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ABSTRACT

Optical interferometers are normally used in magnetically confined plasmas to measure the refractive index of the plasma, from which the line integrated electron density can be derived. Unfortunately, inteferometric measurements are inherently prone to be affected by fringe jumps, which are basically the erroneous phase difference determination, by multiples of 2π, between the reference and the measuring chords. On the other hand, the plasma density has become an essential piece of information for many real time control schemes, which can therefore be completely jeopardised by fringe jumps. To overcome this problem, **the first approach** consists of performing a real time correction of the affected chords, eliminating the spurious effect of the fringe jumps and providing a corrected line integral of acceptable quality. In this respect different algorithms have been developed at JET to correct the fringe jump events and to allow the use of the density measurements for real time purposes. The first category of methods adopted relies only on interferometric signals. The main developed solution is based on the second colour laser available for the lateral channels. Appropriate comparison of the phases of the two lasers allows identification of the fringe jumps and their correction in the vast majority of cases. Different approaches are being developed for the vertical lines of sight, for which the second colour is not available. One alternative is based on the comparison between geometrically similar vertical and lateral channels, with a proper correction taking into the account the plasma shape. A different approach consists of reconstructing the entire density profile with the available signals and of calculating the line integral of the chords affected by the fringe jumps. The second category of solutions tries to exploit other physical phenomena induced on electromagnetic radiation propagating in an optically active medium. The Faraday effect, on one hand, is proportional to the product of the density times the magnetic field parallel to the direction of propagation. Since the field at the edge of the plasma is known in a Tokamak by other diagnostics, this approach can be used to correct the most external interferometric chords. Another alternative is based on the Cotton-Mouton effect, proportional to the density times the magnetic field perpendicular to the direction of propagation, which can be used to correct the vertical lines of sight. Since in some discharges many chords can be so badly affected that their recovery is not feasible with the previous methods, **a second approach** can be adopted based on the observation that, for many real time experiments, an approximate estimate of the density profile is sufficient. This second approach consists therefore of estimating the density profile with a minimum number of available line integrated signals. In JET it was demonstrated that the density profile of the vast majority of configurations could be determined with sufficient accuracy using only two chords, one external and one internal. This is obtained on a simplified elliptical flux surface geometry by performing the Abel inversion of a parameterised analytic line integrated density profile. The various solutions were tested and results compared in order to verify the most suitable for the various plasma configurations and operational scenarios. A “general purpose” version of the correction algorithm was implemented and is not normally running during JET operation. The implementation a second colour (figure 10) also for the vertical channels is under study and developing phase.

1. INTRODUCTION

In general interferometers measure the optical path along a light beam in terms of the radiation wavelength [1]. The optical path is the product of the geometrical path and the refractive index of the medium. In magnetically confinedplasmas, which are very difficult to access and diagnose, interferometry is a very powerful tool to determine the refractive index and derive from it the plasma density. To avoid the absorption of the laser beam inside the plasmas, lasers of long wavelength (far infrared region) are normally chosen. To compensate for the possible variations of the optical path, a second compensation laser is often installed, implementing so-called two-colour interferometers. Unfortunately laser beams with longer wavelengths are also more strongly refracted due to plasma densities gradients that cause variations of the refractive index. In fusion machines abrupt transient changes of the density gradient of the plasma, and therefore of the refractive index, can be the consequence of both plasma phenomena, like Edge Localised Modes (ELMs) or disruptions, and externally triggered events, like pellet injections. During these highly dynamic phases, the signal can be lost or altered for significant periods of time, creating a wrong reconstruction of the measured phase between the measuring and reference beam, which is called a fringe jump (see section 2).

In the last years, the real time control of various plasma scenarios has become one of the most qualifying programs on the route to a next step Tokamak. The feasibility of these control schemes depends crucially on the quality and reliability of the diagnostics involved and the plasma density is one of the most frequently required. In this perspective, on JET a fast acquisition system [2] for the interferometer/polarimeter diagnostic [3] was recently installed (see section 2). It produces a measurement every millisecond and it was fully validated in the last campaigns. The main problem faced by the system consists of the fringe jumps, consequence of the strong variations of the density, which can completely jeopardise several real time control schemes. In this paper a quite exhaustive series of techniques to recover the correct measurement of the electron density after a fringe jump is reviewed and the results of their implementation on JET are reported.

In general ***two main approaches*** can be adopted, one meant to correct the effect of the fringe jumps and recover the correct line integrated signals, and the second aiming at the derivation of an approximated density profile on the basis of a minimum number of chords available. In the first approach the possible methods, which can be used to correct the interferometric measurements after the occurrence of fringe jumps, fall mainly in two groups. The first category includes the approaches that use only the interferometric data (see section 3). The most effective correction algorithm in this class exploits the two colours of the lateral channels. The signals of the two lasers are compared and this allows identifying the most suitable correction of the measurements. In the case of the vertical channels, for which the second colour is not available, one reasonable alternative, very useful for the high time resolution that it guarantees, is based on the comparison of the chord affected by the fringe jump with the closest lateral line of sight. Taking into account the relative length of the chords, available in real time, and a suitable profile factor, the proper value of the measurement can be recovered. A possible different approach consists of reconstructing the entire density profile, with only the chords not affected by the fringe jumps or the horizontal ones corrected using the second colour, and then calculating the missing line integrals.

The second class of solutions includes methods based on the effect of an optically active medium, like fusion plasmas, on the plane of polarisation of the beam light. The two essential physical phenomena investigated so far are the Faraday rotation and Cotton-Mouton effect (see section 4). The polarisation plane of a laser beam is rotated by magnetised plasma of an angle, which depends on the product of the electron density and the magnetic field parallel to the propagation direction. This so-called Faraday rotation can be exploited in a machine like JET, to determine the plasma density at the edge of the plasma column where the magnetic field is known from the external pick up coils (see section 4). The Faraday rotation is indeed normally well below 360 degrees and therefore the loss of the signal for short intervals, due to ELMs or pellets, does not compromise the measurement.

This also because it is an absolute measurements and not history dependent such as in the case of interferometric measurements. This solution is particularly useful for the correction of the external channels during pellet injections, which have such a strong effect on the plasma to sometime compromise the other techniques. The Cotton Mouton effect consists of the change of ellipticity of the radiation propagating perpendicular to a component of the magnetic field (see section 4). In JET geometry, the Cotton-Mouton effect is proportional to the density times the toroidal field, which is also well known from independent diagnostics. This effect, measured with high accuracy with a particular set-up of the diagnostic, doesn’t suffer from the fringe jumps problem and can be exploited to correct the vertical channels along which B_{tor} is constant.

In the case many chords are affected by fringe jumps and cannot be recovered, a second approach can be adopted, which consists of estimating the density profile in a simplified way on the basis of the few chords available. In JET it was demonstrated that the vast majority of line integrated profiles can be represented by a simple analytical expression, whose parameters can be constrained by the signals of only two interferometric chords, provided one is central and one lateral. The obtained function can then be inverted with help of the Abel integral equation (see section 5), providing a density profile of acceptable quality for real-time purposes.

2. JET INTERFEROMETER/POLARIMETER AND THE PROBLEM OF FRINGE JUMPS

2.1. JET INTERFEROMETER/POLARIMETER

In JET the interferometer polarimeter was originally conceived to provide the measurements of the plasma density, Faraday rotation and Cotton-Mouton effects along 4 vertical and 4 nearly horizontal lateral channels (Fig.1). With regard to the plasma density, the diagnostic implements an interferometer of the Mach-Zehnder type. The relation between the phase shift directly measured and the electron density is expressed by the formula:

$$\Delta\phi = C_{int}\lambda\int_{1} n_e(l)dl \tag{1}$$

where λ is the wavelength of the radiation and C_{Int} an appropriate instrumental constant. Given the wavelength used and JET usual densities, the phase difference $\Delta\phi$ between the reference beam and the one passing through the plasma can very rapidly exceed an angle of 2π. Therefore, if in intervals of strong variation of the plasma density the signal is lost, the measurement can be compromised, in the sense that an arbitrary multiple of 2π can be spuriously added to the measurements. This kind of error is called fringe jump because it is normally experienced by the users of the diagnostic as an abrupt and spurious change of the density measurement.

In addition to the interferometric measurements, the use of suitable metallic grids allows the contemporary determination of the polarisation state of the beam. Given the geometry of the chords, the Faraday rotation $\Delta\Psi$ of the beam electric field polarisation plane is linked to the plasma parameters by the relation:

$$\Delta\psi = c_{far}\lambda^2\int_{1} n_e(l)B_{II}(l)dl \tag{2}$$

where λ is the wavelength of the radiation, c_{Far} a constant and B_{II} is the component of the poloidal field along the direction of the propagation.
The Cotton-Mouton effect in its turn, is expressed by the relation:

$$\Delta\Gamma = c_{CM}\lambda^2\int_{1} n_e(l)B_{\perp}^2(l)dl \tag{3}$$

In (3) it must be noticed that the change $\Delta\Gamma$ in the ellipticity of the beam is proportional to the square of the field component perpendicular to the propagation direction of the beam.

All the mirrors of the vertical channels are installed on an isolated C frame (tower) structure meant to provide enough mechanical isolation. The spurious displacements of the mirrors are therefore normally very low and for these vertical channels only a DCN laser (λ = 195μm) was originally foreseen. The lateral channels on the other hand, as it is often the case in Fusion machines, have to make recourse to in-vessel mirrors to reflect the radiation and therefore can suffer from large geometrical path variations due to the vibrations of the machines. As a consequence, for these lateral channels a second alcohol laser (λ=118.8μm) is used to implement a compensated interferometer with path length correction (two colours interferometer). The reference beam of both lasers is frequency shifted by a rotating grating to implement a heterodyne detection scheme [1]. The DCN laser is shifted by 100kHz, whereas the shift of the alcohol laser is only 5kHz. Both lasers are recombined on the same detectors and the separation of the 5 and 100kHz components is obtained electronically by the use of suitable low-pass (0-30kHz) and band-pass (60-140kHz) filters.

With regard to the signal processing electronics, the reference and signal beams are digitised separately at a frequency of 1 MHz and then resampled with 400kHz frequency before the phase computation. The polarisation measurements, in their turn, are digitised with 1KHz sampling rate in order to produce a data each ms.

2.2. THE CAUSES OF THE FRINGE JUMP PROBLEM

The main reasons behind the vulnerability of JET interferometer to fringe jumps in the phase measurements was carefully investigated first. A detailed analysis of the signals sampled and recorded at 1 MHz was performed and the details are reported in [4]. To summarise, the DCN detected signals in general drop almost to zero at each fringe jump event. In the case of the alcohol laser, the situation is a bit more involved because in some occasions, even if the signal is well above zero, it presents a completely non periodic form, indicating the presence of spurious effects. In both situations, it becomes impossible to use the amplitude signal for the calculation of the proper phase difference between the reference and the measuring beam. Since in all the cases, during this period of signal loss or deformation, the reference channels do not show any notable amplitude variation, the fringe jumps are attributed to plasma phenomena. In most of the cases the signal is degraded in presence of plasma events associated to local density build up (like during ELMs), with consequent strong increase in the plasma density gradients, or after very fast big changes of the density amplitude (like during disruptions or pellets injection). In the first case the problem is therefore very likely due to refraction, whereas for very fast variations of the all density the main difficulty probably resides in the too slow frequency modulation.

In the following, the various methods implemented at JET to correct the fringe jumps are reported, with particular attention to the assessment of their relative merits and potential of application. For each category of solutions, the technique to detect the occurrence of fringe jumps is introduced first then the correction technique is described together with a short review of the statistical results.

3. CORRECTION METHODS BASED ON THE INTERFEROMETRIC DATA.

3.1. TWO COLOURS CORRECTION METHOD FOR THE LATERAL CHANNELS

Since, as mentioned before, the lateral channels implement a compensated interferometer, the occurrence of fringe jumps can be detected from the time evolution of the path length. Indicating with V the variations of the optical path, the phase measurement of the two wavelengths can be written as follows:

$$\emptyset_1 = K\lambda_1 \int_l n_e dl + \frac{2\pi V}{\lambda_1} \tag{4a}$$

$$\emptyset_2 = K\lambda_2 \int_l n_e dl + \frac{2\pi V}{\lambda_2} \tag{4b}$$

where λ_1, and λ_2 are the main and compensation wavelengths, *V* is the change in optical path due to vibrations and *K* is a constant equal to:

$$K = \frac{e^2}{4\pi c^2 \varepsilon_0 m_e} = 2.82 \cdot 10^{-15}\,(\mathrm{m}) \tag{5}$$

Multiplying equations (4a) and (4b) respectively by λ_1 and λ_2 then making the difference, it is possible to obtain the line-integrated density and vibration amplitude:

$$n_e dl = \frac{1}{K}\,\frac{\lambda_1\phi_1 - \lambda_2\phi_2}{\lambda_1^2 - \lambda_2^2} \tag{6a}$$

$$V = \frac{1}{2\pi}\,\frac{\dfrac{\phi_2}{\lambda_2} - \dfrac{\phi_1}{\lambda_1}}{\dfrac{1}{\lambda_2^2} - \dfrac{1}{\lambda_1^2}} \tag{6b}$$

This quantity *V*, the variation of the optical path, presents very abrupt changes corresponding when fringe jumps occurs and therefore this measurement can be used to detect them.

Once determined the occurrence of fringe jumps very reliably with the approach discussed above, for their correction a method already devised in Tore Supra [5] was adopted. Since all the details of its implementation at JET have already been reported in [4], in the following only a concise overview of the technique will be given.

The phase variation between two sampled points, one immediately after the signal is recovered and one just before the fringe jump, can be written in the following way:

$$\Delta\phi_1 + 2\pi\Delta F_1 - \frac{2\pi\Delta V}{\lambda_1} = K\lambda_1\Delta\int_1 n_e dl \tag{7a}$$

$$\Delta\phi_2 + 2\pi\Delta F_2 - \frac{2\pi\Delta V}{\lambda_2} = K\lambda_2\Delta\int_1 n_e dl \tag{7b}$$

Where ΔΦ is the phase variation in the range [-2π, 2π] and ΔF is the variation in the number of fringes. Dividing by λ and combining the two equations it is possible to find the relation:

$$\Delta F_1 = \left(\frac{\Delta\Phi_2}{2\pi} + \Delta F_2\right)\frac{\lambda_1}{\lambda_2} - \frac{\Delta\Phi_1}{2\pi} - \frac{\Delta V}{\lambda_1}\left[\left(\frac{\lambda_1}{\lambda_2}\right)^2 - 1\right] \tag{8}$$

where ΔF1 and ΔF2, being fringe jumps, which occur in multiples of 2π, must be integer numbers. For long wavelengths interferometers (typically FIR), on short time intervals the phase variation due to the change in the optical path, ΔV, is usually very small compared to the phase variation due to the density. Neglecting ΔV relation (8) gives:

$$\Delta F_1 = \left(\frac{\Delta\Phi_2}{2\pi} + \Delta F_2\right)\frac{\lambda_1}{\lambda_2} - \frac{\Delta\Phi_1}{2\pi} \tag{9}$$

Various couples of integer values are tried, starting from the lowest numbers, and the one which best satisfies equation (9) is chosen, providing the required correction as shown in fig.2.

Using the previously described method, in discharges with type I ELMs, the density is properly corrected in about 80 % of the cases. The statistics is not equally positive in the case of pellets, which are very dramatic events, which can cause the signal being lost for too long to allow a proper correction. For type III ELMs, the situation is more involved and depends on the frequency and strength of the ELMs. To summarise, it can be stated that if the signal can be recovered sufficiently quickly, the percentage of success can be similar to the case of type I ELMs. On the other hand, the performance can deteriorate significantly, with increasing frequency and strength of the events, if the signal is lost for more than 2 ms.

3.2. METHODS BASED ON INTERFEROMETRIC DATA FOR THE VERTICAL CHANNELS

The vertical channels are not compensated (only the DCN laser was installed) and therefore for them a different solution must be found. First of all an alternative procedure is necessary to identify the occurrence of fringe jumps. This is obtained comparing the difference between corresponding vertical and horizontal chords at two consecutive times (chord 2 with 7, chord 3 with 8 and chord 4 with 5). Fringe jumps cause this difference to exceed an experimentally found value, revealing their presence.

3.2.1. Correction based on the density profile

Having detected the fringe jump, a first approach to correct the vertical channels consists of using the whole density profile reconstruction. On the basis of the four lateral channels, possibly recovered with the method described in the previous section, and the correct vertical ones, the density plasma profile is reconstructed, using a best-fit method on the internal magnetic topology, assuming constant density on the iso-flux surfaces [6]. The internal flux surfaces are described in the usual parametric form, which depends on elongation, triangularity and magnetic shift, quantities that can be deduced in real time from the external magnetic measurements:

$$f\,(R,Z) = \begin{cases} R = R_{axis} + \Delta\,(\rho) + \rho\,cos(\vartheta + \gamma\,(\rho)\,sin\vartheta) \\ \mathrm{Z} = \mathrm{Z}_{\,axis} + \rho K\,(\rho)\,\sin\vartheta \end{cases} \tag{10}$$

where ρ is the minor radius of the flux surface, Δ(ρ) is the magnetic Shafranov shift,γ(ρ) the triangularity and K(ρ) the elongation. On the described magnetic topology, figure 3, interferometric data can than be inverted with a best-fit method and a simple SVD (singular value decomposition). The formula chosen to describe the density profile depends on 3 parameters:

$$n_e\,(\rho) = n_0(1-\rho^2)(1 + p\rho^2 + q\rho^4) \tag{11}$$

A careful statistical analysis of many plasma scenarios proves that this parameterisation of the density profile is more than adequate for real time purposes. This is particularly confirmed by a systematic comparison of the derived density profiles with the LIDAR Thomson scattering data [7]. The profiles obtained with this inversion algorithm can be used to calculate the density of the vertical chords affected by fringe jumps. In figure 4 the raw signal, the off-line corrected line density and the output of the correction algorithm are compared, showing the quality of this solution. This method performs very well in case of fringe jumps due to ELMs and is also quite effective in the case of pellets. In particular for fringe jumps due to both types I and III ELMs, the recover density measurements increases to a rate of 80%, comparable to the performance of time approach for the horizontal chords. Unfortunately the elaboration time is of the order of three milliseconds and therefore not always completely satisfactory. In any case, given the typical time scale of JET, this time resolution is more than adequate for the vast majority of real time experiments.

B.2 *Correction based on comparison of chords*

Since in many applications a faster technique is necessary, a different approach was adopted, based on the direct comparison between vertical and lateral channels, normalised to the length of the line of sight, which is available in JET on a sub-millisecond time scale [8]. An appropriate geometrical factor, to take into account the plasma shape, is also necessary for the proper application of this approach. Fortunately, this can be in general very easily determined by comparison between the corresponding chords just before the fringe jumps. The “geometrical factor” calculated just before the fringe jump with relations of the kind:

$$\int_{Vertical} n_e dl = geomFactor \int_{Lateral} n_e dl \tag{12}$$

can be used to calculate the number of fringes needed to correct the affected vertical chord:

$$nFringes = round\left(\frac{Vertical - geomFactor \cdot Lateral}{1.14 \times 10^{19}}\right) \tag{13}$$

A time resolution of better than one ms is easily achieved with this solution. This method is therefore the one presently implemented at JET. For type I ELMs the percentage of success is around 60% and for sporadic, individual events good correction can be achieved much more often. An example of successful correction for a discharge with significant ELM activity is shown in fig.5 where the density (green) is well recovered after each fringe jump. On the other hand, the main problem is in presence of the high frequency events, like type III ELMs, where the corrupted signals are sometimes recovered only after too long and the correction approach fails. So even the success of this technique is strongly dependent on the nature of type III ELMs, and normally fails if the signal is lost for more than 6ms.

Even if the methods based on purely interferometric measurements are giving positive results and the corresponding algorithms have been implemented and are now routinely used at JET during real time sessions, they are not completely satisfactory yet. There is therefore some scope in investigating alternative approaches, at least to alleviate the most severe weaknesses of the previous techniques. The first results obtained in trying to exploit the Faraday and the Cotton-Mouton effects are described in the following section.

4. CORRECTION METHODS BASED ON THE FARADAY ROTATION AND THE COTTON MOUTON EFFECT.

4.1. TECHNIQUE BASED ON THE FARADAY ROTATION EFFECT

As mentioned in the introduction, the Faraday rotation effect consists of a rotation of the polarisation plane of linearly polarised radiation, consequence of the optical activity induced in certain media by the presence of a magnetising field. The relevant component of the field is the one parallel to the direction of propagation. In fusion plasmas, this rotation depends also on the electron density as expressed by relation (2). In JET geometry the measurement is sensitive according to:

$$\Delta\Psi = c_{Far} \int_l n_e(l) B_{\vartheta !!}(l) dl \tag{14}$$

where C_{Far} is a constant and $B_{\vartheta !!}$ is the poloidal field component along the line of sight

Since the poloidal field (B_ϑ) at the edge of a Tokamak can be accurately determined with the help of pick-up coils, whose signals are already available in real time at JET, the Faraday rotation can be used advantageously to correct the most external chords. Indeed, the previous methods for the vertical channels, based on interferometric information only, present a clear weakness in the case of chord four, which, being the most external, has normally a lower signal to noise ratio. Assuming constant the poloidal field along the line of sight of chord four, relation (14) gives:

$$\Delta\Psi = c_{Far} B_\vartheta \int_l n_e(l) dl = c_{Far} B_\vartheta N_e \tag{15}$$

from which the line-integrated density can be easily calculated:

$$N_e = c_{Far} B_\vartheta / \Delta\Psi \tag{16}$$

For the poloidal field, the average of the two values calculated at the intersections between the last close flux surface and the line of sight is generally used.

This alternative estimate of the line-integrated density can be compared with the interferometric data and used to determine the appropriate correction in terms of fringes. The fringe jump detection is completely analogous to the one adopted for the other methods described in the previous section and consists of comparing the line integral of chord 4 with the corresponding measurement of chord 5. An example of correction of chord four with this method based on the Faraday effect is reported in fig.6. This approach results particularly useful in discharges in which pellets are launched inside the plasma. In this case the density rises very fast, with a consequent strong variation of the interferometric measurements, particularly evident in the edge chord 4. The polarimetric data presents a much smoother evolution during this fast transient phase, allowing a quite reliable correction even in these situations where the other methods normally fail. On the other hand, since in JET polarimeter the bandwidth of the electronics for the Faraday rotation measurements is much slower than the one of the interferometer, it can be difficult to apply this correction approach to events like the ELMS, which can cause fast oscillations of the edge density.

4.2. TECHNIQUE BASED ON THE COTTON-MOUTON EFFECT

The technique based on the Cotton-Mouton [11] effect can be applied only for the vertical channels because the perpendicular field is almoust constant along line of sight. As can be seen in relation (3), the polarisation depends on the field component perpendicular to the line of sight. In JET geometry as in many other machines, the field perpendicular to the vertical channel is the toroidal field (B_ϕ) that is well known in Tokamak plasmas. It is worth mentioning that, from a purely theoretical point of view, also a component of the poloidal field should be included into the total perpendicular field but neglecting this term introduces a negligible error.

Since the vertical lines of sight are at fixed radius, it is easy to evaluate the density from the measurements. In a way analogous to the procedure adopted for the approach based on the Faraday effect, the toroidal field, being constant along the beam path, can be extracted from the integral of relation (3):

$$\Delta\Gamma = c\lambda^2 \int n_e(l) B_\phi^2(l) dl = c\lambda^2 B_\phi^2 N_e \tag{17a}$$

$$N_e = c\lambda^2 B_\phi^2 / \Delta\Gamma \tag{17b}$$

In principal, the method should be very useful for the line integrated density measurements for the vertical channel, as shown in figure 7. The line-integrated density obtained with Cotton-Mouton measurements is compared with the interferometric data with good agreement.

Unfortunately at JET the measurement of the Cotton-Mouton effect is not always available, due to spurious oscillations that sometimes jeopardise the signals [9]. In this respect the diagnostic is not yet reliable enough to be systematically used in real time control schemes. On the other hand the approach has been confirmed, since it has proved effective in all cases (100% success) in which the raw data was of acceptable quality. Indeed, if these measurements are of good quality, the Cotton-Mouton effect should be considered more an alternative way of determining the line integrated density than a correction approach for the interferometer.

5. ESTIMATE OF THE DENSITY PROFILE WITH THE HELP OF ABEL INVERSION OF ONLY TWO INTERFEROMETRIC CHORDS

The techniques described so far were all aimed at recovering the measurements of the chords affected by the fringe jumps in the best possible way and introducing the least amount of additional hypotheses. Even if this is not the best attitude from the experimentalist point of view, it must be kept in mind that in many real time experiments the accurate value of the density is not the main goal**.** In many cases the density profile can just be instrumental to other quantities or necessary for safety reasons. In these contexts only a rough estimate of the density profile can be sufficient to proceed with the experiments. On the other hand, if many of the chords are affected by fringe jumps and cannot be recovered, the previously described approaches fail to provide an estimate of the density profile. To overcome this problem and provide an approximate estimate of the density profile, even in cases of many chords being affected by fringe jumps, the fact that the radial density profile does not vary much in JET can be exploited. Indeed, it turns out that the vast majority of line integrated density profiles can be represented well by the following expression LID(R):

$$LID(R) = C[1 - (1 - p)x^2 - px^6] \qquad x = (R - R_0) / (R_1 - R_0) \tag{18}$$

In (18) R is the radial co-ordinate, R_0 the position of the maximum of the line integrated density and R_1 the radius of the separatrix. The parameter p is higher than 0.5 for monotonic profiles and less than 0.5 for hollow ones. Since the geometry can be determined on the basis of the magnetic signals, this analytical function contains only two free parameters (the profile factor p and the maximum C), and can therefore be constrained with the help of only two measurements, provided one is central and one external. At the same the class expressed by (18) is flexible enough to represent the vast majority of JET density profiles. Assuming that the flux surfaces are concentric ellipses, the function (18) admits an analytic solution [10], which can be expressed in the form:

$$n_e(x) = \frac{2C}{\pi(Z - Z_0)}[1+2p - 4p(1 - x^2) + \frac{8}{5}p(1 - x^2)^2]\sqrt{1 - x^2} \tag{19}$$

where Z_0 is the vertical co-ordinate of the separatrix at R_0. The category of density profiles described by equation (19) is reported in figure 8. The obtained solution was compared with the measurements of the Thomson scattering diagnostic, proving that, if constrained by a central and a lateral channel of the interferometer, it provides an estimate of the density profile within an error of about plus minus 20 %. The quality of the estimate given by equation (19) is shown in figure 9 for a couple of discharges with very different density profiles.

Since the necessary magnetic signals are already available in real time, the implementation of this approach based on relation (19) is straightforward. In terms of elaborational time the algorithm is very fast and fully compatible with JET real time system.

CONCLUSIONS AND FUTURE DEVELOPMENTS

Given the increased interest in feedback experiments at JET, the need for a reliable real time measurement of the density and related quantities, like the q profile, was particularly stringent. This motivated a systematic analysis of the possible approaches for the recovery of the density profile in presence of fringe jumps, which unfortunately affect JET Interferometer/Polarimeter very often in presence of ELMs or pellets. Two main approaches can be adopted, one to recover the lost signals of the line integrals, the other to estimate the density profile even with a minimum number of only two chords available, provided one central and one lateral. The possible solutions in both categories were tested to determine the pros and cons of the various alternatives. To summarise it can be stated that the second colour is a very important feature and its exploitation provides by far the best results for the lateral channels. For the vertical channels, the solutions using the interferometric data are not completely satisfactory but remain the most reliable for the vast majority of plasma scenarios. In order to improve the rate of success of the correction, for the vertical channels also the available signals of the Faraday rotation and the Cotton-Mouton effect were tested. Unfortunately, the Faraday rotation can be applied reliably only to channel 4 whereas the Cotton-Mouton effect, potentially of higher interest, is at present compromised by the not perfect status of the hardware (a problem not fully understood yet and which will require particular attention in the next campaigns). In any case, a compromise, relying on the second colour for the lateral channels and on the chord ratio for the vertical ones, has been implemented and is now systematically used at JET with acceptable performance. The different line of defence, which consists of providing an acceptable estimate of the density profile with a minimum number of correct signals, was also addressed. An analytical expression for the line-integrated density, which can be inverted with the Abel integral in an analytic way, was found. It depends on only two parameters and provides acceptable results provided at least on lateral and one central channel of the interferometer are available.

It is worth mentioning that, irrespective of the detailed implementation to JET, the investigation of the various alternatives is of wider interest, since it could constitute a good guidance to the solution of the same problem in other contexts. The tested solutions, for example, could be implemented in many other fusion devices, since the characteristics of present day interferometers are not too different form one machine to the other.

With regard to future work, given the importance of the information on the density for JET real time programme it is under study for a proposal to implement a second colour with shorter wavelength for the vertical channels. This upgrade should provide a complete new set of measurements of line integrated density on the vertical system and without presenting fringe jumps. This improvement is due to the fact that the refraction effects will be much smaller at shorter wavelength and it will constitute a major step forward in the effectiveness of the correction methods.

Serious consideration is also given to a different approach, meant at investigating whether, with reasonable changes of the hardware, the occurrence of the fringe jumps can be reduced instead of the ability to correct for them once they have happened. It is presently believed, for example, that a faster sampling rate and a better phase difference determination could have a significant beneficial effect in reducing the number of fringe jumps in the first place. If this were true, a relatively minor upgrade of the diagnostic could result in an additional major progress, since at the moment the correction algorithms perform very well if the frequency of the fringe jumps is not too high.

ACKNOWLEDGEMENTS

The authors would like to thank Klaus Guenther for his pioneering work on the Abel -like inversion of JET density profiles.

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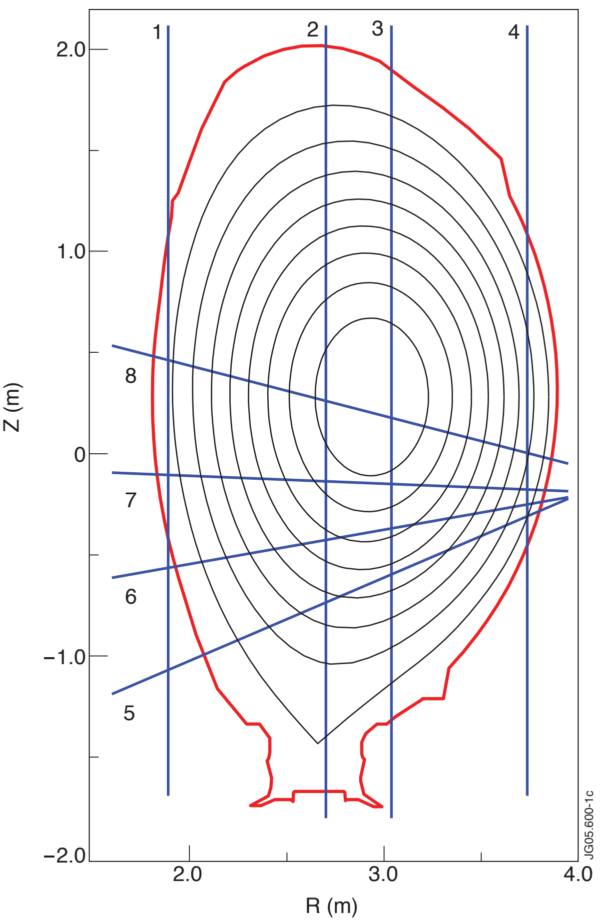

Figure 1: Lines of sight of the interferometric/polarimetric diagnostic at JET.

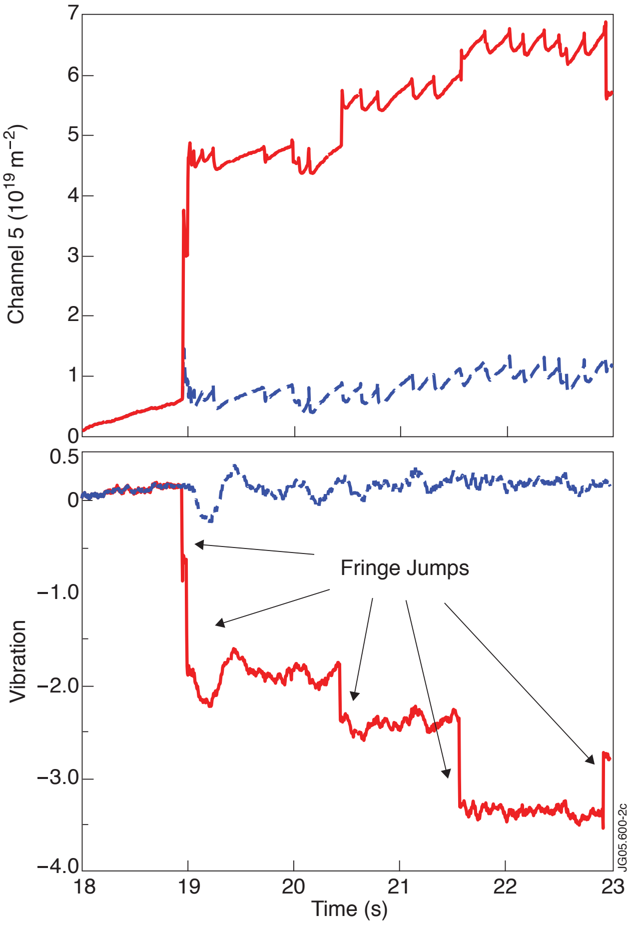

Figure 2: Comparison between uncorrected (red) and corrected (blue) density and vibration.

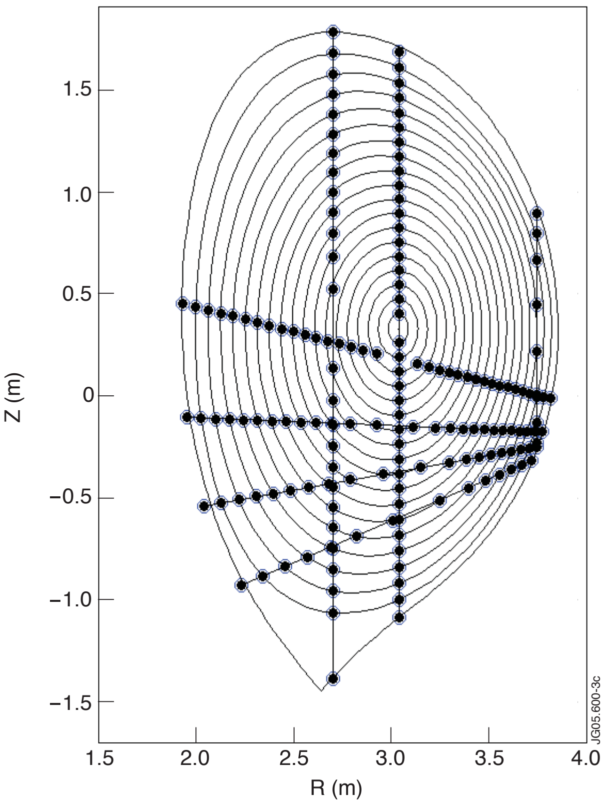

Figure 3: Iso-flux structure for the inversion of the interferometric data.

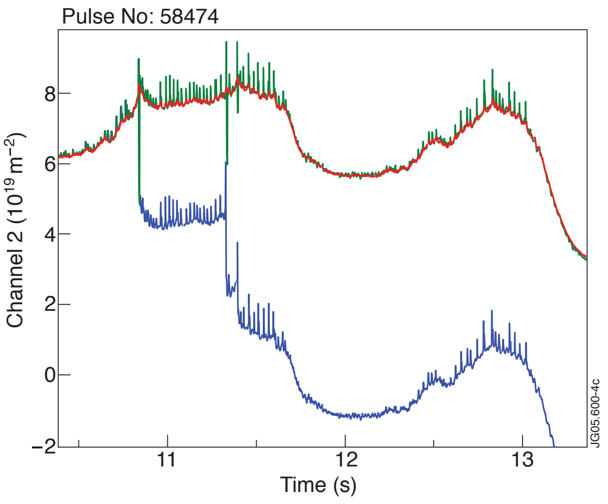

Figure 4: Plotting of the uncorrected (blue), reconstructed (red) and corrected (green) densities.

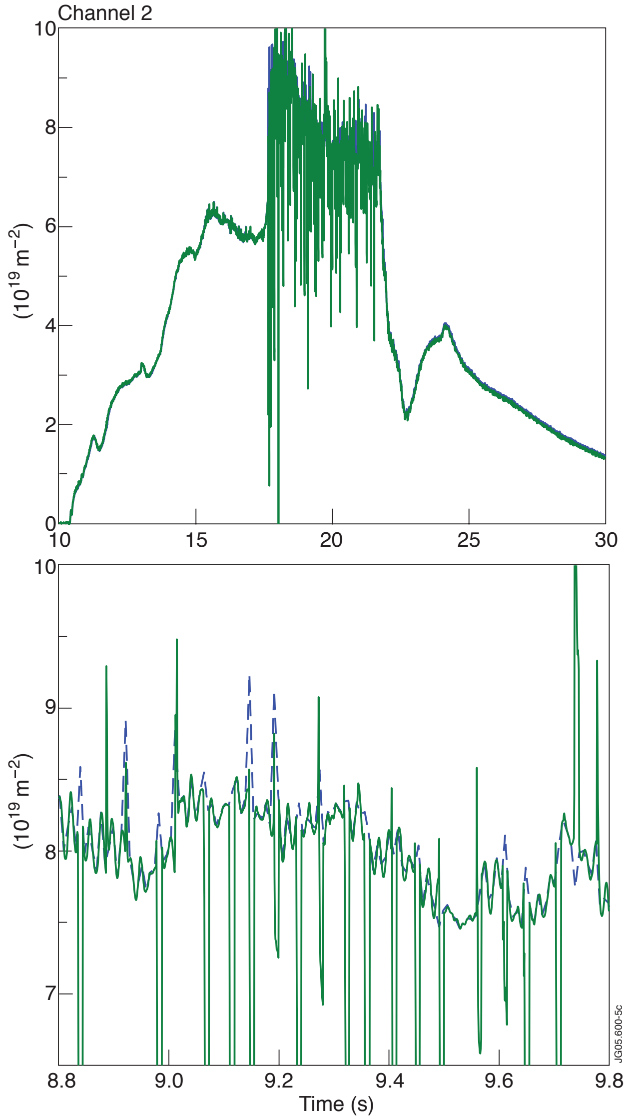

Figure 5: Real-Time recovered line integral density for channel 2 (green line) compare to the corrected offline density (blue line).

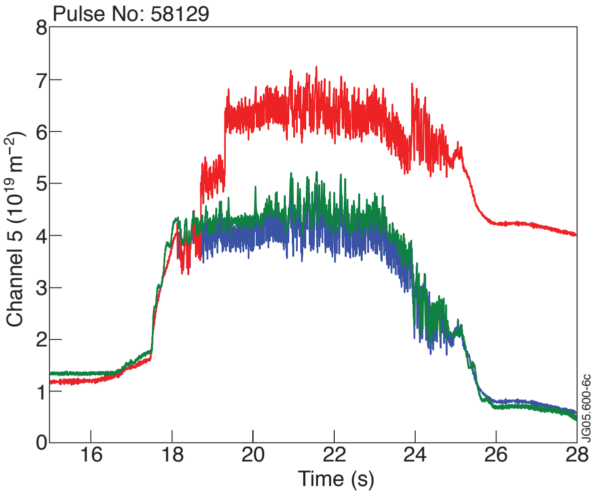

Figure 6: Example of the channel 4 correction using Faraday data. (Uncorrected-red, density from Faraday-green and corrected-blue).

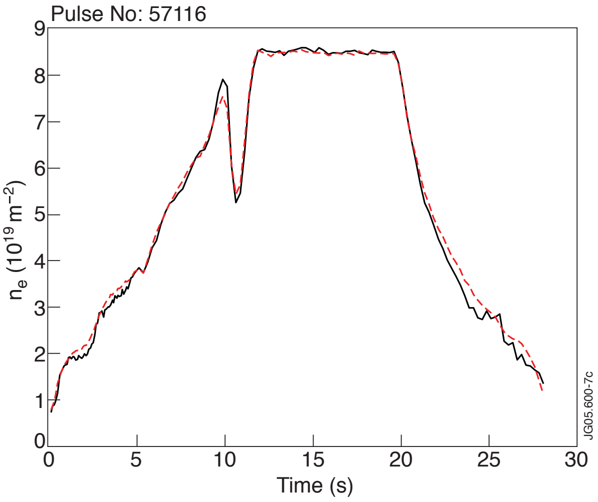

Figure 7: Density for channel 3 (red) compared with Cotton-Mouton measure (blue).

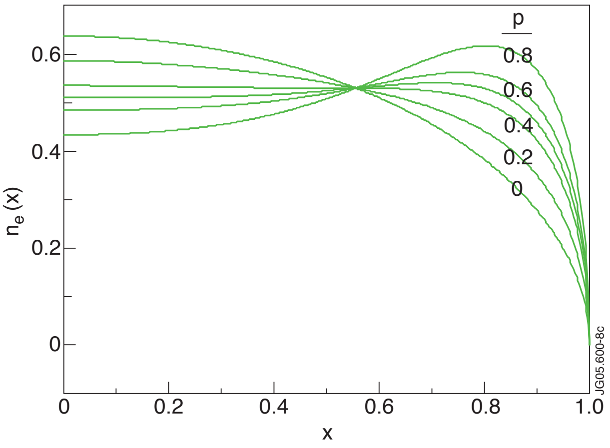

Figure 8: Class of density profiles represented by relation 19.

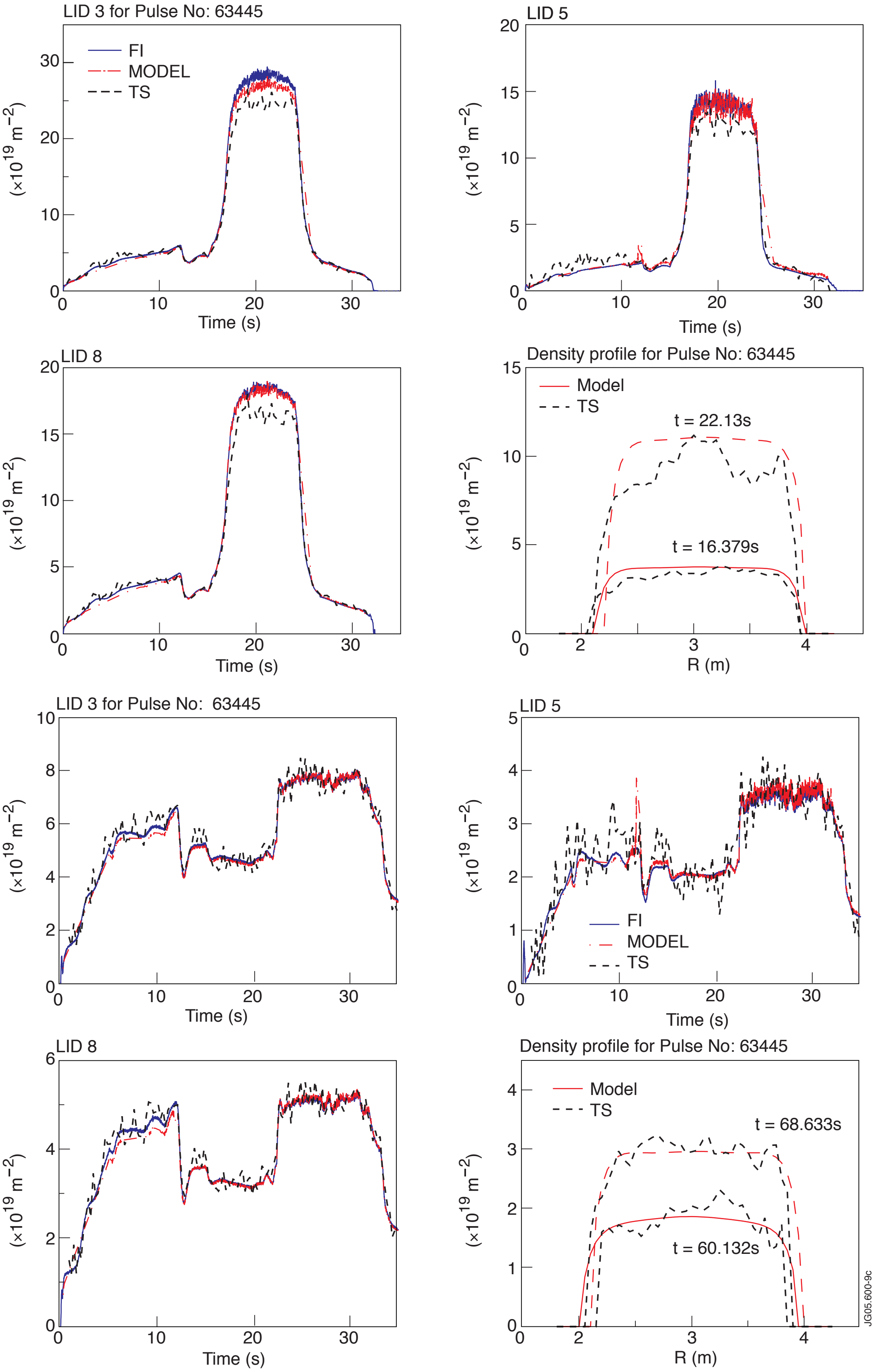

Figure 9: Density profiles for different types of plasmas

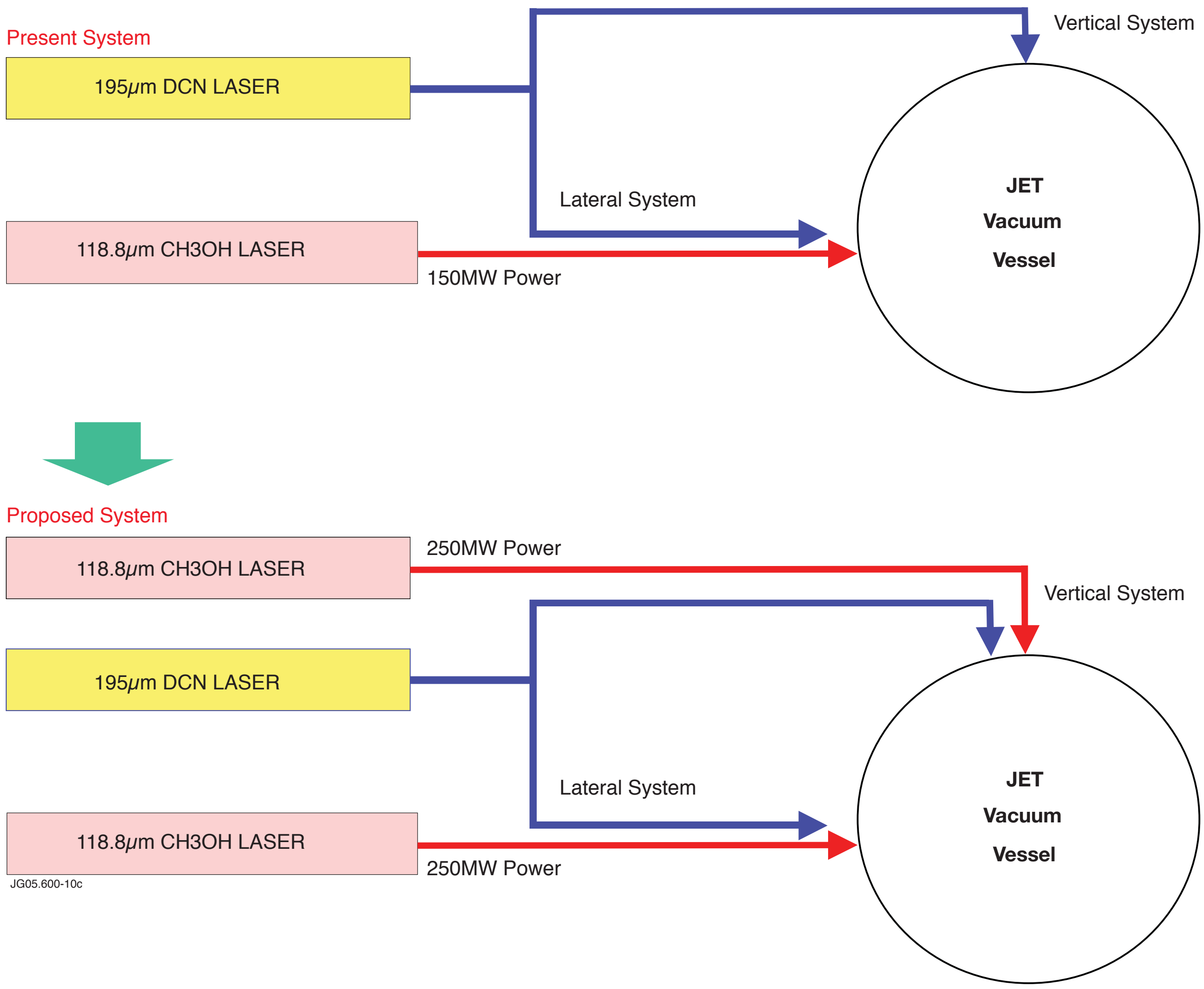

Figure 10: Addition of the second colour on the vertical system