Test of two Nb superstructure prototypes

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An alternative layout of the TESLA linear collider [1], based on weakly coupled multi-cell superconducting structures (superstructures), significantly reduces investment cost due to a simplification in the RF system of the main accelerator. In January 1999, preparation of the beam test of the superstructure began in order to prove the feasibility of this layout. Progress in the preparation was reported frequently in Proceedings of TESLA Collaboration Meetings. Last year, two superstructures were installed in the TESLA Test Facility (TTF) linac at DESY to experimentally verify: methods to balance the accelerating gradient in a weakly coupled system, the stability of the energy gain for the entire train of bunches in macro-pulses and the damping of Higher Order Modes (HOMs). We present results of the first cold and beam test of these two Nb prototypes.

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I. INTRODUCTION

Superstructures (SSTs), chains of superconducting multi-cell cavities (subunits) connected by $\lambda/2$ long tube(s), have been proposed as an alternative layout for the TESLA main accelerator [2, 3]. There are two main advantages of the layout in comparison to the standard one, based on 9-cell cavities. The first, an economic advantage, is that structures made of more cells will reduce the number of 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 fewer openings for the FPCs. The second advantage is the increased filling of the linac tunnel with accelerating structures, since the distance between subunits is only $\lambda/2$. The space saving can be significant. In the case of versions of SSTs discussed later, it is ~1.8 km. When the end energy of the collider is fixed one has a choice to keep the nominal gradient and to make the accelerator shorter or to keep its length and to lower the nominal gradient. The best way to use this additional space is a trade-off between the investment cost and the performance of the collider.

In superstructures, unlike a standard multi-cell structure, the accelerating mode is the π -0 mode (π cell-to-cell phase advance and 0 subunit-to-subunit phase advance). The second difference from a standard long multi-cell structure is the very weak coupling of subunits, k_{ss} . It is smaller roughly by a factor of 50 than cell-to-cell coupling. The energy flow via this coupling was the main objective in the beam test. Although the k_{ss} coupling is very weak we can control the stored energy (gradient) in each subunit by means of cold tuners, which have high frequency resolution (nowadays better than 1 Hz). A further difference is as follows. The π -0 mode is below cut-off in interconnecting tubes. This makes possible the attachment of HOM coupler(s) at interconnection(s), in the "middle" of the multi-cell structure. In this way, good damping of parasitic modes can be maintained, avoiding strong heating of the couplers.

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, of which the best performing four would be assembled in the superstructure. The assembly would be done by means of superconducting gaskets. Meanwhile, a 2x9-cell version (SST-II, see Fig. 1) has been studied and 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 first version reduces the number of FPCs to 33% of the number needed for the base design. Since subunits are shorter (7 cells not 9 cells) it demands more liquid He vessels and cold tuners. The second version, SST-II, reduces the number of FPCs to 50% but it keeps the same number of He vessels and tuners as the base layout (if no additional structures are installed in the linac to fill up saved space). Table I compares three layouts for the other and the most favorable scenario, when the 500 GeV stage

Work supported in part by the Department of Energy Contract DE-AC03-76SF00515 Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309 length of the TESLA tunnel is fixed and the saved space is filled up with additional accelerating elements. RF parameters of superstructures are listed in Table II.



FIG. 1. SST-II: left subunit is assembled in He vessel with cold tuner. The right one is shown with the single FPC needed to transfer RF power to 18 cells.

TABLE I. Number of structures and their auxiliaries for three layouts of the 500 GeV TESLA collider (without 2% energy overhead).

Layout	FPCs	HOM Couplers	Cold Tuners, He Vessels
9-cells	20592	41184	20592
SST-I	7032	35160	28128
SST-II	10926	43704	21852

TABLE II. 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 sub-unit $[\Omega]$	732	985
E_{peak}/E_{acc}	2	2
$B_{peak}/E_{acc} \qquad [mT/(MV/m)]$	4.2	4.2
L _{active} [m]	3.23	2.08

II. PREPARATION OF THE TEST

A. 2x7-cell version

For a few reasons we have "split" the 4x7-cell prototype into two 2x7-cell superstructures. The superconducting gaskets, needed to assemble the SST-I prototype, did not perform reliably when installed on 7-cell subunits. We could not reach stable accelerating gradients testing subunits in the vertical cryostat, even thought the results on a 2-cell test cavity were encouraging. Subunits of 2x7-cell prototypes could be welded together. Fortunately, the infrastructure for cavity preparation at DESY was able to accommodate 2.08 m long cavities without major changes. The second argument to split SST-I was similarity in the computed (HOMDYN, [4]) bunch-to-bunch energy variation of the 2x7-cell and 2x9cell versions. For all bunches in the TESLA macro-pulse the computed variation is very small, $\pm 5 \cdot 10^{-5}$ for the 2x9cell and $\pm 3 \cdot 10^{-5}$ for the 2x7-cell version (Fig. 2). The shape difference of two figure's results only from the different modes beating.



FIG. 2. Computed energy deviation for the TESLA beam: 2820 bunches, 3.2 nC/bunch, spacing 337 ns.

The conclusion was that the beam test of already existing 7-cell subunits assembled in two 2x7-cell prototypes will tell us more about the favorable SST-II version, will benchmark our computation and will give finally twice more statistics for the measured results.

B. TTF linac

Both 2x7-cell superstructures were assembled into a spare cryomodule and installed in the TTF linac next to the injector. Many components limiting the aperture of the beam line which could influence our test were removed from the linac. Additional beam position monitors (BPMs) were installed behind and at the front of the dipole magnet next to the injector to measure the energy of the beam coming out of the injector. The energy measurement at the end of the linac was performed by means of the spectrometer dipole with two BPMs at its front and one BPM behind it. With this arrangement collective betatron motion could be extracted from the displacement measured behind the dipole. The highest estimated accuracy was $2 \cdot 10^{-4}$ and it was limited by the resolution of BPMs. It was better by a factor of 3 than for the operation of standard 9-cell structures during the entire time of experiments at the TTF linac in previous years. Due to a very intense experimental program at the TTF linac in the year 2002, a second cryomodule, housing eight 9-cell cavities, was installed simultaneously with the superstructures for a long-term performance test. The presence of this cryomodule had consequences for the test of the superstructures, as we will see later. Both cryomodules were cooled down in May 2002.

III. THE TEST

The planned cold and beam test was expected to answer the three following questions:

- How to balance the gradient in subunits?
- How stable is the energy gain?
- How good is damping of the HOMs?

We will discuss the answers to these questions in the next three sections.

A. Balance of the stored energy in subunits

The field profiles of the accelerating mode of both superstructures had been measured with the help of beadpull (perturbation) technique before the final chemical treatment and the final high pressure water rinsing were done. Amplitudes of the accelerating field on axis of both prototypes (P-1, P-2) are shown in Fig. 3. Both had good field flatness, better than 92% and 94% respectively. At that stage, the subunits were already equipped with He vessels and there was no access to the cells to make further improvement in the field profile. One may expect that any additional chemical treatment or even cool-down could change the field profile. It was worthwhile to estimate this change experimentally. As usual, after the final chemical polishing and water rinsing there is no more possibility to use the bead-pull technique to measure and to adjust the fields. It is always a risk to contaminate a cleaned superconducting surface by moving a perturbing bead and its holding string in the interior of a cavity. 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. Both prototype's subunits have the same stored energy (or mean gradient) when the same perturbation causes the same frequency shift. For this, the cold tuner of each subunit was moved by 1000, 2000 and 5000 steps and for each position the frequency change Δf of the π -0 mode was measured. Then, the final positions of the tuners were chosen to maintain exact frequency equal to 1.3 GHz of the π -0 mode and simultaneously to ensure that the subunits show the same Δf when their tuners are moved by the same number of steps. The final status of the prototypes was crosschecked 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 very sensitive to relative detuning of subunits or/and frequency perturbation of individual cells (due to possible non-uniform chemistry or non-uniform shrinkage). It is a very good indicator of any change in the field profile. The conclusion drawn from the test of this method and its application to the standard 9-cell cavities was that when the relative deviation of frequencies was below 1.10^{-5} , the change in the field flatness was less than 2%. The deviation we measured for both prototypes (Fig. 4) was below $8 \cdot 10^{-6}$, so we concluded that field profiles remained unchanged after the final chemistry, high pressure water rinsing, and assembly in the cryostat, and after the cool-down procedure.

B. Energy gain stability

This experiment was the "proof of principle" test. As was mentioned already, 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



FIG. 3. Peak-to-peak field flatness. (a) P-1 92% and (b) P-2 94%.



FIG. 4. Relative deviations (zigzag lines) from ideal linear spectrum shifts (straight lines) as measured for 8 highest modes of both prototypes.

means that cells' stored energy is refilled in time between two consecutive bunches. The test was performed in two parts. In the first one, we examined 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 both parts of this test neither prototypes nor injector were pushed to their limits in performance to keep the operation of the linac very stable. Both prototypes could be operated very reliably at 15 MV/m (the subunits had not been thermally treated at 1400 °C). The TTF injector was designed in 1997, when the TESLA beam parameters were different from those optimized later and proposed in TDR in 2001. The operation of the injector, with the smallest charge fluctuation of 2.8% within the macro-pulse, was possible when bunch charge did not exceeded 4 nC. The bunch spacing of $t_b = 1 \mu s$ (the same as for the very first TESLA beam) had been chosen to meet the highest sampling rate of the implemented BPMs' electronics.

The HOMDYN prediction for this TTF beam was that bunch-to-bunch energy variation is in the same range as shown in Fig. 2. The reflection-free operation, when the beam current is 4 mA and the gradient is 15 MV/m, demanded Q_{load} of the FPCs to be $4.2 \cdot 10^6$. The rise time of e-m fields resulting from this Q_{load} value was 790 µs and the longest beam on time was limited to 530 µs (klystron pulse length was in total 1.32 ms). Each prototype was equipped with four field probes, placed one near each end-cell (see Fig. 5). They were used to monitor the field strength during the acceleration.

An example of measured signals is presented in Fig. 6. Without the energy re-filling the beam would take almost 70% of the energy stored in cells and the voltage would drop by 45%. No such phenomenon was observed. Both diagrams confirm the expectation that energy flow via weak coupling is sufficient. Even the signals of probes No. 3 and No. 4 (located at the subunit without FPC) in both prototypes did not decay during the acceleration. All signals had some noisy fluctuations. The strongest oscillation was at 250 kHz. It was caused by downconverters of the low level RF-system controlling the phase and the amplitude of accelerating fields. Zoomed signals of the P2 prototype, in the time range 150-190 µs after the beam was switched on, are shown in Fig. 7. All signals in this figure are normalized: (A-<A>)/<A>.They showed the oscillation at 250 kHz (4 µs period) which is superimposed on the other oscillations, well seen in the



FIG. 5. Prototype of 2x7cells. Field probes:A1-A4. HOM couplers: HOM1-HOM3.



FIG. 6. Signals from field probes (P1 upper diagram, P2 lower diagram) measured during the acceleration of 530 bunches, q = 4 nC, $t_b = 1 \mu s$ at 15 MV/m.



FIG. 7. Prototype P2. Oscillations of signals (normalized) during the acceleration.

signal of probe No. 1. The 250 kHz modulation was also seen during operation of the standard 9-cell cavities. We found, in the second part of the experiment, six more oscillations caused by the feedback loops.

As was mentioned, the second part of this experiment was devoted to measuring directly at the end of the linac the bunch-to-bunch energy variation. 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. 8. One can see 15 oscillations in total, which reacted to the gain change in very different ways. 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, including the 250 kHz one, which we discussed above. Seven peaks were due to the feedback loops; eight (No. 3-10) were caused by the second cryomodule. All eight cavities of this cryomodule were detuned from the 1.3 GHz frequency by roughly 200 kHz and no power was delivered to these cavities during the entire energy gain test. Still, the beam induced voltage in these cavities modulated the energy of bunches. We could change the frequency of an individual peak by driving the cold tuner of the corresponding cavity. Finally, the conclusion from



FIG. 8. Spectrum of the energy modulation as measured at the end of the linac.

the energy stability test was that no slow gradient decay and no modulation caused by superstructure prototypes was seen within the accuracy limit in the measurement of $2 \cdot 10^{-4}$ [5]. One should mention here that this result proves that superstructures fulfill the TDR specification for bunch-to-bunch energy variation, which must be below $5 \cdot 10^{-4}$.

C. HOM damping

Each prototype had three HOM couplers (Fig. 5) which had been attached to the end beam tubes and to the interconnection. The SST-II version will have four more cells 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 transverse modes, since these modes are relevant for the quality of the TESLA beam. Three methods were applied to measure the frequency and impedance, $Z = (R/Q) \cdot Q_{ext}$, of HOMs. At first, we measured the modes' frequency and Qext by means of network analyzers. For both prototypes, we measured modes up to 3.2 GHz including the five dipole passbands and the lowest passbands of monopole, quadrupole and sextupole modes. In total, 420 modes have been measured. The method gives the impedance when one assumes that actual (R/Q) equals 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 frequency errors were misleading for the search of some modes we wanted to check with two other methods.

The second method we applied was the active mode excitation [6]. Modes with potentially high impedance were excited via one of the HOM couplers by means of a 50 W amplifier. By controlling the power coupled out by two other HOM couplers we estimated 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 potentially can give all parameters of an excited mode: Z and the polarization if deflection is measured in both x and y direction. It is sensitive to setting of the beam line optics between the cryomodule and the BPM. One can apply this method to modes which couple well to HOM couplers. Forty seven modes were measured with the active method. An examples of measured BPM signals are shown in Fig. 9 and 10. In this particular case one polarization of the highest impedance dipole (R/Q = 27 Ω/cm^2) at f = 2573.971 MHz was excited with 20 W forward power. The damping of this mode was very good. Its Qext was only $2.1 \cdot 10^4$ (5 times below the specification). We measured the deflection in both directions for 32 bunches (2 nC) in a 32 µs long pulse. Ten consecutive pulses are shown in each figure. The signals measured without the excitation (Fig. 9) indicated that bunch position in both planes was varying about ± 0.6 mm from pulse to pulse (one exception was observed for the x-direction),



FIG. 9. BPM signals without the excitation of the deflecting dipole mode.



FIG. 10. BPM signals with the excitation of the deflecting dipole mode. Note different scales for both signals in the x-plane.

although, within one pulse, the position stability without the excitation was one order of magnitude better. Strong oscillation of the beam position was observed when the amplifier was on (Fig. 10). The mode has been tested six times, for various settings of the optics elements and for various HOM couplers used to transfer RF power into the cavity. The measured and the computed deflections are displayed in Fig.11. The differences were mainly due to the optics whose optimum setting should minimize its influence on the trajectory. The estimation of the beam deflection (R_comp) was done with the assumption that the beam drifts between the cryomodule and the BPM. The second reason for the discrepancy, relevant for modes propagating in beam lines, was the direct coupling of a part of the RF power into the beam line [7]. This made the estimation of the deflecting fields less accurate since an unknown part of the power was radiated directly from the coupler. The mode we discuss in the example is above cut-off and the best method was to use the HOM coupler attached to the interconnection between two subunits to avoid direct radiation into the beam lines. The mean value of the measured deflections was $\langle R \rangle = 1.8$ mm and its computed value was R_comp = 1.7 mm. The measured polarization is shown in Fig. 12. The mean value, which was found for the cold prototype, was $73^{\circ}\pm10^{\circ}$ (angle measured cw from y-direction). The differences were mainly due to calibration errors of the BPM signals in both planes. We could not reliably measure angular position of this mode when the prototype was warm since both polarizations overlapped very strongly. Nevertheless, the measured deflection gave the estimation of Z, which



FIG. 11. Deflection measured for the different optics setting.



FIG. 12. Normalized position of the deflected beam in the x-y-plane.

in the worst case is 2 times higher than expected from the network analyzer measurements and which still would be harmless to the TESLA beam. The polarization measurement showed that this mode, when excited by the accelerated beam, will deflect it almost horizontally. We measured other modes in a similar way.

The third method we applied to measure Z was based on the HOM excitation by the accelerated beam when it passes the cavity off axis. The charge of the beam was modulated to hit modes with side-band spectral lines generated in this way. The method was previously applied

twice to the standard cavities. Here we will not discuss its results, which are presented in more detail in [8]. All three methods proved good damping of HOMs. Damping of dipole modes with $(R/Q) > 1 \Omega/cm^2$ is shown in Fig. 13. All modes relevant for the TESLA collider, up to 2.58 GHz, are damped by a factor 5 to 100 better than the specification ($Q_{ext} \leq 10^5$). The damping of dipoles with $(R/Q) < 1 \ \Omega/cm^2$ and other transverse modes is also good (Fig. 14). We have found few modes only (in the 5th passband, ~3.08 GHz), among 420 measured modes, with $Q_{ext}=10^7-2\cdot10^8$. Their (R/Q)s are almost zero and thus they cannot degrade the quality of the TESLA beam. The group of quadrupoles (~ 2.3 GHz) and sextupoles (~2.7 GHz and ~ 3.06 GHz) with Q_{ext} ~10⁶ are also irrelevant for the TESLA beam dynamics since their impedances scale vs. trajectory offset with 4^{th} (n = 2) and 6^{th} (n = 3) power, respectively.



FIG. 13. Damping of dipoles with $(R/Q) \ge 1 \Omega/cm^2$.



FIG. 14. Damping of modes with $(R/Q) < 1 \Omega/cm^{2n}$.

IV. FINAL REMARKS

A. Summary of the experiment

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 HOMs 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 superstructures. Further improvement of the control system seems to be possible to provide better suppression of the modulations coming from the control system itself.

B. Production and future

The production and preparation of superstructures is more challenging than for standard cavities, but obviously not impossible, especially if the infrastructure for welding, pre-tuning and cleaning is planned from the very beginning to accommodate longer structures.

Now the next logical step would be to demonstrate the performance of the 2x9-cell superstructure. After the beam experiment on 2x7-cells we are convinced that this can be only a challenge for the production, but no fundamental physical problems due to very weak coupling are expected. We will continue measurements on Cu models of SST-II to optimize the angular position of HOM couplers. At the moment the beam experiment on a Nb prototype is neither scheduled nor funded. Meanwhile, a new application of the superstructure concept has been proposed and at present is under study [9]. The very good HOM damping makes superstructures with fewer cells an attractive alternative to standard accelerating structures for a high current linac driving FELs. The next application to energy recovery linacs will be studied in more detail in the future.

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