Nuclear Instruments and Methods in Physics Research A 757 (2014) 1–6

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Design of a low emittance and high repetition rate S-band photoinjector

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ARTICLE INFO

Article history:
Received 26 March 2014
Received in revised form
21 April 2014
Accepted 28 April 2014
Available online 9 May 2014

Keywords:
Photoinjector
Low emittance
High repetition rate
Free-electron laser

ABSTRACT

As an electron beam injector of X-ray free-electron lasers (FELs), photoinjectors have been developed for the past few decades. Such an injector starting with a photocathode RF gun provides high brightness beams and therefore it is being adopted as an injector of X-ray FELs. In this paper we show how to improve photoinjector performance in terms of emittance and repetition rates by means of injector components optimization, especially with the gun. Transverse emittance at the end of an injector is reduced by optimizing the gun design, gun solenoid position, and accelerating section position. The repetition rate of an injector mainly depends on the gun. It is discussed that a repetition rate of 1 kHz at a normal-conducting S-band photoinjector is feasible by adopting a coaxial RF coupler and improving cooling-water channels surrounding the gun.

1. Introduction

During the past few decades, photoinjectors have been developed as high brightness electron sources for linac-based free-electron lasers (FELs) at several laboratories. Even with the limited duty factor, an injector consisting of a normal conducting photocathode RF gun and a normal conducting linac became an widely adopted option for X-ray FEL projects such as LCLS [1], PAL-XFEL [2] and SwissFEL [3] thanks to its ability to generate an electron beam with low transverse emittance and short bunch length. The possibility of variety operation modes, such as bunch charge and initial bunch length, is another merit of photoinjectors. Beam quality requirements at the injectors continue to rise as more advanced FEL schemes or performances are demanded. Any reduction of transverse emittance allows us to reduce the FEL gain length and to enhance the photon beam brightness. With a given maximum beam energy, a shorter FEL wavelength can be achieved with a smaller transverse emittance.

An RF photoinjector typically consists of an RF gun with a photocathode, a drive-laser, focusing solenoids, and accelerating sections (see Fig. 1). By using a drive-laser pulse for the beam generation at the cathode, an optimal initial shape of an electron beam can be obtained. A strong RF field accelerates immediately the beam emitted from the cathode from zero to a relativistic speed. The gun solenoid focuses the beam transversely and aligns the longitudinal slices of the bunch in transverse phase space so that projected emittance growth is minimized [4]. With the help of the accelerating sections, the beam becomes fully relativistic at the end of the injector and the space charge effect does not spoil the beam transverse emittance.

One and half cell guns are popular as a high brightness electron source. Their structures are simple for manufacturing and tuning. They also require relatively low RF power from the high power RF source (e.g., klystron), which eases the RF heating of the RF window and the high power RF coupler. Electron beams from such guns reach a few MeV beam energy, so that the space charge effect does not deteriorate the beam quality significantly. In this injector design, we adopt an S-band (2.998 GHz) photocathode gun with one and half cells.

Technical issues of the cathode and the drive-laser are not discussed in this paper in detail. The cathode front surface is assumed to be perfectly flat so that there is no thermal emittance increase due to the surface roughness [5]. The pulse shape of a drive-laser is assumed to be transversely uniform with hard edge. The longitudinal shape is flat-top with 1 ps rise/fall time. A 8 ps, corresponding to 8° of an RF cycle, fwhm length is chosen for 200 pC bunch generation. Actually, the length was optimized for maximum brightness after simulations with varying pulse lengths. When the length increases transverse emittance is further reduced by a little. However, the electron bunch length becomes longer and the beam brightness decreases. The kinetic energy of emitted electrons is 0.6 eV, which corresponds to a thermal emittance of 0.89 mm mm per 1 mm rms initial beam size.

An optimized gun design reduces the beam emittance. The efficiency of emittance compensation process can be improved when the position and the field strength of the injector components are optimized. In this paper, we discuss how to design practically

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http://dx.doi.org/10.1016/j.nima.2014.04.077

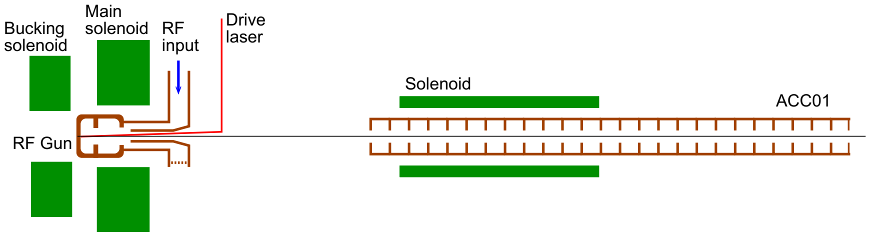

Fig. 1. Layout of the first part of the photoinjector consisting of an RF photocathode gun, focusing solenoids, an accelerating section. Two more identical accelerating sections (now shown) follow ACC01 for accelerating a beam to the ultra-relativistic regime.

and place the accelerator components, such as RF gun, solenoid, and accelerating sections, for best beam quality.

Since we aim at high repetition rate operation even with the low emittance injector design, the gradient of the accelerating section is set to be relatively low, which may not allow possible minimum emittance at the end of injector and maximum RF tolerance. With another RF gradient, a beam may experience different beam dynamics at the linac sections and better beam quality may be achieved.

2. RF gun

The RF gun, where an electron beam is generated, is the most crucial component in a photoinjector. An electron bunch is emitted from the cathode by a drive-laser pulse. The cathode is located at the center of the rear wall of the gun first cell. The emitted electron bunch is accelerated from rest to a relativistic speed by the strong RF accelerating field in the gun cavity. During the beam acceleration through the gun, space charge and position dependence of the RF field may increase the transverse emittance. Such effects can be minimized by a careful design of the gun as will be shown in this and the next sections.

The optimization of the BNL type of S-band (2.856 GHz) guns had been performed by increasing the length of the first cell in order to minimize the beam divergence and to maximize the compression factor (by making the beam launch phase be close to the 0-crossing phase) while producing a minimum impact on the emittance [6]. This gun has been adopted in the LCLS injector and it has provided high quality beams for the X-ray FEL [1]. The first and second cell lengths of the LCLS gun are $0.6432 \times \lambda/2$ and $1.0103 \times \lambda/2$, respectively, where λ is the RF wavelength [7].

During the last two decades, full space charge tracking codes became available, such as ASTRA [8] and IMPACT-T [9], and computing power for tracking simulation progressed dramatically. The gun cell length optimization issue had been revisited for the DESY type of L-band (1.3 GHz) guns [10,11] and later for an L-band (1.3 GHz) gun designed for the New Light Source (NLS) project [12,13] by seeking minimum emittance conditions. Those optimizations were carried out by repeating particle tracking simulations with ASTRA for various sets of first and second cell lengths.

The same method applied to the DESY and NLS L-band guns was used for finding an optimum first cell length for this S-band (2.998 GHz) gun. A set of field profiles for various first cell lengths was produced by using the SUPERFISH code [14]. Transverse emittance at the exit of the gun was simulated for the various first cell lengths with ASTRA (Fig. 2). The second cell was set to be half a wavelength (50 mm) because the emittance is less sensitive to the second cell length. For the comparison of the LCLS and DESY guns with these emittance simulations, the dimensions of both guns were scaled to 2.998 GHz and beam simulations were performed for the scaled LCLS gun (□ in Fig. 2) and DESY gun (△ in Fig. 2).

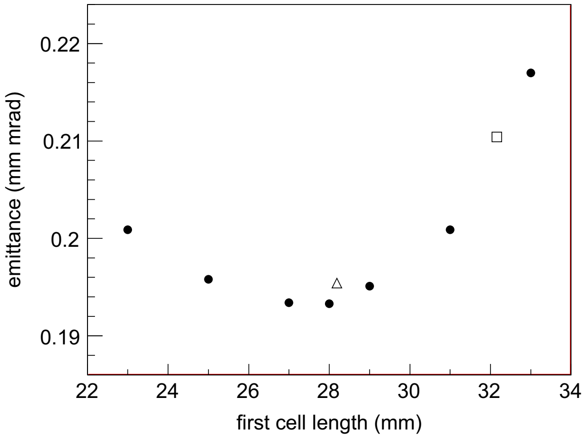

Fig. 2. Normalized transverse emittance at the exit of the guns for various first cell lengths and a fixed second cell length, $\lambda/2$, (●). The cases of the scaled DESY gun (△) and LCLS gun (□) scaled to 2.998 GHz are shown for comparison. ASTRA was used for the beam tracking simulations for 200 pC bunch. The main gun solenoid position was fixed to be 0.1 m from the cathode. The peak RF field at the cathode was 120 MV/m and the beam launch phase was chosen for the maximum beam energies at the exit of the guns. A flat-top laser temporal profile with 8 ps length and 1 ps rise/fall time was used. The gun solenoid field and the laser beam size were optimized for best emittance condition at each simulation point.

Emittance is minimum when the first cell length is 28 mm ($0.56 \times \lambda/2$). The DESY gun, which has $0.5638 \times \lambda/2$ first cell length and $1.0405 \times \lambda/2$ second cell length, was found to be close to the minimum emittance condition. The LCLS gun was found to have an emittance of 8% higher than the optimal case for the simulation condition of this injector design.

For the two cases of 28 mm and 33 mm first cell lengths, the emittances were calculated with ASTRA for various laser beam sizes (Fig. 3). The same laser temporal profile as above was used for these simulations. Compared to the 28 mm case, a larger laser beam is needed for the 33 mm case. For the longer first cell, the beam launch phase for maximum beam energy at the exit of the gun is shifted toward the zero-crossing phase [10–12]. Therefore, the RF accelerating field during beam emission becomes weaker and the space charge force should be reduced by enlarging the initial beam size. Intrinsic (thermal) emittance increases linearly with beam size and the final emittance tends to increase with beam size. As shown in Fig. 3 the emittance for the case of 33 mm first cell length and 0.13 mm rms laser beam size is relatively large because the beam expands quickly near the cathode. The emittance values for the 33 mm length become close to the cases of the 28 mm length as laser beam size becomes larger. The calculated emittance values are compared with the thermal emittance in Fig. 3. For the thermal emittance calculation 0.6 eV kinetic energy of photoemitted electrons, which produces 0.89 mm mrad per 1 mm rms laser beam size, was used. This thermal emittance is also included in the beam dynamics simulations in this paper.

The second issue of the gun design is the axial symmetry. The broken symmetry with a side coupler may increase significantly