HIGHER ORDER MODES IN THE SC CAVITIES OF THE SPL

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Abstract

In this paper is analysed the influence of Higher Order Modes (HOM) on the operation of the superconducting linac section of the SPL, the Superconducting Proton Linac being designed at CERN. For this purpose, the characteristics of the TM Monopoles in the 2 different beta families (5-cell cavities at $\beta = 0.65$, 1.0 both at 704 MHz) of the SPL are calculated to estimate their effect on cryogenics and beam stability. For both criteria the maximum external Q of the HOMs is defined.

CAVITY CHARACTERISTICS

The geometries of the SPL [1] cavities are analyzed with HFSS using a post-processing script, which was benchmarked against the 9-cell TESLA cavities [2]. This script was used to determine the (R/Q) and G values for each mode of the two cavity shapes ($\beta = 0.65$ and $\beta = 1.0$). The TM monopoles with the highest (R/Q) values are listed in Table 1 and were confirmed with Superfish.

Table 1: Monopoles in 704 MHz $\beta = 0.65$ and $\beta = 1.0$ cavity

β	Mode	f $[MHz]$	HFSS $(R/Q)^\dagger[\Omega]$	Superfish $(R/Q)^\dagger[\Omega]$
0.65	$TM_{010} 4/5\pi$	703.7	1	1
0.65	$TM_{010}\pi$	704.4	318	330
0.65	$TM_{011} 3/5\pi$	1765	3	4
0.65	$TM_{011} 4/5\pi$	1774	4	3
1.0	$TM_{010}\pi$	704.4	525	562
1.0	$TM_{011} 4/5\pi$	1328	37	36
1.0	$TM_{011}\pi$	1332	137	135
1.0	TM_{021}	2090	25	21

† linac definition

One can see that the amount of modes with a significant (R/Q) value is much higher for the $\beta = 1.0$ than for the $\beta = 0.65$ cavity.

Monopole Mode Excitation

A beam moving on the z-axis can only excite TM monopoles, while dipoles are excited by off-axis bunches. In this study we focus on longitudinal effects and therefore we only consider monopoles. In order to keep the analysis simple the bunches are modelled as single point charges, which slightly overestimates the induced voltage with respect to a Gaussian bunch (compare e.g. [3]).

The HOM voltage induced by a point charge in a loss-free cavity is

$$\tilde{V}_q = -\frac{\omega_n}{2}\left(\frac{R}{Q}\right) q e^{i\omega_n t} = V_q e^{i\omega_n t} \quad [V] \tag{1}$$

where $|q|$ is the bunch charge, ω_n is the angular frequency of the monopole with its (R/Q) in linac definition.

Taking into account cavity losses, the induced voltage decays exponentially with a decay time

$$T_d = \frac{2Q_{ex}}{\omega_n} \quad [s] \tag{2}$$

From Eq. (1) the steady-state voltage excited by a *CW* or pulsed beams, can be obtained by superposition (compare [3] and [4]):

$$V_n = V_q \sum_n e^{in\omega_n T_b} e^{-n\frac{T_b}{T_d}} \tag{3}$$

where T_b is the nominal bunch spacing.

HOM POWER

The induced HOM voltage leads to an additional heat load in the cavity which has to be removed by the cryogenic system. This mainly concerns TM-monopole modes since the HOM fields induced by multipoles is generally much smaller. One can calculate the additional power dissipation for each mode using

$$P_{c,n} = \frac{1}{T_p R_n}\int_{t_1}^{t_1+T_p} V_n^2(t)dt \quad [W] \tag{4}$$

which is the average power over an interval T_p. Here $V_n(t)$ is the HOM voltage of mode n and $R_n = (R/Q)_n * Q_{0,n}$ is the mode's shunt impedance. The highest voltage is induced if a HOM falls on a multiple of a machine line, which is used in the following to estimate worst case scenarios.

Using a resonant excitation of the HOMs (with the frequency of the HOMs themselves) and the (R/Q) values of Table 1 one can estimate the worst case power dissipation for single modes as shown in Table 2. In order to limit the additional heat load to a few watts per cavity the Q_{ex} should not go beyond 10^7.

LONGITUDINAL DYNAMICS

Jitter of the bunches in energy or phase as caused by the injector and the main RF system and bunch charge scatter

Table 2: Worst case power dissipation for monopole modes in the SPL (5% duty cycle) for different values of Q_{ex} assuming resonant excitation.

β	f_n [MHz]	Q_{ex}: 10^6 P[W]	10^7 P[W]	10^8 P[W]
0.65	1774	$7.74 \cdot 10^{-3}$	0.22	5
1.0	1332	$1.50 \cdot 10^{-2}$	3.10	85.8

from the source can excite HOMs at any frequency, even far away from any machine line; this process may even destroy the beam [5]. On the other hand HOM frequency scatter due to fabrication tolerances of the cavities hinders a perfectly collinear build-up of HOM voltages in the different cavities hence reducing the effect on the beam dynamics. In the following we describe results of a new simulation code, which was written specifically to study longitudinal HOM dynamics.

Code Features

The code models a linac taking into account the changing particle speed along periodic substructures for different cavity types with a given spacing. Field maps are used to derive the $E_0T(\beta)$ for the synchronous bunch in each cavity and a linear interpolation is used for off-momentum or off-phase bunches. The code can assume a certain longitudinal jitter on the input beam, RF errors (not used in this paper), and one HOM with individual values per cavity, being excited by point-like bunches. The interaction with the beam can be controlled individually for each cavity.

The physics and implementation of the beam-HOM interaction is described in [5]. Space-charge effects are neglected and only longitudinal effects are considered.

Simulation Input Parameters

Based on LINAC 4 beam dynamic simulations [6] the SPL input data, used for the following simulations is given in Table 3. The HOM with the highest (R/Q) is chosen in both sections including a certain safety margin. All errors are assumed to have a Gaussian distribution unless otherwise indicated. The beam current is varied between the nominal 0.04 A up to 0.4 A, and a HOM frequency scatter of $\sigma_f = 0.1\,\text{MHz}$ is assumed unless otherwise indicated. As already shown in [5] the beam current scatter is very important exciting a HOM. In our case a 10% scatter ($\sigma_I = 10\%$) was suggested by the SPL source experts [7] and applied in the simulations.

Simulation Results

In all simulations Q_{ex} is varied from 10^4 up to 10^9. The number of simulated pulses are adapted to Q_{ex} to ensure that V_n is in saturation, using a HOM load level of 99%. Using the final energy and phase spread for the different

Table 3: Input beam parameters and assumed variation.

Parameter	Value	σ
E_{Input} [MeV]	160	0.078
ϕ [ps]	0	1.58
I_{beam} [A]	0.04-0.4	10%
$f_{HOM,\beta=0.65}$ / $f_{HOM,\beta=1}$ [MHz]	1774 / 1331	0.1
$(R/Q)_{\beta=0.65}$ / $(R/Q)_{\beta=1}$ [Ω]	10 / 150	

bunches of a pulse, we calculate an effective emittance at the end of the linac, which is then normalised to the case without HOMs (but with input jitter). The increase of this effective emittance is plotted as a function of Q_{ex}.

In the first scenario we study the current dependancy (see Fig 1). At $Q_{ex} = 10^6$ the effective emittance starts to grow

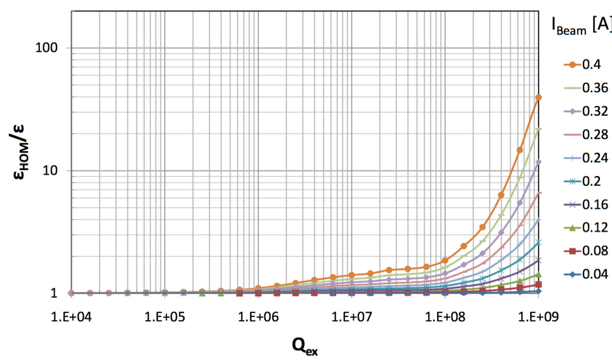

Figure 1: Effective emittance growth rate versus Q_{ex} for different beam currents assuming one HOM per cavity ($\sigma_f = 0.1\,\text{MHz}$, $\sigma_I = 10\%$).

and increases rapidly for values above 10^8, due to the fact that the decay time T_d becomes longer than the gap T_g between two pulses. Increasing the current leads to an exponential growth of the effective emittance. It should be noted that up to 80 mA the effect is barely noticable.

In the second scenario two frequencies are chosen, which are next (1 MHz) to a machine line: $f_{HOM,\beta=0.65} = 2466.4\,\text{MHz}$ and $f_{HOM,\beta=1.0} = 2818.6\,\text{MHz}$, while all other parameters remain unchanged (see Fig.2). The effective emittance grows immediately and is plotted as long as no bunches are lost (longitudinally) in the linac. The plateau between $10^7 < Q_{ex} < 10^8$ can be explained as follows: below $Q_{ex} = 10^6$, V_n saturates during a single pulse passage and decays completely between two pulses. Above $Q_{ex} = 10^6$, V_n is not saturated after a pulse but decays completely as long as $T_d < T_g$, which is the case as long as $Q_{ex} < 10^8$. This is why V_n does not increase significantly in this regime. For higher Q_{ex} values V_n increases from pulse to pulse until saturation.

In the third scenario the HOMs fall directly on a multiple of a machine line ($f_{HOM,\beta=0.65} = 2465.4\,\text{MHz}$ and $f_{HOM,\beta=1.0} = 2817.6\,\text{MHz}$) with a Gaussian HOM frequency spread of 0.1 MHz. Already at the nominal current

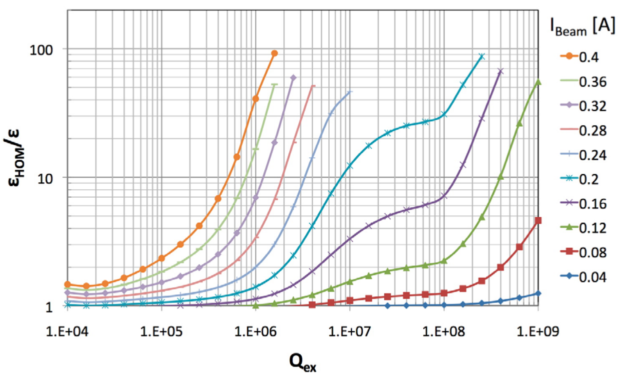

Figure 2: Effective emittance growth versus Q_{ex} for different beam currents with one HOM per cavity next (1 MHz) to a machine line ($\sigma_f = 0.1$ MHz, $\sigma_I = 10\%$).

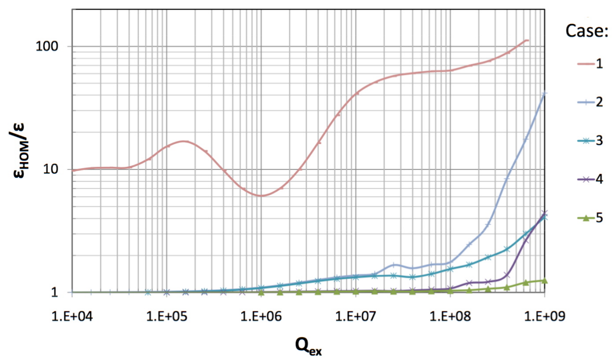

Figure 3: Effective emittance growth rate of the beam against Q_{ex} for the 5 different scenarios listed in Table 4.

of 0.04 A and even for $Q_{ex} = 10^4$ one can observe a significant increase of the effective emittance, which makes reliable operation impossible.

To better understand the influence of the "noise" in the simulations several scenarios with different HOM frequency spreads (σ_f) and bunch charge jitter (σ_I) using a 0.4 A beam have been studied. Input parameters are listed in Table 4 and the simulation results are plotted in Fig. 3.

Table 4: Simulation Scenarios

Case	$f_{HOM,\beta=0.65}$	$f_{HOM,\beta=1}$	σ_f	σ_I
1	2465.4	2817.6	3.0	0.04
2	1774	1331	0.1	0.04
3	1774	1331	3.0	0.04
4	1774	1331	0.1	0.0
5	1774	1331	3.0	0.0

Case 1 corresponds to the third scenario, described above, where the HOMs are directly on multiples of a machine line, but here we use a larger frequency spread of 3 MHz. It is clear from Fig. 3 that operation at 0.4 A is impossible for any value of Q_{ex}, even though the larger frequency spread (3 MHz) of the HOMs considerably reduced the effective emittance increase when compared to a spread of 0.1 MHz. In this case the absence or presence of charge scatter does not change the picture.

For HOMs, which are not "sitting" on multiples of the bunch frequency, charge scatter has a significant influence on longitudinal dynamics (see difference between curve 4 and 2, or 5 and 3). Here one can say that the current variations are in fact providing the "noise", which is necessary to drive a HOM voltage build-up. Removing the charge scatter, one can safely operate the linac with external Qs up to $Q_{ex} = 10^8$, while otherwise a "safe limit" for Q_{ex} would be around 10^6. Ideally one wishes for a minimum charge scatter and a large HOM frequency spread[1].

[1]Increasing the frequency spread is obviously more effective when considering uniform distributions.

CONCLUSION & OUTLOOK

From the cryogenics point of view a $Q_{ex} \leq 10^7$ for the HOM dampers is sufficient to keep the additional (HOM) heat load in the SPL cavities at the level of a few Watts. From longitudinal beam dynamics we obtain much more demanding limits: i) bunch charge fluctuations from the source trigger the excitation of HOMs at any frequency and a Q_{ex} of 10^6 is recommended to limit their induced voltage, ii) for a 1 MHz distance of HOM frequencies from machine lines a Q_{ex} of 10^5 seems advisable, iii) having HOMs in each cavity lying directly on multiples of machine lines (even with a HOM frequency scatter of 3 MHz) will severely limit machine operation even if HOM dampers with a very low Q_{ex} of $< 10^4$ can be employed. A certain design/tuning effort should therefore be made to avoid that HOMs with high (R/Q) values can be found at multiples of machine lines.

In this paper only a few scenarios have been studied and more analysis is needed to make a choice on the Q_{ex} for the SPL HOM dampers. For the time being we conclude that the use of HOM dampers with a Q_{ex} in the range of 10^5 is highly recommended to ensure reliable operation of the machine.

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