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Experience on the interferometry and polarimetry for fusion power plants

7th International Conference Frontiers in Diagnostic Technologies (ICFDT7)

ENEA Frascati, 22nd Oct 2024

Outline

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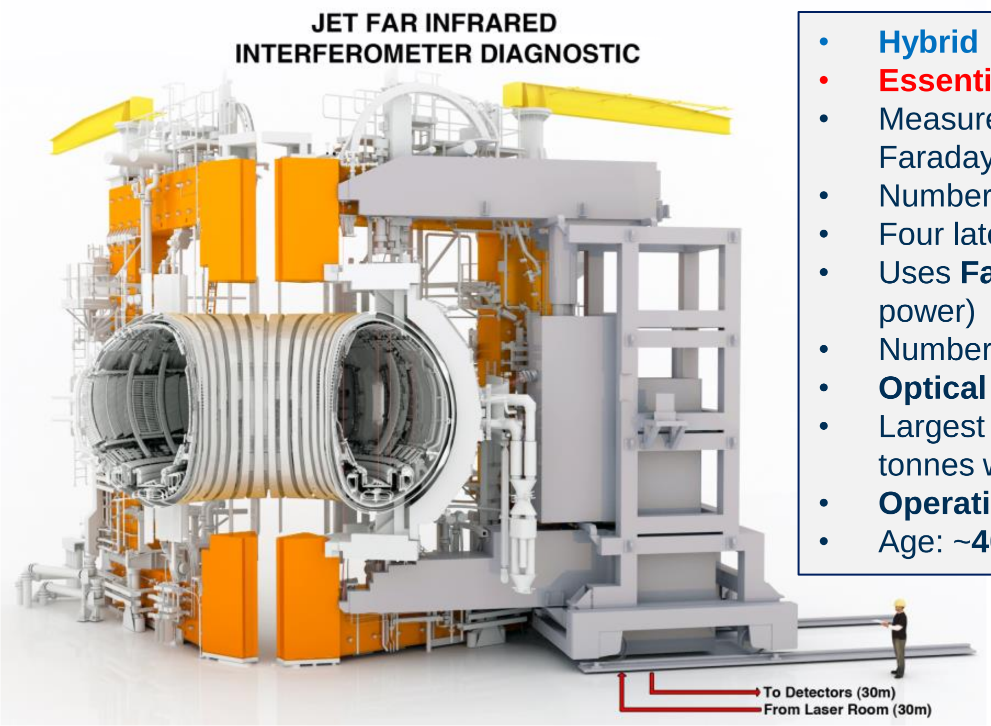
- Few words on JET Far Infrared Diagnostic(FIR)
- Strategy on diagnostics development approach
- How to …. ?
- Examples
- Conclusions

Intro - JET Far InfraRed Interferometer/Polarimeter Diagnostic System

Why Far Infrared (THz) ?
Plasma frequencies (GHz) => plasma is a transparent medium for FIR



- **Hybrid interferometer and polarimeter**
- **Essential for JET Plasma Operation**
- Measures **electron plasma density** and magnetic fields via Faraday Rotation angle
- Number of channels 10 (8 probing the plasma)
- Four lateral channels have double passage due to in-vessel mirrors
- Uses **Far Infrared Lasers(FIR)** (wavelength 100 microns 200mW power)
- Number of optical components ~ 500 over **3 buildings**
- **Optical path length 80 meters** x16 branches
- Largest single component: Diagnostic tower (14 metres high, 70 tonnes weight)
- **Operation time: 16 hr/day**, mostly unattended
- Age: ~**40 years old**

Note 1: Interferometry is based on plasma optical refractive index
Note 2: Polarimetry is based on plasma optical activity and birefringence

JET Far Infrared Diagnostic Status before Deuterium-Tritium Experiment Campaigns no. 2 and no. 3(DTE2 & DTE3)

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1) **Triple redundancy** for laser availability
2) **Triple redundancy** on measurements for density control
3) **Double redundancy** in signal detection + hot spare

4) **Monitoring from remote** designed for non-expert
   (e.g. Shift Technicians, Diagnostic co-ordinators, Responsible Diagnostic Experts)
5) **Three Data Acquisition Systems** with 100% channel reliability
   in terms of signal quality (C40, PowerPC and FPGA architecture)
6) **Spare parts/Ancillary equipment** commissioned/checked and ready to use/swap

How to design power-plant diagnostics based on past experience?

Lesson learned

- Learn from the mistakes done in last 70 years
- Learn from the positives done in last 70 years
- Developments were multi-generational

Current development approach*

- Systems developed to **maximise physics output** and not reliability
- Prototype, one-off, **one measurement - one diagnostic**
- Long time for developing a system (**small team**) => "old design" when required

- "Comfortable" approach of **copying existing validated** systems
- Care for meeting the **minimum requirements only** => no built-in resilience
- Not an agile approach with **not much innovation** => risk of obsolescence

- No clear direction with respect **Human Resources** required for developing, commissioning, operating the system
- **Safety** considered mostly locally within the system or close area
- **Quality control** and tracking to various levels not unitary with the entire plan

** The list is not exhaustive*

Current machine versus Fusion power plants*

- Plasma duration from seconds to non-stop
- Neutron fluences higher order of magnitudes (up to 7 !)
- No human access to most of the parts of the machine for decades

** The list is not exhaustive*

Fusion power plants approach

From day one of development…..

- **Fully engineering approach**
- **Integrated** with other plants and machine design
- Strong **Safety Systems**

- Diagnostics are for **control** and **monitoring** **–** *Physics is optional*
- Clear **parameters to control** and what measurements (sensors) are required
- Each measurement will have a **functional role** for machine control, monitoring and protection

Think how to keep it alive

Think how to keep it alive

Access considerations

	Diagnostic room		Interspace area		Torus(reactor) hall
MAST-U EAST ASDEX-U WEST	Full access Day operation	Bioshield	Full access when not in plasma operation Easy access for manual emergency	Bioshield	Regular access allowed Plasma Vacuum vessel –parts replaceable during shutdown
JET ITER SPARC?	Partial access Day operation Up to 8 hr shift Semi-automation	Bioshield	Full access during long shutdowns Easy access for people entry in an emergency	Bioshield	Partial access Plasma Vacuum vessel –parts replaceable during shutdown
STEP BEST DEMO ARC Nobody done it yet !	Partial access Non-stop operation Turn-key devices	Bioshield	Intermediate area Access every 5-15 years Very limited manual entry	Bioshield	Zero Manual access Plasma Vacuum vessel - No access Parts embedded in first wall

Dr. Alexandru Boboc "Experience on the interferometry and polarimetry for fusion power plants", ICFDT7, Frascati (2024)

Think how to keep it alive

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Tritium barrier

Tritium barrier

Diagnostic room

Diagnostic room

- FIR Lasers
- Ancillary Equipment
- Electronics
- HV Power supplies
- Cryogenics
- Pressure systems
- Hot surfaces
- Service areas
- Access

Bioshield

Interspace area

Basement

Opto-mechanics
Access
Dry air

Bioshield

Torus(reactor) hall

Torus Hall

In-vessel
- Mirrors (not replaceable)
- Vacuum-Windows (replaceable once every 10 years or so)

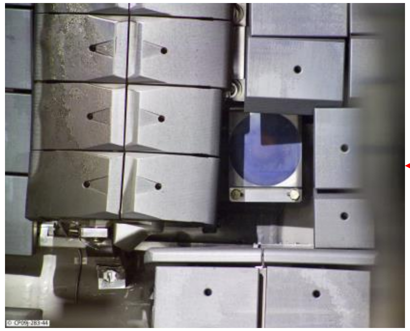
Ex-Vessel

- Diagnostic-Tower
- Access
- Opto-mechanics

Losing dry air requires 3 days for restoring signal power as basement duct account for 50m(80 in total) of the optical path (rate of air 5l/min for a 25mx4mx2m box)

A failed cryostat will take minimum one week to recommission

TPX 90μm thick pellicle windows acting as tritium barrier to the basement



Nickel in-vessel mirror hiding behind limiter 30 years later

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Think about signal losses and errors

Think about signal losses and errors

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Lasers

- ✓ Laser power and power stability ⇒ Better a low power but stable
- ✓ Laser pointing stability ⇒ Essential for 100m optical path
- ✓ Polarisation quality & settings ⇒ Unnecessary losses 100% avoidable

- ✓ Risk associated with operation/maintenance ⇒ High Voltage, heat, pressure, laser
  ⇒ Time required for recovery after fault
- ✓ Long term operation cost ⇒ Cost of spares, people time, number of people

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Think about signal losses and errors

Transmission(T) losses

JET FIR system

- ✓ Vacuum Window transmission ⇒ T of new double vac window: 75%, 56% after 30 years in visible, T for FIR 24% day one (4cm thick z-cut quartz)
- ✓ Tritium barrier losses ⇒ T 50%

No windows	Transmissions in %					
	TPX(90µm)		Mylar (50µm)		Kapton(50µm)	
Wavelength(µm)	*118.8*	*195*	*118.8*	*95*	*118.8*	*195*
1	92.50	89.00	60.00	87.00	64.00	90.00
6	**62.64**	**49.70**	**4.67**	**43.36**	6.87	53.14

- ✓ Waveguides ⇒ T 50%
- ✓ Environmental controls ⇒ T difficult to predict let's assume T 50% here
- ✓ In-vessel reflectors ⇒ Reflection 100% when new (Nickel mirrors) unknown now

Channel 5 (L1) 31-years old in-vessel mirror (Survey from 2024) ("Tokamakium" deposits)

Total transmission level(24%x50%x50%x50%) = > 3 %T in the ideal case scenario so 97% losses !!!

Think about signal losses and errors

Phase shift errors -very hard to model and eliminate

- ✓ Depolarisations due to the transmission lines
- ✓ Hot air turbulence (3 μm laser – first compensation laser on JET FIR)
- ✓ Moisture in air (all FIR lasers)
- ✓ Electronics signal distortion(capacitors dying after 10 years)
- ✓ Windows under high magnetic field – new thing in ITER and beyond
- ✓ Bad or degrading alignment

Think about signal losses and errors

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Calibration errors

- ✓ Wrong wavelength - DCN laser emits in 190 and 195micron leading with 2.5% error if wrongly selected
- ✓ Polarimetry Torus hall encoders(potentiometers) degradation leading to wrong conversion Voltage-Faraday Angle =>solved by regular offline calibration (remote)
- ✓ Polarimetry wrong half-wave plate position – Signal-to-noise issue
- ✓ Mutual interaction of Faraday Angle- Cotton Mouton effects (all papers use cold plasma approximation)
- ✓ 1-D Calibration (Faraday- linear polarisation) for 2-D real problem (Faraday and Cotton-Mouton – elliptical polarisation)

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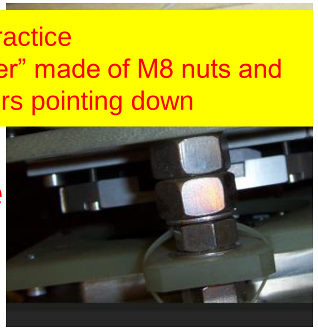
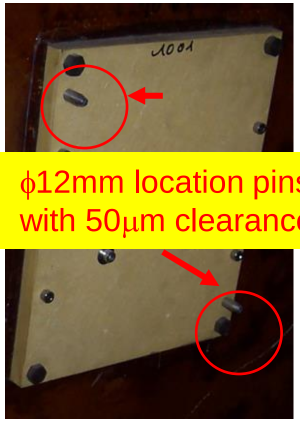
Think about signal losses and errors

Alignment

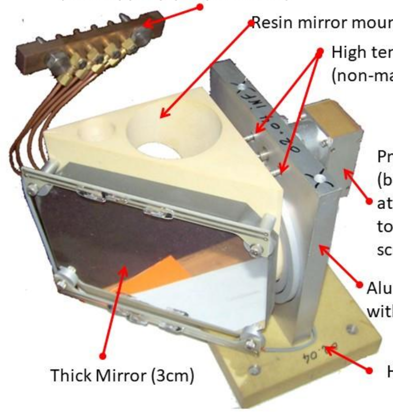
- ✓ All big systems require alignment, in power-plants environment that could be possible only partially every decade - E.g. JET FIR System
- ✓ Integrating alignment scheme at early design phase is crucial
- ✓ Integrate alignment requirement with rest of the plant (including shared space with other diagnostics for example)
- ✓ Choose the most resilient parts where there is no access
- ✓ Use good practices and good old examples
- ✓ Choose right components



Half-wave plate assembly



Opto-mechanics support plate



Torus Hall non-magnetic mirror assembly

Basement optics

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Think for what do you use the measurements

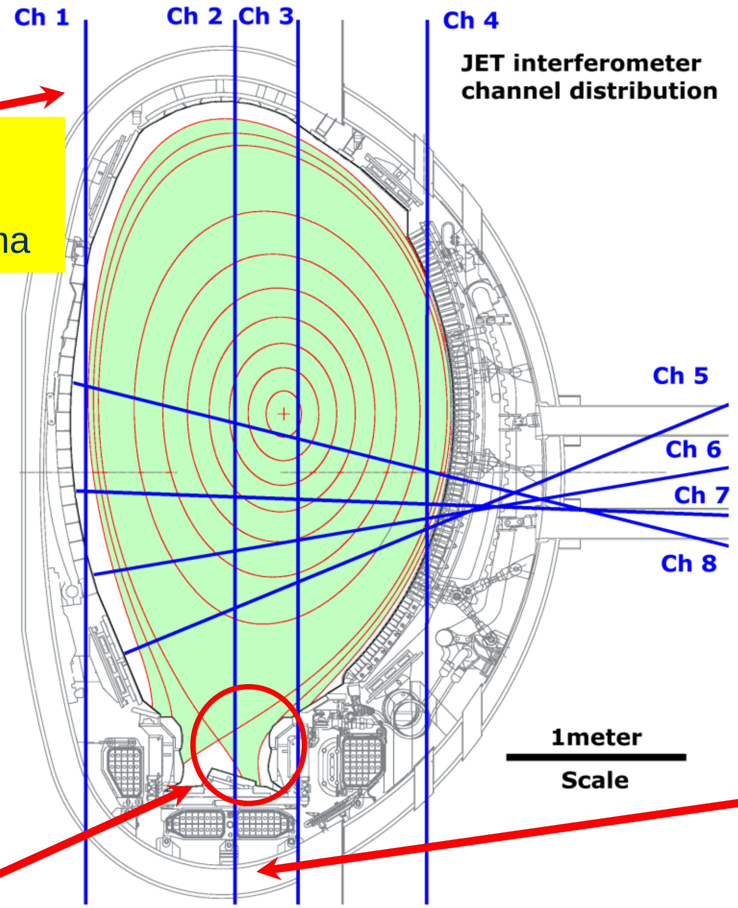
Interferometry

- ✓ Gas feedback and control of plasma density in real-time
- ✓ Additional heating-systems safety interlocks in real-time
- ✓ Reference diagnostic for many systems (E.g. High-Resolution Thomson Scattering)
- ✓ Physics analysis (80% of Physics Data depends on interferometry)

Polarimetry

- ✓ Safety Factor control, including real-time (via Equinox)
- ✓ Gas feedback and control of density (backup)
- ✓ Additional heating-systems safety interlocks(backup)
- ✓ Physics analysis (EFIT constrains)
- ✓ Secondary measurement for density validation

Think what changes to the machine impact to your measurements



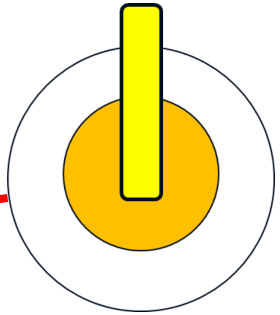
Ch1 tangent to plasma

Additional Line-integrated density component in the divertor not included in EFIT

Example- Divertor introduction impact to the FIR interferometer:

2 channels lost for any H-mode pulse with NBI on

Ch 2 slot in divertor plate 9mmx 44mm x 1 m

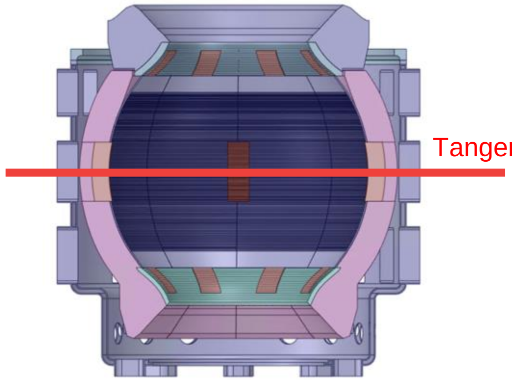


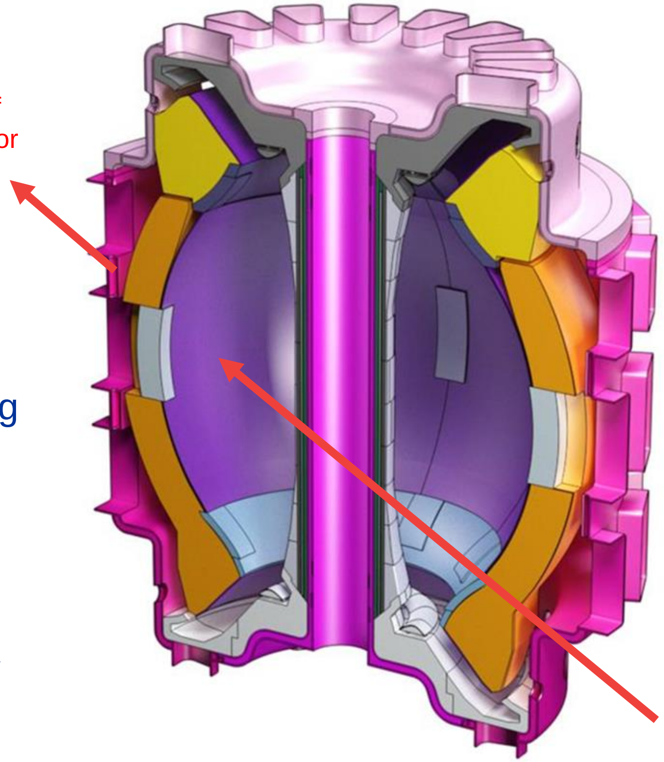
FIR Beam diameter 35mm

Vacuum window 60mm diameter

What is the function of your measurement ?

Example: STEP Interferometer Tangential Channel 4 *





Ch 4 FIR laser beam (RED colour) close to central column (~10cm)
Distance between centre of machine to input mirror ~10 meters

- ✓ Essential for plasma breakdown and ramp-up control for scenario of plasma forming close to inner limiter (very low density, high resolution required)
- ✓ First external adjustable reflector ~10 meters from plasma

Key problem
1cm of beam displacement due to refraction over 25m requires an angular precision of tracking of 0.001 degrees or 17 microradians

**Extract from STEP Interferometer/polarimeter preliminary study*

A word about RAMI

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RAMI (Reliability, Availability, Maintainability and Inspectability) is one of the most severe challenges of Fusion Technologies, and it is probably the engineering branch where the fusion community is the least competent.

Fusion people know/want this*

Measurement	Latency (max)	Parameter range	Time resolution	Specified accuracy
Line-averaged electron density (Initiation)	250µs	<1x10^{19} m^{-3}	1ms	100%
Line-averaged electron density (Ramp-up/down)	250µs	1x10^{19} m^{-3} - 3.5x10^{20} m^{-3}	1ms	10%
Line-averaged electron density (flat-top)	250µs	3.5x10^{19} m^{-3} - 4x10^{20} m^{-3}	1ms	2%

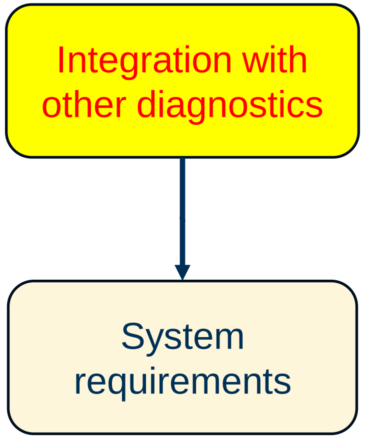
What is required is this*

Table 13 RBD results with mitigation actions for DT phase

	Initial results		Results with mitigation actions	
	Availability (20 years)	Failure rate per calendar year	Availability (20 years)	Failure rate per calendar year
Radial Chord	92,15%	1,32E-01	97,30%	1,08E-01
Tangential Chord	93,73%	1,20E-01	97,39%	1,17E-01
Common functions	99,98%	5,50E-03	99,98%	5,50E-03
55-FA DIP (Tangential and radial chord redundant)	**99,16%**	**2,46E-02**	**99,92%**	**1,19E-02**
55-FA DIP (No redundancy between Tangential and radial chord)	86,69%	2,41E-01	94,86%	2,25E-01

**Extract from ITER Dispersion Interferometer RAMI Analysis Report*

Think about measurement (not-diagnostic) redundancy



RAMI for measurement ?

Magnetic information

- ✓ Magnetic sensors/coils
- ✓ Polarimetry
- ✓ Fiber Optical Current Sensor (FOCS)
- ✓ Real-time profile controller (AI driven)

Electron Density

- ✓ Interferometry
- ✓ Polarimetry
- ✓ Microwave diagnostics
- ✓ Visible spectroscopy
- ✓ Realtime profile controller (AI driven)

Wall protection

- ✓ Visible and Infrared cameras
- ✓ Pyrometers
- ✓ Laser diffusion spectroscopy
- ✓ Thermocouples
- ✓ Real-time controller (Machine Learning)

How to survive ? - example #1

Scenario: Catastrophic failure of in-vessel internal magnetic sensors for vertical stability due to radiation damage of cables/coils

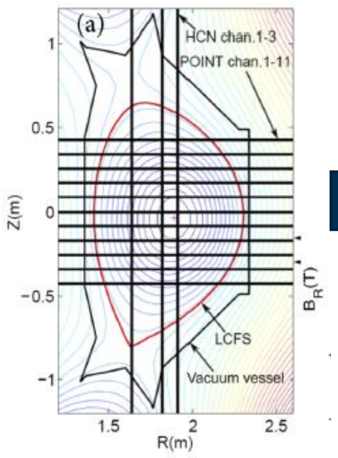
→ Polarimetry is one possible viable alternative

REVIEW OF SCIENTIFIC INSTRUMENTS 89, 10B103 (2018)

Non-inductive vertical position measurements by Faraday-effect polarimetry on EAST tokamak

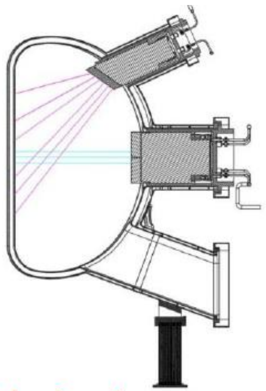
W. X. Ding,[1] H. Q. Liu,[2,a)] J. P. Qian,[2] D. L. Brower,[1] B. J. Xiao,[2] J. Chen,[1]
Z. Y. Zou,[2] Y. X. Jie,[2] Z. P. Luo,[2] X. Z. Gong,[2] L. Q. Hu,[2] and B. N. Wan[2]
[1]*Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA*
[2]*Institute of Plasma Physics, Chinese Academy of Science, Hefei 230031, China*

EAST



Works nicely !

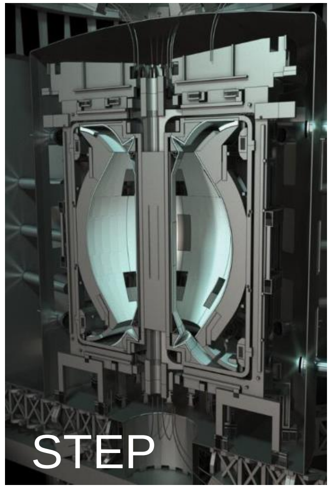
BEST



Polarimeter - Interferometer

Will probably work

(horizontal channels only)



Try again with no in-vessel reflectors and no toroidal symmetry of laser beams !

Conclusions

Suggestions for development for power plants -class diagnostics based on facts and experience

- ✓ Synthetic diagnostics accounts of substantial development time at first phase ➔ feasible solutions for control
- ✓ 1:1 prototyping for part of the system is a must ➔ risk mitigation
- ✓ Turn-key laser sources and detectors(for laser-based diagnostics) ➔ needs developments

- ✓ Zero access for most of parts of the machine ➔ No in-vessel optics (reflectors)/electromechanics
- ✓ 3D-symmetry of sensors(no poloidal symmetry) ➔ very hard physics reconstruction ➔ complicates real-time control
- ✓ Control mechanisms components must be far away from plasma ➔ μm accuracy beam tracking or cameras views via optical fibres

UKAEA supports new diagnostics developments and share lessons learned

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Plasma Physics and Controlled Fusion

Special Issue on the Physics and Engineering of Toroidal Fusion Plasma Operations

https://iopscience.iop.org/journal/0741-3335/page/Special%20Issue%20on%20the%20Physics%20and%20Engineering%20of%20Toroidal%20Fusion%20Plasma%20Operations

PAPER • OPEN ACCESS

JET far-infrared interferometer/polarimeter diagnostic system—40 years of lessons learned

A Boboc[1,3], J Macdonald[1], R Felton[1], M J Brown[1], W Studholme[1], S Cramp[1] and the JET Operations Team[2,1]

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Plasma Physics and Controlled Fusion, Volume 66, Number 8

Special Issue on the Physics and Engineering of Toroidal Fusion Plasma Operations

Citation A Boboc *et al* 2024 *Plasma Phys. Control. Fusion* **66** 085011

DOI 10.1088/1361-6587/ad5376

https://iopscience.iop.org/article/10.1088/1361-6587/ad5376

Plasma Science and Fusion Operations Division new initiative

<< DICE >>
Diagnostics Innovation Centre of Excellence

Operational since September 2024

- ✓ Neutronics and Gamma Lab
- ✓ Magnetics Lab
- ✓ Optics Lab with five optical workstations areas

Acknowledgments

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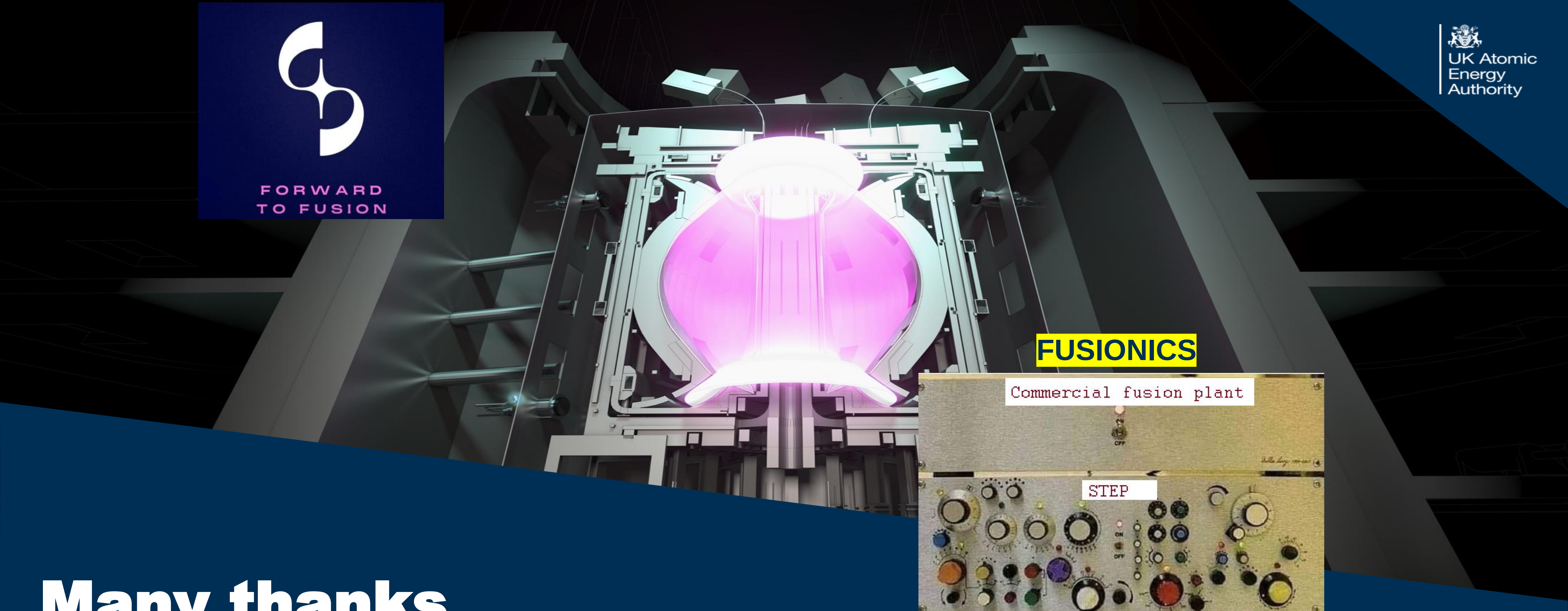
Many people have worked with the FIR team, and it has been a tremendous collaborative effort, so I would like to thank to entire JET Team over the years.

I would like to remember here my predecessors and their deputies: Didier Veron, George Magyar, Jan de Hass, Perry Beaumont, Klaus Guenter, Paulo Puglia and the technicians Geoff Braithwaite, Dave Peach, Paul Trimble.

Interferometer/polarimeter operations in the JET DTE3 campaign would not have been possible without my colleagues James Macdonald, Mark J Brown, the electrical engineers Will Studholme and Simon Cramp.

And last, but not least, we would like to thank for our long-term collaborators F.Orsitto, C.Gil, B.Bieg, A.Murari, D.Mazon and M.Gelfusa.

JET, which was previously a European facility, is now a UK facility collectively used by all European fusion laboratories under the EUROfusion consortium. It is operated by the United Kingdom Atomic Energy Authority, supported by DESNZ and its European partners. This work, which has been carried out within the framework of the Contract for the Operation of the JET Facilities up to 31 October 2021, has been funded by the Euratom Research and Training Programme. Since 31 October 2021, UKAEA has continued to work with the EUROfusion Consortium as an Associated Partner of Max-Plank-Gesellschaft zur Förderung der Wissenschaft e.V represented by Max-Plank-Institut fur Plasmaphysik (“IPP”) pursuant to Article 9.1 of the EUROfusion Grant Agreement for Project No 101052200. The views and opinions expressed herein do not necessarily reflect those of the European Commission.



FORWARD TO FUSION

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FUSIONICS

Many thanks
Any questions ?

Email: Alexandru.Boboc@ukaea.uk