Multipacting tests with a resonant coaxial setup

F. Caspers, J.-M. Laurent, M. Morvillo, and F. Ruggiero

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Summary

In connection with electron-cloud induced heating of the LHC beam screen, multipacting tests have been successfully performed using a resonant coaxial setup and a wideband power amplifier. We have developed a simple and reliable technique, based on amplitude modulation of the input signal, to detect electronically the onset of multipacting and to monitor the field level in the resonator. Several multipacting patterns have been systematically investigated under the effect of a variable DC-bias applied to the inner conductor of the coaxial setup. The results at room temperature are qualitatively similar to those obtained during cold tests with a magnetic field up to about 7.5 T.

1 Introduction

Synchrotron radiation from proton bunches in the LHC creates photoelectrons at the beam screen wall. These photoelectrons are pulled toward the positively charged proton bunch. When they hit the opposite wall, they generate secondary electrons which can in turn be accelerated by the next bunch. Depending on several assumptions about surface reflectivity, photoelectron and secondary electron yield, this mechanism can lead to the fast build-up of an electron cloud with potential implications for beam stability and heat load on the beam screen [1]. The secondary electron yield and its possible reduction by a strong magnetic field can be inferred from the multipacting level reached under suitable conditions in a resonant coaxial setup. Measurements of photoelectron yield may also be possible using UV light (e.g., from a Xe flash lamp mounted near or inside the coaxial tube) and applying a DC-voltage between inner and outer conductors of the coaxial structure. Comparing experimental results and predictions of computer simulations will also provide a very useful ‘calibration’ for the numerical results concerning heat load on the LHC beam screen.

Here we report about successful multipacting tests performed using a resonant coaxial setup and a wideband power amplifier. The coaxial structure consists of two circular stainless steel tubes; an outer one, with 39 mm inner diameter and 1 mm wall thickness, and an inner one of outer diameter 4.5 mm with 0.5 mm wall thickness. Both tubes are copper coated with 50 μm thickness: the inner surface of the outer tube (that according to simulations [2] is the only one playing a role in multipacting) has an electrodeposited copper layer with
average roughness of a few \( \mu m \). It has undergone no thermal treatment and has a measured DC RRR\( \approx 50 \). The inner tube is held by three teflon supports, placed at the nodes of the E-field in standing-wave operation. For resonant excitation, the inner tube is capacitively coupled to two coupling ports at both ends; the setup is similar to the one already used for surface resistance measurements [3], but for power tests one of the ports is operated close to critical coupling. The experimental setup is schematically shown in Fig. 1, while Fig. 2 is a photograph of the instruments used during cold multipacting tests with a strong magnetic field.

With a wide-band power amplifier (1-1000 MHz, 100 W) we have excited TEM modes in a 1 m long coaxial structure accommodated in the cold bore of an 8.4 T magnet. The advantage of the resonant setup is that we can reach high electric fields and RF-voltages between the inner and outer conductor, inspite of the limited power of the amplifier: for a \( Q \) of 1000 and a characteristic impedance of about 100 \( \Omega \), a power of 100 W corresponds to a peak voltage of \( \sqrt{100 \, \text{W} \times 100 \, \Omega \times 1000} \approx 3 \) kV. According to simulations, the minimum voltage required to reach a significant multipacting level is around 1 kV [2]. We have also developed a simple and reliable technique, based on amplitude modulation of the input signal, to detect electronically the onset of multipacting and to monitor the field level in the resonator.

In the next section, we report about the most systematic features of the observed ‘multipacting patterns’ and of their modification by a strong magnetic field, while in Sec. 3 we give a detailed account of the experimental results. Future plans for multipacting tests are discussed in the last section. The most interesting observation is that during multipacting the electric potential of the inner conductor tends to become negative relative to the outer tube. We have measured typical differences around \(-30 \) V: this is confirmed by preliminary simulation results and is mainly due to the effect of image charges [2]. Conversely, a DC-voltage applied to the inner conductor has an effect on the onset of multipacting and on the threshold for a higher multipacting level, sometimes observed. This is related to the electron oscillation period (either double or equal to that of the RF signal) and is again in agreement with simulation results [2]. Although the magnetic field modifies the relative voltage of the inner conductor (that becomes positive for strong field) and decreases the step sometimes observed in the reflected signal at the onset of multipacting, the experimental results at room temperature are globally similar to those obtained at cryogenic temperatures with a strong B-field. This seems to exclude any significant reduction of the secondary electron yield by the magnetic field over most of the outer tube surface, i.e., where the field is not strictly parallel to the metal.

2 Multipacting patterns and effect of the B-field

During most of the multipacting tests, we have applied an amplitude modulated signal to the resonant structure. The main signature of multipacting is

- a discontinuity in the reflected signal or in its slope above a certain threshold value of the input (forward) signal.

\[ Z_0 = \frac{2\pi}{\ln \left( \frac{R_{\text{out}}}{R_{\text{in}}} \right)} = \frac{370.73 \Omega}{2\pi} \ln \left( \frac{30}{4.3} \right) \approx 130 \Omega \]

\(^1\)The characteristic impedance of our coaxial structure is
• a flattening (clamping) of the transmitted signal, corresponding to a constant value of the peak electric field inside the resonant setup.

• This is often accompanied by a negative (sometimes positive) low-frequency signal superimposed on the transmitted RF signal of the weakly coupled port or on the 'resistor probe' signal from the inner conductor, when measured with a 1 MΩ termination on the scope. We refer to this signal as to the 'probe' signal. The high termination impedance enhances the measurable low-frequency voltage and avoids fast discharge; we estimate a capacitance of about 30 pF for the coaxial structure and below 1 pF for the weakly coupled port, corresponding to time constants around 30 μs for the resistor probe and 1 μs for the transmitted signal, respectively.

The (almost 70) oscilloscope pictures, documented in detail in the next section, have been labelled according to the following convention: a bold capital letter, different for different experimental conditions, followed by one or two other letters for the top and bottom trace, respectively. If one of these following letters is capital, it refers to a 'probe' signal measured with a 1 MΩ load. An 'f' or an 'r' refer to the forward or to the reflected signal, respectively, attenuated by about 40 dB and measured on a 50 Ω load. A 't' refers to the transmitted signal, measured with a 50 Ω load, while a capital 'T' refers again to the transmitted signal but measured with a 1 MΩ load. A capital 'R' refers to the 'resistor probe' signal from the inner conductor, measured with a 1 MΩ load. Finally a capital 'B' refers to the 'button-like' pick-up signal of the multi-wire setup (see Sec. 3.1), again measured with a 1 MΩ load. For example Fig. 6-GrT indicates the 12th picture in Fig. 6, showing the reflected signal measured with a 50 Ω load (top) and the transmitted signal measured with a 1 MΩ load (bottom). The experimental conditions are the same as in the previous picture (Fig. 6-Grt, with a DC-bias of 100 V on the inner conductor), which shows the reflected signal (top) and the transmitted signal (bottom) both measured with a 50 Ω load. This happens to be one of the cleanest examples of multipacting signature, with a perfectly matched impedance and a well tuned frequency: in this case there is no reflected signal until the amplitude modulated forward signal reaches a threshold value. Meanwhile the transmitted signal increases and then becomes constant in the multipacting range.

In many cases the excitation frequency of the forward signal is not well tuned to the resonant frequency of the cavity, for example because the latter is changing as a consequence of thermal effects associated with power deposition into the structure (either ohmic or due to multipacting): this effect was particularly severe during the cold tests and we had to retune the forward signal rather frequently, unless a long excitation period with high power level put the cavity in a reasonably steady thermal state. An example of not-well-tuned excitation frequency is shown in Fig. 4-Brt, where the reflected signal (top) first grows following the amplitude modulated forward signal and then drops at the onset of multipacting, that probably reduces the detuning, while the transmitted signal (bottom) increases and then becomes constant in the multipacting range.

In addition to excitation frequency detuning, the reflected signal is also affected by impedance mismatch. When the coupling is critical, i.e., for a well adjusted distance between the two coins used for the capacitive coupling (optimised for a given cavity mode with a certain quality factor Q), the reflected signal at resonance frequency is zero. However, this distance can be adjusted only before the multipacting test and for cold tests we could only
<table>
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<th>REFLECTED</th>
<th>TRANSMITTED</th>
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<tr>
<td>classic Fig. 6-Grt</td>
<td>none until threshold (continuous)</td>
<td>grows and then constant above threshold</td>
<td>with or without arc Fig. 6-GrT</td>
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<tr>
<td>with detuning Fig. 4-Brt</td>
<td>grows, then step down at threshold</td>
<td>grows and then constant above threshold</td>
<td>with or without arc Fig. 4-BfT, 10-ArR</td>
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<tr>
<td>two-level Fig. 4-Ert, 6-Drt, 4-Drt, 6-Hrt(?)</td>
<td>none until threshold, then grows, then step up</td>
<td>grows, then constant, then step up and then either constant or down</td>
<td>with or without arc possibly at 2nd step Fig. 4-DfT</td>
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<tr>
<td>step down Fig. 7-Crt, 5-Hrt(?), 8-ArT, 8-ErT</td>
<td>grows slowly, then small step up, followed by step down</td>
<td>grows, then step down, then constant and then step up</td>
<td>with or without arc either down or up Fig. 7-ER</td>
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<td>big step Fig. 6-Crt, 9-CrR</td>
<td>grows slowly, then big step up and later down</td>
<td>grows and then constant possibly with step down</td>
<td>intermittent signals Fig. 7-BrR</td>
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Table 1: Classification of multipacting patterns observed with amplitude modulated forward signal and references to the main examples illustrated in the figures.

‘pre-correct’ for the expected effect of the cool-down. Since the Q of the mode we intended to use (around 480 MHz) turned out to be very low, we had to chose a higher harmonic (around 790 MHz) and the Q after cool-down was only about 1000, instead of the expected value of 2500. Therefore all the cold tests with B-field have an impedance mismatch and a corresponding reflected signal at resonance frequency, even before reaching the multipacting threshold. In future multipacting tests, we plan to improve the situation by an adjustable capacitive coupling external to the cavity. It is interesting to remark that, even for a perfectly matched impedance, the onset of multipacting changes the cavity impedance (through the index of refraction of the electron plasma) and the observed reflected signal can be explained by a corresponding impedance mismatch.

In Table 1, we have tried to classify the different multipacting patterns observed under different conditions of frequency detuning, (initial) impedance mismatch and intensity of the forward signal. At the moment, we do not completely understand the (transmitted) ‘step down’ and the (reflected) ‘big step’ patterns, that sometimes occur concurrently (see for example Fig. 9-CrR). The case of transmitted ‘glitch up’ in Fig. 5-Ert, accompanied by a corresponding reflected ‘glitch down’ (see also Fig. 8-Ffr) might be classified either as a variant of ‘two-level’ multipacting pattern or as a classic pattern with limited multipacting range (i.e., multipacting is suppressed above a certain value of the forward signal). There is a correlation between magnetic field and sharpness of the (reflected) ‘big step’ pattern: for low B-field there is a step transition, while for high B-field there is a soft transition at the multipacting threshold. This seems to be confirmed by preliminary simulation results [2].

The effect of a positive DC-voltage applied on the inner conductor of the coaxial setup is to increase the multipacting threshold: for example, Figs. 5-Drt and 5-Grt correspond to 100 V and to 150 V of DC-bias, respectively, and the level of the transmitted signal at the onset of multipacting differs by about 70 mV. Multipacting disappears for a positive DC-voltage exceeding about 200 V. We have not studied in a very systematic way the effect of a negative DC-bias.
3 Detailed experimental results

In this section we give a detailed, chronologic account of the experimental results obtained under different conditions, from preliminary warm tests to cold multipacting tests with strong magnetic field. Each of the following subsections refers to a different figure and contains all the relevant information concerning each picture or observation documented in our ‘logbook’.

3.1 Preliminary tests with a multi-wire setup (see Fig. 3)

The results of initial multipacting tests with a multi-wire setup, performed between 23 June and 9 July, are shown in Fig. 3. Instead of a single inner conductor, there are six regularly spaced wires in the structure, located at a radius of about 25 mm, and the outer tube with 100 mm diameter is significantly larger than the one used for cold tests with B-field.

Preliminary tests with pulsed excitation (25 ns pulses with about 50% duty cycle, peak voltage around 50 V) show rather erratic results, the main diagnostic for multipacting being a sudden rise of the residual gas pressure, sometimes by two orders of magnitude. There is an impedance mismatch between the 50 Ω line used for pulse excitation and the multi-wire structure, having a characteristic impedance of about 70 Ω. Furthermore we can not analyse the reflected signal due to the limited bandwidth of the directional coupler. Over time intervals of about one hour, it becomes more and more difficult to observe multipacting in the structure, possibly as a consequence of surface cleaning.

To reach higher voltages in the structure, we then decide to switch to resonant excitation and to amplitude modulate the input signal. We can further use the signal from a button-like probe located at one extreme of the structure: although there is no interesting signal on a 50 Ω load, with a 1 MΩ load we can sometimes measure a direct electron current during multipacting. For resonant excitation we use a capacitive contact external to the multi-wire structure, but the coupling is far from critical since we are limited by discharge in the capacitor (consisting of two small coins 0.1 mm apart). The transmitted signal can be measured on a 1 MΩ load (in addition to the matched 50 Ω load visible on top of the structure in Fig. 3-D).

ArB) amplitude modulation (100% at 2.5 Hz) of CW signal for resonant excitation at 47 MHz. Oscilloscope picture (HP 54610B, with 500 MHz bandwidth) showing discontinuity in the reflected power and collected electron current during multipacting. The upper trace is the reflected signal measured on a 50 Ω load with 40 dB attenuation, having a peak voltage of about 200 mV. The lower trace is the signal from a button-like electron probe with about 400 mV peak value, measured with a 1 MΩ load.

BrB) amplitude modulation (at 0.4? Hz) of CW signal for resonant excitation at 47 MHz. Oscilloscope picture similar to ArB), with less AM depth.

CrB) similar to ArB), with different AM frequency.

D) picture of the multi-wire setup.

ErB) electron signal on probe during multipacting, the top trace is the reflected signal measured on a 50 Ω load, the bottom trace is the probe signal measured on 1 MΩ load.
\( f = 44.815 \text{ MHz}, \) 90% amplitude modulation depth, \( f_{\text{AM}} = 11 \text{ Hz}, \) about 21 W forward peak power measured on amplifier wattmeter and about 20 W reflected power.

FTB) multipacting signal, the top trace is the transmitted signal, the bottom trace is the probe signal (both measured on a 1 M\( \Omega \) load), DC-bias 70 V (applied through 100 k\( \Omega \) resistor between inner wires and outer tube), \( f = 44.45461 \text{ MHz}, \) 90% amplitude modulation depth, amplifier gain 7th tick, pressure \( P = 10^{-5} \) torr, vertical scale 5 V/div (top)--200 mV/div (bottom).

### 3.2 First multipacting tests with the coaxial setup (see Fig. 4)

The results of the first multipacting tests with the resonant coaxial setup, performed between 14 and 17 July, are shown in Fig. 4. No resistor is yet connected to the inner conductor. One port is near critical coupling, the other is weakly coupled. We used semirigid Cu cables and an outer vacuum tank already used (in the Meyrin cryolab) for surface resistance measurements [3]. The generator signal with frequency \( f \) and power \( W \) is amplitude modulated (90% depth) with frequency \( f_{\text{AM}} \) and amplified at maximum gain (about 60 dB for an input power below -20 dBm). In the ‘rt’-pictures the upper trace is the reflected signal attenuated by 40 dB and the lower trace the transmitted signal, both measured with a 50 \( \Omega \) load. In the ‘fT’-pictures the upper trace is the forward amplifier signal attenuated by 40 dB and the lower trace the transmitted signal measured with a 1 M\( \Omega \) load.

A\( \text{fT} \) positive current on transmitted signal probably related to discharge ionization: main frequency \( f = 637.26730 \text{ MHz} \) (4th mode, having maximum field at the central teflon support and some field also at the other two supports), AM frequency \( f_{\text{AM}} = 350 \text{ Hz} \), generator power \( W = -26.4 \text{ dBm} \), pressure at the pump \( P = 8 \times 10^{-5} \) mbar, transmitted signal with 1 M\( \Omega \) load.

B\( \text{rt} \) slightly detuned excitation (large reflected signal), at the onset of multipacting the transmitted signal is limited (clamping) while the reflected signal is first reset (re-matched by multipacting?) and then goes up: \( f = 481.19164 \text{ MHz} \) (3rd mode), \( f_{\text{AM}} = 2 \text{ Hz}, W = -33.4 \text{ dBm} \), horizontal scale 100 ms/div, vertical scale 100 mV/div, pressure \( P = 1.5 \times 10^{-5} \) to \( 2.5 \times 10^{-5} \) mbar (power on or off).

B\( \text{fT} \) same conditions as B\( \text{rt} \), top trace is the forward signal measured at the exit of the amplifier and bottom trace is the transmitted signal with 1 M\( \Omega \) load.

C\( \text{rt} \) two multipacting levels (the first approximately same as in B\( \text{rt} \)), retuned carrier frequency (by about 200 kHz) to reduce reflected signal without multipacting: \( f = 480.99164 \text{ MHz}, f_{\text{AM}} = 2 \text{ Hz}, W = -28.8 \text{ dBm} \) (about 4 times more power than in B\( \text{rt} \)), peak to peak reflected signal 353 mV, transmitted signal 400 mV, no pressure change, horizontal scale 100 ms/div, vertical scale 100 mV/div.

C\( \text{fT} \) same as C\( \text{rt} \), upper trace is forward amplifier signal (peak to peak 431 mV) lower trace is transmitted signal with 1 M\( \Omega \) load, horizontal scale 100 ms/div, vertical scale 200 mV/div.
a few minutes later the second multipacting level starts at a higher power: \( f = 480.77364 \text{ MHz (retuned), } W = -25.5 \text{ dBm (power about twice as in Crt), horizontal scale 100 ms/div, vertical scale 200 mV/div (upper) and 100 mV/div (lower), peak to peak amplitude 500 mV (up) and 506 mV (bottom).}

same conditions as \( \text{Dr} \), upper trace is forward signal from amplifier, bottom trace is transmitted signal with 1 MΩ load. Very unstable situation (changing over seconds) and showing electron signal on the coin of the weakly coupled port. horizontal scale 100 ms/div, vertical scale 200 mV/div (upper) and 1000 mV/div (lower),

again two multipacting levels, in a rather unstable situation, with unexplained ‘glitches’ at the moment of the jumps: \( f = 480.56564 \text{ MHz (retuned again, although not perfectly), } W = -15.15 \text{ dBm (10 times the power in Crt), horizontal scale 100 ms/div, vertical scale 500 mV/div, peak to peak amplitude 1750 mV (up) and, for the two plateaux, 531 and 1297 mV (bottom).}

same conditions as in \( \text{Er} \), upper trace is forward signal from amplifier, bottom trace is transmitted signal with 1 MΩ load. Very unstable situation. Horizontal scale 100 ms/div, vertical scale 1000 mV/div, peak to peak amplitude 1969 mV (upper trace).

same conditions as in \( \text{Ef} \), only transmitted signal with 1 MΩ load: horizontal scale 200 ms/div, vertical scale 1000 mV/div.

single level multipacting with reduced power, after about 10 minutes from \( \text{Ef} \): \( f = 480.60914 \text{ MHz, } W = -24.8 \text{ dBm, } f_{\text{AM}} = 1.6 \text{ Hz, horizontal scale 100 ms/div, vertical scale 100 mV/div (up) and 50 mV/div (bottom), peak to peak amplitude 425 mV (upper trace) and 515 mV (bottom).}

electron signal collected by coin of weakly coupled port during single level multipacting, same conditions as in \( \text{Fr} \), upper trace is forward signal from amplifier, bottom trace is transmitted signal with 1 MΩ load. Stable situation, horizontal scale 100 ms/div, vertical scale 200 mV/div (up) and 500 mV/div (bottom), peak to peak amplitude 593 mV (upper trace) and -1094 mV (bottom, from 0 level downwards).

3.3 Multipacting tests with DC-voltage (see Fig. 5)

The results of new multipacting tests performed on 17 July in the resonant coaxial setup, modified so that we can apply a DC-voltage to the inner conductor, are shown in Fig. 5. A thin wire is radially connected to the middle of the inner conductor through a resistor and comes out of the outer tube via a small hole. Two resistors (33 kΩ and 10 (or 110?) kΩ, but the total measured resistance is 146 kΩ) are connected in series to the centre of the inner conductor, near the teflon support: the inner conductor is isolated unless otherwise specified. When connecting inner and outer conductors (without DC-bias), the multipacting stops and a higher generator power is required to let it start again. Once this happens, however, we can reduce the generator power to the original level without stopping multipacting. This
seems to indicate that the inner conductor acquires an electric charge during multipacting: after removing this charge, it is more difficult to start multipacting again.

The generator signal with frequency $f$ and power $W$ is amplitude modulated (100% depth) with frequency $f_{AM} = 30$ Hz and amplified at maximum gain (about 60 dB). Unless otherwise specified, the upper trace is the reflected signal and the lower trace the transmitted signal. One port is near critical coupling, the other is weakly coupled. We used flexible Cu cables and a bigger outer vacuum tank. In the ‘rt’-pictures the upper trace is the reflected signal attenuated by 40 dB and the lower trace the transmitted signal, both measured with a 50 Ω load. In the ‘ft’-pictures the upper trace is the forward amplifier signal attenuated by 40 dB and the lower trace the transmitted signal measured with a 1 MΩ load.

Art) single level multipacting, main frequency $f = 480.94099$ MHz (3rd mode), AM frequency $f_{AM} = 30$ Hz, generator power $W = -29.1$ dBm, pressure at the pump $P = 2 \times 10^{-5}$ mbar, $2 \times 10^{-4}$ mbar at the opposite extreme, horizontal scale 5 ms/div, vertical scale 100 mV/div, peak to peak amplitude 290 mV (top) and 340 mV (bottom).

Aft) negative low-frequency signal collected by the coin of the weakly coupled port during single level multipacting, same conditions as for Art), the top trace is the forward signal measured at the exit of the amplifier and the bottom trace is the transmitted signal with 1 MΩ load, horizontal scale 5 ms/div, vertical scale 200 mV/div, peak to peak amplitude 450 mV (top) and 662 mV (bottom, average -40 mV). By connecting inner and outer conductors through the resistor(s) the multipacting disappears and the transmitted signal is reduced.

Brt) double multipacting levels, $f = 480.26779$ MHz (retuned to reduce reflected power), $W = -21.9$ dBm (increased power), horizontal scale 5 ms/div, vertical scale 500 mV/div (up) and 100 mV/div (bottom), the second level of multipacting has disappeared after a few minutes.

Crt) no multipacting when connecting inner and outer conductors by resistors, same as in Brt) but with short circuited resistors, horizontal scale 5 ms/div, vertical scale 500 mV/div (up) and 100 mV/div (bottom).

C’rt) (not shown) no multipacting when polarizing inner conductor with -100 V, same as in Brt) but with -100 V on inner conductor, horizontal scale 5 ms/div, vertical scale 500 mV/div (up) and 100 mV/div (bottom).

Drt) single level multipacting when polarizing inner conductor with +100 V, same as in Brt) but with +100 V on inner conductor and horizontal scale 5 ms/div, vertical scale 500 mV/div (up) and 100 mV/div (bottom).

Ert) multipacting transitions (?) when polarizing inner conductor with +23 V, same as in Brt) but with +23 V on inner conductor, horizontal scale 5 ms/div, vertical scale 500 mV/div (up) and 100 mV/div (bottom).

Frt) no multipacting when polarizing inner conductor with +200 V, same as in Brt) but with +200 V on inner conductor, horizontal scale 5 ms/div, vertical scale 500 mV/div (up) and 100 mV/div (bottom).
Grt) single level multipacting when polarizing inner conductor with +150 V, same as in Brt) but with +150 V on inner conductor and horizontal scale 5 ms/div, vertical scale 500 mV/div (up) and 100 mV/div (bottom). The multipacting level is at about 70 mV higher than in Drt for a difference of DC-bias of 50 V: this may allow us to establish an absolute calibration for the electric field in the cavity.

Hrt) multipacting with a ‘hole’ (maybe resistors were burning?), same conditions as in Brt), peak to peak forward power (not shown) 2170 mV in all images after Brt), unstable conditions (the ‘hole’ disappears after about one minute), inner and outer tubes are shorted by means of the resistor(s), horizontal scale 5 ms/div, vertical scale 1000 mV/div (top) and 200 mV (bottom).

3.4 More multipacting tests with DC-voltage (see Fig. 6)

The results of further multipacting tests performed on 18 July with possible DC-voltage on the inner conductor are shown in Fig. 6. We used a new, bigger resistor (63 kΩ) to polarize the inner conductor. Horizontal scale 50 ms/div for all pictures: isolated inner conductor unless otherwise specified. The generator signal with frequency $f$ and power $W$ is amplitude modulated (100% depth) with frequency $f_{AM} = 3$ Hz and amplified at maximum gain (about 60 dB). Unless otherwise specified, the upper trace is the reflected signal and the lower trace the transmitted signal. One port is near critical coupling, the other is weakly coupled. We used flexible Cu cables and the bigger outer vacuum tank. In the ‘rt’-pictures the upper trace is the reflected signal attenuated by 40 dB and the lower trace the transmitted signal, both measured with a 50 Ω load. The ‘f’-pictures show the forward amplifier signal attenuated by 40 dB and the ‘T’-pictures show the transmitted signal measured with a 1 MΩ load.

Art) classic multipacting, reflected and transmitted signals measured on 50 Ω load, no DC-bias, $f = 480.33350$ Hz, $W = -27.9$ dBm, V-scale 100 (up)-500 (down) mV/div.

AT) same as Art), only transmitted signal measured on 1 MΩ load, showing electron current, V-scale 500 mV/div, average signal -160 mV, lowest value 1297 mV.

BT) same as AT), transmitted signal shows no saturation nor electron current after connecting inner and outer conductor through 63 kΩ resistor, after disconnecting resistor no multipacting is observed(?).

Bf) same conditions as BT), forward signal.

When heated by power tests, the cavity frequency changes and one has to retune generator frequency. Multipacting started at $W = -35.3$ dBm, with shorted resistor it disappears, reappears at $W = -23.9$ dBm and persists down to $W = -24.7$ dBm.

Crt) not perfectly tuned cavity, when multipacting starts there is a jump in reflected signal, reflected and transmitted signal on 50 Ω with short circuited resistor, $f = 479.86050$ Hz, $W = -23.4$ dBm, V-scale 200 mV/div (up)-1 V/div (down).

C’rt) same as Crt), after 3-4 minutes, forward signal (not shown) peak-to-peak 721 mV.
Drt) strange asymmetric transmitted signal (lower trace) with long plateau (appearing and disappearing over seconds: detuning?) and 3 levels, reflected and transmitted signal on 50 Ω, forward peak-to-peak 1019 mV, $f = 479.50550$ Hz, $W = -18.9$ dBm, disconnected resistor, V-scale 500 mV/div (up)-1 V/div (down).

Ert) weak (strange) multipacting level(s?), disconnected resistor, reflected and transmitted signals on 50 Ω, $W = -28.2$ dBm, $f = 479.39950$ Hz, forward peak-to-peak 406 mV, V-scale 100 mV/div (up)-200 mV/div (down).

ErT) same as Ert), showing electron current, disconnected resistor, lower trace is transmitted signal measured on 1 MΩ load, V-scale 100 mV/div (up)-500 mV/div (down). Retuned cavity ($f = 479.54250$ Hz), when connecting cables to power supply multipacting disappears (similar to short circuiting).

Frt) no multipacting, $W = -28.2$ dBm, reflected and transmitted signals, 0 V DC-bias, retuned cavity ($f = 479.51850$ Hz), but no multipacting signal, V-scale 100 mV/div (up)-200 mV/div (down).

Grt) multipacting starts again with a positive DC-bias of +100 V, same as Frt), reflected and transmitted signals on 50 Ω, V-scale 100 mV/div (up)-200 mV/div (down). Multipacting disappears at about 210 V of DC-bias.

Hrt) steps in reflected signal during multipacting, higher power $W = -20.3$ dBm, reflected signal 925 mV peak-to-peak, transmitted 2.9 V peak-to-peak, negative DC-bias (-50 V?), reflected and transmitted signals on 50 Ω, forward peak-to-peak 912 mV, V-scale 200 mV/div (up)-1 V/div (down).

Irt) same as Hrt), with -250 V DC-bias, reflected signal is reduced to 500 mV peak-to-peak, transmitted 2.9 V peak-to-peak, same forward signal 912 mV, V-scale 200 mV/div (up)-1 V/div (down).

Jrt) same as Irt) with -440 V DC-bias, reflected signal is up to 650 mV peak-to-peak, transmitted 3.4 V peak-to-peak, same forward signal 912 mV, V-scale 200 mV/div (up)-1 V/div (down).

3.5 Multipacting tests with ‘resistor probe’ (see Fig. 7)

The results of multipacting tests performed on 26 and 27 July and making use of the signal on the inner conductor, collected by the ‘resistor probe’, are shown in Fig. 6. We used a 1 kΩ resistor inside the resonator, connected to the centre of the inner conductor near the teflon support, in series with 100 kΩ resistor outside the resonator: isolated inner conductor unless otherwise specified.

The generator signal with frequency $f$ and power $W$ is amplitude modulated (100% depth) with frequency $f_{AM} = 3$ Hz and amplified at maximum gain (about 60 dB). We start multipacting with $f = 480.26471$ MHz (3rd mode), $W = -35.5$ dBm. After shorting the
resistor (and retuning), with open circuit a generator power $W = -24.1$ dBm is required to let multipacting start again. Reducing the generator power down to $W = -37$ dBm multipacting remains visible. If the 100 kΩ resistor outside the resonator is eliminated, multipacting starts at $W = -37$ dBm (growing from 0). It seems that multipacting is affected by the open circuit impedance: $f = 480.25871$ MHz without 100 kΩ resistor, $f = 480.2471$ MHz with 100 kΩ resistor; $\Delta f = 16$ kHz is insufficient to explain any change (we tried detuning by such an amount with no effect). The explanation is probably the charge of the inner conductor. The signal on the inner conductor, obtained by connecting the 1 kΩ inner resistor plus 100 kΩ outer resistor on the 1 MΩ load of the scope) is almost constant (around 30 V) during multipacting, independent of the power level of the generator.

Unless otherwise specified, the upper trace is the reflected signal and the lower trace the transmitted signal, 100% depth amplitude modulation. One port is near critical coupling, the other is weakly coupled. In the ‘rt’-pictures the upper trace is the reflected signal attenuated by 40 dB and the lower trace the transmitted signal, both measured with a 50 Ω load. The ‘R’-pictures show the ‘resistor probe signal’ measured with a 1 MΩ (or higher) load.

**Art** multipacting with very low power level, positive transmitted signal is only present with bandwidth limit on, forward signal 195.3 mV (not shown), reflected signal (top) and transmitted signal (bottom, with bandwidth limit on) both measured on 50 Ω load, main frequency $f = 480.9531$ MHz (3rd mode), AM frequency $f_{AM} = 2.5$ Hz, generator power $W = -36.7$ dBm, horizontal scale 50 ms/div, vertical scale 5 mV/div, peak to peak amplitude 14 mV (top) and 22.6 mV (bottom, average 4.198 mV).

With $f = 480.72009$ MHz and 100 kΩ open, multipacting starts at $W = -36.6$ dBm. Connecting a long piece of cable to the resistor stops the multipacting. Without cable attached to the resistor multipacting starts again at $W = -22.3$ dBm an persists down to $W = -33.9$ dBm. But reducing the power until it disappears and increasing it again with the long cable connected to the resistor, multipacting starts at $W = -33.3$ dBm. So multipacting has a memory: probably of the voltage of the inner conductor. If the inner conductor and the outer tube are shorted, multipacting starts at about $W = -22$ dBm, but once it has started (so the inner conductor gets electrically charged) the power can be reduced down to zero and it starts again at $W = -33$ dBm. During multipacting the cavity degasses a lot: the pressure measured on the opposite side of the turbo-molecular pump goes from $P = 5 \times 10^{-5}$ to $10^{-2}$ mbar and keeps changing quickly.

**BrR** multipacting with possible discharge in the cavity ($P = 2 \times 10^{-2}$ mbar), reflected signal (top) measured on 50 Ω load and resistor signal (bottom) measured with 10 MΩ in series to 1 MΩ load, main frequency $f = 478.86429$ MHz, $f_{AM} = 2.5$ Hz, generator power $W = -20$ dBm, horizontal scale 50 ms/div, vertical scale 200 mV/div (top)–1 V/div (bottom).

**Crt** multipacting with negative step in the transmitted signal, reflected signal (top) and transmitted signal (bottom) both measured on 50 Ω load, frequency $f = 478.14279$ MHz, $f_{AM} = 2.5$ Hz, generator power $W = -19.3$ dBm, horizontal scale 50 ms/div, vertical scale 1 V/div, peak to peak amplitudes in bottom trace 2.75 V (left) and 1.125 V (plateau).
Drt) attempt to measure rise time of multipacting with high AM frequency and trigger on transmitted signal at 984 mV level, reflected signal (top) and transmitted signal (bottom) both measured on 50 Ω load, main frequency \( f = 478.00379 \) MHz, \( f_{AM} = 9 \) kHz, generator power \( W = -16.1 \) dBm, horizontal scale 1 μs/div, vertical scale 500 mV/div (up)-550 mV/div (bottom).

D’rt) same as Drt), with horizontal scale 10 μs/div.

ER) multipacting signal on the resistor ‘probe’ with superimposed electron current(?), \( f_{AM} = 9 \) kHz, \( W = -22.3 \) dBm, resistor signal (with external 100 kΩ resistor) measured with 1 MΩ load, trigger on transmitted signal at 984 mV level, horizontal scale 10 μs/div, vertical scale 208 mV/div, centre of scope 5 V, top of curve 5.687 V, bottom 4.244 V.

3.6 Cold multipacting tests with ‘low’ B-field (see Fig. 8)

The results of cold multipacting tests (4.2 K measured on the magnet, maximum magnet current limited below 8 kA, corresponding to 5.8 T) performed between 5 and 6 August are shown in Fig. 8. To polarize the inner conductor and to get a ’resistor probe’ signal, we used a 2.2 kΩ Carbon resistor (measured at room temperature, whose resistance should increase by about a factor 30 at cryogenic temperatures) inside the resonator, connected to the centre of the inner conductor near the teflon support, in series with a 100 kΩ resistor outside the resonator: isolated inner conductor unless otherwise specified.

On 5 August, during cool down (magnet temperature between 10 and 20 K), we observe a very low transmission coefficient (-80 dB at 480 MHz) at the resonance frequencies and a correspondingly noisy transmitted signal. According to reflectometric measurements, we have an impedance mismatch at about 25 cm distance from the vacuum-tight RF feedthrough, i.e., at the transition from the semi-rigid cable coming out of the cryostat to the flexible cable leading to the RF feedthrough. We therefore decide to break the vacuum to try and fix this problem. To avoid air to reach the cold part of the cryostat (thus freezing and contaminating the surface of the outer tube), we fill the cryostat with He and open the upper part of the setup, while still pumping He in the cavity at about 1.1 bar through a small flexible tube. The faulty junction can not be repaired: the central pin of the connector is broken. Therefore we decide to close the setup and live with a very weak and noisy transmitted signal.

Preliminary tests on 6 August: our Pt temperature sensor at the top of the cavity is disconnected, after proper working during two days of cool down, and we are left only with a Carbon sensor (also at the top of the cavity), whose readings are valid only below 20 K. The distance of the coupling networks has been adjusted (approximately) to pre-compensate for thermal contraction. We estimated that a doubled vale of \( Q \) (say from 1000 to 2000) would then correspond to critical coupling, i.e., no reflection at the resonance frequency. We measure coupling by measuring reflection coefficient \( S_{11} \) (ratio of reflected to forward signal) at the most coupled port. On third harmonic resonance, at \( f = 483 \) MHz we get \( S_{11} = 0.611 \) (larger than foreseen), while for detuned cavity \( S_{11} = 0.730 \div 0.740 \). On fifth harmonic resonance, at \( f = 797.9 \) MHz we get \( S_{11} = 0.091 \), while for detuned cavity \( S_{11} = 0.652 \).

ArT) multipacting with amplitude modulation (100%), \( f_{AM} = 3 \) Hz, at \( f = 798.48 \) MHz, where we have a minimum of reflected signal (very high reflection at 480 MHz, probably
because of very low \(Q\) with 1 kA magnet current, corresponding to 0.727 T. Reflected signal on 50 \(\Omega\) (top) and transmitted signal on 1 M\(\Omega\) load (bottom), generator power \(W = -10.4\) dBm, maximum amplifier gain. Horizontal scale 50 ms/div, vertical scale 200 mV/div (top)-2 mV/div (bottom). Peak to peak amplitude 862 mV, at the discontinuity 537 mV (top), 2.875 mV (bottom). With the network analyser we see two lateral peaks at 783.015 MHz and 815.58 MHz on the transmitted signal and no peak at 798 MHz.

Brt) multipacting with 1 kA magnet current. Logarithmic power sweep from 0 to 23 dBm (about 5 s linear sweep on the 23 dBm interval), narrow-band measurement (less than 3 kHz bandwidth) with a vector network analyser, at \(f = 792.850\) MHz. Curve 1 (lowest on the left) is the reflected signal, curve 2 is the transmitted signal. Reference line is -20 dBm for the reflected and -65 dBm for the transmitted signal. Horizontal scale 2.3 dBm/div, vertical scale 5 dBm/div. Reflected signal, measured through directional coupler having 20 ± 2 dB and 20 dB additional attenuator, and transmitted signal are both measured on a 50 \(\Omega\) load. At the first discontinuity the forward power is -2.1852 dBm, measured through directional coupler having 20 ± 2 dB attenuation and 26 dB additional attenuators.

Cft) multipacting with 3 kA magnet current (probably with better tuned cavity). Logarithmic power sweep from 0 to 23 dBm (about 5 s linear sweep on the 23 dBm interval), at same frequency \(f = 792.850\) MHz. Bottom curve (memorized) is the same transmitted signal as curve 2 in Brt). Top curve is forward signal (same as in the previous measurement at 1 kA magnet current, maximum value on the right 3.1826 dBm). Middle curve is the new transmitted signal (with 3 kA magnet current). Reference line is -20 dBm for forward and -65 dBm for transmitted signals. Horizontal scale 2.3 dBm/div, vertical scale 5 dBm/div. Maximum forward power measured on the amplifier watt-meter is 15 W (?). These logarithmic power sweeps are not very reproducible because we can not retune the generator frequency.

Drt) Frequency sweep from 767.850 MHz to 817.850 MHz. After the measurement in Cft), we observe three peaks in transmission and two minima in reflection (we sit in one of them). The measured \(Q\) (on reflection curve) is 627. Horizontal scale 5 MHz/div, vertical scale 1 dB/div (reflected), 10 dB/div (transmitted). The peak in transmission, coincident with the minimum in reflection at \(f = 796.06875\) MHz, was absent before the recent multipacting tests (and can be due to cavity heating).

D’rt) Frequency sweep from 767.850 MHz to 817.850 MHz. Same as Drt) after a few minutes: either a thermal effect or an effect due to charge-discharge of the inner conductor (the resonance pattern seems to be affected by shorting the resistor probe).

ErT) multipacting with amplitude modulation (100%), \(f_{AM} = 3\) Hz, at \(f = 795.924\) MHz, with 8 kA magnet current. Reflected signal on 50 \(\Omega\) (top) and transmitted signal on 1 M\(\Omega\) load (bottom), \(W = ?\), maximum amplifier gain. Horizontal scale 50 ms/div, vertical scale 100 mV/div (top)-2 mV/div (bottom). Peak-to-peak 350 mV (top)-2.6 mV (bottom).
Multipacting going on for several minutes with amplitude modulation (100%), \( f_{\text{AM}} = 3 \) Hz, at \( f = 793.355 \) MHz, with 8 kA magnet current. Forward peak power around 10 W. Forward (top) and reflected signal (bottom), both measured on a 50 Ω load by a vector network analyser. Both forward and reflected signals measured through directional coupler having 20±2 dB and 20 dB additional attenuator, total attenuation is about 40 dB. Cable attenuation (half a dB) is double for reflected signal. Horizontal scale 80 ms/div, vertical scale 100 mU/div: signal in linear scale, one unit is 1 mW. Peak forward 772 mU, peak reflected 552 mU, reflection deep 339 mU. Subtracting the peak reflected power from the forward power we estimate about 7 W deposited in the cavity. Note, however, that the pattern of the reflected signal with a deep is rather unusual and reminds the case of double multipacting ‘notch’.

3.7 More multipacting tests with ‘low’ B-field (see Fig. 9)

Further results of cold multipacting tests (4.2 K measured on the magnet, magnet current limited below 8 kA, corresponding to 5.8 T) performed on 6 August are shown in Fig. 9.

6/08/97, 18h10: using spectrum analyzer to see ‘magnetron line’ at cyclotron frequency with 100 A magnet current \( (B = 0.0727 \) T, corresponding to a cyclotron frequency \( f = 2.035 \) GHz). We observe on the resistor (with 50 Ω load) the main peak at 791 MHz and two further peaks at 1.589 GHz and at 2.389 GHz, of intensity about 50 dB \((10^5 \) times) smaller than the main peak at 793 MHz (instead of 791 MHz). For 50 A magnet current these peaks do NOT move. No cyclotron line visible. However, it would have been below cutoff and would probably be suppressed.

6/08/97, 19h00: magnet temperature around 4 K, maximum magnet current still limited to about 8 kA.

Atr) logarithmic power sweeps (lasting about 5 s) from 1 to 15 dBm with vector network analyser, absolute transmitted power (upper frame) and reflected power (lower frame), both measured on 50 Ω load. 50 A magnet current (i.e., minimum), the upper curve of the upper frame (chronologically preceden) corresponds to the lower curve of the lower frame, relative conditions changed only because of cavity heating and corresponding detuning, power sweep at frequency \( f = 480.1 \) MHz. Upper frame: vertical scale 4 dBm/div, reference -53 dBm, Lower frame: vertical scale 2 dBm/div, reference -12 dBm. Frequency sweep before gives \( f = 480.0875 \) MHz, \( Q = 1200 \), after a few power sweeps \( Q \) went down to \( Q = 1039 \) with a frequency \( f = 480.584 \) MHz. Low reproducibility owing to fast cavity detuning. There may be doubts about multipacting taking place during these measurements.

Btr) subsequent logarithmic power sweeps (separated by a few seconds and lasting about 1.2 s) from 5 to 24 dBm (peak power about 40 W, read on the watt-meter of the amplifier) with vector network analyser, absolute transmitted power (upper frame) and reflected power (lower frame), 8 kA magnet current, the upper curve of the upper frame (chronologically following and marked by the cursor) corresponds to the lower curve of the lower frame (also marked by the cursor), this time external relative conditions did not change (no detuning), but the two measurements are not reproducible. Probably power sweeps tend to excite double level multipacting and this is a rather unstable
phenomenon. Power sweep at frequency $f = 479.414$ MHz. Upper frame: vertical scale 5 dBm/div, reference -45.54 dBm, Lower frame: vertical scale 5 dBm/div, reference -21.78 dBm.

CrR) multipacting without magnetic field (0 A on magnet), $f = 479.080$ MHz, $f_{\text{AM}} = 30$ Hz, $W = -22.2$ dBm (15 W peak power), DC-bias +30 V, reflected measured on 50 $\Omega$ load (up) and resistor probe (bottom) measured on 1 M$\Omega$ load, horizontal scale 5 ms/div, vertical scale 200 mV/div (top)–2 V/div (bottom).

DrR) same as CrR) but with 50 A magnet current (i.e., minimum), $f = 479.080$ MHz, $f_{\text{AM}} = 30$ Hz, $W = -22.2$ dBm (15 W peak power), DC-bias +30 V, reflected measured on 50 $\Omega$ load (up) and resistor probe (bottom) measured on 1 M$\Omega$ load, horizontal scale 5 ms/div, vertical scale 200 mV/div (top)–2 V/div (bottom). We disconnect the DC-bias and, using Keithley current-meter (with negligible impedance) with an additional external resistor of 110 k$\Omega$, we measure a maximum of 40 $\mu$A through the resistor probe (still connected to the scope with 1 M$\Omega$).

3.8 Cold multipacting tests with strong B-field (see Fig. 10)

The results of cold multipacting tests with strong B-field (magnet current up to 10 kA, corresponding to 7.3 T) performed on 7 August are shown in Fig. 10.

7/08/1997, 15h24: we apply a DC-bias of 100 V through a 10 k$\Omega$ series resistor. This resistor becomes suddenly hot (around 100 °C) and the residual pressure measured at the top of the setup goes from $10^{-5}$ to $3 \times 10^{-3}$ mbar: this indicates a short circuit, either due to a discharge or more probably to a direct contact of the resistor probe wire with the outer tube. We switch off the DC-bias and measure a significantly higher $Q = 1800$ of the cavity at 480 MHz. The coupling is closer to critical (less reflected signal at resonance). In other words the consequences of this ‘heating accident’ are positive. Multipacting starts again with amplitude modulation and the inner wire shows a negative signal.

ArR) multipacting with slightly detuned frequency, no B-field, reflected (top) measured on 50 $\Omega$ and resistor probe signal (bottom) measured on 1 M$\Omega$ load with 100 k$\Omega$ additional resistor in series. $f_{\text{AM}} = 30$ Hz, average forward power about 20 W (ballistic measurement with the amplifier watt-meter). Horizontal scale 5 ms/div, vertical scale 200 mV/div (top)–5 V/div (bottom).

BrR) multipacting $f=479.893$ MHz, $f_{\text{AM}} = 3$ Hz, 8 kA magnet current, $W = -25.1$ dBm, peak forward power about 10 W, reflected (top) measured on 50 $\Omega$ and resistor probe signal (bottom) measured on 1 M$\Omega$ load with 100 k$\Omega$ additional resistor in series. Horizontal scale 50 ms/div, vertical scale 100 mV/div (top)–5 V/div (bottom), peak to peak amplitudes 425 mV (top) and 8.125 V (bottom).

After 1.5 hours with no multipacting tests (only cool down), the $Q$ of the cavity is no longer measurable (very low) and the coupling very weak. The situation changes after powering the cavity by 60 W forward power for several minutes: $Q = 1375$, $f = 481.556$ MHz, coupling coefficient $S_{11} = -12$ dB. The cavity multipacts easily again: therefore there is probably a thermal effect triggering some short-circuit (of the inner wire?). In both cases the cavity temperature (external conductor) is not much above 30 K.
CrR) multipacting (with two levels), no magnetic field, reflected signal measured on 50 Ω load (top) and resistor probe signal (bottom) measured on 1 MΩ load with 100 kΩ additional resistor in series. \(f = 479.037\) MHz, \(f_{\text{AM}} = 30\) Hz, \(W = -21.2\) dBm, maximum amplification gain (about 60 dB), average forward power about 25 W (balistic measurement with the amplifier watt-meter), pressure \(P = 4 \times 10^{-6}\) mbar, horizontal scale 5 ms/div, vertical scale 200 mV/div (top)--5 V/div (bottom), peak to peak amplitudes 593 mV (top) and 22 V (bottom).

C’rR) multipacting (unstable regime), no magnetic field, same as CrR) after a few minutes.

DrR) multipacting (unstable regime), 8 kA magnet current, same as CrR), horizontal scale 5 ms/div, vertical scale 500 mV/div (top)--1 V/div (bottom). peak to peak amplitudes 1.47 V (top) and 3 V (bottom). The maximum of the resistor probe signal is unstable (it goes down to 1 \(\div 1.5\) V).

ErR) multipacting (unstable regime), 10 kA magnet current, same conditions as in DrR), \(f = 479.01018\) MHz. The maximum of the resistor probe signal is unstable (after a few seconds it doubles). When the peak value of the resistor probe signal changes also the peak to peak amplitude of the reflected signal changes.

Apparently the sign of the resistor voltage changes (from negative to positive) when the magnetic field is switched on, correspondingly the maximum of the reflected signal goes up. However this observation is not confirmed by a systematic study.

We try to estimate the peak power deposited in the cavity during multipacting by recording the peak to peak value of forward and reflected signals (both measured with 40 dB attenuation on the scope, with a 50 Ω load) for different generator powers \(W\): \(f = 479\) MHz, \(Q = 1013\), 100 A magnet current. For \(W = -24.5\), we measure peak to peak \(V_{\text{forward}} = 637\) mV, (when repeated 700 mV), \(V_{\text{reflected}} = 321\) mV, (when repeated 296 mV). For \(W = -26.0\), we measure peak to peak \(V_{\text{forward}} = 600\) mV, (when repeated 609 mV), \(V_{\text{reflected}} = 196.9\) mV, (when repeated 195 mV). The corresponding power is \((V_{\text{forward}}^2 - V_{\text{reflected}}^2)/(50\Omega \times F_{\text{pp}} \times \text{Attenuation})\), where \(\text{Attenuation} = 10^{-4}\) (40 dB) and the conversion factor from peak to peak to effective power is \(F_{\text{pp}} = 8\). For the last measurements, the power deposited in the cavity during multipacting is \(10^4 \times (700^2 - 296^2)/(50 \times 8) \mu\text{W}= 10 \text{W}\) and \(10^4 \times (609^2 - 296^2)/(195 \times 8) \mu\text{W}= 8.3\) W.

### 3.9 Further multipacting tests with strong B-field (see Fig. 11)

Further results of cold multipacting tests with strong B-field (magnet current up to 10 kA, corresponding to 7.3 T) performed on 7 August are shown in Fig. 11.

7/08/1997, 21h15: we decide to learn how to ramp the magnet current up or down, so that we can continue our multipacting tests with B-field during the night. Multipacting relatively stable, 4 kA magnet current, \(f_{\text{AM}} = 30\) Hz. Multipacting starts for a generator power between \(W = -27\) and -26.5 dBm (less than 5 W average forward power). Good coupling (\(Q \sim 1000\)), \(f = 479.82218\) MHz, pressure \(P = 4 \times 10^{-6}\) mbar. The signal from the resistor probe measured on 1 MΩ load (with a peak to peak amplitude of 900 mV) has a 50% step down and then is flat during multipacting. The reflected signal for \(W = -26.5\) dBm
has a significant jump up at the onset of multipacting and reaches a rounded peak to peak amplitude of 275 mV. By increasing the generator power to \( W = -25.5 \, \text{dBm} \) a second multipacting level appears, namely a step up in the middle of the plateau of the resistor probe signal and a corresponding step up also on the reflected signal. At \( W = -23 \, \text{dBm} \) (about 10 W average forward power), the resistor probe signal shows a beginning of upward arc. This remains even when reducing the power down to the multipacting threshold, but is less pronounced, as shown in Fig. 11-Arr).

\[ \text{Arr}) \text{ multipacting with } 4 \, \text{kA magnet current, } f = 479.76818 \, \text{MHz, } f_{\text{AM}} = 30 \, \text{Hz, } W = -26 \, \text{dBm, average forward power } 4 \, \text{W, reflected (top) and resistor probe signal on } 1 \, \Omega \text{ load (bottom), horizontal scale } 5 \, \text{ms/div, vertical scale } 100 \, \text{mV/div (top)}-500 \, \text{mV/div (bottom).} \]

During and after a following ramp to 6 kA the multipacting pattern remains practically unchanged. Only when the magnet current stops at 6 kA, the second multipacting level appears for a few seconds. The second multipacting level appears again systematically at \( W = -25.5 \, \text{dBm} \). The positive arc of the resistor probe signal now starts at \( W = -15 \, \text{dBm} \) (almost 45 W average forward power). We reduce the generator power down to \( W = -26.5 \, \text{dBm} \) (4 W average forward power) and observe that the signal on the resistor probe is rather unstable, with a positive arc irregularly appearing in the middle of the plateau (peak to peak of the resistor probe signal 4.5 V, but sometimes 1 or 2 V). We also observe some glitches on the reflected signal when retuning the generator frequency \( (f = 479.56418 \, \text{MHz, then } 479.56418 \, \text{MHz, } 479.57418 \, \text{MHz and } 479.55218 \, \text{MHz}) \). The peak amplitude of the reflected signal is 165 mV and the resistor probe signal has a positive arc with 1 V peak to peak value. With \( W = -26 \, \text{dBm} \) and \( f = 479.53518 \, \text{MHz} \) we get a relatively stable multipacting and we start a ramp to 8 kA magnet current (with 50 A/s). During the ramp nothing dramatic happens: only a couple of times the second multipacting level becomes visible. We ramp up to 10 kA magnet current at 10 A/s: we observe some fluctuations of the peak reflected power and some positive curvature of the resistor probe signal, again nothing dramatic happens. At 10 kA the multipacting is stable again.

The signal on the resistor probe changes sign: from positive (high B-field) to negative (low B-field). The reflected signal has two different patterns: for low B-field there is a step transition at the multipacting threshold, while for high B-field there is a soft transition at the multipacting threshold.

\[ \text{BrR}) \text{ multipacting with unstable multipacting threshold and slightly detuned cavity), } 50? \, \text{A magnet current, } f = 479.42518 \, \text{MHz, } f_{\text{AM}} = 30 \, \text{Hz, } W = -26 \, \text{dBm, reflected (top) and resistor probe signal on } 1 \, \Omega \text{ load (bottom), horizontal scale } 5 \, \text{ms/div, vertical scale } 50 \, \text{mV/div (top)}-5 \, \text{V/div (bottom).} \]

At 10 kA magnet current, we switch off the RF power and switch it on again: multipacting starts again at 4.5 W average forward power. The DC signal on the resistor probe disappears when we apply a DC-bias with opposite sign.

\[ \text{CrR}) \text{ multipacting with } 10 \, \text{kA magnet current, } f = 479.645 \, \text{MHz, } f_{\text{AM}} = 3.9 \, \text{Hz, } W = -24.3 \, \text{dBm, reflected (top) and resistor probe signal on } 1 \, \Omega \text{ load (bottom), horizontal scale } 50 \, \text{ms/div, vertical scale } 200 \, \text{mV/div (top)}-500 \, \text{mV/div (bottom).} \text{ At the end} \]
of a ramp down, a negative DC-signal on the resistor probe appears at 50 A magnet current.

DrR) multipacting (very detuned cavity) with 50 A magnet current, \( f = 479.55 \text{ MHz} \), \( f_{\text{AM}} = 3.9 \text{ Hz} \), \( W = -22 \text{ dBm} \), reflected (top) and resistor probe signal on 1 M\( \Omega \) load (bottom), horizontal scale 50 ms/div, vertical scale 100 mV/div (top)–5 V/div (bottom), peak to peak amplitude 19.53 V (bottom).

We try to find a threshold magnetic field below which the sign of the resistor probe signal changes (from positive to negative) during ramp down. With \( W = -22.5 \), we change magnetic field and record the peak to peak signal on the resistor probe: 200 A → 812 mV, 300 A → 712 mV, 100 A → 860 mV. After investigating intermediate magnet currents between 50 and 100 A, without success, we conclude that the effect seems related to \( \tilde{B} \) rather than \( B \) value.

8/08/97: the cable connected to the inner conductor is shorted and we cannot apply DC-bias any longer. The cavity does no longer resonate, even after several minutes of high RF power. End of the measurements (we cannot explore 12 kA, now available since the magnet has reached 1.8 K).

### 3.10 Post-mortem analysis of the cavity used for cold tests

The copper coating of the inner tube shows a significant degradation near the end corresponding to the strongly coupled port. The tin used for the welds of the resistor probe is melted (a few drops of tin are along the tube and also on the teflon support located directly below): this implies a temperature of the inner tube above 200 °C. Also the teflon support near the resistor probe is rather dark.

The inner surface of the outer tube shows several rings of different colours, the darkest corresponding to the maxima of the electric field. We observed the same phenomenon already after warm multipacting tests without B-field. However, as shown in Fig. 12, in addition to these rings we can now see two diametrically opposite thin longitudinal strips of red-violet colour, presumably located in correspondence to the N and S poles of the magnet. Along the edges of each strip the colour reaches its maximum intensity. Their maximum width is about 8 mm (the minimum width is 5 mm), while the diameter of the inner tube is measured to be 4.7 mm. Since the inner radius of the outer tube is measured to be 38.6 mm, the maximum angle subtended by each of these strips is about \( \pm 5^\circ \). A possible explanation is that already in presence of a modest B-field, and for the limited RF power that we can put into the cavity, only a small fraction of the outer tube surface contributes to multipacting. This seems to be confirmed by preliminary simulation results [2] and may explain why we do not observe significant changes of power deposition in the resonator at higher values of the B-field. It remains to understand whether this is just a consequence of the limited RF voltage in the cavity (modulo a \( \cos(\theta) \) effect) or a real reduction of secondary electron yield due to the B-field over most of the surface away from the N and S poles.

The post-mortem analysis of the cavity surface also indicates that multipacting does not take place at a few ‘hot spots’, but is rather a diffuse phenomenon involving the whole length of the resonator.

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4 Future plans

We plan to pursue our resonant multipacting tests with four major improvements:

- On-line measurement of the RF power deposited in the resonator. This is possible by electronically subtracting the reflected from the forward power via a detector diode working in the square-law regime, where the output voltage is proportional to the input power, and should allow a more quantitative assessment of the effect of the B-field.

- Adjustable coupling, with coupling network external to the resonator. We hope to increase the power deposition in the cavity during multipacting, by correcting for the corresponding impedance mismatch.

- Synthetic pulse generation by superposition of several resonator harmonics (the corresponding frequencies are not exactly multiple of the fundamental and each of them requires an independent synthesizer, phase-locked via its 10 MHz reference). This may lead to a situation closer to the LHC case, where the 25 ns bunch spacing is much longer than the 1 ns full bunch length, still with the advantage of a significant RF-voltage thanks to the high $Q$ of the resonator.

- Multipacting triggered by photoelectrons created by a Xe flashlamp (operating in vacuo). In conjunction with a better analysis of the transient period during the build-up of the electron cloud (see Fig. 7-Drt), this should give us more direct information about photoelectron and secondary emission yield for different coatings of the outer tube.

In parallel with these developments, we also plan to perform multipacting tests using EPA synchrotron light. In particular we will check again that during multipacting there is no significant ‘magnetron line’ corresponding to the electron cyclotron frequency in presence of a (modest) magnetic field.

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References


Figure 1: Resonant coaxial setup for multipacting tests.

Figure 2: Cold multipacting tests with strong magnetic field (Prevessin, 8 Aug 1997). On the left, from top to bottom: function generator, scope, signal generator and power amplifier. On the right: cryostat containing a two-in-one, 1 m long superconducting dipole.
Figure 3: Preliminary multipacting tests with a multi-wire setup (23 June–9 July 1997). The generator signal with frequency $f = 44 \div 47$ MHz is amplitude modulated with frequency $f_{AM}$. In the ‘rB’-pictures the upper trace is the reflected signal attenuated by 40 dB and measured on a 50 $\Omega$ load, the lower trace is a button-like probe signal measured on 1 M$\Omega$ load. The latter has sometimes superimposed a negative (direct electron) current. The last picture shows the transmitted and button-like probe signals, both measured on a 1 M$\Omega$ load, with a DC-bias of 70 V. The picture in D) is a photograph of the multi-wire setup.
Figure 4: First multipacting tests in the resonant coaxial setup (14/07/1997). The generator signal with frequency $f$ and power $W$ is amplitude modulated (90% depth) with frequency $f_{AM}$ and amplified at maximum gain ($\approx 60$ dB). In the ‘rt’-pictures the upper trace is the reflected signal attenuated by 40 dB and the lower trace the transmitted signal, both measured with a 50 $\Omega$ load. In the ‘fT’-pictures the upper trace is the forward amplifier signal attenuated by 40 dB and the lower trace the transmitted signal measured with a 1 M$\Omega$ load. The latter has sometimes superimposed an electron current collected by the weakly coupled port: the positive current in A) may be due to a discharge.
Figure 5: New multipacting tests in the resonant coaxial setup, modified so that we can apply a DC-voltage to the inner conductor (17/07/1997). A thin wire is radially connected to the middle of the inner conductor through a 50 kΩ resistor and comes out of the outer tube via a small hole. When connecting inner and outer conductors (without DC-bias), the multipacting stops and a higher generator power is required to let it start again. Once this happens, however, we can reduce the generator power to the original level without stopping multipacting. This seems to indicate that the inner conductor acquires an electric charge during multipacting: after removing this charge, it is more difficult to start multipacting again. The generator signal with frequency \( f \) around 480 MHz and power \( W \) is amplitude modulated with frequency \( f_{AM} = 30 \) Hz and amplified at maximum gain (\( \sim 60 \) dB). In the ‘rt’-pictures the upper trace is the reflected signal attenuated by 40 dB and the lower trace the transmitted signal, both measured with a 50 Ω load. In the ‘ft’-pictures the upper trace is the forward amplifier signal attenuated by 40 dB and the lower trace the transmitted signal measured with a 1 MΩ load.
Figure 6: More multipacting tests in the resonant coaxial setup with possible DC-voltage on the inner conductor (18/07/1997). The generator signal with frequency $f$ around 480 MHz and power $W$ is amplitude modulated with frequency $f_{AM} = 3$ Hz and amplified at maximum gain ($\sim 60$ dB). In the ‘rt’-pictures the upper trace is the reflected signal attenuated by 40 dB and the lower trace the transmitted signal, both measured with a 50 $\Omega$ load. The ‘f’-pictures show the forward amplifier signal attenuated by 40 dB and the ‘T’-pictures show the transmitted signal measured with a 1 M$\Omega$ load.
Figure 7: Multipacting tests in the resonant coaxial setup with the ‘resistor probe’ signal (27/07/1997). A thin wire is radially connected to the middle of the inner conductor through a 1 kΩ inner resistor and comes out of the outer tube via a small hole with an external 100 kΩ resistor in series: the corresponding signal can be seen on a scope with high impedance. When connecting inner and outer conductors (without DC-bias), the multipacting stops and a higher generator power is required to let it start again. Once this happens, however, we can reduce the generator power to the original level without stopping multipacting. This seems to indicate that the inner conductor acquires an electric charge during multipacting: after removing this charge, it is more difficult to start multipacting again. The generator signal with frequency $f$ around 480 MHz and power $W$ is amplitude modulated with frequency $f_{AM} = 2.5$ Hz (first three pictures) or $f_{AM} = 9$ kHz (last three pictures) and amplified at maximum gain ($\sim 60$ dB). In the ‘rt’-pictures the upper trace is the reflected signal attenuated by 40 dB and the lower trace the transmitted signal, both measured with a 50 Ω load. The ‘R’-pictures show the ‘resistor probe signal’ measured with a 1 MΩ (or higher) load. The last three pictures show an attempt to measure the multipacting rise time (during the ‘step-down’ of the transmitted signal) with high AM frequency and trigger on the transmitted signal at 984 mV level. Note that the horizontal scale in Drt) is 1 μs/div.
Figure 8: Cold multipacting tests with ‘low’ B-field (5-6/08/1997). In the first and last two pictures the generator signal with frequency $f$ around 790 MHz and power $W$ is amplitude modulated with frequency $f_{\text{AM}} = 3$ Hz and amplified at maximum gain ($\sim 60$ dB). The second and third pictures are logarithmic power sweeps, while pictures $\text{Drt}$) and $\text{D'}rt$) are frequency sweeps, all performed by a vector network analyser. In the ‘rt’-pictures the upper trace is the reflected signal attenuated by 40 dB and the lower trace the transmitted signal, both measured with a 50 Ω load. The ‘f’ refers to the forward signal attenuated by about 40 dB, while the ‘T’ refers to the transmitted signal measured with a 1 MΩ load.
Figure 9: More multipacting tests with ‘low’ B-field (6/08/1997). The first and second picture show logarithmic power sweeps performed by a vector network analyser at a frequency $f$ around 480 MHz. The traces in the upper frame are the transmitted signal and those in the lower frame the reflected signal attenuated by 40 dB, both measured with a 50 Ω load. In the last two pictures the generator signal with frequency $f$ around 479 MHz and power $W$ is amplitude modulated with frequency $f_{\text{AM}} = 30$ Hz and amplified at maximum gain ($\sim 60$ dB). There is a DC-bias of +30 V on the inner conductor. The upper trace shows the reflected signal and the lower trace ‘R’ refers to the ‘resistor probe’ signal measured with a 1 MΩ load.
**Figure 10:** Multipacting tests with strong B-field (7/08/1997). The generator signal with frequency $f$ around 480 MHz and power $W$ is amplitude modulated with frequency $f_{AM} = 30$ Hz (3 Hz in the second picture) and amplified at maximum gain ($\sim 60$ dB). The upper trace shows the reflected signal and the lower trace ‘R’ refers to the ‘resistor probe’ signal measured with a 1 MΩ load.
Figure 11: More multipacting tests with strong B-field (7/08/1997). The generator signal with frequency $f$ around 480 MHz and power $W$ is amplitude modulated with frequency $f_{AM} = 30$ Hz in the first two pictures and 3.9 Hz in the last two, and amplified at maximum gain ($\sim 60$ dB). The upper trace shows the reflected signal and the lower trace ‘R’ refers to the ‘resistor probe’ signal measured with a 1 MΩ load.
Figure 12: The cavity used for multipacting tests with strong magnetic field has been cut longitudinally into two halves: the photograph shows the two halves (side by side) and the inner conductor with one of its teflon supports (near the upper left corner). In addition to several rings of different colours, already observed after warm multipacting tests without B-field, on the inner surface of the outer tube we can see two diametrically opposite thin longitudinal strips of red-violet colour (partly visible at the centre of the photograph), presumably located in correspondence to the N and S poles of the magnet. The colour reaches its maximum intensity along the edges of each strip.