HIGH BRIGHTNESS C-BAND AND X-BAND PHOTOINJECTOR CONCEPTS AND RELATED TECHNOLOGICAL CHALLENGES

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Abstract

Future light sources based on high gain free electron lasers, require the production, acceleration and transport up to the undulator entrance of high brightness (low emittance, high peak current) electron bunches. Wake fields effects in accelerating sections and in magnetic bunch compressors typically contribute to emittance degradation, hence the photo-injector design and its operation is the leading edge for high quality beam production. The state of the art photoinjector beam brightness can be in principle brought close and above the 10^{15} A/m^2 threshold with C-band and X-band guns and a proper emittance compensation scheme. We discuss in this paper optimized designs of split C-band and X-band photoinjectors and the further technological developments required to reach such an appealing goal.

INTRODUCTION

The optimization of a FEL source is quite a complicated task [1] but the main requirement for the electron beam in order to achieve short wavelength radiation in a reasonable long undulator (30-100 m) is clear: high transverse brightness. Transverse beam brightness is defined hereafter with the approximated [2] expression:

$$B_\perp \approx \frac{2I}{\varepsilon_{n,x}\varepsilon_{n,y}}$$

where I is the bunch peak current and ε_n is the bunch transverse normalized emittance. The expected transverse brightness for electron beams driving short wavelength SASE FEL facilities is of the order of 10^{15} – 10^{16} A/m^2. Wake fields effects in accelerating sections and in magnetic bunch compressors typically contribute to emittance degradation, hence the photo-injector design and its operation is the leading edge for high quality beam production. In a photoinjector the emitted electrons are rapidly accelerated to relativistic energies, thus partially mitigating the emittance growth due to space charge effects that is the dominant source of emittance degradation in a high brightness photoinjector. One of the key feature that make RF photoinjectors so actractive is that the emittance growth is reduced when operated at high peak field as the one achievable in the RF gun: up to 140 MV/m in a S-band gun. In addition the technique termed “emittance compensation” [3] has been experimentally verified in many laboratories and theoretically well understood [4].

A lot of efforts has been done in the last years at SPRING-8 and SLAC in the context of the high frequency normal conducting linear collider development, in order to achieve high accelerating gradient in C and X-band accelerating structures. Accelerating gradient in multi-cell TW accelerating structures as high as 40 MV/m (C-band) and 100 MV/m (X-band) has been so far achieved with low breakdown rate. In a different context an X-band standing wave 5.5 cells photoinjector has been developed at SLAC as a compact electron source for Thomson backscattering experiments. As reported in [5] a peak field on the cathode surface of 200 MV/m has been achieved.

The decision to adopt L-band superconducting technology for the next International Linear Collider (ILC) has somehow damped the effort towards high frequency structures development. More recently the choice to adopt X-band technology in the framework of the CLIC project [6], which has a less tight temporal time schedule than ILC, has open up again the interest towards X-band high gradient cavity R&D. FEL sources driven by high brightness linacs will certainly take profit from this new effort in the linear collider community, in particular for the possibility to develop high gradient photoinjectors. To this end we discuss in this paper possible designs of high frequency RF photoinjectors based on C-band or X-band technology, able to produce beams with brightness as high as 10^{15} A/m^2 directly from the injector and the related technological developments required to reach such an appealing goal

SCALING APPROACH TO HIGH FREQUENCY PHOTOINJECTORS

We decided to investigate a split photoinjector configuration, consisting in a 1.6 cells standing wave RF gun followed by a booster, because it is a well know scheme in the L and S band projects and also because is a promising design to achieve ultra-high gradients operating at higher frequency: the reduced wall surfaces implies a lower probability for surface defects that may cause RF breakdown. Another possible scheme has been presented in [17]. In addition following the matching condition discussed in [4] a working point very suitable to damp emittance oscillations has been found [7]. As any well optimised design it can be easily scaled [8,9] to any other frequency, gradient or charge design.

As a reference design we have taken the S-band (2856 MHz) SPARC [15] photoinjector. In its ideal configuration the beam consists in a uniform charge distribution inside a cylinder of length L and radius R, and we have scaled its parameters (charge Q, beam sizes

R and L, peak RF field $\hat{E}$ and solenoid field B) to its second (C-band) and fourth (X-band) harmonic frequencies (5.712 GHz and 11.424 GHz respectively) according to the following wavelength scaling laws [8]:

$$Q \propto \lambda_{rf} \ , \ R, L \propto \lambda_{rf} \ , \ \hat{E} \ \propto \lambda_{rf}^{\ -1} \ , \ \hat{B} \ \propto \lambda_{rf}^{\ -1}$$

As discussed in [8] both the space charge and RF contributions to the total rms emittance scale with λ_{rf}, in addition since the thermal emittance contribution scale with the beam radius we can expect a similar scaling also for $\varepsilon_{th} \propto \lambda_{rf}$. Hence operation at shorter wavelength results a very convenient choice also for the beam brightness: $B_n \propto \lambda_{rf}^{-2}$ [8].

Tab I: Original and scaled parameters

Freq. [GHz]	Q [nC]	R [mm]	L [ps]	E_{peak} [MV/m]	B [T]
2.856	1	1	10	120	0.275
5.712	0.5	0.5	5	240	0.55
11.424	0.25	0.25	2.5	480	1.1

A direct application of the previous scaling laws leads to the set of new parameters, reported in table I. In addition, to fulfil the scaling approach, also the solenoid length has to be scaled with λ_{rf}, from the original 20 cm long solenoid for the S-band gun design to 10 cm for the C-band case and to 5 cm for the X-band gun case, see figure 1.

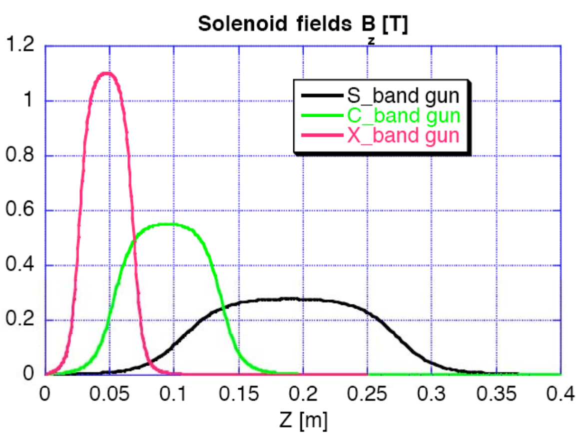

Figure 1: Solenoid fields for the original S-band gun design (black line), the C-band design (green line) and X-band design (red line).

C-BAND PHOTOINJECTOR CASE

HOMDYN simulations for the full C-band injector (1.6 cell RF gun 7. cm long, followed at z = 1 m by 3 C-band travelling wave accelerating structures operating at 40 MV/m accelerating field) show for this case an emittance of 0.49 μm, as reported in figure 2, with a peak current of 92 A, corresponding to a brightness of B_n of 7.7 10^{14} A/m^2, a factor 4 higher than the corresponding S-band design [7]. In this and in the following cases we have assumed a thermal emittance of 0.6 μm/mm for a copper cathode [16].

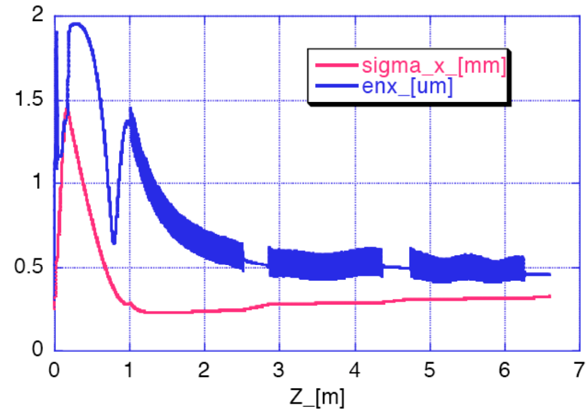

Figure 2: Envelope and rms norm. emittance evolution from the cathode up to the booster exit at 180 MeV for the C-band case.

X-BAND PHOTOINJECTOR CASE

The X-band scaling implies RF and solenoid fields that are too far from the state of the art to be realistic, see Tab. I. A first attempt towards a more realistic design can be done by reducing the solenoid field to 0.575 T and increasing its length, from 5 cm to 10 cm, basically the same solenoid adopted for the C-band case. HOMDYN simulations for the full X-band injector (1.6 cell RF gun, 3.75 cm long, followed at z = 0.6 m by 3 X-band travelling wave accelerating structures of the SLAC type, operating at 56 MV/m accelerating field) show for this optimistic case an emittance of 0.27 μm, as reported in Figure 2, with a peak current of 90 A, corresponding to a brightness of B_n of 2.5 10^{15} A/m^2.

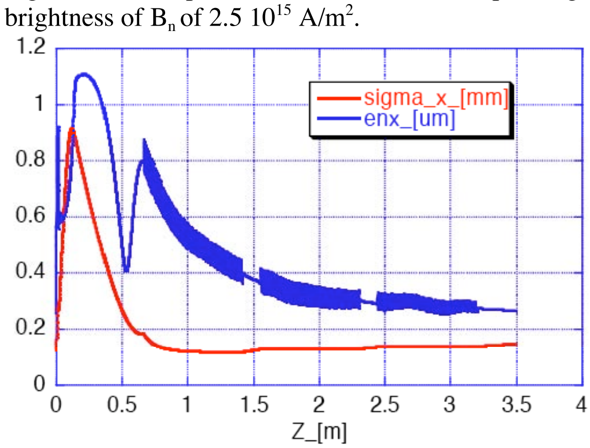

Figure 3: Envelope and rms norm. emittance evolution from the cathode up to the booster exit at 130 MeV for the X-band case.

Again scaling laws can help us to re-optimize the injector parameters in order to obtain a less challenging RF peak field, another important step towards a more realistic design. A reduced gun peak field results in a lower energy gain, hence we have to apply the energy scaling laws derived in [9]:

$$\hat{B} \propto \gamma \ , \ R \propto \gamma^{-2/3} \ , \ L \propto \gamma^{-5/3}$$

Aiming to reduce the peak filed from 480 MV/m to 350 MV/m (reducing the beam energy at the gun exit from 5.5 MeV down to 4.1 MeV) the new parameters computed with the previous equations are reported in table II:

Tab II: Original and scaled parameters

Freq. [MHz]	Q [nC]	R [mm]	L [ps]	E_{peak} [MV/m]	B [T]
11.424	0.25	0.25	2.5	480	0.575
11.424	0.25	0.31	4.2	350	0.420

Envelope and emittance evolution as computed by HOMDYN are reported in figure 4. The final emittance is practically unchanged compared to previous case, resulting 0.28 μm, while the peak current is affected by the lower energy bunch elongation in the drift, resulting 58 A. The corresponding brightness is nevertheless quite high $B_n = 1.5\ 10^{15}$ A/m^2.

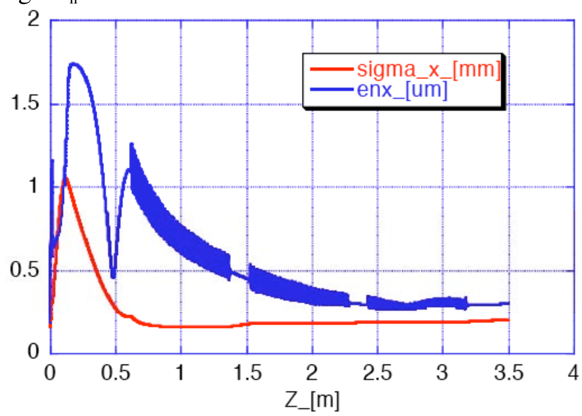

Figure 4: Envelope and rms norm. emittance evolution from the cathode up to the booster exit at 120 MeV for the X-band case with reduced gun peak field .

TECHNOLOGICAL CHALLENGES

In table III are reported for comparison the RF parameters for the S, C and X band guns. As one can see the required peak power from RF source are within the state of the art C and X-band klystron development.

Tab III: RF gun parameters

ν [Ghz]	2.856	5.712	11.424
R_{sh} [MΩ/m]	46	65	92
Q	15335	10843	7668
E_{peak}[MV/m]	120	240	350
P_{RF} [MW]	10	14	10
P_d at 10 Hz [kW/m]	2.6	3.7	2.6
τ [μs]	4	2	1
L_{cav} [cm]	15	7.5	3.75

A serious concern is the compensation scheme to protect the klystron port from RF power reflections since circulators/isolators are not available in C and X-band. A possibility to protect the RF source from reflections is to use a 90 deg hybrid junction as sketched in Fig. 5. The scheme foresees the use of two SW cavities: the gun and a second compensating cavity that can be installed in the injector for acceleration. A first analysis of the sensitivity of such a scheme with respect to the cavity parameters or waveguide electrical length has shown that this solution is not critical. The scheme is commonly implemented in the SLED cavities and has been already and successfully applied to compensate reflections in SW structures for particle accelerators, as illustrated in [10]. It allows to perfectly compensating the "steady state" reflections given by the cavity but it does not allow eliminating the reflected power from discharges or breakdown in one of the two cavities. A second possible scheme is illustrated in Fig. 6. In this case the klystron is coupled to the SW gun through a directional coupler. The power from the source is split in the two waveguide branches: a fraction A(<1) of the input power feed the gun while the fraction (1-A) is dissipated into a load or can feed a matched TW section. In this case, if a discharge occurs in the SW gun the reflected power to the source is, at maximum, a fraction A^2 of the klystron initial output power and can be acceptable if the directional coupler is properly designed. This scheme allows compensating both "steady state" reflected power than that given by a discharge in the SW gun.

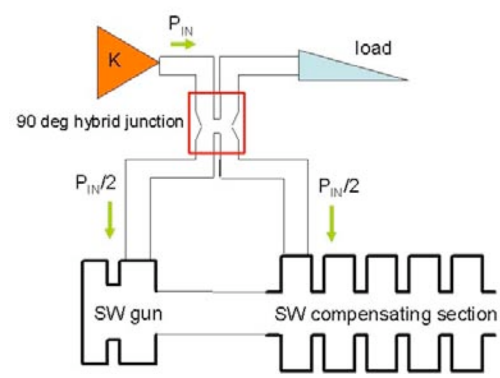

Figure 5: Possible scheme with a 90 deg hybrid junction to protect the klystron from SW gun reflections.

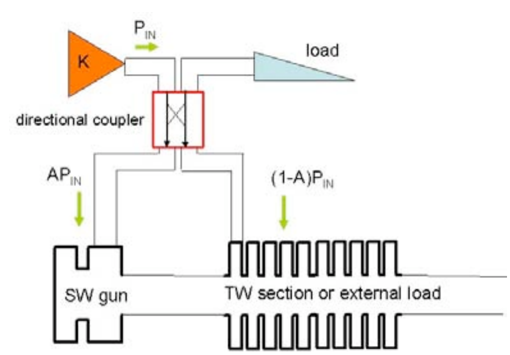

Figure 6: Possible scheme with a directional coupler to protect the klystron from SW gun reflections.

The request of high peak field in the gun cavity is the main challenge at least for the X-band case. It has been demonstrated that a way to increase the RF fields inside the accelerating structure is the use of Molybdenum for cavity irises [11]. An R&D activity on this direction has been recently started also at INFN-LNF [12] in order to define the best brazing geometry among Mo irises and Cu structure [13]. Electroformed structures [14] are also under study at LNF and a first test of deposition of Mo over Cu in a 4 cells X-band structure has been already successfully done, see figure 6. The lack of X-band power sources at the moment prevents us to perform high power RF tests.

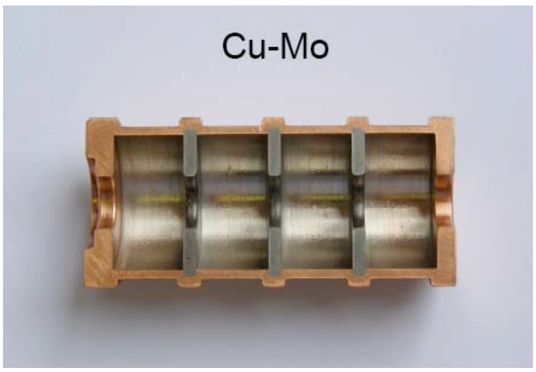

Figure 6: A Mo-Cu electroformed structure produced at INFN-LNF.

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