ON THE USE OF POSITRONS TO PROBE MAGNETIC VERSUS ELECTROSTATIC TURBULENCE

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On the use of positrons to probe magnetic versus electrostatic turbulence

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Kwon, et al. have shown that runaway electron (positron) diffusion is produced by magnetic turbulence and unaffected by electrostatic turbulence. By measuring the diffusion coefficient of positrons at runaway energies (0.1–2 MeV) as a function of radius for two discrete positron energies, the radial correlation length W of the turbulence can be extracted. Then if the thermal electrons are in the weak turbulence regime, the thermal electron diffusion coefficient from magnetic fluctuations alone can be calculated and compared to values from other techniques. We propose to inject charged energetic positrons (100–2000 keV) in few msec bursts from radioactive sources by means of their curvature drift when trapped in toroidal field ripples. The energetic positrons will diffuse over 60–600 msec time scales. At any time the radial profile of the positrons can be sampled by injecting a small solid pellet. A fraction of all the positrons on a flux surface will annihilate in the pellet as it passes that flux surface. The time dependent 0.511 MeV γ -ray signal then can be unfolded into the positron radial profile and the positron diffusion coefficient determined from the time evolution of those profiles.

INTRODUCTION

Recently new vigor has been put into the search for the cause of anomalous cross-field transport in magnetically confined plasmas. A very basic question that remains is whether the transport arises from primarily magnetic or electrostatic fluctuations. What might be called circumstantial evidence¹ at present favors the electrostatic turbulence hypothesis. The direct resolution of this issue is significantly hampered by the difficulty of making fluctuation measurements in the plasma interior. Nevertheless a number of techniques, *e.g.*, FIR scattering and beam emission spectroscopy for $\tilde{n}$ and the heavy ion beam probe for $\tilde{\phi}$, have been developed to pursue the electrostatic turbulence hypothesis. No corresponding approaches to detecting interior magnetic fluctuations at the required level of $\tilde{B}/B \sim 10^{-4}$ in large hot plasmas are now available. Hence the pursuit of the magnetic turbulence hypothesis suffers from a lack of direct evidence and must rely on secondary methods.

Among these secondary methods, the radial transport of runaway electrons is a sensitive probe of magnetic turbulence. If we assume that the same turbulence (either magnetic or electrostatic) produces both the transport of thermal and runaway electrons ($E_R \sim 100 E_{TH}$), then the diffusion coefficient for runaway χ_R will be 1–10 times the bulk plasma χ_{TH} for magnetic turbulence but 1/100 to 1/10 χ_{TH} for electrostatic turbulence. Hence the diffusion of runaways can be used to magnify the difference between electrostatic and magnetic turbulence. Although we can be sure that the measured runaway diffusion, however large it is, is caused by magnetic turbulence, we must also show those levels of fluctuations are sufficient to account for the thermal transport. Kwon, Diamond et al.² have developed the theoretical

formalism necessary to relate runaway transport to thermal transport in their study of runaway transport in ASDEX.

Herein, we propose to improve on that study by using runaway positrons instead of electrons. Since the positrons come from a radioactive source, their energy spectrum and space and time of origin in the plasma can be known much better than for runaway electrons. We also propose to find out at any later time the radial distribution of the positrons by means of their characteristic 2 γ (0.511 MeV each) annihilation in an injected solid pellet. If we are allowed a bit of analogy, studies of fluid turbulence have profited immensely from the use of different colors of fluids which, when mixed, react chemically to form a third color. Positrons represent “colored electrons” and they can be made to “light up” with annihilation radiation in a pellet. Runaway electrons, in contrast are hard to pick out from the larger population of thermal electrons. The idea of using positrons as test particles for studying transport is not new.^{3,4} The use of runaway positrons is a new suggestion.

I. THEORY

We follow the development of Kwon and Diamond.² The diffusion of thermal electrons in magnetic turbulence is given by

$$\chi_{e\text{ TH}} = |v_{\parallel}|_{\text{TH}} b_0 W \quad \text{strong turbulence} \quad (1)$$

$$\chi_{e\text{ TH}} = \frac{\pi |v_{\parallel}|_{\text{TH}} L_s b_0^2}{\bar{k}_\theta \bar{W}_{mI}} \quad \text{weak turbulence} \quad (2)$$

where b_0 is the RMS fluctuation amplitude, $L_s = R q / \tilde{s}$ is the shear length ($\tilde{s} = r q' / q$), $\bar{k}_\theta$ is the average poloidal wavenumber of the turbulence, and $W \sim \bar{W}_{mI}$ is the radial correlation length of the turbulence. The diffusion of runaways is similar to the weak turbulence case except for an additional radial structure function S which reduces the χ owing to the increasing decorrelation of the turbulence and the electron's motion as the excursion of the drift orbit from flux surfaces increases.

For example S might be Gaussian.

$$\chi_{eR} = \frac{\pi (v_{\parallel})_R L_s b_0^2}{\bar{k}_\theta \bar{W}_{mI}} e^{-[L_s v_{DR} / (W v_{\parallel R})]^2} \quad (3)$$

$$v_{DR} = \frac{1}{\Omega_{eR}} \left(v_{\parallel}^2 + \frac{1}{2} v_{\perp}^2 \right) \quad (4)$$

Comparing Eq. (3) to (3), we see that $\chi_{eR} \simeq (1 - 10) \chi_{eTH}$, depending on S . On the other hand, for electrostatic turbulence, $\chi_{eR} / \chi_{eTH} \simeq (v_{\parallel TH} / v_{\parallel R}) S \simeq 1/10$ to $1/100$. If we can measure χ_{eR} for different known runaway energies, we can calculate W from

$$\frac{\chi_{eR}(E_1)}{\chi_{eR}(E_2)} = \frac{v_{\parallel R}(1)}{v_{\parallel R}(2)} e^{-\frac{L_s^2}{W^2} \left\{ \left[\frac{v_{DR}(1)}{v_{\parallel R}} \right]^2 - \left[\frac{v_{DR}(2)}{v_{\parallel R}} \right]^2 \right\}} \quad (5)$$

Knowing W , if we can assume the thermal electrons are in the weak turbulence regime, we can calculate

$$\chi_{e, \text{TH}} = \frac{v_{\parallel \text{TH}}}{v_{\parallel \text{R}}} \chi_{e \text{R}} e^{\left(\frac{L_s}{W} \frac{v_{\text{DR}}}{v_{\parallel \text{R}}} \right)^2} \quad (6)$$

If $\chi_{e, \text{TH}}$ so calculated agrees with power balance results, we will have shown that the thermal transport is accounted for by magnetic turbulence. If the thermal electrons are in the strong turbulence regime then

$$\chi_{e, \text{TH}} = \frac{\chi_{e \text{R}} v_{\parallel \text{TH}} \bar{k}_{\theta} W W_{m \text{I}}}{v_{\parallel \text{R}} \pi L_s b_0} e^{\left(\frac{L_s}{W} \frac{v_{\text{DR}}}{v_{\parallel \text{R}}} \right)^2} \quad (7)$$

In this case, information on $\bar{k}_{\theta}$ and b_0 from other diagnostics and/or parameter scans for $\chi_{e \text{R}}$ (B, I, n , etc.) would be needed to close the problem.

III. EXPERIMENTAL CONSIDERATIONS

A. Introduction of the positrons

Neutral positronium beams for getting positrons into plasma are being developed.³ However, these beams will be of low energy. We have examined ways to get energetic charged positrons into the plasma directly.

Positron sources are available commercially. The sources below have a typical β decay spectrum, a roughly symmetric peak about an average energy and with an upper endpoint energy.

<u>Nuclide</u>	<u>Half-Life</u>	<u>End Point Energy</u>	<u>Average Energy</u>
^{22}Na	2.6 years	545 keV	216 keV
$^{68}\text{Ge}/^{68}\text{Ga}$	288 days	1890 keV	835 keV
^{58}Co	71 days	475 keV	201 keV

To obtain the two different energies needed to measure W [Eq. (5)], both a ^{68}Ge source and a ^{58}Co source would be required.

It appears feasible to use ripple injection to get energetic positrons into the plasma. Ripple injection was proposed by Jassby and Goldston⁵ as a way of extending neutral beam penetration. The idea is that particles trapped in toroidal field ripples at the bottom of the tokamak move approximately straight up at the curvature drift speed $\sim 5 \times 10^4$ m/s for 200 keV positrons in DIII-D at 2 T. The principle was tested with a favorable result in ISX-B.⁶ In that experiment, central fast particle neutral

fluxes were increased 3–10 times by the ripple coils. The ripple fields had a negligible effect on passing fast ions and thermal ions but a large depletion of perpendicular fast ions.

Schematically, a picture frame coil located just outside the TF coils would be used to produce toroidal ripple characterized by $\delta(R, Z) = \Delta B_T / B_T$. Positrons with $v_{\parallel}/v < \delta^{1/2}$ will be trapped in the ripples and will curvature drift up into the plasma. If the positron source strength is S into 4π steradians, then $(\pi \delta^{1/2} / 4\pi) S$ positrons released from a source positioned between TF coil return legs will drift upward. For a 1C source and $\delta = 1\%$, 7.5×10^5 positrons per millisecond will drift up into the plasma.

Since δ decreases as the positrons move up, positrons on the edge of the trapping region $v_{\parallel}/v = \delta^{1/2}(R, Z)$ will become de-trapped. Neglecting pitch angle scattering, a fraction $\delta^{1/2}(R_0, Z=0)/\delta_{\text{coil}}^{1/2}$ of the initially ripple trapped positrons will remain trapped at the magnetic axis. This fraction can be made small by appropriate ripple coil design.

Scattering also de-traps the particles. The slowing down and pitch angle scattering times are about equal for these energetic positrons (Fig. 1). The time to scatter across the trapping boundary will be $\sim [\delta^{1/2}(R, Z) - v_{\parallel}/v] \tau_{90^\circ} \simeq 50\text{--}1000 \mu\text{s}$, a time somewhat longer than the $\sim 40 \mu\text{s}$ drift time to the plasma center. Hence some, but not excessive collisional de-trapping will occur.

The positrons can be put into the plasma in a 5 ms burst by means of a shutter on the source or preferably just pulsing the ripple coil on for only 5 ms. This latter approach has the advantage of removing the B_T ripple from the time in which we

Fig. 1. Slowing down time τ_s and runaway electric field versus positron kinetic energy in a plasma with $n_e = 5 \times 10^{19} \text{ m}^{-3}$.

wish to see the positrons diffuse and also un-trapping all those positrons still drifting up at the time the magnet is switched off.

IV. POSITRON PLASMA INTERACTIONS

Of course the point of injecting the positrons is to see them diffuse. Surko et al.³ modeled the diffusion of positrons assuming a diffusion coefficient D of $0.5 \text{ m}^2/\text{s}$ and

found characteristic times ~ 30 ms for significant changes in the profiles. We would estimate $\chi_{E,R} \sim 1\text{--}10$ m²/s. However, we wish to consider things in terms of particle transport. For magnetic turbulence $D \sim \sqrt{m_e/m_i} \chi \sim 0.025\text{--}0.25$ m²/s and so we expect the diffusion time scales to be 60–600 ms, much longer than the slowing down time.

The positrons “born” into the plasma by de-trapping from the B_T ripple will still be banana trapped particles. Since the banana widths are small (0.8 cm for B_p = 1 T, P_⊥ = 2 MeV/c) it is still of interest to look at the diffusion of these banana trapped positrons. In fact the use of positrons may have some unique advantages in studying trapped particle dynamics. Based on the ISX-B result and the work in Ref. 5, we expect the ripple field to have a deleterious effect on the confinement of the banana trapped positrons. Monte-Carlo guiding center orbit calculations should be done to assess this effect, but are beyond the scope of this survey treatment of runaway positron diffusion studies.

After one τ_s , a substantial fraction of the positrons will have scattered across the banana trapping boundary $v_{\parallel}/v \sim (r/R)^{1/2}$ onto passing orbits. They will also have lost energy. By applying a short high loop voltage, we can accelerate these positrons back to high energies. The toroidal electric field at which positron energy gain equals coulomb drag loss is given in Fig. 1. At 10 V/m, a 100 keV positron will gain 164 keV/ms. By this means we can recover a high energy population of passing particles to observe.

For completeness, we mention some other positron plasma interactions. Recently radial electric fields on the plasma edge of 200 V/cm have been found in H-mode. The $\vec{E} \times \vec{B}$ drift speed in such a field is 10^4 m/s, large enough that positron dynamics in the edge might be of some use in studying H-mode physics. The mean time (non-relativistic) for direct free-free $e^+ e^-$ annihilation is $1/(n_e \pi r_0^2 c)$ (Ref. 7) where r_0 is the classical radius of the electron and is too long (2.6 seconds at $n_{e-} = 5 \times 10^{19} \text{ m}^{-3}$) to be of interest except possibly in very high density devices (CIT, C-MOD, ZTH). The other annihilation process is through the formation of positronium, which is very unlikely for energetic positrons in the plasma interior.⁸

V. DETECTION OF THE POSITRONS

In a solid pellet, the annihilation time is less than $1 \mu\text{s}$. The range of a 1 MeV positron in graphite is ~ 1 mm, so a solid pellet injected across the flux surface will cause the immediate annihilation of the positrons which strike it. Consider a carbon pellet of diameter $d = 2$ mm and a speed of $V_p = 500$ m/s. We can estimate the fraction of the positrons on a flux surface that will strike the pellet as

$$f = \left(v_{\text{pos}} \frac{d}{V_p} \right) / \left(\frac{4 \pi^2 R r \kappa}{d} \right) \simeq 18\%$$

for typical positrons and $R \sim 1$ m, $r \sim 0.2$ m, $\kappa = 1$ parameters. The annihilation γ 's could be detected by NaI crystals viewing the pellet flight path. The time dependence of the count rate will give the positron radial distribution via the known pellet speed.

We can estimate a count rate for a $10\text{ cm} \times 10\text{ cm}$ detector close to the pellet path with a solid angle of $\sim 100\text{ cm}^2 / (4\pi \cdot 10,000\text{ cm}^2) \simeq 10^{-3}$. From the 1C source we estimated $\sim 4 \times 10^6$ positrons ripple injected in 5 ms. We estimate 2/3 would be lost through thermalization and orbit loss. The remainder diffuse to fill the volume of the torus but the pellet recollects $\sim 18\%$ of them. Hence $\sim 2.4 \times 10^5$ annihilation events would occur and, assuming a detector efficiency of 85%, we would detect ~ 200 of them during the 2 ms flight time of the pellet for an instantaneous count rate of 120 kHz. These rates are in the range to make interesting measurements. Of course, the time dependence of the annihilation γ signal from the limiter³ will also be of interest.

VI. CONCLUSION

The study of the diffusion of energetic positrons may enable a discrimination between magnetic and electrostatic turbulence as the cause of anomalous transport in the plasma interior. The connection between runaway positron transport is simple in the weak turbulence regime but requires supplemental information $\bar{k}_\theta$, b_0 , if the thermal electrons are in the strong turbulence regime. Energetic positrons might be put into the plasma by ripple injection. One of the advantages of positrons for these studies, their known initial energy spectrum, will be compromised by the slowing down and pitch angle scattering times being less than expected diffusion times. The energy spectrum of positrons in the plasma may be manipulated by means of short increases in the toroidal electric field. The radial profile of the positrons can be measured at any time after injection by the time dependence of the $e^+ - e^-$ annihilation γ signal

from an injected solid pellet. Estimated count rates appear to be in a useful range. This brief survey of the possible study of magnetic turbulence by means of energetic positrons is encouraging. Many detailed calculations remain but are possible since the physical processes described herein depend mainly on classical scattering and orbit effects.

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