BUNCH-TO-BUNCH ENERGY STABILITY TEST OF THE NB PROTOTYPES OF THE TESLA SUPERSTRUCTURE

V. Ayvazyan, P. Castro, R. Kammering, H. Schlarb*, S. Schreiber, J. Sekutowicz, S. Simrock, M. Wendt, (DESY), M. Hüning (FNAL), M. Ferrario (INFN)

Abstract

Two 2x7-cell Nb superstructures have been tested with beam during the last TESLA Test Facility (TTF) linac run in summer 2002. The structures have been operated at 2 K in the standard TTF cryomodule and have been installed in the linac after the injector. We report on the bunch-to-bunch energy stability test which showed that energy stored in the superstructure could be refilled in the time between two passing bunches. The goal to keep the bunch-to-bunch energy stability below $5 \cdot 10^{-4}$ has been achieved.

INTRODUCTION

An alternative layout of the TESLA linear collider [1, 2, 3], is based on weakly coupled multi-cell superconducting structures, called the superstructures (SST). The weak coupling of 0.04% between the multi-cell structures, the subunits, is achieved by connecting the cavities with $\lambda/2$ tubes. This has two advantages: it reduces significantly the investment cost due to a simplification the RF system and secondly increases the filling factor of the main accelerator. The fundamental power coupler (FPC) supplying the entire chain of subunits with 1.3 GHz RF is mounted at one end of the SST. The energy flow through the superstructure is controlled by means of cold tuners allowing to balance the stored energy and thus the accelerating gradient in each subunit. Unlike a standard multi-cell cavity, the accelerating mode in a SST is the π-0 mode $-$ π cell-to-cell phase advance and 0 subunit-to-subunit phase advance $-$ which is below cut-off in the interconnecting tubes. This allows to attach higher order mode (HOM) couplers at the interconnection, in the middle of the multi-cell structure. In this way, good damping of parasitic modes can be maintained, avoiding extensive heating of the HOM couplers.

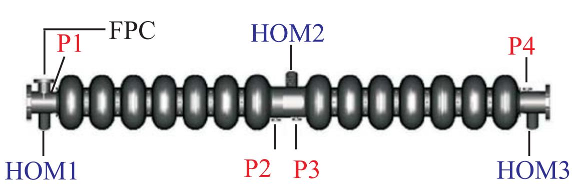

Figure 1: Scheme of a 2x7-cell Nb superstructures.

After several RF test on warm copper models of the superstructure [3] the next step was to study the performance of niobium SST's at 2 K with beam. In summer 2002, two 2x7-cell superstructures, sketched in Fig. 1, have been installed in the TESLA Test Facility linac to address the following questions:

- balancing the acceleration field in subunits,
- damping of the higher order modes,
- achievable energy stability of the electron beam.

In this paper, we adress the third item the refilling process in cavities with high beam loading. A detailed description of the mechanical layout, the cavity tuning, and the HOM damping in a superstructure can be found elsewhere [4, 5]. Numerical simulations of the transient state and the bunch-to-bunch energy spread predict that there is enough time to refill the cells energy before the next bunch arrives. The computed bunch-to-bunch energy deviation for a 2×7-cell and a 2×9-cell (preferred design in TESLA TDR) are shown in Fig. 2. For all bunches in the train the computed

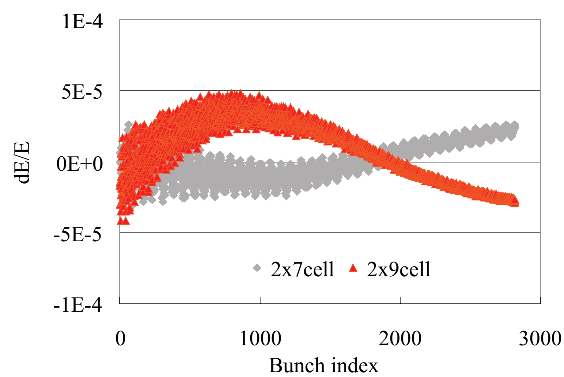

Figure 2: Computed energy deviation for the TESLA beam:2820 bunches, 3.2 nC/bunch, spacing 337 ns.

variation for both versions of the SST was very small, less than $\pm 5 \cdot 10^{-5}$. The difference in shape of the two curves is due to the different mode beating.

EXPERIMENTAL SETUP

The TTF photo injector is based on a normal conducting laser driven L-band RF gun and a single superconducting 9-cell cavity boosting the beam energy to 15.3 MeV. The beam is then accelerated by two acceleration modules. High resolution energy spectrometer are situated at the injector and the end of the linac (see Fig. 3). For this experiment, two 2×7-cell superstructures (SST-1 and SST-2) have been installed after the photo-injector. They have an active length of 3.26 m. Unfortunately, the second accleration module with eight standard 9-cell super-

* schlarb@desy.de

conducting cavities has been installed after the superstructures but before the spectrometer. For the energy stability measurements, the SST's have been operated at a gradient of 14.3 MV/m, while the cavities in the second cryomodule were detuned to reduce the their influence. This results in a total energy E_{tot} of 62 MeV at end of the linac. The bunch spacing was 1 μs to meet the highest possible data aquisition rate of the front-end electronics allowing to sample parameters for each bunch in a pulse train. Bunch charges of typically 4 nC (nominal 8 nC) and beam durations between 530 μs and 760 μs (nominal 800 μs) at 1 Hz repetition rate have been chosen to achieve the required operation stability for this experiment.

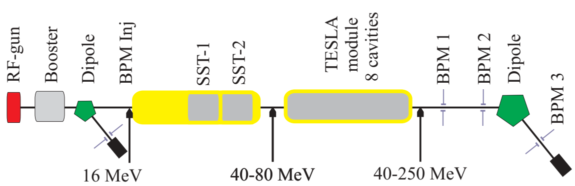

Figure 3: Scheme of TTF linac for the SST test.

MEASUREMENT OF FIELD PROBES

A flat energy distribution of the bunches in a macro-pulse train does not necessarily proof a proper refilling of the weakly coupled subunit. A reduced gradient in one sub-unit may have been compensated by overfilling the other. This would have been possible, since the low level RF system (LLRF) controlles the phase and amplitude of the vectors sum of all cavities and not of each cavity individually. Using the signals of all four field probe (P1-P4 in Fig. 1) the gradients can be monitored at the entrance and the exit celss of both cavities. An example recorded with 4 mA beam current and 530 μs pulse duration is shown in Fig. 4. Without the energy refilling the beam would take almost 70% of the energy stored in cells and the voltage would drop by 45%. No such phenomenon was observed. All probes show noise fluctuations mainly caused by the down-converters of

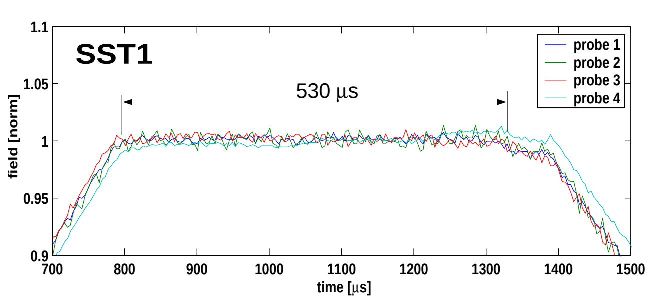

Figure 4: Signals from field probes P1-P4 measured during acceleration of 530 bunches (I = 4 mA, g =14.3 MV/m).

the LLRF-system (250 kHz oscillations).

BEAM ENERGY STABILITY

The TTF linac layout does not provide the possibility to measure the beam energy spread before and behind the SST simultanously. Therefore the energy stability of the beam exiting the injector had to be carefully studied. The goal was to measure bunch to bunch energy variations with a resolution well below 0.01%. It was also necessary to examine effects of the second acceleration module even through their cavities have been detuned.

Energy jitter from the photo-injector

Because the energy gain in the SST is set to be 47 MeV only, phase and amplitude jitter of the laser, the RF gun or the booster cavitiy might seriously spoil the energy measurement for the SST. After tuning the injector parameters properly, a beam energy spread of 0.09% during a time period of 30 min has been achieved. The bunch to bunch energy variation for 100 macro-pulses are plotted in Fig. 5. The energy $E_{i,m}$ of the i^{th} bunch in the m^{th} train can be

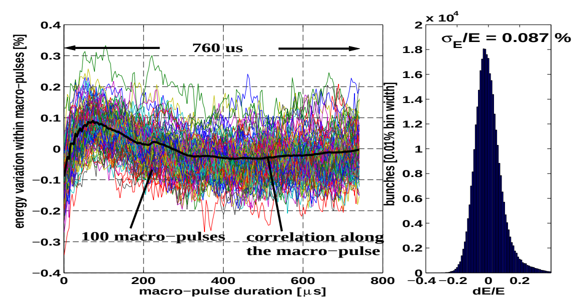

Figure 5: Left: Injector bunch-to-bunch energy variation of 100 macro-pulses (color curved). Right: Energy spread of for all bunches (E = 15.3 MeV).

decomposed as

$$E_{i,m} = E_{inj} + \Delta E_m + \Delta E_{corr,i} + \delta E_{i,m} \quad (1)$$

with E_{inj} the average energy of all bunches, ΔE_m the energy deviation of the m^{th} macro-pulse train, $\Delta E_{corr,i}$ the energy time correlation common in all macro-pulses (black curve in Fig. 5) and $\delta E_{i,m}$ a residual fast bunch-to-bunch energy jitter. Only the later contribution is critical for our purpose. The rms widths of $\delta E_{i,m}$ amounts to 6.7 keV (see Tab.1) and sets the lower limit on the σ_E/E_{tot} measurement at the end of the linac to $1.1 \cdot 10^{-4}$.

Accuracy of the energy measurement

The energy variation of the bunches is calculated by means of two strip-line BPMs upstream the spectrometer dipole to correct for the incoming orbit jitter (see Fig.3) and BPM3 located in the spectrometer line with large dispersion ($\eta_x = -1.48$ m). All BPMs have been calibrated by steering the transverse position of the beam in the BPMs with well known dipole corrector. The control software calculates online the energy of all bunches in the entire bunch train and compensates for the non-linear response of the BPMs for large beam offsets [8]. The accuracy of the BPMs has been determined to be 60 μm rms [9] resulting in a relative energy resolution of $\sigma_{E,res}/E_{tot} = 1.2 \cdot 10^{-4}$.

Influence of the second accleration module

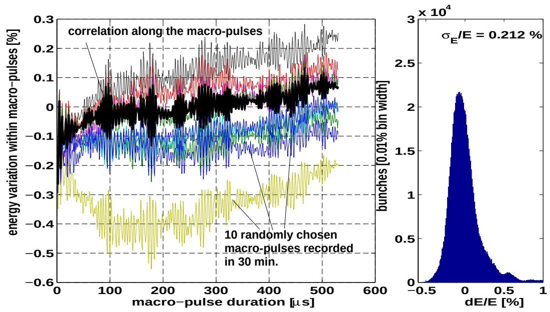

Figure 6: Energy deviation along a pulse train measured in the spectrometer ($I = 3.8$mA, $t = 530\mu$s).

Fig. 6 shows typical energy distributions of pulse trains recorded in 30 minutes. The overall energy spread of the beam amounts to 0.2%. The contributions split according to Eq. 1 are listed in Tab. 1. The dominating contribution of the energy spread comes from the macro-pulse to macro-pulse energy jitter. Unlike the smooth energy distribution observed in the injector, very fast oscillations are superimposed to slow low frequency drifts across the pulse trains. A careful analysis of the energy spectrum obtained by fourier, shown in Fig. 7, states that the largest part of the fast oscillations are induced by the eight detuned cavity. The resonance at 250 kHz is identified as an uncompleted removal of the down-converter noise perturbing the LLRF-regulation. A couple of other smaller resonances are related to the feedback gain of the LLRF feedback loop. Some of the resonances are strongly enhanced if high gains between 50 and 100 are adjusted. This increases the energy spread within the macro-pulse but reduce the energy jitter from pulse train to pulse train. The presented data are taken at a loop gain of 30 (small). If the influence of 2^{nd} acc. module is removed by using an approximation depicted by the dashed lines in Fig. 7, a relative rms energy spread within the 1800 macro-pulses of $4.2{\cdot}10^{-4}$ is calculated. If only 100 macro-pulses with the smallest drifts are taken into account one finds $2.2{\cdot}10^{-4}$ as the lowest achieved value for the intra macro-pulse energy deviation of the bunches.

Table 1: Contributions of energy spread at the injector (E_{inj} =15.3 MeV) and at the end of the linac (E_{tot} =61.5 MeV)

	$\sigma(\Delta E_m)$	$\sigma(\Delta E_{corr,i})$	$\sigma(\delta E_{m,i})$	σ_E
inj	10.1 keV	5.5 keV	6.7 keV	13.4 keV
tot	122.9 keV	32.9 keV	25.4 keV	130 keV

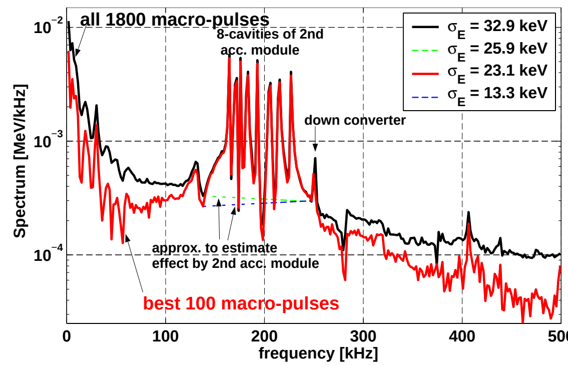

Figure 7: Spectrum of the energy modulation.

SUMMARY

In this experiment with 2×7-cell superstructures we achieved a bunch-to-bunch energy stability in macro-pulses of 0.064% for more than 30 minutes. Significant influences of the second acceleration module and the LLRF on the measurement have been found, while investigation on the incoming energy jitter from the injector states that these influences can be neglected. The upper limit for the bunch-to-bunch energy deviation caused by the cavities of the superstructures only has been estimated to be $\sigma_E/E = 2.2 \cdot 10^{-4}$, well below the TESLA specification of 0.05%.

REFERENCES

[1] "TESLA Technical Design Report, Part II: The Accelerator" , DESY 2001-011, Hamburg; March 2001.

[2] J. Sekutowicz et.al.,"Superconducting Superstructure" , Proc. of LC97, Zvenigorod, Sep. 29-Oct. 3, 1997.

[3] J. Sekutowicz et.al., "Superconducting superstructure for the TESLA collider; A concept", PR-ST A.B, 1999.

[4] J. Sekutowicz et.al., "Active HOMs Excitation in the First Prototype of Superstructure" , Proc. of PAC03, Portland, May 12- 16, 2003.

[5] P. Castro et.al., "Analysis of the HOM damping with Modulated Beam in the First Prototype Superstructure" , Proc. of PAC03, Portland, May 12-16, 2003.

[6] J. Sekutowicz et.al., "A Superstructure for High Current FEL Application" , Proc. of PAC03, Portland, May 12- 16, 2003.

[7] M. Ferrario et.al., "Multi-Bunch Energy Spread Induced by Beam Loading in a Standing Wave Structure" , Par. Accel., Vol. 52, 1996.

[8] N. Sturm,"Energie-Stabilisierung für den Freien Elektronlaser an der TESLA-Test-Anlage" Dipoma Thesis, DESY 2002, Hamburg.

[9] H. Schlarb,"Collimation System for a VUV Free-Eelectron Laser at the TESLA Test Facility", DESY-THESIS-2001-055.