BEAM DYNAMICS IN AN INTEGRATED PLANE WAVE TRANSFORMER PHOTOINJECTOR AT S- AND X-BAND

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The beam dynamics of an integrated S-band rf photo-injector based on the plane wave transformer (PWT) concept, proposed as part of an SBIR collaboration between UCLA and DULY Research, are studied. The design, which calls for an 11.5 cell structure run at a peak accelerating field of 60 MV/m and uses a compact solenoid around the initial 2.5 cells, is based on a recently developed theory of emittance compensation[1]. It calls for matching the beam onto a generalized equilibrium envelope, which produces a beam which diminishes in transverse size monotonically with acceleration. This condition minimizes the emittance, which is 1 mm-rad at Q=1 nC. This design is also scaled to produce nearly identical performance at X-band, giving an injector appropriate to running an FEL at the SLAC NLCTA. These designs are insensitive to rf emittance increase, allowing a wide choice of injection phase, and the option to compress the emitted pulse.

I. INTRODUCTION

An integrated rf photoinjector, in which the rf gun and post-acceleration linac are joined, is attractive for several reasons. Perhaps the primary motivation for this geometry is to allow emittance compensation with a smaller acceleration gradient in the cathode region, ameliorating power demand (a larger total energy is obtained for constant power use) and handling problems, as well as dark current emission levels. This advantage is obtained in the integrated geometry because the beam does not encounter a large exit kick after the final iris (typically second) in the gun structure. This exit kick causes outward motion which must be controlled by a powerful solenoid, and which interferes with the emittance compensation process. The use of lower accelerating gradient in an integrated injector further admits use of a lower launch phase, which allows for pulse compression.

These advantages have been obtained to some degree by the LANL injectors, typified by AFEL[2], which has produced the lowest emittance to charge ratios of any photoinjector. The performance of the PWT integrated photoinjector at both S- and X-band, are discussed below. The S-band device is now being constructed by a collaboration between UCLA and DULY Research. The X-band case represents simple scaling[3] of the S-band device to deliver FEL quality beams to the NLCTA at SLAC.

II. S-BAND PWT INJECTOR RF DESIGN

The rf structure of the S-band PWT[4] injector has been specified in a two-stage process: initial optimization of the field profile for acceleration by SUPERFISH, followed by a three-dimensional analysis using MAFIA (see Ref. 5). In the first stage, we make an initial specification of the fields to provide a baseline geometry and the nominally axisymmetric fields in the beam channel, which are used in PARMELA simulations. This exercise is subject to the following constraints: (1) high shunt impedance (2) low higher spatial harmonic content (3) cell number and gradient yielding 20 MeV beam (4) good coupling, mode separation (5) relatively low Q_0 to allow fast structure (6) minimizing of outer diameter to allow compact focusing solenoid.

The first two constraints can be partially satisfied by using the disk and iris geometry of the present UCLA PWT linac, which has, relative to 1.5-1.625 cell S-band rf gun designs, a thinner disk and smaller iris[4]. This naturally leads to a high shunt impedance, with moderate spatial harmonic content. The near-axis fields are in any case of high enough quality to produce a very high brightness beam, because the beam sizes are controlled to be a fraction of the iris size. All compact guns are coupled cell-to-cell on axis, but this is not possible here due to the small iris size. Fortunately, the PWT structure has very high coupling, allowing a standing-wave, π-mode, multi-cell design with excellent mode separation. The reason for this high level of coupling is the large volume between the outer wall and the disks. This volume, because of its large stored energy, also serves to raise the Q_0 of the device. This high Q_0 makes it is difficult to fill a PWT structure, and thus we choose a smaller outer wall radius than is presently employed at UCLA. This choice is reinforced by the need to have a solenoidal focusing field, which must be localized within the first few cells of the photoinjector.

Given all of these constraints, we have chosen an inner radius of the cavity wall to be 5.5 cm, and proceeded to analyze the detailed performance of the device. According to the recent analytical theory of emittance compensation[1] by Serafini and Rosenzweig (SR), the solenoidal field must begin to assert focusing within the first cells of the device for optimum performance. In addition, the somewhat anti-intuitive result is obtained that for an integrated photoinjector, emittance compensation is not possible for high gradients, in that the parameter $\alpha = eE_0 / k_{RF} m_e c^2$ (E_0 is the on-axis field amplitude, and $k_{RF} = 2\pi/\lambda_{RF}$) must be less than approximately one. We have $\lambda_{rf} = 10.49$ cm, and E_0 =60 MV/m. With such a modest gradient, we must employ an 11+1/2 cell (60.3 cm) structure to obtain 20 MeV electrons. Using the shunt impedance calculated from MAFIA[4] for the four-rod disk-support design we plan to use ($Z'T^2 = 55\ \mathrm{M\Omega/m}$), for the maximum available power input of 24 MW we obtain E_0 =90 MV/m.

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While the shunt impedance in the PWT is mainly dictated by the iris geometry, the cell-to-cell coupling is a function of the distance from the inner radius of the outer wall to the outside of the disks. Here we have chosen the wall radius to be 5.5 cm, while the disk outer radius is 4.07 cm. For these parameters, the coupling is enormous — the width of the lowest pass band is over 900 MHz. The mode separation between the π and the $11\pi/12$ is 16 MHz, which is many times the mode width due to finite Q_0. This separation compares favorably with the 0-π mode separation in the current UCLA 1.5 cell 2856 MHz gun (<2 MHz), and is comparable to the separation of the next generation 1.625 cell guns developed by the BNL-SLAC-UCLA collaboration[6].

The 3-D modeling of structure performance has been studied with MAFIA, as the introduction of 4 support/cooling rods at the nominal on-disc field null significantly perturbs the mode profile[]. It has been found, however, that this perturbation has a negligible effect on the beam dynamics.

III. S-BAND BEAM OPTICS

The design of beam optics in an rf photoinjector is intimately related to the rf design of the injector structure, as well as the design of the focusing solenoid, in sometimes subtle ways. The fundamental mode for obtaining the lowest emittance and highest beam brightness is termed *emittance compensation,* in which the emittance increase due to space charge effects is reversed, leaving a minimized emittance beam for applications such as FELs, wake-field accelerators and precision test beams for advanced accelerators.

Recent work by Serafini and Rosenzweig (SR) has developed both a physical and an analytical understanding of the process[1]. The physical model for the emittance growth and subsequent diminishing (one cycle of an emittance oscillation) is that of transverse plasma oscillations about a generalized equilibrium in an accelerating system. Because the beam has a finite length and non-uniform current profile, these oscillations have amplitudes which are dependent on the longitudinal slice of the beam under consideration. On the other hand, under proper conditions, the frequency of the slice envelope oscillation is not strongly dependent on the current, and the phase space, which after the initial beam expansion has a fanned-out appearance, recoheres after one envelope oscillation. When the proper conditions prevail for emittance minimization (compensation), the beam envelope in the accelerating structure must be focused, after its initial expansion, onto a generalized equilibrium trajectory designated as the *invariant envelope,* which has the form $\sigma_x(z) = \dfrac{2m_e c^2}{E_{acc}}\sqrt{\dfrac{I}{3I_0\gamma(z)}}$,

where for a standing wave structure the average gradient $E_{acc} \cong E_0/2$, I is the rms current, and $I_0 = ec/r_e \cong 17$kA.

This equation displays a diminishing beam size during acceleration which gives a secular damping of the emittance upon which the emittance oscillations are superimposed. In a long photoinjector structure, damping of the beam size at high energy has the additional advantage of mitigating the emittance increase arising from the time dependent rf kick imparted at the structure exit. This allows for freedom in the choice of launch phase, and the possibility to run forward of the rf crest, allowing for longitudinal pulse compression.

The analytical theory developed by SR also allows the beam parameters which give emittance compensation to be specified. This theory predicts that, in order to not let the beam expand much in the initial few cells, that the peak in the focusing field of the solenoid be placed as close to the cathode as possible. This has been done for our design, as the POISSON flux map shown in Fig. 1. The theory also gives $\alpha \le 1$, setting $E_0 = 60$ MV/m and the nominal launch phase $\phi_0 = 32^\circ$. The low gradient can be explained as follows: for higher gradients, the invariant envelope is smaller, and thus the launched beam must be radially smaller in order to match to the invariant envelope well after the solenoid. In this case, the beam is too dense (the beam plasma frequency is too high) and expands excessively in the first half-cell, thus denying the possibility of invariant envelope matching.

In addition to these considerations, we work with the following constraints: (1) The charge, set by the nominal desired for FEL experiments, is 1 nC, and (2) the laser pulse length, set by the available PBPL/Neptune uv (262 nm) system, is 7.5 psec FWHM. Given these constraints, we find that the beam should be launched with an rms radius of 1.1 mm. The theory also predicts that the solenoid field be a rather small $B_0 = 1.8$ kG at the peak, occurring at $z = 7$ cm, or just before the second iris of the structure. The field is roughly 1/2 that used presently at the UCLA photoinjector, where the solenoid must overcome the exit kick of the gun's rf field. In the case of a long photoinjector the beam is small at the gun exit, and if the beam is directly on the invariant envelope, it exits the structure on a parallel trajectory after the exit kick.

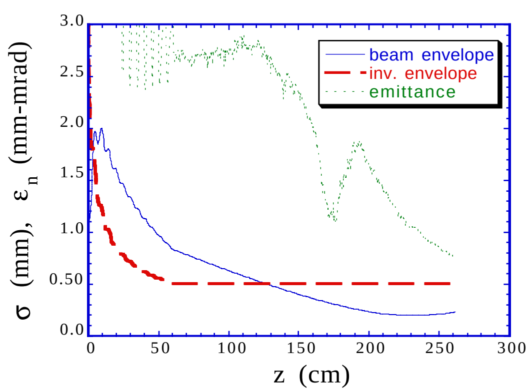

Figure 1. Evolution of the rms beam envelope, emittance in S-band PWT; invariant envelope shown for comparison.

These phenomena are illustrated by the PARMELA simulations of the beam dynamics we have performed. Figure 7 displays the evolution of the rms beam sizes along the photoinjector, along with the invariant envelope for these conditions ($I = 120$ A), shown for reference. It can seen that the beam begins larger, but ends focusing slightly smaller than the invariant envelope. This behavior is in fact typical of emittance compensated photoinjector designs, as one tends to drive the beam a bit smaller, to speed up the compensation process, and make it more effective — the final emittance is roughly proportional to the beam size. There is a limit to how much one can violate the invariant envelope condition, however, dictated by the need to avoid a "cross-over" waist, in which the previously nearly laminar, space-charge dominated beam comes to a nonlaminar, emittance dominated minimum, causing irreversible emittance growth. Our design comfortably avoids this situation, and a beam waist and emittance minimum occur roughly 1.5 m after the end of the PWT. This additional drift is needed because the phase advance of the emittance oscillation, should it all occur inside of the rf structure, would imply accelerating the beam to roughly 200 MeV in a structure 10 times as long.

This injector is also designed to produce low charge (15 pC) ultra-low emittance beams for use in plasma beatwave acceleration experiments[7]. Scaling the charge in the device requires that the beam plasma frequency, and thus the beam density, be kept constant[3]. Using this guide, we have simulated a 16 pC case with the bunch length 1.9 psec FWHM corresponding to the 266 nmlaser system now in use at UCLA. In this case we obtain extremely small emittance, $\varepsilon_n = 0.06$ mm-mrad. We have also performed simulations of pulse compression of the beam using a chicane after the compensation point. We were able to compress the beam by a factor of 3.5 while running at the nominal injection phase. This illustrates the flexibility of the long photoinjector with respect to choice of ϕ_0.

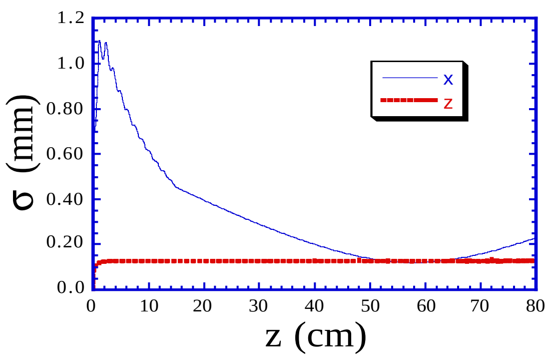

Figure 2. Beam size evolution in the scaled X-band photoinjector (Q=1 nC).

III. X-BAND INJECTOR

In order to have the option of running a SASE FEL at the SLAC NLCTA, a high quality ($\varepsilon_n = 2$ mm-rad, Q=1 nC, with $\sigma_z = 120\ \mu$m) injector beam must be made available. The desire for short bunch length at high charge, plus the availability of the 11.4 GHz (4 x 2.856 GHz) power at the NLCTA[8], make an X-band injector attractive for this application. Happily, the design techniques developed in Ref. 3 include the scaling of designs with respect to λ_{rf}. This technique is based on the appropriate scaling of all frequencies (rf, focusing, plasma) in the problem, and requires

$$E_0, B_0 \propto \lambda_{rf}^{-1},\ \ \sigma_i \propto \lambda_{rf},\ \text{and}\ \ Q \propto \lambda_{rf},$$

to give $\varepsilon_n \propto \lambda_{rf}$ and $\sigma_z \propto \lambda_{rf}^{2/3}$ (at constant Q). Again the bunch dimension scaling is somewhat flexible, especially since we "lost" a factor of 4 in charge in the λ_{rf}-scaling, we must rescale with respect to charge by a factor of 4 to obtain a 1 nC design. As we must choose a 1 psec FWHM laser pulse, we then must have $\sigma_r = 700$ µm. The peak accelerating field E_0=240 MV/m, which is reasonable for this rf frequency, and the peak solenoid field B_0 =7.2 kG, which can be obtained by straightforward water-cooled design. The results of PARMELA simulation of this design is shown in Figs. 2 and 3. It can be seen that the beam envelopes are nearly identical in form to the S-band case, with the desired $\sigma_z = 120$ µm. The emittance performance is also better demanded by the FEL application, which is not surprising - we expect ε_n to diminish by 1/4 in the λ_{rf}-scaling, and grow by ~4 in the charge scaling.

It should be noted that it is unlikely to obtain a good design for the X-band photoinjector with a split photo-injector because of several reasons: (1) the scaling of the fields make the design impractical (an X-band version of the 1.625 cell gun would require $E_0 = 480$ MV/m), (2) the beam debunches in the drift between gun and linac. The PWT is a good candidate for this structure, because it is straightforward to obtain a high shunt impedance with good mode separation and ease of manufacture.

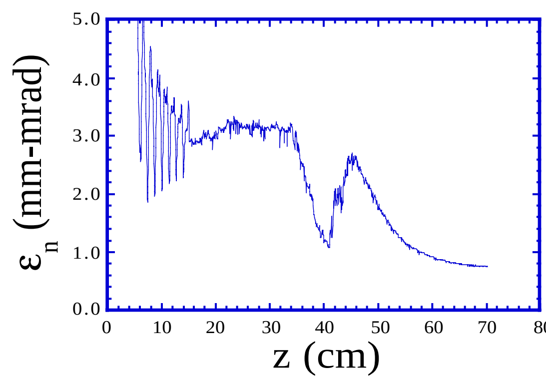

Figure 3. Emittance evolution in scaled X-band photoinjector (Q=1 nC).

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