EXPERIMENTS ON HOM SPECTRUM MANIPULATION IN A 1.3 GHZ ILC SC CAVITY*

T. Khabiboulline, N. Solyak, V. Yakovlev, Batavia, IL 60510, U.S.A.

Abstract

Superconducting cavities with high operating Q will be installed in the Project-X, a superconducting linac, which is under development at Fermilab. Possibility of cavity design without HOM couplers considered. Rich spectrum of the beam and large number of cavities in ProjectX linac can result to resonance excitation of some high order modes with high shunt impedance. Under scope of study of High order modes damping the manipulation with HOM spectrum in cold linac is considered. Results of detuning HOM spectrum of 1.3 GHz cavities at 2K in Horizontal Test Station of Fermilab are presented. Possible explanation of the phenomena is discussed.

INTRODUCTION

Project X is a multi-MW proton source which is under development at Fermilab [1]. The facility is based on a 3 GeV CW linac [2]. The main portion of the H^- beam from the linac is directed to three different experiments. The linac schematic is shown in Figure 1. The superconducting part includes three sections based on 325 MHz single-spoke cavities and two sections of 650 MHz elliptical cavities having geometrical beta values of 0.61 and 0.9.

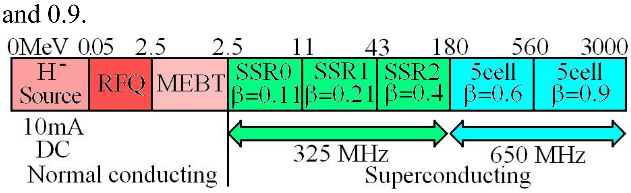

Figure 1: Configuration of the Project X CW Linac.

A superconducting cavity without special damping has very high Q for higher order modes (HOMs) trapped in the cavity. Beam stability can be affected by some of the modes in resonance conditions. On the other hand, integration of HOM dampers in the cavity design can reduce reliability. Table 1 summarizes the ≈200 superconducting cavities to be installed in the Project-X linac [2].

Table 1: Cavities for the Project X Linac

Section	No of C/CM	Max gain/cavity, MeV	Min. band-width, Hz	Max. loaded Q	Power per cavity, kW
SSR0	18/1	1.0	35	9.2e6	1.0
SSR1	20/2	2.2	36	9.1e6	2.2
SSR2	44/4	3.9	24	1.3e7	3.9
LE650	42/7	11.6	21	3.1e7	11.6
HE650	152/19	17.4	24	2.7e7	17.4

HOM couplers are an expensive and complicated part of SC acceleration structures. They can lead to additional problems like manufacturing complexity and multipactoring. They also need installation of the additional hardware – cables, feed-throughs, connectors, loads, etc.

The SNS SC linac experience shows that HOM couplers may cause cavity performance degradation during long-term operation. What the SNS linac experience doesn't show is the necessity of the HOM couplers; analysis of BBU in the SNS linac does not show a significant influence of the HOMs on the beam dynamics. But what if the HOM has a resonance frequency close to the frequency of a beam spectrum line? When is this serious and how serious is it?

Our goal is to understand the HOM influence on the beam dynamics in Project X in order to decide whether we need the HOM dampers in the high energy part of the linac and in the low energy part as well.

From another side, in the ILC HOM dampers are necessary. All 1.3 GHz ILC cavities are equipped by HOM couplers that work successfully in FLASH at DESY. HOMs have a frequency spread caused by manufacturing errors. For ILC cavities the R.M.S. spread of the resonance frequencies is 6-9 MHz depending on the pass band, according to DESY measurement statistics [3]. However, in a process of "technology improvement" R.M.S. frequency spread for HOMs reduced to 1 MHz. In the case of future upgrade Project X couplers may become necessary.

HOMS IN PROJECT X LINAC

Effects of the HOMs in the Project X linac include resonance excitation and collective effects.

Resonance Excitation, Monopole Modes

Monopole modes should not increase the beam longitudinal emittance. If ε is the initial longitudinal emittance ($\varepsilon = 1.6 \cdot 10^3\, nsec \cdot eV$), σ_t is the bunch length and U_{HOM} is the energy gain caused by the HOM, then it is necessary to have

$$U_{HOM}\sigma_t \ll \varepsilon.$$

Energy gain in *eV* can be written as

$$U_{HOM} = \sigma_{V_{HOM}} = \frac{1}{\sqrt{2}} \cdot \frac{f f_0}{(f^2 - f_0^2 - i\, f f_0/Q)} \cdot \frac{\tilde{I}}{2}\left(\frac{R}{Q}\right)$$
$$\approx \frac{1}{\sqrt{2}} \frac{f_0 \tilde{I}}{4\Delta f}\left(\frac{R}{Q}\right),$$

where f is the beam spectrum line frequency and f_0 is the HOM frequency; $\Delta f = f - f_0 \ll f_0 \approx f$ and $\Delta f / f_0 \gg 1/Q$.

*Work supported by the U.S. DOE
#khabibul@fnal.gov

Copyright © 2011 by PAC'11 OC/IEEE — cc Creative Commons Attribution 3.0 (CC BY 3.0)

The limitation on the difference between the HOM resonance frequency and the nearest beam spectrum line frequency Δf looks like

$$\Delta f \gg \frac{f_0 \tilde{I} \sigma_t}{4\sqrt{2}\varepsilon}\left(\frac{R}{Q}\right) = \delta f_\varepsilon,$$

and the probability to cause significant emittance growth can be estimated as

$$\wp = \frac{\delta f_\varepsilon}{\sqrt{2\pi}\sigma} e^{-\frac{\Delta f^2}{2\sigma^2}} = \frac{f_0 \tilde{I} \sigma_t}{8\sqrt{\pi}\sigma\varepsilon}\left(\frac{R}{Q}\right) e^{-\frac{\Delta f^2}{2\sigma^2}}.$$

assuming HOM frequencies are normally distributed. The worst case is in the beginning of the high-beta 650 MHz section, where σ_t=7.7e-3 nsec. For $\tilde{I}$=0.5 mA of beam spectrum line amplitude and *R/Q*=130 Ohms and HOM frequency 1241 MHz one has Δf >> 70 Hz. When the distance between the beam spectrum line and the resonance frequency is 5 MHz, and the frequency spread is also 5 MHz, the probability that the cavity has a resonant frequency close enough to the beam spectrum line is < 1e-5.

The gain caused by the HOM is <300 keV. This is small compared to the operating mode gain (~20 MeV) and does not contribute to the cryogenic losses (δP < 0.15 W). Monopole HOM mode excitation is considered in more detail in [4].

Resonance Excitation, Dipole Modes

Dipole modes should not increase the beam transverse emittance (normalized emittance is 2.5e-7 m). The transverse kick caused by the HOM is:

$$V_{kick} = \frac{c}{4\pi}\left(\frac{r_\parallel}{Q}\right)_1 \cdot \frac{x_0 \tilde{I}}{2\Delta f}.$$

where $\Delta f = f - f_0 \ll f_0 \approx f$ and $\Delta f / f_0 \gg 1/Q$; x_0 is a beam offset. The emittance dilution can be estimated as

$$\varepsilon = \beta\gamma\sigma_x\sigma_{x'}, \qquad \text{where } \sigma_{x'} = \frac{e\sigma_{V_{kick}}}{pc} = \frac{eV_{kick}}{\sqrt{2}pc},$$

since the HOM gives a kick for the bunch that is equal for all the particles inside the bunch (because $\sigma_z \ll \lambda_{HOM}$), but different for different bunches. Thus, this HOM does not increase the emittance of an individual bunch, but gives kicks in different phases for different bunches, increasing the total phase space occupied by the bunches. So taking into account $p = \beta\gamma mc$, the emittance dilution can be written as

$$\varepsilon = \frac{\beta_f}{\beta\gamma}\left(\frac{e x_0 \tilde{I}}{8\sqrt{2}\pi mc\Delta f}\left(\frac{r_\parallel}{Q}\right)_1\right)^2 \ll \varepsilon_{initial} = 2.5 \cdot 10^{-7}\ m \cdot rad.$$

where β_f is the beta function. It gives us a limitation on HOM frequency deviation from a beam spectrum line:

$$\Delta f \gg \frac{e x_0 \tilde{I}}{8\sqrt{2}\pi mc}\left(\frac{r_\parallel}{Q}\right)_1 \sqrt{\frac{\beta_f}{\beta\gamma\varepsilon_{initial}}} = \delta f_\varepsilon.$$

In the worst case for f_0=1376 MHz, $(r_\parallel/Q)_1$=60 kOhm/m^2, proton energy of 500 MeV, beta function 15 m, beam offset 1 mm, and $\tilde{I}$=0.5 mA, Δf>>2.5 Hz. This does not appear to be a problem.

Detuning of the Problem Mode

What can be done if the HOM has resonance frequency close to one of the frequencies of the beam spectrum line? Can we move it away? Even in the case when it happens, it is possible to move the HOM frequency away from the spectrum line simply by detuning the cavity by tens of kHz, and then tuning the operating mode back to the resonance.

HOM MEASUREMENTS IN HTS

S12 measurements were made with the 1.3 GHz, 9-cell ILC cavities at 2 K in the ILC HTS. A simplified schematic of the measurement setup is shown in Figure 2. The cavity is powered from the main coupler and HOM1. This connection allows one to properly measure both the operating (1.3 GHz) and HOM modes without rewiring. The network analyzer is connected to a PC and is controlled by LabView software.

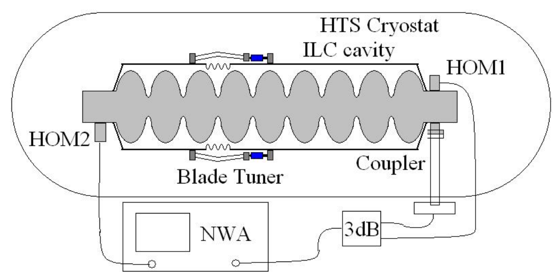

Figure 2: Measurement setup in ILC HTS.

We measure the transmission coefficient S12 in the frequency range from 1.27 GHz to 2.6 GHz and calculate resonance frequencies for several modes (Figure 3). Then the software starts precise measurements of resonant frequencies and Q factors.

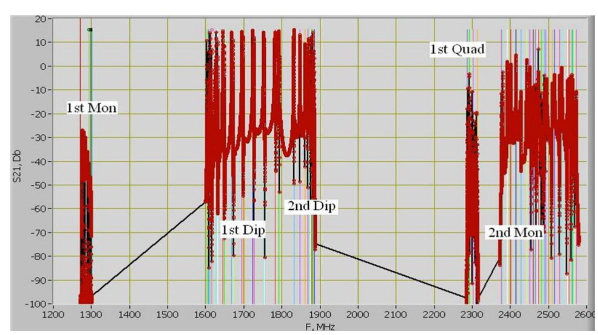

Figure 3: S12 measured on cavity TB9AES008.

At each position of the tuner several measurements are done for calculations of measurement error (Figure 4). After initial measurements #1-7, the operating frequency f_π of the cavity was detuned by -90 kHz (#8-9) and then tuned back (#10-14) to its initial value. Then the frequency f_π was increased by +90 kHz (#15-16) and then tuned back (#19-28). Although stretching an ILC cavity causes the operating mode frequency to increase, the frequencies of the HOMs can move in either direction. The blade tuner of the cavity allows one to tune the

Copyright © 2011 by PAC'11 OC/IEEE — cc Creative Commons Attribution 3.0 (CC BY 3.0)

operating frequency of the cavity by ±250 kHz. During these tests the cavity usually always stays stretched.

In another test the operating mode frequency f_π of the cavity TB9AES009 was detuned by Δf_d=+90 kHz and then was tuned back within an accuracy <20Hz. The frequencies of the HOMs moved after this procedure by δf_{HOM}=100-500 Hz because of small residual deformation of the cavity and/or the cavity helium vessel support (Table 2).

Tests with other cavities give similar results. A total of eight cavities were tested so far. The frequency shift of the HOMs is in the range 200-1000 Hz [5]. More significant distortion of the HOM modes spectrum happened when cavity TB9RI018 was warmed up to room temperature and cooled back down to 2K, Figure 5. Up to 8 kHz of HOM mode frequency shift was observed. The 2nd monopole pass band modes were shifted by 5-6 kHz.

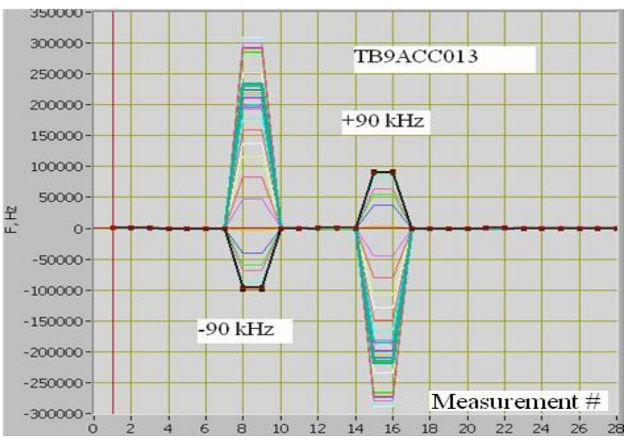

Figure 4: History of frequency spectrum change of the cavity TB9ACC013 during detuning and tuning back.

Table 2: Cavity TB9AES009 in HTS

f_{HOM}, MHz	Δf_d, kHz	δf_{HOM}, Hz	Pass-band	Q
1300	90	0	1Monopole	3e6
1600.09	-218	360	1Dipole	5.1e5
1604.53	-215	240	1Dipole	6.7e5
1621.34	-211	240	1Dipole	9.1e4
1625.45	-208	370	1Dipole	1.3e5
1830.83	-185	370	2Dipople	2.5e4
1859.88	-36	120	2Dipople	2.6e4
2298.80	-278	480	1Quadrupole	6.5e6
2299.34	-278	490	1Quadrupole	7.1e6
2372.33	-224	490	2Monopole	3.5e5
2377.33	-221	490	2Monopole	6.8e4
2399.28	-210	490	2Monopole	3.7e4

SUMMARY

- For the Project-X linac monopole HOMs are more dangerous. To avoid longitudinal emittance growth Δf >>70 Hz detuning is necessary. The probability that a cavity has a resonant frequency close enough to a beam spectrum line is <1e-5 per cavity.
- Increase of the beam transverse emittance caused by transverse HOMs does not appear to be a problem. Δf>>2 Hz detuning will usually arise from regular microphonics.
- Detuning the frequency of a HOM by several hundred Hz is possible without warming up the cavity. The cavity frequency tuner can be exercised in order to shift the frequency of the problem mode.
- HOM frequency detuning can be explained by a small residual deformation of the cavity and residual stresses on the cavity support system that cause a little bending of the cavity.
- Stretching of the cavity by the tuner at room temperature is possible if more detuning is necessary. Plastic deformation of the cavity can change the HOM frequency spectrum by several kHz without significant distortion of the accelerating field distribution.
- If it is decided that HOM couplers will be integrated into Project X cavities, damping to Q<1e7 is enough for complete HOM monopole modes damping even in the resonance case.

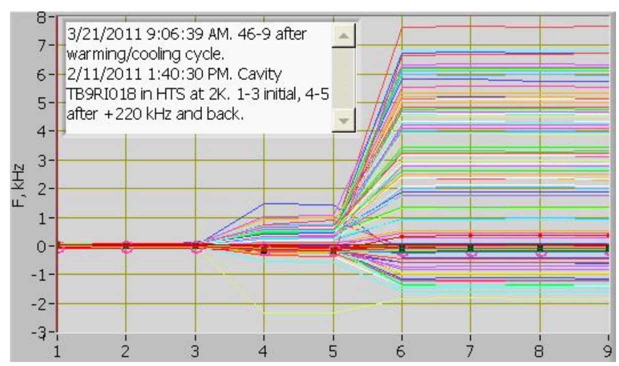

Figure 5: Frequency distortion of the cavity TB9RI018 after warming up and cooling down cycle.

REFERENCES

[1] S. Nagaitsev, "Project X – New Multi Megawatt Proton Source at Fermilab," this Conference, FROBN3.

[2] L.Ristory, et al, "Design of Single Spoke Resonators for Project X," this Conference, MOP145.

[3] J. Sekutowicz, HOM damping," ILC Workshop, KEK, November 13-15, 2004.

[4] V. Yakovlev, et al, "HOMs in the Project X Linac," This Conference, TUP088.

[5] T. Khabiboulline, et al, "Experiments on HOM Spectrum Manipulation In A 1.3 GHZ ILC SC Cavity," International Workshop on High order Mode Damping in Superconducting RF Cavities, Cornell University, October 11-13, 2010.

Copyright © 2011 by PAC'11 OC/IEEE — cc Creative Commons Attribution 3.0 (CC BY 3.0)