

COHERENT EFFECTS OF HIGH CURRENT BEAM IN PROJECT-X LINAC

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Abstract

Resonance excitation of longitudinal high order modes in superconducting RF structures of Project-X continuous wave linac is studied. We analyze regimes of operation of the linac with high beam current, which can be used to provide an intense muon source for the future Neutrino Factory or Muon Collider, and also important for the Accelerator-Driven Subcritical systems. We calculate power loss and associated heat load to the cryogenic system. Longitudinal emittance growth is estimated. We consider an alternative design of the elliptical cavity for the high energy part of the linac, which is more suitable for high current operation.

INTRODUCTION

A multi-megawatt proton source, Project-X (PX) is now under development at Fermilab [1]. PX will provide high quality muon, kaon and neutrino beam, unavailable at existing facilities, and support physics program at the intensity frontier. Eventually, PX may become a driver for a future Neutrino Factory and/or Muon Collider at Fermilab.

Technology, which is being developed for Project-X, may be directly applied to Accelerator-Driven Subcritical systems (ADS) for energy generation and transmutation of nuclear waste [2]. ADS applications require continuous wave (CW) multi-MW proton beam with high average current and high availability. Thus, exploration of the capability of PX technology to deliver beam of ≥ 10 mA is important.

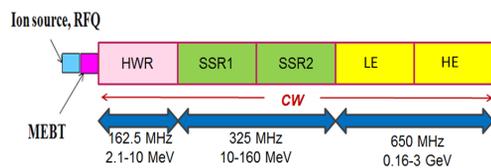


Figure 1: Project-X linac layout.

A key component of Project-X is the CW superconducting RF linear accelerator. It accelerates bunches of H^- ions from 2.1 MeV to 3 GeV. Layout of the linac is shown in Fig. 1. The high energy (HE) section of the linac uses 650 MHz 5-cell elliptical cavities. Coherent excitation of monopole high order modes (HOMs) in these cavities may affect stable operation of the linac due to rise of cryogenic losses and deterioration of beam quality. Our study [3]

shows, that it is not a problem for the present PX parameters, CW regime, and 1 mA average beam current. However, HE cavities have a potential problem, when monopole HOMs of the 5th passband may become trapped in the internal cells of a cavity [4]. This, together with the fact that cryogenic losses increase as square of an average beam current, $P_{loss} \sim I_{beam}^2$, may lead to losses up to hundred Watt for 10 mA beam.

In this paper we calculate cryogenic heat load and estimate growth of the longitudinal beam emittance due to coherent excitation of monopole HOMs during operation of PX CW linac with an average beam current up to 10 mA. We compare results of these calculations for the present and alternative [4] designs of the HE elliptical cavities.

COHERENT HOM EXCITATION

A bunched continuous beam passing through a superconducting cavity may coherently excite one of the cavity HOM with a high quality factor, Q . The bunch sequence frequency in PX linac is 162.5 MHz. A broad-band chopper provides the beam structure needed for experiments. A typical bunch timing structure required for muon, kaon and nuclear experiments running in parallel at 3 GeV is shown in Fig. 2. Average beam current in this mode is 1 mA. Fig. 3 shows the spectrum for the idealized 3 GeV beam structure, assuming very short bunches of equal charge and in the absence of timing jitter.

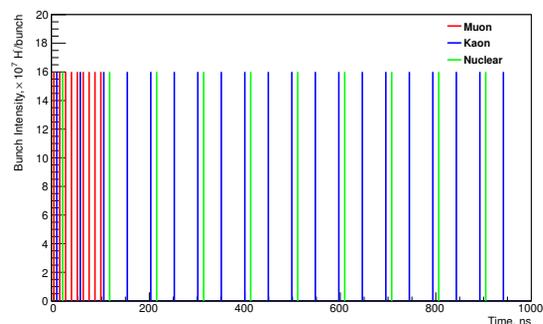


Figure 2: Beam structure for 3 GeV program.

Spectrum and (R/Q) values of PX HE structure are shown in Fig. 4. Amplitude of an excited monopole HOM depends on the amplitude of the nearest beam spectrum line, \tilde{I} , and detuning δf , the distance between the HOM frequency f and the beam spectrum line frequency, and

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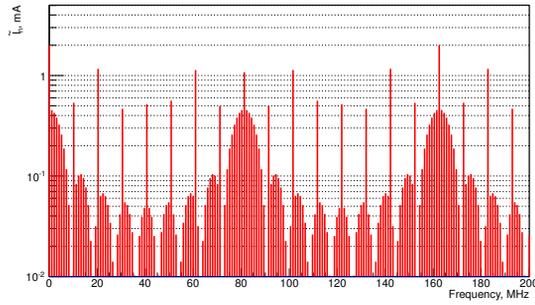
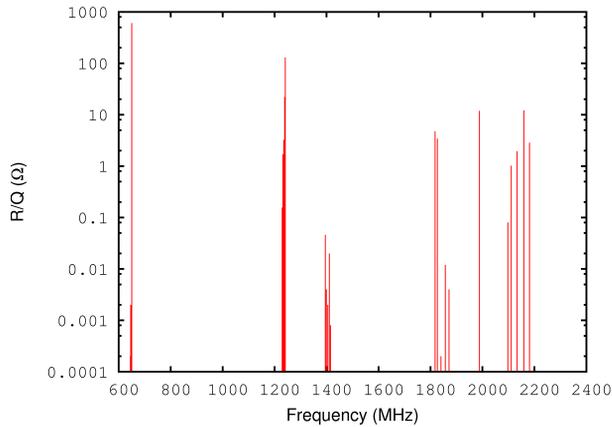


Figure 3: Beam spectrum of 3 GeV program.

Figure 4: (R/Q) of the monopole HOMs in PX HE section.

for a high Q resonance¹ can be estimated as $U_{HOM} \approx \frac{\tilde{I}(R/Q)}{4\sqrt{2}\delta f/f}$. If the HOM mode is exactly at the resonance, $U_{HOM} = \frac{1}{2}\tilde{I}(R/Q)Q_L$, where Q_L the loaded quality factor of the mode.² The cryogenic losses depend on square of HOM amplitude: $P_{loss} \approx \frac{U_{HOM}^2}{(R/Q)Q_0}$. Requiring that P_{loss} is much smaller than the sum of the static heat load and the cryogenic losses due to accelerating mode (~ 20 W), and assuming that the intrinsic quality factor is $Q_0 = 5 \times 10^9$, we estimate that the maximum allowable value of the monopole HOM loaded quality factor is $Q_L \ll 6 \times 10^7$.

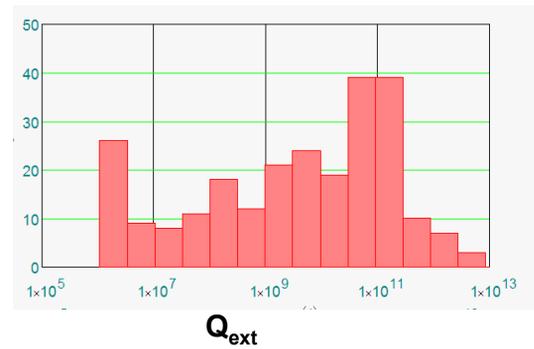
Similarly, requiring, that excitation of a monopole mode does not increase longitudinal emittance, $\varepsilon_z \gg U_{HOM}\sigma_z/c$, where σ_z is a bunch length, and c is speed of light, we obtain estimation of safe frequency detuning: $\delta f \gg f \frac{\tilde{I}(R/Q)\sigma_z}{4\sqrt{2}\varepsilon_z c}$. We have the worst case at the start of the HE section, where the bunch length is at the maximum ($\sigma_z/c = 7.7 \times 10^{-3}$ ns), the second pass-band monopole HOM (1241 MHz and highest $R/Q = 130 \Omega$), the nearest large amplitude beam spectrum line ($\tilde{I} = 1$ mA). Using value of emittance $\varepsilon_z = 1.5$ keV·ns (see [5] for more details), we find $\delta f \gg 140$ Hz.

For a more accurate estimation of the probability of co-

¹Here we assume that $\delta f/f \ll 1/Q$.

² $1/Q_L = 1/Q_0 + 1/Q_{ext}$, where Q_0 is intrinsic quality factor, and Q_{ext} is external quality factor of HOM.

herent HOM excitation in PX linac we perform statistical analysis based on spread of the data for the HOM parameters (frequency, impedance and quality factor). Since experimental data on HOM parameters are not available, we obtain this information from simulation of cavity HOMs taking into account manufacturing mechanical tolerances. While running the simulation, we allow random variations of the cavity profile within ± 0.2 mm of the ideal shape. We tune the individual cell frequency by changing its length but preserving the field flatness along the cavity. Finally, we calculate HOM spectrum, (R/Q) , and Q_{ext} of the derived 5-cell structure. Fig. 5 shows results of simulation of Q_{ext} of the 5th passband. One can see from this plot, that variations of the cavity geometry within the manufacturing tolerances may result in very high values for Q_{ext} , which violate condition for Q_L , established above, and may possibly lead to high cryogenic losses.

Figure 5: Variation of Q_{ext} for the monopole HOMs in the 5th passband of HE cavity.

An alternative design of HE cavity with larger aperture and $\beta_G = 0.92$ is suggested (see [4], and [6, 7] for more details). The new cavity shape suppresses high Q_L of the monopole HOM completely and mitigates the problem of large cryogenic losses.

RESULTS

In order to estimate probability of cryogenic losses per cryomodule, and relative change of longitudinal emittance, we generate $\sim 10^5$ random linacs using predicted deviations of frequency, Q_L , and (R/Q) value of monopole HOMs.

Cryogenic losses

The results of computation of losses for both present and alternative PX HE cavities are presented in Fig. 6 for 1 mA (top) and 5 mA (bottom) average beam current. We can see from these plots, that for the present HE cavity the probability to have losses above 0.1 W per cryomodule increases from 10^{-4} to 10^{-3} , when the average beam current changes from 1 mA to 5 mA. For the alternative HE cavity probability of the same losses is less than 10^{-5} , even for 5 mA PX operation.

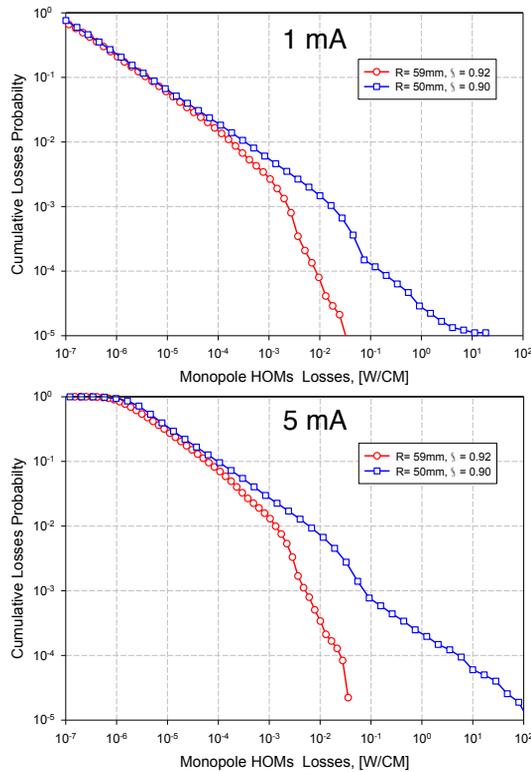


Figure 6: Probability of power loss per cryomodule for the monopole HOMs for the present (blue) and alternative (red) HE cavities.

Longitudinal emittance growth

Beam structure of PX consists of three sub-components (1 MHz, 10 Mhz and 20 MHz, see Fig. 2). The phase of the voltage of an HOM excited by the resonance with one of the beam components is random with respect to two other components of the beam. In case of a high- Q resonance, such an HOM may introduce a significant energy variation and longitudinal emittance growth along the beam train.

The results of statistical analysis are summarized in Fig. 7. For the present PX HE cavity the probability of the emittance to increase by 100% is changing from 10^{-3} to $\sim 2 \times 10^{-2}$, when average beam current increases from 1 mA to 10 mA. The high probability of emittance growth is explained by presence of high Q resonances in the 2nd and the 5th passbands of HE cavity. As expected, for the alternative cavity the probability of the same change in the emittance is much smaller and is below 10^{-4} for 10 mA PX linac operation.

CONCLUSION

We analyze regimes of high beam current operation of PX CW linac. We calculate cryogenic power loss and growth of longitudinal emittance. We find that PX linac of the present design can be safely operated with an average beam current up to 5 mA. High Q monopole HOM resonances in PX HE cavities may create problems for operation with a higher beam current. An alternative design

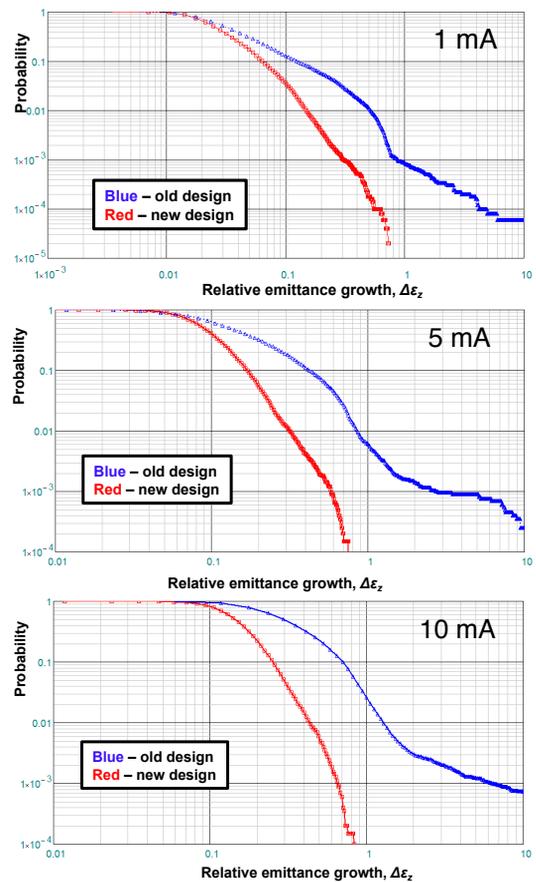


Figure 7: Probability of longitudinal emittance growth in the HE section of PX linac for 1 mA (top), 5 mA (middle), and 10 mA (bottom) average beam current. Data for the present design of the cavity are shown in blue, data for the alternative design are in red.

of HE cavity mitigates these issues and allows to run PX linac with an average beam current of 10 mA and higher.

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