FERMILAB-CONF-11-078-TD

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 3 GeV CW linac [2]. The main portion of H– beam from the linac is directed to three different experiments. The linac schematic is shown on the Figure 1. 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 correspondingly.

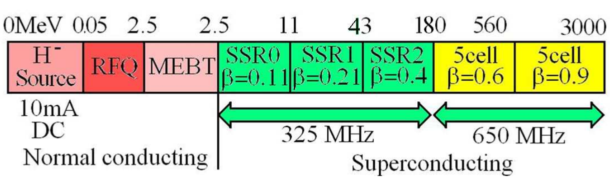

Figure 1: Configuration of the Project X CW Linac.

Superconducting cavity without special damping has very high Q for high order modes trapped between in the cavity. Beam stability can be affected by some of the modes in resonance conditions. In other hand integration of the HOM dampers in the cavity design can reduce reliability. Table 1 includes about 200 superconducting cavities will be installed in 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

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

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

SNS SC linac experience show that HOM couplers may cause cavity performance degradation during long - term operation. SNS linac experience doesn't show necessity of the HOM couplers; Analysis of the BBU in SNS linac does not show critical influence of the HOMs on the beam dynamics. But what to do if the HOM has resonance frequency close to frequency of the beam spectrum line amd when and how it is serious?

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 high energy part of the linac and in the low energy part as well.

From other side, in 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 frequency spread caused by manufacturing errors. For ILC cavity 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 initial longitudinal emittance ($\varepsilon = 1.6 \cdot 10^3\, nsec \cdot eV$), σ_t is bunch length and U_{HOM} is energy gain caused by HOM, then it is necessary to have

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

Energy gain in eV can be written like

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

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 $\Delta f / f_0 \gg 1/Q$.

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 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 5 MHz too, the probability that the cavity has the resonant frequency close enough to the beam spectrum line is < 1e-5.

The gain caused by the HOM is <300 keV that is small compared to the operating mode gain, ~20 MeV, and does not contribute to the cryogenic losses, δP < 0.15 W. In more details monopole HOM mode excitation is considered in [4].

Resonance excitation, dipole modes

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

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

if $\Delta f = f - f_0 \ll f_0 \approx f$ and $\Delta f / f_0 \gg 1/Q$; x_0 is a beam offset. 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 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 emittance of an individual bunch, but gives kicks in different phase for different bunches increasing total phase space occupied by the bunches. So taking into account $p = \beta\gamma mc$, emittance dilution can be written like

$$\varepsilon = \frac{\beta_f}{\beta\gamma}\left(\frac{ex_0\tilde{I}}{8\sqrt{2}\pi mc\Delta f}\left(\frac{r_\parallel}{Q}\right)_1\right)^2 \ll \varepsilon_{initial} = 2.5 \cdot 10^{-7}\ m \cdot rad.$$

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

$$\Delta f \gg \frac{ex_0\tilde{I}}{8\sqrt{2}\pi mc}\left(\frac{r_\parallel}{Q}\right)_1 \sqrt{\frac{\beta_f}{\beta\gamma\varepsilon_{initial}}} = \delta f_\varepsilon.$$

In the worth 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 look to be a problem.

Detuning of the problem mode

What to do if the HOM has resonance frequency close to one of the frequency 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 detuning the cavity by tens of kHz, and then tune the operating mode back to the resonance.

HOM MEASUREMENTS IN HTS

S21 measurements were made with the 1.3 GHz, 9-cell ILC cavities at 2 K in the ILC HTS. Simplified schematics of the measurements setup is shown in Figure 2. Cavity powered from main coupler and HOM1. This connection allows to measure properly both operating (1.3 GHz) and HOM modes without rewiring. Network Analyzer to PC and controlled by Labview software.

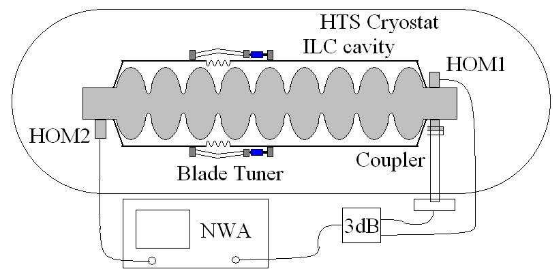

Figure 2: Measurement setup in ILC HTS.

We measure the transmission coefficient S21 in the frequency range of from 1.27 GHz to 2.6 GHz and calculate resonance frequencies several modes, Figure 3. Then software starts precise measurements of resonant frequencies and Q factors.

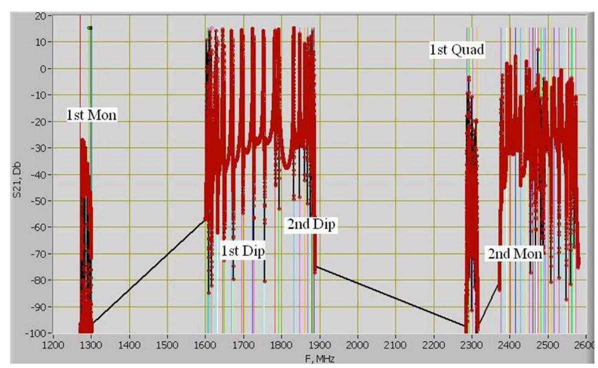

Figure 3: S21 measured on cavity TB9AES008.

At each position of the tuner several measurements done for calculations of measurement error, Figure 4. After initial measurements #1-7 operating frequency f_π of the cavity was detuned by -90 kHz (#8-9) and then tuned back (#10-14) to initial value. Then frequency f_π was increased by +90 kHz (#15-16) and then tuned back (#19-28). Although after stretching of ILC cavity operating mode frequency increase, frequency of the HOMs can move in both directions. Blade Tuner of the cavity allows to tune operating frequency of the cavity by ±300 kHz. During these tests cavity usually always stay 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 with the accuracy of <20Hz. The frequencies of HOMs moved after this procedure by δf_{HOM}=100-500 Hz because of small residual deformation of the cavity or/and cavity helium vessel support, Table 2.

Results of the tests with other different cavities give similar results. Total of eight cavities were tested so far. Frequency shift of HOMs is in the range of 200-1000 Hz [5]. More significant distortion of the HOM modes spectrum happened when cavity TB9RI018 was warmed up with opening doors of the cryostat and cooled down back to 2K, Figure 5. The cavity TB9RI018 was just warmed up and cooled down without any additional mechanical work on cavity. Up to 8 kHz of HOM mode frequency shift was observed. 2nd monopole pass band modes were shifted by 5-6 kHz.

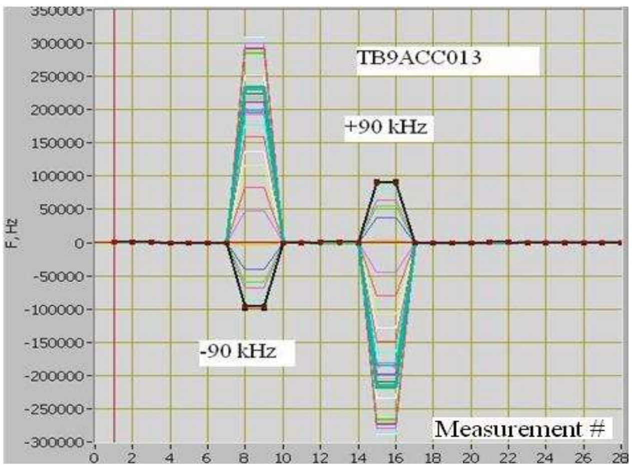

Figure 4: History of frequency spectrum change of the cavity TB9ACC013 during detuning and tuning back.

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

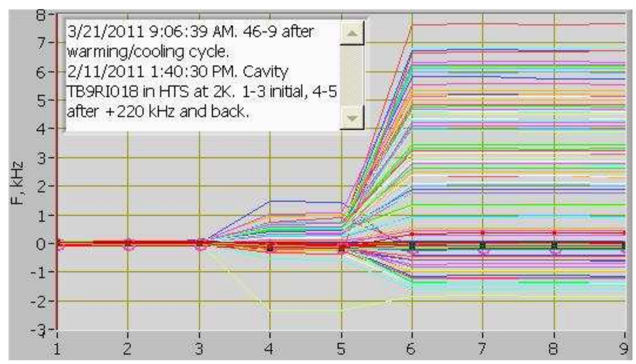

Figure 5: Frequency distortion of the cavity TB9RI018 after warming up and cooling down cycle.

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