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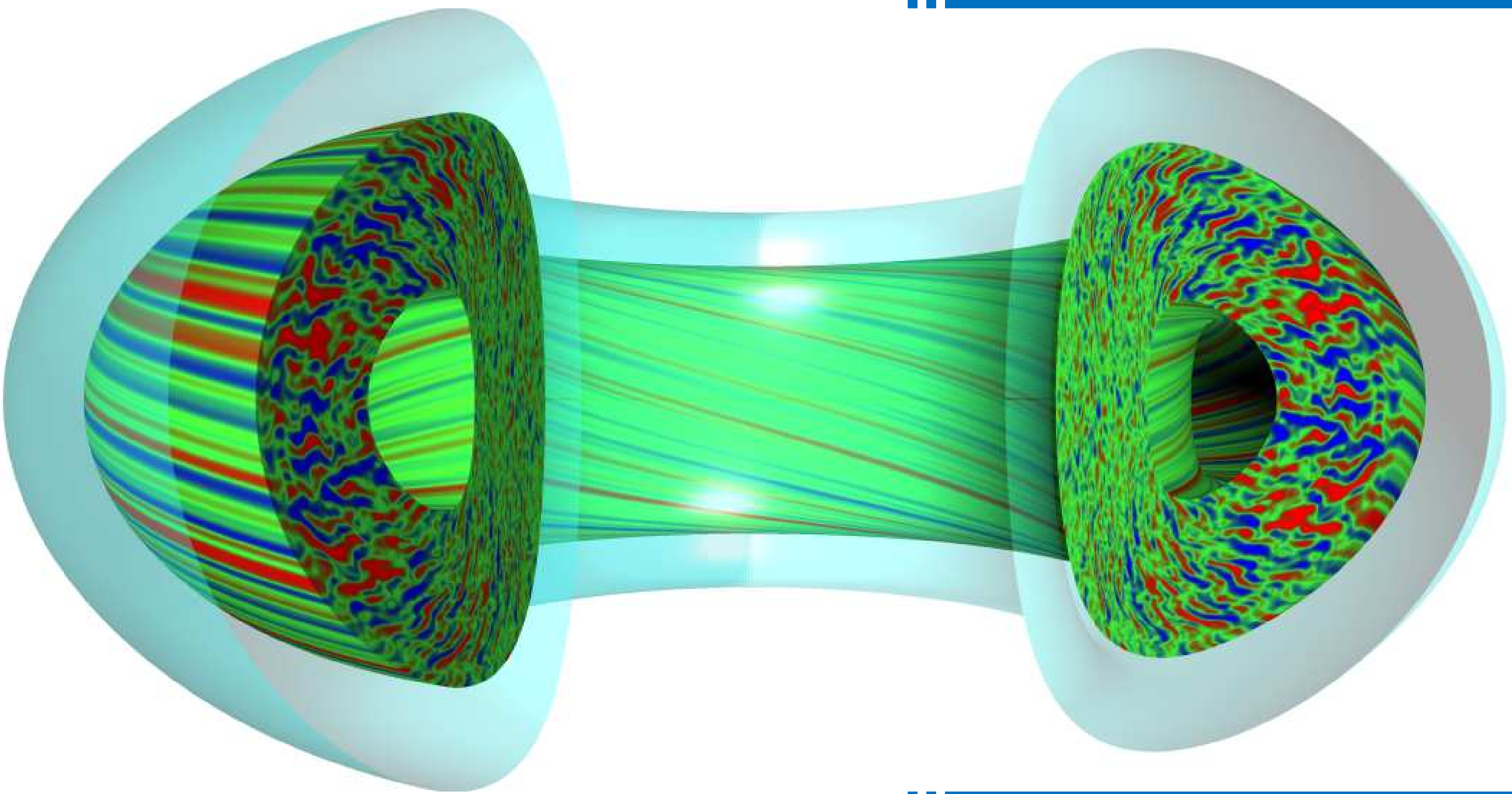
Programme & Book of Abstracts

1st IAEA Technical Meeting on Fusion Data Processing, Validation and Analysis



1st - 3rd June, 2015

Castle of Valrose University,

Nice, France

First IAEA Technical Meeting on Fusion Data Processing, Validation and Analysis

Hosted by the Institut de Recherche sur la Fusion par confinement Magnetique, IRFM, CEA Cadarache

1 – 3 June 2015

Nice, France

Venue: Castle of Valrose University

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International Programme Advisory Committee

Chair: D. Mazon (France)

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Meeting Website: http://irfm.cea.fr/TMFDPVA15/

Topics

I. **Error analysis and propagation (EAP)**

II. **Probability theory and statistics (PTS)**

III. **Parameter estimation, inverse problems, equilibrium reconstruction (PPR)**

IV. **Integrated data analysis (IDA)**

V. **Data mining (DM)**

VI. **Pattern recognition and machine learning (PRL)**

VII. **Signal, image and video processing (SIV)**

VIII. **Real-time data analysis (RDA)**

IX. **Model selection and validation (MSV)**

X. **Experimental design and synthetic diagnostics (EDD)**

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SCHEDULE

Invited Orals (I) are allotted 25 min + 5 min for discussion.

Regular Orals (O) are allotted 20 min + 5 min for discussion.

Monday, 1st June

08:30-09:00	Welcome and registration
09:00-09:30	**Welcome and opening address** S.M. Gonzalez de Vicente, Nice Council representative, D. Mazon
Session 1	**Disruption prediction and classification. Chair: J. Vega**
09:30-10:00	**I-1: P. de Vries** *Requirements for triggers of the ITER Disruption Mitigation System*
10:00-10:25	**O-1: G. Sias** *Physics-based indicators for disruption prediction at JET and AUG*
10:25-10:50	**O-2: J. Vega** *Investigation of plasma dynamics to detect the approach to the disruption boundaries*
10:50-11:10	**Coffee Break**
11:10-11:35	**O-3: R. Moreno** *Overview of disruption prediction at JET during the ILW experimental campaigns*
11:35-12:00	**O-4: G. Sias** *A multivariate analysis of disruption precursors on JET and AUG*
12:00-13:00	**Lunch Break**
Session 2	**Inverse problem and error treatment. Chair: Didier Mazon**
13:00-13:30	**I-2: J. Blum** *Equilibrium reconstruction and identification of the current density profile*
13:30-13:55	**O-5: B. Faugeras** *Boundary reconstruction using toroidal harmonics and an optimal control method*
13:55-14:20	**O-6: H. Liu** *First results of Polarimeter-Interferometer System for current density measurement on EAST*
14:20-14:45	**O-7: Y. Yang** *Systematic Investigations on Atomic Structure and Spectroscopy of Tungsten Ions related to ITER Diagnostics in Shanghai EBIT Laboratory*

14:45-15:10	**O-8: T. Craciunescu** *New developments in JET gamma emission tomography*
15:10-15:30:	**Coffee Break**
15:30-15:55	**O-9: J. Mlynar** *Tikhonov regularisation adapted to the real-time tomography*
15:55-16:20	**O-10: F. Keisuke** *Measurement of the neutral hydrogen atom density in the LHD core plasmas based on the spectral inversion*
16:20-16:45	**O-11: C. Rapson** *Real-time data fusion for nuclear fusion*
17:00	**Adjourn**

Tuesday, 2nd June

Session 3	<u>**Integrated Data Analysis. Chair: Rainer Fischer**</u>
08:30-09:00	**I-3: L. M. Reusch** *Electron Temperature Measurements Combining Soft X-ray Tomography with Thomson Scattering Using MCMC*
09:00-09:25	**O-12: L. M. Reusch** on behalf of **M. E. Galante** *Impurity Density Profiles and Their Effect on Zeff by Integrating Measurements from the Soft X-ray Tomography System and Charge Exchange Recombination Spectroscopy*
09:25-09:50	**O-13: F. Imbeaux** *Applications of Bayesian temperature profile reconstruction to automated comparison with heat transport models and uncertainty quantification of current diffusion*
09:50-10:15	**O-14: R. Fischer** *Recent developments of Integrated Data Analysis at ASDEX Upgrade: Kinetic profiles, current diffusion and equilibrium*
10:15-10:35	**Coffee Break**
Session 4	<u>**New mathematical methods for extracting models directly from the data. Chair: Andrea Murari**</u>
10:35-11:00	**O-15: A. Murari** *Symbolic regression for the derivation of mathematical models directly from the data*
11:00-11:30	**I-4: E. Peluso** *Genetic programming for the data driven formulation of scaling laws: the case of the L-H and H-L transitions"*
11:30-11:55	**O-16: S. Talebzadeh** *From machine learning tools to mathematical models: the case of disruption prediction and avoidance*
11:55-12:20	**O-17: G. Verdoolaege** *Demonstration of the robustness of geodesic least squares regression for scaling of the energy confinement and power threshold in tokamaks*
12:20-13:20:	**Lunch Break**

Session 5	<u>**Physics model validation. Chair: Nathan Howard**</u>
13:20-13:50	**I-5: T. Goerler** *Recent progress in comparing gyrokinetic GENE simulations with experimental measurements*
13:50-14:15	**O-18: P. Ricci** *Verification & Validation of plasmas turbulence codes in scrape-off layer conditions*
14:15-14:40	**O-19: A. E. White** *Comparing transport in Alcator C-Mod high confinement I-mode plasmas with GYRO nonlinear gyrokinetic simulations*
14:40-15:05	**O-20: S. Äkäslompolo** *Validating the Monte Carlo test particle code ASCOT*
15:05-15:30	**O-21: M. Churchill** *Edge physics discovery and validation by synthetic diagnostics using the XGC gyro-kinetic codes*
15:30-15:55	**O-22: N.T Howard** *Progress validating the gyrokinetic model in Alcator C-Mod and DIII-D plasmas*
15:55-16:20	**O-23: K. Mc Collam** *Comparing MHD simulations to experiments*
16:20-16:40:	**Coffee Break**
Session 6	<u>**Synthetic diagnostics. Chair: A. Dinklage**</u>
16:40-17:10	**I-6: U. von Toussaint** *Bayesian Gaussian Processes as surrogate models for complex computer codes*
17:10-17:35	**O-24: C. Lechte** *Doppler Reflectometry Simulations for ASDEX Upgrade*
17:35-18:00	**O-25: A. Langenberg** *Forward Modeling of an X-ray Imaging Crystal Spectrometer within the Minerva Bayesian Analysis Framework*
18:00-18:25	**O-26: S. Lisgo on behalf of A. Kukushkin** *Synthetic H-alpha diagnostics for ITER: inverse problems and error estimations for strong non-Maxwellian effects and intense divertor stray light*
18:30	**Adjourn**

Wednesday, 3rd June

Session 7	**Data Calibration, Validation and Analysis. Chair: Yasunori Kawano**
08:00-08:30	**I-7: H. Tojo** *An in-situ spectral calibration method of Thomson scattering diagnostics for severe radiation circumstances*
08:30-08:55	**O-27: M. A. Naveed** *Magnetic Diagnostics for GLAST-III Tokamak*
08:55-09:20	**O-28: M.A. Chilenski** *Towards a Bayesian analysis of impurity transport data*
09:20-09:45	**O-29: S.G. Lee** *Toroidal Rotation and Ion Temperature Validations in KSTAR Plasmas*
09:45-10:00	**Coffee Break**
10:00-10:25	**O-30: J. C. Chorley** *GPU – based data analysis for SAMI*
10:25-10:50	**O-31: B. J. Xiao** *Parallel Plasma Equilibrium Reconstruction Based on GPU in EAST and DIII-D*
10:50-11:15	**O-32: M. Takeuchi** *Development of the In-situ Calibration Method for ITER Divertor IR Thermography*
11:15-11:40	**O-33: A. Wojenski** *Concept and current status of data acquisition technique for GEM detector based SXR diagnostics*
11:40-12:05	**O-34: I. Semenov** *Grid Technology for Controlled Fusion: Conception of the Unified Cyberspace and ITER Data Management*
12:05-13:05	**Lunch Break**
Session 8	**Image processing for advance data analysis and Real time. Chair: Didier Mazon**
13:05-13:35	**I-8: A. Herrmann** *Surface temperature measurement of in-vessel components and its real-time validation*
13:35-14:00	**O-35: S. Martinov** *Real Time Machine Protection at ASDEX Upgrade using Near Infrared Cameras*

14:00-14:25	**O-36: B. Sieglin** *Real Time IR Thermography at ASDEX Upgrade: Current Status and Future Prospects*
14:25-14:50	**O-37: X Courtois** *Design of WEST Infrared thermography diagnostics*
14:50-15:15	**O-38: M.H Aumenier** *A fully synthetic diagnostic for the evaluation of measurement performances of WEST Infrared Imaging System*
15:15-15:30	**Coffee Break**
Session 9	**Stochastic modelling and time series analysis. Chair: G. Verdoolaege**
15:30-16:00	**I-9: F. Felici** *Real-time diagnostic data fusion using the RAPTOR transport code in combination with an Extended Kalman Filter, with application to diagnostic fault detection and disruption prediction*
16:00-16:25	**O-39: A. Shabbir** *Analysis of the dependence between inter-ELM time intervals and energy losses*
16:25-16:50	**O-40: F. Pisano on behalf of B. Cannas** *Testing for chaos in type-I ELM dynamics on JET with the ILW*
16:50-17:15	**O-41: G. Hornung** *Bayesian inference of plasma turbulence properties from reflectometry Measurements*
17:15-17:40	**O-42: F. Zaitsev** *Evaluation of epsilon-net calculated equilibrium reconstruction error bars in the EUROfusion WP-CD platform*
17:40-18:05	**O-43: L. Zabeo** *Data for the ITER Plasma Control System*
18:05-18:30	**O-44: E. Kurt** *Simulation studies on the ion trajectories and energy spectra for a new inertial electrostatic confinement fusion device*
18:30	**Closing**

List of Invited Orals:

I-1: P.C. de Vries**,** *Requirements for triggers of the ITER disruption mitigation system*

I-2: J. Blum, *Equilibrium reconstruction and identification of the current density profile*

I-3: L. M. Reusch, *Electron Temperature Measurements Combining Soft X-ray Tomography with Thomson Scattering Using MCMC*

I-4: E. Peluso, *Genetic programming for the data driven formulation of scaling laws: the case of the L-H and H-L transitions"*

I-5: T. Goerler, *Recent progress in comparing gyrokinetic GENE simulations with experimental measurements*

I-6: U. von Toussaint, *Bayesian Gaussian Processes as surrogate models for complex computer codes*

I-7: H. Tojo, *An in-situ spectral calibration method of Thomson scattering diagnostics for severe radiation circumstances*

I-8: A. Herrmann, *Surface temperature measurement of in-vessel components and its real-time validation*

I-9: F. Felici, *Real-time diagnostic data fusion using the RAPTOR transport code in combination with an Extended Kalman Filter, with application to diagnostic fault detection and disruption prediction*

I-1. Requirements for triggers of the ITER disruption mitigation system

P.C. de Vries[1], G. Pautasso[2], D. Humphreys[3], M. Lehnen[1], S. Maruyama[1], J.A. Snipes[1], A. Vergara[1], L. Zabeo[1]

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[2] *Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany.*
[3] *General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA.*

A disruption of a tokamak discharge is the rapid loss of a large fraction of the thermal energy (i.e. the thermal quench), leading to a plasma current quench on a slower time scale. This is often accompanied by a loss of vertical stability, or a vertical displacement event (VDE). Although, in the worst case, it is also possible that a VDE precedes the thermal and current quench. Moreover, a highly energetic runaway electron beam can develop in the process.

To protect ITER from the high thermal and electromagnetic loads resulting from disruptions, prevention of such events is an essential part of the ITER plasma control system, backed up by an effective and reliable disruption mitigation system (DMS). An important aspect of the mitigation action is its trigger, the balanced decision that a disruption can no longer be prevented by scenario or stability control action and mitigating action needs to be taken. Disruption prediction is a broader concept that could provide triggers for a wide variety of actions taken to prevent disruptions. This paper will only discuss the requirements for the trigger to the ITER DMS and the approach to how these may be developed and commissioned.

The requirements for the DMS trigger are to be determined by the ITER design constraints (the vessel and first wall in particular), the technical limitations of the control and mitigation system, as well as the physics basis of disruptions and their mitigation. The paper will justify the required warning time, success rate and false alarm rate, and control of the mitigating action itself. Hence, information needs to be provided to the DMS on how to react and mitigate. The amount of injected material needs to be controlled avoiding too fast a current quench while independent mitigating actions have to be provided to deal with the effects of the thermal/current quench as well as preventing the development of a runaway electron beam.

Requirements for the DMS trigger will develop progressively along with ITER operations, from low current non-active (H/He) operation to 15MA high performance (DT) operations. Initially, triggers may be based on straightforward thresholds, such as those that simply detect the thermal or current quench. Such triggers generally provide a very short warning time and a moderate success rate with a very low false alarm rate, but this may be sufficient for early ITER operations. During this first operational phase, more advanced triggers must be developed that will fulfil the more stringent requirements for high current and high performance operation and enable reduction in the general disruption rate. The paper will show how the development of advanced triggers can be in-line with the present ITER research and operations plan.

I-2. Equilibrium reconstruction and identification of the current density profile

Jacques Blum, Cedric Boulbe, Blaise Faugeras

CASTOR Team-Project INRIA and Laboratoire J.A. Dieudonné CNRS UMR 7351bIPP/MPG, Greifswald, Germany

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The reconstruction of the equilibrium of a plasma in a Tokamak is a free boundary problem described by the Grad-Shafranov equation in axisymmetric configuration. The right-hand side of this equation is a nonlinear source which represents the toroidal component of the plasma current density.

This work deals with the identification of this nonlinearity from experimental measurements: magnetics on the vacuum vessel, but also polarimetric and interferometric measurements on several chords, as well as motional Stark effect measurements. The proposed method is based on a fixed point algorithm, a finite element resolution and a least-square optimization formulation. This method has led to the development of a software, EQUINOX, which enables to follow in real-time the quasi-static evolution of the plasma equilibrium in any Tokamak.

Several numerical experiments have been conducted to explore the identification problem. This has shown that the identification of the prole of the averaged current density and of the safety factor as a function of the poloidalflux is very robust. The sensitivity to noise in the experimental measurements has been studied for the reconstruction of the plasma current density profile and a regularization technique optimized with respect to the amount of noise.

I-3. Electron Temperature Measurements Combining Soft X-ray Tomography with Thomson Scattering Using MCMC

L. M. Reusch[1], M. E. Galante[1], D. J. Den Hartog[1], P. Franz[2], J. R. Johnson[1], M. B. McGarry[1], and H. D. Stephens[1,3]

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[2]*Consorzio RFX, Associazione EURATOM-ENEA sulla Fusione, Padova, Italy*
[3]*Pierce College Fort Steilacoom, Lakewood, WA 98498, USA*

The Madison Symmetric Torus (MST) Reversed-Field Pinch is equipped with two independent electron temperature (T_e) diagnostics: Thomson scattering and double-filter soft x-ray tomography system. Both diagnostics are able to measure T_e at a rate up to 25 kHz and are in good qualitative agreement across much of the plasma radius. Using integrated data analysis (IDA) to take advantage of the redundant information provided by these diagnostics produces a factor of 2-3 improvement in the core T_e uncertainty in axisymmetric plasmas. The IDA technique uses Bayesian probability theory (BPT), which provides a framework for easily combining information from different diagnostics and background information, and consistent error analysis. Parameter estimation in BPT relies on scanning the input parameters to a forward model and comparing the results to data. For axisymmetric plasmas, a three-parameter model for the temperature profile was used, and the most likely profile was found using a grid search. However, MST is capable of sustaining potentially non-axisymmetric temperature structures. These more complicated situations necessitate a model with more parameters, which makes an exhaustive grid search impractical. For this reason, a Markov Chain Monte Carlo (MCMC) search method was implemented to more efficiently search the parameter space. A three-parameter MCMC was heavily benchmarked against the initial grid search to assess behavior. An eight-parameter model is being used to estimate temperature structures using the MCMC sampling technique.

I-4. Genetic programming for the data driven formulation of scaling laws: the case of the L-H and H-L transitions

E.Peluso[1], A. Murari[2], M.Gelfusa[1], M.Lungaroni[1], P.Gaudio[1] and JET Contributors§

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[2] *Consorzio RFX (CNR, ENEA, INFN, Universita' di Padova, Acciaierie Venete SpA),Corso Stati Uniti 4, 35127 Padova, Italy.*

§*See the Appendix of F.Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

Reliable scaling expressions, for the power threshold to access and leave the H mode of confinement, remain a subject of active research, because up to now no theoretical relation has proved to be general enough to interpret reliably these critical phenomena. In this contribution, reports on a series of advanced statistical methods developed to extract scaling expressions directly from the data without "a priori" assumptions on their mathematical form.

They are applied to the investigation of the power to access and leave the H mode. The long term objective of this line of research is the identification of reliable scaling expressions for the planning of the experiments and the design of future devices. The developed statistical tools, which combine Symbolic Regression and Genetic Programming, are deployed to analyse all available JET discharges with the ITER Like Wall explicitly designed to address the L-H transition. The best scaling expressions for both the L-H and the H-L transitions are not power laws and depend on the pressure and plasma shape. The scalings of the same mathematical form fit quite well also the data of the previous campaigns with the carbon wall.

The scalings obtained with these regressors are significantly better than the ones obtained with alternative quantities, such as the plasma current, Zeff etc. The extrapolations to ITER, even if they have to be taken with great caution given the limited amount of examples available, seem to indicate more favourable conditions for the access to the H mode than normally expected on the basis of traditional power laws. The issue of hysteresis has also been investigated in detail, trying to separate time dependent from time independent hysteresis. The obtained results, even if not absolutely conclusive, seem to indicate the presence of time independent hysteresis.

I-5. Recent progress in comparing gyrokinetic GENE simulations with experimental measurements

T. Görler[1], A.E. White[2], D. Told[1,3], F. Jenko[1, 3], C. Holland[4], and T.L. Rhodes[3]

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[2] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[3] *Department of Physics&Astronomy, University of California, Los Angeles, CA 90095, USA*
[4] *Center for Energy Research, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA*

Over the last decade plasma turbulence simulations based on the gyrokinetic theory have reached an amazing degree of physical comprehensiveness and realism. In contrast to early gyrokinetic studies which were restricted to qualitative statements, state-of-the-art investigations may now be compared quantitatively, therefore enabling validation and detailed analysis of their predictive capabilities. Here, applications of the gyrokinetic code GENE[1] to DIII-D [2] and ASDEX Upgrade[3] plasmas will be discussed. Particular attention is paid to outer-core L-mode discharges where some previous gyrokinetic studies have found an ion heat transport underprediction by almost one order of magnitude[4]. Since then, this so-called shortfall issue has been subject to various speculations on possible reasons and has received lots of attention. Carrying out radially local and non-local GENE simulations using actual plasma profiles/parameters and MHD equilibria and employing as much physics as available, only a mild underprediction is found which can furthermore be overcome by varying the ion temperature gradient within the error bars associated with the experimental measurement. The significance and reliability of these simulations is demonstrated by benchmarks, numerical convergence tests and furthermore by extensive comparison with experimental measurements.
The latter involve sophisticated synthetic beam emission spectroscopy (BES) and correlation electron cyclotron emission data analysis as well as cross-phase comparisons. The agreement found between the measurements and the state-of-the-art post-processed simulation data confirms a high degree of realism.

[1] http://gene code.org; F. Jenko et al., Phys. Plasmas 7, 1904 (2000); T. Görler et al., J. Comput. Phys. 230, 7053 (2011).
[2] J.L. Luxon, Nucl. Fusion 42, 614 (2002).
[3] A. Kallenbach et al., Nucl. Fusion 51, 094012 (2011).
[4] C. Holland et al., Phys. Plasmas 16, 052301 (2009).

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I-6. Bayesian Gaussian Processes as surrogate models for complex computer codes

U. von Toussaint, R. Preuss

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The simulation of complex computer models, e.g. the simulation of plasma-wall interactions of fusion plasmas is extremely costly in computer power and time -- the running time for a single parameter setting is easily in the order of weeks or months.

To exploit the already gathered results in order to predict the outcome and the associated uncertainty for parametric studies within the high dimensional parameter space we propose investigate the use of Gaussian processes within the Bayesian framework. Validation is performed with mock and real-world data and the interpolation properties are studied on selected test cases.

Finally, the approach is applied to simulation data from the scrape-off layer of a fusion plasma. Uncertainties of the predictions are provided which point the way to optimized parameter settings of subsequent simulations.

I-7. An in-situ spectral calibration method of Thomson scattering diagnostics for severe radiation circumstances

[1]Hiroshi Tojo, [2]Ichihiro Yamada, [2]Ryo Yasuhara, [3]Akira Ejiri, [1]Junichi Hiratsuka, [3]Hiro Togashi, [3]Takashi Yamaguchi, [1]Eiichi Yatsuka, [1]Takaki Hatae, [2]Hisamichi Funaba, [2]Hiroshi Hayashi, [3]Yuichi Takase, and [1]Kiyoshi Itami

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For Thomson scattering diagnostics utilizing optical lenses and fibers, degradation of their spectral transmissivities (reflectivities) under harsh radiation environments is a crucial issue. In such conditions, electron temperature (T_e) determined from the measured scattered spectra cannot be correctly estimated. To cope with this issue, an in-situ calibration method using a double-pass scattering system where a laser goes through the plasma twice by installing a reflection mirror has been proposed. The scattered lights from both the first and the second passes are separately measured using fast-response detectors and/or optical delay path. Use of the ratio of the two sets of the measured spectra enables determining T_e without knowing the spectral transmissivities. Once T_e is determined, the spectral transmissivities can be derived from a simple linear regression. Experimental tests have been performed on TST-2 and LHD. The electron temperature obtained by this new method was in good agreement with that obtained by a standard method (single pass). Relative transmissivities evaluated from this method are compared with that measured before the experiments. In a range of 0.8 – 1.5 keV, good accuracies were confirmed (<10%) in LHD. Simulations for cases with high T_e (> 10 keV) and wide scattering angle will be also presented for high performance plasmas such as ITER.

I-8. Surface temperature measurement of in-vessel components and its real-time validation

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Systems to measure the temperature of in-vessel components are foreseen with a high priority for ITER. The highest priority is given to systems for machine protection. Other systems are planned for physics investigation. Machine protection is only as good as reliable the supervision systems and the measured data are. Formal requirements of ITER, like spatial and temporal resolution as well as dynamic range and resolution can be considered during the design of the protection system. To consider effects of higher order such as back ground radiation, target morphology, deposited layers and plasma radiation is more difficult and nearly impossible to consider during the calibration process. Engineering restrictions like surface or interface temperature limits are the driving part for machine protection systems. The range that can be used for machine operation depends on the uncertainties of the temperature measurement. If this is large, the machine limits have to be reduced to avoid operation above the engineering limits.

Assuming a reliable calibration of a system in terms of photon flux for diode based detectors or power for micro-bolometers there are two origins for 'wrong' temperature measurements. (i) The measured photon flux is the superposition of temperature signal and a parasitic photon flux due to plasma radiation. The main tool to discriminate between both sources is its wavelength dependence. (ii) The measured photon flux is due to the temperature of the measuring object, but this temperature is not the relevant temperature for machine safety requirements due to surface effects. Here the wavelength dependence and the temporal evolution allow detecting 'wrong' temperature measurements.

This paper discusses routes for real-time temperature validation and the underlying effects considering the experiences from ASDEX Ugrade.

I-9. Real-time diagnostic data fusion using the RAPTOR transport code in combination with an Extended Kalman Filter, with application to diagnostic fault detection and disruption prediction.

Federico Felici[1], Thomas Blanken[1], Chris Rapson[2], Wolfgang Treutterer[2], Olivier Sauter[3] and the ASDEX-Upgrade team[2]

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[2] *Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany*
[3] *CRPP-EPFL, École Federale Polytechnique de Lausanne. CH-1015 Lausanne, Switzerland*

The development of control-oriented physics models for tokamak plasma dynamics have paved the way for use of model-based state estimation techniques for real-time interpretation of diagnostic data. A data 'fusion' algorithm based on the Extended Kalman Filter has been developed [1] using the RAPTOR profile simulation code [2] as the predictive model. It has recently been implemented and tested on the ASDEX-Upgrade tokamak, showing successful reconstruction of the temperature and current density profile using data from several sources, including ECE, auxiliary power and magnetic equilibrium, in real-time. The deviation between real-time predicted diagnostic signals and measured signals, i.e. the measurement residual, is constantly monitored for signs of diagnostic failure or unexpected plasma behaviour. If a diagnostic fault is detected, the faulty channels are eliminated from the reconstruction on-the-fly. Signatures in the measurement residual pointing to unexpected behaviour of the entire plasma are monitored by a higher-level plasma supervision system. Examples of both cases will be shown based on ASDEX-Upgrade data from the 2014 campaign. Plans for implementation of a more advanced disruption classification system based on the measurement residuals, to be implemented on ASDEX-Upgrade and TCV, are also discussed.

[1] F. Felici et al., American Control Conference, Portland USA, (2014) 4816-4823

[2] F. Felici et al., Plasma Physics and Controlled Fusion 54 2 (2012) 025002

List of Regular Orals:

O-1: G. Sias, *Physics-based indicators for disruption prediction at JET and AUG*

O-2: J. Vega**,** *Investigation of plasma dynamics to detect the approach to the disruption boundaries*

O-3: R. Moreno, *Overview of disruption prediction at JET during the ILW experimental campaigns*

O-4: G. Sias, *A multivariate analysis of disruption precursors on JET and AUG*

O-5: B. Faugeras, *Boundary reconstruction using toroidal harmonics and an optimal control method*

O-6: H. Liu, *First results of Polarimeter-Interferometer System for current density measurement on EAST*

O-7: Y. Yang, *Systematic Investigations on Atomic Structure and Spectroscopy of Tungsten Ions related to ITER Diagnostics in Shanghai EBIT Laboratory*

O-8: T. Craciunescu, *New developments in JET gamma emission tomography*

O-9: J. Mlynar, *Tikhonov regularisation adapted to the real-time tomography*

O-10: F. Keisuke, *Measurement of the neutral hydrogen atom density in the LHD core plasmas based on the spectral inversion*

O-11: C. Rapson, *Real-time data fusion for nuclear fusion*

O-12: M. E. Galante, *Impurity Density Profiles and Their Effect on Zeff by Integrating Measurements from the Soft X-ray Tomography System and Charge Exchange Recombination Spectroscopy*

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O-32: M. Takeuchi, *Development of the In-situ Calibration Method for ITER Divertor IR Thermography*

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O-41: G. Hornung, *Bayesian inference of plasma turbulence properties from reflectometry Measurements*

O-42: F. Zaitsev, *Evaluation of epsilon-net calculated equilibrium reconstruction error bars in the EUROfusion WP-CD platform*

O-43: L. Zabeo, *Data for the ITER Plasma Control System*

O-44: E. Kurt, *Simulation studies on the ion trajectories and energy spectra for a new inertial electrostatic confinement fusion device*

O-1. Physics-based indicators for disruption prediction at JET and AUG

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*See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

In the past years, different approaches have been exploited for the prediction of disruptions, from first principle models, based on the physics underlying disruptive processes, to data-driven methods, mainly based on machine and statistical learning. Nevertheless, present disruption predictors do not allow yet a confident extrapolation to ITER for several reasons. Data-driven approaches have proved to achieve very good results, if optimized and applied to their training domain, but their generalization capability and their portability to other machines have still to be assessed. On the other hand, some predictors rely mainly on the locked mode signal, which is the most common and clearest signature of an approaching disruption but does not provide always a sufficient warning time to put in place an effective avoidance strategy.

In this work, the attempt to build indicators representative of typical disruptive processes will be described, evaluating their prediction capabilities for both JET and AUG.

In particular, signal processing and feature extraction techniques have been exploited to find, when possible, dimensionless parameters to be properly combined for disruption prediction. Analyses have been focused on identifying those quantities that show interesting features in relation to their amplitude and/or their variability in time, trying to understand how they can be interpreted to effectively describe the typical chain of events, which give rise to disruption, such as the onset of MARFEs, impurity accumulation, time evolution of the main profiles, MHD markers, etc..

Particular emphasis will be put on the analysis of the most relevant similarities between the two machines and the indicators' predictive capability will be statistically assessed.

O-2. Investigation of plasma dynamics to detect the approach to the disruption boundaries

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This contribution shows a machine learning technique to detect when the plasma starts to move away from a safe region in the parameter space and, therefore, it begins to approach a disruptive zone. The recognition method is based on an accurate and reliable disruption predictor based on the formalism of conformal predictions.

The technique allows following the plasma dynamics during a discharge. In general, the plasma evolves in a steady way, far enough from the disruptive region. However, some events can push the plasma towards the dangerous region. Most of times, the plasma goes back to the initial safe zone. But sometimes, the plasma reaches a non-return point and the disruption is inevitable. This has been analysed with 297 JET unintentional disruptions during the ILW campaigns. On average, the transit from the non-return point and the disruption takes 749 ms (with a standard deviation of 1.060 s). This transit shows three phases. In a first period, the plasma goes from the non-return point (in the safe region) to an intermediate zone, where the plasma state (disruptive or non-disruptive) is not clearly defined. On average, this first phase takes 180±436 ms. In the second phase, the plasma maintains its undefined state during 244±686 ms. Finally, the plasma enters the disruptive region and this phase lasts 325±536 ms.

O-3. Overview of disruption prediction at JET during the ILW experimental campaigns

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The advanced predictor of disruptions, APODIS, has been working in the JET real time network since the beginning of the ILW campaigns. APODIS is a data driven system based on a multilayer structure of SVM classifiers. APODIS was trained with JET data corresponding to carbon wall discharges between April 2006 and October 2009. The total number of training discharges was 8407: 7648 non-disruptive discharges and 512 non intentional disruptions. This article has two main parts. Firstly, the APODIS disruption prediction capabilities in the period July 2013-October 2014 are analysed. During these experimental campaigns (over 1059 non-disruptive discharges and 390 non intentional disruptions), APODIS shows 2.46% of false alarms, 14.62% of missed alarms, 2.56% of tardy detections (alarms triggered with less than 10ms), 3.33% of premature alarms (alarms triggered with more than 1.5s) and, finally, 79.49% of valid alarms (warning times between 10ms and 1.5s). It is important to note that the average warning time of valid alarms is 262ms and the standard deviation is 293ms.

As mentioned, the above results are obtained with APODIS trained with C wall data and without any retraining in spite of its use with metallic wall discharges. The purpose of the second part of this study is to compare the APODIS results with predictors trained with the JET data from the ILW campaigns. A single predictor, which has been trained with data between September 2011 and July 2012 (1036 non-disruptive discharges and 201 non intentional disruptions), has been developed. It has been tested with experimental data in the period July 2013 – October 2014 (1051 non-disruptive discharges and 390 non intentional disruptions). It shows 2.1% of false alarms, 9.23% of missed alarms, 10.51% of tardy detections, 4.1% of premature alarms and, finally, 76.16% of valid alarms. The average warning time of valid alarms is 263ms and the standard deviation is 276ms.

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O-4. A multivariate analysis of disruption precursors on JET and AUG

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Current tokamaks make routinely use of few individual diagnostic signals, such as locked mode and vertical stabilization measurements, for triggering disruption mitigation systems. In ITER it will likely be necessary to employ a wider set of signals for disruption prediction. This is because presumably individual diagnostic signals will not be capable of detecting all disruptions type with enough warning time to allow effective mitigation actions. Nowadays, the interpretation of the physical mechanisms leading to disruptions in the existing experiments is the only viable way for extrapolating results to ITER. To this end, a comparison among similar disruption types and their corresponding precursors at JET and AUG would be valuable. Recently, criteria for manual disruption classification have been proposed both for JET [1] and AUG [2]. The analysis of disruption causes performed in [2] highlights that several physics instabilities in AUG are also typical disruption precursors in JET. In this paper, 121 disruptive discharges occurred in AUG during the 2013-2014 experimental campaigns have been clustered. In particular, the chain of events characterizing an upcoming disruption has been identified and disruptions which follow similar paths have been categorized following the classification adopted for JET. A comparative multivariate statistical analysis of similar disruption types on JET and AUG has been performed in order to provide information on how the mechanisms leading to a disruption type can be generalized. Then, for each disruption class, the most significant precursors have been identified on both machines. Moreover, multisensor data fusion strategies will be applied with the aim of developing a real time detection system based on the complementary information of several diagnostic signals.

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O-5. Boundary reconstruction using toroidal harmonics and an optimal control method

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We present a new fast and stable algorithm for the reconstruction of the plasma boundary from discrete magnetic measurements taken at several locations surrounding the vacuum vessel: B probes measuring the value of the poloidal magnetic field and flux loops measuring the value of the poloidal flux ψ.

The resolution of this inverse problem takes two steps:

In the first one we transform the set of discrete measurements into Cauchy conditions, ψ and its normal derivative, on a fixed contour Γ_o close to the measurement points. This is done by least square fitting a truncated series of toroidal harmonic functions to the magnetic measurements. This first step can be sufficient to determine the plasma boundary. Indeed the toroidal harmonics expansion is valid anywhere in the vacuum surrounding the plasma. However, due to the ill-posedness of the inverse problem, the plasma boundary reconstructed after this first step can in some cases be very inaccurate.

The second step consists in solving a Cauchy problem for the elliptic equation $\Delta^*\psi = 0$ satisfied by the flux and for the overdetermined boundary conditions on Γ_o obtained with the help of toroidal harmonics as explained above. The proposed method consists in a reformulation of the problem as an optimal control problem on a fixed annular domain of external boundary Γ_o and inner boundary Γ_i. We aim at minimizing a regularized "Kohn-Vogelius" cost function depending on the value of the flux on Γ_i and measuring the discrepancy between the solution to the equation satisfied by ψ obtained using Dirichlet conditions on Γ_o and the one obtained using Neumann conditions.

The method presented here has led to the development of a software: VACTH-KV. In the algorithm many quantities can be precomputed and some computations can be parallelized. The software enables to follow in real-time the evolution of the plasma boundary in any Tokamak.

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O-6. First results of Polarimeter-Interferometer System for current density measurement on EAST*

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A multichannel far-infrared laser-based **PO**larimeter-**INT**erferometer (POINT) system utilizing the three-wave technique has been implemented for current density and electron density profile measurements in the EAST tokamak. Double-pass, horizontal, radially-viewing chords access the plasma via an equatorial port. The laser source consists of three CW formic acid (HCOOH) FIR lasers at nominal wavelength 432.5 μm which are optically pumped by independent infrared CO_2 lasers. Each of the three FIR lasers can generate output power of more than 30 mW per cavity. Two lasers, with slight frequency offset (~1 MHz), are made collinear with counter-rotating circular polarization in order to determine the Faraday effect by measuring their phase difference in the plasma. The third laser, frequency offset (~ 2 MHz), is used as a reference providing local oscillator (LO) power to each mixer so that one can obtain the phase shift caused by the plasma electron density. Novel molybdenum retro-reflectors are mounted in the inside wall for the double-pass optical arrangement. The retro-reflectors can withstand baking temperature up to 350^{o}C and discharge duration more than 1000s. VDI planar-diode Integrated Conical Horn Fundamental Mixers optimized for high sensitivity, ~750 V/W, are used in the heterodyne detection system. A five-chord layout has been installed with expansion to 11 chords anticipated to fully diagnose the core region of EAST plasmas in next campaign. A Digital Phase Detector with 250 kHz bandwidth, which will provide real-time Faraday rotation angle and density phase shift output for use in plasma control, have been developed for use on the POINT system. Reliability of both polarimetric and interferometric measurement are obtained in 22s H mode discharge and 52s long pulse discharge, indicating the density gradient in H-mode discharge does not impact POINT measurements and that system works for any heating scheme on EAST so far. The electron line-integrated density resolution of POINT is less than 1×10^{16} m^{-2} (<1^o), and the Faraday rotation angle rms phase noise is <0.1^o. With the high temporal(~1 μsec) and phase resolution(<0.1^o), perturbations associated with the sawtooth cycle and MHD activity have been observed. The current profile, density profile and safety factor(q) profile are reconstructed by using EFIT code from the external magnetic and the validation POINT data. Realtime EFIT with Faraday angle and density phase shift constraints will be implemented in the plasma control system in the future.

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O-7. Systematic Investigations on Atomic Structure and Spectroscopy of Tungsten Ions related to ITER Diagnostics in Shanghai EBIT Laboratory

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There has been a strong interest in tungsten spectroscopy as such data may be highly required for the ITER project. Nevertheless there is still very little spectroscopic data for$W^{6+}$to$W^{28+,}$ due to the complexity of these atomic systems. Due to this fact, our group at the Shanghai EBIT Laboratory has made a dedicated effort on systematic investigations into these ions.

One of the main properties of Electron Beam Ion Trap is a nearly monoenergetic electron beam which in our case can be varied in energy over a range of 30eV to 180KeV.By tuning the beam energy we could identify the charge states of tungsten both according to their ionization energy and also the difference in the spectra recorded by spectrometers working in wavelength regions covered from 0.1nm to 800nmin our lab[1].We also carried out the systematic calculations of atomic structures and transitions by using MCDF,RMBPT and CRM methods incorporated in atomic codes like FAC and Grasp. This allowed us to distinguish which transitions were responsible for the various spectra lines and thus correct the atomic structures and revise the calculation methods.

Until now we have investigated spectral of tungsten ions with charge states of 26+, 27+, 28+,13+ in the visible region[2-5]and from 11+ to 15+ in the EUV region[5], while X-ray spectral from 45+,46+ are also observed and have been compared with spectral from the JET Tokamak. Issues such as identification of the ground state of W^{13+}[5] and existence of meta-stable levels with extremely long lifetimesofW^{28+}[4]as well as correction of atomic structures of these ions have been studied as part of our work. Extended study for isoelectronic ions is in progress too, for example the Ag-like sequence[6]. More investigations to the remaining charged states are planned and will be carried in the near future.

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O-8. New developments in JET gamma emission tomography

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JET neutron profile monitor is a unique instrument among neutron diagnostics available on large fusion research facilities [1-2]. The plasma coverage of the emissive region enables tomographic reconstruction of the spatial profiles of the γ-ray emission [3]. However, due to the availability of only two projection angles and to the coarse sampling, tomography is a highly limited data set problem. Information on plasma equilibrium from EFIT/EFTM is essential in order to compensate for the lack of experimental data and to obtain reconstruction with physical relevance. Several techniques have been developed to cope with this problem (see e.g. Refs 3-4).

Among them the method based on the maximum likelihood principle, which incorporates a regularizing procedure that assumes smoothness on magnetic surfaces, given by plasma equilibrium proved to be a robust solution [5]. Recently several improvements have been performed in order to allow routinely analysis during the JET experimental campaigns. The method implementation has been optimized in order to allow extensive runs in inter-shot analysis. Integration with data acquisition software has been also accomplished.

Recent developments have been dedicated to the problem of evaluating the errors associated with the reconstructed emissivity profile. A methodology for the numerical evaluation of the statistical properties of the uncertainties has been developed. Artefacts related to the experimental conditions for recording the projection data and to the restrictive measuring geometry have been identified and quantified. A detailed analysis of the main sources of artefacts, related to the neutron induced gamma-ray background and to the use of magnetic equilibrium profiles for compensating the lack of experimental data, has been performed.

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O-9. Tikhonov regularisation adapted to the real-time tomography

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The choice of tungsten for the plasma facing components of ITER and probably also DEMO means that impurity control in fusion plasmas is now a crucial challenge. In this respect, a real-time (RT) reconstruction of spatial characteristics of soft X-ray radiation from its line-integrated measurements may be required as a sensor input of the RT control of burning plasmas in tokamaks. To this end, reliable diagnostic setup will have to be combined with a rapid reconstruction technique. In this contribution, we shall focus on the latter challenge. The inverse reconstruction - referred to as plasma tomography – is an ill-posed problem which may easily result in substantial errors (artefacts). A dependable solution of the problem is typically conditioned by strong constraints or a-priori information, a robust algorithm (e.g. based on regularisation) and an iterative refinement of the reconstructed image. Previous works demonstrated that the iterative codes would not qualify in near future for the RT algorithms due to their requirements on the processing time. In this contribution, a novel method for RT relevant image refinement is presented based on the assumption of slow evolution of data. It is shown that in case of Tikhonov regularisation the new method is robust, reliable and very rapid even in the sophisticated MFR (Minimum Fisher Regularisation) scheme. Performance of the method will be demonstrated on both phantom and real data in comparison with the standard (iterative) regularisation, including cases where the assumption of slow data evolution is briefly disrupted. Next, we shall discuss possible implementation of the modified tomography algorithm into the RT control hardware. Two options will be compared, first based on a standard processor, and second on massively parallel solution with FPGA units. Given the achieved status of the project, its possible continuation shall be outlined.

O-10. Measurement of the neutral hydrogen atom density in LHD core plasmas based on the spectral inversion

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In fusion oriented plasmas, significant amount of neutral hydrogen atoms penetrate deeply inside the plasma through several repetitions of charge exchange collisions. Since ionization of such atoms is directly connected to the particle balance of the plasma, it has been desired to evaluate the atom density (n_H) in the core region quantitatively. n_H has been widely evaluated with transport models, however, it has been difficult to reduce uncertainties of the model result by experiments since the atom emission in the core region, which is weaker than the edge emission by an order of more than 3, has been practically unobservable.

Recently, we have found that the atoms in the core region are heated through charge exchange collision and their Doppler-shifted emission can be separately observed in the far wing parts of the Balmer-α line profile [1]. We have also proposed that the Balmer-α line profile can be approximated as a sum of narrow and broad profiles, intensities of which are proportional to n_H in the edge and core regions, respectively [2].

In this work, we propose an inversion method of the spectral profile to evaluate n_H distribution in the core region based on Bayesian statistics. As a prior estimate, we adopt a result given by a 1-dimensional transport model, which simulates the relative distribution of nH by a diffusion principle. We assume that its logarithmic gradient, $d(\log n_H)/dr$, contains 30% uncertainty due to 1-dimensional approximation. We update it by fitting the far wing profile of the Balmer-α line observed with the dynamic range of 10^6. Based on this method, we can estimate a distribution of n_H that is consistent to the transport model and the observed spectral profile.

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O-11. Real-time data fusion for nuclear fusion

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Data fusion is the science of combining multiple uncertain measurements to obtain an estimate of a parameter which is better than any of the individual measurements. It has been used offline for nuclear fusion experiments, where it improves the physics analysis [e.g. 1, 2]. In other disciplines, real-time data fusion is commonly used to boost performance, by providing improved estimates to the control system. In nuclear fusion experiments to date, this potential remains largely untapped, but this may be changing. Disruption predictors are one exception, and another prominent recent example is RAPTOR [3]. This presentation will outline two new concepts for real-time data fusion.

In experiments to date, the NTM location has been estimated either from the rational q surface from an equilibrium reconstruction, **or** from the correlation of ECE channels with Mirnov signals, **or** from the reaction of the NTM amplitude to the location of the Electron Cyclotron Current Drive. Each method has intrinsic strengths and weaknesses. Simulations will be shown to demonstrate that the weaknesses can be compensated by combining their measurements. The new method will be trialled in experiments in the ASDEX Upgrade 2015 campaign, possibly even before this conference.

The second concept relates to plasma position control, motivated by the problems expected if the current standard practice of using magnetic diagnostics is applied to next generation nuclear fusion devices. Reflectometry has already been demonstrated as one alternative [4].

This presentation will show how a similar approach could be applied for ECE or soft X-ray measurements, and how these measurements can be used, not as alternatives, but as complementary contributions to an optimal estimate of the true plasma position.

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O-12. Impurity Density Profiles and Their Effect on Z_{eff} by Integrating Measurements from the Soft X-ray Tomography System and Charge Exchange Recombination Spectroscopy

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The effective ionic charge (Z_{eff}) is a critical, though difficult to measure, parameter in high temperature plasma physics. Along with electron temperature, it determines the plasma resistivity, which plays a key role in Ohmic power absorption, energy confinement time, and resistive MHD modeling. Due to its importance, significant efforts have been made both experimentally and computationally to determine Z_{eff} in the Madison Symmetric Torus (MST). As part of the on-going Integrated Data Analysis (IDA) effort at MST, we have combined soft x-ray tomography and charge exchange recombination spectroscopy impurity density measurements, along with their systematic and statistical uncertainties, to determine Z_{eff}. Bayesian probability theory was used as a framework for integrating these two diagnostics, and a Markov Chain Monte Carlo sampling technique was used to efficiently sample the parameter space. Using IDA allowed us to characterize Z_{eff} in MST with much higher confidence in than previous single–diagnostic attempts using near-infrared bremsstrahlung or x-ray spectroscopy. The core value is found is be 1.9 ± 0.2 in high temperature, high current, improved confinement discharges, with a slightly hollow profile peaking near mid-radius.

O-13. Applications of Bayesian temperature profile reconstruction to automated comparison with heat transport models and uncertainty quantification of current diffusion

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In the context of present and future long pulse tokamak experiments yielding a growing size of measured data per pulse, automating data consistency analysis and comparisons of measurements with models is a critical matter. To address these issues, the present work describes an expert system that carries out in an integrated and fully automated way i) a reconstruction of plasma profiles from the measurements, using Bayesian analysis ii) a prediction of the reconstructed quantities, according to some models and iii) a comparison of the first two steps. The first application shown is devoted to the development of an automated comparison method between the experimental plasma profiles reconstructed using Bayesian methods and time dependent solutions of the transport equations. The method was applied to model validation of a simple heat transport model with three radial shape options. It has been tested on a database of 21 Tore Supra and 14 JET shots. The second application aims at quantifying uncertainties due to the electron temperature profile in current diffusion simulations. A systematic reconstruction of the Ne, Te, Ti profiles was first carried out for all time slices of the pulse. The Bayesian 95% highest probability intervals on the Te profile reconstruction were then used for i) data consistency check of the flux consumption and ii) defining a confidence interval for the current profile simulation. The method has been applied to one Tore Supra pulse and one JET pulse.

[1] *See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*
[2] *See the Appendix to G. Falchetto et al., Nucl. Fusion 54 (2014) 043018*

O-14. Recent developments of Integrated Data Analysis at ASDEX Upgrade: Kinetic profiles, current diffusion and equilibrium

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In nuclear fusion research the coherent combination of measured data from heterogeneous diagnostics with modelling codes providing physical restrictions on the parameter space allows for an improved treatment of ill-posed inversion problems such as the equilibrium reconstruction. Different techniques for measuring the same subset of physical parameters provide complementary and redundant data for, e.g., improving the reliability of physical parameters, increasing the spatial and temporal resolution of profiles, and resolving data inconsistencies. The combination of the measurements forward models with physical modelling to reduce reasonably the parameter space beneficially helps to reduce the ambiguity of the parameters to be estimated without employing non-physical constraints.

Integrated Data Analysis (IDA) at ASDEX Upgrade routinely combines measurements of lithium beam emission (LIB), interferometry, electron cyclotron emission (ECE), and Thomson scattering, for a joint estimation of electron density and temperature profiles. The close correlation of the profile analysis with the magnetic equilibrium requires the integration of profile and equilibrium analyses. As the kinetic profiles provide valuable information to restrict the equilibrium pressure profile, a poloidal flux diffusion modelling code provides constraints on the poloidal profile of the flux surface averaged toroidal current density. The combination of measured and modelled data allows to overcome the persisting problem of missing regular and reliable magnetic measurements in the plasma core for the reconstruction of full current profiles.

The recent progress in profile reconstruction due to improvements in the diagnostics LIB, ECE and interferometry and the progress in the equilibrium reconstruction combining kinetic profiles with current diffusion modelling will be shown.

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O-15. Symbolic regression for the derivation of mathematical models directly from the data

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§See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

Nowadays, machine-learning tools are routinely used to extract knowledge from enormous amount of data; in fact they are typically deployed to handle theory-less applications, from the identification of trends in customer behaviour to voice recognition, fields where formulation of models in consolidated mathematical terms is not a priority. The penetration of these more traditional machine learning tools in many scientific fields, such as physics or engineering, has been more limited, given their limitations. Indeed, their results are often difficult to interpret and/or to express in terms of easily manageable mathematical forms, so their integration with theoretical models, based on first principles, proves problematic if not impossible. Moreover, they are not always capable of properly handling error bars in the measurements; the confidence in their results and their extrapolability can therefore be questioned. In this contribution, Symbolic Regression (SR) via Genetic Programming is introduced to prove its capability of deriving models, directly from the data, to be compared with theories. The power of the method is investigated with a series of systematic numerical tests and classification problems. To exemplify the potential of the approach in Nuclear Fusion, it is applied to the problem of deriving empirical scaling expressions directly from multimachine data bases, without the common "*a priori*" assumption that these have to be power laws. Indeed the results for the case of the energy confinement time and the power to access the H modes show how power laws are not necessarily the best expressions. More advanced applications of SR are also presented, in particular a method to determine the most adequate dimensionless quantity for the problem at hand. Information geometry concepts, such as Geodesic Distance on Gaussian Manifolds, are also applied to the problem of handling probability distributions and to increase the robustness of the results to noise and outliers. Particular attention is also devoted to the statistical properties of the presented new data analysis tools, to quantify their advantages and limitations.

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O-16. From machine learning tools to mathematical models: the case of disruption prediction and avoidance

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Disruptions remain the most serious issue to be faced by the next generation of Tokamak machines and are also a serious problem for the present largest devices. For example, they are one of the main impediments to systematic high current operation in JET. Given their potential impact on the integrity of the devices, various methods of disruption avoidance and mitigation are being investigated. Of course, reliable prediction tools are a prerequisite to any mitigation or avoidance action. Unfortunately, the theoretical understanding of the causes of disruptions is not sufficient to guarantee reliable predictions. The inadequacies of theoretical and empirical models of disruptions have motivated the development of data driven predictors, some of which, such as APODIS on JET, have shown impressive performance. The main remaining issue with these advanced machine learning tools is now the interpretability. In order to overcome this limitation, a new methodology has been developed to profit from the knowledge, acquired by the machine learning tools, by presenting it in terms of manageable formulas. This approach reconciles the prediction and knowledge discovery capability of machine learning tools with the need to formulate the results in such a way that they can be related to physical theories capable of extrapolation to larger devices. This knowledge discovery step is based on Support Vector Machines (SVM). To formulate the output of SVM in an interpretable way, extensive used is made of Symbolic Regression via Genetic programming. The actual combination of the two methods provides the equation of the boundary between two regions of operational space, safe and disruptive. The potential of the method is illustrated by examples using JET database with the new ITER Like Wall.

O-17. Demonstration of the robustness of geodesic least squares regression for scaling of the energy confinement and power threshold in tokamaks

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Regression analysis is an essential instrument for data interpretation in numerous areas of science, in particular for estimating scaling laws in disciplines such as astronomy, climatology, finance and nuclear fusion. The standard problem of multilinear regression of a single response variable on a number of predictor variables is easily solved by means of ordinary least squares regression. However, this approach assumes that the predictor variables have been measured with infinite precision, which in many applications is an unrealistic ideal. In addition, while a linear regression function is often a convenient and safe choice, the true functional form is usually unknown and possibly nonlinear, as is the case in scaling studies. Apart from the problems of predictor and model uncertainty, various other issues may complicate the analysis, including atypical observations (outliers) and heterogeneous or non-Gaussian error distributions.

The statistics literature abounds with tests and solutions to address each issue individually, but few approaches are sufficiently general to successfully handle the complexity of (fusion) scaling laws. To this end we have developed a new regression method that generalizes various existing techniques, including errors-in-variables models, the generalized linear model and standard Bayesian approaches. The method operates on a Riemannian manifold of probability distributions equipped with the Fisher metric. Presently, it is implemented through minimization of the Rao geodesic distance between modelled and measured distributions of the response variable. In this contribution, we briefly introduce the method, which we refer to as *geodesic least squares regression* (GLS) and we present two applications to the scaling laws of the energy confinement time and the L-H power threshold in tokamaks, based on multi-machine data. We demonstrate the robustness of the method when confronted with different regression models, subsets of the data and data transformations. Given the excellent performance of the method in the presence of considerable model and data uncertainty, we propose GLS regression as a robust tool for future scaling studies towards ITER and DEMO.

O-18. Verification & Validation of plasma turbulence codes in scrape-off layer conditions

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In the present work, a rigorous Verification & Validation (V&V) procedure is presented and applied to the study of plasma turbulence in scrape-off layer conditions. First, bridging the gap between plasma physics and other scientific domains, in particular the computational fluid dynamics community, a rigorous methodology for the verification of a plasma simulation code is presented, based on the method of manufactured solutions, to assess that the model equation are correctly implemented in the code. Second, the technique to carry out the solution verification is described to provide a rigorous estimate of the uncertainty affecting the numerical results. Third, a methodology for plasma turbulence code validation is also discussed, focusing on quantitative assessment of the agreement between experiments and simulations. The V&V methodology is then applied to the study of plasma turbulence in the basic plasma physics experiment TORPEX [Fasoli et al., Phys. Plasmas 13, 055902 (2006)], considering both two-dimensional and three-dimensional simulations carried out with the GBS code [P. Ricci et al., Plasma Phys. Contr. Fusion 54, 124047 (2012)].

TORPEX is an ideal setting to carry out a validation exercise, as it features the key elements of tokamak scrape-off layer turbulence (such as open field line, curvature and plasma gradient driven instabilities, sheath physics), but in a very well diagnosed and simpler magnetic configuration. Building on the TORPEX V&V exercise, we have started a project aiming at validating the simulations of tokamak scrape-off layer turbulence. We will report on the initial results of this validation project.

This work was carried out within the framework of the EUROfusion Consortium. It was supported in part by the Swiss National Science Foundation and received funding from the European Union's Horizon 2020 research and innovation program under grant agreement number 633053.

O-19. Comparing transport in Alcator C-Mod high confinement I-mode plasmas with GYRO nonlinear gyrokinetic simulations

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Understanding transport in high performance ELM-suppressed tokamak plasmas is of great interest for ITER and other future experiments. The 'I-mode' regime on Alcator C-Mod, also known as 'improved L-mode' on ASDEX Upgrade, has several favorable characteristics: pedestals in electron and ion temperature, with ITER98y2 H-factors similar to and exceeding H-mode [Hubbard et al Phys. Plasmas 18, 056115 (2011)], but without a density pedestal and without impurity accumulation and without ELMs. Most research on I-mode and H-mode focuses on changes in edge and pedestal turbulence/transport and stability. In this work, core transport in I-mode is probed at Alcator C-Mod by comparing experimentally inferred heat flux levels with results from a series of nonlinear gyrokinetic simulations, run with the GYRO code [https://fusion.gat.com/theory/Gyro]. Nonlinear imulations that include electrostatic long wavelength turbulence can match experimental levels of ion and electron heat fluxes in I-mode. Simulation results show that the ExB shear generated by the intrinsic rotation profile is sufficient in the core of I-mode plasma to suppress the turbulence, leading to predicted reductions in long wavelength density fluctuation levels that are consistent with experimental measurements. In addition to direct comparisons of experiment with GYRO simulations, different models of profile stiffness will be used to explore the relationship among core turbulence reductions, transport and energy confinement.

O-20. Validating the Monte Carlo test particle code ASCOT

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Modelling of diagnostics is important not only for the optimization of the experimental setup but, at least in the case of energetic particles, most notably fusion alphas, for building a more comprehensive picture of the physical reality from the limited data obtained by the diagnostics.

ASCOT is a test particle orbit-following Monte Carlo code for toroidal magnetically confined fusion devices. The code solves the distribution of particles by following their trajectories. The particles undergo collisions with a static Maxwellian background plasma. The detailed magnetic fields and the first wall can be fully three-dimensional. The code models exactly the neoclassical and classical transport of particles as well as any effects due to a toroidally asymmetric magnetic field, but it also features a model for MHD modes relevant for fast ions (NTMs, TAEs)

ASCOT is mainly used for transport studies of fast ions and impurities in realistic tokamak geometries. It has been developed and maintained since the early 1990's. Since then, there have been multiple projects aimed at (or benefitting) code validation and improved interpretation of diagnostic measurements by comparing them to ASCOT simulations. The results range from conceptual designs to full quantitative comparisons.

This contribution describes the comparison of simulation results against various diagnostics including CTS, FIDA, NPA, FILD, activation probe, neutron camera, marker tiles and IR camera. The measurements were taken in devices including JET, ASDEX Upgrade and DIII-D.

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O-21. Edge physics discovery and validation by synthetic diagnostics using the XGC gyro-kinetic codes

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Understanding the multi-scale physics in the edge region (pedestal + scrape-off layer) is required in order to reliably predict performance in future fusion devices. The family of XGC codes, the massively parallel, full-f gyro-kinetic codes, contain many of the physics important in setting the transport in the edge region, including neoclassical and turbulent transport effects, kinetic electrons, impurities, full magnetic geometry including X-point, and neutrals with atomic cross-sections.

Several important edge topics have been explored with the XGC codes, including predictions of SOL heat flux width, radial electric field wells, pedestal bootstrap current, poloidal variation of pedestal density/temperature, and blobs. To give confidence in using XGC simulations to predict plasma characteristics in future machines, these simulation results must be validated by identifying observables to compare to experiments. Synthetic diagnostics are created, focusing not only on the effects of the measuring instruments themselves, but also of the reduction algorithms used to extract physics quantities of interest.

Algorithms to extract additional physics from the large data sets generated by the XGC codes will be described, along with the need for in-memory analysis. An example will be given of applying blob detection algorithms to an entire poloidal cross-section, instead of the usual narrow experimental diagnostic window. This gives understanding of the blob birth location and dynamics, which would be difficult to obtain through experiment alone.

O-22. Progress validating the gyrokinetic model in Alcator C-Mod and DIII-D tokamak plasmas

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The development of validated models of plasmas dynamics is essential to ensure confidence in predictions of performance in both current and future fusion devices. Through comparison of simulation and experiment on tokamaks worldwide, significant progress has been made towards the validation of the gyrokinetic model for prediction of transport in the tokamak core. In this talk, we present results from recent validation exercises performed on the Alcator C-Mod and DIII-D tokamaks. This work focused on rigorous comparisons between gyrokinetic simulation with dedicated validation experiments to test the limits of the gyrokinetic model and to shed light onto the physics fidelity needed to reproduce experimental measurements. We discuss the development of new validation metrics, essential for moving beyond the subjective assessment of model performance and fidelity, and apply some of the proposed metrics to the analysis of DIII-D L-mode discharges. On Alcator C-Mod, a robust disagreement between experimental electron heat fluxes and ion-scale gyrokinetic simulation was identified and recently reported. This disagreement motivated first-of-a-kind, multi-scale (coupled ITG/TEM/ETG) gyrokinetic simulations of Alcator C-Mod discharges. These simulations capture both the ion and electron spatio-temporal scales, capturing turbulence dynamics up to $k_{\theta\rho e} = 0.8$, and utilizing 3 gyrokinetic species (ions, electrons, and impurities), realistic electron mass $((m_D/m_e)^{.5} = 60.0)$, collisions, and rotation effects. The results of this work have begun to shed light on the important, even dominant, role of electron-scale turbulence in standard plasma conditions on Alcator C-Mod. These coupled simulations also reveal a complex interaction between the turbulent scales, indicating that in addition to driving significant electron heat flux at high-k ($k_{\theta\rho s} > 1.0$), electron-scale turbulence can enhance the turbulence present at the low-k ($k_{\theta\rho s} < 1.0$). The results of this validation exercise performed using multi-scale gyrokinetic simulation and a discussion of cross-scale coupling of turbulence will be presented.

O-23. Comparing MHD simulations to experiments

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For fusion-relevant plasmas, the practical demands of formal validation methodology are considerable: on the experimental side, extensive data sets of precise internal measurements, and on the simulation side, sufficient computing resources to generate scans of nonlinear results along with their uncertainties, often in the most challenging parameter regimes. Reversed-field pinch (RFP) plasmas exhibiting cyclic magnetic-relaxation behavior are useful as test cases for visco-resistive MHD models in nonlinear simulations. We present plans for validation comparisons of the single-fluid DEBS and two-fluid NIMROD codes to experiments on the MST device, along with updates on results to date. We have developed and begun to test validation metrics involving a hierarchy of different equilibrium and fluctuation quantities.

A chief goal is an MHD validation study of the Lundquist-number scaling of magnetic-fluctuation amplitudes in the RFP, enabled by MST's advanced diagnostic set paired with integrated data analysis. We also discuss the importance of properly modeling the fluid viscosity in MHD simulations. As distinguished from the rigorously quantitative comparisons of formal validation, more qualitative comparisons remain essential to clarifying the respective roles of fundamental processes in self-organizing plasmas like the standard RFP. In zero-beta, single-fluid DEBS code simulations of MST plasmas with the experimental Lundquist number, the dynamically evolving magnetic equilibrium quantities are well reproduced, but the simulated tearing-mode fluctuation amplitudes are much larger than in the experiment (Reusch et al., PRL, 2011). The additional Hall effect and warm-ion gyroviscosity used in two-fluid NIMROD simulations may be needed to resolve such discrepancies (King et al., POP, 2012).

Comparisons of NIMROD simulations to MST magnetic and flow profile behavior expose complicated interactions between fluctuation-induced MHD and Hall dynamos and Maxwell and Reynolds stresses (Sauppe et al., APS-DPP, 2014). New experiments with a deep-insertion magnetic probe provide excellent measurements of the equilibrium profile and Hall dynamo (Triana et al., APS-DPP, 2014). This material is based upon work supported by the U.S. Department of Energy Office of Science, Office of Fusion Energy Sciences program under Award Number DE-FC02-05ER54814 and by the National Science Foundation under Grant No. PHY 08-21899.

O-24. Doppler Reflectometry Simulations for ASDEX Upgrade

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Doppler reflectometry is a microwave scattering diagnostic used for measuring turbulent density fluctuations in fusion experiments. In a typical tokamak plasma, the density fluctuation strength can be several percent. The density fluctuations themselves can then nonlinearly influence the instrument function of the reflectometer. In order to investigate this effect, we use the gyrokinetic code GENE to generate a turbulence field at the same conditions as in the experiment, and simulate the Doppler reflectometer response to it with the fullwave code IPF-FD3D. From the known wavenumber spectrum of the GENE output, and the resultant spectrum from IPF-FD3D, the instrument function can be estimated, and its reverse subsequently applied to the experimental results.

This paper concentrates on the fullwave simulations of the reflectometer with a given turbulence field. The effect of the turbulence strength and polarisation on the scattering process is investigated, and shown to drastically change the overall shape of the spectrum, especially shifting the apparent position of the turbulent drive. Means of recovering the turbulent wavenumber spectrum are explored. Finally, the experimentally measured wavenumber spectra of the turbulence are compared to the simulation.

O-25. Forward Modeling of an X-ray Imaging Crystal Spectrometer within the Minerva Bayesian Analysis Framework

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The X-ray Imaging Crystal Spectrometer XICS is currently being assembled for installation at the stellarator Wendelstein 7-X. It is expected to be ready for the first plasma operation in 2015. The spectrometer will provide line integrated measurements of standard plasma parameters like ion and electron temperatures (T_e, T_i), plasma rotation (Φ_{rot}) and argon impurity densities [1].
A forward model [2] based on the planned installation geometry has been performed using the Minerva Bayesian Analysis framework [3]. This model uses Gaussian processes [4] for the generation and inference of arbitrary shaped plasma parameter profiles for a wide range of different scenarios (like impurity hole [5] or electron density hole [6]). For the simulation of line integrated spectra as measured by the (virtual) detector, the geometry and Gaussian detection noise is assumed. The inversion is done within the framework using the maximum posterior (MAP) method for the estimation of the plasma parameter profiles from noisy spectral data.
Capabilities and limitations of the model and method will be discussed through the examples of several forward simulated data of different plasma parameter profiles.

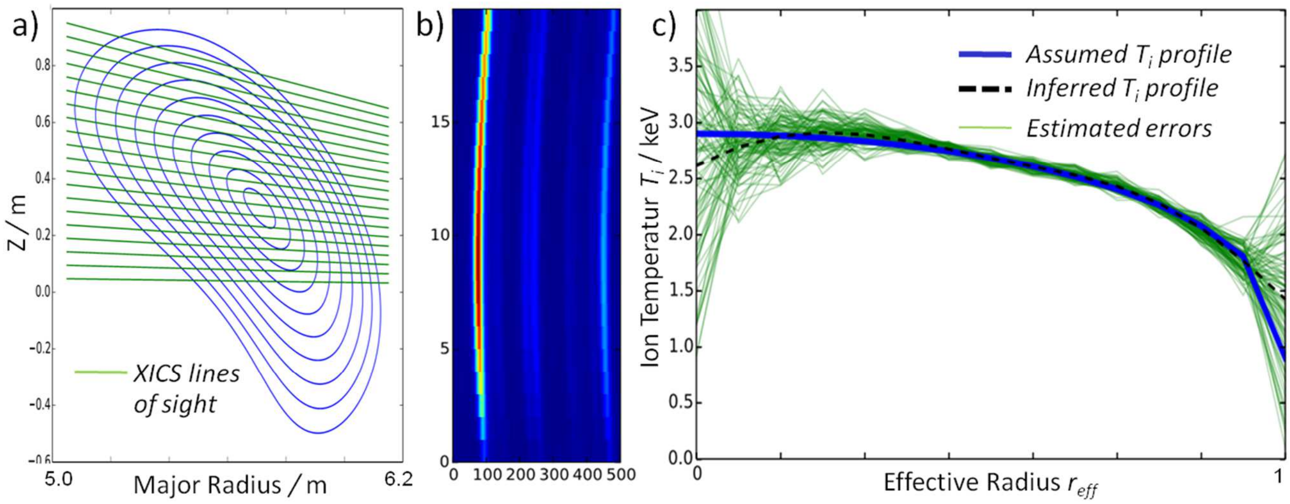

Fig.1: Forward modeling of an X-ray imaging crystal spectrometer: a) Magnetic flux surfaces and lines of sight of XICS. b) Modeled 2D intensity pattern on the detector. c) Assumed and inferred ion temperature profile including uncertainties of the inferred profile.

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O-26. Synthetic H-alpha diagnostics for ITER: inverse problems and error estimations for strong non-Maxwellian effects and intense divertor stray light

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The use of an all-metal first wall in future magnetic fusion reactors equipped with a divertor may impose severe limitations on the capabilities of optical diagnostics in the main chamber because of the divertor stray light (DSL) produced by reflections of the intense light emitted in the divertor. For optical diagnostics of the hydrogen isotopes and various neutral and low ionized impurities in the far scrape-off layer (SOL) of the main chamber, one should expect a strong contribution of the DSL in the same spectral lines. Theoretical model [1] suggested for the ITER H-alpha High-Resolution Spectroscopy (HRS) was extended and applied [2] for the interpretation of the data from the JET ITER-like wall (ILW) experiments.

Here we formulate the inverse problems for estimating the measurement errors of the synthetic diagnostics aimed at reconstruction of the neutral hydrogen isotope density in the SOL and the isotope ratio, with allowance for (i) a strong DSL on the lines-of-sight in the main chamber, (ii) a substantial deviation of the neutral atom velocity distribution function (VDF) from the Maxwellian in the SOL and (iii) the data from the direct observation of the divertor. The present study is based on (a) predictive modeling, with the SOLPS4.3 (B2-EIRENE) code, of the background plasma on the flat-top stage of Q=10 inductive operation of ITER; (b) stand-alone calculations, with the EIRENE code, of the neutral deuterium velocity distribution function (VDF) on the SOLPS4.3 background; (c) a model for the spectral line shape asymmetry in the SOL, caused by the inward flux of relatively fast atoms, and (d) a model for the DSL spectral intensity. A partial test of the synthetic diagnostics has been done in [2, 3]. Ways for further development and verification of the synthetic diagnostics in application to the error assessment on ITER and JET-ILW are considered.

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O-27. Magnetic Diagnostics for GLAST-III Tokamak

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GLAST-III is a small spherical tokamak with an insulating vacuum vessel and major and minor radii of 20 and 10 cm respectively. The purpose of this experiment is to understand different aspects of tokamak operation such as startup phase and then sustaining the tokamak plasma for a sufficiently long time. This becomes a challenging job in a nonmetallic chamber because in the absence of passive stabilization provided by the metallic chamber, the plasma is prone the many instabilities. In this situation measurement and then corrections for various types of currents and fields responsible for plasma generation becomes very important. This may be done by efficient design of magnetic diagnostics. As GLAST-III has a nonmetallic chamber, the magnetic probes and flux loops installed outside the chamber will be sufficient for recoding the fastest events occurring inside the plasma. This also provides an opportunity for modifying the scheme of magmatic diagnostics after online (real time) analysis of data. For GLAST-III keeping in view the small space available, magnetic coils such as Rogowski coil for plasma current measurement, flux loops for measurement of loop voltage and poliodal flux at various locations and small probes for measurement of plasma position and MHD activities are fabricated, calibrated and installed on GLAST-III. The differential signals obtained from various coils are integrated with passive integrators and also by using numerical techniques. The results obtained by these signals during first operation of GLAST-III are presented and discussed.

O-28. Towards a Bayesian analysis of impurity transport data

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Work is underway on the development of a novel technique to estimate impurity transport coefficient profiles *and their uncertainties* in tokamak plasmas using Bayesian inference. In Alcator C-Mod, the impurity diffusivity D_Z and convective velocity V_Z are inferred using laser blow-off impurity injection of a non-intrinsic, non-recycling impurity and a high-resolution x-ray imaging crystal spectrometer (XICS). The estimation of D_Z and V_Z is a nonlinear inverse problem: guesses for the profiles are propagated through a forward model built around the STRAHL code (Dux 2006) to obtain a prediction of the temporal evolution of the signal observed by the XICS following an injection. The parameters are then adjusted until the modeled emission matches the experimentally-observed emission. Previous work (Howard *et al.* 2012 *Nucl. Fusion* **52** 063002, Chilenski *et al.* 2015 *Nucl. Fusion* **55** 023012) used piecewise linear functions for D_Z and V_Z and found the best profiles by maximizing the likelihood. Uncertainties in the n_e and T_e profiles were propagated through this analysis with Monte Carlo sampling. This point estimate can end up underestimating the uncertainty and, depending on the choice of basis functions, can exhibit multiple maxima. In order to rectify this situation a new approach based on Bayesian inference is under development. A joint probability distribution for the D_Z, V_Z, n_e and T_e profiles is defined, and Markov chain Monte Carlo (MCMC) sampling is used to marginalize (average) over the parameters of the model, thereby ensuring a complete accounting of uncertainty. The mathematical and statistical framework for this new approach will be described, and preliminary results from applying it to calcium transport in Alcator C-Mod will be shown.

O-29. Toroidal Rotation and Ion Temperature Validations in KSTAR Plasmas

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Investigation of the toroidal rotation (V_ϕ) is one of the most important topics for the magnetically confined fusion plasma researches since it is essential for the stabilization of resistive wall modes and its shear plays an important role to improve plasma confinement by suppressing turbulent transport. The most advantage of KSTAR tokamak for toroidal rotation studies is that it equips two main diagnostics including the X-ray imaging crystal spectrometer (XICS) and charge exchange spectroscopy (CES). Simultaneous core toroidal rotation and ion temperature measurements of different impurity species from the XICS and CES have validated in reasonable agreement as shown in Fig. 1, and similar results are measured with various plasma discharges in KSTAR. Recently, a two-Gauss fitting for the CES measurements is studied to apply plasmas without beam modulations. This paper will describe the experimental results of the toroidal rotation and ion temperature validation studies and data analysis processes in the KSTAR device.

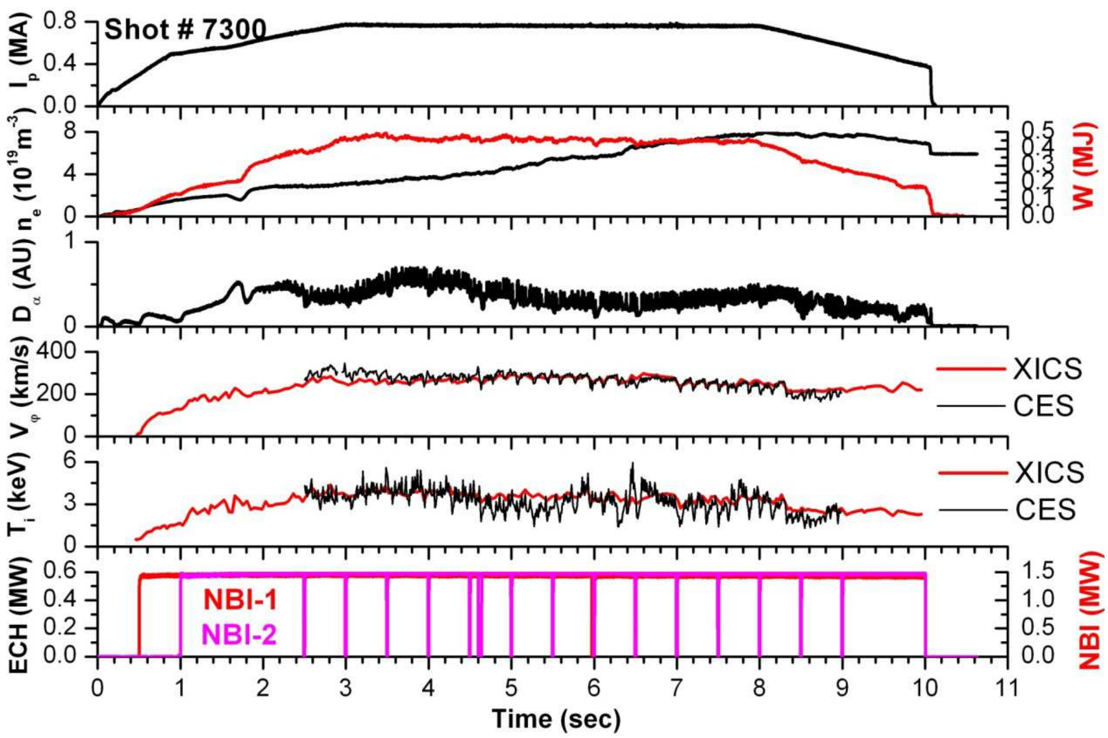

Fig. 1. Toroidal rotation and ion temperature validation from the XICS and CES.

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O-30. GPU – based data analysis for SAMI

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The SAMI diagnostic as installed on MAST acquires 4GB raw data per shot. The original IDL data processing code which calculates the cross-correlations between antenna pairs took approximately 20 minutes per shot to run and as such was unsuitable for inter-shot analysis. To improve on this situation, a GPU – based CUDA code was developed which has demonstrated close to real time data analysis, making it possible for inter-shot analysis in future campaigns, greatly improving the capabilities of the SAMI diagnostic for MAST-U. Further, the GPU code has enabled data-mining of many MAST shots from previous campaigns which has previously been difficult due to the length of time the IDL code takes to process each shot. For the first time the behaviour of many shots has been characterised. We present the benchmarking of the new CUDA code and some preliminary results of the campaign analysis.

O-31. Parallel Plasma Equilibrium Reconstruction Based on GPU in EAST and DIII-D

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Further improvements on a parallel code named P-EFIT [1], which could complete one full equilibrium reconstruction iteration in 300µs on 65*65 grids, and its more applications are presented. P-EFIT is based on the EFIT framework described in [2,3], but takes advantage of massively parallel Graphical Processing Unit (GPU) cores to significantly accelerate the computation. It is built with the CUDA™ architecture to optimize the middle-scale matrix multiplication and the algorithm which could solve block tri-diagonal linear system efficiently in parallel by using GPU.

Results from EAST and DIII-D single static equilibrium benchmark tests indicate that P-EFIT could accurately reproduce the EFIT reconstruction algorithms at a fraction cost time of the computation. Although P-EFIT could obtain a well-converged and accurate enough equilibrium result in 8-9 iterations in about 2.5ms which more than ten times faster than EFIT, it still can not satisfy the requirement of real-time control in tokamak operation. For this reason, a strategy similar to RT-EFIT is adopted [4], whose basic premise is to use the equilibrium result of last time-slice as the initial input for next computation, and perform new equilibrium reconstruction iteration using the most recent diagnostic data. For each time slice, only one iteration is conducted. With the very strategy, 65×65 spatial grids P-EFIT can satisfy the accuracy and time feasibility requirements in real-time reconstruction for plasma discharge control.

The simulated testing including EAST plasma control model implemented in PCS, based on EAST whole real discharge shot shows that the calculated control errors by P-EFIT and RT-EFIT are consistent with each other. Successful control using ISOFLUX/P-EFIT was established in the dedicated experiment during the EAST 2014 campaign. This work is a stepping-stone towards versatile ISOFLUX/P-EFIT control, such as the snowflake diverted shape control in next campaign and more precise real-time equilibrium reconstruction with more diagnostics.

With the new modules on surface tracing, parameters computing such as βp, li, energy, safety factor and I/O interface between P-EFIT and EFIT, P-EFIT achieves even 100 acceleration ratio compared with EFIT of DIII-D whole discharge experimental reconstruction on 257×257 spatial grids.

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O-32. Development of the In-situ Calibration Method for ITER Divertor IR Thermography

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ITER divertor infrared (IR) thermography is a diagnostic system for the measurement of a surface temperature profile in the temperature range of 200 °C - 3600 °C on the tungsten divertor targets by the observed IR light with the wavelength range of 1.5 µm - 5 µm. One of the important issues is that the emissivity change of the divertor targets due to depositions, erosions and a re-crystallization affects the temperature measurement which is required the accuracy of 10 %. Furthermore, the emissivity also changes due to the dependences on the temperature, wavelength and surface roughness. Therefore, the purpose of this study is to clarify the emissivity dependence of the tungsten sample in the ITER-grade and to develop an in-situ calibration method of the emissivity. We investigated the emissivity dependence and the availability of the in-situ calibration method under 1000 °C by the laboratory experiments using an IR camera and an IR laser.

The two main results are shown. First, the emissivity was evaluated in a vacuum chamber by heating the tungsten sample with the surface roughness of 0.3 µm, 1.0 µm, 2.3 µm and 5.9 µm. The emissivity had a strong dependence on the surface roughness, whereas the emissivity changed less than 10 % in the ranges of both wavelength of 3 µm - 5 µm and temperature of 400 °C - 1000 °C. Thus, the measurement accuracy in 400 °C - 1000 °C could be satisfied by the temperature derivation from the ratio of the IR lights in two wavelength bands. Secondly, the angular distributions of the scattered light of the IR laser irradiated from the angle of 5° against to the line of sight of the IR camera were measured by changing the normal angle of the tungsten sample from -55° to 75° to the line of sight of the IR camera because the observed divertor target is inclined to from -60° to -20° in ITER. In the case of the surface roughness of 0.3 µm, the scattered light was not observed in the irradiation angle of ITER. In the case of the surface roughness of 1.0 µm, 2.3 µm and 5.9 µm, the scattered lights were observed and the angular distribution of the scattered light became broader as the surface roughness was larger. Therefore, the emissivity could be calibrated in the irradiation angle of ITER in the condition that the surface roughness is more than 1.0 µm.

O-33. Concept and current status of data acquisition technique for GEM detector based SXR diagnostics

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This work refers to the currently developed measurement system for SXR diagnostics using GEM detectors. In term of plasma parameters optimization, it is important to determine level of the soft X-ray radiation generated by plasma. The overall system overview will be described including GEM detector, electronic modules and data acquisition paths. Construction of the system will be presented in term of hardware, firmware and software parts. Current hardware implementation allows to sample signals from the GEM detector with 125MHz speed, resulting in processing of data with high rate. Developed firmware allows registering signals with high rates and storing them in local memory. Therefore, it is possible to build energy spectra based on high count rate statistics. Software part allows performing startup configuration and provides user interface for modifications of system setup, i.e. in term of data acquisition path. The first preliminary results of laboratory tests will be also presented.

ACKNOWLEDGEMENTS

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O-34. Grid Technology for Controlled Fusion: Conception of the Unified Cyberspace and ITER Data Management

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The conception of the cyberspace for laboratories working in the field of controlled fusion is considered on the basis of Grid technology. Realization of this conception may allow sharing the computing resources; interchange the experimental data and data processing. Also it make possible the integration of ITER (International Thermonuclear Experimental Reactor) IT infrastructure into IT infrastructure of fusion community. This approach may increase research efficiency by automation of data analysis, decision making support, validation of modeling codes, computing load balancing and further systematization and formalization of fusion knowledge domain. Combined technical solutions developed for cyberspace in High Energy Physics and other sciences were applied for fusion data analysis.

O-35. Real-Time Machine Protection at ASDEX Upgrade with Near Infrared Cameras

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For save operation of ASDEX Upgrade (AUG) the surface temperature of the plasma facing components needs to be monitored in real-time. For this purpose cameras are operated inside the AUG experiment hall, where they are exposed to strong magnetic fields and high neutron fluxes. So far only a system based on analog near infrared (NIR) cameras could be operated at a sufficiently high reliably in this harsh environment. After testing different camera hardware a new system with digital cameras is now being established at AUG that provides the same reliability and beyond that a higher spatial- and temporal resolution together with the possibility to remotely control the camera settings. On the data acquisition side it is necessary to process the data of about 30 video streams at 120 frames per second in real-time. Regions of interest can be defined in which the detection of hot spots is active. If a hot spot is detected a signal is sent to Discharge Control System (DCS) which in turn will initiate measures to protect the machine. In order to suppress both false-positive and false-negative detection of events filtering is required to remove the strong noise on the camera detectors caused by the fusion neutrons produced during the discharge. For this purpose a combination of spatial- and temporal median filtering is applied.

The data acquisition- and evaluation system operates LabVIEW Real-Time and is equipped with National Instruments data acquisition hardware. The software is implemented in C interfacing with LabVIEW for initialization. For the communication with the DCS a timing card is installed providing a time stamp every 20 ns that is synchronized and universal for the entire experiment. In addition to NIR cameras the system can be operated with a wide variety of cameras including visible- and infrared spectral range.

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O-36. Real Time IR Thermography at ASDEX Upgrade: Current Status and Future Prospects

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Power exhaust is a major challenge for the design and operation of future fusion devices such as ITER and DEMO. Infrared (IR) thermography is widely used in present fusion experiments to measure the heat flux onto the plasma facing components. Current IR systems are designed for pure data acquisition, with the data analysis taking place offline after the plasma discharge. With long pulse experiments in sight, such as Wendel- stein 7-X, this procedure is questionable. An online data analysis of the target heat flux is desired. For this reason a new real time IR thermography system is designed, built and tested at ASDEX Upgrade.

For the system a new IR camera was developed using a commercially available IR detector measuring at a wavelength of 3:6 - 4:9 µm and using the Camera Link standard for communication. The camera housing is built out of soft iron to shield the detector and the electronics from the magnetic fields occurring during the operation of ASDEX Upgrade. Data acquisition is based on National Instruments hardware in the torus hall connecting to an industry computer on the outside via fiber optics.

Data acquisition and evaluation are implemented in C interfacing with LabVIEW for the setup of the acquisition. During the acquisition the data is directly streamed to a solid state disk in the industry computer allowing for long pulse operation. Correction and calibration of the acquired frames are performed in real time giving a continuous measurement of the surface temperature. For the calculation of the heat flux a real time version of THEODOR is implemented.

The integration time of the detector can be changed during the acquisition. Operation of the system with adaptive integration time based on the measured signal is possible. This opens the prospect of having automated IR measurements without the need of human intervention, which might be needed for long pulse operation.

O-37. Design of WEST Infrared thermography diagnostics

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The WEST (Tungsten (W) Environment in Steady state Tokamak) project is a major update of Tore Supra which aims to operate the tokamak with an X-point magnetic configuration, in a fully metallic environment over long plasma discharges. In that frame, a new infra-red (IR) thermography diagnostic is developed to measure the plasma facing components (PFCs) surface temperature, in order to prevent overheating and provide relevant data for the study of the new metallic environment.

In that aim, 7 endoscopes will be located in upper ports, each of them fitted with 3 optical lines, providing a total of 21 lines-of-sight as follow: 14 lines for the integral view of the new W divertor, 2 lines for zoomed views of the divertor with a high spatial resolution, and 5 lines for the RF heating antennas views (3 ICRH + 2 LHCD) by means of an innovative deflecting mirror located in the inner vacuum vessel protecting panels. An extra endoscope located in an equatorial port will provide a wide angle tangential view, allowing the monitoring of the upper divertor, the inner guard limiters, and the upper port protections. All the lines will be equipped with wide IR wavelength band (1.5-5μm) cameras, and real time date processing.

The paper describes the main diagnostic components, at the end of the studies phase: optical and mechanical design, hydraulic and thermo-mechanical calculations, cameras, real time data handling and integration are addressed. The metrological performances of the diagnostic are assessed by a full instrument simulation.

O-38. A fully synthetic diagnostic for the evaluation of measurement performances of WEST Infrared Imaging System

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A new Infrared (IR) Imaging System for the monitoring of plasma facing components (PFC) and for the physics understanding of the plasma interaction have to be implemented for the project WEST (Tungsten (W) Environment for Steady State Tokamak)- which goal is to equip the tokamak Tore Supra (TS) with an actively cooled tungsten divertor . The primary role of IR thermography system is to measure the surface temperature of the full W-divertor and the five heating antennas through seven endoscopes located in upper ports. Each endoscope is composed of 3 lines-of-sight: two for viewing 2x30° of the lower divertor, one for viewing the antenna. Two endoscopes will be also equipped of a high resolution camera viewing a small field of view about 20° of low divertor focusing on the area receiving the maximum heat flux. The diagnostics should be able to measure a maximum temperature of 3400°C with a resolution about 4-8 mm for standard divertor views and better than 1 mm for the high resolution view.

The goal of this paper is to determine accurately the system measurement performances in order to validate the optical design. For that, a synthetic diagnostic has been developed and applied to a variety of optical and integration designs. Simulations are carried out in two stages: the first stage uses a ray tracing Monte Carlo to reproduce the 3D thermal scene observed from the camera views taking into account the detector resolution only. The second stage simulates the optical effects which causes image blur. This is deduced from the calculation of the Point Spread Function which expresses the spread of punctual sources due to the diffraction and aberrations effects. The quantitative interpretation of the predicted measured signals in terms of spatial resolution and temperature threshold is given and system performances are compared and discussed.

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O-39. Analysis of the dependence between inter-ELM time intervals and energy losses

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Edge-localized modes (ELMs) are repetitive plasma instabilities occurring in the edge of high confinement (H-mode) tokamak plasmas. ELMs result in a sudden exhaust of particles and energy, causing significant transient heat loads to be released onto the plasma-facing components. Large ELMs, such as those that are predicted to occur in ITER, need to be controlled or completely mitigated in order to avoid a significant reduction in divertor lifetime. Currently, one of the most viable options for ELM control in high-current ITER plasmas is the injection of pellets to trigger a plasma edge instability leading to an ELM. This enables an increase in ELM frequency which is expected to reduce ELM energy loss, under the empirically observed inverse relationship between the plasma's average ELM energy and average ELM frequency. This necessitates a rigorous study of the relationship be-tween ELM frequency and energy losses for natural ELMs.

In this work, the relationship between inter-ELM time intervals and energy loss for individual ELMs is studied, in contrast to studying the relationship between the average quantities. For each individual ELM, two distinct time intervals are considered, i.e. time since the previous ELM and time until the next ELM. The study was conducted on 37 carbon wall plasmas from JET, comprising 20 type I ELM plasmas and 17 type III ELM plasmas. This was followed by a comparative analysis with a set of JET ITER-like wall plasmas. The results indicate a relatively strongly varying dependence between inter-ELM time intervals and ELM energy losses, with the global inverse relationship not being ubiquitously obeyed. Consequences for ELM control schemes are discussed.

**See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia.*

O-40. Testing for chaos in type-I ELM dynamics on JET with the ILW

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In H-mode plasmas, Edge Localized Modes are one of the main causes of the first wall erosion, especially in the divertor tiles. On the other hand, ELMs contribute to maintaining a stable plasma density, reducing the risks of disruptions. Moreover ELMs play a complex role in the amount and spatial distribution of impurities. Understanding and controlling ELMs are crucial issues for the operations of ITER where the type-I ELMy H-mode has been chosen as the standard operation scenario.

The new full-metal ITER-like wall (ILW) at JET was found to have a deep impact on the physics of ELMs in JET. The change in the wall composition was found to be at the root of the different baseline H-mode behaviour in ILW, in which a significant change of the ELM dynamics is observed for spontaneous type-I ELMs. The ELM duration for example is much longer for the ILW than in similar cases with a C wall (CW). [1]

In this paper, the differences between the dynamical properties of ELMs in both the CW and ILW shots have been investigated by means of surrogate data analysis.

In order to make this comparison, several nonlinear measures, such as the mutual information, the correlation dimension and the maximum Lyapunov exponent have been evaluated for the original series and for the surrogate series. These measures have been severely limited by some typical experimental conditions, e.g. measurement noise, making a signal pre-processing stage necessary to draw conclusions.

The results obtained by the analysis of the Be-II and D_α radiations confirm the suitability of D_α also for the characterisation of ELMs in the ILW campaigns, and generally confirm the results obtained in the CW campaigns on the pseudoperiodic dynamics of ELMs.

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O-41. Bayesian inference of plasma turbulence properties from reflectometry measurements

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Reflectometry is a powerful diagnostic for investigating electron density fluctuations in fusion plasmas. The interpretation of the reflectometer signal is a complex task that is difficult to address by analytical means. There is generally no simple relation between the measured reflectometer signal and the underlying density fluctuations. As a consequence, their statistical properties are often considered the same. This assumption might be too simplistic and can therefore lead to unreliable conclusions.

We have developed a novel approach rooted in inverse problem theory and Bayesian probability, which may allow us to infer the *true* statistical properties of the turbulence from the measured signal. In this contribution, we investigate numerically the validity of such an approach by considering a simplified plasma model.

The turbulence is modelled by a time-dependent Gaussian random surface parameterized by three quantities, namely the amplitude of the fluctuations h, and their characteristic length L_c and time scale t_c. As we are constrained by the computational cost, the interaction between the plasma and the probing beam is described in the framework of the physical optics approximation. A Markov chain Monte Carlo method is used to explore the parameter space. The likelihood is estimated by comparing histograms computed on the time series of the real signal component. The marginal posterior obtained for the fluctuation amplitude h peaks at the correct value and is rather narrow. We show that the characteristic length L_c can also be inferred from the histograms if the underlying time series is sufficiently long (~2.104 samples) and much longer that than the fluctuation time scale t_c. The fluctuation time scale has a very week influence on the histogram, consequently inferring t_c requires additional statistics such as the autocorrelation function of the reflectometer signal.

We finally consider the effect of the instrumental noise on the inferred parameters and we discuss the validity of our assumptions (Gaussian turbulence and physical optics model). These are key issues that need to be considered prior to the application of our method to experimental signals.

O-42. Evaluation of epsilon-net calculated equilibrium reconstruction error bars in the EUROfusion WP-CD platform

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One of the most essential fields in fusion research is the reconstruction of plasma equilibrium. Reconstructed data is used as input to most of the plasma modelling codes and to plasma control systems. Therefore, the accuracy as well as the associated uncertainties of reconstructions plays a crucial role in fundamental understanding of processes in present devices and fusion reactors ITER and DEMO. The results of previous and recent [1-3] research show that the traditional methods of equilibrium reconstructions cannot be trusted without rigorous calculation of the reconstructed functions error bars. One can get substantially different plasma current densities and safety factors, which fit the measurements even within a relatively small inaccuracy.

A recently developed new technique, based on epsilon-nets and SDSS code [1-3], addresses the fundamental challenges of the equilibrium reconstruction problem: calculate the reconstructed functions error bars; validate the existence of very different solutions of the inverse problem, which fit the measurement errors; find the efficiency of a diagnostic (constraint) in selecting a reconstruction appropriate to the real physical process; determine the required accuracy of the measurements for a diagnostic; validate the effect of advancements in plasma model, used for reconstruction, on the error bars magnitude.

In this paper, some basics of the epsilon-nets approach are given and preliminary results on epsilon-nets reconstruction error bar analysis for ASDEX Upgrade equilibrium reconstructions are presented. The toolset, integrated in the EUROfusion Code Development for Integrated Modeling Work Package (WPCD) software environment, allows for a seamlessly routine analysis of the epsilon-nets reconstruction error bars for any tokamak device.

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O-43. Data for the ITER Plasma Control System

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ITER, presently in its construction phase, will make use of a complex control system to drive the plasma to high performance. Since ITER plasmas will have substantial magnetic and kinetic energies, abrupt plasma disruptions should be avoided or mitigated to ensure the expected lifetime of in-vessel components. The double roles of plasma execution/optimization and the first line of defence for investment protection are reserved for the Plasma Control System (PCS). To achieve ITER goals, the PCS has to implement and integrate a significant number of control functions, which span basic to advanced plasma scenarios, while simultaneously heeding event handling as a key element to avoid or mitigate conditions that could impact machine protection (failure of plant systems or plasma disrupting events) or the optimization of a discharge.

The PCS is now in the preliminary design phase and focuses on the initial basic operation of ITER. This includes primarily basic magnetic control, fuelling and heating control, while still developing event handling and, importantly, disruption prediction, avoidance, and mitigation. To perform its role, the PCS has to account for many inputs generated by a large set of diagnostics and plant systems. The load of information will be significant, not only because of the number of required plasma parameters but also because of the redundancy and diversification required for robustness, and the correct management and integration is strategic for the success of the PCS.

Data will be available both in a raw format as direct output from the diagnostic, and as processed data. The latter could either be produced at the diagnostic level or within the PCS. In addition to the control algorithms, the PCS will implement data processing and data management (i.e. data comparison techniques), especially where multiple diagnostics are required to provide reliable and robust input for control. The PCS will have access to all of the real-time data. Control techniques will be developed primarily offline, to be deployed in the PCS as soon as a sufficient degree of confidence is achieved. To get to this point, data are needed for simulating control schemes. At the present ITER cannot rely on real data and also their availability at the beginning of operations will be limited. Synthetic data simulating diagnostic output is the only option. Data simulation is achievable by means of developing both realistic models of the diagnostics and plasma modelling to be integrated in the Plasma Control System Simulation Platform (PCSSP).

The paper will briefly introduce the areas of control allocated to the PCS to justify the specifications of the plasma parameters required by these controls within the present ITER operational plan. Thereafter, a description of the complexity of the relationship between plasma parameters and the diagnostics that measure these is presented. In particular, the paper will focus on the areas where integration and multi-diagnostic data-processing are required, with particular emphasis on the robustness and reliability essential for plasma control. The importance of synthetic data and modelling will also be discussed together with the present PCS road map for data requirements.

O-44. Simulation studies on the ion trajectories and energy spectra for a new Inertial Electrostatic Confinement fusion device

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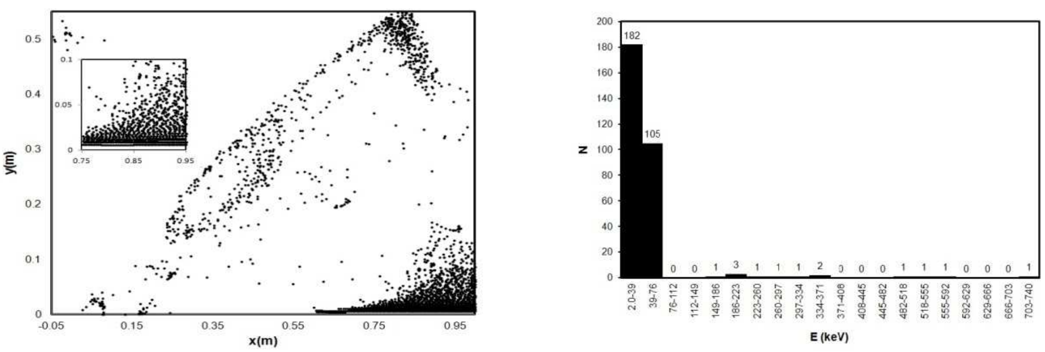
Inertial electrostatic confinement (IEC) fusion draws attention because of many scientific and technical applications [1,2,3]. Since it has a cheap maintenance for the fusion energy explorations, many university labs and institutes have different devices under various energy scales and geometry.

In this study, design, modelling and real-time data acquisition issues of a new cylindrical-shaped device have been explored and preliminary theoretical results based on the real-time data acquisition are reported. This study only presents the results of the *D-D* reaction as a preliminary work. The model includes the interactions of the fully-ionized media with electron-electron, ion-ion, electron-ion and their interactions with the central cathode having a certain negative potential (V) and the azimuthal homogeneous magnetic field (B) [4]. The system equations are solved by using the many body interactions and the data is stored in the MatLab environment in order to explore the positions, velocities and energies of the particles confined in the device. The system has run under the potential of V=-150 kV with the preliminary particle test number of 600 and the current value for the homogeneous magnetic field generation is I= 10 kA.



(a) **(b)**

Figure 1. (a) The horizontal positions of the ions inside the IEC chamber. (b) The energy spectrum of the ions.

It has been understood that ions can form a helical pattern around the central cathodes, however some proportion of the ions intensify at the lateral region (Fig. 1(a)). According to the energy spectra, most ions have values around 2-80 keV and some others can have energy values up to 0.7 MeV.

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