HIGH-ENERGY RUNAWAY-ELECTRON TRANSPORT DEDUCED FROM
PHOTONUCLEAR ACTIVATION OF THE PLT LIMITER

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In large tokamaks, runaway electrons may be accelerated up to energies over 20 MeV by the toroidal electric field. When these particles leave the plasma, they impact the material limiters and emit bremsstrahlung hard X-rays. This bremsstrahlung may cause photonuclear reactions in the limiter, leaving radioisotopes behind. Both the amount of activation and its spatial distribution on the limiter provide information on the confinement of high energy electrons. We have analyzed the stainless steel poloidal ring limiter from the Princeton Large Torus and have found six observable photonuclear reactions with energy thresholds for the reactions varying from 8 to 23 MeV. The amount of activation from each reaction determines the average number of runaway electrons above each activation threshold energy. The inferred runaway electron population decreases exponentially with energy as $\exp(-E/3.2 \text{ MeV})$ implying an energetic runaway electron confinement time of 50-80 msec. The poloidal variation of the activation can be described by a 0.02 cm scrape-off layer step size which implies about a 90 msec confinement time.

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This steel ring limiter was used on PLT for about 2 years prior to its removal in August 1980. Before its use, the PLT limiter had been tungsten on which runaway electron-induced activation was also observed [1]. The aim of that earlier PLT work, as well as TFR limiter activation work [2] and PDX limiter activation studies [3], was to understand the photoneutron production that was a "noise" problem for $d(d,n)$ fusion neutron diagnostics. The purpose of this work and recent TFR activation work [4] is to characterize the loss processes of the energetic runaway electrons causing the activation. In this regard, the PLT steel activation has the advantage of several observable photo-reactions with threshold energies spread between 8 and 23 MeV allowing a quantitative determination of the runaway electron population in this energy range. By contrast, the observed PDX $Ti(\gamma,p)$ activities all had thresholds of about 11 MeV and the observed PLT $W(\gamma,n)$ activities all had thresholds of about 7 MeV. The TFR measurements [4] of the depth of activation in a stainless steel ring limiter were explained by a runaway electron scrape-off thickness of $\approx 4 \times 10^{-2}$ cm. Their published data also shows a poloidal variation of the activation with a HWHM of 2.0 cm or 5.7° , an angle similar to that seen on PLT. Using a 100 kA plasma current to calculate the drift orbit displacement for the 8.2 MeV electrons causing the activation, this angle would imply a scrape-off layer of 4.2×10^{-2} cm, which is a value that agrees reasonably with the PLT values reported here.

The PLT ring limiter was made of type 305 stainless steel, with a radius of curvature of $a = 45$ cm, and was located on the outside in major radius extending poloidally about 120° (Fig. 1). The plasma minor radius was typically 40 cm as determined by the top and bottom carbon rail limiters. Runaway electrons of sufficiently high energy to have an outward drift orbit displacement, d_y , of more than a few centimeters could reach the outside limiter without first striking the rail limiters. The steel ring limiter consisted of 2 sets of 3.5 cm wide segments separated by 3 cm (Fig. 2). For the six months prior to the limiter removal, PLT discharges had typically low runaway electron levels. The final three run weeks featured modest runaway electron levels during low density, high powered ICRF heating. These discharges were typical of those for the prior year on PLT with major radius $R = 135$ cm, B_ϕ of 24 to 32 kG, I_ϕ of 350 to 450 kA (averaging about 430 kA), V_ϕ of 1.0 to 1.8 V in steady state, and line averaged densities $\bar{n}_e$ of 1 to $4 \times 10^{13} \text{ cm}^{-3}$.

The γ -radioactivity of the steel limiter was measured several times with a GeLi detector, beginning about 1 week after the last PLT discharge. We have identified six radioisotopes (Table I). Correcting the decay rate to the time of the final PLT discharge, dividing by the efficiencies of the detector and of the gamma emission process, and normalizing for the abundance of each element and isotope, the number of activated atoms in the central segment of the limiter can be estimated (Table I). The difference in activation extends over

4 orders of magnitude, with a consistent decrease in the observed activation at the higher energies. In part, this is due to a consistent decrease in the cross-sections and half-lives for the higher energy reactions; however, there is also a considerable (factor of 10^2) reduction in the number of higher energy runaway electrons.

The amount of activation is proportional to the number of electrons striking the limiter times the yield per electron which depends upon the cross-section. The yield is obtained by computing an average cross-section for each reaction by weighting the yield of photo-reactions per electron [5] by the electron energy distribution obtained from the analysis and proceeding in an iterative manner. Making the simple assumption that on average all PLT shots for the previous eight months contributed equally to the creation of the radionuclides, and weighting the shot history by the decay half-lives of the activation, we calculated the number of electrons above each reaction's threshold energy needed per shot to create the observed activation. This can then be expressed as an average runaway electron density in the plasma volume for each discharge (Fig. 3). Despite the increase in the cross-section with energy, most of the activation from each reaction tends to originate from electrons just above threshold since the runaway electron population decreases strongly with energy.

The runaway electron spectrum has a best fit slope of $(3.2 \text{ MeV})^{-1}$. This corresponds to a confinement time of 62 milliseconds; that is, the time required for acceleration to

3.2 MeV by a loop voltage of 1.4 volts. The data point from the ^{55}Mn activation is relatively uncertain since the abundance of manganese in type 305 stainless steel is small and undetermined (i.e., "less than 2%"). Other uncertainties, such as variations in the time history of activation or the depth of the activation region with energy, could change the density values by factors of 2. These systematic errors can change the estimate of the confinement time by plus 20 or minus 10 milliseconds with about 90% confidence. In equilibrium, the loss rate of runaway electrons, estimated by integration of the exponential spectrum in energy divided by the confinement time

$$\bar{n}_R(0) \times 3.2 \text{ MeV}/62 \text{ msec} \sim 5 \times 10^7 \text{ cm}^{-3} \text{ sec}^{-1}$$

should be balanced by the creation rate, whose value for PLT parameters varies from 10^3 - $10^{10} \text{ cm}^{-3} \text{ sec}^{-1}$ [6] since the toroidal electric field is ~1-5% of the critical electric field. Both the value of $\bar{n}_R(0)$ and the calculation of the runaway electron creation rate are uncertain by several orders of magnitude; however, the estimate for the loss rate of $\sim 10^7 \text{ cm}^{-3} \text{ sec}^{-1}$ is of a realistic magnitude.

In order to determine the poloidal distribution of the activation without the contribution of decays from neighboring angles, the limiter was cut into 2" segments and the activation measured for each piece. Analysis of the limiter segments on the ion side showed a shift in the central positions of the angular activation peaks from those on the electron side consistent

with the pitch of the magnetic field. The poloidal extent of the activation was several cm, with half-width half-maximum (HWHM) poloidal angles of 3-6°, which decreased systematically with higher runaway electron energy (Fig. 4). The activation along the limiter could be due in part to a varying up-down plasma position from shot to shot. However, the expected variation of the poloidal spread with energy due to the forward cone of the emission of the bremsstrahlung ($\theta_{1/2 \text{ brems}}$) is quite small (Fig. 4).

The magnitude of this poloidal angle also can be interpreted as a consequence of a scrape-off layer thickness, δ , allowing the runaway electrons to strike the limiter anywhere within the angle of intersection of their orbits and the limiter (Fig. 1). The experimental results are best fit by a $\delta \sim 0.021$ cm for the scrape-off length. The reduction of the poloidal angle with increased runaway electron energy arises from increased drift-orbit displacement of the higher energy runaway electrons (8 to 17 cm for 8 to 22 MeV electrons) which thus reduces the radius of the drift orbit in contact with the outside limiter. Taking this step size to be the radial step size for the electrons to transit around PLT and return near the limiter, then

$$\tau_R \approx \frac{a^2}{4} \frac{2\pi\bar{q}R/c}{\delta^2} = 90 \text{ msec} \quad \text{for } \bar{q} \approx 3.5.$$

We note that this number for δ is the lower limit for the radial extent of high frequency oscillations seen on the flux of runaway electrons striking the PLT limiter ($2+13 \times 10^{-2}$ cm in Ref. 7).

The value of the runaway electron confinement time inferred from the above limiter activation measurements ($\sim 50\text{--}90$ msec) is uncertain, primarily due to the approximately two year exposure time of the limiters and to the great variety of plasma conditions this entailed. In particular, the activation may occur primarily on low density, high impurity and, consequently, high runaway electron level discharges. Alternatively, the long confinement times might arise selectively from discharges where many of the other plasma parameters are also good and the overall plasma confinement (as well as the runaway electron confinement) is high. At any rate, the energetic runaway electron confinement (for energies > 8 MeV) is probably in the range of $2\text{--}10$ times the thermal electron energy confinement time. This is consistent with concepts about the confinement of collisionless particles being enhanced when the drift orbit displacement ($d_Y \sim 8\text{--}17$ cm) is large compared to the radial step size of the thermal electron transport [8].

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TABLE I. PHOTONUCLEAR REACTIONS PRODUCED IN PLT STAINLESS STEEL LIMITER

reaction	threshold energy (-Q) MeV	half-life secs	target abundance in limiter (isotopic $\times$ elemental)	cross-section (weighted by electron distribution) (mbarns)	activation inferred from midplane decay rate
$^{58}\text{Ni}(\gamma, p)^{57}\text{Co}$	8.17	2.37(7) (272d)	$0.678 \times 0.10 = 6.78\%$	3.51	2.69(12)
$^{61}\text{Ni}(\gamma, p)^{60}\text{Co}$	9.86	1.66(8) (1924d)	$0.0125 \times 0.10 = 0.125\%$	1.20	8.43(11)
$^{55}\text{Mn}(\gamma, n)^{54}\text{Mn}$	10.23	2.70(7) (312.6d)	$1.0 \times 0.01 = 1.0\%$	2.46	2.94(12)
$^{52}\text{Cr}(\gamma, n)^{51}\text{Cr}$	12.04	2.40(6) (27.72d)	$0.838 \times 0.19 = 15.9\%$	4.11	1.97(11)
$^{58}\text{Ni}(\gamma, pn)^{56}\text{Co}$	19.6	6.68(6) (77.3d)	$0.678 \times 0.10 = 6.78\%$	0.41	2.82(9)
$^{58}\text{Ni}(\gamma, 2n)^{56}\text{Ni}$	22.5	5.27(5) (6.10d)	$0.678 \times 0.10 = 6.78\%$	0.063	4.78(7)

FIGURE CAPTIONS

- Fig. 1. Schematic of PLT limiter configuration. Graph at right represents activation as a function of poloidal angle measured from the midplane. R - major radius; a - radius of curvature of ring limiter; d_v - drift orbit displacement; δ - scrape-off layer thickness; θ - poloidal angle defined by intersection of drift orbit and ring limiter; B_p - poloidal magnetic field; HWHM - half-width half-maximum.
- Fig. 2. Photograph of steel ring limiter construction.
- Fig. 3. Average runaway electron density as a function of energy. An exponential fit of the data yields a slope of $(3.2 \text{ MeV})^{-1}$ which corresponds to a confinement time $\tau_R \approx 62 \text{ msec}$ for a loop voltage $V_L \approx 1.4 \text{ volts}$. Extrapolation of the spectrum back to zero energy gives a density $\bar{n}_R(0) \approx 10^6 \text{ cm}^{-3}$.
- Fig. 4. Poloidal distribution of activation for (a) ^{54}Mn and (b) ^{56}Co . (c) HWHM as a function of the threshold energy of the reactions. The curves represent the poloidal variation expected for various scrape-off thicknesses, δ . Also shown is the poloidal spread due to the forward cone of the emission of the bremsstrahlung, $\theta_{1/2} \text{ hrem}\beta$.

Fig. 1

fig. 2

Fig. 3

FIG. 4