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CCDTL prototype : status report

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Abstract

A Cell-Coupled Drift Tube Linac (CCDTL) pre-prototype structure has been built at CERN as part of the R&D for the new Linac4 injector. The electromagnetic properties have been measured at low and high power and a summary is given in this report.

Introduction

For the new Linac4 injector under study at CERN [1] a Cell-Coupled Drift Tube Linac (CCDTL) structure [2] has been proposed for the energy range between 40 and 90 MeV. A pre-prototype consisting in two half accelerating cells connected by a coupling cell has been fabricated at full scale in order to define the mechanical engineering of the structure and to test the cooling and the high power behavior. This report aims to present the status of the measurements together with an overview of the problems encountered during the assembly and testing of the pre-prototype.

The CCDTL cavity

The CCDTL half-tanks are made out of copper-plated stainless steel, with cooling channels directly machined in the external part of the tank cylinder. Each half-tank contains a drift tube made in copper and cooled via the supporting stem. The half-tanks are connected via coupling slots to a coupling cell, resulting in a Radio-Frequency cavity resonating at 352 MHz in a so-called $\pi/2$ mode. This is the smallest geometry presenting the same electric field and thermal distribution as the final CCDTL structure. The two half tanks are closed by simple covers (disks), which are not present in the final configuration, where half-tanks will be connected to form a complete tank. Vacuum and RF conductivity between half tanks and covers are provided by "helicoflex" type contacts. The end walls instead are welded to the tank cylinder. **Figure 1** to **Figure 3** show some mechanical drawings of the assembled pre-prototype. **Figure 4** to **Figure 7** show the cavity at different stages during the assembly and testing.

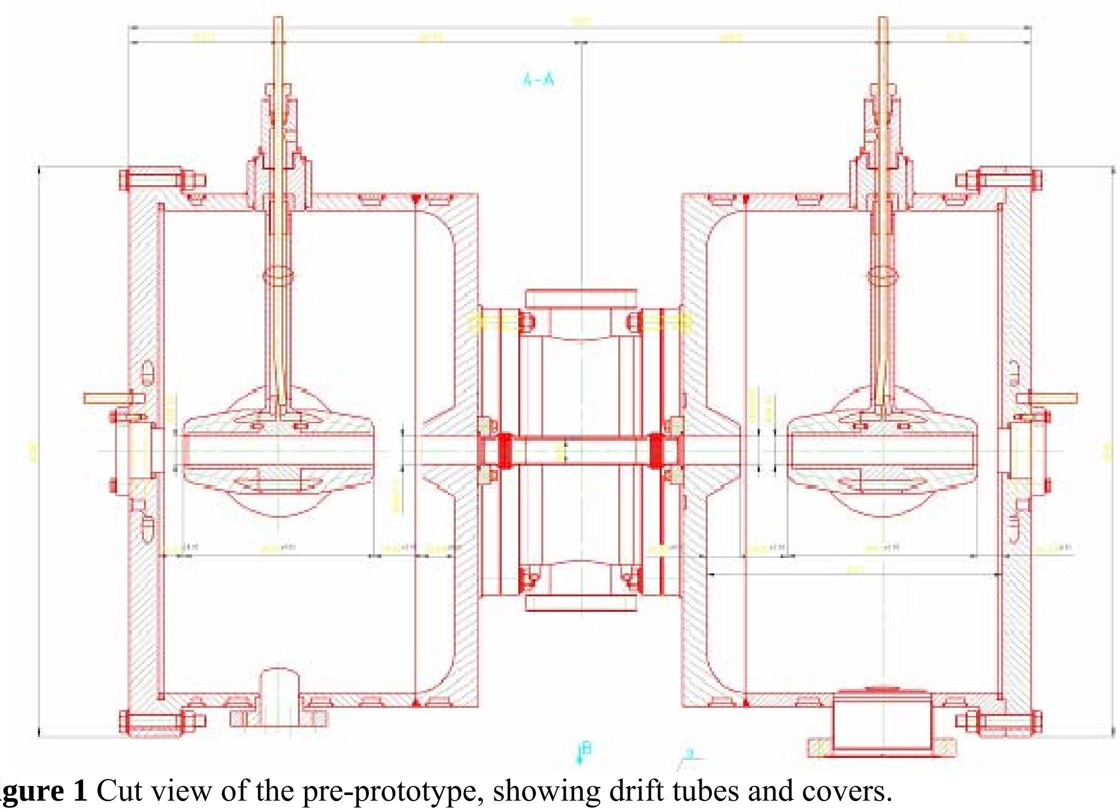


Figure 1 Cut view of the pre-prototype, showing drift tubes and covers.

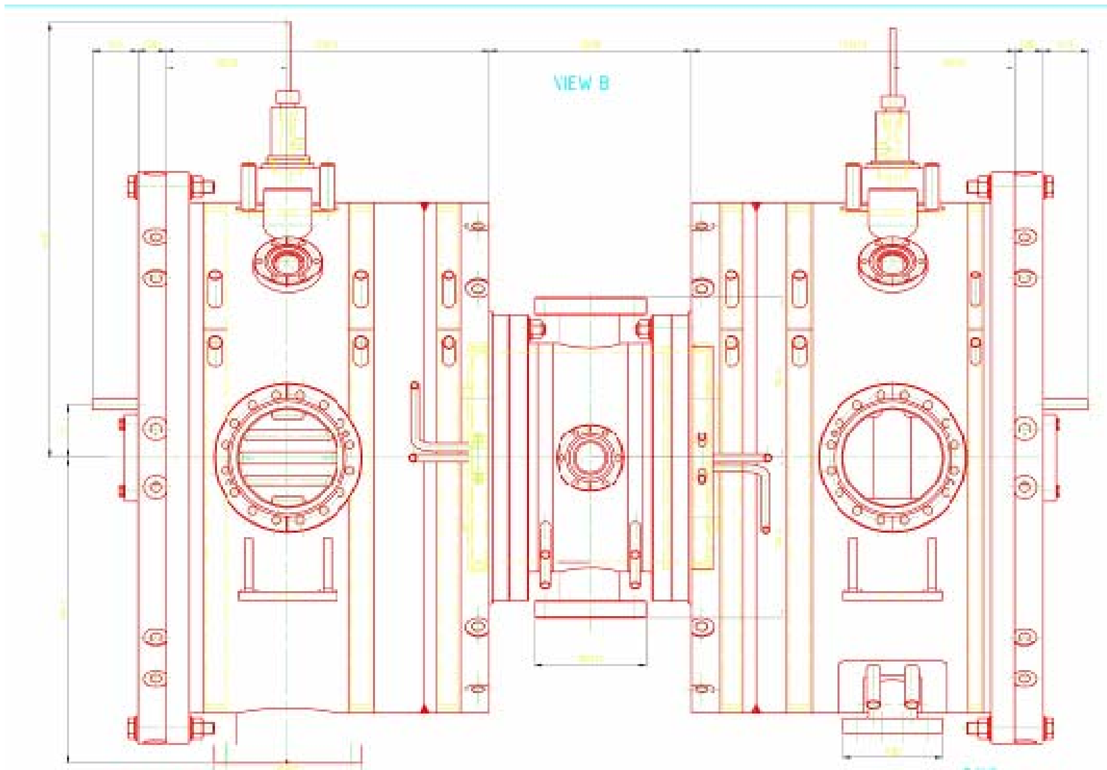


Figure 2 View from the side.

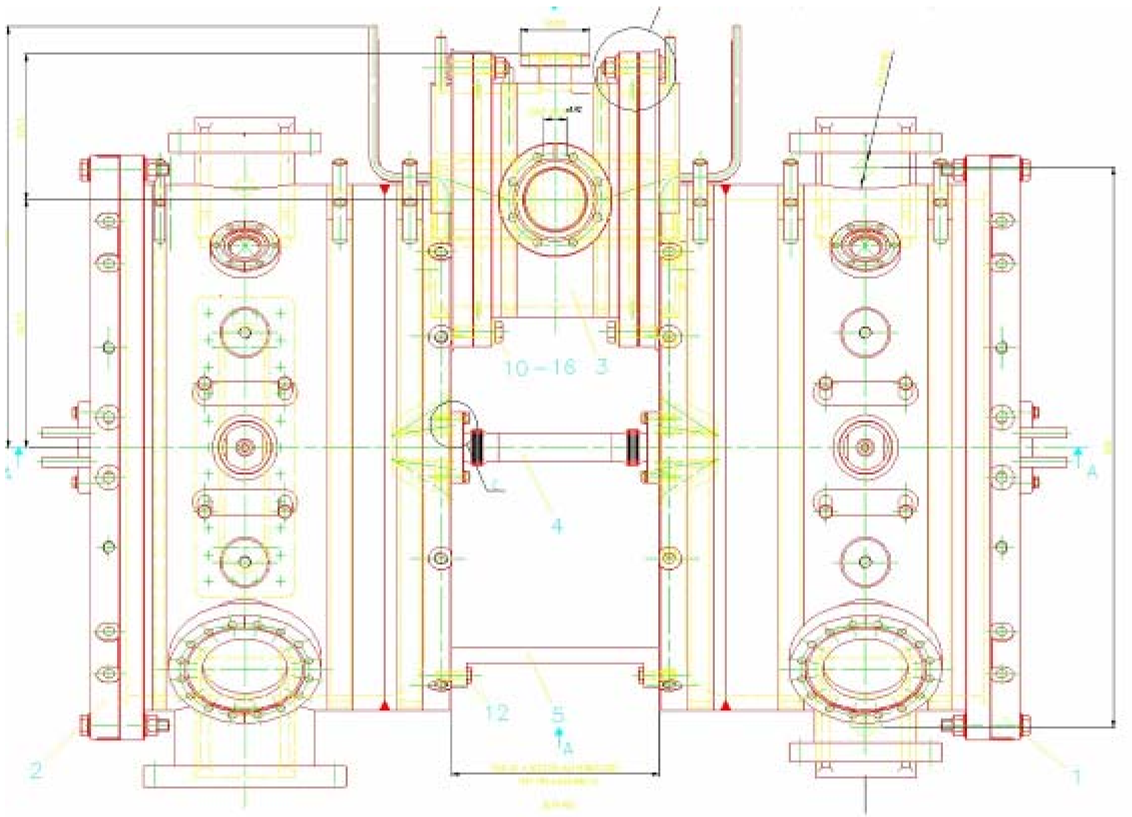


Figure 3 View from top. The coupling cell is off-axis, to allow installation of a quadrupole.

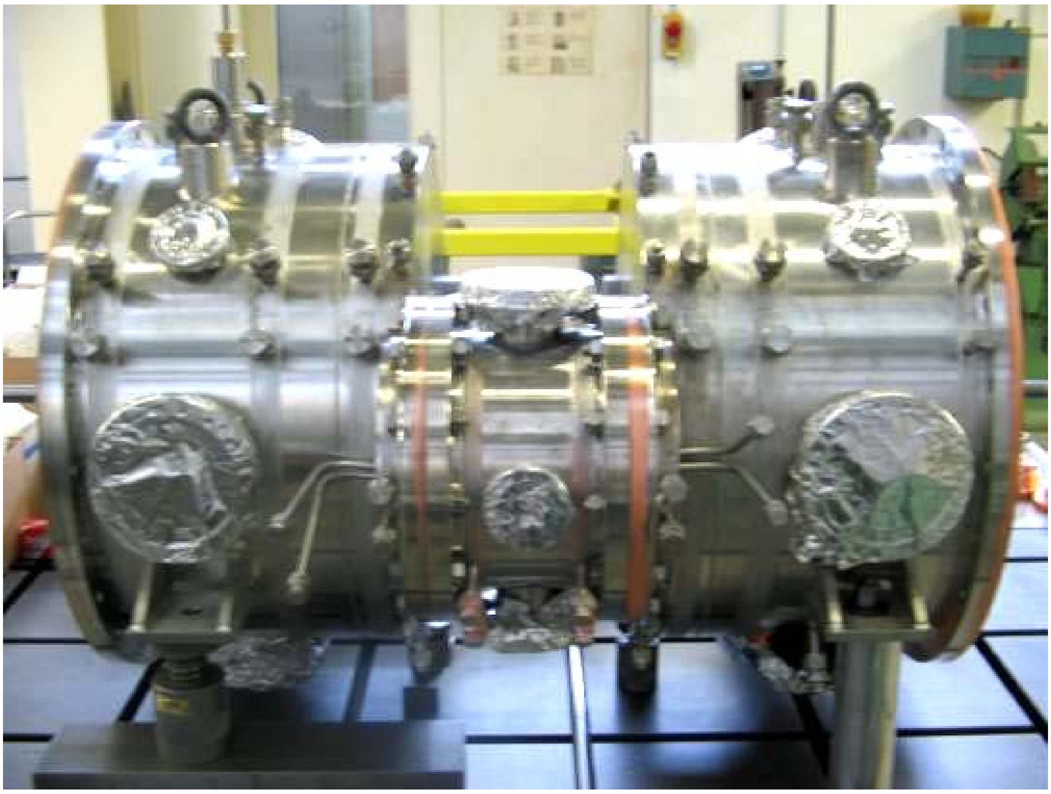


Figure 4 CCDTL during assembly in the workshop

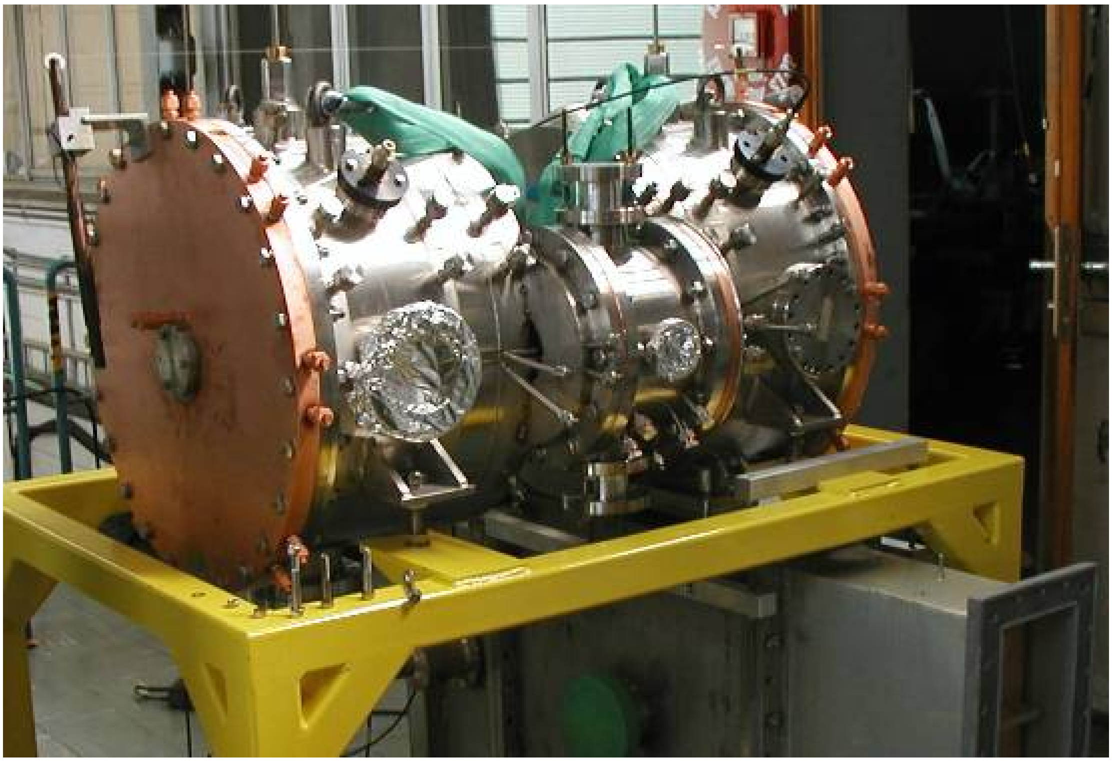


Figure 5 CCDTL cavity assembled for low level RF measurements

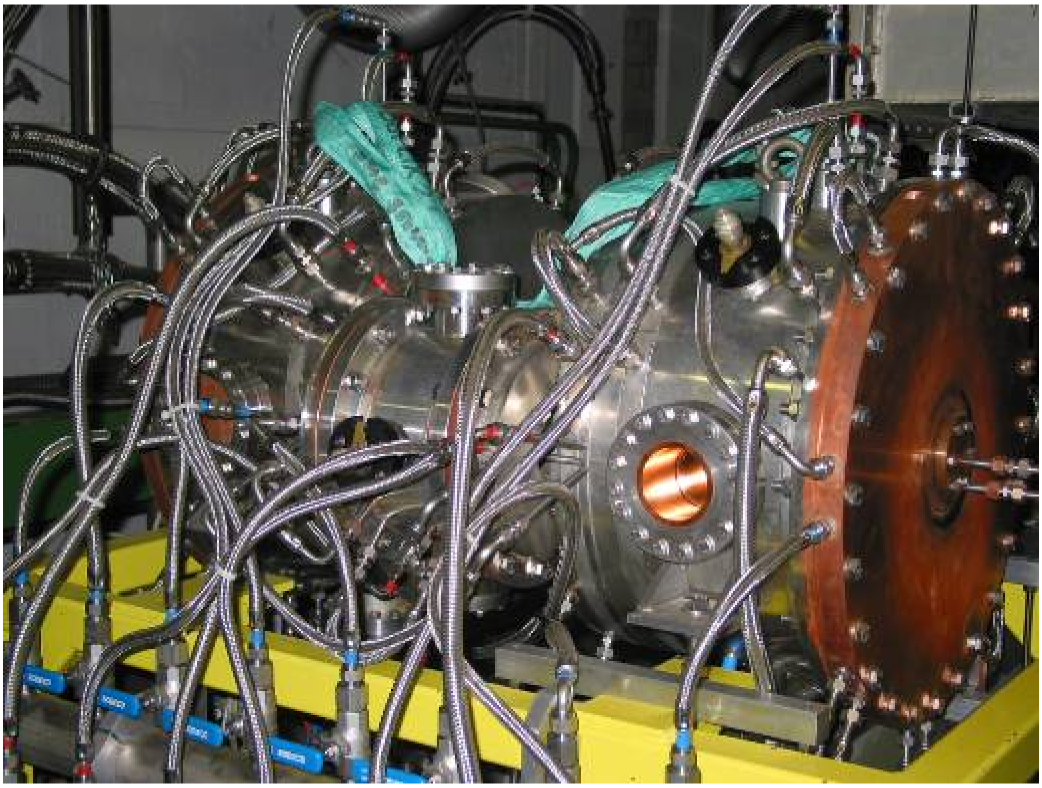


Figure 6 CCDTL cavity assembled, tuned, vacuum tested and with cooling system connected

Figure 7 CCDTL in the high power stand connected to the wave guide ready for high power test.

CCDTL Measurements

Low level measurements

First low level measurements were performed in June 2005. The cavity was first assembled without the wave-guide coupler and the first measurements were done in order to characterize each cell. No piston tuners plungers were installed at this stage. We define here as “AC 1” the accelerating cell without the iris for the waveguide coupling, “AC 2” as the accelerating cell with the iris and “CC” the coupling cell.
In order to measure the frequency and Q-value of the individual cells, the cell under measurement was separated by detuning the remaining cells with the insertion of a metallic bar in the beam aperture, or for the coupling cell by short-circuiting the gap with a spring contact. The measured parameters are listed in **Table 1**

Table 1 Single cell initial parameters

	Frequency	Q-value
AC1	353.219	18300
AC2	352.138	11000
CC	350.895	5600

The difference in frequency between AC1 and AC2 is due to their geometrical difference, i.e. the presence in AC2 of a large circular opening for an initially proposed loop coupler and of the large iris opening for connection to the waveguide coupler.
Next step was to insert piston tuners and to measure the sensitivity of the individual cells to the tuner position (Figure 8). As an additional mean for tuning, some end cups can be inserted via the central aperture in the end covers. Sensitivity to end cups is shown in Figure 9.

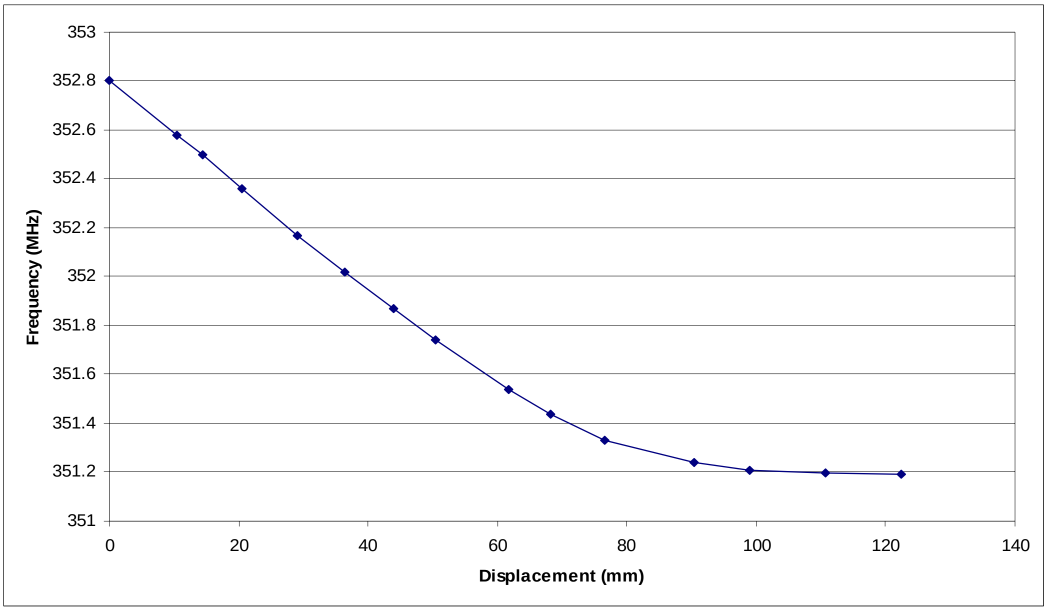


Figure 8 Frequency variation as a function of the displacement of the tuner (0mm = plunger all inside)

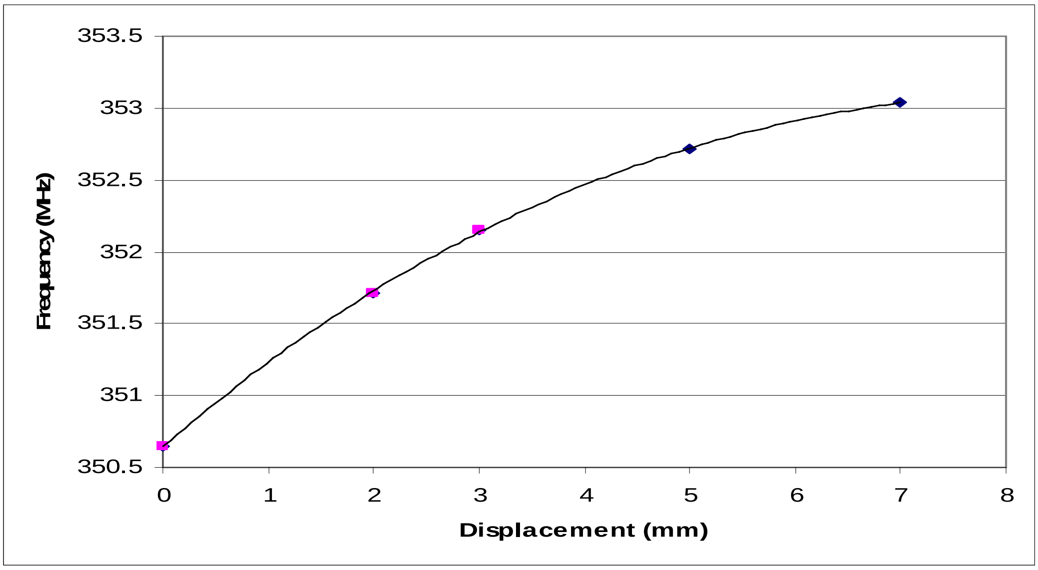


Figure 9 Frequency variation as a function of the displacement of the end-cup (0mm = end-cup all in)

After this series of measurement, the overall resonant frequency (π/2 mode) was roughly tuned to 352.2 MHz, the input waveguide coupler was mounted (Figure 11) and matched to the waveguide impedance. The half-height WR2300 waveguide from the RF generator is terminated into a movable short-circuit (a sliding plate) at about λ/4 distance from an iris coupling the waveguide to the resonator. By moving the short-circuit plate, the voltage on the iris can be varied, allowing to change the coupling between waveguide and resonator until the critical coupling, corresponding to zero reflected power, is achieved. The coupling β[1] was measured for different short-circuit positions. The measured data are reported in Figure 10. The curve follows the sinusoidal variation predicted by theory, and a maximum coupling of 1.04 could be achieved. Table 2 summarizes the measurement results, i.e. maximum β and short-circuit position and reflected power corresponding to the critical coupling (β=1).

Table 2 Results from the measurements of the waveguide to cavity coupling measurements

β_{max}	1.04
L @ minimum reflection	310mm
P_{fw}/P_{rv}	-28dB

[1] The coupling is given by: $\beta \equiv P_{ext}/P_{cav} = Q_0/Q_{ext}$ [3].

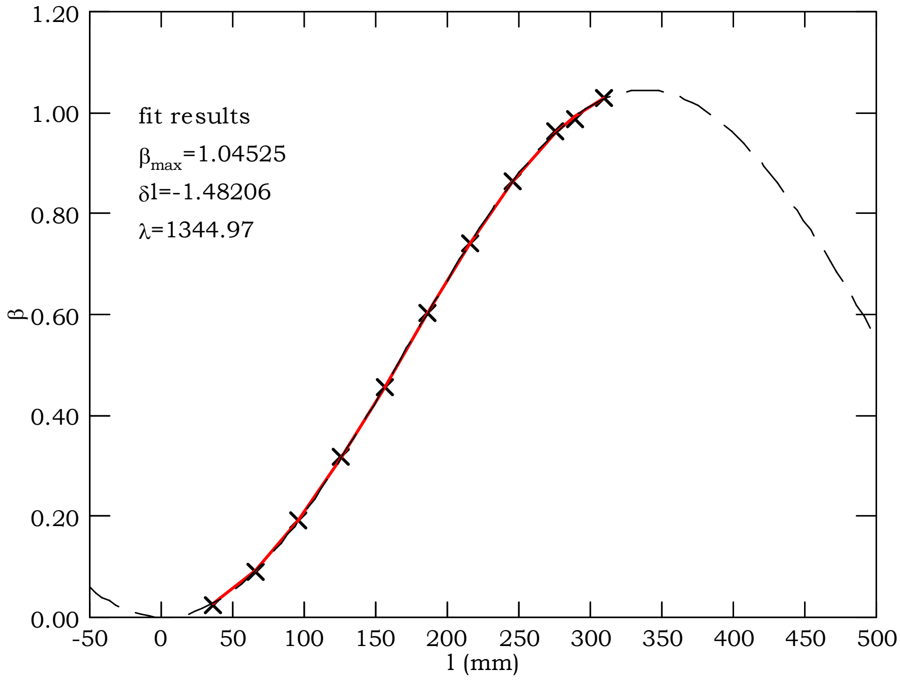


Figure 10 Coupling coefficient as a function of short-circuiting plate position. (l=0 mm corresponds to positioning the plate at the external edge of the wave guide shown in Figure 11)

Figure 11. Mechanical set-up for waveguide to cavity coupling measurements

Finally the cavity was accurately tuned to the design frequency, and frequency, Q-values and bead-pull measurements of electric field on axis were taken. The results are listed in Table 3, Figure 12 and
Figure **13**.

Table 3 Result from the frequency and bead pull measurements.

	Frequency (MHz)	Q-value (unloaded)
0-mode	350.686	
π/2-mode	352.187	22700
π-mode	353.725	
k (coupling between cells)	0.88%	
Field Flatness error	<1%	

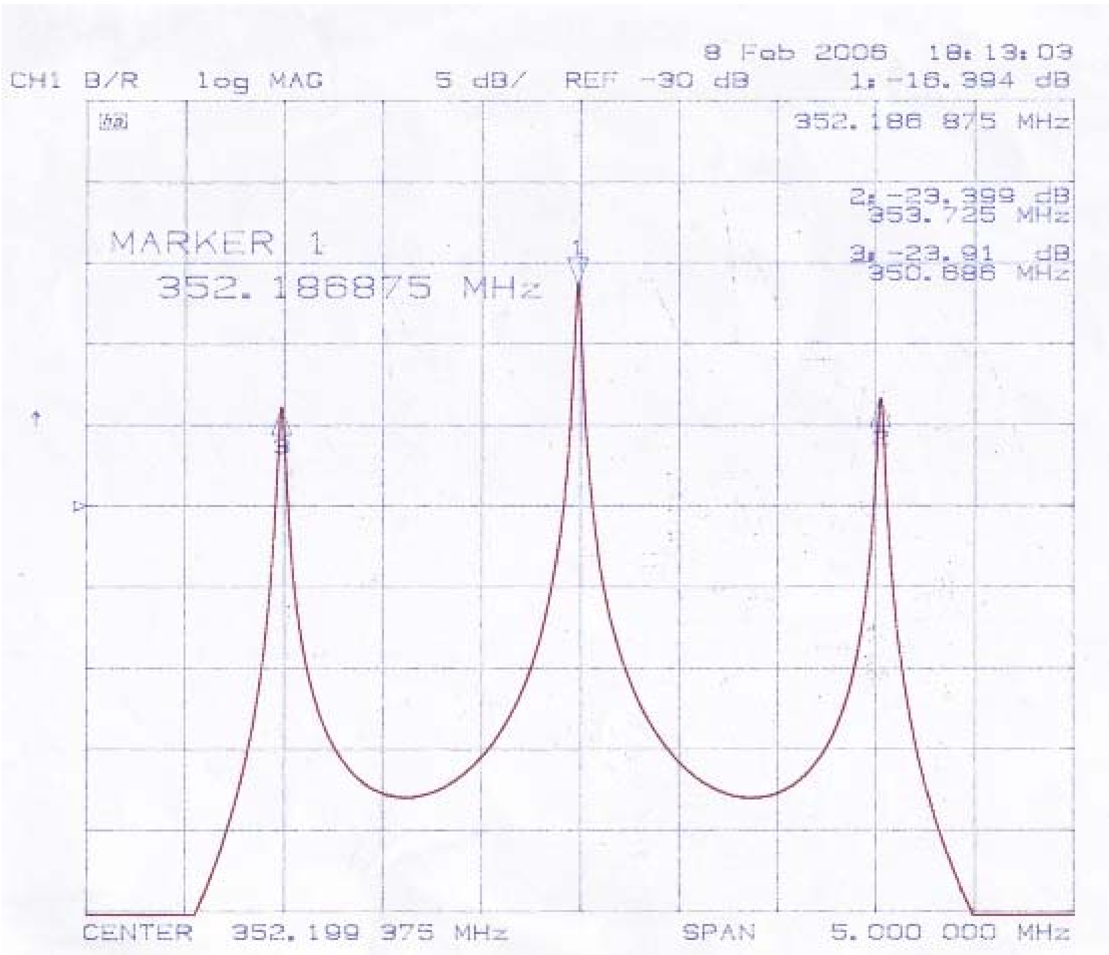


Figure 12 Frequency spectrum of the CCDTL cavity after final closing of the tuners port.

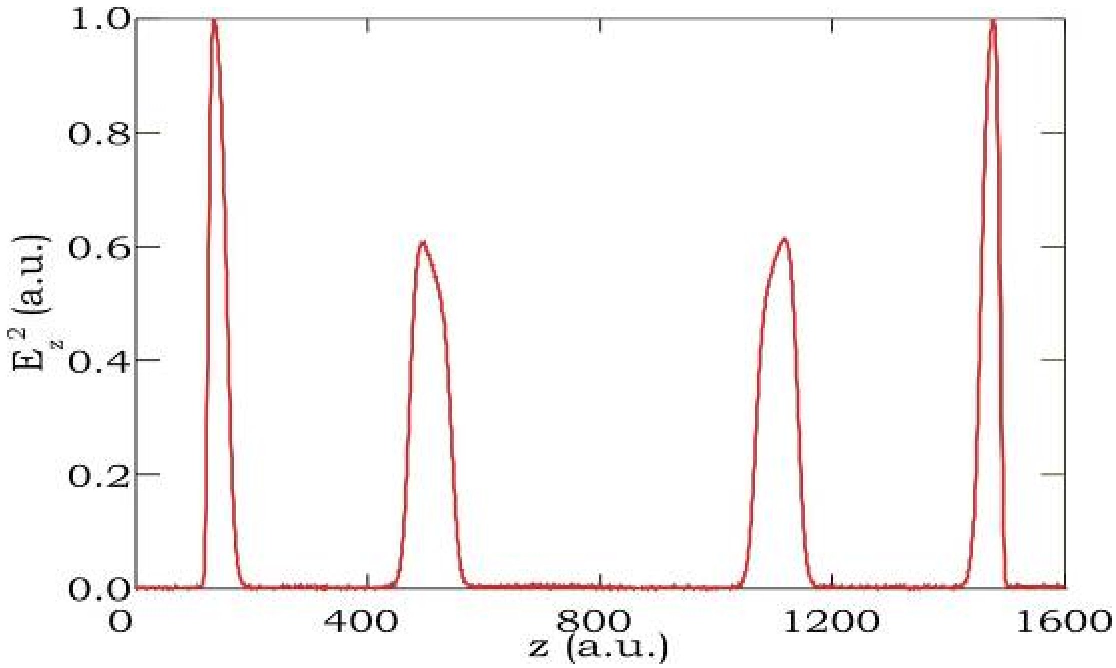


Figure 13 Bead-pull measurements of the CCDTL pre-prototype. The measurement shows the profile of the (squared) accelerating field along the beam axis. The difference in field level between gaps in the middle and gaps at the ends is typical of the CCDTL.

After the low-level measurements on the pre-prototype, some effort has been devoted to understanding the reason for the low Q-value (65% of the theoretical one) measured. Finally, computer simulations indicated that the decision not to copper plate the surface of the vacuum (and RF) joints was at the origin of the low Q-value. From the vacuum point of view, it is considered easier to seal if the joint sits on stainless steel. However, in many systems at CERN the joints are placed on copper-plated surfaces, without particular problems. Now the simulations have indicated that the very small path that the RF currents make into the stainless steel is sufficient to reduce the Q-value by a substantial amount, and for this reason in the continuation of the project the joint surfaces will be copper plated.

After measurements, the pre-prototype went to vacuum testing. After a delay of several months due to the unavailability of vacuum experts during the CERN machine shut-down, the testing started in earnest only in April 2006. An important leak was found at the level of one of the pick-up ports. Finally, the origin of the leak was traced to a weak external welding reinforcement, with the consequence that a stress during transportation or handling could have affected the internal vacuum welding. Repairing of the leak took a long time, because of the difficult access to the weld region, but was finally successful. Another smaller leak was detected on the rectangular flange for the waveguide connection. Some repair attempts failed, and the reason was finally attributed to the bad surface finishing of the rectangular flange. However, the leak level is low and the vacuum could reach the 10^{-7} mbar range. For this reason it was decided to continue the test of the prototype even in presence of this small leak, the vacuum being more than sufficient for the tests. The pre-prototype was finally transported at the high-power test area at the beginning of July, and connected to the klystron and to the cooling circuit.

High power measurements

High power test started in September 2006. The power source consists of a LEP-type klystron (1 MW, CW), however fed by a power supply that is limited to 58 kV klystron voltage. The consequence is that the RF power out of the klystron is limited to about 300 kW. It took some time to correctly calibrate the measurement system. Initially, the output RF power was computed by comparison with a test run in CW mode. Unfortunately this method was found to have an error of more than 2 dB, forcing to adopt another calibration technique.
Finally, a calibrated directional coupler was installed close to the cavity in order to measure the forward power directly with an RF detector. Two more RF detectors were connected to the pick-up loops in the two half accelerating cells. Readings were taken directly on a 500 MHz oscilloscope.
Complementary to the power measurements, a system to monitor the temperature in different spots of the cavity was installed. **Figure 14** shows the position of some of the 11 thermocouples installed in the cavity.

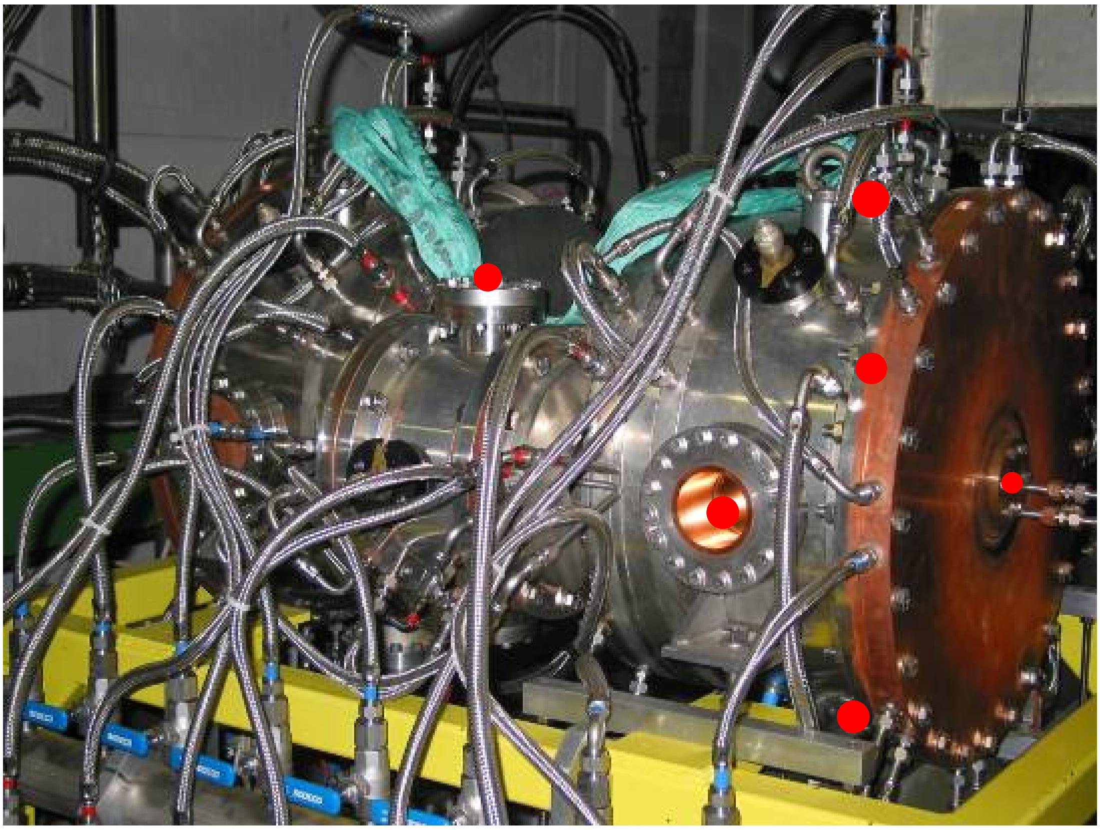
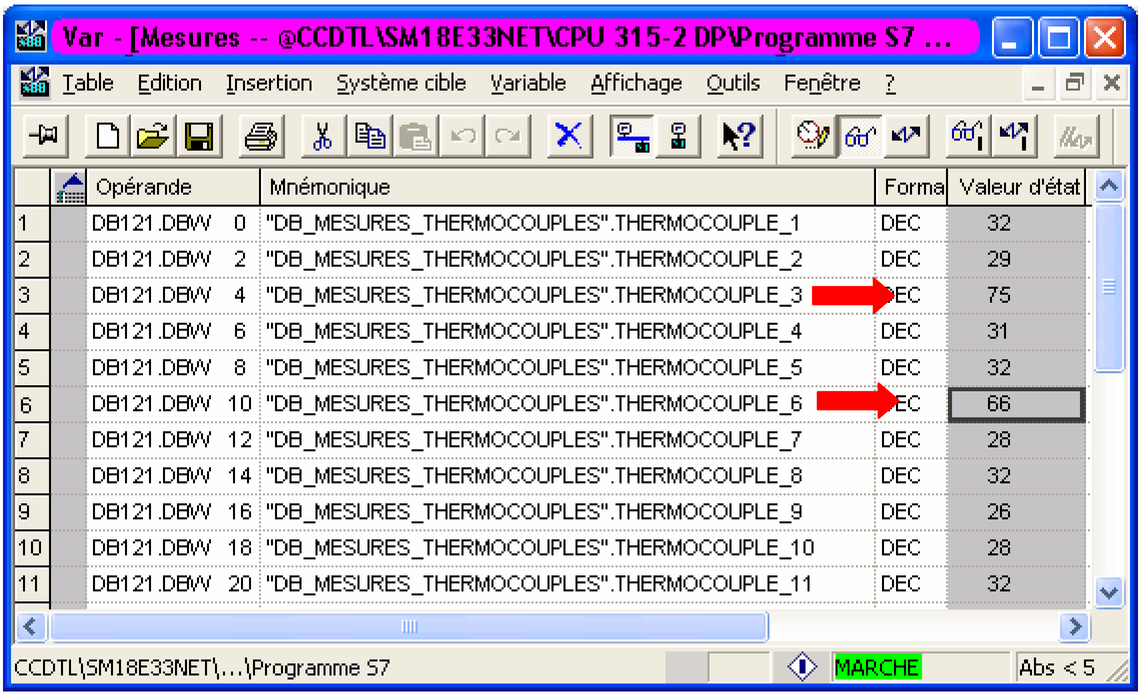


Figure 14 The CCDTL pre-prototype in the bunker. The red dots indicate the position of some of the 11 installed thermocouples.

The conditioning of the cavity went smoothly: the vacuum level before putting RF inside the cavity was in the order of 10^{-8} mbar, and using a 100 μs pulse at a repetition rate of 5 Hz, allowed us to outgas and condition the surface efficiently without spoiling the vacuum too much. Within few hours it was possible to reach in the cavity the maximum power delivered by the klystron, and no multipactoring was observed during the conditioning process. However, at high power levels the frequency of the cavity was continuously drifting, indicating an excessive heating of some of the cavity elements. The replacement of the thermocouple placed in the holder of the drift tube allowed to measure an external temperature above 70 degrees (position 3 in the table shown in **Figure 15**). Since the drift tube was getting hot the capacitance changed and hence the resonant frequency of the cavity. Unfortunately, the reason why a drift tube was heating was that the cooling circuit inside the tube was blocked and no water was flowing. For this reason, the high power test was interrupted, and as a temporary solution a reduced water flow was induced inside the stem, so to provide a minimum cooling by conductance to the drift tube.



	Opérande	Mnémonique	Forma	Valeur d'état
1	DB121.DBW 0	"DB_MESURES_THERMOCOUPLES".THERMOCOUPLE_1	DEC	32
2	DB121.DBW 2	"DB_MESURES_THERMOCOUPLES".THERMOCOUPLE_2	DEC	29
3	DB121.DBW 4	"DB_MESURES_THERMOCOUPLES".THERMOCOUPLE_3	EC	75
4	DB121.DBW 6	"DB_MESURES_THERMOCOUPLES".THERMOCOUPLE_4	DEC	31
5	DB121.DBW 8	"DB_MESURES_THERMOCOUPLES".THERMOCOUPLE_5	DEC	32
6	DB121.DBW 10	"DB_MESURES_THERMOCOUPLES".THERMOCOUPLE_6	EC	66
7	DB121.DBW 12	"DB_MESURES_THERMOCOUPLES".THERMOCOUPLE_7	DEC	28
8	DB121.DBW 14	"DB_MESURES_THERMOCOUPLES".THERMOCOUPLE_8	DEC	32
9	DB121.DBW 16	"DB_MESURES_THERMOCOUPLES".THERMOCOUPLE_9	DEC	26
10	DB121.DBW 18	"DB_MESURES_THERMOCOUPLES".THERMOCOUPLE_10	DEC	28
11	DB121.DBW 20	"DB_MESURES_THERMOCOUPLES".THERMOCOUPLE_11	DEC	32

Figure 15 Screen shot of the temperature measurements. The red arrows show the temperature of the external holder of the drift tubes

The test was then resumed at the Linac4 limiting operating mode, corresponding to 2 Hz repetition rate and 500 μs pulse length. With a reduced cooling of the drift tubes, the frequency was stable.
The maximum power level in the cavity was measured to be 305±10% kW corresponding to an effective voltage (VT) of 1.1MV and a peak field on the drift tube of 32.4 MV/m (1.76 Kilpatrick). The mean electric field inside the cavity was E0= 4 MV/m, calculated for a length of 306.4. The present CCDTL design foresees a mean electric field ranging between 2.8 and 3.9 MV/m. The gradient achieved during the tests was therefore 2% higher than the maximum gradient presently foreseen in the CCDTL for Linac4 operation.
Figure 16 shows a plot of the power level in the cavity measured at the input directional coupler (forward power) and at the output pick-up in one of the half-tanks. The two measured powers are identical over all the measurement range, indicating that no dark current was present during the test and hence that the voltage was still far from the breakdown limit.

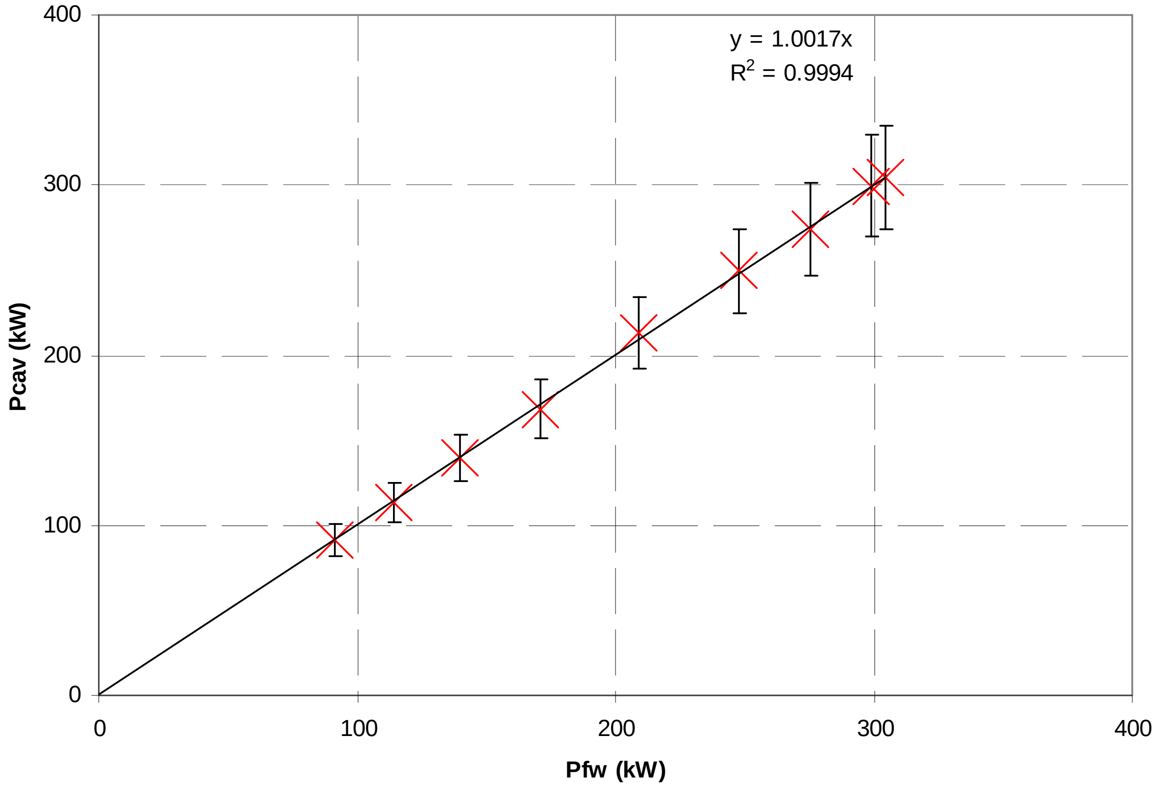


Figure 16 Power in the cavity vs. Power forward from the klystron

After these measurements, the tests have been temporarily stopped to allow the repair of the drift tube cooling channels. An inspection of the blocked drift tube indicates that the two parts of the tube have been welded with a wrong orientation and that the cooling channels are not facing each other. During the time required for the repair, the test stand will be improved by installing a cooling water flow-meter and the two end covers will be copper plated, in order to improve the Q-value.

References

[1] R. Garoby *et al.* "Linac4, a new injector for the CERN PS booster" Proc. of the EPAC06 Conf. Edinburgh, UK, 26-30 June 2006
[2] M. Vretenar et al. "Development of a 352 MHz Cell-Coupled Drift Tube Linac Prototype" Proc. of the LINAC 2004 Conf., Lübeck, Germany
[3] T. P. Wangler "Principles of RF Linear Accelerators", ISBN 0-471-16814-9, pag. 131-139

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