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PHYSICAL MODEL OF PARTIAL RF DISCHARGE IN ISOCHRONOUS CYCLOTRONS

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Abstract

The physical model of partial RF discharge, based on the residual gases molecules ionization by detached electrons produced in collisions of negative hydrogen ions with residual gases, as well as electro-dissociation of H^- ions in isochronous cyclotrons, is proposed in this paper. The following problems are discussed in this article: the influence of magnetic field on the properties of partial RF discharge, the analysis of conductivity of RF plasma (partial RF discharge), the results of proposed model application for 11 MeV Eclipse cyclotrons.

INTRODUCTION

A partial electrical discharge is the first stage of forming the radiofrequency (rf) discharge in the cavities (cavity consists of dee and cooper surfaces of magnet valleys) of isochronous cyclotron which takes place before full breakdown (the so called crowbar). The main question of the discharge appearance is a question of origin of preliminary electrons that initiate rf discharge. The vacuum conditions in isochronous cyclotrons with internal ion source have large influence on loses of H^- ions. The time of processes of forming the rf partial discharge is not stable and stochastic. The analysis of existing rf discharge in charged particle accelerators [1, 2] shows that the used physical models cannot hitherto describe partial discharge appearance in low energy isochronous cyclotrons (for instance, 11 MeV Siemens Eclipse cyclotron). The partial discharge can lead to full rf discharge and consequently determines the time of irradiation. One can point, for example, that decreasing the total time of irradiation on the 15% leads to reduction of short-lived isotope activity on the 15% ultimately. A new physical model of partial discharge for isochronous cyclotrons with internal ion source is presented in this paper. Furthermore, the paper has practical aspect related to efficiency of medical radioisotopes production during target irradiation by protons.

PHYSICAL MODEL OF PARTIAL RF DISCHARGE

The main idea of proposed physical model is based on the ionization of residual gas molecules by electrons. These freed electrons appear due to stripping and electrodissociation of H^- ions. The ionization result in formation of plasma clouds between dees and trimbars with enough conductivity to decrease rf voltage (Fig. 1). This proposal makes a difference from other models of electrical discharge presented in Ref. [3]. Waveforms illustrating the partial discharge and crowbar are shown in Fig. 2. Curves in Fig. 2a are cyclotron magnet current (CH1) and a signal on RF probe (CH2) correspondingly.

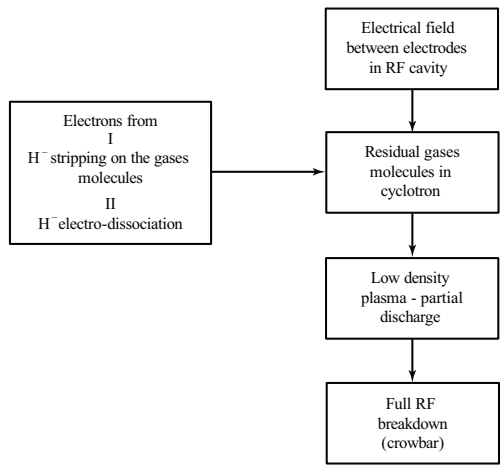

Figure 1: Physical model structure of forming the RF discharge in cyclotron cavity.

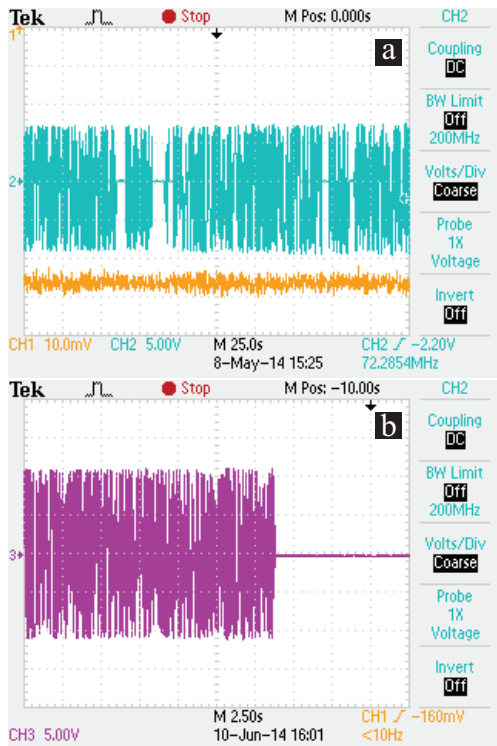

Figure 2: The waveforms of RF partial discharge (a); RF partial discharge & full electrical one (b).

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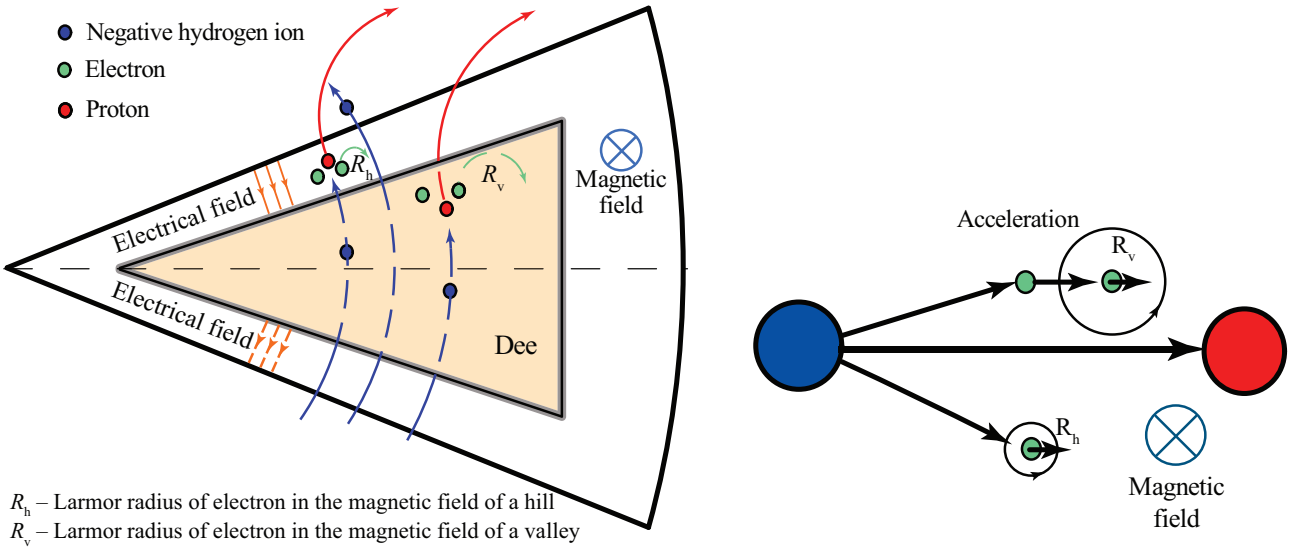

Figure 3: Physical processes scheme of electrons production and ionization of residual gas molecules.

Detached electrons from H^-, due to ions collisions with residual gas molecules, are accelerated in gaps between dees and trimbars where its kinetic energy is increased. Accelerated electrons can cause an effective ionization of residual gases molecules, such as N_2, O_2, H_2O and CH group. CH group is produced with diffusion pump oil. It is clear that cyclotron magnetic field plays an important role in plasma generation process on account of the increase in the probability of residual gas ionization. The magnetic field in the hills (approximately 1.8 T) leads to small value of Larmor radius of rotated electrons in compare with Larmor radius of rotation in valleys (approximately 0.7 T), where magnetic field is lower (see Fig. 3). Rotated and accelerated electrons can cause as well the secondary electron emission from cyclotron tank cooper surfaces.

The analysis of conditions of primary electron formation from H^- shows, that stripping effect is more significant as compared to electrodissociation process. The stripping effect under residual gas real pressure in the range $(5–10)\cdot10^{-6}$ Torr (diffusion pumps and internal Penning ion source are supposed to be used) is about (7–10)% of beam current [4]. For example, if H^- beam current from ion source is equal to 300 μA then one can produce (42–60) μA of electron current, that presents total average number of primary electrons for 1 sec is about $(2.6–3.8)\cdot10^{14}$. If one considers factor of ionization about 0.1% then it is possible to use in 1000 time lower number of plasma electrons and create relative low plasma conductivity. Plasma of partial discharge can be described as some nonlinear shunt connected to one or a few cyclotron cavities and can result in rf generation shut down in cyclotron totally. The plasma conductivity will grow up with an increase of rf power dissipation because of partial discharges. The average level of rf power decrease is about (5–10)%. It means that rf power dissipated by partial discharge is equal to (0.4–0.8) kW under forward rf power is equal to 8 kW. The impedance of partial discharge plasma is nonlinear and its value is in the range (5–150) kΩ under parameters of Eclipse cyclotrons.

Analysis of physical processes indicates that H^- electrodissociation under 11 MeV is low [5] and not greater than 2% from beam current.

APPLICATION OF PROPOSED MODEL OF PARTIAL DISCHARGE

The application of proposed model for Eclipse cyclotrons is associated with a decrease in probability of partial discharge and, consequently, crowbar appearances. Crowbar leads to irradiation time decrease of target by proton beams. An example of beam dumping during irradiation process on Faraday cup (target) owing to crowbars is shown in Fig. 4a. Cyclotrons efficiency for medical radioisotopes production is expected to be increased thanks to proposed model.

One should improve vacuum conditions in the isochronous cyclotrons to decrease the partial discharge probability. This solution was considered in Ref. [6] taking into account beam losses because of charge exchange on gas molecules (gas stripping) but without partial rf discharge.

One can use Eq. 1 - 4 in order to estimate partial discharge plasma resistivity in the framework of proposed model.

The concentration of ions $n_{pi}(t)$ and electrons $n_{pe}(t)$ of partial discharge plasma ($n_{pi} \simeq n_{pe}$) is defined by kinetics of its accumulation

$$n_{pe} = n_0 n_e \upsilon_e \sigma_i, \quad (1)$$

where n_0 is Loschmidt number, n_e is the concentration of detached electrons from negative hydrogen ions, υ_e is detached electron velocity,σ_i is gas ionization cross-section for detached electrons. Note that maximum of nitrogen molecules ionization cross-section is equal to $2.5\cdot10^{-6}\text{cm}^2$ and corresponds electron energy is about 100 eV.

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Gas molecules concentration (Loschmidt number) can be calculated by means of Eq. 2:

$$n_0 = 2.687 \cdot 10^{19} \left(\frac{p}{760}\right)\left(\frac{273}{T}\right) \text{ cm}^{-3}, \quad (2)$$

p is residual gas pressure [Torr], T is gas temperature [K].

Electrons velocity υ_e can be presented as

$$\upsilon_e = \sqrt{\frac{2eU}{m_e}}. \quad (3)$$

Here e is elementary charge, m_e is electron rest mass, U is absolute value of accelerating voltage, which is acting between dee and trimbar.

The resistivity of plasma $\rho(t)$ determines by equation

$$\rho \simeq \frac{2\pi\Lambda\left(n_{pe}\right)e^2 m_e^{1/2}}{T_e^{3/2}}, \quad (4)$$

where Λ is plasma parameter, T_e is the temperature of plasma electrons.

The dependence of resistivity of partial discharge plasma on residual gas pressure in cyclotron tank is shown in Fig. 4b. This figure shows that requisite residual gas pressure should be on the level of 10^{-7} Torr in order to decrease the partial discharge probability.

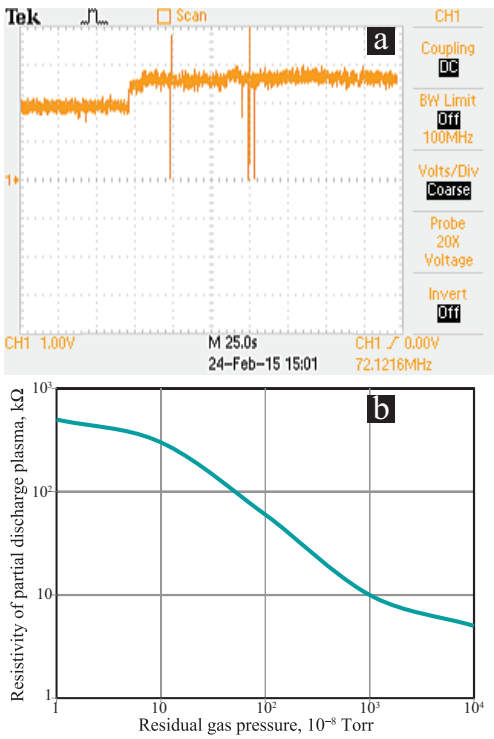

Figure 4: Waveform of beam current on Faraday Cup with full electrical discharge (a) & the resistivity of partial discharge plasma vs residual gas pressure in cyclotron (b).

CONCLUSION

The new considered physical model of partial discharge is the first step in the explanation of physical processes in the cavities of cyclotron tank. The proposed physical model is useful for the improvement of low energy isochronous cyclotrons (up to 15 MeV) and for the increase of yield of medical isotopes.

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