CAVITY MODE RELATED WIRE BREAKING OF THE SPS WIRE
SCANNERS AND LOSS MEASUREMENTS OF WIRE MATERIALS

F. Caspers, B. Dehning, E. Jensen, J. Koopman, J.F. Malo, CERN, Geneva, Switzerland
F. Roncarolo, CERN/University of Lausanne, Switzerland

Abstract

During the SPS high intensity run 2002 with LHC type beam, the breaking of several of the carbon wires in the wire scanners has been observed in their parking position. The observation of large changes in the wire resistivity and thermionic electron emission clearly indicated strong RF heating that was depending on the bunch length. A subsequent analysis in the laboratory, simulating the beam by two probe antennas or by a powered stretched wire, showed two main problems:

i) the housing of the wire scanner acts as a cavity with a mode spectrum starting around 350 MHz and high impedance values around 700 MHz;

ii) the carbon wire used so far appears to be an excellent RF absorber and thus dissipates a significant part of the beam-induced power.

Different wire materials are compared with the classical cavity mode technique for the determination of the complex permittivity in the range of 2–4 GHz. As a resonator a rectangular $TE_{01n}$ type device is utilized.

WIRE HEATING IN THE SPS TUNNEL

During the two last Machine Development periods in the SPS 2002 run, several wires were found broken. Such breaking can be typically related to the wire heating due to some energy deposition by the traversing protons on the wire. Dedicated electronics has been installed in order to have an indication of the wires heating during the LHC type beam injection and ramp in the SPS. In particular a constant current was supplied to the wire and the voltage drop across the wire scanner tank acts as a cavity with a mode spectrum starting around 350 MHz and high impedance values around 700 MHz; the carbon wire used so far appears to be an excellent RF absorber and thus dissipates a significant part of the beam-induced power.

Different wire materials are compared with the classical cavity mode technique for the determination of the complex permittivity in the range of 2–4 GHz. As a resonator a rectangular $TE_{01n}$ type device is utilized.

LABORATORY MEASUREMENTS

A spare SPS wire scanner tank has been equipped in the laboratory with two probe antennas connected to a Vector Network Analyzer (VNA) in order to simulate the RF modes in the beam spectrum frequency.

Beam-Wire coupling

Two connections to the ends of the wires of the wire scanner are used during normal operation to check the wire integrity (measuring the resistance) or to detect the secondary emission signal. In the laboratory they were applied to estimate the proton beam-wire coupling while simulating the beam with a stretched wire. A $0^\circ/180^\circ$ RF signal combiner circuit has been used to measure the differential signal at the wire ends. One port of the VNA has been connected to one end of the stretched wire, the other one at the combiner output giving the differential signal. Fig. 2 is well describing the effect. The plot gives the $S_{21}$ signal together with the differential signal on the wire scanner tank. Where the frequency peak of the transmitted signal matches a peak of the differential signal, the power present...
in the cavity can be absorbed by the wire. Different config-
urations have been set up in order to better understand the
phenomenon:
1. none of the wires mounted on the forks, without ferrite
tiles inserted,
2. one copper and one carbon wires mounted and kept in
   the parking position, without ferrite tiles,
3. two carbon wires mounted and kept in the parking po-
   sition, without ferrite tiles,
4. two carbon wires mounted, the horizontal wire kept in
   the parking position and the vertical wire in proximity
   of the beam position, without ferrite tiles,
5. two carbon wires mounted, the horizontal wire kept in
   the proximity of the beam position and the vertical
   wire in the parking position, without ferrite tiles,
6. none of the wires mounted, nine ferrite tiles inserted
   in the tank,
7. one carbon wire mounted, nine ferrite tiles inserted in
   the tank,
8. two carbon wire mounted, nine ferrite tiles inserted in
   the tank.

For each measurement the \( Q \) factor has been evaluated
by mean of the VNA, zooming in the resonance interval. For
each resonance the antenna-probes position has been ad-
justed in order to reach the condition of weak coupling
(\( S_{11} \) and \( S_{22} \) signals minimized to < .5 dB) thus allowing
the evaluation of the unloaded \( Q \). Fig. 3 shows two of the
recorded signals, one with no wires mounted and no ferrite
tiles inserted and one with no wires installed and nine fer-
rite tiles inserted. Fig. 4 summarizes all the quality factors
as function of frequency, for all the measurement config-
urations. The RF modes damping by inserting the ferrite
tiles is evident and suggested such configuration to reduce
the power absorbed by the wire scanners wires. The ferrite
type is TT2-111R (from Transtech, Maryland, USA) and
its properties can be found in [2].

WIRE MATERIALS STUDIES

The classical cavity mode technique has been used for
the determination of the complex permittivity of different
wires in the range from 2–4 GHz. As a resonator a rect-
angular TE\(_{01n}\) type device is utilized. Different materials

\[
\vec{f} = \epsilon_0 \epsilon_r \left( \epsilon_r'' - j \epsilon_r' \right) \tag{1}
\]

from where the loss factor can be defined:

\[
\tan \delta_r = \frac{\epsilon_r''}{\epsilon_r'} \tag{2}
\]

In the test cavity there are locations, in which either the
electric or the magnetic field vanishes. If one puts a suf-
iciently small sample, which does not disturb the field,
in these locations only the magnetic or electric properties
of the cavity are influenced by the sample. In both cases
the resonance frequency \( f_r \) and the quality factor \( Q \) are
changed. \( \epsilon_r'' \), \( \epsilon_r' \) and \( \tan \delta_r \) respectively can be found from
these changes. [1] provides:

\[
\frac{\Delta f_r}{f_r} = -\frac{\Delta W}{W} \tag{3}
\]

The variables in this equation are complex. \( \text{Im}(f_r) \) and
\( \text{Im}(W) \) describe the losses in the empty cavity, and given
the high \( Q \) they will be neglected in the following. If the
sample is non-magnetic and positioned in a zero-magneti-
field region, then \( \tilde{W} \) and \( \Delta \tilde{W} \) in Eq. (3) are only calculated
from the electrical fields:

\[
\frac{\Delta f_r}{f_r} = \frac{f_r - f_r'}{f_r'} = -\frac{\epsilon_0}{4\pi} \frac{\int_{r'} (\epsilon_r'' - 1) E(x, y, z) E(x, y, z) dV}{2\epsilon_0 \int_{r'} E_r^2 dV} \tag{4}
\]
The subscripts \(e\) and \(s\) indicate the empty cavity and the cavity with sample, whilst \(V_e\) and \(V_s\) are the volumes of the sample and of the resonator. When the electric field is tangential to the surface of the sample and the sample ends on the resonator walls, then the internal field equals the external field:

\[ E_e = E_s \]  (5)

Given a small volume of the sample:

\[ E_e^e(x, y, z) = E_e^0 \]  (6)

and can be pulled out from the integrals of Eq. (4). The imaginary part of the resonant frequency shift is related to the change in quality factor:

\[ \text{Im}(\Delta f_r) = \Delta f_r' = \frac{f_r}{2} \left( \frac{1}{Q_{L_e}} - \frac{1}{Q_{L_s}} \right) \]  (7)

Eq. (4) to Eq. (7) lead to the evaluation of the real and imaginary part of the dielectric constant:

\[ \epsilon_r' = 1 - \frac{f_r}{f_r} \frac{V_r}{2V_e} \]  (8)

\[ \epsilon_r'' = \left[ \frac{Q_{L_s}}{Q_{L_e}} - 1 \right] \frac{1}{Q_{L_e}} \frac{V_r}{4V_e} \]  (9)

and therefore to the characteristic loss factor as defined in Eq. (2). \(\epsilon_r''\) can also be deduced from the material conductivity \(\sigma\) and the resonant frequency \(f\) according to:

\[ \sigma = \omega \epsilon'' = 2\pi f \epsilon'' = 2\pi f \epsilon_0 \epsilon'' \]  (10)

**Experimental Results**

In the laboratory fibers of three different materials were considered: Carbon, Silicon Carbide and Quartz. Fig. 5 shows the measurements results as signal intensity versus frequency, around one of the resonating modes with maximum electric field at the sample location. The plot qualitatively proves the RF power absorption of Carbon, and the non-absorption of Silicon Carbide and Quartz. Fig. 5 also includes the results of a numeric simulation and measurement concerning the SiC material which is presently considered as a suitable RF absorber for the Compact Linear Collider (CLIC). A pyramid shaped piece of such material was inserted in the resonator at the same location where the wire scanner wires were placed. The fact that this material is absorbing RF power as shown by the simulation and by the measurements, proved that this is a SiC compound different from the one used for the wire scanners wires.

The insertion of one carbon fiber \((d=36 \mu m)\) is reducing the signal amplitude to a level where the mode frequency is not well defined since the resonance curve is strongly asymmetric. Therefore, for this material, we could not apply Eq. (8). The imaginary part of the dielectric constant was evaluated both from Eq. (9) and Eq. (10). The insertion of 500 SiC fibers \((d=15 \mu m)\) allowed the evaluation of both the real and imaginary part of the dielectric constant by mean of Eq. (8) and Eq. (9). The results for the TE\(_{103}\) are summarized in the table below, together with the available data for the CLIC SiC bulk material [3]. Being Quartz a weakly absorbing material, in order to evaluate \(\epsilon_r'\) and \(\epsilon_r''\) one should insert a large number of fibers as it has been done for SiC. However not enough Quartz material was available.

![Figure 5: Resonant cavity signal in presence of Carbon, Silicon Carbide and Quartz](image)

<table>
<thead>
<tr>
<th>Material</th>
<th>(\epsilon_r')</th>
<th>(\epsilon_r'')</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>(10.790 \pm 0.016)</td>
<td>(2.30 \pm 0.05 \cdot 10^5)</td>
</tr>
<tr>
<td>SiC</td>
<td>(14.4)</td>
<td>(6.6)</td>
</tr>
</tbody>
</table>

Table 1: Real and imaginary part of the dielectric constant for the TE\(_{103}\) mode, at 2.5 GHz.

**CONCLUSIONS**

The laboratory measurements investigated the RF coupling nature responsible for the wire breaking in the SPS wire scanners. The wire scanners tanks proved to act as resonant RF cavities in the beam spectrum frequency range. As a cure for the wire heating due to the beam-wire coupling, the SPS wire scanner tanks have been equipped with low outgassing ferrite tiles in order to damp the resonance modes. Carbon, used in the SPS until 2003, provided evidence of RF absorption properties. Therefore the wire material of few monitors were changed from carbon to silicon carbide, which has been characterized as a weakly absorbing material, and will be tested during the 2003 SPS run.

**ACKNOWLEDGMENTS**

We thank G. Burtin for the useful discussions.

**REFERENCES**

