A HIGH CHARGE, HIGH DUTY FACTOR RF PHOTOINJECTOR FOR THE NEXT GENERATION LINEAR COLLIDER

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Abstract

Testing of the prototype TESLA Test Facility (TTF) RF photoinjector has been completed, and fabrication of the high duty factor TTF injector is underway. Experimental results from the prototype tests conducted at Argonne National Laboratory will be presented. Engineering design work for the high power TTF gun will be discussed together with initial operating experience with a Cesium telluride photocathode in short (50 microbunch) pulse trains, and long RF pulses (1000 millisecond), conducted at Fermilab[1]. An outline of future advanced accelerator R&D activities at Fermilab will also be presented.

1 INTRODUCTION

The TeV Superconducting Linear Accelerator (TESLA) is unique among the world's linear electron accelerator proposals as the only scheme using superconducting radiofrequency (scrf) cavities for acceleration. The TESLA Test Facility (TTF) is being constructed at the Deutsches Elektronen-Synchrotron (DESY) to address engineering and economic questions about the viability of constructing superconducting electron accelerators at energies reaching to 0.5 TeV and beyond. Table 1, reproduced from the design report [1], outlines the parameters of both TESLA-500, a 0.5 TeV collider proposed as the first step towards a 5 TeV machine, and the parameters for the TTF.

Fermilab's participation in the planning and construction of the TTF has been extensive, including key contributions to the cryogen handling systems, cryomodule design, rf input power couplers, and the rf photocathode electron source for the second phase of the TTF testing program.

Initially, a conventional thermionic source was used to supply low bunch charge (37 pC) bunches to the TTF linac at a 216 MHz micropulse repetition rate to provide the correct beam loading current (8 mA) for rf and transport studies. The thermionic injector will be replaced by an rf photocathode gun capable of delivering the TESLA-500 bunch charge (8 nC) at the required repetition rate (1 MHz). Higher order mode power deposited by the bunch wakefields will be studied with the nearly 1 kA beams produced.

Table 1: TESLA-500 and TTF Parameters

Parameter	TESLA 500	TTF
Linac Energy	250 GeV	500 MeV
RF Frequency	1300 MHz	1300 MHz
Gradient	25 MeV/m	15 MeV/m
No. Cryomodules	~2500	4
Bunch population	5 x 10^9	5 x 10^9
Energy Spread[1]	0.15 %	0.1%
Energy Spread[2]	0.1 %	0.2%
Bunch Length[3]	1 mm	1 mm
Beam Current	8 mA	8 mA
Macropulse length	0.8 ms	0.8 ms
Injection Energy	20 MeV	20 MeV
Emittances[4]	20 x 1 μm	20 x 20 μm
Beam Size[5]	260 x 60 μm	3.5 mm
Beam Size	50 x 12 μm	0.5 mm
Micropulse spacing	1 μs	1 μs
Macropulse spacing	100 ms	100 ms

[1]RMS, single bunch
[2]RMS, bunch-to-bunch
[3]RMS, one-sigma
[4]RMS, one-sigma, normalized
[5]RMS, one-sigma

Once the wakefield and transport studies have been completed, plans call for replacement of the high charge gun with a low-charge low-emittance photocathode gun for the FEL experiments. A Self-Amplified Spontaneous Emission Free Electron Laser (SASE-FEL) will be installed, initially operating in the 100-25 nm range. Ultimately, plans call for a doubling of the linac energy, and modification of the undulator to produce radiation in the 20-6nm range [2]. Operation of the high-charge gun, with suitably altered laser parameters, may provide an effective interim alternative [3] for the first phase of the SASE-FEL studies while the new gun is being constructed.

2 INJECTOR DESIGN

Two rf photocathode guns have been built, and a third is currently in fabrication: a low duty cycle($<10^{-3}$) gun for single bunch testing, and two high duty factor guns incorporating differing methods of water channel fabrication.

The design has been described in detail elsewhere [4,5], with only a brief summary provided here. Electrons are produced from a cesium telluride photocathode (plain copper in the low duty cycle prototype) which is on the

[1]Operated by the Universities Research Association for the U. S. Department of Energy. Work also supported in part by grants DE-FG03-ER40796 and W-31-109-ENG-38.

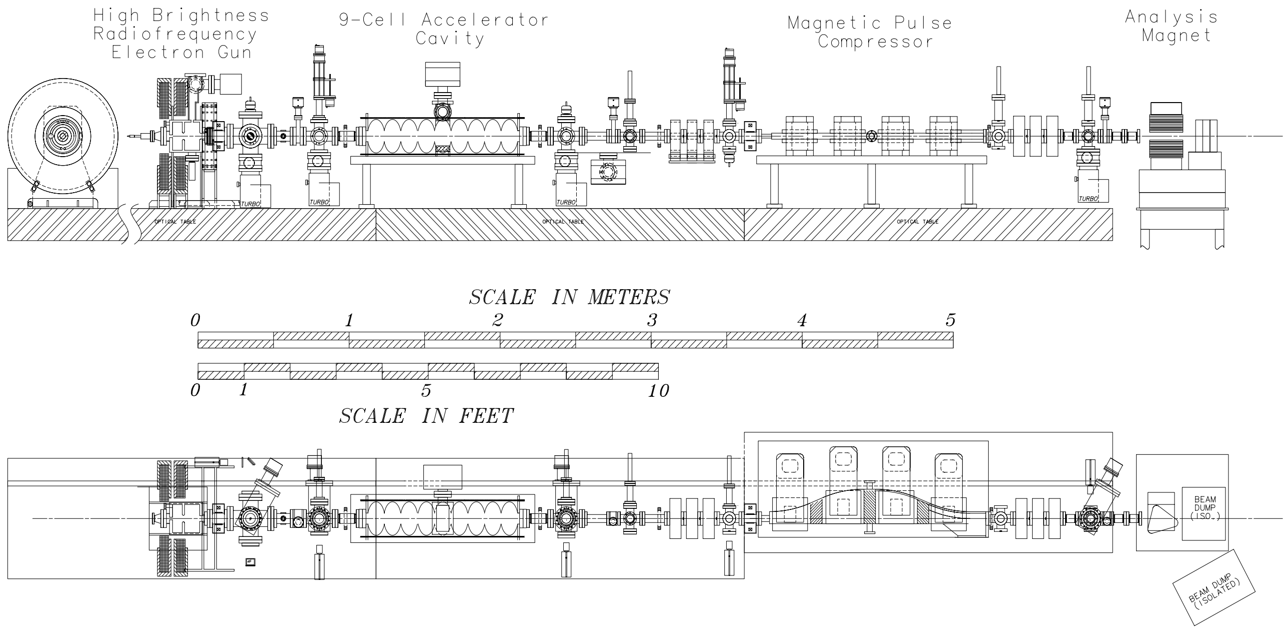

Figure 1: Layout of photoinjector components

rear conducting wall of a 25% elongated half cell. A system of four external solenoids (two focussing and two bucking) provide adjustment of both the strength and longitudinal profile of the magnetic field used to simultaneously focus and space charge correlation compensate (“emittance compensate” [7]) the electron bunch, permitting correlation compensation to be attained over a wide range of accelerating gradients. The bunch is accelerated in the low gradient (18 MeV/m) gun structure of 1.625 cells. The 3.9 MeV electron bunch exits the gun and drifts approximately half a plasma wavelength to the entrance of a superconducting 9-cell booster linac (normal conducting for the prototype).

In the booster it receives moderate acceleration (15 MeV/m) to approximately 18 MeV, and a modest phase-energy correlation. To preserve the transverse emittances, the initial bunch length is 2.2 mm, which is compressed to 1 mm in a dipole chicane (temporal dispersion: $(\phi|dp/p)=2.50$ rad) using the phase-energy correlation developed in the booster linac, which is run off-crest by some 15-20°.

An entrance quadrupole doublet and exit triplet permit beta function matching to the pulse compressor. At the TTF, several quadrupole doublets and triplets relay the beam from the exit of the pulse compressor to the first cryomodule. At Fermilab’s A0 Photoinjector installation, quadrupole triplets will provide an interaction region for a variety of advanced accelerator experiments.

Experimental testing of the injector has been taking place in three separate phases:

- With single electron bunches and the low duty factor gun to establish the basic design;
- With short bunch trains (<50 microbunches) and the cesium telluride photocathode to study cathode lifetime effects [6], and with long rf pulses (1 ms), but low duty factor to test for rf breakdown problems;
- With the high duty cycle gun operated with long rf pulses (1 ms) and acceleration provided by a superconducting cavity to study long pulse train operation of the injector.

3 PROTOTYPE TEST PHASE

The prototype injector was installed in two steps at the Argonne Wakefield Accelerator Facility at Argonne National Laboratory. The gun was assembled with a short test beamline, to permit direct diagnosis of the beam produced by the gun, then the test beamline was removed and the booster linac and pulse compressor installed to permit testing of the completed injector.

Shown in figure 2 below is a slit mask emittance measurement of the horizontal emittance as a function of the gun solenoid field strength, made at 16.5 MeV. The emittance compensation minimum is clearly visible.

The energy spectrum of the uncompressed 8 nC bunch is shown in figure 3 below.

Measurement of the bunch length was done with a Hamamatsu streak camera (C1587 streak tube, 1 ps quoted resolution) examining the Cerenkov radiation from an aerojel target. Measured pulse lengths generally showed poor pulse compression, which from subsequent simulations of wakefield effects [8] is believed to have arisen from interactions with the irises in the gun and booster linac. Electron bunches as short as 12 ps FWHM were observed, corresponding to a peak current of more than 850 amperes. Table 2 below outlines the desired, predicted and measured parameters for the injector.

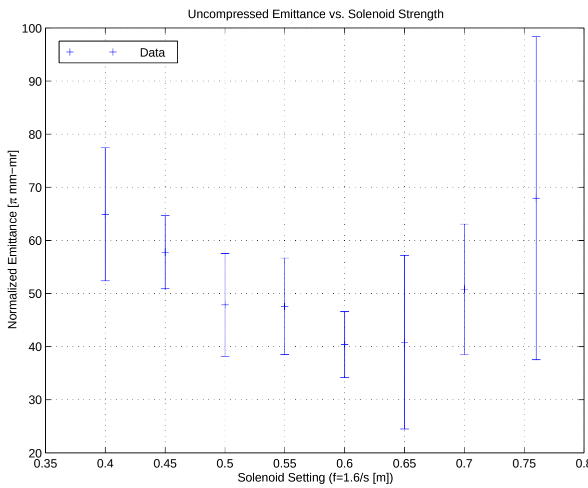

Figure 2: Horizontal emittance measurement versus gun solenoid strength. Error bars are sample variances from ten trials per point.

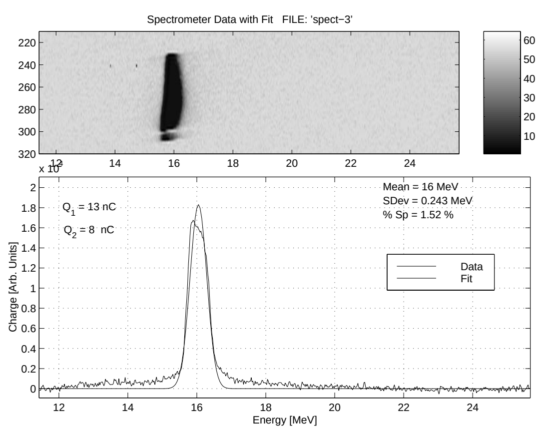

Figure 3: Energy spectrum of uncompressed 16 MeV beam at exit of injector.

Although design values for the injector meet or exceed the requirements for the TTF installation, the conditions under which the injector was tested were different from the idealization in the design. Simulation of the injector using a modified version of PARMELA and the measured values for the rf structure field balances and the measured spatio-temporal distribution of the laser pulse, but excluding wakefield effects shows reasonable correspondence to the measurements, as listed in table 2 below.

As before, quantities are RMS, one-sigma, and the emittances are normalized. It is worth noting that the dominant contributions to the emittance over the design values arise primarily from strong transverse filamentation and Gaussian temporal profile of the laser pulse, and from the unbalanced field strengths in the half and full cell of the gun. Incomplete pulse compression is seen in simulations [8] to be most likely from wakefield effects in the rf structures, which can be compensated effectively by further advancing the phase of the linac.

Table 2: Desired (D), predicted (P), and measured (M) Injector II parameters. 'NM'=not measured.

Parameter	D	P	M	Unit
Charge	8	8	8	nC
Energy	>10	18.3	17 ± 0.2	MeV
Energy Spread	<500	234	260 ± 200	keV
H. Emittance	20	37	40 ± 7	µm
V. Emittance	20	37	N.M.	µm
Bunch Length	1.0	1.6	1.4 ± 0.3	mm
Current, Peak	960	600	<850	A

4 HIGH DUTY CYCLE INJECTOR

With experimental evidence accumulating that the basic injector design was sound, work began to design a gun capable of sustaining the 1% duty factor (50 kW average power deposited in approximately a cubic foot) photocathode gun.

Detailed thermo-mechanical simulations were carried out [9] using Swanson's Ansys analysis system to establish that surface temperature rise due to rf pulse heating, peak surface stress levels, average temperature and average stress levels did not exceed the yield strength of OFE copper.

Given the long rf pulse length (Δt=1 ms) the expected thermal diffusion depth in copper is approximately:

$$\delta = \sqrt{4\alpha\Delta t} \approx 0.67mm$$

where α is the linear coefficient of thermal expansion for copper. This implies that the deposited power does not reach the water channels during the rf pulse. Hence, the problem breaks into two parts: the pulsed-heating problem, which influences only the material choice and peak power, and the average power problem, which controls the water channel placement.

Peak surface temperature rise determines the peak surface stress and the vacuum outgassing, and is approximately:

$$\Delta T = 2\frac{dP}{dA}\frac{1}{\rho C}\sqrt{\frac{\Delta t}{\pi\alpha_{\varepsilon}}} \approx 29\,^{o}C$$

where dP/dA is the power flux (30 MW/m^2), ρ and c_ε the density and specific heat of copper, respectively.

Figure 4 below shows the predicted thermal cycling at depths of 0.0mm to 4.0mm in 0.5 mm steps, showing the peak surface temperature rise is ≈28°C, as predicted.

Simulation of the volumetric stress induced by the surface temperature rise shows that the peak stress of 79.7 MPa occurs on the iris, where the power density is a maximum. This value is comparable to the yield strength for pure copper, 76 Mpa, but as the surface is constrained by the underlying bulk material, it is not expected that surface spalling will occur at an appreciable rate.

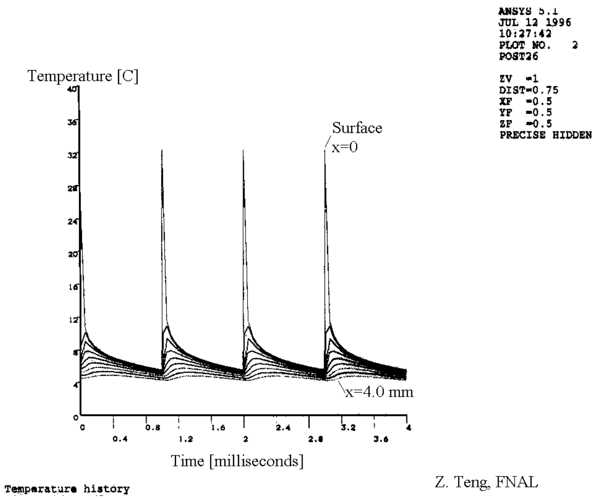

Figure 4: RF Pulse heating in the gun as a function of time.

Computation of the outer wall deflection was also carried out to determine the net cavity detuning that would take place during the RF pulse. The radial displacement before (lower trace) and after (upper trace) the 1 ms rf pulse are shown in figure 5 below. The initial net deflection corresponds to the "steady state" thermal distribution of the gun. The vertical scale is units of 10 microns, the horizontal is units of cm. An outward deflection (by ≈100 microns) of the outer wall close to the iris separating the half and full cell indicates the iris reaches a temperature slightly above the body at steady state.

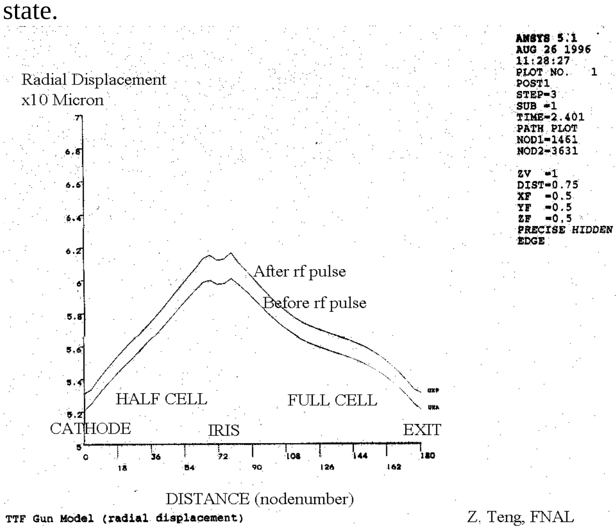

Figure 5: Outer wall radius change before and after rf pulse.

Owing to the high heat load in the thin iris separating the half and full cells of the gun, a cooling channel was machined into the iris to extract the heat. The low duty cycle gun and first high duty cycle gun had the iris cooling channel machined as an open channel (machined in from the full cell side) that was sealed shut by an electron beam welded annular cover. The iris face was machined after the electron beam weld some 0.080" to remove the weld fillet and produce a smooth surface for the high rf fields. This technique succeeded in the low duty cycle gun, but failed in two subsequent trials, fracturing open along and across the weld joint, and succeeded on the third trial with the high duty cycle gun. The reason for the failures is believed to be higher than acceptable impurity content in the copper, a problem worsened by annealing, which concentrates the impurities at the grain boundaries, giving sites of material weakness from which cracks can propagate. XDS analysis of the copper showed elevated levels of oxygen (but below the ASTM-F68-82 specification) and chlorine.

Consequently, another copper billet was purchased from Hitachi, and a fourth gun body produced, but with the iris cooling channel machined in from the gun exterior (not through the face of the full cell), and the channels brazed shut with copper water barriers.

5 HIGH DUTY CYCLE TESTS

Upon completion of the single bunch test at Argonne, the low duty factor injector was disassembled, transported to Fermilab's A-Zero experimental hall, and reassembled with a short diagnostic beamline. After brief rf testing to establish that the gun would successfully hold off much longer rf pulses (50 μs), the gun was dismounted and modified to accept the cesium telluride photocathode. RF conditioning, cathode lifetime and low energy beam experiments took place over the ensuing 6 months while the high duty cycle gun was being fabricated.

As the low and high duty cycle guns were in many respects equivalent for pulsed heating purposes (but not in average power dissipation) extensive rf conditioning of the low duty cycle gun was undertaken to discover limitations of the design. The low duty cycle gun conditioned unexpectedly well, holding off full klystron power (3.4 MW) for more than a millisecond with only occasional breakdown. Conditioning was halted by damage to the rf window incurred during the study. Vacuum was observed to rise from a base value in the 10^{-10} Torr range to the mid-10^{-8} Torr range during the long rf pulses, indicating that substantial rf conditioning will be necessary to obtain good vacuum at the full 1% duty cycle.

Photocathode lifetime was also investigated with the low duty cycle gun, and is described in detail elsewhere in these proceedings [4]. Once vacuum conditions had stabilized in the gun and beamline, we obtained 1.0% or better quantum efficiency from a cesium telluride cathode for more than four months, beginning from an initial QE value in excess of 10%.

Dark current was observed to be substantial (≈4 mA) from the low duty factor gun, and when imaged with the gun solenoid to a screen was seen to be composed of a ring with four or five bright spots on the periphery, implicating either (1) the cathode rf choke-joint spring,

(2) a sharp but recessed ridge in the cathode hole, (3) multipactoring brought on in the cathode-gun gap, perhaps exacerbated by the choke spring's silver plating, or (4) plasma formation, fed with gas by a nearby suspected virtual leak. The geometric features giving rise to (2) and (4) have been eliminated in the high duty cycle gun, and a plain beryllium copper spring has been used to reduce or eliminate the cause of (3).

Beam studies with short (10 microbunch) and longer (50 microbunch) pulse trains were undertaken, with the results being reported elsewhere in these proceedings[9]. Limitations of laser pulse energy limited the bunch charges to a nanocoulomb or less for long pulse trains, but short pulse trains of high charge bunches were also produced.

The first of the two high duty cycle guns was completed at the end of April, and has been successfully conditioned to accept full power, 1 ms rf pulses, with results reported in these proceedings [10]. The second high duty cycle gun should be completed by mid-September.

6 OPEN QUESTIONS

A number of physics issues remain to be resolved. The effect of variation of the solenoid "position" by adjusting the two gun focussing solenoid strengths has not been experimentally observed, and remains an interesting exploration of one facet of the space charge correlation compensation process. Pulse compression (to 1 mm and below) remains to be thoroughly investigated, both in itself, and for its potentially serious effects on the transverse phase space. Finally, finding the source and cure for the large dark current observed from the low duty cycle gun will be important.

7 FUTURE RESEARCH AT A-ZERO

A somewhat modified version of the photoinjector commissioned at DESY will be commissioned at Fermilab for use in an advanced accelerator R&D program. R&D projects which have real resources currently committed are:

- Electro-optically detected wakefield bunch profile measurement (Ph.D. research of M. Fitch, University of Rochester);
- Plasma wakefield acceleration experiments in the under-dense regime (J. Rosenzweig, UCLA, and P. Colestock, FNAL);
- High-efficiency photocathode material preparation and lifetime testing in RF cavity environment (Led by C. Pagani, Istituto Nazionale Di Fisica Nucleare, Milano)
- Fabrication and testing of superconducting rf cavities (H. Edwards, FNAL).

In addition, many more applications of the A0 facilities have been discussed:

- Polarized photocathode source development for RF injectors;
- Testing of next generation photoinjector structures;
- Bunched beam stochastic cooling;
- Impedance probing of stochastic cooling pickup/kicker antennae;
- Beam-beam tune shift neutralization in the Tevatron.

8 ACKNOWLEDGEMENTS

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