DEVELOPMENT STATUS OF THE PI-MODE ACCELERATING STRUCTURE (PIMS) FOR LINAC4

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Abstract

The high-energy section of Linac4, between 100 and 160 MeV, will be made of a sequence of 12 seven-cell accelerating cavities of the Pi-Mode Structure (PIMS) type, resonating at 352 MHz. The cell length is the same within a cavity, but changes from cavity to cavity according to the beam velocity profile. Compared to other structures used in this energy range, π-mode cavities with a low number of cells have the advantage of simplified construction and tuning, compensating for the fact that the shunt impedance is about 10% lower because of the lower frequency. Field stability in steady state and in presence of transients is assured by the low number of cells and by the relatively high coupling factor of 5%. Standardising the linac RF system to a single frequency is considered as an additional economical and operational advantage.

The mechanical design of the PIMS will be very similar to that of the 352 MHz normal conducting 5-cell LEP (Large Electron Proton collider at CERN) accelerating cavities, which have been successfully operated at CERN for 15 years. After reviewing the basic design principles, the paper will focus on the tuning strategy, on the field stability calculations and on the mechanical design. It will also report the results of measurement on a cold model and the design of a full-scale prototype.

RF DESIGN

The PIMS replaces a Side Coupled Linac (SCL), which was originally foreseen in the high energy section of Linac4 [1]. The SCL was using a total of 468 cells (220 accelerating cells plus coupling cells) operating at 704 MHz to accelerate beam from 90 to 160 MeV, while the PIMS now covers 102 to 160 MeV using only 84 cells (12 cavities of 7 cells). Since the construction and tuning of π-mode cavities is already well known at CERN, and since the SCL entails the use of 2 different RF frequencies in Linac4 it was decided to give preference to the PIMS [2] despite the $\approx 12\%$ lower shunt impedance (see Fig. 1).

The basic design is a scaled (in geometrical β) version of the normal conducting LEP accelerating structure [3], which was then modified for higher cell-to-cell coupling. The accelerating gradient in the first 10 cavities has been adjusted to a relatively high value of 4 MV/m, resulting in a maximum power of ≈ 1 MW per cavity. Using a high gradient limits the number of cells per cavity to 7, and thus makes it easier to obtain a flat field distribution. The last 2 cavities are used not only for acceleration but also for energy painting for injection into the subsequent Proton Syn-
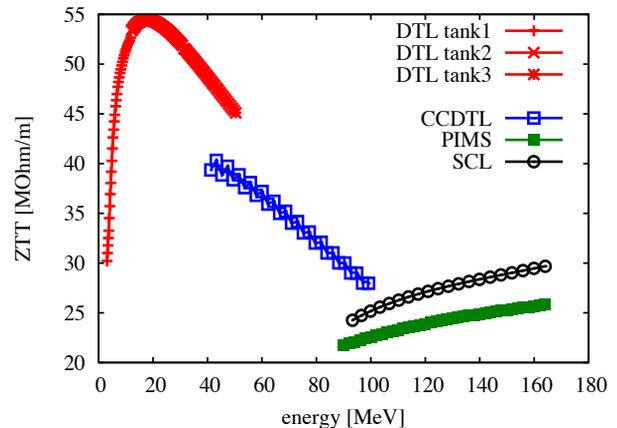
Figure 1: Shunt impdance (ZT^2) for the Linac4 accelerating structures (80% of simulated values, including additional losses on stems, coupling holes, tuning rings).

chrotron Booster (PSB). In order to achieve a high ramping speed in these cavities (≈ 2 MeV/10 μs), the nominal accelerating gradient was lowered to 3.1 MV/m. An overview of the main parameters is given in Table 1. The basic design was made with Superfish and the 3D calculations to determine the coupling coefficients, shunt impedance degradation (due to coupling, tuners, etc), end-cell tuning were made with GdfidL [4] (see Fig. 2).

Table 1: Main Parameters

parameter		value
frequency	MHz	352.2
input energy	MeV	102
output energy	MeV	160
electric gradient	MV/m	4
peak power/cav.*	MW	1
max. surface field	kilpatrick	1.8
design duty cycle	%	10
max. expected d.c.	%	6
Linac4 d.c.	%	0.1
cells/cavity		7
number of cavities		12
beam aperture	mm	40

* including beam loading

Using a coupled circuit model one can evaluate the voltage error due to the expected spread in cell frequencies, which is linked to the production tolerances and the tuning precision. Assuming the same frequency scatter (± 25 kHz)
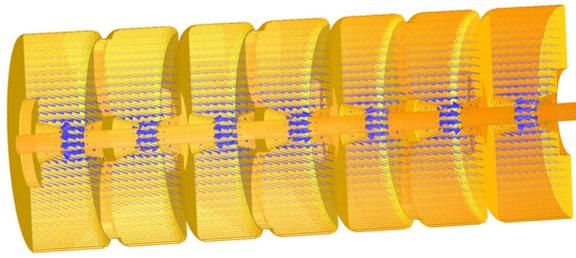
Figure 2: GdfidL simulation of the 7-cell structure.

as for the LEP cavities one can calculate the expected voltage error versus coupling factor as shown in Fig. 3.
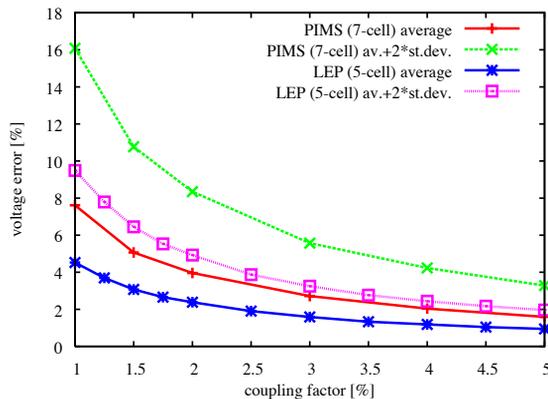
Figure 3: Voltage error versus coupling factor (3000 error cases per point).

One can see that we can achieve the same level of voltage errors (av. + 2x st. dev:6.5%) as in LEP (5 cells, 1.5% coupling), when increasing the coupling to 2.7% for a 7-cell structure. After calculating the loss in shunt impedance for various coupling factors, we decided to use 5% coupling, for which we expect a 11% reduction in ZT^2. Further reductions in shunt impedance are coming from: surface roughness ($\approx -7\%$), RF coupler ($\approx -2\%$), increased volume of end cells ($\approx +4\%$), heating during high-duty cycle operation ($\approx -3.5\%$), welding grooves ($\approx -2\%$), tuning rings and tuners ($\approx -4\%$). For Linac4/SPL operation this means a total reduction of $\approx 22/26\%$ with respect to Superfish. For power calculations we use an additional safety margin and reduce the calculated values by 30%.

The frequency tuning of the structure is done in 2 steps: i) Before the joining of the discs and cylinders the machined cells are clamped together and the cell frequencies are measured. Deviations are then corrected by machining the "tuning islands", which are shown in Fig. 4, taking into account the expected frequency shifts due to vacuum, welding, heating, etc, which are listed in Table 2. ii) Each cell is equipped with a tuner, which can change the cell-frequency by ± 0.5 MHz. Cells 2 and 6 have movable tuners and all other cells have fixed tuners, which are cut to length after the assembly of the complete cavities.
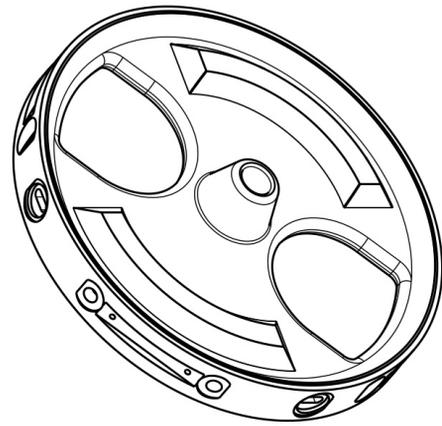
Figure 4: 3D disc geometry with tuning islands.

Table 2: Expected Frequency Shifts for the Full Cavity

effect	Δf [kHz]
machining tolerances	± 200
thermal expansion	-200
welding rings	-190
weld shrinkage (disc/cylinder weld)*	-310
air to vacuum	+114

* assuming 0.2 mm shrinkage per weld (to be confirmed)

COLD MODEL MEASUREMENTS

A scaled (to 704 MHz) 7-cell aluminium cold model was constructed at CERN to test the RF design procedure for cell frequencies, coupling factor, end-cell tuning, and field flatness. Two cells of the model are shown in Fig. 5 and a field profile measured via bead-pull is shown in Fig. 6. The measured field flatness was better than expected and is within 0.8% ($\Delta E/E_0$).
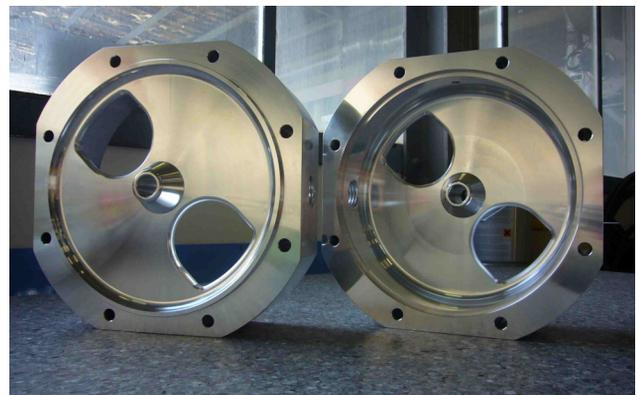
Figure 5: Aluminium cold model.

When detuning the end cells the coupled circuit model predicts a tilt sensitivity of 66%/MHz (at 352 MHz), which could be confirmed by measurements.
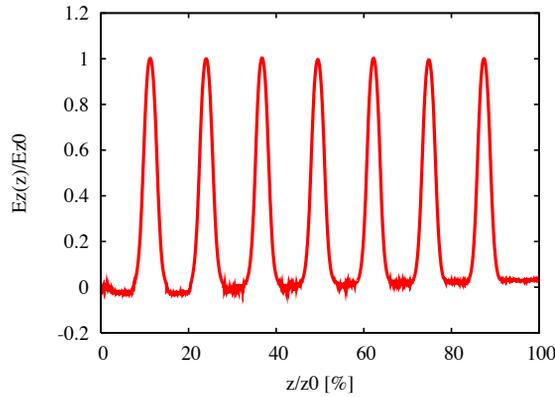
Figure 6: Measured field profile of cold model (bead-pull).

SERIES CONSTRUCTION

The structure is composed of discs (as in Fig. 4) and cylinders, which are joined via electron-beam (EB) welding around the circumference. The welding is applied from the outside with full penetration as shown in Fig. 7.
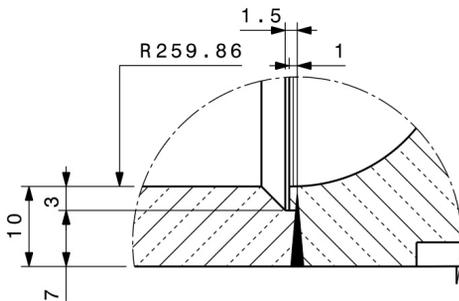
Figure 7: Electron-beam welding joint between discs (right) and cylinders (left).

Discs and cylinders are machined out of pre-shaped 3D forged OFE copper. The option of using copper plated steel was abandoned after cooling simulations showed excessive heating of the structure. All copper ports (including the brazed steel vacuum flanges) are EB welded onto the cylinders before joining the whole structure. The only exception is the RF port together with its cooling channels, which are machined out of a thick cylinder. In this case, in order to braze the 316 LN vacuum flanges onto the RF and tuner ports, the whole cylinder is put into the brazing oven. All other discs and cylinders do not undergo any heat treatment and thus maintain their original material properties.

For the cooling of the cells water channels are drilled from the outside into the discs as shown in Fig. 8. Due to the high heat load around the edges of the coupling slots additional channels were introduced to avoid any deformation of the coupling slot shape due to increased temperatures during operation. In contrast to the LEP cavities no cooling channels are used on the cylinders. ANSYS$^{©}$ simulations, which assume a constant water temperature of 21 deg and an average normal flow velocity of 1.4 m/s, show maximum temperatures of ≈ 60 deg at the nose tips and the inner cor-
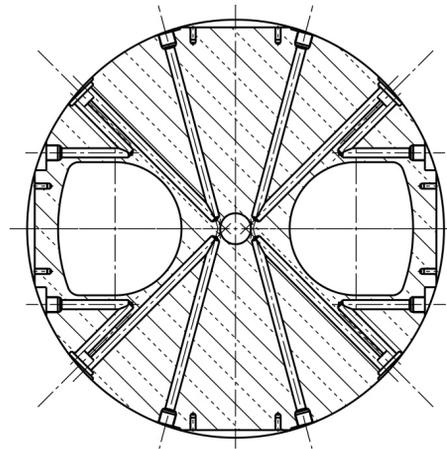
Figure 8: Cooling channels in the discs.

ner radius of the slots for a 10% duty cycle (see Fig. 9).
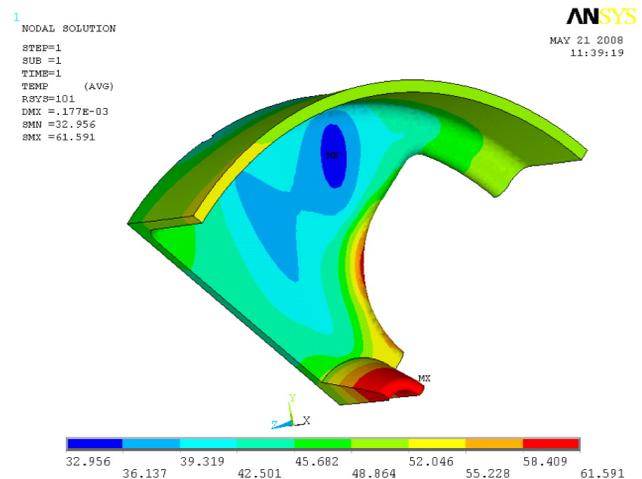
Figure 9: Cooling simulation with ANSYS$^{©}$, assuming constant average water temperature of 21 deg, average normal flow velocity of 1.4 m/s, and a duty cycle of 10%.

The stress values due the structures own weight, the weight of attached wave-guide and the cooling thermal stresses, are well below the limits for plastic deformation, following the von Mises criterion. The construction of a "hot" prototype starts in October in the CERN workshops and high-power tests are expected in summer 2009.

REFERENCES

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