EFDA–JET–CP(13)05/06

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** See annex of F. Romanelli et al, "Overview of JET Results",*
(24th IAEA Fusion Energy Conference, San Diego, USA (2012)).

Preprint of Paper to be submitted for publication in Proceedings of the
11th International Symposium on Fusion Nuclear Technology, Barcelona, Spain
16th September 2013 - 20th September 2013

ABSTRACT
Simulations of massive noble gas (NG) injection into the JET plasma have been performed using the TOKES code. The results of these simulations have been verified by comparison with JET experiments. Further simulations performed showed that the amount of NG for triggering the thermal quench can be reduced 40 times. Such small amount of injected NG should generate runaway electrons (RE) with rather large probability. For mitigation of the wall damage with these RE a special sacrificial diaphragm, consisting from several W 'nails' with the characteristic thickness of 2cm has been proposed. The diaphragm erosion with RE beam has been roughly estimated from above as less than 0.5 cm per disruption. Taking into account the plasma shielding may decrease erosion ~10 times.

1. INTRODUCTION
Disruption is a spontaneous break down of the tokamak discharge stability, due to inherent processes in plasma. Unmitigated disruptions in ITER will damage the first wall causing its melting, brittle destruction and erosion. Mitigation of the first wall damage is one of the most important issues for ITER performance. Experiments performed in modern tokamaks have proved that fast injection of a massive amount of noble gas (MGI – massive gas injection) can effectively mitigate the disruption, transforming both, the plasma energy and the poloidal magnetic field energy into radiation, which loads the first wall more uniformly than the unmitigated plasma impact [1].

The TOKES code, developed in FZK – KIT for integrated simulations of the plasma performance and plasma–wall interactions in tokamaks is used for simulations of MGI. Previous simulations of the plasma evolution and its thermal energy irradiation during thermal quench (TQ) of MGI in JET [2,3] have been done for verifications of the physical models implemented in TOKES. Verification of the TOKES simulations is essential for predictions of the first wall damage in ITER.

MGI is an emergency method for mitigation of disruptions. A side effect of MGI is contamination of the vacuum vessel with large amount of noble gas (NG), which should be pumped out for further operation of tokamak. Hence, it is important to determine the minimum amount of the noble gas for mitigation of disruptions.

In this paper the experimental data on electron density during MGI available from JET is compared with the results of TOKES simulations with the aim to verify the TOKES results and additional simulations has been performed to determine the minimum amount of the injected gas for reliable shut down of the JET discharge.

2. ELECTRON DENSITY EVOLUTION DURING TQ OF MGI
2.1 SIMULATION RESULTS
In JET NG is injected through 4m long tube. After reaching the plasma edge NG interacts with confined D plasma and is ionized. The NG plasma flows mainly along the magnetic field lines (MFL). Initially, the NG plasma density profile is Gaussian-like along the MFL and the same is the plasma

pressure profile because the plasma temperature along MFL is almost constant due to extremely high parallel thermoconductivity. The pressure gradient is the main driving force for NG plasma to spread along the MFL. Under action of the pressure gradient the plasma flows in both directions from the source with characteristic velocity comparable with the sound velocity, see lower panel of Fig.1. When the plasma temperature along the MFL drops to very small values, further ionization of the incoming NG terminates, so the NG plasma source at the given MFL disappears, but the plasma flies away from the initial spot, so the Gaussian density profile is split into two Gaussians moving in the opposite directions, see upper panel of Fig.1. After this drop of electron temperature the NG penetrates deeper into the confined D plasma and the similar scenario is developed in the next MFL, namely, NG plasma initially having a Gaussian profile, with slightly larger full width at half maximum (FWHM) due to NG stream widening. Then the sole Gaussian splits in two Gaussian profiles moving in opposite directions with higher velocity than in previous MFL because of higher NG plasma temperature, so higher sound velocity. The injected NG permanently flowing across the magnetic surfaces penetrates still deeper into the confinement. Evolution of the resulting 2D pattern of the NG plasma calculated using the TOKES code is shown in Fig. 2. The NG plasma density increases drastically with NG penetration deeper into the pedestal because of higher energy density of the confined plasma, which is spent for NG ionization. After few milliseconds the NG plasma spreads on a large distance, so the plasma density pattern became more turbulent.

2.2 COMPARISON WITH JET EXPERIMENT

The described transport of the NG plasma density peaks is seen in the time dependence for line integrated density (LID), registered in the JET H mode Pulse No: 77806 with $T_{max} = 4.7$keV, $n_{max} = 5\times10^{19}$m^{-3}, see Fig. 3. The positions of two interferometers lines of sight (LID3 and LID4) are shown in Fig.2. The first peak in LID3 signal appears at ~21.753s when the expanding NG plasma crosses the LID3 line of sight (LOS). LID3 LOS is closer to the injection point than that of LID4 as it is indicated in Fig.2, so corresponding peak in LID4 signal appears later because the NG plasma peak needs time to reach the LID4 line of sight. The increase of LID over the stationary value is larger for LID4 despite the fact that the electron density due to NG plasma there is smaller than the density rise across LID3. This can be explained by much smaller distance which LID3 beam runs inside the NG plasma comparing with the LID4 beam, which crosses NG plasma stream nearly parallel to the flow.

Line-integrated densities provided by the fast interferometer [4,5] are the only measurements of density during TQ at JET because of its fast sampling rate, but even this diagnostic fails after TQ in H mode. First of all it is useful to analyze the measured LID time dependences and to understand what is important for revealing the plasma dynamics during MGI. For this purpose it is very informative to compare two pulses, Pulse No's: 77806 and 77808 which are identical with the exception of the additional heating, which rises the maximum temperature in Pulse No: 77808: $T_{max} = 6.8$keV. Surprisingly, the LID4 signal in this pulse is much less pronounced in comparison with the LID4 signal of Pulse No: 77806, see Fig. 3. Injection of the same amount of NG into the pedestal should result in higher electron density for the Pulse No: 77808 which has higher thermal energy density because this energy is available for NG ionization. The fact that the electron density is really higher for Pulse No: 77808 is seen from the LID3 signals comparison. The stationary LID3 values for both pulses are approximately equal $1.2\times10^{20}m^{-2}$, the maximum of the LID3 is $2\times10^{20}m^{-2}$, for Pulse No: 77806 and $2.4\times10^{20}m^{-2}$, for Pulse No: 77808 in accordance with higher electron density for this pulse. The opposite relation between LID4 signals can be explained with small shift of the LID4 LOS relative to the plasma edge. Indeed, the stationary value of LID4 in Pulse No: 77808 $2.5\times10^{19}m^{-2}$ is noticeably smaller than that of Pulse No: 77806 – $3.5\times10^{19}m^{-2}$. This means the Pulse No: 77808 line of sight is closer to the separatrix. TOKES simulations show that the density of electrons due to ionization of the injected NG is a steep function of the minor radius, as it is seen from the Fig.4, so even small shift of the LID4 LOS can result in much smaller LID increase for Pulse No: 77808. The same arguments are valid for one pulse – one can expect that small shifts of the line of sight may result in considerable increase of the LID4 signal. LID3 LOS crosses the NG plasma almost perpendicularly, so its amplitude is not very dependent of the confinement shape and position. Most important for comparison of the measured and simulated LID time dependences are the sequence of the peaks – first the peak on LID3, which is closer to the injection point and later – the peak on LID4, which needs time for travel till the LID4 line of sight.

Ne ion density for the L-mode Pulse No: 76314 with much lower electron temperature T_{max} = 2keV evolutes similar to the described Ar density in the Pulse No: 77806, but the peaks divergence is much smaller because of lower Ne plasma velocity and less pre-TQ time duration: 4ms and 8ms correspondingly. This is why the LID3 and LID4 behavior for the Pulse No: 76314 are less peaked in time. The measured and the calculated time dependences for LID3 and LID4 for the 3 JET Pulse No's: 77806, 77808 and 76314, shown in Fig.3 are in reasonable agreement, taking into account that MGI in JET is not fully two-dimensional due to toroidally unsymmetrical injection. The results show similar sequence of peaks and less than 30% deviation one from another at times, when the measured signal is valid.

2.3 OPTIMIZATION OF INJECTED GAS AMOUNT

The results of the TOKES code simulations for TQ caused by MGI has been validated against the JET experiments and described in [2,3] and in the previous section of this paper. The accuracy of the modeling results allows concluding that the main features of MGI are simulated properly. According to the physical scenario of the MGI, described in [3], at the pre-TQ phase the injected noble gas cools down the edge of the confined plasma, but does not influence on the bulk plasma. Cooling down of the plasma edge redistributes the current density inside the plasma, sharpening the current density gradient at the front of the cooling wave; this wave propagates from separatrix inside the confined hot plasma due to the edge cooling by the injected gas. Then, a plasma instability develops in the bulk plasma when the steep current density gradient crosses the magnetic surface with the safety factor $q = 2$. Development of the instability leads to stochastization of the magnetic surfaces which, in turn, drastically increases the cross transport of energy and particles, thus triggering the TQ.

Basing on the sequence of events during pre-TQ, described above, it is natural to put a question on the minimum amount of the noble gas, which necessary for TQ triggering. It is evident that if the amount of the injected NG is not enough to drive the current density gradient to the $q = 2$ surface, then the instability is not developed, so the bulk plasma remains untouched and the discharge will be gradually recovered.

For assessment of the minimum amount of the injected gas the JET Pulse No: 77806 has been chosen. This pulse has been interrupted with injection of 5.6×10^{22} particles of gas mixture containing 90% D_2 and 10% Ar and the pre-TQ time has been measured as 8ms. A parametric study has been performed using the TOKES code with sequentially decreasing amounts of injected gas. The results of these simulations show that the pre-TQ time (the time, needed for TQ triggering) monotonically increased with decreasing the amount of injected gas. It has been found that a thermal quench could be triggered with 40 times less gas than usually done in the JET experiment. The calculated pre-TQ time for this case is 30ms. Simulation of MGI with 80 times less injected gas does not triggered TQ.

3. DISCUSSION

Injection of huge amount of NG inside the tokamak vacuum vessel for disruption mitigation creates problem for the next pulses because pumping out of this gas is rather difficult problem: in JET with CFC wall it was usual to perform a parasitic pulse after MGI to remove the rest of NG. With ILW the situation is improved [6], but in ITER this problem can be aggravated because of much larger amount of the injected gas. So, drastic decrease of the injected NG is desirable, but in this case the probability of runaway electrons (RE) generation is also drastically increased. Interaction of the RE with tokamak walls is believed to be a big problem, causing melting and even vaporization. Extrapolation of the wall damage on ITER conditions predicts wall melting up to 4-5 mm in the worst case. To avoid the RE generation the disruption mitigation is performed with huge amount of NG, much more than it needed for the thermal energy irradiation.

4. FIRST WALL PROTECTION AGAINST RE

We propose completely different approach to mitigation of the wall damage. The thermal energy of the confined plasma should be converted into radiation using MGI with a minimum amount of NG. Then, one can allow RE generation and the energy of RE beam should be deposited onto special sacrificial diaphragm. RE beam moves in radial and vertical directions much slower than its toroidal gyration does, the gyration proceeds with the velocity of light. That means that the radial and vertical shifts of RE trajectory during one toroidal gyration are very small, much less than 1 mm, so all the RE deposited to the most protruding part of the tokamak wall. If one assumes that the RE beam is moving to arbitrary part of wall keeping toroidal symmetry, than it would be enough to have the diaphragm in one poloidal plane, but this assumption is too optimistic. In reality, one should provide the diaphragm at few toroidal positions, depending on the anticipated toroidal asymmetry of the RE beam. More of that, the diaphragm should not be gapless in poloidal plane also: one may propose it as a set of 'nails' protruding on few cm from the wall. Optimization of the diaphragm material, design and position depending on RE spectrum, energy deposition, toroidal and poloidal asymmetry of the RE beam is a separate engineering problem to be solved, but it is worthwhile to estimate roughly the diaphragm damage with the RE beam.

Preliminary modeling for interaction of RE beam with one 'nail' has been done using ENDEP and MEMOS codes for RE beam parameters characteristic for ITER: total kinetic energy 20MJ and exponential energy spectrum $f(E) \sim \exp(E/E_0)$ with $E_0 = 12$MeV. The results of the simulations for the 'nail' of 2×2cm cross section and for the bar with 20cm poloidal width and 2cm thickness are shown in Fig.5. The simulations have been done without taking into account the plasma shielding effect which may drastically decrease the wall damage in case of high heat flux because the shielding became more efficient with increasing the flux.

The shielding effect consists in a reduction of heat flux to the wall due to irradiation of the RE beam energy from the plasma produced from vaporized nail material. RE beam melts and vaporizes solid tungsten and ionizes the W vapor in front of the heated surface after 0.1ms of heating. Then, this W plasma expands mainly along the strong magnetic field. Stopping of next RE does not depend on the W density, but mainly on the amount of W, which the electron passes till it stops. That is, the RE power deposition to the W plasma is the same as inside the solid W layer before vaporization. However the energy deposited into the W plasma does not affect the nail, but rather reradiated to the vacuum vessel and to the near wall. So, vaporization of solid (or liquid at that time) nail stops. This is true only if one can neglect the W plasma diffusion across the magnetic field. The diffusion decreases the amount of W on the way of RE, so due to the diffusion some additional heat flux can reach the W wall causing further vaporization and ionization. Simulations of plasma shielding done in [7,8] for carbon have shown that the diffusion, which depletes the plasma shield and the additional wall vaporization are compensating each other, maintaining quasi-stationary process. As a result, after initial W nail vaporization all the rest of RE energy deposited to the W plasma shield and reradiated to all directions, thus redistributing the heat load to much larger wall area.

All these processes should be accurately simulated, but one can roughly estimate the importance of shielding effect for RE. Power deposition from RE to the W plasma is huge, but the plasma temperature cannot be much larger than ~10eV because of 'radiation barrier' – tungsten plasma have extremely high luminosity at such temperatures, so all the deposited energy is irradiated. From this approximate value one can estimate the W plasma expansion. W plasma propagation along the magnetic field is similar to the 1D gas expansion to the vacuum. It is well known that this expansion proceeds with the velocity up to 3 sound velocities [9]. From this one can estimate the plasma cloud length as ~30cm after 0.1ms and as ~15m after 5ms. RE beam energy irradiated from this thin and elongated W plasma layer and redistributed over the neighboring wall area, which is several orders of the magnitude larger than the area of the diaphragm wetted by the RE beam.

CONCLUSIONS

Simulations of massive noble gas injection into the JET plasma have been performed using the TOKES code. The results of these simulations have been verified by comparison with time dependences of line integrated densities for JET H-mode Pulse No's: 77806 and 77808 terminated with MGI of the gas mixture of 90% D_2 and 10% Ar and with L-mode Pulse No: 76314 terminated with Ne injection. Characteristic features of the LID signals have been explained by the simulated plasma dynamics and reasonable agreement between measured and simulated signals have been obtained.

A parametric study with TOKES code has been performed for estimation of minimum amount of injected gas, needed for triggering TQ in JET Pulse No: 77806. According to the simulation results the amount of the gas mixture, used for termination of this pulse can be reduced 40 times. The simulations performed show that even this small amount of injected gas is enough for irradiation of the thermal energy.

Massive injection of such small amount of the gas should generate RE in ITER with rather large probability. For mitigation of the tokamak wall damage with these RE a special sacrificial diaphragm, consisting of several W 'nails' with sizes 2×2cm or of bars with 20×2cm has been proposed. The 'nails' should protrude on 5-10cm from the wall; their distribution in toroidal and poloidal directions depends on the toroidal and poloidal asymmetry of RE beam. The diaphragm design should be optimized separately.

Rough estimation for the sacrificial diaphragm damage with RE beam of 20MJ shows that the erosion of nail is 2.5 cm and erosion of the bar is 0.5cm. Shielding with plasma, produced from vaporized diaphragm material can decrease this value more than one order of the magnitude, so this effect should be simulated. But, even without shielding one can estimate that each bar can survive ~10 disruptions and the diaphragm may consist of several tens of such bars, so the diaphragm can survive at least 10^2-10^3 disruptions.

Being stopped in the sacrificing diaphragm the RE beam induced currents in the wall. These Ohmic currents heat the wall, depositing the poloidal magnetic field energy. This additional heating should be simulated in the next paper, but for rough estimation one can mention that these Ohmic currents distributed over whole toroidal circumference of the wall, neighboring the RE beam. This area of the magnetic energy deposition is huge in comparison with the RE beam deposition area at the diaphragm, so this heating is most probably tolerable.

ACKNOWLEDGMENTS

This work, supported by the European Communities under the EFDA Task Agreement WP10-PWI between EURATOM and Karlsruhe Institute of Technology, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The authors would also like to thank Dr. Michael Lehnen for helpful discussions of the RE problems.

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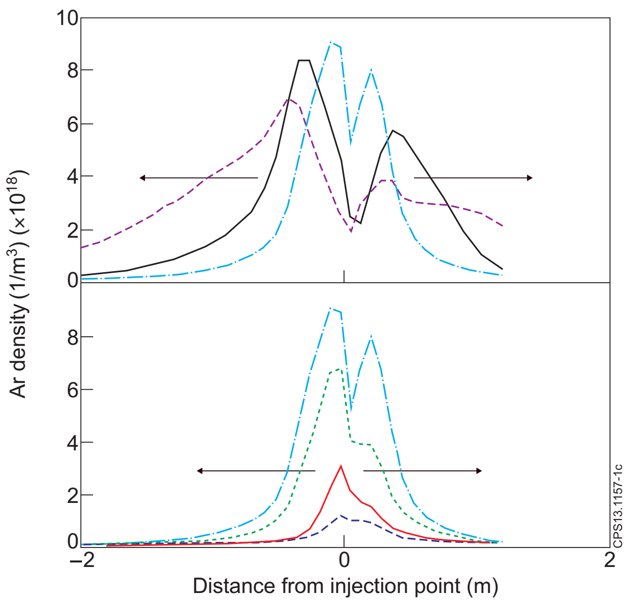

Figure 1: NG plasma density profiles at consequent time moments simulated with TOKES code. The plasma spreads along the magnetic field line. The source of NG plasma situated at the origin, where NG flow crosses the MFL and produces the NG plasma due to ionization. In the lower panel are shown Gaussian-like profiles, when the plasma source is active, in the upper panel – continuation of the plasma expansion and split of the profile onto two Gaussians, moving in opposite directions.

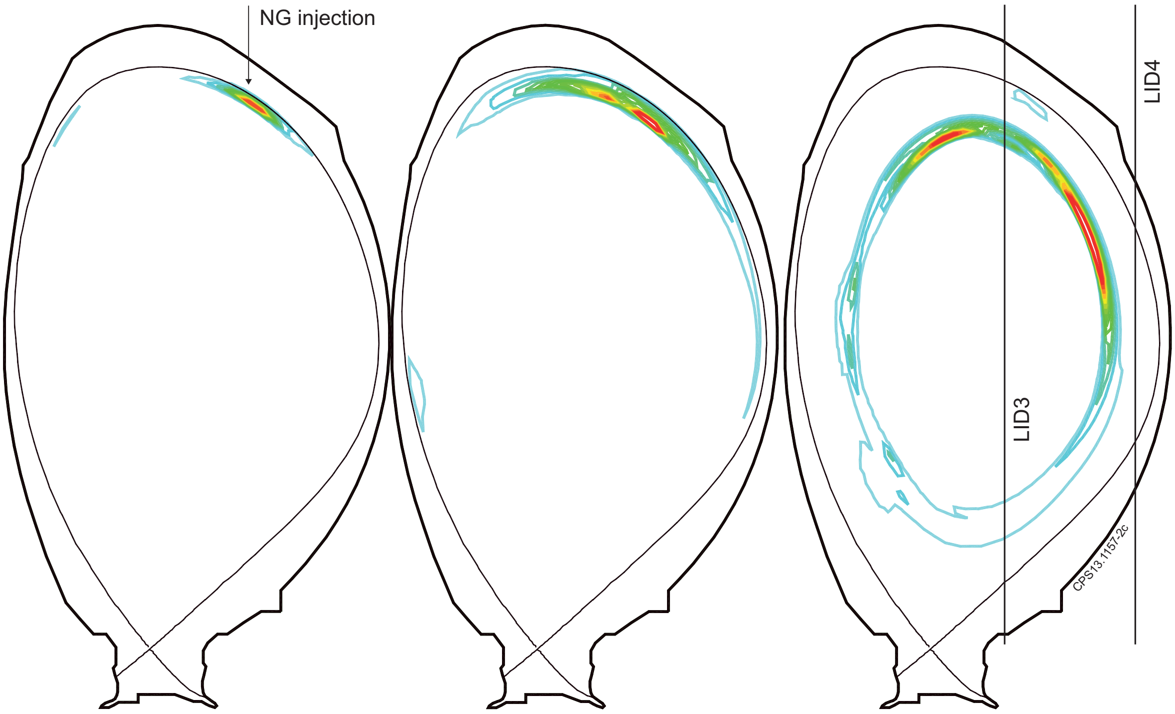

Figure 2: Result of TOKES simulation of the JET Pulse No:77806 terminated with MGI. Shown are 2D Ar plasma density contours at 3 consequent time moments. Two vertical lines are the lines of sight for LID3 and LID4 measuring devices.

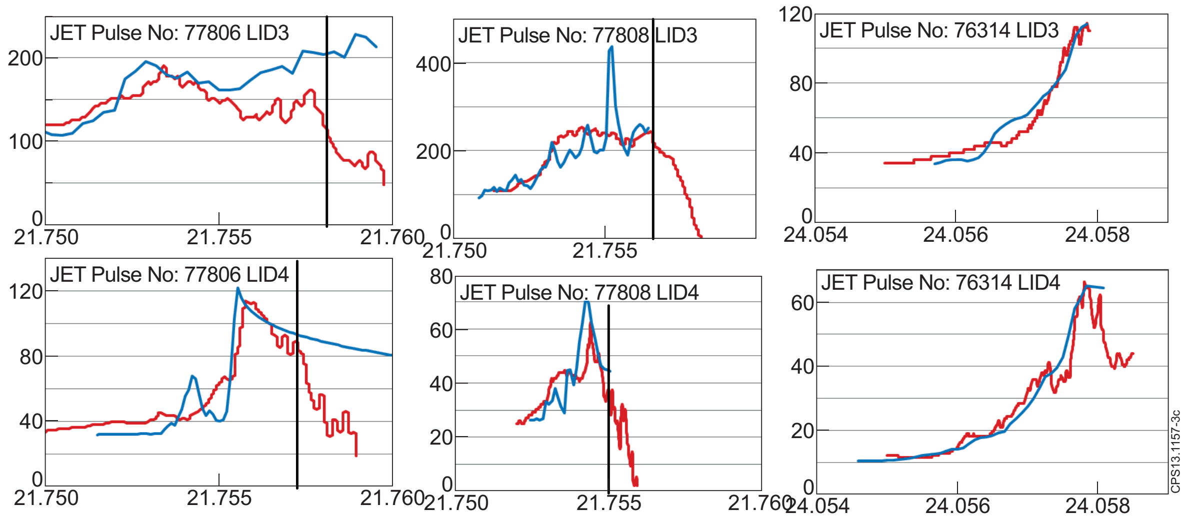

Figure 3: Comparison for line integrated densities LID3 and LID4 measured in JET (red lines) and simulated with the TOKES code (blue lines). Lines of sight for these LIDs are shown in Fig.2. The measured curves are valid till the vertical black lines; at later time the diagnostic fails.

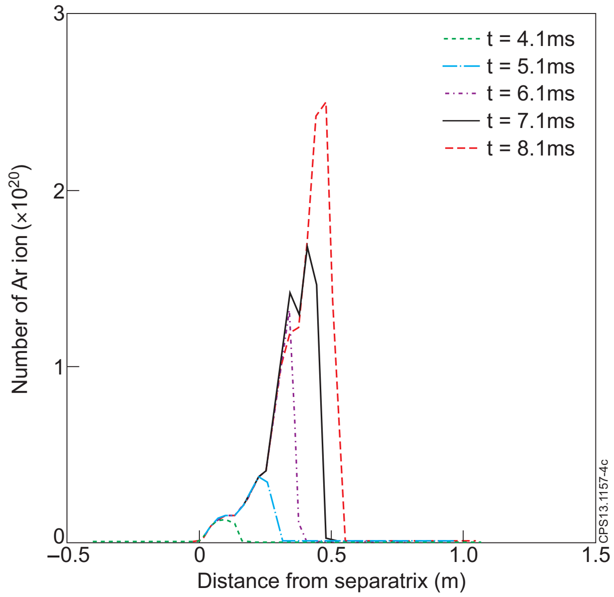

Figure 4: The result of TOKES simulations shows that the radial dependence of total number of Ar ions on the magnetic surface is very steep function. Shown are the profiles at 5 time moments.

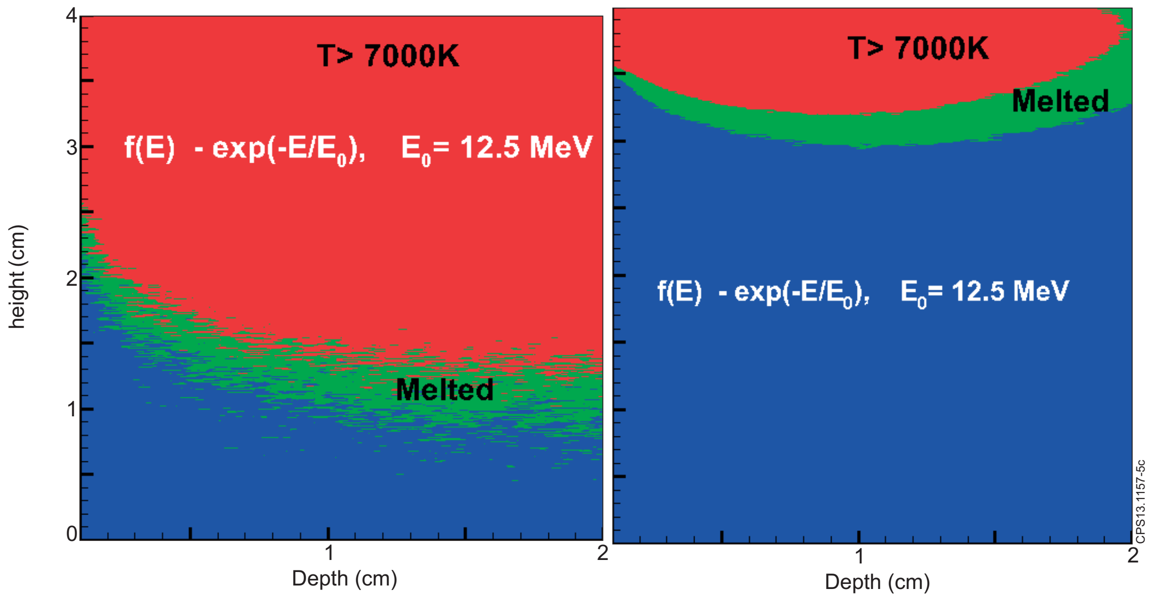

Figure 5: ENDEP and MEMOS codes simulations without shielding effect show that the RE beam of 20MJ total energy evaporates and ionizes ~2.5cm of W from the 'nail' with 2×2cm cross section (left panel) and ~0.5cm from the bar of 20×2cm (right panel).