AN INJECTION SCHEME FOR THE BROOKHAVEN ATF UTILIZING SPACE-CHARGE EMITTANCE GROWTH COMPENSATION

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Abstract

We consider possible configurations for injection of photocathode-produced electron beams straight into linear accelerating sections. A slightly convergent beam into the linac is required for maximum transmission through the linac sections and therefore a solenoid pair is considered. We describe strategies for placing the rf gun injector and the strength of the solenoids so as to minimize the emittance growth of the beam as it traverses the linac sections. The simulation codes PARMELA and TRACE 3-D were used for this design study.

I. INTRODUCTION

The Brookhaven Accelerator Test Facility consists of a photocathode loaded rf gun, a double-bend, low-energy transport system, two traveling-wave accelerating sections and a high-energy transport to an experimental hall [1]. Our goal in this paper is to examine beam line configurations which will permit straight injection into the linac sections without having to resort to bending magnets. The control of emittance growth is a primary design objective.

The issue of emittance growth and containment in high-brightness electron beams has been studied extensively. It has been argued that to study the physical phenomena that produces emittance dilution in the transport and acceleration of a high-brightness electron beam it is desirable to divide the electron bunch in longitudinal slices. These slices provide a tool to probe and extract the different dynamical behavior of the slices of the electron pulse. It is well known that emittance dilution due to the rf dynamics within the rf gun [2] is quite different from that due to space charge [3] within the bunch structure of the electron beam.

Using the code PARMELA [4], we track each slice through the system and observe that the intrinsic emittance within each slice can be very small ($\epsilon_n \approx 1\ \pi$ mm-mrad) but the projection on the phase space of all slices give rise to a larger global emittance. Although, the area in phase space (emittance) swept by each slice is small, the area covering all the slices is significantly larger and consequently, the emittance of the total beam is larger in magnitude. Since the space-charge effects are greater at the longitudinal center of the beam than at the ends, the core tends to develop larger values of $< x >$ and $< x' >$. This leads to each slice evolving differently in phase space as time evolves.

II. NUMERICAL ANALYSIS AND RESULTS

2.1 Long Drift Solution

Injecting beam straight into the linacs entails placing an rf gun inline with the linacs and utilizing a solenoid-gun-solenoid arrangement while possibly incorporating the present inline triplet for matching beam into the linac. The solenoid preceeding the gun is used so as to buck the magnetic field of the second solenoid, thus insuring that an emittance degrading magnetic field is not present at the photocathode. In this configuration the cathode plane is located 2.5 meters from the linac entrance. The advantage of this approach is that it preserves the present double-bend for injection into the linac [5] thus providing for valuable redundancy thereby reducing program downtime.

Matching the beam into the linac so as to encounter no beam loss after traversing the two linac sections requires the electron beam to be slightly converging as it enters the first linac section. We have checked that this is not possible for a 1 nC, 10 ps beam if we wish to rely exclusively on the focusing of a solenoid. By utilizing the inline triplet, it is possible to present a properly matched beam to the linac. We find, however, that a solenoid placed immediately after the gun is still required in order to contain the beam during the 70 cm drift to the triplet entrance. We used TRACE 3-D [6] to develop the intial conditions for matching the electron beam into the linac and then used PARMELA to calculate the full beam dynamics from the plane of the photocathode through to the emergence from the two linac sections.

We show in Fig. 1 a typical solution for delivering full beam through the linac. The electron beam parameters for this solution entail beginning at the photocathode with a beam with a uniform radial distribution of $r = 0.9$ mm and a uniform longitudinal pulse length of 10 ps. The use of a uniform distribution was found to offer significant advantages over gaussian distributions in terms of minimizing the final beam emittance. The beam emerges from the linac sections with an rms radius of 1.6 mm and a transverse emittance of 3.5 π mm-mrad.

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2.2 Close-in Solution

We explore placing the rf gun inline as close as possible to the linac entrance. Matching into the linac, however, requires at a minimum a solenoidal focusing magnet between the gun and the linac entrance. The principal variables explored for this study are: the strength of the solenoid field, the gun-to-linac distance, and the phase of the linac sections relative to the rf gun. The length of the solenoid was fixed at 16 cm and the average accelerating gradient of the linac sections was set at 7 MV/m. While we did vary the radius of the initial electron beam, the bunch charge was fixed at 1nC and the bunch length was fixed at 10 ps.

Fig. 2 shows the solution of the z=62 cm case, presenting a beam identical to the previous example displayed in Fig. 1. The beam emerges from the two linac sections with an rms radius of 0.28 mm, an rms divergence of 0.050 mrad, and an invariant emittance $\epsilon_n = 0.75\ \pi$ mm-mrad. We find that the energy spread of the emerging beam is particularly sensitive to the phasing of the linac sections while the final beam emittance is rather insensitive to this variable (see Fig. 3). The optimum setting of the phase delivers a beam with an rms dp/p of 2 x 10^{-3}. In Fig. 4, we display the results of varying the drift distance between the gun-solenoid and the linac entrance. We find that the optimum distance from the photocathode plane to the linac is 70 cm.

2.3 Electron Bunch Dynamics

We have examined the process whereby the emittance of the electron first grows then diminishes as the beam drifts then accelerates after it leaves the rf gun. The emittance growth experienced during the drift period immediately after the beam leaves the rf gun results from defocusing forces due to space charge within the electron bunch. These defocusing forces are stronger in the center of the bunch than on the leading and trailing edges of the beam. This results in a time-dependent, phase-space structure which can be neutralized if the space charge forces are inverted so as to make the defocusing forces stronger in the ends of the electron bunch than the center. The can be achieved though a focusing action on the beam followed by a drift. In Fig. 5 , we see the trajectories in x-x$'$ phase space of an ensemble of electrons first at the longitudinal ends of the bunch and then at the longitudinal center of the bunch. Notice that after the focusing action is complete both ensembles move toward the left (toward negative x) due to drift and simultaneously up (toward positive x$'$) due to defocusing space-charge forces. The interesting feature observed in this plot is that a cross-over occurs going from negative to positive x$'$ (defocusing action) instead of the standard positive to negative x (drift action). Clearly seen in the figure is that the end sections of the electron bunch are spatially compressed more than the center of the bunch. This results in an increase of the space-charge defocusing forces in the ends relative to the center thus compensating in part the global emittance growth observed before the focussing action.

III. CONCLUSIONS

We observe an increase of the electron beam emittance ϵ_n, immediately after the gun and a subsequent reduction to a rather broad minimum (in some cases there is a gentle asymptotic decrease) located inside the linac sections. This behavior of ϵ_n reflects the interplay of focusing, drifting and defocusing space charge fields [7]. The net result is to close the fan in phase space which results in a decrease of the global emittance of the beam. If at this point the beam is accelerated, then the phase spaces of the slice ellipses are locked in with respect to each other due to the decrease of the space charge forces ($F_\perp \approx O(\frac{1}{\gamma^2})$). The electron beam emerging from the linac exhibits a high-brightness characterized by, $B = \frac{I_p}{\pi\epsilon_{N,x}\epsilon_{N,y}} = 6 \times 10^{13}$.

We give in Table I a summary of the parameters for the beam entering the high-energy transport system following the linacs. We find that the optimum photocathode plane to linac entrance distance for our initial conditions is 70 cm.

IV. ACKNOWLEDGEMENT

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TABLE I. Parameters used in the PARMELA simulations for an axially symmetric 1 $\frac{1}{2}$-cell gun in a π -mode configuration with a solenoid pair.

RF frequency [MHz]	2856
Radius of aperture [cm]	1.0
Field on cathode [MV/m]	100.0
Initial phase [degree]	43.0
Laser spot size[a] [mm]	0.9
Laser pulse full width[a] [ps]	10.0
Charge [nC]	1.0
B_0 [kG]	2.2
Average linac accelerating gradient [MV/m]	7.0
ϵ_n , π mm-mrad	0.75
dp/p [%]	0.2

[a]Uniform profile

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FIG. 1. Normalized transverse emittance ϵ_n vs. distance z utilizing a solenoid and quadrupole triplet

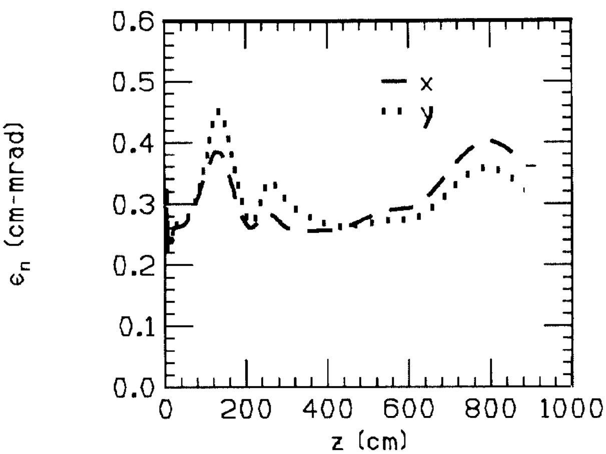

FIG. 2. Normalized transverse emittance ϵ_n vs. distance z utilizing only a solenoid pair—the plane of the photocathode is 62 cm from the linac entrance

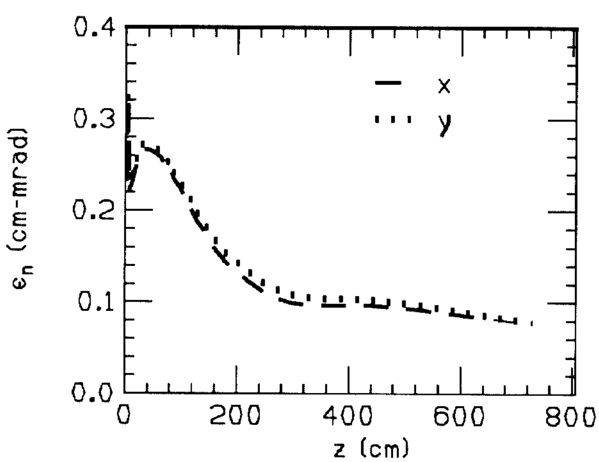

FIG. 3. The dp and normalized emittance of the electron beam exiting the two linac sections as a function of phase relative to the electron beam launch phase at the photocathode

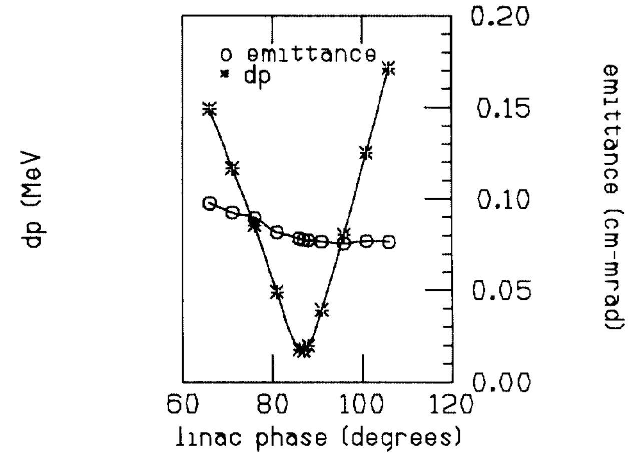

FIG. 4. The normalized emittance of the electron beam exiting the linac sections as a function of the longitudinal distance between the photocathode plane and the linac entrance

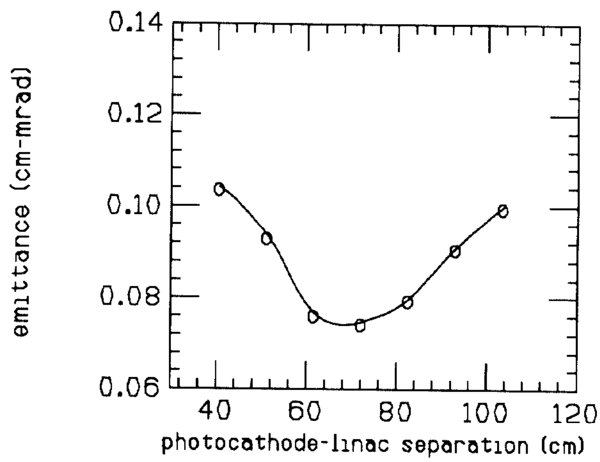

FIG. 5. The trajectories of the end and center slices of the electron beam in x-x′ phase space