STUDY OF HIGHER ORDER MODES IN THE PROJECT X LINAC*

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Abstract

High-order mode (HOM) influence on the beam longitudinal and transverse dynamics is considered for the 650 MHz section of the Project X linac. RF losses caused by HOMs are analyzed. Necessity of HOM dampers in the Superconducting (SC) cavities of the Linac is discussed.

INTRODUCTION

Project-X is a high intensity multi MW facility to be built at Fermilab [1]. The proposed facility is based on 3 GeV 1mA CW SC linac. The main portion of H^- beam from the linac is directed to three different experiments: Mu2e, Kaon and other. The linac is divided into two sections on the basis of operating frequencies i.e. 325 MHz and 650 MHz. The high energy section of the linac (160MeV- 3GeV) will be operated at 650 MHz frequency and it is composed of two families of 5-cell SC elliptical cavities which are designed for the geometrical beta (β_G) values of 0.61 and 0.90. In this work, these cavities have been investigated for trapped modes and dangerous HOMs. The linac of the Project X provides H^- beam with average current of 1 mA and has a special time structure in order to satisfy the requirements of the different experiments, which is shown in Fig. 1.

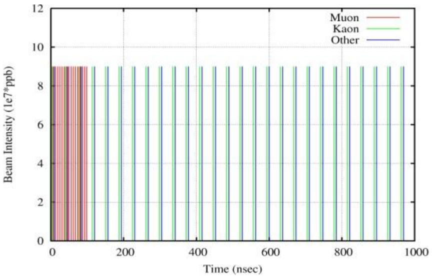

Figure 1: Time structure of the H^- beam. The bunches for Mu2e are shown in red, the bunches for Kaon experiments are shown in green, and for other experiments are shown in blue.

Each bunch contains $9 \cdot 10^7$ of H^- ions. The bunch sequence frequency for the Mu2e is 162.5 MHz (for the RFQ frequency of 325 MHz), the bunch train width is 100 nsec and the train repetition rate is 1 MHz. The bunch sequence frequency for Kaons and other experiment is 27.08 MHz. The beam power for Mu2e is 400 kW, and 800 kW for each other experiment. Thus, the beam current spectrum contains (i) harmonics of the bunch sequence frequency 27.08 MHz and (ii) sidebands of the harmonics of 162.5 MHz separated by 1 MHz.

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HOMs may play an important role in beam dynamics so it is necessary to investigate transverse (dipole) and longitudinal (monopole) mode spectrum of a RF cavity.

The effective impedance distribution for monopole each pass band of β_G=0.61 & β_G=0.90 cavities are shown in Fig. 2. The operating mode has highest effective impedance *(r/Q)* i.e. 378 Ohm & 638 Ohm for β_G=0.61 & β_G=0.90 cavities respectively. The most concerned HOM in longitudinal spectrum of β_G=0.90 has resonance frequency of 1241MHz with an effective impedance of 130 Ohm. Modes with resonant frequency of 1988 MHz & 2159 MHz also have effective impedance of ~10 Ohm. All HOMs in β_G=0.61 cavity have effective impedance below 10 Ohm.

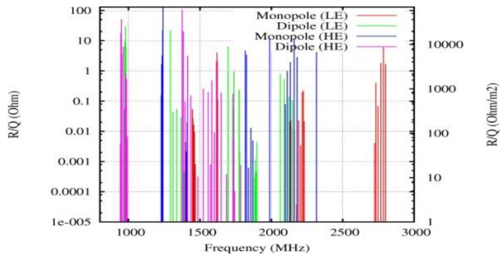

Figure 2: HOM spectrum for 650 MHz cavities. Monopole (red) and dipole (green) for β_G=0.61, monopole (blue) and dipole (pink) for β_G=0.9. Scale for the monopole modes is on the left (in Ohm), scale for the dipole modes is on the right (in Ohm/m^2).

The dipole mode spectrum is also shown in Fig.2 for both β_G=0.61 & β_G=0.9 cavities. There are three modes in β_G=0.61 cavities in dipole spectrum with frequencies 974 MHz, 978 MHz, 1293 MHz and four modes in β_G=0.9 cavities with frequencies 946.6 MHz, 950.3 MHz, 1376 MHz, 1383 MHz whose transverse impedance $(r/Q)_1$ are greater than 10^4 Ohm/m^2.

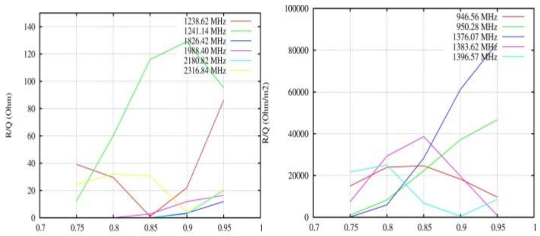

Figure 3: Monopole (left) and dipole (right) impedances of "the most dangerous" modes for β_G=0.9 cavity versus accelerated particle velocity.

Beta dependence of the dangerous longitudinal and transverse HOM modes for β_G=0.9 cavity is shown in Fig. 3.

Requirements for the quality factors of HOMs are determined (a) by possible resonance excitation of HOM, if its resonance frequency is close to the beam current harmonic or its sideband, and (b) by collective effects. There is also spread of HOM frequencies. For ILC-type cavities the r.m.s. frequency spread of the HOMs is in order of few MHz.

In the absence of the collective effects one of the cavities may have a dipole HOM frequency close to the beam spectrum line, and the cavity may be excited by the beam that may lead to emittance dilution. Dipole modes should not significantly increase the beam transverse emittance (ε=2.5.10^{-7} m). Transverse kick caused by the HOM is given by

$$U_{kick} = \frac{1}{4}\cdot\frac{f}{\delta f}\cdot\left(\frac{\lambda x_0}{2\pi}\right)\cdot I_0\left(\frac{r}{Q}\right)$$

where x_0 is the cavity transverse displacement, f and λ are the resonance frequency and wavelength of the HOM respectively, δf is the difference between the HOM frequency and spectrum line frequency ($\delta f/f >> 1/Q$), Q is its quality factor and I_0 is the average beam current. The resulting increase in emittance ($\delta\varepsilon$) is given by $\frac{U_{kick}}{pc\sqrt{2}}\sqrt{\varepsilon\beta_f}$,

where β_f is beta-function near the cavity, $p(=m\beta\gamma c)$ is the longitudinal momentum of the proton, and β and γ are relativistic factors. In order to ensure that $\delta\varepsilon << \varepsilon$, we get the following condition on δf:

$$\delta f >> \frac{x_0}{8\sqrt{2}\pi U_{kick}\, p}\cdot\left(\sqrt{\frac{\beta_f}{\varepsilon}}\right)\cdot I_0\left(\frac{r}{Q}\right)$$

If the emittance increase has the order of the initial emittance ($2.5\cdot10^{-7}$ m), then for f=1376 MHz, $(r/Q)_1$=60 kOhm/m^2 (worst case), I_0 = 0.5 mA, x_0=1 mm, we get δf >>1 Hz. Thus, dipole modes don't seem to pose any problem. If the HOM is in resonance then the Q-factor has to be less than $1.4\bullet10^9$.

Similarly, emittance dilution ($\delta\varepsilon_z = U_{HOM}.\sigma_t$) because of monopole modes should be smaller than the beam longitudinal emittance (ε_z=1.6.10^{3}eV-nsec), where U_{HOM} is average energy gain caused by HOM and σ_t is bunch length. For high-Q resonances, U_{HOM} is given by $\frac{I_0}{4\sqrt{2}}\left(\frac{r}{Q}\right)\cdot\frac{f}{\delta f}$, where δf is the difference between the HOM

frequency (f) and spectrum line frequency ($\delta f/f >> 1/Q$). To ensure that HOMs do not cause significant emittance growth, i.e. $\delta\varepsilon_z << \varepsilon_z$, we get the following condition:

$$\delta f >> f\sigma_t\cdot\frac{I_0}{4\sqrt{2}\varepsilon_z}\left(\frac{r}{Q}\right)$$

For the worst case, i.e. beginning of the high beta 650 MHz section, σ_t =7.7x10^{-3} nsec, I_0 = 0.5 mA, (r/Q) =130 Ohm (HOM with frequency of 1241 MHz), we get δf >>70 Hz. The gain caused by HOM is < 300 keV, which is much smaller than the operating mode gain of 20 MeV. This results in a very small power loss of 0.15W (Q_0 = $5\bullet10^9$) and hence does not contribute to the cryogenic losses. If the HOM is in resonance then the Q-factor has to be less than $1.8\bullet10^7$. HOM frequency has to differ ~70 Hz of the spectrum line in order to provide significant emittance dilution.

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 [3].

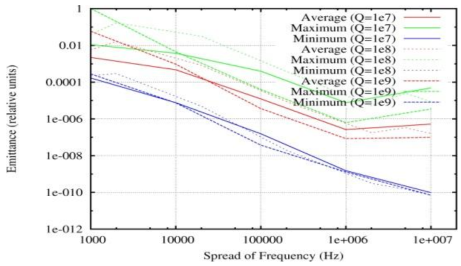

Figure 4: Emittance dilution caused by HOMs versus the cavity frequency spread. Red curve is the result averaged over 100 machines. Green curve is a maximal value, blue one is a minimal value. Solid line is for Q=10^7, dotted line is for Q=10^8, dashed line is for Q=10^9.

In order to estimate the collective effects, a simple model described in [2] was improved taking into account a realistic lattice. R.m.s. transverse cavity misalignments of 0.5 mm are distributed randomly. One dipole mode in each of the 650 MHz section was taken into account having maximal transverse impedance, mode with the frequency of 978 MHz and $(r/Q)_1$=20 kOhm/m^2 for the β_G=0.61 section, and mode with the frequency of 1376 MHz and $(r/Q)_1$=60 kOhm/m^2 for the β_G=0.90 section. Transverse emittance dilution caused by HOMs normalized to the initial emittance ($2.5\cdot10^{-7}$ m) versus the frequency spread is shown in Fig. 4. One can see that the emittance dilution caused by HOMs drops with the frequency spread (σ_f) as $1/\sigma_f^2$. For reasonable values of the frequency spread ~1 MHz the relative emittance dilution is below 10^{-4}.

CONCLUSION

Both families of 650 MHz cavities have been studied for HOMs. Trapped modes and dangerous HOMs are investigated. Q-factor requirement is formulated. Transverse and longitudinal effects of HOMs are small. Studies show that requirement of HOM damper is not necessary but as a precaution, it is proposed to keep space for the HOM damper in the cavity so that this fixture can be used to install the coupler with lattice.

REFERENCES

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