FIRST EXPERIMENTS WITH THE RF GUN BASED INJECTOR FOR THE TESLA TEST FACILITY LINAC

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Abstract

During 1997 and 1998 a first accelerator module was tested successfully at the TESLA Test Facility Linac (TTFL) at DESY. Eight superconducting cavities have accelerated the beam to an energy of more than 120 MeV. The injected 10 MeV electron beam was produced by a sub-harmonic injector using a thermionic gun, a buncher cavity, and one standard superconducting acceleration cavity. Since the achieved single bunch charge is not as high as required for a TESLA Linear Collider, a laser driven rf gun has been developed and been brought in operation late fall 1998. The aim of the new injector is to achieve the TESLA bunch charge and time structure, i.e. 8 nC bunches with 1 MHz repetition rate in 0.8 ms long bunch trains. This allows beam dynamics experiments in the TTFL. An overview of the injector is given and results of first experiments are described.

1 INTRODUCTION

The TESLA Test Facility (TTF) built by an international collaboration [1] is a test bed situated at DESY to prove that superconducting cavities as proposed for a TeV scale linear e^+e^- collider can be assembled into a linac test string (TTFL), and that accelerating gradients above 15 MV/m are consistently obtainable [2], [3].

During the running periods in 1997 and 1998, a low bunch charge injector with full beam current of 8 mA and full pulse length of 800 μs has been used to establish beam acceleration and stable operation of the acceleration modules. Among basic measurements of the beam parameters [4], beam induced high order modes in cavities of the acceleration module have been investigated [5].

In 1998, the injector has been upgraded with a laser-driven rf gun [6] to generate high bunch charges up to 8 nC with 1 MHz repetition rate to match as close as possible the TESLA beam structure. This is necessary to perform various experiments at the TTFL concerning higher order mode losses, space charge, and wake field effects. In addition, the new injector will be used for the proof-of-principle experiment of the proposed free electron laser TTF-FEL [7].

The rf gun has been commissioned end of 1998 together with a second acceleration module [8] and is being operated since then.

2 OVERVIEW

A schematic overview of the TTF injector is shown in Fig. 1, further details can be found in [9].

The electron source is a laser-driven 1 1/2-cell rf gun operating at 1.3 GHz using a Cs_2Te cathode. A load lock cathode system allows mounting and changing of cathodes while maintaining excellent ultra-high vacuum conditions. The cathode is illuminated by a train of UV laser pulses generated in a mode-locked solid-state laser system synchronized with the rf.

The gun section is followed by a superconducting capture cavity, a bunch compressor, a dispersive arm, and a section to match the beam optics to the accelerating structures. The capture cavity is identical to a 9-cell TESLA accelerating structure. It boosts the beam energy up to 20 MeV. For some beam experiments, the magnetic chicane bunch compressor is used to compress the bunch length by a factor of 2. Several diagnostic instruments allow to measure basic beam parameters as well as to perform dedicated experiments.

The design parameters of the injector are listed in Table 1 together with parameters required for TTF-FEL operation.

Table 1: Injector design parameters for TTFL and TTF-FEL operation.

Parameter		**TTFL**	**FEL**
RF Frequency gun/booster	GHz	1.3	
Rep. Rate	Hz	10	
Macro Pulse Length	μs	800	
Macro Pulse Current	mA	8	9
Bunch Frequency	MHz	1	9
Bunch Charge	nC	8	1
Bunch Length (rms)	mm	1	0.8
Emittance, norm. (x,y)	10^{-6} m	20	2
ΔE/E (single bunch, rms)		$1{\cdot}10^{-3}$	
ΔE/E (bunch to bunch, rms)		$2{\cdot}10^{-3}$	
Injection Energy	MeV	20	

3 THE RF GUN

The rf gun consists of a 1 1/2 cell TM_{010} π-mode structure operated at 1.3 GHz. The design is based on work reported in [10], and has been adapted to L-band and to specific requirements for TTF, especially to the long rf pulse (1 ms) operation [11]. The gun has been built and tested in the framework of the TESLA collaboration at the A0 Test Facility at Fermilab [12], where a second gun is being tested now. At DESY, a low emittance gun dedicated to FEL operation is in development [13].

The geometrical dimensions, like the iris radius (2 cm) and the half cell length (5/4 λ/2) have been optimized to

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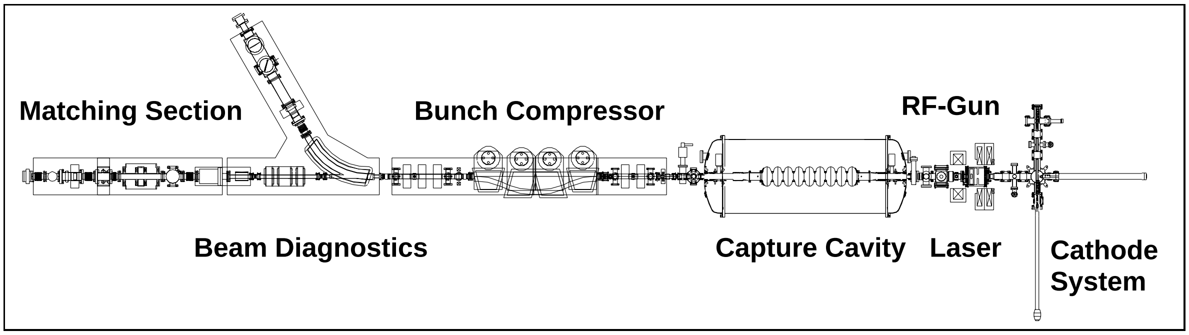

Figure 1: Schematic overview of the rf gun based TTF injector. (The laser system is not shown.)

improve the beam quality and to minimize the rf induced emittance growth. Although the rf is coupled transversely into the full cell, the distortion of the accelerating field is kept small. The focusing kick from a pair of solenoids is used to compensate [14] for space charge induced emittance growth. A 5 MW Klystron together with a modulator delivers rf pulses up to 1.2 ms length. The klystron power allows an accelerating gradient close to 50 MV/m. An extensive water cooling system is required for operation at full power. Since the gun is operated with very long rf pulses, a low level rf control system has been developed to stabilize amplitude and phase during the rf pulse. A system based on digital signal processors similar to the system used for the accelerating modules is used [15].

A summary of rf gun design and typical operating parameters is shown in Tab. 2.

Table 2: Some RF gun design parameters compared to typical operating values during the last runs.

Parameter		Design	Operated at
Ave. Gradient	MV/m	35	35 . . . 43
Klystron Power	MW	2.2	2.2 . . . 3.3
Av. Diss. Power	kW	22	0.11 . . . 3.5
Rep. Rate	Hz	10	1 . . . 5
RF Pulse Length	μs	800	50 . . . 800
Bunch Charge	nC	8	1 . . . 8
Bunch Spacing	μs	1	1
Bunch Length (rms)	mm	2	2 . . . 4

4 THE CATHODE SYSTEM

Operating an rf gun with multiple high peak current bunches per train, a cathode with a high quantum efficiency is required to reduce the effort in laser construction. Cs_2Te was chosen, because high quantum efficiency for ps pulses (1 %) and high charge extraction over a reasonable operating time (more than 1000 h) was already obtained elsewhere [16]. Furthermore, the cathode response time is below 1° of 1.3 GHz (2 ps) [17], and is operated at a UV wavelength accessible to standard solid-state lasers ($\approx$ 260 nm).

However, its lifetime depends strongly on the vacuum quality, namely impurities like oxygen, CO_2, water, and hydrocarbons can considerable lower the lifetime. Their partial pressure has to be kept below $1{\cdot}10^{-11}$ mbar [18]. Therefore, a load-lock system has been developed allowing insertion and replacement of cathodes while maintaining ultra-high vacuum conditions. A prototype system has been built and is in operation at Fermilab [19].

The system at DESY was brought into operation in May 1998. It consists of three 3 major parts: a separate preparation chamber to prepare a stack of up to five cathodes, a transport chamber to transfer the fresh cathodes to the loading system, which is itself connected to the rf gun. Up to now, the transfer of cathodes was performed two times. One cathode was used from the first stack. It obtained a stable quantum efficiency of 0.5 % during the whole running period from December 1998 to March 1999. The second stack prepared in December 1998 contained a cathode of a novel type: the Molybdenum surface was polished to mirror quality prior to coating with Cs_2Te. This cathode was tested in the last week of the run. It reached a remarkable 5.9$\pm$0.6 % efficiency with beam in the rf gun, stable over the whole test period. Furthermore, the dark current was reduced by a factor of 100 compared to the first cathode to less than 20 μA at 35 MV/m.

5 THE LASER SYSTEM

The laser design is challenged by the unusual requirement of providing synchronized ps UV pulses in very long trains of 1 ms length with ambitious stability requirements. The UV pulse energy has to be adapted to the charge required and the quantum efficiency obtained with the cathode: up to 800 pulses with 5 μJ for 8 nC and 1 % efficiency at 10 Hz. The decision for the specific design was also driven by the requirement of an operational system with a very high reliability and an up-time close to 100 % during running periods.

The laser is based entirely on the well known solid-state material Nd:YLF pumped with flash lamps. This material has a long fluorescence lifetime, high induced emission cross section, and very small thermal lensing. In a pulse train oscillator (PTO) a 2 ms long 54 MHz pulse train is generated. The pulses are locked to the TTF master rf oscillator. An electro-optic modulator driven with 1.3 GHz enhances the phase stability to 1 ps (min/max). A pulse to pulse energy stability of better than 1 % (rms) before amplification is achieved. A Pockels-cell based pulse picker reduces the 54 MHz bunch train to 1 MHz with variable train length. This train is amplified by three single pass amplifiers to 250 μJ per single pulse. The UV (262 nm) generation with two nonlinear crystals has an efficiency of 10 %. A feed-forward system is applied to preset the shape of the flash lamp current pulse to obtain a flat pulse train [20]. A UV shot-to-shot energy variation integrated over 10 micro pulses of 2 % (rms) is achieved. The UV pulse length was measured with a streak camera [21] to be σ_t = 8$\pm$1 ps. The system was running 24 h per day during the last 3 month running period. The laser was available for beam 98 % of the running time.

6 EXPERIMENTAL RESULTS AND RUNNING EXPERIENCE

Since the rf gun has already been tested at Fermilab, the rf conditioning at DESY went smooth. The design field gradient of 35 MV/m was routinely achieved during the whole running period. For some experiments, the gradient was raised to 43 MV/m. The rf pulse length was limited to 50 μs and 1 Hz during the run for machine safety reasons, although the gun was conditioned at Fermilab up to 800 μs. It is planned to go to full rf pulse length at DESY during the next running period.

The charge transmission of the gun is linear up to 16 nC for nominal field and a hard edge laser spot size on the cathode of r = 5 mm. For charge densities above 20 nC/cm^2 we start to loose transmission. From Gauss' law we expect the limit at 35 nC/cm^2, were the space charge field compensates the acceleration field.

The beam energy has been measured with and without capture cavity: 3.8$\pm$0.1 MeV and 16.5$\pm$0.1 MeV resp. This corresponds well to the expected gradients deduced from the forward power. The view screen used for the energy spread measurements at 16.5 MeV allows at the moment only an estimate of the upper limit of $2.5\cdot10^{-3}$.

Two different techniques have been used to measure the emittance: a tomographic reconstruction of the phase space using the quadrupole doublet [22], and a slit system to mask out small bunchlets. From the bunch size and the divergence of the drifting bunchlets the emittance can be reconstructed. Both method use transition radiation created on aluminum foils to measure the bunch profiles. The data are still in evaluation, preliminary results for a 1 nC beam show a transverse emittance in the order of 5 to $8\cdot10^{-6}$m depending on the solenoid field settings.

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