TOOLS FOR IMAGE ANALYSIS AND FIRST WALL PROTECTION AT W7-X

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1. INTRODUCTION
- Wendelstein 7-X Stellarator
- Plasma Facing Components (PFCs)
- Thermographic Diagnostics

2. IMAGING DATA
- Data Acquisition
- Temperature Calibration
- Scene Modeling
- Thermal Map
- Spatial Calibration
- Heat-Flux Calculation

3. IMAGE ANALYSIS
- StrikeLine Segmentation
- Strike-Line Characterization
- Strike-Line Control
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WENDELSTEIN 7-X STELLARATOR

- **Optimized stellarator:**
  5-fold symmetry, 3D shape
- **Heating power:**
  10 MW ECRH (30min), 10MW NBI (10s)
- **10 divertors:** 5 lower, 5 upper

**OP1.2** (2017-2018) (T.S. Pedersen et al., EPS 2018):
- Inertially cooled **test divertor**
- **High performance** discharge 150MJ: 30s @ 5MW
- **100s** plasmas (2MW): 200 MJ
Wendelstein 7-X Stellarator

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  5-fold symmetry, 3D shape
- **Heating power:**
  10 MW ECRH (30min), 10MW NBI (10s)
- **10 divertors:** 5 lower, 5 upper

**OP2 (> 2021):**
- **High Heat Flux (HHF)** water-cooled divertor
- **Steady state operation:** 30 min
**Plasma Facing Components (PFCs)**

- **10 divertors**
- **Baffles** and wall **heat shields** (graphite tiles)
- **Wall** and pumping gap stainless steel panels
- Need to **detect** thermal events, **analyse** them automatically and choose the proper **control** action

*M. Jakubowski et al. (2018), Rev. Sci. Instr. 89, 10E116*
10 IR systems with **frontal** view of divertors

**OP1.2 (2017-18): inertially cooled**

test divertors

- 9 **immersion tubes** (1x IR camera)
- 1 endoscope (1x IR camera)

**OP2 (>2021): HHF water-cooled divertors**

- 10 **endoscopes** (1x IR camera)

*M. Jakubowski et al. (2018), Rev. Sci. Instr. 89, 10E116*
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DATA ACQUISITION

![Diagram of data acquisition system]

- Visualization and control
- Thermal events DB
- Network
- IR acquisition & analysis
  - Frame grabber
  - Local storage
  - GPU
  - IO board
  - Archive
  - Interlock System
  - Trigger system

*Courtesy of A. Puig Sitjes*
**Temperature Calibration**

![Diagram of temperature calibration process]

\[ T_{xy} = LUT_{xy} [I_{xy}] \]

- Raw image
- Scene model
- NUC
- LUT map
- Thermal image

\[ T_{xy} \]

\[ LUT_{xy} \]

\[ \varepsilon_{XY} \]

\[ t_{exp} \]

**Fast Real-time Processing**

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Courtesy of P. Drewelow
**Scene Modeling**

- A **scene-model** contains a pixel-based segmentation of the field of view.

- Pixel-wise correspondence with CAD:
  - PFC hierarchical indexing
  - Emissivity $\varepsilon$ of the target material
  - Target distance, $d$
  - Angle $\alpha$ with respect to target surface normal
  - 3D world coordinates: $X, Y, Z, \phi, \theta$

- Spatial calibration needed
  - 3D coordinates $\leftrightarrow$ 2D coordinates

---

**THERMAL MAP**

- A **thermal map** is a CAD-based 2D map which unfolds the first wall of the stellarator, including all the PFCs.

- All the thermal events taken from different cameras can be projected in one single thermal map for monitoring during experiments.

- Spatial calibration needed
  
  2D Thermal Map coordinates  ⇔ 3D coordinates  ⇔ 2D camera coordinates
**SPATIAL CALIBRATION**

**PROBLEM:**
Given the 3D coordinates of a set of control points and their projection on the image plane, reconstruct the projection model of the camera.

**CAMERA MODEL:**
Projection of 3D points on a 2D grid (camera image plane).

- **6 extrinsic parameters:**
  camera position and orientation

- **5 intrinsic parameters:**
  focal, skew factor, principal point

- **9 distortion parameters:**
  lens distortion effect (radial, tangential, prism)
PROBLEM:
Given the 3D coordinates of a set of control points and their projection on the image plane, reconstruct the projection model of the camera.

\[ x = F\left( X, p \right) \]

nonlinear regression
**Spatial Calibration**

Prism distortion

\[ k_p = [k_{px}, k_{py}, 0] \]

\[
\begin{aligned}
    x &= \left( \frac{x_c}{z_c} K_{rt} + k_p \frac{r_c^2}{z_c^2} \right) K \\
    x_c &= \begin{bmatrix} x_c & y_c & z_c \end{bmatrix} = (X - X_0) R \\
\end{aligned}
\]

Camera coordinates

Camera position

Camera orientation matrix

Prism distortion function

\[ k_t = [k_{tx}, k_{ty}, 0] \]

Tangential distortion function

\[
K_{rt} = \begin{bmatrix}
    f \left( \frac{r_c}{z_c} \right) + 2 \frac{p_c}{z_c} k_t^T & 0 & 0 \\
    0 & f \left( \frac{r_c}{z_c} \right) + 2 \frac{p_c}{z_c} k_t^T & 0 \\
    0 & 0 & 1 \\
\end{bmatrix}
\]

Radial distortion function

\[
r_c = \sqrt{x_c^2 + y_c^2}
\]
**Spatial Calibration**

Fish-eye radial distortion model:

\[
f(r) = \left\{ \begin{array}{ll}
(1 - \lambda) \frac{G_n(t_1)}{t_1} + \lambda \frac{G_n(t_2)}{t_2} & r \geq 0 \\
0 & r < 0
\end{array} \right.
\]

Continuation:
from \( r = +\infty \) (\( z_c = 0^+ \))
to \( r = -\infty \) (\( z_c = 0^- \))
panoramic view (complex optics with high FOV)

\[
r = \frac{r_c}{z_c}
\]

2D radius \( r_c = \sqrt{x_c^2 + y_c^2} \)

Depth

\[
G_n(t) = \int_0^t \frac{1}{1 + \tau^2} d\tau
\]

\[
t_1 = \frac{\beta |r|}{r_{\gamma}} G_n(\infty)
\]

\[
t_2 = \frac{|r|}{\beta r_{\gamma}} G_n(\infty)
\]
SPATIAL CALIBRATION

• A set of several (≈20) checkerboard images is collected before the beginning of the experimental campaign

• 3D reference coordinates from checkerboard

Calibration of **intrinsic** and **distortion** parameters of the camera

**CAMERA POSITION/ORIENTATION INDEPENDENT**
**SPATIAL CALIBRATION**

A *background image* is collected:
- at the beginning of the experimental campaign
- everytime the camera moves, due to maintenance or vibrations

3D reference coordinates from simplified *CAD model*

Calibration of *extrinsic* parameters of the camera

**CAMERA POSITION/ORIENTATION**
HEAT-FLUX CALCULATION

IR MEASUREMENT
Heat-Flux Calculation

IR Measurement

\[ T(t; x,y) \]
Heat-Flux Calculation

Scene Model Overlay

\[ T(t; X, Y, Z) \]
**HEAT-FLUX CALCULATION**

- **IR MEASUREMENT**
  \[ T(t; x,y) \]

- **SCENE MODEL OVERLAY**
  \[ T(t; X, Y, Z) \]

- **HEATFLUX PROFILES**
  \[ q(t; s_i(X, Y, Z)) \]

**REGULAR GRID 1296x324**

**RESOLUTION: 3mm**

- Y. Gao et al. 2019 Nucl. Fusion 59 066007
Heat-Flux Calculation

- The heat flux profile on the divertor element is calculated by solving a 2D heat diffusion equation by explicit Euler method (2D THEODOR code)

\[ \rho c_p \frac{\partial T}{\partial t} = \nabla \left( \kappa \nabla T \right) \]

- \( \rho \): Volumetric mass density
- \( c_p \): Specific heat capacity
- \( \kappa \): Heat conductivity


PhD Thesis, Bernhard Sieglin
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STRIKE-LINE SEGMENTATION

It is important to **segment** the image, i.e. isolate the **thermal events** with respect to image background and noise, in order to **automatically**:

- **analyse** separately the properties of each single thermal event
- implement the proper **control** strategies in case of dangerous events

- Strike-line
- Hot spots
- Leading edges
  ...
- Other thermal events
**Strike-Line Segmentation**

It is important to **segment** the image, i.e. isolate the **thermal events** with respect to image background and noise, in order to **automatically**:

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![Image of thermal events](image)

- Strike-line
- Hot spots
- Leading edges
  ...
- Other thermal events
Strike-line properties can change for several reasons:

- Magnetic configuration
- Plasma beta
- Heating power
- Toroidal current
- Control coil currents
STRIKE-LINE SEGMENTATION

As a first attempt of isolating the strike-line and remove the effect of noise, hot spots and leading edges, a spatiotemporal *prefiltering* is applied to the video.

Prefiltering helps avoiding fragmentation

*Gaussian spatial filter size 31x31, $\sigma \approx 15\text{mm}$*

*moving average time filter, $w = 0.03\text{s}$*
STRIKE-LINE SEGMENTATION

For each profile (each vertical line) of the horizontal and vertical divertor target, the strike-line width is estimated, using the formula for the wetted area*, as

\[ w = \frac{Q_{\text{profile}}}{q_{\text{max}}} \]

- \( Q_{\text{profile}} \): line integrated heat-flux along the profile [MW/m]
- \( q_{\text{max}} \): maximum heat-flux in the profile [MW/m²]

The segmentation is equivalent to consider an equivalent rectangular profile having:
- heat-flux equal to \( q_{\text{max}} \)
- line integrated heat-flux equal to \( Q_{\text{profile}} \)

*M. Jakubowski et al., IAEA FEC 2018

Red area = Blu area

profile width
**STRIKE-LINE SEGMENTATION**

For each profile (each vertical line) of the horizontal and vertical divertor target, the strike-line width is estimated, using the formula for the wetted area*, as

\[
w = \frac{Q_{\text{profile}}}{q_{\text{max}}} = \frac{Q_{\text{profile},L} + Q_{\text{profile},R}}{q_{\text{max}}} = w_L + w_R
\]

- \(Q_{\text{profile}}\): line integrated heat-flux along the profile [MW/m]
- \(q_{\text{max}}\): maximum heat-flux in the profile [MW/m²]

The asymmetry with respect to the peak position is estimated on the basis of the ratio between the line integrated heat-fluxes at both sides of the profile.

\[
\frac{Q_{\text{profile},L}}{Q_{\text{profile},R}} = \frac{w_L}{w_R}
\]

*M. Jakubowski et al., IAEA FEC 2018
**Strike-line Segmentation**

For each profile (each vertical line) of the horizontal and vertical divertor target, the strike-line width is estimated, using the formula for the wetted area*, as

\[
w = \frac{Q_{\text{profile}}}{q_{\text{max}}} = \frac{Q_{\text{profile},L} + Q_{\text{profile},R}}{q_{\text{max}}} = w_L + w_R
\]

- \(Q_{\text{profile}}\): line integrated heat-flux along the profile [MW/m]
- \(q_{\text{max}}\): maximum heat-flux in the profile [MW/m\(^2\)]

**Applicable only in the case of a single strike-line for each target!**

*Only heat-fluxes greater than 0.15MW/m\(^2\) are taken into account.

\[
\text{Red area (L/R)} = \text{Blu area (L/R)}
\]

*M. Jakubowski et al., IAEA FEC 2018*
STRIKE-LINE SEGMENTATION

example of strike-line segmentation for standard configuration

3 main objects
**STRIKE-LINE CHARACTERIZATION**

For each object a set of features is calculated.

**SPATIAL**
- Area
- Perimeter
- Centroid Position
- Orientation
- etc.

**THERMAL**
- Maximum heat-flux
- Minimum heat-flux
- Mean heat-flux
- Median heat-flux
- etc.
**Strike-Line Control**

- The strike-line shape and position can be controlled through the action on the *magnetic islands* intersecting the divertor targets, in order to avoid excessive heat loads on unprotected areas or damaged tiles.

- The size and position of the magnetic islands can be controlled by means of a set of *control coils* located inside the plasma vessel below each of the 10 divertor units.
**STRIKE-LINE CONTROL**

**OBJECTIVE:** learn the relationship between strike-line features and strike-line control actuators (e.g. control coils) in order to develop a control system able to automatically sweep and change the strike-line shape as desired for the protection of PFCs

**TWO APPROACHES UNDER STUDY:**

**MACHINE LEARNING APPROACH:**
- Feature extraction with image processing (i.e. strike-line segmentation and characterization)
- Learning of the relationship between strike-line features and control actuators (direct and inverse)

**DEEP LEARNING APPROACH:**
- Bypass feature extraction
- Learn the relationship between strike-line images and control actuators (direct and inverse)
**STRIKE-LINE CONTROL**

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**Machine Learning Approach:**
- Feature extraction with image processing (i.e. strike-line segmentation and characterization)
- Learning of the relationship between strike-line features and control actuators (direct and inverse)

**Deep Learning Approach:**
- Bypass feature extraction
- Learn the relationship between strike-line images and control actuators (direct and inverse)
STRIKE-LINE CONTROL

Strike Line Image (heatflux, AEF10 IR camera)

Toroidal Current

CONVOLUTIONAL NEURAL NETWORK (CNN)

Lower Divertor Control Coil

Upper Divertor Control Coil
STRIKE-LINE CONTROL

CNN Architecture

The CNN is a static network: doesn’t take care of previous time evolution

CONVOLUTIONAL BLOCKS

FULLY CONNECTED BLOCK

30/05/2019 F. Pisano et al., “Tools for Image Analysis and First Wall Protection at W7-X” fabio.pisano@diee.unica.it
**STRIKE-LINE CONTROL**

Strike line control experiments in standard configuration (OP1.2b, XP: 20180816.#)

<table>
<thead>
<tr>
<th>Max(‖I_{cc}‖) = 1.36MA</th>
<th>Training</th>
<th>Validation</th>
<th>Test</th>
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<td></td>
<td>RMSE</td>
<td>(5.31%)</td>
<td>(5.42%)</td>
</tr>
<tr>
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The output of the CNN follows quite well the control coils evolution!
**Strike-Line Control**

Strike line control experiments in standard configuration (OP1.2b, XP: 20180816."

**AC Experiment**

The output of the CNN follows quite well the control coils evolution!
CONCLUSION

• An overview of imaging tools for strike-line characterization and control at W7-X is provided

• Strike-line control will be very important during steady-state operation

• PFCs protection against dangerous thermal events will be mandatory

• Strategies under study and test
THANKS FOR YOUR ATTENTION!

QUESTIONS?
DATA ACQUISITION

Courtesy of A. Puig Sitjes
**STRIKE-LINE CONTROL**

Strike line control experiments in standard configuration (OP1.2b, XP: 20180816.)

- **Original database**: 6903 examples
  - 6 experiments
  - Reference discharge, CC ramp up/down, AC

- **Reduced database**: 1839 examples
  - **Training**: 1380 examples
  - **Validation**: 230 examples
  - **Test**: 229 examples