Design of High Brightness Symmetric and Asymmetric Emittance RF Photoinjectors for TESLA

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Abstract
Development work leading to emittance-compensated symmetric emittance and asymmetric emittance RF photoinjectors is discussed. A mature design for a symmetric emittance photoinjector is described, and current work leading to an asymmetric design is detailed. An experimental program to characterize both injectors and to explore the physical mechanism of emittance compensation using the facilities of the Argonne Wakefield Accelerator is outlined.
Introduction

The needs for excellent beam quality and high peak current beams for free electron laser (FEL) applications have led to the development of the radiofrequency (RF) electron photoinjector as a high brightness electron source. The demands of a high luminosity linear collider similarly require excellent beam quality, although usually achieved with the aid of a damping ring. The development of normal and superconducting linac structures for linear colliders requires testing the structures under conditions as similar to the planned operating conditions as possible. Wakefield analysis, beam loading, multi-bunch instabilities and other beam-cavity interactions require beams of similar charge, bunch length, bunch spacing, and approximate transverse emittance as the eventual collider beam. Analysis of the superconducting structures for the Tera-Electron volt Superconducting Linear Accelerator (TESLA), normal conducting structures for the Next Linear Collider (NLC), or for a proposed [3] superconducting injector for the Fermilab Main Injector will all require high brightness test beams. The construction of an injector to achieve the needed beam quality will require state-of-the-art accelerator technology. To this end, we discuss the applicability of an RF electron photoinjector as a very compact source of high quality beams with high bunch charge, very short bunch length, that is capable of high repetition rates (better than 1 MHz).

The design for a photoinjector satisfying the immediate needs of the TESLA Test Facility (TTF) for a symmetric emittance beam and the longer-term needs for a very high brightness asymmetric emittance beam for TESLA500 are presented below. Current TTF and TESLA500 (the next design phase of the TESLA program) requirements are summarized in table 1 below.

The experimental program to construct and commission the photoinjectors will have three phases. The first phase involves the testing of both photoinjectors under essentially single-pulse operation to address single bunch beam dynamics issues, and to complete the optimization of the emittance compensation and magnetic compression assemblies. The beamline outlined below is chosen with flexibility in mind to permit some exploration of parameters, including high-gradient operation of the photoinjector, potentially obviating the need for a magnetic compression chicane altogether, and different emittance compensation lens strengths and positions. Optics for splitting and delaying the photocathode excitation laser pulse to provide a train of six pulses spaced a few nanoseconds apart will be fitted towards the end of phase I to begin the study of wakefield and beam loading effects. Phase I forms part of an established research and development collaboration between Fermilab and UCLA to address beam dynamics issues of very high brightness symmetric and asymmetric emittance electron photoinjectors. Tests of the asymmetric injector will proceed after the completion of symmetric tests beginning mid-1995. Beam physics results are expected for both symmetric and asymmetric injectors by late-1995.

Phase II will commence with the installation of the prototype laser system, which is presently under study by both industry and colleagues at the Max Born Institut für Physik in Berlin. Industry has already demonstrated both the technology and the willingness to pursue the design of the laser system. The three stage Ti:Sa/LiSaF system will produce the required train of 1000 pulses spaced 1\,\mu s apart, allowing testing of the photoinjector under conditions identical to those of the TESLA500 linear collider. Appendix B details
Table 1: Summary of TESLA Injector II Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
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<tr>
<td>Bunches per macropulse</td>
<td>$N_m$</td>
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<td>Macropulse spacing</td>
<td>$\tau_m$</td>
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<td>Bunch spacing</td>
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<td>Overall Duty Cycle</td>
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<td>RF Power per klystron</td>
<td>$P_{RF}$</td>
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</table>

**TESLA Test Facility**
- Symmetric
  - Horizontal Emittance $\epsilon_x < 20\pi$ mm-mr
  - Vertical Emittance $\epsilon_y < 20\pi$ mm-mr
  - Brightness $B = 4.8 \times 10^{12} A/m^2$

**TESLA500**
- Asymmetric
  - Horizontal Emittance $\epsilon_x = 20\pi$ mm-mr
  - Vertical Emittance $\epsilon_y = 1\pi$ mm-mr
  - Brightness $B = 95.8 \times 10^{12} A/m^2$

the requirements of the photocathode drive laser. Funding and the precise scheduling of activities during phase II have yet to be fully decided.

Phase III entails delivery of the laser system, photoinjector, linac section, magnetic compression chicane and diagnostics to the TTF at DESY in the winter of 1996-97. Commissioning of the photoinjector assembly at DESY will complete the symmetric emittance photoinjector project.

**Beam Dynamics Considerations**

The need for substantial bunch charge with good beam quality requires that the RF accelerating gradient in the photoinjector be relatively high to reduce space charge induced emittance growth, and that emittance compensation described by Carlsten et al [4] be implemented to reduce the correlated space charge emittance growth. RF contributions to the emittance must be carefully controlled, requiring that nonlinear variations of the accelerating field in both the radial and longitudinal direction be minimized, and that the beam dimensions and accelerating gradient be carefully optimized.

The Carlsten emittance compensation scheme requires that the bunch be given a focussing kick early on to start the gradual reclosure of the phase space “fan” that results from the longitudinal variation of the transverse space charge fields. The variation of the space charge fields results in a correlated emittance growth that can be partially reversed with a focussing kick from a linear lens. Ideally, the kick should take place ahead of the beam’s exit
from the RF photoinjector, as the time-dependent defocussing that takes place within the RF structure, which can interfere with the proper implementation of emittance compensation, depends on the square of the transverse beam size [9] and will be significantly smaller if the beam is focussed as close to the cathode as possible. As the emittance compensation scheme is sensitive both to the strength and to the longitudinal position of the focussing kick, a second focussing element, downstream of the RF feed for the full cell, is added to allow exploration of the efficacy of the compensation as a function of lens strength and position, with the ratio of the currents in the upstream and downstream elements determining the effective magnetic center of the lens, and the sum of the currents determining the overall focal length. A bucking solenoid to cancel the longitudinal magnetic field on the cathode completes the symmetric injector focussing assembly, while it has not been determined if special compensation will be necessary for the quadrupoles used for the asymmetric gun. Figure 1 provides a schematic representation of where the three solenoids are positioned for the symmetric gun. The bevelled edge on the downstream side of the first focussing solenoid is to accommodate two laser ports at $\pm 54^\circ$ to the axis. The bucking coil manifests the same bevel for symmetry, not for mechanical clearance reasons.

The asymmetric emittance injector design is motivated largely by the need to maintain the vertical emittance at better than $1 \pi$ mm-mr. The basic design philosophy is to make the beam dynamics independent of the horizontal coordinate. A horizontally uniform charge distribution has space charge fields that rise slowly and linearly towards the beam edge, rising rapidly and nonlinearly only as the last 15% of the charge is enclosed. By launching excess “guard charge” at the edges of the beam, and subsequently collimating horizontally, the portion of the beam that has undergone the worst nonlinear space charge emittance growth will be removed. An elliptic cavity with an extremely long, narrow aperture serves to greatly reduce the horizontal variation of the accelerating and focussing components of the RF fields.

An additional complication that arises in the flat beam design is the need to focus with quadrupoles. The initial vertically focussing quadrupole needed to begin the vertical compensation process and lower the vertical beam size at the gun exit to minimize RF emittance growth has precisely the opposite effect on the horizontal plane. In the process of defocussing the beam horizontally the space charge forces in all planes are reduced. The Carlsten scheme for emittance compensation relies on the space charge forces of the beam being relatively slowly varying to kick the beam back out after the focussing kick, a process that will be impacted by the changing horizontal beam size. Careful optimization of the initial quad strength and position will be key to optimizing flat beam emittance compensation. A quad triplet is placed immediately following the gun to refocus the beam in both planes, continuing the vertical emittance compensation process, and matching both phase planes into the subsequent linac.

A short section is introduced after the photoinjector to allow the positioning of a six way cross for diagnostics, a vacuum gate valve, and a drift to allow the emittance compensation the required time to act before accelerating the beam further, thus “freezing out” the space charge forces. Variation of the length of this drift space has shown that there is a fair degree of flexibility, allowing for the relaxed and straightforward location of diagnostics.

As the photoinjector is optimized to deliver the required transverse beam quality with reasonable RF power, the lower accelerating gradient will require a longer bunch length to
reduce the space charge emittance growth during the relatively longer acceleration time. As a result, compression of the beam must be undertaken once the beam reaches moderate energy. Magnetic compression requires that the beam pass through a dispersive optical element, making use of a linear energy-phase correlation to reduce the bunch length. Space charges forces will degrade all three emittances during compression, resulting in poor beam quality if compression proceeds for too long or at too low a beam energy. It is therefore optimal to compress at the highest energy possible (thereby reducing the space charge forces) that beamline space allows. The TTF experimental area has rather limited space, motivating the choice to place a magnetic compression chicane at a lower energy (20 MeV). The proposed beamline is depicted in schematic form in figure 2 below. Detailed simulations of the photoinjector performance were completed using a modified version of PARMELA that accepts field maps for both RF cavity fields and static solenoid fields. The modified code also calculates the effects due to image charges on a metallic photocathode, and has several diagnostics tailored specifically to reveal the underlying phase space dynamics of emittance compensation.

Present beam dynamics work for the asymmetric emittance photoinjector centers on the development of a new technique for computing space charge forces for the flat beam. The existing point-by-point method has been carefully extended to allow for elliptic macropar-
articles in an effort to reduce computational noise, but has not reduced the noise enough that simulations of beams with transverse emittances on the order of $1\pi$ mm-mr or less can be achieved with a reasonable number of simulation particles. Therefore a Green’s function approach has been undertaken to approximate the beam fields on a mesh (as opposed to point-by-point) as the sum of a smaller number (400) of finite line charges, oriented with the long axis directed along the x-axis (the bunch aspect ratios at the photocathode are roughly $\frac{x}{z} \approx 1, \frac{y}{z} \approx 20$).

Compression is estimated using the longitudinal emittance of the beam and assuming an ideal linear transformation on the phase space to produce the compressed bunch. Emittance growth resulting from compression is estimated from Carlsten’s analysis \cite{5}, assuming a short bunch with a radially uniform charge distribution:

\[ \epsilon_N = \frac{ISG}{4IA \beta^2 \gamma^2} \quad (1) \]

where $I$ is the peak compressed current, $S$ is the path length over which the compressor dipole fields act on the beam, $G$ is a geometric factor between 0.2 and 0.5, and the Alfven current $I_A = 4\pi e \gamma m_e c^3 / e$.

Table 2 below details the predicted performance of the symmetric photoinjector setup. Emittance values quoted are one sigma normalized values enclosing 100% of the stated bunch charge. (In each case, this represents 80% of the total initially launched charge, with the 20% excess “guard charge” being collimated away) Two different operating scenarios were examined: high bunch charge (8 nC/bunch) operation for testing of HOM energy deposition in superconducting RF linac structures, and low bunch charge (1 nC/bunch) operation for injecting into a free electron laser (FEL). Field and bunch parameters for the 1nC case were derived from the 10nC case using simple scaling arguments. Significant effort was devoted to optimizing the 8 nC scenario, both for highest beam quality, and for lowest possible RF power consumption. The low charge (1 nC) case was derived by scaling the bunch radius and length to preserve the bunch core charge density, thereby allowing the emittance compensating lens configuration and strength to remain essentially unchanged. Although the 1 nC case outlined below has not been fully optimized, good beam quality ($\epsilon = 2.5\pi$ mm-mr) and moderately high peak current (80 Amperes) are present before compression, which contributes approximately 0.52 $\pi$ mm-mr to the transverse emittance while raising the peak current to 120 Amperes.

Shown in figure 3 below are the evolution of the transverse beam emittance, bunch length, and bunch radius throughout the injector for the high bunch charge case. Four emittance traces are shown, representing the FWHM one-sigma normalized emittances of 95%, 90%, 80%, and 70% of the bunch particles. (viz. An 80% emittance represents the emittance the bunch would have if the outermost 20% of the beam particles were collimated away) The onset of emittance compensation is clearly visible in the decrease of all emittances after the solenoid focussing kick. Transverse and longitudinal phase space plots at the end of the injector beamline (prior to compression) are shown at right. Figure 4 shows analogous plots for operation at 1 nC bunch charge. For reference, the gun exit is located at $z = 20.7$ cm, is followed by a drift up to $z = 96.2$ cm where the beam enters a 9 cell linac extending to $z = 200.$ cm, where the beam is again in a drift.
Figure 3: Emittance and envelope evolution for 10 nC operation, final phase space plots

Figure 4: Emittance and envelope evolution for 1 nC operation, final phase space plots
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<thead>
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<th>Parameter</th>
<th>Symbol</th>
<th>Predicted Value</th>
<th>Predicted Value</th>
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<td></td>
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<td>FEL</td>
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<tr>
<td>Bunch Charge</td>
<td>$Q_b$</td>
<td>$8 \text{nC} = 5 \times 10^{10} e^-$</td>
<td>$1 \text{nC} = 6 \times 10^9 e^-$</td>
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<td>Laser pulse length FWHM</td>
<td>$\Gamma_t$</td>
<td>28 ps</td>
<td>13.5 ps</td>
</tr>
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<td>Launch Phase (w.r.t. $E_z = 0$)</td>
<td>$\phi_o$</td>
<td>45°</td>
<td>35°</td>
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<td>Beam radius at cathode</td>
<td>$r_o$</td>
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<td>$\gamma_1$</td>
<td>12.3</td>
<td>12.3</td>
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<tr>
<td>Post-Linac Gamma</td>
<td>$\gamma_f$</td>
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<td>41.5</td>
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<td>Horizontal Emittance</td>
<td>$\epsilon_x$</td>
<td>$15\pi \text{ mm-mr}$</td>
<td>$2.5\pi \text{ mm-mr}$</td>
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<td>Vertical Emittance</td>
<td>$\epsilon_y$</td>
<td>$15\pi \text{ mm-mr}$</td>
<td>$2.5\pi \text{ mm-mr}$</td>
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<td>Longitudinal Emittance</td>
<td>$\epsilon_z$</td>
<td>1500 deg-keV</td>
<td>1200 deg-keV</td>
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<td>Momentum Spread</td>
<td>$\delta p/p_0$</td>
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<td>1.2 %</td>
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<td>Bunch Length</td>
<td>$\sigma_b$</td>
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<td>1.27 mm</td>
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<tr>
<td>Peak Current</td>
<td>$I_p$</td>
<td>386 Amperes</td>
<td>80 Amperes</td>
</tr>
<tr>
<td><strong>After Compression</strong></td>
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<td></td>
<td></td>
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<tr>
<td>Horizontal Emittance</td>
<td>$\epsilon_x$</td>
<td>$19.4\pi \text{ mm-mr}$</td>
<td>$3.02 \pi \text{ mm-mr}$</td>
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<tr>
<td>Vertical Emittance</td>
<td>$\epsilon_y$</td>
<td>$19.4\pi \text{ mm-mr}$</td>
<td>$3.02 \pi \text{ mm-mr}$</td>
</tr>
<tr>
<td>Bunch Length</td>
<td>$\sigma_b$</td>
<td>1 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>Peak Current</td>
<td>$I_p$</td>
<td>958 Amperes</td>
<td>120 Amperes</td>
</tr>
</tbody>
</table>

Table 2: Predicted performance of the Symmetric Emittance Photoinjector

**RF Design of the Photoinjector**

Simplicity, high shunt impedance, and the ability to accommodate an externally mounted focussing solenoid close to the cathode region motivated the choice of a 1.5 cell $TM_{010,\pi}$ mode structure. The need to induce a strong on-axis magnetic field made the use of a superconducting cavity problematic, and the need for a high accelerating gradient eliminated the choice of a superconducting gun altogether. The Brookhaven/Grumman [Gun I] S-band photoinjector [10] was taken as a starting point for the design of the TTF injector; the resonant frequency, waveguide coupling, intercavity coupling, and longitudinal exit aperture profile were modified to yield an L-band structure with good shunt impedance and field balance characteristics. RF design of the asymmetric gun structure proceeds analogously, with two obvious and significant differences: the cavities are made elliptic to reduce the transverse variation of $E_z$ and the overall strength of $B_y$, and the irises are made to be very long and narrow, spanning nearly the entire large dimension of the cavity. In so doing, the fields in the cavity are made to depend less on the horizontal position offset, reducing the RF contribution to the emittance. Placement of a focussing element (solenoid or quad) around the first half cell of the gun completely occludes all reasonable locations for an RF coupling slot, requiring power for the half cell to be coupled in either magnetically through a series of coupling slots placed at the maximum of the azimuthal magnetic field, or electrically by widening the iris. Slot coupling is known to excite...
higher order azimuthal spatial harmonics in the RF field causing unwanted nonlinear RF transverse emittance growth. Widening the iris for improved group velocity lowers the shunt impedance and affects the radial spatial harmonics (flattening the near-axis radial variation of $E_z$ as a benefit) and reduces the strength of the higher order longitudinal spatial harmonics. This somewhat unusual coupling scheme has already been employed successfully in a photoinjector for a free electron laser [15, 14]. Although RF power efficiency was of prime concern in designing the photoinjector, the standard shunt-impedance increasing procedure of decreasing the gap length with the addition of “reentrant noses” on the entrance and exit irises was not undertaken. Although such a geometric modification can appreciably improve the power efficiency of an RF structure, it does so at the expense of significantly enhancing the nonlinear components of the accelerating field. As the rms bunch radius for the high-charge symmetric case is significant (7 mm at the maximum, 10 cm from the photocathode), nonlinear RF emittance growth in such a cavity would be unacceptably large. Also, the large accelerating gradient (twice the Kilpatrick threshold) makes an RF structure with a low peak-field to accelerating-field ratio especially desirable, making the addition of any geometric disturbances in the high electric field region of the cavity undesirable. An elongated half cell was chosen to provide improved beam divergence control (A small amount of RF focussing occurs in the region right off the cathode as a result of the lengthening) and additional time to start the solenoidal focussing kick to initiate the emittance compensation before the time-dependent kick of the first iris becomes appreciable. After some optimization, a half cell length equal to $\frac{5 \lambda_{ir}}{4}$ was chosen. To ameliorate further higher spatial harmonic pollution of the accelerating mode, the full cell has a length that is exactly $\frac{\lambda_{ir}}{2}$. The iris area between the full cell, where RF power is coupled in, and the half cell was chosen to yield strong enough coupling that the longitudinal position of the photocathode could be used as a frequency tuning mechanism without causing a substantial shift in the field balance between the two cells. Various field balance options were considered, motivated by the possibility of using RF focussing at the first iris on the one hand, and by the possibility of improved longitudinal phase space linearity (and thus compressibility) on the other. A field imbalance between the half and full cell could be made to enhance the time dependent focussing kick centered at the first iris, but was found to significantly interfere with emittance compensation, degrading final beam quality, and was not pursued further. Thus a balanced ($E_{z,\text{half cell}} = E_{z,\text{full cell}}$) field profile was chosen. To ensure the field balance, the mode separation was chosen to be approximately 2.5 MHz (40 times the -3dB cavity bandwidth), implying a coupling constant of $\gamma = 0.19\%$. Assuming the half cell field to be $E_1 = 45$ MV/m, the full cell field $E_2 = 35$ MV/m, the stored energy $U = 10.5$J, the iris thickness to be $d = 1.5$cm, and the free space wavelength $\lambda = 23.061$ cm, the electrical coupling iris radius needs to be [6]:

$$r_o = \left[ \frac{3\gamma U}{2\epsilon_0 E_1 E_2 e^{-\alpha d}} \right]^{\frac{1}{\gamma}} \approx 2.0\, cm$$

where $\alpha = k_o \sqrt{(\lambda/\lambda_c)^2 - 1}$ is the attenuation length for the $TE_{11}$ mode. Simulation of the symmetric gun cavities using the Superfish code yields $\gamma = 0.189$ for an iris radius of 2.0 cm, in good agreement with prediction. As the hole is not uniform in radius, (rather the edges are rounded to prevent field line concentration) the coupling constant for the
simulated and actual photoinjector will be somewhat higher than equation 2 predicts. RF simulations of the full 1.5 cell asymmetric RF structure are underway at the time of this writing.

The effects of beam loading also bear directly on the choice of coupling strength, as loading in each cell of the photoinjector is different, leaving the fields slightly imbalanced (i.e., the zero mode is weakly excited) after the bunch has passed. The coupling strength will influence the recovery time of the photoinjector, which must be significantly less than the time between bunches. In view of the short time between successive bunches, and the large number of bunches per pulse, a simple examination of the RF transient response of the photoinjector was made. A lumped circuit model, shown in figure 5, was used to analyze the fill rates of the two cavities, and verify that the coupling was adequate. The coupled differential equations governing the currents \( I_1(t) \), \( I_2(t) \) and \( I_k(t) \) may be solved in the weak coupling approximation to yield the fill times for the two cavities:

\[
\tau_1 \approx \tau_2 \approx \frac{2L}{R} = \frac{2Q}{\omega} \approx 2.91 \mu s
\]

where the lumped circuit component values were estimated using the loaded Q, structure impedance \( Z \), (not \( ZT^2 \)), and the resonant frequency of the individual cavities as calculated by Superfish.

Direct numerical integration of the exact coupled equations using a 4th order Runge-Kutta algorithm reproduced the approximate fill time values given above.

The RF input coupler for the symmetric photoinjector was simulated using Hewlett Packard’s High Frequency Structure Simulator (HFSS), which is a fully three-dimensional finite element frequency domain electromagnetic code. As a guide for choosing the dimensions of the coupling slot, Gao’s expression [7] for the coupling constant, \( \beta \), derived using Bethe’s formalism for computing the perturbation of cavity fields due to apertures [2], was employed, with the dissipated power \( P_o \) taken to be the total power dissipated in both cavities:

\[
\beta = \frac{\pi Z_o k_o \Gamma_{10}}{9 \frac{1}{W_{wg}} (K(e_o) - \varepsilon(e_o))^2} \frac{H_0^2}{P_o}
\]

With the impedance of free space \( Z_o = 120 \pi \), the free space RF wavenumber \( k_o = \frac{2\pi}{\lambda_o} \), the waveguide propagation constant \( \Gamma_{10} = k_o/\sqrt{1 - (\lambda/2a)^2} \), the aperture mode attenuation constant \( \alpha = k_o \sqrt{((\lambda/\lambda_c)^2 - 1)} \) with cutoff wavelength \( \lambda_c = 3.41 \sqrt{l_1 l_2} \), \( \delta \) being the

\[ \ \]
aperture depth, \(W_{wg}\) and \(H_{wg}\) the width and height of the waveguide, respectively, \(H_0\) the tangential magnetic field strength at the aperture location, and the aperture eccentricity \(e_0 = \sqrt{1 - (\frac{H_0}{H})^2}\).

In view of the very light beam loading (18.5 kW at \(E_o = 35\) MV/m), the unloaded cavity coupling coefficient need not be adjusted much to assure critical coupling with the beam present. The adjusted unloaded cavity coupling coefficient should be \(\beta_o = 1 + \frac{P_{beam}}{P_{cav}}\) or approximately 1.02 for this case. In addition, this effect can be controlled by feed-forward on the rf amplitude.

The opening of the coupling slot on the outer wall lowers the cavity frequency because of the effective increase in the cavity volume in an H-field dominated region. We examined the possibility of compensating for the frequency depression by a simple technique. The waveguide end may be pushed into the volume of the cavity, producing a flat region that not only decreases the volume of the cavity, thereby raising the frequency, but makes the thickness of the waveguide coupling slot more uniform. The two frequency perturbations can be made to cancel by an astute choice of the waveguide’s penetration distance into the cavity, once the required dimensions of the coupling slot are known. The intrusion depth for this RF structure was calculated and found to be too small to warrant the added machining complication. Instead, the radius of the full cell has been adjusted to provide the required equal and opposite frequency shift.

Lastly, the waveguide taper, required to allow space for the first focussing solenoid (see figure 1) and to match the WR650 waveguide to the cavity, was chosen to be a standard \(\lambda/4\) stepped transformer. Simulations with HFSS indicate that suppressing reflections by 20 dB or more is straightforward. The electrical properties of the symmetric photoinjector accelerating structure are summarized in table 3 below.

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<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
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<td>Frequency</td>
<td>(f)</td>
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<td>Transit time factor</td>
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<td>Structure quality factor</td>
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<td>Structure fill time</td>
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<td>Effective Shunt Impedance</td>
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<td>Peak-to-accel field ratio</td>
<td>(E_{pk}/E_{acc})</td>
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<td>Power diss at (E_{acc} = 50) MV/m</td>
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<tr>
<td>Average Power diss at (E_{acc} = 50) MV/m</td>
<td>(P_{ave})</td>
<td>45.0 kW</td>
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Table 3: Electrical Properties of the Symmetric Photoinjector

As with any asymmetrically iris-coupled structure, the electrical center of the fields is shifted towards the driving iris. A least squares fit of the near-axis data from HFSS reveals that the displacement of the field maximum is \(\leq 0.39\) mm from the geometric center of the cavity. Such a small shift (which is present only in the full cell, owing to the RF
coupling scheme used) is not enough to warrant a cavity geometry alteration to compensate. The shift in electrical center is expected to be smaller (owing to the greater distance between the coupling iris and the geometric center of the cavity) for the elliptic cavities as well.

Run time tuning of both photoinjectors will be accomplished with the aid of four largely separate controls. Gross frequency tuning of the photoinjector as a whole will be accomplished by regulating the cooling water temperature. Thermal analysis of a similar L-band structure dissipating much higher average power (150 kW, versus 45.0 kW for the present case) found no serious difficulties in providing adequate cooling[11]. Indeed, an S-band structure sustaining the same duty cycle (1%) but higher accelerating gradient (by a factor of 2), and thus substantially higher dissipated power density (by a factor of 20), has been designed and successfully operated at Brookhaven National Lab [10].

Diagnostics and Instrumentation

The layout of the Argonne National Laboratory photoinjector test setup is shown in Figure 6 below. Instrumentation of the beamline has been chosen to permit exploration both of the injector performance in general, and to allow direct observation of emittance compensation. The linac, under electrical design at the present, will be specifically designed to accommodate expanded dimensions of the flat beam to permit its use in testing both symmetric and asymmetric injectors. A new approach to emittance measurement has been proposed to explore the physical basis for emittance compensation. A time-resolved vari-
eration of a slit emittance measurement technique (similar in principle to the pepper pot) employed at UCLA[13] will be used, providing emittance measurement in one transverse plane as a function of longitudinal position within the beam. While prior time-resolved measurements of electron beam emittance on the nanosecond time scale at Los Alamos [8], and of three-dimensional spatial distribution at LEP [1] have been successfully undertaken, measurements with sufficient resolution (picosecond or better) to observe the emittance compensation process have not. Figure 7 provides a schematic of the proposed measurement. A detailed analysis of the apparatus will appear in the near future, but a brief description is included here for completeness.

![Figure 7: Schematic of time resolving emittance measurement apparatus](image)

The space charge dominated beam is brought to a non-ballistic waist (ie particles do not cross the axis) and collimated into several emittance dominated beamlets by a slit emittance mask. The beamlets retain the transverse temperature of the original beam, but at such reduced charge that space charge forces within the individual beamlets contribute negligibly to their momentum spread. The beamlets then drift several meters to allow the correlated transverse momentum time to impart a measurable transverse distance offset, and are passed through a Čerenkov radiator to produce an optical signal that can be extracted
from the beamline. The light is focussed (optics not shown) onto the photocathode of a streak camera, and the streaked image recorded with a high resolution CCD camera. The spread of the light from each beamlet may be analyzed to unfold the contribution due to the transverse temperature of the beam from the natural spread angle of the Čerenkov radiation. The centroid of the beamlets at the radiator provides the centroid of the transverse momentum spread, while the transverse position centroid is known immediately from the separation of the collimator slits. From these data the transverse phase space of the beam may be reconstructed as a function of longitudinal position within the beam. The slit separations are chosen to ensure that the light from adjacent beamlets does not overlap at the CCD camera.

The measurement will be made at two locations, once at the photoinjector exit, and again at the exit of the linac, allowing comparison of the beam’s slice emittances immediately after the focussing kick, and shortly after the emittance compensation minimum has occured.

With this diagnostic, investigation of the effectiveness of emittance compensation will be explored as a function of compensating lens position and strength by adjusting the current sum and the current ratio, respectively, of the two focussing solenoids depicted in figure 1 above. With information about the actual slice emittances (viz. the emittance of a subset of the beam electrons between $z$ and $z + \Delta z$) and the orientation of the slice emittance ellipses before and after compensation, detailed study of emittance compensation will be possible for the first time.

In addition, two integrating current transformers will be mounted, one immediately downstream of the photoinjector to non-destructively monitor bunch charge at emission, and another after the collimators downstream of the first linac section to monitor final beam charge. Ordinary fluorescent screens, fitted with CCD cameras, used with the emittance slit mask, will provide ensemble emittance measurements as a cross check for the time resolving emittance measurement. A dipole spectrometer (not shown) will be mounted at the end of the beamline for beam momentum analysis.

The RF and laser systems at Argonne National Laboratory Wakefield Accelerator Facility are under computer control through a combination of LabView and custom Tcl/Tk based software. Both photoinjectors will make use of the existing RF and laser systems, adding a separate LabView-based control system to run the diagnostics. A number of LabView “virtual instruments” (VIs) have been developed to operate similar equipment at the UCLA Particle Beam Physics Laboratory, and will be transferred to the photoinjector test setup with minimal additional programming effort. The time-resolved emittance diagnostic will require the development of custom software to process the streak data.

**Timetable**

A timetable indicating the expected start and end dates of the three phases of the photoinjector design program is shown in figure 8 below. Annual boundaries shown are those of the fiscal year. Work begun on the hardware development at the time of this writing includes emittance measurement system development, and construction of a cold test model of the 1.5 cell gun.
Timeline for Photoinjector R & D Activities

Figure 8: Projected timetable for symmetric and asymmetric photoinjector design and commissioning activities

**Conclusion**

An RF and beam optics design for a Tesla Test Facility compatible symmetric emittance electron photoinjector has been developed and presented here in brief. Further work to improve the beam dynamical aspects of the photoinjector assembly will continue, focusing on improvements in beam compressibility and a careful examination of the photoinjector’s operation at reduced charge, of particular interest for the proposed FEL user facility that may evolve from the TTF. Work to understand the novel beam physics manifest in an asymmetric emittance gun will also continue, with the goal of producing a working prototype by mid-1995.

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