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ABSTRACT

The integrated tokamak simulation code TOKES is proposed for estimation of the ITER first wall radiation damage during massive injection of noble gas inside the core for mitigation of the disruptions. Simulations of MGI processes ab initio are impossible because of complexity of the problem, but one can get reliable results extrapolating the MGI experiments available from JET to ITER conditions. With this aim the TOKES code is applied for simulation of JET shots disrupted with MGI. The TOKES scenario for the thermal quench of MGI at JET and its extrapolation to ITER have been developed basing on analysis of the available JET database and on comparison with the simulations performed.

1. INTRODUCTION

Thermonuclear plasma confined in the ITER reactor core with closed magnetic field surfaces, but the stability of the core plasma may be violated due to intrinsic instabilities or due to strong external influences, so the discharge may run into the disruption.

Unmitigated ITER disruption will probably damage the first wall of its vacuum vessel with direct plasma impact causing significant melting and vaporization [1]. Fast injection of a Noble Gas (NG) can mitigate the disruption, transforming the thermonuclear plasma energy and the poloidal magnetic field energy into radiation [2]. Radiation redistributes the heat load over the first wall more evenly than the direct plasma impact does. Experiments in existing tokamaks demonstrated effectiveness of Ne, Ar and He gases or their mixtures with D_2 for mitigation of the thermonuclear plasma impact on the first wall. Estimation of radiation heat loads during Massive Gas Injection (MGI) of NG in ITER is the issue of main importance for its performance. We intend to use the TOKES code for evaluation of the ITER first wall damage during mitigated disruptions. Despite the lack of reliable scaling for the enhanced cross transport during the MGI, extrapolation of the MGI heat loads from JET, DIII-D, ASDEX-U and other modern tokamaks to ITER is possible.

The TOKES code is developed in FZK - KIT for integrated two-dimensional simulations of thermonuclear reactors during last 5 years. The simulations include interaction of the thermonuclear plasma with the divertor armour and vacuum vessel walls in configurations with diverted magnetic field. Initially the TOKES code model included one-dimensional simulation of the thermonuclear plasma inside the core using the magnetic flux coordinates. Recently the TOKES code has been developed for 2D multi-fluid, multi-ion species simulations in the confined region. This upgrade of the code is aimed for simulations of MGI. MGI in ITER is a very fast process lasting few milliseconds only, so the plasma and the radiation flux are essentially non-one-dimensional. This work is done for development of TOKES model and for verification of the 2D TOKES modeling of the thermal quench (TQ) of MGI against the available experimental results from JET.

2. TOKES MODEL FOR MGI SIMULATIONS

2.1 TOKES CODE PRINCIPLES

The TOKES code performs simulations using the triangular grid, covering the interior of the tokamak wall poloidal section and assuming toroidal symmetry for all physical fields. The poloidal magnetic field is calculated solving the Grad-Shafranov equations using the magnetic flux determined in the peaks of the triangular meshes. After determination of the magnetic field the Magnetic Flux Coordinates (MFC) are calculated. Both grids are illustrated in Fig.1. The plasma parameters are given on the MFC grid. The plasma transport is simulated in fluid approximation and assumed to be two-dimensional: in directions parallel and perpendicular to the magnetic field.

Neutral gas parameters are defined in the centres of triangular meshes. The grid meshes are non-uniform, the mesh sizes are refined at the regions important for neutral gas transport simulations – along the direction of NG injection – and in sites important for the magnetic field calculation that is at magnetic axis and around the x-point. The neutrals interact with the plasma defined on MFC grid via thermal energy and momentum exchange, ionization, recombination and the charge-exchange. The plasma transport is calculated in confined region with closed magnetic surfaces as well as in the SOL and in the private region, where they crosses the wall. For facilitation of the MGI simulations we assume that the initial equilibrium configuration of the magnetic field does not changed during pre-TQ and TQ, so the plasma transport proceed in the same MFC grid. This approximation is reasonable for pre-TQ and TQ and violates at Current Quench (CQ) stage. Here we restrict ourselves with MGI simulation from start to the end of TQ only. Simulation of CQ stage of MGI is more challenging task, it needs simulation of the magnetic configuration evolution and modelling of run-away electrons generation and transport to the vessel wall. This is the aim of future activity for our group.

2.2 TOKES SCENARIO

The TOKES scenario describes phenomenologically the enhanced cross-transport for different MGI stages. It defines the effective transport coefficients and the time moments for switching off and on the enhanced transport. It does not describe the physics of enhanced cross-transport and does not allow simulation of the MGI caused disruption ab initio. It based mainly on energy conservation arguments, on the effective thermoconductivity value $\chi_{\perp eff}$ and on the timings observed from experiments.

Two JET pulses [3,4] have been chosen for simulation of MGI. Most informative JET discharge disrupted with massive gas injection is JET Pulse No: 76314. For this pulse time dependences for the edge temperature, T_{edge} for the temperature at the magnetic axis, T_c the total radiation power P_{rad} and the power at outer and inner divertor plates are available, see Fig.2. Besides, during this pulse the radial and time dependence for temperature has been measured at the edge of the confined region in the midplane for approximately 30cm from the separatrix as is seen in Fig.3. But the pulse has been performed with Ohmic heating only and the plasma energy was relatively small, W_{dia} = 0.67MJ in comparison with 6.9±0.3MJ of the poloidal field energy [3].

The JET Pulse No: 77806 pulse is more representative for extrapolation to ITER. The discharge have been performed in the H-mode with neutral beam heating and with W_{dia} = 3.2MJ. The time dependences for the total plasma energy and for the total radiation power are also available, see Fig. 4. Time dependences for the edge temperature and for the temperature at the magnetic axis are absent, but the time moments for edge cooling start as well as the TQ start and time duration are available. Moreover, the bolometry reconstructions for radiation power source distribution in the poloidal plane have been performed for several time moments: for pre-TQ, for TQ itself and for transition to CQ, see Fig.5.

Massive gas injection in JET is from the vessel of 36 l volume, containing pure Ne (JET Pulse No: 76314) or D_2-Ar mixture in proportion 90%-10% (JET Pulse No: 77806). Injected were 4×10^{22} Ne particles and 5×10^{21} Ar particles correspondingly through the drift tube of 4 m length.

Analysis of these experiments allows developing the TOKES scenario for MGI simulations. According to the scenario at the initial pre-TQ phase of MGI-caused disruption cross magnetic field transport plays minor role and the edge plasma cooling is mainly due to the noble gas propagation inside the separatrix, its ionisation and the edge thermal energy conversion into radiation. This assumption is verified by comparison of the simulation results with experimental ones. From this fact immediately follows that the energy irradiated during the pre-TQ phase cannot be larger than the thermonuclear plasma energy confined between the separatrix and the critical magnetic surface. The scenario assumes that after cooling down the critical surface cross transport of the thermal energy is increased by factor of $10^2\times10^3$ due to development of the thermonuclear plasma turbulence. From bolometry reconstruction for the radiation power source it is evident that the turbulence should produce small-scale fluctuations, which does not cause large scale convective mixing of the pure thermonuclear plasma situated inside the critical magnetic surface with the plasma highly contaminated with NG impurity outside the surface. As is seen from Fig.5 the region of main radiation during TQ is always close to some magnetic surface at the outskirts of the core. Large scale mixing and radiation from the discharge centre arises at the very end of TQ and full mixing with impurity developed at the Current Quench (CQ) stage see, for example Fig.8 in [2].

From this conclusion immediately follows that the energy transport from the core centre to the contaminated outskirts of the discharge can be simulated with increase of the thermoconductivity. We assume that the effective turbulent thermoconductivity coefficient $\chi_{\perp eff}$ is due to the magnetic field fluctuations in radial direction which forms the ergodic field configuration, described in [5]. This means that $\chi_{\perp eff}$ is equal to the parallel thermoconductivity coefficient with some small empiric amplitude, which can be fitted from experiments. Additional argument against the large-scale convective transport across the tokamak core before CQ follows from the fact that the total heat flux to the divertor outer and inner armour plates is negligibly small during TQ. According to [5,6] the energy delivered to the divertor armour during TQ is approximately 7% of the total thermal energy.

2.3 TOKES MODEL APPROXIMATIONS

The TOKES code uses fluid approximation for NG plasma dynamics inside the core. Despite the fact that, the D-T plasma dynamics along the magnetic field inside the core is essentially kinetic, injection of huge amount of NG and its ionization produces plasma with high density and low temperature which is enough for validity of fluid approximation for this plasma. For example, ion collision length $\lambda \sim T^2/n \sim 0.5$-2m independent of the ion mass for densities $n = 10^{20}$ m^{-3} and temperature $T = 50$-100 eV characteristic for start of MGI. This is to be compared with the toroidal length for the NG plasma expansion – $2\pi R \sim 20$m. according to the simulation results the maximum NG plasma density is at least ten times more, so the validity of fluid approximation for the main impurity plasma is even better.

TOKES is the 2D code assuming toroidal symmetry, but MGI in JET runs through one valve, which injects NG at one spot, so at the MGI start the NG density is extremely toroidally asymmetric. Nevertheless, for simulation of radiation heat load to the wall this asymmetry plays minor role, because this toroidally asymmetric plasma distribution occurs during pre-TQ stage only, when radiation power is small, 10-15% of the peak value, see the radiation power curves in Figs.1 and 3. During the TQ itself, when the radiation power increases approximately one order of the magnitude, the NG density became more toroidally symmetric. Indeed, the Ar plasma of the temperature $T_{Ar} = 100$-50eV expands with velocity of $V_{||} = 2.5C_s \sim 5\times10^6$ cm/s and make one toroidal turn during ~0.5ms, which is much smaller than 4–8 ms of the pre-TQ stage in JET. In fact, the results of 2D simulations of MGI should be verified and corrected with 3D code simulations and we intend to upgrade TOKES to 3D in future, but the above mentioned arguments allow expecting that the 2D results are not very different from more precise 3D simulations, so the conclusion whether Be wall melts or not under the action of the radiation will be accurate enough.

3. SIMULATION RESULTS

For simulation of the JET Pulse No: 76314 the pre-TQ stage duration is estimated as 4 ms as one can see from Fig. 2. Start of the pre-TQ stage in this figure is indicated with edge temperature T_{edge} decrease and its finish indicated with sudden jump of T_{edge}. From simulations it follows that this jump is due to the increase of thermoconductivity at start of TQ.

The simulation results are in good agreement with the measurements if we compare them till the end of TQ only, which is indicated by zero T_c. At that point the total radiation power $P_{rad} = 0.6$ GW and further increase of the measured P_{rad} up to ~1 GW is due to start of CQ because all the thermal energy has been already spent for the radiation. In JET Pulse No:76314 the poloidal magnetic field energy is almost ten times larger than the plasma thermal energy [3], so CQ contribution to the radiation flux should be dominant.

Figure 3 shows comparison of the edge temperature profiles during the pre-TQ and TQ stage of JET Pulse No: 76314. First 4 profiles correspond to pre-TQ and separated by 1ms time intervals. As is seen from the measurements the temperature $T_c = 1.4$keV at 30cm distance from the separatrix remains unchanged during these 4 ms, confirming the assumption that heat transport is negligible at pre-TQ stage. The same behavior is seen in lower panel showing the simulation result. The next 3 calculated curves are separated with 0.5 ms intervals and correspond to TQ itself, when the transport increased on 3 orders of the magnitude, the central temperature drops almost to zero, but T_{edge} increases at this time, as it is seen from the insert in the lower panel. This increase of the edge temperature corresponds to the peak on T_{edge} in Fig. 2.

Comparison of the time dependences for total radiation power P_{rad} and plasma thermal energy W_{dia} measured in JET Pulse No: 77806 with the results of TOKES simulation is shown in Fig. 4. 8 ms time delay between start of edge cooling and switching on the enhanced cross transport has been determined from the experimental curve; 2 ms rise time for P_{rad} and the maximum P_{rad} value are fitted varying the amplitude of the enhanced thermoconductivity. The thermal plasma energy drop $\Delta W_{dia} \sim 1$MJ at the pre-TQ stage is in a good agreement with the experiment. The fact, that the thermal plasma energy drop ΔW_{dia} during pre-TQ agrees with experiment, verifies the suggestion that during pre-TQ heat transport plays minor role, so the energy drop simply equal to the energy of the discharge edge till the critical magnetic surface, cooled down by the injected gas. CQ phase is not simulated, so one should not compare the curves after the time moment when $W_{dia} = 0$.

For the JET Pulse No: 77806 the bolometry reconstructions for radiation power source Q_{rad} are available for several time moments. Fig.5 shows comparison of the poloidal distribution for the radiation source with the result of TOKES simulation. The first plot corresponds to the mid of pre-TQ stage, ~3-4ms after the start, the middle plot is just before the TQ start, at ~7ms, and the last plot corresponds to the transition between TQ and CQ. Calculated Q_{rad} maxima for these 3 plots, 4 MW/m^3, 8 MW/m^3 and 40 MW/m^3 as well as the radiation source pattern are in reasonable agreement with experimental ones. One should notice that the radiation power is a sharp function of the plasma temperature, the radiation source maximum moves rather fast as it is seen from the simulations, so one should take into account only qualitative agreement between the patterns. Additional confidence in the obtained result gives a good agreement between the measured and the calculated time dependences for the total radiation power P_{rad}.

3. DISCUSSION

Massive injection of noble gas is proposed for mitigation of the ITER wall damage by disruptions. The integrated tokamak simulation code TOKES will be used for estimation of the ITER first wall radiation damage during MGI. Simulations of MGI processes are impossible because of complexity of the problem, but one can get reliable results using extrapolations of available MGI experiments in JET to ITER conditions. With this aim the TOKES code is applied for simulation of JET shots disrupted with MGI.

Experimental results on MGI of NGs into the various JET discharges have been analysed and two of them has been chosen for simulations. These are JET Pulse No: 76314 with ohmic heating only and $W_{dia} = 0.67$MJ and more appropriate for ITER conditions the H-mode discharge JET Pulse No: 77806 with $W_{dia} = 3.2$MJ. Simulations for these two experiments have been performed. Analysis of these experiments and the simulation results allows developing the TOKES scenario for pre-thermal quench and thermal quench phases of disruptions caused by MGI. The scenario does not describe the physics of MGI, the discharge instabilities and turbulence in the thermonuclear plasma and does not allow simulation of the MGI caused disruption ab initio. The scenario based mainly on energy conservation arguments, uses the effective electron thermoconductivity value $\chi_{\perp eff}$, which increases almost three orders of the magnitude during TQ, and the timings observed from the JET experiments. The scenario is to be used for simulations of radiation heat loads on the first wall and the plasma heat loads on the divertor armour of the ITER tokamak.

Comparison of experiments and simulations with TOKES code allows conclusion that for initial pre-TQ phase of MGI-disruption cross magnetic field transport of energy and particles plays minor role and the edge plasma cooling is mainly due to the NG propagation inside the separatrix, its ionisation and the edge thermal energy conversion into radiation. From this fact the conclusion has been made that the energy irradiated during the pre-TQ phase cannot be larger than the thermonuclear plasma energy confined between the separatrix and the critical magnetic surface. The scenario assumes that after cooling down the critical magnetic surface the thermal energy cross transport is increased due to development of the thermonuclear plasma turbulence caused by fine scale instabilities.

From bolometry reconstruction for the radiation power source it is evident that the turbulence should produce small-scale fluctuations, which does not cause large scale convective mixing of the pure thermonuclear plasma situated inside the critical magnetic surface with the plasma highly contaminated with NG impurity outside the surface. From this conclusion immediately follows that the energy transport from the core centre to the contaminated outskirts of the discharge can be simulated with increase of the thermoconductivity coefficient.

CONCLUSIONS

The TOKES scenario for the first two stages of MGI, pre-TQ and TQ has been developed analyzing the experiments and simulations. The scenario assumes, that (i) at pre-TQ the cross transport is negligible and the time duration is determined with the NG velocity, the ionization and excitation rate and the radiation power; (ii) pre-TQ finishes when the critical magnetic surface is cooled down; (iii) at TQ the cross transport is due to the fine-scale turbulence without large-scale mixing, it can be simulated with phenomenological enhancement of thermoconductivity; (iv) $\chi_{\perp eff}$ is due to ergodization of the magnetic surfaces in radial direction, so it proportional to the parallel one with small amplitude, which is fitted equal for the two simulated JET discharges.

Extrapolation of the results on ITER is straightforward. Analysing the database if MGI at JET one can reveal the critical magnetic surface (presumably $q = 2$, but one should determine it from the experimental database). For reliable extrapolation of the JET results to ITER one should perform a series of simulations using the available database on MGI. This activity is planned for the nearest future.

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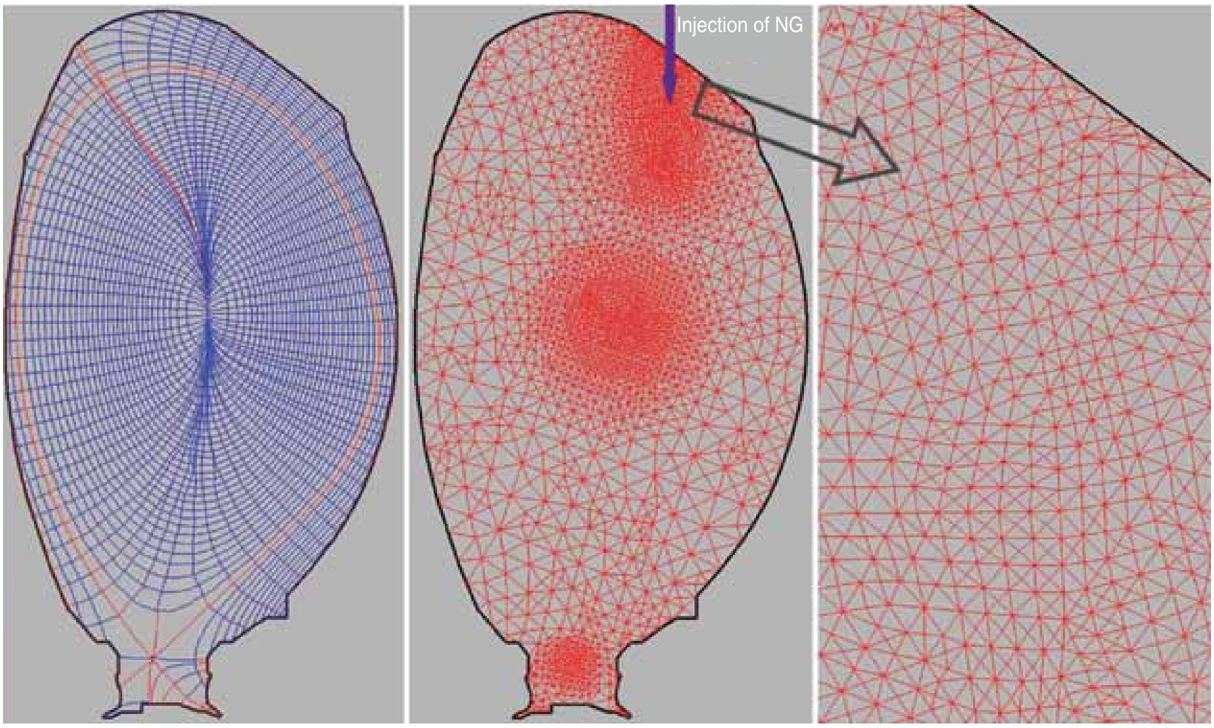

Figure 1: Orthogonal magnetic flux coordinates for simulation of plasma dynamics and the triangular grid for propagation of neutral gas and for solution of the Grad-Shafranov equation. The triangular grid is densified along the NG injection line, near the magnetic axis and the x-point for better accuracy of the calculations.

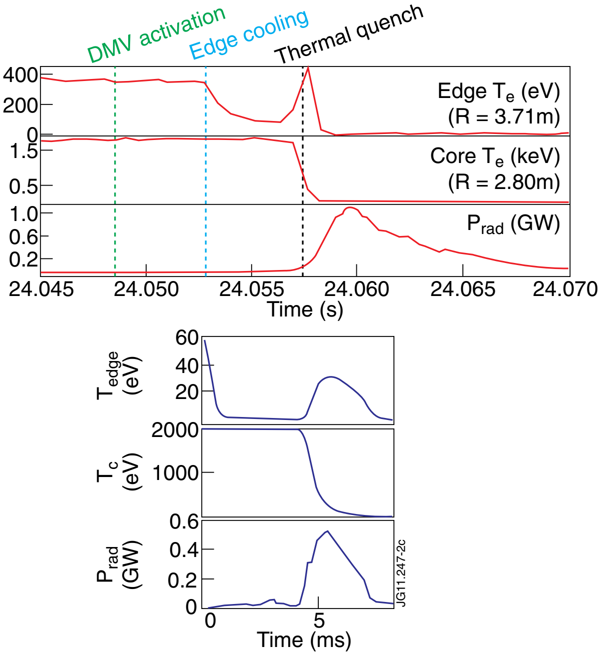

Figure 2: Comparison of time dependences for T_{edge}, T_c and P_{rad} measured in JET Pulse No: 76314 (upper panel) with the result of TOKES simulation for this pulse (lower panel).

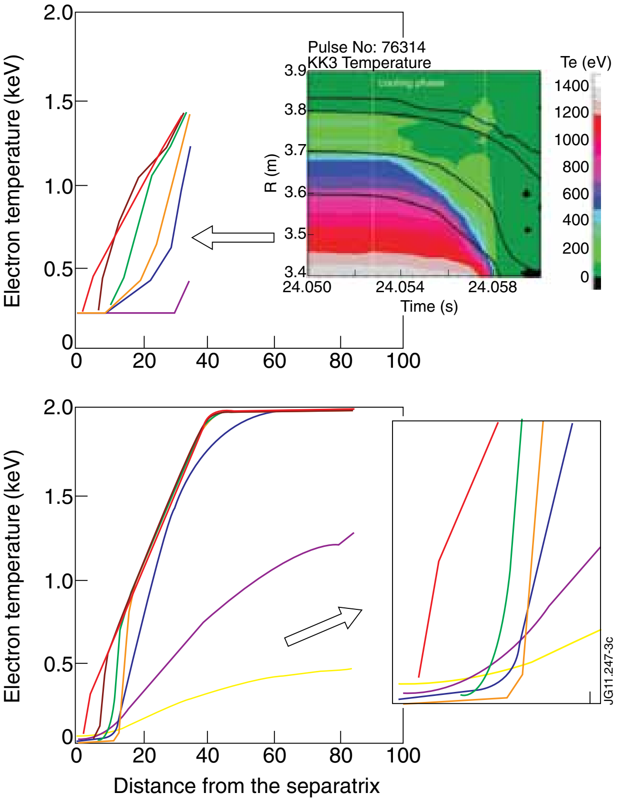

Figure 3: Comparison of the measured (upper panel) radial and time dependences for edge temperature in JET pulse JET Pulse No: 76314 with the result of TOKES simulation (lower panel). Upper left panel shows temperature profiles from the right plot at 6 time moments, the same as on the lower panel. The insert in lower panel is the magnification of the left plot close to the separatrix for illustration of the edge temperature jump at TQ start.

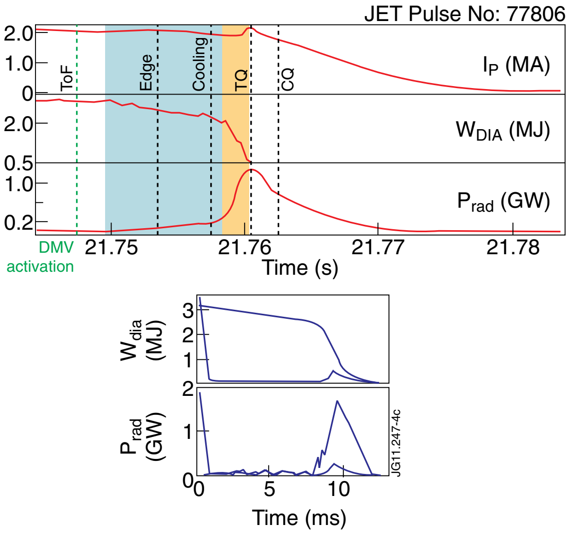

Figure 4:Comparison of the time dependences for radiation power P_{rad} and thermal energy W_{dia} measured in JET pulse JET Pulse No: 77806 (upper panel) with the results of TOKES simulation (lower panel). 2ms rise time of P_{rad}, the drop of W_{dia} at pre-TQ and the maximum P_{rad} value are in good agreement, CQ phase is not simulated. On both calculated plots the edge temperature is given for indication of timing for pre-TQ and TQ stages.

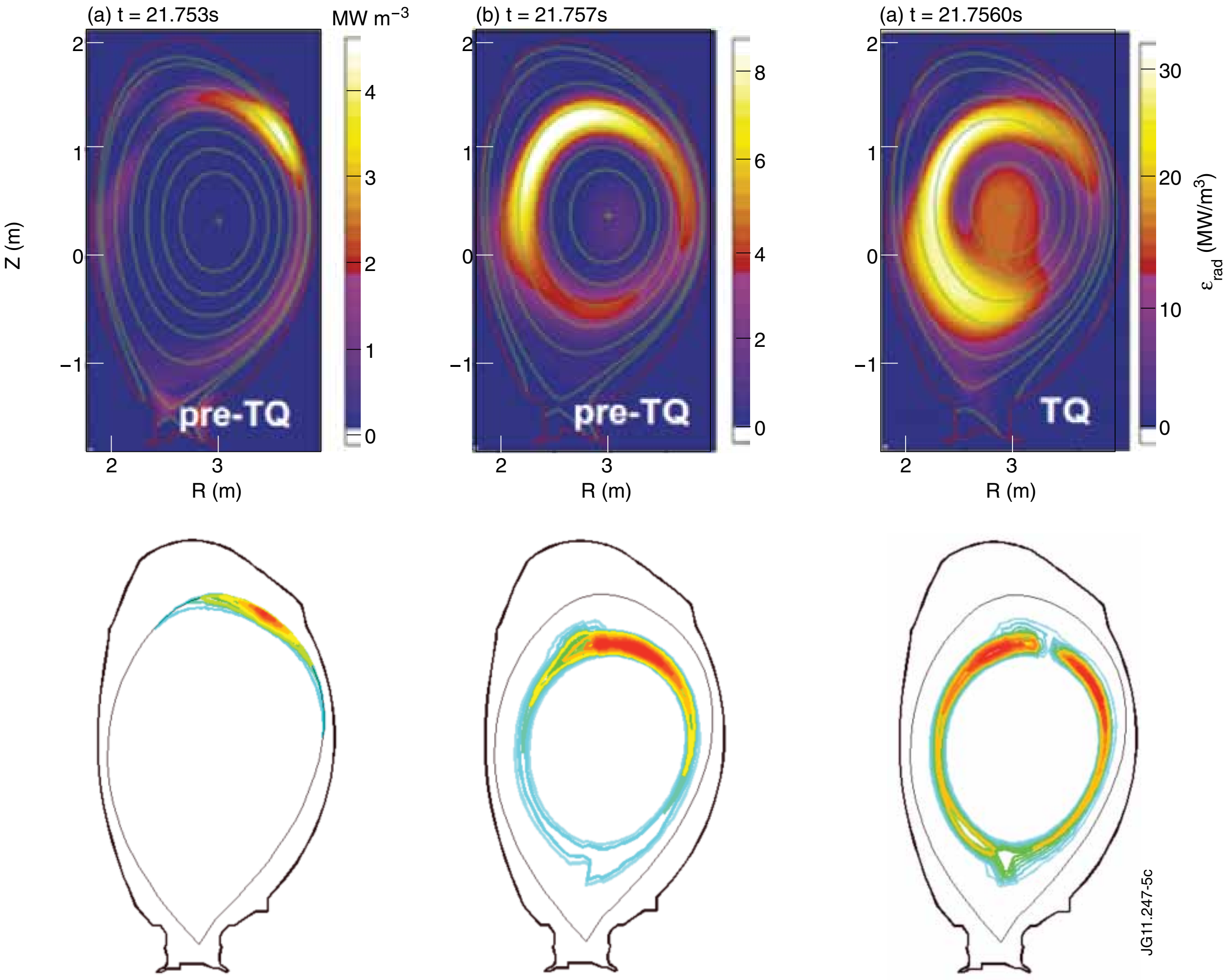

Figure 5: Comparison of the bolometry reconstructions for radiation power source in JET Pulse No: 77806 (upper panel) with the result of TOKES simulation (lower panel). The power source Q_{rad} maxima, 4MW/m^3, 8MW/m^3 and 40MW/m^3 correspondingly shows good agreement between the simulations and the experiment.