Local plasma radiation loss rate determination in tokamaks and stellarators

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A modified tomography technique was developed to provide, from two radiation detector arrays covering an entire plasma cross section at a fixed toroidal angle, the local distribution of the time rate of change of the radiated power. The radiated power is the least unambiguously measured of all the components involved in plasma thermal equilibrium and its time evolution could be the most indicative of any perturbation of such equilibrium. The tomography technique has been checked by using simulated thermal perturbations, assuming a 1D transport model for the resulting transport. Experimental setups are presented for the TJ-I tokamak and TJ-IU stellarator. © *1995 American Institute of Physics.*

I. INTRODUCTION

Breaking of the local thermal equilibrium could be the mechanism responsible for plasma collapse in stellarators,[1] and is related to the density limit in these devices and tokamaks.[2] Two important questions to address are (a) spatial localization of that breaking, and (b) determination of precursors, whose detection could help to prevent this catastrophic phenomenon. Thermal equilibrium determination requires knowledge of the different power components (i.e., radiation, conduction, and convection). Radiation losses are the least unambiguously measured and, through their time evolution, the most indicative of any perturbation of such equilibrium. We have developed a tomography technique[3] to deduce, from the chord measurements of the radiation losses provided by two detector arrays covering an entire plasma cross section at a fixed toroidal angle, the local distribution of the rate of change of the radiation losses. Comparison with average loss rate enables more precise determination of the radial location of the perturbation. In addition, analysis of the time evolution of the rate at these locations provides information on the characteristics of such perturbation. Section II describes in detail the tomography inversion technique used in these studies. To check this method we have simulated a thermal perturbation of the plasma using a 1D transport code. Results are summarised in Sec. III. Finally, Sec. IV describes the experimental setups for two toroidal devices in operation in our laboratory and with very similar parameters: the TJ-I tokamak ($R_0=0.3$ m, $a=0.1$ m, $B=1$ T) and the TJ-IU stellarator ($R_0=0.6$ m, $a=0.1$ m, $B=0.5$ T), where studies of thermal collapse and their similarities and differences for these two types of configurations are planned.

II. TOMOGRAPHY TECHNIQUE

Stellarator, and nowadays also many tokamak, plasmas present a remarkable noncircular cross section. Under these conditions, determination of local plasma emissivity from integrated measurements along detector lines of sight is not possible using standard or modified Abel inversion techniques. Other tomography methods, using several detector arrays, are required. In the case of perturbations of the thermal equilibrium, the noncircularity can be even stronger with very localized features. This fact rules out tomography techniques based on a modal structure when using a number of modes limited by the available number of arrays, due to their implicit assumption of smooth spatial variation of the local emissivity function. To avoid these assumptions, algorithms based on numerical iterative techniques are used. They allow for determination of very localized structures with two main drawbacks: high computer time consumption and the possibility of nonreal solutions. To avoid both, we have developed an iterative method that uses as initial weight for the contribution of each plasma element to a detector signal the toroidal magnetic-flux value at that element. With these weights, we are likely to be close to the real emissivity distribution, saving computing time and diminishing the possibility for nonreal solutions. We have modified the method to provide the local distribution of the variation rate of the radiation losses in the plasma. Defining the signal variation rate as:

$$\dot{S}(\delta_n,\rho_i)=\sum_{j=1}^{NX}\sum_{k=1}^{NY}\dot{P}_{\rm rad}(x_j,y_k)M(n,i,j,k) \tag{1}$$

for a detector with impact parameter ρ_i, in an array at a poloidal position δ_n. We are assuming a rectangular grid, $NX\times NY$, to cover the entire plasma cross section. $P_{\rm rad}$ is the radiated power rate and the matrix M takes into account the contribution of each grid element to the detector signal.

Local value for the power loss variation rate is deduced by:[3]

$$\dot{P}_{\rm rad}(x_j,y_k)=\frac{W(j,k)}{NC(j,k)}\sum_{n=1}^{NA}\sum_{i=1}^{ND}\dot{S}(\delta_n,\rho_i)\,\frac{M(n,i,j,k)}{WN(n,i)}, \tag{2}$$

where $W(j,k)$ is the initial weight, $WN(n,i)$ the normalization factor for each detector signal, and $NC(j,k)$ the number of contributions from the pixel (j,k) to different detector lines of view. We are assuming NA arrays with ND detectors each.

Substituting in Eq. (1) the emissivity rate values calculated using Eq. (2), it is possible to reconstruct the detector signals. Comparison between these signals and the real values provides an estimation of the inversion error. The evolution of this error with the number of iterations indicates the degree of convergence of the method.

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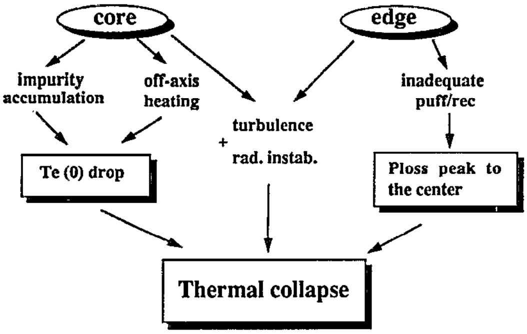

FIG. 1. Diagram of different scenarios leading to plasma thermal collapse.

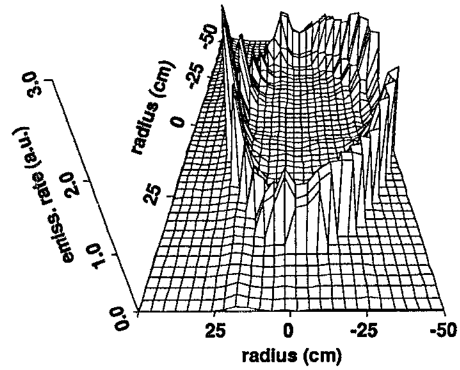

FIG. 3. Reconstruction of radiation losses rate 0.3 ms after the Te perturbation.

III. SIMULATION RESULTS

A 1D transport code has been developed to deduce plasma parameters from the calculation of the power balance between input heating power and radiative, conductive, and convective losses, both at the initial equilibrium and during the perturbation evolution. The goal is to use the code to simulate plasma evolution for different scenarios leading to thermal collapse, as summarised in the schematic diagram of Fig. 1. Code results have been bench-marked with the PROCTOR code,[4] obtaining a reasonable agreement. As an initial check for this analysis technique, the code has been used to simulate the evolution of the plasma in response to an instantaneous perturbation of the electron temperature at a particular radius. The evolution of temperature and radiated power is displayed in Fig. 2. For the time we have simulated, approximately 1 ms, spread out and attenuation of the Te perturbation is obtained together with an increase in radiation losses that seems to move toward the plasma center. Besides, edge cooling produces a peaking in radiated power at this region.

Signals have been calculated, using these simulation results, for two detector arrays, 14 detectors each, on the top and the side of the plasma. Using the time evolution of these signals as input for the inversion technique, we deduce the radiation loss rate evolution. In Fig. 3 is shown the reconstructed distribution at a particular time. When observing the whole temporal sequence we find a clear indication of a perturbation spreading out with an increase of radiation for in-

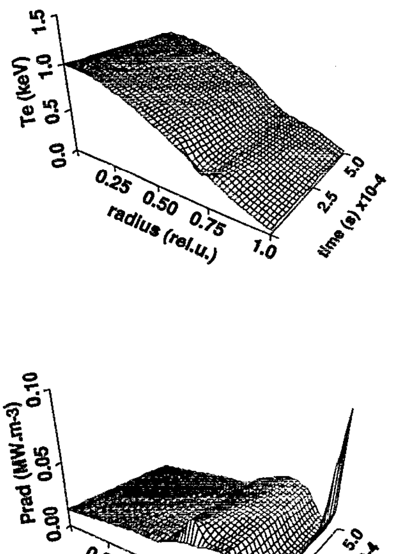

FIG. 2. Simulated electron temperature and radiated power evolution for an initial perturbation at $r=0.6$.

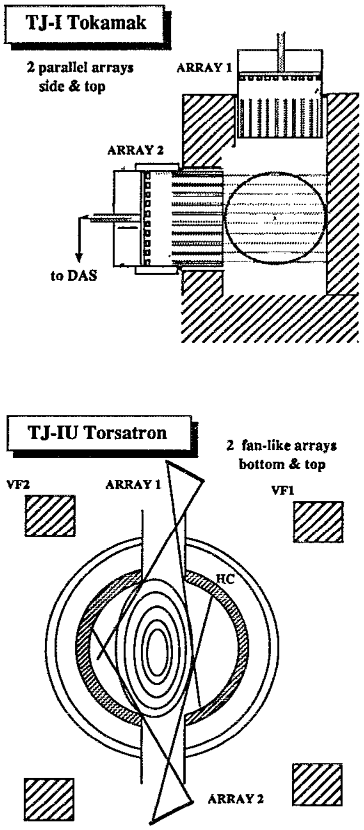

FIG. 4. Planned experimental setup for thermal collapse studies in the TJ-I tokamak and TJ-IU stellarator.

ner plasma regions, in good agreement with the transport simulation used as input for this reconstruction. It must be emphasized that reconstructions present a high sensitivity to small rate increases in inner parts of the plasma, even in the case of large absolute values at the edge.

IV. EXPERIMENTAL SYSTEMS FOR TJ-I AND TJ-IU

The experimental setup to obtain radiation signals for these two plasma devices are displayed in Fig. 4. In the case of TJ-I, it consists of two germanium bolometer parallel arrays[5] looking at the plasma through an upper and a lateral port, respectively. The radial resolution at the plasma center of the nonoverlapping chords is about 2 cm. The data-acquisition system (DAS) will be improved with the use of DPS elements. Those will enable real time derivation of the raw signals to be used as inputs for the tomography algorithm with a time resolution in the submillisecond range. For the TJ-IU torsatron two ten-channel monolithic arrays, based on the detector structure described elsewhere,[6] are going to be installed at the same poloidal cross section ($\Phi=0°$), and collimated to yield a fanlike geometry. The DAS will be the same as for the TJ-I tokamak.

V. CONCLUSIONS

Simulation results using a 1D transport code to follow plasma thermal equilibrium evolution prove that a tomography inversion technique based on the use of an iterative numerical scheme, with weights proportional to equilibrium toroidal magnetic-flux values, applied to the signals of two independent radiation detector arrays, can provide the local value of the radiation losses variation rate. If plasma collapse is linked to thermal instabilities, the magnitude, spatial location, and spatial evolution of this loss rate would be indicators of the onset of the thermal collapse. Experimental systems have been designed to address these studies in the TJ-I tokamak and the TJ-IU stellarator.

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