MEASUREMENT OF LIMITER HEATING DUE TO FUSION PRODUCT LOSSES DURING HIGH FUSION POWER DEUTERIUM-TRITIUM OPERATION OF TFTR

BY

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Princeton University
Plasma Physics Laboratory

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Abstract

Preliminary analysis has been completed on measurements of limiter heating during high fusion power deuterium-tritium (D-T) operation of TFTR, in an attempt to identify heating from alpha particle losses. Recent operation of TFTR with a 50-50 mix of D-T has resulted in fusion power output (≈ 6.2 MW) orders of magnitude above what was previously achieved on TFTR. A significantly larger absolute number of particles and energy from fusion products (in particular, alpha particles) compared to D-D operation is expected to be lost to the limiters. Measurements were made in the vicinity of the midplane (± 30°) with thermocouples mounted on the tiles of an outboard limiter. Comparisons were made between discharges which were similar except for the mix of deuterium and tritium beam sources. Power and energy estimates of predicted alpha losses were as high as 0.13 MW and 64 kJ. Depending on what portion of the limiters absorbed this energy, temperature rises of up to 42 °C could be expected, corresponding to a heat load of 0.69 MJ/m^2 over a 0.5 sec period, or a power load of 1.4 MW/m^2. There was a measurable increase in the limiter tile temperature as the fusion power (and alpha) yield increased with a more reactive mixture of D and T at constant beam power during high power D-T operation. Analysis of the data is being conducted to see if the alpha heating component can be extracted. Measured temperature increases were no greater than 1 °C, indicating that there was probably neither an unexpectedly large fraction of lost particles nor unexpected localization of the losses. Limits on the stochastic ripple loss contribution from alphas can be deduced.

I. INTRODUCTION

Limiter heating due to lost alpha particles is one of the most important issues for future fusion reactor type devices such as ITER[1-3]. Ripple and banana losses of fast particles are expected to play a negligible role in the power balance but these losses will be an important issue in heat loads on the first wall/limiter, especially because of the potentially high heat loads possible depending on the localization of the losses. Even a small fractional loss of α-particle power, if incident on the first wall in the form of hot spots, has the potential to cause unacceptable erosion. If the alpha loss is only 5% of the total alpha population, it is a serious problem for first wall protection in ITER. Additional losses of several percent are very important.

In TFTR, we have attempted to use a limiter tile/thermocouple system as relatively large area detectors for detection of fast particles lost from the plasma. We have attempted to extract that component of wall heating due to alpha particle losses from the plasmas during the recent high fusion power D-T operation. We look at the outboard limiter part of the wall since this is where the lost particles are most likely to hit based on simulation codes. We used existing limiter tiles and their thermocouple instrumentation.

No anomalous loss of a major fraction of the α-particles was measured. Also, no localization in the form of excessively high measured temperatures (hot spots) was observed. The thermocouple/RFL tile system set an upper limit on the energy lost from fast particles, including both fusion products and beam ions.

II. LIMITER TILE AND THERMOCOUPLE INSTRUMENTATION

A. Description of Diagnostic System

In TFTR, the outboard limiter system consists of three separate limiters at different toroidal angles (Figs. 1,2). Each limiter consists of separate tiles. One of the limiters is instrumented with thermocouples in the vicinity of the midplane area (Fig. 3).

These tiles and instrumentation were not designed specifically for purposes such as α-particle detection, but instead for general protection against operating the tokamak and any internal components at excessively high temperatures. They were especially designed and installed for protecting the radio frequency antennas on the outboard side of the plasma, and hence the outboard limiters are called the RF limiters (RFLs).

The thermocouples complement other measurements made with scintillator-based escaping fast-ion detectors[4,5] located at 45°, 60°, and 90° below the outer midplane. The thermocouple/RFL tile system has advantages and disadvantages compared to the scintillator-based detectors. While the lost alpha detectors have been extremely useful, the thermocouple system has some distinct attributes and complements the scintillator-based detectors:

Firstly, there is a midplane scintillator-based detector, but it must be operated manually, since overheating of the probe may occur and therefore it is not always used. Secondly, the cross section of each of these scintillator-based detectors is very small (≈1 mm aperture). Therefore, they are highly sensitive to spatial variations or localization of the impact regions of the lost particles. The thermocouple/RFL tile system serves as large area detectors; even then, one sees variations in spatial position. Thirdly, these scintillator-based detectors respond to only certain pitch angles of the incoming particles.

Also, because α-particle confinement has not yet been clearly and positively identified with other existing α-particle diagnostics, it is valuable to look at the losses over as wide an area as possible to try to account for all of the alphas.

B. Expected Location of Heating

Most of the heating from first orbit and ripple losses is expected on the lower side of the midplane due to the orbit trajectories (Fig. 4). With respect to poloidal angles, a large peak in ripple losses is expected between 0 and -30°. Therefore, these thermocouples are ideally situated. Heating is expected mostly from the CCW direction (as viewed from above); this means that most of the heating is expected on the right-hand side of each limiter in Figs. 1-3.

III. DESCRIPTION OF EXPERIMENT

Heating of the limiter tiles during D-T experiments is due to a combination of sources: alpha particle losses, radiation, beam ion losses, nuclear heating, and charge exchange losses involving the beam ions:

$$P_{lim} = P_{\alpha} + P_{rad} + P_{NB} + P_{n} + P_{CX}$$

In principle, the heating from alphas could be isolated by operating a number of identical discharges with the only parameter varying being the number of alphas. The number of alphas (and neutrons) could be varied by changing the ratio of the D and T ions in the plasma. For each D-T neutron, there is one alpha born. For anything more than trace amounts (≈2%) of tritium, the D-T neutrons overwhelm the D-D neutrons. Therefore, the number of neutrons can be used as a rough measure of the number of alphas created. The D-T ratio is primarily controlled by the combination of D and T beam sources used in the neutral beams. In order to try to isolate effects due to alpha particles alone and to extract that portion of the heating due to alphas only, it is important to maintain as many parameters constant as possible, while varying only the alpha production rate.

The plasma discharges in the data set used for the present analysis are a subset of all the D-T discharges on TFTR to date. Some of the parameters of the discharges were: plasma current I_P = 2.0 MA, toroidal magnetic field B_T = 5.0 T, plasma size R = 2.52 m and a = 0.87 m. At this R, discharges were limited in size by the inboard limiter. This inboard limiter is a full 360° toroidal belt limiter installed in the vacuum vessel on the small-major-radius side of the vacuum vessel. It extends ±60° poloidally with respect to the midplane. This limiter is the primary power handling surface for most operation modes (R ≤ 2.62 m).

The outboard limiter used for temperature measurements in this study was not in direct contact with the plasma. With this R, the RF limiter tiles on the low field side are ≈ 20 cm from the last closed flux surface.

The nominal neutral beam power was chosen to achieve sufficient confinement to produce substantial fusion power while maintaining good MHD stability and discharge reproducibility so that the effects of the change in isotopic composition and the presence of energetic fusion alpha particles could be assessed. There is a total of 12 beam sources; each one could be operated in either D or T. For this study, the total number of beam sources was restricted to 10 or 11.

IV. MEASUREMENTS AND ANALYSIS

Figure 5 shows the time history of one of the thermocouples. Figure 6 shows the rise in temperature averaged over the tiles closest to the midplane as a function of total number of neutrons (and alphas) for each discharge, as the fusion power was increased by switching from pure D-sources to combinations of D and T sources.

Much of the scatter in data points originates from the fact that the thermocouple system was designed and configured to digitize data to only 1 °C temperature resolution. (The thermocouple system is presently being upgraded to improve the temperature resolution for the forthcoming D-T experiments.) By fitting the data from many discharges, we are effectively averaging the data and increasing the resolution of the measurement. The error in the dependence of temperature vs number of neutrons should scale as $1/(\text{number of discharges})^{1/2}$.

There are two important features of the data that deserve mention and should be treated separately as well as together. First, the data has an offset, which is that value for the pure D discharges at the far left of Fig. 6. The average offset is 1.75 °C. Second, there is the incremental increase in the temperature data (≈ 0.4 °C) with the neutron production (and alpha production) as T sources are substituted for some of the D sources. In principle, if the radiation, beam ion losses and charge exchange losses associated with the beams could be maintained constant as the D-T ratio is varied, even if they are large, then most of the incremental increase could be attributable to the alpha losses. It is shown below that the nuclear heating is a small fraction of the estimated alpha heating.

The offset could be separately used to calibrate the limiter/thermocouple system using the heating mechanisms not dependent on the alpha population. Also, comparison of the relative magnitudes of the offset and the incremental increase could be of interest.

V. ESTIMATION OF HEATING FROM CONTRIBUTING SOURCES

A variety of codes were referenced to estimate the contributions from alpha particles and beam ions: TRANSP, SNAP, MAPLOS, and a Guiding Center Code (GCC). The GCC was used as a primary reference for the lost alphas since it included first orbit losses, ripple induced losses, collisionally enhanced ripple induced losses, and also accounted for the Shafranov shift of the plasma. It assumes, however, an isotropic distribution of the alphas and a beam deposition profile for each beam source based on the net profile obtained from TRANSP. It does not include plasma rotation effects. It also assumes that the limiter is at the plasma edge, which is not a bad assumption for the R = 2.60 m case in which the plasma fills the vacuum vessel.

Alpha Particles

Taking the upper limit of neutron production of $\approx 2 \bullet 10^{18}$ n/sec, the corresponding power in alphas, using 3.5 MeV/α, would be 1.1 MW. Results from the GCC code indicate that for a case similar to the D-T discharges in this study (R=2.6 m, I_p=1.8 MA), the total fraction of alpha losses is 23%. This includes first orbit losses (6%), which are prompt, and ripple-induced losses (17%). The ripple induced losses are more strongly localized than the first orbit losses (Fig. 4). Since the actual R is smaller, and the actual Ip is larger, the actual losses are estimated to be 50% lower. Thus, the power deposited on the wall is 0.13 MW. Over the $\approx$ 0.5 sec of high power fusion reactivity, this corresponds to $\approx$ 64 kJ of alphas. If all of this energy were confined to hitting one RFL tile, then the energy load would be 0.69 MJ/m^2 which would result in a temperature rise of 42 °C for that one tile. Instead, this energy is distributed over the wall because of the orbits. Due to the orbits, only approximately 1/4 of the energy is deposited on the RF limiter system. Dividing that energy by 6 tiles per limiter (corresponding to the ±30° range) and all three RF limiters, the final estimate would be an energy load of 9.6 kJ/m^2, or 0.89 kJ/tile, corresponding to a temperature rise of 0.58°C for each of the affected tiles.

If not 23%, but 100%, of the alpha particles were lost before thermalization, then the losses and energy and power loads estimated above would increase by a factor of 4.3: The original estimate of $\Delta T = 0.58$ °C would become $\Delta T \approx$ 2.5 °C, which would easily be measurable with substantial accuracy.

The measured temperature incremental increase as the alpha population increases is ≈ 0.36 °C. Thus, the measured temperature incremental increase of the midplane tiles is ≈62% or within a factor of two of the estimated temperature incremental increase due to alpha particle losses (Fig. 7). It is interesting to note that quantitative measurements from the lost alpha scintillator-based detectors are a factor of two low compared to predictions also.

Radiated Power

The radiated power is measured by arrays of bolometers. The time-integrated (over the entire discharge) radiated power for each discharge was computed. The average radiated power over all the discharges was 7.35 MJ. With a vessel area of 103 m^2, this corresponds to an approximate average energy flux of 71 kJ/m^2, or 7.1 W/cm^2. Assuming this radiation is isotropic and taking into account the toroidal geometry and the poloidal distribution of radiated energy, the energy load on an outer midplane RF limiter tile would be 4.3 kJ . This corresponds to a temperature rise of 2.8 °C per tile.

Thus, the measured temperature offset of one tile is ≈ 63%, or within a factor of two, of the estimated total radiation heating of one tile. Also, the estimated temperature incremental increase due to alpha particle heating of one tile on the outboard limiter near the midplane is ≈21% of the estimated total radiation heating on each tile, while the measured temperature incremental increase is ≈13% of the estimated total radiation heating of one tile.

Neutron Heating

The heating of the RFL tiles from absorption of neutrons from the fusion process is estimated to be small compared to heating from radiation, beam ion losses, and alpha particle losses.

Again taking the upper limit of neutron production of $\approx 2 \bullet 10^{18}$ n/sec, the corresponding power in neutrons, using 14 MeV/n, would be 4.5 MW. This corresponds to an average power load of 44 kW/m^2. It is estimated that the 1 cm thick tiles absorb 5% [6] of the neutron flux. Therefore, taking into account toroidal effects, the input power to each tile on the outer midplane limiter is estimated to be 0.16 kW. For a one second heating pulse, each RF limiter tile receives 0.16 kJ, corresponding to a temperature rise of 0.10 °C. Thus, the ratio of estimated total neutron heating to estimated lost alpha heating is only 18%.

Beam Ion Losses

Beam ions in TFTR are injected tangentially using up to 12 different beam sources. Beam ions are lost due to first orbit losses and ripple losses. The estimation of beam ion losses are complicated by several factors. First, each beam source has a different tangency radius in the plasma. The source location of the ions in the plasma determines their trajectory and the likelihood of being lost. Second, half of the sources are co-injected (relative to the plasma current direction) and half are counter-injected. The co- and counter-ness of the beam sources affects the loss of fast particles. Co-beam ions have orbits at smaller major radii and thus smaller orbits and are therefore lost at a lower rate. Third, the type of gas (tritium or deuterium) in each beam source also affects the loss rates. Tritium gas results in more energy injected into the plasma, and the beam ions are deposited at larger major radii due to the higher cross section for ionization. In TFTR, each source can be operated with either D or T gas. Fourth, both the amount and distribution of losses are dependent on the above factors. The alphas which are lost to the limiter are expected to have a particular poloidal angle distribution. The lost beam particles also are expected to have a particular poloidal distribution and this distribution is expected to be different from that for the alphas.

Estimates of the beam ion losses relative to the alpha losses has been done for some cases using results from Guiding Center Code ripple transport studies. Although the exact discharge conditions relevant to the present experiments were not treated for beam ion losses, one can make estimates from a variety of cases which limit or bracket the ones of interest. Also, results from a number of other code results such as TRANSP, SNAP, and MAPLOS help to make estimates.

The injected neutral beam power for these discharges is $P_{NBI} = 30$ MW. It is estimated that 2% of the beam ions will be lost, corresponding to 0.6 MW of power. Over one sec, this would be 0.6 MJ. The beam ion loss poloidal distribution is broader than that for alphas. Also, the toroidal extent of the neutral beam orbits are typically shorter (on the order of 10° toroidally), and ions are lost more locally (toroidally) than alphas. Taking these factors into account, and dividing the resulting energy among 6 tiles per limiter, each tile would receive 1.4 kJ or 15 kJ/m^2, corresponding to a temperature rise of 0.91 °C.

This is less than a factor of two less than the measured temperature offset. It is less than a factor of two greater than the estimated temperature incremental increase due to alpha particle heating. It is also less than a factor of two greater than the measured temperature incremental increase.

VI. DISCUSSION OF RESULTS

In the high fusion power D-T experiments on TFTR, preliminary measurements and analysis have been completed to try to identify the wall/limiter heating due to lost alpha particles. The average temperature of the outer midplane limiter increases as the alpha particle losses increase with increased fusion reactions during D-T operation in TFTR. The measured increase in the average temperature with increasing alpha population is less than 1°C, corresponding to less than 17 kJ/m^2 heat load. This measured temperature increment is within a factor of two of the estimate for alpha losses alone. No unexpectedly large loss fraction of fusion products was measured at the limiter midplane. No locally concentrated heating (hot spots) was measured at the limiter midplane due to fusion products.

These preliminary results are being followed by further analysis, better characterization of the limiter/thermocouple system, more data with more tightly controlled limits to improve the statistics, and better estimates of the expected heating due to the different heating mechanisms.

A. Improvements

There are a number of improvements which would improve this analysis. First, acquisition of higher resolution data would decrease the scatter; this only requires modifications to the acquisition hardware and the microprocessor software which ships the data from the local memory to the main computer for archiving. This improvement is planned for the near term. Second, more data with tighter controls on the limits of the operational parameters, such as number of beam sources and beam energy in a source on a shot to shot basis, would clarify the contribution of beam ion losses to the total heating. Third, selective choice of plasma parameters and beam sources would maximize the alpha to beam-ion losses, again clarifying the contribution of the alphas relative to the beam ions. Fourth, design, fabrication and installation of a specially designed instrumented limiter would further benefit these measurements.

B. Relevance to ITER

In the ITER design[3], 60 m^2 of area is devoted to limiter surface. The peaking factor is assumed to be four, and includes effects from random variations, misalignments, and the predicted spatial dependence of the particle loss. This means that the effective limiter area is only 10-15 m^2. This translates into 1 MW/m^2 wall loading from alpha losses alone, five times larger than that due to radiation from the plasma. The uncertainty factor is two. The actual loading depends on the design of the first wall; ITER has multiple limiters.

Estimations above for TFTR for the power density on the limiter from alphas losses reached as high as 1.4 MW/m^2 for the case where all the losses were to one tile. This is of the same magnitude as that stated above for the limiter of ITER. In TFTR, the measured power loads were much lower (<17 kW/m^2).

Acknowledgments

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Figures

Fig. 1. Schematic of array of outboard limiters. These limiters are called RF (radio frequency) limiters since they are located to protect the four RF antennas. View is looking in the large major radius direction from plasma, at the midplane of TFTR. There are 20 toroidal bays, A through T, corresponding to the 20 toroidal field coils.

Fig. 2. Picture of inside of TFTR vessel showing section with the four RF antennas and the three RF limiters.

Fig. 3. Schematic of one of the three RF limiters, showing the individual tiles and the locations of thermocouples on the tiles.

Fig. 4. Calculated poloidal distribution of alpha particles losses for first orbit and ripple losses using guiding center code.

Fig. 5. Time history of one RF limiter midplane thermocouple. Shows one day's run during high power D-T operation in TFTR. Shot numbers are indicated along with number of deuterium and tritium sources used for each shot.

Fig. 6. Average increase in midplane limiter temperature versus total number of neutrons (and alphas) per discharge for the high fusion power D-T operation of TFTR. The average midplane limiter temperature rises ≈ 0.18 °C per 10^{18} neutrons. The large scatter in the data is due largely to the finite resolution of the temperature measurement system.

Fig. 7. Estimations of the contributions to the heating of the outer midplane limiter. Also shown is the fit to the measured values from Fig. 6.

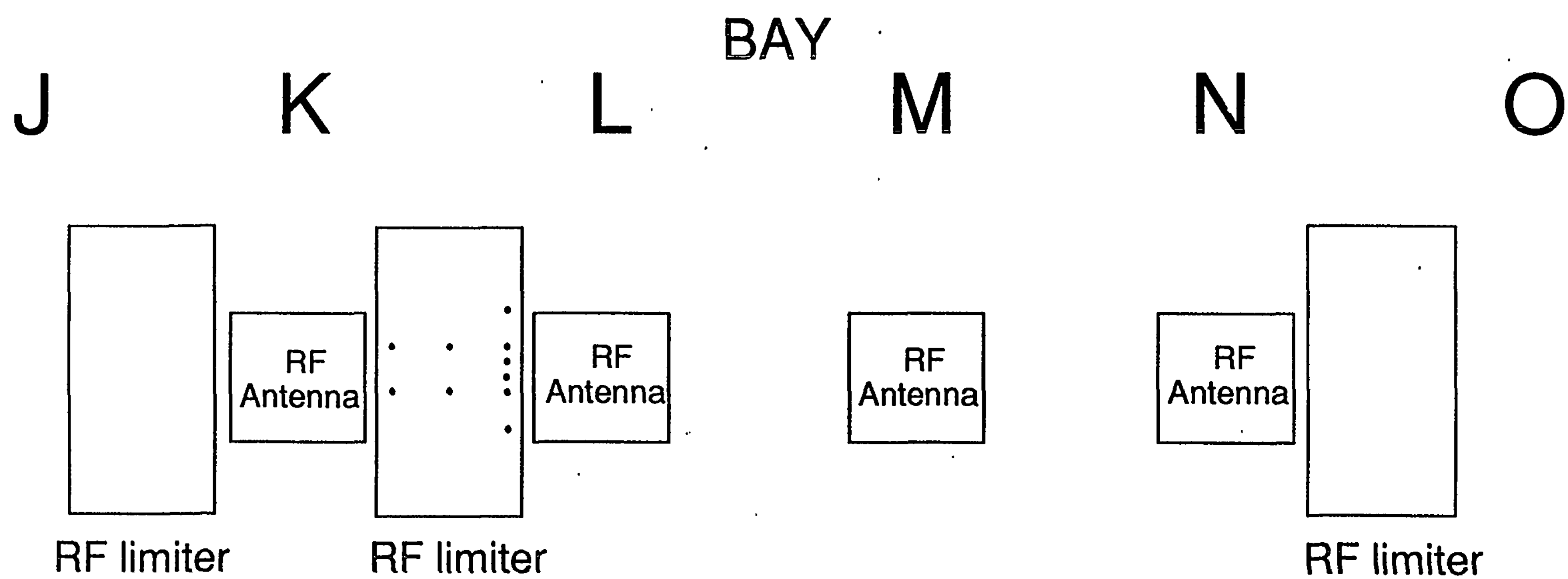
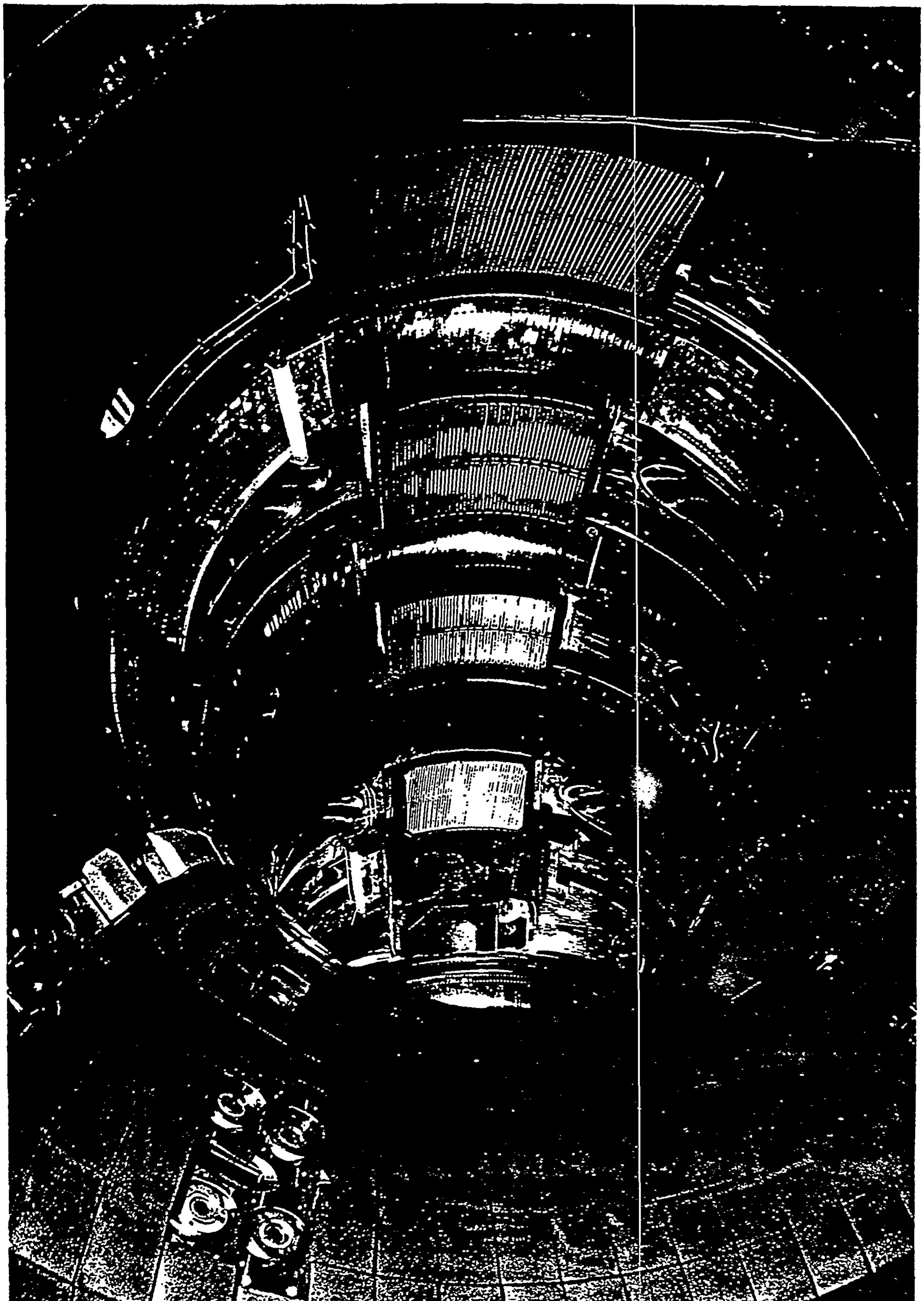

BAY
J
K
L
M
N
O
RF Antenna
RF Antenna
RF Antenna
RF Antenna
RF limiter
RF limiter
RF limiter

Fig. 1



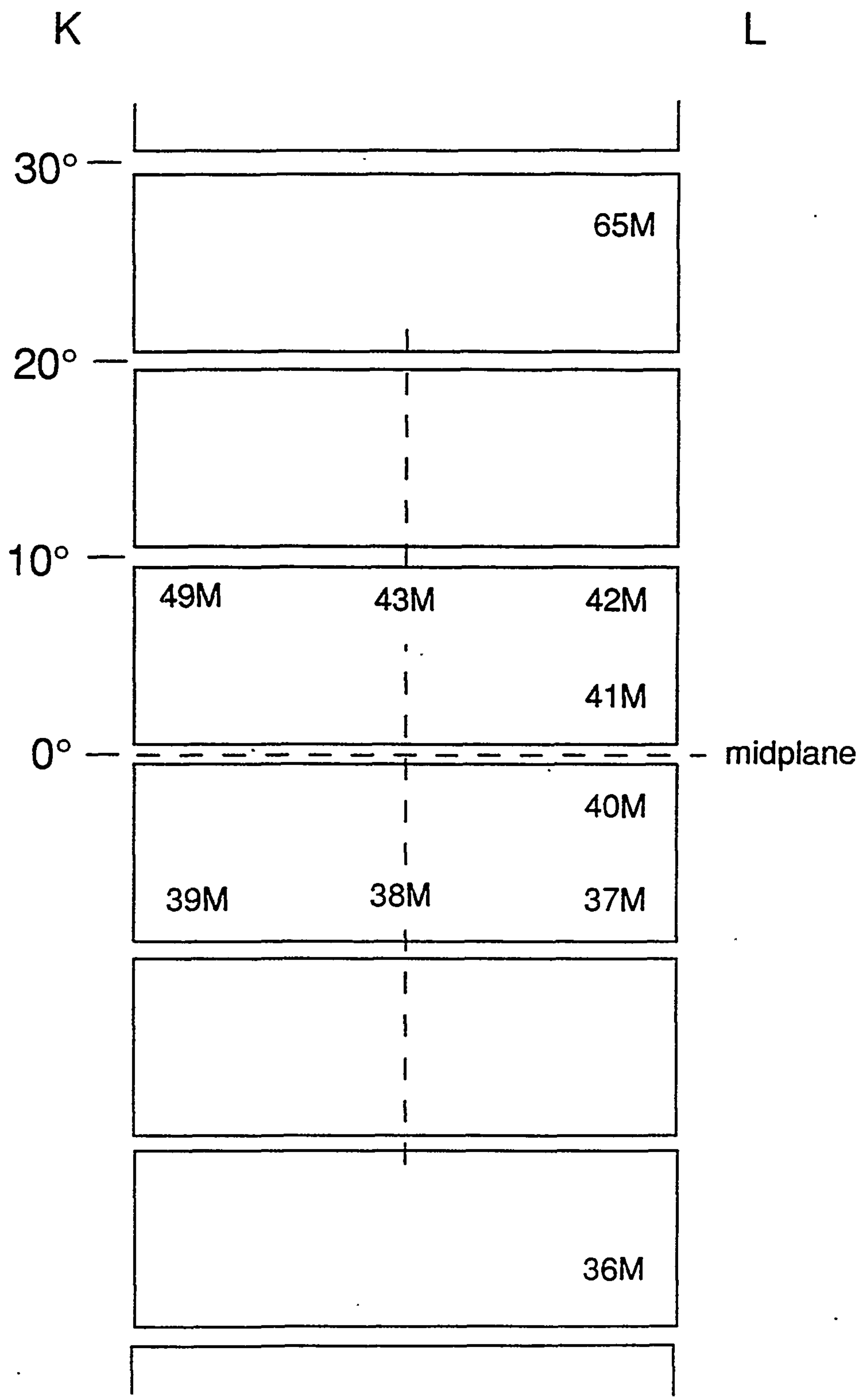


Fig. 3

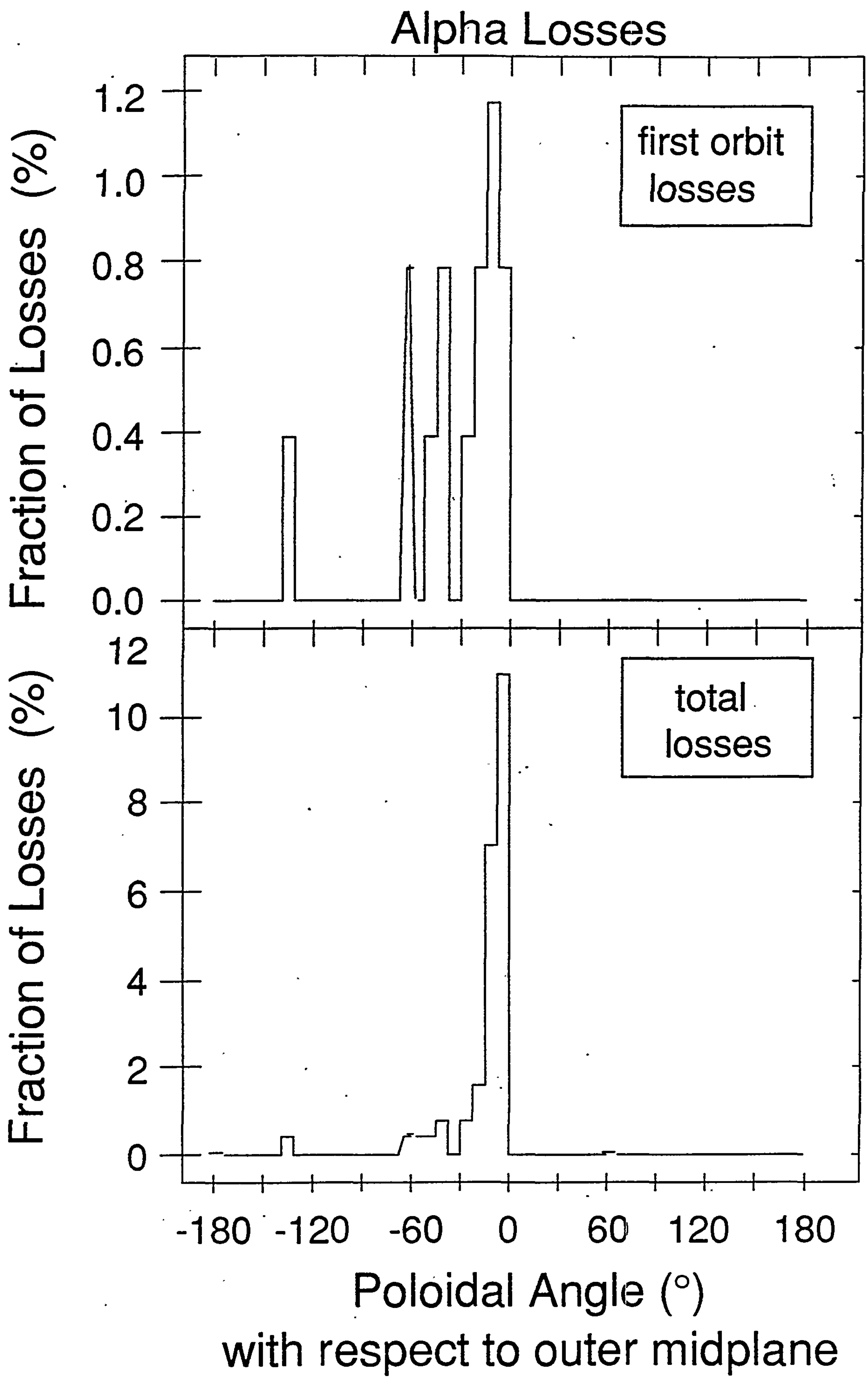
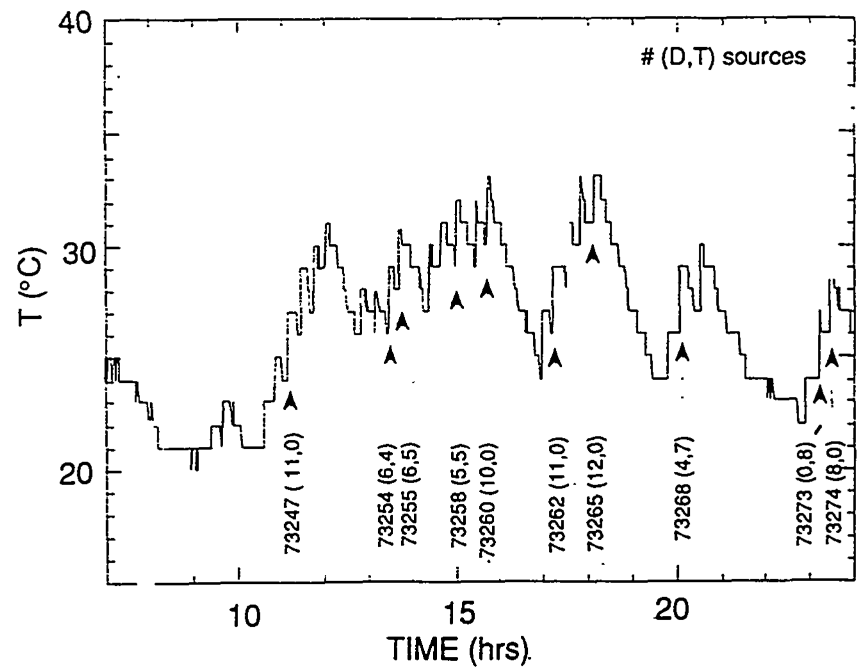
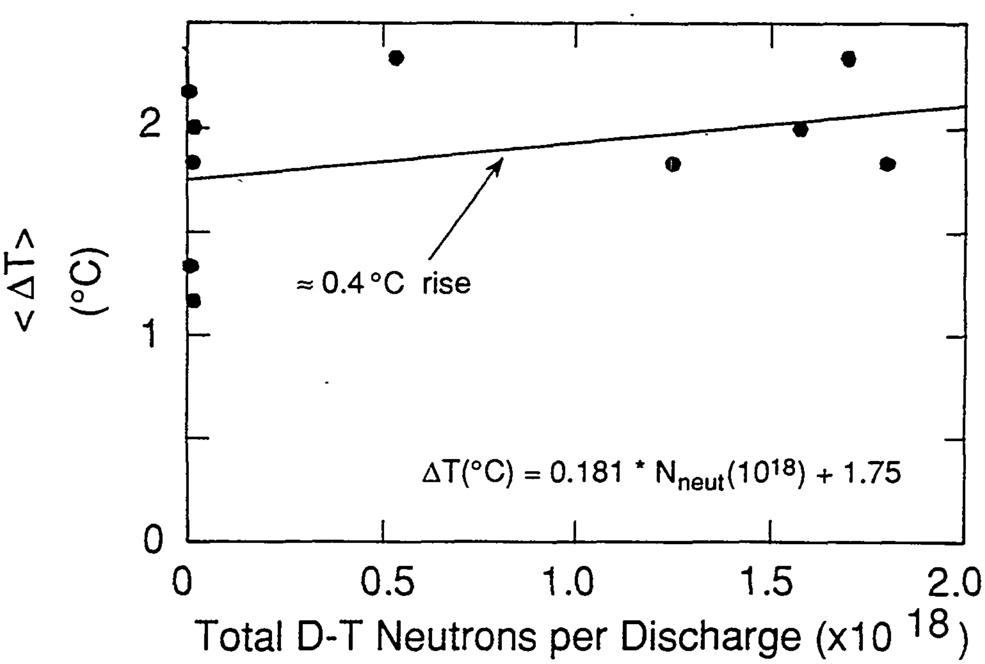

Alpha Losses
Fraction of Losses (%)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
first orbit losses
12
10
8
6
4
2
0
total losses
-180 -120 -60 0 60 120 180
Poloidal Angle (°) with respect to outer midplane

Fig. 4

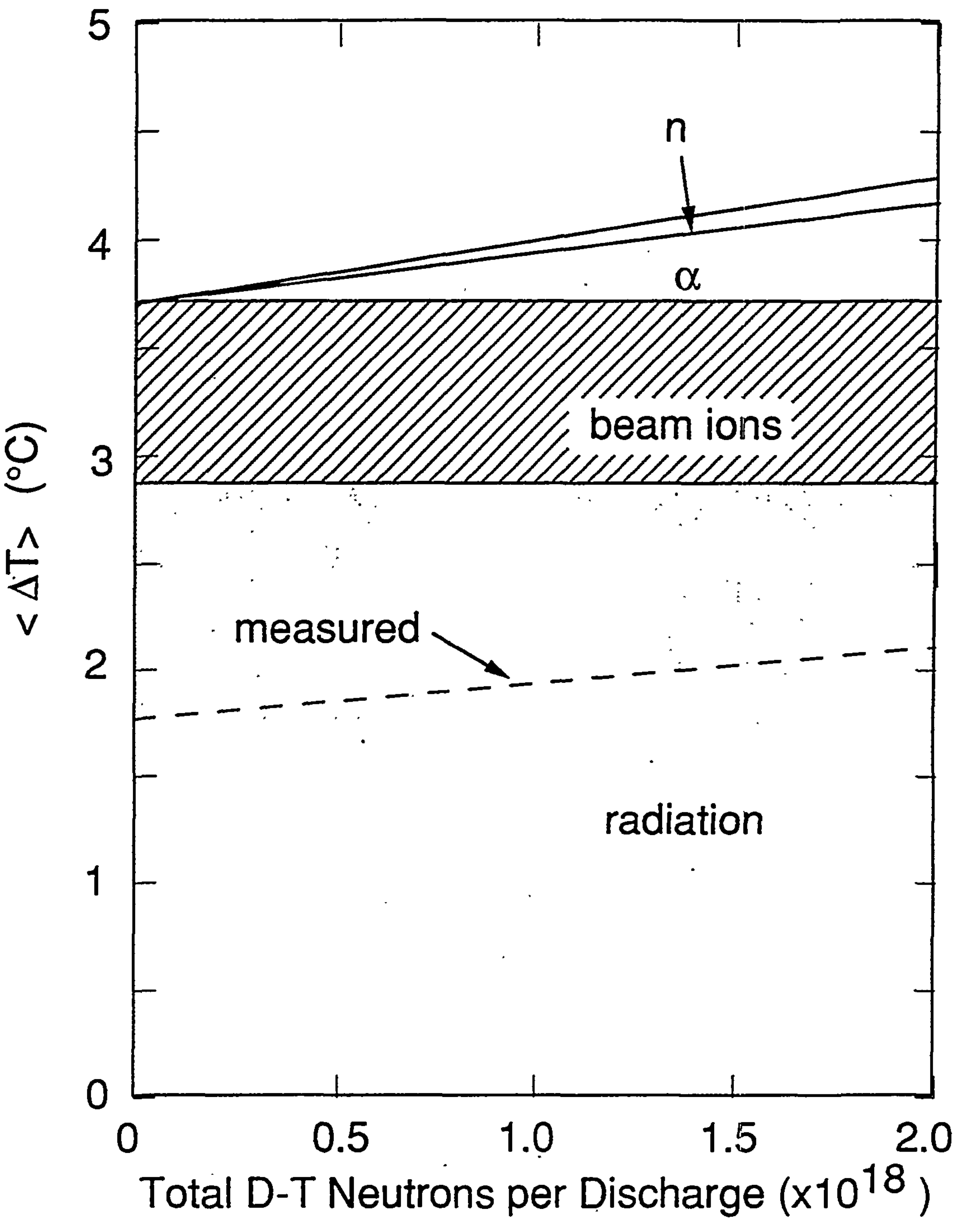


(D,T) sources
T (°C)
TIME (hrs)
73247 (11,0)
73254 (6,4)
73255 (6,5)
73258 (5,5)
73260 (10,0)
73262 (11,0)
73265 (12,0)
73268 (4,7)
73273 (0,8)
73274 (8,0)



< ΔT > (°C)
≈ 0.4 °C rise
ΔT(°C) = 0.181 * N_neut(10^18) + 1.75
Total D-T Neutrons per Discharge (x10 18)

Fig. 5



5
4
3
2
1
0
n
α
beam ions
measured
radiation
0
0.5
1.0
1.5
2.0
< ΔT > (°C)
Total D-T Neutrons per Discharge (x10^{18})

Fig. 6

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