Design and Construction of High Brightness RF Photoinjectors for TESLA

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Abstract

The design, construction and testing of a high brightness high bunch charge RF photoinjector matching the requirements of the TESLA Test Facility is discussed. Engineering design work, the results of cold test measurements, and the planned experimental program are presented. Conceptual design work leading to an advanced high-brightness asymmetric emittance RF photoinjector for application to TESLA500 is also briefly discussed.

I. INTRODUCTION

The TESLA Test Facility (TTF), as proposed, is a 500 MeV superconducting linac designed to study technological issues involved in constructing and operating TESLA500, a 0.5 TeV superconducting linear accelerator. Studies of higher order mode power deposition at cryogenic temperatures will require a train of bunches with the same frequency spectrum as will be present at TESLA500. The combination of relatively high bunch charge (8 nC), short pulse length (1 mm), moderate transverse emittances ($< 20\ \pi$ mm-mr) and long pulse train (800 pulses with 1μs spacing) make the design challenging. In addition, the potential for operating the gun over a large range of bunch charges (0.5 nC to 10 nC), a range of accelerating gradients (35 MV/m to 50 MV/m) and with different focussing fields required a flexible focussing assembly. Asymmetric transverse emittances of 1 π mm-mr vertically and 20 π mm-mr horizontally are required for TESLA500, and are potentially achievable directly from an RF photoinjector, eliminating the need for an electron damping ring. Given that the long pulse trains demand large damping rings, elimination of the electron damping ring would represent a significant cost savings.

II. DEVELOPMENT

A. Symmetric Emittance Photoinjector for TTF

An injector producing the required bunch properties and pulse train structure was designed with the space and RF power constraints of the TTF in mind. A Brookhaven-style[2] 1 1/2 cell π-mode structure was modified to operate at 1.3 GHz with substantially increased (factor of 5) intercell coupling to reduce field balance tuning sensitivity. A single-cell iris coupler drives the full cell only, leaving clear sufficient space to mount a focussing solenoid over the half cell, shown in figure 1. An additional focussing solenoid follows immediately after the gun to provide a continuously variable magnetic center of the focussing lens, a flexibility that will allow wide ranging examination of space charge emittance compensation[3] over a wide range of bunch charges.

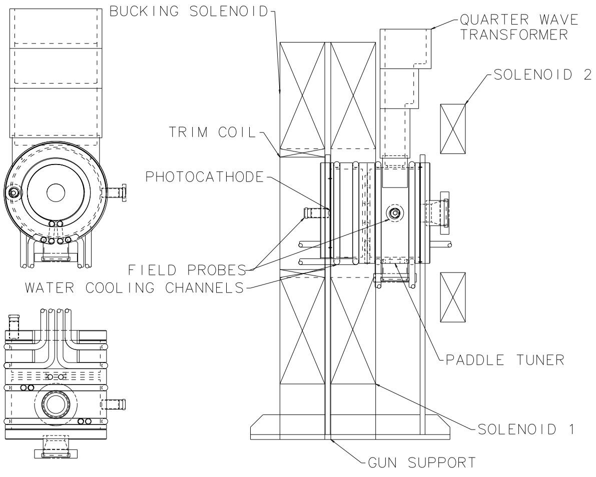

Figure. 1. Symmetric emittance photoinjector

The gun is followed by a drift to allow the space charge induced correlated emittance growth to reverse before entering a moderate gradient (15 MV/m) linac. At the TTF, the linac will be a 9-cell superconducting structure, and thus studies of dark current deposition were carried out, and have shown that strategic placement of several collimators ahead of the linac, together with the strong overfocussing that naturally occurs from the emittance compensating solenoid, are enough to reduce the dark current reaching the linac by two orders of magnitude. Initial testing of the injector at the Argonne Wakefield Accelerator (AWA) Facility will be carried out with a retrofitted copper 9-cell TESLA structure to reproduce the spatial field profiles of the actual structure.

The linac is rephased to impart a negative α_ϕ sufficient to permit pulse compression by a factor of two in a dispersive chicane. A positive time dispersion in the chicane is chosen to cause the space charge forces to oppose the compression, stabilizing against charge fluctuations. The compression chicane is composed of four identical C-frame dipoles with moderate field strength (0.9 kG) and a suitably formed vacuum chamber with collimation slits placed in the maximum dispersion region to permit momentum collimation of the beam.

Numerical simulation of all components of the injector was carried out using a version of the beam dynamics code PARMELA modified to accept externally generated field maps for RF cavity and static magnetic focussing fields. RF field profiles for the gun and linac cavities were derived from Superfish runs, and static field profiles for the solenoid focussing assembly were derived from Poisson runs. Table I below outlines the

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*Operated by the University Research Association, Inc., under contract with the U.S. Department of Energy

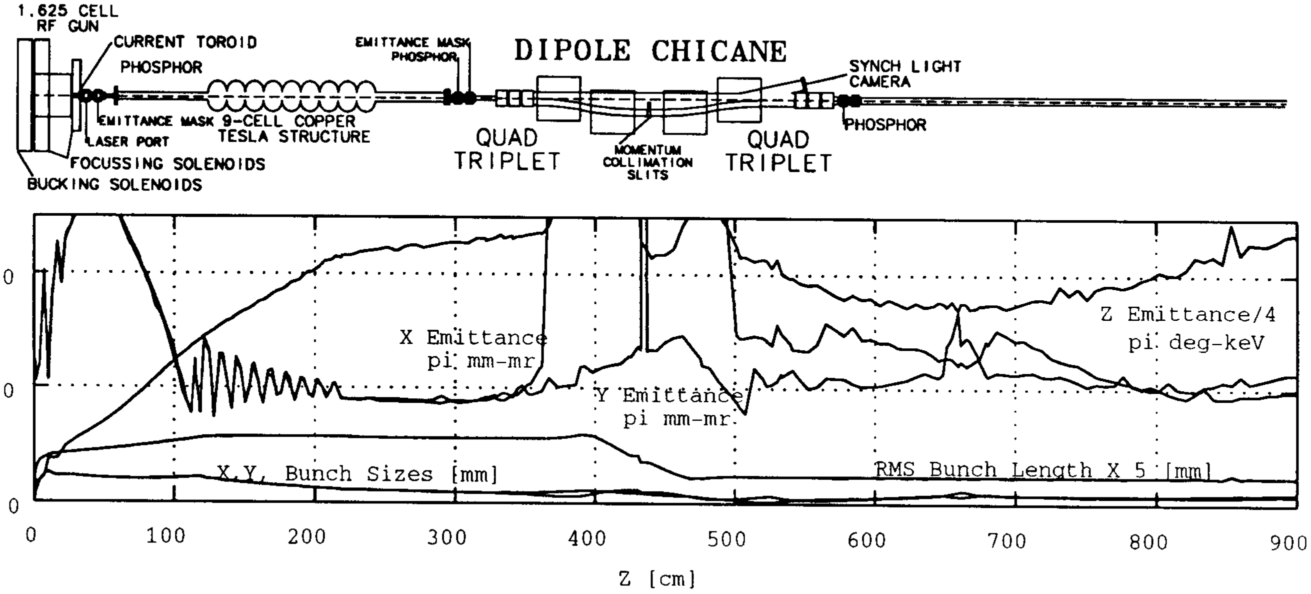

Figure. 2. Symmetric RF Photoinjector Test Layout (top), Emittance and Beam Size Evolution the Injector (bottom)

predicted performance of the TTF injector prototype from simulations. Transverse emittances are listed as full-width-at-half-maximum emittances, as would be measured using a slit emittance mask and phosphor screen, while longitudinal emittance is listed as 100% RMS. All emittances are normalized. Figure 2 shows the proposed beamline layout for the prototype tests at Argonne, together with emittance and beam size evolution. The longitudinal emittance has been scaled by a factor of 0.25 and the bunch length has been scaled by a factor of 5 to permit display on the same axis as the other quantities.

Parameter	*Value*
Bunch Charge	8 nC $= 5 \times 10^{10} e^-$
Laser pulse length FWHM	7.4 ps
Launch Phase (w.r.t. $E_z = 0$)	50^o
Beam radius at cathode	6.53 mm
Peak field on cathode	35 MV/m
Post-Gun Energy	3.8 MeV
Average Linac Gradient	15 MV/m
Post-Linac Energy	18.5 MeV
Horizontal Emittance	19.3π mm-mr
Vertical Emittance	19.7π mm-mr
Longitudinal Emittance	189 deg-keV
Momentum Spread	1.15 %
Bunch Length	0.74 mm
Peak Current	1.28 kA

Table I

Predicted performance of the symmetric injector

Thermal analysis of the injector structure under the 1% duty cycle of TTF has been carried out. The peak power dissipation of 4.5 MW (corresponding to a peak cathode field of 50 MV/m) during the $>$ 1 ms RF pulse has been found to cause less than 6 kHz detuning of the cavity, or less than a twentieth of the cavity's 3 dB bandwidth, a frequency change that can be compensated for by a low bandwidth feedforward system. Structural stress analysis using ANSYS shows that the peak stress intensity does not exceed 40 MPa, safely below the yield strength of OFHC copper, 76 MPa. In anticipation of possible microphonic detuning of the cavity from turbulent water flow in the cooling channels, a channel of geometry similar to the proposed cooling channels for the high duty cycle gun have been included in the prototype. Deformation measurements show the deformation due to 110 psi pressurization is 1.7 μm. Pressure fluctuations due to turbulence are generally less than $\Delta P/P_o \propto 10^{-2}$ for non-erosive flow rates, and thus the amplitude of wall vibrations will be completely negligible.

Cold testing of the gun structure has been carried out on a composite copper/brass model. The coupling has been measured at 0.21 %, in reasonable agreement with the Superfish-calculated value of 0.19 %. Tuning characteristics of the cathode (which is mounted on a micrometer) and a separate paddle-style tuner in the full cell have been examined, and also found in reasonable agreement with simulation. Field profiles derived from resonant frequency perturbation methods closely correspond to expectations from Superfish calculations, as shown in figure 3 below. Measurements of the dipole shift in the full cell induced by the input coupler show less than 1.1 mm (1/200 of an RF wavelength) deviation from the geometric center of the structure, as is shown in figure 3 below. Data for the longitudinal field profile were taken at monotonically increasing longitudinal coordinate, while transverse data were taken in random order, illustrating more clearly the contribution to the resonant frequency shift from thermal effects during the measurement.

Preliminary calculations[4] have shown that the beam density is high enough to generate significant coherent synchrotron radiation in the compression chicane at wavelengths comparable

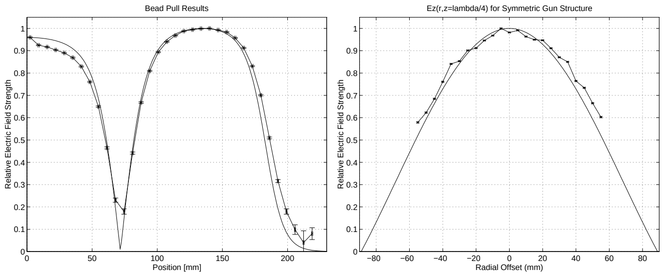

Figure. 3. Measured and calculated longitudinal and transverse field profiles for the symmetric gun structure

to the bunch length (1 mm). Further simulation work is underway at this time, including modification to PARMELA to include retardation and radiation effects in the space charge calculation. The vacuum chamber in the dipole chicane will be fitted with a tangent optical viewport in the final dipole (where beam density and radiation intensity are maximum) to allow observation of the emitted IR synchrotron radiation.

Commissioning of the symmetric emittance photoinjector is scheduled to take place mid-summer, with preliminary high power RF testing of the linac structure occurring earlier. Full testing of the injector including pulse compression is expected by year's end. In addition to a full characterization of the gun, emittance compensation studies will be carried out using the double solenoid to examine the effects of lens location and strength on emittance compensation. A unique time-resolved emittance measurement using a streak camera to streak the light from a Čerenkov gas cell placed to intercept the beamlets generated from a slit emittance mask will be attempted, to provide the first experimental verification of the physical mechanism of emittance compensation.

B. *Asymmetric Emittance Photoinjector for TESLA500*

Emittance compensation for the flat beam photoinjector requires the use of quadrupoles to focus the beam in both planes, as solenoidal focussing would couple the transverse phase planes and results in severe degradation of the small vertical emittance. A quadrupole doublet, positioned around the gun itself, provides the initial focussing kick for compensation. A subsequent triplet at the exit of the gun allows for matching the beam into the subsequent linac section for further acceleration. Initial studies have demonstrated compensation for the vertical emittance, while the planned approach of using substantial guard charge at the horizontal extrema of the bunch to minimize the nonlinear space charge emittance growth of the core, followed by collimation of the nonlinearly heated portions of the bunch at the horizontal edges after further acceleration has reduced the space charge forces.

After considering a number of geometries, an RF structure suitable for accelerating a flat beam with minimal energy spread and minimal coupling of the transverse phase planes a structure composed of shorted sections of ridged waveguide was chosen[5]. Field profiles from Hewlett Packard's High Frequency Structure Simulator in figure 4 below show that a very large flat-field region is available for accelerating large aspect ratio beams.

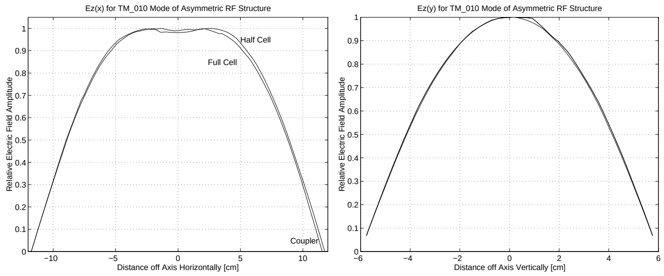

Figure. 4. Transverse field profiles of the TM_{010} mode

Testing of the asymmetric gun structure will proceed with fabrication of a cold test model to examine field balance and field flatness issues. Powered testing of the injector at the AWA reusing the injector beamline and diagnostics developed for the symmetric TTF gun prototype is tentatively planned in the coming year.

III. CONCLUSION

Design of an input coupler for the normal conducting 9-cell TESLA structure and subsequent testing at operating RF power levels will complement the gun construction activities, leading to first beam dynamics studies of the gun by mid summer. The linac and compression chicane will be commissioned in early fall, with design of the full-power TTF gun structure following shortly thereafter. A continued attack on the beam dynamics issues, and construction of a cold test model of the RF structure will form the main asymmetric injector effort.

References

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