Measurement of the residual stresses dynamics in tungsten during heating

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Motivation

- In a fusion reactor plasma impacts the divertor in the form of periodic heat pulses as well as constant heat loads. The heat pulses cause residual plastic deformations and mechanical stresses in the divertor which leads to the divertor's material being destroyed.
- Residual deformations and stresses can be relieved due to high temperature of the divertor which is caused by the constant flow of plasma.
- The relaxation of deformations and stresses may bring the material back to its initial state during the time interval between two subsequent heat pulses, so that after the second plasma pulse stresses would not exceed ultimate tensile strength and the material would not be destroyed.

X-ray diffractometry

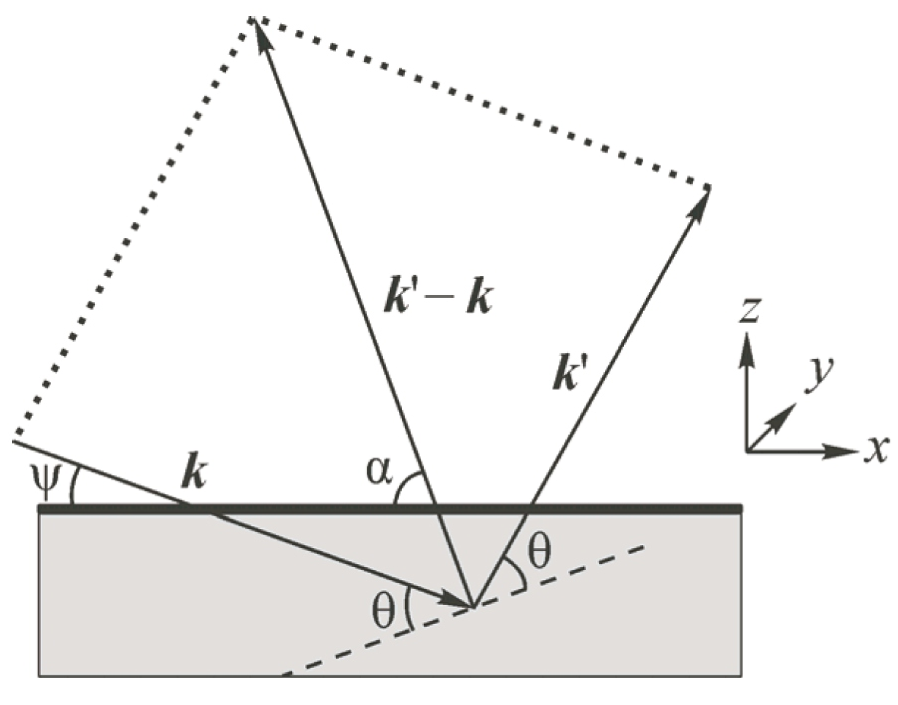

Figure 1: Diffraction scheme in the scattering plane

- Wulff–Bragg's condition:
  $n\lambda = 2d \sin\theta$
- Alteration of the interplanar distance:
  $\delta d = d_0 \varepsilon_{ij} n_i n_j$
- Scattering angle - tilt angle dependence:

$$\frac{1}{\sin\theta} = \frac{2d_0}{n\lambda}\Big(1 - \varepsilon_{xx}(\sin(\psi-\theta))^2(\cos\varphi)^2 - \varepsilon_{yy}(\sin(\psi-\theta))^2(\sin\varphi)^2 - \varepsilon_{zz}(\cos(\psi-\theta))^2 - 2\varepsilon_{xy}(\sin(\psi-\theta))^2\cos\varphi\sin\varphi - 2\varepsilon_{xz}\sin(\psi-\theta)\cos(\psi-\theta)\cos\varphi - 2\varepsilon_{yz}\sin(\psi-\theta)\cos(\psi-\theta)\sin\varphi\Big),$$

n – diffraction order, λ – radiation wavelength, d – interplanar distance (d_0 – initial), θ – angle between a falling ray and the crystallic plane, ε_{ij} – tensor of deformations, n_i – unit vector in the direction of *k-k'*, φ – angle of rotation around Z axis, ψ – angle between a falling ray and surface of the sample.

BETA facility

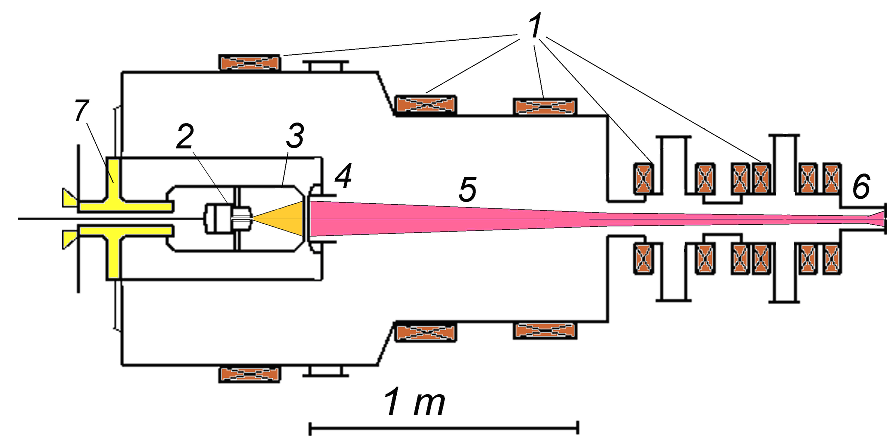

Figure 2: Scheme of the BETA facility experiment; 1-magnetic field coil, 2-arc generator, 3-cathode, 4-anode, 5-electron beam, 6-beam receiver, 7-insulator

The BETA facility was used for creating residual stresses in tungsten samples.

BETA facility characteristics:
- Power output up to 5 MW
- Impulse length up to 0.2 ms
- Heat load up to 3 MJ/m^2
- Magnetic field up to 0.22 T

Static measurements

"Anomalous scattering" experimental station

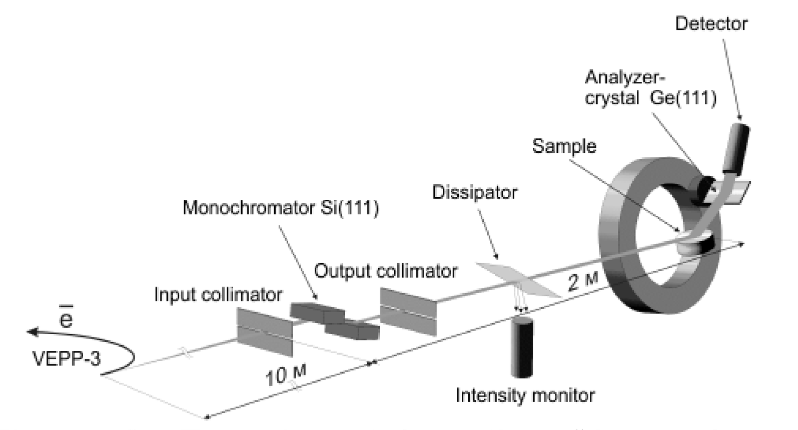

Figure 3: Experimental station "Anomalous scattering" on beam line 2 of VEPP-3

Experimental station on beam line 2 of VEPP-3 was used for measuring residual stresses at a constant temperature.
- Beam's wavelength - 0.5÷4 Å
- Analyzer-crystal makes it possible to precisely measure scattering angle
- Point detector with minimal angle step of 0.001°
- Subject table position can be adjusted in the goniometer plane with accuracy up to 0.1 mm

Scattering angle measurement

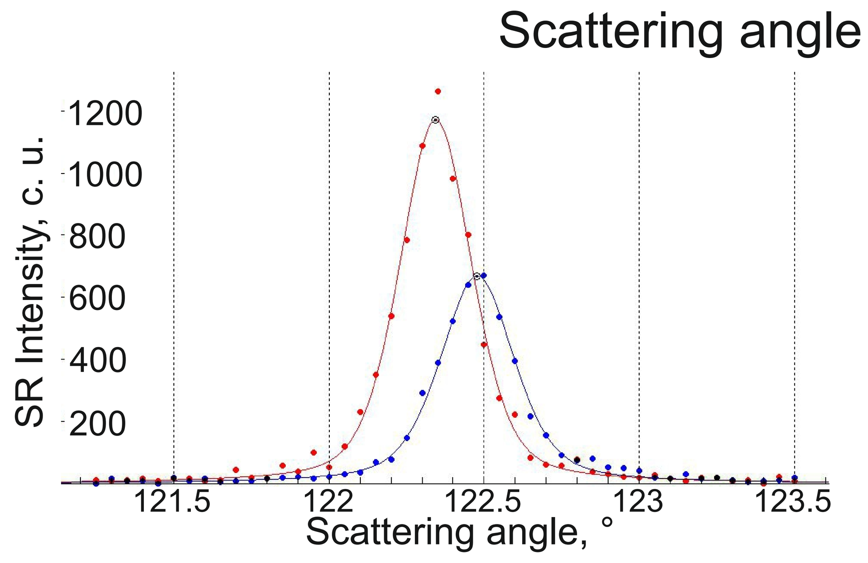

Figure 4: Angular distribution of SR intensity at different tilt angles

- Diffraction peaks were obtained at different tilt angles of the irradiated tungsten samples.
- Each diffraction peak was approximated by the sum of Lorentz and Gauss profiles.
- Approximated centers of the peaks were taken as scattering angles for the related sample orientations.

Calculation of stresses and deformations

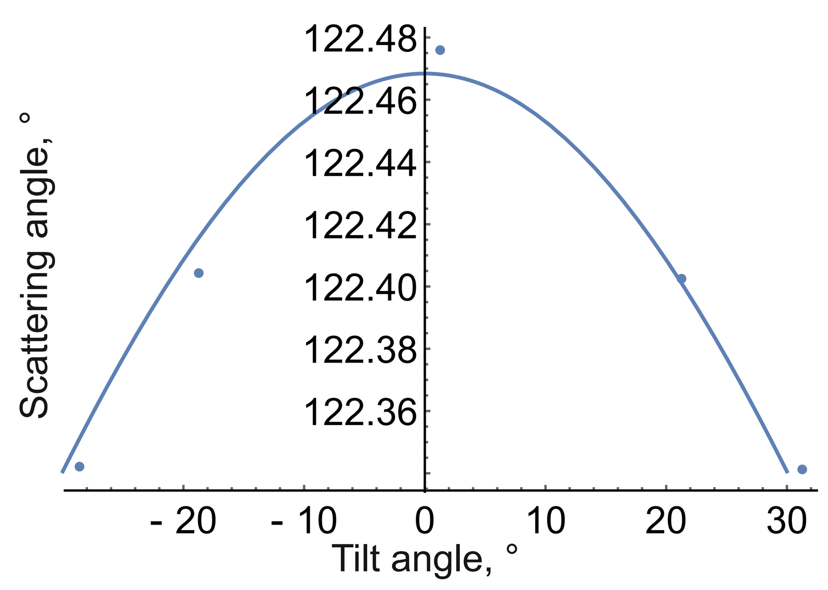

Figure 5: Scattering angle-tilt angle dependence

Deformation tensor components	№43	№56
ε_{xx}, 10^{-3}	1.31	1.32
ε_{yy}, 10^{-3}	1.19	1.45
ε_{zz}, 10^{-3}	-1.02	-1.13
ε_{xz}, 10^{-3}	0.03	-0.05
ε_{yz}, 10^{-3}	0.04	-0.1

Stress tensor components	№43	№56
σ_{xx}, MPa	631	663
σ_{yy}, MPa	600	699
σ_{xz}, MPa	7	-13
σ_{yz}, MPa	12	-26

Figure 6: Calculated deformation tensor and stress tensor components

- Experimental data was used for calculation of deformation tensor components with scattering angle - tilt angle dependence.
- Stress tensor components were calculated according to Hooke's law.
- Stress tensor possesses axial symmetry. Diagonal stress tensor components do not exceed tungsten's ultimate tensile strength.

Heat load and residual stress spatial profiles comparison

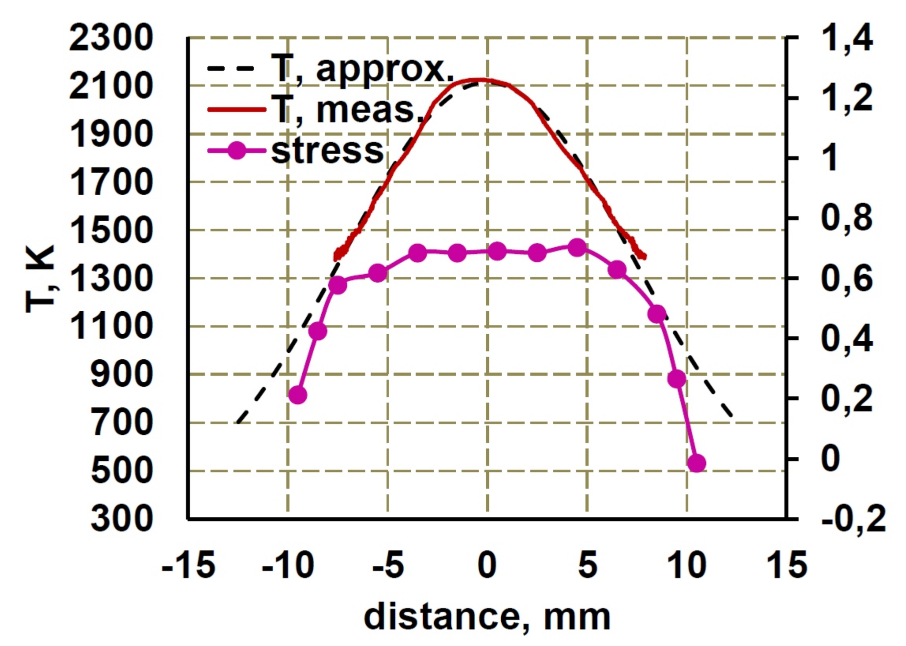

Figure 7: Heat load and residual stress profiles

- Measurements were conducted with spatial resolution for the purpose of comparing heat load and residual stress profiles.
- Within 7 mm from the irradiation spot center the residual stress remains at the level of ~650 MPa.
- The profiles have similar shapes as long as heating does not exceed 1300 K.

Dynamic measurements

"Diffraction movie" experimental station

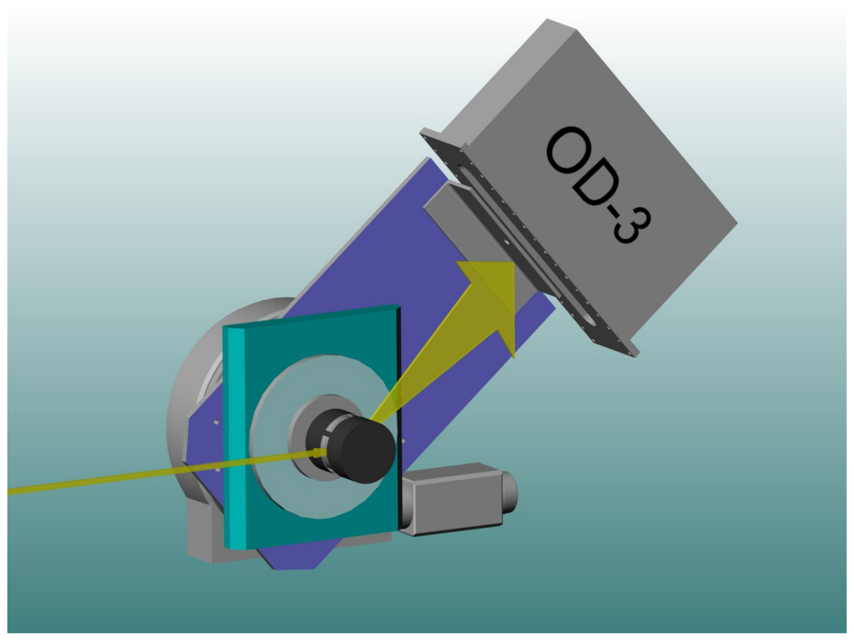

Figure 8: Experimental station "Diffraction movie" on beam line 5b of VEPP-3

Experimental station on beam line 5b of VEPP-3 was used for measuring residual stresses in the conditions of changing temperature.
- One-dimensional detector OD-3 makes cross-section of diffraction cones, allowing to conduct real-time measurements.
- The detector has 3328 channels (angular definition ~0.01°), minimal frame time of 10^{-6} seconds, total frame count of 64.
- Furnace of the original design is used for carrying out thermal investigations. The furnace is controlled via "Termodat" module.

Temperature measurements

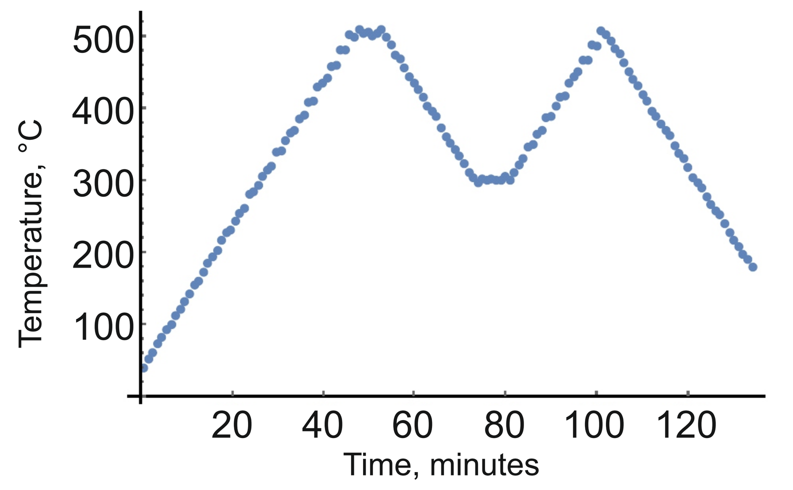

Figure 9: Temperature of the irradiated sample

- Samples were heated for relaxation of the residual stresses.
- Temperature of the samples was being changed so that behavior of the diffraction peak could be examined at rising, declining and constant temperatures.

Results

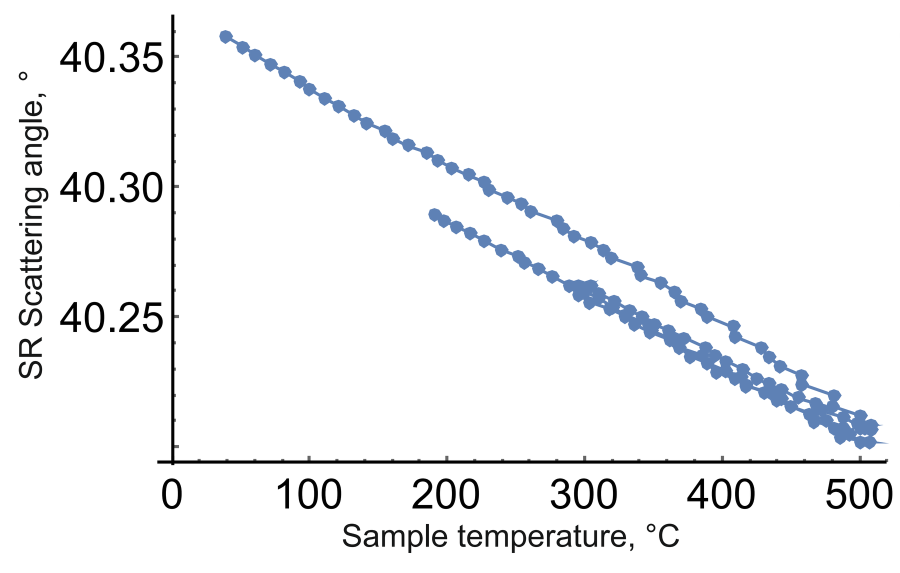

Figure 10: Scattering angle - temperature dependence

- Scattering angle - temperature dependencies were obtained by combining scattering angle - time and temperature - time dependencies measured during the experiment.
- During the heating of the irradiated sample two effects took place: thermal expansion (also present in the control sample) and relaxation.

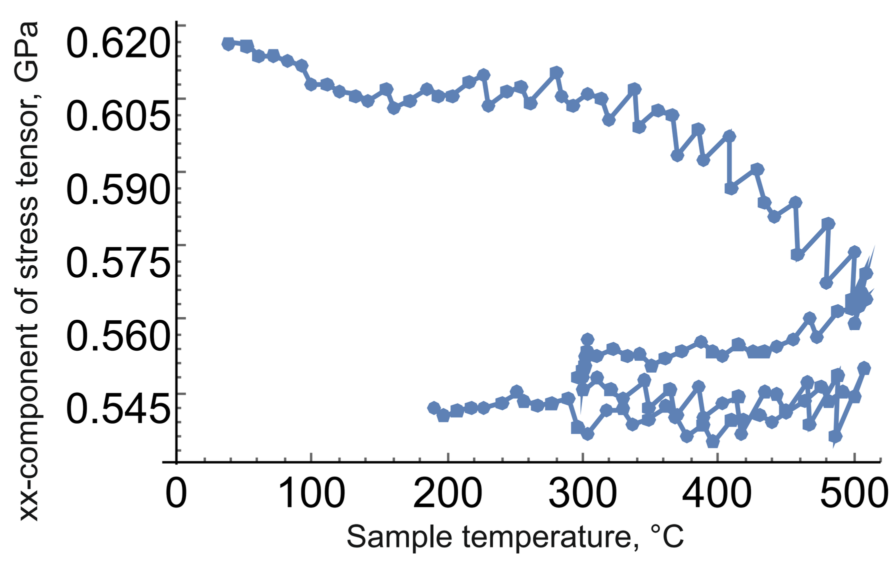

Figure 11: Stress dynamics during heating

- Thermal expansion was subtracted from the experimental data in the form of a linear function. That was done for the purpose of studying the relaxation effect.
- Previously made static measurements were used to convert scattering angle to stress.

Conclusions

- Residual stresses were measured with spatial resolution.
- Diffraction peak position - temperature dependencies were measured.
- Residual stress relaxation dynamics were measured, the result turned out to be close to what was expected.