SIMULATIONS OF PROPOSED ACCELERATING CAVITIES FOR THE CERN SPL

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Abstract

The Superconducting Proton Linac (SPL) study performs R&D at CERN with international participation on a proposed proton driver. SPL will rely on two classes of superconducting cavities; beta=0.65 and beta=1; each containing 5-cells resonant at 704 MHz. Presented here are the results of simulations of the beta=1 design performed at the NERSC supercomputing facility with the ACE3P codes developed by the Advanced Computations Department at SLAC National Accelerator Laboratory. Of particular interest are the simulations of the behaviour of multi-cavity cryomodules that show strong coupling of EM modes between cavities, and which suggest strategies for the construction of the inter-cavity beam-pipe region.

INTRODUCTION

The Superconducting Proton Linac (SPL) [1] is a proposed extension to the Linac4 project to create a high power, multi-GeV, H- linac for future high intensity proton users at CERN. Its layout is illustrated in figure 1.

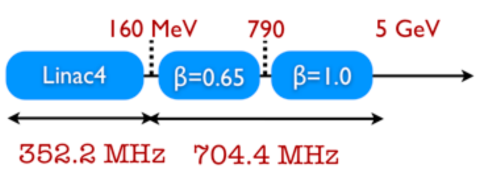

Figure 1: Basic layout of the proposed SPL.

Figure 1 shows SPL as comprising of two main components; $\beta = 0.65$ and $\beta = 1$. These sections are accelerating regions that make use of superconducting, elliptical, cavities, and the naming of each region indicates the relativistic β for which each is designed.

While Higher Order Modes (HOMs) are not usually considered to be of particular importance for high energy H- machines, the high beam power expected at SPL (4–5 MW), combined with the requirement that the beam losses amount to less than 1 W/m, implies that the distribution and extraction of HOM must be considered in the design of these cavities [2].

CAVITY DESIGN

Figure 2 shows the current CEA design [3] of the 704 MHz $\beta = 1$ cavity in SuperFish formalism.

Of particular importance to this study are the details of the beam-pipe region between cavities, and this is also indicated on figure 2. The transition to a radius of 40 mm is intended to limit the coupling of resonant modes between cavities, and the results of this will be shown later.

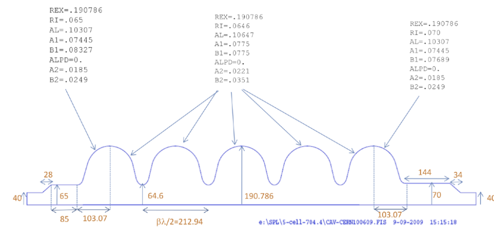

Figure 2: CEA-Saclay design for the SPL cavity.

Figure 3 shows the dimensions and location of the fundamental power coupler, and it can be seen that the large size of this may provide a significant perturbation to the way in which EM power is coupled between cavities.

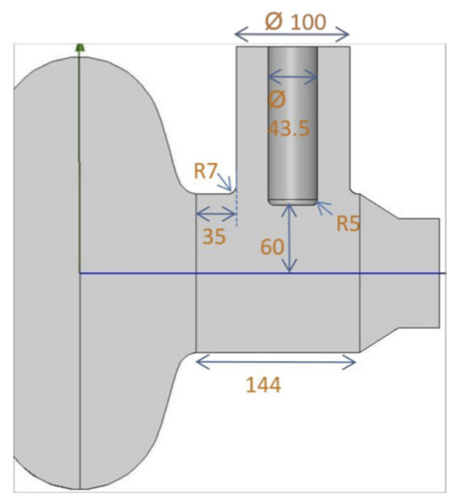

Figure 3: Design of the coupler region of the SPL cavity.

The design foresees HOM ports, but the precise layout is under study and not yet known. HOM couplers were therefore neglected from the simulations described in this paper. Although omitting these may be seen as unrealistic, it should be noted that no decision has yet been made on their location and particular design.

The calculated R/Q for the mode spectrum found in this cavity is shown in figure 4.

CAVITY MODES

In the case of the cavity design in figure 2, each of the five cells may be thought of as a resonant cavity with a certain amount of coupling to neighbouring cells via the

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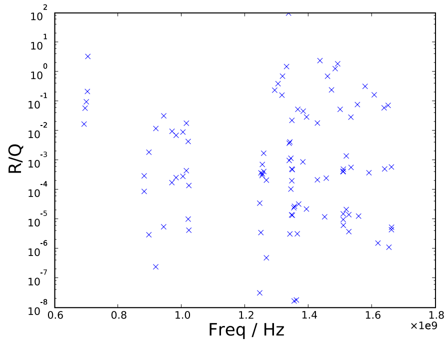

Figure 4: Calculated R/Q spectrum.

64.6 mm radius irises. Thus the resonance is more akin to that found in a system of coupled oscillators. In this case, each mode in the TM_{mnp}/TE_{mnp} formalism will appear multiple times (one for each cell), with each being distinguished by the phase difference between the oscillations in neighbouring cells.

For an n-cell cavity, the phase differences will be, $i \cdot \pi / n$, where i is an integer runnning from 1 to n.

CRYOMODULE MODES

Although the beam-pipe region between cavities is below the cut-off frequencies for the fundamental passband modes and most of the high R/Q modes, it should be remembered that this cut-off is not a hard-edged boundary, but that an exponentially decaying evanescent field will extend outwards from the cavity. It is, therefore, possible that this field will extend far enough to couple to similar modes in a neighbouring cavity.

The oscillation at a fixed time in the beam-pipe may be described as, $exp(ikx)$, where x is the position, and k is the wavenumber. The wave number, k, can be written as,

$$k = \frac{1}{c} \cdot \sqrt{\omega^2 - \omega_c^2} \tag{1}$$

Therefore a frequency, ω, of less than the cut-off frequency, ω_c, leads to a complex value for the wave number, resulting in an exponentially decaying wave. Since ω_c is inversely proportional to the radius of the beam-pipe, a smaller aperture will have a larger cut-off frequency, and, therefore, larger evanescent damping.

INTERCONNECT REGIONS

Although not indicated in figure 2, the design length of the radius=40 mm beam-pipe in the CEA design is 60 mm. Since this region is the smallest aperture in the system, and, therefore, the strongest limitation on the decay length of the evanescent field, it was decided to investigate the coupling of modes for three different designs for this aperture. These are illustrated in figure 5, and the parameters are shown in table 1.

Table 1: Simulated Designs

Name	Radius	Length
Nominal	40 mm	60 mm
Extended	40 mm	120 mm
No taper	65 mm	60 mm

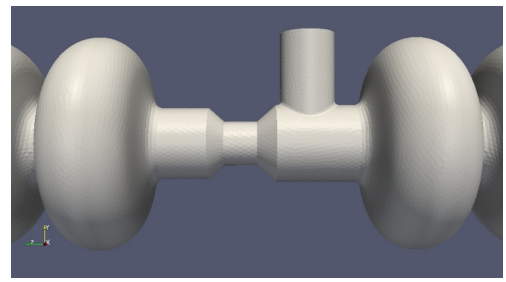

Figure 5: Nominal design for interconnection region.

SIMULATIONS

The simulations were performed on the Franklin machine at NERSC [4] using Omega3P [5]. Despite the SPL design calling for an eight cavity cryomodule, these initial simulations have been done with a shorter, four cavity, cryomodule in order to save on computational resources.

Since Omega3P uses a second–order mesh, it was not necessary to subdivide the volume into millions of mesh points, as may be required with other codes. For these results, the entire, four-cavity, volume, was subdivided into ∼760k mesh points with an average volume of $\sim 4.5 \times 10^{-7}$ m^3. The maximum edge length of any mesh element was ∼33 mm.

RESULTS

As described previously, modes in a multi-cavity system will not be terminated by a hard cutoff, and will instead exponentially decay. Thus, even in the case where the beam-pipe is many decay lengths long, some small residue of the mode will exist in neighbouring cavities.

In many cases the cutoff will be strong enough that the coupling is not measureable, however, in the case of these simulations, the coupling will always be detected by the software. Thus, each cavity mode will appear four times (one for each cavity), at slightly different frequencies. Since the frequencies are determined by the shapes of the individual cavities, they will be almost identical, with any differences being due to statistical differences in the meshes of each of the four cavities.

Thus the coupling for each of the modes found by simulation may be defined at the ratio of the field magnitude in the cavity with the largest amplitude, to that in the cavity with the next largest. This is plotted in figure 6.

In figure 6 it can be seen how the modes cluster around several points, with the frequency being mostly determined by the single-cavity geometry, while the coupling is spread

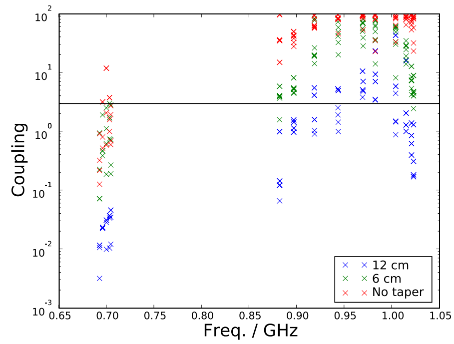

Figure 6: Simulated intercavity coupling for the three different designs in table 1. The black line indicates the design coupling between cells in a single cavity.

due to the differing phase advances causing coherent or incoherent of the coupled modes. For the purposes of comparison, the black line indicates the design coupling (3%) between the cells of a single cavity.

In the case of the "Long" geometry (12 cm), it can be seen that the coupling for the accelerating mode (the lowest passband) is $\sim 10^{-4}$, and may be considered negligible.

In the nominal case, the coupling appears to be of the order of 1%. Of particular interest is the comparison between this design, and that of the case where there is no taper, and it can be seen that the difference between these two designs is quite small.

The reason for the addition of the tapered beampipe was to restrict the coupling of these modes between cavities, however it would appear that this amount of taper is not sufficient for this purpose, and that longer inter-cavity beampipes may have to be considered.

In the case of the dipole modes – the higher frequency modes shown in figure 6, it can be seen that the coupling problem is very significant indeed. The electric field amplitude in a cross section of one of the most strongly coupled modes is shown in figure 7, and it can be seen that this mode is so strongly coupled (almost 100%) that it is more sensible to discuss it as a full cryomodule mode, rather than a single cavity phenomenon.

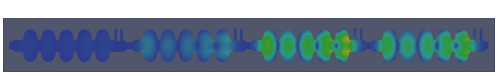

Figure 7: Electric field amplitude in a cross section of a highly coupled dipole mode.

In the case of the dipole modes, however, the operation of a HOM coupler located in this cavity interconnection region is significantly improved by increased coupling, so, if HOM couplers are installed, the enhanced mode coupling illustrated in figure 6 is desirable. This is not the case for the accelerating mode since the couplers are normally tuned to reject this frequency, and will not assist in absorbing power flowing between adjacent cavities.

CONCLUSIONS

It has been shown that studies of the evanescent sharing of HOMs between cavities are helpful in determining the minimum required inter-cavity beam-pipe length. These simulations also demonstrate that intuitive solutions to this problem – such as introducing the taper seen in figure 5 – may not suppress these unwanted effects as much as intended.

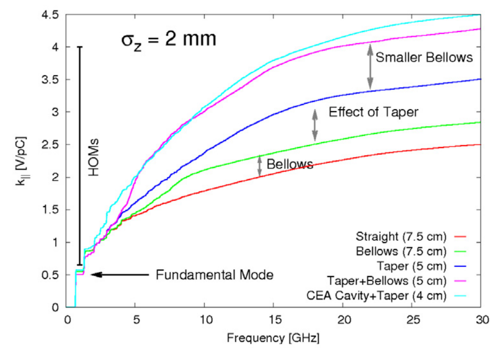

Figure 8: Longitudinal loss factor due to the various interconnection components.

As can be seen from figure 8, the introduction of a taper exacerbates the longitudinal loss factor experienced by the beam, which will translate into increased energy spread and beam losses throughout the machine. If the taper does not serve to reduce the coupling as intended, yet leads to these negative effects, a redesign of this region of the cavity may be necessary.

ACKNOWLEDGEMENTS

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REFERENCES

[1] "Conceptual design of the SPL II: A high-power superconducting H^- linac at CERN", M. Baylac, et al., 2006

[2] "Higher Order Mode Analysis of the SPL Cavities", M. Schuh, et al., these proceedings.

[3] "SPL cavity design by CEA-Saclay", J. Plouin, 3rd SPL Collaboration Meeting, 11-13 November 2009, CERN

[4] http://www.nersc.gov/

[5] "State of the Art in Finite-element Electromagnetic Codes for Accelerator Modeling under SciDAC", C. Ng et al., this conference