Design of a High Brightness RF Photoinjector for the SLAC Linac Coherent Light Source

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Abstract

The electron injector for the SLAC Linear Coherent Light Source[1] (LCLS) must produce a low jitter, high brightness beam. This beam must be accelerated and longitudinally compressed to yield a sub-picosecond beam which radiates a burst of self-amplified spontaneous emission x-rays upon passing through a long undulator. As the gain of this amplifier is very sensitive to the emittance, energy spread and peak current the electron source and subsequent transport, acceleration, and compression systems must reproducibly give a very high quality beam. The conceptual design of an rf photocathode gun which satisfies the requirements of the LCLS is presented here.

I. INTRODUCTION

The proposed SLAC LCLS is designed to be an R&D facility based on the FEL principle which provides sub-picosecond pulses of x-rays in the 2-4 nm spectral region. The LCLS injector, which must produce the electron beam which is then accelerated in the SLAC linac to an energy of ≤ 7 GeV, must satisfy fairly stringent requirements on beam quality. The beam emittance must be very small, while producing a nanocoulomb of charge in a picosecond bunch length. The parameters of the injector we have studied are listed in Table 1.

Final energy E	10 MeV
Norm. emittance ε_n	3 mm-mrad
Number of electrons N	6×10^9
Bunch length σ_t	2 psec
Rf structure	$3+\frac{1}{2}$ cell, π - mode
Shunt impedance ZT^2	$40\ \mathrm{M\Omega/m}$
Rf frequency	2856 MHz
Laser wavelength λ	248 nm
Cathode material	LaB_6

Table 1: Parameters of SLAC LCLS photoinjector.

While the design peak current emitted by this gun is above 200 A, the requirements of gain length in the undulator are such that the beam must undergo longitudinal compression to raise the peak current by an order of magnitude. This compression is very much dependent on both the phase of the accelerating rf wave and the longitudinal wake-fields in the linac, and so the final bunch length will not be reproducible if the time of beam emission (laser beam injection) and/or the charge per bunch have large variations. Because of concerns on reliability and feasibility of the photoinjector, a design which takes maximum advantage of proven technology, and recent experience in photoinjector development has been explored, and is outlined below.

II. RF DESIGN

The rf gun structure chosen is of a type evolved from the high gradient guns in use at BNL and UCLA. It is a three-and-one half cell standing wave π-mode cavity, which is nominally operated with a peak accelerating gradient of $E_{rf}=100$ MV/m. The frequency was chosen to coincide with the that of the SLAC linac structure, mainly because of ready availability of the power source, but also because of the proven ability to reach high fields in other S-band structures. The large accelerating field is chosen to minimize the contribution of space charge to the emittance growth the beam undergoes during acceleration. Both a replica of the BNL structure and a modified structure with larger iris openings were examined for use in this gun; the modified structure, with its higher intercell coupling, allowed superior mode separation, more linear transverse rf fields, and greater flexibility in regard to coupling of the cavity to the wave-guide.

The high field levels in the gun imply that a peak power of 13.6 MW must be supplied to the structure, well within the reach of a SLAC XK5 klystron. Assuming a maximum repetition rate of 120 Hz, and a minimum pulse length of 2.25 microseconds (three rf fill times), the average rf power in the structure is 50 kW, which is

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approximately one-half that dissipated in a similar, optimally cooled gun designed by Grumman and BNL[2].

The use of a high gradient standing wave accelerating field also mitigates the need for external focusing, due to the strong ponderomotive (alternating gradient, AG) rf focusing provided by the backward wave[3]. A design with a lower field in the initial half-cell was also studied, to enhance the rf focusing effect, and yield a smaller beam, with a smaller divergence at the exit of the gun.

III. BEAM DYNAMICS

The beam dynamics in the gun were analyzed using the simulation codes PARMELA, which is calculates the particle trajectories using an approximate (radiation free) treatment of the beam self-fields, and ITACA[4], an axisymmetric particle-in-cell (PIC) code which calculates the fully self-consistent electromagnetic cavity, space-charge and (radiation) wake-fields.

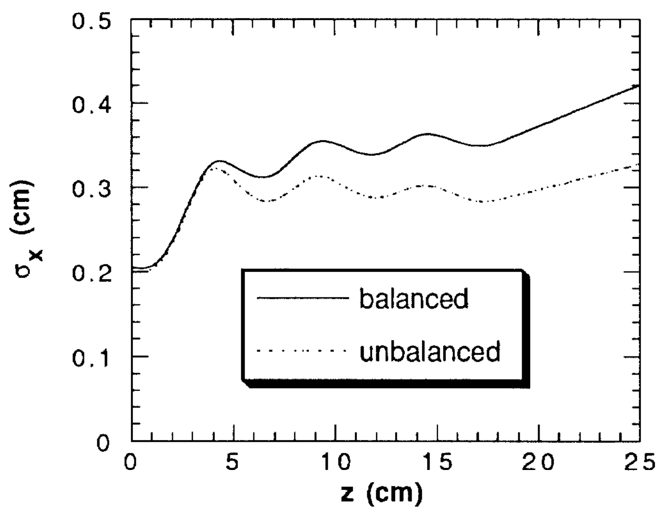

Figure 1: The rms transverse beam envelope, calculated by PARMELA, for the cases of equal (solid) and unequal (dots) field in half and full cells.

The behavior of the beam envelope, obtained from 1000 particle PARMELA simulations, is shown in Fig. 1. The dotted line corresponds to a uniform 100 MV/m field, and the AG rf focusing provided (which is equivalent to a solenoidal magnetic field of $B_z = E_{rf} / \sqrt{2} =$ 2.3 kG) controls the beam expansion inside of the gun. The exit of the gun is effectively a powerful unmatched defocusing lens of focal length $f = 2E_b / E_{rf}$=20 cm[5]. It is thus desirable to keep the beam even smaller at this point, which can be accomplished by using a smaller field at half-cell, so that the kicks are unmatched at the first iris, and the focusing there is made stronger than the balanced AG focusing. This case is shown by the solid line, where the half-cell field amplitude is 82 MV/m, and the full cells are run at 108 MV/m. The beam size and divergence at exit of the gun are reduced by a factor of two over the balanced field case. These reductions are quite important, as too strong of focusing employed after the gun tends to give significant transverse emittance growth from chromatic effects.

These effects can also be minimized by controlling the energy spread at the gun exit. The longitudinal phase space at the gun exit, as calculated by PARMELA for an optimum initial launch phase of 62 degrees, is shown in Fig. 2. The energy spread in this case is $\delta p / p = 0.18\%$. This phase space distribution was used as input for the transport and longitudinal compression simulations performed by Seeman, *et al.*[6]

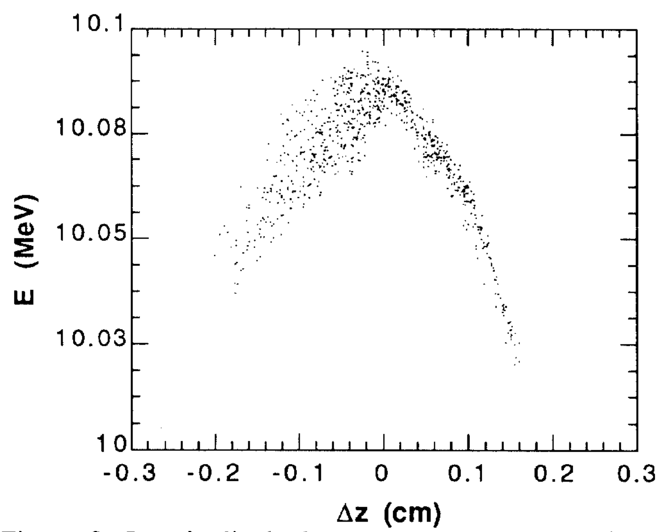

Figure 2: Longitudinal phase space at gun exit, from PARMELA simulation.

For the accurate calculation of the expected emittance the PIC code ITACA, with its lower inherent numerical noise level, was used. Several methods of tailoring the beam distribution were used to minimize the final emittance, including use of a longitudinally uniform beam pulse, and a cutoff transverse gaussian distribution. The latter can be trivially achieved by collimation; the former is perhaps more problematic, but might be achieved by use of a saturable optical element.

The normalized rms emittance calculated by ITACA using a nonoptimized beam distribution was 3 mm-mrad. If an optimized distribution[7], which employs a beam with a transverse gaussian cut-off at 1.5 σ_r is used, then the transverse emittance is below 1.5 mm-mrad, which is near the thermal limit. This is shown in Fig. 3. Only the dynamics in the first half of the gun, where nearly all of the emittance growth occurs, is shown due to the excessive computing time demanded for analyzing the full structure.

The beam transverse dynamics after the gun are still investigation. The preservation of the emittance during subsequent transport and acceleration must be examined in detail. This region of the beamline does not just present a challenge in preserving emittance, however. There are schemes which have been studied and implemented[8] in which the space-charge derived emittance has been removed by appropriate beam transport.

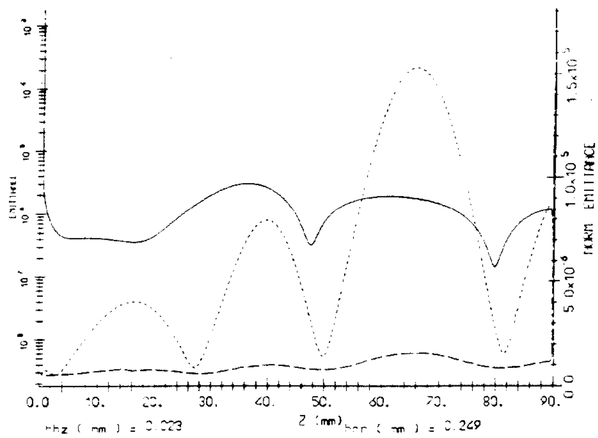

Figure 3: ITACA simulation of the evolution of the transverse rms emittance for the optimized beam distribution, in the first half of the gun. Shown: rms normalized (whole beam, solid; beam core, large dash) and unnormalized (small dash).

IV. LASER AND PHOTOCATHODE

The reproducibility of the x-ray pulse derived from the LCLS is critically dependent on the beam peak current. In order for the pulse compression to work properly, the beam's bunch-to-bunch charge fluctuations must be below one percent , and the timing jitter of initial injection (which is dependent on the laser) must be somewhat less than one picosecond (a degree of rf phase).

These requirements have not been met by photoinjectors in the past mainly because of difficulties associated with the laser. With the advances made recently in the technology of diode pumped solid-state, short pulse lasers, this may no longer be the case.

As an example of a system developed recently in industry, Lightwave Electronics has tested a diode pumped Nd:YLF regenerative amplifier which amplifies 1047 nm, 8 psec FWHM (3 psec rms) pulses derived from a mode-locked diode pumped Nd:YLF oscillator[9]. The oscillator produces a 500 kHz pulse train which has very small energy fluctuations, and which are, by a phase feed-back system, timing stabilized with respect to the rf phase to within 0.7 picoseconds. The energy output per pulse of the amplifier is 92 μJ, which after two stages of frequency doubling through nonlinear crystals, yields 10 μJ at 262 nm. The fluctuations in output energy, even with the nonlinear elements in the system, are at the 0.5% level.

In order for this laser to be useful for exciting a photocathode, the cathode material must havea relatively high quantum efficiency. Recent work by Bamford, *et al.*,[10] has shown that a quantum efficiency of 0.1% with 266 nm light at 45 degree incidence on a properly prepared LaB_6 cathode is possible. This choice of cathode is well suited to our application, since it is rugged (like a relatively low quantum efficiency metal) but has no lifetime problems or stringent vacuum requirements (like a multi-alkali cathode). Using this cathode material and the Lightwave laser system, one can expect about 2.1 nC of charge, which is well above our design criterion.

Using these emerging technologies, this photoinjector design should be able to produce a high brightness electron beam which meets the stringent beam quality and jitter requirements of the LCLS project.

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