START-TO-END BEAM-DYNAMICS SIMULATIONS OF A COMPACT C-BAND ELECTRON BEAM SOURCE FOR HIGH SPECTRAL BRILLIANCE APPLICATIONS

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Abstract

Proposals for new linear accelerator-based facilities are flourishing world-wide with the aim of high spectral brilliance radiation sources. Most of these accelerators are based on electron beams, with a variety of applications in industry, research and medicine such as colliders, freeelectron lasers, wake-field accelerators, coherent THz and inverse Compton scattering X/γ sources as well as highresolution diagnostics tools in biomedical science. In order to obtain high-quality electron beams in a small footprint, we present the optimization design of a C-band linear accelerator machine. Driven by a novel compact C-band hybrid photoinjector, it will yield ultra-short electron bunches of few 100's pC directly from injection with ultralow emittance, fraction of mm-mrad, and a few hundred fs length simultaneously, therefore satisfying full 6D emittance compensation. The normal-conducting linacs are based on a novel high-efficiency design with gradients up to 50 MV/m. The beam maximum energy can be easily adjusted in the mid-GeV's range. In this paper, we discuss the start-to-end beam-dynamics simulations in details.

INTRODUCTION

Electron beams with high peak currents and ultra-low normalized emittances, therefore ultra-bright, are essential for the new linear accelerator-based facilities promising numerous applications, such as electron-positron or photon-photon colliders [1,2], X-ray free-electron lasers [3,4], wakefield accelerator experimentation, coherent THz and inverse Compton scattering X-ray or γ-ray sources [5]. Other applications reside in the field of biomedical science, where low emittance photon beams are used to obtain high quality images for diagnostics due to the increased resolution and contrast they can provide [6, 7]. In order to obtain high brightness electron beams, photoinjectors [8-10], in which electron bunches are generated from the cathode metallic surface by illumination via a femtosecond-to-picosecond laser, have been the essential instrument in worldwide use for that last three decades.

RF DESIGN OF THE HYBRID PHOTOINJECTOR

The proposed *hybrid* RF photoinjector is composed of a photocathode embedded in an initial 2.5 gun cell standing-wave (SW) section connected through an input coupling cell directly to a traveling-wave (TW) section (see Fig. 1).

The are several advantages of this hybrid system compared with conventional split SW/TW injectors:

- Cancellation of RF reflections from the SW section (no circulator needed);
- Bunch lengthening effect, due to the ballistic drift, is reduced (the cell that couples the two structures replaces the long beam pipe and matching-section following the RF gun);
- The RF coupling between the SW and the TW sections optimally results in a 90 deg phase shift of the accelerating field → strong velocity bunching effect applied to the beam;
- Production of very short bunch lengths, over an order of magnitude smaller.



Figure 1: electromagnetic model of the gun.

The RF design was performed with the Ansys 3D code [11]. The main RF parameters are given in Table 1, and previously reported in [12-14]. The required rf input power is about 40 MW in order to obtain a peak surface electric field at the cathode equal to 120 MV/m. The ratio between the SW on-axis peak electric field and the average TW electric field is equal to $E_{z,p,SW}$ /($E_{z,TW}$) = 3.25, where

 $E_{z,p,SW}$ is also the maximum field value E_{max} of the on-axis accelerating electric field.

In order to improve the power efficiency of the hybrid photoinjector, we have also investigated a tapered TW section and it was possible to reduce rf input power to about 20 MW versus the 40 MW required for the original design.

Table	1:	Main	Parameters	of the	e C-band	Photoinjecto	or

RF Parameter	SW	TW
Operation mode	π	2π/3
Quality factor,	9,900	9,900
Q		
Eff. shunt	$52 \text{ M}\Omega/\text{m}$	65 MΩ/m
impedance, R _{sh}		
Mode	21.5 MHz	40 MHz
separation		
Build-up time, $ au$	530 ns	-
Group velocity,	-	2.73 %
v_g		
Attenuation, α	-	0.23 m^{-1}
Filling time, T_f	-	21.3 ns

The on-axis electric field amplitude profile and phase distribution are shown in Figs. 2 and 3, respectively. The $\pi/2$ phase-shift between the SW and TW section, a particular feature of this hybrid structure, allows for velocity bunching thus obtaining ultra-short beams.

The photoinjector prototype has been recently fabricated and tested with high RF power. The preliminary beam measurements have also been carried out, showing good agreement with simulations. Results will be published in a forthcoming paper.

BEAM DYNAMICS SIMULATIONS

The start-to-end simulations were carried out with the GPT code [15] and details are found in [16]. The beam input parameters are listed in Table 2. The beam exit energy is about 4 MeV. Two energy scenarios are investigated:







Figure 3: On-axis electric field phase distribution.

medium-energy (220 MeV) for the Compton source and high-energy (400 MeV) for the FEL scenario, in which case the photoinjector is followed by eight high-gradient Tantawi-style C-band linacs at 50 MV/m [17].

All parameters were optimized in order to obtain beam emittance minimization, to $\epsilon_n = 0.5$ mm-mrad. This condition is reached simultaneously with bunch compression down to $\sigma_z = 200$ fs.

More in-depth beam slice analysis and wakefields/beam break-up studies can be found in [18, 19].

COMPTON AND FEL APPLICATIONS

In Fig. 4 are shown the RMS beam sizes σ_x and σ_y in the inverse Compton scattering (ICS) system operated at 220 MeV, from GPT start-to end simulation. The focal



Figure 4: RMS beam sizes σ_x and σ_y in the ICS system operated at 220 MeV, from GPT start-to end simulation.

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system is composed of a tunable permanent magnet triplet array with lengths of 6 cm - 12 cm - 6 cm and nominal gradients of 102 T/m - 94 T/m - 102 T/m, respectively. The interaction region which illustrates the predicted very compact (below 9 µm) spot sizes.

Table 2: Beam Dynamics Simulations Beam Input Parameters

Parameter	Value		
Beam Charge, Q	250 pC		
Spot sizes, $\sigma_{x,y}$	500 μm		
$(\operatorname{cut}@1\sigma)$			
Laser Pulse Length	0.5 ps		
E-field at cathode	120 MV/m		
# particles	50,000		

Due to the considerable longitudinal compression the hybrid design imparts, the corresponding high peak current is beneficial for an x-ray FEL, in terms of the gain length and photon-per-pulse output. Linear transformations matching the transverse phase-space orientation were performed to optimize the gain through an 8 m FD lattice with 15 T/m quadrupoles in GENESIS. These optimal matching dimensions, along with other relevant simulation parameters, are reported below in Table 3. The GENESIS simulation results, as shown in Fig. 5, indicate saturation and lasing at $\lambda = 6.0$ nm, with a mean single shot energy output of 62 µJ.

Table 3: FEL Simulations Input Parameters

Parameter	Value	
Beam Charge, Q	250 pC	
Spot Dimensions, $\sigma_{x,y}$	22x15 μm	
Normalized Emittance, $\varepsilon_{n,r}$	0.5 mm-mrad	
Bunch Length, σ_z	190 fs	
Mean Energy, γmc^2	400 MeV	
Fractional Energy Spread	0.054 %	



Figure 5: Instantaneous gain length (orange) and laser power(blue) as calculated in GENESIS. The peak power at saturation is approximately 830 MW.

Moreover, by adding two more linac sections (thus increasing to the final energy and permitting off-crest operation in part of the linac) and a compact (~ 1 m) chicane, we can enable a soft x-ray FEL operating in the water window at $\lambda = 4$ nm. The increased current has a dramatic effect on the peak power (4.2 GW is predicted).

CONCLUSIONS

We have presented a new class of a compact hybrid (SW/TW) photoinjector, operating in C-band at 5.712 GHz with an electric field of 120 MV/m at the cathode. Such an electron source is meant for next generation linac accelerator-based research facilities.

The RF design and beam dynamics analysis have been performed in order to obtain a full 6D emittance compensation (both on the transverse and longitudinal planes) with a 250 pC electron bunch. There is a large number of advanced scenarios for the application of the compact C-band hybrid photoinjector, e.g. wakefield accelerators, THz sources and applications requiring a compact mobile source. We have simulated two applications: examination as the injector of an intermediate-energy (220 MeV) ICS monochromatic gamma-ray source, which takes advantage of the beam focusability and its short pulse length. Indeed, we have studied a working point which utilizes a beam spot size less than 10 μ m at the interaction point located at less than 6 m from the cathode; investigation of a higher energy (400 MeV) soft X-ray FEL. Again with a modest footprint, we demonstrated the possibility of lasing at 4 nm, producing a compact water-window free-electron laser in 10 m length. For completeness we note that the utility of the hybrid injector in application is validated by studies of beam stability and alignment tolerances, issues which are more challenging in this very high-performance system.

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