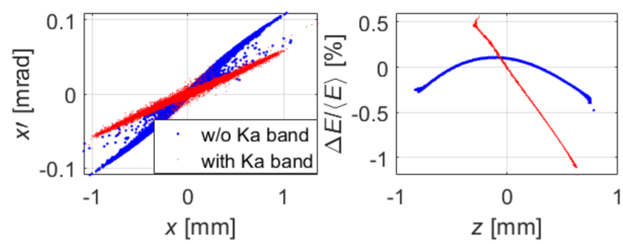

Figure 5: Transverse and longitudinal phase space at the photo-injector exit spaces with (red line) and without (blue line) the Ka-band linearizer.

The RF Compression Operation

Among others, the velocity bunching technique has been chosen because it permits to compress the beam inside the first RF structure after the gun and can be integrated in the emittance compensation process. For soft compression factors it is possible, in principle, restore the intrinsic emittance value. The velocity bunching is a longitudinal phase space rotation based on a correlated time-velocity chirp of the electron bunch (electrons on the tail faster than electrons in the head). The injected beam must be slightly slower than the phase velocity of the RF wave so that when injected at the zero crossing field phase, it slips back to phases where the field is accelerating, being simultaneously chirped and compressed [9, 10].

The main electron beam parameters, without the Ka-Band structure, at the photo-injector exit, are listed in Table 3.

Figure 6 shows us the rms transverse normalized emittance and the bunch length evolution respectively, with (red line) without linearizer (blue line), along the machine until the photo-injector exit.

Figure 7 illustrates the slice analysis in terms of electron beam slice emittance and the peak current.

It is important to underline that beams compressed by means of velocity bunching presents: the typical marked spike-like current distribution and an almost linear LPS in case of a gentle compression factor (< 3). In this case the HHC placed

Table 3: The RF Compression Working Point: Main Electron Beam Parameters at the RF Photo-Injector Exit

Parameters	Sim. result	Units
Q	75	pC
Rep.Rate	1000	Hz
Energy	110	MeV
$\frac{\sigma_E}{E}$	0.5	%
$\epsilon_{n,rms}$	0.2	µmrad
σ_z	105	µm
I_{peak}	70	A

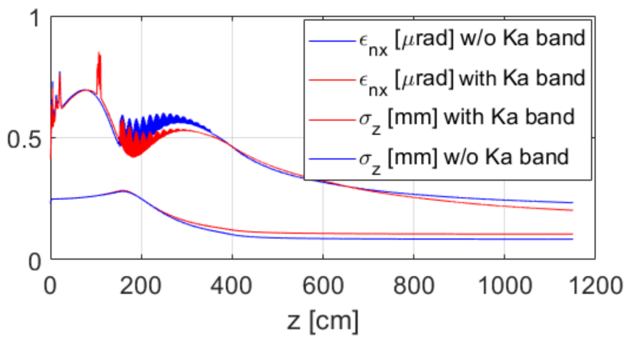

Figure 6: Evolution of the electron beam transverse normalized emittance and bunch length with (red line) and without (blue line) the Ka-band linearizer until the photo-injector exit.

between the gun and the RF compressor, acts both on the shape of the beam current distribution, bunching the beam in the centre, and on the LPS cancelling its residual non-linear correlation. Instead the Fig. 8 reports the simulation

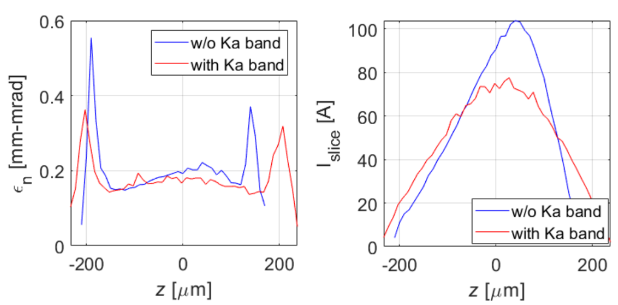

Figure 7: Electron beam slice analysis in terms of emittance (left) and peak current (right) at the photo-injector exit spaces with (red line) and without (blue line) the Ka-band linearizer.

results about the transverse and longitudinal phase space at the photo-injector exit with and with (red line) and without (blue line) the Ka-band linearizer.

CONCLUSION

The electron beam dynamics with the insertion of a Ka-band structure has been investigated, by using the ASTRA simulation code, both as linearization of the longitudinal phase space and shaping of the beam current profile. In the future, the study will include both the short-range wakefield and a larger transverse size of iris to avoid the beam charge cut.

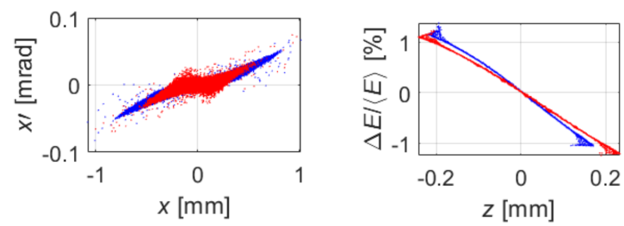

Figure 8: Transverse and longitudinal phase space at the photo-injector exit spaces with (red line) and without (blue line) the Ka-band linearizer.

ACKNOWLEDGEMENTS

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