An Injector for the TESLA Test Facility Linac

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Abstract

We describe the studies in progress at LAL towards the design of a phase 1 injector for the TESLA Test Facility Linac. The front end of the injector is composed of a grid-controlled 250 kV electron gun and a 216.7 MHz pre-buncher cavity This is followed by a superconducting capture cavity to further bunch and accelerate the beam before transport to the TTF linac. The longitudinal beam dynamics of the bunching process are being investigated using PARMELA to fix the final layout of the injector and to determine the sensitivity of its operation to small changes in parameters.

Introduction

The TESLA Test Facility (TTF) is a superconducting RF linac to be constructed at DESY (Hamburg) by an international collaboration in order to demonstrate the viability of the superconducting RF approach to a future e^+e^- linear collider[1]. The linac consists essentially of an injector and four 12 meter long cryomodules. Each cryomodule contains eight 9-cell superconducting (SC) 1.3 GHz cavities of length 1.04 m. In order to fully test issues such as wakefield excitation and higher-order-mode dissipation the TTF linac requires an injector capable of producing a train of bunches with essentially the same charge and time structure required by the TESLA proposal itself[2]. Such an injector would have bunch populations of 2 to 5 x 10^{10} electons per micro-bunch with a bunch repetition frequency of 1 MHz during a macro-pulse length of 800 µs.

In contrast, the problem of operating high-gradient (15 to 25 MV/m) SC cavities in pulsed mode under heavy beam loading can be studied with a beam of equivalent average current (8 mA) during the 800 µs pulse, independently of the bunch population / time-structure. As the high bunch charge required for TESLA is not easy to realise it has been decided to construct two injectors for TTF. The first (phase 1) would produce the 8 mA average current with reduced charge per micro-bunch at an elevated repetition frequency. The second injector (phase 2) would have the characteristics required of the TESLA proposal.

Within the collaboration three French laboratories, LAL (Orsay), IPN (Orsay) and DAPNIA-CE (Saclay), have undertaken to construct the phase 1 injector for TTF. Broadly speaking the injector can be considered to consist of three main elements; (i) a pre-injector to provide beams of variable time structure, (ii) a superconducting capture cavity (1.3 GHz) and its associated cryostat to pre-accelerate the beam to the required energy (5 to 15 MeV) for injection into the main linac, (iii) a diagnostic beam line to verify the correct adjustment of the injector and a beam transport line to deliver the correctly tuned beam to the 1st cryomodule. Elements (i), (ii) and (iii) are the responsibility of LAL, IPN and DAPNIA respectively. This paper deals essentially with the studies in progress at LAL towards the design of the pre-injector.

Injector Specification

The main characteristics of the phase 1 injector are as follows;

energy	> 5 MeV
average current	8 mA
pulse length	800 µs
bunch length	1 mm (rms)
energy spread	< 1% (rms)
emittance	20 π mm-mrad (normalised)
repetition rate	10 Hz

The Pre-Injector

General

In order to allow flexible operation of the injector bunch repetition frequency we propose to use a grid modulated thermionic electron gun providing pulses of width < 1 ns at intervals of 4.6 ns and multiples thereof. The 4.6 ns corresponds to the period of the sub-harmonic buncher (216.7 MHz) which will be used to provide the initial pre-bunching of the beam before it enters the capture cavity. The intention is that the capture cavity will be identical to the 9 cell strucure used in the 12 m cryomodules. Therefore the cavity is not β graded to the low injection energy. In addition, as the strucure has a large beam pipe iris (70 mm diameter), it exhibits a substantial fringe field which initially decelerates the incident beam.

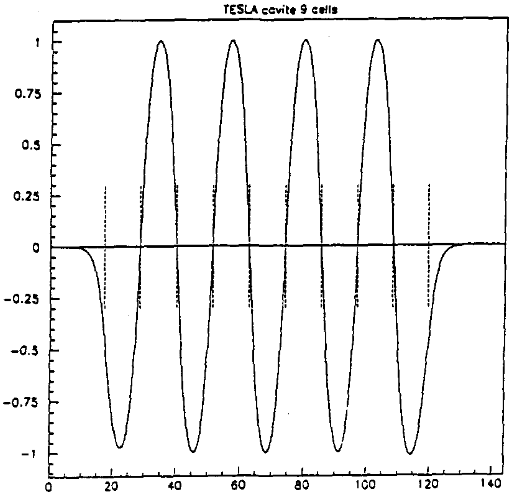

Figure1. Field distribution of 9 cell TESLA cavity with fringe field extending beyond the irises (dotted).

In order to ensure proper capture and acceleration of the beam, therefore, it is necessary to employ a gun voltage higher than normally used in electron injectors. We have settled on a value of 250 kV so that the gun can be operated in air thus avoiding complicated high-voltage insulation procedures.

The Electron Gun

The choice of a grid controlled gun is strongly influenced by the design of a previous injector at LAL for the CLIO Free Electron Laser project[3]. The CLIO gun uses a fast pulse from a wide band amplifier to modulate the cathode allowing the generation of quasi-triangular gun pulses of 1 A peak and base-width inferior to 2 ns.

To provide the 8 mA average current during the 800 μs pulse for TTF will require peak currents of 115 mA from the gun for pulse-widths of, say, 640 ps (50° rf phase width at 216.7 MHz). As we envisage operating the linac at integral intervals of the sub-harmonic buncher period we need to be able to generate currents in excess of this. Operation at 72 MHz would require gun currents of 350 mA and we take this as the design goal of the gun. To reach the 250 kV output voltage we intend to construct a gun in which the initial 30 kV is produced by the anode-cathode voltage difference and the remaining 220 kV is obtained in an electrostatic post acceleration column. The electrostatic column divides the 220 kV across a number of field-grading rings. Such a design has already been sucessfully employed on the injector for the S-DALINAC superconducting linac at TH-Darmstadt[4] where the column is approximately 1 m long.

We intend to use a modified version of a spare Saclay gun originally designed by R. Koontz for use on the ALS. The gun employs a classical Pierce-like geometry with an Eimac Y-845 cathode having an emitting surface of 0.5 cm^2. In its present configuration the gun has perveance of 1.75×10^{-8} $A/V^{3/2}$. In order to increase the perveance we plan to decrease the anode-cathode gap spacing from its existing 96.5 mm to 37.5 mm and to modify the geometry of the focus electrode.

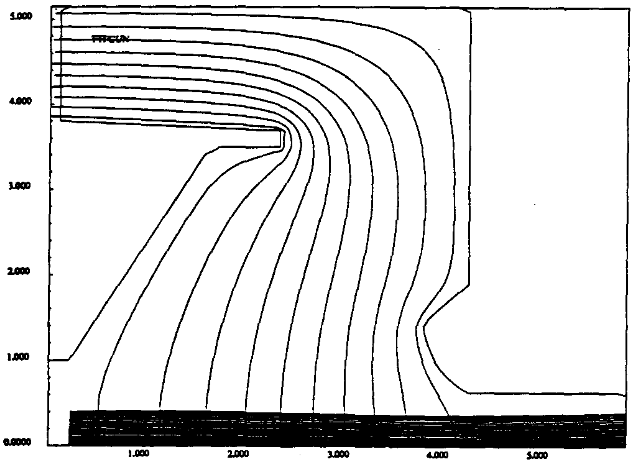

Figure 2. Beam trajectories and equipotentials for the TTF gun as calculated by EGUN. The anode-cathode voltage is 30 kV and the current is 300 mA. Scale is in centimetres.

Simulations with the SLAC code E-GUN[5] are in progress to fix the geometry and to help determine the potentials best employed on the first few field-grading rings, the number being restricted by the limited amount of available mesh points. Figure 2 shows beam trajectories for the reduced-gap Saclay gun. The calculated emittance for this case is 4 π mm-mrad but this is likely to be too low as the calculation does not include the effects of the grid bias.

The Pre-Buncher

The pre-buncher frequency (216.7 MHz) is chosen to be 1/6 that of the linac frequency such that its period (4.6 ns) is comfortably larger than the width of the gun pulse. It is a single cell cavity with a re-entrant geometry, chosen in order to minimise its transverse dimension so that it can be machined with existing facilities at LAL. Optimising the design with SUPERFISH we have settled on the geometry shown in figure 3. The cavity has a calculated transit-time corrected shunt impedance of 3.11 MΩ and an unloaded Q of 20,000. Calculations (see below) indicate that a peak cavity voltage of 50 kV is sufficient to produce the required energy modulation of the beam leading to a modest power dissipation of 400 W. The conical shape of the cavity nose allows more efficient cooling of this part of the cavity. The pre-buncher will be fabricated from inox on which a thin film of copper will be deposited. Frequency de-tuning as a result of cavity temperature variations or beam loading will be compensated for by one or two tuning plungers.

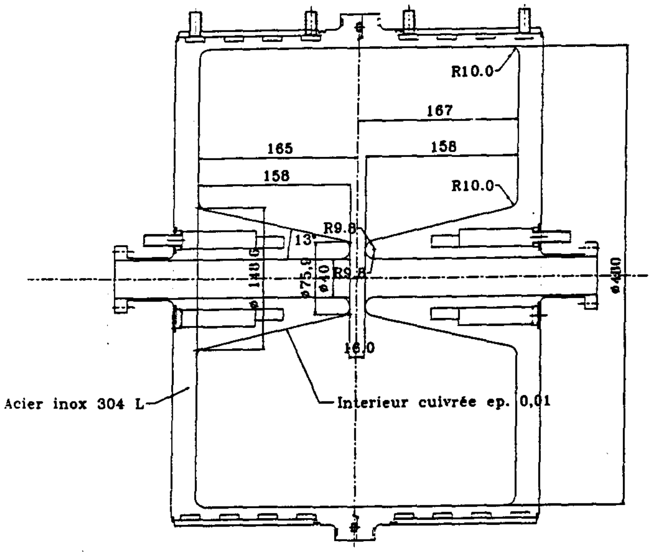

Figure 3. Section of sub-harmonic pre-buncher geometry.

Longitudinal Dynamics

In order to study the evolution of the longitudinal bunching in the injector we have made use of the simulation code PARMELA. As starting conditions we assume that the beam will exit the gun with a phase width of +/- 150° at 1.3 GHz, an energy of 250 kV, a radial size of 2.5 mm and a normalised emittance ($\pi\varepsilon_n = 4\pi\beta\gamma\varepsilon_{rms}$) of 15 π mm-mrad. As our reference case we assume an accelerating field of 15 MV/m in the capture cavity and a bunch population of 2.3×10^8 electrons, corresponding to 8 mA at 216.7 MHz. The simulation uses the electromagnetic fields of both the pre-buncher and capture cavity as calculated from their geometry using SUPERFISH. In the case of the capture cavity the very important contribution from the leakage field is included. The code is then used to optimise the phase and amplitude of the sub-harmonic buncher and its distance from the gun as well as the phase of the capture cavity and its distance from the buncher. As the capture cavity consists of 9 $\lambda/2$ cells operating in standing wave mode adjacent cells are obliged to have phase differences of 180° and so we have only one parameter free to chose here. In order to preserve a small transverse beam size in the presence of the self space-charge fields of the beam we employ 3 solenoidal fields along the injector having peak amplitudes of 140, 120, and 170 Gauss respectively. The final layout of the injector is shown in figure 4. The beam parameters at the exit of the capture cavity are shown in table 1 and can be seen to be compatible with the injector specification.

The initial requirement of 8 mA for TTF was to study the cavities under full beam-loading at an accelerating gradient of 25 MV/m. However initial operation of TTF is expected to be at the reduced field of 15 MV/m and consequently a reduced current and reduced bunch population will be of interest. Accordingly, table 1 also shows beam parameters for a bunch population of 1.6×10^8. This calculation was carried out with all injector elements at the same location as for the 8 mA case with only the amplitudes and phases being changed. The horizontal transverse phase space of the beam at the exit of the capture cavity is shown in figure 5. The calculated beam parameters can serve as input for the design of the transport optics after the capture cavity. The longitudinal phase space and the beam distribution as a function of phase and energy are shown in figure 6.

No. e's / bunch ($\times10^8$)	2.31	1.6
average current (mA)	8	5.4
energy (MeV)	14.4	14.6
rms phase width	0.73°	0.46°
total phase width	3.6°	2.2°
rms bunch length (mm)	0.47	0.3
rms energy spread, σ_E (MeV)	0.12	0.07
total energy spread (MeV)	0.48	0.32
σ_E/E (%)	0.8	0.5
norm. emittance (mm-mrad)	20	15

Table 1 Possible operating scenarios for the TTF Injector.

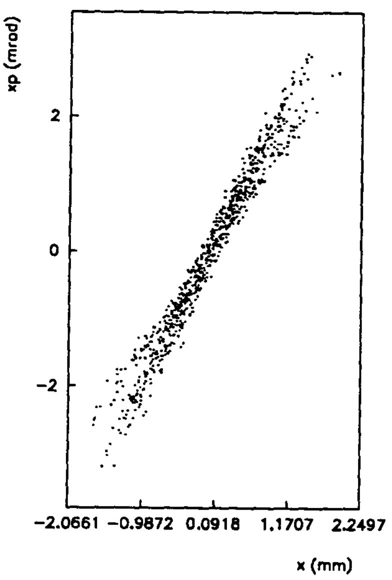

Figure 5. Horizontal transverse phase space at exit of capture cavity. Normalised emittance = 20 π mm-mrad.

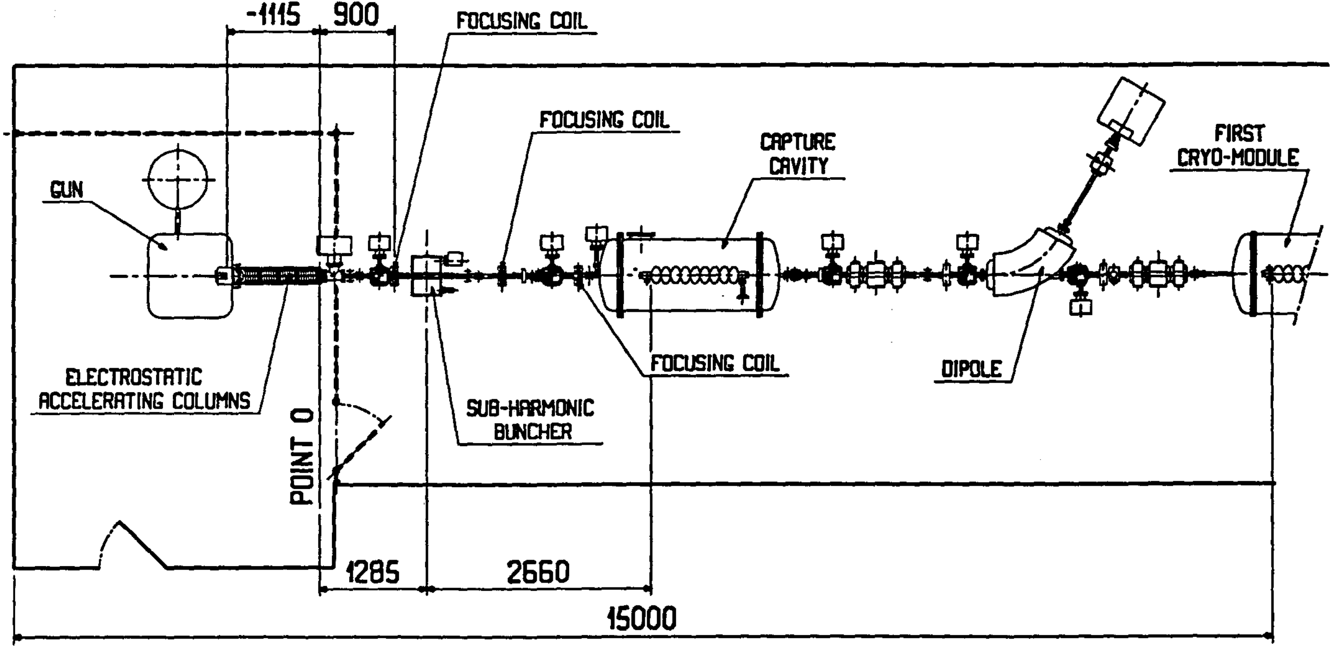

Figure 4. Schematic of TTF Injector (units are millimetres).

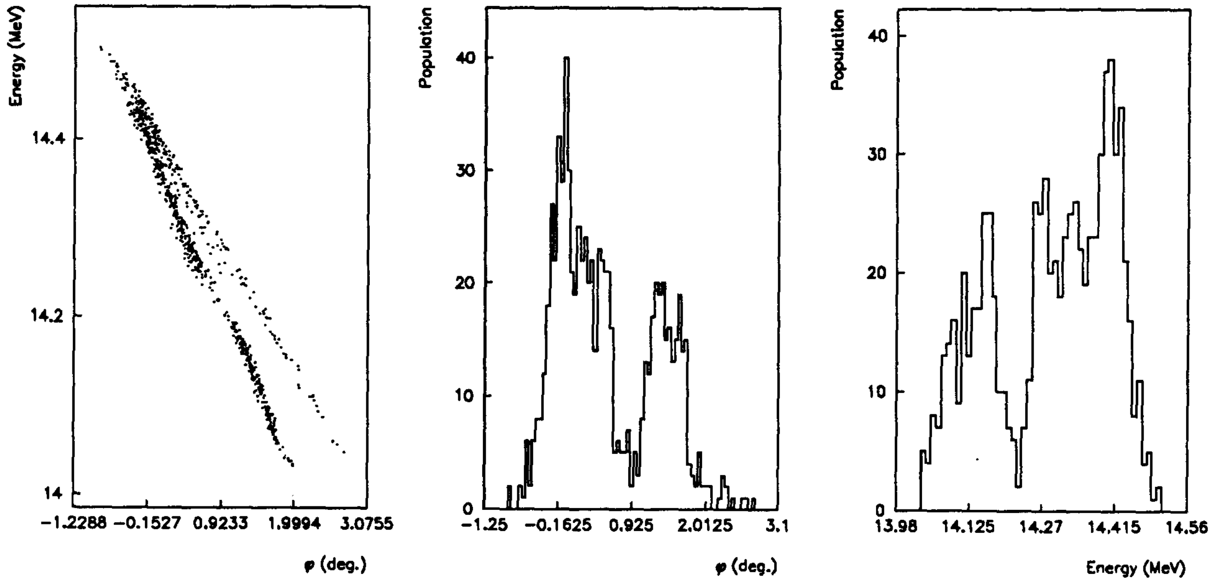

Figure 6. (l. to r.) PARMELA calculation of longitudinal phase space, electron population vs. phase and electron population vs. energy (800 particles).

Sensitivity Studies

In order to determine the specifications on the required stability of the power supplies, such as the high voltage pulse to the gun or the RF amplifier for the pre-buncher, we have used PARMELA to check the effect on the output beam parameters for small changes in the input values. For the gun we find that a change of 1% on the high-voltage pulse increases the total rf phase extent, $\Delta\phi$, at the output from the 3.6° (table 1) to 13°. However a change of two parts per thousand in the HV pulse results in a $\Delta\phi$ of only 4°. Accordingly the HV power supply will be specified to be stable within $5\text{x}10^{-4}$ during a pulse width of 1 millisecond. Variations in bunch population, which might result from gun voltage fluctuations, are seen to have negligible effects for changes up to 10%.

For variations of +/- 0.5° in the phase of the sub-harmonic buncher (SHB) we see an increase of $\Delta\phi$ to 4°. This increases to 5° if the SHB phase changes by +/- 1°. The amplifier for the SHB will be specified to have a phase stability of +/- 0.5° and an amplitude stability of 1% during the beam pulse. A tighter specification on the amplifier phase stability would have required the use of a feedback system with a consequent increase in cost.

Instrumentation

To ensure careful tuning of the injector a range of diagnostics will be used to monitor the beam parameters. The transverse profile will be monitored at several locations on the beamline by retractable view screens inserted in the beam path. Quantitative profile measurements will be performed by an SEM-grid[6] (secondary electron emission) and/or by optical transition radiation (OTR) measurements. Profile measurements for differing strengths of one of the focusing elements will allow calculation of the emittance by the method of 3-gradients. Initially it is intended to make beam position measurements using button electrodes of the type employed at the ESRF[7] while resonant BPM's, under study at the Technical University (Berlin) for TESLA, may prove attractive at a later date. Toroidal current monitors will be used to measure the beam intensity with a differential measurement allowing the detection of beam losses. Streak photography of the OTR will provide knowledge of the bunch length. Energy dispersion measurements on the beam analysis line will be made with an SEM-grid having forty 0.5 mm diameter tungsten wires spaced by 2 mm and giving an energy resolution of 0.1%.

Acknowledgements

Thanks are due to our colleagues at DAPNIA-CE (Saclay) for discussions on all aspects of the TTF injector design. In particular the contributions of B. Aune, M. Jablonka and J.M. Joly are noted. We are grateful to H. Weise for discussions on his experience with the S-DALINAC at TH-Darmstadt.

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