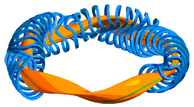


Imaging Challenges in Long Pulse Nuclear Fusion Experiments

R. König[1], T. Bluhm[1], K. Grosser, D. Hildebrandt[1], T. Hübner[1], F. Klinkhamer[2], K. Moddemeijer[2], M. Otte[1] and W. Vliegenthart[2]

[1]Max-Planck-Institut für Plasmaphysik, EURATOM ASS., D-17489 Greifswald, Germany, [2]TNO Science and Industry, Stieltjesweg 1, 2600 AD Delft, The Netherlands

Introduction

Imaging diagnostics play a significant role in any long pulse nuclear fusion experiment, even more so in stellarators due to their intrinsic 3 dimensional magnetic field geometry as well as edge and divertor plasma structures.

Typical Imaging Diagnostics

- Thermography
- Video observation
- Ha, C II, C III edge/divertor plasma observation
- Flux-Surface Measurements (Stellarator)

Technical Problems faced

High heat loads due to

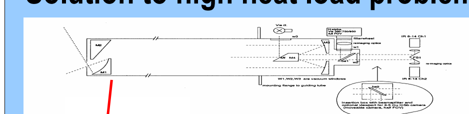
- plasma radiation
- ECRH stray radiation

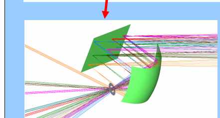
Achievement of required spatial resolution

Spatial view changes due to

- endoscope viewing direction changes due to plasma vessel shape changes caused by gradual vessel heat-up
- transition to hot liner operation (150°C in W7-X)

Solution to high heat load problem:





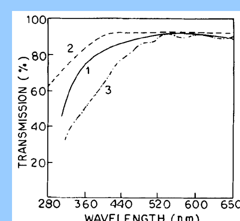
Significant heat load reduction on first optical element by observation through pinhole (entrance pupil) in water cooled SS plasma facing front plate

How to attack the ECRH stray radiation problem:

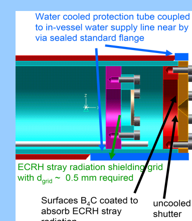
W7-X: Up to 200 kW/m^2 ECRH stray radiation @ 140 GHz (λ = 2mm) for high density OXB heated plasma expected

Shielding for cameras & electronics required

- micro-mesh (grid openings < $\lambda/4$ = 0.5 mm, skin depth d ~ 1 µm for Al or Cu)
- ITO Idium Tin Oxyde transparent coating: Curve 2: layer thickness d = 1 µm, resistivity ρ = 8 e-5 Ωcm, skin depth δ = 1.2 µm



S. Ray,et al., J. Appl. Phys. **54**, 3497 (1983)

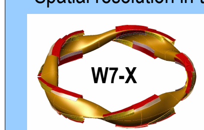


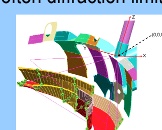
Front-end of W7-X video diagnostic

Detailed tests will be performed in the ECRH stray radiation test chamber at IPP Greifswald

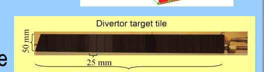
Spatial resolution

Spatial resolution in the IR region often diffraction limited





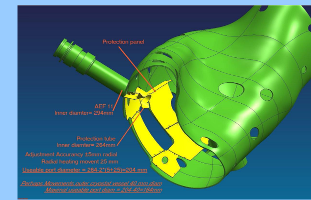
Temperature of 10 discrete divertor modules needs to be controlled with µ-bolometers (λ~10 µm) to avoid damage.



Due to apparent overheating of re-deposited carbon at edges of CFC structure spatial resolution of about 5 - 8 mm required.

For divertor extension 4000 mm, endoscope length 2m, largest existing micro-bolometer 640 x 480 pxl., pitch 25 µm
➔ resolution of ideal optical system fully determined by f/#: required spatial resolution of ~6 mm needs f/# = 0.95, actual design with one camera: f/# = 2.15 with Δx = 25 mm,
➔ two cameras required: present design f/#=4, Δx= 9mm

Spatial view changes



W7-X: IR(vis. endoscopes fixed to outer cryostat vessel
➔global FEM of the machine needed to investigate expected movements for various load cases

Software Challenges I

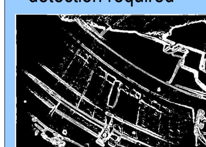
Large number of cameras (~50) requires fully automated

- in-vessel component identification via edge detection for co-ordinate grid generation

flux surface mapping and field line tracing connected to theoretical field line tracing codes

Automated alignment/co-ordinate grid determination

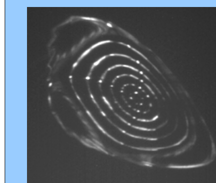
Co-ordinate systems need to be defined for large number of cameras systems, prior to start of operation as well as during long pulses with high heating power.
➔ Automated component identification via edge detection required

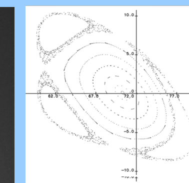


Example of divertor structure in W7-AS stellarator. Left: detected edges of artificially illuminated divertor. Right: Overlay of automatically oriented CAD model and observed image.

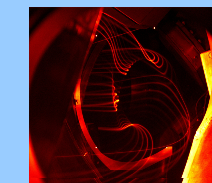
View changes during long pulses can be followed by flash light illumination (see endoscope design bottom left) of single frames at suitable time intervals.

Flux Surface measurements





Fuzzy structures of measured flux surfaces and flux tubes need to be characterised by lines, e.g. with techniques used to trace arteries in medicine. From matching with calculated Poincare plots and field lines in 2D and 3D using Gourdon and w7 vacuum field calculation codes information can be gained on sources for observed discrepancies.



Magnetic flux tube visualised by electron beam excitation of the H (or Ar) background gas

Software Challenges II

Large number of data: 50 cameras:
~ 5 TByte / 30 min discharge

Storing and retrieving large amounts of data requires extensive, fully automated post processing:

- Image distortion corrections, co-ordinate system mapping onto common grid
- multi-resolution, fuzzy image content analysis
- feature extraction, categorisation, hierarchical image classification
- video sequencing driven by internal analysis and externally supplied events
- content based, multi-resolution image and video sequence query and retrieval

Edge/divertor plasma observation:

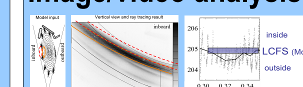
- symmetry investigations (stellarator) across all 10 divertor modules of W7-X
- tracing feature movements (strike lines, MARFEs, blobs, etc.) using CNNs, NNs, conventional methods
- real time thermal load control and hot spot detection (machine safety)

Data handling

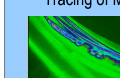
Existing technology already sufficient:

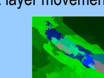
- 10 Gbit/s Ethernet and 0.5 TB hard disks with few GByte/s
- 0.5TB tapes with 0.1TB/s, 10 TB tapes expected by 2011, expected data volume ~1 PB/ year ≙ 1/10 of LHC at CERN / year

Image/video analysis



Tracing of MARFE layer movement





Divertor strike line characterisation and pattern segmentation by pyramid-linking method (right)

Hot Spot detection

Real time analysis: Two limits, reaction and safety limit, can be set.