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# COLD- AND BEAM TEST OF THE FIRST PROTOTYPES OF THE SUPERSTRUCTURE FOR THE TESLA COLLIDER

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*Abstract*

After three years of preparation, two superstructures, each made of two superconducting 7-cell weakly coupled subunits, have been installed in the TESLA Test Facility linac (TTF) for the cold- and beam test. The energy stability, the HOMs damping, the frequency and the field adjustment methods were tested. The measured results confirmed expectation on the superstructure performance and proved that alternative layout for the 800 GeV upgrade of the TESLA collider, as it was proposed in TDR [1], is feasible. We report on the test and give here an overview of its results which are commented in more detail elsewhere in these Proceedings.

## INTRODUCTION

The superstructures (SSTs), chains of superconducting multi-cell cavities (subunits) connected by λ/2 long tube(s) have been proposed as an alternative layout for the TESLA main accelerator. This concept is discussed in more detail in [2, 3]. We re-call here two main advantages of the layout in comparison to the standard one, based on 9-cell cavities. The first economical advantage is that structures made of more cells will reduce the number of the Fundamental Power Couplers (FPC) in the linac. Consequently, the number of all auxiliaries needed to distribute the RF power, like: waveguides, bends, circulators, 3-stub transformers, loads etc., can be reduced too. In addition, the layout reduces the amount of electronics controlling phase and amplitude of cavities in the linac and simplifies the design of cryomodules due to less openings for the FPCs. The second advantage is the increased filling of the linac tunnel with accelerating structures, since the distance between subunits is λ/2 only. The space saving can be significant and in the case of here discussed versions of SSTs it amounts to ~1.8 km. The first superstructure (SST-I), as it has been proposed in [2], was meant to be made of four 7-cell cavities. We have built a Cu model of this version and six Nb 7-cell subunits.Meanwhile, a 2x9-cell version (SST-II) was studied and was found to be more attractive for the TESLA collider. This version keeps the same fill factor of the tunnel as the first one. SST-II is shorter and its production, cleaning and handling will be easier. Savings in the investment cost are of the same order for both superstructures. The RF parameters of both versions are listed in Table 1.

Table 1. RF parameters of both superstructures.

| Parameter | | SST-I | SST-II |
|---|---|---|---|
| Number of cells in subunit | | 7 | 9 |
| Number of subunits | | 4 | 2 |
| (R/Q) per subunit | [Ω] | 732 | 985 |
| $E_{peak} / E_{acc}$ | | 2 | 2 |
| $B_{peak} / E_{acc}$ | [mT/(MV/m)] | 4.2 | 4.2 |
| $L_{active}$ | [m] | 3.23 | 2.08 |

## PREPARATION OF THE TEST

### *2x7-cell prototype*

We have “split” the 4x7-cell prototype in two 2x7-cell prototypes. The main argument to split the prototype of SST-I was similarity in the RF-properties of the 2x7-cell and the favorable 2x9-cell versions. The computed bunch-to-bunch energy variation for all bunches in the TESLA macro-pulse (HOMDYN [4]) was very similar, $\pm 5\cdot10^{-5}$ for 2x9-cell and $\pm 3\cdot10^{-5}$ for 2x7-cell version. The scheme of the Higher Order Modes (HOM) suppression in both versions is very similar also and is based on the HOM couplers of the same type as those used for standard 9-cell TTF cavities. The conclusion was that the beam test of already existing 7-cells subunits assembled in two 2x7-cell prototypes will tell us more about the favorable SST-II superstructure, will benchmark our computation and will give finally twice as much statistics for the measured results.

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## *TTF Linac*

Both 2x7cell superstructures were assembled into a spare cryomodule and installed in the TTF linac next to the injector. The bunch-to-bunch energy measurement at the end of the linac, which was the main purpose of the experiment, was performed by means of the spectrometer dipole with two BPMs at its front and one BPM behind it. The highest estimated energy measurement accuracy was better than $2 \cdot 10^{-4}$. Due to a very intense experimental program at the TTF linac in the year 2002, a second cryomodule, housing eight 9-cell cavities, has been installed for a long-term performance test simultaneously with the superstructures. The presence of this cryomodule had consequences for the test as discussed below.

# THE TEST

## *Balance of the stored energy in subunits*

The field profiles of the accelerating mode of both superstructures have been measured with the help of the bead-pull (perturbation) technique before the final chemical treatment and the final high pressure water rinsing. Both prototypes (P1, P2) had a good field flatness, better than 92 % and 94 %, respectively. As usual, after final preparation and cool-down there is no more possibility to use a bead for the field measurement. Still, one can apply the perturbation method to balance the mean gradient in both subunits using the cold tuners instead of a bead to perturb the e-m fields. For this, the cold tuner of each subunit was moved by 1000, 2000 and 5000 steps and for each position the frequency change of the $\pi$-0 mode was measured. Then, the final positions of the tuners were chosen to maintain exactly f = 1.3 GHz of the $\pi$-0 mode and simultaneously to ensure that the change of frequency is the same, when the tuners are moved by the same number of steps. The final status of the prototypes was cross-checked in the following way. We compared, for each cold prototype, the fundamental passband frequencies with the frequencies measured at room temperature when the bead-pull method showed the best achievable field profile. The deviation from an ideal linear shift of frequencies is a very good indicator of any change in the profile. The measured deviation for both prototypes was very small, below $8 \cdot 10^{-6}$ and we concluded that profiles remained unchanged after the final preparation and after the cool-down.

## *Energy gain stability*

This experiment was the “proof of principle” test. Our main concern was the energy flow via very weak coupling between subunits. The stability of the energy gain for all bunches in the train means that the cells’ stored energy is refilled in time between two consecutive bunches. The test was performed in two parts. In the first one, we subjected the prototypes to a slow decay of the stored energy during the acceleration. In the second part we measured directly bunch-to-bunch energy modulation at the end of the linac.

In this test both prototypes were operated very reliably at 15 MV/m. The operation of the injector, with the smallest charge fluctuation of 2.8 % within the macro-pulse, was possible, when the bunch charge did not exceeded 4 nC. We chose the bunch spacing of $t_b$ = 1 µs to meet the highest sampling rate of the implemented BPMs’ electronics. The rise time of e-m fields resulting from the matched $Q_{load}$ value was 790 µs and the longest beam on time was limited to 530 µs by the klystron pulse length. Each prototype has been equipped with four field probes, placed one near each end-cell. They were used to monitor the field strength during the acceleration. An example of measured signals is shown in Fig. 1. Without the energy re-filling the beam would take almost 70% of the energy stored in the cells and the voltage would drop by 45 %. No such phenomenon was observed. All signals had noisy fluctuations. The strongest oscillation was at 250 kHz. It was caused by down-converters of the low level RF-system controlling the phase and the amplitude of accelerating fields. We found, in the second part of the experiment, six more oscillations caused by the feedback loops. The Fourier transformation of three signals (from the BPM behind the dipole), measured for three different gains in the feedback loop, is shown in Fig. 2. One can see in total 15 oscillations. Peaks No. 1, 2, 12 and 13 increased when the loop gain increased. Peaks No. 14 and 15 decreased vs. the gain. All other peaks remained unchanged. Seven peaks were due to the feedback loops, eight (No. 3÷10) were caused by the second cryomodule. All eight cavities of this cryomodule have been detuned from 1.3 GHz by roughly 200 kHz and no power was delivered to them during the entire energy gain test. Still, the beam induced voltage in these cavities has modulated the energy of bunches. Finally, the conclusion from the energy stability test was that, no slow gradient decay and

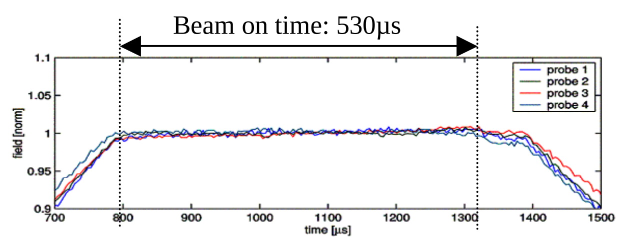


Figure 1: Signals from field probes of P2 measured during the acceleration of 530 bunches, q = 4 nC, $t_b$ = 1 µs.

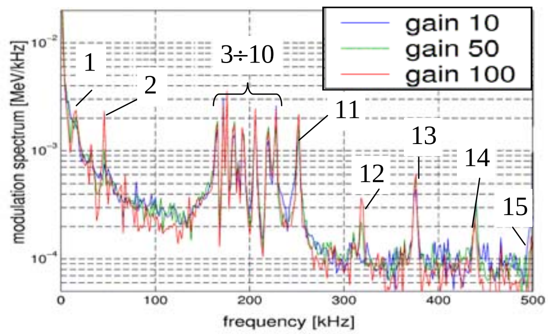


Figure 2: Spectrum of the energy modulation as measured at the end of the linac.

no modulation caused by superstructure prototypes was seen within the accuracy limit in the measurement [5]. This result proves that superstructures fulfill the TDR specification for the energy variation, which must be below $5\cdot10^{-4}$.

### *HOM damping*

Each prototype had three HOM couplers, which had been attached to the end beam tubes and to the interconnection. The SST-II version will have four cells more and we plan to attach two HOM couplers at the interconnection to compensate for that. We will report on the results we measured for the transversal modes, since these modes are relevant for the quality of the TESLA beam. Three methods were applied to measure frequency and impedance, $Z = (R/Q)\cdot Q_{ext}$, of HOMs. At first, we measured the modes' frequency and $Q_{ext}$ with a network analyzer. We measured modes up to 3.2 GHz. The method gives the mode impedance when one assumes that the actual (R/Q) is equal to its computed value. The method is limited to well "isolated" modes. The error in frequency measurement increases when $Q_{ext}$ of a mode gets lower and when neighboring modes overlap.

The second method we applied was the active mode excitation [6]. Modes with high impedance were excited via one of the HOM couplers by means of a cw amplifier. By controlling the power coupled out by two other HOM couplers we estimated transversal kick (Z) and deflection of the on axis injected beam. It was compared to the value measured in the BPM, 15 m downstream from the cryomodule. The method can give all actual parameters of an excited mode: Z and the polarization if deflection is measured in x and y direction. It is sensitive to the setting of the beam line optics between cryomodule and the BPM. One can apply this method to modes, which couple well to HOM couplers. Forty-seven modes were measured with this method. The third method, applied to measure Z, was based on the HOM excitation by the accelerated beam when it passes the cavity off axis. The results are reported in [7]. All three methods verified a very good damping of HOMs. The suppression of dipoles with $(R/Q) > 1\ \Omega/cm^2$ is shown in Fig. 3. All modes relevant

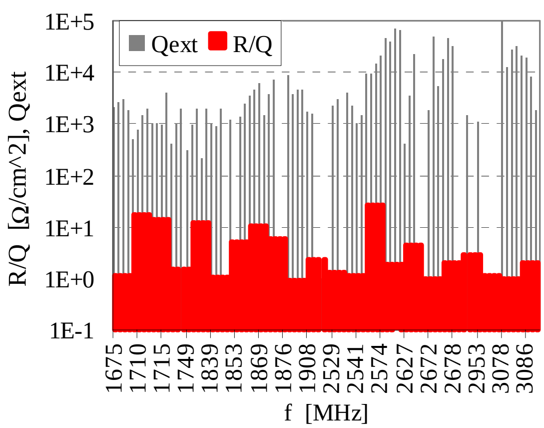


Figure 3: Damping of dipoles with $(R/Q) \geq 1\ \Omega/cm^2$.

for the TESLA collider, up to 2.58 GHz, were damped by a factor 5 to 100 better than the specification ($Q_{ext} \leq 10^5$). We have found a few modes only (in 5th passband, ~3.08 GHz), among 420 measured modes, with $Q_{ext}=10^7\div2\cdot10^8$. Their (R/Q)s are almost zero and thus they cannot degrade the quality of the TESLA beam.

## FINAL REMARKS

The cold- and beam test of both prototypes has confirmed that one can use weakly coupled structures for the acceleration. Neither beam energy modulation, slow gradient decay nor insufficient HOM's damping resulting from the coupling of two subunits have been observed. The stability of the bunch-to-bunch energy gain was measured within the limit of the beam diagnostics in the TTF linac. Although, the accuracy of the energy gain measurement has not reached the level of the theoretical estimation, which was one order of magnitude smaller, the experiment showed that the TESLA specification already has been fulfilled. We have demonstrated two methods to balance the gradient in the weakly coupled subunits. The agreement of both methods was good and both confirmed that final chemical cleaning may be performed without additional degradation in the field flatness.

The experiment showed that the electronics for phase and amplitude control, used routinely to operate standard 9-cell cavities in the TTF linac, can be applied to operate the superstructures. Further improvement of the control system seems to be possible to provide better suppression of the modulations coming from the control system itself.

## ACKNOWLEDGMENTS

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