

DESIGN OF THE PI-MODE STRUCTURE (PIMS) FOR LINAC4

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Abstract

The PIMS will accelerate an H^- beam from 100 to 160 MeV, the output energy of Linac4. The cell length is constant within each of the 12 seven-cell cavities, but increases from cavity to cavity according to the increasing beam velocity. Its mechanical design is derived from the five-cell normal conducting LEP cavities, which were in operation at CERN for approximately 15 years. Even though the shunt impedance is around 20% lower than for a Side-Coupled Linac (SCL) operating at 704 MHz, the PIMS has the advantage of using the same RF frequency (352 MHz) as all the other accelerating structures in Linac4, thus simplifying and standardising the linac RF system. Furthermore, the simplified mechanical construction of the PIMS, which uses only 84 cells instead of over 400 for the SCL, also reduces construction costs and tuning effort. In this paper we present the electromagnetic design of the PIMS, including the arguments for the choice of a 5% cell-to-cell coupling factor, the shape of the coupling cells, and the expected field errors during operation.

INTRODUCTION

Linac4 [1, 2] is presently under construction at CERN as a replacement for Linac2, and is part of the LHC injector upgrade [3]. In the 1st stage Linac4 will operate with low duty cycle (0.1%) as an injector for the CERN PS Booster (PSB). In the 2nd stage Linac4 will be the front-end for a low-power Superconducting Linac (LP-SPL), still operating at a modest duty cycle, while in the 3^d stage it is foreseen to operate as a high duty cycle injector (6%) for a high-power version of the SPL (HP-SPL) [4]. For this reason the design duty cycle for the PIMS was chosen to be 10%. Some of the design features described in the following were verified on a set of scaled (704 MHz) cold models, the design of which was presented in [5]. 2D simulations were made with Superfish and 3D simulations were done with GdfidL [6]. A complete report on all design features of the PIMS can be found in [7]. The main characteristics of the PIMS section in Linac4 is summarised in Table 1 and a comparison of its shunt impedance with a SCL at 704 MHz [1] is shown in Fig. 1.

CAVITY DESIGN

Shape of Coupling Slot & Coupling Factor

The slots couple the electromagnetic fields magnetically between the cells and their shape was optimised to reduce additional losses. Between 1 and 4 slots were used in simulations between the cells and it was found that 2 slots per wall cause the minimum amount of additional losses. The

Table 1: Main Parameters of the PIMS

frequency	352.2	MHz
energy range	102 - 160	MeV
accelerating gradient	3.9	MV/m
number of cavities	12	
cells per cavity	7	
coupling factor†	5.6 - 5.0	%
effective shunt impedance‡	23.1 - 26	MΩ/m
peak surface field	1.8	kilpatrick
design duty cycle	10	%
total power per cavity	960 - 1020	kW
beam loading	180 - 210	kW

† for intermediate cells, ‡ ZT^2 scaled by 0.7 with respect to Superfish

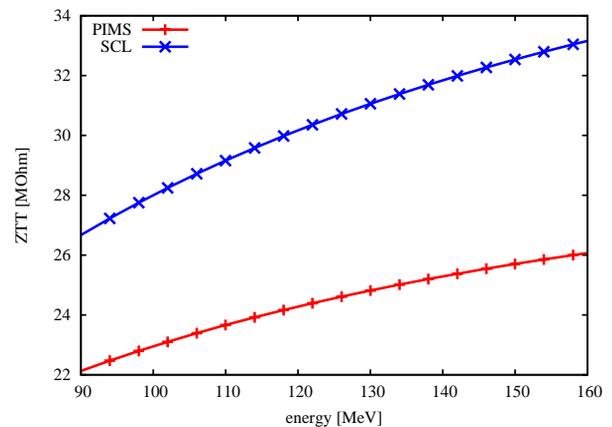


Figure 1: Expected shunt impedance for SCL the PIMS.

slots are then rotated by 90° from cell to cell to minimise the 2nd neighbour coupling.

The optimisation of the slot shape started with the “standard” shape, which is usually employed for magnetic coupling (see left picture in Fig. 2). The radial opening dR is usually increased up to the point where electric coupling through the slots starts to counteract the magnetic coupling (reached at 100 mm). In the optimisation it was found that: if one compensates the loss of coupling for large dR by an increased opening in the angular direction ($d\Phi$), one can achieve a better shunt impedance for the same coupling factor than for slots with smaller dR . The difference can be appreciated in Fig. 3 (curves for $dR = 100$ mm and $dR = \text{full}$). Further optimisation could be achieved by having parallel slot side walls (in angular direction) and by having a convex, rather than a concave, lower slot curvature. The resulting shunt impedance versus coupling factor is again shown in Fig. 3.

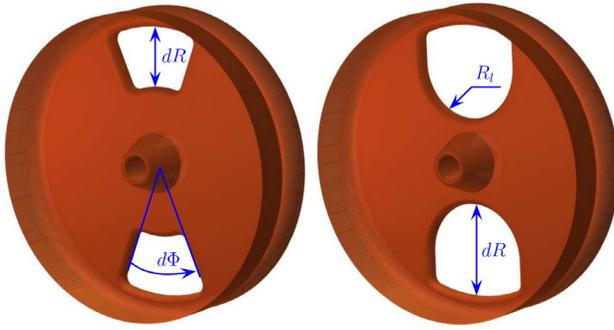


Figure 2: Different coupling slot shapes: left: standard shape, right: modified shape.

Since inaccuracies in simulations often occur when there are high losses on edges, the results were verified with measurements on cold models with different slot shapes. Using measurements of the coupling factor k , (R/Q) , and Q , the shunt impedance could be determined experimentally (see [7]) and compared to the simulation results. As one can see from the comparison in Table 2 the results agree quite well, meaning that the slot modifications can indeed be used to increase the shunt impedance for a certain coupling factor. In the case of the PIMS, the optimisation resulted in a higher shunt impedance for 5% coupling, than for 3% coupling using the standard slot shape.

Table 2: Comparison of Experimentally Determined and Simulated Shunt Impedance for Different Slot Shapes

slot type	k [%]	Q (exp)	R_{rel} (exp)	R_{rel} (sim)
std	3.2	9330 (± 74)	100	100
mod	3.1	9430 (± 74)	105.2 (± 1.6)	104.1
mod	5.0	9180 (± 74)	105.1 (± 1.6)	103.1

A statistical equivalent circuit analysis was made to determine the expected cell to cell voltage variations, assum-

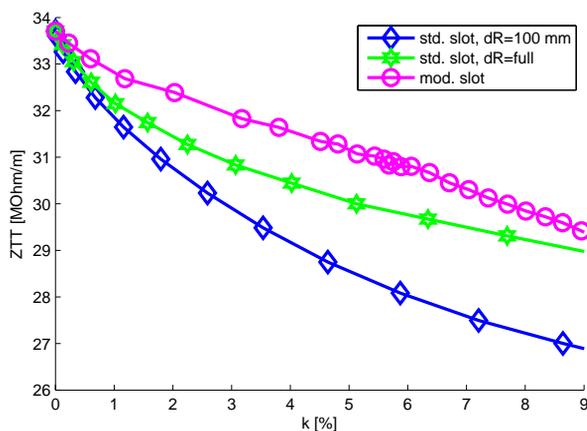


Figure 3: ZTT versus coupling factor for different coupling slot shapes.

ing a cell frequency error of ± 25 kHz. The resulting voltage error depends linearly on the chosen frequency error and is inversely proportional to the coupling factor. In our case a coupling factor of 5% results in a voltage error (average plus 2 times standard deviation) of $\pm 1.75\%$. Beam dynamics simulations [8] showed that voltage errors of up to 10% can be accepted as long as the average energy gain per cavity remains constant. With the 7-cell cold model a field flatness (maximum difference of peak electric fields) of 0.74% could be achieved after tuning.

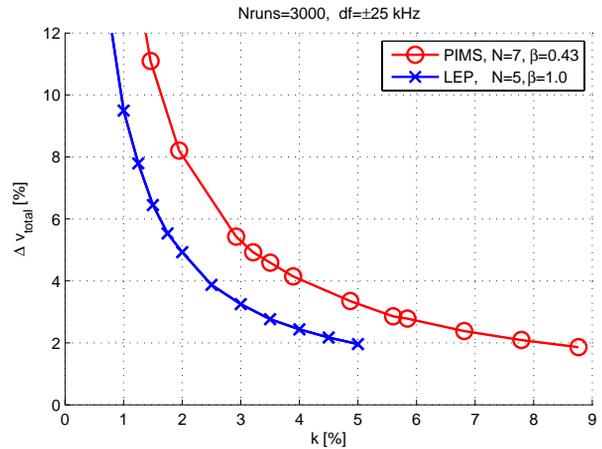


Figure 4: Voltage error versus coupling factor for the Linac4 PIMS and the 5-cell LEP cavities.

Tuning

Each cavity is equipped with 5 fixed and 2 movable tuners, which have a tuning range of ± 0.5 MHz. Before welding the discs and cylinders each cell can be tuned individually by removing thin layers of material from the “tuning islands”, which are located between the coupling slots on each disc (see Fig. 5). These islands provide a tuning range of -1.5 MHz to $+1.0$ MHz and are meant to correct systematic errors. The expected weld shrinkage of 0.2 mm causes a frequency shift of ≈ -310 kHz, which will be verified experimentally and which will be taken into account in the drawings. The difference between air and vacuum will cause a shift of $+114$ kHz, and the shape of welding groove causes a shift of -190 kHz. Between low and high duty cycle operation a frequency shift of -200 kHz was calculated, which will be compensated by the piston tuners. Another effect of the heating up of the structure is an increased surface resistance, which reduces the shunt impedance.

The tuning of the end-cells requires a larger volume in these cells, which in turn reduces the coupling factor between the end-cells and the “ $N - 1$ ” cells. In the PIMS hot model we will have a coupling factor of 5.65% for the inner cells and a factor of 5.25% between the 2 first and last cells of each cavity. In order to achieve a flat field the 2nd and 6th cell frequency have to be lowered by 0.5 MHz. The frequency shift in the centre cell, caused by the wave-guide coupler amounts to ≈ -3.9 MHz and is compensated by the shape of the nose cones in this cell.

Transient Response

In steady state the voltages of all 7 cells are exactly equal (apart from machining errors). During the filling of the structure, however, the electromagnetic waves bounce between the two end walls and cause different voltages in the cells. As long as there is no beam loading the voltage profile is symmetric to the centre cell, where the RF coupler is located. This situation changes with the arrival of the beam, which presents a time dependent load in the cavities and which results in an irregular voltage profile. This behaviour is typically worse in π -mode structures, than in the naturally stabilised $\pi/2$ mode structures. For this reason we studied the differential equations of a transient circuit model to assess the effects of a chopped beam on the voltage distribution within a PIMS cavity (see [7]). Assuming the chopping scenario for Linac4 with 222 filled and 133 empty bunches, and applying a 40 mA average beam current the model produces the voltage profile shown in Fig. 6.

One can observe that the cell to cell voltage is indeed different for a chopped beam, but only by a maximum of 0.5%. The triangular profile of the voltage evolution comes from the fact that a constant generator voltage was assumed, which only covers the average cavity load and which is not modified by a LLRF feed-forward. If one removes the triangular profile, the variation of the average cavity voltage due to the loading with a chopped beam is in the order of 10^{-6} .

CONCLUSION & OUTLOOK

A 7-cell π -mode structure was designed for the use in Linac4 at CERN. The coupling slots were chosen to minimise cell-to-cell voltage errors and their shape was optimised for maximum shunt impedance. The positive effect of this new shape on the shunt impedance was verified

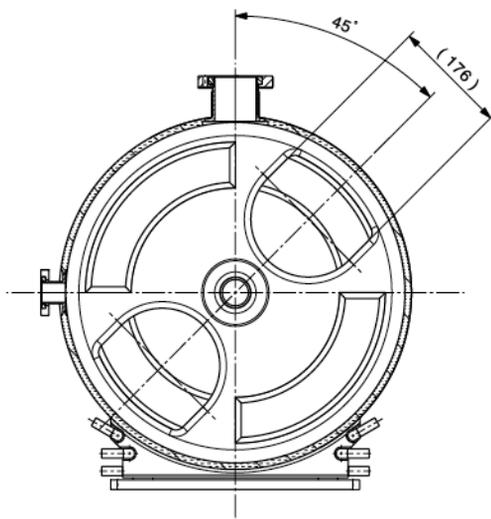


Figure 5: Tuning islands between the coupling slots on the walls between the cells.

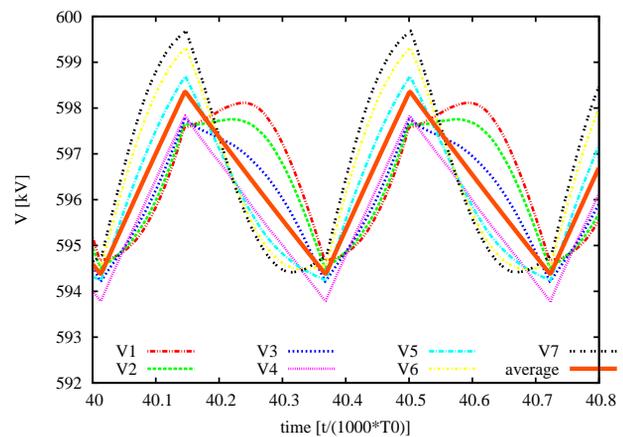


Figure 6: Voltage evolution when loading a PIMS cavity with a chopped beam: $I_{av} = 40$ mA, 222 full and 133 empty bunches.

with measurements on a scaled cold model, where it was also shown that a flat field profile can be achieved. The frequency shifts of: air/vacuum transition, welding, power coupler, end-cells, and heating of the structure were estimated and a tuning strategy is presented in this paper. The transient behaviour under beam loading with a chopped beam was analysed and can be considered as negligible. At present a 7-cell hot prototype is under construction at the CERN workshops and measurements are expected for 2010.

ACKNOWLEDGEMENTS

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