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ABSTRACT.
Mechanisms of arc formation have been analyzed and the critical electric fields for the multipactor effect calculated, compared to the experimental values and found to be within the normal operational space of the LH system on JET. It has been shown that the characteristic electron energy (20-1000)eV for the highest multipactor resonances (N = 4-9) are within the limits of secondary electron yield above 1 required for multipactoring. Electrons with these energies provide the highest gas desorption efficiency when hitting the waveguide walls. The effect of higher waveguide modes and magnetic field on the multipactor was also considered. The distribution function for electrons accelerated by LH waves in front of the launcher has been calculated. The field emission currents have been estimated and found to be small. It is proposed that emission of Fe15,16 lines, which can be obtained with improved diagnostics, could be used to detect arcs that are missed by a protection system based on the reflected power. The reliability and time response of these signals are discussed. A similar technique based on the observation of the emission of low ionized atoms can be used for a fast detection of other undesirable events to avoid sputtering or melting of the plasma facing components such as RF antenna. These techniques are especially powerful if they are based on emission uniquely associated with specific locations and components.

1. MECHANISMS OF ARC FORMATION IN LH GRILL WAVEGUIDES

Field emission current [1] and multipactor effect [2] are believed to be responsible for the arc initiation in the waveguides in the presence of RF electric field. Very large electric field of the order of 500-600kV/cm is required for electric breakdown in waveguides at a frequency of f = 3.7GHz and waveguide width of $\delta = 0.9$cm according to empirical Kilpatrick criterion [1]. The maximum electric field in the waveguides of LH grill on JET varies in the range of 0-5kV/cm for the operation power range of 0-300kW per klystron.

The multipactor effect may occur when the electron fly time τ between the waveguide walls in the RF electric field is close to (N+1/2)/f [2], where N is an integer number defining the resonance order. In a simple stationary multipactor theory neglecting the energy of emitting electrons [3] such resonances occur only in a narrow range of electric fields $E_{min}(kV/cm) = 2.25\ 10^4(f\ d)^2/(((2*N+1)\pi)^2+4)^{1/2}/d$, $E_{max}(kV/cm) = 2.25\ 10^4(f\ d)^2/((2N+1)\pi)/d$, where d is the width of the waveguide in cm and f is the frequency in GHz. Exponentially rising avalanche of electrons is formed if the resonance electrons acquire an energy sufficient to knock out more than one secondary electron. The Secondary Electron Yield (SEY) characterizes the number of knocked out electrons. The SEY depends on the characteristics of the wall material.

Clearly, the result of the stationary theory [3] in Fig.1 allows only high order resonances N>8 in the range of accessible electric fields E<5kV/cm for the TE_{01} mode with additional limitation imposed by electron energies acquired in the RF field and condition SEY>1. Higher TM modes existing in the waveguides may modify resonance fields as discussed below.

More rigorous approach [4] allows modeling of the avalanche evolution taking into account the

SEY. The waveguide surface of the stainless steel grill on JET was covered by a thin copper layer, originally. However, the surface has been modified to a smaller or greater degree by the arcs and long exposure to the plasma. The SEY of the wall surface can be assessed only approximately. Using available data for iron, copper, Cu-Be and Ni-Be SEY we assumed that for electron energies in the range of W_1-W_2 the SEY>1, where W_1 = 20-200eV and W_2 = 1-3keV. The threshold energies $W_{1,2}$ and SEY depend on the composition of the surface layer and its temperature. The maximum value of SEY may vary considerably: it is close to 1.4 for Cu and Fe and increases to 4-6 for Cu-Be and Ni-Be. The birth energy of the secondary electrons W_b is of the order of 1eV and does not play significant role as it is small compared to the averaged energy.

Figure 2 shows results of the modeling of the multipactor effect in the grill waveguides for different energies of W_1 (Fig.2a,b) for TE_{01} mode only and for a combination of TE_{01} and TM_{11}(Fig.2a,c). The number of electrons increases exponentially by factor of 1500 and 8 for critical fields $E_{cr1,2}$ ≈1.55 and 1.7kV/cm, respectively, in the case of W_1 = 20eV (fig.2a). These two narrow resonances disappear with increase in the threshold energy up to W_1 = 40eV (fig.2b). Increase in the W_1 causes increase in the critical electric field E_{cr} required for the multipactoring. For example, E_{cr} rises to 2.75kV/cm, when W_1 increases to 50eV. Increase in the max(SEY) leads to a faster rise in number of electrons N_p involved in the avalanche. The avalanche process can be modified by a presence of the higher modes in the waveguide (Fig.2c).

In a typical tokamak geometry the magnetic field is practically parallel to the electric field in the waveguides. It prevents a spread of electron beam involved in the avalanche perpendicular to the magnetic field lines. Magnetic field in such configuration facilitates the arc formation [5].

2. ARC DETECTION AND PROTECTION IN LH LAUNCHER ON JET

A complex procedure of LH grill conditioning is carried out before each experimental campaign on JET to increase the maximum applicable power. The detection and protection system is used to prevent or reduce a possible damage from the arcs. It detects a variation in the reflected power from the grill mouth. Figure 3a shows an arc in waveguides E1 and E4 separated spatially by two other waveguides (E2,E3). The arc was detected, when reflected power in the lower arm of the multijunction E1b and E4b increased above the critical level. The protection system tripped LH power generated by corresponding klystrons. Increased radiation and rise in the iron emission (iron is the predominant component of the grill material) are typical manifestations of the arcs and are also shown. The arcs are stopped by the power trip and only short bursts of the radiation and iron emission are observed. LH power is reapplied after some delay sufficient to quench an arc.

Figure 3b shows an example of the arc, which is not detected by the protection system. The arc starts at $t \approx 30.8$s based on the bolometer signal. A significant increase in the radiation and iron emission are observed from the start of the arc until the end of the LH pulse. This indicates that the waveguide melting occurs during arcs.

3. ARC DETECTION IMPROVEMENT

The LH system designed for arc detection and protection fails sometime as has been shown in fig.3b. The arcs in LH grill always produce enhanced emission of the iron ions. Recently improved diagnostic of the iron emission of low ionization state (Fe15,16) allows detection of arcs in the early phase of their development (Fig.3). According to the database, a correlation in the increase of d(Fe15,16)/dt signals above a certain limit ($C_{th} = 10^7 Cnts/s^2$) should identify the arcs undetected by the protection system. The response time is limited by the diagnostic sensitivity and it is close to 20-25ms at the moment. A system based on a detection of the visible light and infra-red emission from the grill mouth is being installed on JET. It should give even better response time and definition of the affected waveguides. A system based on the combination of the iron emission and bolometer measured radiation is being also discussed.

SUMMARY

It has been shown by the modeling that the high order multipactoring is possibly responsible for the arc formation in LH grill on JET. The electric field critical for the RF breakdown has been assessed. It was found to be in the operation LH power range on JET. Impact of the higher TM modes on the multipactoring has been modeled and shown to be important. The secondary electron yield dependence on the waveguide material has been estimated and its effect on the variation in the avalanche process has been demonstrated. A proposal has been made on the improvement of the LH arc detection and protection system based on the detection of low ionized stages of iron emission. Similar technique can be used for a detection of other undesirable events leading to erosion of the plasma phasing components using unique elements in the construction materials.

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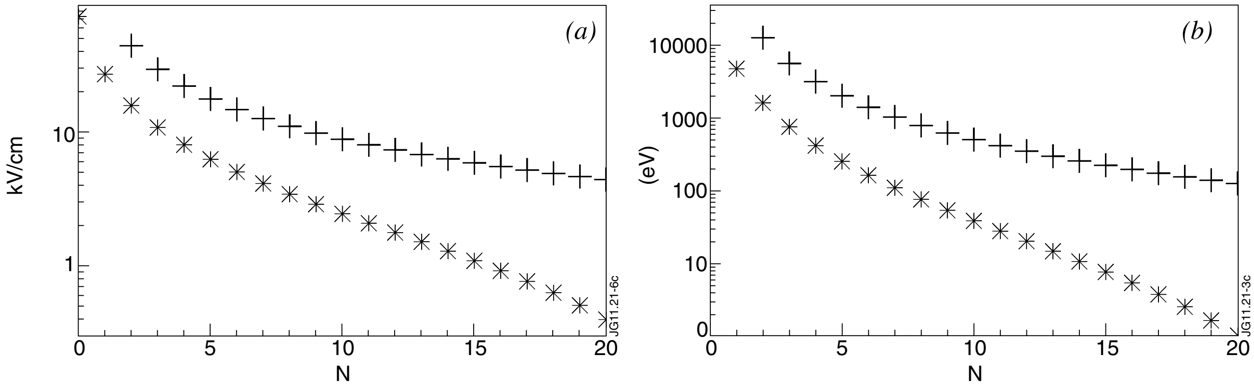

Figure 1: (a) Minimum and maximum electric field required for multipactoring as a function of the resonance order N, according to stationary theory [3]. (b) Minimum and maximum energy acquired by electrons in the E_{min} and E_{max} fields. F = 3.7GHz, d = 0.9cm. TE_{01} mode considered only.

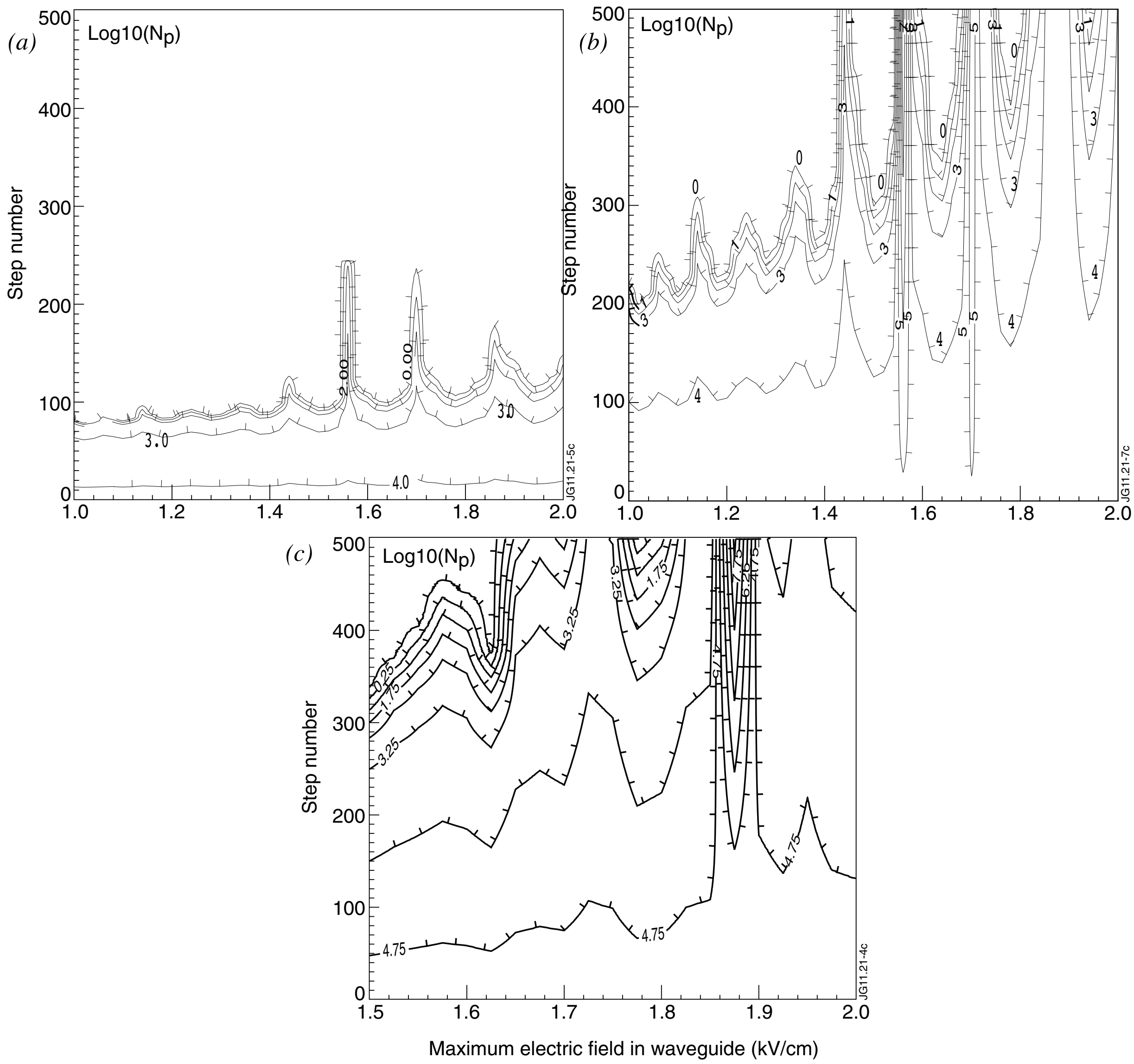

Figure 2: Contour plot of Log10(N_p). a) Variation of a number of electrons N_p as a function of maximum electric field $E(TE_{01})$ in the grill waveguide for W_1=20eV and b) for W_1=40eV, TE_{01} mode considered only. c) $E(TM_{11})=0.25*E(TE_{01})$ and the wave phase $\varphi(TM_{11})=\varphi(TE_{01})$, W_1=20eV. Electrons at a random phase are launched at the first step with initial $N_p=5\ 10^4$ particles. Each step corresponds to one pass of electron between walls of the waveguide. Downhill direction is shown by ticks on each line. Distance between lines corresponds to variation in N_p by factor of 10. W_2=1.1keV. $SEY=1.5\exp(4(W-W_m)^2/(W_2-W_1)^2)$, $W_m=(W_1+W_2)/2$, waveguide width d=0.9cm, birth energy W_b=1eV.

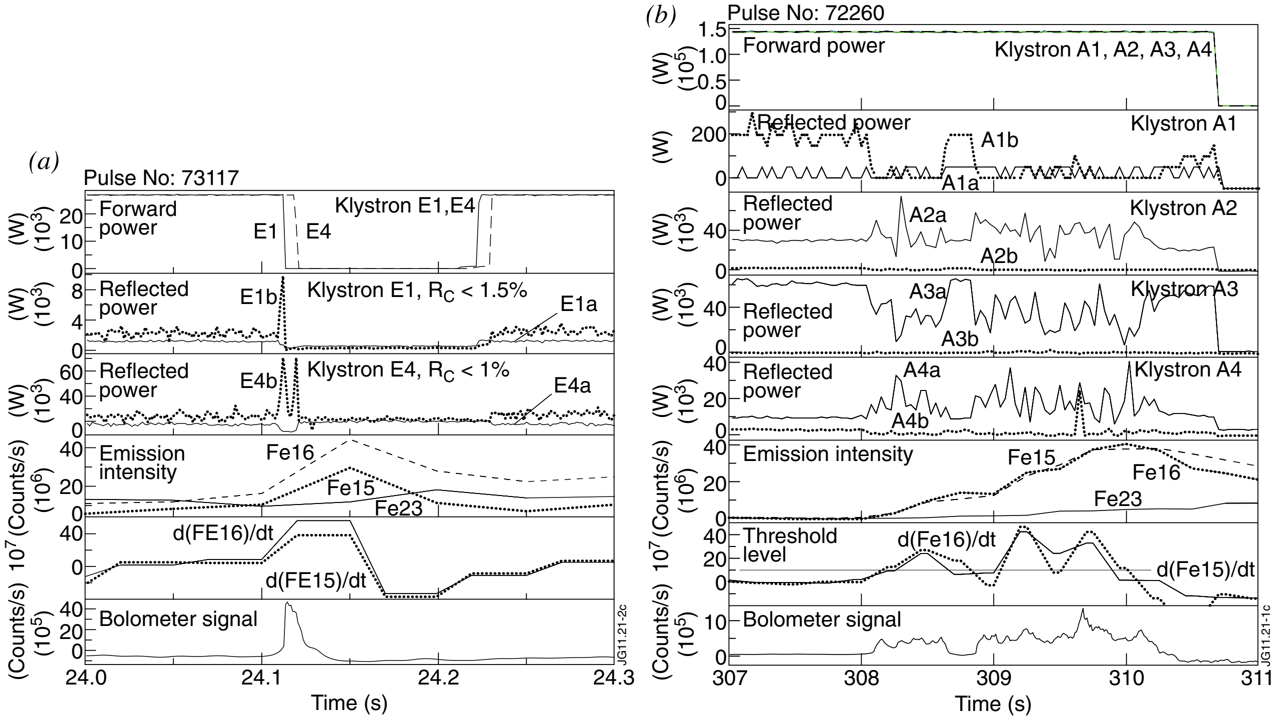

Figure 3: a) LH power is tripped in klystrons E1 and E4 by the protection system, when reflected power E1b and E4b increased above a critical level. Short bursts of iron emission and radiation are triggered by the arc and stopped, when the arc is quenched. b) An arc undetected by the protection system in adjacent waveguides A1-4. Reflected power fluctuates, but remains within the prescribed limits. The radiation and iron emission increase at the start of the arc and continues until the end of the LH pulse. The emission of low ionized ions (Fe15,16) rises at the start of the arc. It was found from the JET LH database that a correlated rise in d(Fe15,16)/dt signals indicates the start of the arc.