# CYCLOTRON CAVITY POLLUTION RECOVERY

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## INTRODUCTION

In a cyclotron, RF cavities are usually among the most reliable subsystems, provided minimal care and maintenance. Nevertheless, several parameters may affect cavity performance after several years of operation and lead to an increase of the dissipated power inside the RF system. The problem was qualified as “poisoning” or “pollution” of the cavities, because in every case an external contaminant was found in the system.

### ➢ Power characterization

The mathematical expression of the power can give us an insight on what is actually happening when poisoning occurs. Figure (1) shows that RF system of a cyclotron seen as a RLC circuit.

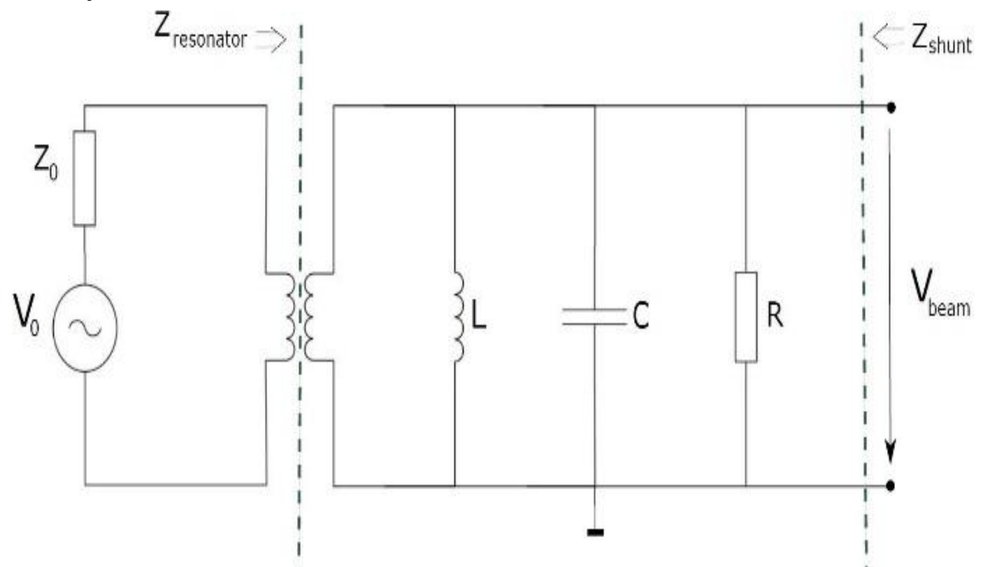


*Figure 1: RLC Equivalent circuit of a RF system. Adapted from F. Caspers [1].*

The average dissipated power is defined as the power emitted by Joule losses.

$$P = \frac{V_{max}^2}{2R} \quad (1)$$

where $R$ is the shunt impedance at resonance frequency.

The power can also be derived by introducing the surface resistance of the RF cavity:

$$P = \frac{1}{2} R_{surf} \oint |H|^2 dS \quad (2)$$

$$R_{surf} = \frac{1}{\sigma\delta} \quad (3)$$

where $H$ is the magnetic field induced by the RF electric field, $\sigma$ is the electric conductivity and $\delta$ is the skin depth.

The shunt impedance and the surface resistance affect thus the power inversely.

### ➢ Multipactor

Multipactor refers to RF discharges occurring inside particle accelerators. Secondary electron emission resulting from electronic bombardment of an emissive surface, coupled to a RF field, leads to a sinusoidal electron avalanche phenomenon. This can cause large power dissipation and RF loading becomes so high that running the RF can become impossible.
A primordial parameter for multipactor is the secondary emission yield (SEY) of a surface, which represents the number of secondary electrons emitted per incident primary electron.

## SYMPTOMS OF POISONING

Observations have revealed typical and recurring traces on all cavities suffering that kind of issue.

*Figure 2: Typical poisoning traces inside RF cavity.*

A common symptom can be observed through measuring the shunt impedance of the cavities: the shunt impedance drops and no longer stays constant with the applied cavity RF voltage. The drop is easily understandable as the shunt impedance is inversely proportional to the power. The variability may lead one to believe that a multipactor phenomenon is occurring with a different intensity in function of the amplitude of the RF voltage.

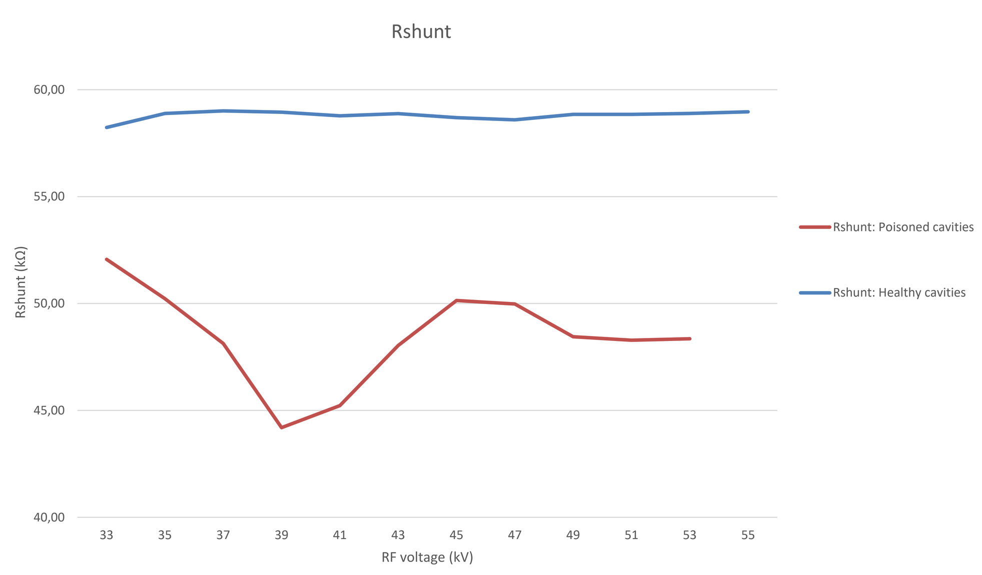


*Figure 3: Rshunt of an healthy RF system vs Rshunt of a poisoned RF system.*

## ANALYSIS & HYPOTHESIS

### ➢ Oxygen poisoning

When poisoning occurs, traces of copper oxide are most often found on the RF cavities. It is therefore believed that an oxygen plasma is created because of the RF multipactor: the electrons oscillating between the dees and the valleys hit and ionize oxygen molecules, and the free radicals recombine with the ionized surface of the copper.
It was shown that copper oxide exhibits a higher SEY than pure copper [2]. This increase in SEY leads to a more intense multipactor phenomenon, and therefore more power is dissipated inside the RF cavities. Furthermore, this phenomenon is self-maintaining / self-enhancing as the increase in multipactor will induce more oxygen ionization, and therefore a larger production of copper oxide.

### ➢ Water poisoning

It was shown by Baglin et al. [2] that deposition/adsorption of water on a copper surface also increases the SEY. This can happen when the cooling lines of the dees and cavities suffer from a leak

### ➢ Cadmium poisoning

The brazing of a few components of IBA RF cavities is partially composed of cadmium. Defects in the brazing sometimes occur, and localize the power, leading in some extremely rare cases to outgassing of the brazing and deposition of cadmium inside the RF cavities.

*Figure 4: Traces of cadmium poisoning.*

It was shown by Walker et al. [3] that the cadmium SEY is lower than copper. Therefore another phenomenon must be responsible for the increase of power dissipation. Because cadmium has a lower conductivity than copper, it can be shown that the skin depth at 106 MHz will double its thickness up to 13.2 µm. As this depth is within the probable thickness of the cadmium layers deposited on the cavity surface, we can assume that all the current will flow into this layer.

The surface resistance of a cadmium layer with this skin depth is also twice the one of copper, at the same frequency. Therefore, as shown by Eq. (2), the power could theoretically double if all the cavity surface was plated or recovered with cadmium.

## RECOVERY METHODS

### ➢ High vacuum and ODP oil effect

In order to flush the system from its contaminants, it is necessary to allow time for the system to be under high vacuum: the hydrogen and oxygen load should be stopped for at least two to four hours each night in order to let the vacuum system pump to its maximum abilities. If the contaminant has been adsorbed by the surface, it can be useful to heat the system in order to help its desorption.
The secondary emission yield will slowly drop, and it is believed that this can be helped and enhanced with the natural deposition of ODP oil in the RF system.

### ➢ H2 bake

If copper oxide has developed in the RF system, high vacuum is not sufficient to get rid of it. So called “H2 bakes” are performed by flooding the cyclotron with hydrogen and running high power RF (60 to 70 kW) in order to induce heating, catalysing the reduction reaction. The reducing power of the hydrogen helps to unravel the copper oxide molecules, reducing them to solid metallic copper and water vapor, which is then pumped out of the machine. It was shown by Kim et al. [4] that temperature and time are intricated for the reduction process of the two types of copper oxides: the higher the temperature, the faster the reduction (CuO reduces to metallic Cu slightly quicker than $Cu_2O$).

$$CuO(solid) + H_2(gas) \rightarrow Cu(solid) + H_2O(gas) \quad (4)$$

$$Cu_2O(solid) + H_2(gas) \rightarrow 2Cu(solid) + H_2O(gas) \quad (5)$$

For temperatures inferior to 300°C, one can observe an induction period before the start of the reduction process : during this induction period, the reduction takes place at a much slower pace. Therefore, the recovery process for RF systems takes time and patience; when performing H2 bakes a few hours per night, sites usually see lasting effects after several weeks.

### ➢ Mechanical & chemical cleaning

In some cases, the poisoning is too intense and opening the cyclotron for cleaning the RF cavities becomes necessary. In order to remove the contaminants of the surface, the dees must be dismantled from the cavities. In some extreme cases, the cavities should be. One needs to use abrasive hand pads to remove the contaminated layers over the copper and rinse with alcohol.
IBA also experimented chemical cleaning on a site facing cadmium poisoning. A mild hydrochloric acid solution was used to remove the contaminated layers, and then rinsed with bi-carbonated water to neutralize the acid action. A reduction of around 20kW of RF power was observed after the intervention.

## REFERENCES

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