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Detection of tokamak plasma positrons using annihilation photons

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HIGHLIGHTS

- A design for detection of tokamak plasma positrons is given.
- Identify the main obstacle toward experimental confirmation of fusion plasma positrons.
- Signal to noise ratio in a plasma disruption is estimated.
- Unique potential applications of fusion plasma positrons are discussed.

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ABSTRACT

A massive amount of positrons (plasma positrons), produced by the collision between runaway electrons and nuclei during fusion plasma disruption, was first predicted theoretically in 2003. To help confirm this prediction, we report here the design of an experimental system to detect tokamak plasma positrons. Because a substantial amount of positrons (material positrons) are produced when runaway electrons impact plasma-facing materials, we proposed maximizing the ratio of plasma to material positrons by inserting a thin carbon target at the plasma edge as a plasma positron bombing target and producing a plasma disruption scenario triggered by massive gas injection. Meanwhile, the coincidence detection of positron annihilation photons was used to filter out the noise of annihilation photons from locations other than the carbon target and that of bremsstrahlung photons near 511 keV. According to our simulation, the overall signal-to-noise ratio should be more than 10:1.

1. Introduction

Fusion plasma positrons have received growing attention because of their potential for use as positron sources and in plasma diagnostics. However, there has been no suitable method to experimentally prove the existence of fusion plasma positrons. Two ways detect plasma positrons have been proposed: using annihilation signals [1] and synchrotron radiation [2]. Fusion plasma positrons are produced by runaway electrons of several megaelectronvolts colliding with nuclei inside the plasma, but the runaway electrons also create a larger amount of material positrons outside the plasma when impacting plasma-facing materials. Thus, because we are only interested in plasma positrons, which are buried by the abundant material positrons, direct detection of annihilation photons is meaningless. Besides the noise of material positrons, annihilation signals also tend to be overwhelmed by the strong background of bremsstrahlung photons near 511 keV. Like runaway electrons, fusion plasma positrons also emit synchrotron radiation from positron peaks in the toroidal direction opposite to that from runaway electrons. However, the synchrotron radiation is very weak and tends to be overwhelmed by the strong background of visible or infrared photons during a plasma disruption. This partly explains why fusion plasma positrons have not been experimentally proved through synchrotron radiation measurements despite the fact that almost all experimental tokamaks are equipped with synchrotron cameras looking at both toroidal directions. There are also high-energy particle diagnostic approaches based on the orbit of the particle, such as using a Cherenkov probe [3] or fast ion probe [4]. However, because these probes often use a scintillator or other medium that tends to be affected by gamma background through pair production or the photoelectric effect, it seems inevitable that the signals of plasma positrons would be overwhelmed by the gamma radiation from the runaway electrons impacting the probe.

In this paper, we design an experiment to confirm fusion plasma positrons by detecting annihilation photons. To minimize the noise of material positrons, a bombing target made of carbon is designed

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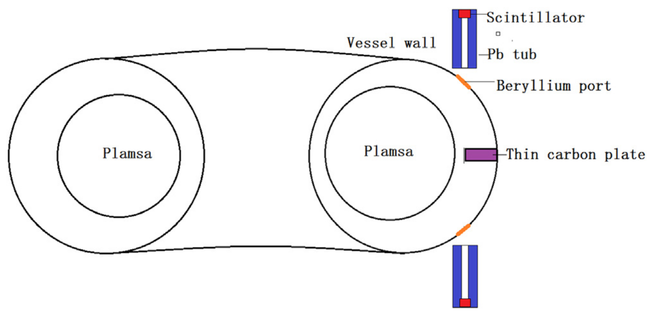

Fig. 1. Experimental design consisting of a thin carbon plate inserted at the plasma edge where plasma positron annihilation occurs, two beryllium ports to prevent the scattering of annihilation photons, and two scintillators with collimators to detect coincident annihilation photons.

to be inserted at the plasma edge, and a plasma disruption triggered by massive gas injection is proposed. A coincidence detection system is used to filter out background photons near 511 keV.

2. Description of the experimental design

A massive amount of positrons has been theoretically predicted to exist in tokamak plasmas [2]. These positrons are produced by a multitude of runaway electrons (runaway current), which have been accelerated to energies of tens of megaelectronvolts in the tokamak environment, colliding with ions and impurities. Most positrons drift out of the plasma after being generated and eventually impact the plasma-facing materials [5]. After impact, each positron will be slowed down to several electronvolts before annihilating to produce two annihilation photons in opposite directions.

A thin carbon plate (Fig. 1) was inserted at the plasma edge as a bombing target for plasma positrons that drifted out of the plasma. However, a number of positrons produced by runaway electrons impacting the carbon plate also create annihilation photons. Because annihilation photons generated from positrons produced inside plasma (plasma positrons) and positrons produced by runaway electrons impacting the carbon target (material positrons) are identical in energy (511 keV), the ratio of material positrons to plasma positrons needs to be sufficiently small to ensure a clear signal. Carbon was used as the bombing target because of its low efficiency at creating material positrons. As shown in Fig. 2, when impacted by a runaway electron of 20 or 40 MeV, numerous material positrons are generated in the case of a tungsten target but not for a carbon target. The carbon plate, although thin, is able to block most incoming plasma positrons. Because the energy of most plasma positrons is less than 5 MeV [1], the penetration depth of plasma positrons into the carbon plate is less than 5 mm. We also propose that a plasma disruption scenario triggered by massive gas injection should maximize the ratio of plasma positrons to material positrons.

Even if the ratio of plasma positrons to material positrons annihilated at the carbon target is sufficiently large, it is inevitable that the detector would receive annihilation photons from locations other than the carbon plate or the overwhelming background bremsstrahlung photons. To overcome this obstacle, a system based on coincidence detection of positron annihilation photons is used, as shown schematically in Fig. 1. When a single positron from the plasma annihilates at the carbon plate, two 511-keV photons are simultaneously emitted in opposite directions from the plate. Because of the constant value of light speed and the identical distances from the carbon plate to each of the two detectors, if one annihilation photon arrives at one of the two detectors, the other photon definitely reaches the other detector simultaneously. Therefore, annihilation photons originating from locations other than the carbon target and bremsstrahlung photons near 511 keV can be filtered out because of the high time resolution of the system.

2.1. Ratio of plasma positrons to material positrons

Plasma positrons are created in plasma through a trident process [6]:

$$e^- + Z \rightarrow e^+ + 2e^- + Z, \tag{1}$$

where e^- is a runaway electron and Z is the charge of the nucleus in the plasma. A fit for the cross section for this process over the entire energy range is:

$$\sigma_{tot} = aZ^2 ln^3\left(\frac{\gamma_e + x_0}{3 + x_0}\right), \tag{2}$$

where a = 5.22 μb ($1b = 10^{-28} m^2$), x_0 = 3.6, and γ_e is the Lorentz factor of a runaway electron. Thus, the number of plasma positrons created per runaway electron in one second is estimated to be:

$$P_p = \sigma_{tot} c n_z, \tag{3}$$

where P_p is the positron production rate (/s), c is the speed of light, and n_z is the nucleus density.

Fig. 3 gives P_p with respect to γ_e when the hydrogen n_z is $5 \times 10^{19}/m^3$.

Material positrons are created when runaway electrons impact plasma-facing materials predominantly through the bremsstrahlung–nucleus reaction [7]:

$$\gamma + Z \rightarrow e^+ + e^- + Z \tag{4}$$

The number of material positrons in the carbon target is computed in two steps:

1) Calculate the overall energy distribution of bremsstrahlung photons above 1.1 MeV from one runaway electron of different energies impacting the target using the Monte Carlo N-particle transport (MCNP) code.
2) Obtain the number of material positrons produced by one runaway electron of different energies impacting the target by calculating the bremsstrahlung–nucleus reaction rate according to the energy distribution of bremsstrahlung photons and the corresponding cross section for positron production:

$$P_m = \int_{1.1MeV}^{Er} f(E)\sigma(E) nl. \tag{5}$$

Here, P_m is the number of material positrons produced by a single runaway electron; E is the energy of the bremsstrahlung photon; $f(E)$ is the energy distribution of bremsstrahlung photons; $\sigma(E)$ is the cross section for the bremsstrahlung–nucleus reaction; n is the target density (atoms/m^3); l is the target length (5 mm); 1.1 MeV is the threshold energy for the bremsstrahlung–nucleus reaction; Er is the energy of the impacting runaway electron.

In fact, because most bremsstrahlung photons are not created at the impacting surface of the target, P_m overestimates the production of material positrons.

Fig. 4(a) and (b) shows the analytical cross section for the bremsstrahlung–nucleus reaction [8] and the number of material positrons created by one runaway electron at different energies impacting the target, respectively.

To estimate the signal of plasma positrons and the noise of material positrons annihilating on the thin carbon target, we consider the ratio between the fluxes of the two kinds of positrons on the carbon target:

$$F_p = P_p, \tag{6}$$