MEASUREMENT OF THE ENERGY DISTRIBUTION FUNCTION OF ELECTRONS GENERATED BY RADIO-FREQUENCY INDUCED MULTIPACTING IN A BEAM PIPE.

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Abstract

Electron multipacting in beam pipes leads to the formation of Electron Clouds (EC) and is one of the phenomena limiting the operation of high intensity particle accelerators. The development of the multipacting depends on the beam pipe geometry, beam structure, the magnetic field and on the Secondary Electron Yield (SEY) of the surfaces facing the beam. In-situ studies of EC in particle accelerators must cope with the schedule of machine operation and with several technical constrains. To overcome these difficulties, CERN implemented a Multipactor test bench, where electron multipacting is generated by Radio-Frequency (RF), using the beam pipes as a coaxial resonator. This tool was already successfully used to assess the effectiveness of low SEY carbon coatings on dipoles of the Super Proton Synchrotron (SPS) at CERN and to study the dynamics of the conditioning of beam pipes. In this paper we present the development of an in-house built Retarding Field Energy Analyser (RFEA), using a control unit from a commercially available RFEA for plasma diagnostics, to measure the Electrons Energy Distribution Function (EEDF) in the Multipactor test bench. The design of the electrodes was based on simulations (OPERA3D) in order to find a good compromise between sensitivity and energy resolution. A low SEY carbon thin film was applied to some of the electrodes in order to study the impact of secondary electrons on the performance of the RFEA. The setup was first tested with an electron gun at different energies and then used to measure the EEDF of the electrons in the Multipactor test bench. The evolution of the EEDF is measured at different RF powers. Feasibility to perform measurements in the machine will be discussed.

INTRODUCTION

The decrease of the SEY of the internal walls of the beam pipes under the bombardment of the electrons form the EC is called conditioning. During the first phase, (electron doses below ~1x10^{-4} C/mm^2), conditioning is attributed to the cleaning of the surface by electron stimulated desorption, while in a second phase, (doses above 1×10^{-4} C/mm^2), the decrease of SEY is due to the growth of a graphite like carbon film. [1-3].

Cimino et al. [4] observed that with primary electrons with energies below 20 eV the graphitization of the carbon layer was not complete and the lowest obtainable SEY remained above 1.35 even after a dose of 10^{-2} C/mm^2. Above 50 eV, the SEY went down to 1.1 for doses below 10^{-2} C/mm^2, and the higher the energy of the electrons, the lower the dose required to achieve this value, indicating that the EEDF of the impinging electrons is a key parameter to understand the dynamics of conditioning of surfaces.

The Multipactor test bench at CERN was conceived to mimic the EC observed in the CERN SPS and has been used to study the dynamics of conditioning in laboratory [5], including the impact of the presence of hydrocarbons in the residual gas and the resilience of the conditioned surface to air exposure. Witness samples exposed to the multipacting were analysed by X-ray Photo-electron Spectroscopy, after transfer through air, to evaluate the amount and chemical state of the carbon after each conditioning cycle.

Although the transversal profile of the electron cloud observed in this system is similar to measurements with the electron cloud monitors in the SPS, the energy of the electrons bombarding the surface remained unknown. On a first attempt to measure it, a commercially available RFEA probe (used for plasma diagnostics) was used, but the sensitivity was poor due to the low transparency of the grids setup. To overcome this problem, a new RFEA probe compatible with the same electronics unit but with larger collection area and grid transparency was built.

EXPERIMENTAL SETUP

In the Multipactor test bench, the beam pipe to be conditioned, (in this case a chamber from a MBB type dipole of the SPS), is the external conductor of a coaxial resonator. The RF power is fed in the system through the inner conductor, (a tungsten wire drawn along the beam pipe), at a frequency around 100 MHz and in a dipolar magnetic field of 0.0036 T. During standard conditioning studies, the RF excitations are applied in the form of power ramps, followed by a pause to avoid overheating the tungsten wire. Further details about the setup can be found in [5-7]. In the present work, constant power excitations are applied for 40 s and the electron flux measured at different retarding voltages, (from -350 V to 20 V), using the high precision low-current measurement system, (60×10^{-6} A range with the noise level at ~10^{-8} A), from a SemIonTM Single Sensor Unit coupled to the CERN built RFEA. Normalizing the measured electron flux as a function of the retarding voltage relative to its maximum (at 0 V retarding field), we get the Cumulative Distribution Function (CDF) of the electrons striking the walls of the beam pipe. The EEDF is obtained by computing the derivative of the CDF with respect to the retarding voltage. The measurements were done at five RF power levels: 2.0 W, 3.9 W, 7.9 W, 10.5 W and 15.0 W.

The design of the RFEA probe was optimised with the help of OPERA3D and a configuration with three electrodes was chosen: the first one, (a grid), is at the potential of the beam pipe (grounded); the second one is the retarding grid and the third one is the collector, positively biased relative to the retarding electrode (~ + 18 V). For the first two electrodes, a double grid solution was adopted. This was a compromise between grid transparency and accuracy: very thin grids (-0.1 mm) with large square holes (1 mm) assure a total transparency of 65%, but the potential drop at the centre of the holes can lead to errors of about 37% on the retarding energy. Using double grids, spaced by 1 mm, the total transparency is reduced to 43%, still clearly above the 12% transparency of the SemIonTM probe and with a calculated error for the minimum pass energy below 5%. The distance between the first electrode and the retarding electrode is 2 mm and between this last one and the collector is 1 mm. The RFEA was mounted on the back of the beam pipe to be tested, in the same configuration used for the electron cloud monitors in the SPS and in the Multipactor system (Fig. 1). Holes with 2 mm in diameter assures a transparency of 7% between the beam pipe and the RFEA.

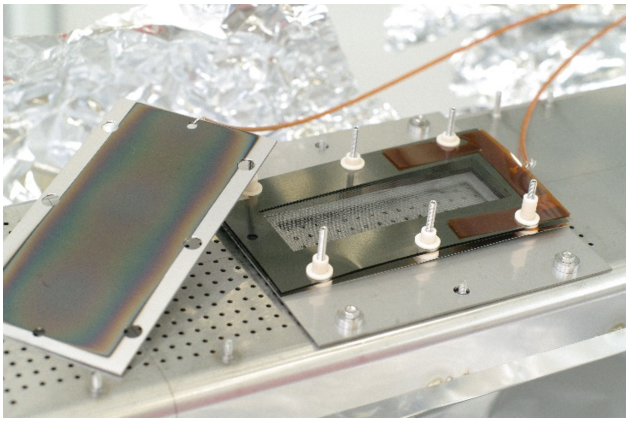

Figure 1: The RFEA built at CERN with the grids and the collector coated with low SEY carbon.

To evaluate the accuracy of the RFEA, an electron flood gun, (Specs FG 15/40), was used. The energy of the electrons from the gun was varied from 25 eV to 400 eV in steps of 25 eV and compared with the energy for the maximum of the EEDF measured by the RFEA. Two versions of the RFEA were tested: one in bare stainless steel and another one coated with a low secondary electron yield amorphous carbon thin film (SEY ~ 0.95). The goal was to evaluate the impact of secondary electrons generated in the RFEA itself.

RESULTS AND DISCUSSION

The tests with the electron flood gun beam, which is nearly mono energetic, proofs the positive effect of the carbon coating on the accuracy of the RFEA (Fig. 2). For the uncoated version, the error in the measured energy varies with the energy of the incoming electrons, from about 8% at 25 eV to -6% above 200 eV, while for the coated one coated one the error remains almost constant at around 1%, increasing to 2% at 25 eV. Although the absolute value of the error measured with the coated RFEA is about a factor 5 lower than the simulated one, the dependence of the error on the retarding voltage is the same. Based on these results, the coated version was adopted for the tests with RF power.

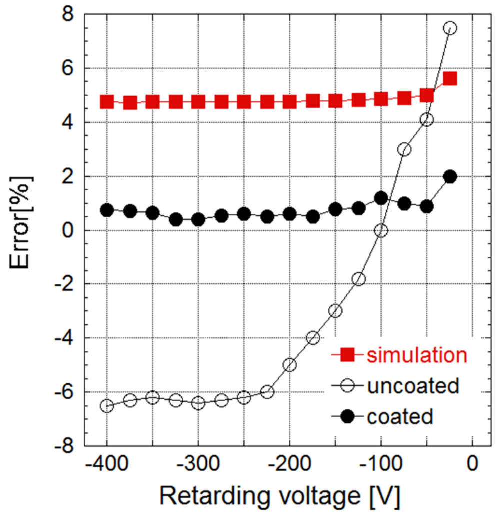

Figure 2: Error of the kinetic energy of the electrons passing the grids relative to the retarding voltage.

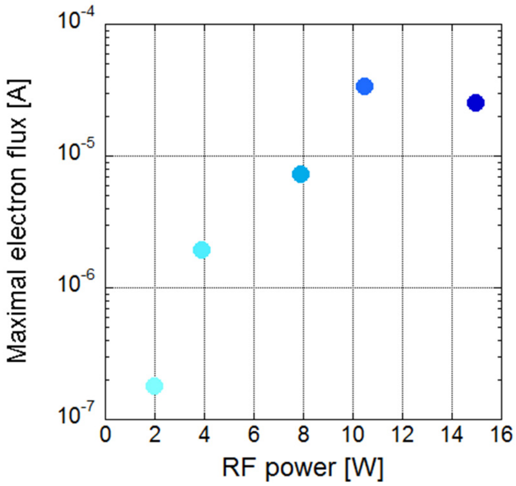

Figure 3: Maximal electron flux measured at the collector, (retarding voltage at 0 V), for different RF powers.

When RF power is injected in the resonator, multipacting occurs and the density of electrons in the beam pipe rises. The total electron flux impinging on the walls is measured with the retarding voltage set to 0 V and increases with the RF power up to 10.5 W (Fig. 3). For 15 W, no further increase was observed.

In Fig. 4, the normalized electron fluxes as a function of the retarding voltages are plotted for different RF powers. The normalized curves represent the CDF of the electrons which is the fraction of electrons with energies above a certain level. This information, summarized in Fig. 5 for different energy levels, enables to extract the relevant dose accumulated during conditioning runs in the Multipactor test bench and to compare with conditioning studies performed with electron guns. At 3.9 W, only 13% of the electrons have energies above 50 eV, and may contribute to reach a final maximal SEY of 1.10, while at 10.5 W this number reaches 28% and 36% at 15 W.

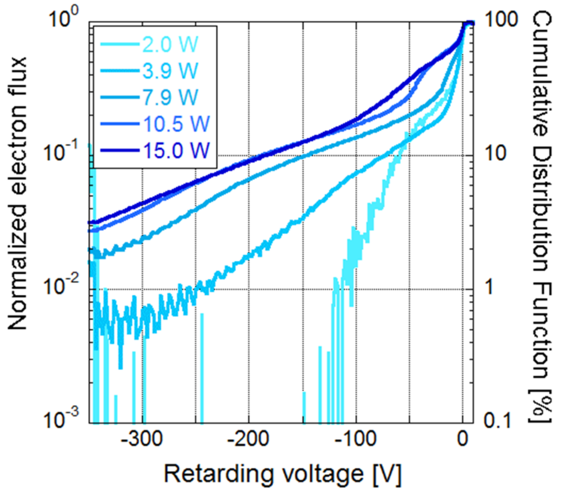

Figure 4: Electron flux in function of the retarding voltage, normalized to the maximum obtained at 0 V.

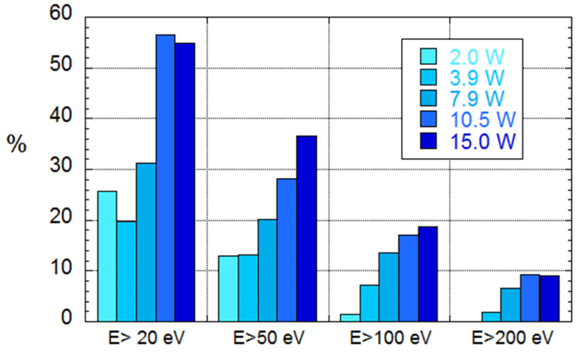

Figure 5: Fractions of the electron flux for different RF powers.

The EEDF computed from the electron flux curves measured at different powers are plotted in Fig. 6 (to keep the clarity of the plot, the curve at 2 W is left out). All curves present a main peak below 10 eV, (attributed to secondary electrons emitted by the walls, that have not gained energy from the resonator electric field), and a high energy tail, that increases in intensity for higher powers. This indicates that with higher RF power the transfer of energy from the resonator to the secondary electrons is enhanced (the population of high energy electrons increase relative to the electrons below 10 eV). A second peak is also observed at an energy that depends on the applied power: at 16 eV for 7.9 W, 40 eV for 10.5 W and 90 eV for 15 W, becoming broader at higher energies. Although the mechanism is not yet understood, the data suggest that this peak is a fingerprint of the multipacting process. In fact, increasing the power from 10.5 W to 15 W, the total electron flux remains constant but the energy of the electrons increases substantially. A "peak structure" at higher energies can also be observed in the EEDF obtained by simulation of electron cloud (dotted and dashed lines in Fig. 6). The simulations were done with the py-ECLOUD code [8] and the parameters are chosen to be representative of a MBB type test chamber installed in the electron cloud monitors of the SPS [9], (0.1 T dipolar magnetic field, 26 GeV beam with 1.2 x 10^{11} protons per bunch spaced by 25 ns). Three levels of conditioning were considered: initial, SEY=1.75; partially conditioned, SEY=1.30, (close to threshold for electron cloud); and fully conditioned (SEY=1.00). For SEY 1.75 and 1.30, the "peak structure" is relatively similar with two broad peaks around 150 eV and 250 eV (with a third peak at ~100 eV for SEY=1.75), while for SEY=1.00, (no electron cloud), the peak structure changes completely.

We can see that the EEDF simulated for SEY=1.75 lies between the curves measured at 10.5 W and 15 W, indicating the conditioning process in the multipactor test bench is representative of the conditioning in the e-cloud monitors in the SPS (based on the calculated dose applied during the RFEA tests, the SEY of the chamber remained between 1.90 and 1.60). Calculating the CDF of the EEDF simulated at SEY=1.75 we obtain that 44% of the electrons have energies above 50 eV, compared to 36% measured at 15 W.

Further measurements of the EEDF in the multipactor test bench are necessary to confirm this behaviour holds for lower SEY.

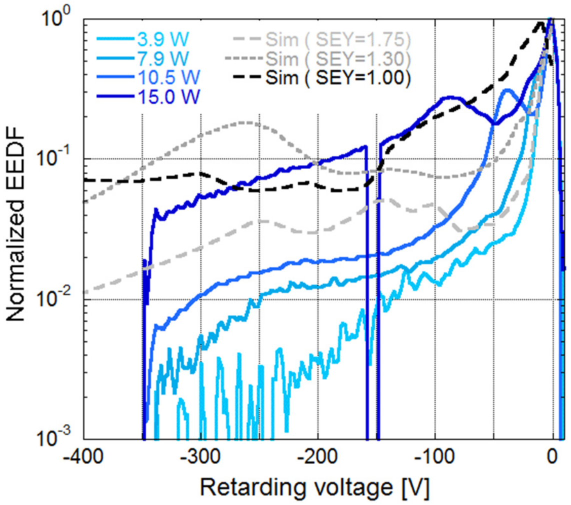

Figure 6: Normalized Electrons Energy Distribution Functions.

CONCLUSIONS

The dedicated RFEA developed at CERN for the Multipactor test bench was benchmarked. Coating the electrodes with a low SEY thin film increased the accuracy of the RFEA. For low levels of conditioning, (SEY between 1.90 and 1.60) the EEDF is comparable with the one simulated for the e-cloud monitors in the SPS. Further studies at higher level of conditioning must be done to corroborate the conditioning studies in the multipactor test bench. The RFEA presented in this work can potentially be applied in accelerators.

REFERENCES

[1] N. Hilleret et al, "The Secondary Electron Yield of Technical Materials and its Variation With Surface Treatments", proceedings of EPAC 2000, Wien, Austria.

[2] M. Taborelli et al, “An AES study of the room temperature conditioning of technological metal surfaces by electron irradiation”, Applied Surface Science 202 (2002) pp 57–67.

[3] Shigeki Kato et al. “Graphitization of Inner Surface of Copper Beam Duct of KEKB Positron Ring”, Vacuum 84 (2010), pp 743-746.

[4] R. Cimino et al, “Nature of the Decrease of the Secondary-Electron Yield by Electron Bombardment and its Energy Dependence”, PRL 109, 064801 (2012).

[5] P. Costa Pinto et al. ‘Reduction of E-cloud in Particle Accelerators Beam Pipes Studied by Radio-Frequency Multipacting.’ Conference Proceedings IPAC 2015, Richemond, USA, pp 472.

[6] P. Costa Pinto et al. ‘Multipactor For E-Cloud Diagnostics.’ Conference Proceedings IPAC 2012, New Orleans, USA, p 139.

[7] P. Costa Pinto et al. ‘Radio-Frequency Multipacting as Quality Control of Coatings for E-Cloud Suppression.’ Conference Proceedings IPAC 2013, Shanghai, China, p 3403.

[8] G. Iadarola et al, ‘Py-ECLOUD and build-up simulations at CERN.’ CERN Yellow Report CERN-2013-002, pp.189-194, DOI:10.5170/CERN-2013-002.189.

[9] G. Arduini et al, ‘Measurement of the Electron Cloud Properties by Means of a Multi-Strip Detector in the CERN SPS’, proceedings of EPAC 2002, Paris, France.