THE HOT PROTOTYPE OF THE PI-MODE STRUCTURE FOR LINAC4

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Abstract

The PIMS (Pi-Mode-Structure) cavities for Linac4 are made of 7 coupled cells operating in π-mode at a frequency of 352 MHz. The mechanical concept is derived from the 5-cell cavities used in the LEP machine, whereas cell length and coupling are adapted for proton acceleration in the range from 50 to 160 MeV. Linac4 will be the first machine to employ this type of cavities for low-beta protons. During the first years of operation the PIMS will be used at low duty cycle (0.1%) as part of the consolidated LHC proton injector complex. It is designed, however, to operate eventually in a high duty cycle (10%) proton injector, which could be used as proton front-end for neutrino or RIB applications. To prepare for the series construction of the 12 PIMS units the first cavity (102 MeV beam energy) has been designed and constructed at CERN, to be used as a hot prototype for RF tests and as a pre-series mechanical unit. In this paper we report on some of the design features, the construction experience, and first measurements.

MECHANICAL CONSTRUCTION

The RF design [1, 2] and mechanical design [3] of the PIMS has been re-developed based on the original drawings of the LEP cavities [4]. Each cavity consists of discs and rings (see Fig. 1), which are joined via Electron Beam Welding (EBW). Before the final welding operation the structure is clamped and connected to the waveguide coupler (see Fig. 2) to perform bead-pull measurements. Taking into account the expected weld shrinkage and frequency change due to the air/vacuum transition, one can then define the final height of the tuning rings on each disc, such that a flat field can be achieved within the tuning range of the piston tuners (5 fixed tuners plus 2 movable tuners).

With respect to the LEP cavities a number of changes were introduced, which are described in the following: i) The cell-to-cell coupling was increased from $\approx 1.3\%$ to $> 5\%$ for increased field stability, and the shape of the coupling hole was optimised for increased shunt impedance, so that the increased coupling factor does not result in excessive RF losses [1]. ii) The pre-assembly frequency tuning is now done with tuning rings on the disc walls, instead of changing the inner diameter of the rings. With this measure one can reduce the thickness of the copper rings, which are ordered from the forgery. iii) The tuner ports are now welded (EBW) to the rings instead of brazed. This results in increased rigidity of the copper, which can be used to further reduce the thickness of the rings and also to reduce the thickness of the weldings, which join discs and rings. The only piece, which undergoes heat treatments is the central ring with the wave-guide coupler port, where a rectangular stainless steel flange is brazed onto the port opening. The waveguide port itself is machined out of bulk copper together with the central ring, which means that "thick" rings of copper are needed for these cells. iv) High quality 3D forged OFE copper in half-hard temper was used,

Figure 1: Discs and rings before welding.

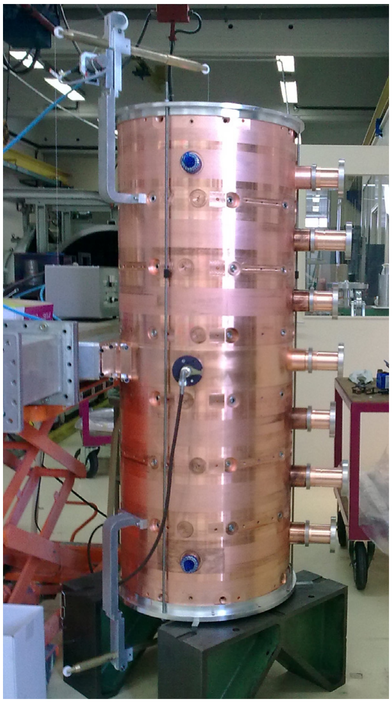

Figure 2: First tuning step: Bead-pull measurements on the clamped PIMS prototype before welding.

having a smaller and homogeneous grain size and lower oxygen content than the copper used for LEP. The main benefits are improved weldability, better mechanical stability, increased yield strength (important for high duty cycle operation) allowed by the half-hard temper. Ready weldability by EBW was proved, with limited risk of formation of porosity in the weld root. Figure 3 shows the worst case results of welding tests performed with standard OFE copper and 3D forged OFE copper. The latter now conforms to ISO standard 13919-1, level B, with limited risk of porosity inducing so-called virtual leaks for the vacuum system.

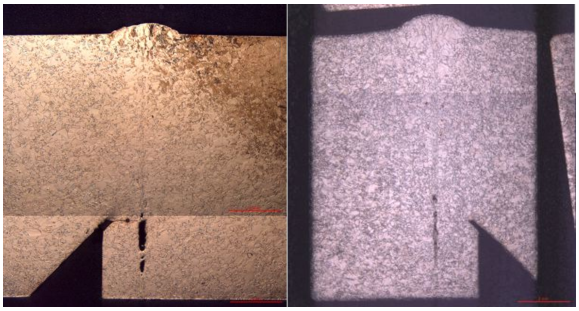

Figure 3: EBW on standard OFE copper (left) and 3D forged OFE copper (right).

The required machining precision in the range of 20 μm was achieved on most pieces as shown in Fig. 4. Cells containing the few pieces with larger tolerances could be tuned to their correct frequencies using the tuning islands.

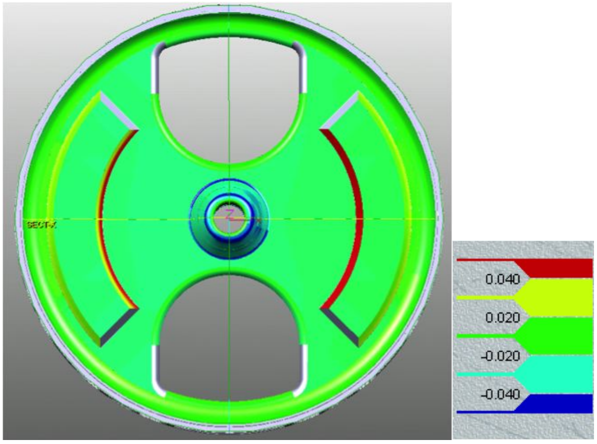

Figure 4: Metrology result for a disc face with tuning rings. The colour scale indicates the tolerances in mm.

The average weld shrinkage of the large orbital welds is between 0.18 mm and 0.25 mm and rises to maximum values of 0.3 mm in the overlap areas (start and end point of the weld). To avoid a “banana” shape of the complete cavity, the position of the overlap areas is rotated by 90° from weld to weld.

RF TUNING AND LOW POWER MEASUREMENTS

The diameter of the piston tuners is limited to 62 mm to allow the discs and cylinders to be welded together by EBW. In consequence, the provided tuning range of 1 MHz is insufficient with respect to the frequency deviations caused by machining errors and the range needed for flat field tuning. Therefore, each disc is equipped with tuning rings, also called tuning islands, which can lower the resonant frequency of each cell by up to 2.2 MHz. The tuning of the PIMS cavity is done in two steps, which are described in the following.

Tuning Before Welding

After the first bead-pull measurements on the clamped structure (Fig. 2) the piston tuners are adjusted to achieve a flat field distribution. The cavity is tuned to the desired frequency (352.485 MHz), considering various effects that will still influence the frequency (see Table 1). This results in a symmetry of the tuner positions with respect to the central cell and confirms that all parts were machined within tolerances. It was expected that the tuners of cell 2 and 6 penetrate less as the coupling coefficient of the end cells is smaller than the one of the other cells (due to a bigger volume of the end cells). The central cell is 0.16 mm shorter than the other cells which lowers its frequency by ≈300 kHz. Hence, the central tuner is also less penetrated. Initially it was foreseen to define the nominal tuner position for a penetration that corresponds to a frequency increase of +500 kHz. But since the tuning procedure turned out to be very accurate, it was decided to choose +350 kHz as the nominal position for the fixed tuners (in cells 1,3,4,5 and 7) which lowers the cavity losses, and to keep +500 kHz for the movable tuners in cells 2 and 6.

Table 1: Effects that change the resonant frequency of the PIMS cavity after the first tuning. df denotes the expected frequency shift and f_0 the expected resonant frequency. Measurements in air were performed at a temperature of 25.6°C, a humidity of 53% and a pressure of 976 hPa.

effect	df [kHz]	f_0 [MHz]
		352.485
re-machining of tuning islands	-145	352.340
weld shrinkage	-250	352.090
use of RF contacts for tuners	+35	352.125
air to vacuum	+89	352.214
operating temperature 28°C	-14	352.200

Once a flat field distribution is achieved, all 7 TM_{01} mode’s frequencies are measured (see Table 2). These measurements allow to adjust the coupling coefficients used in the equivalent circuit model to obtain a good agreement of all 7 resonant frequencies. In this case, the following coupling factors were found: $k_1 = 5.70\%$ (1st order coupling), $k_2 = -0.099\%$ (2nd order coupling), $k_{end} = 5.36\%$ (coupling between end and penultimate cell). The design values are: $k_1 = 5.65\%$, $k_2 = -0.10\%$, $k_{end} = 5.20\%$. The adjusted equivalent circuit model is extremely important because it is applied to calculate the resonant frequency of each cell. After the flat field distribution has been achieved, the tuner in cell n is removed completely and the change in frequency of the π-mode is recorded. The equivalent circuit model can then be applied to obtain the corresponding frequency of the considered cell n.

Table 2: Resonant frequencies of all 7 TM_{01} modes, the measured ones and the simulated ones using an equivalent circuit model and the 3D field simulator GdfidL, respectively.

mode	measurement [MHz]	equivalent circuit [MHz]	GdfidL [MHz]
1	352.485	352.485	352.485
2	353.553	353.472	353.474
3	356.081	356.149	356.119
4	360.224	359.911	360.079
5	364.500	364.247	364.675
6	368.960	368.587	369.002
7	371.910	371.912	372.104

Once the resonant frequency of a cell is known, its tuning islands can be re-machined to decrease the frequency shift of the tuners to the desired amount. Tuning islands of different heights were simulated for all cell types (end, intermediate and central cell) and the results were verified with cold model measurements. These curves were used to define the re-machining operation for each tuning island. It was foreseen to perform 3 machining steps but as the first operation agreed extremely well with the predictions, all tuning islands were directly machined to their final height in one step. The maximum error found is 21 kHz, corresponding to 0.10 mm in height, which is the tolerance for re-machining. The Q-value with all tuners in their nominal position before welding was 16’650.

Tuning After Welding

After the electron beam welding of the entire cavity the measurements are repeated, this time in horizontal position to avoid turning the complete prototype (650 kg). The field flatness was tuned to be better than ±0.5% (required are $\pm 5\%$). The Q-value increased to 18’600 after welding (tuners inserted), which is 85% of the value simulated with HFSS, including the effects of tuners, tuning islands, welding rings and measurement temperature. The mechanically measured shrinkage due to the EBW was confirmed by the RF measurements to be ≈0.20 mm. The main RF design parameters of the PIMS section are summarised in Table 3.

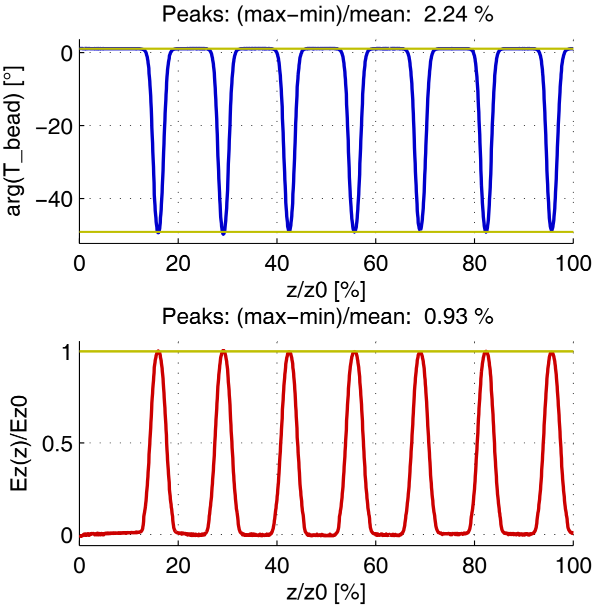

Figure 5: Bead-pull measurement results, upper plot: phase shift due to the perturbating bead at a fixed frequency, lower plot: field distribution within the cavity.

Table 3: Main PIMS Parameters

frequency	352.2	MHz
input/output energy	102/160	MeV
electric gradient	4.0	MV/m
peak power/cav.	960 - 1020	kW
beam loading	180 - 210	kW
design duty cycle	10	%
cells/cavity	7	
number of cavities	12	
cavity length (inside)	1.30 - 1.55	m
beam aperture	40	mm

SUMMARY AND OUTLOOK

The RF and mechanical design of the PIMS was verified on a full scale prototype, to be used as module number 1 in the PIMS section of Linac4. High-power RF tests are foreseen before the end of year, once the construction of the waveguide coupler is finished. In parallel the material orders for all 12 cavities have been placed and series construction is expected to start in the beginning of 2011.

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