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HIGH POWER TEST OF THE FIRST PIMS CAVITY FOR LINAC4

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Abstract

The first cavity of the PI Mode Structure (PIMS) section of Linac4 has been high power tested at Linac4 conditions and under high average power to simulate the operating conditions of Linac4 as a high duty cycle injector for the SPL. The PIMS section consists of 12 seven cell cavities, which accelerate the Linac4 beam from 102 MeV to 160 MeV at an RF frequency of 352.2 MHz. The cell length is constant per cavity but is adapted to the particle speed from cavity to cavity.

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INTRODUCTION

A full scale (also called 'hot') prototype of the PI Mode Structure (PIMS) has been designed [1], constructed, tuned [2] and high power tested at CERN. The prototype has the same dimensions as the 1st PIMS cavity (design energy 104.3 MeV) of Linac4 [3] and due to its excellent performance this prototype will be used as the first module of the PIMS section in Linac4.

Linac4 operates at a relatively low duty cycle of 0.8‰ (RF pulse length 400 µs and repetition frequency 2 Hz). However, all accelerating structures have been designed to operate at a duty cycle of up to 10% for future upgrades as front-end of a high power SPL [4].

Set-up

A frequency generator was used to generate pulses with the desired frequency, amplitude and length. The timing was sent to the HV modulator and the signal was amplified by a chain of amplifiers with a modified LEP klystron (max. output power 1.3 MW) as the last stage. The pulsed modulator limited the repetition frequency to 2 Hz. In the second high power test, using a different klystron and modulator set-up, operation CW power was limited by the HV supply and cooling circuit to about 100 kW. In both cases WR2300 waveguides transported the RF power to the cavity, which was installed in a bunker to shield the produced X-rays.

Inside the bunker, as shown in Figure 1, several temperature sensors were attached to the cavity in order to study the evolution of the temperature while increasing the power level. Sixteen thermocouples were used to monitor the temperature, seven on the cavity (one on each cell), three on tuners 2, 4 and 6, two on the water outlets and inlets and four on the waveguide and in the coupling iris area.

For RF measurements, RF pickups were placed in cells 1, 4 and 7 for monitoring the field levels.

GENERAL CONDITIONING PROCESS (0.1% DUTY CYCLE)

The conditioning process started with a pulse length of 800 µs and a peak power level of 1 kW in order to evaluate the setup (even though the generator was not yet synchronized to the modulator). The parameters that were monitored were the vacuum level inside the cavity, two radiation levels, one on the beam axis and the other outside the cavity, the energy stored inside the cavity, and the temperature measured by the thermocouples. Several interlocks were used to avoid any damage. The interlock most frequently triggered was linked to the vacuum level. It stopped the RF when the pressure level increased above $8\cdot10^{-6}$ mbar.

Figure 1: The PIMS cavity connected inside the bunker.

Once the RF generator was synchronized to the modulator, the procedure was slightly changed: a certain power level was maintained while the pulse length was gradually increased. When an interlock was triggered due to the vacuum levels inside the cavity, the amplifier had to be restarted. Table 1 shows the evolution of the conditioning process. During the first days, the acceptable peak power was limited by the vacuum level due to multipactor, but once these power levels were exceeded, the conditioning went fast. After 28 hours the cavity was conditioned to the nominal peak power P_{peak} = 700 kW at a repetition rate of 2 Hz and a pulse length of 800 µs.

After these measurements, the maximum power level of the klystron was increased further in order to test the limits. After 14 hours of cavity conditioning with 1.1 MW, the pulse length could be increased to 760 µs. This time the limiting factor was not only the vacuum level, but also the radiation levels of 500 mSv/h and 180 µSv/h on beam axis and outside the bunker, respectively.

Table 1 : Conditioning Process of the prototype. T_{RF} summarizes the number of hours the cavity was tested, P_{peak} is the maximum power fed into the cavity, T_{pulse} is the maximum pulse length, X-ray$_{axis}$ is the maximum level of radiation measured on the beam axis and X-ray$_{ext}$ is the maximum level of radiation close to the waveguide connection. All values refer to the day of operation, given in the first column.

Day 2010	**T_{RF} [h]**	**P_{peak}**	**T_{pulse} [µs]**	**Vacuum [mbar]**	**X-ray$_{axis}$ [mSv/h]**	**X-ray$_{ext}$ [µSv/h]**
2.11	2	1 kW	800	$5\cdot10^{-6}$	0	0
3.11	6	1 .. 10 kW	25	$8\cdot10^{-6}$	0	0
4.11	6	700 kW	180	$8\cdot10^{-6}$	12	14
5.11	2	700 kW	300	$4\cdot10^{-6}$	15	20
8.11	4	700 kW	500	$1\cdot10^{-6}$	17	30
9.11	5	~ 500 kW	800	$8\cdot10^{-6}$	17	36
10.11	3	700 kW	800	$1\cdot10^{-6}$	25	44
sum	**28**					

TEMPERATURE AND POWER MEASUREMENTS

After the cavity was fully conditioned, several measurements were done in order to check the behaviour of the prototype in different extreme situations.

One of these measurements was to completely stop the cooling and evaluate temperature differences in the thermocouples, the power levels in the three pickups and the frequency difference between cold and hot cases. The initial power levels were: 1165 kW for pickup 1 (cell 1), 1129 kW for pickup 2 (cell 4), 1123 kW for pickup 3 (cell 7) and 1106 kW for the forward power (all power readings have a tolerance of about ±5%). After 3 hours of operation without cooling, the temperatures increased by 26.5 K on average and the resonant frequency decreased by 243 kHz (about 9 kHz per Kelvin). Table 2 lists the relative power levels measured. In all cells, the field level dropped. The input power from the klystron slightly increased (frequency dependent output power level) due to a degradation of the Q-value with higher temperature (reduction of copper conductivity). The observed Q-value reduction with temperature is similar to the theoretical value of 3.9%/K for a homogeneous heating of a bulk copper block. Another effect that was measured is the tilt of the cavity field distribution which amounted to only 2% within the tolerance given by beam dynamics. It shows that even in this extreme condition the cavity is thermally stable and that there is no run-away of the field due to operation in the pi-mode, even without cooling. Two movable tuners placed in cell 2 and 6 can easily correct this tilt.

Another point of investigation was to quantify the missing energy (dark currents) in the operating regime and to find the operational limit. The design value of the peak electric surface field is 1.8 Kilpatrick (33MV/m). In order to check if this value is maintainable, the forward power from the klystron was adjusted in small steps from 0 kW to the maximum available power of 1.1 MW and the field level in the cavity given by a calibrated voltage probe, was measured for all points. Figure 2 shows the relation between the two quantities. The stored energy in the cavity rises linearly with the forward power for all levels. The cavity is operating indicating voltages below the field emission limit. The point of saturation is above 1.1 MW, corresponding to 2.3 Kilpatrick (42 MV/m). We can therefore conclude that the PIMS cavities design is conservative and that its operation at nominal parameters is therefore expected to be reliable.

Table 2: Power differences measured and temperatures after operating the PIMS cavity for 3 hours without cooling. The last column shows the relative difference to the average power readings from pickups 1 to 3. The sensor placed on cell 6 was defective.

Power Difference	**kW**	**%**	**$(P-P_{avgpickup})/P_{avgpickup}$ [%]**
Pickup 1 (cell 1)	-50.5	-4.3	1.7
Pickup 2 (cell 4)	-63.0	-5.6	0.4
Pickup 3 (cell 7)	-89.5	-8.0	-2.0
Forward Power	26.1	2.4	8.4

Temperature

Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 7
44ºC	46ºC	47ºC	47ºC	45ºC	42ºC

Frequency Difference -242.9 kHz

Df/dT (kHz/degree) -9.2

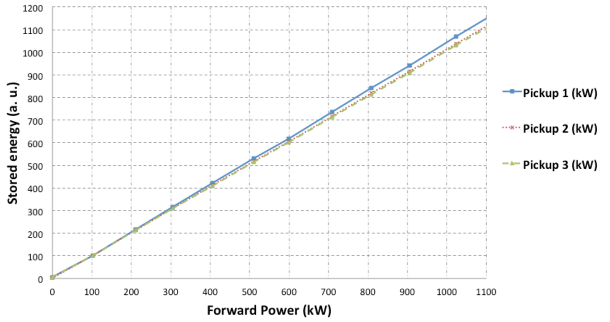

Figure 2: The stored energy in the cavity versus forward power to investigate the cavity's operational limit.

HIGH AVERAGE POWER TEST

The PIMS prototype has also been tested at a higher duty cycle at the SM18 test stand. The aim of this test was to validate the cavity's ability to work under the SPL heat load of up to 10% duty cycle and to investigate potential thermal instabilities.

Since the cavity was exposed to air during the installation, it was first re-conditioned for a few hours. However, multipactor activities that still occurred from time to time quickly triggered the vacuum interlock due to operation in continuous wave mode. The water flow (38 l/min per disc) was so high that the cavity's resonant frequency quickly (within minutes) decreased, making a re-start from low power levels at the initial frequency of 352.193 MHz necessary.

The maximum value tested was about 85 kW CW – which corresponds to a duty cycle of 12% at a peak dissipated power of 700 kW. The maximum input power that could be used for this test was not limited by the cavity itself but by the fixed tuners that became very hot (up to 150°C). For Linac4 these tuners are not water cooled, for high duty cycle operation it is foreseen to replace them with water cooled versions, which will also have a different penetration depth (due to the different operating temperature).

A considerable increase of the inlet temperature was noticed (from initially 25°C to 48°C) as the cooling station for this test stand approached its limit. The average temperature on the outside of the cells stabilised at a difference of about 20°C to the inlet temperature. This temperature increase was predicted by thermal simulations. Accordingly, the temperature on the hottest parts, the nose cone tips, is assumed to have reached 85°C. No thermal instabilities were found. However, the temperatures measured on individual cells differ by 9°C. This was caused by the individually cooled discs (4 separated channels per disc, 2 of them connected in series) where the flow rate was not controlled individually. In a machine, this effect will partly be compensated by the movable tuners and could further be optimized by adjusting the water flow of the discs individually. The beam can tolerate irregularities of the field distribution within a PIMS cavity of up to ±5% as long as the total accelerating voltage is kept constant. Challenges are rather seen on the operational side when interlocks are triggered.

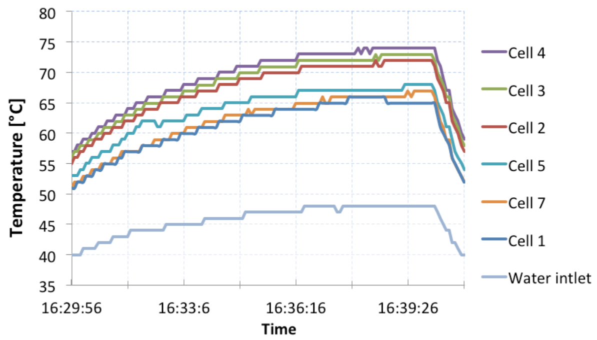

Figure 3: Temperatures measured at the outside of the PIMS cavity (at the center of the ring). The sensor of the cell 6 was detached during the test. The water temperature of the cooling water inlet rose to 48ºC. The order from top to bottom in the legend corresponds to the order in the plot.

SUMMARY

The PIMS prototype has been high power tested at Linac4 conditions up to a peak power of 1.1 MW, 60% above the nominal level. The cavity conditioned quickly (28 hours to the nominal level and in total 42 hours to 1.1 MW), even without prior bake-out. The relation between input power and the stored energy in the cavity remained linear up to 1.1 MW. The cavity is thermally stable and can even be operated for several hours without cooling.

At a second high power test, the cavity was tested under a high average heat load that corresponds to a SPL duty cycle of 12%. No thermal instabilities have been seen.

The prototype has the same dimensions as the first PIMS cavity for Linac4. Since the prototype performed as desired (and better) in all test, it has been decided to use this prototype directly as the first PIMS module in Linac4.

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