LONGITUDINAL AND TRANSVERSE EFFECTS OF HOMS IN THE PROJECT X LINAC*

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Abstract

Results of analysis are presented for the longitudinal and transverse effects of High-Order Mode (HOM) excitation in the acceleration RF system of the CW proton linac of the Project X facility. Necessity of HOM dampers in the SC cavities of the linac is discussed.

INTRODUCTION

The Project X, a multi-MW proton source, is under development at Fermilab [1]. The facility is based on 3 GeV CW linac [2]. 5–9% of the H^- beam is accelerated in a SRF pulse linac or RCS for injection to Recycler/Main Injector. The main portion of H^- beam from the linac is directed to three different experiments: Mu2e, Kaon and other. The linac schematic is shown in Figure 1. It includes (i) ion source, (ii) RFQ operating at 325 MHz, (iii) medium energy beam transport (MEBT), (iv) three sections based on 325 MHz Single-Spoke Resonators (SSR), two sections of 650 MHz elliptical cavities having betas of 0.61 and 0.9 respectively [3], and (v) final section of 1.3 GHz ILC-type cavities.

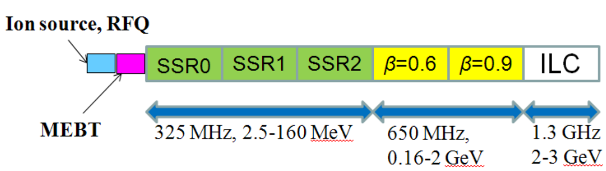

Figure 1: 3 GeV CW Project X linac schematic.

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 experiments.

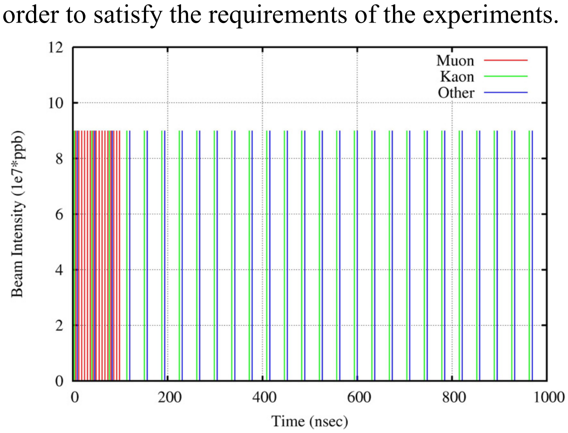

Figure 2: Time structure of the H^- beam. The bunches for Mu2e are shown in blue the bunches for Kaon experiments are shown in red, and for other experiments are shown in green.

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Each bunch contains $9 \cdot 10^7$ of H^-. The bunch sequence frequency for the Mu2e is 162.5 MHz (for the RFQ frequency of 325 MHz) and the bunch train width is 100 nsec when the train repetition rate is 1 MHz. The bunch sequence 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, see Figure 3, where the spectrum is shown.

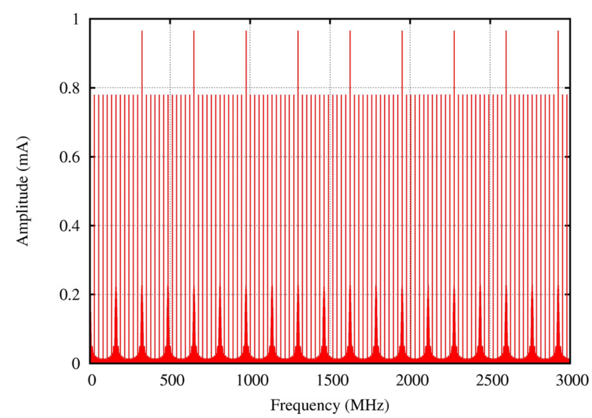

Figure 3: The idealized beam spectrum.

The ILC-type 1.3 GHz cavities contain HOM couplers that reduce the loaded Q-factors for transverse and longitudinal HOMs down to 10^5. The 5-cell 650 MHz cavities (see Figure 4) are under development and it is necessary to formulate requirements for Qs of HOMs for these cavities.

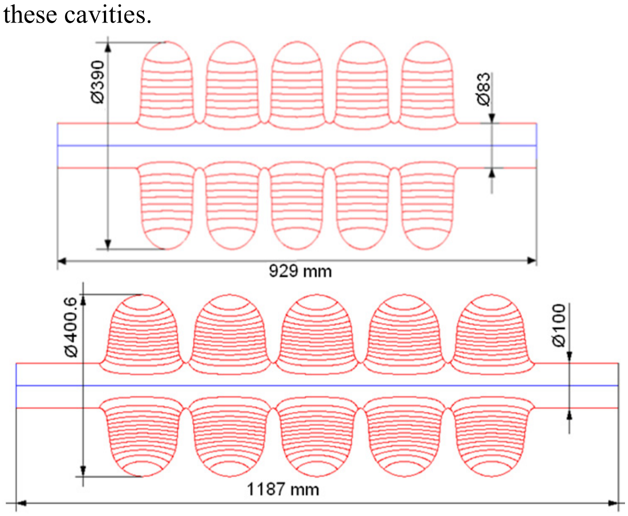

Figure 4: Layout of 650 MHz cavities. Beta=0.61 (top) and beta=0.9 (bottom).

GENERAL

Requirements for quality factors of HOMs are determined by possible resonance excitation of HOM, if its resonance frequency is close to the beam current harmonic or its sideband, and by collective effects. Beta=0.61 section contains 7 cryomodules having 6 cavities each, and beta=0.9 section contains 12 cryomodules having 8 cavities each [3]. R.m.s transverse misalignment of the cavities is about 0.5 mm. Spectrum of the dipole and monopole modes of the 650 MHz cavities for design velocities of beta=0.61 and beta=0.9 is shown in Figure 5. One can see that HOM impedance *(r/Q)* for monopole modes reaches ~130 Ohm, and $(r/Q)_1$ for dipole modes reaches 60 kOhm/m^2 in beta=0.9 cavities. For beta=0.61 they reach 7 Ohm and 20 kOhm/m^2 respectively. Note that the impedance of the cavities depends on the particle velocity that reduces the probability of the beam break-up (BBU) and longitudinal collective "klystron-type" instability [4]. This dependence is shown in Figure 6 for monopole and dipole modes in beta=0.9 cavity. There is also spread of HOM frequencies. For ILC-type cavities the r.m.s. frequency spread of the HOMs is more than 6–9 MHz [5].

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. Maximal emittance increase caused by the cavity excitation may be estimated as

$$\varepsilon_{max} \approx \frac{\beta_f}{\beta\gamma}\left(\frac{ex_0 I_0}{4\pi f_0 mc}\left(\frac{r}{Q}\right)_1\right)^2 Q^2,$$

where β_f is beta-function near the cavity, β and γ are relativistic factors, x_0 is the cavity transverse displacement, $(r/Q)_1$ is transverse impedance in Ohm/m^2, f_0 is the resonance frequency of the HOM, Q is its quality factor, I_0 is the average beam current.

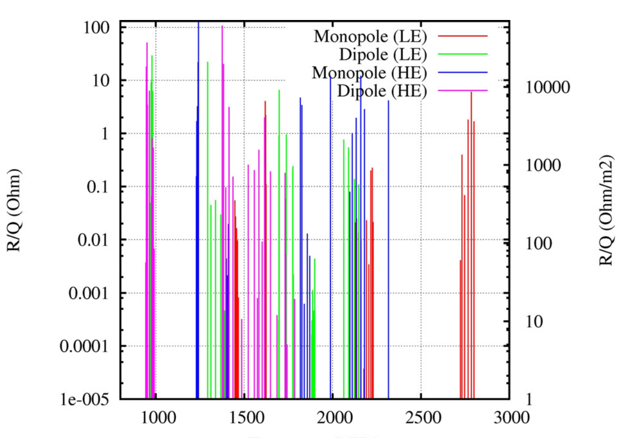

Figure 5: HOM spectrum for 650 MHz cavities. Monopole (red) and dipole (green) for beta = 0.61, monopole (blue) and dipole (pink) for beta=0.9. Scale for the monopole modes is on the left (in Ohm), scale for the dipole modes is on the right (in Ohm/m^2).

The emittance increase reaches a maximum determined by the formula above when the resonanse frequency differs of the beam spectrum line frequency by ~ f_0/Q. If the realtive difference between the HOM frequency and spectrum line frequency df/f>>1/Q, emittance dilution will be $(Qdf/f)^2$ times smaller. If the emitannce increase has the order of the initial emittance (2.5·10^{-7} m), the Q-factor has to be $1.3 \cdot 10^8$ for f_0=1376 MHz, $(r/Q)_1$=60 kOhm/m^2 (worst case) and x_0=1 mm. The frequency of the HOM should differ of the spectrum line frequency by ~10 Hz, that is compatible to the amplitude of microphonics. Needless to say that the probability of this situation is small.

The maximal voltage V induced by the beam for a monopole HOM should be much less than the energy gain per cavity:

$$V \approx I_0\left(\frac{r}{Q}\right)\frac{2f}{df} \ll V_0,$$

df is the deference between the HOM frequency and spectrum line frequency (df/f>>1/Q). If V_0 is ~20 MeV, and (r/Q) =130 Ohm (worst case, see Fig. 5), $2f/df$<<10^8. HOM frequency has to differ ~8 Hz only of the spectrum line in order to provide significant induced HOM voltage.

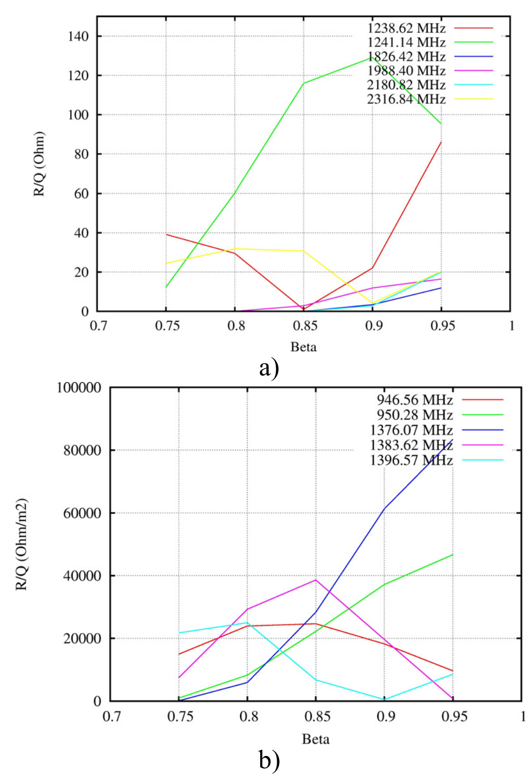

Figure 6: Monopole (a) and dipole (b) impedances of " the most dangerous" modes for beta = 0.9 cavity versus accelerated particle velocity.

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. A special test was made with the 1.3 GHz, 9-cell ILC cavity. The operating mode was detuned by ΔF=90 kHz, see Table 1, and then was tuned back. The frequencies of HOMs moved after this procedure by δF>100 Hz because of small inelastic deformation of the cavity.

Table 1: HOM Frequencies Shift after the Cavity Detuning, and after the Cavity Tuning Back

F, MHz	ΔF, kHz	δF, Hz	Passband
1300	90	0	1Monopole
1600.093	-218	360	1Dipole
1604.536	-215	240	1Dipole
1607.951	-214	360	1Dipole
1612.189	-210	360	1Dipole
1621.344	-211	240	1Dipole
1625.458	-208	370	1Dipole
1830.836	-185	370	2Dipople
1859.882	-36	120	2Dipople
2298.807	-278	480	1Quadrupole
2299.346	-278	490	1Quadrupole
2372.333	-224	490	2Monopole
2377.333	-221	490	2Monopole
2383.575	-213	240	2Monopole
2399.289	-210	490	2Monopole

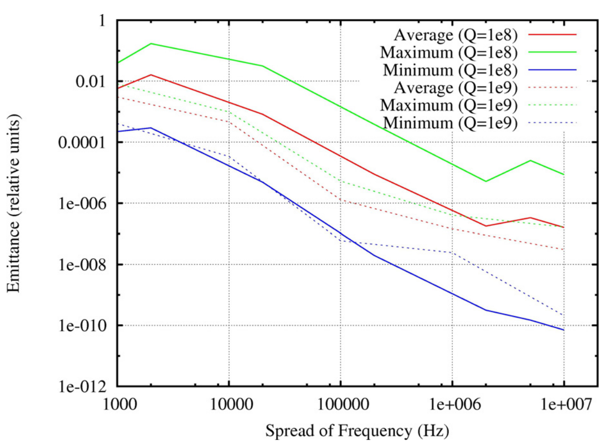

Figure 7: Emittance dilution caused by HOMs over the initial emittance versus the cavity frequency spread. Red curve is the result averaged over 100 machines. Green curve is a maximal value, blue one is a minimal value over all the machines. Solid line is for $Q=10^8$, dashed line is for $Q=10^9$. Time of simulation for each case was equal to three time constants: 120 msec for $Q=10^8$, 900 msec for $Q=10^9$. Results do not depend on Q for large values of Q.

In order to estimate the collective effects, a simple model described in [6] was improved taking into account a realistic lattice. Transverse cavity misalignments are distributed randomly. The cavities have random frequency spread that is essential for BBU. The bunch having the time structure (Figure 2) excites the cavity chain one by one. The beam dynamics were simulated for two 650 MHz sections with beta=0.61 and beta=0.9. One dipole mode in each section was taking into account having maximal transverse impedance, mode with the frequency of 978 MHz and $(r/Q)_l$=20 kOhm/m^2 for the beta=0.61 section, and mode with the frequency of 1376 MHz and $(r/Q)_l$=60 kOhm/m^2 for the beta=0.9 section. Impedance change with the particle velocity was not taken into account. R.m.s. transverse cavity displacement is 0.5 mm. Transverse emittance dilution cause by HOMs normalized to the initial emittance ($2.5\cdot10^{-7}$ m) versus the frequency spread is shown in Figure 7 for $Q=10^8$ and $Q=10^9$. 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}.

DISCUSSION

Results of the estimations of the emittance dilution caused by the accidental resonance excitation of one of the cavities and simulations of the BBU show that even for $Q=10^8$–10^9 the effect HOMs on the transverse beam dynamics is small enough. It is shown that the accidental resonance excitation may be eliminated by simple detuning of the operating mode by ~100 kHz and tuning it back. It may allow to get rid of the HOM dampers for the cavities in both 650 MHz sections. HOM dampers are an expensive and complicated part of SC acceleration structure that create different problems – multipactoring; leak of the operating modes, etc. HOM dampers require additional hardware – cables, feedthrough, connectors, loads, etc. Experience of existing proton SC linac, SNS, shows that HOM dampers may cause cavity performance degradation during long-term operation [7]. For another hand, SNS linac experience doesn't show necessity of the HOM couplers.

Impedance dependence on the proton velocity, spread of the resonance frequencies of HOMS of the cavities and their fluctuation caused by microphonics (that may exist even when the frequency of the operating mode is stabilized by the tuner) and possibility to detune the HOM frequencies by the operating mode tuning-detuning may allow get rid of the HOM dampers in the 650 MHz sections of the CW linac of the Project X.

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