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Runaway electron damage to the Tore Supra Phase III outboard pump limiter [1]

R. Nygren [a,*], T. Lutz [a], D. Walsh [a], G. Martin [b], M. Chatelier [b], T. Loarer [b], D. Guilhem [b]

[a] *Sandia National Laboratories, Albuquerque, NM 87185, USA*
[b] *Centre de Cadarache, St. Paul-lez-Durance, F13108 Cedex, France*

Abstract

Operation of the Phase III outboard pump limiter (OPL) in Tore Supra in 1994 was terminated prematurely when runaway electrons generated during the current decay following a disruption pierced a leading edge tube on the electron side and caused a water leak. The location, about 20 mm outside the last closed flux surface during normal operation, and the infrared (IR) images of the limiter indicate that the runaways moved in large outward steps, i.e., tens of millimeters, in one toroidal revolution. For plasma (runaway) currents in the range of 150 to 250 kA, the drift orbits open to the outside. Basic trajectory computations suggest that such motion is possible under the conditions present for this experiment. Activation measurements made on sections of the tube to indicate the area of local damage are presented here. An understanding of this event may provide important guidance regarding potential damage from runaways in future tokamaks.

Keywords: Tore Supra; Limiter; Boundary plasma; Energy deposition; Disruptions

1. Introduction

The Phase III outboard pump limiter (OPL) is a mid-plane, water-cooled modular pump limiter with a radially adjustable position that was built by Sandia National Laboratories in collaboration with the staff at the Centre d'Etudes de Cadarache (CE) and operated in Tore Supra during portions of the 1993 and 1994 experimental campaigns [1-3]. This limiter and the inertially cooled Phase II OPL used before and after the Phase III OPL provided protection for (i.e., a radial location just inside of) the RF antennas and were used in experiments on power and particle handling.

The Phase III OPL head (Figs. 1 and 2) consists of copper tubes with brazed pyrolytic graphite tiles curved poloidally to fit the plasma and shaped toroidally to distribute heat across the limiter. An infrared (IR) camera and water calorimetry from 10 flow meters and 34 thermocouples on the OPL recorded evidence of the heat deposition during the runaway strike, and global diagnostics (X-rays, etc.) recorded the typical signature of a runaway electron event.

Plasma disruptions can generate runaway electrons that preserve a significant fraction of the original plasma current; activation and melting are typical results when these relatively high energy electrons strike plasma facing components. Such runaway events have been observed in many large tokamaks, the phenomenology has been described and models for the generation of runaways have been developed [4-7].

Runaway electron events are common in Tore Supra. Martin [8] has examined past shots in Tore Supra and found that disruptions during the ramp-up phase occur in

* Corresponding author. Tel.: +1-505 845 3135; fax: +1-505 845 3130; e-mail: renygre@sandia.gov.

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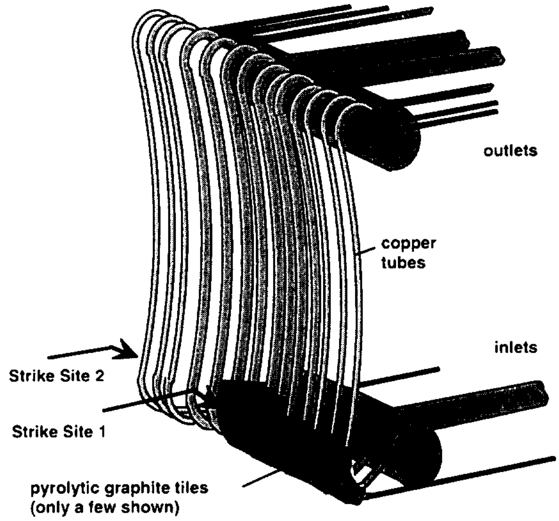

Fig. 1. Piping in Tore Supra Phase III Limiter head with locations of hot spots from runaway electron event. Most pyrolytic graphite armor tiles are not shown.

about 5% of all shots. Runaway electrons are always observed for disruptions with plasma currents above 0.7 MA (predisruption value). These runaways are accelerated to 20–40 MeV in 5–10 ms and produce a characteristic signature of photo-neutrons when they collide with the surrounding structures.

2. Observations of the runaway electron event

2.1. Plasma conditions and runaway electron signature

Damage to the Phase III OPL from runaway electrons occurred after preliminary experiments on heat deposition during ohmic shots had been completed, and experiments with small amounts of ion cyclotron (ICRF) power and lower hybrid (LH) power had commenced. The plasma was run on the inner wall, and the OPL was 20 mm from the last closed flux surface established by the inner wall; the ICRF antenna was 15 mm behind the OPL. ICRF shots were stopped due to problems in engaging the ICRF system, and shots were run with ~ 8 s flattops and LH power levels of 0.8, 1.0, 1.2 and 1.5 MW for 2 s.

Shot 14843 ended during the current ramp-up with a disruption at about 0.38 s. The LH power had accidentally started briefly during the ramp-up. It must be stressed that any ramp-up disruption whether due to bad wall conditioning or any other reason would have caused the same damage to the limiter. Of the 93 shots of this type observed on Tore-Supra, only a very few of them have been related to an early start of the LH power.

In this type of event, the poloidal field system is operated with zero voltage but finite current during the post-disruption period. The equilibrium field is provided only by a 'shell' effect from the coil structure. Then, after 0.2 s, the generators stop the coil currents and thus equilibrium, plasma current and runaway electrons are lost.

Fig. 3 shows selected signals recorded during shot 14843. The photo-neutron signal indicates the appearance of a strong runaway electron population in coincidence with the thermal disruption. The drop in magnetic flux at the time of the current quench suggests that the electrons were accelerated during this period. An estimated 20 MeV/Wb is gained by the electrons during this short phase (0.38–0.4 s). Steps in the final current decay from 0.62 to 0.75 s (after equilibrium was lost) that correlate with spikes in the neutron signal suggest that bursts of runaways are lost. These spikes also correlate with intense magneto-hydrodynamic (MHD) activity.

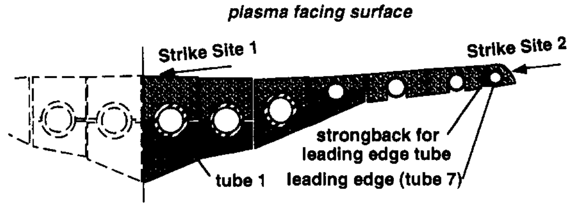

Fig. 2. Cross-section view of the electron side half of the Phase III OPL limiter head with approximate locations of runaway electron strikes indicated. The width of the half limiter shown is about 210 mm.

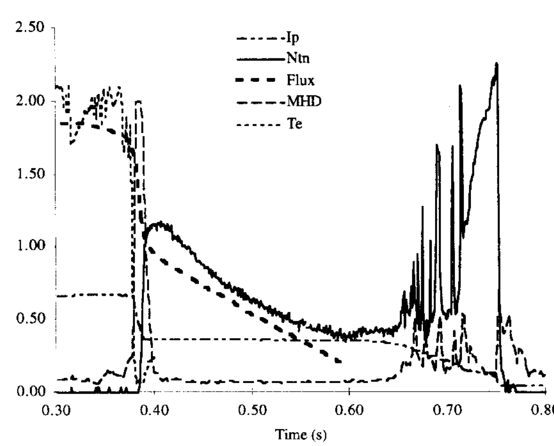

Fig. 3. Time evolution of the main plasma parameters: plasma current, photo-neutrons, magnetic flux, MHD activity (Mirnov loop).

2.2. IR camera observations

Infrared (IR) camera images showed a progression consistent with the above description of the disruption. At about 0.44 s, shortly after the onset of the disruption, some heating of the lower half of the electron side face of the limiter was evident, and the wall behind the limiter showed what was presumably the reflection of heat deposited elsewhere in the early period of the disruption. From 0.44 to 0.64 s the plasma current decayed from 360 and 280 kA.

At about 0.64 s, the first hot spot appeared on the OPL (upper photo in Fig. 4). Heat was deposited near the surfaces of a cluster of six graphite tiles (three high by two across) that span the peaked vertical centerline of the limiter ('Strike Site 1' in Fig. 2). Energetic electrons entering the electron side center tile would pass through it and continue with some scattering through the ion side center tile. The timing of this strike does not correspond with a neutron signal, but this is to be expected if the electrons passed through only 20–40 mm of graphite and encountered no heavy elements. (X-rays would be produced but the loss of energy would not necessarily be sufficient to produce neutrons from nuclear reactions in carbon.)

About 80 ms later (0.72 s), a hot spot appeared on the electron-side leading edge ('Strike Site 2' in Fig. 2 and lower photo in Fig. 4). The time coincides with a large spike in the neutron signal. The indicated surface temperature of the graphite armor (spot 3) in the figure is likely well below the peak temperature at the location in the underlying copper tube where most of the energy deposition occurred.

The two hot spots cooled somewhat but were still evident Is after the event. The leading edge tile cooled more quickly than the much thicker center tile. The persistence of these hot spots indicate significant volumetric heating of the graphite tiles (and the leading edge tube) rather than heating of a cracked graphite flake at the surface.

Table 1
Power to OPL measured by water calorimetry in shot 14843

Tube(s)	Electron side	Ion side	Total
Centertubes	11.0 kW	8.9 kW	19.9 kW
(1-3)	19%	15%	34%
Intermediate tubes			13.1 kW
(4-6)			23%
Leading edge	20.7 kW	4.2 kW	24.8 kW
(tube 7)	36%	7%	43%
	31.7 kW	13.1 kW	57.8 kW
	55%	22%	100%

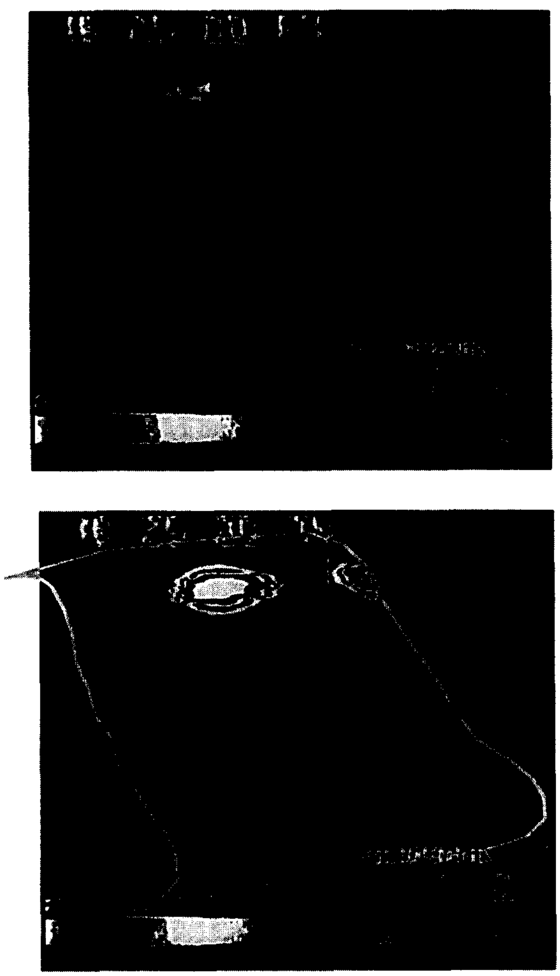

Fig. 4. Infrared photos of Phase III OPL with outline of limiter head in bottom photo. Oblique view is rotated 180 deg; bottom of limiter is at top of photo. Upper photo (0.64 s) shows first hot spot at the tangency point of the limiter near the bottom. Lower photo (0.72 s) shows second hot spot at leading edge.

2.3. Water calorimetry

The results in Table 1 from the water calorimetry for shot 14843 provide a gross estimate of the power deposition during this shot. The entire limiter received some heat during shot 14843 but the electron side leading edge tube and the center tubes 1–3 on each side (a single exhaust manifold serves each group of three center tubes) together received about 70% of the deposited power.

It is also apparent from the calorimetry obtained on the

Table 2
Preliminary activation measurements on electron side leading edge tube

Isotope	Activity (Bq) on 21 July 1994	Probable sources	Location
^{7}Be	0.325	^{12}C(X, nα)	graphite
^{51}Cr	46	^{52}Cr(X, n)	steel
^{54}Mn	1.840	^{55}Mn(X, n)/^{56}Fe(X, np)	steel
^{56}Co	0.480	^{58}Ni(X, 2n)/(X, np)	steel
^{57}Co	8.1	^{58}Ni(X, n)/(X, p)	steel
^{58}Co	0.590	^{60}Ni(X, np)/^{63}Cu(X, nα)	steel/copper
^{60}Co	0.0077	^{61}Ni(X, p)/^{65}Cu(X, nα)	copper
^{106}Ag	0.410	^{107}Ag(X, 2n)	copper

ion side leading edge tube and the intermediate tubes on each side (tubes 4–6) that the whole face of the limiter received some heating from the plasma.

Water flow in the electron-side leading edge tube increased briefly (possibly due to local water vaporization); this was followed by a slight drop in the flow. There was no change in flow rate in the ion-side leading edge tube.

2.4. Activation measurements

Radioactive species result from transmutations produced by X-rays generated as energetic runaway electrons collide with the structure. Reactions that release one or two neutrons (n or 2n), a neutron and a proton (np), a neutron or a proton (n or p), or a neutron and an alpha particle (nα) are possible. The measured activation of the limiter is associated with the runaway event on July 21, 1994 since no other disruptions had occurred with the limiter present.

Two types of measurement of the radioactivity of the leading edge tube were performed at CE on approximately 0.25 m cut from the lower end of the electron side leading edge tube using a high purity germanium (HPGe) detector. Results from a global assessment of activity are given in Table 2. The measurements were done about a year after the runaway event and the tabulated values are extrapolated back to the date of the event. There were 20 measurements with a lead collimator, 12 mm in diameter in a 10 mm thick foil, to show the activation profile along the tube. The main results were obtained with Co-57 the γ-rays of which are best collimated by lead (lowest energy).

At Sandia, the 0.25 m section of the leading edge tube was cut into smaller pieces (Fig. 5), and each of these was split along the axis of the tube. Activation measurements were performed with a liquid–nitrogen cooled HPGe detector; the active crystal is a coaxial element of HPGe 39.8 mm in diameter by 32.9 mm long located 5 mm inside an aluminum end cap. (This system has an energy resolution of ~ 3 keV FWHM for 1.33 MeV gamma rays.) The samples were placed in a lead enclosure (~ 6 inches thick) directly next to the Al end cap. Only the 'back' half of the tube, which contained the stainless steel strongback, produced activity significantly above background levels; as expected, Co-57 and Mn-54, representative of the activation of steel, were the dominant forms of activity. These results, together with the earlier measurements done by CE, are shown in Fig. 6. Both data sets have a broad peak and a maximum at about 210 mm below midplane.

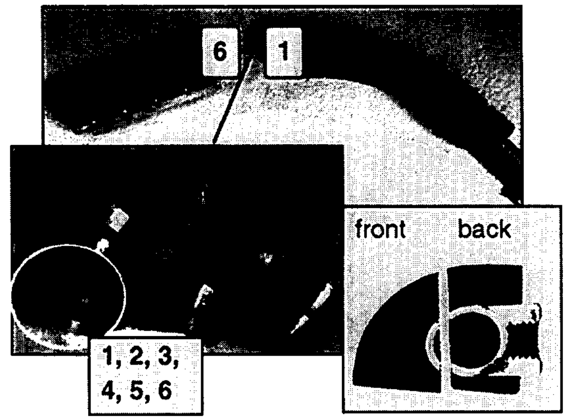

Fig. 5. Six segments cut from leading edge tube. Photo on lower right shows front/back longitudinal cut. Sample 4 is circled at lower left.

2.5. Physical damage

At the site of the first runaway electron strike (see Fig. 2) was a heat-affected region about two tiles wide (71 mm)

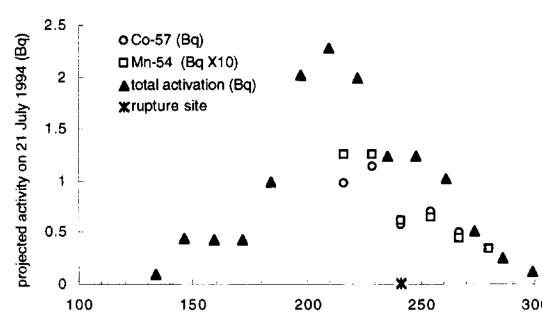

Fig. 6. Measurements of radioactivity on electron side leading edge tube. Measurements were done by CE on 0.25 m tube section. Co-57 and Mn-54 measurements were done at Sandia on segments of tube shown in Fig. 5. Rupture location (×) is indicated.

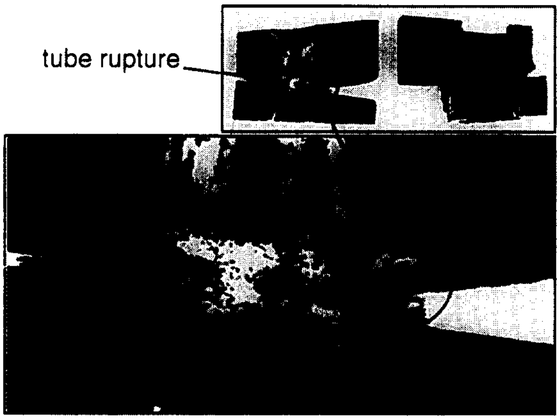

Fig. 7. Cross section of sample 4 (see Fig. 5) with rupture site indicated.

and three tiles high (38 mm) with a darkened central portion where graphite had sublimated. The center of this spot was about 231 mm below midplane.

At the second runaway strike, the tiles on the leading edge tube had no apparent damage. The tube was cut to produce six segments, each of which preserved the open space between the tiles, as shown in Fig. 5. The six segments were then cut parallel to the axis of the tube to divide the front 'leading edge' portion from the back of the tube that contained the stainless steel strongback. Fig. 7 shows the longitudinal sections of sample 4; the rupture site, located about 241 mm below midplane, is indicated in the photo.

As might be expected, the rupture occurred in the opening between sections where the pyrolytic graphite armor was brazed to the tube. The brazed sections would tend to support the copper as it softened, whereas the copper would be unsupported in the open sections. Across the tube from the rupture site there also appears to be a surface crack on the outside of the tube, although this is somewhat difficult to see in the reproduced photograph.

3. Discussion

The most important evidence from this runaway event is that the second runaway strike, which resulted in a leak in the leading edge tube, occurred at a point that, during normal operation, was approximately 20 mm outside the last closed flux surface. Had the runaways moved onto the OPL, passed repeatedly through the graphite armor and moved radially outward in many steps, then there would have been some evidence in the IR camera record, i.e., the resulting surface heating would have produced a 'hot stripe' across the face of the limiter from the center to the leading edge. However, the second strike point appeared to be localized and the implication is that the runaways that hit this location moved outward by tens of millimeters in one toroidal revolution, from (radially) inside the OPL outward to the leading edge.

There appears to be an explanation for this behavior based upon trajectory computations of the type done by Doloc and Martin [9] and upon the opening of flux surfaces for energetic electrons. Trajectory calculations suggest that such motion is possible under the conditions present for this experiment. For plasma (runaway) currents in the range of 150/250 kA, the drift orbits open to the outside. A lateral X-point is formed inside the position of the OPL and the outer legs of the separatrix intersect the OPL at locations above and below midplane. Runaway electrons follow this X geometry toward the lowest branch, where they are lost on the outboard limiter within a few toroidal turns.

In the evaluations of radioactivity, the global dose rates of 0.034 μGy/h (3.4 μrad/h) close to the tube are of the same order of natural dose rate levels, and the detected isotopes are typical for 20/40 MeV X-rays on steel. The width at half maximum of the activity profile along the tube is about 70 mm. This width is very similar to the size of the heat-affected area in the first strike site. At the second strike site, there was no 'footprint' from sublimation of the graphite; however, the IR record and the activity profile suggest that the runaway strike was of similar width.

The rupture occurred in sample 4, but the peak activity occurred in samples 5 and 6 in the Sandia analysis and just above the location of sample 6 in the CE analysis. The maximum of activity is about 30 mm toward midplane from the location of the rupture. As may be seen in Fig. 6, the tiles along the tube down those in sample 4 are quite close together, while those in samples 1–4 are further apart because of the curvature of the tube. It seems likely that the entire 'strike' region indicated by the activity profile could have been heated during the runaway strike, but that the rupture may have occurred at the closest overheated location where there was copper between the tiles that was less well supported than in the region above this location.

4. Conclusions

Two major conclusions were drawn from the runaway event that damaged the Phase III outboard pump limiter. The first is that there are possible trajectories of runaways in which large (tens of millimeters) steps toward the outboard side of the machine are possible in a single toroidal pass. The second major conclusion follows from the first. The possibility that runaway electrons can make large steps toward the outboard wall in a single toroidal pass means that modular structures with (poloidal) leading edges are vulnerable to runaway electron strikes even in areas that are well within the scrape-off layer during normal operation. It was primarily this vulnerability to further damage that led to the termination of further experiments with the Phase III OPL.

For the overall Tore Supra program, the mitigation of damage from runaway electrons has been cited as an active area for research. Techniques proposed for study include: (1) extended plasma control and detection of runaways, (2) in-flight termination by reversing the loop voltage or by high Z gas puffing, e.g. xenon, and (3) impact resistant components. In the design planning for a full toroidal belt limiter that has been proposed for Tore Supra, the continuous toroidal surface that provides only grazing angle incidence for runaway electrons is advantageous.

While there have certainly been observations of runaway electron damage in many tokamaks, the damage from runaway electrons to the Phase III OPL in Tore Supra is a dramatic demonstration of the vulnerability of actively cooled plasma-facing components to runaway electron strikes. It is clear that future fusion devices must in some way protect against this vulnerability. The designs for plasma-facing components of future fusion devices will of necessity include provisions for ports, cooling manifolds, remote access, etc. It will be important to ensure that the possible trajectories of runaways (on the flux surfaces that can evolve during disruptions) can impinge only at grazing angles onto the surfaces of components. Where toroidal grooves or other openings exist, for example, around the edges of a 'startup' limiter, there must be some design criteria that requires mitigation, such as tapering the armor near openings, to accommodate the stepwise outboard motion of the runaways over the length of the opening. The design analysis should be based upon magnetic configurations that evolve during the types of disruptions analyzed in the design. A more drastic measure would be to operate the device (e.g., ITER) with a preferred direction for the plasma current and to design toroidally asymmetric protection against runaway electrons.

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