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The Linac4 DTL Prototype: Low and High Power Measurements

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Summary

The prototype of the Linac4 Drift Tube Linac (DTL) has undergone low power measurements in order to verify the RF coupling and to adjust the post-coupler lengths based on bead-pull and spectrum measurements. Following the installation at the test stand, the cavity has been subjected to high power operation at Linac4 and SPL duty cycles. Saturation effects and multipacting have been observed and linked to X-ray emission. Voltage holding is reported in the presence of magnetic fields from permanent magnet quadrupoles installed in the first drift tubes.

1. Introduction

A 103.4 cm long prototype of the Linac4 Drift Tube Linac operating at a frequency of 352.2 MHz and an average field of 3.3 MV/m has been built in collaboration with INFN, Legnaro [1]. After machining at CINEL s.r.l., Vigonza, the cavity has been assembled at CERN. The drift tube parts have been welded and the cavity has been copper plated at CERN. After plating, the tank has been assembled with the aluminium girder and drift tubes have been installed in the tank. The DTL prototype consists of 13 cells with a tank diameter of 52 cm and a drift tube (DT) diameter of 9 cm. The prototype features four post-couplers (PCs) for field stabilization and three plungers for tuning (Figure 1). The unloaded *Q* value calculated with Superfish is 42,670 with a peak power dissipation of 184 kW including stems and post-couplers (PCs). After the low power measurements [2], the prototype was moved to the high power test stand at SM18 at CERN. On 21st October 2009 the klystron was switched on and operated until the first phase of the high power test came to an end on 25th November. The next stage was to test a fully featured drift tube containing a permanent magnet quadrupole (PMQ). The purpose was to verify the drift tube cooling at high RF power, to test the behaviour of PMQs in vacuum, and to study the effect of magnetic fields on breakdown. In addition, different PMQs have been inserted in the half drift tube of the end wall and tested at maximum field from 8th April 2010 to 17th August 2010 in order to acquire a basis for a decision on the material of the holding matrix of the PMQ.

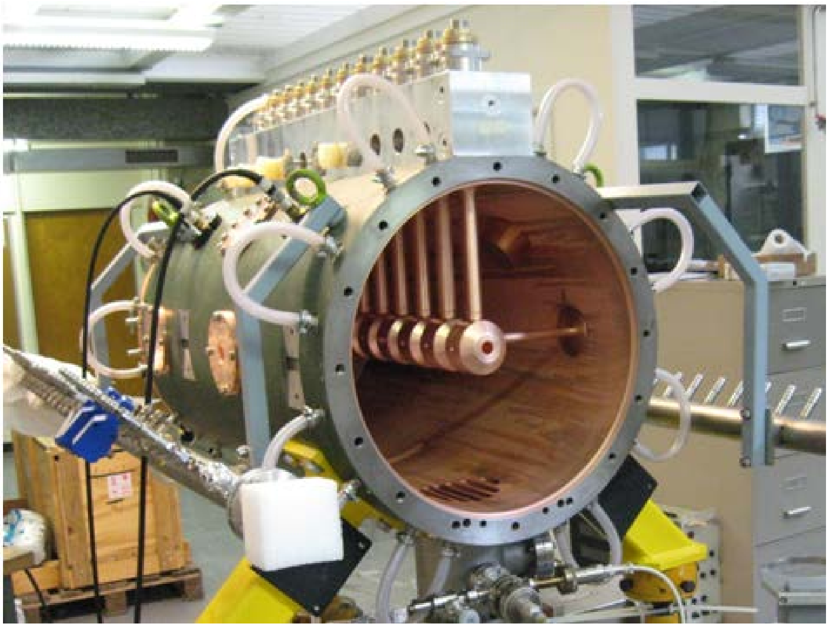

Figure 1 The Linac4 DTL prototype at the low power test stand.

2 Low power measurements

Low power measurements have been performed in order to find the resonance frequency, quality factor Q_{cav} of the cavity and coupling parameter β of the iris coupler. The DTL hot prototype is equipped with two pick-ups for low power measurements and RF monitoring in high power operation. Vacuum and RF tightness are provided by Helicoflex® seals. For low power measurements, an Agilent Network Analyzer was used.

The resonance frequency with all tuners completely inserted (5 cm inside) and post couplers at nominal length is f_0 = 351.973 MHz, lower than the design frequency because of a re-machining step which enlarged the tank diameter by about 1.2 mm.

Table 1 Nominal length of post-couplers.

PC1 [mm]	PC2 [mm]	PC3 [mm]	PC4 [mm]
186	184	182	180

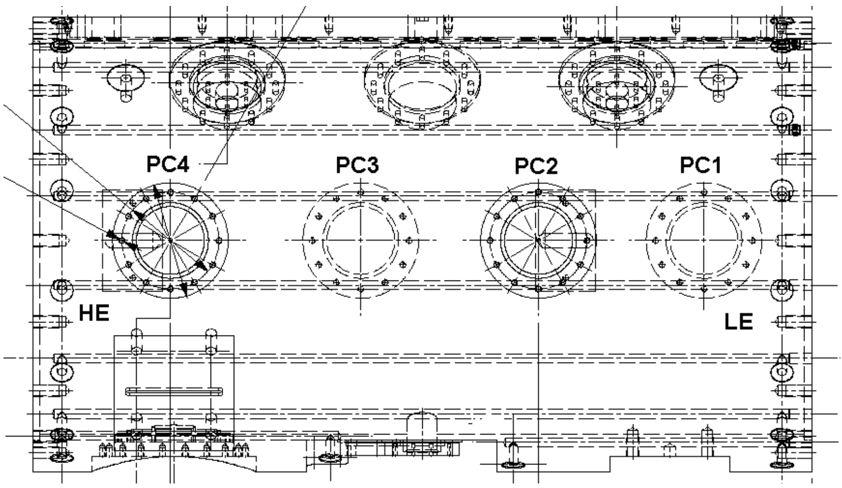

Figure 2 Nomenclature of post-couplers.

The quality factor Q_{cav} has been measured using 2 pick-ups as input and output ports. The bandwidth of an oscillator is defined as the frequency difference Δf between the two points on either side of the resonance curve, where the voltage amounts to the peak value divided by $\sqrt{2}$. On the Network Analyzer showing transmission parameter S_{21} from port 1 to port 2 measured in dB, the two half power points are at -3 dB with respect to the resonance peak. This measurement provides the loaded quality factor $Q_L = f/\Delta f = Q_{cav}/(1+\beta_1+\beta_2)$ where β_1 and β_2 are the coupling coefficients of the two cavity pick-ups. Since β_1 and β_2 are much smaller than one, $Q_{cav} \approx Q_L$ = 33,700 measured (80% of the nominal Q_0 = 42,000).

The input waveguide (half-height WR2300) has been connected to the iris coupler, in order to measure the coupling parameter β between waveguide and cavity. In this case, port 1 is connected to the transition from the coaxial cable to the waveguide (N to WR2300 transition) and port 2 is connected to one of the two pick-ups on the cavity. Measurement of half power points provides $Q_L = f/\Delta f = Q_{cav}/(1+\beta+\beta_{pick\text{-}up})$, and with $\beta_{pick\text{-}up} << \beta$, $Q_L = Q_{cav}/(1+\beta)$ = 18,500. For the previous value of Q_{cav} = 33,700 the coupling factor thus is β = 0.82.

From measurements of the standing wave ratio SWR and reflection coefficient Γ at resonance, it is possible to check β. Using $|\Gamma| = |(\beta-1)/(\beta+1)|$ and $SWR = (1+|\Gamma|)/(1-|\Gamma|)$ [3], β = 1/SWR if waveguide and cavity are under-coupled ($\beta < 1$), β = SWR if they are over-coupled ($\beta > 1$), and β = SWR = 1 if they are critically coupled ($\beta = 1$) with $\Gamma = 0$ (no reflection). In the Smith chart, the scattering parameter S_{11} represented by a circle has a diameter < 1 (Figure 3), indicating that this case is under-coupled. The measurement of SWR = 1.14 corresponds to β = 0.88. A measurement performed after cavity installation in the SM18 test area confirms this result (Figure 4). In fact, with S_{11} = -22.3 dB one finds $|\Gamma|$ = 0.0767, SWR = 1.17 and β = 0.85. With the previous value of Q_L, $Q_{cav} = Q_L(1+\beta)$ = 18,500 · 1.85 = 34,200.

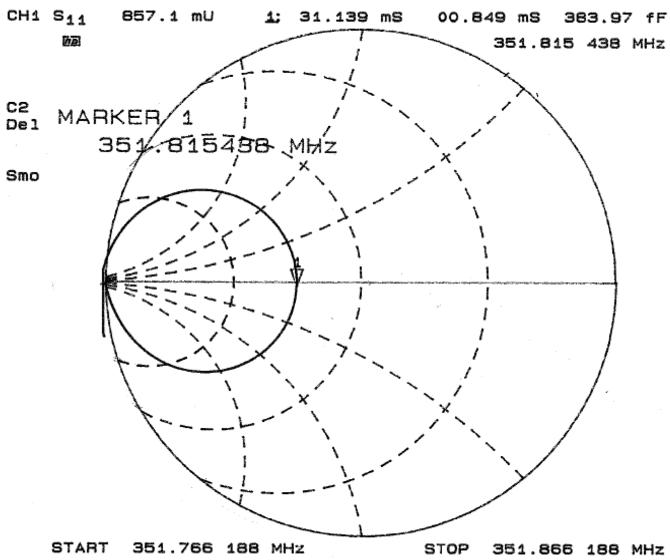

Figure 3 The S11 circle in the Smith chart indicates that waveguide and cavity are under-coupled.

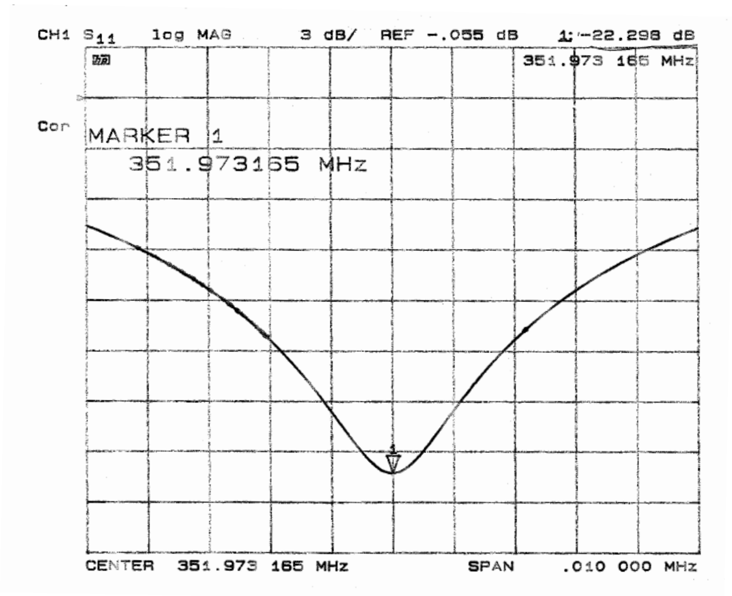

Figure 4 S_{11} measurement of DTL prototype.

3D simulations with CST MICROWAVE STUDIO® (CST MWS) confirm these measurements. Only cells 7 and 8 of the prototype are simulated because of their location just below the iris coupler. Simulation results are scaled to the real power dissipation of the prototype ($Q_{cav} = 0.8 \cdot Q_0$). Two different methods are applied: a) the CST MWS eigenmode solver yields the external and the unloaded Q from which the coupling parameter can be deduced; b) Balleyguier's method using two eigenmode simulations with different boundary conditions at the reference plane (perfect magnetic or perfect electric) [4]. Simulation results are listed in Table 2 in comparison to measurements. The agreement between simulations and measurements is within 10%.

Table 2 Waveguide-to-cavity coupling parameter

	Measurements	Eigenmode solver	Balleyguier's method
β	0.85	0.87	0.93

In summary, the cavity RF parameters are:

- the cavity frequency f_0 = 351.973 MHz with tuners completely inserted and post couplers at nominal lengths
- the quality factor Q_{cav} = 34,500, about 80% of the value simulated with Superfish
- the coupling parameter β = 0.85, for a power reflection of $\Gamma^2 = P_-/P_+ = 0.6\%$.

2.1 Bead-pull measurements and post couplers setting

Bead-pull measurements have been performed in order to check the field flatness and to set the post coupler lengths for stabilization. Figure 5 shows a bead-pull measurement result on the prototype equipped with all tuners and PCs and the ratio between the measured and the designed average field.

Post coupler lengths are calculated using an equivalent circuit [2]. The stabilized field shown in Figure 5 is obtained with nominal post coupler lengths. Using this setting, a perturbation of up to 1 MHz in the cavity can be stabilized.

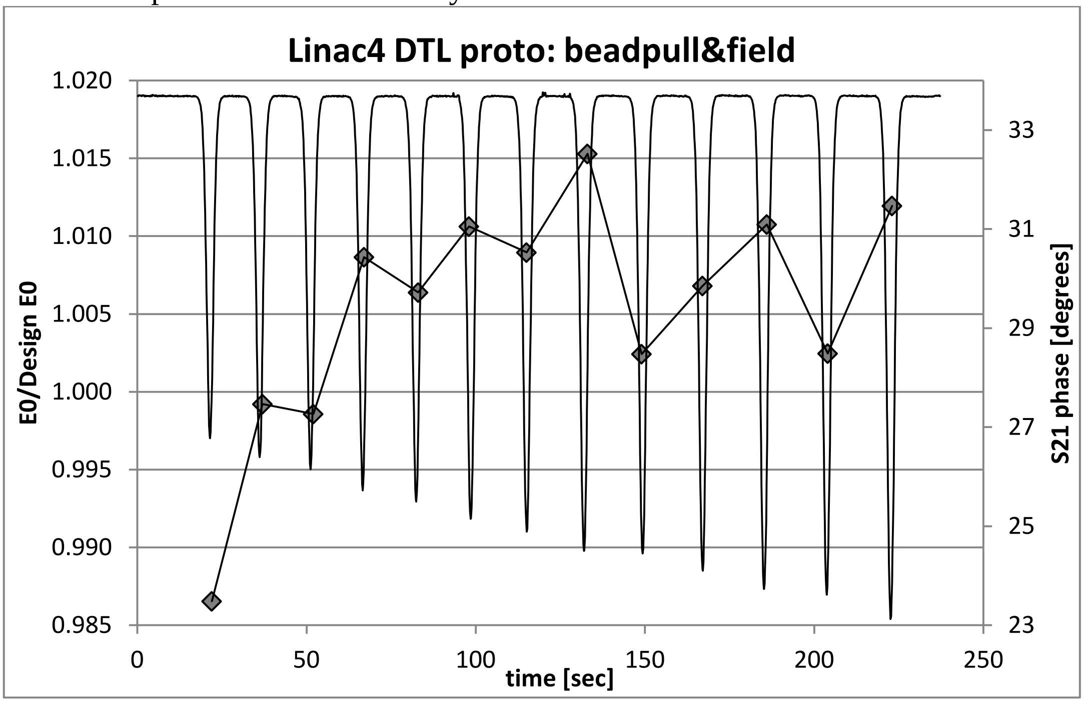

Figure 5 Bead-pull measurement (continuous) and field ratio (marked line) of the Linac4 DTL prototype.

3 High power measurements

The goal of this test phase was to achieve the nominal field level of 3.3 MV/m. Considering the quality factor of the cavity, a peak power of P_{cav} = 220 kW is required to reach the design field level. The design duty cycle for Linac4 is 0.08% with a repetition rate of 2 Hz and a pulse width of 400 µs. The structure has also been tested at the maximum 7.5% duty cycle (50 Hz, 1.5 ms) of the High Power Super Conducting Proton Linac (HP-SPL)[5].

The power source is a LEP-type klystron (1 MW, CW). The klystron operates with dc power and the input signal is generated by a Rhode & Schwartz signal generator in the control room. The signal frequency and the input signal level are supplied to a pre-amplifier connected to the klystron. Pulse length and repetition rate are remotely controlled by LabVIEW software. The klystron cathode voltage is limited to -58 kV; the maximum applied current is 9.6 A for a dc power of about 560 kW. As the klystron efficiency is estimated to be around 60%, maximum expected input power from the klystron should be $P_+ \approx$ 330 kW.

Temperatures are monitored by a set of thermocouples that are installed on drift tubes (DT1, DT5, DT8, DT12), tuners (three), post-couplers (four), iris coupler (two) and on the two end-covers. The overall water flow is 30 l/min, the water temperature is 26 °C. Water flows are also locally monitored on the iris coupler (1 circuit), on the cavity tank (1 circuit) and on the PCs (1 circuit) and DTs (4 circuits: DT1, DT5, DT8, DT13). The input water pressure is 6.5 bar, the output pressure is 3.5 bar. The water flow is maximum in the drift tubes (DT1=2.2 l/min, DT5=2.8 l/min, DT8=2.9 l/min, DT12=1.7 l/min), and the water temperatures of the drift tubes remained constant at 26 °C during the test. Other elements, like tuners and end cones, reached 44 °C and 66 °C respectively at 220 kW and 7.5% duty cycle (50 Hz, 1.5 ms).

The vacuum level in the cavity was about $6 \cdot 10^{-7}$ mbar, the interlock was set $9.0 \cdot 10^{-6}$ mbar. Without RF the vacuum reached $3.8 \cdot 10^{-8}$ mbar.

Figure 6 View of the high power installation of the DTL prototype in the SM18 bunker.

Figure 7 View of the instrumentation in the control room.

Three power signals have been measured during the cavity conditioning:

1. P_+: the incident power from the klystron to the DTL, measured by a directional coupler on the waveguide, located about 1 meter before the iris coupler;
2. P_-: the power reflected from the DTL to the waveguide, measured by a second directional coupler located at the same point;
3. P_{cav}: the power in the cavity, measured by the two pick-ups (PUs) at the tank wall.

During conditioning, the RF duty cycle was increased with different values of pulse length and repetition rate. The incident power from the klystron P_+ was raised by setting the level of the signal generator. The signal generator frequency has been adjusted to follow the cavity resonance frequency and to maximize P_{cav}. Each level of P_+ has been kept up to the stabilization of vacuum and power level in the cavity. Under the assumption that all the power serves to increase the cavity field level, the energy balance would be $P_+ = P_{cav} + P_-$. In the measured case however, the maximum of P_{cav} does not agree with the minimum of P_- and when $P_- = 0$, P_{cav} is different from P_+. Part of P_+ is lost by dissipative phenomena (dark currents, and electron emission phenomena).

We assume to be at the resonance frequency when $P_- = 0$. Figure 8 shows that P_+ and P_{cav} curves match up to a level of -24 dBm in signal generator power ($P_- = 0$). Above -24 dBm, power increases non-linearly because of the klystron saturation. Furthermore the difference between P_+ and P_{cav} indicates that some power is lost in electron field emission phenomena (Figure 9).

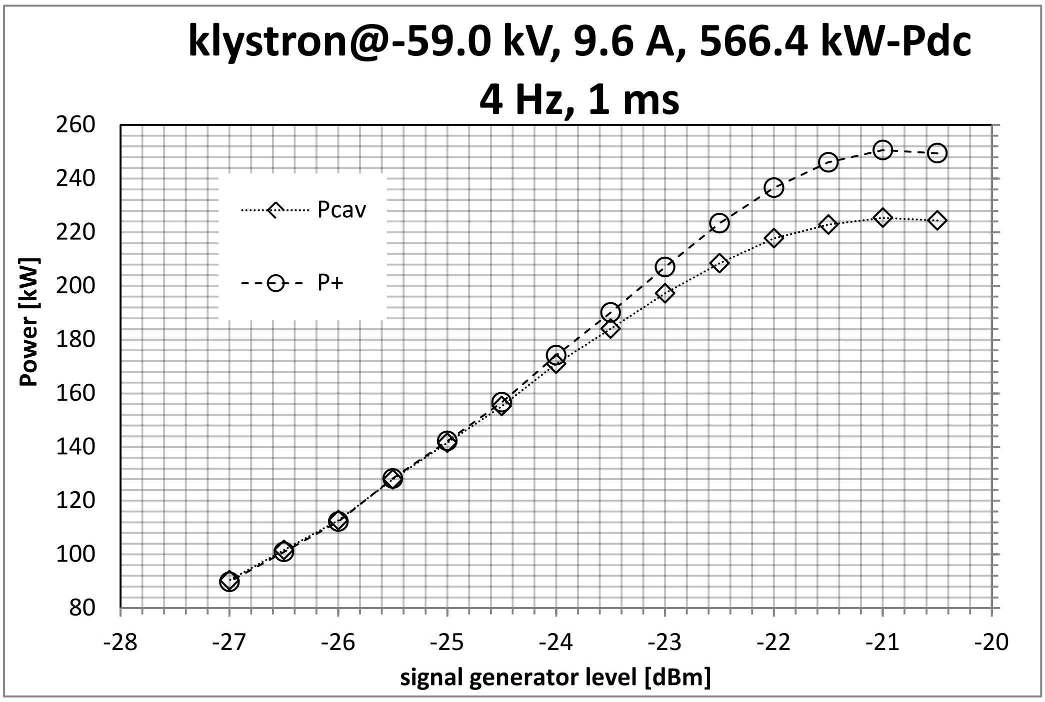

Figure 8 P_{cav} and P_+ as a function of the signal generator level.

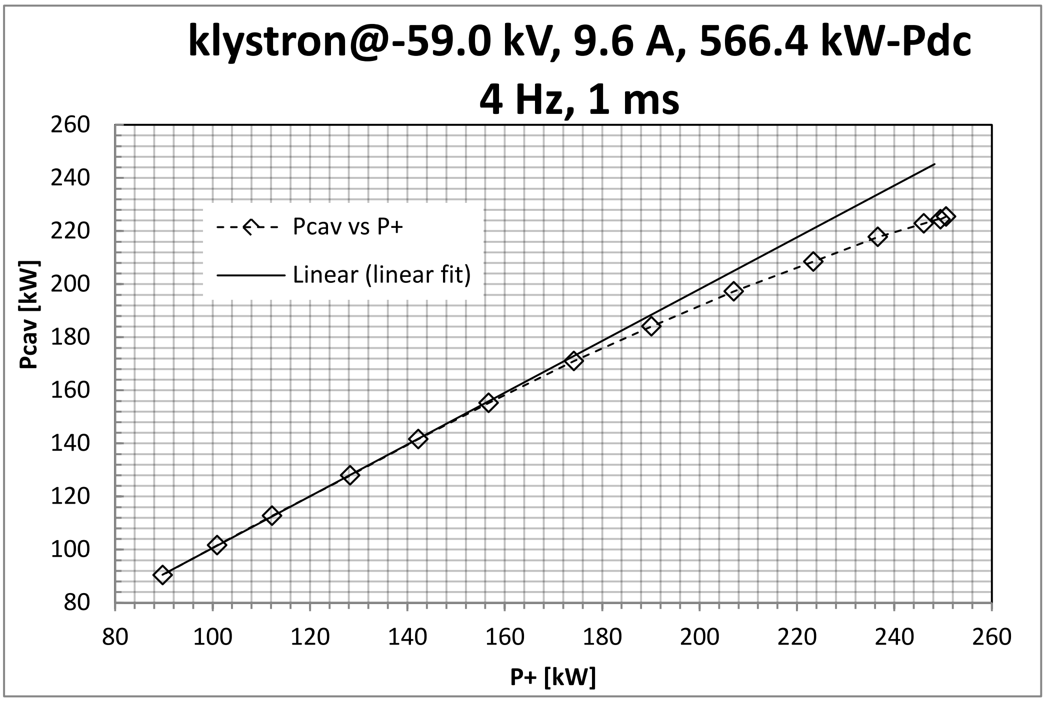

Figure 9 P_{cav} as a function of P_+ from klystron at different levels of conditioning. P_- is zero.

During conditioning, multipacting in the cavity has been observed by looking at the pattern of the reflected voltage measured by a RF diode on the directional coupler on the waveguide. Figure 10 shows a screen shot of the reflected voltage (green curve) in under-coupled conditions of the cavity. If the cavity is over-coupled then the slope of the saw-tooth shape becomes negative.

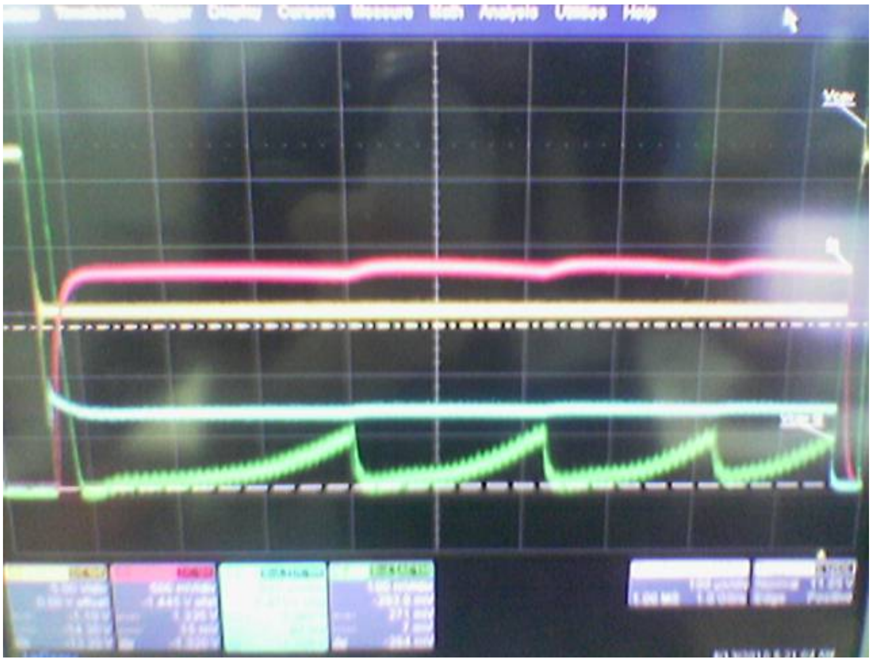

Figure 10 Reflected voltage monitored by the RF detector (green), cavity voltage (red), forward voltage (blue). The reflected voltage shows a saw-tooth pattern that indicates electron emission.

The second phase of measurements started on 8th April 2010. In this phase the prototype was conditioned with 3% duty cycle (20 Hz; 1.5 ms) and with different PMQs.
PMQs are assembled from rods or wedges of permanent magnet material in a matrix made of non-magnetic material. For accelerator applications typically Sm_2Co_{17} material is used as permanent magnetic material due to its radiation hardness compared to other materials and composites. PMQs with different matrix materials have been tested (aluminium blank and anodized, stainless steel, titanium). The following list summarizes the test configurations of the prototype:

I. 1st CERN DT w/ aluminium[1] PMQ and end-cone w/ aluminium PMQ
II. 1st CERN DT w/ aluminium PMQ and end-cone w/ anodized[2] aluminium matrix
III. 1st DT w/o PMQ and end-cone w/ anodized aluminium matrix
IV. 1st DT w/o PMQ and end-cone w/ aluminium PMQ
V. 1st DT w/o PMQ and end-cone w/ stainless steel PMQ
VI. 1st DT w/o PMQ and end-cone w/ titanium PMQ

During test I. bursts on the reflected power have been seen (Figure 11); the periodic effect on the reflected power has always been observed (Figure 10). After opening the cavity, traces of

[1] Aluminium, stainless steel and titanium refer to the material of the matrix that holds the PMQ.
[2] Anodizing is an electrolytic passivation process used to increase the thickness of the natural oxide layer on the surface of metal parts. The process is called "anodizing" because the part to be treated forms the anode electrode of an electrical circuit. Anodizing increases corrosion resistance and wear resistance, and provides better adhesion for paint primers and glues than bare metal.

suspected multipacting have been noticed (Figure 12). The half-circle shape of the black spots can be linked to the RF magnetic fields around the tuner.

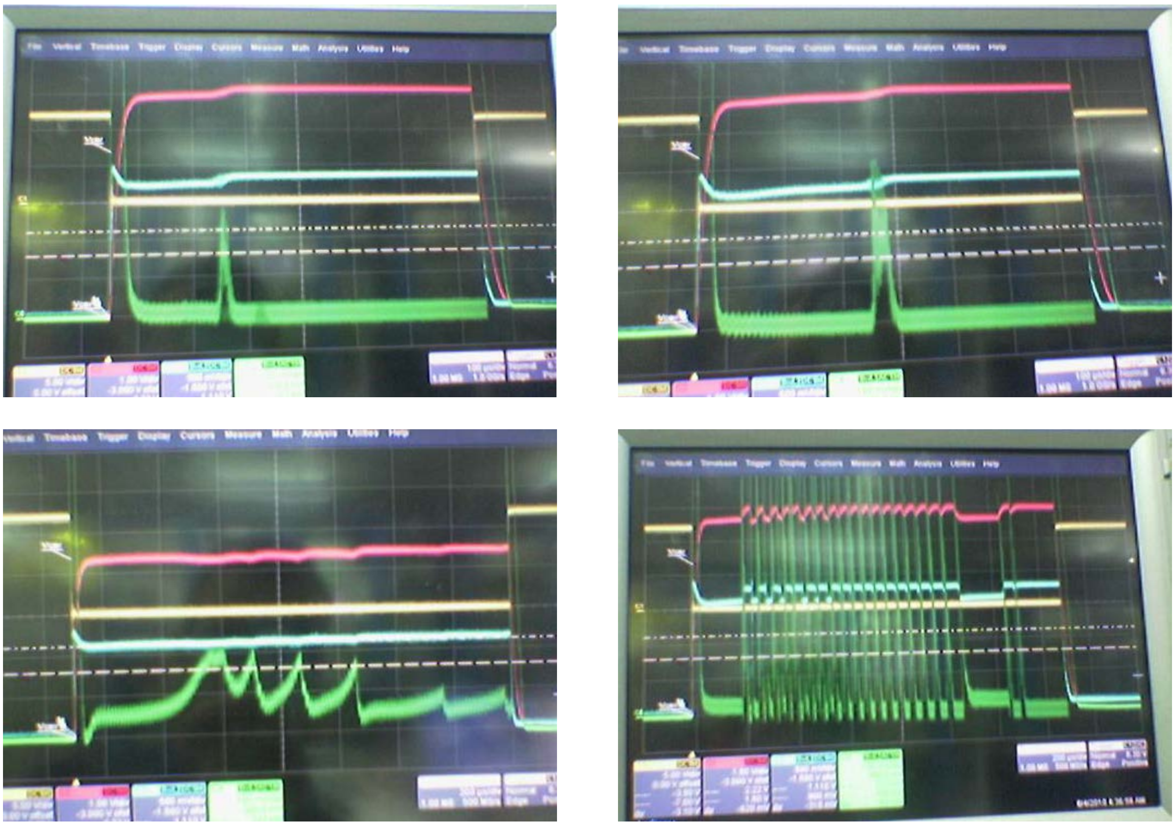

Figure 11 Bursts on the reflected power (green curve).

3.1 Power measurement calibration

Directional couplers on the waveguide are calibrated using a Network Analyzer, two N to WR2300 transitions and 50 Ω matched loads (Figure 13). One directional coupler measures P_+ and the other P_-. For each, one needs to know its attenuation, which is the ratio between the

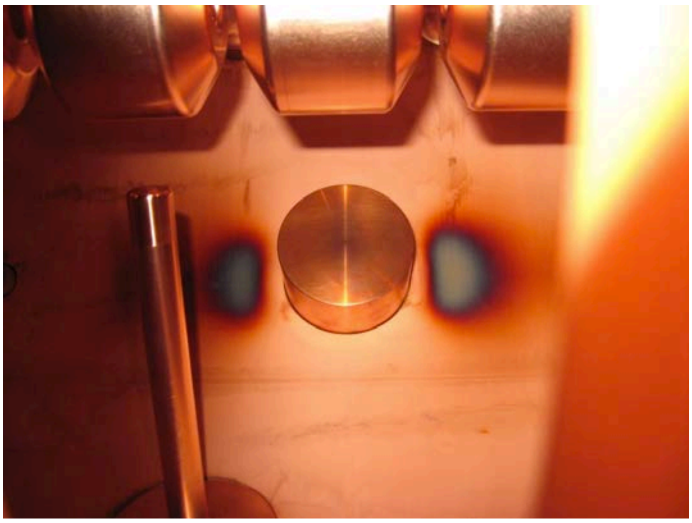

Figure 12 Traces of multipacting due to sharp edges on tuners.

power in the waveguide and the power extracted by the coupler. As a second parameter one needs to know the directivity of the directional couplers. Directivity is a measure of how well the coupler isolates two counter-travelling (forward and reverse) signals and thus it is a crucial parameter in the uncertainty of the measurement. Measurements at 352 MHz yield:

- P_+: attenuation = -50 dB, directivity = 32 dB;
- P_-: attenuation = -50 dB, directivity = 22 dB.

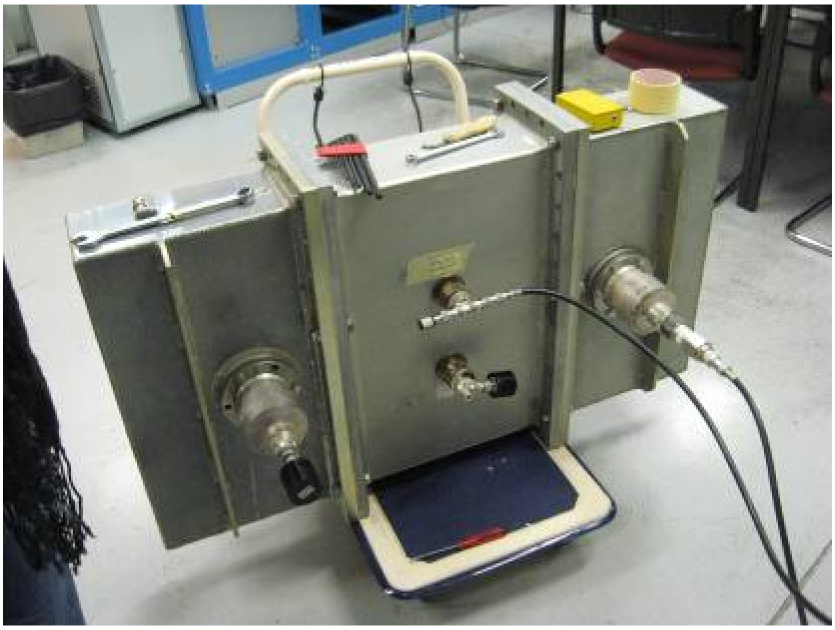

Figure 13 Directional coupler calibration.

In order to characterize the attenuation of the cavity pick-ups, the input waveguide has been set up with an N to WR2300 transition. The pick-up is rotated in order to measure an attenuation $P_{pu}/P_+ = -50$ dB. This quantity in decibel is actually equivalent to the magnitude of the scattering parameter S_{21}. One can thus write:

$$\beta_{PU} = \frac{Q_0}{Q_{PU}} = \frac{P_{PU}}{P_{CAV}} \cdot \frac{P_+}{P_+} = |S_{21}|_{dB} \cdot \frac{P_+}{P_{CAV}}$$

and

$$P_{\text{cav}} = P_+ - P_- - P_{PU} \cong P_+ \cdot (1 - |\Gamma|^2)$$

or:

$$P_{\text{cav}} \cong \frac{P_{CAV} \cdot \beta_{PU}}{|S_{21}|_{dB}} \cdot (1 - |\Gamma|^2) = \frac{P_{PU}}{|S_{21}|_{dB}} \cdot (1 - |\Gamma|^2)$$

The quantity $1 - |\Gamma|^2$ is equal to $4\beta/(1+\beta)^2$ and indicates how much of the forward power enters the cavity. It is a measure for the quality of the matching between the waveguide and the cavity (all considerations are without beam loading so far). The approximation in the formulas above is $\beta_{PU} \ll 1$ ($P_{PU} \ll P_{CAV}$). Figure 14 shows how the ratio P_{CAV}/P_+ depends on the coupling strength beta considering the previous approximation.

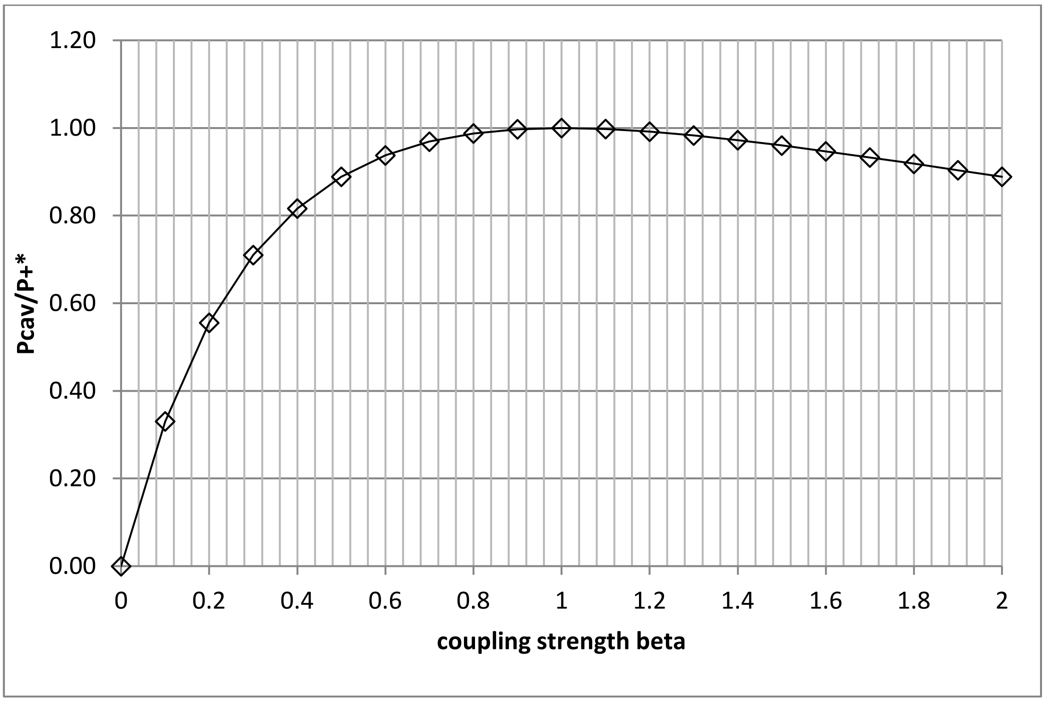

Figure 14 Estimated effective cavity power versus coupling strength β.

Finally attenuation of cables from the pick-up to the control room is measured with a signal generator at the beginning of the line and a power meter at the end, showing 26.54 dB attenuation. The overall attenuation for RF power signals from the cavity is then 76.54 dB.

4 X-ray measurements

X-ray emission has been measured during the first phase of conditioning of the prototype. Their estimation is difficult without detailed information on the X-ray source such as its geometry and material composition. The measurements have been performed on the side and on the axis of the cavity with an ionization chamber PTW TM 23361, 30 cm^3 vented volume, S/N 429. The characteristics of the RF pulse were 50 Hz repetition rate and 1.5 ms pulse width. A 25 Hz repetition rate was used in order to check the linearity of the emissions and to validate the detector choice and setup. The radiation measurements have been performed on 17th and 19th November 2009 [6]. In the second phase of conditioning these measurements were repeated at 20 Hz repetition rate and 1.5 ms pulse width. Table 3 shows a summary and a comparison between measurements performed in 2009 and 2010 [7].

Table 3 Dose rates measured at different positions and operational conditions. The last but one column gives the values measured in 2009 for the same power and position (the values have been scaled for the lower repetition rate).

Position	Peak Power [kW]	Repetition rate [Hz]	Hx(10) [Graetz] [μSv/h]	D[PTW] [μGy/h]	D[PTW] 2009 [μGy/h]	Ratio 2010/2009
Lateral	100	20	4	21	20	1.0
Lateral	120	20	22	74	80	0.9
Lateral	140	20	30	230	280	0.8
Lateral	160	20	61	480	880	0.5
Lateral	195	20	157	1300	3120	0.4
Lateral	203	20	170	1450	n.a.	n.a.
Longitudinal	100	20	4	340	680	0.5
Longitudinal	120	20	23	900	2380	0.4
Longitudinal	140	20	25	2500	6400	0.4
Longitudinal	160	20	133	5400	16800	0.3
Longitudinal	195	20	172	13000	60000	0.2
Longitudinal	203	20	180	17500	n.a.	n.a.
Longitudinal	220	20	275	25400	n.a.	n.a.

5 Conclusions

After three weeks of conditioning, the nominal field level has been reached with P_{cav} = 220 kW, and the Linac4 duty cycle has been exceeded with 20 Hz repetition rate and 2 ms pulse length (duty cycle = 4%). In further two weeks even a 7.5% SPL duty cycle has been reached with 50 Hz repetition rate and 1.5 ms pulse length. X-ray measurements have been performed and have shown that for higher power levels and especially for longitudinal measurement positions, due to better conditioning, radiation levels in 2010 were up to a factor of 5 lower than in 2009.

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