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HIGHER ORDER MODE ANALYSIS OF THE SPL CAVITIES

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Abstract

Higher Order Modes (HOMs) can severely limit the operation of superconducting cavities in a linac with high beam current, high duty factor and complex pulse structure. The full HOM spectrum has to be analyzed in order to identify potentially dangerous modes already during the design phase and to define their damping requirements. For this purpose a dedicated beam simulation code focused on beam-HOM interaction was developed, taking into account important effects like the HOM frequency spread, beam input jitter, different chopping patterns, as well as klystron and alignment errors. Here, the code is used to investigate in detail the HOM properties of the cavities foreseen in the Superconducting Proton Linac (SPL) at CERN and their potential to drive beam instabilities. Special attention is given to HOM excitation by chopped pulses with high repetition rate.

INTRODUCTION

The Superconducting Proton Linac (SPL) [1], [2] is planned as a 4 MW machine in pulsed operation. Two families ($\beta_d = 0.65$ and $\beta_d = 1.0$) of 5 cell superconducting elliptical π-mode cavities, operating at 704.4 MHz, will be used to accelerate H^- from 160 MeV up to 5 GeV. All further machine parameters used in this study are listed in Table 1.

As shown in earlier studies [3], [4] for this machine, HOMs can cause instabilities in the longitudinal and transversal plane if no sufficient HOM damping is present.

In all simulations one or more pulses consisting of 350,000 point-like bunches are tracked through the linac and then the phase space area created by the last pulse is recorded. Then an effective emittance of the pulse in the longitudinal plane

$$\epsilon = \pi\sqrt{\langle dE^2\rangle\langle d\phi^2\rangle - \langle dEd\phi\rangle^2} \quad (1)$$

is calculated. For the case where only injection beam jitter (see Tab.1) is present, lead to a value of about $0.2\,\mathrm{MeVdeg@704HMz}$. The effective emittance of all simulations is normalised to the case where only the injection beam noise, and no other effect is present. The resulting effective emittance growth is a good measure for the impact of HOMs or other effects and is independent of the input phase space.

Table 1: Simulation Input Parameters

Parameter		Value	σ
E_{Input}	[MeV]	160	0.078
ϕ_{sync}	[deg]	-15	0.4
I_b	[mA]	40-400	1%
No. Cavities (β_d=0.65/1.0)		54/192	
Design gradient	[MV/m]	19.5/25	
R/Q_d at design β	[Ω]†	290/570	
Bunch frequency f_b	[MHz]	352.2	
Pulse length T_p	[ms]	1.00	
Repetition rate	[Hz]	50	

† linac definition

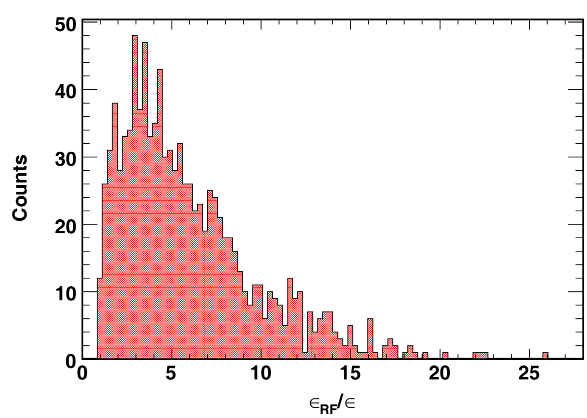

Figure 1: Effective emittance growth due to rf errors ($\pm0.5\,^\circ$ in phase and $\pm0.5\,\%$ in amplitude - uniform distributed) of 1000 linacs. The phase space area is increased on average by a factor of six.

RF ERRORS

One of the main sources of energy and phase jitter are the rf power sources. The SPL design aims for rms-errors of $0.5\,^\circ$ in phase and $0.5\,\%$ in amplitude. 1000 different linac set-ups are simulated with a uniform rf error distribution and the resulting distribution of the effective longitudinal emittance is normalised to the case where no rf errors are present. The peak of the histogram (see Fig. 1) is at ~ 3 times the nominal effective longitudinal emittance and the average value is at ~ 6. In the following simulations this six-fold increase in effective longitudinal emittance is used as the tolerable limit for HOM induced beam degradation.

SUB-STRUCTURED PULSES

Any substructure in the beam pulse, created by chopping, introduces new spectral lines beside the fundamental machine lines ($nf_b, n \in \mathbb{N}$) The chopping resonance frequency $f_c = f_b/N$ is defined by the periodicity of the substructure, where m out of N bunches are used. To keep all possibilities open and to allow any chopping pattern means that stable operation with a resonant HOM excitation must be guaranteed. Therefore the three different patterns (m/N) listed in Table 2 are investigated in more detail. The charge per bunch is increased by a factor $8/5$ to keep the total charge per pulse constant. A frequency scan between the 3rd and 4th fundamental machine line is performed where the mean HOM frequency ($\sigma_{f,HOM} = 1\,\mathrm{MHz}$) is set to a chopping machine line and the R/Q-map ($R/Q_{max} = 110\Omega$) of the $TM_{011,4/5\pi}$ mode in both cavities is used.

Table 2: Used Chopping Patterns

Pattern (m/N)	f_c [MHz]
5/8	44.025
50/80	4.4025
500/800	0.44025

The effective longitudinal emittance growth at nominal beam current and $Q_{ex} = 10^7$ versus the frequency is shown in Figure 2, where also the simulated TM_{011} monopole frequencies of the $\beta = 1$ cavity are indicated. Away from the fundamental machine line only the $5/8$ pattern triggers a certain growth. One of the $5/8$ chopping resonance lines is close to the expected frequency of the $TM_{011,3/5\pi}$ mode. In general the impact of the chopping machine lines on beam degradation increases with the repetition rate, which can be explained by looking at its Fourier components. Below $Q_{ex} = 10^5$ no growth is observed for all chopping patterns at nominal current and this ensures stable operation for any chopping pattern.

TM_{010} MODES

The modes in the fundamental pass band beside the $\mathrm{TM}_{010,\pi}$ have to be studied carefully because of their small frequency spread and their significant $R/Q(\beta)$ values for relative particle velocities different from the design β of the cavities. In order to estimate the Q_{ex} provided by the fundamental power coupler to the fundamental band pass modes, 3D EM simulations with Ansoft HFSS 12 [5] and CST MWS 2009 [6] are carried out. The results are listed in Table 3.

For comparison reasons also 2D superfish results without power coupler are added. Values for the R/Q at design β and the maximum value in the used β-range are calculated from the MWS results. The frequencies found with HFSS are always higher than the one found with MWS.

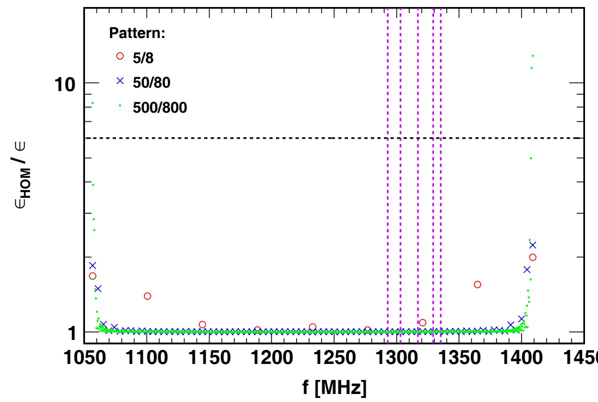

Figure 2: Plot of the longitudinal effective emittance growth for a HOM falling on a chopping machine line at nominal current and $Q_{ex} = 10^7$ for different chopping patterns: 5/8 (circle), 50/80 (cross), 500/800(dot); rf growth (black dashed line); monopole modes (violet dashed lines)

In case of the high beta cavity the difference is only about 200 kHz and the results also agree very well with the 2D simulations. In the medium beta cavity the differences are slightly higher, but still less than 1 MHz. Comparing the values with superfish simulations, there is a good agreement with the MWS results, but the HFSS values are all about 500 kHz higher. Looking at the Q_{ex} values, the max. difference for the high beta cavity is only $\sim 4\%$, but up to 13% for the medium beta cavity. Further EM simulation results are presented in [7] and [8].

The modes ($TM_{010,3/5\pi}$, $TM_{010,4/5\pi}$) with the highest R/Q values are used for further beam dynamic studies. The mode frequency spread is significantly lower than for HOM modes and in all simulations a spread of 10 kHz is used.

In the first simulation the $TM_{010,4/5\pi}$ modes are excited by an unchopped beam for five different I_b as shown in Figure 3. Above $Q_{ex} = 10^5$ the effective longitudinal emittance increases significantly for $I_b = 400\,\mathrm{mA}$, but is still just below the rf limit (factor 6) at the expected Q_{ex} ($\sim 6 \cdot 10^5$).

The $TM_{010,3/5\pi}$ modes in both cavities are close to a chopping machine line (699.998 MHz) created by a 50/80 chopping pattern. A worst case scenario would be if the mode frequency in both cavities is the same as the chopping machine line (CML). This worst case scenario is simulated and compared with the scenarios where the simulated mode frequency is used (see. Fig 4). There the chopped beam (C) and the unchopped beam are simulated with ten times the nominal beam current. If the mean mode frequency falls directly on that chopping machine line, the effective longitudinal emittance increases significantly. In case of 400 mA the beam is lost above $Q_{ex} = 5 \cdot 10^4$. At the nominal beam current the beam stays stable, but the effective longitudinal emittance starts to grow above $Q_{ex} = 10^4$ and is a factor three higher than nominal at the simulated Q_{ex}. The simulations with the chopped beam but away from the resonance

Table 3: EM Simulation Results $\beta_g = 0.65$ and $\beta = 1$ Cavity

β	Mode	Superfish f [MHz]	HFSS v12 f [MHz]	HFSS v12 Q_{ex} [10^6]	MWS 2009 f [MHz]	MWS 2009 Q_{ex} [10^6]	MWS 2009 R/Q_d [Ω]†	MWS 2009 $R/Q^\ddagger_{max}$ [Ω]†
0.65	$TM_{010,0}$	695.4	696.0	6.46	695.2	5.73	0.003	0.8
0.65	$TM_{010,2/5\pi}$	697.9	698.5	1.78	697.8	1.60	0.203	0.5
0.65	$TM_{010,3/5\pi}$	701.0	701.6	0.91	700.9	0.81	0.198	52
0.65	$TM_{010,4/5\pi}$	703.5	704.1	0.61	703.4	0.57	0.475	268
0.65	$TM_{010,\pi}$	704.4	705.0	1.10	704.4	1.03	299	324
1	$TM_{010,0}$	692.5	692.5	6.32	692.3	6.07	0.001	0.1
1	$TM_{010,2/5\pi}$	695.7	695.7	1.73	695.5	1.67	0.037	0.4
1	$TM_{010,3/5\pi}$	699.8	699.7	0.91	699.6	0.88	0.011	25
1	$TM_{010,4/5\pi}$	703.1	703.1	0.65	703.0	0.63	0.100	167
1	$TM_{010,\pi}$	704.4	704.4	1.17	704.3	1.15	565	547

† linac definition; ‡ maximum value in used velocity range

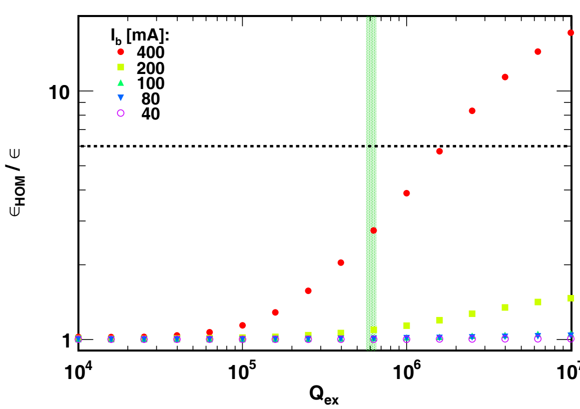

Figure 3: Plot of the longitudinal effective emittance growth versus Q_{ex} caused by the $TM_{010,4/5\pi}$ modes and different currents; rf growth (dashed black line); simulated Q_{ex} (shaded area).

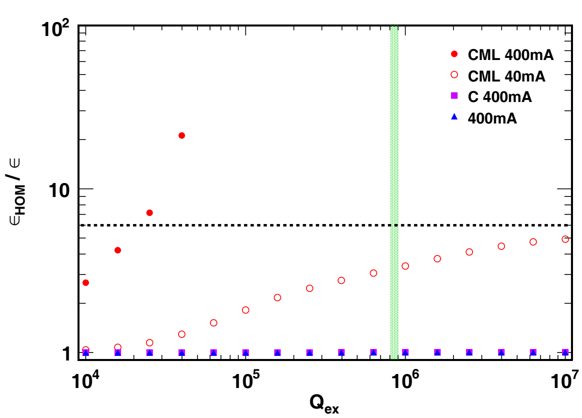

Figure 4: Plot of the longitudinal effective emittance growth versus Q_{ex} caused by the $TM_{010,3/5\pi}$ modes and different settings: unchopped beam (triangles), chopped beam (squares) and chopped beam with shifted frequency (circles); rf growth (dashed line), simulated Q_{ex} (shaded area).

show as well as the not chopped beam no significant effective emittance growth using ten times the nominal current. A distance of a few 100 kHz to the chopping machine line is sufficient to avoid resonance excitation and an significant effective longitudinal emittance growth.

CONCLUSION

The energy and phase jitter, created by the RF system, yield an effective longitudinal emittance growth for beam pulses of a factor of 6. This value is used to judge whether HOM induced effective longitudinal emittance growth is significant or not. The damping of the TM_{010} modes via the power coupler was calculated and found to be sufficient for the case of unchopped beams. For chopped beams significant effective longitudinal emittance growth was observed for the case of HOMs coinciding with machine lines, which are created by the chopping. A Q_{ex} of 10^5 is recommended for this case.

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