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CCDTL prototypes : test results

M. Pasini, M. Vretenar, R. Wegner

CERN, Geneva, Switzerland

Abstract

Cell-Coupled Drift Tube Linac (CCDTL) prototypes structures have been built at CERN and in Russia (ISTC contract 2875) as part of the R&D for the new Linac4 injector. Both prototypes have been tested and results are given in this report.

Introduction

For the new Linac4 injector at CERN two prototypes of CCDTL structure have been designed and fabricated. The first smaller prototype (indicated as CCDTL pre-prototype in the HIPPI planning, two half cells and one coupling cell) was entirely fabricated at CERN [1], while the second larger one (CCDTL prototype in the HIPPI planning) was constructed in collaboration with two Russian laboratories, (RFNC-VNIITF, Snezhinsk and BINP, Novosibirsk) through the ISTC contract 2875. Initial high power tests of the CERN CCDTL prototype started in September 2006 [2], but they were stopped due to faulty cooling channel in one of the drift tubes. It was then decided to stop the test and to dismount the drift tubes in order to repair the cooling channel. Moreover, the first measurement showed a low Q-value and the cause was identified in the non-copper-plated region of the Helicoflex joint groove. Part of this “incriminated” region was located at the end-cover of the CCDTL. These covers were then removed and prepared for new extended copper plating.

The ISTC prototype was delivered to CERN in January 2007. The assembly and tuning of the cavity was nearly completed at the end of May 2007. Some delays occurred due to late delivery of Helicoflex joints. Missing part for the high power test was the wave guide short circuit which was built at CERN after the low level measurements were completed. The prototype was then moved to the test area SM18 and initial calibration measurements for high power tests started only in June.

The CERN CCDTL prototype

The reparation and the re-installation of the faulty drift tube and end-covers were completed in June and low level measurements could start in the second half of June. The $\pi/2$ frequency with the tuners in the original position moved from 352.19 to 352.36 MHz. The frequency has changed in both the half accelerating cells, indicating that it is related to the increased thickness of the cover grooves after plating.

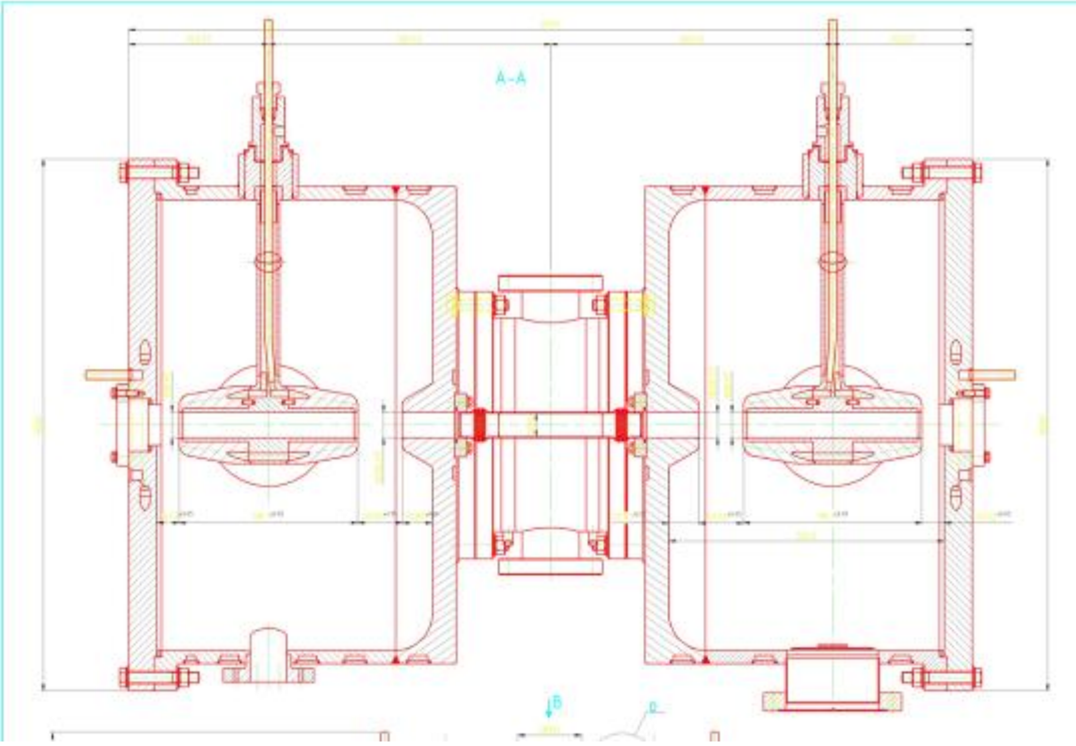

Figure 1 Mechanical drawing of the CERN prototype.

Figure 1 shows a mechanical drawing of the CERN CCDTL, while Figure 2 shows a detail of the previously non-copper-plated region.

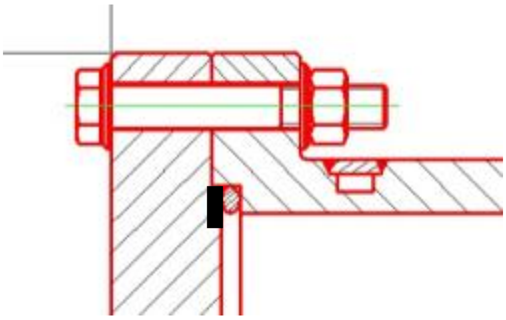

Figure 2 Detail of the mechanical joint between the half accelerating cavity and the end-cover. The black mark indicates the region of the end cover that initially was not copper plated.

In order to perform the low level measurement and to re-calibrate the pick-ups for the high power measurements, part of the wave guide line was dismounted and a transition coaxial to wave-guide was installed. The tuning of the structure was performed with two methods: in the first one we isolate each cell from the others by strongly detuning the other cells (typically we insert a short circuit in the accelerating gaps), then we tune the frequency on each cell to the nominal frequency, i.e. 352.2MHz, and we repeat this operation for the remaining cells.

Usually, after one single iteration the π/2 resonant frequency is matching the reference value within 20 kHz, and the stop-band is kept below 150 kHz. This method follows a relative simple procedure but the final result depends on how well is possible to isolate each single cell. The second method allows us to extract the tuning information directly from the frequencies spectrum hence to fine tune the cavities without perturbing the natural electromagnetic field distribution. In fact from the theory of the coupled oscillators [3] we have that the power dissipated in the coupling cell for a π/2 mode is proportional only to the frequency error of the accelerating cells while the 0 and π-mode frequencies are proportional only to the square root of the frequency error of the coupling cell. If one then measures the frequency spectrum in the coupling cell and tune the accelerating cells in order to minimize the π/2 signal, then automatically set the frequency of the accelerating cells to have the same value. The coupling cell is then tuned looking at the symmetry of the 0 and π mode: once the lateral modes are equidistant to the central mode the stop-band is then closed.

As mentioned above the frequency of the π/2 mode has increased by 170 kHz after the installation of the drift tube and new copper plating, and in one of the accelerating cell it was not possible to restore the previous frequency. It was decided then to tune the structure to 352.287 MHz. Figure 3 shows a plot of the frequency spectrum at the coupling cell after the tuning procedure.

The Q-value was then measured: in order to compensate for the non critical coupling β between the cavity and waveguide one must take into consideration the reflection coefficient. This coefficient in case of over-coupling is equal to the SWR factor. Given this factor, one find that the unloaded Q_0 of the cavity is equal to:

$$Q_0 = Q_l \cdot (1+\beta)$$

Where Q_l is the value that is directly measured

Figure 4 shows the measurements of the reflection coefficient from the cavity while Figure 5 shows the measurement of the Q_l-value with the 3dB method.

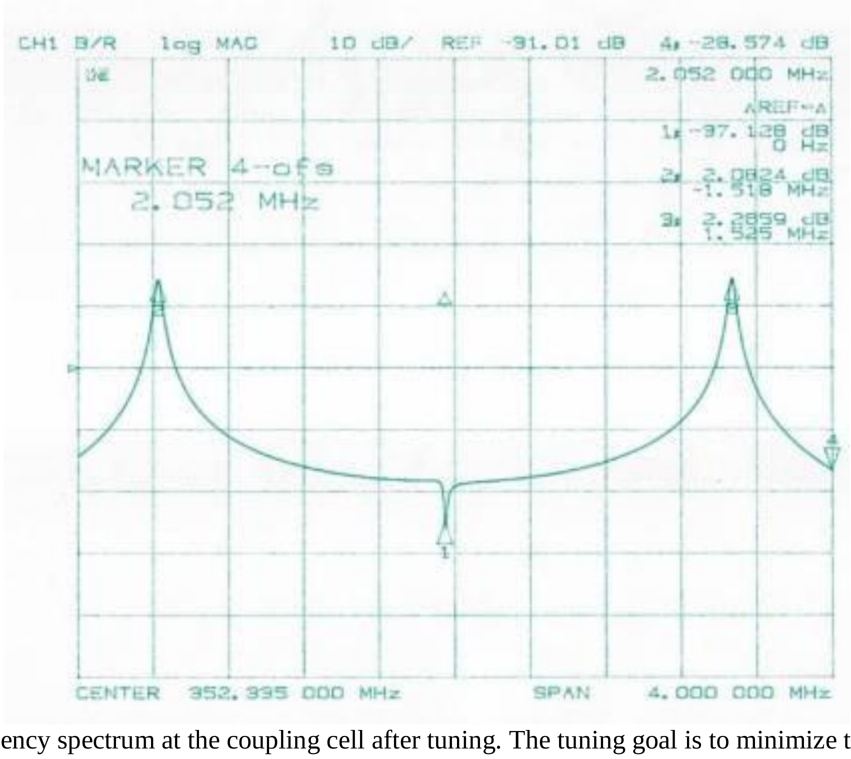

Figure 3 Frequency spectrum at the coupling cell after tuning. The tuning goal is to minimize the power of the π/2 mode (central arrow of the window) and to have equal frequency difference of the 0 and π-mode with respect to the π/2-mode.

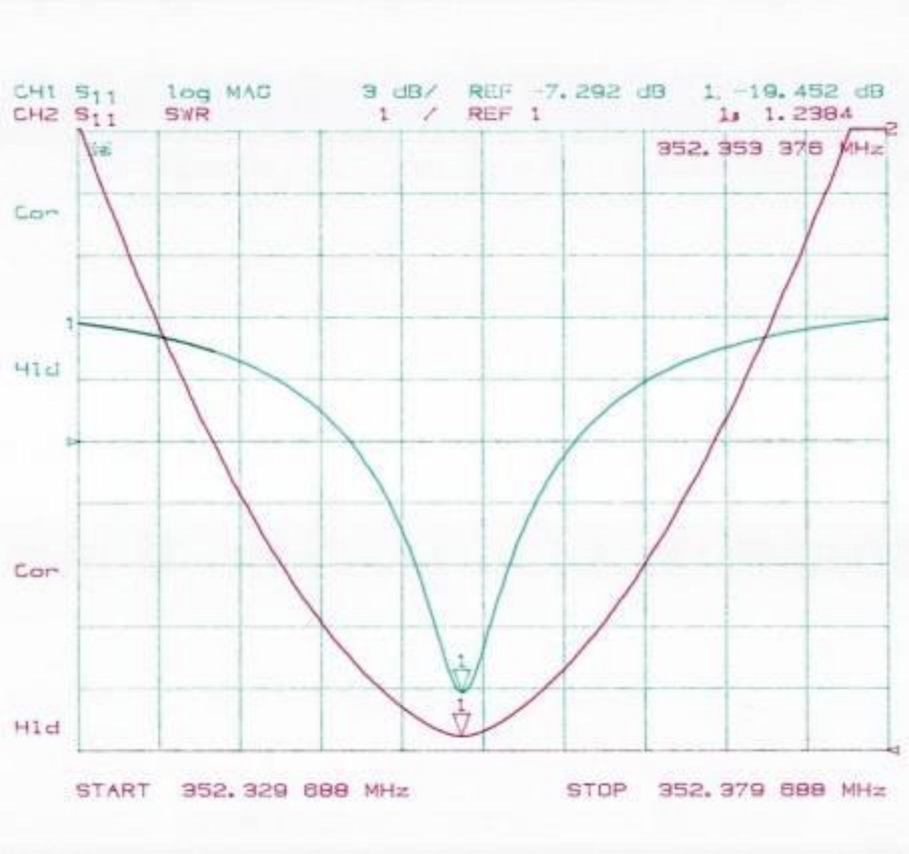

Figure 4 Measurements of the Standing Wave Ratio (magenta trace) and S11 parameter (green trace) of the CCDTL with new copper-plated end-covers.

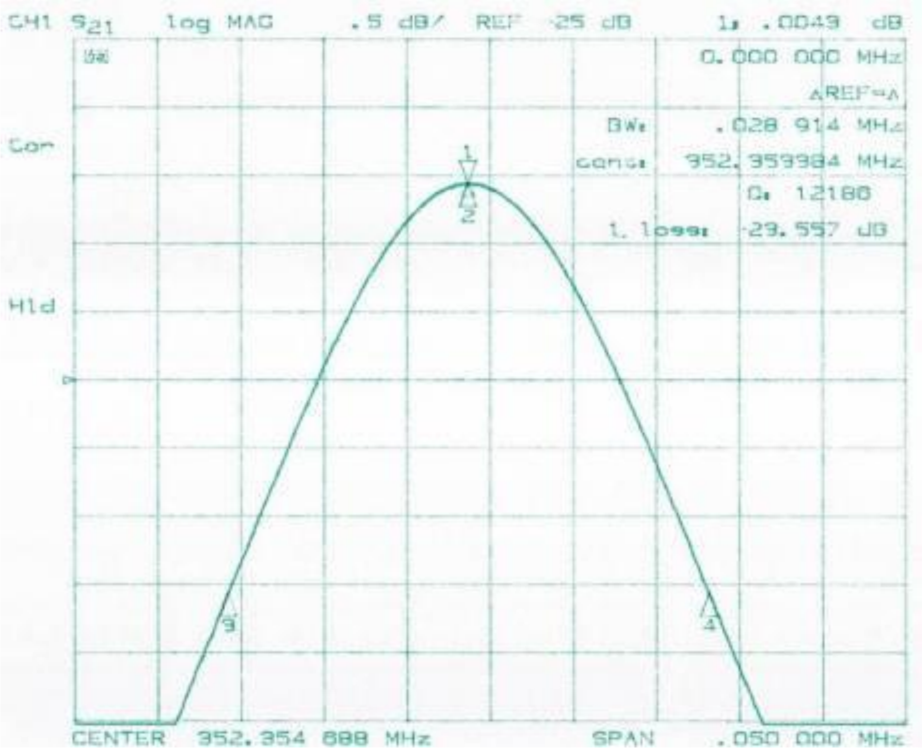

Figure 5 Q-loaded measurement

In the table here below we summarize the results of the low level measurements for the CERN CCDTL prototype.

Table 1 Results of the low level measurements for the CERN CCDTL prototype

Frequency 0-mode	350.8185	MHz
Frequency π/2- mode	352.3547	MHz
Frequency π-mode	353.8653	MHz
Coupling β	0.86	%
Stop band	45	kHz
SWR = reflection coeff. β	1.2384	#
Q_0	27281	#

The new Q-value has increased by 14% with respect to the old measurement, hence confirming that the non copper plated region of the joint groove was the cause of the low Q of the cavity. The frequency values in the table are the ones that were measured with the cavity under vacuum; at a pressure level of 10^{-8} mbar, a frequency shift of +67 kHz was observed for the π/2 mode and the stop-band changed from 20 to 45 kHz.

The ISTC CCDTL prototype

The ISTC CCDTL prototype consists of 2 full accelerating cavities and one coupling cell. The structures have been designed to follow a certain velocity profile; hence the two cavities as well as the drift tubes have slightly different lengths. The construction technology is the same as of the CERN prototype and in particular all the joints are of the Helicoflex type. Pre-assembly and pre-tuning of the cavities was performed at BINP institute in Novosibirsk. The tuning of the cavities was actually done keeping the plunger tuners at the level of the internal diameter while slice-cutting a dummy drift tube. Once the wanted resonant frequency is found, precise dimensional measurements are performed on the dummy drift tube and a new copper drift tube is then produced with those dimensions. Figure 6 and Figure 7 show respectively a model of the ISTC CCDTL prototype and the real cavity at CERN during low level measurements.

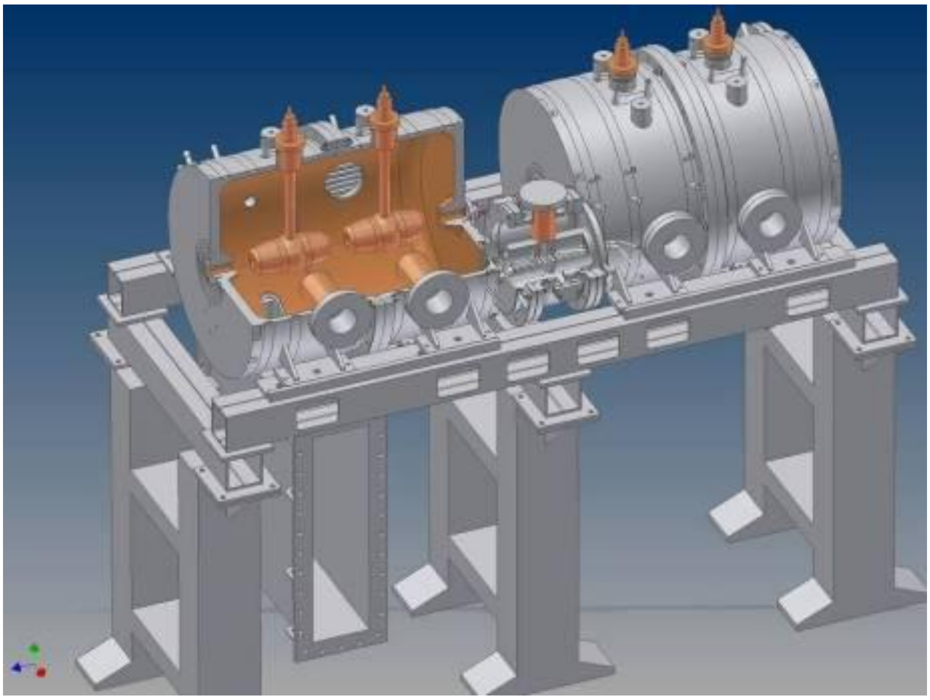

Figure 6 Model of the ISTC CCDTL prototype

Figure 7 ISTC CCDTL prototype during low level measurements in the assembly area.

Before the final assembly of the cavities, the alignment of the drift tubes was checked. The set-up for this measurement consists in a rod that is inserted into the drift tubes whose ends protrudes in one side into the beam port, on the other side into an alignment flange which is mounted at the half cell position. (See Figure 8) Measuring the space between the rod and the aperture of the alignment flange or the beam port with calibrated pin gauges gives a measurement of the position of the drift tubes in the frame of each half accelerating cavity.

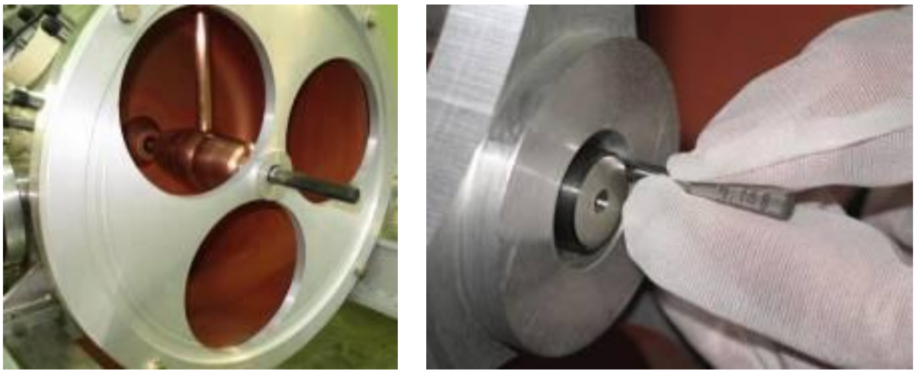

Figure 8 Set-up for alignment checks. On the left the shaft and the alignment flange are mounted in the half cavity, on the right a pin gauge is inserted to verify the distance between the shaft and the aperture of the alignment flange.

The result of this alignment check was that all the drift tubes were found centered within a radius of less then 0.1 mm. The drift tube alignment tolerance from the RF point of view is ± 0.3 mm.

Once the ISTC CCDTL was completely assembled, with all the joints and the waveguide coupler, a bead-pull measurement was performed. Figure 9 shows a plot of the accelerating field profile; the field flatness achieved was within 1%.

A final measurement of the waveguide to cavity coupling coefficient was performed in order to determine the distance of the short circuit plate from the center of the coupling iris. In order to perform this measurement a sliding plate with RF contacts is inserted into a piece of wave guide. The SWR is then measured at different positions of the short circuit plate (See Figure 10).

Table 2 summarizes the results of the low level measurements for the ISTC CCDTL prototype.

Table 2 Results of the low level measurements for the ISTC CCDTL prototype. The ISTC model has full cell terminations so in the equivalent electric circuit the coupling is calculated taking into account modes at different phases

Frequency π /4-mode	350.8835	MHz
Frequency π/2- mode	352.1444	MHz
Frequency 3π/4-mode	353.1497	MHz
Coupling β	0.9	%
Stop-band	62	kHz
Q_0	36700	#

The frequency values in the table are the ones that were measured with the cavity under vacuum; at a pressure level of $5 \cdot 10^{-7}$ mbar, a frequency shift of +84 kHz was observed for the π/2 mode. The Q_0 value is 82% of the theoretical value calculated with Superfish and meets the design specifications.

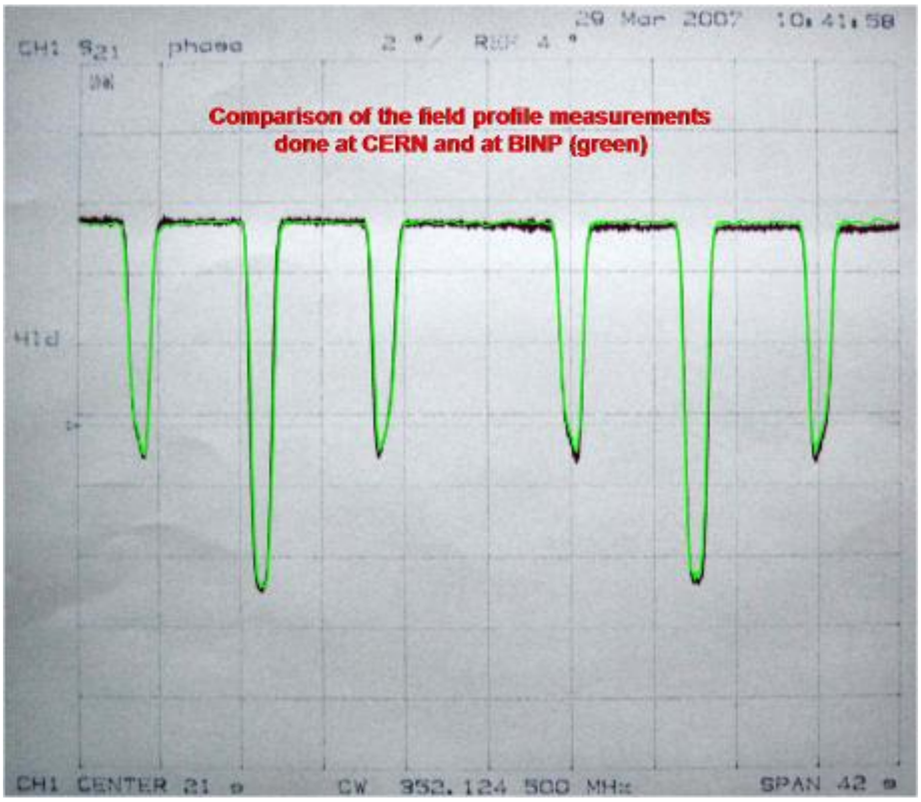

Figure 9 Bead-pull measurement of the CCDTL. The black trace corresponds to the measurement done at CERN, the green one to the measurement done at BINP

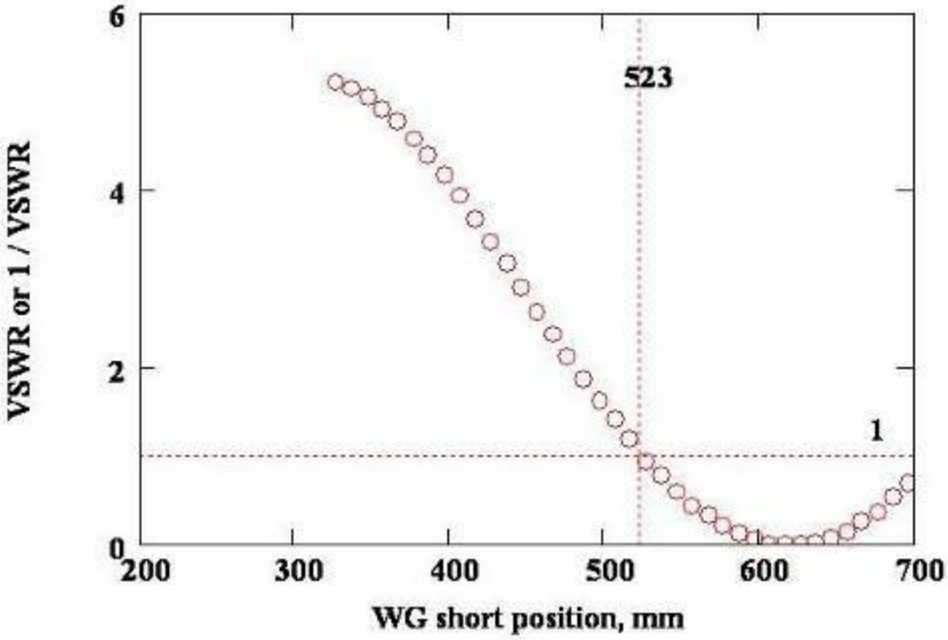

Figure 10 Graph of the coupling factor as a function of the sliding plate position from the center of the coupling iris.

High power RF measurement system and its precision

To measure the RF power level in our cavities and waveguides, RF pickups are employed to couple a small fraction of the electromagnetic field into RF detectors. They transform the incident power into a voltage by rectifying the high frequency signal via a diode. Several RF detectors were investigated to be used for our purpose, namely detectors of the HP8471 family and CERN-made types: red box, yellow box and grey box. To characterise these detectors it was found to be necessary to perform three basic measurements: firstly to determine the reflection at fundamental frequency (352 MHz), secondly to quantify the effect of higher harmonics that are produced by the detectors themselves and finally to perform power-voltage calibrations.

All detectors with the exception of the red boxes have reflection coefficients of $|R| \leq -15$ dB up to an input power level of 20 dBm.

The diodes inside each RF detector are non-linear devices. They produce higher harmonics of the incident wave and reflect them back towards the RF pickup. The amount of power contained by the generated harmonics strongly depends on the detector type. When these higher harmonics are again reflected from the pickup and returning to the detector, the power measurement is disturbed. All detectors apart from the HP8471 ones show less than 10% increase of the measured power in presence of full reflection of the higher harmonics from the pickup. The yellow boxes are the best detectors with less than 3% increase in power. Therefore, they were chosen as RF detectors for the high power tests. Furthermore, attenuators of at least 10dB were mounted between each RF pickup and its corresponding detector.

Several yellow box detectors were numbered once and calibrated. As buffer amplifiers are needed to process the differential output signals, each detector was calibrated with its "personal" amplifier channel to enhance the precision.

The overall error for the present power measurement set-up has been estimated to be ±15%.

High power measurements

The power source consists of a LEP-type klystron (1 MW, CW), however fed by a power supply that is limited to 60 kV klystron voltage. The consequence is that the RF power out of the klystron is limited to about 350 kW.

The test area was originally equipped with motorized waveguide splitter so it was possible to install the two prototypes at the same time. This layout allowed us to perform power tests in both the prototypes with virtually no waiting for mounting and dismounting of the waveguides. Figure 11 and Figure 12 show the two prototypes installed inside the bunker at SM18.

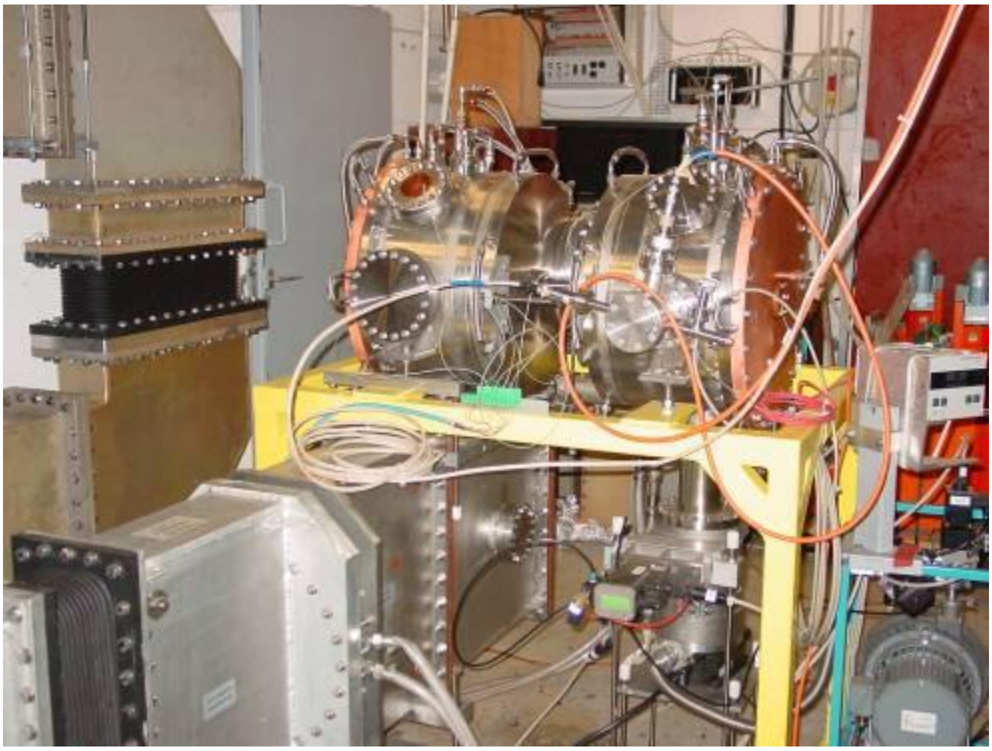

Figure 11 Cern CCDTL prototype inside the bunker at SM18

Figure 12 ISTC CCDTL prototype installed inside the bunker at SM18

The CERN CCDTL prototype, thanks also to a large pumping group, was conditioned up to Linac4 duty cycle in less then a day. A set of thermocouples was installed to monitor the temperature during the test. The vacuum in the prototype was of the order of 10^{-8} mbar. No strong multipacting levels were observed during the conditioning. Nominal field level requires 246 kW for 1.1 MV of effective voltage in each half cell. In the cavity, power in excess of 290 kW was measured at the pick-up. The temperature that initially was 27 deg. was stabilized at around 30 deg. with a minimum water flow of 5 l/min only in the drift tubes; the resonant frequency decreased by 7 kHz from cold to warm cavity condition.

After 2 more days of conditioning the CERN prototype was also tested at SPL duty cycle (50 Hz, 1ms): power in excess of 290 kW was measured at the pick-up in the accelerating cells.

In order to withstand the power dissipation of the cavity all the cooling channels were opened and a total flow of more that 30[1] l/m was circulating inside the cavity. The temperature of the drift tube holder, coupling iris and plunger tuner reached, respectively 58, 76 and 80 degrees. In particular the temperature rise in the coupling iris is due to the over-coupled matching between waveguide and cavity; the resonant frequency decreased by 128 kHz from cold to hot condition.

Finally, Figure 13 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. This measurement was performed only for the CERN CCDTL prototype during the first high power test [2]. 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.

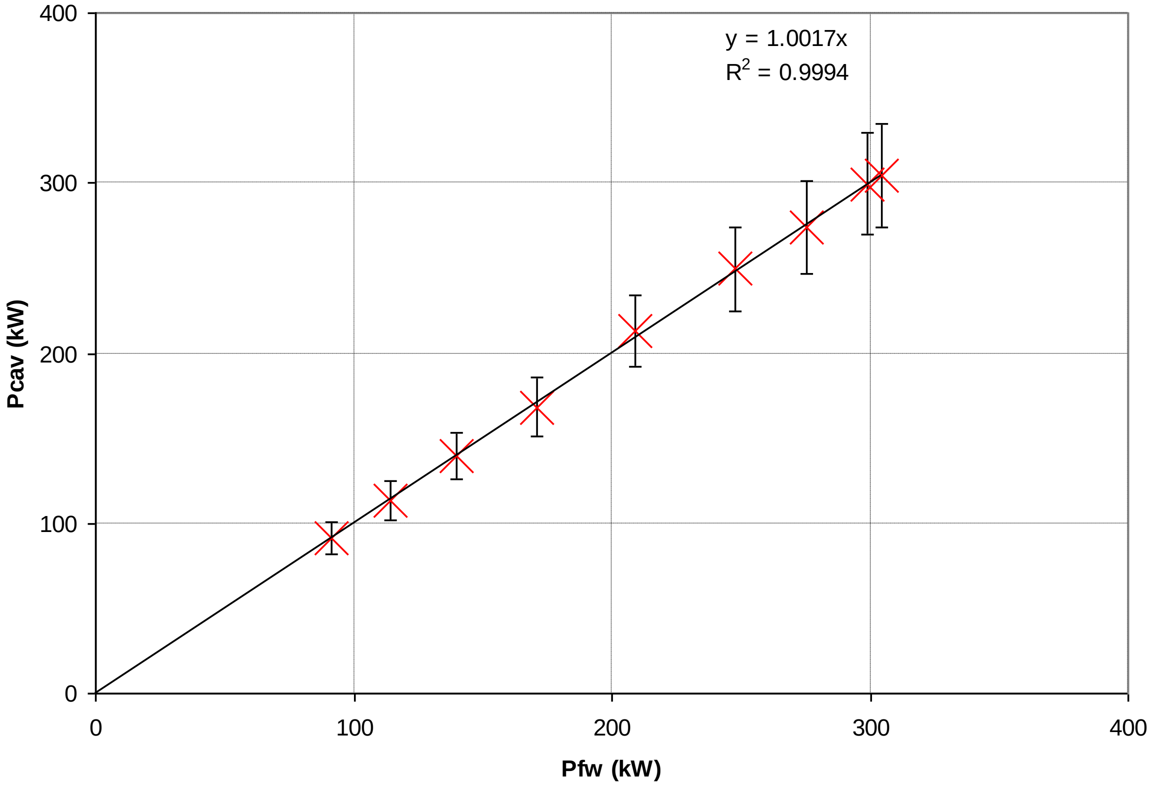

Figure 13 Power in the cavity vs. Power forward from the klystron

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[1] The measurement of the total water flow was limited by the flow-meter that saturates for value higher then 30 l/m

Conditioning of the ISTC prototype lasted about a week. Minor multipactoring activity was observed at low power levels. Nominal field level requires 310 kW for 2.2 MV of effective voltage in each accelerating cavity. A power in excess of 330 kW at both Linac4 (0.1%) and SPL (5%) was measured in the cavity. The temperature on the cavity was monitored: at 5% duty cycle the temperature on the external part of the drift tube raised by 40 degrees, while tuners in the accelerating cell went up to 100 degrees. With the full water flow it was possible to stabilize the temperature with 330 kW power level at 11% duty cycle: (9 ms pulse period, 1 ms pulse length).

Conclusions

The CERN CCDTL was repaired and new measurements of the Q-value show that the reason of the previously low Q-value stands in the non-copper plated groove.

A power of 290kW was measured in the cavity (18% more then nominal power) at both 0.1% and 5% duty cycle. In the first case only limited water flow of 5 l/min is required to stabilize the temperature of the drift tubes.

ISTC prototype was tested and 330kW (6% more than nominal power) were measured in the cavity at both Linac4 duty cycle (0.1%) and SPL duty cycle (5%). In this latter case, a -74 kHz of frequency shift with respect to “cold” condition was observed.

References

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[2] M. Pasini, M. Vretenar, “CCDTL prototype: status report” CARE-Note-2006-021-HIPPI
[3] T. P. Wangler “Principles of RF Linear Accelerators”, ISBN 0-471-16814-9, pag. 106-107

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