BEAM BASED HOM ANALYSIS OF ACCELERATING STRUCTURES AT THE TESLA TEST FACILITY LINAC

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Abstract

The beam emittance in future linear accelerators for high energy physics and SASE-FEL applications depends highly on the field performance in the accelerating structures, i.e. the damping of higher order modes (HOM). Besides theoretical and laboratory analysis, a beam based analysis technique was established [1] at the TESLA Test Facility (TTF) linac. It uses a charge modulated beam of variable modulation frequency to excite dipole modes. This causes a modulation of the transverse beam displacement, which is observed at a downstream BPM and associated with a direct analysis of the modes at the HOM-couplers. A brief introduction of eigenmodes of a resonator and the concept of the wakepotential is given. Emphasis is put on beam instrumentation and signal analysis aspects, required for this beam based HOM measurement technique.

INTRODUCTION

Well controlled electron beam parameters are essential in future linear accelerators, like linear colliders for high energy physics or SASE-FEL driver linacs for applied science. The transport of very low emittance beams through the entire accelerator requires low transverse *wake-potentials* and therefore well damped *higher order modes* (HOM) in the accelerating structures. At the TESLA Test Facility (TTF) linac a series of beam based HOM measurement experiments has been performed [1, 2, 3]. Beam instrumentation, in terms of a broadband beam position monitor (BPM) and HOM-couplers, was used to characterize beam excited dipole modes of the accelerating structures.

An intensity modulated bunched beam was used, which causes tunable sideband at frequencies

$$f_{\text{side}} = n\, f_b \pm f_{\text{mod}} \qquad (1)$$

where f_b is the bunch repetition frequency, f_{mod} is the modulation frequency and n is an integer. Resonant modes are excited if $f_{\text{side}} = f_{\text{HOM}}$. A beam bump offsets the beam trajectory in the accelerating structure by an amount δx to ensure the excitation of dipole modes. Two measurements are required to find and analyze HOM's:

1. On a downstream located broadband BPM an automatic routine searches for beam excited dipole modes by analyzing it's transverse kick proportional to $(R/Q)\,\delta x$.
2. A measurement on the HOM-couplers of the accelerating structures is required to identify mode frequency and Q-value.

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HIGHER ORDER MODES

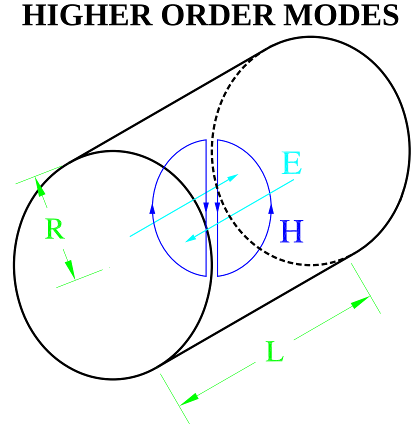

Figure 1: Cylindrical "pill-box" cavity, shown with the field lines of the TM_{110} dipole mode (horizontal polarized).

A cylindrical cavity ("pill-box" cavity) forms a simple single-cell accelerating structure (Fig. 1). By neglecting the vacuum chamber ports the resonant behavior in terms of the eigenmodes can be derived analytically, which results in a infinite number of eigenfrequencies at:

$$f_{npq}^{\text{TM(TE)}} = \frac{1}{2\pi R\sqrt{\epsilon\mu}} \sqrt{x_{np}^{(\prime)2} + \left(\frac{q\pi R}{L}\right)^2}$$

where x_{np} and x'_{np} are the zeros of the n$^{\text{th}}$-order Bessel-function respectively its derivative.

Each mode behaves equivalent to a parallel resonant circuit, driven by a current source. The fundamental TM_{010} mode is used for particle acceleration and driven by the rf-transmitter. All other *higher order modes* (HOM) are unwanted, but may be excited by the beam itself. Due to the finite conductivity of the cavity walls, power P_d is dissipated which limits Q-value of the resonances:

$$Q_0 = \frac{2\pi f_0 U}{P_d} = \frac{f_0}{\Delta f} \qquad R_0 = \frac{V^2}{2\,P_d}$$

(U: stored energy, V: voltage gain of a resonant mode)

Each deflecting mode is characterized by the quality factor Q_0 and the beam-coupling impedance $R_0 = 2\,R_{sh}$ (R_{sh}: shunt-impedance). The normalized impedance R/Q depends only on the cavity geometry, and can be evaluated in most cases by computer simulation. The eigenfrequencies f_0 and Q-factors are measured in the laboratory (network analyzer). The "strength" of the mode, i.e. its ability to kick off the bunch train in a linac at resonance, is then proportional to $R = (R/Q)\,Q$.

HOM effects can be reduced in several ways, like: Optimizing the cavity shape or absorbing HOM power (with special coupling antennas – so-called HOM-couplers – or through the vacuum chamber, which acts as a waveguide port).

Dipole modes, as well as all other higher modes, have a so-called polarization axis. In practice this axes orientates along imperfections, e.g. coupler ports, HOM-couplers, etc. This requires two HOM measurements with horizontal and vertical beam displacement, particular in our mulicell, multi-cavity configuration with all the exotic effects (trapped modes, propagation modes,...).

THE WAKEPOTENTIAL

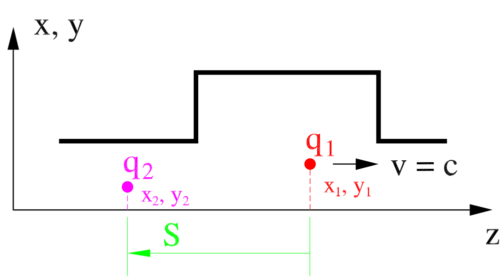

Figure 2: Wakefields are generated by q_1 and seen by q_2.

Consider a test charge q_2, which follows a point charge q_1 at a distance s and some displacement under relativistic conditions (see Fig. 2). Due to the discontinuities in the vacuum chamber, here a simple cavity, the electromagnetic fields of q_1 act on the test charge with the Lorenz force:

$$\mathbf{F} = \frac{d\,\mathbf{p}}{dt} = q_2(\mathbf{E} + c\,\mathbf{e_z} \times \mathbf{B})$$

The *wake potential* of the point charge q_1 is defined as:

$$\mathbf{W}(x_2, y_2, x_1, y_1, s) = \frac{1}{q_1}\int_0^L dz(\mathbf{E} + c\,\mathbf{e_z} \times \mathbf{B})_{t=(z+s)/c}$$

Transverse and longitudinal components of the wake potential are connected (*Panofsky-Wenzel* theorem). For beam emittance issues only transverse wakefields are of concern. In case of cylindrically symmetric structures a multipole expansion is made to describe the wake potential. The n-pole transverse wake potential is given by the sum of the eigenmodes of same kind of the structure:

$$W_\perp^{(n)}(s) = c\sum_i \left(\frac{R^{(n)}}{Q}\right)_i \sin(\frac{\omega_i\,s}{c})\,\exp(\frac{-\omega_i\,s}{2\,(Q_{ext})_i\,c})$$

Depending on the shape of the structure the damping time $\tau \approx 2\,Q_{ext}/\omega$ of the eigenmodes varies. In case of low damping *long range wakefields* can act over the bunch-to-bunch distance in a train of bunches. Due to the kicks of the dipole wakefields ($n = 1$) a cumulative beam-breakup instability (BBU) can be driven. Therefore the HOM measurement experiments are focused on the observation of dipole modes.

BEAM BASED HOM MEASUREMENTS

Experimental Setup

Fig. 3 shows the experimental setup for the beam based HOM measurements performed at TTF. The laser driven rf-gun was modified to generate bunches with 18.5 ns spacing ($f_b = 54$ MHz). The length of the macropulse was in the range 300...500 μs with a repetition rate of 1 Hz. A GPIB-controlled rf-source was used to modulate the intensity of the laser beam and therefore the charge of the electron bunches. The modulation frequency could be varied ($0.5 < f_{\mathrm{mod}} < 27$ MHz), the modulation depth was set to 80 %. For the excitation of dipole modes a "dog-leg" magnet was used to give the required displacement of the beam trajectory in the accelerating structures. *Device under test* (DUT) were different types of 1.3 GHz superconducting TESLA accelerating structures:

- 9-cell standard structures
- Pairs of weakly coupled 7-cell structures (so-called "superstructures")

Two kind of signals were used for the HOM measurements:

HOM signals delivered from the HOM-couplers of the accelerating structures are switched on a spectrum analyzer via a GPIB-controlled coaxial relais.

BPM signals delivered from a downstream, broadband BPM (re-entrant cavity type) are fed via a passive Δ-hybrid on another spectrum analyzer.

Measurement of the BPM signal

The deflection caused by a dipole mode is measured by analyzing the difference signal of a broadband, re-entrant cavity BPM. The bandwidth of the BPM and the passive Δ-hybrid is sufficient to resolve a single bunch position measurement in the 18.5 ns frame. For the analysis a external trigged spectrum analyzer was used in the zero-span mode as AM-receiver. The passband (center) frequency was set to 12×54 MHz $\pm f_{\mathrm{mod}}$, as the BPM offers the highest sensitivity around 650 MHz. The first part of the macropulse is intensity modulated, trying to excite a dipole mode; while

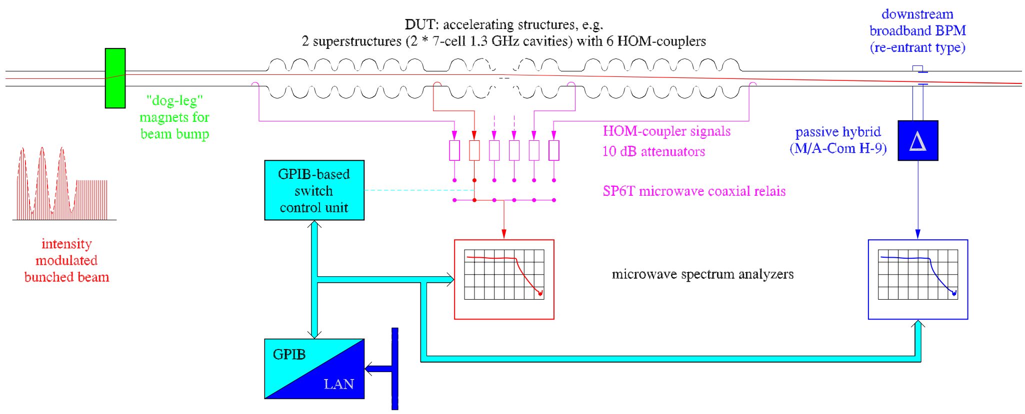

Figure 3: Experimental setup for the beam based HOM measurements at TTF.

the unmodulated second part was used to analyze it's decaying deflection effect sensitively in absence of a common mode beam signal ("pump-and-probe" technique).

Fig. 4 shows BPM signals of two different resonances, one with low, the other with high Q-value. By calibration of all related components (beam current and energy, DUT-to-BPM drift, BPM characteristic, etc.) the R/Q of the mode can be estimated. A fully automated search routine (*LabView*) scans f_{mod} in steps of 1 kHz by analyzing the second part of the BPM signal for HOM effects. Dipole modes can be distinguished from other mode types by testing for a linear response of the BPM deflection signal to a variation of the beam displacement in the accelerating structure.

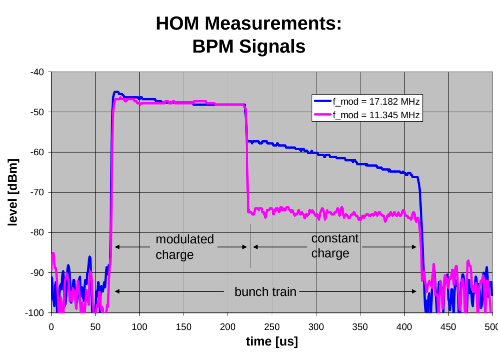

Figure 4: BPM signals at presence of higher order modes.

Measurement of the HOM signal

For each modulation frequency f_{mod}, where a HOM effect at the BPM was observed, the associated eigenfrequency of the mode f_{HOM} has to be determined. Therefore the complete macropulse is modulated with this frequency f_{mod}. Again the spectrum analyzer is used in zero span mode, but now scanned through the signals of the HOM-couplers of the accelerating structure. With a semi-automatic routine (*VEEPro*) center frequencies according to (1) are scanned ($n = 26 \ldots 54$ and both signs), by observation of the spectrum analyzer signal. The mode is identified, if the signal shows a decaying slope after the actual macropulse, i.e. the beam excited resonance continues to oscillate in the cavity (Fig. 5). The Q-value of the resonance is determined from the decay-time of the slope. It's physical location can be estimated by the HOM-coupler in which the signal appears. Detuning of individual cavities can give further details.

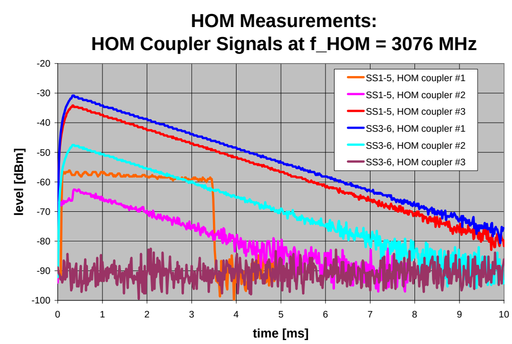

Figure 5: HOM-coupler signals of a high-Q mode.

CONCLUSIONS

This beam based HOM measurement technique led to the finding of unexpected, harmful dipole modes on TTF, which could not be forecast by computer simulations or network analyzer measurements in the laboratory. One consequence of these experiments is the modification of the HOM-coupler orientation in the TESLA accelerating structures. An interesting aspect for beam instrumentation is the use of HOM-couplers as beam monitor, which may result in new BPM's, located inside the accelerating structures.

REFERENCES

[1] S. Fartoukh, et.al., Proc. of the 1999 Particle Accelerator Conference, New York, U.S.A., pp.922-924.

[2] Ch. Magne, et.al., Proc. of the 2001 Particle Accelerator Conference, Chicago, U.S.A., pp.3771-3773.

[3] G. Devanz, et.al., Proc. of the 2002 European Particle Accelerator Conference, Paris, France, pp.230-232.