SUMMER SCHOOL OF PLASMA DIAGNOSTICS

PhDiaFusion 2023

Artifical intelligence for plasma diagnostics
and controlled fusion

Book of Abstracts

19 – 23 June
Niepołomice Royal Castle, Poland

Organizers:

The Henryk Niewodniczański
Institute of Nuclear Physics
Polish Academy of Sciences,
Krakow, Poland

Institute for
Magnetic Fusion Research (IRFM)
CEA, Cadarache, France

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Summer School of Plasma Diagnostics

Artificial intelligence for plasma diagnostics and controlled fusion

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General Assumptions of the School

Diagnostic measurements are essential in plasma experiments to infer the relevant plasma properties, both for physical interpretation and for real-time control. In modern fusion devices such as ITER, DEMO, or DONES neutron facility, the huge amount of generated data may require fast and efficient processes to infer the physical quantities with a reasonable computational cost. The use of artificial intelligence can be of a great help to achieve this goal, by feeding learning systems with experimental data and/or simulation results.

The fifth edition of the PhDiaFusion Summer School of Plasma Diagnostics "**Artificial intelligence for plasma diagnostics and controlled fusion**" will take place in **Niepołomice** on **June 19 - 23, 2023,** and will cover the diagnostics data processing, interpretation, validation, and real-time control aspects with a focus on artificial intelligence methods.

The School is addressed to graduate students and their tutors. The School will be held in the spirit of "the master and apprentice" approach:

- Lectures supported by "hands-on" tutorials will be given by eminent world experts in the field of plasma physics.
- Oral presentations will be also given by PhD students.
- The selected papers will be, after the proper evaluation, published in a scientific peer-reviewed journal.

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Lecturers

Mauro Cappelli, ENEA Frascati
Marco De Baar, Eindhoven University
Javier Díaz, University of Granada
Rainer Fischer, IPP Garching
Michela Gelfusa, Rome University
Marcin Jakubowski, IPP Greifswald
Dariusz Makowski, Łódź University
Jan Mlynar, IPP Prague
Simon Pinches, ITER Organization
Cristina Rea, MIT
Claudio Torregrosa, University of Granada
Geert Verdoolaege, Ghent University
Cong Wang, Zhejiang Lab
Zhijun Wang, Zhejiang Lab

Students presentations & Awards

Students are requested to prepare a 10-minute presentation that will be followed by a 5-minute discussion.
The three best student presentations will be awarded. The prizes are books funded by **Springer**.

Proceedings

The selected school proceedings will be published as a special issue of **Journal of Fusion Energy, Springer** based on the high quality of the submitted manuscripts.

Each manuscript must be accompanied by a statement that it has not been published elsewhere and that it has not been submitted simultaneously for publication elsewhere. All papers should be prepared according to "Instruction for Authors" available on the website of the Journal of Fusion Energy.

General Information

Venue:

The conference is held at the Royal Castle in town of **Niepołomice**.
All participants are accommodated on site.

Address:

The Royal Castle in Niepołomice
2 Zamkowa Street
PL 32-005 Niepołomice
Poland
Office - telephone: +48 12 281 32 32
Hotel - telephone: +48 12 261 98 00
Fax: +48 12 281 32 32
E-mail: HOTEL@ZAMEKKROLEWSKI.COM.PL

GPS coordinates:

50^0 2' 3.507" N
20^0 13' 2.918" E

Approximated distances to the selected place:

- City center of Kraków - 25 km
- International Airport Kraków-Balice - 40 km

About the place of the event

The **Royal Castle** is located in the heart of **Niepołomice**, 25 km from the centre of **Kraków**. The Niepołomice community is positioned in the very centre of a communication triangle, marked by three different roads: Kraków – Wieliczka – Tarnów, Kraków – Nowa Huta – Sandomierz, Nowa Huta – Niepołomice – Kłaj – Bochnia. The national road 75 (direction: north-south), the motorway A4 from Kraków – Tarnów, including the provincial route no. 964 Wieliczka – Niepołomice – Szczurowa and county roads no. K2009 and K2011 ensure that there is a good link between Kraków and the neighboring communities. The community area of Niepołomice is supported by the **John Paul II International Airport Kraków-Balice**. The distance between the town of Niepołomice and the airport is about 40 km. Since the new A4 motorway from Kraków to Szarów opened, the journey to the airport has vastly improved, the travel time can take around 45 minutes. The motorway is accessible in two places, on the Wielicka by-pass or in Targowisko.

Source: *http://www.zamekkrolewski.com.pl/en/*

The castle in Niepołomice began as one of many fortifications throughout Małopolska initiated by King Kazimierz the Great in the 14th century, however this one soon became his favorite residence which he used as a retreat from the royal seat in Kraków. Kazimierz was not the only king to favor the isolated outpost however, as his successors all invested themselves in further embellishing and expanding the castle into a magnificent royal residence where much time was spent. The castle’s heyday came during the rule of Władysław Jagieło who held meetings of the royal council here, often entertaining foreign dignitaries and passing official court judgements from Niepołomice rather than Wawel. It was also from here that the famous royal hunts set out, bringing back the big game trophies of bison, bears and boars that would line the castle halls. In the mid-16th century, King Zygmunt August rebuilt the residence on the model of contemporary Renaissance palaces – the appearance of which has been restored today. The ‘Second Wawel’ (as it was known) maintained its splendor for another hundred years before the Swedish deluge brought an end to its golden age and, along with the country, the castle gradually fell into ruin during Poland’s eras of partition and occupation.

A long and costly reconstruction began in 1991 and was finally completed in 2007. Today the castle is a multi-functional space hosting several museum exhibits, an excellent restaurant, a 3-star boutique hotel, a spa, and conference facilities. Despite all that, however, the space retains its authentic historical character. Perfect for a family outing, across from the Castle entrance is a park with a large playground, Queen Bona's picturesque gardens lie beside it, and the Wisła River flows just beyond it.

Source: *https://www.inyourpocket.com/krakow/the-royal-castle-in-niepolomice_137710v*

Social event: Guided tour of the Old Town of Kraków

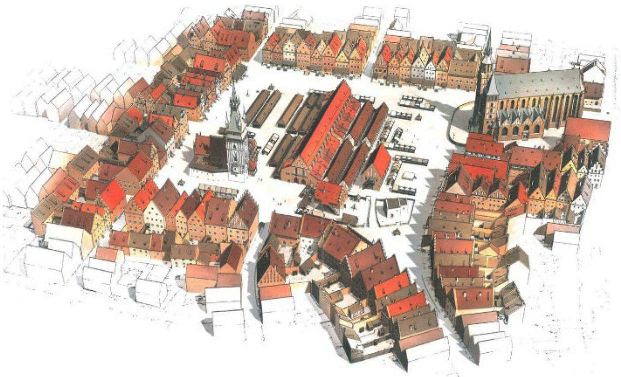
Kraków Old Town is the historic central district of Kraków, Poland. It is one of the most famous old districts in Poland today and was the centre of Poland's political life from 1038 until King Sigismund III Vasa relocated his court to Warsaw in 1596.

Today the **Old Town** attracts visitors from all over the world. The historic centre is one of 14 places in Poland that are included in the UNESCO World Heritage Sites. The architectural design of the Old Town has survived many cataclysms of the past and has retained the original form that was established in medieval times.

The old town is also one of Poland's official national Historic Monuments (*Pomnik historii*) chosen in the first round, as designated on 16 September 1994, and tracked by the National Heritage Board of Poland.

Throughout the year the Old Town is lively and crowded. There are many tourists, indefatigable florists, and lined up horse-drawn carriages waiting to give a ride. The place is always vibrant with life especially in and around the Main Market Square, one of the biggest squares in Europe, which came into existence when the city was given Magdeburg Rights in 1257. Tourist attractions such as the Town Hall Tower, the Sukiennice (also known as the Cloth Hall), old tenements with fine shops, and Adam Mickiewicz Monument are all located there. While near the monument, one can listen to the heynal, which is played each hour from the highest tower of St. Mary's Church.

Obwarzanki krakowskie, or twisted ring-shaped bread, is undoubtedly a symbol of Kraków. On the Square, there is a obwarzanki seller every few steps. Traditional obwarzanki are sprinkled with poppy seeds. Today, sellers offer a whole variety of them; apart from poppy seed, there are also sesame seeds, rock salt, and even pizza sprinkles. One can eat them while strolling or in a horse-drawn carriage while cruising around and glancing at yet another symbol of the old city, namely Kraków pigeons. One can also come across various buskers and mimes.



Numerous legends purport to explain the presence of numerous pigeons on the Main Square. According to one legend, Henry IV Probus, who tried to take over the Senioral Province during the period of regional disintegration of Poland, attempted to go to Rome with financial offerings in order to gain papal approval for his coronation. However, a certain enchantress turned his knights into pigeons. They pecked out some pebbles from the walls of St. Mary's Church, which then turned into gold. With these riches the prince set off to the Vatican, but while on his way he lost everything and never managed to reach his destination. He returned to Kraków. None of his knights ever regained a human form.

Source: https://en.wikipedia.org/wiki/Krak%C3%B3w_Old_Town#References
https://medievalheritage.eu/en/main-page/heritage/poland/krakow-clergy-house/

Program of the School

MONDAY, June 19th, 2023

Arrival

12.00 – ***Lunch***

13.30 - 16.00 ***Registration***

16.00 ***Opening of the School***

Dariusz Bocian - IFJ Scientific & Technical Director **–** *Welcoming words*

Didier Mazon – *Welcome – Introduction and Objectives of the School*

Jean-Luc Schneider - *French Embassy Welcome & Introductory lecture*

17.00 ***Welcome reception***

19.00 – ***Dinner***

TUESDAY, June 20th, 2023

8.00 – ***Breakfast***

9.00 – 12.00 ***Lecture Session I***

Chairman: **Didier Mazon**

9.00 **Lectures 1** **Simon Pinches –** *Integrated plasma modelling and the role of plasma diagnostics on ITER*

9.45 **Lectures 2** **Marco De Baar –** *Real time plasma control and the use of AI for the real Time analysis of complex data*

10.30 – ***Coffee break***

11.00 **Lecture 3** **Zhijun Wang** – *Introduction to AI technology of Zhejiang Laboratory*

12.00 – ***Lunch***

13.30 – 14.15 ***Lecture Session II***

Chairman: **Marco De Baar**

13.30 **Lecture 4** **Cristina Rea –** *A review of explainable ML accelerating Fusion science*

14.15 – 17.30 ***Student Session I***

Chairman: **Marco De Baar**

14.15 SS1 Jeffrey De Rycke
14.30 SS2 Giulia Marcer
14.45 SS3 Gabriel Amorosetti
15.00 SS4 Valentin Gorse
15.15 SS5 Adam Kwaśnik

15.30 – ***Coffee break***

Chairman: **Marek Scholz**

16.00 SS6 Johannes Illerhaus
16.15 SS7 Kimberley Lennon
16.30 SS8 Agnieszka Jardin
16.45 SS9 Javier Cruz Miranda

17.00 SS10 Michał Jagielski

17.15 SS11 Andrzej Brosławski

19.00 – ***Dinner***

WEDNESDAY, June 21st, 2023

8.00 – ***Breakfast***

9.00 – 11.45 ***Lecture Session III***

Chairman: **Simon Pinches**

9.00 Lecture 5 Claudio Torregrosa – *Diagnostics techniques in the IFMIF-DONES facility: Monitoring an Accelerator, a MW target and irradiation modules, all at once*

9.45 Lecture 6 Mauro Cappelli – *Design of a central instrumentation and control system: the case of the IFMIF-DONES Plant*

10.30 – ***Coffee break***

11.00 Lecture 7 Marcin Jakubowski – *Controlling divertor power loads at Wendelstein 7-X*

12.00 – ***Lunch***

13.30 – ***Social Event***

THURSDAY, June 22nd 2023

8.00 – ***Breakfast***

9.00 – 11.45 ***Lecture Session IV***

Chairman: **Michela Gelfusa**

9.00 Lecture 8 Rainer Fischer – *Integrated data analysys: Concept and applications in nuclear fusion*

9.45 Lecture 9 Jan Mlynar – *Tomography of experiments aimed at Runaway ecelctron studies on a small tokamak GOLEM*

10.30 – ***Coffee break***

11.00 Lecture 10 Javier Diaz – *IFMIF-DONES: AI for design, control and operations*

12.00 - ***Lunch***

13.30 – 14.45 ***Lecture Session V***

Chairman: **Claudio Torregrosa**

13.30 Lecture 11 Dariusz Makowski – *Real – time data acquisition and processing for plasma diagnostics and machine control*

14.*15* Lecture 12 Cong Wang – *AI – based integrated data analysis for tokamak diagnostics*

14.45 – 17.30 ***Student Session II***

Chairman: **Claudio Torregrosa**

14.45 SS12 Jiri Malinak

15.00 SS13 Bartłomiej Jabłoński

15.15 SS14 Krzysztof Król

15.30 – *Coffee break*

***Chairman:* Axel Jardin**

16.00 SS15 Gabriele Grapow
16.15 SS16 Sara Abbasi
16.30 SS17 Patryk Nowak vel Nowakowski
16.45 SS18 Hao Wu
17.00 SS19 Dariusz Morawski
17.15 SS20 Piotr Pietrzak

19.00 – ***Conference Dinner***

FRIDAY, June 23rd 2023

8.00 – Breakfast

9.00 – 13.00 Lecture Session VI
***Chairman:* Rainer Fischer**

9.00 Lecture 13 Geert Verdoolaege *-Bayesian probability for integrated data analysis and pattern recognition in fusion plasmas*

10.00 Lecture 14 Michela Gelfusa - *Artificial intelligence techniques for disruption prediction in tokamak*

10.30 – Coffee break

11.00 – 12.00 Round Table Discussion & Closing of the School
***Chairman:* Didier Mazon & Marek Scholz**

12.00 – **Lunch**

Departure

Lecture Session I

Tuesday, 20th June 2023

Lecture 1

Integrated Plasma Modelling and the Role of Plasma Diagnostics on ITER

S.D. Pinches, P. Abreu, O. Hoenen, S.C. McIntosh, M. Schneider

ITER Organization, Route de Vinon-sur-Verdon, 13067 St Paul-lez-Durance, France

The Integrated Modelling & Analysis Suite (IMAS) is the software infrastructure that is being developed to support the execution of the ITER Research Plan [1]. It is built around a standardised representation of data described by a Data Dictionary that is both machine independent and extensible. The use of standardised Interface Data Structures (IDSs) fosters the creation of modular physics components and (sub-)workflows that can be flexibly re-used to address different needs. The inclusion of Machine Description data allows the development and application of analysis software that not only works for any configuration of the ITER machine, but also for other machines which adopt the same self-describing data model. This allows software to be extensively validated within the ITER Members' programmes before it is deployed on ITER.

There are two main focuses of ITER integrated modelling programme: the development of high-fidelity predictive plasma simulation capabilities to allow the detailed assessment of plasma scenarios in ITER; and the creation of high performance off-line data processing pipelines to robustly infer plasma properties and their uncertainties.

Forward models of diagnostics that emulate a measurement signal from a plasma simulation, so-called synthetic diagnostics, have an important role to play in both the interpretation of diagnostic measurements and in predictive plasma simulations where they provide the input to actuator controllers.

ITER's strategy for diagnostic data analysis is to extract the maximum possible information from the available diagnostics at each phase of ITER operation. As is common on today's machines, a hierarchy of approaches will be taken for the processing of diagnostic signals. These will cover interpretation and parameter inference and include simple scalings using calibration factors, sophisticated physics analysis including the generation of kinetically constrained equilibria and interpretive transport analyses, to a rigorous inference approach in which as few, but explicitly stated, prior assumptions as possible are made in order to have the most objective interpretation of the measurements.

Acknowledgements:
The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

References:
[1] ITER Research Plan within the Staged Approach: https://www.iter.org/technical-reports

Lecture 2

Data-driven methods in nuclear fusion plasma control

Marco de Baar[1], Matthijs van Berkel,[1] Basil Duval,[2] Jesse Koenders,[1] Artur Perek,[2] Timo Ravensbergen[3]

1 NWO institute DIFFER, de Zaale 20, Eindhoven, The Netherlands
2 Swiss Plasma Centre, EPFL, Lausanne, Switserland
3 ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durance Cedex, France

Real-time control systems consists of actuators, sensors, models, and controllers. Modern controllers are model-based. The starting point is a model that includes the plasma dynamics, or more precisely, the input-output dynamics of the actuator-plasma-sensor system. Such models can be inferred from white, or grey, box modelling, or can be inferred from experimental or modelled data. This presentation aims to introduce some basic concepts of real-time control [1].

The lecture will focus upon the problem of exhaust control [2]. First, I will explain the exhaust control problem. Second, it will be shown how data-driven modelling can capture the plasma dynamics and then synthesize controllers [3,4, 5,6]. Third, the role of Machine Learning and Artificial intelligence in complex multi-agent sensor-data analysis will be explained [7].

Acknowledgments:
We thank the TCV, DIII-D, and AUG teams for their support and access to hardware and data.

References:

[1] Modern Control Systems, Dorf and Bishop, Pearson Education Limited
[2] Loarte A et al 2007 Progress in the ITER physics basis, chapter 4: power and particle control Nucl. Fusion 47 203
[3] Ravensbergen et al 2021 Nature Communications volume 12, Article number: 1105
[4] Koenders et al Nucl. Fus. 63, 2, 11 p., 026006
[5] M. Bernert et al Nucl. Mater. Energy (IF 3.037)
[6] Ceelen MSc Thesis
https://research.tue.nl/nl/studentTheses/identification-and-control-of-the-divertor-plasma-in-the-diii-d-t
[7] van Leeuwen, L. MSc Thesis,
https://pure.tue.nl/ws/portalfiles/portal/268853135/0929945_Leeuwen_L.S._van_MSc_thesis_Thesis_NF.pdf

Lecture 3

Introduction to AI technology of Zhejiang Laboratory

Zhijun Wang[1], Yixiong Wei[1],Fei Yang [1], Fedor Enikeev[1], Zhifeng Zhao[1,*],Zongyu Yang[2]

1 Zhejiang Lab, Hangzhou 310000, China
2 Southwestern Institute of Physics, ChengDu 610041, China

Zhejiang Laboratory is a major science and technology innovation platform located in Zhejiang Hangzhou. In the past five years, the lab has achieved excellent results in gathering high-end talents, realizing scientific and technological innovation, developing and applying intelligent computing platforms. The Laboratory acurrently focuses on five scientific research directions: Intelligent Perception, Artificial Intelligence, Intelligent Networks, Intelligent Computing, and Intelligent Systems. Among them, the an Zhijiang Alkaid OS under the Center for Intelligent Computing, with the idea of combining domain knowledge with AI computation and big data, has produced a series of landmark results and developed several open-source platforms for genetics, medicine, astronomy, cultivation and other directions.The official version 1.0 of those five application platforms was launched in November 2022, and a certain scale of application ecology has been initially built. Based on the operating results of the platform and related data, the lab published several articles on Nature/Science journals and/or sub-journals in 2022 and achieved a series of major academic breakthroughs[1.2.3]. Particularly, the group start to develop a fusion and plasma science computing platform based on Zhijiang Alkaid OS.

Acknowledgements:
This work was supported by Zhijiang Alkaid OS group and by Zhejiang Lab under the project of Digital twin system for intelligent simulation and control of nuclear fusion.

References:
[1] Flexoelectric Engineering of Van Der Waals Ferroelectric CuInP2S6. Science Advances Vol 8.Issue 33
[2] Precise Tumor Immune Rewiring via Synthetic CRISPRa Circuits Gated by Concurrent Gain/Loss of Transcription Factors. Nature Communications13,1454(2022)
[3] Frequency Dependent Polarization of Repeating Fast Radio Bursts - Implications for Their Origin. Science Vol. 375. Issue 6586

Lecture Session II

Wednesday, 20th June 2023

Lecture 4

A review of explainable Machine Learning accelerating Fusion science

C. Rea[1], J.X. Zhu[1], R.S. Granetz[1], Z. Keith[1], R.A. Tinguely[1],
J. Barr[2], M.D. Boyer[3], K. Felker[4], K.G. Erickson[5]

1 MIT Plasma Science and Fusion Center, Cambridge, MA USA
2 General Atomics, San Diego, CA USA
3 Commonwealth Fusion Systems, Cambridge, MA USA
4 Argonne National Laboratory, Lemont, IL USA
5 Princeton Plasma Physics Laboratory, Princeton, NJ USA

It has become widely accepted that Machine Learning (ML) accelerated research can enable reactor-relevant solutions for a broad spectrum of fusion challenges. Both inertial and magnetic confinement fusion need to address complex multi-scale, multi-physics systems whose integrated modeling implies extremely expensive computations, and ML can assist via surrogate modeling for accelerating such demanding simulation loops [1,2]. Further relevant examples of ML applications in fusion include its adoption to enhance the analysis of instrumentation data [3], to optimize experimental design and performances [4,5], and for real-time monitoring of the proximity to different boundaries of plasma stability [6].

This talk will first present a general description of Artificial Intelligence concepts, navigating through the Universal Approximation Theorem and focusing on the specifics of Machine Learning and Deep Learning paradigms. Particular attention will be given to reviewing ML techniques that guarantee an explainable and interpretable predictive output, thus enabling effective controllers for magnetically confined fusion plasmas [7]. Transfer learning and domain adaptation will also be discussed, since a common need exists to understand how to extrapolate knowledge to devices yet to be built or to experiments with different statistical properties [8,9]. Finally, several examples of data-driven fusion applications will be provided, with particular emphasis given to active ML research conducted at the DIII-D facility.

Acknowledgements:
This work is supported by the U.S. DOE under Award(s) DE-FC02-99ER54512, DE-SC0014264, DE-SC0010720, DE-SC0010492, and DE-FC02-04ER54698.

References:
[1] Rodriguez-Fernandez P 2022 Nucl Fusion 62 076036
[2] Humbird K 2021 Phys of Plasma 28 042709
[3] Samuell C 2021 Rev Sci Instr 92 043520
[4] Gopalaswamy 2019 Nature 565 581
[5] Humphreys D 2020 Journal of Fusion Energy 39 123–55
[6] Rea C 2021 IAEA Fusion Energy Conference Proceedings EX/P1–25
[7] Barr J 2021 Nucl Fusion 61 126019
[8] Zhu J X 2021 Nucl. Fusion 61 114005
[9] Gaffney J 2021 Phys of Plasma 26 082704

Lecture Session III

Wednesday, 21st June 2023

Lecture 5

Diagnostics Techniques in the IFMIF-DONES Facility: Monitoring an Accelerator, a MW Target and Irradiation Modules, all at once

C. Torregrosa-Martín[1], A. Ibarra[2], F. Arbeiter[3], S. Becerril[2], D. Bernardi[4], B. Brenneis[3], M. Cappelli[9], P. Cara[2], J. Castellanos[6], C. De la Morena[7], T. Dezsi[8], S. Fiore[9], W. Krolas[10], J. Maestre[1], G. Micciché[4], S. Nitti[4], I. Podadera[2], R. Prokopowicz[11], Y. Qiu[3], D. Regidor[7], A. Talarowska[11], U. Wiacek[10]

1 Universidad de Granada, Spain
2 Consorcio IFMIF-DONES España, Spain
3 KIT, Germany
4 ENEA Brasimone, Italy
5 F4E, Germany
6 Universidad de Castilla la Mancha, Ciudad Real, Spain
7 CIEMAT, Spain
8 CER, Hungary
9 ENEA Frascati, Italy
10 IFJ PAN, Poland
11 NCBJ, Poland

The International Fusion Materials Irradiation Facility-DEMO Oriented Neutron Source (IFMIF-DONES) will be a unique first-class scientific infrastructure consisting in an accelerator-driven neutron source delivering $5 \cdot 10^{14}$ n/cm^{2}s with a broad peak at 14 MeV and 80% of them above 1 MeV. Such neutron flux will be created in a Liquid Lithium jet Target and impinges the material specimens placed a few millimeters downstream, inside the so-called High Flux Test Module (HFTM). Strong integration efforts are being made at the current project phase aiming at harmonizing the ongoing design of the different and complex Systems of the facility. The consolidation of the Diagnostics and Instrumentation, transversal across many of them, is a key element of this purpose. For the successful operation of the facility, online monitoring of specific variables such as beam parameters, temperatures, vacuum pressures, atmosphere impurities, neutron flux and spectrum, Li levels, Li flow, Li leaks, Li jet thickness and beam footprint on target are required. Some of this monitoring shall be done in a very harsh environment, where estimated peaks of Si-eq absorbed doses reach values in the order of 10^4 MGy/year. In addition, very limited maintenance is possible in critical areas of the facility, only by means of Remote Handling once per year, whereas very high reliability is required. The current instrument design solutions consider among others the use of beam position and beam loss monitors, neutron detectors such as SPNDs (Self-Powered Neutron Detectors) and micro-fission chambers, electric contact Li leak detectors, and level-meters, as well as distance measurement methods based on laser interferometry and radiofrequency. This lecture contribution provides an overview of the mentioned Diagnostics, their current design status, and roadmaps to overcome such challenges.

Acknowledgments:
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Lecture 6

Design of a central instrumentation and control system: the case of the IFMIF-DONES plant

Mauro Cappelli

ENEA, Frascati, 00044 Frascati (RM), Italy

This lecture presents the status of the art of the ongoing development of the Central Instrumentation and Control Systems (CICS) for the IFMIF-DONES plant. IFMIF-DONES is the International Fusion Materials Irradiation Facility-DEMO Oriented Neutron Source, which employs an accelerator-based source of a focused beam of high-energy deuterons directed at a fast-flowing liquid lithium jet that produces the required neutrons via D-Li stripping reactions. The intensity and irradiation capabilities of IFMIF-DONES are well-suited for generating essential material irradiation data necessary for the design, licensing, construction, and safe operation of the DEMO fusion reactor.

From a functional perspective, CICS consists of three systems: COntrol Data Access and Communication (CODAC) System; Machine Protection System (MPS); Safety Control System (SCS). Each system at the central level is in continuous, bidirectional communication with the corresponding system at the local level by means of dedicated instrumentation and control networks and/or buses. The lecture describes the current status of the overall architectural design, thus highlighting the main components and technologies. Lastly, the lecture briefly shows the forthcoming design steps, mentions possible research improvements, and outlines future work in this area.

Lecture 7

Controlling divertor power loads at Wendelstein 7-X

M. Jakubowski[1], E. Aymerich[2], D. Böckenhoff[1], B. Cannas[2], A. Fanni[2], J. Fellinger[1], Y. Gao[1], B. Jabłoński[3], D. Makowski[3], F. Pisano[2], A. Puig Sitjes[1], G. Sias[2] and the W7-X team

[1] *Max-Planck-Institut für Plasmaphysik, Greifswald, Germany*
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Wendelstein 7-X (W7-X), the largest advanced stellarator in the world, aims to demonstrate a possible path for a future power plant based on the HELIAS design. Therefore, one of its main objectives is to demonstrate quasi-steady-state operation in a reactor-relevant parameter regime. Monitoring and control of the power deposition onto the water-cooled plasma-facing components (PFCs) is essential to ensure safe steady-state operation at high heat flux. W7-X uses ten thermographic systems [1] to fully cover the entire surface of the HHF divertors, the main plasma-facing components that receive power from the plasma. The system must detect thermal events in real-time, and interrupt operation on time if a critical event is detected [2]. The fast response times required to prevent damage to the equipment make it imperative to fully automate the image analysis algorithms [3]. A typical thermographic protection system is based on manual analysis of the data after the pulse has been performed. At W7-X a real-time PFC protection system based on image processing techniques is being developed [2]. It uses precise registration of the full field of view against the CAD model to determine the temperature limits and thermal characteristics of the various PFCs. Instead of reacting when the temperature limits are exceeded in certain regions of interest, the system predicts when an overload will occur based on a heat flow estimation and activates the interlock system in advance to compensate for the system delay.

At W7-X, power exhaust is mainly controlled by adjusting the plasma radiation, but efforts are also being made to control the shape and position of the strike line. In [4] the relationship between the heat-flux distribution in the divertor strike-lines and the actuators influencing them has been modelled by means of deep convolutional neural networks. Therefore, real-time heat flux estimation is pivotal for controlling the divertor heat loads during the experiments. To calculate the heat flux, the solution of the Partial Differential Equation (PDE) needs to be approximated. Since the traditional numerical approximation is computationally expensive, in a new approach Physics Informed Neural Networks (PINNs) are utilized instead for real-time capability [5]. PINN models are neural networks that learn PDEs by minimizing the PDE loss.

Moreover, artificial neural networks can be used to accurately and efficiently predict details of the magnetic topology at the plasma edge of the Wendelstein 7-X stellarator based on simulated and measured heat load patterns onto plasma-facing components observed with infrared cameras [6].

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Lecture Session IV

Thursday, 22nd June 2023

Lecture 8

Integrated Data Analysis: Concept and Applications in Nuclear Fusion

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A major challenge in nuclear fusion research is the coherent combination of data from heterogeneous diagnostics, magnetic equilibrium and modelling codes. Measured data from different diagnostics often provide information about the same subset of physical parameters. Additionally, information provided by some diagnostics might be needed for the analysis of other diagnostics. A joint analysis of complementary and redundant data allows, e.g., to improve the reliability of parameter estimation, to increase the spatial and temporal resolution of profiles, to obtain synergistic effects, to consider diagnostics interdependencies and to find and resolve data inconsistencies. Modelling codes may provide additional physical information allowing for an improved treatment in case of data deficiencies. Key for reliable estimation of plasma parameters is a magnetic equilibrium consistent with all diagnostics data and physics modelling. A coherent combination of all kind of available information within a probabilistic framework allows for improved data analysis results.

The concept of Integrated Data Analysis (IDA) in the framework of Bayesian probability theory will be introduced and contrasted with conventional data analysis. Applications from nuclear fusion research will highlight various aspects of IDA and the respective benefits.

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Lecture 9

Tomography of experiments aimed at Runaway electron studies on a small tokamak GOLE

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The GOLEM tokamak at the Czech Technical University is currently the only operating tokamak in the Czech Republic since the Academy of Sciences has been designing a new machine, the COMPASS Upgrade tokamak. In the meantime, the GOLEM tokamak [1] plays a significant role in training and maintaining former experimental expertise of the COMPASS team in both areas of their research interest, i.e., in the plasma edge research and in the Runaway electron research. In this contribution we focus on the latter research subject with special attention to the inverse reconstruction (tomography) of some of the spatially resolved measurements, in particular on measurements using fast matrix cameras. The production of Runaway electrons at GOLEM is reliable, although it is limited to a rather fundamental case of the Dreicer mechanism that originates in the plasma breakthrough of the initial high loop voltage. The advantages of a simpler physics of Runaway electron generation for data interpretation is obvious, still we badly need to extend the diagnostic capabilities of the facility and its operation flexibility.

The challenge of tomography as an ill-posed data analyses will be clearly put and explained in an easy-to-grasp introductory part. As usual, our attitude to resolving the task is based on Minimum Fisher regularization method that stems from a rather powerful and universal Tikhonov regularization method [2]. However, in this talk we will also introduce basics on rather novel and powerful methods based on Neural Networks and applications of Artificial Intelligence in the inverse problems.

In the second part of the lecture we shall clearly present the main challenges of application of tomography on spatially limited sets of data, discussing role of artifacts, systematic errors and noise, accuracy and reliability of tomographic reconstruction and share also some hints on how to avoid disappointment. In conclusion, we will exemplify the method on recent results-based o reconstruction of data form fast visible light matrix cameras possibly combined with different GOLEM discharge condition. We shall also strive to interpret role of the runaway electrons in the presented results.

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Lecture 10

IFMIF-DONES: AI for design, control, and operations

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The International Fusion Materials Irradiation Facility-DEMO Oriented NEutron Source (IFMIF-DONES) is currently in the design phase and planned for start the construction in Granada, Spain before 2030. Its primary objective is to generate high-energy neutrons to replicate the neutron radiation pattern of a nuclear fusion reactor like DEMO [1]. The generated neutrons will be used to irradiate materials for analysis of their suitability in constructing the vessels of future fusion reactors.

This endeavor poses various significant challenges, including the requirement for a large beam current, the need to establish a perfect liquid lithium wall, and an operational availability beyond 87% uptime. Meeting these challenges necessitates robust engineering methodologies to ensure the dependability of the facility. Consequently, the entire design process must be meticulously implemented and optimized, with special emphasis on the control system [2]. It plays a critical role in ensuring plant reliability, safety, and availability.

The design of IFMIF-DONES has incorporated the use of Artificial Intelligence (AI) methods from the start. On one hand, beam dynamics and neutronics utilize simulation tools like TraceWin or Monte Carlo techniques. Recognizing the time-intensive and complex nature of these tasks, researchers at IFMIF-DONES are exploring methods to automate and optimize these simulations. Additionally, AI methods are employed to reduce computational load. On the other hand, AI techniques can be applied during operations for tasks such as plant optimization (e.g., minimizing energy consumption or maximizing beam energy transfer to particles), predictive maintenance, failure analysis, or the design of a comprehensive plant Digital Twin. They are crucial for achieving the availability requirement in an efficient manner.

It is worth noting that these objectives have substantial implications for the design of the control system. From networks and data acquisition (DAQ) systems to processing elements or database structures, seamless integration of AI capabilities is essential from the early design stages since it cannot be retrofitted at later stages. This talk will present how these objectives are addressed in IFMIF-DONES, including projects such as Neuron-DONES [3].

Acknowledgements:
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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Lecture Session V

Thursday, 22nd June 2023

Lecture 11

Real-time Data Acquisition and Processing for Plasma Diagnostics and Machine Control

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Plasma diagnostics is an essential tool to understand and improve plasma stability in fusion devices. It provides useful information for analysis of physical phenomena, machine protection and plasma control. Data Acquisition and Processing (DAP) systems are commonly applied for physical parameters measurements. The acquired and processed data provide useful information describing plasma conditions and its parameters. Nowadays, digital data acquisition and processing systems are commonly used for accurate and reliable measurements. First, the physical parameters are measured by analogue sensors. Next, the analogue signal, after suitable conditioning, is digitalized and further processed to extract the required information describing plasma parameters.

A real-time control system with well-defined data processing time is required when the measured parameters are used to control thermonuclear fusion. Plasma diagnostic system could measure and analyse large number of signals (hundred and thousands of parameters) and therefore requires a suitable architecture of the DAP system. Some of plasma diagnostic systems also use digital cameras as sensors to measure plasma parameters and control the machine in real-time. In this case, the image acquisition and processing system is composed of an image detector (digital camera), a frame grabber device that receives video stream and a device responsible for image acquisition and further processing. In case of vision systems, a significant processing power could be required to process in real-time video stream. Acquiring and processing of such large number of signals requires a flexible hardware platform that provides large enough capability, processing power and synchronization. Various architectures and hardware platforms can be used to design DAP systems for fusion diagnostics.

The lecture will provide basic knowledge how to design complex as well as scalable data acquisition and processing systems for plasma diagnostics applications. The whole chain of data acquisition, including a signal conditioning, digitalization, data processing and timestamping will be discussed. Various hardware platforms and their crucial parameters will be compared and debated during the lecture. Data processing components including Central Processing Units (CPUs), Field Programmable Gate Arrays (FPGAs) and Graphics Processing Units (GPUs) will be compared during the presentation. Finally, a few examples of typical data acquisition and processing systems will be presented.

The lecture will provide also a basic information concerning firmware and software development for digital data acquisition and processing systems used in plasma diagnostic systems.

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Lecture 12

AI-based integrated data analysis for tokamak diagnostic systems

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As an important research content of the nuclear fusion device, the diagnostic system plays a vital role. At present, hundreds of complex diagnostic systems have been developed in the field of fusion. Based on the diagnostic results, research on magnetohydrodynamic instability (MHD), turbulence-related abnormal transport and other physical topics has been carried out. Traditional diagnostic data analysis is based on a single diagnostic system, and the diagnostic results have many disadvantages such as large errors, inconsistency, and poor timeliness, which are not conducive to the induction and refinement of deep-level physical laws and the feedback control of plasma. This work intends to promote the development of integrated data analysis (IDA) of nuclear fusion diagnostic systems in China by carrying out research on integrated data analysis of electron density with multiple diagnostic systems, and providing self-consistent plasma profile parameters for plasma feedback control and physical analysis. In addition, a quasi-real-time neural network proxy model is constructed to improve the timeliness of the integrated data analysis and help realize the application of diagnostic data integration analysis results in real-time plasma feedback control.

Acknowledgements:
This work was supported by Zhijiang Alkaid OS group and by Zhejiang Lab under the project of Digital twin platform for nuclear fusion simulation and control.

Lecture Session VI

Friday, 23rd June 2023

Lecture 13

Bayesian Probability for Integrated Data Analysis and Pattern Recognition in Fusion Plasmas

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Fusion research and development can benefit greatly from modern data science methods, both for increasing the understanding of the underlying plasma physics and for optimizing the design and operation of fusion machines. From basic statistical techniques for model fitting, to Bayesian methods for probabilistic analysis of data from single or multiple diagnostics, to the latest machine learning techniques for anomaly detection and uncertainty quantification: the applications are numerous and the possible approaches originate from a broad range of subfields of the information sciences. In this talk, a number of recent applications of Bayesian inference in fusion will be highlighted. After introducing the principles and treating a few general applications, we discuss the important area of integrated analysis of fusion diagnostic data. We focus in particular on speeding up or approximating the inference process with a view to real-time implementations. We then proceed to applications of Bayesian inference in pattern recognition, concentrating on robust estimation of scaling laws in complex, multi-machine data sets, as well as anomaly detection for predictive maintenance in fusion devices.

Lecture 14

Artificial intelligence techniques for disruption prediction in Tokamaks

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Disruptions are sudden and abrupt losses of plasma confinement that happen in tens of ms (or even faster) and can cause irreversible damage to fusion devices implementing the tokamak configuration of the magnetic fields [1]. Disruptions have proved to be unavoidable in tokamaks and their potential damage is more severe the larger the machine. Predicting their occurrence with sufficient warning time is therefore crucial in any reactor grade tokamak, to deploy the appropriate remedial actions in real time [2].If disruptions turned out to be unavoidable and impossible to control, Tokamaks would not be candidates to nuclear fusion reactors.

Unfortunately, disruptions are a very complex and nonlinear phenomenon involving several non-separable effects such as the kinetic profiles, the pedestal properties, centrifugal forces, plasma rotation, and radiation emission to mention just a few. Consequently, no theoretical mode based on first principle is capable of predicting the approach of a disruptive instability. Therefore, empirical models, derived either manually or with artificial intelligence techniques, are the only practical approaches to disruption prediction. In reality, the manual alternative is a poor option for phenomena as complex as disruptions. Indeed, in the last decades the most performing empirical models have been inferred with machine learning methods.

All the main families of machine learning tools have been explored, from neural networks and support vector machines to classification trees and fuzzy classifiers. To improve the generalization capability and the portability of the predictors, the new approach of open world training has been recently implemented [3]. In addition to developing classifiers for prediction, physical models of the boundary between the safe and disruptive regions of the operational space have also been derived with the help of genetic programming methods, which could help also in the design of specific experiments to further investigate the plasma dynamics leading to the collapse of the configuration [4-6].

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Student Session I

Tuesday, 21st June 2023

SS1

A Bayesian approach for estimating the kinematic viscosity model in reversed-field pinch fusion plasmas

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A fundamental feature of reversed-field pinch fusion plasmas is helical self-organized states. In the past few decades, MHD theory and numerical simulations have played a key role in describing these states. An important parameter is the dimensionless Hartmann number [1], which is determined by the resistivity and the viscosity. It can be interpreted as the electromagnetic equivalent of the Reynolds number and it turns out to be the ruling parameter in the 3D nonlinear visco-resistive magnetohydrodynamics activity. However, there is no consensus regarding the theoretical model for the kinematic viscosity coefficient.

There are five candidate models according to the various momentum transport theories developed for hot magnetized plasmas: three classical viscosities derived from the closure procedure leading to the Braginskii equations, the ion temperature gradient viscosity, describing a mode that damps the velocity fluctuations, and the Finn anomalous viscosity according to the Rechester-Rosenbluth model.

We calculated the viscosities and the Hartmann number using measurements from RFX-mod. A power-law dependence was then sought between the Hartmann number and the amplitude of the $m = 0, 1$ secondary modes. Our approach, using Bayesian statistics, outperforms the previous analysis based on simple least squares fitting.

First, by computing the Bayes factor [2], we inferred that a constant relative error is a better model for the uncertainty in the regression analysis. Second, errors on the plasma parameters and their role in error propagation were taken into consideration. Third, Bayes factors between the different viscosity models were used to infer the optimal viscosity model, in a more robust way compared to the earlier approach based on correlation coefficients and simulations.

The optimal model, identified through the Bayesian procedure, agrees with physical motivation [3]. More generally, our work has demonstrated the potential of the Bayesian approach in other model selection problems in fusion, using a rigorous and robust statistical methodology.

Acknowledgements:
We thank Consorzio-RFX for providing the RFX-mod data.

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SS2

Degenerate pile-up correction in pulse height spectra from gamma-ray spectromers

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During the last deuterium-tritium experimental campaign conduced at JET, neutron yields up to $5 \cdot 10^{18}$ neutrons per second were achieved [1]. Such high neutron yields posed significant challenges in accurately measuring fast-ion emissions, as the gamma-ray signals were inevitably overshadowed by piled-up neutron events [2].

One of the primary obstacles faced by diagnostics operating under high counting rates is pile-up, which occurs when two or more events are detected within a time lapse short enough to result in a superposition of the events waveforms. These cannot hence be integrated separately in order to get their amplitudes.

Piled-up events are typically identified and resolved using pile-up rejection or recovery algorithms. In the latter case, the constituent single waveforms and their amplitudes are also restored. However, there are instances where the pulses overlap so closely that that it is impossible to identify the occurrence of pile-up, resulting in the integration of these pulses into a single spurious event. This phenomenon is known as degenerate pile-up.

We have developed a method to rectify the incorrect reconstruction of degenerate pile-up events based on a statistical approach, which can be directly applied to the pulse height spectra distributions. Our approach was tested on a number of synthetic spectra, with counting rates ranging from 20kHz to 1MHz. The recovered spectra were compared to those purely analysed with a pile-up recovery algorithm, demonstrating an improvement of the reconstructed spectrum of tens percentage when compared to the true synthetic counterpart.

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SS3

Characterization of a new deep learning approach for data recovery in the Soft X-Ray fusion plasma diagnostics in RFX-mod

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Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA)

The RFX Consortium (Padua, Italy) hosts the Reversed Field eXperiment (RFX-mod), a large Reversed Field Pinch device, and one of the most controllable fusion experiments in the field of thermonuclear fusion research. This device has been meant to work both on tokamak and RFP configurations and, due to the very high amount of sensors and control coils, it is very well suited to study the physics of magnetically confined plasmas [1]. RFX-mod2 is an ongoing upgrade of the device with new components, aimed at controlling even better the plasma parameters in real-time thanks to a further increase in the amount of sensors and to the improvement of the control system.

The tight control of the active coil system must provide a complex feedback in a very short time evaluating data coming from the plasma diagnostics. In the extreme conditions that are present close to the plasma, these signals are also very often affected by high noise, and sometimes sensors can even fail. In this context, a new approach of "diagnostic data integration" using a variational autoencoder architecture [2] has been assessed to test the real time recovery of the Soft X-Ray camera diagnostics [3] and to look at the possible link with magnetic configuration. The final goal would be to see how a machine learning model can successfully link the temperature profiles with the MHD state of the plasma, and possibly to find signatures of magnetic instabilities during the plasma evolution. Furthermore, a proper quantization of the deep neural network model will then allow us to run the model in an embedded programmable logic device, to use it in a real scenario.

To do so, we need to characterize the model with an input dataset similar to the real one coming from the diagnostics, to evaluate the ability to reconstruct the temperature profiles even with missing or inaccurate data. A first step of this work was using a set of gaussian curves, with various free parameters, such as the amplitude, mean or width. Although the model was able to reconstruct these curves, the input data had to match the real one to produce a physically valid output. For this reason we are building a model that should be able to reproduce the temperature profiles just like the ones of the real experiment, but with the possibility to control the generation of the free parameters. This will permit us to prepare the dataset for a semi supervised pre-training trying to disentangle physical quantities within the latent space dimensions.

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SS4

Thermal event characterization for machine protection

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The large amounts of power and energy involved in the WEST tokamak are evacuated through the walls, acting as thermal shields. They operate in a stationary manner with surface temperatures of 500 to 1000°C. In addition to the normal power evacuation, which must be monitored, parasitic phenomena (magnetic instabilities, additional heating power losses) send occasionally hot plasma to undesirable locations, resulting in potentially damaging thermal events. These phenomena are monitored for optimal machine operation, and sometimes require counter-reaction or other safety actions. This work presents an automated process for detecting thermal events in infrared images using a Region-Based Convolutional Neural Network (R-CNN), a deep learning model. The R-CNN is trained on a dataset of manually annotated thermal events from movies captured by the 12 infrared cameras of the WEST tokamak. These cameras provide information on the surface temperature of in-vessel components. A custom-designed ontology is used to characterize the thermal events. The automated process can accurately detect, track, and classify most of the regular thermal events in the WEST infrared movies in a real-time compatible way.

This deep learning based method is intended to increasingly incorporate physical prior knowledge that is well understood by physicists. The integration of physical knowledge into deep learning models is a crucial step towards enhancing wall monitoring. The second aspect of this study concentrates on incorporating a priori knowledge into deep learning models to enhance the analysis of thermal events. A method based on max-tree [1] representation and attributes of infrared images is developed to obtain new information on previously detected strikelines and classify normal from abnormal ones. The proposed method requires only high-level prior knowledge of abnormal temperatures and divertor structure and does not require any labelled data. The max-tree classifier method is tested on real IR images from the WEST tokamak and shows that 88% of thermal events are accurately classified with a small enough calculation duration, which can be performed between two experiments.

Acknowledgements:
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 | EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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SS5

Application of machine learning in analysis of humidity influence on dual-pulse LIBS spectra

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Laser-induced breakdown spectroscopy has emerged as a promising diagnostic method in material analysis. LIBS has been also recognized as relevant for monitoring plasma-wall interactions in thermonuclear fusion technology [1]. The advantage of the method is the possibility to acquire a large amount of data. However, analyzing such data requires the use of significant resources. Moreover, during LIBS measurements various set-up parameters and external conditions have an impact on the obtained spectra virtually leading to further increase of the produced data. One of the external factors of not fully understood influence is the humidity level.

This contribution describes numerous LIBS experiments in various humidity levels with the dual-pulse LIBS set-up. The study aims to investigate the potential influence of humidity on the spectra for a broad range of parameters of laser exposition (pulse energy, pulse separation time) and signal acquisition (delay and acquisition times). A potential solution to analyze large amounts of acquired data is the application of machine learning algorithms. To achieve the objectives several machine learning methods such as Support Vector Machine – SVM, K-means clustering and decision tree were implemented.

As a part of the research, it was needed to design and construct a laboratory setup with instruments capable of measuring and adjusting the humidity level throughout the LIBS experiment.

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SS6

Machine Learning Applications in Control at ASDEX Upgrade

J. Illerhaus[1,2], W. Treutterer[1], A. Bock[1], R. Fischer[1], P. Heinrich[1,2], O. Kudláček[1], G. Papp[1], T. Peherstorfer[3], B. Sieglin[1], U. v. Toussaint[1,4], H. Zohm[1,5], F. Jenko[1,2] and the ASDEX Upgrade Team[6]

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A robust plasma control system is a prerequisite for the safe and precise operation of tokamaks, such as ASDEX Upgrade (AUG). The control task has very specialized requirements, making it quite challenging in practice. Control decisions need to be made at latencies on the order of milliseconds based on the limited amount of sometimes unreliable information available during discharges.

Machine Learning (ML) models are well-suited for many of the tasks of plasma control. Even though training models can be computationally expensive, the inference process is typically cheap. This allows even comparatively complex ML models to make predictions at low latencies. Additionally, particularly deep learning models have routinely been state of the art in tasks requiring the extraction of highly complex connections hidden in noisy data, such as autonomous driving.

This contribution will focus on two ML applications in control: the use of computer vision deep learning models to automate steps in the analysis of videos of the shattered pellet injection disruption mitigation system, and real-time capable reconstructions of high-fidelity kinetic profiles using deep learning models.

A highly flexible shattered pellet injection (SPI) system has been installed at AUG in order to support the design of the ITER disruption mitigation system. Here, pellets of a mixture of Ne and D_2 are shattered against different shatter head geometries during injection into the plasma. The goal is to produce fragment distributions that minimize the mechanical and thermal loads on the vessel by radiating off confined energy isotropically, maximizing the area over which the energy is dissipated. Computer vision deep learning is used to label the pellet shards on frames of the shattering videos and track the shards moving through video frames in order to compare the shattering patterns to theoretical predictions.

The ML-based real time reconstruction of kinetic profiles generates approximations of the high-fidelity Integrated Data Analysis profiles (IDA, see invited talk by R. Fischer), but reconstruction is executed in real time (~20 µs inference time) by deep learning models based on only the diagnostic data available. The deep learning models have so far proven to be capable of accurate and robust reconstruction of the profiles, based on the limited and sometimes unreliable and corrupted information available to them. These models will increase both the amount and quality of data available to the Discharge Control System (DCS) during discharges, improving the quality of control and thereby enhancing the reproducibility of discharges and the capabilities of the plasma control system.

SS7

Machine Learning for Gamma Spectroscopy as a Plasma Diagnostic Tool in Nuclear Fusion

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Fusion diagnostics are critical on the path to commercial fusion reactors, since the ability to understand and measure plasma features is important to sustaining fusion reactions. Gamma spectroscopy is a technique that can be used to aid fusion diagnostics, to provide information in neutron activation analysis to calculate fusion power. The detection limits for measuring nuclear dosimetry reactions used in such diagnostics are fundamentally related to Compton scattering events making up a background continuum. This background reduces the likelihood of detecting peaks from low-energy gamma rays, leading to higher detection and characterisation limitations.

We present the groundwork for a digital Compton suppression algorithm that uses state-of-the-art machine learning techniques to perform Pulse Shape Discrimination. The algorithm identifies key pulse features to differentiate which are generated from photopeaks and Compton scatter events. Compton events are then rejected, reducing the low energy background.

This novel suppression algorithm improves gamma spectroscopy results by lowering detection limits and reducing measurement times. This will have positive implications on any area that uses gamma spectroscopy, including fusion diagnostic methods. It also has the potential to be detector agnostic, which will increase its applications.

Acknowledgements:

This work has been part-funded by the EPSRC Energy Programme [grant number EP/W006839/1]. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ukaea.uk

SS8

Symmetrized Dot Pattern as an alternative method to visualize Hall Effect Thruster current waveforms

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Symmetrized Dot Pattern (SDP) is a method proposed by Pickover in 1990 [1], which allows visualizing a time series in order to emphasize its characteristics. SDP displays changes in the amplitude and frequency of a signal in an easy-to-understand visual representation that maps a normalized time waveform into symmetrical patterns on a polar plot. According to this, it is possible to examine the present and future states of the examined process and, among others, it can be used to study periodic, stochastic or chaotic behavior of the system.

The results of applying SDP method will be shown on the example of the measurement data from the krypton Hall Effect Thruster (HET), which was developed in the Institute of Plasma Physics and Laser Microfusion in Warsaw [2]. Due to the occurrence of non-linear processes, the behavior of the plasma in such thruster is turbulent and fluctuating [3], therefore the evolution of the dynamics of the collected ion current and discharge current signals as a function of the discharge voltage will be presented and visualized with SDP. For the analysis, ion signals were taken with a home-made Faraday probe adjusted at a distance of half a meter from the front of the thruster. At the same time, the discharge current was recorded with a Tektronix TCP 0030 current probe.

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SS9

Platforms of Control and Data Analysis for Particle Accelerators

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International Fusion Materials Irradiation Facility - Demo Oriented NEutron Source (IFMIF-DONES) is a research infrastructure being built in Escúzar, Granada (Spain) to test, validate and qualify materials to be used in future fusion power plants as DEMO (a prototype of fusion reactor with demonstration purpose).

The main objective of this research is the proposal of an architecture and a platform for the control systems and data analysis for the IFMIF-DONES plant, with focus (but not exclusive) on the particle accelerator. Specifically, this activity covers:

- The study of the LIPAc accelerator (Rokkasho, Japan) [1] as a precursor to IFMIF-DONES. This will allow learning from the problems encountered and reusing all the relevant elements developed. It will imply the deployment of a Mirror Room in Granada, that will emulate the real control room existing in LIPAc, connecting also to the data.
- The design of a new reference architecture for IFMIF-DONES control systems. It will emphasize the high availability and criticality of the processes, considering the latest industrial and computer technologies. It will contemplate the integration of simulation models of devices (digital twins), remote handling systems (robotics), Virtual Reality, data mining, AI, etc. And it will propose the use of standards such as OPC-UA or HTML5.
- The definition of interfaces of the central control systems for their integration and communication with all plant systems.
- The structuring and modeling of the information generated by the control systems, and the integration with tools for data analysis, paying special attention to artificial intelligence techniques. The objectives are, among others, the automated finding of relationships, the optimization of operations, the detection of problems and predictive maintenance and so on.

Acknowledgements:
- Project: "Amiga 8: Study with SKA Precursors of Galaxy Evolution in Extreme Environments"
- Project: "DAIS - Distributed Artificial Intelligent Systems"
- Project: "WPENS (I) and (II): Early Neutron Source Definition and Design. Contribution: Design of Control Systems, Timing System and Remote Handling"
- Project: "Actions for the implementation of IFMIF-DONES (International Fusion Materials Irradiation facility - DEMO Oriented NEutron Source) at Escúzar, Granada"

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SS10

Role of full-detector simulations in design of GEM-based diagnostics for DEMO

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This contribution provides an overview of computational activities relating to design of planned DEMO diagnostics for real time radiated power monitoring and soft X-ray (SXR) spectroscopy. High radiation environment in DEMO introduces a new set of challenges in detector design. For this, micropattern proportional counters based on Thick Gas Electron Multiplier foils (THGEMs) in lateral configuration are proposed.

To meet design requirements, extensive simulations are needed to assess the system's operation. Simulations will test impact of high energy gammas and neutrons, influence of non-uniform magnetic fields and fluorescence from various parts on the operation of the detector and provide feedback on the geometry of various elements in the design and choice of materials and active gas mixture.

This work describes technical details of the full-detector simulator implementation, initially developed and parallelly used for WEST SXR system simulations, here adapted for DEMO. Interaction of high energy X-rays with standard perpendicular configuration will be compared against planned lateral geometry. Finally, preliminary results regarding the influence of magnetic field on the detector's operation will be presented.

Acknowledgements:

This scientific paper has been published as part of the international project co-financed by the Polish Ministry of Science and Higher Education within the programme called 'PMW' for 2023.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

SS11

Determination of plasma ion temperature in high-rotation discharges of JET by X-ray spectroscopy

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One of the most important parameters describing the tokamak plasma are the ion temperature and the electron temperature, so it is important to be able to accurately determine their absolute values. In the case of plasma from the JET tokamak, X-ray spectra measurements of helium-like nickel Ni^{26+} ions and their dielectronic satellites are very useful in determination of such plasma parameters. Due to the possible overlapping of the satellite lines from the Ni^{25+} ion with the main resonance line of the Ni^{26+} ion, detailed analyzes of the recorded X-ray structure are necessary. An additional complication may be cases when the plasma rotation reaches high values. This may result in additional broadening of the resonance line registered by high-resolution x-ray diagnostic. In our previous paper [1] we analyzed the influence of both the satellites and the toroidal plasma rotation, in particular for plasma discharges characterized by inhomogeneous rotation (so called rotation shear). In addition to the analysis of data obtained from the upgraded KX1 diagnostics [2-4] from the JET tokamak, the collisional-radiative modeling of spectral lines was also performed using the FAC software [5], which allowed to estimate the degree of overlap of the specific x-ray lines. Further analyzes will concern studies of the effect of change in the rotation profile over time during the JET discharge and its impact on the broadening of the resonance line of the Ni^{26+} ion.

Acknowledgements:

This scientific work was published within the framework of the international project called "PMW", co-financed by the Polish Ministry of Science and Higher Education in 2021 under the contract No. 5182/H2020/EURATOM/2021/2.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No.101052200—EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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Student Session II

Thursday, 22nd June 2023

SS12

Tomotok Tomography on the JET Tokamak

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This contribution focuses on the computer tomography on the JET tokamak, specifically the reconstruction of data from soft X-ray cameras, bolometry and neutron profile monitor. To find the optimal parameters and estimate systematic errors, an analysis is performed on phantom data. A demonstration of tomographic reconstructions from JET tokamak data will be given.

Using tomography it is possible to reconstruct the 2D plasma emissivity distribution from the plasma projections. Unfortunately, the use of computer tomography on tokamaks has several obstacles. One of them is the limited number of lines of sight and viewing directions due to the lack of access to the tokamak chamber. For this reason, computer tomography is an underdetermined problem that needs to be regularized. The chosen method is Minimum Fisher regularization (MFR), which combines Tikhonov regularization with the minimization of Fisher Information. The tomographic reconstructions are obtained using the open-source Python package Tomotok. [1]

The above-mentioned method can smooth the reconstruction along the magnetic flux surfaces using the regularization matrix. It is created using numerical differentiation matrices in parallel or perpendicular directions with respect to the magnetic flux surfaces and anisotropy factor. It can be adjusted to achieve higher smoothness along the parallel direction. The optimal value of this factor is determined by analysis of phantom data and varies for each diagnostic system. It turns out that in the case of complete loss of vertical soft X-ray cameras, with the choice of a high value of anisotropy factor, the tomographic inversion can be solved. [2]

Another difficulty is the relatively high level of noise in the measured signals or even the malfunction of some of the detector channels. For this reason, it is crucial to understand the influence of individual channels on the final reconstruction. Some channels play a more significant role than others due to the different viewing angles. Again, analysis is performed on the phantom data by comparing reconstructions obtained using all channels and omitting selected ones. The effect on the total radiated power and relative deviation is investigated.

Tomographic reconstructions from soft X-ray cameras, bolometers and neutron profile monitor are obtained from the JET tokamak data. A method for comparing individual reconstructions using Singular value decomposition (SVD) will be introduced. The time evolution of the emissivity profile can be decomposed into spatial and temporal singular vectors, known as topos and chronos. Using this method, for example in the soft X-ray range, the transport of impurities can be detected and quantified.

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SS13

Enabling Instance Segmentation: A Method for Automating Annotation of Wendelstein 7-X Infrared Images

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Tokamaks and stellarators are devices to produce controlled magnetic confinement fusion. In these devices, imaging systems observe plasma-facing components, where an intelligent understanding of acquired images is essential for advanced machine protection and control. For instance, to discriminate between true overloads and non-damaging thermal events that affect the monitored surface temperature in infrared images, such as reflections, leading edges or surface layers.

Deep learning has proven to deliver state-of-the-art performance in computer vision tasks such as instance segmentation, which detects, delineates and classifies object instances. However, it requires a large amount of annotated data. Manual instance annotation of infrared images is a time-consuming process prone to producing inconsistent annotations, especially in high-framerate sequences. Therefore, a semi-automatic approach for infrared image annotation for thermonuclear fusion devices is mandatory to accelerate the annotation process and impose consistency while integrating expert knowledge.

The proposed approach incorporates image processing techniques to resolve annotations by analysing characteristics of thermal events and the fact that discharge images are traversable forward and backwards, i.e., considering temporal discharge evolution. Firstly, a representative reference image is computed from a discharge sequence. Then, all thermal event instances are segmented in the reference image, and the expert just assigns corresponding classes to the segmented instances. At last, annotations are automatically resolved in all actual discharge images. Five thermal events observed in the Wendelstein 7-X (W7-X) stellarator are supported, i.e., strike-line, reflection, hot-spot, leading edge and UFO.

The quality of semi-automatic annotations is evaluated by comparing their similarity to manual annotations. The proposed method reduces annotation efforts and improves annotation consistency. Furthermore, it is a flexible approach adaptable to new requirements, e.g., modifying thermal event ontology without requiring manual re-labelling of the dataset. A dataset generated with this approach adheres to a Microsoft Common Objects in Context (COCO) format and is suitable for deep learning instance segmentation tasks.

Last but not least, the initial results of training an instance segmentation model – Mask Region-based Convolutional Neural Networks (R-CNN) on a dataset of generated annotations are presented, as well as the initial results when the proposed method and the trained model are applied to the W Environment in Steady-state Tokamak (WEST) data. Future efforts will be devoted to generating a large dataset with the proposed method to train and evaluate resulting instance segmentation.

SS14

SLUKE – a Set of Numerical Tools for Modelling of Fast Electron Dynamics

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In the framework of this work, the possibility of fast electron modelling with the SLUKE environment will be described based on simulation examples for the case of the WEST tokamak. The whole framework consists of five codes ALOHA/METIS/C3PO/LUKE/R5-X2. These numerical tools allow us to model the dynamics of fast electrons in tokamak plasmas as well as the associated emission of non-thermal bremsstrahlung [1, 2]. In the last years, several upgrades have been developed. In particular, four important aspects will be emphasized. Firstly, the code allows for modification of the used power spectrum with the so-called tail model allowing us to deal with the spectral gap problem extensively described in the literature. Secondly, to obtain even more precise results, the use of a more detailed power spectrum with ALOHA has been fully implemented into the suite of codes in comparison to the simplified one provided by METIS. The third important aspect that will be described is crucial for the correct modelling of fast electron dynamics in the case of modern tokamaks like ITER or WEST that will be containing heavy impurities in the plasma like tungsten. To deal with this problem, a theoretical description of the so-called partial screening effect has been developed and implemented into the suite of codes, making it the only currently existing environment able to obtain precise results for non-thermal emission of bremsstrahlung from fast electrons in a tokamak plasma. As the last aspect, the upgrade of code from LUKE to its statistical version SLUKE will be described, allowing to perform statistical simulations for many different discharges, times and tokamaks.

Acknowledgements:
This work has been partially funded by the National Science Centre, Poland (NCN) grant HARMONIA 10 no. 2018/30/M/ST2/00799. We gratefully acknowledge Poland's high-performance computing infrastructure PLGrid (HPC Centers: ACK Cyfronet AGH) for providing computer facilities and support within computational grant no. PLG/2022/015994. This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. This work has been published in the framework of the international project co-financed by the Polish Ministry of Education and Science, as program "PMW", contracts 5235/HEU - EURATOM/2022/2 and 5253/HEU-EURATOM/2022/2.

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SS15

Control-Oriented Modeling of ITER's Electron Cyclotron Heating and its interface with the Plasma Control System

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Nuclear fusion power is one of the most promising energy sources for the future, and ITER is going to play a prominent role in demonstrating this technology. For a plasma to reach fusion conditions, it must be heated and controlled. One of ITER's main heating systems is the Electron Cyclotron Resonance Heating (ECH), which supplies 170 GHz radio-frequency power generated by 24 1MW gyrotrons to the plasma. The ITER ECH system will provide both Bulk Heating and Current Drive from an Equatorial Launcher (EL) and advanced profile control for current profile tailoring and the mitigation of MHD instabilities (sawtooth, NTMs) from 4 Upper Launchers (UL).

In most tokamaks, the Plasma Control System (PCS) has direct control over its gyrotrons. However, in ITER, the gyrotrons are managed by a local control (EC Control System, ECCS). The modelling of the interface between these two systems is key for PFPO-1 PCS controller design and assessment. In this work, we will present the results of the preliminary modelling of this interface, which is delineated in the following conceptual terms.

Each of the 24 gyrotrons can be allocated through 24 + 8 switches to 1 of the 3 Equatorial Mirrors and between up to 2 Upper Mirrors for each Upper Launchers. This configuration leads to 56 launching points, defined as the power and k vector for each beam position on the mirror.

The PCS will need real-time information on the status of every launching point to trace the power deposition inside the plasma. Then, using real-time measurements from multiple plasma diagnostics, the PCS may request a change in mirror angle (one for all the launching points on the same mirror) and/or power, presumably from the EL to the UL to provide MHD instability control. The ECCS will accordingly move the switches.

However, several challenges persist for the PCS-ECCS interface. Firstly, moving switches takes up to 3 seconds during which no power from the moving beam can be delivered to the plasma. To guarantee power is always available, some gyrotrons could be kept inactive and the switches in a fixed position, effectively pre-allocating their power. However, for advanced ITER operation, such power allocation may not be possible given the high auxiliary heating power that is required. In that case the PCS will have to predict when power is necessary on a finite horizon, considering the 3s delay. Furthermore, the gyrotrons are powered in pairs by a single power supply unit, which means that the power requested to each pair must match.

Due to those issues, and the immoderate number of gyrotron – launcher couplings, an efficient optimization strategy must be implemented, for which machine learning could applied.

Acknowledgements:
The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

SS16

Tomographic Reconstruction of Radiation Distribution with Impurity Injection in the GOLEM Tokamak Plasma Using Fast Visible Cameras

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Impurities play a considerable role in plasma radiation distribution and material migration in the fusion reactor plasma. Therefore, plasma radiation provides valuable information on the impurity transport in fusion plasmas [1]. Tomography inversion is a method to determine the radiation distribution function by using line integrated plasma projections data [2]. Various diagnostic systems such as fast visible radiation matrix cameras are applied to capture the projection data in high temperature plasma studies.

The present work focuses on tomographic reconstruction of the plasma radiation distribution in presence of impurity injection in the GOLEM tokamak of the Czech Technical University in Prague using the Tomotok package [3]. For this purpose, the radiation caught by two crossed monochrome visible cameras (radial and vertical) with a frame rate of 40,000 fps (1280 × 56 pixels) is used for reconstruction. In addition, the radiation of injected impurities is shown by the plasma spectroscopy measurements.

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SS17

PMT Pulse Processing for Future Tokamaks Hard X-Ray Diagnostics

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Hard X-Ray (HXR) spectrometry is well established diagnostic technique for the detection of runaway electrons and it is applied in several tokamaks[1-3]. In the future tokamaks such as ITER or DEMO, the diagnostic instruments will have to withstand even higher temperatures, magnetic fields, and radiation levels. In the case of ITER, the photomultiplier tube (PMT) is decoupled from the scintillator and located in a port cell about 12 m away from the scintillator. Pulses from the scintillator are transmitted to the PMT via optical fibre bundles. Light transmission efficiency is estimated to be as low as 0.05 – 0.10%[4].

High attenuation of the optical path causes the majority of photons to be lost during transmission. As a result, PMT generates short pulses corresponding to the single photons reaching the photocathode. Such a signal is quite different from the b-exponentially decaying PMT pulses[5]. A new approach for pulse processing is required to discriminate the energy properly. The development of digitizers in the past years made it possible to digitize fast analogue pulses with gigabit sampling rates and process them in real-time. It is now possible to use Digital Pulse Processing (DPP) to implement complex algorithms that could be used for data processing in future plasma spectroscopy systems.

The second problem is that the signal from PMT has to be transmitted to the digitizer via a more than 100 m long cable over the RF-noisy environment of the tokamak. Low-noise amplification and proper grounding of the coaxial cables are required to minimize signal degradation and protect the signal from electromagnetic interference.

Challenges faced during the design of the ITER's Hard X-Ray Monitor (HXRM) and results of the HXRM system prototype test trials will be presented and discussed.

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SS18

Estimation of tungsten impurity concentration at WEST with integrated data analysis

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Accumulation of heavy impurities in the plasma poses a major risk to the performance of fusion devices. Therefore, accurate estimation of impurity concentrations is highly desirable, and plasma emission serves as a valuable diagnostic tool for this purpose. However, the various sources of uncertainty affecting the required measurements from multiple diagnostics greatly complicate the reconstruction of the desired concentrations. To overcome these challenges, we employ integrated data analysis (IDA) using Bayesian probability theory. This approach allows us to jointly estimate impurity concentrations and kinetic profiles at WEST by incorporating measurements from soft X-ray (SXR) emission, interferometry and electron cyclotron emission (ECE). IDA helps to avoid the accumulation of errors commonly seen in sequential analysis of diagnostic measurements and allows exploiting diagnostic interdependencies [1]. At WEST, two 1D cameras are planned for observing the SXR emissivity with a horizontal and vertical view [2]. To reconstruct the 2D SXR emissivity profile in real time, we apply Gaussian process tomography and validate the technique using synthetic data generated for both cameras [3]. Currently, an additional challenge is posed by the availability of SXR data from only a single camera with 45 horizontally viewing lines-of-sight. To address this, we adopt a nonstationary Gaussian process with a flux-dependent length scale. We also investigate techniques for accelerating the inference process towards real-time applications. We demonstrate fast reconstruction results of density profiles obtained by a neural network surrogate model trained on synthetic interferometry data corresponding to realistic profiles. Ultimately, this approach will be extended to the joint estimation of impurity concentration profiles, as well as density and temperature profiles.

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SS19

High Resolution Neutron Spectrometer for ITER facility – engineering challenges

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The High Resolution Neutron Spectrometer (HRNS) plays an essential role in machine protection and control for fusion plasma operation in ITER (International Thermonuclear Experimental Reactor) [1]. This crucial neutron diagnostic system will collect data on the neutron emission from the plasma and derive a certain number of plasma parameters.

The HRNS system consists of four independent spectrometric sub-systems: Time of Flight (ToF), Back - Time of Flight (bToF), Thin Foil Proton Recoil (TPR), and Neutron Diamond Detector (NDD) system. ITER Organization collaborates with scientists from across Europe, including a team from the Institute of Nuclear Physics PAN to deliver a fully functional HRNS system for the Fusion Power Operation Phase.

The goal of this contribution is to highlight certain aspects that need to be taken into account from the engineering point of view:

- The radiation shielding - An extremely important element directly impacting the HRNS system performance.
- TPR vacuum system – TPR operates on the principle of recoil protons generated from the fast neutron–hydrogenous material interactions. Proton energy attenuation is an unwanted effect.
- Electronic and cable routing – HRNS as a spectrometric system requires a robust system for data transmission over long distances without loss of signal quality.

The HRNS system has to be able to withstand thermal, structural, EM, and neutron loads. An additional challenge is to provide all necessary interfaces.

The use of advanced engineering tools allows for the rapid 3D design of the HRNS structure. In addition, the design process is aided by an engineering software package for simulating the effects of loads on the HRNS structure. Neutron (MCNP), electromagnetic (EM), and thermo-structural calculations are planned.

Currently, the HRNS project is in the preliminary design phase.

Acknowledgments:
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SS20

Universal Data Acquisition Software for MicroTCA.4 Imaging Systems for Plasma Diagnostics

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The Image Acquisition Systems (IASs) in fusion applications are designed to acquire images from vision and infrared cameras. In the case of plasma diagnostics, IAS can be used in real-time for plasma control and machine protection. Due to that IAS requires a high-data throughput to data processing unit (CPU, GPU or FPGA device) and to the data archiving as well as a real-time, low-latency connection.

MicroTCA.4 architecture was chosen to fulfill the requirements for IAS, because of its high-level reliability, availability, and maintainability. The universal data acquisition software was developed for MicroTCA.4 based systems. The software provides a basic functionality of IAS i.e. acquiring and archiving images from multiple cameras. Furthermore, the framework was designed to assure low latency, maximize the data throughput and precise synchronization using timing module. This approach allows for real-time system operation.

The software was designed to work with multiple cameras with different hardware interfaces. The presented software was tested on two cameras: Mikrotron EoSens 3CL MC3011 with Camera Link interface and Dalsa Genie TS-C2500 with 1GigE Vision interface. For precise synchronization and triggering of all the cameras in the system over MicroTCA.4 backplane the PTM-1588 timing module was used. Data Archiving Network (DAN) was used to archive the acquired data. The presentation will show the initial results of performance measurements for the system acquiring images from cameras with Camera Link (CL) and 1 GigE Vision interfaces. Particularly for the CL camera the EPICS device support was developed. It consists of basic Human Machine Interface (HMI) panels and supporting libraries. Besides basic IAS functionality, it allows processing the images in runtime and publishing results using the Synchronous Databus Network (SDN).

The software with its all features can be used to further develop the final image diagnostics systems for ITER tokamak. It can be the starting point to collect a database of images with corresponding metadata that can be used in the development of image processing algorithms based on artificial intelligence and machine learning.

List of Participants

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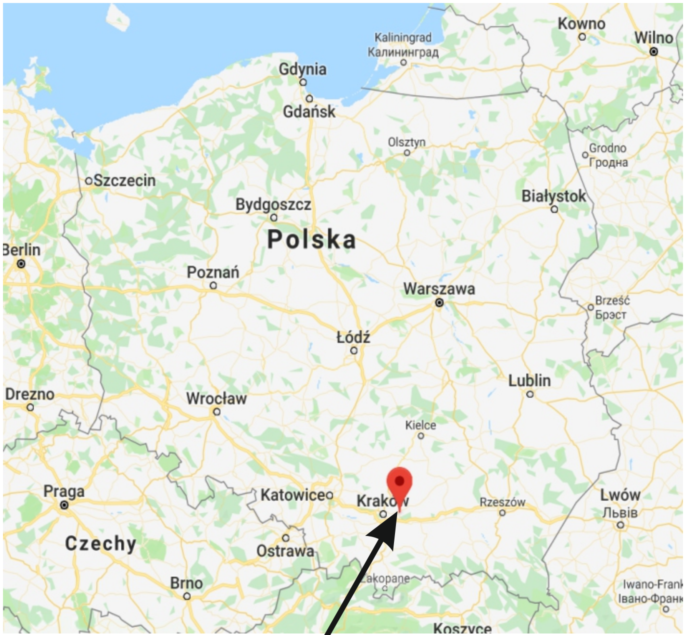
12. Michela Gelfusa, Rome University, Italy
13. Valentin Gerenton, ENSICAEN, Caen, France
14. Valentin Gorse, IRFM, CEA, France
15. Gabriele Grapow, La Sapienza University of Rome, Italy
16. Johannes Illerhaus, IPP, Garching, Germany
17. Bartłomiej Jabłonski, Lodz University of Technology, Poland
18. Michał Jagielski, IPPLM, Warsaw, Poland
19. Marcin Jakubowski, IPP Greifswald, Germany
20. Agnieszka Jardin, IPPLM, Warsaw, Poland
21. Axel Jardin, IFJ PAN Kraków, Poland
22. Krzysztof Król, IFJ PAN Kraków, Poland
23. Wojciech Królas, IFJ Pan, Kraków, Poland
24. Agnieszka Kulińska, IFJ PAN Kraków, Poland
25. Adam Kwaśnik, IPPLM Warsaw, Poland
26. Grzegorz Lak, s2innovation, Poland
27. Kimberley Lennon, UKAEA, Culham Science Centre, Abingdon, UK
28. Michele Lungaroni, University of Rome "Tor Vergata", Italy
29. Dariusz Makowski, Lodz University of Technology, Poland
30. Jiri Malinak, Czech Technical University, Prague, , Czech Republic
31. Giulia Marcer, Università degli Studi di Milano-Bicocca, Milan, Italy
32. Didier Mazon, IRFM CEA, France
33. Jan Mlynar, IPP Prague, Czech Republic
34. Dariusz Morawski, IFJ PAN Kraków, Poland
35. Patryk Nowak vel Nowakowski, Łódź University, Poland
36. Piotr Perek, Lodz University of Technology, Poland
37. Piotr Pietrzak, Lodz University of Technology, Poland
38. Simon Pinches, ITER Organization, France
39. Cristina Rea, MIT, Cambridge, MA USA
40. Jean-Luc Schneider, French Embassy
41. Marek Scholz, IFJ PAN, Kraków, Poland
42. Marta Ternero Gutierrez, University of Granada, Spain
43. Claudio Torregrosa, University of Granada, Spain

44. Maciej Turzański, IFJ PAN, Kraków, Poland
45. Geert Verdoolaege, Ghent University, Belgium
46. Cong Wang, Zhejiang Lab, China
47. Zhijun Wang, Zhejiang Lab, China
48. Urszula Wiącek, IFJ PAN, Kraków, Poland
49. Urszula Woźnicka, IFJ PAN, Kraków, Poland
50. Hao Wu, Ghent University, Belgium



The Royal Castle in Niepołomice

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Poland

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GPS coordinates:
500 2' 3.507" N
200 13' 2.918" E

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Source: https://www.google.pl/maps

PhDiaFusion Summer School 2023 AGENDA

8:00	Arrival	Breakfast	Breakfast	Breakfast	Breakfast
9:00		Lecture 1 – S. Pinches Integrated Plasma Modelling and the Role of Plasma Diagnostics on ITER	Lecture 5 – C. Torregrosa Diagnostics Techniques in the IFMIF-DONES Facility: Monitoring an Accelerator, a MW Target and Irradiation Modules, all at once	Lecture 8 – R. Fischer Integrated Data Analysis: Concept and Applications in Nuclear Fusion	Lecture 13 – G. Verdoolaege Bayesian probability for integrated data analysis and pattern recognition in fusion plasmas
9:45		Lecture 2 – M. De Baar Real time plasma control and the use of AI for the Real Time analysis of complex data	Lecture 6 – M. Cappelli Design of a Central Instrumentation and Control System: the case of the IFMIF-DONES Plant	Lecture 9 – J. Mlynar Tomography of experiments aimed at Runaway electron studies on a small tokamak GOLEM	Lecture 14 – M. Gelfusa Artificial intelligence techniques for disruption prediction in tokamaks
10:30		Coffee break	Coffee break	Coffee break	Coffee break
11:00		Lecture 3 – Z. Wang Introduction to AI technology of Zhejiang Laboratory	Lecture 7 – M. Jakubowski Controlling divertor power loads at Wendelstein 7-X	Lecture 10 – J. Diaz IFMIF-DONES: AI for design, control and operations	Round Table Discussion + Closing of the School
11:45					
12:00	Lunch	Lunch	Lunch	Lunch	Lunch
13:30	Registration	Lecture 4 – C. Rea A review of explainable ML accelerating Fusion science	SOCIAL EVENT	Lecture 11 – D. Makowski Real-time Data Acquisition and Processing for Plasma Diagnostics and Machine Control	Departure
14:15		Students presentations 1. Jeffrey De Rycke 2. Giulia Marcer 3. Gabriel Amorosetti 4. Valentin Gorse 5. Adam Kwaśnik		Lecture 12 – C. Wang AI-based integrated data analysis for tokamak diagnostics	
15:00				Students presentations 12. Jiri Malinak 13. Bartłomiej Jabłonski 14. Krzysztof Król	
15:30		Coffee break		Coffee break	
16:00	Opening of the School: Welcoming words – D. Bocian (IFJ PAN) School opening – D. Mazon (CEA) Introductory lecture – J.L. Schneider (FR Embassy)	Students presentations 6. Johannes Illerhaus 7. Kimberley Lennon 8. Agnieszka Jardin 9. Javier Cruz Miranda 10. Michał Jagielski 11. Andrzej Brosławski		Students presentations 15. Gabriele Grapow 16. Sara Abbasi 17. Patryk Nowak vel Nowakowski 18. Hao Wu 19. Dariusz Morawski 20. Piotr Pietrzak	
17:00	Welcome reception				
17:30					
19:00	Dinner	Dinner		Conference dinner	