PERFORMANCE OF THE TESLA TEST FACILITY LINAC

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Abstract

In order to test the performance of a superconducting linac, the TESLA Collaboration has built and operated a 120 m long linac which includes an RF electron gun, two 12 m long superconducting accelerator modules, two bunch compressors and a 13.5 m long undulator for a VUV FEL. This linac serves as a test bench for high gradient operation of 9-cell superconducting cavities with full beam loading as required for the TESLA design. Results of recent running periods will be summarized in this paper.

1 INTRODUCTION

A superconduncting electron-positron collider of initially 500 GeV total energy, extendable to 800 GeV, with an integrated X-ray laser laboratory has been proposed by the TESLA (TeV-Energy Superconducting Linear Accelerator) collaboration [1]. The challenge to the TESLA collaboration (with more than 40 participant institutions from 9 countries) was to demonstrate the viability of its design. Cavity R&D has demonstrated the reliable production of 9-cell superconducting cavities achieving gradients above 25 MV/m at high quality factor Q and the possibility to achieve even higher gradients applying new techniques like, e.g., electrolytic polishing.

The TESLA Test Facility linac (TTFL) at DESY was constructed to show that the high gradients achieved in the cavities could be maintained during assembly into a linac test string, and then successfully operated with auxiliary systems to accelerate an electron beam to a few hundred MeV. The basic characteristics of the TTFL were designed to be as consistent as possible with the parameters of the TESLA linear collider design (see table 1). The original proposal for the TTF [2] was adapted [3, 4] to perform a proof-of-principle experiment of a Free Electron Laser (FEL) based on the principle of Self Amplified Spontaneous Emission (SASE).

2 TTF LINAC PERFORMANCE

The schematic of the TTF linac is shown in figure 1.

2.1 Injector

The injector is based on a laser-driven photocathode installed in a 1.6-cell rf cavity operating at 1.3 GHz [5] with a peak accelerating electric field of 37 MV/m on the photocathode. At the exit of the cavity the electron energy is approximately 4 MeV. The Cs_2Te cathode [6, 7] is illuminated by a train of UV laser pulses generated in a mode-locked solid-state laser system [8] synchronized with the gun rf. It generates bunch charges of several nC at up to 2.25 MHz repetition rate. The laser, RF supply (∼2.2 MW), amplitude and phase controller, water cooling system, and cathode preparation and handling system are all used routinely. At gradients above 30 MV/m we routinely have 800 μs long RF pulses in the gun.

The gun section is followed by a 9-cell superconducting cavity, boosting the energy to 16 MeV. A feedback system [9] allows the cavity to operate with an amplitude stability better than 0.1%, and a phase stability of better than 1°. The cavity was operated with full beam loading and with the design beam parameters. The typical relative energy spread downstream of the booster cavity is 0.2 % (rms). At 1 nC the optimized normalized emittance was measured at 4 mm mrad, and at 8 nC approximately 15 mm mrad [10, 11, 12].

2.2 Accelerator modules

The two installed cryomodules (each 12.2 m in length) comprise the main body of the linac. Each cryomodule contains eight nine-cell cavities, a superconducting quadrupole / steerer package, and a cold cavity type beam position monitor. Each accelerating structure has an input coupler for RF power, a pickup antenna to measure the cavity field amplitude and phase, two HOM damping couplers, and a frequency tuning mechanism.

As of writing six accelerator modules have been built since the beginning of the TTF programme. Three of them have been installed in the TTFL; the last three are foreseen for the extension of the linac to higher energies. The maximum gradients achieved (at quality factors higher or equal to the design value of $Q_0 = 10^{10}$) with the three modules are given in table 2. Cavities operated in the TTFL have shown slightly lower gradients compared to the vertical or horizontal cavity tests. This is because of different field emission onsets, and because the operation of several cavities connected to one single klystron is limited by the worst cavity.

In the linac a total of 16 cavities are driven by one klystron. The cavities have been routinely operated at a gradient of about 14 MV/m providing a 240 MeV beam for different experiments including stable FEL operation (see Sec. 3). The achieved relative amplitude stability of $2{\times}10^{-3}$ and absolute phase stability of $0.5°$ complies with the requirements.

2.3 HOM tests

The transport of very low emittance beams along the TESLA linac requires transverse higher-order mode

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Linac	TESLA	TTF Linac design/achieved
Accel. grad. [MV/m] with beam	23.4	15 / 14, 19, 22
Unloaded quality factor [10^{10}]	1.0	0.3 / > 1.0
No. of cryomodules	2628	4 / 3 + 2
Energy spread, single bunch rms	5×10^{-4}	$\approx 10^{-3}/10^{-3}$
Energy variation, bunch to bunch	5×10^{-4}	$\approx 2\times10^{-3}/2\times10^{-3}$
Bunch length, rms [μm]	300	1000 / 400
Beam current [mA]	9.5	8 / 7
Beam macro pulse length [μs]	950	800 / 800

Table 1: TESLA-500 – TTF Linac parameters comparison.

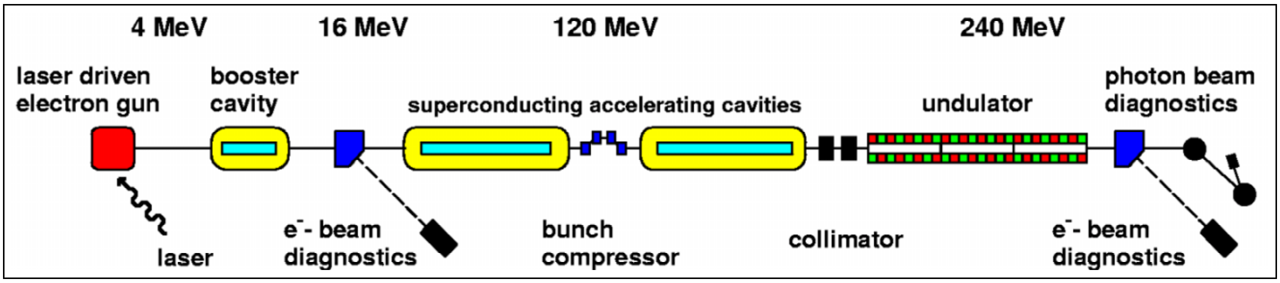

Figure 1: Schematic layout of the TESLA Test Facility Linac (TTFL). The total length is about 120 m.

module No.	RF test ($Q_0 > 10^{10}$)	beam operation
1	17.5	14
2	21.2	19
3	23.6	22.7
4	25.4	to be tested
1*	25.3	to be tested
5		to be tested

Table 2: Gradients achieved in the TTF Linac accelerator modules. Module 1* will be tested in July 2002. Modules 4 and 5 are to be tested in Feb. 2003

(HOM) damping. In order to maintain a multibunch emittance smaller than the design single bunch emittance, damping factors Q smaller than $\sim 10^5$ must be achieved in the TESLA superconducting cavities for the few modes, specially in the first two dipole passbands, with a large coupling impendance R/Q. Modes from higher passbands, which are above cutoff, are expected to couple efficiently to the HOM couplers mounted on the beam tubes, except for a few so-called ”trapped” modes concentrated in the central cells of the cavity. These trapped modes can only be detected using the accelerated electron beam [13]. The experiment consists of exciting HOMs resonantly by modulating the bunch charge of a long train of bunches. Once excited, the HOM deflects the bunch train and a singal can be observed with a downstream BPM.

A first experiment was performed at accelerating module 1 using a thermoionic gun as injector. Results were reported in [14]. With the present layout, a second experiment was performed at accelerating module 3. For that experiment, the rf gun delivered up to 5 mA of beam current at a pulse duration of 500 μs with bunch frequency of 54 MHz with 10-90% charge modulation. With this experimental setup, it was possible to detect the strongest resonances, identify their HOM frequency and the cavity source, characterize their type of HOM (dipole, quadrupole, etc.) and their polarization. The results are presented in [15] and in this conference [16].

2.4 Long pulse operation

One of the measurements performed with long beam pulses is shown in figure 2. A 800 μs long macro pulse comprising 1800 bunches with more than 3 nC bunch charge each was accelerated in the TTF Linac. With the macro pulse current being about 7 mA, the bunch charge was stable within ∼10%, the achieved energy stability was σ_E/E=0.07%. This measurement was carried out with module 3 (see table 2) at an average gradient of 21.5 MV/m (5% below quench). Same results were obtained in a previous long pulse operation reported in [17], with both modules 2 and 3 running at an average gradient of 14 MV/m. The above mentioned RF control of the superconducting cavities was used together with a beam loading compensation. The performance of the fast linac protection systems is reported in this conference [18].

(see Fig. 2).

3 TTF FEL OPERATION

3.1 Bunch Compressor

The bunch compressor section between the two cryomodules is used to reduce the electron bunch length produced in the electron gun by roughly a factor of four. The shortening of the bunch increases the peak bunch current to

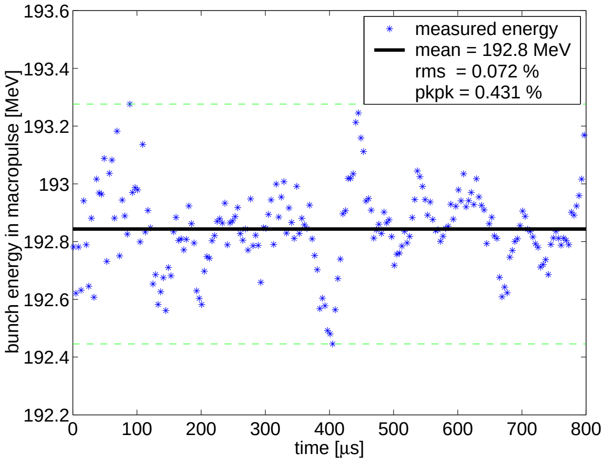

Figure 2: Acceleration of long macro pulses. The beam energy within one single macro pulse are shown. The RF control system is operated with beam loading compensation. The bunch spacing is 444 ns.

several hundred Amperes, which is required for a high gain of the FEL.

3.2 Undulator

A collimator section in front of the undulator protects the vacuum system as well as the permanent magnets of the undulator. Its performance during the long pulse operation has been presented at this conference [19]. The undulator is a permanent magnet device [20] with a 12 mm gap and has a period of 2.73 cm. The undulator system is subdivided into three segments, each 4.5 m long and containing 10 permanent-magnet quadrupoles with alternating gradients, which are superimposed on the periodic undulator field.

3.3 TTF FEL Performance

The first lasing of the high gain FEL at the TTF linac was observed in February 2000 [21]. Since then the performance of the SASE FEL has been steadily improved. By varying the energy of the linear accelerator, full wavelength tunability in a wide range from 80 to 180 nm [22] has been demonstrated, as depicted in Figure 3. Further work has been focused on the range from 80 nm to 120 nm by request of first scientific users. Recently, saturation has been achieved in this entire wavelength range.

The two most relevant technical factors that have made possible the successful test and operation of the high gain FEL are the field quality of the undulator magnet [24] which assures a good interaction between the photon and the electron beams, and the capability of the linac components to generate electron bunches with small emittance and high peak current and accelerate them while preserving their high charge density. The performance of the photoinjector for the FEL has been reported in [25].

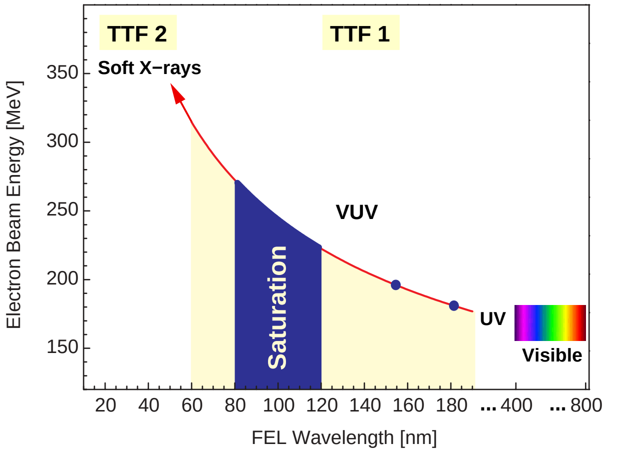

Figure 3: VUV wavelength range within which lasing has been obtained at the TTF FEL, phase 1 (TTF1). The wavelength was tuned by changing the electron beam energy. The individual dots outside the range in which saturation has been achieved represent an FEL gain of typically > 1000 demonstrated in an earlier stage of the experiment [22]. After a linac upgrade to electron beam energies of up to 1 GeV (TTF 2), the FEL will enter the soft X-ray region [23].

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