EVIDENCE FOR A STRONGLY COUPLED DIPOLE MODE WITH INSUFFICIENT DAMPING IN TTF FIRST ACCELERATING MODULE

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Abstract

A beam experiment has been conducted on the first accelerating module of the TESLA Test Facility (TTF) to investigate transverse higher order modes (HOM) in the superconducting cavities. By injecting the beam with a transverse offset and by modulating the intensity of the 216 MHz bunch train with a tunable frequency in the 0-108 MHz range, transverse HOMs can be excited resonantly. On a resonance the outgoing bunch orbits, measured with a broadband BPM, are transversely modulated at the same frequency. A dipole mode at about 2585 MHz, belonging to the third passband of the TESLA cavities, has been excited and observed in this way, with unexpected low damping in 2 out of the 8 cavities of the module.

1 AIM OF THE EXPERIMENT

The transport of very low emittance beams along the TESLA linac requires transverse higher order mode damping at a level defined in [1]. HOM couplers mounted on the beam tubes of the TESLA 9-cell superconducting cavities, have been designed to achieve damping with Q factors of the order of 10^4 to 10^5, depending on the mode coupling impedance, especially for the first two dipole passbands. Modes from higher passbands, supposedly above cutoff, are expected to propagate and therefore to couple efficiently to the HOM couplers except for few so-called "trapped" modes whose energy is concentrated in the central cells of the cavity. Of the experiments proposed at the TTF to verify with beam that the HOM damping is adequate and to detect unwanted trapped modes, the one reported here, described in [2], consists of excitation of higher order modes with the sidebands of the bunch train $f_b = 216$ MHz harmonics generated by modulation of the bunch charge with a variable frequency F in the range of 0 to 108 MHz. If the beam is injected off axis in the accelerating module, these sidebands build up in the Fourier transform of beam dipole moment and a resonant transverse instability can develop when one of the sidebands and one transverse HOM frequency coincide, i.e. $nf_b \pm F = f_{HOM}$. Hence, at the cavity exit, the transverse position of the beam is modulated at the frequency F with in phase and out of phase components.

A broadband BPM can be used to detect these oscillations.

2 EXPERIMENTAL SETUP

The first accelerating module of TTF includes eight 9-cell superconducting cavities at 1.3 GHz RF frequency. HOM couplers are located on both sides of each cavity to extract the power lost by the beam at high current. During the experiment, the thermoionic gun delivered up to 8 mA of beam current at a pulse duration of 600 µs with bunch frequency of 216.7 MHz. The additional experimental set-up includes the following devices:

- A tuneable voltage modulator at the cathode of the gun, providing the required charge modulation along the bunch train, with a modulation amplitude nearly up to 100 % of the nominal 37 pC bunch charge.
- A 'dog-leg' magnet (half a chicane) in front of the accelerating module providing a steady horizontal offset, in the range from 0 to 20 mm.
- A broadband cavity BPM [3] to measure individual positions of the bunches located about 10 m downstream of the accelerating module exit.

Entering the module, beam energy was about 9 MeV. The gradients of the eight cavities in the module were set to a minimum value of 2 MV/m in order to maximise the sensitivity of the beam to HOM deflections. With such energy settings and quadrupole magnets off, the BPM is at a focal point for parallel trajectories entering the module. This makes it easier to measure HOM kicks in the cavities.

3 OBSERVATION OF THE 2585 MHz HOM

As discussed in [2], all HOMs can be excited by sidebands of the beam harmonics, at frequencies $nf_b \pm F$, by scanning the charge modulation frequency F through half a Brillouin zone [0, f_b/2]. Dipole modes are in principle excited by injecting the beam off-axis in the cavities. By doing so, a beam instability was observed on the broadband BPM for $F = 15.022$ MHz with a short beam pulse of 35 µs and 5 mA current, and a large injection offset of about 20 mm. The beam pulse length could be increased to up to 500 µs while remaining on the HOM resonance. Fig.1 shows the comparison of the BPM envelope signals with charge modulation off or on for a 400 µs long beam pulse. With modulation off, the

broadband BPM integrates a high but constant 100 mV level of beam induced noise, although the beam is steered through its centre. This is due to the rejection of the *sum* signal into the *difference* signal BPM antennas. While the modulation is on, the beam offset reaches a maximum of about 10 mm but, due to the excessive noise no quantitative measurement could be made. A damped oscillatory behaviour of the envelope signal is visible in Fig.1 with a period of about 125 µs, on top of the constant envelope of the beam oscillations reached at the steady state. This behaviour was later explained, and reproduced by simulations, by the fact that the modulation frequency was off HOM-resonance by about 8 kHz (1/125 µs). The resonant oscillations then reach a steady state after some damped overshooting. Simulations predict that for a perfectly on-resonance excitation, the oscillations reach the aperture limit within the 35 µs short pulse: this agrees with the observed veto from the beam loss protection system occurring at every attempt to fine tune the modulation frequency towards lower values of *F*.
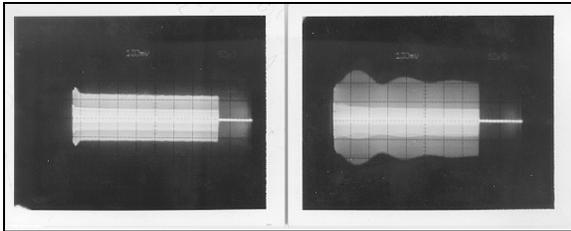

Figure 1: BPM signal on oscilloscope for 400 µs beam pulse without (left) and with (right) charge modulation

4 HOM RF CHARACTERISATION

The beam experiment revealed the existence of a HOM with a frequency $f_{HOM} = n\, f_b \pm (15.022 \text{ MHz} - 8 \text{ kHz})$ in the accelerating module. While detuning cavities #1 and #2 had no effect on the beam instability, detuning cavity #3 by about ±16 kHz in the fundamental mode did suppress the instability. It was then possible to measure and identify the mode at the HOM coupler outputs of cavity #3 (cavity S10 in Table 1) with a spectrum analyser. The frequency domain signal around the 12th beam harmonics at 2.6 GHz in Fig.2 shows a beam modulation side-band peak enhanced by the HOM resonance on the low side of this harmonics. The same signal, when analysed in time domain in Fig.3, shows the 35 µs beam-pulse cavity loading, followed by the relaxation of the field amplitude with a characteristic time $\tau = 110$ µs. The dipolar nature of the mode was demonstrated by checking the perfect linear dependance of the height of the amplitude maximum with the offset of the beam entering the module, over a range from 0 to 20 mm.

The resonant modes of cavity #3 were studied over a wider range of frequencies while the beam was turned off. As shown by Fig.4, the measured HOM is the highest frequency mode of the 3rd dipole passband. Its frequency is:

$$f_{HOM} = 2584.986 \text{ MHz} \pm 1 \text{ kHz}.$$

The damping factor is then given by :

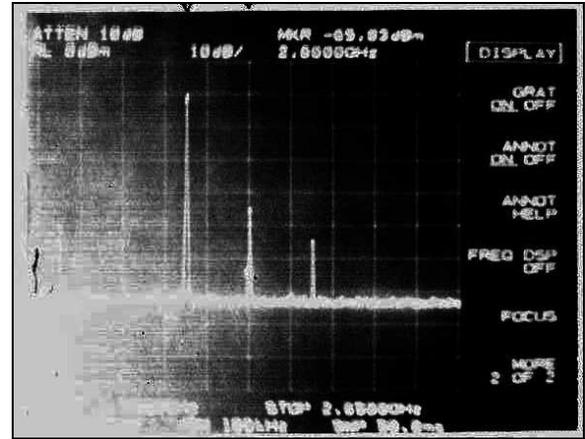$$Q = \frac{2\pi f_{HOM}\, W}{P_d} = \frac{2\pi f_{HOM}\, \tau}{2} \approx 9 \times 10^5$$
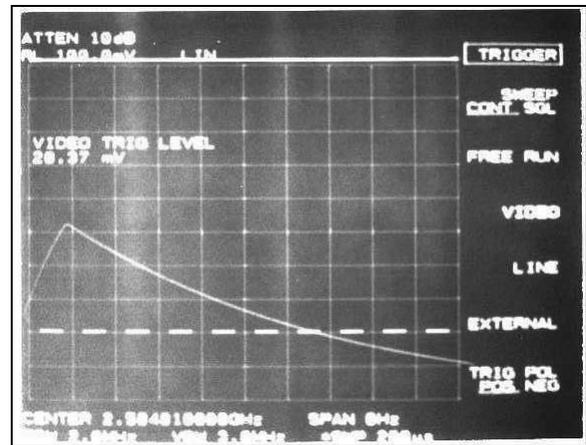

Fig.2 Sidebands around the 2.6 GHz beam harmonics

Fig.3 Time domain signal from HOM pickup on the 2585 MHz mode

An URMEL [4] calculation of the 3rd passband of the TESLA cavity was performed in parallel [5] showing that the highest frequency mode of this passband has indeed a large beam coupling impedance

$$\frac{1}{a^2}\left(\frac{R}{Q}\right) \approx 15 \ \Omega/\text{cm}^2.$$

It is foreseen to compare this prediction with a quantitative measurement of the beam displacement

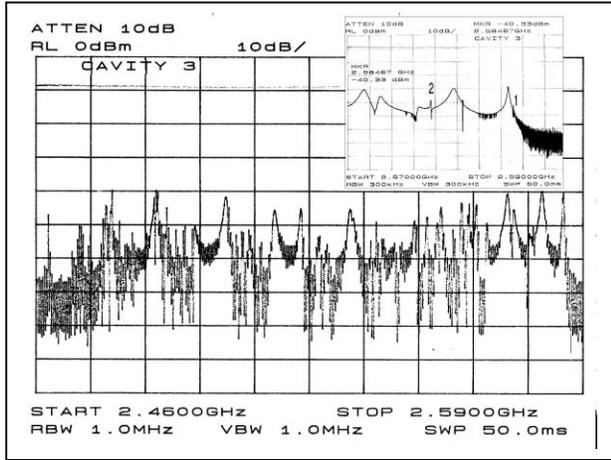using a BPM with an improved resolution in a future experiment.

Fig.4: Third dipole passband of cavity #3. The high frequency edge of this passband is zoomed, showing the 2585 MHz (1) and 2577.5 MHz (2) very sharp modes discussed in the text.

5   OTHER MEASURED MODES

Three other modes have been excited and observed with the intensity modulated beam. The HOM excitation signal, taken either from the HOM coupler outputs or from the BPM itself, was analysed with a spectrum analyser, like in the previous section.

- 2586 MHz mode in cavity #6: a close inspection of the last mode of third dipole passband of the eight cavities (cf. Table 1) showed, in cavity #6 (S11), the same excitation curve as the one shown in Fig.3 with a time decay constant of $\tau = 8$ μs. It corresponds to a quality factor $Q = 6.5\times10^4$. No measurable excitation could be observed in other cavities.
- 2577.5 MHz mode in cavity #3: this mode also belongs to the 3rd dipole passband, as can be seen in Fig.4. Its coupling impedance [5] is also large, about 9 Ω/cm^2. Its excitation curve gave $\tau = 22$ μs which corresponds to $Q = 1.8\times10^5$.
- 1876 MHz mode in cavity #3: this well-known TM110 mode of the first dipole passband has a high coupling impedance of about 9 Ω/cm^2. In cavity #3, and for one polarisation, it appears to be less efficiently damped than in the other cavities [6] with a measured $\tau = 20$ μs, corresponding to $Q = 1.2\times10^5$. This damping is at the limit of the TESLA tolerances [1].

Table 1: Cavities of TTF Module #1

Name	HOM coupler type	3rd dipole passband
D3	fixed	2458 – 2548 MHz
S8	dismountable	2458 – 2576 MHz
S10	dismountable	2471 – 2585 MHz
D1	fixed	2464 – 2562 MHz
D2	fixed	2462 – 2560 MHz
S11	dismountable	2480 – 2586 MHz
D4	fixed	2456 – 2556 MHz
S7	dismountable	2472 – 2576 MHz

6   CONCLUSION

A higher order 2585 MHz dipole mode has been observed and excited with beam with low damping, $Q = 9\times10^5$ in cavity #3 and $Q = 6.5\times10^4$ in cavity #6, in two out of eight cavities of the first TTF cryomodule. Identifying this mode with the highest mode of the third dipole passband leads to quite a high transverse coupling parameter $1/a^2 (R/Q_\perp) \cong 15$ Ω/cm^2. This is notably above the TESLA tolerance for the preservation of the vertical emittance in the linac. The origin of the insufficient damping of this mode and of its non-systematic character is not yet understood. A localised HOM coupler defect is of course one possibility. The large cavity-to-cavity spread in HOM frequencies, with highest and similar frequencies in cavities #3 and #6, may also be a clue. This observation is currently being completed by RF and beam measurements at the cold module. On the other hand, in order to complete the search of dangerous HOMs, it is foreseen to equip the new TTF photo-injector with a pockell-cell device which allows to modulate the charge of a 54 MHz bunch train.

7   REFERENCES

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[3] "High Resolution BPM for Future Colliders", C. Magne, M. Juillard, M. Lalot, A. Mosnier, B. Phung, Y. Lussignol and R. Bossart, LINAC98 Conf., Chicago, (1998)

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[5] We thank S. Chel for doing this calculation while the experiment was going on.

[6] G. Kreps, unpublished.