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EFFECTS OF MODE LAUNCHER ON BEAM DYNAMICS IN NEXT GENERATION HIGH BRIGHTNESS C-BAND GUNS

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Abstract

High-brightness RF photo-injectors plays nowadays a crucial role in the fields of radiation generation and advanced acceleration schemes. A high gradient C-band photo-injector consisting of a 2.5 cell gun followed by TW sections is here proposed as an electron source for radiation user facilities. The paper reports on beam dynamics studies in the RF injector and illustrates the effects on the beam quality of the mode launcher with a focus on the compensation of the quadrupolar RF components.

INTRODUCTION

Photo-injectors are nowadays key devices to generate high brightness electron beams, with the brightness B proportional to the ratio between the peak current I and the transverse normalised emittance $\epsilon_{n_{x,y}}$. This requirement results in a large number of quasi-monochromatic electrons, concentrated in very short bunches, with small transverse size and divergence, that is a high particle density 6D phase space. The 6D brightness B is defined as:

$$B[A/m^2] = \frac{Q}{\varepsilon_{nx}\varepsilon_{ny}\sigma_t\sigma_\gamma} \tag{1}$$

where Q is the beam charge, ε_{nx} and ε_{ny} are respectively the normalized xx' and yy' transverse emittances, σ_t is the bunch length and σ_γ is the energy spread. It follows that the main challenge for an RF high brightness photo-injector is generating electron beams with low transverse emittance ($\epsilon_{n_{x,y}}$ of the order of µm) with up to kA peak currents.

Generally, a photo-injector consists of an RF gun, equipped with a laser driven photo-cathode system and a solenoid surrounding the gun, followed by one or more accelerating structures as booster section. The C-band injector here described has been designed in the framework of the CompactLight collaboration [1] that is studying an X-band linac-based FEL radiation source with wavelengths ranging from infrared to X-rays. The X-band linac will be driven by a normal conducting - high gradient C-band injector operating at up to 1 KHz rep rate - desired to enhance the capabilities of modern FELs. The C-band technology has been chosen, after almost an year of design study, being a good compromise between the S- and the X-band technology in terms of available field gradient in the gun, that reverses in beam brightness, and in the booster, to compact the machine; available working points, since it allows more flexibility in terms of electron beam charge and length if compared to the X-band solution; repetition rate order of magnitude and high gradient fields if compered to an S-band solution.

THE XLS CASE STUDY

The C-band photo-injector has been designed and simulated at LNF. It consists of a 2.5 cell gun followed by four accelerating structures, the first one surrounded by a solenoid.

The reference working point for the XLS case study foresees a 75 pC electron beam that reaches the laser heater entrance with 0.15 mm-mrad transverse normalised emittance, 0.40 mm length and 125 MeV energy. For this purpose the photo-injector is operated on-crest nearly according to the invariant envelope criteria [2], that consists in imposing at the booster entrance a laminar envelope ($\sigma'_{x,y} = 0$) with the beam spot size $\sigma_{x,y}$ matched to the accelerating and focusing gradients to stay close to an equilibrium mode

$$\sigma_{x,y} = \frac{1}{k}\sqrt{\frac{I_0}{4\gamma_0 I_A}\left(1+\sqrt{1+\left(4\frac{\epsilon_{n_{x,y}}\gamma_0 k I_A}{I_0}\right)^2}\right)} \tag{2}$$

with I_A=17 kA the Alven current and k the strength of the external focusing channel.

The generation of the electron beam has been studied in detail by means of beam dynamics simulations. Simulations have been performed with the multi-particle codes Astra [3] and TStep [4], which take into account the space charge effects, relevant at very low energies, and the beam features defined in the emission from the cathode. In our calculations the cylindrical symmetry of the beam has been assumed to allow us adopting a 2D model, which requires a reasonable number of particles and mesh points, and so computational time, with respect to a 3D one. In this specific case, 30 k macro-particles have been considered as a good compromise between reliability and computational time.

An extensive simulation campaign led to consider a photocathode laser pulse with a flat-top longitudinal profile of 4.5 ps RMS duration with 1 ps rise time and a transverse uniform distribution of $\sigma_{x,y} = 125$ µm. Given this laser pulse parameters and an e.m. peak field at the cathode of 160 MV/m, the transverse intrinsic emittance, in case of a copper cathode, is of the order of 0.1 mm mrad.

In this configuration the RMS parameters of the electron beam exiting the photo-injector are listed in Table 1. Figure 1 illustrates the transverse and longitudinal phase space at the

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photo-injector exit, while the slice analysis in terms of beam emittance and peak current - adopting a 10 µm slice length - is reported in Fig. 2.

Table 1: Main RMS Electron Beam Parameters at Laser Heater Entrance Obtained by Means of Simulations

Parameters	RF Photo-Injector Exit
Charge [pC]	75
Energy [MeV]	126
Energy spread [%]	0.11
Transverse emittance [µm]	0.12
Length [µm]	380
Peak current [A]	20

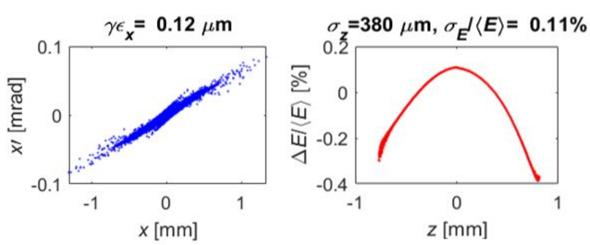

Figure 1: Transverse and longitudinal phase space at the photo-injector exit.

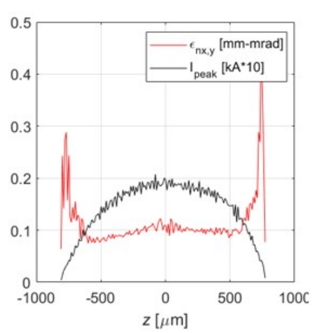

Figure 2: Slice analysis in terms of beam emittance and peak current - adopting a 10 µm slice length.

THE 2.5 CELL C-BAND GUN

The new 2.5 cell gun has been introduced, instead of the 1.5 cell design reported in [5], to face with the limitation on the peak field at the cathode forced by the high rep rate operation - 160 MV/m at 1 kHz rep rate. The RF injector design here described starts from the SwissFEL-like photo-injector [6], based on a 2.5 cell S-band gun operating at 80-100 MV/m, and from the well-known wavelength scaling laws [7] and is able to provide final beam parameters compliant with the XLS goal ones. Also with this configuration, the drift between the booster linac and the cathode plane results to be 1.5 meter, almost doubled with respect to the layout illustrated in [5], making room for the beam characterization after the gun.

The gun is fed with short RF pulses (τ < 300 ns) and the coupling with the input waveguide is axial, through the last iris, with a mode launcher [8] a device able to convert a rectangular TE10 mode to a circular TM01 mode. These two implementations allow to contemporary reduce the pulsed heating (that scales with the square root of the RF pulse length), the breakdown rate (that scales with τ^5), the average dissipated power and the surface magnetic field on the input coupler. Also, the introduction of a mode launcher opens to an increased flexibility in positioning the input waveguide relative to the gun body that turns in more powerful cooling capability of the accelerating cells especially useful for the high repetition rate operation. The gun design, with the mode launcher, and the on-axis electromagnetic field are reported in Fig. 3. This layout also presents two main disadvantages: the continuation of the electromagnetic field in the mode launcher region, that can affect the beam dynamics, and a more challenging design for the gun solenoid requiring a bigger bore and the introduction of a bucking coil to zero the field at the cathode in order to reduce the magnetic field contribution to the emittance of the emitted beam.

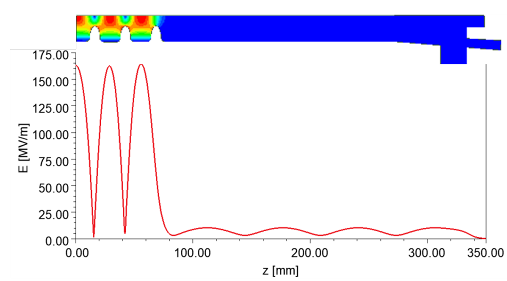

Figure 3: Magnitude of the longitudinal field on axis and gun geometry simulated by ANSYS-HFSS.

BEAM DYNAMICS STUDIES

The investigation of the effects of the e.m. field tails in the mode launcher region on the beam quality has been performed by means of 3D simulations with the ASTRA code.

Longitudinal Beam Dynamics

The longitudinal beam dynamics is mainly affected by the fluctuations of the fields in the mode launcher. It has been studied by means of both numerical integration methods and simulations and the result is an energy oscillating evolution around a mean value with a final energy slightly higher than the ideal case. The Fig. 4 illustrates the beam energy evolution in the gun region with (red) and without (blue) the insertion of the mode launcher calculated by means of the numerical integration method (lines) and simulations (dashed-lines).

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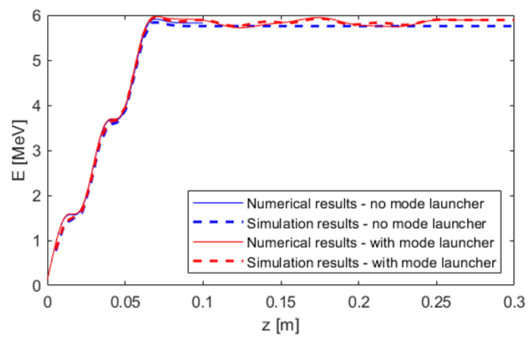

Figure 4: Beam energy evolution in the gun region with (red) and without (blue) inserting the mode launcher calculated by means of the numerical integration method (lines) and simulations (dashed-lines).

Transverse Beam Dynamics

The transverse beam dynamics has been studied by using 3D field maps in order to avoid any assumption of the cylindrical symmetry of the mode launcher. The residual numerical noise of the 3D field maps can lead to fictitious contributions to the beam quality in terms of transverse beam asymmetry and emittance increase. Simulations have been performed in case of a cylindrical symmetric gun geometry with and without a coaxial mode launcher in order to quantify and distinguish the magnitude of the beam quality worsening due to the numerical noise calculation and to the mode launcher insertion. The Fig. 5 illustrates the evolution of the beam transverse spot size (left) and emittance (right) through the injector with and without the insertion of the mode launcher. Looking at these figures one can conclude that the beam quality deterioration is mainly due to the residual numerical noise of the field maps.

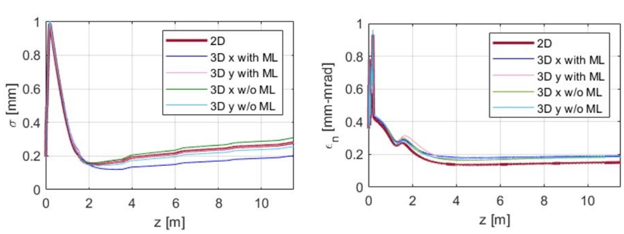

Figure 5: Evolution of the beam transverse spot size (left) and emittance (right) through the injector with and without the insertion of a coaxial mode launcher.

Different configurations have been considered for the mode launcher. The final layout relies on a fully symmetric four port waveguide mode launcher so to avoid spurious and unwanted quadrupolar component of the field. The Fig. 6 illustrates the evolution of the beam transverse spot size (left) and emittance (right) through the injector with the insertion of a coaxial (red lines) and a four port (blue lines) mode launcher. The study suggests that the effect on the beam quality are not quantifiable and that one can account for a complete recovery of the beam quality by suppressing the numerical noise or by inserting some skew quadrupoles just after the gun, if still needed.

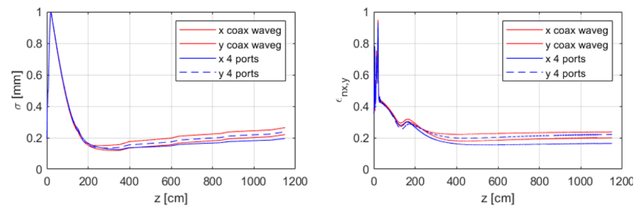

Figure 6: Evolution of the beam transverse spot size (left) and emittance (right) through the injector with the insertion of a coaxial (red lines) and a four port (blue lines) mode launcher.

CONCLUSION

A C-band photo-injector based on a new 2.5 cell C-band gun has been proposed and results suitable for the XLS collaboration conceptual design study. The beam dynamics has been extensively investigated also including the effect on the beam quality of the project of a gun which will be fed by a mode launcher, breaking the cylindrical symmetry of the device. Finally, the study has shown that the adoption of a four port mode launcher would help preventing from affecting negatively both the transverse and longitudinal beam quality. In the future, the study will include the insertion of skew quadrupole in order to correct any spurious quadrupolar component of the fields.

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