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Abstract

Originally designed for five years of plasma operations, the JET Far Infrared (FIR) interferometer/polarimeter diagnostic system was still operating at its full capabilities nearly forty years later in ITER relevant conditions (eg. metal-wall, tungsten divertor) for multiple D-T campaigns, albeit with significantly lower neutron fluences. The original design had to adapt substantially over the years due to machine changes, leading to reduced signal and access to mirrors etc, and the diagnostic still worked due to the excellent dynamic range of the detectors.

This paper will discuss invaluable lessons learned designing, operating, optimising, and enhancing such a complex system and how these can be used for developing the new class of laser-based diagnostics for the next generation reactor grade machines.

Keywords: plasma diagnostics, interferometry, polarimetry, basic control, Far Infrared, Terahertz

1. Introduction

The first-generation burning plasma devices such as ITER, STEP or DEMO will operate in a very challenging environment for diagnostic systems which can only be found in some of the existing fusion devices around the world such as JET[1]. Some of these conditions include high ambient temperatures, strong electro-dynamic forces due to high magnetic fields, long pulse lengths and uninterrupted periods of operation and, most notably, very low or zero access to some parts of diagnostics. Additionally, the presence of tritium and of D-T neutrons and resulting activation constraint the diagnostic design and operation. With that in mind one must develop a system with enough redundancy and robustness to survive the reactor-relevant plasma conditions for many years.

The original design changed substantially over the years, for example: the introduction of the divertor significantly reduced access and the number of laser beams; D-T readiness required double vacuum windows that greatly reduced the laser signal level through plasma to 5% and the diagnostic still worked due to the excellent dynamic range of the detectors.

On JET, complete alignment of the FIR system was required only once every decade, like the timescale for fusion reactor maintenance shutdowns. The FIR system operates as a hybrid interferometer and polarimeter system, nearly fully automated, with state-of-the-art electronics for phase counting, improved redundancy in both optical hardware (multiple lasers) and data acquisition and control, real-time integration of measurements with the JET plant (active plasma control and additional heating system interlocks). This was done in conjunction with other diagnostic systems and magnetic reconstruction codes that JET developed and enhanced over the years.

One notable enhancement was the integration and use of polarimetry for real-time plasma density control and machine protection in a fusion plant for the first time. This is being replicated in most of the current FIR developments. Also, during the latest D-T campaign on JET, the FIR system was the single point failure device for density control, replacing the original backup system based on visible spectroscopy which could not be used since the introduction of the metal ITER-like wall in 2011. The FIR system operated with nearly 100% reliability 16hrs/day, 5 days a week. This paper will discuss invaluable lessons learned designing, operating, optimising, and enhancing such a complex system and how these can be used for developing the new class of laser-based diagnostics for the next generation reactor grade machines.

2 Latest diagnostic capabilities

The JET Far Infrared diagnostic[2] (see Figure 1), as per end of JET plasma operation on 18th of December 2023, operated as a hybrid Mach-Zehnder interferometer/polarimeter type with diffraction grating wheels used as beam modulators [3] probing the plasma with four vertical channels and four lateral channels (see figure 2).

The instrument uses Far Infrared or Terahertz lasers as these frequencies (2.5THz and 1.5THz corresponding to 195μm and 118.8 μm in wavelength terms) are far away from the plasma frequencies, which are typically in Gigahertz range, therefore the plasma is a transparent medium for this type of lasers. Therefore, by analysing the change in the optical properties of a laser beam passing through the magnetically confined plasma, one can get important information on electron density (interferometry), as well as information on the magnetic structure using internal measurements (polarimetry).

If a sufficiently large number of probing channels is used, one can also derive a profile.

Both diagnostic systems operated in real-time, 16h/day, for all JET Plasma Operation Days and are in the essential diagnostics category (sometime referred to as “basic control”) without which JET cannot operate.

2.1 Lasers

The lasers used by JET FIR system are as follows: for 195μm - two Continuous Wave (CW) Deuterated Cyanide (DCN) Far Infrared lasers (high voltage driven at 4kV and 1.2A) using a mix of CD_4, N_2 and He gases with a typical power of 200mW; for 118.8μm – three CW methanol lasers optical pumped from a 10 μm CO_2 laser (high voltage driven at 16kV and 40mA) using a laser mix CO_2:He. These methanol lasers are commercial products by Edinburgh Instruments Ltd that were modified by us to improve their performance to nearly steady-state.
The use of these 118.8μm lasers is for interferometry compensation and we had two sets: the original on PL4/FIR295, generating around 100mW FIR power, and the second set (originally installed on the UKAEA COMPASS machine) that is PL6/FIR395 twin cavity with power in the range of 250-350mW each.

Only one DCN and one compensation laser were used at a time, the secondary ones are for redundancy reasons.

The DCN laser is based on 1971 design from CEA Cadarache, France and was deployed on several machines (JET, Tore Supra, FTU, ASDEX-Upgrade, START).
The latest implementation of the interferometer provided line-integrated electron plasma density with time resolution of 1ms in real-time but also with ability for offline measurements with 10μs time resolution. This later one proved to be a very valuable addition for Magnetohydrodynamics (MHD) studies [4,5] as well as for characterising fast events such as Edge Localised Modes (ELMs), pellet and more recently Shattered Pellet Injection (SPI) for disruption mitigation experiments[6,7].
The polarimeter diagnostics were implemented later (1988) to measure Faraday Rotation angle and line-integrated density measurements from Cotton-Mouton angles with 1ms time resolution[8,9].
For alignment, originally, only an 18mW 632nm Red He-Ne gas was used. Later, in 2008 a 10mW 532nm green Diode-Pumped Solid State visible laser) was added due to the poor reflectivity of the original red laser beam that made the alignment impossible for some lateral channels.
All FIR and alignment lasers have a very low full beam divergence of about 0.1mrad

2.2 Mechanics

The diagnostic components span over three areas within the JET main building called J1 as depicted in the schematics from figure 3:

Diagnostic room (J1D)

This area hosts many of the JET Diagnostics and in the case of the FIR system, it is the place where all lasers, large granite optical tables (11x6m approx.), ancillary equipment, data acquisition and control as well as detectors are sealed (see figure 4).

Basement(J1B)

The JET basement (below the torus hall) contains a lot of equipment typically linked with JET ventilation, vessel pumping but also a lot of areas dedicated to diagnostics.

With respect the FIR diagnostic, the basement area only contains opto-mechanics and optics used for beam transfer to/from diagnostic area to the JET machine area, which is all enclosed in a large duct approx. 25mx1.5mx1.5m (see Figure 5). More specifically, this duct contains the optics for the four input and ten return laser beams.

Torus Hall (J1T)

The JET FIR diagnostic is the largest element inside the JET Torus Hall (followed by Neutral Beam Injection boxes) and consists of a ~15m diagnostic tower, as shown in figure 6, weighting 70 tons. It was installed on a crane carriage (to be moved out ~7m if access to the Octant 7 median port windows area is required) and with re-positioning accuracy of about 100 μm. Inside the tower there are the optics for splitting the beams in the eight probing channels and two reference channels as well as the recombination interference plates (z-cut quartz) that generate the beat-signals.

Due to long optical path of 80m and strong transient magnetic fields, to minimise vibrations (below 10μm as required by the interferometer, all the optics were over-engineered and driven by pneumatic motors and made of non-magnetic metals (aluminium, brass) with fixings of glass resin. An example of such mirror assembly is displayed in figure 7. The duct and tower enclosure panels were made of a sandwich of two plates containing a honeycomb structure of a phenolic based resin to increase mechanical stability resistance and minimise weight.

2.3 Detection and Data Acquisition and Control (DAQ)

The system had several parallel systems and architectures installed over the years as per figure 8.

The detection system contains three cryostats each containing up to seven high quality cryogenic detectors. Their type is Indium antimonide (InSb) bolometers operating at temperature of 4 Kelvin with Noise Optical Power less than 10^{-12} $WHz^{-1/2}$ made by QMC Instruments[10]. Each detector is coupled with a pre-amplifier set (with fixed gain -40dB, -60dB and -80dB) that uses bias currents of μA.

The system was split to two branches. One set is sent, via a CODAS developed Unity Gain Amplifier to an UKAEA proprietary fast transient recorder[11] that can acquire data up to 2MHz used for fast interferometry measurements.

The second set connects to a set of analogue filters for laser modulation frequencies. The original set contain a set of filters for 100kHz and 5 kHz corresponding to DCN 195μm and Methanol 118.8μm laser wavelengths respectively and later another system with 23kHz for the second colour (118.8μm laser) on vertical channels. These signals are then amplified and sent to two DAQs based on CAMAC (1984), C40(1995), and PowerPC (2001)[12] architectures. The amplifier gain was controlled by a standard PC operating Microsoft MSDOS Operating system until 2018 when it was upgraded to an industrial PC based on Beckhoff technologies [13].

In 2012, a new FPGA based system was developed, in collaboration with our colleagues from CEA Cadarache, and contains two sets of EUROcards for filtering raw data, zero crossing phase counting, built in fringe-jump correction based on FPGA and Linux technologies [14,15,16].

Interferometry as an instrument provide history dependent measurements, meaning that at any measurement time point one records only the phase variations between the probe beam that pass the plasma and the reference outside the plasma in a specific time interval and this value is added to the total measurement. The phase variations are measured in fringes and that can be easily converted in line-integrated electron density measurements (eg. for 195μm laser wavelength one fringe corresponds to 360 degrees phase variations that translates in a value of line integrated density of $1.143x10^{19}/m^2$).

However if the signal is lost for some reason (eg. beam refraction, absorption) the phase measurements are not possible causing the so-called “fringe-jumps”.

Most of the laser controls and environmental controls were based on Beckhoff and ADAM technology [17,18].

The DAQ is remotely controlled via Solaris UNIX systems for both monitoring and setting up the parameters.

2.4 Physics Data available

The system routinely produced measurements of Line Integrated electron density (LID), Faraday Rotation angle (FAR) and Cotton-Mouton phase shift angle (CM) measurements as part of the real-time systems used for basic density control or machine and protection (e.g. additional interlocks for heating systems on JET).

The Physics data produced was saved in what is called JET Pulse Processed File (PPFs) and was manually validated for interferometry and with automatic validation for polarimetry.

For advanced studies, it was possible to generate PPFs for several channels of interferometry with time resolution up to 10μs. This was a very useful for fast transient data events such as disruptions, pellets, or Edge Localised Modes. Raw data from the fast interferometer was already integrated in a dedicated code for spectrogram analysis providing important qualitative information on the MHD modes using internal plasma measurements.

Over the years, several codes were developed using various channels of interferometry to reconstruct a density profile, to compare and bench-mark other diagnostics (E.g. High-Resolution Thomson Scattering diagnostic other Microwave diagnostics).

The polarimetry data was integrated into various magnetic reconstruction codes such as Equinox[12], EFIT++[19].

The diagnostic capabilities are listed in Table 1 below.

Interferometer			
Measurement	Range	Accuracy	Time Resolution
Line-integrated electron Density (LID)	10^{18}-$4x10^{22}/m^2$	$3x10^{17}/m^2$	1ms(real-time) 10ms(offline)
Polarimeter			
Faraday Rotation angle (FAR)	0-70 deg.	0.05-0.2deg	1ms (real-time)
Cotton-Mouton Angle	0-40	0.5-2 deg.	1ms
Line-integrated electron Density (LID3 only)	10^{18}-$4x10^{22}$/m2	$2x10^{18}/m^2$	1ms(real-time)

Table 1: Diagnostics capabilities

3 System evolution in time

3.1 The Original 1984/85 version

The original diagnostic was designed for a much simpler JET machine with Ohmic plasmas (up to 7MA plasma current), no divertor, no additional heating systems, no H-mode plasmas, and no pellet injector.

The DCN laser technologies at the time (see figure 9) were still in the prototyping[20] period and the lasers were operating at maximum power capabilities (up to 400mW) which caused regular tube breakages and higher running costs.

The original setup had six vertical channels (see figure 10) and vacuum windows had a single window made of Z-cut quartz (to minimise birefringence effects).

The power losses were substantial and were found to be mainly due to water absorption (moisture in air) of the FIR radiation through the long optical path of 80 meters.

A Perspex enclosure was added to the lab optical tables (see figure 4) and focusing optics telescopes under the detectors, and all were fed with dry air (DewPoint -50degC). The duct enclosures in the basement were sealed with bitumen tape to try to minimise the ingress of moisture with a dry air supply again from the basement.

To get better profile information on the electron density from the interferometer, a lateral system with four channels was originally envisaged (see figure 11) with two new sets of vacuum windows (one for the input beam and one for the reflected beam) and a set of in-vessel reflectors for three channels.

The first implementation of the lateral system had three in-vessel retro reflectors with beam profiling set of mirrors before and after the vessel and one additional edge channel with main reflectors on the JET mechanical structure.

Due to the vacuum vessel vibration, a compensating interferometer was required to discriminate between phase changes of the laser beam due to plasma and in-vessel vibration.

The original laser was a 3.3μm He-Ne laser as this wavelength was compatible with the beam splitters and window materials.

Alignment setup

A complicated telescope viewing system was designed, to be able to observe the beam position along the beamlines directly from diagnostic labs. The implementation had a set of lights that can be enabled, one set at a time for each torus hall mirror and evaluate the position of the visible alignment beam with respect to the side illuminated edges of the mirror. The rationale behind it was that there was an expectation that the JET Torus Hall would be so radioactive after the D-T experiments that people would not be allowed inside the torus hall for tasks such as alignment.

However, due to losses of the visible beam from for example Kapton foils around the system, mirror flatness quality for FIR not designed for visible laser beams) this never actually worked.

Also, the original 3.3μm He-Ne laser was found not suitable due to large displacement of the in-vessel mirrors of 10mm and large phase change perturbation due to air turbulence in front of heated vacuum windows (around 150 deg. C).

Visible alignment was very hard to achieve due to bad ergonomics and physical access for a human being (see figure 12) and some captive optics sealed inside enclosures. This was valid for the entire life of JET.

Due to all these factors, four out of ten channels were not operational for the first 4 years, nearly half of the expected JET Operation lifetime at the time.

In 1987, another type of laser, to replace the original 3.3μm, produced by the manufacturer Edinburgh Instruments was installed. This consisted of a 40W CO2 CW wave laser called PL4 optically pumping a methanol cavity (FIR295) for a FIR power of about 100mW at 118.8 μm wavelength. This wavelength was partially compatible with current transmissive optics designed for DCN operation and made the system operational within the parameters deemed acceptable at the time.

3.3 1987 Polarimetry

In 1987, polarimetry capabilities were added with the installation of eight half wave plate rotator assemblies in the Torus Hall in front of vacuum windows. All these rotators were pneumatically driven (see figure 13) but were very slow (3 second/step), which was not practical for a regular calibration.

In the detection section eight wire grid analysers, were installed to separate the two orthogonal polarisations of the incoming FIR beam plus a new cryostat with seven detectors dedicated for polarimetry.

The wire-grid analysers were manually adjusted and there was a lot of prototyping required to adapt these to the detection section to fit the existing opto-mechanics and allow redirection of the two orthogonal polarisations to the detectors.

The calibration was based on ideal mathematical formulas[8] and ignored mutual interaction of the various effects (e.g. Birefringence of transmissive optics, interaction of Faraday with Cotton-Mouton and so on).

Another important aspect was that the polarimetry physics data was only available and the calibration for one channel took hours to be performed. There were some weaknesses in the design that caused loss of the optical axis of the half-wave plate after few months of operation requiring manual reset in the holder requiring a lot of logistics (e.g. Moving the tower out, raising scaffolding etc). This was corrected later with the new design(see next sections).

3.4 1991 Divertor introduction

The divertor introduction had a great impact on the interferometer as, due to the divertor coils, two vertical channels were blocked and one was nearly tangent to the plasma, reducing its usefulness for physics measurements. For example, during all high-performance plasmas (H-mode), the beam was outside of plasma during flat-top.

The beam apertures were reduced from 130mm to 12-60 mm for vertical channels causing some vignetting as the original window dimensions assumed a beam waist (1/e) at the window of about 35mm.

3.5 1992 in vessel mirror re-design

The original mirrors (see figure 14) suffered severe displacement (up to 10mm) during the plasma shots, so the JET central column needed reinforcement. The second set was affected by arcing/carbon deposition due to very close proximity to the plasma therefore reducing reflectivity and beam profile and these were redesigned to be hidden behind a limiter as well as being recessed by a few cm below the front of the first wall tiles(see figure 15). They were aligned in-vessel, then secured with bolts to the first layer of the wall. The associated locking nuts were then welded in place. These were used successfully since then (1992) to the last day of operation in December 2023. As part of JET Decommissioning Programme, there is a plan to retrieve them to be analysed.

3.6 DCN laser controls and DAQ upgrades

In 1995, there were upgrades in preparation for the first high power D-T campaign (DTE1).

The manual flow control for the HeNe and CD_4 gases was replaced with mass flow controllers and associated valves controlled by PIDs *(*proportional integral derivative) controllers linked with the High Voltage Power supply. UKAEA developed unique CD_4 gas introduction control modules with built-in timers and functionalities for remote control.

Also, new analogue filters and amplifiers for 100kHz and 5kHz modulation frequencies were added, as well as an automatic gain controller running on MSDOS PC technologies.

3.7 1997 Deuterium Tritium Experiments 1 (DTE1)

In preparation for the DTE1, the diagnostic hall, the basement and torus hall, as a requirement for tritium safety barrier, were separated and isolated with negative pressures of about 100 Pascals. In the case of the FIR Diagnostic, a secondary tritium barrier was required, and this translated in adding additional pellicle windows at interfaces between areas and in replacing vacuum windows with double windows.

All these measures reduced the FIR signal level by an additional 90%, causing losses of the laser power in the range of 99.9%.

Only the fact that the detectors had an exceptionally large dynamic range allowed the system to be still operational to the end but the signal-to-noise -ratio (SNR) was reduced from 40000 to about 100-400.

The FIR system was one of the few diagnostics fully operational during the DTE1 campaign, used for plasma density control as the primary diagnostic. Apart from upgrades in previous years, no special requirements were defined specifically for D-T Operation.

3.8 2002 Real-time DAQ and Polarimetry upgrade calibration

A program to upgrade the real-time system using PPC technology as well as new polarimeter controls started in 2001 and was completed in 2002. This was part of a large program to develop a real-time current control called EQUINOX[12].

Part of the polarimeter upgrade related to controls as follows: the half-wave plate and wire grids mechanisms were upgraded using high torque stepper motors (see figure 16 and figure 17) as well as an automatic in-pulse calibration mechanism that took only 10 seconds (7 seconds for actual rotation and 3 second for damping to neutral-position)[8].

This allowed automatic Faraday Rotation angle calibration at the start of each pulse as well as the integration of raw data with EQUINOX. However, the system relies on calibration data from the previous pulse running from a FORTRAN offline code.

However, no real-time data quality tracking was implemented and therefore polarimetry system was not usable for basic control but only for advanced control[21].

3.10 2004 Cotton-Mouton addition

By altering the initial polarisation angle of the laser beam polarisation with respect to the toroidal field direction from zero degrees to 45 degrees, Cotton-Mouton measurements were made possible. These measurements are very important for control since they provide absolute information on the line-integrated electron density. This was demonstrated as feasible on a small scale[8] and later a more comprehensive statistical analysis for a large group of JET pulses was performed [9,22].

3.11 2007 Fast Data Acquisition for interferometry

A relatively modest upgrade in terms of hardware cost greatly expanded the diagnostic capability by recording the raw unfiltered data from the detector using UKAEA own fast transient recorder electronics[11] on three vertical channels (and later for the lateral channels). This was tried earlier when the fast magnetic system was originally developed but due to the capacitance of long cables the noise level was very high.

The upgrade enabled high contrast spectrograms of a core channel of interferometer, making it possible to observe core localised Toroidal Alfvén Eigenmodes (TAEs)[23], which are instabilities driven by energetic particles, as well as the ability to provide line-integrated measurements with 10 microseconds time resolution by analysing laser intensity variations smaller by a factor of 10^{-3} compared to the main carrier frequency. The new measurements allowed a fuller description of fast events such as Edge Localised Modes or Pellet injection with 150—300 points versus 3-5 points previously[4]. This system was replicated at the CEA Tore Supra (now WEST) tokamak in Cadarache, France.

3.12 2008 CEA FPGA Prototype

Following the ITER-like wall programme we investigated a way to upgrade the DAQ to ensure FIR diagnostic operation for another decade.

Our approach, together with our colleagues from CEA Cadarache, was to use the more modern FPGA technologies. The first step was to test viability of this technology by installing a full rack FPGA prototype to record the data during a plasma experimental campaign.[14] This proved to be 100% reliable and allowed for the first time on-the-fly fringe-jump correction algorithm and direct integration with JET real-time control network.

3.13 2012 Real-Time EP2 Programme Upgrade

With the decommissioning of the UKAEA COMPASS (2008) machine, the FIR laser became available. This was based on an Edinburgh Instruments PL6 laser feeding a twin cavity providing completely independent laser beams. We used this laser to add redundancy to the existing compensation laser by adding a second wavelength (sometime described as second colour) laser measurement. The power level of the new laser compared with the original compensation laser was three times more on each laser cavity, including much better power stability. A new DAQ system was developed using COTS component and FPGA technologies with CEA Cadarache as mentioned in Section 2. A novelty for this implementation is that we used a full engineering approach for direct integration with machine control and a unique design suitable for both Tore Supra and JET, including the firmware. To select the right machine, one needed only to change position of an on-board switch (zero for CEA mode, one for JET mode).[14,15,16].

This data acquisition hardware has proven to be 100% reliable from the outset.

Since 2014, the new system has, in fact, become the primary system used for density basic control extending the lifetime of the interferometer for another decade as the old DAQ was failing increasingly regularly.

3.14 2014 PPC Real-time polarimetry upgrade

In 2014, we completed and validated a major upgrade of the real-time software including an innovative calibration using complex-amplitude-ratio[24] and a comprehensive mechanism for self-validation polarimetry physics measurements every millisecond during a plasma pulse. This was challenging as the PPC VME software implementation did not have mathematical libraries to compute basic operations with complex numbers, so we had to build and test these libraries even for elementary operations such as addition or simple trigonometric functions.

Due to these upgrades JET was the first ever machine where polarimetry was used unattended for basic control[24]. The impact of this upgrade was so relevant that any future interferometer in the fusion world will probably have polarimetry capability for backup (due to lower resolution than interferometry) measurements of electron density.

3.15 2016 DCN laser automation and optics upgrade

As part of preparations for the second high power D-T campaign (DTE2), were upgraded all of the DCN local controls from manual to fully automatic using hybrid IPC technology from Beckhoff[13,17]. The rationale to use this technology was as follows: due to the criticality of the diagnostic we have chosen technology that had proven successful for four years by then, since 2010, on the JET Plant Essential Monitoring Modules system; secondly, this was fully supported by the JET Information Technology team. This system was upgraded further in 2019, when the automatic gain control of the old analogue electronics was implemented. This reduced the daily start-up/shutdown operation operator times by 90as most of the time sequences did not required presence of personnel in the lab anymore to go to the next step (eg. waiting 5 minutes for vacuum level to go down to expected value before gas is activated)

3.16 2017 New integrated control DAQ for Deuterium Tritium Experiments (DTE2)

In preparation for DTE2, we transferred most of the local control and environmental monitoring (e.g. lasers status and power, voltages, humidity levels etc) to remote.

An integrated software package was developed with the scope to unify all the interferometer/polarimeter systems on a simple single page control panel mimic using only a four-colour coded system. This simplified tracking errors by exception only and proved easy to monitor even for non-experts.

This proved essential during the COVID pandemic when, together with the Beckhoff upgrade, we were able to manage the JET FIR operation during DTE2 with extremely limited number of staff and under very stringent health related controls (e.g. 2m rule between individuals when working in the same area).

3.17 Post-DTE2 DCN modular laser tube upgrade

The DCN modular laser tube upgrade was done as part of a resilience programme started in early 2016 to ensure JET remained in operation until 2024. Since the time that the upgrade was approved the JET plans changed significantly for various reasons including delays to the DTE2 schedule and COVID Nevertheless the upgrade proved useful in JET final years of experiments.

The project started at a time when the sole manufacturer closed the business leaving no supply chain available, which led to the team developing, together with our CEA colleagues, a modular laser tube using mostly commercial-off-the-shelf (COTS) components that doubled the laser power, increased laser mode performance and halved maintenance time. This new design was tested for the last two years of JET operations on both DCN lasers during Deuterium Tritium Experiments (DTE3) with no faults.

4 Diagnostic Operation

The FIR diagnostic was required whenever JET was in operation and the any work on diagnostic including regular maintenance and daily operation depended strictly to the JET Shutdown/Intervention operation planning.

4.1 Daily Operation

The system was the only diagnostic that was still fully supported with shift personnel at the end of JET. This was mostly to ensure the availability of the right personnel for emergency recovery of diagnostic capabilities during JET Operations. Some of the daily operations activities were covered by JET Shift Technicians and the Diagnostic Coordinator, and some by Responsible Officers or their Deputy.

The daily activities were as follows:

- Start-up/Shutdown of lasers
- Refill of detectors cryostats with liquid nitrogen (twice a day)
- Tuning of lasers when required (few times a day)
- CO_2 bottle change (every 1.5 days of laser operation)
- Interaction with JET Control Room staff
- Provide support to Scientific team with respect to measurements at any time during operation shifts.
- Emergency recovery actions (ideally between pulses within a 20-minute timeframe that was the typical waiting time between two consecutive pulses)

4.2 Weekly Operation

There were several tasks to be performed on a weekly basis, typically by the Responsible Officer and Deputy and they were as follows.

- Refill of cryostats with liquid helium
- Check CO_2 laser gas stock.
- Maintenance of the DCN laser when required (typically 2-3 hours)

4.2 Monthly Operations

These mostly concerned logistics and planning.

- DCN laser maintenance
- Monthly roster preparation
- CO_2 gas bottle ordering
- Spare parts stock checks

4.3 JET Shutdown operations

During shutdowns and interventions there were several activities to be covered. The key ones are listed in the next paragraphs.

As a note, not all of these were necessary every shutdown or intervention depending on various factors such as access to areas of diagnostics, how long since the last time were performed or observations during operations.

All the activities related to the diagnostic were recorded in the Diagnostic Commissioning checklist document.

4.3.1 Record status of diagnostic

This could be done at any time during shutdown, but when access to torus hall was allowed a complete checklist had to be completed.

The checklist contains the following parameters:

- Lasers power before shutdown at source
- Environmental control parameters (e.g. humidity)
- Detector settings, preamplifier set-up, voltages
- Gain level at the last operation day
- Visible/FIR alignment position for the probe beam at specific points (e.g. Torus Hall floor input/floor windows, return floor windows in diagnostic hall, position of FIR/visible laser beam at the recombination beam splitters inside the tower.)

4.3.2 Diagnostic Tower operations

Due to the very close proximity to the machine, the diagnostic tower must be moved out of its location for access to Octant 7, to allow vacuum leak checks, and inspections and commissioning of other diagnostics. This operation was always strictly controlled by the Responsible Officer and was done via the Machine Operation Group Document, requiring a team of up to six observers due to the proximity to the machine (5mm only in few points). This operation could be a problem when re-instating the tower following a shutdown when new installations could impede a full re-position. This happened for example prior to the DTE2 when the pipework attached to the newly installed Tritium Injection Module no. 7 was in direct line of contact with the top of the tower for about 20 cm and required modification to the pipework. The speed of the move is typically 1mm/second but could be up to 10mm/second. When one uses the “faster” speed, there is a stopping distance, due to mass inertia, of about 25cm. In 2010 that was deemed too dangerous as there are no brakes on the tower wheel mechanisms, so the procedures were changed. It is important to note that any time the tower is moved from its operating position there is a risk to the alignment.

4.3.3 Vacuum cleaning of the vacuum windows

Due to the carbon-wall there was always debris generated inside the torus. This impacted on interferometer operation as carbon dust made its way to the bottom of vacuum windows blocking the laser beams and therefore needing cleaning at any opportunity during shutdowns. This operation was always done by the Remote Handling team to clear up the debris typically inside Channels 2 and 3. This is done from in-vessel using a very long pipe with a plastic tip attached to the Remote-Handling arm, (see figure 18). Underneath the window was always an isolator enclosure, certified by the Health Physics department, to capture any debris in case of catastrophic damage to the vacuum windows during this procedure.

4.3.4 Refurbishments

The diagnostics had a lot of ancillary equipment and required close inspection for potential replacements/maintenance. Even if some of them can be done during JET operations, most of them were strictly performed during shutdown/intervention operation as follows (the list is not comprehensive):

- Review laser operation manuals and safe system of work (Risk assessments, work procedure)

- Training of new people or refreshers courses
- Vacuum pump services
- Detector cryostats vacuum recommissioning
- Chiller maintenance including water pipe replacement if necessary.
- Pressure regulators/Gas lines/airlines inspection
- PAT Electrical testing
- Optical components inspection (e.g. Pellicle windows, wire grids)
- Laser maintenance by the manufacturer (CO_2 laser)
- Software/firmware upgrades
- Power supplies checks

4.4 Diagnostic commissioning

All diagnostics on JET must follow strict Facilities Commissioning Procedures that must be approved by the Nominated Safety Authority, various specialist Safety Risk Specialists and discussed at the weekly JET Co-ordination meeting. Any modification of procedures, hardware and software of basic control/essential systems must also be discussed and approved by the JET Machine Protection Working Group.

At the end of any diagnostic commissioning, the Responsible Officer and Group Leader must sign a Readiness for Operation form before enabling use of this diagnostic within JET Facilities.

JET plasma operation could not go ahead until the FIR interferometer system readiness for operation was approved. The documents for commissioning the interferometer and polarimeter are very large, comprehensive and complex; here are the key points.

- **Prerequisite/Inspections before commissioning**
  - Vacuum-vessel windows and in-vessel mirrors (via scaffolding/remote handling)
  - Pellicle windows
  - Wire grid status for polarimetry
  - Half-wave plates
  - Penetration pellicle windows (part of Safety Tritium Barrier)
  - Cabling and insulation
  - Pressure systems
  - Main cubicles power
  - High voltage laser power supplies
  - Local Control supplies
- **Lasers**
  - Power of lasers at various settings (gas pressure, voltages etc)
  - Perform Maintenance if required.
- **Alignment**
  - Visible alignment for vertical and lateral system
  - Matching FIR lasers with visible in diagnostic hall
  - FIR optimisation on vertical and lateral channels
- **Data acquisition control electronics and software**
  - Restart of power supplies
  - Start/stop of control programs on Solaris/Linux
  - Reboot of diagnostics PC
  - Check functionalities of monitoring/control programs by simulating faults (e.g. disconnect laser power supply voltage monitoring cable)
  - Frequency modulators motors and controllers
- **Test reports**
  - Check interferometry phase counting correctly (using a two-channel wave-form generator with a triangular phase shift between reference and probe signal offline), blind runs for half-wave plate rotator tests for encoder(potentiometer) and Faraday Rotation calibration.
  - Local pulse with no plasma
  - Dry run pulse

- Check results of first Ohmic plasma with pre-set density in controls and with Session Leader density settings

- **Complete Readiness for Operations document**

5 Lessons learned

During forty years of operation the diagnostic went through a lot of changes, but some original design choices proved to be relevant in ensuring operation for such long time. In this section, only a subset of lessons learned are shared, that I have either discovered myself or that were passed down by my predecessors.
As a general comment, one must consider the entire functionalities of the design phase with the same importance: measurement requirements, maintenance requirements and long-term operation.

Lesson learned #1

The mechanical parts of the system were over-engineered to keep vibration level below 10μm, also due to very low data acquisition capabilities. That proved important in the long term, as full alignment was required every 10 years with checks and small optimisations during each shutdown.

The original design proved impossible to align with the remote system designed originally.

- ✓ *Over-engineering in mechanics and opto-mechanics, together with oversize mounts allowed long optical-stability.*

Lesson learned #2

For many years, a good signal level was very difficult to achieve following an alignment. There were many causes, but many were simple and relatively easy to fix.
A few examples:

a) Kapton/Mylar absorption level very high for visible and methanol lasers, fixed by replacing with TPX 90 μm thick.
b) Lack of proper sealing of large optical enclosures (e.g. Duct 25mx1.5x1.5m, tower 14mx7m x3m) making it impossible to reach the required level of dryness (of order of -50deg DewPoint) thus delaying the time that FIR beam detection became possible only after one week; this was easily fixed by adding 5mm neoprene seals on most of enclosures panels that we could access.
c) 30% loss of methanol laser power due to wrong design of the half wave plate placed in front of the laser. Replacing it with a similar one but just 5 micron thicker improved transmission to 99%
d) Poorly maintained DCN laser pumps and seals/gaskets around the system caused laser glass tubes to break often (up to 6/year in 2004 down to none in four years at the end of JET). Replacing the seals every year and servicing as advised by the manufacturer fixed this problem.
e) A catastrophic failure of vacuum pump caused oil to contaminate and damage all the mass flow-controllers. Replacing these oil-based pumps with dry pumps eliminated this potential issue at source.

- ✓ *Typically, big problems/faults are caused by many small issues in cumulative ways.*

Lessons learned #3

The performance of the original polarimeter design, especially the calibration, was not acceptable. Upgrading to motorised opto-mechanics and real-time estimation of physics measurements yielded to a very powerful diagnostic that was elevated to the level of basic control.
The upgrades to the real-time system to actively check data between pulses and during plasma pulse ensured diagnostic resilience for a decade.

- ✓ *Consider how you will calibrate the instrument to get the proper data for the actual physics application.*
- ✓ *Identify sources of error that would impact on final deliverables.*
- ✓ *Software development has same importance & cost if not more than hardware development.*

Lesson learned #4

During the lifetime of the instrument, we increased redundancy as follows: we had multiple redundancy for laser availability, in detection and on measurements for density control and so we ensured that JET Operation was not stopped on even a single day due to the FIR system not being operational.

- ✓ *Increased redundancy provided seamless availability and increase machine performance.*

Lesson learned #5

The interferometer was not designed for H-mode plasmas and with 30MW of Neutral Beam Injection heating, suffered signal loss during plasmas (eg. high density gradients due to hollow density profile at ramp). However, second colour lasers (smaller FIR wavelength, smaller refraction, and smaller losses) plus the LID measurements via Cotton-Mouton from polarimetry were used routinely as a backup system and seamlessly allowed the correct plasma control during high-power, high-performance pulses that ensured JET success. Modifications done for DTE1 requirements caused a loss of laser power reaching the detector by a factor of 99.9%, However, the high dynamic range of the detectors (for down to pW level) allowed the system to operate during DTE1 and another few decades more.

- ✓ *Have most reliable and powerful sources(lasers) and detectors from day one.*
- ✓ *Involving diagnosticians in mechanical design/modifications of vacuum vessel is essential.*

Lesson learned #6

The first major upgrade of lasers, optics and data acquisition systems in nearly two decades of the JET FIR system lasers added another lesson:

- ✓ *Safety considerations at any step of design*
- ✓ *Collaboration is key in developing new diagnostics.*
- ✓ *Built-in safety measures in design from day one*
- ✓ *Non-biased feedback from external experts is extremely valuable.*
- ✓ *Use upgrades to add extra redundancy.*
- ✓ *Use COTS to reduce substantially operation cost.*

Lesson learned #7

Over forty years the system had many small modifications, ad-hoc fixes, patching and software upgrades but that sometimes proved counterproductive for the entire system.

- ✓ *Ask expert colleagues in various fields for suggestions/ideas and to help and review.*
- ✓ *Software integration/development is often not properly evaluated and beta-tested when upgrading.*
- ✓ *Reserve lots of time for beta-testing the new/upgraded software functionalities.*

Lesson learned #8

This was learned during preparation before DTE2 in 2017 and it was based on the following assumptions:

- No access in torus hall after first D-T pulse
- Components must be radiation hardened.
- Very limited access to diagnostics area.

Several actions were implemented and are listed below.

Torus Hall

- Check & secure ALL accessible wiring, optics and opto-mechanics.
- Perform final optical alignment optimisation of the diagnostic.
- Ensure the space around vacuum windows is clear from obstructions.

Diagnostics area

- Lasers and ancillary equipment extensive refurbishment
- Make as much as possible of the monitoring remotely available.
- Revise operation/maintenance procedures

- ✓ *Preparation for failure is critical in situations with no-access areas.*
- ✓ *Allow plenty of time for planning in and implementing deep refurbishments.*

Lesson learned #9

Another aspect not often considered are design choices that can have a negative impact on long term system performance, such as the equipment service cost and frequency, limited access, so that this becomes very rare and very expensive, system flexibility for upgrade in medium term (e.g. every 5 years), system degradation in long term (e.g. in vessel mirror degradation, or slow loss of alignment).

- ✓ *Consider staged development for build/operation and chose more carefully equipment with cheap long-term running/maintenance cost.*

Lesson learned #10

Regular maintenance is rarely covered in design reports. There are logistics considerations to be taken into account such as lead time of parts, number of spare parts on site, time to recover after a fault that sometimes can be substantial (e.g. vacuum failure of one single JET FIR detector cryostat will take a minimum of one week to recommission, assuming nothing is wrong), tasks that require large teams of people (e.g. a full alignment of the system requires large scaffoldings and 10 working days for a team of four people).

Spare parts for most components were kept ready and available and various emergency action procedures to restore diagnostic capabilities as fast as possible (under 20 minutes that was the time between two consecutive JET pulses) were developed. The lesson to learn here is:

- ✓ *Challenge your procedures to improve maintenance.*
- ✓ *Standardise common tech between systems (COTS)*
- ✓ *Preventative maintenance is key for smooth operation.*

Lesson learned #11

There is one single aspect that is rarely considered at the early design phase of any diagnostics project, in particular the ones that will be operating over decades, and yet has important implications: human resources capability to maintain and operate the system. Having only one Responsible Officer is a serious single-point of failure business risk for projects such as JET when the weekly operation cost was of order of millions of pounds.

- ✓ *Collaboration and succession planning is key for sharing decades of know-how and to ensure multi-generational operation.*

Lesson learned #12

In the case of JET FIR, the long-term operational cost was very high. Two examples are: the cost of, or refilling of, Liquid He and Liquid Nitrogen detector cryostats was, over 18 years of operation, over £1.2 million. A plan to upgrade the detector cryostats for a cryo free system was £100k in 2005 but was rejected due to the plan at the time to close JET in 2008. The second example is the CO2 laser. The cost of gas mixture (CO2/He) alone amounts to about £250k in 1 year due to high He costs up from £18k in 2010. Choosing a sealed CO_2 system could have reduce the costs by millions of pounds.

For future fusion plants, the operating cost could be so great that it could endanger the entire project.

- ✓ *Budgeting the diagnostic only for build & commissioning is not acceptable.*
- ✓ *Evaluate the yearly cost of operation assuming 5-10 years operation time.*
- ✓ *Consider different technology to reduce cost for entire lifetime of instrument.*

Concluding remarks

This paper presents an overview of the system and a few of the lessons learned.
It shows how essential it is to consider, from the very early phase of the design, a fully integrated engineering approach with strong interaction with other teams (e.g. controls, engineering, safety teams).
It is vital to understand long-term operation and maintenance requirements and include them to the initial specifications' requirements.
Key points for future reactor grade machines to consider from day one of the design are:

- ✓ Built-in safety and redundancy requirements
- ✓ Running costs
- ✓ Human resources and succession planning from day one.

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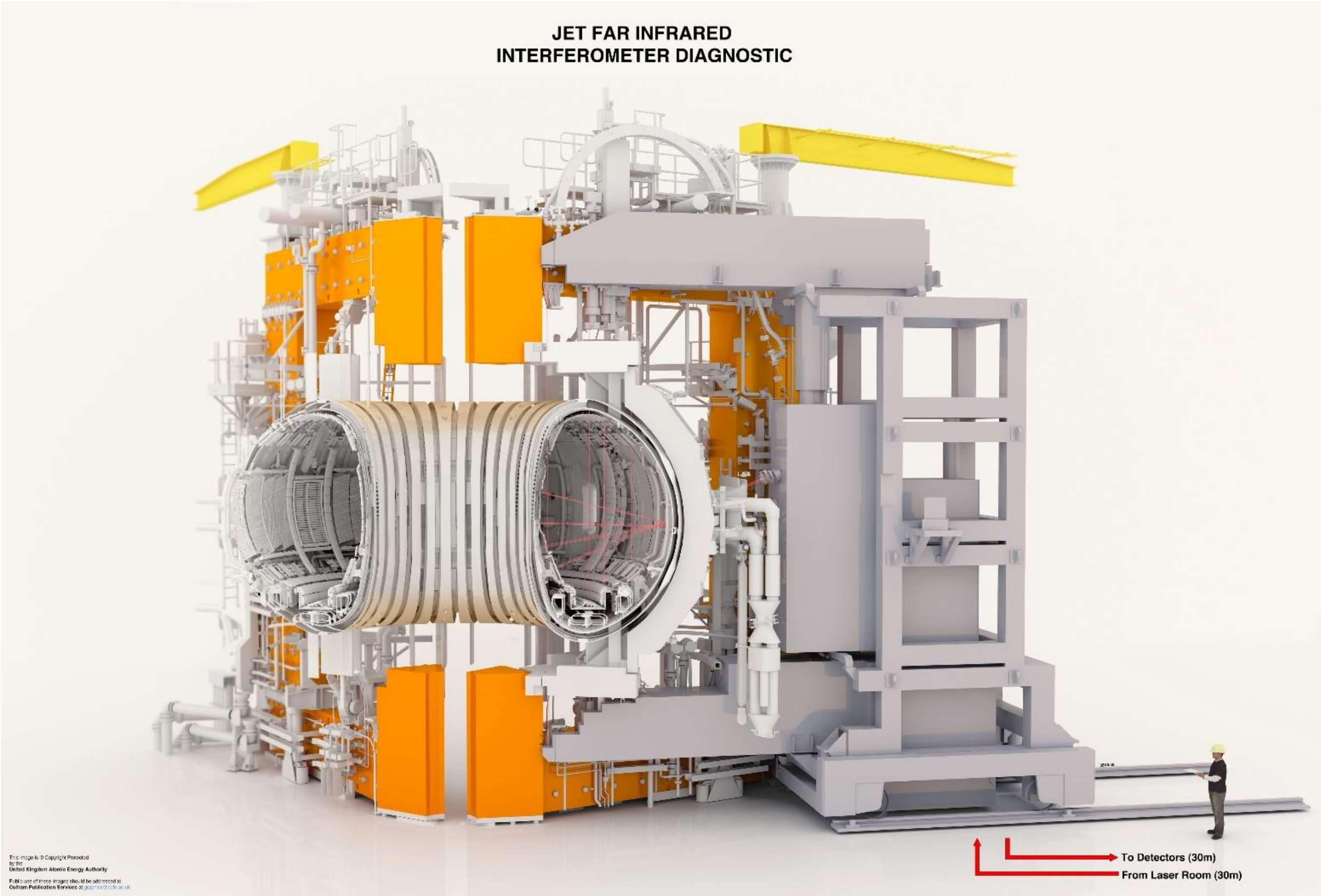

Figure 1 Artistic view based on real CAD of the JET Machine section and JET FIR C-Frame tower System in Torus Hall on the carriage (right side)

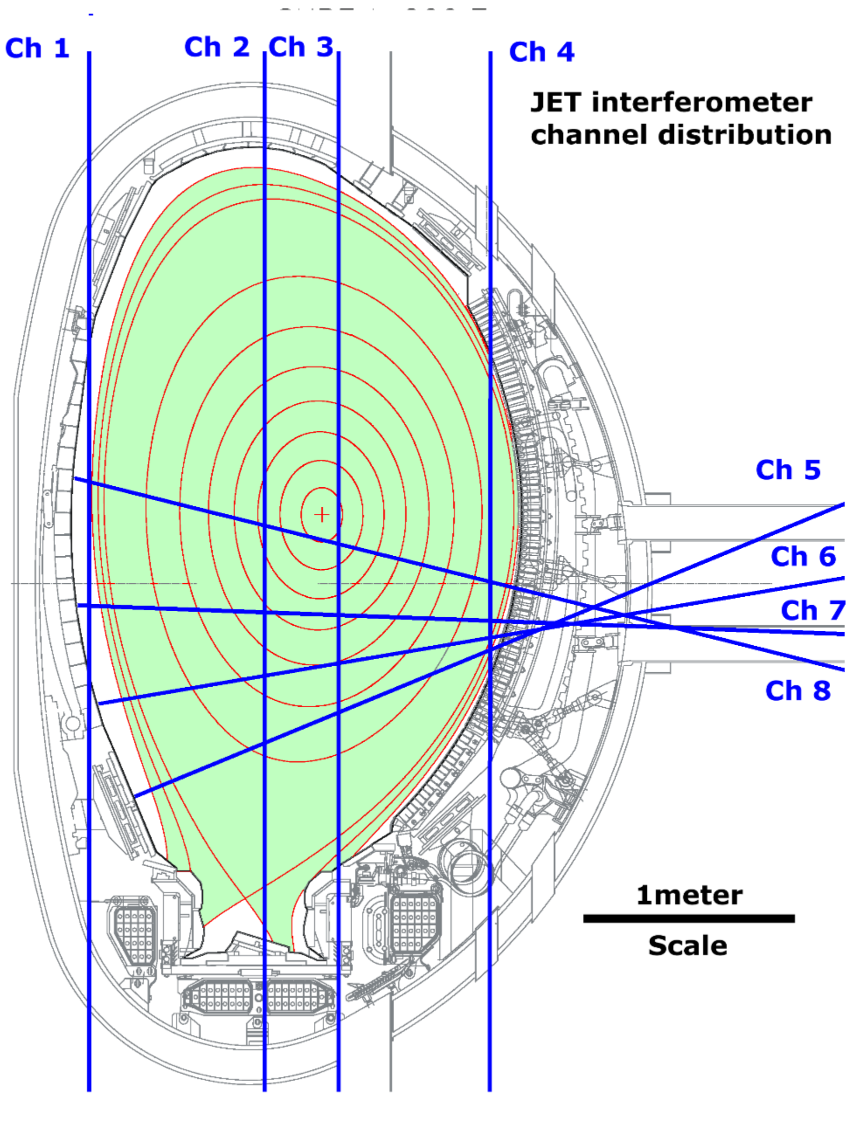

Figure 2 Overview of JET FIR channels (blue colour) through the plasma (indicated with green colour) and with magnetic flux surfaces indicated by red curves.

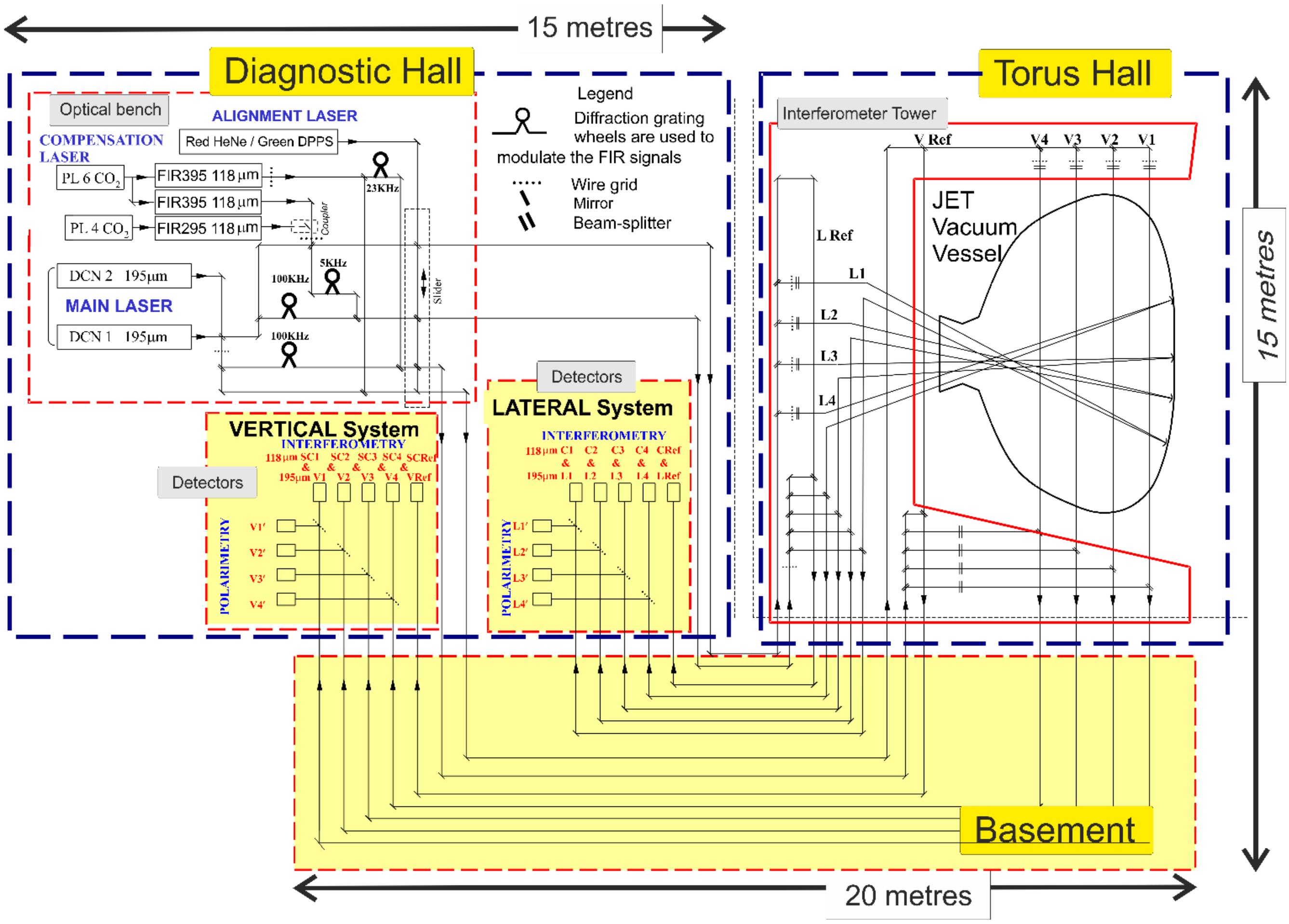

Figure 3 Schematic of the JET Far Infrared Interferometer areas and laser beam structure with relative approximative dimensions in meters

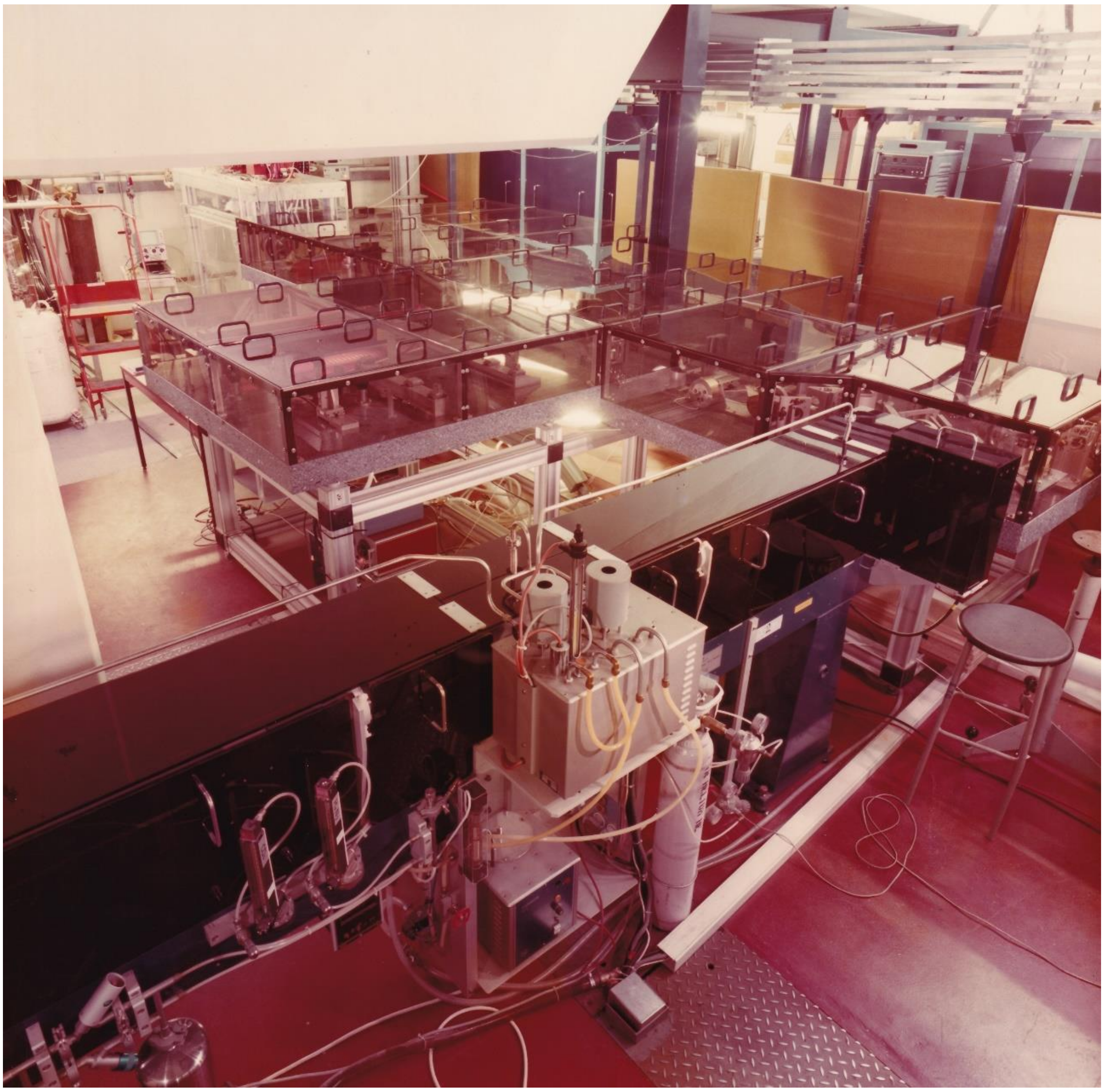

Figure 4 JET FIR Diagnostic Lab area as per 1985 implementation showing DCN No 2. laser(front) and granites optical tables with Perspex covers (middle)

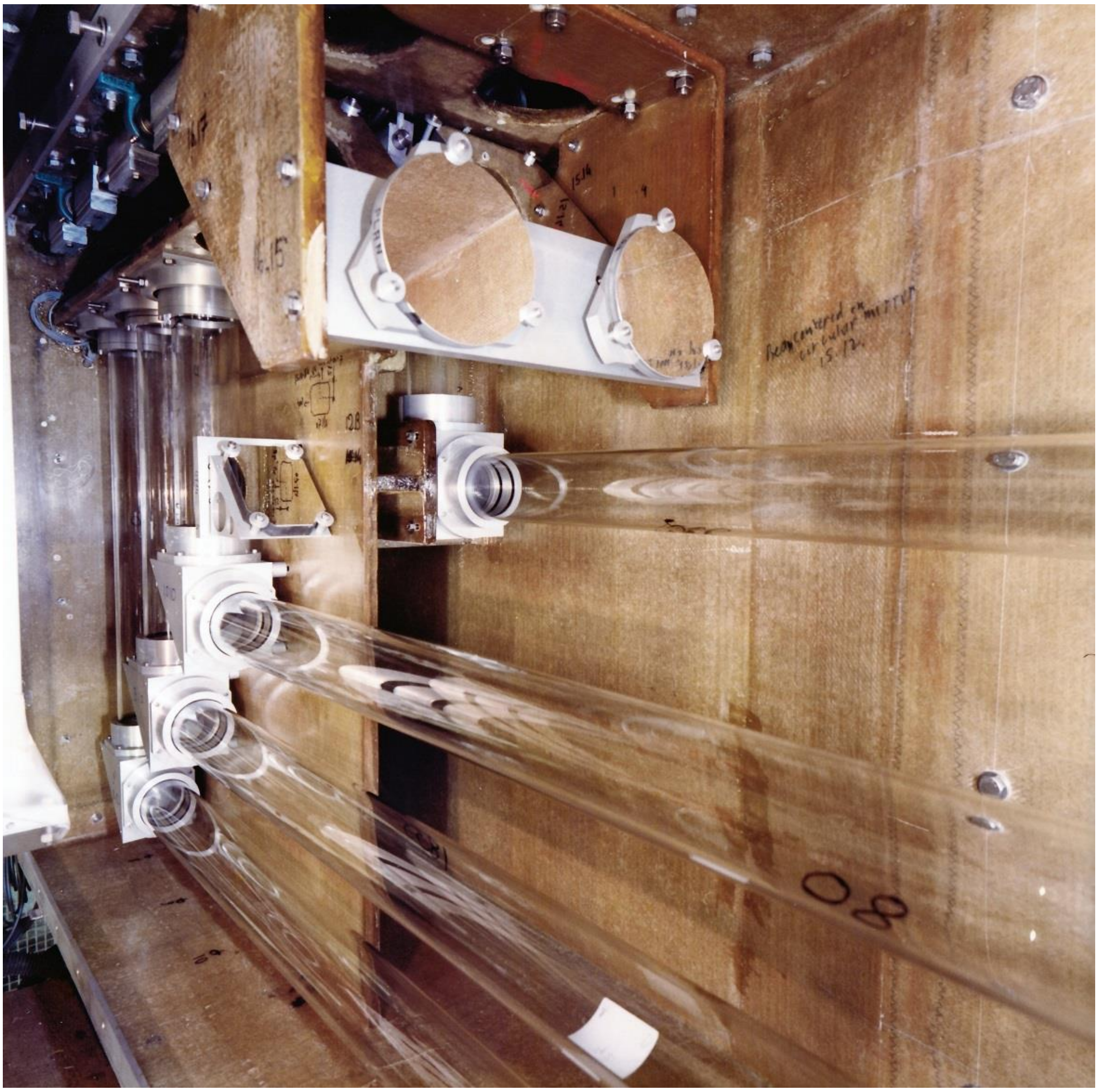

Figure 5 Section of the FIR Basement duct as per 1984 containing four returning FIR beams enclosed in 80mm Pyrex waveguides and two of the focusing mirror part of beam profiling telescopes

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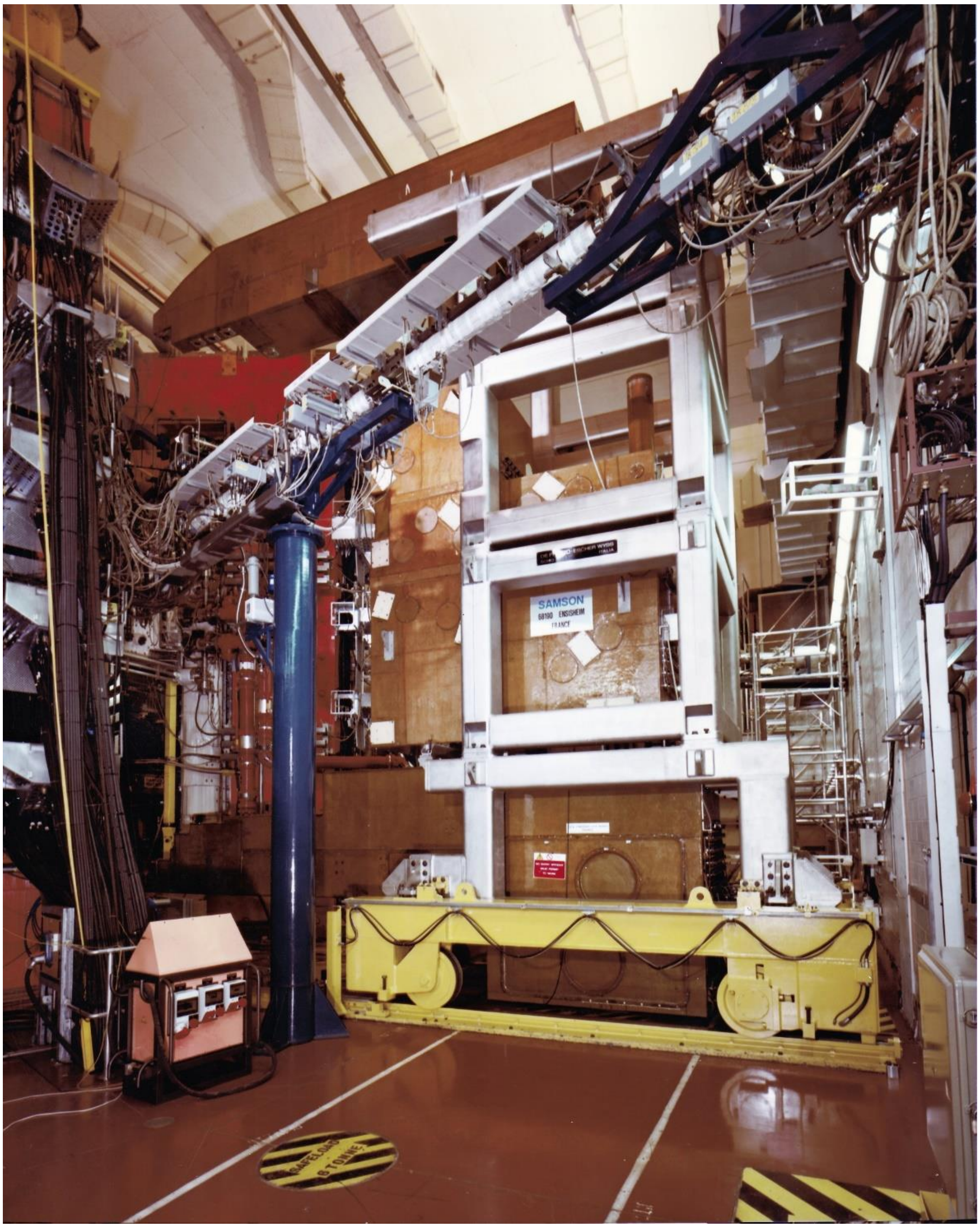

Figure 6 JET FIR Diagnostic Tower inside JET Torus Hall moved back from its working position as per 1985 installation.

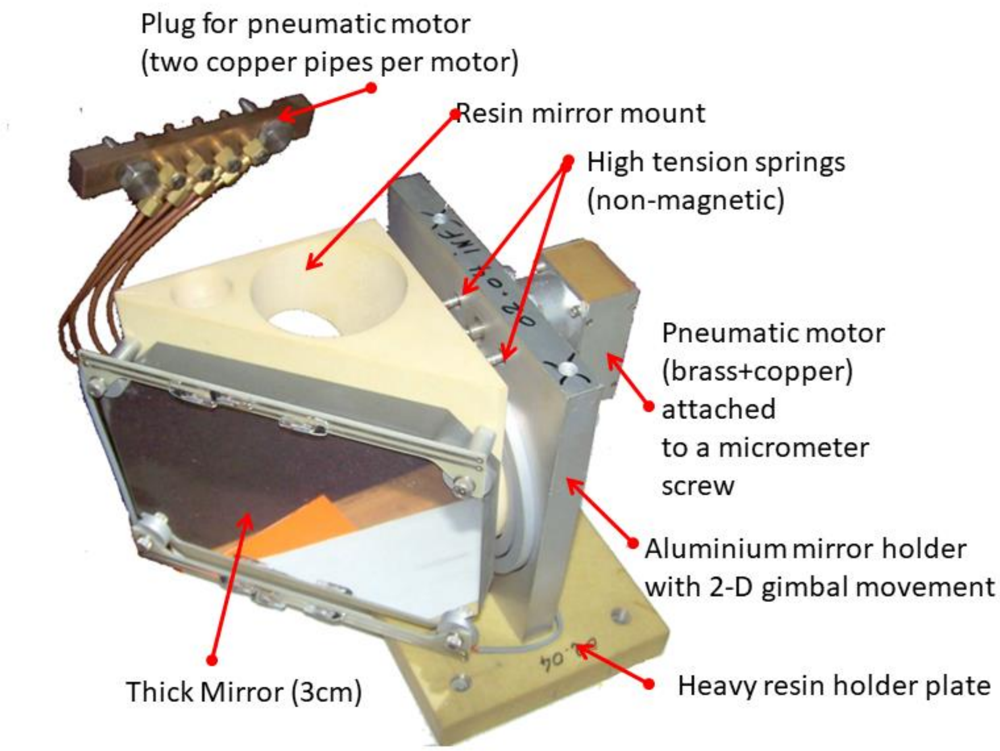

Figure 7 JET FIR Mirror Opto-mechanics assembly used in Jet Torus Hall diagnostic tower.

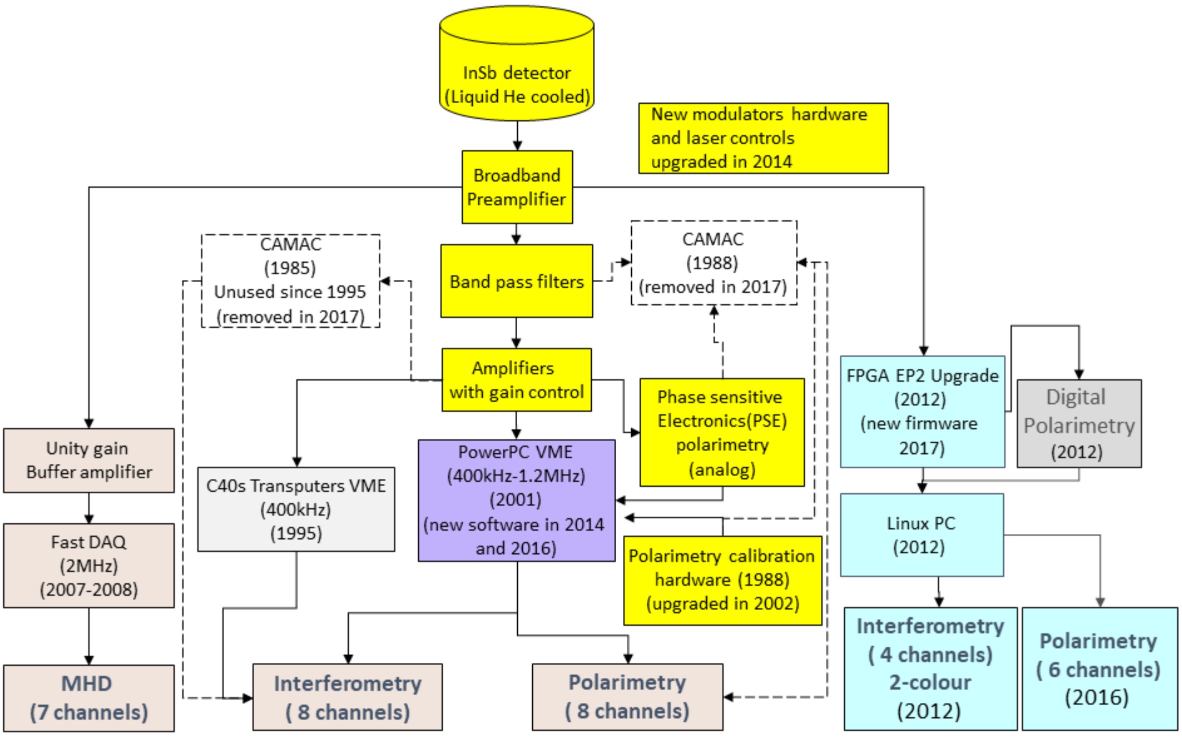

Figure 8 Overview of the JET FIR Diagnostic DAQ

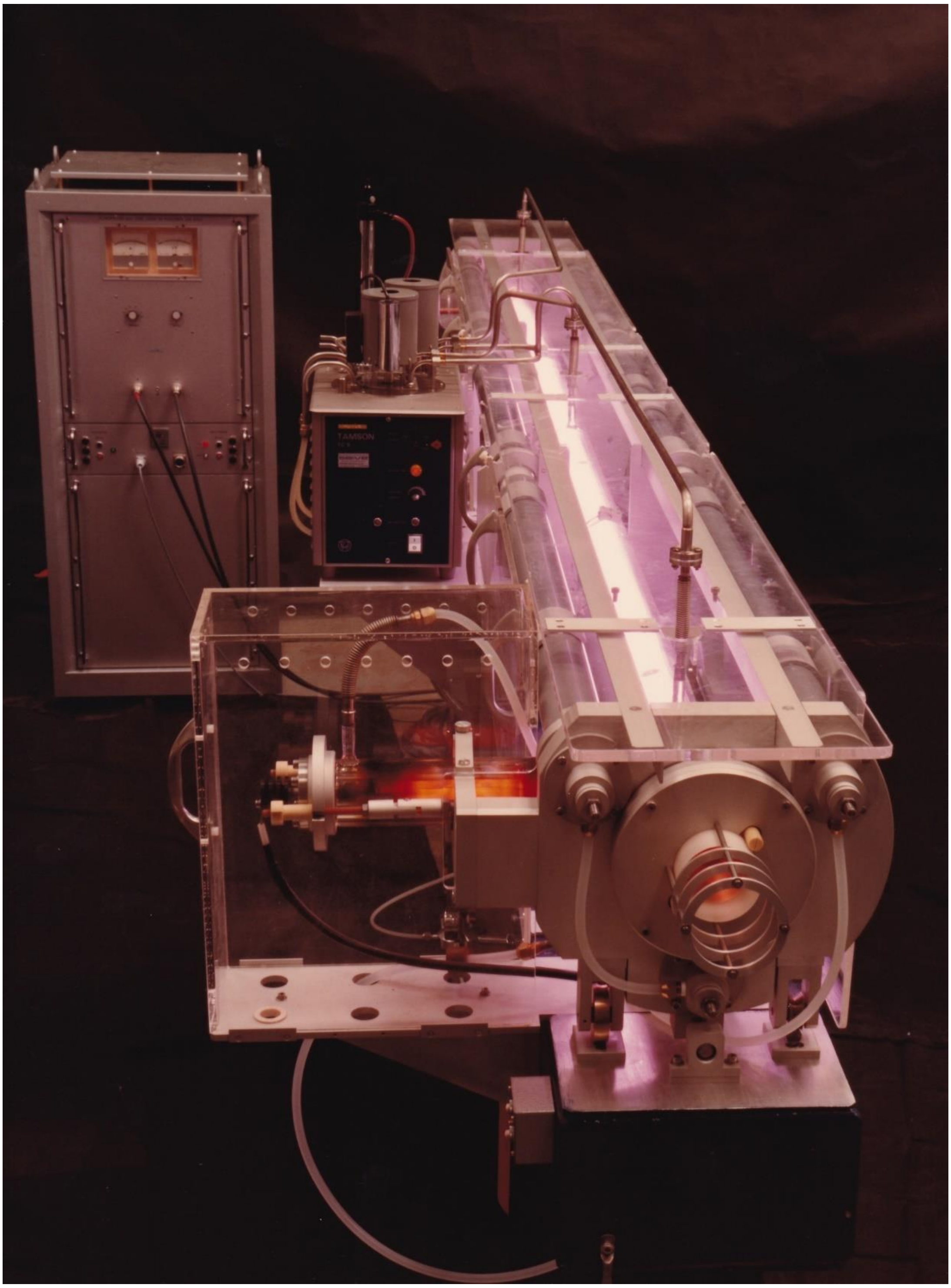

Figure 9 Overview of the FIR Terahertz/FIR lasers platform used for JET interferometer, ToreSupra, FT-U and ASDEX

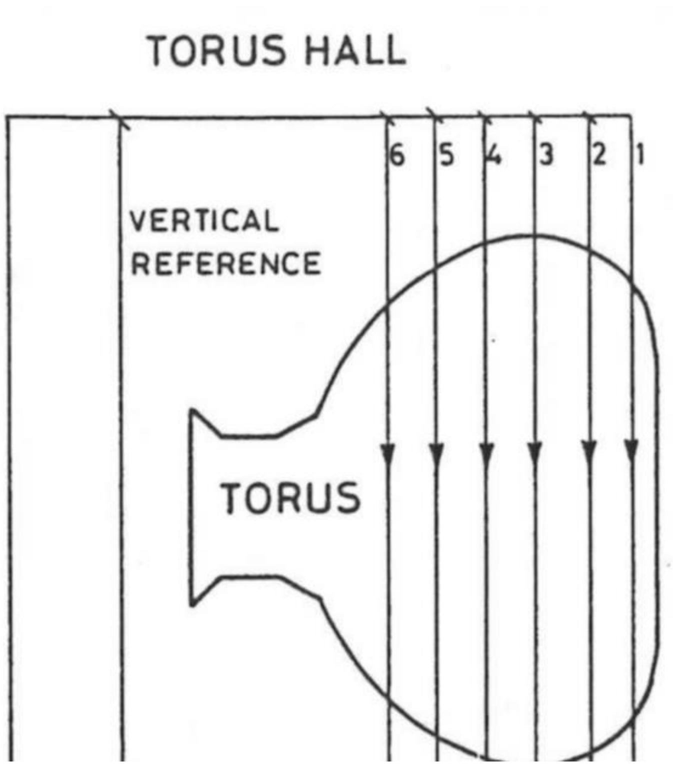

Figure 10 JET FIR diagnostics vertical distribution channels as per 1986 (from 1991 only channels 2,3,4,5 were available)

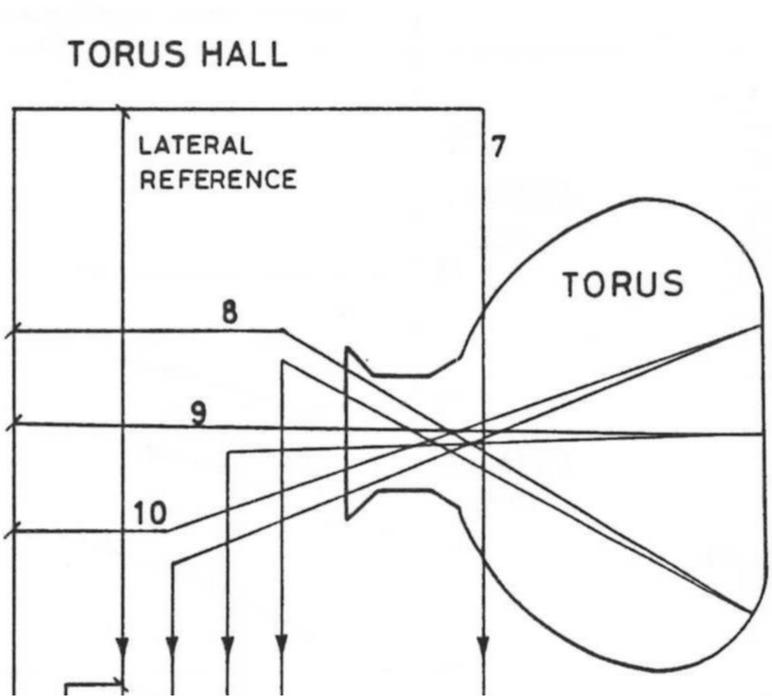

Figure 11 JET FIR diagnostics lateral distribution channels as per 1986 (three channels having in-vessel reflectors)

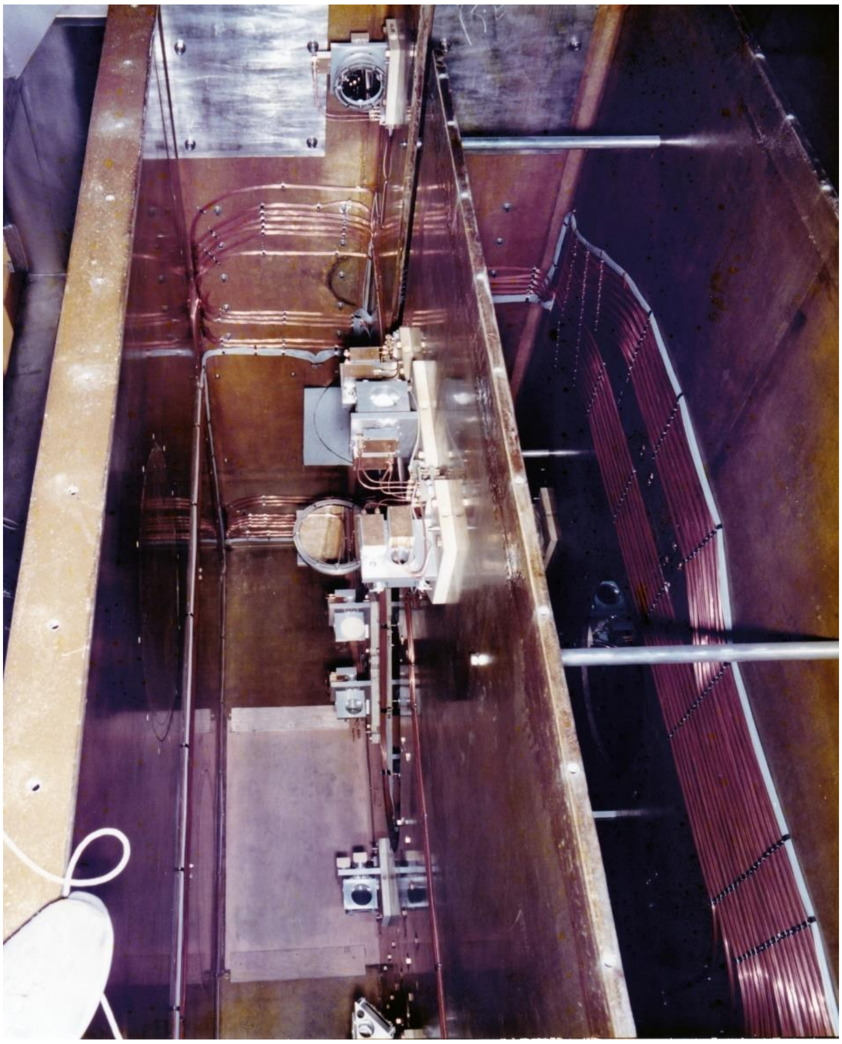

Figure 12 Details of the lower boom of the JET FIR Diagnostic tower with mirrors assemblies inside a very narrow enclosure 50cm wide and 1.5m depth difficult for access even with the cover removed (human white shoe visible on the bottom left side for reference)

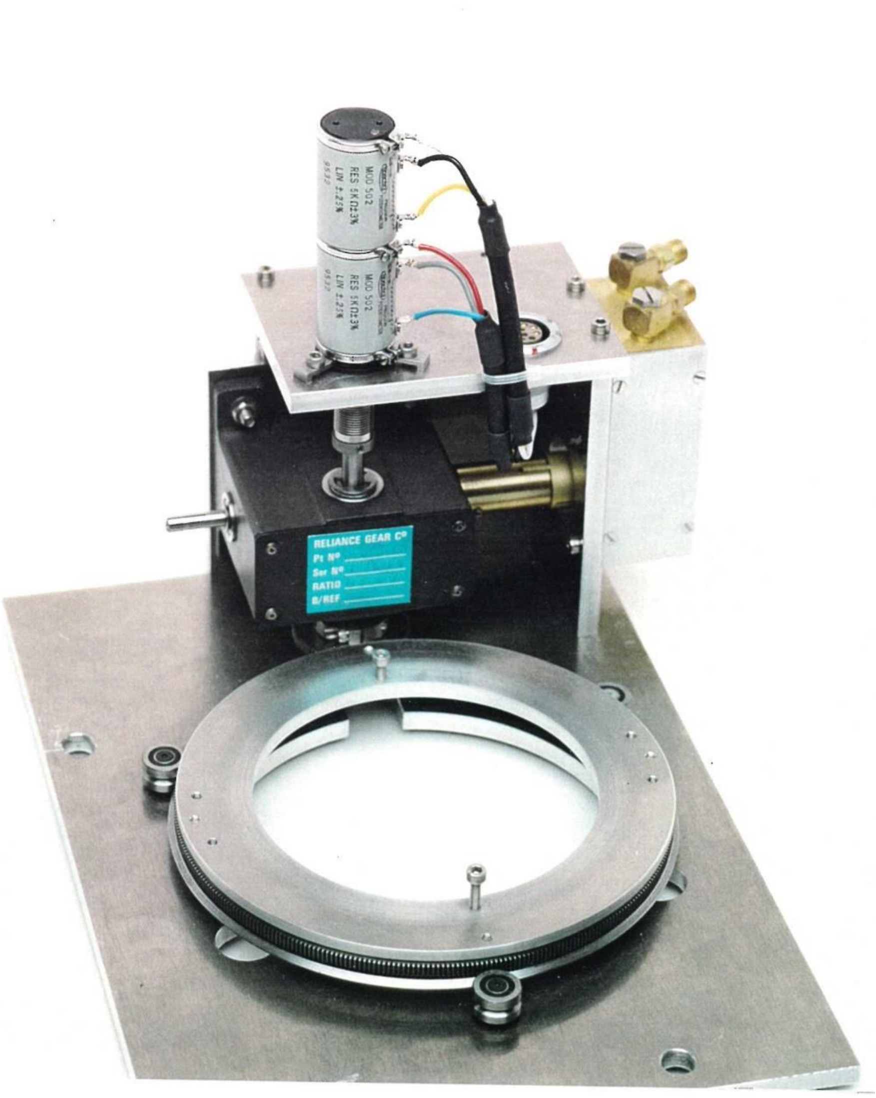

Figure 13 JET FIR Half-wave plate rotator assembly for polarimetry (1987 version)

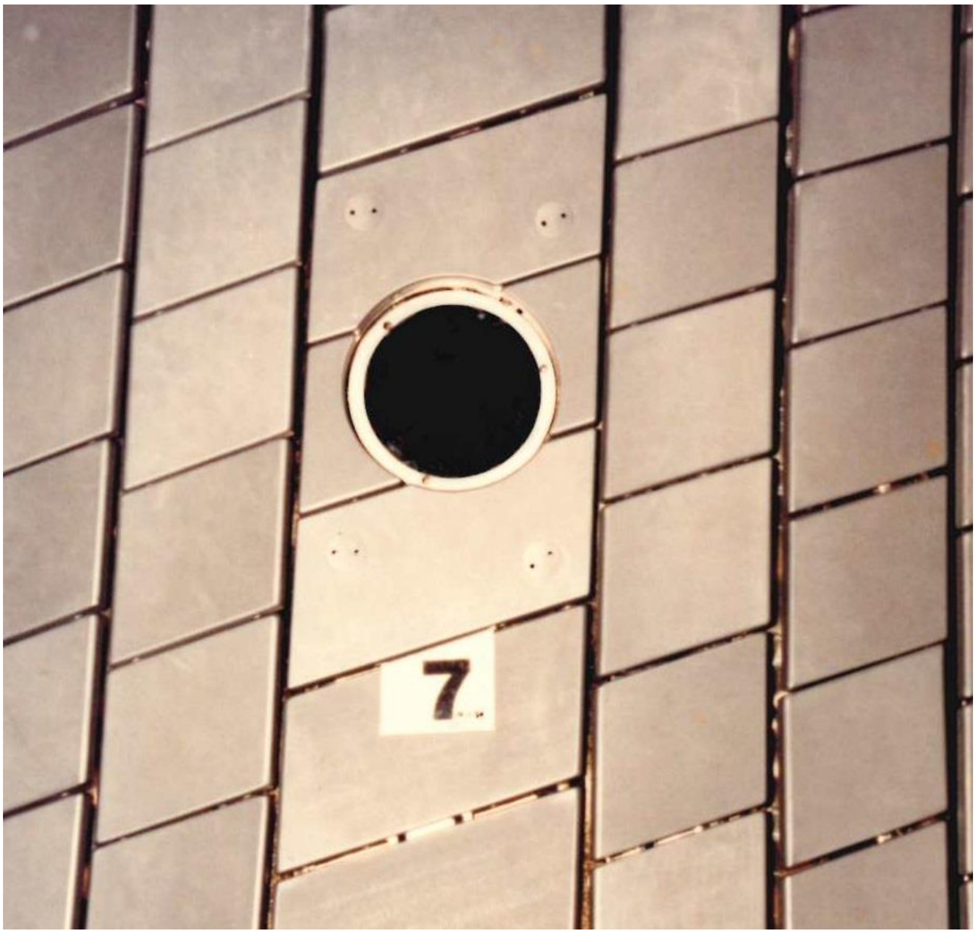

Figure 14 JET FIR In-vessel mirror (1987)

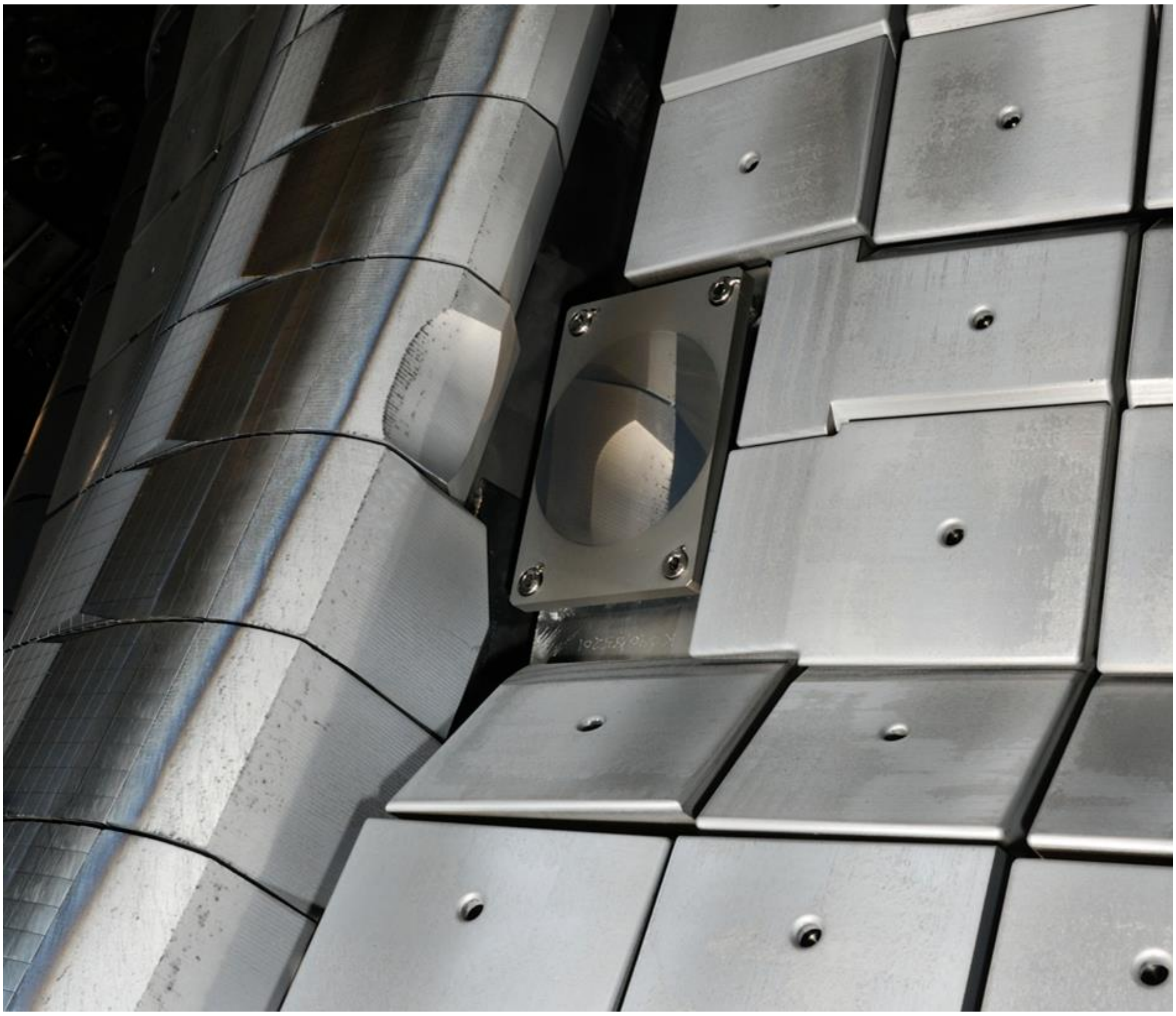

Figure 15 In-vessel mirror for JET FIR diagnostic (installed in 1992, photographed in 2014 during in-vessel photographic survey)

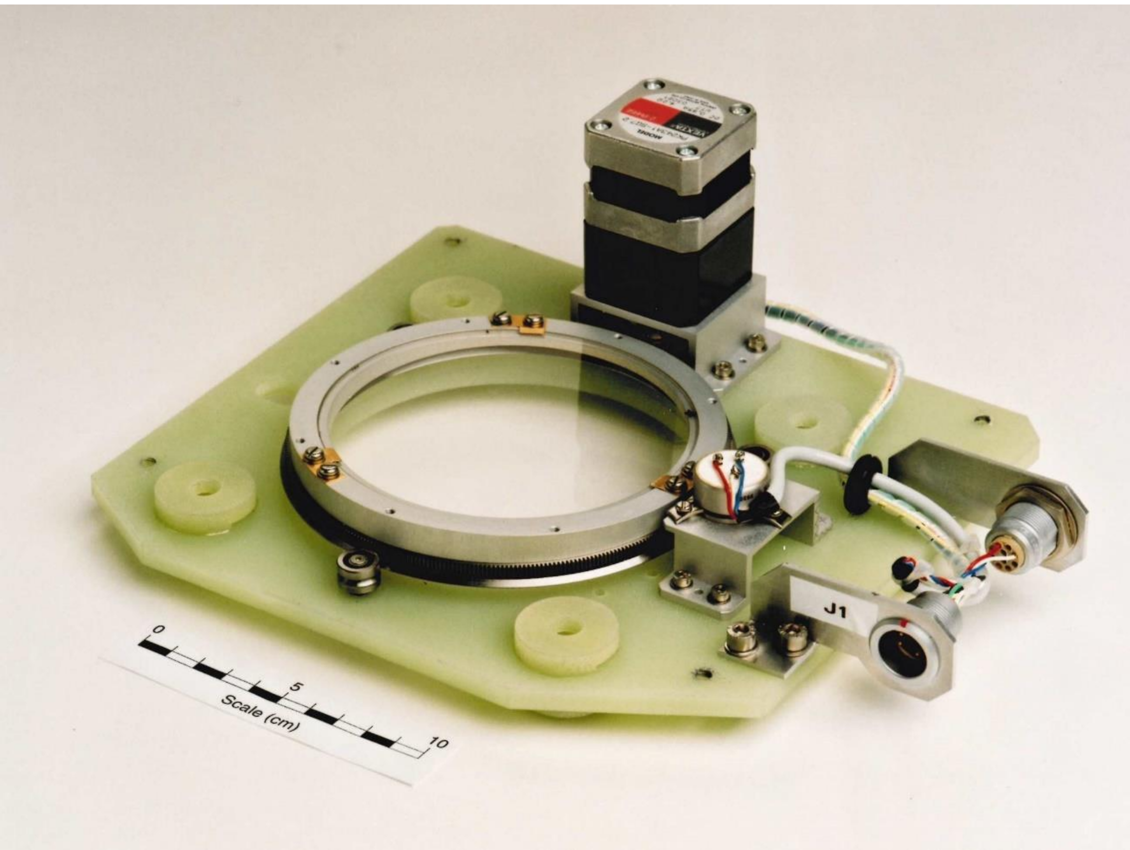

Figure 16 JET FIR Polarimetry Half-wave plate assembly installed in front on JET vacuum windows on the diagnostic tower.

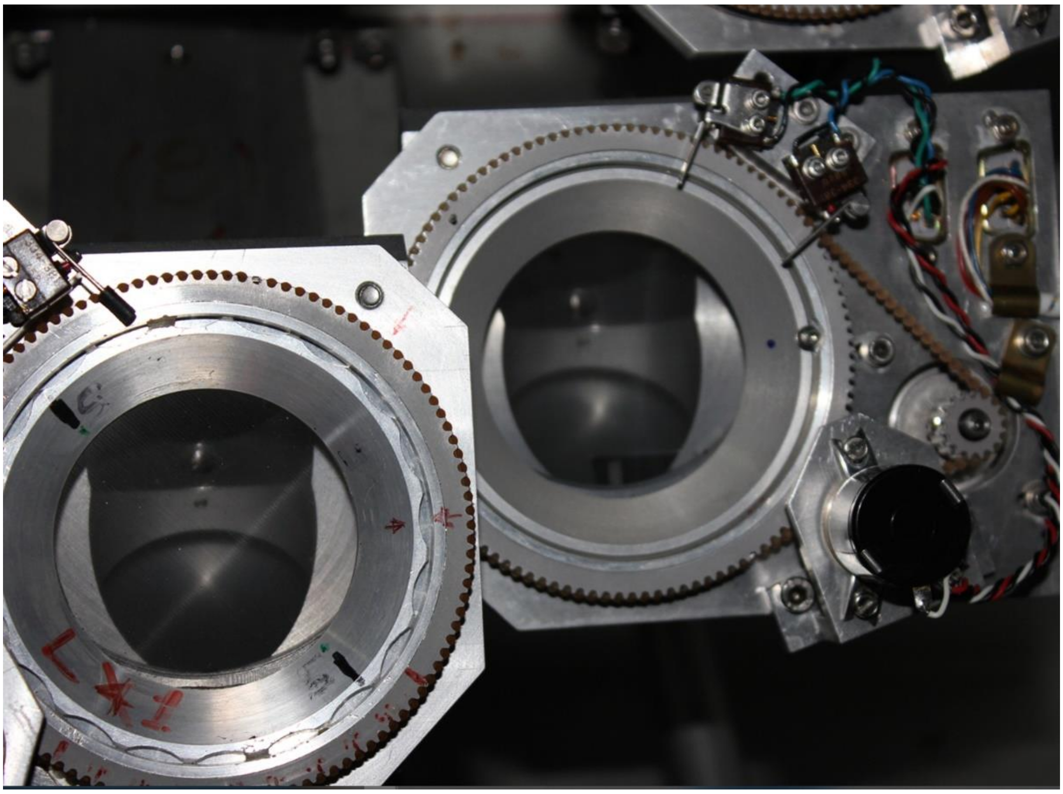

Figure 17 JET FIR Polarimetry motorised Wire-grid analysers (Nickel wires 10μm diameter, 25μm interspace center-to-center) assemblies installed in front on JET FIR detector inside diagnostic lab.

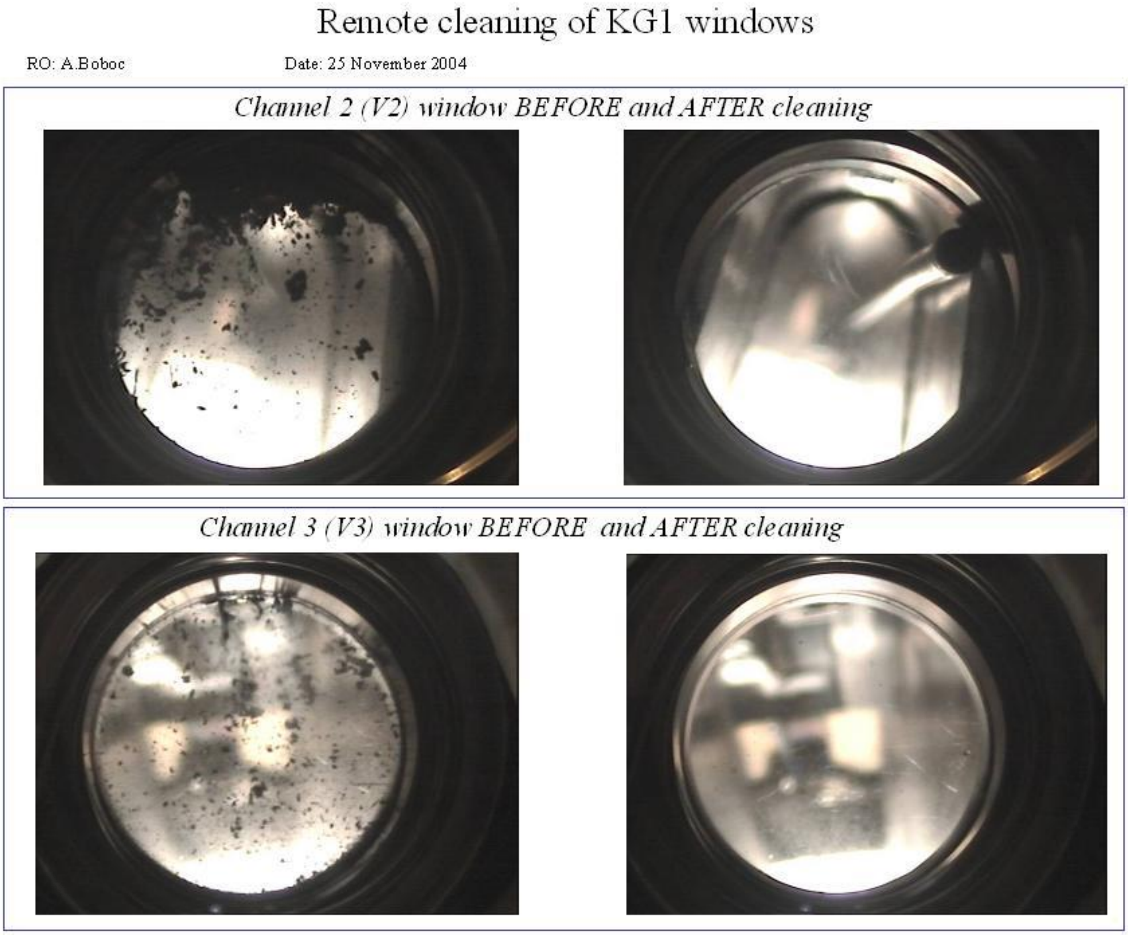

Figure 18 Lower vacuum windows for JET FIR diagnostics corresponding to channels 2 and 3 before and after cleaning.