SUPERSTRUCTURES: FIRST COLD TEST AND FUTURE APPLICATIONS*

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Abstract

Superstructures, 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 [1]. After three years of preparation, two superstructures, each made of two weakly coupled superconducting 7-cell subunits driven by a single Fundamental Power Coupler (FPC), have been installed in the Tesla Test Facility linac for beam tests. Energy stability, HOM damping, frequency and field adjustment methods were tested. The measured results confirmed expectations on the superstructure performance and proved that an alternative layout for the 800 GeV upgrade of the TESLA collider is feasible. We report on the test and give here an overview of its results.

The tests confirmed very good damping of HOMs in superstructures and thus has opened a possible new application of this concept to high current energy recovery machines. We have built two 1.5 GHz copper models of two superstructures: 2x5-cells and 2x2-cells to prove further improvement of HOM damping. This contribution presents also measured results on these models.

INTRODUCTION

The concept of superstructures (SSTs), was discussed in [2, 3]. There are two main advantages of this layout in comparison to the standard one, based on 9-cell cavities. The first, economic advantage is that structures made of more cells will reduce the number of FPCs in the linac. Consequently, the number of all components needed to distribute the RF power, such as waveguides, bends, circulators, 3-stub transformers, loads etc., could also be reduced. In addition, the layout reduces the amount of electronic systems controlling phase and amplitude of the accelerating field 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 λ/2. The space saving can be significant. In the case of versions of SSTs to be discussed later, it is ~1.8 km. The first superstructure (SST-I), as 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 SST-I, but is shorter and its production, cleaning and handling will be easier. Savings in 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

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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 Higher Order Mode (HOM) suppression in both versions is very similar also and is based on HOM couplers of the same type used for standard 9-cell TTF cavities. The conclusion was that the beam test of existing 7-cells subunits assembled in two 2x7-cell prototypes would tell us more about the favorable SST-II super-structure, will benchmark our computation and will give finally twice as much statistics for the measured results. The 2x7 prototype is shown in Fig. 1.

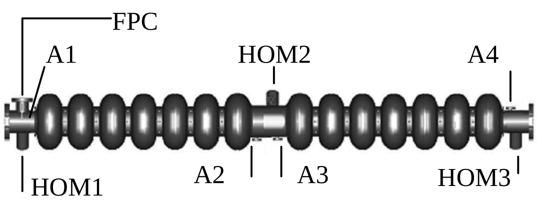

Figure 1: Prototype of 2x7-cell SST. Field probes:A1-A4. HOM couplers: HOM1-HOM3.

THE TEST

Balance of the Stored Energy in Subunits

The field profiles of the accelerating mode of both superstructures were measured by a bead-pull (perturbation) technique before the final chemical treatment and the final high pressure water rinsing. Both prototypes (P1, P2) had good field flatness, better than 92 % and 94 %, respectively (Fig.2). As usual, after final preparation and cool-down there is no further 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 test, the cold tuner of each subunit was moved by 1000, 2000 and 5000 steps and for each

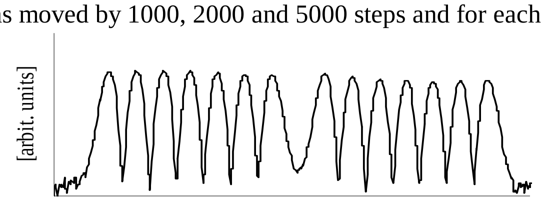

Figure 2a: P-1: Field flatness 92 % (peak-to-peak).

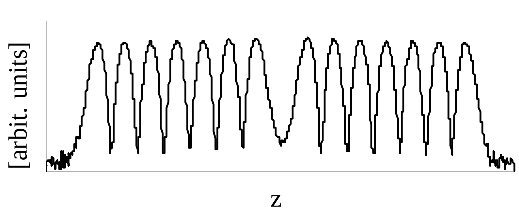

Figure 2b: P-2: Field flatness 94 % (peak-to-peak).

position the frequency change of the accelerating π-0 mode (π cell-to-cell phase advance and 0 subunit-to-subunit phase advance) was measured. Then, final positions of the tuners were chosen that maintained π-0 mode frequency exactly 1.3 GHz and simultaneously ensured that the change of that frequency is the same for the same movements of the tuners on the two subunits. 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 $8\cdot10^{-6}$ and we concluded that profiles remained unchanged after final preparation and after 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 the time between two consecutive bunches. The test was performed in two parts. In the first, 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. 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 installed BPM electronics. The rise time of e-m fields resulting from the matched Q_{load} value was 790 µs

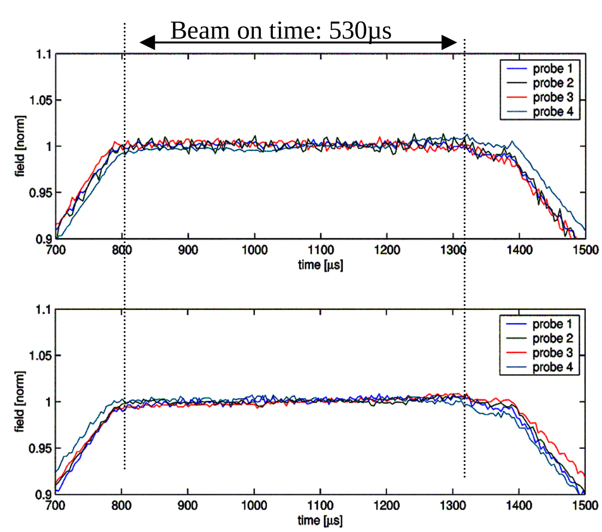

Figure 3: Signals from field probes (P1 upper diagram, P2 lower diagram) measured during the acceleration of 530 bunches, q = 4 nC, t_b = 1 µs at 15 MV/m.

and the longest beam on time was limited to 530 µs by the klystron pulse length. Each prototype was equipped with four field probes, one near each end-cell. They were used to monitor the field strength during acceleration. An example of measured signals is shown in Fig. 3. Without 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 some 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 amplitude of accelerating fields. We found, in the second part of the experiment, six more oscillations caused by the feedback loops. The Fourier transform of three signals (from the BPM behind the dipole), measured for three different gains in the feedback loop, is shown in Fig. 4. One can see in total 15 oscillations. Peaks No. 1, 2, 12 and 13

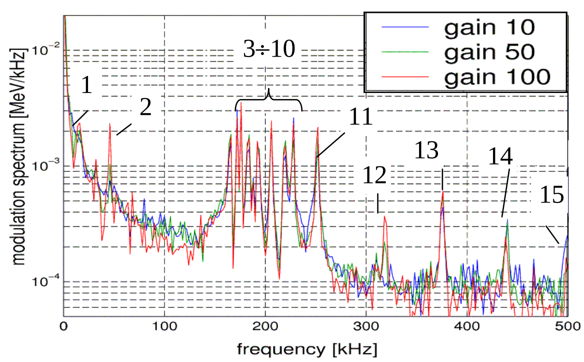

Figure 4: Spectrum of the energy modulation as measured at the end of the linac.

increased when the loop gain increased. Peaks No. 14 and 15 decreased with increased 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 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, 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 frequency and impedance, $Z = (R/Q)\cdot Q_{ext}$, of HOMs. 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 neighboring modes overlap.

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. Controlling the power coupled out by two others 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 cryomodule and the BPM. One can apply this method to modes that couple well to HOM couplers. Forty-seven modes were measured with the active method. An example of measured BPM signals is shown in Fig. 5a and 5b. In this particular case one polarization of the highest impedance dipole ($R/Q = 27\ \Omega/cm^2$) at f = 2573.971 MHz has been excited with 20 W forward power. The damping of this mode was very good. Its Q_{ext} was only $2.1\cdot10^4$ (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. 5a) 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), 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 amplifier was on (Fig. 5b). The mode has been tested six

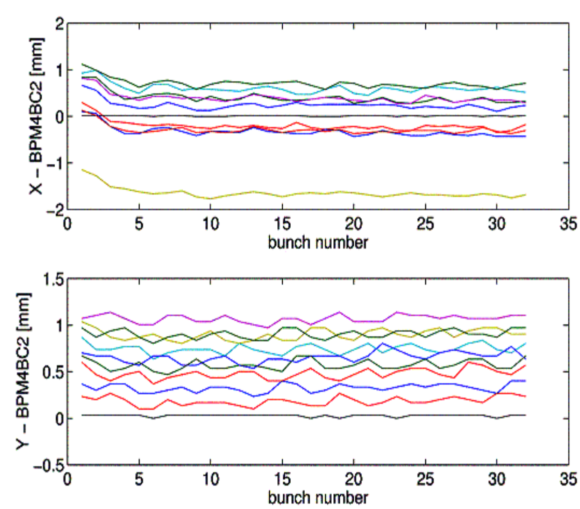

Figure 5a: BPM signals without the excitation of the deflecting dipole mode.

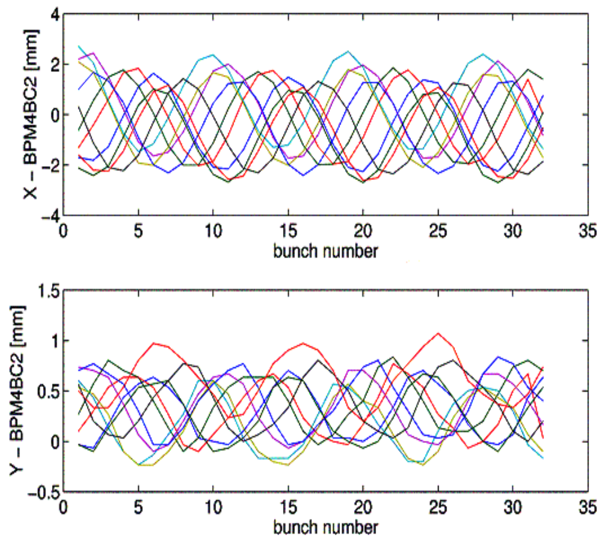

Figure 5b: BPM signals with the excitation of the deflecting dipole mode. Reader should note different scales for both signals in X-plane.

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.6. 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. The mean value of the measured deflections was <R> = 1.8 mm and its computed value was R_comp = 1.7 mm. The measured polarization is shown in Fig. 7. The mean value, which was found for the cold prototype, was 73°±10° (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 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 used 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 [8].

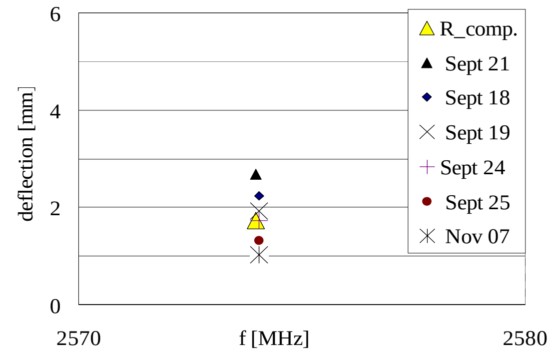

Figure 6: Deflection measured for the different optics setting.

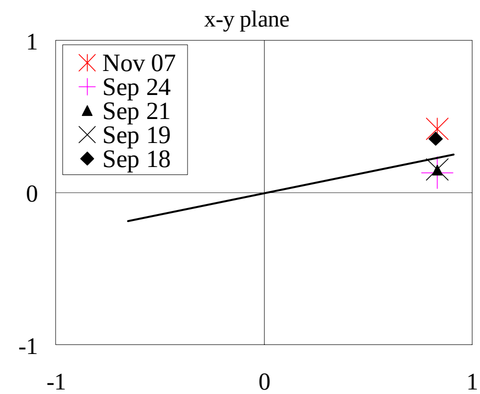

Figure 7: Normalized position of the deflected beam in the x-y-plane.

All three methods verified a very good damping of HOMs. The suppression of dipoles with (R/Q) > 1 Ω/cm^2 is shown in Fig. 8. All modes relevant 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 only few modes (in 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.

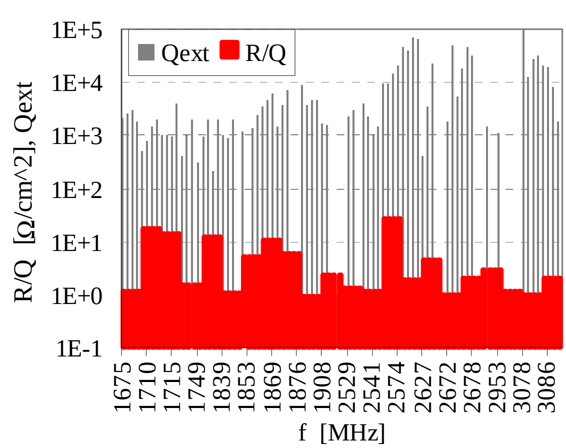

Figure 8: Damping of dipoles with (R/Q) ≥ 1 Ω/cm^2.

OTHER APPLICATIONS

Superconducting accelerating structures used in energy recovery accelerators should have good suppression of HOMs. Two beams, accelerated and decelerated, when passing these devices, may excite parasitic modes degrading the quality of both beams. This calls for structures with fewer cells when beam currents are in the range of 10-1000 mA. On the other hand, operation with energy recovery demands transfer of less RF power from external sources to an accelerated beam and thus one FPC can serve more cells. Both features, better damping and more cells per FPC are features of the superstructure concept. Accordingly, we propose two new superstructures for high current application [9, 10]. The first, 2x5-cells 1.5 GHz, was meant as a replacement for the standard 7-cell structures used in the 10 kW upgrade of the FEL laser at JLab. The idea was to utilize forty existing, spare CEBAF cavities to build these superstructures. MATHBBU [11] simulations showed that the beam instability threshold current, which was only 3 mA for the standard 7-cell cavities, increased to 103 mA with these superstructures. The superstructure is shown in Fig. 9. HOM damping, as measured on the copper model is displayed in Fig. 10.

The second superstructure, 2x2-cells, is proposed for future stage of the FEL upgrade at JLab, which would be operated with beam currents above 500 mA. Another possible application of this superstructures is electron cooling of ions in RHIC. The operating frequency of this

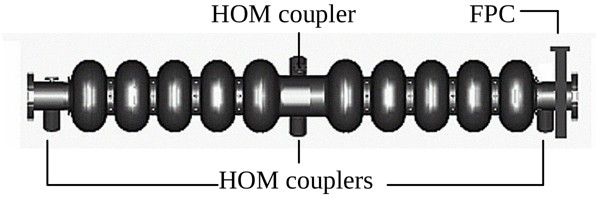

Figure 9: 2x5-cell SST equipped with four HOM couplers and only one FPC to feed 10 cells with RF-power.

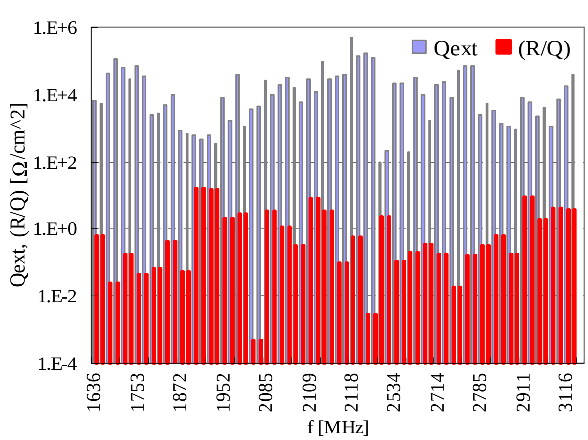

Figure 10: An example of the measured Q_{ext} of dipole modes. The (R/Q) values are shown to illustrate which mode is dangerous for the beam quality.

superstructure can be matched to 704 MHz (RHIC) or 750 MHz (JLab) by scaling dimensions. We have built a scaled copper model of this SST to study HOM damping. First results are reported in [10].

Finally, it seems to us that for big linear accelerators of 10-30 GeV beam energies driving CW operated XFELs with beam currents in the 1 mA range, one may use a 2x9-cell SST. This application is discussed in [12].

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