Developments and Achievements at the TESLA Test Facility (TTF)

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Abstract—The TESLA Test Facility (TTF), under construction and commissioning at DESY by an International Collaboration, is an R&D test bench for the superconducting option for future linear electron-position colliders. TTF consists of an infrastructure to process and test the SC cavities and of a 400 MeV linac (Phase I), to be upgraded up to 1.2 GeV (Phase II). The infrastructure is fully operational and the first cryomodule of the three planned for Phase I has been successfully in operation since June 1997. Each cryomodule contains eight nine cell interactions. Nevertheless, above the LEP2 centre-of-mass radiation energy loss asks for a linear solution.

Linear Colliders. The designs can be divided in two main categories: the high frequency, room temperature approach (NLC, JLC, VLEPP & CLIC) and the low frequency, superconducting one (TESLA). The combination of high conversion efficiency from mains to beam power (17-23%), together with small emittance dilution in the low-frequency (1.3 GHz) linac, makes the last choice ideal for an optimum performance in terms of the achievable luminosity [2].

With respect to the existing large-scale installations [3] of superconducting cavities (e.g. at LEP and CEBAF), the major challenge for the feasibility a superconducting linear collider was clear from the beginning to be that to reduce the cost per unit energy gain (MeV) by more than an order of magnitude. This means both to reduce the cost per unit length and to increase the accelerating gradient by about a factor of five, to 25 MV/m and more.

Encouraged by the R&D results from different labs [4,5,6], in 1991 several institutions decided to join the efforts in the TESLA Collaboration – formally established in 1994 – to set up at DESY the necessary infrastructures while building a new generation superconducting linac, that is the TESLA Test Facility (TTF) [7]. At present, more than 30 institutes from Armenia, P.R. China, Finland, France, Germany, Italy, Poland, Russia and USA participate in the TESLA Collaboration and contribute to TTF.

From the work started in 1990 [5], a concept of a 500 GeV centre-of-mass energy superconducting linear collider emerged, based on 9-cell cavities operating at 1.3 GHz. An accelerating field of 25 MV/m @ Q=5.10^6 is required, the expected luminosity being 5.10^30 cm^-2 sec^-1. The conceptual design report (CDR) was published in May 1997 [9] giving a complete description of the machine, including all the subsystems.

Due to the low RF frequency, which implies better emittance preservation, and the long macro-pulses, a superconducting linac based on the foreseen TESLA technology lends itself as the best choice for the driver of a X-ray FEL user facility. This is why both TESLA and TTF include such an option as an integral part of the program [7,8,9].

II. THE TESLA TEST FACILITY (TTF)

The TESLA Test Facility (TTF) is under construction at DESY, with major components flowing in from the members of the TESLA Collaboration. Figure 1 shows the general layout of TTF Phase I, in Building 28 (Hall 3).

A. The TTF infrastructure

In order to obtain a usable gradient of 25 MV/m or more in 9-cell cavities it is necessary to 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 particles on the surface, requires extreme cleanliness in processing and installation of the cavities. The TTF infrastructure for cavity preparation [11], completely operational since the end of 1995, 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 high pressure water rinsing (100 bar).

The cavities are first tested in a vertical cryostat in which, high peak power processing (up to 1 MW in short pulses) can be applied. Temperature mapping and local RRR measurements through eddy currents are also available [12].

After welding of the helium tank and mounting the 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 main coupler, the HOM absorbers and the tuning mechanism are here checked before the cavity is installed in the linac cryomodule.

Heat losses at 2 K are measured with a resolution of less than 0.1 W (as a reference, with the TTF time structure, a field of 20 MV/m at a Q of 10⁶ gives a dissipation of 0.5 W).

B. The TTF Linac

During the last years, the original design of the TTF Linac, as discussed in Ref. [7], underwent important evolutions, to take advantage of the experience gained in the development of the main components and to include from the beginning the important option of the SASE FEL.

As for TESLA, the TTF linac is based on 12.2 m long cryomodules, each containing eight, 9-cell, superconducting cavities and a quadrupole doublet, combined with a cold resonant cavity 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 module as long as possible and combine them to strings fed by a single cold box. This results in low static losses (typically less then 0.2 W/m at 2 K) and a significant cost reduction [13]. The cavities are suspended from the helium gas return pipe which serves as a reference girder. Each cavity is equipped with its RF power coupler, two higher-order-mode (HOM) output couplers, an RF fundamental pick up, and a frequency tuning mechanism. Including the inter-module connections, this scheme produce a 75% filling factor, defined as the ratio of active cavity length and the total linac length.

Downstream of the electron gun and the superconducting capture cavity, the original proposal was a four module linac, with 28 cavities operating at a Q of 3×10⁶ and at 15 MV/m of accelerating field. This value was 3 times higher with respect to that obtained in the existing large scale installations [3] and 2/3 of TESLA requirements. The present scheme asks for a linac composed by 8 modules, divided in three groups, respectively of 1, 2 and 5 modules each.

The first module has been successfully in operation (with the first thermoionic injector [14] and the capture cavity) since spring 1997, showing that the goal on cavity performance was already achieved and the other modules could then approach closer the TESLA requirements. All the eight cavities which have been included in the second module outreach $E_{acc}=20$ MV/m @ Q≥5×10⁶ and two of them are already above the TESLA specs ($E_{acc}=25$ MV/m @ Q≥6×10⁶). The cavities we are preparing for module three should all satisfy the TESLA requirements.

Once the new RF injector [15] and the bunch compressors are installed, we expect to operate the first two cryomodules
by middle of November. The third module will be installed at
the beginning of next year, together with the undulator for the
SASE FEL experiment that is planned by next summer [16].

This will conclude the TTF Linac Phase I. The following
Phase II, that is a five cryomodule extension in one string, give us the possibility to implement and test components
closer to the TESLA requirements in term of performances,
reliability and cost. Considering that we expect for the last
modules an accelerating field for all the cavities of 25 MV/m,
each cryomodule will add 200 MeV to the beam energy.

The new cryostats are smaller in diameter and are already
designed to include the possibility of using semi-rigid main
couplers and superstructures.

The completion of Phase II is expected in fall 2001, when
an user facility for VUV FEL will also be operational. A
photon energy up to 200 eV is foreseen in ultra-short (rms
length of 50 μm), ultra-bright bunches (4·10^13 photons per
bunch). Bunch train of 800 μs, containing up to 7200 bunches
will be allowable for the experiments, at a 10 Hz repetition
rate [16].

The necessary building extension for TTF Phase II will be
completed during next year, in time to install the first of the
new cryomodules. Modules will be located in a 5m diameter
tunnel, simulating a section of the TESLA collider.

From the end of the eighth module to the FEL undulator a
25 m free space is left for a possible further installation of
two cryomodules, equipped with the final TESLA cavities.

III. DEVELOPMENTS AND ACHIEVEMENTS

In this chapter I will outline the results obtained so far in
the development of the major components for TESLA. This
list is surely incomplete and the choice of topics is somewhat
arbitrary. Apologizing for that, I suggest interested people
look at the quoted papers, including the references therein.

It is worth noting that superconductivity is also used in
beam diagnostic at TTF: Bunch length measurements are
done with Hilbert transform spectroscopy using a high-Tc
Josephson junction [17].

A. Superconducting Cavities

A first set of 26, 9-cell, cavities [7] has been produced by
four European companies and another batch of 26 cavities is
now under production and delivery. The cavities of this last
batch are almost identical to the previous ones, but for the EB
electron beam) welded Nb-Ti flanges.

The present, optimized, cavity fabrication procedure,
includes the following milestones:

- Complete scanning of the 2.8 mm, RRR 300, Nb sheets
by an eddy current apparatus [18], to discard all sheets
with detected, 100 μm size, inclusions or cracks.
- EB welding of the deep-drawn half cells to realize the
dumb-bells, including the stiffening ring. The iris
welding is “finished” from inside.

- Completion of the cavity by the equatorial EB welds
performed from the outside in two subsequent passages
with a fast wiggling beam. This technique, suggested by
J. Brawley of the Jefferson Lab [19], was found to be
very powerful to reduce the high criticality of the
welding parameters.

These three production steps, among the many others more
conventional [7,20], are quoted because their proven
importance for a high quality standard production with very
few discards.

Once checked for surface status, dimensions and vacuum
tightness, the cavity is delivered to DESY for acceptance
tests, treatments, RF measurements and assembly. Among
the large number of steps which are required [20] to prepare the
cavity for vertical test, a partial, although significant, list is
given in the following:

- Removing 80 μm by buffered chemical etching (BCP);
- Hydrogen degassing at 800 °C;
- High temperature heat treatment at 1400 °C (4 hours with
  Ti gettering) to rise the Nb RRR from 300 to 500-700.
- 80 μm internal BCP for Ti removal and 30 μm external
  BCP to improve Kapitza conductance;
- Tuning and field profile adjustment;
- High pressure (100 bar) water rinsing (HPR);
- Assembly, additional HPR and drying by pumping.

RF tests include high power processing (HPP) [21], to cure
field emission, and excitation of the other 8 modes of the
fundamental band, to determine the performances of the
individual cells. T-mapping and local eddy current
measurements are used to determine defect locations.

By the end of July 1998, 26 9-cell cavities have been tested
at the TESLA Test Facility: The majority of the cavities
exceeded the design goal of 15 MV/m and gradients up to 29
MV/m have been reached in the vertical test stand. Field
values up to 36 MV/m (E_m) have been achieved in individual
cells by mode excitation [22].

Figure 2 shows the vertical test results of the 17 cavities
with no identified fabrication error. On average a gradient of
24 MV/m at Q=8·10^9 has been obtained.
The performance of six cavities, with field limited below 16 MV/m in most cells, was due to an improper cleaning of the welding area [23]. Once the problem was identified, with improved weld parameters and weld preparation, the same manufacturer produced cavities reaching 25 MV/m without quenches. One cavity was limited to 6.4 MV/m by the repairing of an equatorial welding, while the other cells were all above the TTF specs. The remaining two cavities not performing to expectations showed inclusion of Tantalum all above the TTF specs. The remaining two cavities not reaching quenches. One cavity was limited to the welding area procedure, which includes wiggling beam EB welding and grains in the Niobium. The new implemented fabrication was expected to solve the last two problems.

Presently field emission above 20 MV/m limits most cavities and does not allow to find the real quench limit. In order to safely obtain usable gradients above 25 MV/m in 9-cell structure, the reduction of field emission loading is of highest importance.

After being welded into the Titanium He-tank, equipped with a motorized tuning system [24], the RF power coupler and the HOM couplers assembled, the last test prior to the assembly into a cryomodule is performed in a horizontal test stand, CHECHIA, designed and built at Saclay. The cavity performance in the horizontal cryostat in pulsed mode is comparable with the results of the vertical tests [25], and with their performance in the module. The small differences revealed in some cases, in both directions, can be interpreted respectively as due by dust particles in the further assembly or by the further conditioning of the field emission limit.

One particular case is represented by cavity C23 that reached, in the horizontal test, 33 MV/m with a quality factor Q=4×10^9, measured throughout the cryogenic losses. At 34 MV/m a quench occurred. In the vertical test, the cavity was limited to 25 MV/m by available RF power. Figure 3 shows the test results of this record cavity.

In early summer 1997 the first cryomodule has been assembled and commissioned successfully, being operated until August 1998. An average gradient of 15 MV/m, consistent with vertical and horizontal tests, has been established with beam [25].

B. Cryostats

Operational experience on the first module has shown that the basic cryostat design criteria were adequate. Very low static heat leak values for the 70 K, 4.5 k and 1.8 K temperature levels have been measured (90 W, 23 W and 6 W respectively), showing that they are already close to the TESLA design values [13]. The difference is consistent with the heat leak produced by the presence in the first cryomodule of the endcap, feedcap and diagnostic components which are not foreseen in a standard TESLA module (2 quartz windows for optical alignment, 144 Coax cables for the wire position monitors [26] and hundreds of redundant instrumentation cables).

The experience gained during the design and commissioning of the prototype suggested new solution to improve the technical design, while substantially cutting the fabrication cost. In the cryostats for module #2 and #3 the special copper braids and the hundreds of threaded fasteners have been eliminated, and substituted by an original scheme to connect the Al shield panels to the Al cooling pipes, base on the so called “finger welding” [27]. The first of these two cryostat has been successfully assembled, while the last is waiting for the completion of the 25 MV/m cavity string, expected by the end of this year.

The cryostat design for modules #4 to #8 has been approved and fabrication is starting. These cryostats are smaller in diameter (38” standard pipe) and use roll bearing based fixtures to support the cold elements. In this design, during the cooldown, the cavities are free to move along the beam axis direction, while maintaining the alignment [28]. This improvement opens the possibility for simpler semi-rigid couplers and superstructures [29].

C. Couplers

Being considered a crucial component, two coupler designs have been implemented for TTF, respectively by FNAL [7] and DESY [30]. Both have be successfully developed and are in operation in module #1. The required power of 220 kW, for a pulse length of 800 µs, is routinely delivered to the cavity and both have shown the capability to sustain short 1 MW pulses.

Since the present components are quite expensive, a new simplified version, designed at DESY, is in the fabrication stage [31]. Another version, which takes advantage of the new cryostat design [28] is being designed in France [32].
D. RF Controls

Outstanding results have been reached for RF controls. The task of obtaining the required amplitude and phase stability during the 800 μs flat top of the RF pulse was a very challenging one.

The digital RF control system, implemented for the TTF beam operation, showed by itself an excellent performance, stabilizing the amplitude and phase, during the 800 μs flat top of the RF pulse, to better than 0.5 % and 0.1° respectively. With the addition of a new adaptive feed forward system, amplitude and phase stability have been both improved by a factor of 10 [33], outreaching the TESLA requirements. The accelerating gradient in a cavity as a function of time during a 800 μs RF pulse is shown in Fig. 4.

IV. R&D ACTIVITIES ON SC CAVITIES

Driven by the TESLA collider goal, the R&D activity on superconducting cavity development has grown worldwide in the recent years. This activity, that is more and more concentrated on the TESLA cavity parameters, is being done in different laboratories which are either part of the International Collaboration, or linked throughout specific Memoranda of Understanding.

A rather complete overview of the R&D work on superconducting cavities can be found in the proceedings of the last two Workshops on RF Superconductivity [34] and the proceedings of the few dedicated workshops organized at DESY and focussed on the TESLA requirements [35].

Two lines can be identified according to the main task that is at the basis of the TESLA activity: cost reduction and/or field enhancement. In the following I just want to quote some promising example that can be taken as a reference. For simplicity they are divided in two subchapters: understanding field emission and Q drop and new fabrication techniques for cost reduction.

A. Understanding field emission and Q drop

Applying the standard fabrication and processing technique developed at TTF, which includes high peak power processing, we are now routinely obtaining cavities which exceed 20 MV/m, at Q=10⁷, without field emission. Above this field level, Q starts to drop and x-ray, associated with electron emission, are usually observed.

The improvement of the EB welding technique, associated with 1400 °C Ti-gettering and eddy current scanning of the Niobium sheets, moved the quench limit beyond the Q drop and field emission limits.

The present field level before field emission starts has been obtained through a wide R&D effort pursued in many laboratories and universities: Cornell, Wuppertal, Saclay, CERN, KEK, CEBAF and DESY [34]. Extremely clean assembly (class 10 clean room) and high pressure (~ 100 bar) rinsing with ultra pure water are now considered as mandatory [36]. In the case of TTF, a fine tuning of the procedure, including chemistry, has been obtained through the field emission analysis, performed at Wuppertal, on samples following the cavity along treatments and handling.

The Q drop at high field level, observed in those cavities not limited by field emission, has different interpretations and the R&D work is still under way. Magnetic flux pinning and microscopic surface contaminants (not detected by the eddy current scanning) are particularly studied [34]. The associated losses have a field dependence that is usually more than quadratic.

One special mention has to be dedicated to the recent outstanding results obtained at KEK on a number of single cell cavities, reaching accelerating field up to 40 MV/m with a moderate Q drop [37]. Commercial high purity Niobium, by different suppliers, was used but a different production technique has been applied, based on electropolishing. The 1400 °C Ti-gettering treatment was limited to the components (half cells), before the EB welding.

Since this technique could have good potentiality for TESLA, both for field enhancement and cost reduction, in collaboration with KEK and CERN, an R&D activity in this direction has started and results are expected soon.

B. New fabrication techniques

The aim to cut the cavity cost in the large scale production foreseen for TESLA drove an important R&D activity to find new cheaper techniques for cavity fabrication. Two lines have been pursued:

- seamless Nb cavities, by spinning or hydroforming, to eliminate the equatorial welding and to slightly reduce the required material inventory [38];
- sputtering Niobium on Copper to strongly reduce the Nb material cost [39].

Because on the two subjects there is a dedicated paper at this conference, I refer to that for the discussion of the promising results obtained so far [38].

![Figure 4: The accelerating gradient in a cavity as a function of time during an RF pulse. The zoomed region shows the amplitude stability given by digital feedback and with the addition of the feed forward compensation.](image)
Conversely I want to separately quote the rather new technique of plasma jet spraying Copper on a thin Niobium cavity [40]. This technique, once implemented for high performing, pretreated, cavities, should produce a real breakthrough in the cavity cost reduction. In fact the Niobium performances, pretreated, cavities, should produce a real breakthrough in the cavity cost reduction. The plasma jet coating. The measurements done of the contact and Kapitza resistance are encouraging and do not set fundamental limits.

V. CONCLUSIONS

The results obtained so far in the framework of TTF are very encouraging and the technical possibility to build TESLA is becoming a reality. In particular the cavities are now routinely reaching the TESLA requirements and recent results and ideas show that a substantial cost reduction, associated to even higher fields, can be reached in the near future.

VI. ACKNOWLEDGEMENTS

I want to thank all the members of the TESLA Collaboration for the excellent work done so far, a small part of which I tried to summarize in this paper.

REFERENCES