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Fiber-optic sensor for monitoring of liquid Li limiter surface temperature

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Application of liquid Lithium limiter (LLL) is proved to be an effective tool for lithization of the tokamak vacuum vessel resulting in significant reduction of recycling of hydrogen isotopes, lower average ion charge Z_{eff} and plasma radiation losses [1, 2]. However, relatively fast LLL surface thermal sensor is needed in order to provide a proper control of the process with the temporal resolution not worse than 0.1…1 ms. An ultimate goal is to establish some kind of thermal feedback in the plasma position control loop for preventing LLL surface overheating and excessive Li evaporation.

Thermal emission monitoring is the well-known option meeting the requirement of fast surface temperature control. Unfortunately, popular commercially available pyrometers and IR cameras are not well suited for this task due to the long response time 5…40 ms, the absence of any analog output, and reduced applicability for the low-emissive metal surfaces. Most of them are based on semiconductor Si or InGaAs photodetectors with 1…1.5 μm cut-off wavelength, which are sensitive to intensive plasma background emission in the UV and visible light spectral ranges. Hence the development of some special device is needed [3].

Remote temperature measurements with the use of fiber-optic sensors have a number of well-known advantages: enhanced immunity to electromagnetic interference (EMI noises) and vibrations, application flexibility and easy redirection to another object. Specific requirements of modern plasma devices are related to limited access inside the experimental hall, and the necessity of periodic re-calibration of the detector response due to possible variations of optical window transmission and the LLL surface emissivity after long-term operation under the high power load in the range 1…10 MW/cm^2.

In order to control fast variations of the surface temperature of three LLL modules installed into the FTU tokamak in autumn 2005, four-channel fiber-optic thermal sensor (FOTS) had been developed and applied for the FTU Lithium wall conditioning experiment. The device comprises the cryogenic detector assembly of four HgCdTe photodiodes located at the bottom of immersion cryostat inserted into the commercial liquid nitrogen storage dewar (Fig.1, 2), silver halide polycrystalline infrared optical fibers, and front-end objectives made of Ge lens with broad-band antireflection coating. With the use of common LN_2 dewar of 16 l capacity, no refill of liquid nitrogen is needed along 2-3-week experimental campaign.

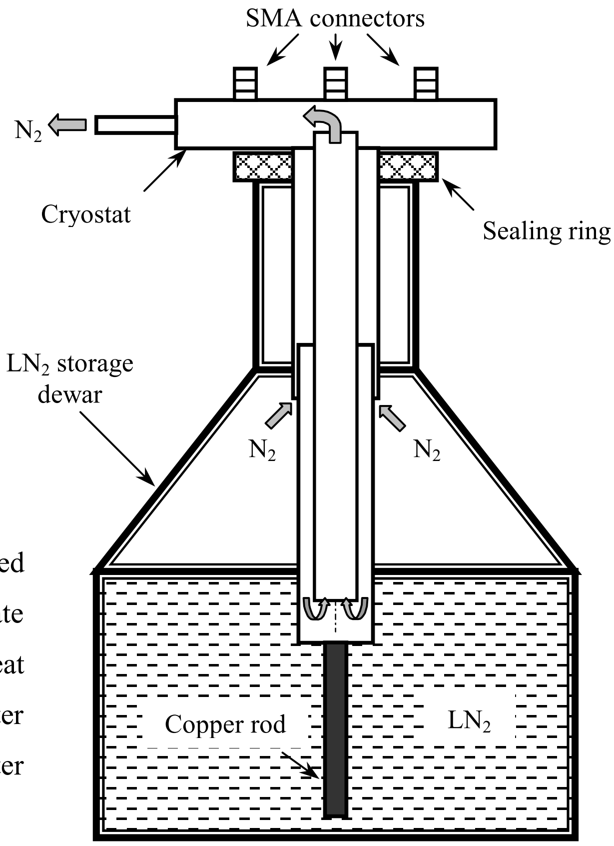

Fig.1. Schematic of immersion cryostat installed into LN_2 storage dewar. Arrows indicate evaporated N_2 flows for the proper heat recuperation and preventing air water condensation. Copper rod provides better cooling when LN_2 level is low.

Since the melted lithium at the plasma facing side commonly has mirror-like surface, its emissivity in the temperature range of interest 200…600°C, is quite low – within 5…10% of the blackbody radiation [4]. This circumstance, together with the necessity of effective suppression of the plasma radiation background mostly concentrated in the UV and visible optical bands, results in the requirement of mid- or even long-wavelength infrared sensing. Therefore the detector cut-off wavelength was chosen λ_{co}= 6.7 μm for main 3 channels, and λ_{co}= 9 μm for the forth channel in order to decrease the lower temperature limit, if desired.

IR radiation is transmitted to the detectors by 6 m long polycrystalline silver halide AgBr-AgI-AgCl optical fibers with 1 mm core diameter, transparent in IR spectral range up to λ = 20 μm [5]. Single-lens objective (F = 25.4, D = 24 mm) with broadband ARC in 4…8 μm spectral range is used for the focusing of input radiation to the front-end fiber terminal. It provides 80 mm diameter field of view at 2 m distance. In addition, the front-end Ge lens effectively rejects UV, visible and near-IR background emission with $\lambda < 2$ μm.

Four-channel DC-10 kHz bandwidth preamplifier is located in the upper part of the cryostat. Preamplifier inputs and outputs are DC coupled in order to provide an option of direct response calibration with slowly varying LLL temperature by electric heating, and also for easy alignment of the front-end objectives to the pre-heated LLL modules.

Fig.2. FOTS cryostat connected to one optical channel.

The detector assembly was installed at the main floor level of the FTU experimental hall, 1.5 m apart from the outer FTU cryostat wall. The distant detector location provides an effective reduction of the influence of electromagnetic and vibration pick-up during the plasma discharges. Three front-end objectives were installed at the upper diagnostic port watching downwards across ZnSe windows and plasma column, to LLL modules located at the distance 1.9 m inside the lower vacuum port in section 1 of the vacuum vessel.

Response calibration is the major factor limiting the absolute accuracy of thermal measurements. An important feature of Lithium is some reduction of IR emissivity after an interaction with plasmas caused by removal of chemical compounds and formation of clean mirror-like metal surface. Therefore a correct calibration should be done after a few plasma shots with LLL inserted into the SOL and pre-heated above the Li melting point (180.6ºC). An example of calibration curve for one of the FOTS channels is shown in Fig. 3. The maximum LLL temperature is limited to 350ºC in order to prevent an excessive Li evaporation during the calibration procedure, which takes more than one hour per each channel. The calibration curve above this point is derived by extrapolation fitted to the blackbody response curve slope, assuming relatively small variation of Li surface emissivity in 350…600ºC range.

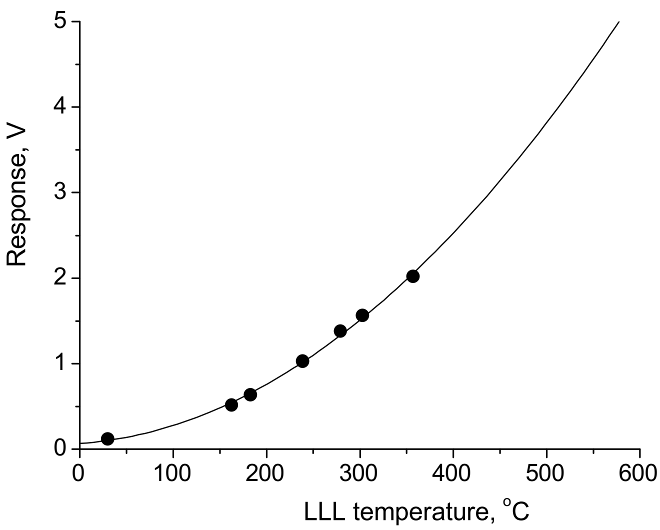

Fig.3. Response calibration curve for the FOTS channel #2.

The evolution of LLL surface temperature and recovered power loading during the FTU shot # 28525 is shown in Fig.4. The LLL front edge was located in the SOL just behind the main limiter. It should be noted, that the FOTS response provides an average temperature over the total visible LLL area. Therefore some corrections were made taking into account the actual plasma-surface interaction areas for each LLL module, which were evaluated visually after the experimental campaign, when the modules were taken off the FTU vacuum port. The recovery of thermal power loading of the LLL surfaces had been proceeded by Fourier method assuming the cylinder symmetry and taking into account actual LLL design with ~1 mm thick Lithium layer upon a massive Molybdenum body.

No “lithium bloom” or another anomalous phenomena were observed when the LLL surface temperature and power load rise up to ~500ºC and 4…5 MW/m^2, respectively.

In more detail, the experiments with LLL on the FTU tokamak are analysed elsewhere [2, 6].

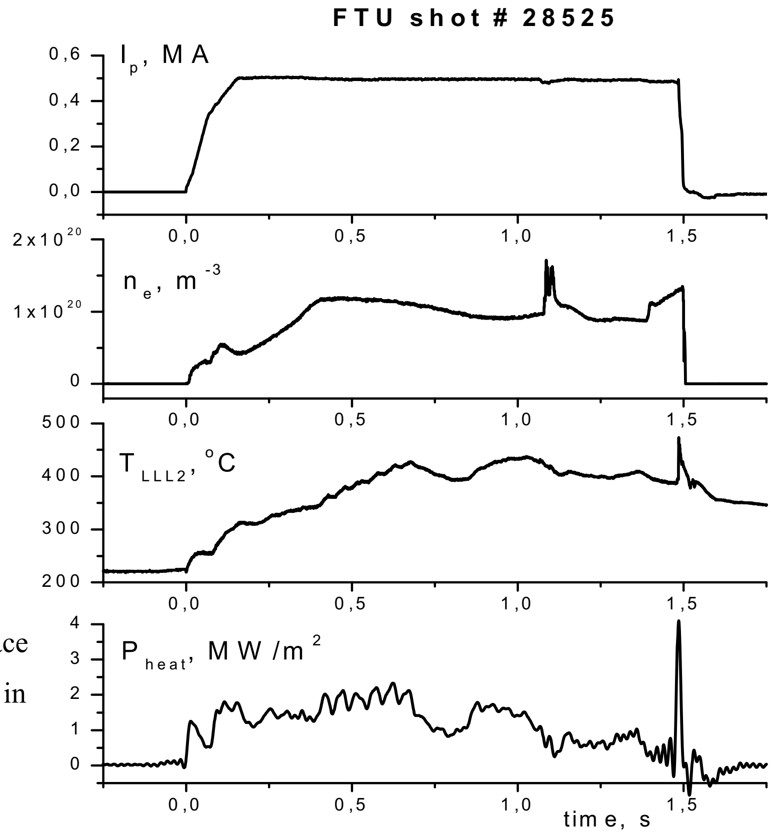

Fig.4. Evolution of LLL-2 surface temperature and power load in the FTU shot #28525

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