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* See annex of F. Romanelli et al, "Overview of JET Results",
(23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).

ABSTRACT

In recent years there has been a major upgrade of the JET Far Infrared (FIR) diagnostic system consisting of a new laser system with the wavelength at 118.8mm at and more advanced processing electronics for phase counting. This provides a second colour measurement of the electron plasma density on the vertical system, Due to the shorter wavelength, the plasma induced laser beam refraction is reduced by a factor of three alleviating density errors caused by loss of signal (so-called "fringe-jumps" [2]), in particular during high performance plasmas experiments in JET.

1. INTRODUCTION

Originally designed for five years operation, thirty years later the JET Far Infrared diagnostic (FIR) system [1, 2, 3] is still operating at its full capabilities and in ITER relevant conditions (4.5MA plasmas, 30MW additional plasma heating power and more recently ITER-like wall). This diagnostic system is essential for JET operation as it allow the measurement of the plasma electron density as well as the magnetic field structure in real-time, via interferometry and polarimetry techniques respectively. Reliable density measurements are important for the protection against density limit disruptions and shine-through damage of the inner-wall of JET machine by the neutral beam heating systems.

2. SECOND COLOUR LASER UPGRADE

2.1. GENERAL CONSIDERATIONS

In the original design [1] of the JET FIR interferometer was considered to use only 200mW DCN (Deuterated cyanide) lasers operating at a wavelength of 195mm with a channel distribution of eight vertical channels. Later modification of the vacuum vessel caused the obstruction of some channels and the system has been modified to add several lateral channels, initially two [2] and later four. To compensate the vibrations of the in-vessel mirrors, a compensation laser was necessary. The choice was a new 120mW methanol laser optically pumped by a 40W CO_2 (made by Edinburgh Instruments) and operating at 118.8mm was integrated within the old system. In this way the optics, designed for l95mm, was compatible within to a certain extent with 118.8μm.

Today JET machine operates in completely different regimes from the times when the interferometer was designed. The problems of the FIR interferometer are mainly linked with strong refraction [2] of the DCN beams. This effect, combined with a poor access through the vac-vessel structure (10-60mm clearance apertures) it makes sometimes the measurements very hard to achieve. As the refraction effect varies with the square of the wavelength, a laser with a smaller wavelength was necessary. Due to decommissioning of the Compass-D experiment, we were able to use its FIR laser system for this upgrade. This laser system is a 200W CO_2 laser optically pumping two FIR cavities that can each provide up to 250mW of FIR power at 118.8μm. At this wavelength the refraction effect is reduced by a factor of three and reduces the number of times that the beams are lost due refraction. A secondary advantage of this upgrade is that it creates a redundancy of the plasma density measurements provided by the interferometer.

2.2. MAIN ELEMENTS FOR OPTICAL DESIGN

The main design had to take into account the following constraints:

- 100% backward compatible(no removal of any existing component
- existing optics had been designed for different wavelengths
- very limited available space on the optical tables
- need of the use of Gaussian optics propagation formalism [4]
- use of the second FIR cavity to add a backup to the present compensation laser (increased laser redundancy)
- very small angle of incidence at focusing elements to minimise optical aberrations
- large focal lengths for focusing elements to minimise distortions of Gaussian beams

In order to ensure the proper beam transport for the new beam the ratio between the beam-waists of the two wavelengths has to be equal with the square root of the wavelengths ratio. For example, to a 10mm diameter beam-waist of the DCN beam, an equivalent methanol beam has to have the diameter of 7.8mm.

The final design contains 22 new optical components spanned across three beam paths: lateral beam, vertical probe beam and vertical modulated beam. Gaussian beam propagation formalism was used in evaluating the optical properties of the beams at different stages along the beam path.

2.3. VERTICAL CHANNELS

Two beams have been designed, one for the so-called "probe" beam that passes through the plasma and the second one for the called "modulated" beam required for the beat-signal generation. The beam-waist diameter error, of the new colour, at a distance of 30m along optical path was less than 1% for both beams.

2.3.1 Probe beam

As can be noticed in figure 1 the vertical probe DCN beam is expanding until the first focussing mirror $M_{13.09}$ (FL $= 466$mm). The equivalent beam-waist for the methanol beam is at a distance $z_1 = 498$mm with a diameter of $w_1 = 0.99$mm from $M_{13.09}$. Calculating backwards we obtain an equivalent starting beam-waist at $z_2 = 6.2$m with a diameter of $w_2 = 13.3$mm. This long path was obtained with two plane mirrors (M6V, M7V) and the coupling beam-splitter BS3 to extend the beam. The match of this beam waist with the output of the laser (w_0) was obtained with a two focusing mirror telescope (M2V, M3V) as shown in figure 2.

2.3.2 Modulated beam

The phase modulation of the signal at was obtained with the help of a grating wheel used very often in interferometry [4]. In the design phase one has to take into account that the beam at the grating has to be small enough in order to compensate the curvature of the wheel but large enough to cover

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a minimum of 20 grooves to avoid amplitude modulation. For 118.8mm this diameter has then to be in the order of 1-2mm. This was achieved with the first telescope M2M-M3M as in figure 3. The second telescope it contains a single focusing element M4M and it has the role of matching the beam-waists of the two lasers.

3. PHASE DETECTION ELECTRONICS

The upgrade included a complete review of the phase detection, including analog signal conditioning [5], in collaboration with CEA Cadarache from France. A schematic of the full electronics for one two-colour channel is represented in figure 4. As one InSb FIR cryogenic detector is common to both wavelengths, the signal separation has to be done at the electronics level. In order to avoid interferences between the two colours the frequency of the second colour was chosen 23kHz. This is far from the DCN laser modulation (100kHz). Due to the fact that the signal level between the two colours for each channel can vary substantially it was decided to add a notch filter together with 4th order Bessel band pass filter. The filtered signal can be amplified (30dB range) using a digital potentiometer either manually or remotely. The remote gain control is done via digital input/outputs mapping provided by Ethernet based industrial control ADAM modules (made by Advantech).

Pulse trains are obtained from zero-crossing detection of the sine signals [5] and are then transmitted via optical fibres to digital processing boards containing FPGA's [5,6]. The phase is calculated by time delay counting using a 25MHz clock and correcting the possible fringe-jumps in real time [7]. These boards are fully controlled remotely and send data packets every millisecond in using UDP network protocol to a dedicated Linux PC. The later converts the output to line-integrated density measurements. These are further sent across JET networks (real-time via ATM, JET Pulse File (JPF) data collection etc).

The new method to evaluate the phase by zero-crossing is much more robust and precise than the old "4-point method"2 used currently in our VME and PowerPC (RT) systems that requires a very good quality of the signal, both in shape and amplitude and it has limitation in fringe counting (max. one fringe variation in 10ms). The new system does not have this fringe number limit. Another advantage of the new electronics and control system is that it will have low operational cost in medium/long term (single board cost, short time to replace/set-up, easy commissioning procedure etc).

4. MEASUREMENTS

The two colour operation was achieved recently. One of the first requirements of the new interferometer data was that that the phase error has to be less than 5% of a fringe ($1.143e19/m^2$ particles). This was successfully achieved on both colours from the first measurements with or without plasma (during a plasma pulse there are more vibrations of the interferometer mechanical structure that could affect the performance of the measurements).

Due to the fact that we commissioned the second colour after the start of the JET campaign, the

optical alignment was not optimised for the second colour along the full optical path (two branches of 80meters) and therefore the signal level was lower than expected on some channels. Even with this constraint, the second colour measurements were very good from the first time. Figure 5 displays first ever line-integrated density measurements on the core channel during a JET plasma pulse using simultaneously the two colours. The new built-in fringe-jump detection algorithm that works under FPGA performs much better than the current real-time system and is using both wavelengths simultaneously. In the example shown in figure 6 a perturbation of the plasma that cause a fringe-jump on the DCN (195mm) interferometer signal is detected and corrected by the new hardware.

CONCLUSIONS

The commissioning of the new laser system and additional optics of this upgrade is complete. We routinely measure the line integrated electron density of the both colours. At present is in progress an assessment of the full performance of this upgrade during high performance plasma experiments (24MW additional heating power, gas-injection and pellet experiments, disruptions etc). Next step will be the integration of this new electronics to the JET safety systems.

ACKNOWLEDGMENTS

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[6]. C. Gil et al, Review of Scientific Instruments, **81**, 10D536(2010)

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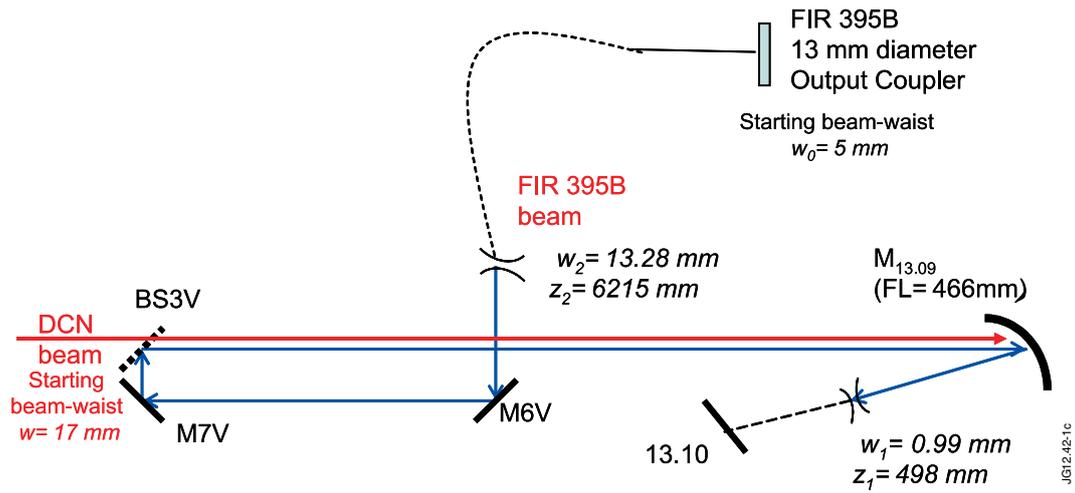
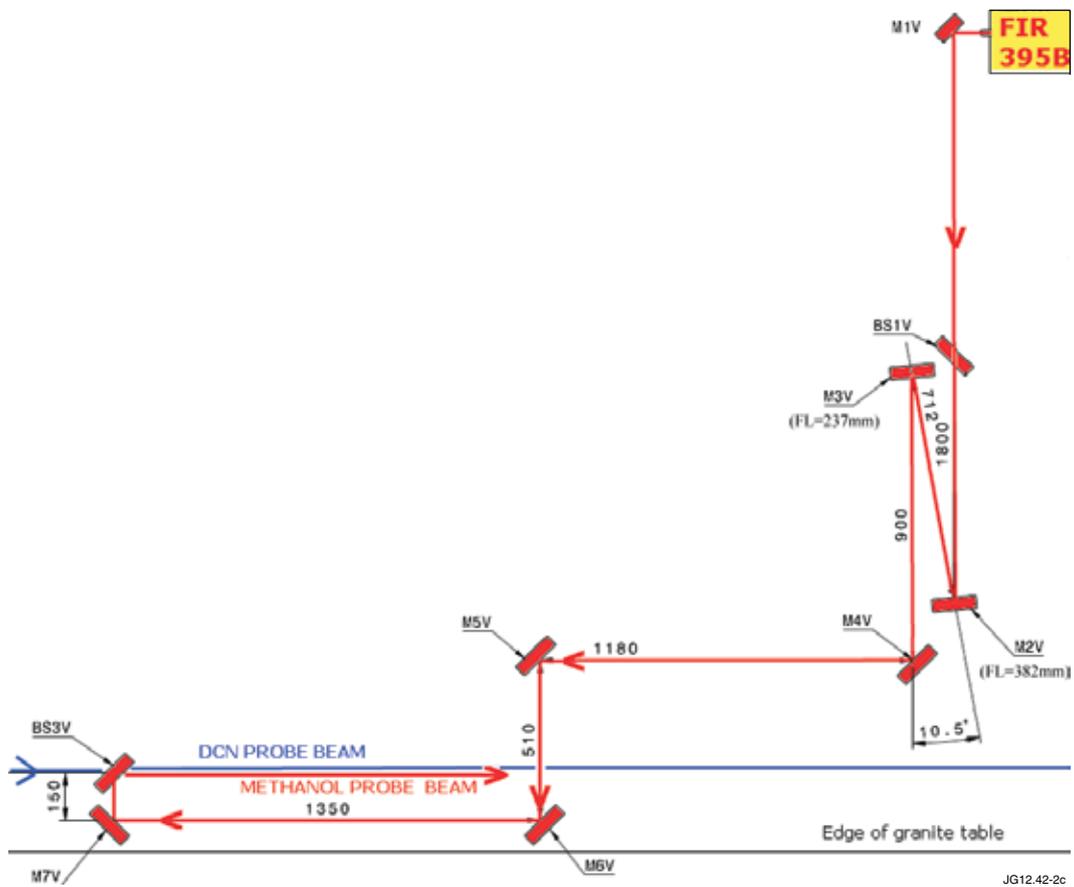*Figure 1: Schematic of the design for the vertical probe beam.*

Figure 2: Spatial distribution of the new optics for vertical probe channels (dimensions are in mm for distances).
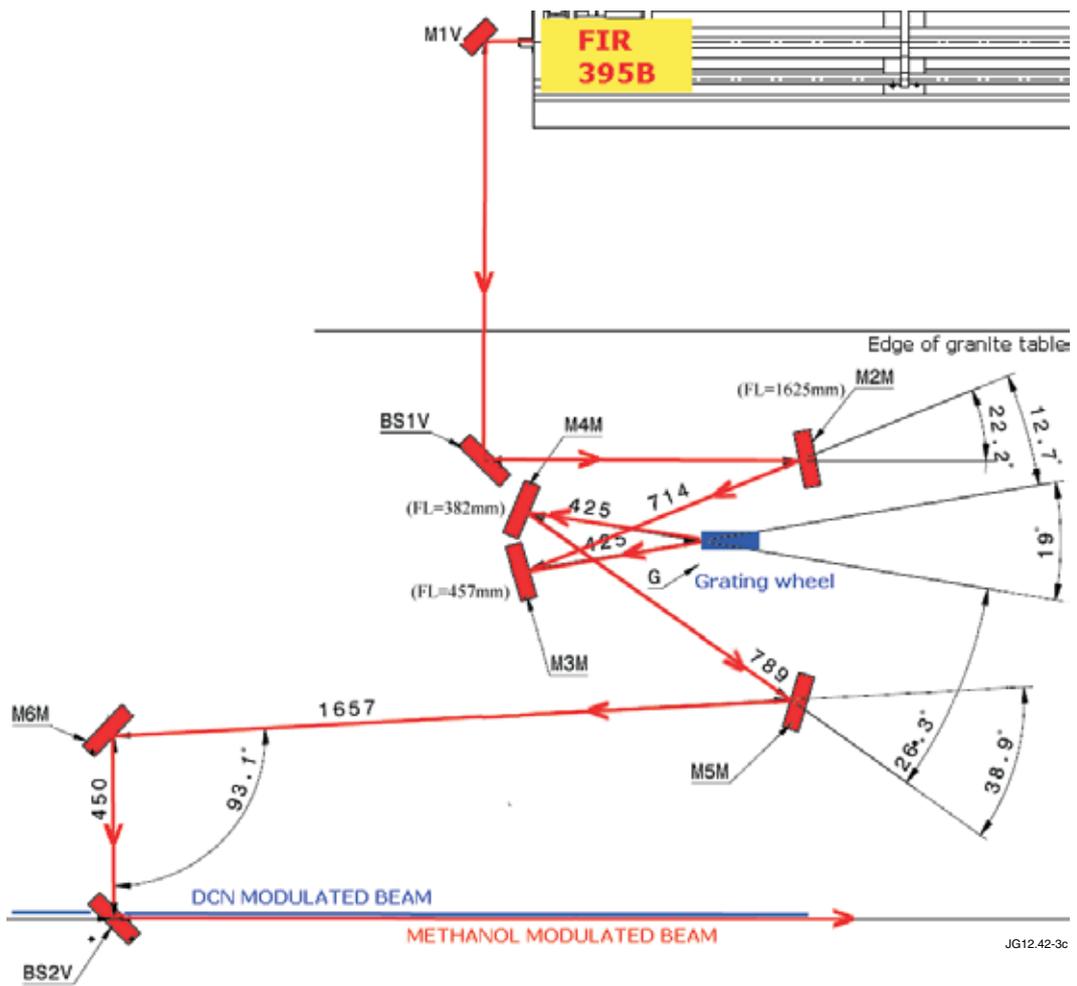
FIR 395B

M1V

Edge of granite table

(FL=1625mm) M2M

BS1V   M4M

22.2°   12.7°

(FL=382mm)   425   714

425   19.°

(FL=457mm)   G Grating wheel

M3M

789

M6M   1657

450   93.1°   M5M

26.3°   38.6°

DCN MODULATED BEAM

BS2V   METHANOL MODULATED BEAM

JG12.42-3c

Figure 3: Spatial distribution of the new optics for vertical modulated channels (dimensions are in mm for distances).

CEA TSE184 Analog board

InSb Detectors (differential output)

23kHz Notch filter → 80-120kHz band-pass filter → Amplifier (AD8220) Gain controller (Altera EPM570Z) → Zero crossing detection

Manual

Remote via Ethernet (ADAM module) → Gain control → RMS → Analog output (monitoring)

ADAM

100 kHz Notch filter → 11-35 kHz band-pass filter → Amplifier (AD8220) Gain controller (Altera EPM570Z) → Zero crossing detection

Pulse trails via optical cables   Probe and reference

Dedicated Linux PC ← Network switch ← UDP packet   **CEA TSE188 Digital board**

FPGA Cyclone III 3C25(40)F324-7

VHDL process for phase calculation and Fringe-jumps correction algorithms built-in

Line integrated density information in real-time (ATM) from the two colour lasers

JET Network

Parameters via Ethernet   CTTS 2MHz Synchronisation clock   Reset
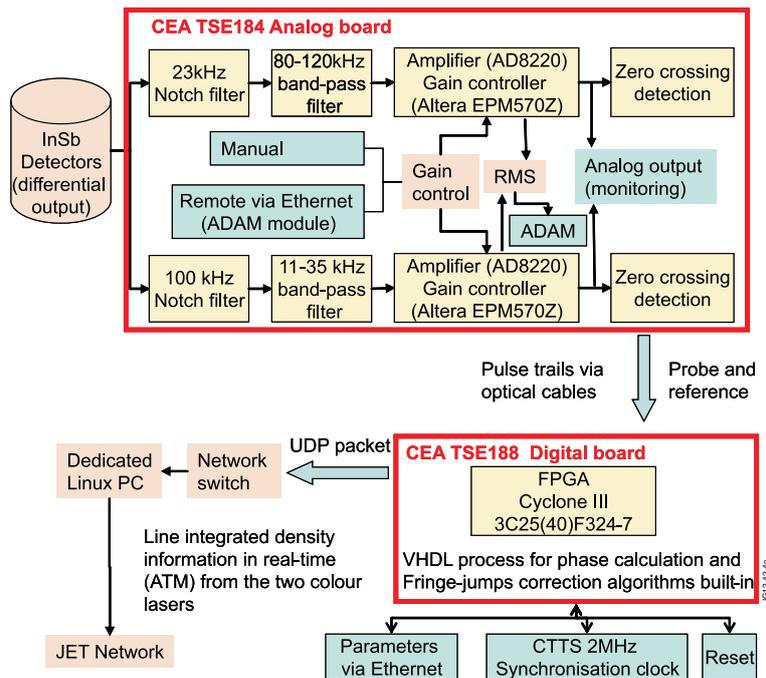
JG12.42-4c

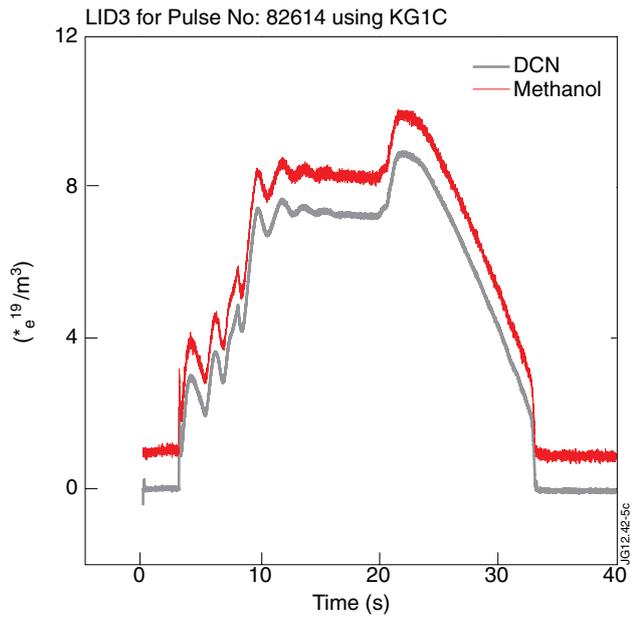*Figure 4: Schematic of the electronics.*

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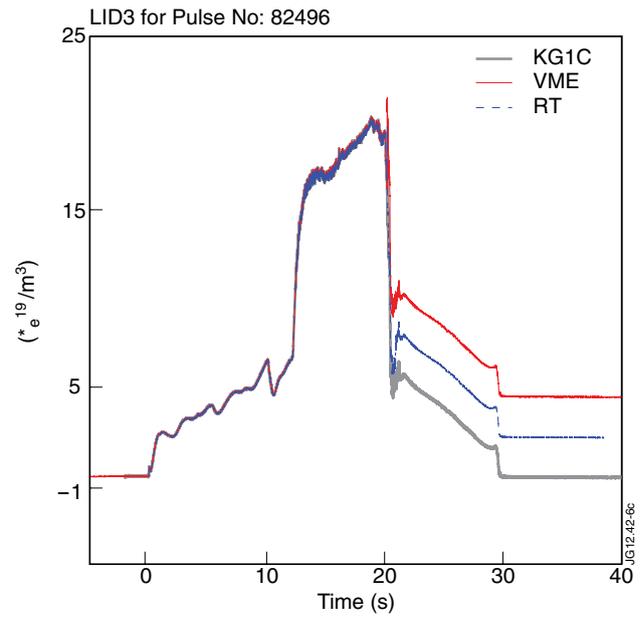*Figure 5: First measurements of the two colours during plasma (methanol signal is offset by +1e19).*

Figure 6: Line-integrated electron density of the core channel using new system (KG1C) and compared with old systems (RT and VME).