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Effects of oblique impinging of optical pulsed on performances of RF photo-injectors.

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Abstract

In this report we present the analysis of the effects of oblique impinging of laser pulse onto photo-cathodes on the performances of a typical RF photo-injector. The layout (that of SPARC experiment) is aimed at minimizing the emittance growth due to space charge effects. The numerical code used for simulations is TREDI.

INTRODUCTION

In the last decade, laser driven photo-injectors have become essential devices in all applications requiring high brightness electron beams. In the case of FELs the role played by emittance becomes crucial at sub-nm wavelengths where the emittance is related to the transverse coherence of the output radiation. Most of the emittance growth affecting the beam at the undulator is produced at the injector in the first stages of the beam acceleration. The emittance optimization procedure rely on a well established linear theory[1] which has been verified both experimentally and numerically. The optimized working point is the result of a careful design based on the assumption of highly ideal conditions (e.g. flat time structure, steep boundaries of the optical pulse impinging onto the cathode, perfect axi-symmetry of both electron beam and fields, homogeneous transverse structure of the bunch, etc), which can at the best be only partially fulfilled in practise. Many of the sources of emittance growth are genuinely three-dimensional effects, usually not accounted for by many of the available numerical codes. The results presented here have been obtained with the parallel version of TREDI[2] code. As a last remark, it should be noted that while TREDI can take into account "retarded" effects (i.e. associated to finiteness of signal propagation within the bunch), the results discussed below were derived in "static" approximation, that is assuming that self-interaction within the bunch propagate instantaneously.

PROBLEM DESCRIPTION

In order to study the effect of oblique impinging we have considered the layout of SPARC[3]experiment, with a standard S-Band (2856 MHz), 1.6 cells, BNL type photo-injector configuration[5], and a focusing solenoid counteracting space charge effects followed by a drift and TW cavities for further acceleration. In absence of linac sections, a characteristic emittance double minimum[?] is expected to occur at the end of the drift. Theory dictates that careful placement of first accelerating structure at the position of the local maximum between the minima is the optimal choice to postpone the second emittance minimum at the end of acceleration. The actual working point needs to be optimized by tuning accelerating gradient, extracted charge, extraction RF phase, beam spot size, focusing solenoid strength etc. A crucial point is the requirement that both transverse and longitudinal (time) charge profile be flat at extraction. In the case considered the charge extracted is -1.1nC, the longitudinal (time) pulse has a duration of ≈ 11.25ps (see fig. 1) and a spot radius $R = 1.13$mm. The extraction RF phase for the centre of the bunch is 32^{o}. No thermal emittance is included. The layout parameters are resumed in table 1.

Table 1: Photo injector parameters.

Peak accelerating field	100-120 MV/m
Frequency	2.856 GHz
Phase (beam centre)	32^{o}
Charge	-1.1 nC
Laser spot radius (homogeneous)	1.13 mm
Laser pulse length (flat-top)	11.2 ps
Focusing solenoid peak field	2.73 kG

In figure 2 the longitudinal section of a typical 1.6 cell, BNL type RF-gun as the one used in SPARC[3] experiment is shown, with the optical beam impinging onto the photo-cathode through the laser port forming a 72^{o} angle with the normal to the cathode's surfacte itself. There are basically two unwanted effects:

- the laser beam (which possess usually a circular symmetry) produces onto the cathode an elliptical spot;
- the side of the cathode closer to the entrance laser port starts to emit at earlier times.

While correction of the first effect can be achieved fairly easily by means of cylindrical lenses, the "time slew" effect is usually removed by means of a reflective grating tilting the wave front to be parallel to the surface of the cathode. The figure 3 sketches the situation for the uncorrected (upper, optical wave front orthogonal to the propagation vector) and corrected (lower, wave front parallel to the cathode surface) cases, respectively. It should be kept in mind that such a grating may pose severe limitations to the energy budget available (i.e. the maximum charge that can be extracted). For this reason we examine hereafter the case in which only the ellipticity of the optical pulse is corrected.

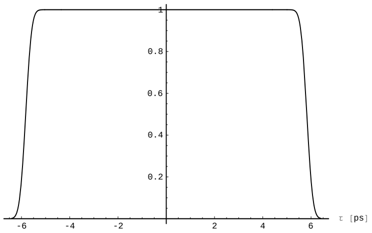

Figure 1: Longitudinal (time) profile of the laser pulse impinging onto the cathode.

In the study the code was run with quite a large number of macro-particles ($\approx 1 \cdot 10^5$). In the cases examined the angle at which the laser pulse impinges onto the cathode was varied from $\theta = 12^{o}$ to $\theta = 72^{o}$. The emphasis is devoted to the normalized rms emittance. For the nominal case ($\theta = 0^{o}$), a previous comparison with other codes has shown a good agreement[6].

RESULTS

In figure 4 is shown the time profile of the laser pulse as it illuminates the cathode. The lenghtening due to oblique incidence for $\theta = 72^{o}$ is $\approx$ 6ps. Setting aside genuine 3D effects, time profile distortion translates to a big rise/fall times of $\approx$4ps. While this is not of major concern whenever one adopts laser pulses with a gaussian longitudinal structure, it is well known that small rise/fall times are critical to optimize performances of layouts based on flat-top time profiles.

Of course fig. 4 does not tell the whole story:

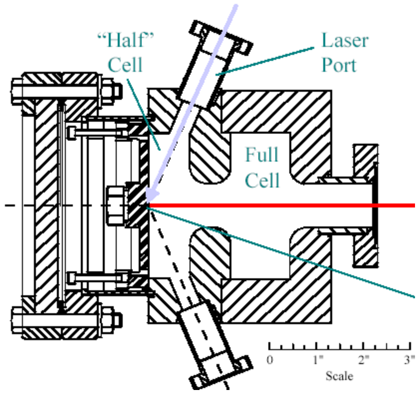

Figure 2: Section of a 1.6 cell, BNL-type RF-gun with symmetrical injection and virtual cathode ports. In this case, the laser beam forms a 72° angle with the electron beam direction.

the points of any uncorrected wave front reach the cathode at different times. This effect is clear (fig.5) where are shown the 2D transverse (left) and transverse-longitudinal (right) spaces of the 1^{st} beam slice extracted. In the transverse space charge density is higher on one side, the excess being visible as well as a rarefied halo of charge extracted and accelerated pristinely in the transverse-longitudinal (transverse-time) space. In fig. 6 the same picture is diplayed after completion of the extraction process. The transverse space has recovered a (projected!) axi-symmetry, but longitudinally is clear that a portion of the bunch detached earlier from the cathode. In order to tell the effects of pulse broadening on emittance from those of 3D bunch distortion two distinct cases have been considered assuming:

- 2D, axi-symmetric case: only the temporal profile is affected;
- 3D full fledged case: both the temporal profile lenghtening AND bunch spatial distortion space is included.

In both cases simulations were continued to the end of the three TW accelerating structures to reach the nominal Sparc energy of 155 MeV.

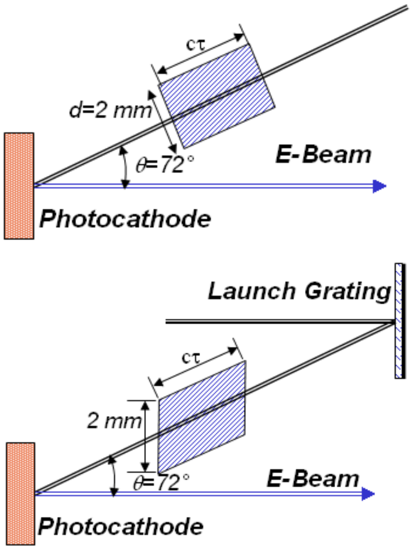

Figure 3: The "uncorrected" (upper) and "corrected" (lower) casea, with pulse wave fronts forming an angle and parallel with repsect to the cathode's surface, respectively.

In Figs. 7 and 8 the behaviour of the emittance as a function of the extraction RF phase and focusing solenoid magnetic field, respectively, is plotted vs longitudinal coordinate. It can be seen that the pulse lenghtening *per se* does not alter the optimal parameters ($\phi = 32^o, B_{\rm peak} = 2.74$kG) but dilutes substantially the emittance.

Strong non-linearities are clearly responsible for the emittance growth, as can be easily inferred from transverse and longitudinal spaces after the three TW accelerating structures (fig.10). The bunch is highly distorted with respect to the "canned beer" shape needed to keep emittance small. As a final remark it should be considered that although projected quality parameters are highly degraded, a slice analysis shows (see fig. 11) that in the central part the bunch emittances and currents remain well under 1mm·mrad and above 95A, respectively.

All the simulations described in this report were run on the parallel cluster set up with Eurofel funding at ENEA-Frascati Computer Center as one of the

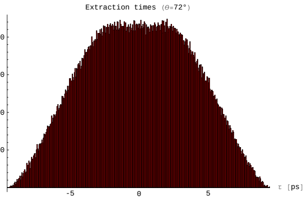

Figure 4: Longitudinal (time) profile of the laser pulse impinging onto the cathode at an angle of $\theta = 72^{\text{o}}$. The distribution shown has been used for the generation of extraction times of the macroparticles from the cathode. The overal duration is ≈6 ps longer than in fig. 1, with a long rise/fall time of ≈4ps.

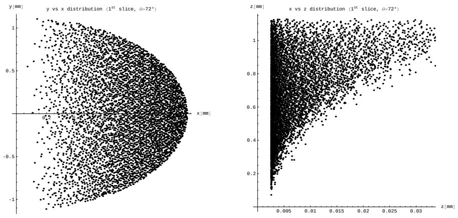

Figure 5: Transverse ($x - y$, left) and $x - z$ (right) space of the 1^{st} charge slice extracted from the cathode. Coordinate system is oriented in such a way that the laser pulse comes prom $+x$ direction.

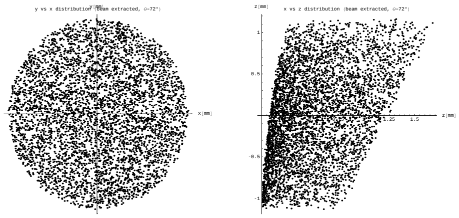

Figure 6: The same as fig. 5, after complete extraction of the bunch.

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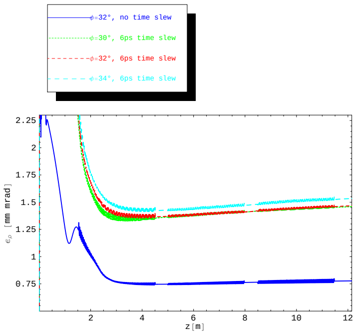

Figure 7: Effect of pulse lengthening on emittance. The optimal phase is not changed from its value ($\phi = 32^o$), yet the minimum emittance almost doubles. No 3D bunch distortion was included in the simulation.

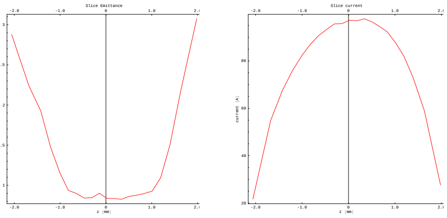

Figure 11: Slice emittance (left) and current (right) as a function of the longitudinal coordinate along the bunch after the 3 TW accelerating structures.

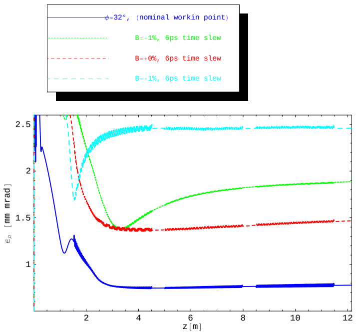

Figure 8: Effect of pulse lengthening on emittance for slightly different strengths of the focusing solenoid. The optimal value of the magnetic field is left unchanged by the time lenghtening of the pulse. No 3D bunch distortion was included in the simulation.

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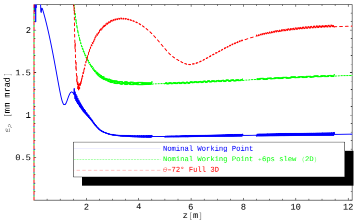

Figure 9: Comparison of the optimal working point (blue) with the case including the 2D effect of pulse lenghtening (green) and the full 3D effect of bunch spatial distortion (red).

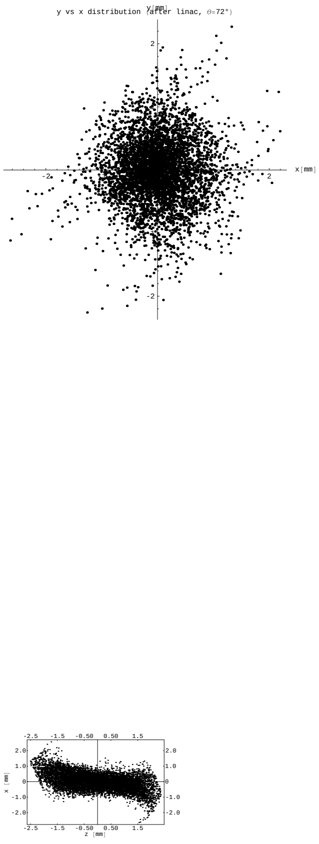

Figure 10: Transverse (upper) and longitudinal ($x-z$) space after the 3 TW accelerating structures.