SOME CONSIDERATIONS ON THE CHOICE OF FREQUENCY AND GEOMETRICAL BETA IN HIGH POWER PROTON LINACS IN THE CONTEXT OF HIGHER ORDER MODES

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Abstract

Several high power superconducting (SC) proton linear accelerators are currently in the design stage around the world, such as for example the European Spallation Source (ESS) in Lund, Project X at Fermilab, the European ADS demonstrator MYRRAH in Mol, and the Superconducting Proton linac (SPL) at CERN. In this contribution, the influence of Higher Order Modes (HOMs) in elliptical SC cavities is discussed as a function of the operation frequency, the number of cells, and the geometrical beta of the cavity. Based on cavity design data, beam dynamics simulations are executed for different linac layouts to quantify the influence of HOMs.

INTRODUCTION

In the design stage of a SC proton linac a complex optimisation task has to be done in order to minimise the linac length and cost while maintaining good beam quality. This task is done by looking at properties such as the acceleration voltage $V_{\text{acc}}(\beta)$ or the gradient of the accelerating $\text{TM}_{010,\pi}$ mode as a function of the beam velocity to maximise the real estate accelerating gradient along the linac. The main parameters to optimise in the longitudinal plane are the following: number of sections and cavity types, operation frequency, number of cavity cells, geometrical β of the different cavities, and section transition energy. There are also other constraints such as maximum power transfer of the fundamental power coupler or phase advance limitations per focusing period. Another property is the mode efficiency in terms of $(R/Q)(\beta)$ which is defined as

$$(R/Q)(\beta) = \frac{|V_{\text{acc}}|^2}{\omega U}, \qquad (1)$$

where ω is the angular frequency and U the energy stored in the mode.

In the following we focus on the medium and high energy part ($\beta > 0.4$), where elliptical cavities with fixed geometrical β_{g} per linac section are used. The number of cells affect the β dependency of the transit time factor and hence $V_{\text{acc}}(\beta)$ and $(R/Q)(\beta)$ as shown in Figure 1.

The complete optimisation is usually done for the acceleration mode, but all other modes are affected as well.

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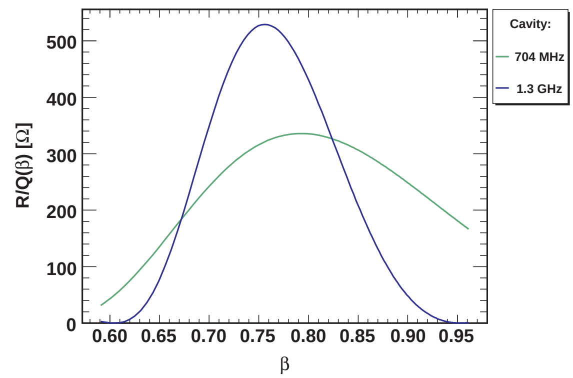


Figure 1: $(R/Q)(\beta)$ plot of the $\text{TM}_{010,\pi}$ mode in a 5 cell 704 MHz and a 9 cell 1.3 GHz cavity. The cavities have the same β_{g}=0.74.

Different scenarios are evaluated using the HOM dynamics code SMD [1] which takes into account the effects of higher order modes.

OPERATION FREQUENCY

The influence of the frequency and the number of cells on the HOMs including other TM_{010} modes is investigated in detail in a case study of two 2.5 GeV linac layouts [2] operating at 704.4 MHz and 1.3 GHz. The layout and cavity properties are summarised in Tables 2 and 1.

Table 1: Cavity parameters; cavity shape from [3]

		704.4 MHz		1.3 GHz	
β_{g}		0.63	0.74	0.74	0.84
Cells		5	5	9	9
L	[m]	0.99	1.11	1.09	1.19
$(R/Q)(\beta_{\text{g}})$	[Ω]†	238	307	513	715
$E_0T(\beta_{\text{g}})$	[MV/m]	14	20	15	21

† linac definition

In order to directly compare both linac options all simulations start at 380 MeV and go up to 2.5 GeV.

The HOM with the highest $(R/Q)(\beta)$ value is chosen individually in each cavity for the corresponding β. In Figure 2 the maximum value of each mode is shown. The $(R/Q)(\beta)$ values of the 1.3 GHz cavities are about a factor two higher due to a higher number of cells. A HOM frequency spread of 1 MHz in the 704 MHz option and 2 MHz

Table 2: Section parameters of the studied linac options

Option	Section	β_g	cells	f [MHz]	E_{in} [MeV]	length [m]	cavities
704 MHz	Medium β	0.63	5	704.4	225	52	36
	High β	0.74	5	704.4	500	237	168
1.3 GHz	Medium β	0.74	9	1300	380	59	40
	High β	0.84	9	1300	660	240	160

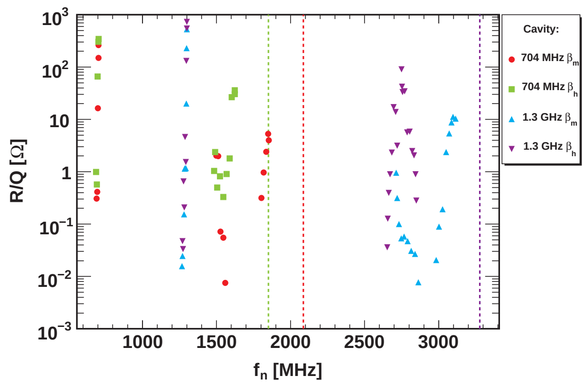


Figure 2: $(R/Q)_{max}$ of the first three monopole bands. The dashed lines indicate the beam pipe cut-off frequency.

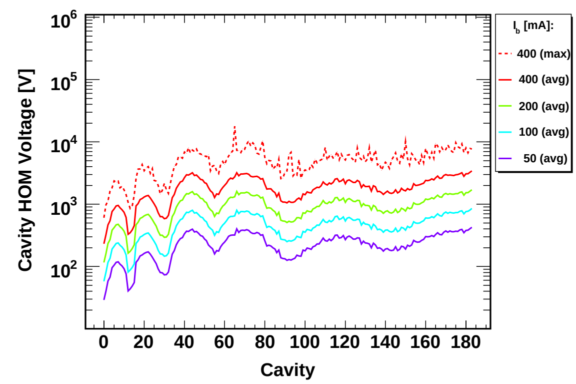
in the 1.3 GHz option is used. In order to avoid pulse-to-pulse coupling the HOM damping in terms of Q_{ex} is set to 10^8 in all cavities for both options. The beam current is varied between 50 mA and 400 mA to explore the safety margin.

100 different error sets for the HOM frequency distribution along the linac are simulated for different beam currents. The average HOM voltage, present at the end of the pulse in each cavity, is shown in Figure 3 for both linacs. In addition, the maximum observed HOM voltages are plotted for 400 mA.

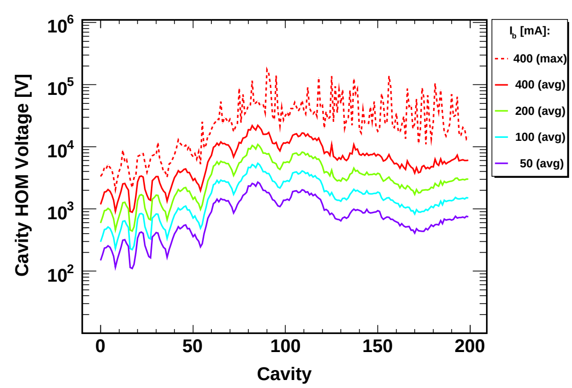
The HOM voltage scales linearly with the beam current, and the variations along the linac are due to the $(R/Q)(\beta)$ change. In the 1.3 GHz option the voltages are on average about one order of magnitude higher than in the 704 MHz case. The observed peak voltages at 400 mA exceed 100 kV, while in the 704 MHz linac the maximum is about 10 kV. This result can be explained by the higher HOM frequencies and $(R/Q)(\beta)$ values in the 1.3 GHz linac. Both lead to a higher induced HOM voltage per each bunch. At 50 mA the HOM voltage is at a very moderate level in both options and causes no significant growth in the energy and phase spread at the end of the linac in contrast to RF errors.

TRANSITION ENERGY AND CAVITY BETA IN THE SPL

The general influence of the non accelerating TM_{010} modes in case of the SPL has been studied in [1]. Here two SPL layouts listed in Table 3 are analysed. BL is the



(a) 704 MHz linac



(b) 1.3 GHz linac

Figure 3: Average and maximum HOM voltages after one pulse for 100 linacs (different HOM frequency patterns) and different beam currents where one HOM per cavity is present. The maximum observed HOM voltage at 400 mA is about 10 kV in the 704 MHz linac and exceeds 100 kV in some cavities in the 1.3 GHz linac.

SPL baseline layout and MS is a modified one where the injection energy is increased and the geometrical beta of the high beta is reduced in order to reduce the transition energy from the medium beta cavity section to the high beta cavity section.

$(R/Q)(\beta)$ dependency of the $TM_{010,4/5\pi}$ and the accelerating $TM_{010,\pi}$ modes in the SPL baseline cavities ($\beta_g = 0.65$, $\beta_g = 1.0$) as well as in a $\beta_g = 0.92$ cavity is shown in Figure 4. For values very different form β_g the $(R/Q)(\beta)$ values of the $TM_{010,4/5\pi}$ exceeds the one of the accelerating mode. In this region the excitation efficiency of the $TM_{010,4/5\pi}$ mode is very high. Damping can only

Table 3: SPL simulation layout parameters

		BL[†]	MS
E_{in}	[MeV]	160	180
E_{tr}	[MeV]	744	594
E_{out}	[MeV]	5095	4916
Periods	(med/high)	9 / 24	6 / 26
Cavities	(med/high)	54/192	36/208
β_{g}	(med/high)	0.65 / 1	0.65 / 0.92
$E_{\text{acc}}(\beta_{\text{g}})$	[MV/m]	19.4 / 25	19.4 / 24.2
$(R/Q)(\beta_{\text{g}})$	[Ω][‡]	300/565	300/430

[†] as in [1]; not latest SPL layout. [‡] linac definition

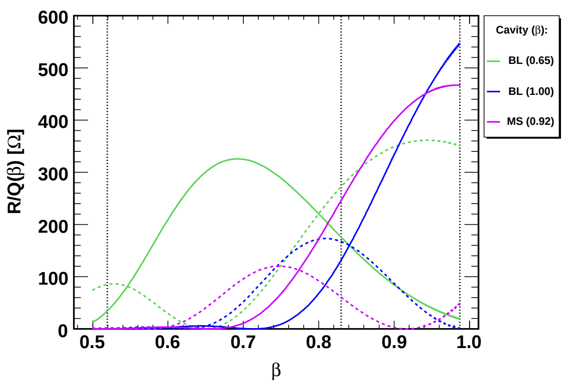


Figure 4: $(R/Q)(\beta)$ plot of the $\text{TM}_{010,4/5\pi}$ (dashed) and $\text{TM}_{010,\pi}$ (solid) modes. The entrance, transition, and output energy is indicated with vertical dotted lines.

be provided by the fundamental power coupler (FPC) and is based on CST and HFSS simulations [4] and found to be of the order of $Q_{\text{ex}} = 10^6$. However, this damping will only be present if the mode propagates through the complete cavity and is not separated into two modes located in the opposing end cells caused by mechanical imperfections. Then only one of the two modes can be damped by the FPC, since it is located at one side and the overall damping is significantly lower.

Beam dynamics simulations for the $\text{TM}_{010,4/5\pi}$ mode are carried out to compare this linac layout with the reference layout used in [1]. In the simulation, one 1 ms pulse with 400 mA, which is ten times the nominal current, is tracked through the linac with a bunch-to-bunch charge variation of 3%. As HOM, the $\text{TM}_{010,4/5\pi}$ mode is present with a frequency spread of 10 kHz, and a global HOM damping of $Q_{\text{ex}} = 10^6$. Additionally, RF errors are present with a uniform error distribution of 0.5% in amplitude and 0.5 degree at 704 MHz in phase.

100 linacs are simulated for each layout where the HOM frequency distribution is varied in each simulation. The average and maximum HOM voltage present in the cavities along the linac is shown in Figure 5. It is clearly visible that the HOM voltage increases significantly in the regions with high $(R/Q)(\beta)$ values. In case the HOM voltage is higher

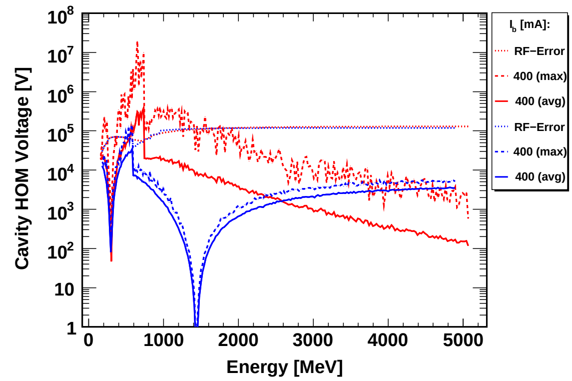


Figure 5: Average (solid) and maximum (dashed) cavity HOM voltages over the beam energy in the cavity centre. The maximum RF voltage error is indicated with dotted lines. The upper (red) curves are the BL layout and the lower (blue) the MS layout.

than the RF amplitude error, the beam is affected more by the HOMs than by the RF errors, and causes an additional beam blow-up in the longitudinal plane. By changing the injection energy and reducing the geometrical beta, the impact of the $\text{TM}_{010,4/5\pi}$ mode can be reduced significantly. In this case, the peak of the HOM voltage is shifted and decreases more than one order of magnitude, and the average HOM voltage is not larger than the RF voltage errors any more.

CONCLUSION

The influences of the operation frequency and number of cavity cells on the HOM excitation in proton linacs is illustrated. In case of a lower operation frequency and fewer cells the overall acceleration efficiency is better, and the potential of a HOM excitation is smaller. Furthermore, the excitation of fundamental passband modes can be reduced significantly by carefully choosing the geometrical beta and the energy range covered by each cavity. This issue should be considered during the linac design optimisation stage to reduce the overall risk of HOM-caused beam instabilities.

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