Status of dynamic diagnostics of plasma material interaction based on synchrotron radiation scattering at the VEPP-4 beamline 8

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Synchrotron and Free electron laser Radiation: generation and application (SFR-2016), 06.07.2016
Motivation
Fusion reactor

- Plasma volume: 837m³.
- Fusion power: \( \sim 500 \text{MW} \).
- Plasma pulse time: \( \sim 3000 \text{s} \).
- First plasma data: 2025.
- Strong erosion of the first wall and divertor plates under powerful plasma flow.
Conditions at the first wall

- **Ion flow**: $10^{24}$ ion/m$^2$s,
- **Fusion neutron flow**: $10^{13}$ neutron/m$^2$s,
- **Thermal loads**:
  - **Permanent**: $40 - 60$ MW/m$^2$,
  - **Edge localized mods (ELM)**: $\sim 10$ MJ/m$^2$ during $0.1 - 1$ ms,
  - **Thermal quench**: $\sim 150$ MJ/m$^2$ during $1 - 5$ ms,
  - **Runaway electrons**: $\sim 30$ MJ/m$^2$. 
Material erosion and degradation

- **Sputtering:**
  - Physical sputtering,
  - Chemical sputtering.
- **Evaporation,**
- **Surface and structure modifications (including DPA and recrystallization),**
- **Impurities retention (including α-particles):**
  - Bubble growth,
  - Blistering,
  - Flaking,
  - “Fuzz” growth.
- **Brittle destruction:**
  - Cracking,
  - Dust particles formation and ejection.
- Melting and flowing away,
- Boiling and splashing.

The most promising materials: W, C, Be, Li.
Overview of ex-situ studies
Recrystallization

The growth of the material grains significantly spoils the material properties.

2D detector was used to measure the average grain size.

Tungsten-molybdenum composite material for the recrystallisation preventing was tested.

Current status: measurements are completed, data analysis is in progress.
Overview of ex-situ studies

Dissolved impurities

![Graph showing diffraction peaks](image)

- The dissolved in metals impurities could lead to embrittlement and several specific types of erosion.
- The change of the diffraction peaks at irradiated tungsten was detected.
- Current status: much more experiments and interpretations should be done to understand something.

Diffraction peaks measured at station “Precision diffractometry and anomalous scattering”
Modification of material structure

- The strong change of the diffraction intensity and the ratio of the different peaks intensity are measured.
- The orientation of the irradiated surface layer could significantly change the material properties.
- Possible explanation: the columnar structure of molten and crystallized tungsten.

Diffraction peaks measured at station “Precision diffractometry and anomalous scattering”
Overview of ex-situ studies

Residual stresses and deformations

- The periodical pulsed ejections of the plasma to divertor plates are expected during the standard operation regime.
- The cracks cause overheating, dust particle formation, intensify material retention, etc.
- The pulsed heat loads are reason of the tungsten cracking.
- The mechanical stress causing the cracking appears due to plastic deformation of the material.
The variation of the sample orientation changes the SR scattering angle due to residual deformation.

Geometry:
\[ n_x = \cos \alpha \cos \phi = \sin(\psi - \theta) \cos \phi, \]
\[ n_y = \cos \alpha \sin \phi = \sin(\psi - \theta) \sin \phi, \]
\[ n_z = \sin \alpha = \cos(\psi - \theta). \]

Effect:
\[ \frac{1}{\sin \theta} = \frac{2(d_0 + \delta d)}{n\lambda} = \frac{2d_0}{n\lambda} (1 - u_{xx} \sin^2(\psi - \theta) \cos^2 \phi - u_{yy} \sin^2(\psi - \theta) \sin^2 \phi - u_{zz} \cos^2(\psi - \theta) - 2u_{xy} \sin^2(\psi - \theta) \cos \phi \sin \phi - 2u_{xz} \sin(\psi - \theta) \cos(\psi - \theta) \cos \phi - 2u_{yz} \sin(\psi - \theta) \cos(\psi - \theta) \sin \phi). \]
Residual stresses and deformations

- The variation of the sample orientation changes the SR scattering angle due to residual deformation.

- Geometry:
  \[ n_x = \cos \alpha \cos \phi = \sin(\psi - \theta) \cos \phi, \]
  \[ n_y = \cos \alpha \sin \phi = \sin(\psi - \theta) \sin \phi, \]
  \[ n_z = \sin \alpha = \cos(\psi - \theta). \]

- Effect:
  \[
  \frac{1}{\sin \theta} = \frac{2(d_0 + \delta d)}{n\lambda} = \frac{2d_0}{n\lambda} \left(1 - u_{xx} \sin^2(\psi - \theta) \cos^2 \phi - u_{yy} \sin^2(\psi - \theta) \sin^2 \phi - u_{zz} \cos^2(\psi - \theta) - 2u_{xy} \sin^2(\psi - \theta) \cos \phi \sin \phi - 2u_{xz} \sin(\psi - \theta) \cos(\psi - \theta) \cos \phi - 2u_{yz} \sin(\psi - \theta) \cos(\psi - \theta) \sin \phi\right). \]
Residual stresses and deformations

Table: Components of the deformation and stress tensors.

<table>
<thead>
<tr>
<th></th>
<th>&lt;211&gt;</th>
<th>&lt;321&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_{xx}$</td>
<td>$2.22 \cdot 10^{-3}$</td>
<td>$2.44 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$u_{yy}$</td>
<td>$0.2 \cdot 10^{-3}$</td>
<td>$0.22 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$u_{zz}$</td>
<td>$-0.94 \cdot 10^{-3}$</td>
<td>$-1.04 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$u_{xz}$</td>
<td>$0.13 \cdot 10^{-3}$</td>
<td>$0.05 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$u_{yz}$</td>
<td>$0.13 \cdot 10^{-3}$</td>
<td>$-0.02 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$\sigma_{xx}$, MPa</td>
<td>1010</td>
<td>1115</td>
</tr>
<tr>
<td>$\sigma_{yy}$, MPa</td>
<td>364</td>
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<tr>
<td>$\sigma_{xz}$, MPa</td>
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<td>15</td>
</tr>
<tr>
<td>$\sigma_{yz}$, MPa</td>
<td>40</td>
<td>5</td>
</tr>
</tbody>
</table>

Axis $x$ is the rolling direction.
Residual stresses and deformations

In the case of thin heated area there are simple expressions for elastic stresses and deformations:

\[ u^e_x = u^e_y = 0, \]
\[ u^e_{zz} = \frac{1 - \sigma}{1 + \sigma} \alpha \left( T(z) - T_0 \right), \]
\[ \sigma^e_{zz} = \sigma^e_{xy} = \sigma^e_{xz} = \sigma^e_{yz} = 0, \]
\[ \sigma^e_{xx} = \sigma^e_{yy} = -\frac{\alpha E (T(z) - T_0)}{1 - \sigma}, \]

where \( \vec{u}^e \) is the elastic displacements, \( \sigma^e_{ij} \) is the stress tensor, \( \alpha \) is the linear thermal extension coefficient, \( E \) is the Young’s modulus, \( \sigma \) is the Poisson’s ratio, \( T \) is the temperature, \( T_0 \) is the initial temperature.

Axis \( z \) is perpendicular to the surface,
\( x \) and \( y \) are parallel to the surface.
In-situ experiments
In-situ experiments

Fast processes during plasma irradiation:

- Deformation during pulsed heat load,
- Recrystallization during pulsed heat load,
- Hydrogen and helium retention and diffusion.

Why did we choose deformation during pulsed heat load for first experiments?

- The measured residual effects,
- Well-understood theoretical description,
- Easy experimental simulation.
Initial conditions

SR sources VEPP-3 and VEPP-4

Model of deformation

The deformation of crystal structure

Pulsed heat load simulation

Laser:
- Energy: 1J,
- Duration: 140μs,
- Wavelength: 1064nm.
In-situ experiments

Requirements to the measurements

- Dynamical measurements during pulsed heating,
- Measurements inside material,
- Spatial resolution inside material.
Restrictions to scheme of experiment

![Graph showing SR energy, Initial SR intensity, and Attenuation distance]

**SR energy**: 69 keV
Restrictions to scheme of experiment

SR energy: 69 keV
Restrictions to scheme of experiment

1. SR energy: 69keV
2. Laue diffraction
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In-situ experiments

Scheme of experiment

Restrictions to scheme of experiment

1. SR energy: 69 keV
2. Laue diffraction
3. Single crystal
Restrictions to scheme of experiment

Channel width of the 1D detector: 100\(\mu\)m.
Typical shift at the parallel scattering: 10\(\mu\)m.

1. SR energy: 69keV
2. Laue diffraction
3. Single crystal
4. Diverging diffracted SR

The effect causing the divergence of the diffracted SR is necessary for spatial resolution!
Scheme of experiment

Basic variant:

- The deep penetration into material.
- Spatial resolution.
- Thin samples.

Reserve variant:

- Single crystal surface.
- Only surface measurements.
Scheme of experiment

Basic variant:

**In-situ experiments**
“Diverging” effect

Rotation of crystal planes at the heating of the surface layer:

- Compression or expansion of the surface layer result in rotation of the “reflecting” crystal plane.

\[ \delta 2\theta \sim \sin(2\alpha) \]

- The variation of the scattering angle changes the energy of the diffracted SR. It makes possible to use the sharp change of the intensity near K-edge.
“Diverging” effect

The distribution of the deformations can be calculated using the shape of the diffraction peak.
What did we expect?

Experiment parameters:

- SR cross-section: 2mm × 2mm.
- Laser diameter: 1mm.
- Laser energy: 1J.
- Laser duration: 140 µs.
- Temporal resolution: 20 µs.
- Single crystal thickness: 250 µm.
- Distance to detector: 300mm.
- Geometry:

Consequences:

- Temperature propagation distance during irradiation: 200 µm.
- Heating up to 500°C.
- Expected effect:
  \[ \delta 2\theta = \frac{1+\sigma}{4} \alpha (T - T_0) \approx 0.7 \text{mrad} \approx 0.04^\circ. \]
- Detector channel width:
  \[ 1\text{channel} = 100 \mu m \approx 0.3 \text{mrad} \approx 0.02^\circ. \]
- The method of the taking into account plastic deformation is under discussion.
First results

Frame obtained during 20 $\mu$s.

- Frames number: 30.
- Channel number: 512.
- Frame duration: from 25ns to 200 $\mu$s.
First results

- The scattering angle changes during laser heating and quickly returns back.
- The intensity of the scattered SR and the width of the diffraction peak do not change significantly.
Bending of crystal

- 1, 2, 3, 4, 5 – laser heating.
- 5 – SR.
Bending of crystal

1 2 3 4

In-situ experiments

Results

- No effect.
- No effect.
Bending of crystal

- The bending is result of the small thickness of the sample.
- The bending does not correspond to real situation at the first wall in fusion reactor.
- The thicker samples will be used at next experiments.
- We tried to prove the effect of the crystal plane rotation.
Crystal plane rotation

- The direction of the bending could be changes, while the direction of the crystal plane rotation always is positive.

- The bending is proportional to temperature gradient, while the crystal plane rotation is proportional to the temperature.
Crystal plane rotation

The reverse of the scattering angle change was measured.
Crystal plane rotation

The SR beam cross-section was decreased to be smaller than laser cross-section.
Crystal plane rotation

The rotation of the crystal plane fits experimental results better than bending.
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In-situ experiments

Results

Diffraction peak shape

Diffraction peak before irradiation

Diffraction peak during irradiation

The diffraction peak shape processing is in progress.
Conclusions
Facility

Operable:
- Goniometers.
- Gas 1D X-ray detector.
- 1J laser.

Under construction:
- Silicon 1D X-ray detector.
- 100J laser.
- Pirometer.
- Vacuum vessel.
Theory and mathematical processing

Done:

- Proved rotation of crystal plane during pulsed heating

In progress:

- Analysis of diffraction peak shape to calculate stress and deformation distributions
Main result

The fast *in-situ* X-ray diffractometry of solid is demonstrated.
Thank you for attention