3 Euratom fusion programme

Work in fusion plasma physics and technology within the FP7 Euratom fusion programme includes the following tasks:

- Tokamak modelling
- Portable LIBS device for calibrated measurements of material deposition and composition of the walls on plasma source
- Study of laser based diagnostic methods, photonic cleaning and spectroscopy (including LIBS) in perspective of next-step fusion devices (including ITER)
- Spectroscopic and ion diagnostics for laser-induced removal of fuel and co-deposits from PFCs in tokamaks
  Including:
  - Removal of the deposited materials by laser ablation techniques. Investigation of carbon layers with varying concentrations of Al (Be analogue), W and W-Be
  - Investigation of film break-up processes during laser cleaning. Monitoring of the composition of gases and particles released from the target
  - Irradiation of TEXTOR and AUG samples containing material mix of carbon and tungsten by the Nd:YAG pulsed repetitive laser. Use of optical spectroscopy together with ion diagnostics to characterize chemical composition of samples
  - Photonic cleaning methods
  - Conversion of deposits to dust
- Activation technique in a cross-check experiment for high resolution neutron spectrometry
- Development of gas detectors for 2.5 and 14 MeV neutron measurements utilizing activation method and for soft X-ray detection
- Analysis of emerging options of IFE on the basis of results of experiments and numerical modelling

3.1 Integrated Tokamak Modelling

Tokamak modelling

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The effort to develop modular system of codes, modeling various physical processes, has been undertaken in TF-ITM project. The modules should be implemented in the frame of data processing system KEPLER. The participation in TF-ITM Project 3 in developing ETS (European Transport Solver) is presented in this report. The ETS was tested for cases of transport barrier and stiff problem. For some transport model the diffusion coefficient depends nonlinearly on gradient of the solution. In this case the numerical instabilities can appear for the acceptable small time step. The several methods of the suppression of the numerical instability was considered. The work in this field will be continued next year.

The ITS (Impurities Transport Solver) was tested by comparing the results of the codes ETS/ITS with the results of the codes Jetto/Sanco. The Amns data obtained from ADAS has been included into ITS. The Kepler actor was generated for ITS and included into general Kepler workflow.

Test of ETS for case of transport barrier

The testing of barrier dynamics was performed for single diffusion equation in cylindrical geometry for two models of diffusion. In the first model the diffusion coefficient is discontinuous with discontinuity position defined by critical value of e-folding length

$$D_i = D_1 \text{ for } -\frac{n_i}{(\partial n_i / \partial \rho)} > L_{cr}$$

$$\text{and } D_i = D_2 << D_1 \text{ for } -\frac{n_i}{(\partial n_i / \partial \rho)} < L_{cr}$$

In the second model the diffusion is defined by function $D=D_0 + D_1/(1+(|n'|/n'_{cr})^n)$. The dynamics was considered for two scenario:

- the source term increased in time
- constant source and initial distribution function *n* equals zero.

The numerical results are compare with the analytical ones obtained by manufactured solution method. The obtained results using solver 3 and solver 7 from ETS reproduced the position of the barrier with significant error The decreasing of mesh size and time step only partly reduced the error.

Stiff transport problem

For the stiff transport model the several method of suppression of numerical instability was consider. In the first method the extra diffusion term is introduced and compensated by source term defined by the solution from previous time step.

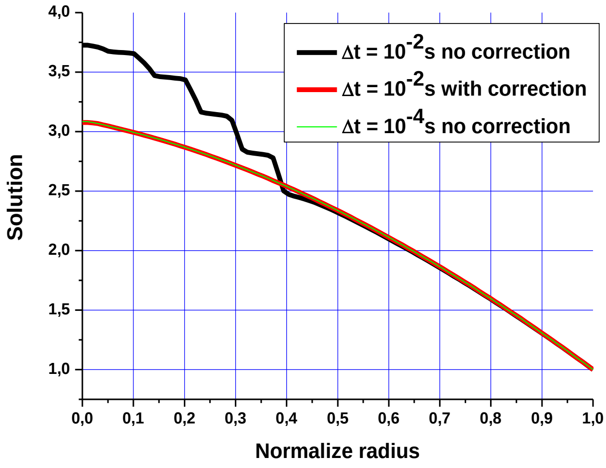
$$\frac{\partial \rho n}{\partial t} - \frac{1}{\rho}\frac{\partial}{\partial \rho}\left(\rho (D_1 + D_{ad}) \frac{\partial n}{\partial \rho} \right) = S - \frac{1}{\rho}\frac{\partial}{\partial \rho}\left(\rho D_{ad} \frac{\partial n_{\acute{o}ld}}{\partial \rho} \right)$$

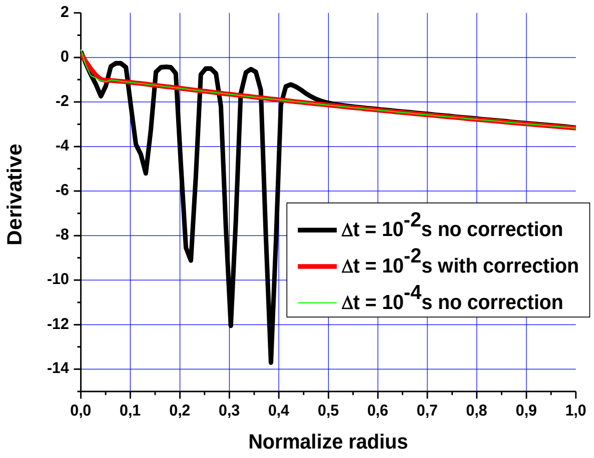
In the second method the compensation is done by extra convection term.

$$\frac{\partial \rho n}{\partial t} - \frac{1}{\rho}\frac{\partial}{\partial \rho}\left(\rho (D_1 + D_{ad}) \frac{\partial n}{\partial \rho} - Vn \right) = S \qquad V = D_{ad} \frac{\partial n_{old} / \partial \rho}{n_{old}}$$

$$D = 0.1 + (|n'| - n'_{cr})^{0.5} H(|n'| - n'_{cr})$$

The smoothing procedure can be used to check if the numerical instability is suppressed.
The results for the first method are presented below. The solution and space derivative of the solution for initial distribution equals zero and for time equal 1 s. It follows from the results that for presented case the time step can be increased by two order with preserving the accuracy.





The work will be continued in order to have the procedure able to adjuste automatically the time step and the value of extra diffusion .

Impurity transport solver

ITS solves the 1.5D transport equations for the density of each ionization state for each impurity. Different ionization states are coupled by the ionization and recombination processes. The time step is divided into two subintervals. In the first half step the equation are solved starting from the lowest ionization stage to the highest ionization stage. In the second half step, the 1D equation are solved starting form the highest ionization stage to the lowest one. In the solution of each ionisation stage the new value of impurity density calculated in previous ionization stage is used.

ITS was tested by comparing the results of the codes ETS/ITS with the results of the codes Jetto/Sanco. The Amns data obtained from ADAS has been included into ITS. The Kepler actor was generated for ITS and included into general Kepler workflow.

3.2 Plasma-Wall Interaction

Portable LIBS device for calibrated measurements of material deposition and composition of the walls on plasma source

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Among other candidate methods, Laser Induced Breakdown Spectroscopy (LIBS) offers the possibility of non-contact real-time measurements of contents of different components in a sample under analysis. This specific feature looks to be very convenient in perspective of in-vessel tokamak monitoring of the fuel retention in plasma facing components. Moreover, flexibility of the method allows for a distant observation of the laser induced plasma and easy transmission of the signal to detectors with the use of fibers. To assess the possibilities of the method, the task was aimed on investigation calibrated
samples and comparison of the results obtained by collaborating laboratories.

The investigated samples were produced by magnetron sputtering by NILPRP, Romania and contained material mix relevant to the one foreseen for components of the next step fusion devices. Glow Discharge Optical Spectrometry (GDOS) was used as a quality control technique for measurement of the coating thickness and impurities under production conditions. In particular two sets of samples have been investigated:

- Titanium substrates with 10 μm tungsten layer with 1-2 μm Molybdenum interlayer. Carbon and oxygen as surface contamination.
- Titanium with C:W layers of two fixed ratios contaminated with O on the surface.

The experiments with the use of the Mechelle5000 spectrometer equipped with iCCD camera of the laser plasma generated by 3-3.5 ns, 300 mJ pulses of Nd:YAG laser system operating on 1064 nm wavelength with repetition rate up to 10 Hz allowed for reliable qualitative analysis of all samples and for preliminary estimation of the calibration curve for carbon component in the samples of the second type.

The main part of the experiment was carried on with a beam of power density of 5 MW/cm^2. In case of the presence of carbon it was important to adjust a proper value of time delay (time between the laser pulse and start of acquisition) which had to be short enough to observe recombination of speedily propagating carbon ions. The delay at level of 100 ns was applied. To reconcile observation of carbon lines and tungsten which appears later (about 300-500 ns after laser pulse in applied experimental conditions) relatively long acquisition time has been used – 500 ns. Comparison of spectra evolution for two types of samples with 70 and 82 % of carbon are presented in fig.1.

Integration of the lines of carbon for subsequent shots, in the same irradiation and optical system collection conditions, in samples with different composition ratio of carbon allowed for the estimation of the calibration curve (line) for line intensity in dependence on carbon ratio in the range from 70 to 82 %. The curve is presented in fig. 2.

The results gathered at this stage of experiment allowed for a proper qualitative analysis of the sample and for an attempt to estimate a calibration curve for carbon in a narrow range of concentration, however, further experiments and study are needed for quantitative analysis of the samples. Nevertheless, as far as the present study was firm to assess, such an analysis is possible mainly due to a good stability of the signals attributed to different components in most of the experiments (in which variations of the line magnitudes in steady conditions were not higher than 10 % in subsequent shots).

Although in described experiments, the set-up with a plasma observation in parallel direction to the target was applied, it is more advisable to study set-up with collinear plasma observation (i.e. in direction of the laser beam). Such a set-up was successfully tested in other experiments at IPPLM and gave repetitive results, however, with a bit worse S/N ratio. The optimistic premise for such a set-up is that in the real device diagnostics will work in high vacuum conditions in which the influence of the background is less deteriorating for the measurement signal.

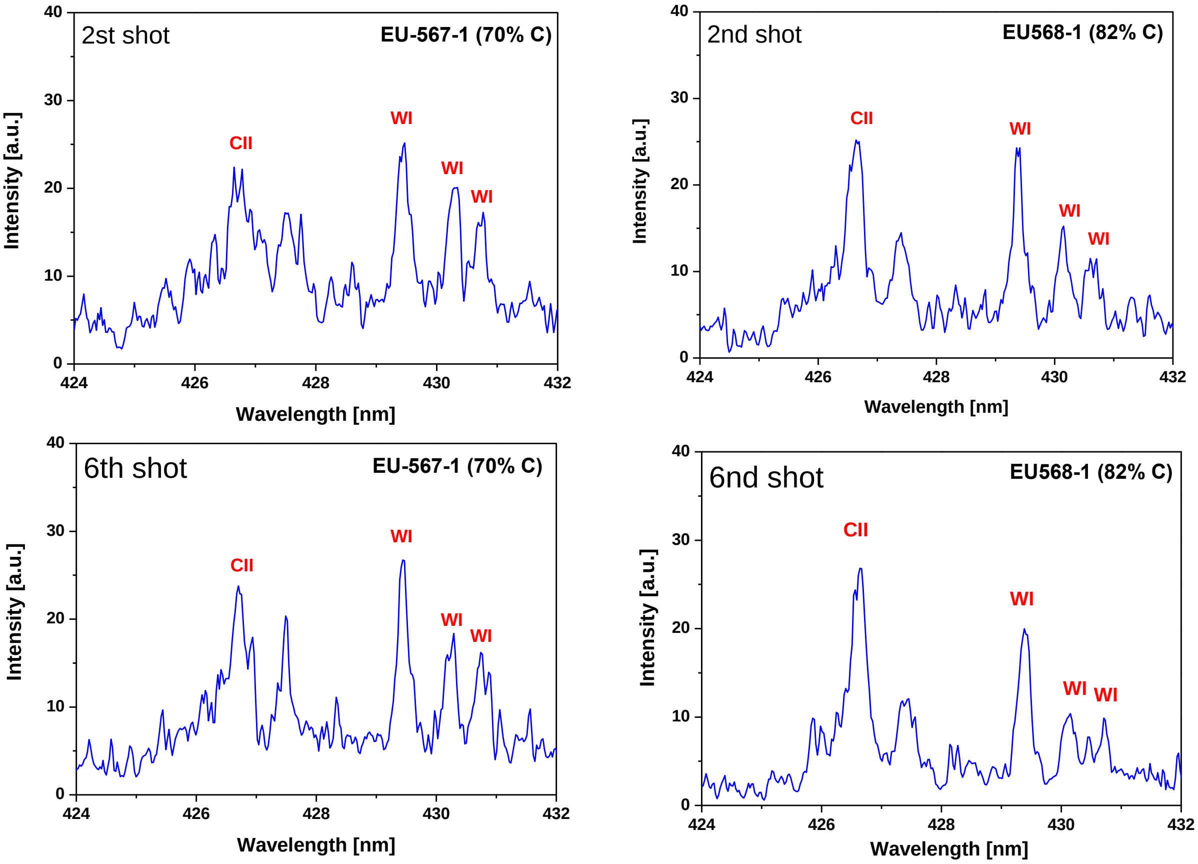

Fig.1. Comparison of spectra evolution for samples with different C concentration

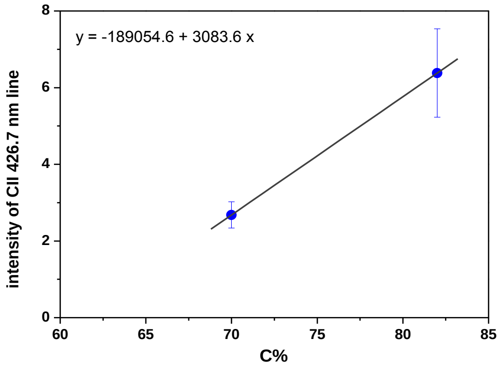

Fig. 2. Calibration curve for carbon ratio in linear dynamic range

The attempt of estimation of the calibration curve was a natural step in the project and even it was not very firm it was a big step forwards, because the features of the laser induced plasma appeared to be stable enough to give results in a reasonable range of confidence. The clearly difference between the spread of obtained intensities of Carbon line for both calibrate samples is seen. The reason could be a fact that sample contained 82 % of Carbon was prepared with larger inaccuracy. The further steps should be aimed on the broadening of the calibration range for carbon (which is accompanied with co-deposition in present device) and on estimating of such curves for hydrogen isotopes which is a goal of this task itself.

Study of laser based diagnostic methods, photonic cleaning and spectroscopy (including LIBS) in perspective of next-step fusion devices (including ITER)

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The project consisted of three following tasks: Divertor Erosion Monitor study, review of the spectroscopic diagnostics foreseen in ITER, and study of periodic dust mobilization from hot surfaces with the use of laser scanning method.
The system for monitoring divertor erosion is of a great importance for ITER as it gives not only information on the condition of the divertor wall which is required for its maintenance but also helps to estimate the amount of material which was removed from the wall and may influence plasma operation as well as safety issues.

The basic feature of such a system is the need of remote operation which makes laser-based and in general, optical non-contact techniques favorable. Laser beams make it possible to probe distant surfaces and moreover do not provide any interference with other systems and are immune against interference resulted from electromagnetic fields. The laser and optical market offers a variety of solutions in terms of laser sources, detectors, waveguides and other optical elements which make it possible to develop a strictly specialized system for given requirements.

Independently on advanced and flexible components laser technology offers the advantage of a few methods with countless variants to measure the quantities of interests which, in case of ITER, divertor are displacement, deformation, thickness/distance difference and vibration with time and spatial resolution dependent on the method, variant and parameters of the used equipment.

In case of the development of the diagnostic system, besides of such issues as demanded accuracy, resolution, operating speed and the range of quantities which are to be measured, the main concern is in the integration of the diagnostics with the device, which part it will constitute. In ITER it is a special issue as the characteristics of the device are rather uncommon with most of available applications. The issue is not only in the specific conditions of thermonuclear device but also in strict spatial conditions also due to presence of other diagnostic and maintenance systems which cannot be interfered by the divertor erosion monitor.

In preparation of the diagnostic system for such a device as ITER, one should also take into account that the other components, although they were designed, are not yet built and mounted which entails some unexpected modifications to the full set-up. To be up to this risk the system should offer enough flexibility to have its set-up modified without lost of performance or in other case to have enough excess in parameters which could be given up while demands are still satisfied.

The basic problem in application of any laser method for ITER is vibration which, if not being dealt with, would corrupt any results for erosion measured as a displacement of the wall surface. Without knowledge about the parameters of the vibration at this stage, we must be prepared that its amplitude will be significantly higher component in the common optical signal than the component which can be attributed to erosion. Moreover, we cannot be sure if the vibration will have a harmonic character, what frequency components it can include or what will be its boundary frequency. As the remedy for this problems only precise measurements of the vibration may be applied.

The most popular approach for the vibration measurement is application of vibration sensors which, in fact, measure the acceleration of the object they are mounted in and are called accelerometers. Many types of the miniature accelerometers which can be mounted inside mechanical components are commercially available. They offer measurements of vibration in range of single Hz to kHz and acceleration even higher than 500 g. Commercially available miniature vibration sensors have dimension not exceeding 1 cm which maybe would allow to mount such sensors on the back side of the wall and in the head of DEM (as we cannot expect that vibration in this location is the same in terms of the amplitude and phase as the one in the wall). The sensors provide an electrical signal dependent on the magnitude of the acceleration which makes it possible to measure amplitude and phase of the vibration. Application of such sensors would not only make the evaluation of erosion rate with the use of laser techniques much easier but would also provide very useful information of the vibration of the components of the device. Such an information would be very convenient for example for evaluation of mechanical stresses and also wear of mechanical components especially in significantly more intensive exploitation than it takes place in presently operating thermonuclear devices.

Another issue is the location of the set-up elements themselves. The solution which offers the best flexibility is putting the device with collection optics under the dom and providing all necessary signals in an optical form with the use of fibers, but if the solution is not possible, the device may be also port-plugged. Regardless of the location the device should be screened against electromagnetic fields which can be obtained by application of a special box designed by an expert.

For installation of a optical diagnostic system in a tokamak, an important issue is also concerned on deterioration of the optical components due to deposition of contamination. Due to this a possible solution can be offered which relies on application of a high-powered pulsed fiber laser for cleaning of the elements. The fiber lasers offer a choice of adjustment of power density which may remove deposits from windows and mirrors without damaging the elements themselves, however its value depends on the properties of the deposits which are not known at the moment with a satisfactory accuracy. Nevertheless the optimal parameters of the laser beams can be adjusted later due to a great flexibility in control of lasing parameters in fiber system.

Industry offer in the field of laser measurements of distance includes a variety of devices which provide satisfactory parameters for DEM for ITER. Instruments of companies as Metron, LDI, Romer, Capture3D, Nvision and others offer remarkable resolution, accuracy and time resolution. The products contain not only apparatus but also software with extensive capabilities as automatic searching for areas of given properties or generating so called ‘wather maps’. A sample photo of a set-up provided by ROMER is presented in fig 1. Disadvantage of application of such a device is its adaptation for DEM needs as commonly they are used on stages with a specialized set-up. Industry ready-to-use devices are inflexible in accessing to their components which probably makes their application for ITER extremely difficult.

Fig. 1. An arm for laser scanning inspection system provided by ROMER

In the second task a review of the spectroscopic diagnostics foreseen in ITER has been done. Monitoring of the erosion in a tokamak is an important issue from a point of view of the device operation and safety. Besides of development of system for its measurements it is also important to investigate if in the present ITER design any systems which would be helpful for the same purpose. As the candidate method the spectroscopy has been suggested due to its capability to measure the radiation of particles eroded from the wall. The goal of this task was to review the spectroscopic systems foreseen for ITER in terms of their usability for monitoring the erosion in the main chamber and divertor zones. To reach this goal the following problems should be solved:

- specification of the spectral range of a spectrometer to observe the lines which may be useful to characterize influxes of materials eroded from the wall
- establishment of the candidate systems present in ITER design which would be suitable for observation of the demanded lines,
- assessment of the efficacy of the methods for quantitative erosion measurements.

To monitor the erosion of the divertor and main wall spectral lines of carbon, tungsten and beryllium should be under observation. Together with them, it may be also useful to observe spectral lines of hydrogen isotopes. The study describes the choice of lines which may be most convenient for such observations together with specification of the diagnostics which could be applied in this purpose.

Unfortunately an important conclusion is also that the dependence between the impurity influx and spectroscopic data is complex enough to make drawing any estimation on the erosion in dependence of measured spectra extremely difficult. The disadvantages of the method which amplify the difficulties are its incapability to measure the erosion due to non-local deposition, prompt redeposition and melting/brittle destruction. Based on this, it is possible to conclude that the spectroscopic diagnostics cannot be used as the only diagnostics for erosion measurements; however; it can be implemented as an auxiliary system for monitoring erosion phenomena especially in regions which erosion processes are more isolated i.e. main wall.

The study in the framework of the last task was based mainly on the recent results as well as on previous results obtained at IPPLM and other labs and described in the literature. In general, the study leads to conclusion that removal/mobilization is easy to be obtained with the use of laser irradiation, both for thick or thin deposits, but still optimization of the process in regard of application is needed and must be performed carefully with special consideration for the properties of materials which are to be removed. In the case of application of the Nd:YAG laser, regardless on the power density (in the range of parameters of the used system, i.e. ~10^6-10^{10} W/cm^2), the removal is inescapably accompanied by the macroscopic and microscopic dust generation. In these terms the removal of co-deposites (especially those which are thick) can be refereed to removal/mobilization of dust particles. In the experiments the dust was collected by the means of various type of collectors (aluminum cylinders, glass plates, special nets for TEM measurements) and thoroughly analyzed which confirmed that it still contains some amounts of fuel.

The application of the solution in ITER is complicated mainly due to the need of application of asophisticated mechanical set-up especially designed for the harsh environment of a thermonuclear reactor. Two possible solutions can be taken under consideration: port plugged set-up and set-up on a remote handling system.

The first one may be designed in two possible configurations:

- The laser beam can be directed by movable/rotating mirrors which allows to scan the laser beam over the areas which may have deposited hot dust particles. In this case the dust particles are released from surface (in form of ablated material in the case of carbon or metallic droplets in the case of Tungsten or Beryllium) and fall down in case of vertical surfaces or are deposited in closes or further vicinity of the laser interaction area. This phenomena enforces the need of application of the dust collectors (possible in form of a specialized vacuum cleaner or an electrostatic collector) which cannot be integrated with a port-plugged system. There is a possibility of application of such a collector on the remote handling system and integrating it with a port plug laser head, but in this case integrating of both laser head and dust collector on the one remote handling system seems to be more reasonable.
- In order to move the hot dust from hot zones to cold zones laser-induced shock wave can be used; however; it requires some pressure in the vessel. The surface needs to be irradiated with a significant incident angle ($\leq 60°$). Then the irradiation of the all the surface will require the use of several port plugs (around 8) to have a good coverage of the surface vessel.

The remotely handled solution can be developed by designing an integrated device which can consist of a laser head (or just a laser light delivering system ended with light guiding optics) and a dust collector. In this system the crucial issue is a possibility of the design of an appropriate system of delivering of optical pulses of a given pulse parameters and at given wavelength. Another important issue is the design of the light collecting device. This problems are in scope of the another task of this program.

Spectroscopic and ion diagnostics for laser-induced removal of fuel and co-deposits from PFCs in tokamaks

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The research conducted in the framework of this project in 2010 included numerous tasks under contracts with EFDA-PWI and JET-FT. The tasks were aimed at various issues consistently covering the area of fuel removal, dust production, first wall erosion and diagnostics for these concomitant phenomena.

Development of the laser removal methods as well as the suitable diagnostics to evaluate their performance has been in the scope of the works at Division of Laser Plasma which fruited in optimization of the method based on the application of Nd:YAG pulse laser for carbon based material and components, development of the LIBS method for the real time characterization of removal and wall composition, application of the LIBS diagnostics for mixed-material analysis or extensive material investigation of the laser treated components and surfaces in collaborating labs.

The experimental set-up has been upgraded and completed in 2010 what is shown in fig. 1. In comparison with the previous years set-ups, the vacuum chamber was equipped with two microvalves which allowed to conduct experiments in ambient of gases and their mixes. In this part of the research, the experiments were conducted in the atmospheres of H_2, N_2, O_2, Ar and their mixes in pressures range from 100 Pa – 100 hPa.

A number of calibrated samples with different mixes of ITER relevant materials have been investigated with the use of LIBS in the same set-up as for the AUG samples. In frame of the project the series of experiments performed in close collaboration with CIEMAT have been done. They were aimed on investigation of the influence of the application of various gasses on the process of laser removal of thick co-deposit from a TEXTOR limiter sample. As concomitant aims the investigation of the influence of the fiber-laser irradiation on the fuel inventory and behavior of dust during the laser interaction should be highlighted.

In all experimental series the removal rate during laser irradiation was positively correlated with the increase of the gas pressure as well as in all cases the process of removal needed less Nd:YAG laser pulses when the Yb:fiber laser had been used for pre-irradiation.

For the vacuum conditions, the comparison of the process of removal preceded or not by the fiber laser treatment illustrated as spectral changes corresponding to subsequent pulses of Nd:YAG laser is shown in fig. 2. It can be clearly seen that in the case of fiber-laser pre-irradiation the level of the ratio of the intensities of deuterium and carbon lines (D/C) started from a significantly lower level than in the case when the virgin co-deposit layer was irradiated. As during the Yb:fiber laser pre-irradiation no dust particles were observed it suggests that a significant part of fuel inventory was released during this process by the means of desorption. In case of the removal in vacuum it was also noted that the D/C ratio after five Nd:YAG laser shots was also notably lower in the case when the pre-irradiation were applied.

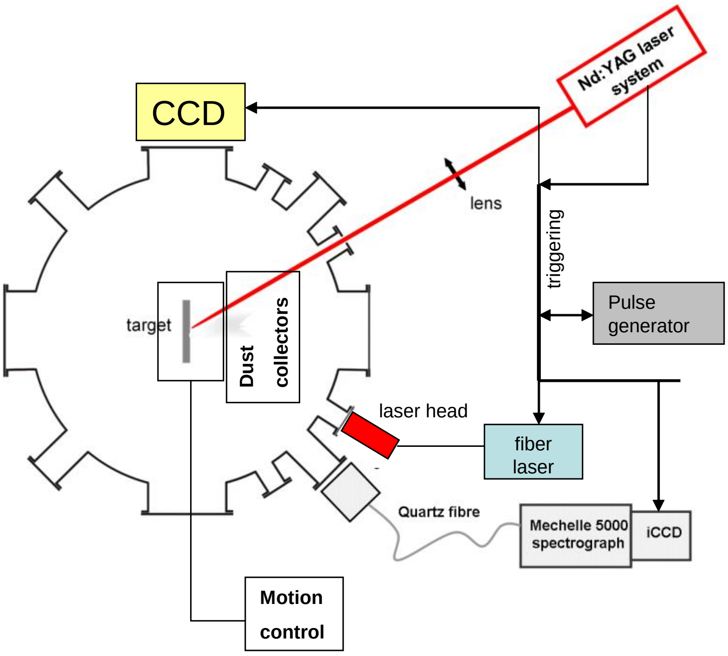


Fig. 1. Upgraded experimental set-up for PWI measurements

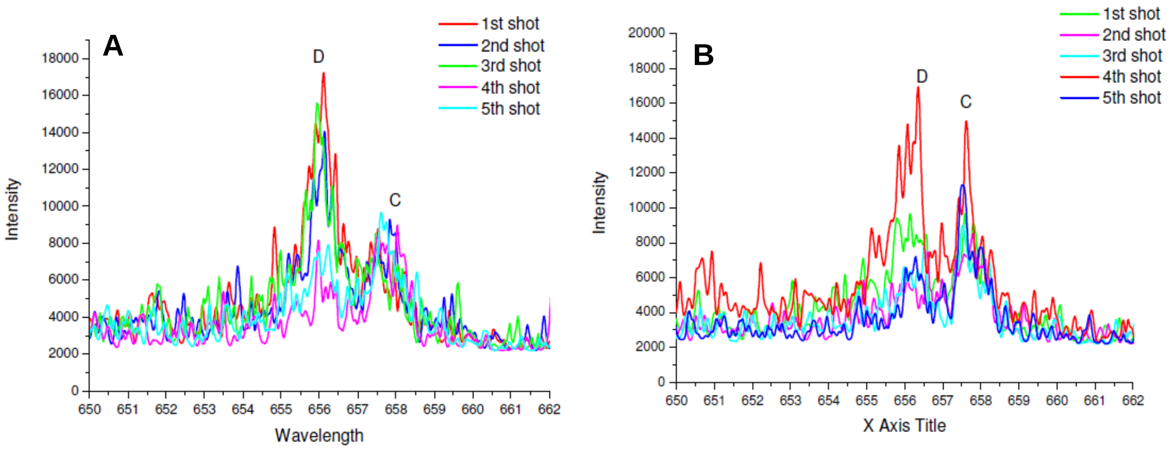
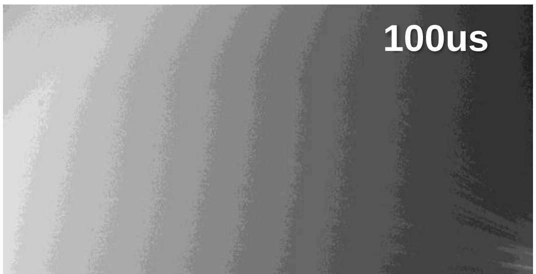


Fig. 2 Comparison of the spectra obtained in vacuum for 5 subsequent laser pulses without (A) and with (B) fiber laser pre-irradiation

Together with LIBS investigation the CCD camera observation has been carried on for the same experimental series. As it has been found in previous experiments the observable dust was being released 40 μs after the laser impact. The velocity of dust particles was estimated in range of 100 m/s in vacuum and it was decreasing with mass and pressure of the gas when it was applied. Moreover, after the image processing and zooming of the dust traces, the "comet" effect for the high pressure of active gases became apparent which suggested that dust particles were "burning" during their flight. Especially for higher pressures artifacts of long-living plasma even after 100 μs were seen (fig.3).



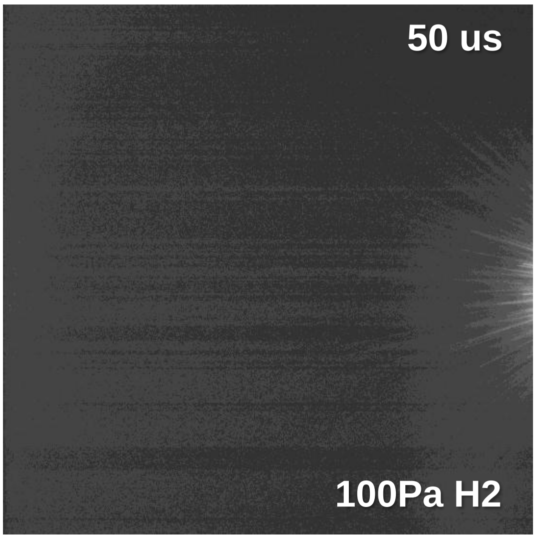


Fig. 3. Images from CCD taken in different experimental conditions with the use of TEXTOR limiter sample (located on the right side of the images). Both images were taken 40 μs after laser pulse

The results obtained in 2010 suggest that the works in this field should be continued with focus at mixed material and optimization of the fiber-laser operation. In the upcoming year the research will be upgraded by the application of a new profilometer system which was purchased in the end of 2010 and will be especially for the characterization of laser induced craters and tracks.

3.3 Fusion plasma diagnostics

Activation technique in a cross-check experiment for high resolution neutron spectrometry

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The activation method is commonly used (mainly in fission reactors and accelerator-driven generators) to determine neutron fluence or energy spectrum. It is basing on recovering the information about neutrons by registering the products of induced reactions.

As the detectors there are used the samples of selected materials. In those samples irradiated in neutron field there are induced reactions creating radioactive nuclei. The chosen materials have relatively high cross-section for reaction with neutrons in specified energy range. The reactions are chosen in such way that they products decay with emission of gamma-ray. Therefore they can be detected by means of gamma-spectrometry.

For every registered reaction there is calculated reaction rate:

$$\alpha_i = \int_0^\infty \sigma_i(E)\cdot\varphi(E)\cdot dE \qquad i = 1, \ldots, n \qquad \text{(R1)}$$

where $\sigma_i(E)$ – i-th reaction cross-section, $\phi(E)$ – neutron flux density, E – incident energy, n – quantity of reactions.

The set on n degenerate equations (R1), which are a special form of Fredholm integral equations, makes ill-conditioned problem, i.e. it does not allow to unique determine neutron flux or spectrum because there is infinity number of ϕ(E) functions which satisfy the set of equations (R1) but only one of them is physical correct. It causes that such problem should be solved by means of approximate (numerical) methods. In general such kind of equations is solvable in discrete form and leads to the set of n linear equations:

$$\alpha_i = \sum_{j=1}^{m} \sigma_{i,j} \cdot \varphi_j \qquad i = 1,...,n \tag{R2}$$

where m is the number of energy bins (groups), $\sigma_{i,j}$ – mean value of i-th reaction cross-section in j-th energy bin, ϕ_j – mean value of neutron flux density in j-th energy bin.

To determine neutron spectrum in n energy ranges by means of activation method there should be registered n nuclear reactions (and therefore n reaction rates). It is not possible to obtain accurate solution for more than n ranges. Usually the number of energy bins needed to precise description of the spectrum is greater than the number of registered reactions (m > n). It causes that the problem is not solvable without providing some additional information about demanded spectrum being it the best available approximation. This information arise usually from physics of investigated phenomenon or from neutron transport calculations, e.g. by means of MCNP code. Deconvolution algorithms are used to modify such initial information until obtain compatibility with experimental data.

The method is basing on recovering the information about neutrons by registering the products of induced reactions. As the detectors there are used the samples of selected materials. In those samples irradiated in neutron field there are induced reactions creating radioactive nuclei. The chosen materials have relatively high cross-section for reaction with neutrons in specified energy range. The reactions are selected in such way that they products decay with emission of gamma-ray, therefore they can be detected by means of gamma-spectrometry. Exceptionally, there are also used reactions leading to beta-radiation.

Additionally, materials of the samples can to be chosen in such a way, that neutrons with energies of 14.1 and 2.45 MeV and scattered neutrons can be measured separately.

The uncertainty depends mainly on the accuracy in the cross sections and in the geometry factor. It is acknowledge that the yield of the 2.45 MeV neutrons can be determined with an accuracy less than 10%.

Selection of the activation materials

Apart from indium which is particularly well suited as an activation detector for plasma devices, also other materials are needed. Developing the activation method of neutron measurements at JET we are still searching for suitable activation materials

To carry out the activation measurements at JET there were selected the reactions which meet the requirements of measuring procedure.

It means that isotopes naturally occurring in activation materials must have high enough reaction cross-section in relevant neutron energy range. At the same time, the products of these reactions should decay with appropriate half-live and emit suitable gamma-photons.

The neutrons at JET come from d-d fusion and in small part from tritium burn-up. Originally they are 2.45 and 14.1 MeV in energy respectively which is broadening by reason of plasma temperature and applied heating systems. The plasma pulse at JET takes usually about 0.5 minute, whereas the main neutron emission occurs only during Neutral Beam Injection (NBI) heating which lasts for a few seconds only. Applying procedure demands about 0.5 minute more of time for operation. Therefore there were chosen reactions sensitive to characteristic plasma neutron energies which products decay with half-live counted in more than a few seconds. Because of properties of applying gamma-spectrometer the reaction products must emit during decay gamma-line of energy from 100 keV up to 2000 keV. During selection there were assumed that the most useful cross-section is counting at least in hundreds of milibarns. The materials selected in our laboratories have been subjected to numerous of testing measurements.

Table R1

№	Reaction	Threshold [MeV]	Product half-live
1	Ti-47 (n,p) Sc-47	1.8	3.3 d
2	Fe-54 (n,p) Mn-54	1.8	312 d
3	Ni-58 (n,p) Co-58	1.6	71 d
4	Se-77 (n,n’) Se-77m	0.2	17 s
5	Br-79 (n,n’) Br-79m	0.2	5 s
6	Sr-87 (n,n’) Sr-87m	0.4	2.8 h
7	Y-89 (n,n’) Y-89m	1.2	15.7 s
8	Zr-90 (n,n’) Zr-90m	2.3	0.8 s
9	Cd-111 (n,n’) Cd-111m	0.5	49 m
10	In-115 (n,n’) In-115m	0.6	4.5 h
11	Er-167 (n,n’) Er-167m	0.3	2.2 s
12	Hf-177 (n,n’) Hf-177m	1.3	51 m
13	Au-197 (n,n’) Au-197m	0.5	7.7 s
14	Pb-207 (n,n’) Pb-207m	1.6	0.8 s

Table R2

№	Reaction	Threshold [MeV]	Product half-live
1	Al-27 (n,p) Mg-27	4.3	9.5 m
2	Al-27 (n,α) Na-24	6.8	15 h
3	Ti-46 (n,p) Sc-46	3.8	84 d
4	Ti-48 (n,p) Sc-48	7.4	44 h
5	Fe-56 (n,p) Mn-56	7.0	2.6 h
6	Co-59 (n,α) Mn-56	8.5	2.6 h
7	Co-59 (n,2n) Co-58	10.8	71 d
8	Zn-64 (n,2n) Zn-63	12.6	38.5 m
9	Zr-90 (n,p) Y-90	7.6	3.2 h
10	Zr-90 (n,2n) Zr-89	12.2	4.2 m
11	Nb-93 (n,2n) Nb-92	9.1	10.1 d
12	Mo-92 (n,2n) Mo-91	12.8	15.5 m
13	Au-197 (n,2n) Au-196	8.8	9.6 h
14	Pb-204(n,n’)Pb-204m	2.7	67 m

An important part of measurement by activation technique is spectrum unfolding.It is based on measurements of radioactivity induced in samples by neutron fluxes. From mathematical point of view this process is identical as solving Fredholm integral equation of the first kind. Analyses of seven unfolding methods were carried out – least squares method, minuit routine, Tikhonov regularization method, neural networks, genetic algorithm, Gold and SAND-II algorithms. Computer programs were developed using Gold and SAND-II algorithms. Activation measurement made during shots at JET were used in this process. Results obtained with GOLD were evaluated negatively, it is not the right method for unfolding spectra in the broad energy range (0 – 15 MeV) and several (15-16) activation detectors. Spectra unfolded with the SAND-II algorithm were evaluated better but mainly jagged spectrum below 1 MeV is appeared, due to resonance cross section influence (Fig. 1).

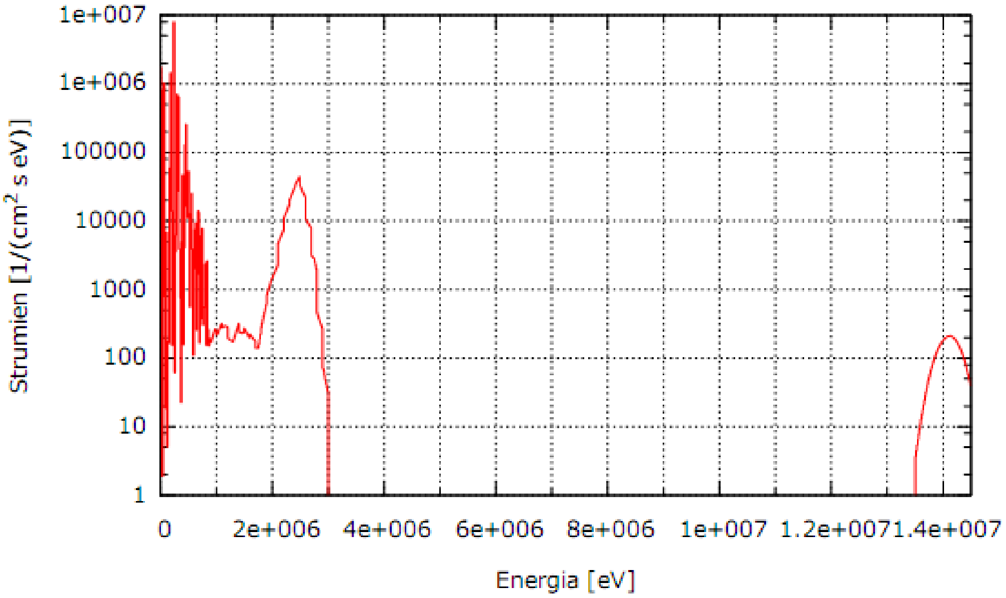

Fig.1. Neutron spectrum for JET shot 78055 unfolded by SAND-II

Development of gas detectors for 2.5 and 14 MeV neutron measurements utilizing activation method

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The idea of the counter based on detection the charged particles produced in the following reaction $^9Be + n \rightarrow \alpha$ (1.0 MeV) + $^6He(T_{1/2}=0.8\ s) \rightarrow {}^6Li + \beta^-$ (1.5 MeV). The prompt alpha particles or delayed beta particles can be recorded. Because the prototype of the counter has been tested on the PF-1000 device with neutron pulse taking a few ns, we decided to record the beta particles. The proportional detector (Canberra SP-126C filled with P-10, i.e. Ar-90%+CH_4-10%) equipped with beryllium plate (2 x 100 x 100 mm, 1.8 g/cm^{-3}) has been chosen. In order to prepare the counter calibration, the MCNP calculations have been performed. The MCNP input needed to calibration of the detector is presented in Fig. 1.

The following steps of the proportional counter calibration procedure have been done:

- Simulation the ^{6}He beta spectrum inside the counter (MCNP);
- Shaping the ^{90}Sr/^{90}Y beta calibration source spectrum (MCNP);
- Calculation the counter response to ^{90}Sr/^{90}Y calibration source;
- Measurements of the counter response to ^{90}Sr/^{90}Y calibration source (10x10cm);
- Obtaining of „calculation to experiment” (C/E) ratio for ^{90}Sr/^{90}Y source;
- Simulation of the counter response to ^{6}He source in beryllium;
- Application of C/E ratio for ^{90}Sr/^{90}Y source to the beta ^{6}He source simulations;
- Simulation of beryllium plate response to neutron source (MCNP);
- Obtaining efficiency of the Beryllium Activation Counter;
- Testing measurements on PF-1000.

The simulation of energy spectrum the beta particles coming from beryllium activation as it occurs inside the counter is presented on the Fig. 1 (dark blue line).

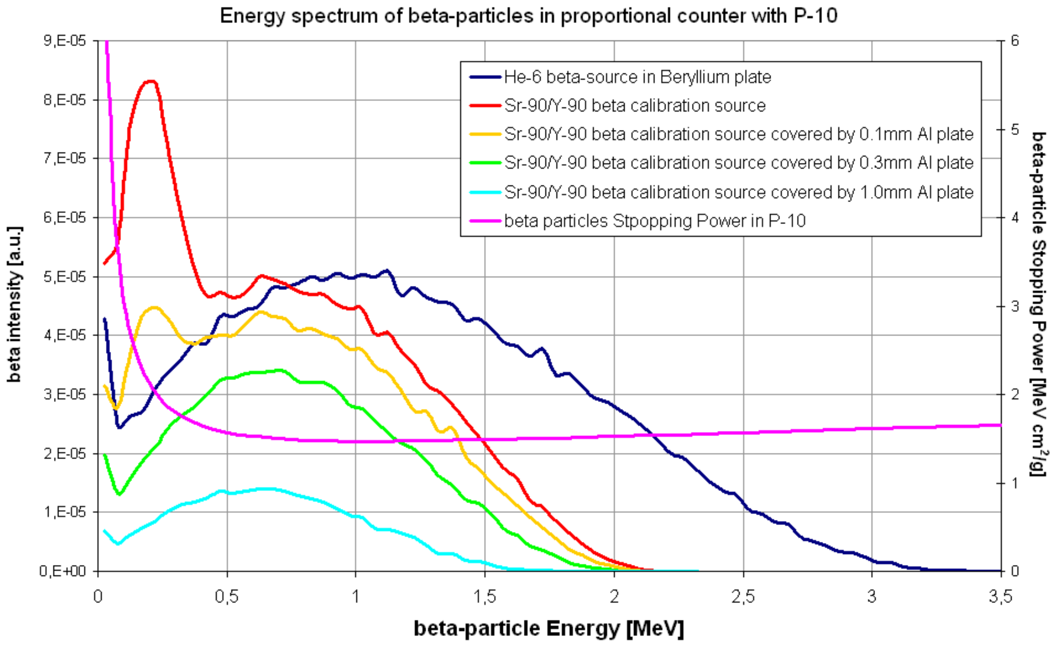

Fig.1.

The calibration of the counter has been performed by means of the ^{90}Sr/^{90}Y source with energy spectrum shown as red line on the Fig. 1. In order to make it similar to the ^{6}He source, the spectrum has been shaped using aluminium plate with different thickness. The 0.3 mm thick aluminium plate has been selected (green line on Fig. 1).

The electronic components essential to the proportional counter containing beryllium target and data acquisition system have been prepared (see Fig. 2).

The system includes:

- Two separate channels for two proportional counters
- Battery operated preamplifiers with fibre optics links to the computer in order to avoid the electro-magnetic noises and interference problems.

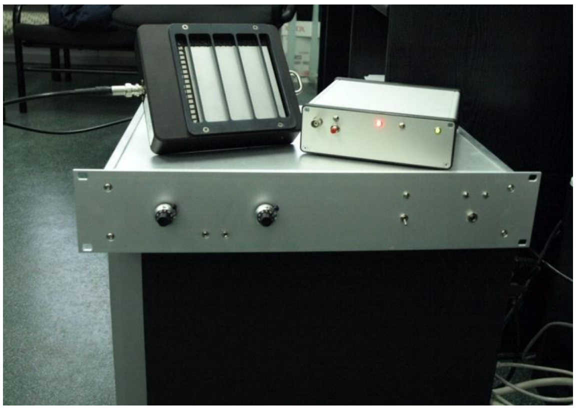

Fig. 2.

Preamplifier – Discriminator settings: sensitivity - 105 electrons, dead time - 0.5 μs, output pulse width - 250 ns. HV power supply with output voltage 1650 V. Two independent gating times for both channelsA series of measurements by means of the Beryllium Activation Counter have been performed during the experimental campaign on PF-1000 device.

3.4 Inertial fusion energy “keep-in-touch” activity

Analysis of emerging options of IFE on the basis of results of experiments and numerical modelling

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The experiment was carried out at the Prague Asterix Laser System. The investigations were aimed at testing the possibility of plasma jet creation by using different constructions of targets with conically shaped thin foils. Fig. 1. The cones were irradiated directly or indirectly by a focused pulsed high-power laser beam. In the investigations the following target irradiation parameters were used: the first harmonic of laser radiation (λ=1.315 μm), laser energies 120 and 600 J, and pulse duration 250 ps (full width at half maximum).

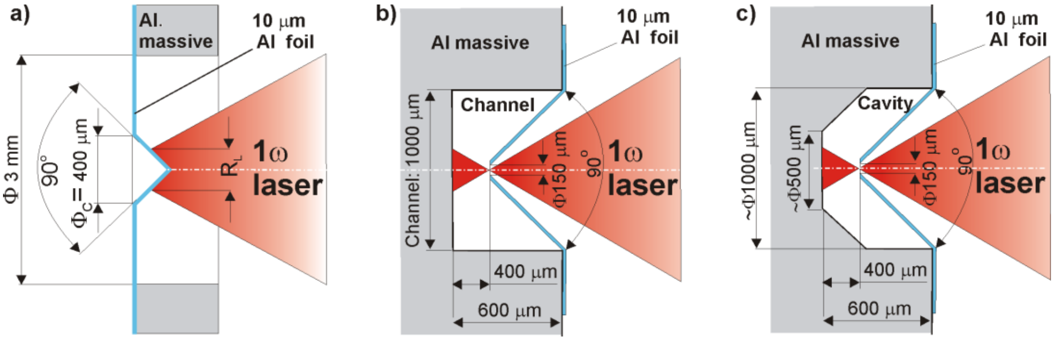

Fig. 1. The target constructions with a conically shaped thin foil: a) – target with direct cone irradiation, b) - double target with free ablative plasma expansion (TF), and c) - double target with pressure cavity (TP)

Our interferometric investigations show that in the case of the direct cone irradiation (Fig. 1a). The initial axial velocity of plasma contour reaches a value lying in the range of (5-8)x10^7 cm/s, however it drops very fast below 2x10^7 cm/s.

To improve the plasma jest parameters we tested the possibility to accelerate the foils by exploiting the ablative plasma pressure: (i) Reverse Acceleration Scheme and (ii) Cavity Pressure Acceleration Scheme method. Two new target constructions were designed: (i) double target with free ablative plasma expansion (TF) and (ii) double target with pressure cavity (TP), as presented in Fig. 1b and Fig. 1c, respectively. The performed experiments with both the targets types show that the plasma jets parameters are considerably better than those obtained with direct cone irradiation at the same laser energy. The average plasma jet velocities in the observation period are higher than 10^7 cm/s, whereas in the direct irradiation case the velocity was decreasing very fast below that value. Moreover, it should be emphasized that the maximum electron density in the jets is twice higher than in the case of the direct cone irradiation. However, the plasma jet propagation starts with a longer delay (several ns), which is characteristic for both TP and TF targets.

The investigations of plasma stream parameters for the three target constructions used allowed us to come to the conclusion that a proper ratio of the laser energy part used for heating to that exploited for acceleration of the cone wall is very important for launching a good-quality jet. If a majority of laser energy is used for the cone wall heating, the collapse of the cone is not effective, whereas in the opposite case the too fast acceleration of the cone wall results in conservation of its steady state and in subsequent cone reversal and destruction. However, in the case of TP target there is a certain possibility to control the above energy ratio by means of fitting the cavity volume to target irradiation parameters. For that reason some additional numerical modeling will be very useful. In the case of indirect methods of plasma jet generation a certain disadvantage may consist in some delay of the plasma jet creation.