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CYCLOTRON CAVITY POLLUTION RECOVERY

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Abstract

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. To name a few typical causes of degradation: decreasing vacuum quality, various gas loads or gas qualities triggering adverse effects, deposition of highly emissive material on the cavity due to overheating of components like pass-through connectors, accidental use of chemicals or not-suited greases. The cavity status can be monitored but, in the worst cases, the RF tuning may become difficult and it is important to apply methods in order to recover a better cavity Q-factor. In this paper, cases of cavity pollution will be shown, their potential root causes discussed and some recovery methods described.

INTRODUCTION

RF Cavities, Equivalent Circuit and Power Characterization

RF cavities are a key subsystem of cyclotrons. They create the necessary electric field required to accelerate charged particles. The RF system of a cyclotron can be seen as a RLC circuit that resonates at the pulsation $\omega_{res} = \frac{1}{\sqrt{LC}}$.

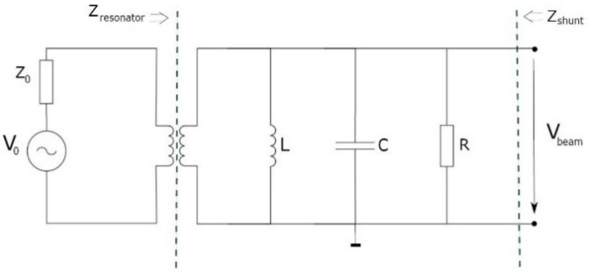

Figure 1: RLC equivalent circuit of a RF system. Adapted from F. Caspers [1].

The inductor and capacitor represent a lossless resonator, while the resistor characterizes the losses of the circuit. Equation (1) gives the impedance seen by the beam, called the shunt impedance, and at resonance it is equal to the ohmic resistor.

$$Z(\omega) = \frac{1}{\frac{1}{R}+j\omega C+\frac{1}{j\omega L}} \text{ and } Z(\omega_{res}) = R \quad . \qquad (1)$$

The average dissipated power is defined as the power emitted by Joule losses. Therefore, for a constant accelerating voltage, the higher the shunt impedance, the lower the dissipated power.

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

The challenge faced by cyclotron users is therefore the following: tune the system to work at resonance and limit the power dissipated by the cavities by maximizing the shunt impedance. In order to understand the parameters involved in this challenge, we need to introduce the cavity scaling laws given by Eqs. (3) and (4) and the skin depth depicting the surface thickness where most of the RF current flows (8):

$$\frac{R}{Q} = const \quad , \qquad (3)$$

$$Q * \frac{\delta}{\lambda} = const \quad , \qquad (4)$$

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu}} \quad , \qquad (5)$$

where Q is the quality factor of the RF system, $\frac{R}{Q}$ is called the characteristic or geometric impedance, δ is the skin depth, σ is the electric conductivity and μ is the magnetic permeability.

From these relationships, we can conclude that if the skin depth of the cavity increases (by decreasing the conductivity at the same resonance frequency) the Q factor must decrease, and so does the shunt impedance. The power dissipated rises, for a set voltage.

This phenomenon can be also understood by introducing the surface resistance of the RF cavity:

$$R_{surf} = \frac{1}{\sigma\delta} = \sqrt{\frac{\omega\mu}{2\sigma}} \quad . \qquad (6)$$

And the power dissipated in the cavity walls due to ohmic heating is given by [2]:

$$P = \frac{1}{2} R_{surf} \int |H|^2 dS \quad , \qquad (7)$$

where H is the magnetic field [A/m] induced by the RF electric field.

Increasing the skin depth (by decreasing the conductivity at the same resonance frequency) increases the surface resistance seen by the current and therefore also increases the power dissipated. The shunt impedance and the surface resistance behave thus inversely.

In the equivalent RLC model described in Fig. 1, R is the resistor across which the voltage driving the beam is generated. It represents the losses of the resonator for that given voltage. The surface resistance describes the losses due to the ohmic heating as well, but from an electric and magnetic field point of view. The oscillating electric field creates in turn an oscillating magnetic field, inducing cur-

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rent that shapes the total current to flow mainly on the surface of the cavity (skin effect). For a given magnetic field, the higher the surface resistance, the higher the ohmic losses.

Multipactor and Secondary Electron Emission

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. When that happens, the RF load to achieve beam performances becomes so high that running the RF can become impossible.

It was shown by Yves Jongen [3] that the essential conditions for multipactor to happen can be met in the C230 cyclotron (gap between dee and valley, voltage, frequency, electrons starting phase).

Another 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. For multipactor to happen, the SEY needs to be equal or superior to one.

$$SEY = \frac{I_s}{I_p} \quad . \tag{8}$$

POISONING OF RF CAVITIES

A recurring problem observed over time on multiple IBA sites consists in a sudden and increasing change in the forward power fed to the RF cavities, becoming more and more problematic to handle over time, to the point where the RF drops and extracting beam must pause until RF is resumed. The power dissipation seems not to be localized, but rather spread over the 4 dees and cavities. While a typical power lies around 50 kW, when this issue arises the power can increase by 20 or 30 kW. Observations have revealed typical and recurring traces on all cavities suffering that kind of issue.

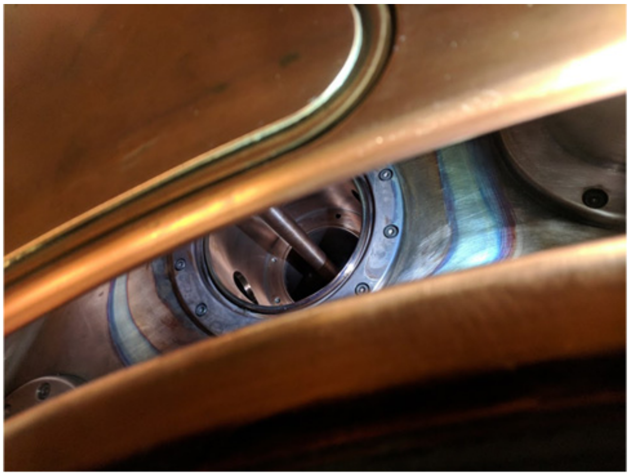

Figure 2: Typical poisoning traces inside RF cavities.

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 observed change further increasing over time). 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, meaning that the power is not evolving as the square root of the dee voltage anymore because the intensity of the multipactor leads to dissipating more or less heat.

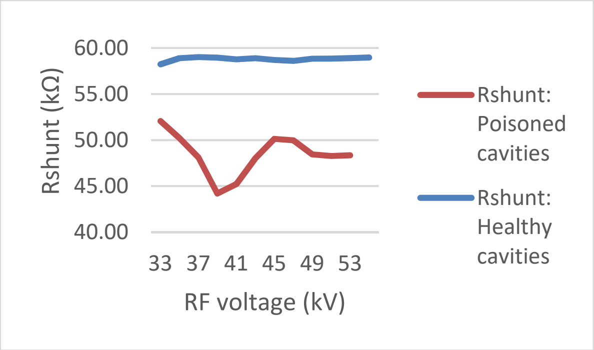

Figure 3: Rshunt of a healthy RF system vs Rshunt of a poisoned RF system.

ANALYSIS & HYPOTHESIS

The problem was qualified as “poisoning”, or sometimes “pollution” of the cavities because in every case, an external contaminant was found in the RF system. Most of the time, a strong correlation between the oxygen partial pressure and the increase in forward power was found. In some other cases, water, cadmium or silicon oxide was found on the cavities.

Oxygen Poisoning

Oxygen inside a cyclotron can originate from different sources: a leak with the atmosphere, a water leak or from the oxygen sprayed on the extraction electrostatic deflector.

When oxygen 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. While the SEY of copper lies around 1.3, the secondary emission yield of copper oxide can exceed 2 [4]. 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. The cycle continues and the situation further degrades.

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Silicon Oxide Poisoning

Silicon-based greases are to be prohibited inside cyclotrons. Indeed, silicon oxide also exhibits a high SEY, leading once again to enhanced multipactor. Instead, if lubrication can't be avoided, it is encouraged to use ODP oil, as it can have a beneficial effect on the secondary emission yield of the cavities as explained in the next section.

Water Poisoning

It was shown by Baglin et al. [4] 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. It can be easily diagnosed by observing the vacuum level: a water leak most often describes successive vacuum peaks, as the water freezes under vacuum, sealing the leak source, until it vaporizes with sufficient heating.

Cadmium Poisoning

The brazing of a few components of IBA RF cavities is partially composed of cadmium. This is for instance the case for the capacitive cavity tuner flaps, connecting the capacitor to the RF cavity, which are constantly solicitated in order to adapt the resonance frequency of the system. As the flaps move, defects in the brazing sometimes occur. This leads to an increase of temperature due to the induced RF currents in that area, leading in turn and in some extremely rare cases to outgassing of the brazing and deposition of cadmium inside the RF cavities.

It was shown by Walker et al. [5] that the cadmium secondary emission yield is lower than copper (maximum SEY around 1.1). This means that the increase in RF power is not due to a multipactor increase. Moreover, most of the traces of cadmium were found on the top of the dees and side of the cavities, where the multipactor is less likely to occur. Therefore, another phenomenon must be responsible for the power dissipation increase.

Figure 4: Cadmium deposition on RF system after outgassing of the mobile capacitor brazing.

Because cadmium has a lower conductivity than copper (around 5 times smaller), it can be shown that the skin depth at 106 MHz will double its thickness (from 6.3 µm for copper, to 13.2 µm for cadmium). 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 therefore twice the one of copper, at the same frequency. As shown by Eq. (7), the local power dissipation could double if all the cavity surface was plated or recovered with cadmium.

This hypothesis is valid only for materials with electric conductivity and magnetic permeability in the range of e.g. copper and cadmium. Indeed, as long as the skin depth is in the range of the layer deposited on the surface, we can consider that the surface resistance will be solely influenced by the poisoning material. For copper oxide, the behaviour is different: the physical properties of the cavity surface are modified as its structure gets oxidized. A. Ogwu et al. [6] have shown that for CuO and Cu_2O formed with RF power, the resistivity lies around 25 Ohm.cm, which translates to a conductivity in the range of 10^{-4} S/m, while it is in the range of 10^{+7} S/m for copper and cadmium. The resulting theoretical skin depth is extremely large (5 meters), showing that the copper oxide behaves as an insulator. Therefore, the current will mainly flow in the copper bulk and not the oxidized surface. As a result, the power dissipation is not impacted by the surface resistance, but rather by the previously discussed increase of SEY.

PREVENTIVE ACTIONS & RECOVERY METHODS

Preventive Actions

Decreasing the O_2 Load Any cyclotron operator should minimize the O_2 load of the accelerator by reducing the partial pressure of O_2 willingly injected in the cyclotron to avoid some poisoning factors.

Leak Checking & Fixing Even minor vacuum leaks that have little impact on the cyclotron base vacuum are potential pollution factors. A good practice is therefore to make sure that sensitive locations are regularly checked. Cooling pipes, for instance, are first-hand potential culprits and should be checked, i.e. by injecting pressurized air and monitoring the vacuum level. In case of pollution, the very first measure to be taken is to diagnose, localize and repair potential leaks.

Recovery Methods

Once vacuum has been validated, it is necessary to evacuate the contaminants from the system. In order to do so, different recovery methods exist, with or without opening the cyclotron. Recovering with a closed cyclotron takes time, usually a few weeks to a month, and hence require patience combined with rigor. Other methods require to open the cyclotron; they have a higher impact on system uptime but are sometimes much more effective and/or simply mandatory.

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. When pumping with oil diffusion pumps, the vaporized hydrocarbon oil often finds its way out of the pump, and deposits itself on the dees and in the valleys, lowering the SEY.

H_2 Bake If copper oxide has developed in the RF system, high vacuum is not sufficient to get rid of it. So called "H_2 bakes" are performed by flooding the cyclotron with hydrogen (up to a global pressure approaching the 10^{-4} mbar) 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. [7] 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).

$$CuO(solid) + H_2(gas) \rightarrow Cu(solid) + H_2O(gas) \quad (9)$$

$$Cu_2O(solid) + H_2(gas) \rightarrow 2Cu(solid) + H_2O(gas) \quad (10)$$

For temperatures below 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 than afterwards). This induction period gets larger with the decrease of temperature (around 60 min for a temperature of 230 °C, around 100 min at 200 °C). Therefore, the recovery process for RF systems takes time and patience; when performing H_2 bakes a few hours per night, sites usually see lasting effects after several weeks.

Pulse Conditioning During "pulse conditioning", RF is pulsed inside the cavities, leading to a behaviour resembling to the charge and the discharge of a capacitor. This induces outgassing of the surface of the cavities, purging it from its contaminants. This can also be coupled with a high H_2 load in order to induce the reduction of the copper oxide (the O_2 gas load being once again totally shut off during the conditioning).

Simultaneously, it is possible to sweep the current of the main coil, modifying the magnetic field seen by the RF plasma induced, and modifying the trajectories of its particles. It is believed that this method allows a real sweep of the cavities surfaces by this plasma, however no simulation or systematic studies of the results have yet been done, nor any systematic comparison to a simple H_2 bake (without RF pulsing and magnetic sweeping).

Performing this method should be avoided if the presence of any leak of O_2 is still suspected. Indeed, the plasma induced with oxygen would have an adverse effect, as described in the section about oxygen poisoning.

Mechanical Cleaning In some cases, the poisoning is too intense for any conditioning methods described hereabove to be efficient. In some other cases, the situation is not viable for the cyclotron users as the symptoms are too painful to pursue the activity (i.e. patient treatment) and opening the cyclotron and 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 case, the cavities should be removed if the back is poisoned as well. One needs to use abrasive hand pads to remove the contaminated layers over the copper. To ensure the rest of the machine is not polluted with the dust, the cyclotron subsystems such as deflectors, poles, central region etc are protected with protective rugs or removed. The dust is then vacuumed out of the cyclotron, and all the cavities and dees surfaces are cleaned with isopropyl alcohol.

Chemical Cleaning IBA recently experimented chemical cleaning on a site facing cadmium poisoning. The purpose was to avoid etching the surface with any abrasive pads, but rather by using a mild hydrochloric acid solution (mass diluted to 15%) that would remove the cadmium from the copper surfaces, and then rinsing the surfaces with bi-carbonated water in order to neutralize the acid action and protect the copper. The effectiveness of the method has been observed through a significant drop in RF forward power; initially at 60 kW for 50 kV of dee voltage, it dropped to 38 kW for the same dee voltage after the chemical cleaning. It has also been observed that the cavity copper turned slightly pink, with no impact on RF system operation.

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