A QUALITATIVE APPROACH TO EXPLAINING THE MECHANISM OF ION ACCELERATION BY AN ELECTRON BEAM IN PLASMA

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Acceleration of ions in a vacuum discharge, accompanied by electron beam, is known. Recently this effect is probably observed in connection with investigation of a high current non-sputtering magnetron discharge. In the present note a qualitative approach in the framework of a one-dimensional model of this phenomenon is considered without taking into account collisions. A high-current electron beam, when injected into the plasma, generates power oscillations. With the loss of energy for the excitation of oscillations and in the process of increasing the current of the electron beam, a virtual cathode appears. The ions are captured by the virtual cathode and accelerated in the direction of the electron collector.

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INTRODUCTION

Acceleration of ions in a vacuum discharge, accompanied by generation of an electron beam, was observed in the first half of 20th century. Significant progress has been made in the experiments largely related to the activities of A.A. Plyutto with co-workers [1-3]. Despite the success of this approach to the problem of collective acceleration in the experiment, even a satisfactory qualitative theory of this phenomenon has not yet been created. The acceleration of ions in a longitudinal magnetic field, observed by Plyutto [4], indicates that the effect is most likely not related to transverse motion, what allows considering the acceleration process as a one-dimensional. Such an approach greatly simplifies both the theoretical analysis and computer simulation. Usually, the acceleration of ions in an electron beam is observed in an arc discharge or in the plasma, created by an arc discharge. An explosive emission [5] has a common nature with an arc discharge. Namely, the explosive emission is considered as the first stage of the arc ignition. However, there is known the mode of a magnetron discharge without sputtering and arc spots [6], with high current and high current density. Recently a positive current pulse to the collector was observed in a similar discharge [7]. The discharge was ignited at low pressure and had similar features which were observed in the Plyutto experiments [1-3]. Thus, the positive current pulse can be associated with accelerated ions.

PROPOSED MECHANISM OF ION ACCELERATION BY AN ELECTRON BEAM

Here a qualitative approach is considered in the framework of a one-dimensional model without collisions. A high-current electron beam generates intense oscillations when it is injected into plasma. Such oscillations were also observed under the assumed acceleration of ions [7] and in a reliable case of ion acceleration by a relativistic electron beam [8]. These are high-frequency oscillations of plasma electrons. The beam donating energy to plasma electrons slows down. Because the joint momentum is conserved, the plasma electrons have to be accelerated. Due to the initial neutrality of the beam-plasma system, an electron depleted region is formed behind the beam front. When the electron beam is slowing down, the current limit decreases. As a result, a virtual cathode is formed at the beam front. An additional contribution to the creation of a virtual cathode can be made by plasma electrons accelerated by the beam. Ions from the electron-depleted region repel each other. The ions are drawn into the potential well of the virtual cathode. The edge of the potential well, the opposite of the motion of the electron beam, begins to neutralize and move in the direction of the beam. The ions will continue to accelerate until the ion bunch reaches the collector. It should be noted that the proposed mechanism corresponds to the latest experimental data on the acceleration of ions by a relativistic electron beam [8]. To implement the proposed scheme, the plasma density should be limited both from above and below. The most natural upper limit is the restriction of the model, which does not take into account collisions and is not applicable at high plasma densities. On the other hand, if the ions become too many, a heavy ion bunch will have a low acceleration rate. Such a situation is not beneficial for achieving high energy ions. This does limit the plasma density from above. The lower limit for the plasma density is associated with a small number of ions trapped by the virtual cathode, what reduces the current of accelerated ions. In addition, this can reduce the speed of the virtual cathode. Thus, the acceleration rate will also decrease. The upper limit of the ion energy will be corresponding to ion velocity that is equal to an electron beam velocity. It may be assumed that the optimum density of the plasma will be close to the beam density. At least this will be true in a logarithmic scale. It corresponds to results of computer simulation [9]. Such low density is quite difficult to maintain constantly in experiments. Apparently this is the reason for the poor repeatability of a number of experiments on ion acceleration. The proposed qualitative model makes it possible to explain some other features of the acceleration process. In particular, it explains the directly proportional dependence of the ion energy on its mass.

CONCLUSIONS

The acceleration of ions is a direct consequence of the injection of a high-current electron beam into the plasma at a high rate of rise of the beam current. The upper limit of the ion energy in such a model is apparently related to the velocity of the electron beam in such a way that the ion velocity cannot exceed the velocity of the beam electrons. It can be assumed that the optimum plasma density will be close to the beam density. This low density was difficult to sustain stably in experiments based on sources of electrons with explosive emission (includes arc with cathode spots). However, a positive pulse at the collector of the electron beam is observed [7], when electron emission was not associated with the formation of cathode spots. The pulse arises when an electron beam is introduced from a cold cathode magnetron gun. The presence of the positive pulse indicates the possibility of accelerated ions to the collector. This positive current to the collector [7] is almost two orders of magnitude greater than the current of accelerated ions in the Plyutto experiments, with similar parameters of the electron beam [3]. The excellent repeatability of the process and the suppression of cathode erosion indicate a high-current emission, without formation of cathode spots. If assumption of ion acceleration is confirmed, collective accelerators of heavy particles based on a magnetron gun can be an effective tool for science and technology.

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КАЧЕСТВЕННЫЙ ПОДХОД ДЛЯ ОБЪЯСНЕНИЯ МЕХАНИЗМА УСКОРЕНИЯ ИОНОВ ЭЛЕКТРОННЫМ ПУЧКОМ В ПЛАЗМЕ

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Известно ускорение ионов в вакуумном разряде, сопровождаемое образованием электронного пучка. В последнее время этот эффект, вероятно, наблюдался в связи с сильноточным нераспыляющим магнетронным разрядом. Здесь рассматриваются качественные соображения в рамках одномерной модели без учета столкновений. Сильноточный электронный пучок, вводимый в плазму, генерирует мощные колебания. С потерей энергии на возбуждение колебаний и в процессе увеличения тока электронного пучка возникает виртуальный катод. Ионы захватываются виртуальным катодом и ускоряются в направлении электронного коллектора.

ЯКІСНИЙ ПІДХІД ДЛЯ ПОЯСНЕННЯ МЕХАНІЗМУ ПРИСКОРЕННЯ ИОНІВ ЕЛЕКТРОННИМ ПУЧКОМ У ПЛАЗМІ

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Відомо прискорення іонів у вакуумному розряді, що супроводжується утворенням електронного пучка. Останнім часом цей ефект, ймовірно, спостерігався у зв'язку з потужнострумовим нерозпилюючим магнетронним розрядом. Тут розглядаються якісні міркування в рамках одновимірної моделі без урахування зіткнень. Потужнострумовий електронний пучок, що вводиться в плазму, генерує потужні коливання. З втратою енергії на збудження коливань і в процесі збільшення струму електронного пучка виникає віртуальний катод. Іони захоплюються віртуальним катодом і прискорюються в напрямку електронного колектора.