

TESLA TEST FACILITY: STATUS AND RESULTS

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ABSTRACT

The TESLA Test Facility (TTF), under construction at DESY by an international collaboration, is an R&D test bed for the superconducting option for future linear e⁺/e⁻ colliders. It consists of an infrastructure to process and test the cavities and of a 500 MeV linac. The infrastructure has been installed and is fully operational. It includes a complex of clean rooms, an ultraclean water plant, a chemical etching installation and a ultra-high vacuum furnace. The linac will consist of four cryomodules, each containing eight 1 meter long nine-cell cavities operated at 1.3 GHz. The base accelerating field is 15 MV/m, with a Q of 3×10^9 . Two 5 MW klystrons feed the 32 cavities. A first injector delivers the full average current (8 mA in pulses of 800 μ s) with reduced bunch charge at an energy of 10 MeV. A more powerful injector based on RF gun technology will ultimately deliver a beam with high charge and low emittance. By the end of 96, a beam of 140 MeV through the first module is expected. Overview and status of the facility are given. Plans for the future use of the linac are presented.

1. INTRODUCTION

The superconducting option for an electron-positron linear collider of 500 GeV center of mass energy (TESLA) is being studied by an international collaboration [1], in parallel with similar efforts by other groups on various technical solutions. Several prototype tests facilities are now under construction to establish well-developed collider designs.

The TESLA approach uses superconducting structures operating at a frequency of 1.3 GHz with a gradient of 25 MV/m and a quality factor of 5×10^9 at T=2K. This choice presents advantages for the design of the collider, linked to the low rf frequency and the high AC-to-beam power efficiency of a SC linac. Many well-separated bunches are accelerated in a long rf pulse, the tolerances are relaxed compared to other approaches. Another characteristic of this choice is the low peak rf power needed and the availability of klystrons [2].

The technical challenge of TESLA is to operate a large number of cavities (20000) at very high gradient and to design the linac at a reasonable cost.

The TESLA Test Facility (TTF) is under construction at DESY with major components flowing in from the members of the TESLA collaboration. Its aim is to demonstrate the ability to accelerate a beam

with proper qualities through a chain of 32 cavities operating at a field level of at least 15 MV/m and to reach an overall design of cavities, cryostats, couplers and auxiliary systems which leads to costs competitive with the other approaches based on conventional structures.

2. INFRASTRUCTURE AND CAVITY PERFORMANCE

2.1 Cavity processing

Obtaining a useable gradient of 25 MV/m or more in 9-cell cavities requires that one can overcome the usual field limitations: quenches and field emission. The quench limit is due to heat dissipation in local defects, the solution to the problem is to use very high purity Nb with increased thermal conductivity. The field emission, mainly due to the presence of micron sized particules on the surface, requires extreme cleanliness in the processing and installation of the cavities [3].

The infrastructure for cavity preparation [4] is composed of a complex of clean rooms (from class 10000 to class 10), a chemical etching facility and ultra-clean water supply. In addition, a UHV furnace is used to improve the niobium material properties via heat treatment at 1400 C in presence of Ti gettering. The last step of cavity preparation consists of a high pressure water rinsing (100 bar).

2.2 Cavity testing

The cavities are first tested in a vertical cryostat in which, in addition to the standard measurement in CW mode of Q vs E_{acc} characteristics, high peak power processing (up to 1 MW in short pulses) can be applied. Temperature mapping is also available.

After welding of the helium tank and mounting of couplers and tuner, a cold test is performed in a special horizontal cryostat, where the complete accelerating system is tested in the TTF pulsed mode (field flat top of 0.8 ms). The behavior of the HOM couplers, the tuning mechanism and other components are checked before the cavity is installed in the linac. Heat losses at 2 K are measured with a resolution of less than 0.1 W (with the TTF time structure, a field of 20 MV/m at a Q of 10^{10} corresponds to 0.5 W).

2.3 Cavity and coupler performance

Forty cavities will be fabricated by several companies, processed and tested at DESY and installed in the linac. The installation of the injector and the first module by the end of this year requires 9 cavities. At this moment, 14 cavities have been delivered, and tests have been performed on 10 of them [5]. Very encouraging results have been obtained. In CW mode, fields in excess of 20 MV/m with Q higher than 5×10^9 have been reached. In the last series of tests, the quench field was always reached without field emission and no rf processing was needed. The best result is a field of 26 MV/m with a Q of 3×10^{10} . In some cases, however, the quench field is around 12 MV/m and an increase of surface resistance with field appears, but, again, without field emission. Investigations are underway to understand this effect which might be due to Ti migration in the grain boundaries during heat treatment.

One cavity has been tested in the horizontal cryostat. No degradation in performance from the vertical test has been observed: a field of about 20 MV/m was reached without sign of field emission. The input rf power was 140 kW during the filling and reduced to 1/4 during flat top to simulate the beam loading.

During this test, the coaxial input coupler [6] has been processed up to a power of 1 MW in 0.5 ms pulses. After conditioning of some multipactor levels in the coaxial region or in the cold window, the design rf power of 200 kW in long pulses (corresponding to 25 MV/m) can be obtained easily.

3. THE TTF LINAC

The experience gained on the TTF linac will feed directly into the TESLA collider design. There are a number of aspects in which both designs are similar. A detailed description can be found in [7].

The main components of the linac are: the injector, a first cryomodule housing 8 cavities, a 12 m long warm section in which a bunch compressor will be later installed, three cryomodules connected in series and a diagnostic area. The main parameters of the linac are given in table 1.

The TESLA design values for the beam current (old parameters) will be reached in two stages: the 1st injector delivers 8 mA with a bunch frequency of 216 MHz and a bunch charge of 37 pC, while the 2nd one will give the same current with a frequency of 1 MHz and a bunch charge of 8 nC. In both cases, the rms bunch length is 1 mm.

Injector I delivers a beam of 12 to 15 MeV. It consists of a thermoionic 250 kV source (40 kV gun followed by an electrostatic column), a 216 MHz (f/6) prebunching cavity and a standard nine-cell SC cavity

housed in its own cryostat and powered by a 200 kW klystron [8]. A beam analysis station allows the tuning of the injector linac.

Table 1 TTF linac parameters

Energy	500 MeV
Beam current	8 mA
pulse length	0.8 ms
repet. frequency	10 Hz
Accel. gradient	15 MV/m
Q ₀	3×10^9
Heat load at 2 K	115 W
Number of cavities	32
Number of modules	4
Number of klystrons	2

Injector II will be composed of an rf gun followed by the same SC cavity giving a total energy of about 20 MeV. A bunch compressor will be used at this level to obtain the bunch length of 1 mm [9]. Two models of rf gun are under development: one for the full TESLA bunch charge (8 nC) and another one optimized for very low emittance (~ 1 mm.mr) at reduced charge (1 nC) for FEL experiments. They both use a 1.5 cell 1.3 GHz cavity fed by a 5 MW klystron and a Cs₂Te photocathode [10]. The installation will permit the use of injector I or injector II alternatively.

Four cryomodules, each 12.2 m in length, constitute the main body of the linac. Each one contains eight cavities, a SC quadrupole doublet and a cold beam position monitor. The liquid helium distribution and cold gas recovery system are incorporated into the cryostat. The cryostat design principle is to make the individual accelerating modules as long as possible and combine them to strings fed by a single cold box. This should result in low static losses (0.23 W/m at 2K) and important cost reduction [11]. The cavities are suspended from the helium gas return pipe which serves as a reference girder. Each cavity is equipped with its own Ti helium vessel welded around it, the beam tubes and the connections for couplers being inside the insulating vacuum.

The 9-cell cavities are made of 2.8 mm, high RRR niobium. In addition to the standard fabrication technique, stiffening rings between adjacent cells have been added in order to reduce the detuning due to radiation pressure. With this technique a detuning parameter of ~ 1 Hz/(MV/m)² is obtained. The main parameters of the accelerating cavity are given in table 2.

Each cavity is equipped with an RF input coaxial coupler, two HOM couplers [6] and an RF pick-up. The input coupler allows an adjustment of the coupling by a factor of 3 around the design value of 3×10^6 and

tolerates a displacement during cooldown of up to 15 mm. There is a cold window at 70 K, which is installed in the clean room, and a warm window.

Table 2 Parameters of the TTF cavity

Frequency	1.3 GHz
Number of cells	9
Coupling	1.87 %
E _{peak} /E _{acc}	2
R/Q	1011 Ohms
long. loss factor ($\sigma=1\text{mm}$)	8.5 V/pC
Effective length	1.036 m
Iris diameter	70 mm
RF power at 25 MV/m	206 kW
External Q	3×10^6

Two models of HOM couplers exist, a welded version and a dismountable one. Both have been tested on a SC single cell cavity, the dismountable one was tested on the 9-cell cavity in the horizontal test at the full rf power.

The tuning mechanism acts on the overall length of the cavity, driven by a stepping motor located in the isolation vacuum. The tuning range is 800 kHz, corresponding to about 10^6 motor steps.

RF power for the 32 cavities of the linac is provided by two klystrons and two modulators, each klystron delivering a power of 4.5 MW with pulse length of up to 2 ms. The power is distributed to the cavities by means of directional couplers. For each cavity, there is a three stub wave guide tuner for impedance matching and adjustment of phase by ± 30 deg. Individual low power circulators are installed on each cavity.

4. PRESENT STATUS

4.1 Injector

The complete 250 kV beam line has been installed at DESY. The design beam characteristics have been obtained and tests on different components and monitors have been performed [12]. Table 3 gives the results of some measurements.

table 3 Injector tests results

	Design	Measured
current	8 mA	>8 mA
energy	250 keV	250 keV
pulse length	0.8 ms	0.8 ms
rep. rate	216MHz	216 MHz
micro pulse width	<640 ps	600 ps
rms emittance	<5 mm.mr	3-4 mm.mr

After successful test in the horizontal cryostat (see above), the SC cavity is being mounted in its cryostat. The complete injector will be ready for delivering a 15 MeV beam in September.

4.2 Cryostat, cryogenic system

The complete tooling for assembling the string of 8 cavities and the SC quadrupoles in the cryostat has been installed at the end of 95. The vacuum vessel and the other components of the cryostat have been delivered. The vacuum vessel, made of carbon steel has been demagnetized. A complete test mounting with one cavity has been performed, which permitted optimization of the tooling and the mounting procedure. It has been checked that the cavities can be aligned with an accuracy of 0.2 mm.

The cryogenic system [13], with a cooling capacity of 100 W in a first stage, will be fully operational in September.

4.3 RF system

RF power for the linac will be provided by two klystrons and two modulators, each delivering 4.5 MW at a pulse length of 2 ms. The first rf power source exists [14] and is extensively used for testing cavities and components. It will be used for the first module of 8 cavities for which the wave-guide system is installed.

The low level rf control system is under tests on cavities in the horizontal cryostat under full power. The bunch to bunch energy dispersion must be reduced to very low level (in TESLA a value of $\sim 3 \times 10^{-4}$ is assumed). The control system will regulate the vector-sum of 16 cavities which are fed by a common klystron. Its operation should keep the extra-power needed at a minimum value [15]. The design for TTF is challenging:

- The Lorentz force detunes the cavity by more than one bandwidth during the beam pulse.
- Microphonics modulate the initial detuning of the cavity.
- The calibration of the vector-sum must be very accurate.
- Dispersions in the characteristics of the cavities must be taken into account.

Two systems are developed at DESY, with the goal to compare the performance of analog versus digital feedback system [16,17]. With both system, a field regulation which meets the specifications for the 1st module has been obtained under high gradient operation (a few tenths of a degree in phase and a few 10^{-3} in amplitude). In addition, the control system for the injector cavity has been tested successfully at Saclay on the MACSE linac.

4.4 Beam lines and monitors

Most of the components of the beam line exist and are being installed. The first low energy beam (140 MeV) will be transported to the end station through a temporary beam line. The complete installation will be accomplished in September 96.

All components of the beam monitoring system will be installed on the warm beam lines in September. The system includes the following elements:

- Toroid ferrite transformers for beam intensity measurements and beam loss detection during the pulse [18]. The system has been tested with the 250 keV beam.
- Beam position monitors: Strip-line BPM, with a resolution of $\sim 100 \mu\text{m}$, and cavity BPM, with resolution of $\sim 10 \mu\text{m}$ will be used. The cavity BPM is also used at cold temperature inside the cryomodules.
- Beam profile monitors: OTR monitors, wire-scanners and SEM-grids will be used. The OTR stations will be equipped with different detectors and give measurements of several beam parameters in addition to profile: bunch length (streak camera and measurement of coherent radiation) and beam energy (angular distribution). The SEM-grids will be mainly used to measure the energy distribution.

5. SCHEDULE AND EXPERIMENTS

5.1 First module, injector I

The injector I will deliver a 15 MeV beam in September 96. The first module with 8 cavities should be installed by the end of the year giving a beam energy of about 140 MeV. The experimental program [19] for the year 97 includes:

- Measurements of cavity performance in linac environment.
- Cryostat behavior: losses, alignment of cavities.
- RF to beam power transfer: test of the rf control system.
- RF steering effect of couplers by measuring the beam displacement for various rf phases.
- Measurement of dark current.

5.2 Modules 2 and 3, injector II

By the end of 97, two more 8-cavity modules will be installed, resulting in an energy of about 400 MeV. The injector II will also be available. The experimental program with this equipment, starting in 98 is twofold: TESLA and FEL.

TESLA: With the high charge beam, the parameters involved in the design of the collider will be measured.

- HOM power deposited at $T=2 \text{ K}$ and choice of absorber at intermediate temperature.

- Cavity offset measurement with HOM power on dipole modes.
- short range and long range wakefields evaluation, damping of HOM with beam on axis and off axis.

FEL: A demonstration of feasibility of a free electron laser operating in the SASE mode is scheduled at this stage [20]. A bunch compressor will be installed after the 1st module to reduce the bunch length to 0.2 mm.

5.3 Future plans

For the longer term future, it is planned to double the length of the linac to 1 GeV and to operate a VUV light source yielding a coherent, very bright beam of photons with wavelength tuneable between 20 nm and 6 nm.

The linac extension would be composed of optimized versions of the components of TESLA.

6. CONCLUSION

The first part of the TTF linac is being installed and should deliver a 140 MeV beam by the end of 96. The year 97 will be devoted to experiments with this beam and the preparation of the remaining modules and the high charge injector. Experiments on free electron laser are scheduled in 98.

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