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Design analysis of Motional Stark Effect diagnostic for ITER
EFDA Technology Workprogramme 2002

Combined report on the MSE tasks of EFDA Contracts 02-1003 (CEA),
02-1005 (UKAEA), and 02-1006 (VR).

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Introduction.

The Motional Stark Effect diagnostic is now considered as an essential diagnostic for an accurate determination of the current profiles in Tokamak discharges. For this reason, this diagnostic, which is based on the polarisation pattern of the Balmer-Alpha spectrum emitted by a fast neutral beam injected into a fully ionised plasma, is implemented on most of the existing machines. It mainly allows a measurement of the direction of the total magnetic field, a very powerful constraint for the determination of the safety factor profile.

On ITER, the knowledge and the control of current profiles will be of crucial importance to realise the long-lasting, high-performance discharges. This is why it was initially proposed [CEA-ref4] to install a MSE diagnostic on one of the heating beams.

The possibility of installing a MSE diagnostic viewing one of the heating beams on ITER was studied under contracts between EFDA and three European associations, CEA, UKAEA and VR. Their corresponding reports are included as annexes.

In parallel, MSE on the diagnostic neutral beam was proposed as a complement to CXS diagnostic by FOM association [CEA-ref.8]. This report will not include the FOM report, which is mainly devoted to CXS diagnostic, but we will nevertheless refer to its conclusions for comparing both methods.

The installation of a MSE diagnostic on ITER implies to face new challenges, because of the bigger size of the machine and of its hard environment. The main points we identified as serious problems for the feasibility of the diagnostic were the following:

- Study if the MSE method is still valid at much higher Lorentz electric field.
- Find a position for the diagnostic around the machine satisfying the spatial resolution requirements.
- Show that the beam penetration and emissivity is high enough to compensate the high Bremsstrahlung signal considered as the major source of noise for the measurement.
- Calculate the emitted spectrum and show that measurements with a high polarisation fraction are possible, and that no intense line interferes with the spectrum.
- Elaborate a design of the diagnostic in the port compatible with a low escaping neutron flux (ITER team).
- Evaluate the influence of the radial electric field on the measurement
- Prove that the MSE measurement is still possible with a high accuracy while using several mirrors.
- Evaluate the effect of the probable coating on the first mirror and propose solutions to cope with this effect.

1) MSE at high Lorentz field

The validity of MSE measurements at high field was studied by CEA. For this, the quadratic Stark term was added to the usual linear Stark term in the calculation of the energy levels of the Hydrogen atom, and the corresponding transition were deduced. For the Lorentz electric field expected for ITER, it appears that the quadratic correction is small so that there is no mixing between the sigma and pi lines. It is also shown that no strong attenuation in the line intensity is expected due to quenching effects. Consequently the usual polarimetry method is still valid.

2) Spatial resolution

The spatial resolution was a major problem since the first calculations done by CEA show that no central MSE measurement was possible with the proposed position of the diagnostic on the machine. The spatial resolution was then calculated for all the positions of the diagnostic around the machine and a solution proposed to ITER team for central MSE.

Since this solution implied major changes in the port allocation, it was necessary to verify the CEA calculations. This was done by UKAEA with a more precise 3D code, which confirmed the previous results. (It must be mentioned here that the adaptation of the different codes of each association to ITER geometry allowed the cross checking of many results).

The final configuration, after reallocation of the ports, is composed of two MSE diagnostics, one for the core and one for the edge, and it allows a spatial resolution approaching the ITPA requirements. For the moment, the diagnostic was studied for only the ‘on-axis’ position of the beam. The need to have a steerable diagnostic to follow the beam vertical displacement must be studied since this will introduce a lot of complexity in the design.

3) Beam emissivity

Beam attenuation and emissivity was calculated independently by three associations (CEA, UKAEA, FOM) and the results are in good agreement. The plasma Bremsstrahlung considered as the major source of noise for the measurement was estimated (CEA, FOM). The comparison of the SNR with TFTR (CEA) and JET (UKAEA) measurements allows to deduce that the MSE measurements on ITER are possible up to R= 6.5m with a time resolution of a few tens of ms with the present detection technique.

4) MSE spectrum

The expected spectrum show a clear separation between the sigma and pi lines (CEA, UKAEA), with no plasma parasitic line (UKAEA deduced from JET observations), so that measurements with a high polarisation fraction are possible, even at low magnetic field. It was nevertheless pointed out that a correct elevation of the diagnostic in the port is necessary to avoid spectral interference between beams, mainly for the core MSE. UKAEA also pointed out that the height of the beam source could induce errors of several degrees in the measurements if the plasma source homogeneity is not constant during plasmas.

5) Radial electric field

MSE measurements on present machines must be corrected from the contribution of the radial electric field Er during some plasma scenarios. The first estimations of Er available in the literature indicate that its contribution will be small compared to the Lorentz electric field contribution, and that it can be neglected (CEA, VR). The important consequence is that the

MSE measurements will not have to be corrected. On the other hand, a direct measurement of Er by MSE does not seem possible because of the small value of Er first, and then of the impossibility to find a second view of the same plasma volume (with a high spatial resolution) from another port of the machine.

6) MSE with multi mirrors

A first design of the diagnostic in the ports associated with a ray tracing show that four mirrors at least are necessary to transport the image of the beam outside of the machine, while keeping the escaping neutron flux low (ITER team).

This is a strong constraint to MSE diagnostic since reflections on mirrors are known to alter the initial polarisation direction. As MSE will be done for the first time with more than one mirror, it was necessary to prove that accurate measurements were still possible with such a configuration.

For this purpose, laboratory experiments using the same geometry as in the ITER design were done by VR in collaboration with UKAEA. They prove that the measurement is still possible with a good accuracy if the incidence angles of light on mirrors are low. An improvement of the design of the mirror labyrinth for minimising the polarisation modification seems possible, even if one mirror must be added.

A modelling of the mirror properties was developed by VR and tested successfully for different materials on clean and on plasma-exposed mirrors. It appears that the choice of the material is also very important to minimise the initial polarisation modification.

7) Mirror coating and calibration

The probable coating of the first mirror is also a serious problem pointed out by the three associations since it could affect the correctness of the measurement if increasing rapidly with time. This is why they recommend trying to include an in-situ calibration system for the diagnostic during the design. For instance, the qualification of the mirror with a probing beam using the perpendicular direction is proposed by UKAEA.

Simultaneous measurements of sigma and pi lines proposed by CEA and tested by UKAEA and VR on JET seems to give promising results for determining the validity of the measurements. Analysis of JET measurements by VR and UKAEA pointed out the difficulty to get correct measurements during Elms. This method can also be used to determine the mirror parameters (CEA, JET).

Conclusion

Solutions have been proposed for all the points that were identified as serious problems for the feasibility of the diagnostic, and it appears now that MSE diagnostic on the heating beams is possible with a spatial and time resolution close to the ITPA requirements.

The parallel development of a MSE diagnostic on the DNB is highly recommended, since it will allow a cross checking of the measurements when possible, and to have MSE measurements in the scenarios without heating beams.

Annex A: CEA report

Support to ITER Diagnostic Design

EFDA contract 02-1003

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Motional Stark Effect

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CEA Cadarache France

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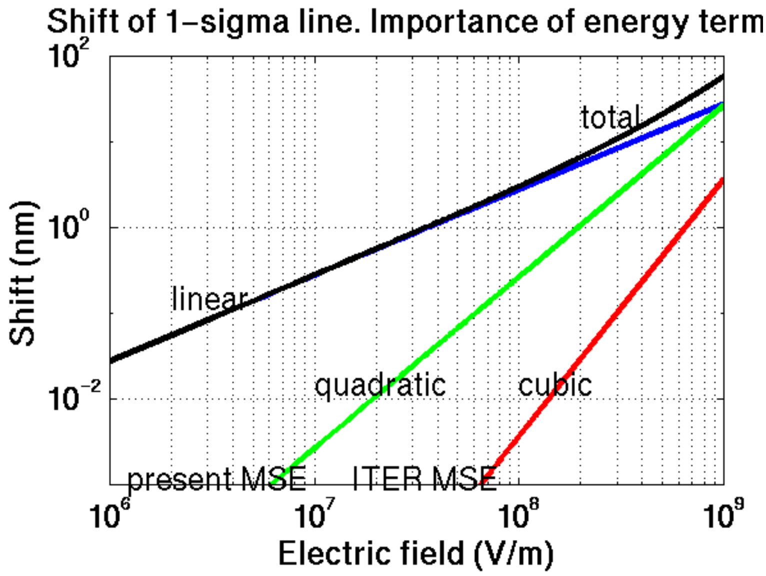
I) Feasibility of MSE diagnostic on HNB

a) Feasibility of MSE measurements at higher Lorentz electric field.

One of the first questions arising after the first proposal [4] to install a MSE diagnostic looking at one of the heating beam of ITER was the feasibility of the measurement due to the much higher Lorentz electric field.

The reason was that on present machines, the Lorentz electric field E_L is lower than 10^7 V/m, so that only the linear Stark effect has to be considered. For ITER, as the magnetic field and mainly the velocity of the beam increase (expected E_L could be as high as 7 10^7 V/m), the quadratic effect has to be considered too. This is illustrated on figure 1, where the evolution of the splitting between the σ_0 and σ_1 lines as a function of E_L is represented.



For *F = 7 10^7 V/m* (maximum value expected for ITER), the quadratic term is about 6 % of the linear term, and the cubic term (two orders of magnitude lower) can be neglected.

Figure 1. Comparison of linear, quadratic and cubic Stark terms for the splitting of 1-σ line of Hydrogen [10]

Line splitting adding the Stark quadratic term:

The energy levels of the ground states of the hydrogen atom in an external electric field are the solution of the Schrödinger equation, and can be expressed in atomic units [1]:

$$E_n = -1/(2n^2) + 3/2\ F\ n(n1-n2) - 1/16\, F^2 n^4 (17n^2 - 3(n1-n2)^2 - 9m^2 + 19) \qquad n = 1,2,3,\ldots$$

n1, n2 and *m* are the parabolic quantum numbers satisfying $n = n1+n2+|m|+1$

The first term represents the energy level without an external field, as the second term is the usual first order Stark effect.
The quadratic correction (third term), smaller for the low *n*, is always negative, which means that the line transitions are slightly shifted towards the smaller wavelengths with respect to their first order position. The spectrum is not any more symmetrical about the central σ_0 line.

If we calculate and plot the corrected energy levels (solid lines in top of figure 2) for the Balmer Hα line for an electric field of 21.10^7 *V/m* (3 times the ITER expected level so as to see clearer effects), and compare them to the first order Stark levels (dashed lines) we see that the corrections are quite small and cannot easily be distinguished on the figure scale.

The corresponding transitions are plotted in the bottom of figure 2. Their relative intensities are plotted in arbitrary units (y axis), as the x-axis is scaled in Stark first order energy splitting instead of wavelength. (the transitions σ5, σ6, and π8 have been omitted since too small on this scale)

The second order corrected line positions are shown in the bottom of the figure (in blue) for the σ (solid) and π lines (dashed) and compared to the corresponding first order positions (in red).
A noticeable effect due to the second order correction is that the central σ_0 line is split in two lines of different intensity (but equal polarisation) because of the separation between the *n=3* levels *|110> and |002>, |00-2>.*

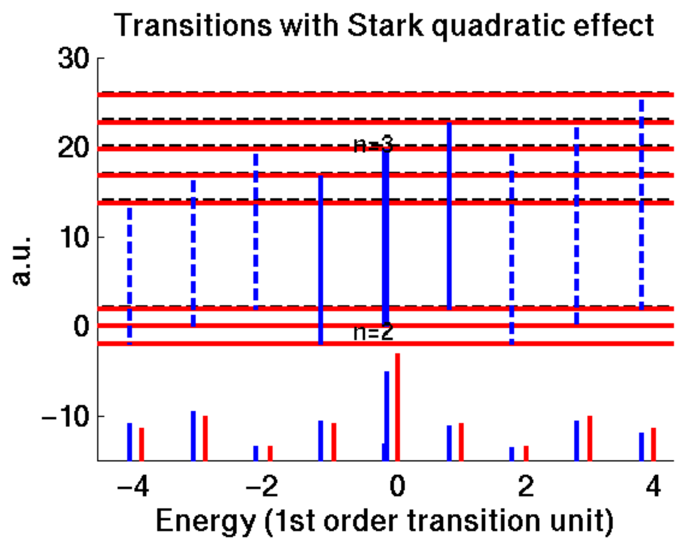


Figure 2. Energy levels n= 3 and n=2 with linear (red lines) and quadratic (blue dotted lines) Stark effect, and the corresponding transitions (sigma in solid and pi in dashed lines), for E_L= 21.10[7] V/m.
The transitions are plotted in first order Stark term energy unit (x-axis), their intensity is in arbitrary unit. The distance between the n=2 and n=3 systems is not in scale
The electric field used for the plot is 3 times the value expected for ITER for illustrative reasons.

Intensity of the emitted lines in the presence of a high electric field:

The intensities of the lines, also electric field dependent, can be calculated using a simple formula such $I= I_0*(1+ \beta.F + \gamma.F^2)$, I_0 being the intensity without electric field. The coefficient β and γ are deduced from analytic calculations done in the dipole electric field approximation and are given for each transition in a table [2.bis].

As can be seen on figure 2, the effect of the electric field on the line intensity (in blue) is small on the modification of the initial intensities I_0(in red). The intensity of the low frequency component (right of σ0) is slightly reduced, as the intensity of the high frequency component (left of σ0) is slightly increased.
The variation depends on the line itself and is more important for the lines with smaller intensity. For instance the correction is 10% for σ5 or σ6 lines, 4% and 5% for π3 and π4, but only 2% for σ1 and π2, the correction being positive for the high frequencies and negative for the low frequencies.

Quenching of the lines:
Another point examined was the possible quenching of the Hα line in the presence of a very high Lorentz electric field. This is due to the fact that in the presence of a high external electric field, the electrons can be extracted from their orbits and removed from the atoms.

This effect is stronger for the electrons located at higher distances from the orbit centre, that is for levels with higher principal quantum number *n*. For a given *n*, the electrons on the anode side (*n1* low, *n2* high) will be more affected, which means that the red components of the spectrum will disappear first.
So, when the electric field F increases, there will be a quenching of the emitted Stark lines over a critical value of the field.

To calculate the value for which the line transition starts to vanish, an analytic approximation was used [2].

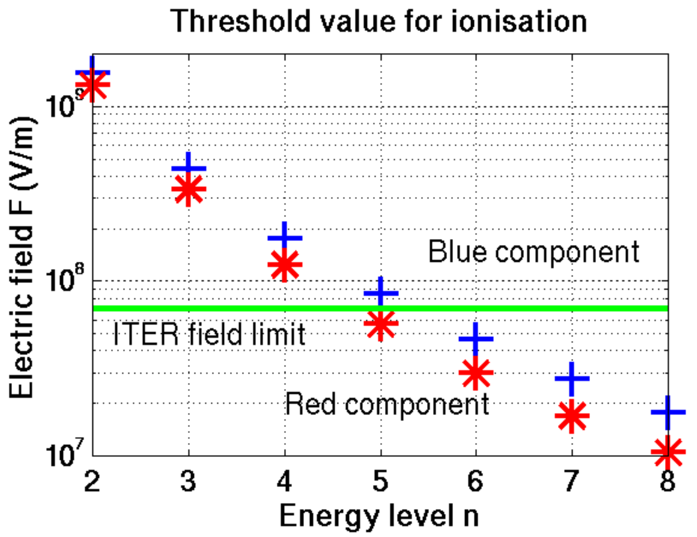


Figure 3. Threshold value of external electric field for starting depopulation of energy level n, corresponding to reddest light component (red stars), and bluest light component (blue crosses) of the spectrum.

It appears that the critical value of electric field necessary to start to depopulate significantly n=3 (Hα) level is much over the Lorentz electric field expected for ITER. As no significant depopulation is expected for n=3 level, the Hα transitions will not be affected, and consequently **no additional attenuation of the signal is expected.**

But all the excited particles having their electrons move to energy levels higher than n=6 will be ionised and lost for the heating beam. The consequence could be a slight decrease of the neutral beam power, having some consequences not only for MSE, but also for ITER plasma scenarios with neutral beam heating and current drive. The proportion of electrons moving to levels > 5 should be small, but this needs to be evaluated more precisely.

Conclusion:
For the electric field expected for ITER, there is no mixing between the σ and π lines, and only a negligible variation of the line intensities compared to present measurements, **which means that the polarimetry method is still valid**.

The ratiometric method can also be applied on the heating beam. The only difference is that the quadratic term has to be considered in the determination of the module of E_L (the electric field is obtained by solving the second order equation: $\Delta\lambda = b\, E_L + a\, E_L^2$, a and *b* being known). The direction of E_L is still given by the ratio of σ to π line intensities.

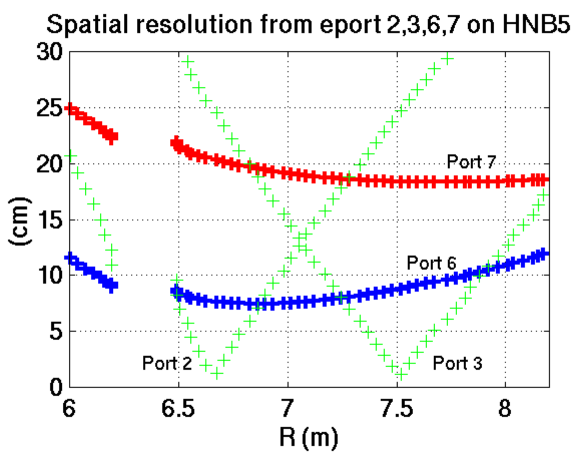
b,c) Spatial resolution of the diagnostic and recommended ports:

The code used for Tore Supra was adapted to ITER geometry. But the Tore Supra code is mainly 2-Dimensional since the neutral beam and the diagnostic are in the equatorial plane. This is precise enough to answer the question of the best choice of equatorial port. Nevertheless, to study some particular aspects, like for instance the fact that the beam passes under the magnetic axis, calculations were also done in the other dimension, where a realistic ITER equilibrium was added in the poloïdal plane.

The results must then be considered as optimistic, but are precise enough to compare the spatial resolutions from the different ports. They will serve as a cross checking of the 3D calculations done by UKAEA [3] (see later).

The results are plotted on figure 4a. As expected the best spatial resolution on the red shift side is obtained with installation of the MSE diagnostic in the adjacent port, that is in e-port 6 (e for equatorial) viewing the heating beam in port 5 (or in a symmetric way, MSE in e-port 7 if a third beam is in e-port 6). But this solution is impossible due to machine and beam constraints. The installation of the diagnostic in the following port (e-port 7) viewing HNB5 gives a almost constant resolution of 20 cm, higher than ITER requirements (spatial resolution < a/20).

The other possibility is to use two observation ports on the blue shift side, **e-port 2 for the central measurement, and e-port 3 for the edge measurement, both viewing HNB5**. The spatial resolution is better than a/20 almost everywhere, and very good (2cm) near 6.7 m and 7.5 m (the diagnostic is supposed to be for the moment installed in the middle of the port).



A symmetric solution is possible with MSE diagnostics placed in e-port 1 and e-port 2 viewing HNB4.

Mixed solutions using two beams are also possible, with MSE in e-port 1 and e-port3 viewing respectively HNB4 and HNB5, or MSE in e-port 2 viewing HNB4 and HNB5.

These configurations are the only ones that satisfy the ITER measurement requirements. The corresponding Doppler shifts are large enough to clearly separate the emitted lines from the edge Hα line.

Figure 4a. MSE Spatial resolution for the best configurations viewing HNB5. The gap in the curves near the plasma centre is due to the fact that the beam does not cross the magnetic axis

Consequently our initial recommendation to ITER IT was to install the MSE diagnostic in e-port 2 and 3, because in this case, **only one beam** was necessary to measure a full profile.

ITER International Team started then a large review of the ports allocation so as to find a solution for the central MSE measurement. The compromise with the other diagnostics requirements is now to use e-port1 for central MSE and e-port3 for edge MSE. This solution

is not the optimum one because two beams are needed, but the spatial resolution is the same as in the recommended configuration.
It is interesting to present the spatial resolution in rho (figure 4.b), using a typical ITER equilibrium.

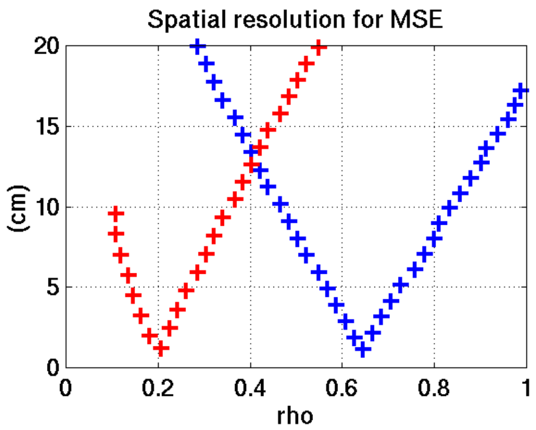


Figure 4b. MSE Spatial resolution as a function of rho.

It can be seen that the regions around rho=0.4 and rho > 0.8 are not measured with a good enough precision, but the spatial resolution is better than a/40 around rho= 0.2 and rho= 0.65.

The MSE measurement on HNB is possible until rho= 0.1 when the beam is set in its on axis position. The case of off axis beam has not been studied. The fact that the diagnostic should be steerable to follow the vertical displacement of the beam introduces additional complexity. This point must be decided later.

The positions of the minima can be slightly shifted by moving the diagnostic position towards the sides of the ports. For instance if the position of the first mirror (our reference) and all the diagnostic is shifted 30 cm toward the left of the port (when viewed from outside), the position of the minima are shifted respectively of 0.05 towards smaller rho (in red on Fig. 5), and towards higher rho for a shift of 30cm towards the right of the port (in blue on Fig. 5)

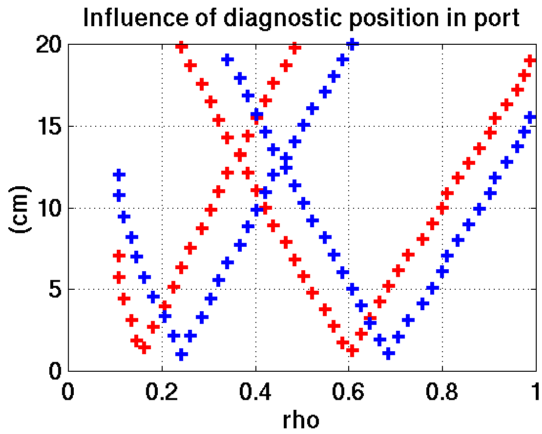


Figure 5. Influence of diagnostic position in the port on the position of the minimum of spatial resolution.

The position can be chosen depending which region of plasma must be privileged. We have many recommendations from the ITPA expert group, wishing to increase spatial resolution over a/20 to study some particular physics (region of ITB, of pedestal…) but not all of them can be satisfied. Of course this decision also depends on other constraints external to MSE.

d) Beam attenuation, beam emission, SNR. Diagnostic time resolution

The calculations done in 2D were used as a first estimation and as a cross checking with 3D calculations (see later), the additional attenuation given by the fact that the beam is moving slightly in the third direction being small.

The beam attenuation cross-sections for high energies were kindly given from ADAS by Manfred von Hellermann [5]. In the simulations the beam characteristics are 1 Mev energy (in Deuterium), 16.5 MW power, the plasma parameters are Te0= 20 keV (central electron temperature), ne= 10^{20} m^{-3} (constant flat density), He=4%, C=1%, Be=2%, D=77%, Zeff= 1.6 (plasma composition).

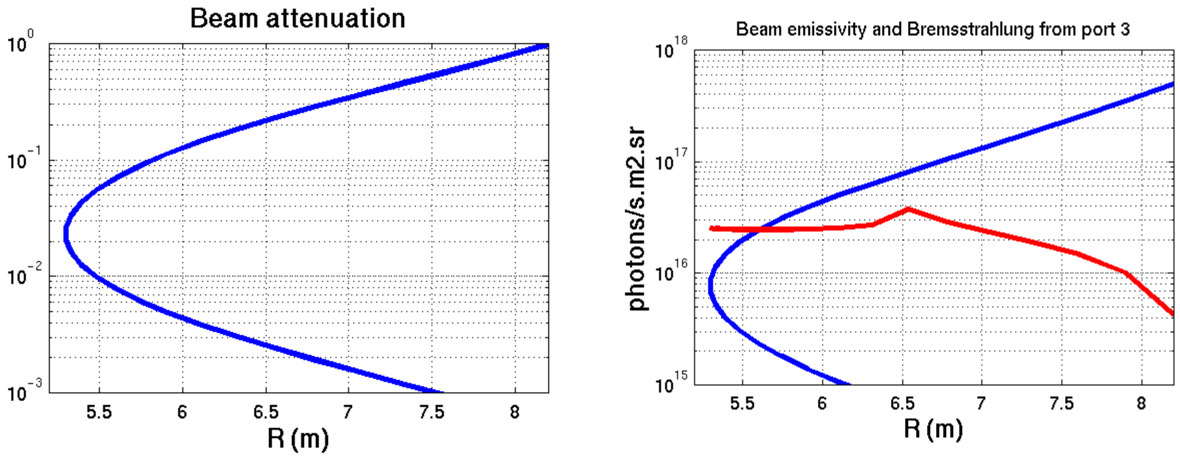


Figure 6. (a) Beam attenuation as a function of major radius. (b) Beam emission and plasma bremsstrahlung (in red) seen from eport3 as a function of major radius.

Even if the beam energy is higher than on the present machines, the beam attenuation is also higher, because of a higher density and a longer path in the plasma (figure 6a).
The beam emission in ITER (figure 6b) varies from 5.10^{17} at the edge of the plasma to 5.10^{16} photons/s.m^2.sr in the centre, and is comparable to TFTR values (due to a higher plasma density).

The major source of noise while measuring the MSE signal will be the plasma Bremsstrahlung. For each line of sight of the diagnostic installed in port 3, the Bremsstrahlung signal was integrated along the viewing line, assuming interference filters 0.5 nm widths. The averaged value is 2 10^{16} photons/s.m^2.sr, in any case lower than the beam emission, but around 3 times higher than in TFTR. The Bremsstrahlung calculated for the diagnostic installed in e-port 1 is very similar.

The signal to noise ratio for MSE (Figure 7) was then estimated, using the solid angles of the design and parameters from the present machines for the signal attenuation and for the detector quantum efficiency.

The time resolution for the MSE diagnostic recommended by ITPA is 10 ms. If the SNR estimations are compared to TFTR values, it appears that a **time resolution of a few tens of ms is necessary** using the same parameters.
But the signal to noise ratio can be improved by increasing the étendue of the viewing optics, or by using higher quantum efficiency detectors.

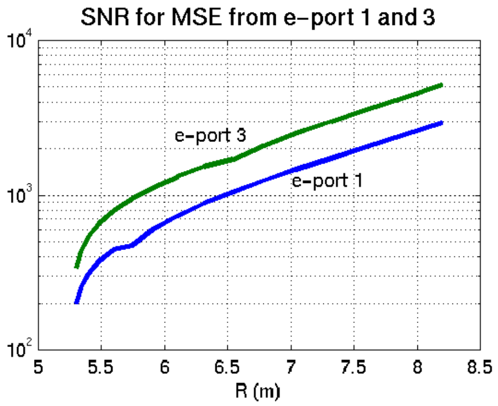


Figure 7. Signal to noise ratio for MSE diagnostic in eport3.

e) Beam Hα spectrum

The spatial resolution calculations already showed that the Doppler shift was high enough to separate the beam emission lines from the intense edge Dα line for all the plasma radius.
Another condition for being able to perform a good MSE measurement is that the Stark separation of the lines is high enough to distinguish the σ and π lines (polarised respectively perpendicular and parallel to the Lorentz electric field).

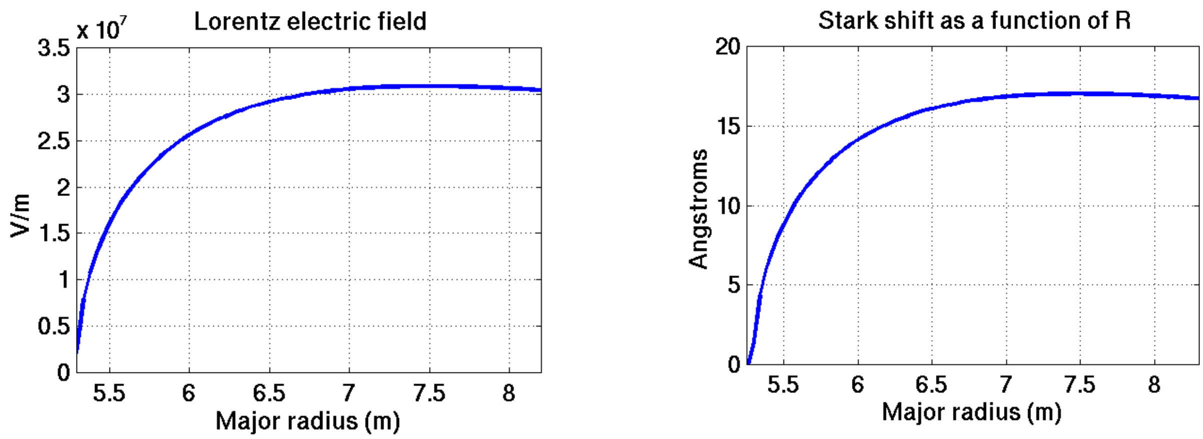


Figure 8. (a) Lorentz electric field and (b) corresponding Stark shift as a function of R for B_0= 5.3 T

If we consider the toroidal component of the magnetic field only (B_0= 5.3 T), the Lorentz electric field is around 3 10^7 V/m for all radii between the plasma centre and the edge. The corresponding Stark shift is higher than 15 Ä, compared to 4 to 5 Ä on the present machines. (figure 8)

This high Stark separation can be illustrated by the calculation of the full Hα spectrum at mid radius for instance (figure 9). Since the diagnostic is situated in the equatorial port, the π lines

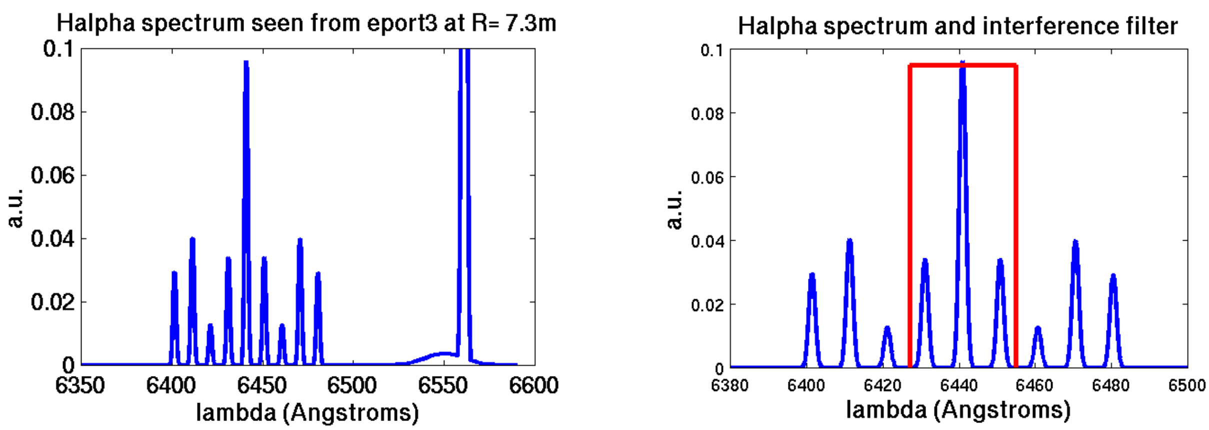


Figure 9. (a) HNB and edge Hα spectrum at R= 7.3m and (b) possible position of the interference filter in red.

are seen almost with their maximum intensity, in opposition with a view from an upper port where the intensity of the π lines is small.

It is clearly seen that the beam Hα spectrum (which is blue shifted) is very separated from the edge Hα line, so that no interference with these spectral lines is expected. It was verified on JET [3] that no intense parasitic line is present at these wavelengths to disturb the measurement.

As the neutral beams are produced by the acceleration of negative ions, only the full energy components exist. All the σ and π lines are clearly separated and not mixed as on present machines. Since the σ line is the more intense one, it seems reasonable to use it for the measurement. The π lines could be used in parallel for cross checking the validity of the measurements as already tested at UKAEA [3].

If the three central σ lines are used as we use to do it now with the polarimetry method, the interference filter will be 2.5 nm width. But the measurement will also integrate the plasma Bremsstrahlung through the filter width.
Now with the much larger separation of the lines than on present machines, if we use only the central σ_0 line, the MSE signal will be around one half of the previous one.
The central line can be measured with a 0.5nm width filter only, so that the noise will be 5 times lower than previously. As a consequence the Signal to Noise Ratio will be 2.5 higher.
It seems thus better to use a single component to perform the measurement, but this first estimation has to be verified when our model will be more precise (line broadening mainly)

Due to the clear lines separation, an accurate measurement with a high polarisation fraction is possible with the polarimetry method.

Diagnostic capability at low magnetic field.

On present tokamaks, a limitation of MSE diagnostic exists for the measurements at low magnetic field (below 2T). For ITER, as the beam energy and thus the Lorentz electric field is higher, MSE measurements can be done at very low fields.

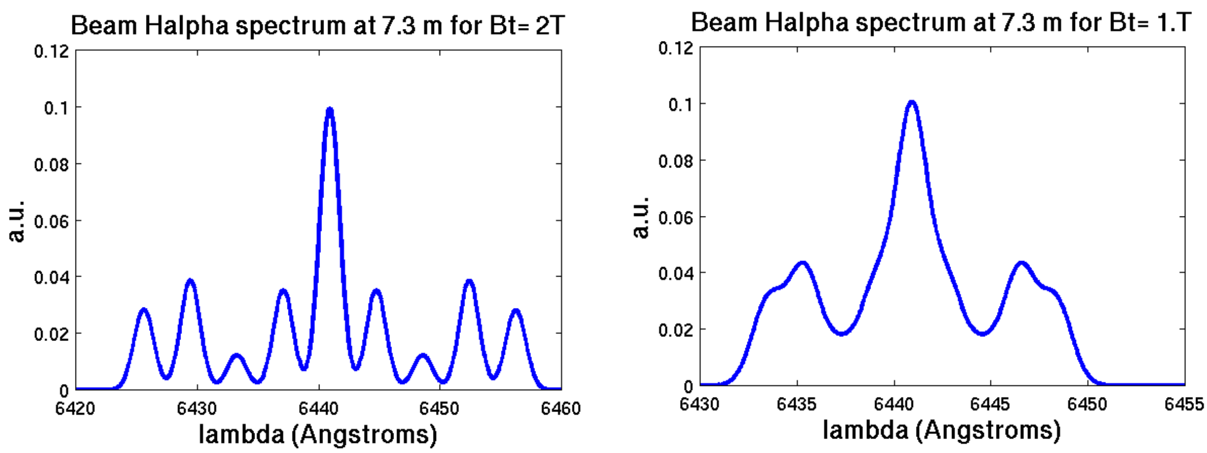


Figure 10. Beam Hα spectrum for a toroidal filed of (a) 2T and (b) 1T.

For a toroidal filed of 2T (fig.10a), the components are still clearly separated, the measurement can be performed with 1 or 3 components without mixing the σ and π components.

For a toroidal field of 1T (fig.10b), even if the components do not appear individually, the group of σ and π can be distinguished. The measurement is still possible with a high polarisation fraction.

The polarimetry method on HNB can be used for magnetic fields below 1T.

f) Influence of the radial electric field on the measurement

The present experiments on TFTR, DIID or JET for instance show that the Tokamak radial electric field can influence the measured MSE angle. During specific scenarios, when a strong rotation is initiated by a high power of tangential neutral beam injection or when a high pressure gradient exists, this field can be as high as 150 kV/m, compared to a Lorentz electric field of 10^4 kV/m.
The electric field correction is done with the installation of a second viewing geometry, or directly with the values deduced from the Charge Exchange diagnostic measurements.

The contributions to the radial electric field Er are linked by the force balance equation for each species: $Er = 1/neZ.\nabla(P) - v_\theta B_\varphi + B_\theta v_\varphi$ where P is the plasma pressure, n and Z the density and charge of the considered species, B the magnetic field, v the plasma rotation velocity, and the subscripts θ and φ refer to the poloidal and toroidal components.

For ITER, as the injectors as well as the MSE diagnostic are not situated in the equatorial plane, the measured MSE angle depends on the different components of the magnetic field (B_R radial, Bz vertical, B_T toroidal) , and on the radial electric field projections:

$$tg(\gamma_m) = (A_0.Bz + A_1.B_R + A_2.B_T + A_6.E_R) / (A_3.Bz + A_4.B_R + A_5.B_T + A_7.E_R + A_8.Ez)$$

The terms A_0 to A_8 are constants depending on the geometry and on the beam velocity v.

Since all these terms are not of equal importance, a simplification can be done at this level of our study, so as to keep the three most important terms:

$$tg(\gamma_m) \approx (A_0.Bz + A_6.E_R) / A_5.B_T = (v.\cos(\alpha+\Omega).Bz + E_R\cos(\Omega)) / (v.\sin(\alpha).B_T)$$

where α is the angle between the beam and the toroidal field, and Ω the angle between the line of sight and the toroidal field.

When designing the MSE diagnostic, the choice of the ports is also determined to a large extent by the sensitivity of the measurement as the position of the minor radius is varied.

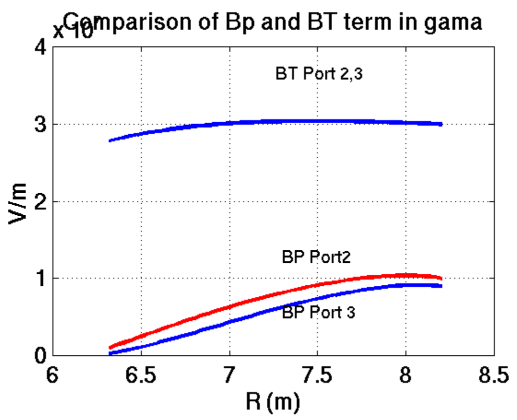


Figure 11. Magnetic field contributions to the Lorentz electric field (Y scale is in 10^7 V/m)

The toroidal contribution to the Lorentz electric field $v.\sin(\alpha).B_T$ for B_T= 5.3 T is represented on

figure 11. This field does not depend on the port choice, and tends to zero when the beam tangency radius is approached, but is high and around 3.10^7 V/m for all outer radii.
The poloidal contribution (assuming a parabolic current profile model with Ip= 15 MA) depends on the port choice, is also high and varies between 0 and 10^7 V/m along minor radius. This means that the γ **angle will have a good sensitivity to the measurement position** if the diagnostic is installed in port 1 (HNB4) in port2 (HNB5) or in port3 (HNB5).

For the moment no estimation of the radial electric field was found in the literature.
The result of a TRANSP simulation was kindly given by R. Budny, PPPL (see attached figure at the end of the report). The value of the electric field corresponding to this scenario in which the rotation due to the NNBI was calculated is very low (1.5 kV/m). In fact, the pressure gradient term may be small in most scenarios where the density profile is quite flat. Some other simulations indicate that the plasma rotation may also be smaller than in the present machines.

We have used this model of Er profile and applied a scaling to it so as to explore the incidence of larger values of Er.

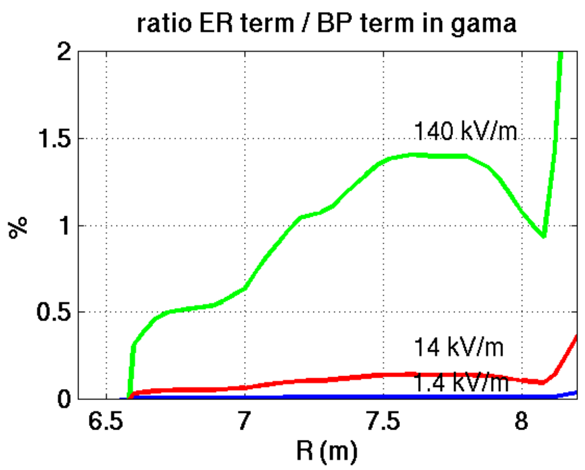


Figure 12 represents the ratio in percent between the Er term and the Bp term in the expression of γ for different values of the maximum of the radial electric field indicated.

It seems that as long as Er is lower than a hundred of kV/m, its influence on the MSE measurement is negligible for most of the minor radius positions. The influence of Er on the edge and plasma centre depends strongly on the shape of Er, as seen on the figure.

Fig 12. Influence of Er on the measurement of γ. Ratio of Er term on Bp term in percent in the expression of γ for the different values of the radial electric field indicated.

With these hypothesis, the relative error on gamma is lower than 2% in the region where Er is maximum, corresponding to an absolute error of 0.2 degrees in gamma. This error is of the same order as the expected incertitude in the measurements (see also [3,11]).

It appears at this stage of our study that the influence of the radial electric field on the MSE measurement is small. This must be taken as a first estimation which will have to be revaluated as the simulations of the scenarios will progress.

If this is confirmed, the important consequence is that the MSE q profile measurement will be independent and will not have to be Er corrected by another diagnostic.

On the other side, it does not seem possible to deduce Er from MSE measurements.

Possibility of a second MSE measurement:

In case the Er electric field would be higher than considered, we have examined the possibilities to measure Bp and Er with two MSE system

The installation of two diagnostics in the same port near the right and left side of the port and at the same elevation would lead to measurements of very close values of γ, differing from less than one degree at the plasma edge and almost zero for the plasma centre. Although this study needs to be done in 3D, it seems that the geometries would not be sufficiently different to make a precise measurement of Bp and Er.

The section (a) shows that the number of ports allowing a good resolution for the diagnostic is very limited. If an additional MSE measurement is necessary, there is a possibility to use e-port 7 viewing HNB5 if HNB6 is not installed (blind port becomes available). A second full MSE profile measurement will be possible, even if the spatial resolution from there is higher than required.

The use of symmetric configurations at the same time will not bring additional information, except if the beams are working at a different energy. But as a single measurement already needs two beams, the only possibility is to use HNB6 seen from e-port 3 to get a second central measurement (and at a different energy from HNB4 seen from e-port1). No solution was found for a second MSE edge measurement

g) Calibration of the diagnostic.

As already mentioned, the use of a multi mirror system, and more importantly the probable coating of the first mirror, reinforces the importance of the diagnostic calibration. We do not know for the moment the frequency of calibration needed, day to day, between shots, or in real time, but we must already think about it for the design phase.

A in-situ system (light+polariser or polariser only using the beam light) coupled with a retractable shutter should be envisaged during the design. It would allow a calibration of the mirrors system between shots. Of course, the implementation of such a system may be difficult due to the limited available space and the machine environment, but it could be essential during operations.

In case of variation of mirror reflectivity during the long shots, we envisage in parallel to develop **real time calculations of the mirror reflectivity**.

For that purpose, the idea is to use the fact that **the σ and π polarisations when emitted are perpendicular, and should be reflected differently by the mirrors**[3,11]. The measurement of their orientation after reflection would allow the deduction of the mirror parameters, r and δ (relative reflectivity and dephasing between the light s and p components).

This can be done independently of MSE measurement with additional viewing lines, using interference filters to select the correct lines and then appropriate polarisers (for MSE on DNB). But this can also be done in parallel with the MSE measurement on HNB, using the polarimeters as a detection system.

The measurement of the 4 Stokes coefficients S of the resulting light through the mirror system is necessary. The mirror system (representing the combined effect of the 4 mirrors used) is described by a 4*4 matrix having r and δ as parameters.

The incident light coming from the plasma is generally the sum of the linearly polarised light to be measured, Iπ for instance, plus a non polarised light Inp (bremssthrahlung), plus a circular component Ic due to multi-reflections on the machine walls (we neglect the other parasitic linear polarisations).
The reflection of the incident light on the mirror system can be expressed:

$$\begin{bmatrix} (1+r^2)/2 & (1-r^2)/2 & 0 & 0 \\ (1-r^2)/2 & (1+r^2)/2 & 0 & 0 \\ 0 & 0 & r.\cos(\delta) & r.\sin(\delta) \\ 0 & 0 & -r.\sin(\delta) & r.\cos(\delta) \end{bmatrix} * \begin{pmatrix} I1 \\ I\pi.\cos(2\alpha) \\ I\pi.\sin(2\alpha) \\ Ic \end{pmatrix} = \begin{pmatrix} S_0(\pi) \\ S_1(\pi) \\ S_2(\pi) \\ S_3(\pi) \end{pmatrix}$$

With I1= Inp+Iπ+Ic

This system has 6 unknowns for 4 equations, 2 for the mirror, one for the polarisation direction, and 3 for the intensities. If we add the same set of equations for the σ line using the same mirror ; as sin2(α+π/2)= -sin(α) , and cos2(α+π/2)= -cos(α), we have 3 additional unknowns in the system, that is 9 for 8 equations.

Since the sigma and pi lines are very close to each other in the emitted spectrum, it is reasonable to make the hypothesis that the circular component, coming from the plasma, is the same for both lines. The unpolarised light can be different for σ and π, since depending on the viewing angle, the sigma line can bring an additional contribution to the unpolarized plasma light.
We have thus 8 equations for 8 unknowns, and the system can in principle be solved analytically.

The mirror coefficients are expressed as a function of the measured Stokes coefficients:

$$\tan(\delta) = \frac{S_3(\sigma) - S_3(\pi)}{S_2(\pi) - S_2(\sigma)}$$

$$r^2 = \frac{(S_1(\pi) - S_0(\pi)) * (-S_2(\sigma) + S_3(\sigma).\tan(\delta)) - (S_1(\sigma) - S_0(\sigma)) * (-S_2(\pi) + S_3(\pi).\tan(\delta))}{(S_1(\sigma) - S_0(\sigma)) * (-S_2(\pi) + S_3(\pi).\tan(\delta)) - (S_1(\pi) - S_0(\pi)) * (-S_2(\sigma) + S_3(\sigma).\tan(\delta))}$$

The MSE angle, as well as the other parameters can then be determined as a function of r and δ (but directly from the measurements with some more analytic calculations):

$$\tan(2\alpha) = 2 * \frac{S_2(\pi).\cos(\delta) - S_3(\pi).\sin(\delta)}{S_1(\pi).(1+r^2) - S_0(\pi).(1-r^2)}$$

This is just an illustration of what could be done with these combined measurements. Other methods are certainly possible and will have to be developed.

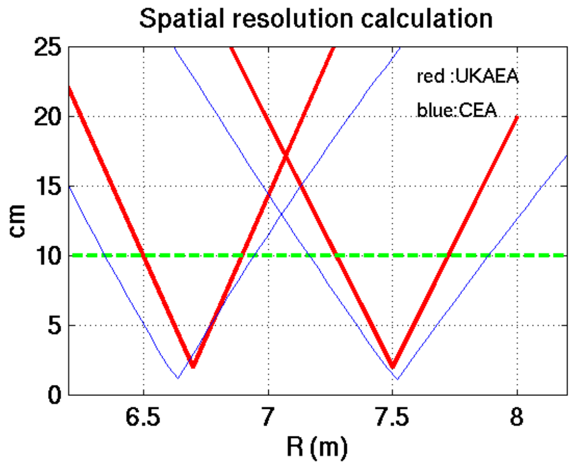
Encouraging experiments with σ and π measurements have already been done on JET by UKAEA [3] and VR [11].

II) Coordination of European activities on MSE and status of the work

1) Spatial resolution calculations:

The question of the best choice of ports for the installation of MSE diagnostic being very important, the spatial resolution calculations needed to be done independently by 2 associations.

The calculations done by UKAEA [3] with a 3D code confirm that **the best choice is equatorial ports 2 and 3 viewing HNB5 (or the symmetric configurations).** As expected the spatial resolution is 4 cm worse than with Cadarache 2D calculations in the regions of interest (figure 11) but the agreement is quite good.



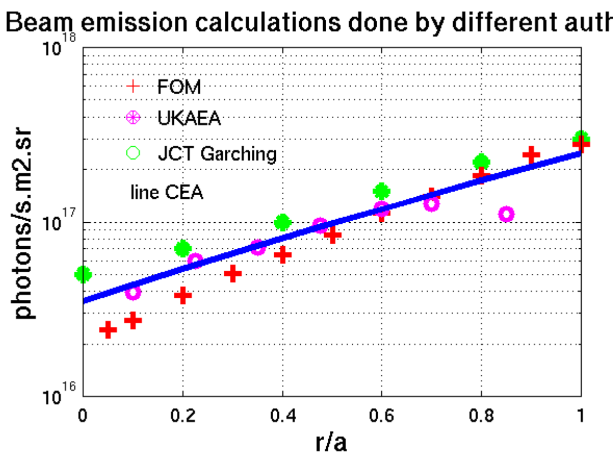
The positions of the minimum of spatial resolution are the same, but the slopes of the curves are slightly different due to the third dimension.

The green line shows that the spatial resolution requirement (<a/20= 10 cm) is satisfied on a smaller region now, but it remains under 15 cm almost everywhere.

Figure 11. Comparison of spatial resolution calculations done by UKAEA and CEA.

2) Beam emission, SNR

The calculation of beam emission was done independently by 3 associations [3], [5] following a first estimation done by ITER IT [6].



The results are in good agreement, if we take into account the fact that the plasma models were not strictly the same (plasma edge density in particular). Some additional effort is necessary to reduce the discrepancy, in particular the use of the updated cross sections.

Figure 12. Beam emission calculation by FOM (+), UKAEA (o), ITER IT (*) and CEA (line).

The plasma bremsstrahlung calculations are still in progress in the associations, but two first estimations can nevertheless be compared [5].
In addition, the upper limit of noise for doing a measurement with a good accuracy at JET is also represented [3]. The plasma bremsstrahlung could be close to this limit in the plasma centre (rho < 0.2).

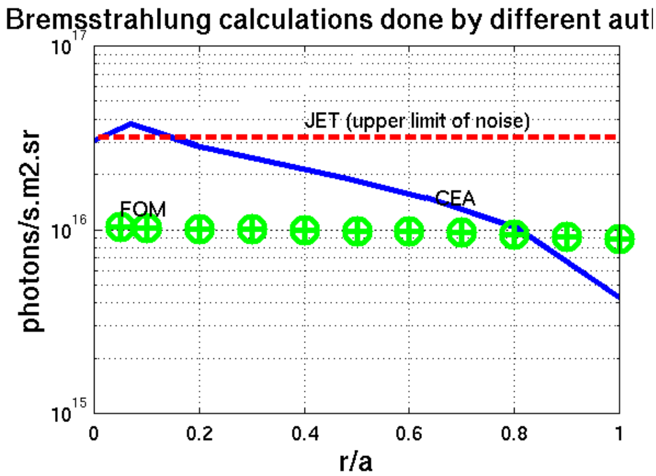


Figure 13. Bremsstrahlung calculations done by FOM (o) and CEA (line). The maximum level of noise estimated for a good measurement at JET is also represented.

The first beam emission calculations are in good agreement, but additional work is needed on Bremsstrahlung calculations so as to have a better SNR estimation, in particular for the plasma centre, where the limit of detection is approached. **This confirms that the plasma core measurements could require integration times longer than 10 ms.**

3) Diagnostic design, mirrors studies and calibrations

A design of the diagnostic in equatorial port 3 was done by ITER IT [6]. It was shown that it was possible to design an optical path using 4 mirrors compatible with a low neutron flux at the exit of the duct.

Since it is the first time that a MSE diagnostic will use 4 mirrors, it was important to show that the change in polarisation induced by the mirror system still allows a high accuracy measurement. This experiment was done at UKAEA [3], in collaboration with VR [11], where this feasibility was demonstrated, with the condition of keeping incidence angles on mirrors low. These experiments should lead to an improvement of the port labyrinth still compatible with a low neutron flux (in collaboration with ITER IT).

Another difficulty (common to all the diagnostics having a first mirror in the machine) is due to the probable first mirror reflectivity degradation with time. Erosion of and deposition on first mirrors is studied in several ITER parties and new mirror types developed. This work is coordinated by a Specialist Working Group under the ITPA Topical Group on Diagnostics.

For MSE, the effect of Be coating on the first mirror on the signal polarisation has already been evaluated [7]. A change of several degrees in the direction of the initial polarisation is expected, as well as an increase of the circular polarisation fraction. Measurements on plasma exposed mirrors by VR [11] confirm this result.
For this reason, calibration methods and check-up techniques for the diagnostic must be developed and tested on present machines. For instance, simultaneous measurement of σ and π lines (known to have perpendicular directions before reflection on mirrors), has been suggested. A first promising use of this technique was experimented on JET [3].

III) MSE from Diagnostic neutral beam.

MSE on the DNB is proposed in addition to CXRS and BES diagnostic [8]. The same optics and viewing lines as the CXRS system are used. This diagnostic uses a 100 keV/amu negative ion beam, corresponding to an optimum in the compromise between beam penetration and charge exchange cross sections, and the ratiometric method between the σ and π lines to determine the MSE angle.

MSE diagnostic on the DNB will be installed in e-port3-low (edge MSE) and in upper-port3 (core MSE) for which ITER spatial resolution requirement is satisfied respectively for all plasma radii (Figure 14). The sensitivity to σ to π ratio seen from these two positions, and thus to q-profile is high.

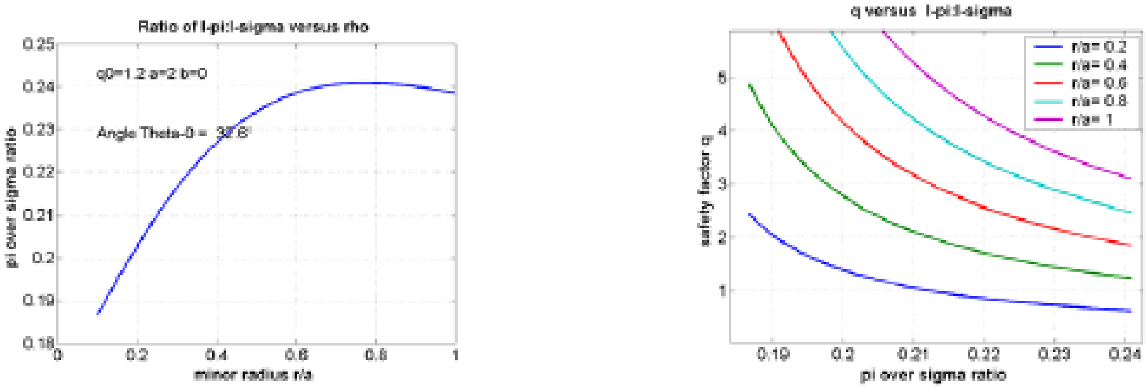


Figure 14. Top periscope. (a) π over σ ratio as a function of normalised radius, (b) q derived from this ratio for 5 radial positions

Although DNB penetration is less than for HNB due to a smaller energy, DNB is radial and the path to reach magnetic axis is smaller. The estimated SNR is good and a time resolution of a few tens of ms can be envisaged.

The design of the CXRS diagnostic shows that an optical path including several mirrors is needed. The difficulties to be faced are the same as in the polarimetry method. The multi reflections as well as the mirrors coating will change the initial σ/π ratio and these effects will have to be calibrated. Pilot experiments and sensitivity studies are envisaged for a full demonstration of this method.

DNB MSE or HNB MSE ?

The foreseen effects of mirror coating will bring some additional sources of errors in both methods, and even if real time calibrations are done, **cross checking of the measurements from both methods will be necessary when possible**.

From the scenarios point of view, MSE on HNB has the advantage of a good plasma core penetration, and to allow continuous measurements. With e-port 1 in complement of e-port 3, a MSE profile can be measured with the two heating beams, and without external electric field correction.

Feed back control of q profile with the other heating systems is possible for some scenarios where NBI is the continuous basic heating system, and ECRH or ICRH are added to modify the current profile.

But to realise a full MSE profile on HNB, two heating beams are needed. This means that in scenarios where no beam or only one beam is present, no MSE measurement will be possible (or half profile measurement only).

MSE on DNB on the contrary is not continuous, but is available in all plasma scenarios. In plasmas without heating beams, MSE measurements, and thus calculation of current profile will be available only from the DNB diagnostic.

Even if DNB becomes a steady state beam, it is not realistic to base MSE diagnostic on these measurements only. The sensitivity to electric field should be higher than for MSE on HNB, plasma core measurement with high accuracy may be difficult, and the possible measurement error due to mirrors coating is the same as for HNB MSE.

Performing reliable MSE measurements will be possible only with the combination of the two methods, each one having its own calibration technique. Cross checking of the measurements will allow a validation of both methods, so that only one could be used in scenarios when the other is not possible.

The use of both MSE methods is thus highly recommended on ITER.

Conclusions:

Most of the difficulties foreseen to install a MSE diagnostic on ITER are now solved or on the point to be solved.

* The MSE measurement at high Lorentz electric field is possible.

* The diagnostic spatial resolution is better than 15 cm everywhere, and better than a/40 around rho= 0.2 and 0.65.

* The high energy of the neutral beam allows a good plasma penetration, and the signal to noise estimations indicate that a time resolution of a few tens of ms could be envisaged.

* The vertical size of the beam could bring additional difficulties of measurement if the density profile of the beam in the vertical direction is not constant during the discharge. But this should lead to an anomalous power deposition along the injector and should be detected by the NBI system.

* The clear separation of the σ and π components will allow MSE measurements with a high polarisation fraction as well as the possibility to work at low toroidal field.

* The influence of the radial electric field appears negligible for most scenarios. The important consequence is that the diagnostic is independent and does not need to be Er corrected. On the other side, it does not seem possible to deduce Er from MSE measurements.

* Laboratory demonstration of the use of 4 mirrors to perform a MSE measurement was done.

* The possible modification of the initial polarisation due to the first mirror coating has been calculated and measured experimentally on plasma-exposed mirrors.

* To cope with these effects, in-situ calibrations will be essential and will have to be integrated in the design. In parallel, simultaneous measurement of σ and π lines is proposed to detect the reliability of the measurements and deduce information on the mirrors.

* In parallel the feasibility of a MSE diagnostic on the Diagnostic beam in complement to the CXS diagnostic was demonstrated (FOM). The combination of two observation ports allows MSE measurements with a spatial resolution satisfying ITPA requirements. The sensitivity of the measurement on the σ/π ratio and thus to q profile is very good from these two ports.
Multi-mirror and coating effects are also in this case a major source of concern. Calibration methods based on atomic modelling of line emissions and on the use of the plasma itself are proposed.

* The lack of heating beams for some scenarios as well as the additional difficulties due to the mirrors coating indicate that the two MSE diagnostics (on HNB and DNB) are necessary on ITER. Cross checking of the measurements will be done when possible, so as to validate each method.

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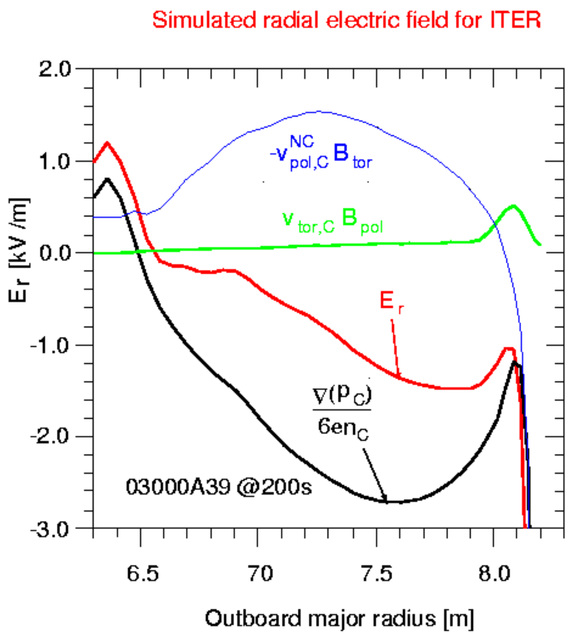
Annexe 1

Radial Electric field in ITER due to NNBI (Courtesy R. Budny PPPL)



Design analysis of the ITER Motional Stark Effect diagnostic

Final Report, Contract EFDA 02-1005

N C Hawkes
with acknowledgements to M. Kuldkepp,
P. Lotte, A. Malaquis and E. Rachlew

March 3, 2004

1 Introduction

This report considers some of the difficulties that will be encountered in the design and operation of a motional Stark effect (MSE) diagnostic for ITER. The issues addressed are: the geometric space resolution available from with the ITER ports; spectral overlap of light from different beam sources; the effect of vertical beam source divergence and the tolerance to first mirror degradation. Some possible solutions to these problems are suggested, but much more work is required to adequately deal with these issues.

1.1 Simulation Program

The MSE simulation program, first written to test the design of the JET Motional Stark Effect diagnostic, has been modified to incorporate the ITER machine and beam geometries. This program has been used to study the space resolution and polarised fractions of the MSE emission from the ITER heating and diagnostic neutral beams. The ITER heating beams are composed of four segments, each aligned to a convergent focus in the plasma. The program models the light emission from the beams from each segment, describing the wavelength and polarisation characteristics (using Stokes vectors), and sums the contributions from all light sources along each viewing line of the diagnostic. The spectral broadening of the light emission from each point, from effects such as beam divergence, finite beam source temperature, power supply stability and viewing optics f-number, can be included as a single linewidth parameter. This polarisation resolved synthetic spectrum is decomposed to give a measure of the angle and degree of polarisation. Space resolution is calculated in 3-D assuming cylindrical beams of a specified circular diameter. The intensity weighted integral of major radius along a viewing line is used to calculate the space resolution of the diagnostic. (All the beams are described with circular cross-sections and the intensity is that which lies within the passband of the filters used to select the specific Stark feature.) Further work is needed to include a realistic equilibrium and the contribution of Bremsstrahlung to the background light.

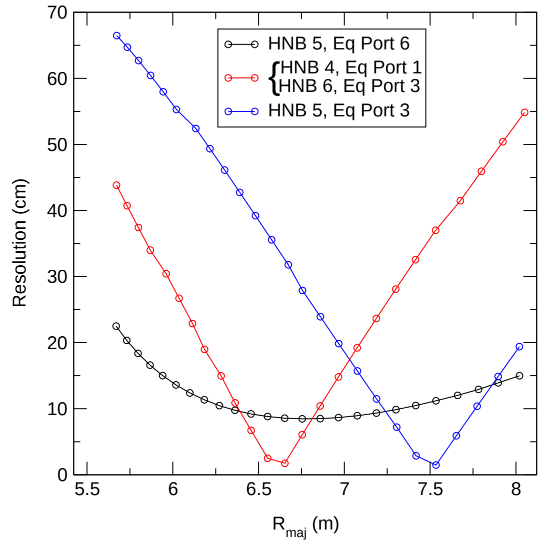


Figure 1: *Spatial resolution calculated for views of heating beams 4 and 5 from equatorial ports 1, 3 and 6.*

2 Space Resolution and Signal Intensities

2.1 Space Resolution and Port Selection

Work with this program has confirmed the general conclusions of previous 2-D estimates[1] of the space resolution, showing that the optimum viewing geometry is that of a red-shifted view from equatorial port 6 viewing MSE emission from HNB 5. Such a view would meet the design requirements for the diagnostic space resolution, being between 10 and 15 cm over the entire outer minor radius, figure 1. Unfortunately this port is not available for diagnostics (except in a dominantly RF heated ITER, so-called heating scenario 1). Simulations of other configurations on the midplane show that two MSE diagnostics could achieve similar resolution, but not over the entire minor radius. A diagnostic in port 1, viewing the beam HNB 4, would give a space resolution of 20 cm or better from 6.2–7.1 m. A diagnostic in port 3 viewing HNB 5 would give the same space resolution over the rest of the minor radius. These calculations assume that the diagnostic is mounted in the middle of the port. Some 'fine-tuning' is in principle possible if the collection optics are mounted to one side or other of the port, although there are undoubtedly engineering constraints that would need to be considered. An alternative to a diagnostic in port 1 viewing HNB 4 would be to have the diagnostic in port 3 viewing HNB 6.

2.2 Doppler Shifts

For the edge viewing part of the diagnostic (HNB 5/Eq Port 3) the MSE spectrum from the target beam lies between those from the other two heating beams, with, for the most part, well isolated spectral lines. The closest approach to spectral overlap with light from the other heating beams occurs between 7.0 and 7.3 m.

For the core viewing part of the diagnostic (HNB 4/Eq Port 1) the issue of spectral overlap (with the emission from HNB 5) is serious, with some overlap affecting the views covering from 6.0 to 6.8 m. Views beyond 6.8 m do not intersect the beam from HNB 5 because the crossing point is outside the plasma. Some improvement may be possible by moving the collection optics to one side of the port plug and raising it to the top of the plug in order to minimise the interception with HNB 5 or with careful choice of Stark components to analyse and perhaps adjustment of the beam voltages. However, this issue requires further study. Note that HNB 6, viewed from port 3 would have the equivalent geometry and hence space resolution. This configuration would be almost completely free of spectral overlap problems, but is dependent on the installation of a heating beam in port 6.

2.3 Spectral Survey

A survey of the emission spectrum from JET has been made covering the regions of spectrum where the beam emission spectrum from the ITER heating beams would occur. The JET measurements were made with a line of sight intersecting the heating beams, such that any charge-exchange features would necessarily be present in the spectra. Prior to these measurements JET had undertaken a series of experiments in helium plasmas and the remaining helium in the vessel walls led to a significant level of helium impurity in the plasma. JET also has carbon and beryllium components. Thus the range of impurities in the JET plasma covers most of the likely impurities to be found in the ITER plasma. (No high-Z metals were in use, however, nor any radiating impurities for ELM control.)

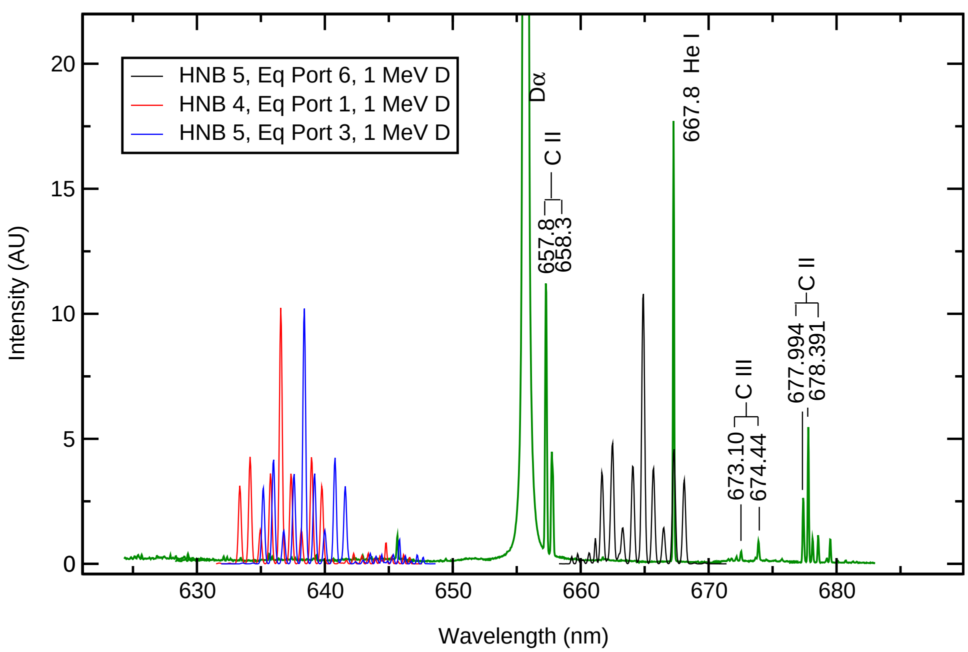


Figure 2: *Composite spectrum from a sequence of JET discharges covering the spectral ranges of the beam-emission features of ITER from different port positions. The measured spectra have been overlaid with the calculated MSE emission features for 1 MeV deuterium beam injection.*

A sequence of spectra were recorded at different wavelengths and assembled into a single composite survey of the region 656 nm±25 nm. This spectrum, overlaid with the calculated beam emission spectra for the different proposed ITER MSE geometries is shown in figure 2. From this figure it can be seen that there are no serious impurity emission features affecting the red-shifted MSE spectra, as proposed for ITER. The blue-shifted emission spectrum (as would be obtained from an octant 6 view on ITER) shows a single helium line at 667.8 nm which could interfere with measurements for some chords.

2.4 Achievable Resolution with Upper Port

Calculations of the space resolution available from the upper diagnostic ports shows that this is considerably poorer than that achievable with the equatorial ports, worse than 30 cm at all radii and becoming extremely poor at the plasma edge,

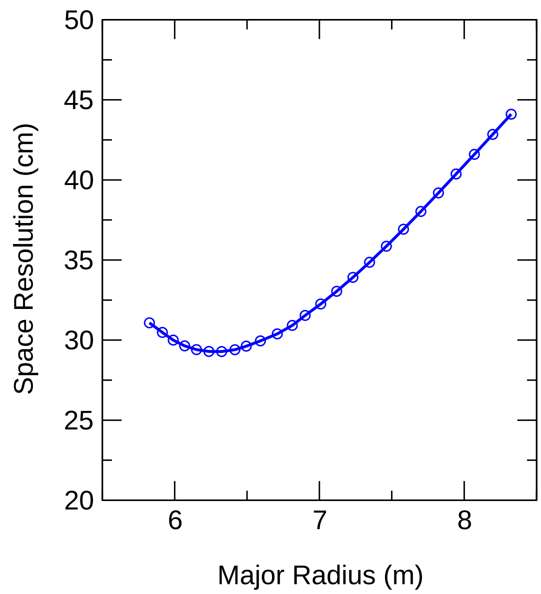


Figure 3: *Space resolution viewing HNB 5 from upper port 6*

figure 3. This poor resolution arises from the steep intersection angle between the viewing lines and the flux surfaces. Furthermore, the polarised light fraction is significantly reduced for these upper views, due to the fact that the viewing lines of sight have a large component parallel to the electric field direction.

2.5 Measurement inaccuracies caused by multiple injector segments

The heating beams of ITER are divided into four vertical 'segments', which are all aligned to a focus in the plasma. This results in a difference in the angle in the vertical plane between the uppermost and lowest injector of 2.5 degrees. This in turn results in a variation of 3.5 degrees in the measured polarisation angle for the contributions from the different beam segments. The overall polarisation angle measured by the MSE diagnostic will be an average of these angles, with the overall angle sensitive to the relative power density in the different segments. Such a situation existed on JET and required that the relative contribution from each injector be calibrated by firing the injectors sequentially. In ITER it will not be possible to energise the separate beam segments and the lack of such a facility poses a major difficulty to the diagnostic. (The sequential operation of the injector segments would also provide an excellent in-situ calibration for the diagnostic.)

While it is not possible to operate individual beam segments independently, it may be possible to selectively power different portions of the ion source. This might enable a calibration to be made of the influence of each source segment on the overall polarisation angle. However, this would only be a crude method of controlling the spread of angles present in the beam since plasma formed in one part of the ion source will diffuse into other regions. The separate portions of the ion source are not, in any case, matched to the segments of the accelerator.

The most attractive method for dealing with the issue of different segments to the beam is to use the beamline calorimeter to measure the relative intensity of each segment. The calorimeter is mounted close enough to the source that the profile of the beam can be measured and the contributions from the individual segments measured.

Further work is required on this issue, with an examination of the options. An outcome is likely to be a specification for the detail with which the calorimeter thermocouples record the beam profiles. Both beam profile monitoring and ion source control may be required to enable adequate interpretation of the measured Stark angles.

2.6 Requirement to track beam steering

The heating beams of ITER are designed to operate at different vertical angles, in order to be able to perform on-axis and off-axis current drive. To be able to make MSE measurements from the heating beams in all their steering positions would require that the MSE collection optics also be steerable. The heating beams are also designed to operate with a range of acceleration voltages, between 400 and 1000 KeV. This represents a larger range of Doppler shifts than is encountered with the JET beams and might prohibit the use of tilt-tuned interference filters, demanding instead either multiple filters or a spectrometer solution.

2.7 Beam penetration

Despite the difficulties, there are some significant advantages in the use of the heating beam over the diagnostic beam for MSE measurements, the most significant being the improved penetration of the higher energy heating beams, figure 4. In the figure the dashed line represents the lower limit of detection for MSE measurements in JET, the code results showing that heating beam would allow measurements a further 0.5 m deeper into the plasma than the diagnostic beam. Penetration still falls short of the plasma axis and some improvement in detection techniques would be desirable. (A more peaked density profile, likely in Advanced Tokamak scenarios, will be more favourable for beam penetration to the plasma centre.)

2.8 Polarised fraction

The simulation program predicts very high polarisation fractions, 90–100%. These figures are higher than achieved in practice on JET, typically 30%, the improvements arising from the higher beam energy and consequent increase in the separation of the spectral features. Factors which can degrade the polarised fraction have been considered. The effect of the 5% beam voltage stability is to broaden the emission lines by 0.35 nm while beam horizontal focusing adds a further 0.2 nm to the idealised linewidths. Because of the relatively large line spacing these broadening mechanisms do not result in a significant degradation of the polarised fraction. Some caution is necessary in the interpretation of these results since similar calculations for the JET beams yield an over-optimistic assessment of the polarised

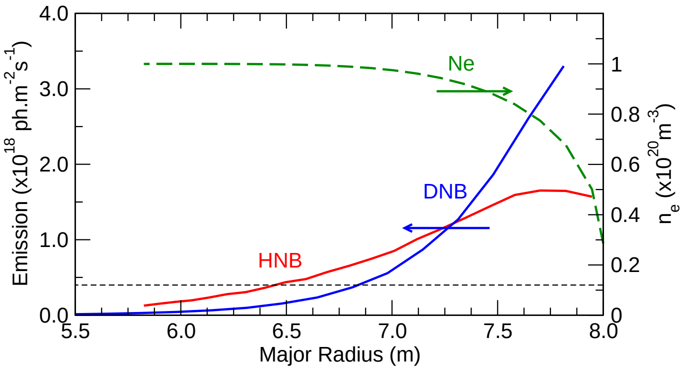


Figure 4: *Results of the simulation program showing the calculated signal level from a 17 MW 1 MeV T heating beam compared to a 2.2 MW 100 KeV diagnostic H beam for an ITER H-mode density profile. The dashed line represents the practical lower limit of detection for JET, below this level the contamination by background light prevents accurate measurement.*

fraction due to a larger than expected line width. However, since the ITER spectral separations will be larger than JET it will be less vulnerable to small extra line broadenings.

3 Mirror Labyrinth Requirements

The mirrors in the proposed optical labyrinth of the MSE diagnostic will have an effect on the polarisation of light passing through the system[2]. Although such effects could be measured during a calibration procedure, either before installation on ITER or between plasma pulses using an in-situ calibration facility, the first mirror properties are expected to change with time (perhaps even during a single ITER pulse) as a result of deposition of impurities on the mirror surface.[3]. Therefore, the ITER MSE system must incorporate a method for the in-situ monitoring of the first mirror properties. (It is assumed that only the first mirror will be subject to deposition or erosion effects and that therefore this is the only mirror requiring monitoring. This seems a reasonable assumption, presuming that the first mirror is the only one which has a direct line-of-sight to the plasma. In principle, material sputtered off the first mirror could be deposited on the second mirror. Considerations of solid angle would imply that such a process must be at least one order of magnitude less effective than damage to the first mirror, but given the considerable difficulties in estimating the damage to the first mirror, deposition at the second mirror can be little better than guessed at.)

3.1 Monitoring of First Mirror Optical Properties

Measurements have been made by the Swedish Association[4] (VR) of the optical properties of a number of different mirror materials, including freshly prepared gold mirrors and samples of various metal mirrors overcoated with different dielectrics. Their results have shown that the coefficients of the complex refractive index, the optical constants n and k (where the metal complex refractive index is $\mathbf{n} = n - ik$, can be determined in the case of a fresh metal mirror and that the optical performance of such mirrors as a function of incidence angle obeys the dependence predicted by the Fresnel equations.

In principle the measurement of the optical constants at one angle would determine the performance of the first mirror at all angles, enabling the effect of the mirror on the MSE signals to taken into account for each incidence angle. In particular the optical constants could be measured by an on-line calibration system monitoring at, for example, 35° while MSE measurements were recorded over the range 10-25°, as illustrated in figure 5. Since the optical constants are determined

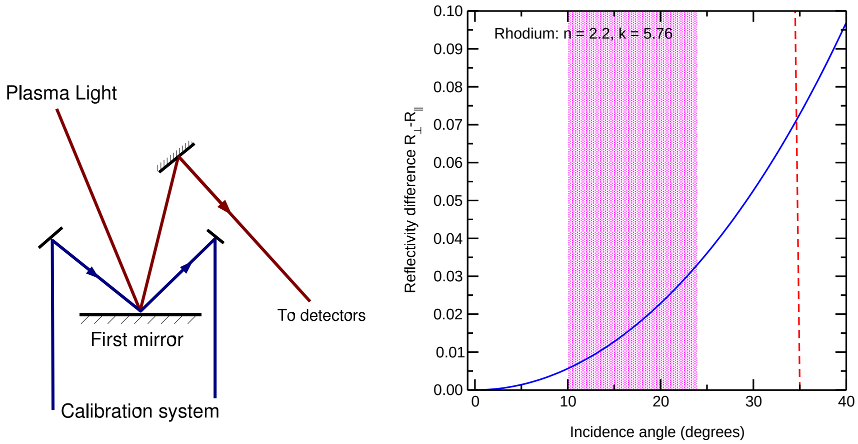


Figure 5: *Illustration of a first mirror monitor geometry in the same plane as the measured light. The monitor optical system measures the mirror performance at 35° in this example while the application of the Fresnel equations allow the results of this measurement to be applied to the measurement angles in the 10-25° range.*

at a larger angle than the operating range of the diagnostic, the calculation of the mirror properties at its operating angle is in the nature of an interpolation and should provide the best accuracy for the technique.

However the work by VR demonstrated that there are still relatively large uncertainties in the determination of the optical constants and that these could only be overcome by measurements at a range of incidence angles, including the angles over which the mirror properties would need to be known. Thus, the model used to convert monitor measurements at the higher incidence angle down to the operating angle would itself depend on measurements made at the operating angle. Apart from the engineering difficulty of making online measurements at the operating incidence angle, this dependence removes the advantage of making a monitor measurement at a high angle of incidence.

The VR work also showed that obtaining the optical constants became far more difficult in the presence of a coating on the mirror, either a deliberately applied protective dielectric layer or a layer of unknown composition deposited by tokamak exposure. However, it was demonstrated that a mirror's properties could be more reliably expressed in terms of its relative reflectivity (to S- and P-polarised light), r_m, and phase retardance, δ, at a specific incidence angle, than in terms of complex refractive indicies.

In view of the problems associated with the accurate conversion of optical properties measured at one angle of incidence to another it is necessary for the ITER MSE diagnostic to incorporate measurements of the first mirror at its operating angle. This can be achieved by rotating the measuring beams by 90° about the mirror normal, figure 6. In this arrangement it is possible to monitor the mirror properties at the same incidence angle as typically used to measure plasma emission. The

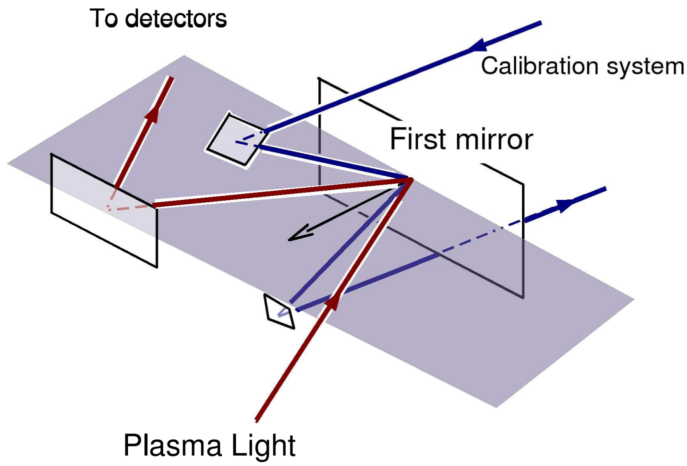


Figure 6: *Proposed geometry of first mirror monitor using orthogonal measurement beams to probe the mirror properties at the same incidence angle used to record plasma light. The orthogonal geometry allows the monitor measurements to be made in parallel with measurement of MSE emission.*

variation of optical properties over the restricted range used by different chords of the diagnostic can probably be neglected, or will at least be sufficently small that calculations can be used to extend the single measurement to all operation angles. It is also possible to ensure that the mirror surface probed by the monitor beam is the same as that used for the measurement, such that the effect of non-uniform surface deposition is fully taken into account. However, if the entrance pupil of the optical system is placed at the shield penetration (desirable to reduce neutron fluence and mirror contamination, then different viewing chords will use different portions of the mirror surface. To fully monitor this situation would require multiple monitor beams each probing the equivalent parts of the mirror surface. Such a system could be envisaged, and could perhaps be constructed such that the variation in incidence angle across the mirror surface was also matched, but would result in a system of considerable complexity, bearing in mind that each monitor beam would require a labyrinth to convey it both to and from the diagnostic mirror.

4 Parallel Monitor of σ and π Polarised Emission

The MSE emission features include components that are mutually orthogonally polarised, the σ and π components. Measurement of the polarisation of these two features yields information about the retardance and relative reflectivity of the first mirror.

The first mirror of the JET MSE system is a partially transmitting multilayer dielectric device which has both a phase retardance and a relative reflectivity difference between the S- and P-polarisations. (Although the mirrors anticipated for the ITER MSE labyrinth will be metallic, they will also suffer from the same optical effects as the JET dielectric mirror.) Measurements have been made on JET by scanning the wavelength of the detection spectrometers through the Stark spectrum during steady plasma conditions. The requirement that the measured polarisation angle change promptly by exactly $\frac{\pi}{2}$ between the σ and π wavelengths has been used to successfully calibrate the relative reflectivity of the S and P reflections. The principle of the technique is shown in figure 7 where the signal from a polarimeter is calculated for a sweep through the orthogonally polarised σ and π emission, including a fraction of circular polarised emission, necessary for the extraction of the mirror retardance (and observed in the experiments). The change in measured angle depends on both the retardance of the optical system and the relative reflectivity. The corresponding diagram for actual measurements is shown in figure 8. The numerical simulation illustrate how the separate extraction of r_m

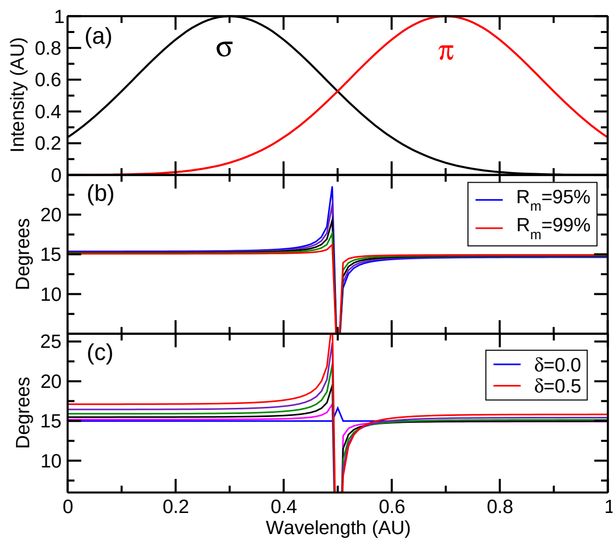


Figure 7: *Polarisation angle (modulo 90°) during a sweep of the spectrum through the MSE σ and π features. (a) intensity profile of σ and π emission, polarisation angle measured as (b) r_m is varied from 0.95 to 1.00 and (c) δ is varied from 0.0 to 0.5 radians. (The MSE emission includes a 5% circular polarised fraction—typical of the level observed in real measurements.)*

and δ is accomplished. There is, however, not exact agreement between the simulation and the behaviour seen in the experimental measurements, indicating that the numerical model is incomplete. The JET system appears to benefit from a particular geometry that allows the extraction of r_m and δ to be achieved, we cannot rely on being in the same favourable situation on ITER and so must make provision for the separate measurement of the mirror optical parameters.

4.1 Validation of Polarisation Angles using σ and π Measurements.

Simultaneous measurements of the σ and π emission from JET have been demonstrated to be useful for establishing when MSE measurements become unreliable due to interfering polarised light. Unpolarised light should not affect a properly calibrated MSE system, but interfering polarised light will damage the accuracy of the results. Measurements on JET, figure 9, using adjacent channels tuned to σ and π emission during conditions of high background optical radiation have shown that the deviation from a $\frac{\pi}{2}$ difference in angle can be used to detect conditions where the MSE measurements become unreliable.

Parallel measurements of the σ and π emission can therefore be used in different ways to characterise the MSE diagnostic and to validate its measurements. However, these two functions cannot be performed at the same time, in particular the first function demands uncontaminated emission from the plasma.

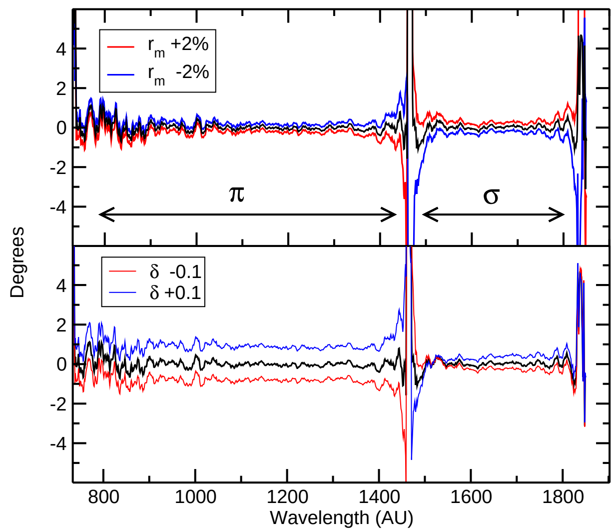


Figure 8: *Data from JET taken during a sweep of the filter spectrometer through the MSE spectrum and fitted with different values of first mirror relative reflectivity and retardance. (The black curves are with the optimum fitted parameters while the values shown in the legends are perturbations from these optima.)*

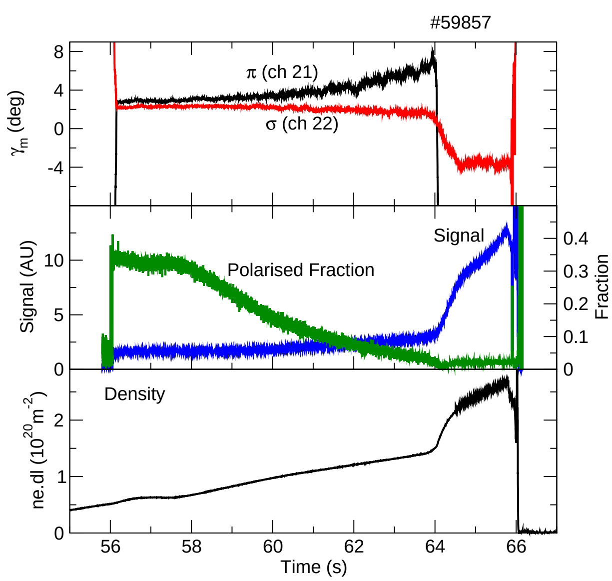


Figure 9: *Adjacent channels of the JET MSE system tuned to σ and π Stark features showing the deviation from $\frac{\pi}{2}$ angle difference as the background light signal increases.*

5 Further Work

Several difficulties have been discussed in this report, and some outline suggestions for dealing with the issues have been proposed. Further work is needed to develop these and any other ideas into workable solutions for the diagnostic. In particular the problems caused by the multiple segments of the injector sources, the spectral interference between beams for part of the core-viewing system, and the engineering details of monitoring the first mirror optical properties need more detailed analysis. An assessment of the level of detail and accuracy that is needed from the beam line calorimeters is required if this emerges as the best strategy for dealing with the source segment problem.

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ITER Motional Stark effect diagnostic: experimental analysis of polarization effects of mirror labyrinth and other assessments

Final Report, September 2004

EFDA Contract 02-1006 (FU06-CT-2003-00021)
with EURATOM-Association-VR
Deliverable 5.3: Design analysis of the ITER Motional Stark Effect diagnostic

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Technical specifications of the contract

VR will contribute the following analysis

1. analyse mirror labyrinth geometry and mirror polarisation effects on the MSE measurements
2. assess the influence of ELM's on the MSE spectroscopy
3. assess the influence of electric fields on the intensity distribution of the π and σ components of the MSE spectrum
4. validate the beam attenuation atomic physics input and where possible verify via comparisons with JET data

Introduction

This final report describes the results achieved in the experiments on the mirror labyrinth carried out in the newly set-up laboratory at Culham Science Centre. These results have recently been presented at the AIP High Temperature Plasma Diagnostic conference in San Diego, April 2004 and the adapted paper for this meeting is included in this report. In addition to our work several complementary works on the ITER MSE system have been presented and we have included these as references to this final report.

1. First mirror contamination studies for polarimetry MSE measurements for ITER

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The Motional Stark Effect (MSE) diagnostic on ITER will need to guide the light through a labyrinth of mirrors to provide neutron shielding. Knowledge of how the mirrors change the polarisation is essential for accurate determination of the q-profile. The optical properties of the plasma facing mirror are also expected to change with time due to deposition/erosion. For the purpose of examining this experimentally a detector system, identical to the JET MSE system, using twin Photo Elastic Modulators (PEM) was constructed. Measurements have been performed on freshly prepared mirrors , on mirrors after exposure to plasmas in Tore Supra and on a few labyrinth designs. The result shows a significant effect on the optical properties and demonstrates the need for in situ monitoring. We propose strategies to control the problem of changes in the polarization properties.

I. INTRODUCTION

The Motional Stark Effect (MSE) diagnostic has proven to be an essential instrument for accurate determination of the q-profile in plasmas[1-3]. Since this knowledge is of vital importance for the plasma behaviour, an MSE diagnostic is planned for ITER[4]. The most common way to acquire the q-profile, called polarimetry using MSE measurements, includes measurement of the linear polarisation angle of the MSE-shifted components of D_α. For this method to work well it is therefore necessary to know the impact on polarisation of all components in the collecting optics.

On ITER it is expected that the high neutron flux will damage the diagnostics and other tokamak systems unless they are properly shielded. The light will pass the shield through a labyrinth of mirrors before it reaches the detector and the impact of these mirrors on the polarisation direction is of great concern. This concern is twofold. Firstly, it is in the best interest to keep the overall influence small and, secondly, it is important to know how it evolves in time.

The plasma facing mirror will change its optical properties due to erosion/deposition of particles[1,5]. The details are difficult to predict accurately but it is possible to get more insight by measurements on mirrors that have been exposed to a tokamak plasma.

These two important aspects of the mirror labyrinth have been measured on a miniature of the proposed configuration.

The fist mirror samples were supplied by CEA after measurements on Tore Supra (EFDA task TW2-TPDS-DIADEV), and had been situated approximately 50 cm outside the LCFS. The total plasma exposure time was estimated to be close to 12 hours (One sample had been exposed for a shorter time but with a significant level of LHCD heating, resulting in surface currents and mirror damage). Unexposed mirrors were tested for the characterisation of the non plasma facing labyrinth part.

The experimental set-up is shown in figure 1. It consists of a white light source, a rotary stage with a linear polariser and a labyrinth of mirrors. These are followed by a polarisation detection system similar to the current MSE diagnostic at JET[6], composed of a twin photo-elastic modulator (PEM), a linear polariser, an optical filter, an avalanche photodiode (APD) detector with preamplifier and an ADC card. Signals from the detector, the rotary stage and the PEMs were collected and a digital lock-in program was used to calculate the detected polarisation angle and to compare it with the angle of the rotary stage.

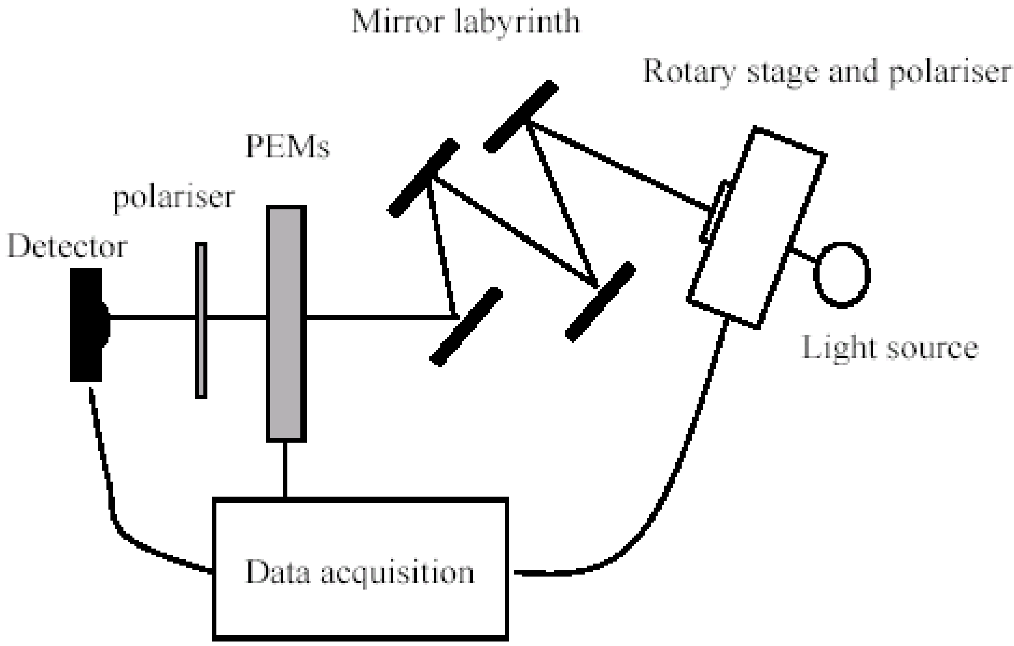

Fig 1. Experimental setup. All parts were fastened on an optical table and the detector was shielded from background radiation.

II. THEORETICAL MODEL

The Stokes representation of light is suitable for models where coherence effects are small and unpolarised light may exist[7]. In this approach the light is represented by a 4x1 vector with components corresponding to different polarisation. Interaction with optical elements is performed by multiplying the vector with an appropriate 4x4 matrix, called the Mueller matrix.

The Mueller matrix for a mirror contains four unknown parameters, R_s, R_p, φ_s, φ_p, the absolute reflectivities and the phase change upon reflection in the S and P plane. In this study these parameters are unknown and we seek to evaluate them through experimental measurements. These constants are different for each kind of mirror and prediction of them from first principles is very difficult since it depends on several optical and physical properties (incl surface roughness) of the mirror. Of special interest are the single and double interface models corresponding to a clean mirror or a mirror with a thin surface structure/layer.

Common ways to describe the optical properties of a material are the complex index of refraction $n_c = n - i \cdot k$ or the complex dielectric constant $\varepsilon_c = \varepsilon' + i \cdot \varepsilon''$. In this study we have used the former description.

In the single interface model the reflectivity and phase changes are calculated with the Fresnel equations whereas in the two-interface model interference effects in the surface layer also have to be considered[8]. Several approaches are possible. Our choice was to use the equation.

$$r = \frac{r_{12} + r_{23} \cdot e^{i \cdot 2\beta}}{1 + r_{12} r_{23} e^{i \cdot 2\beta}} \qquad \textbf{(1)}$$

$$\beta = 2\pi \cdot n_{c2} \cdot \frac{h}{\lambda} \cdot \cos(\theta_2)$$

r_{12} and r_{23} are the reflection coefficients for the two interfaces, λ is the wavelength, θ_2 is the complex angle of light in the layer, n_{c2} its refractive index and h is its thickness.
In practice it proved to be difficult to extract more than two unknowns from the measurement. The model was therefore constrained to a substrate of known properties and the two fitted parameters were the thickness of the coating and the real part of its refractive index. The imaginary part was assumed to be zero.

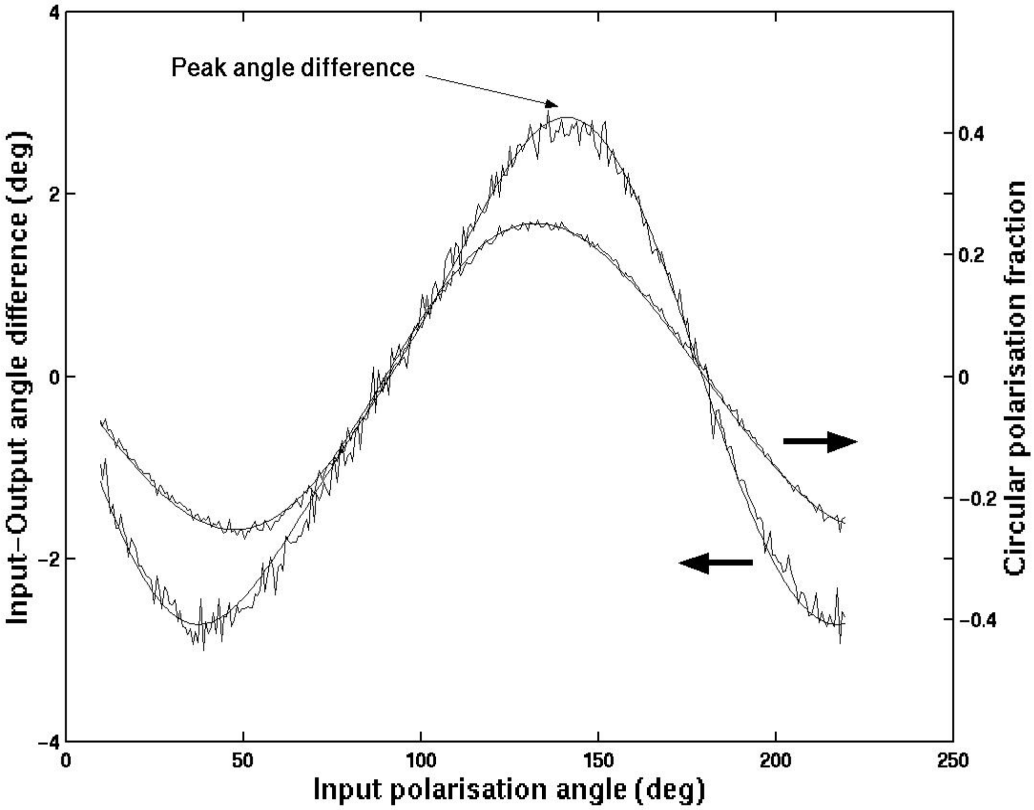

Fig 2. Measurement and fit of linear polarisation change and circular polarisation fraction after a 4 Rh-mirror labyrinth.

III. EXPERIMENTAL RESULTS

The set-up and model was firstly tested on a number of freshly prepared unexposed metal mirrors, Au, Ag, Al, Rh and stainless steel (SS). These mirrors were chosen to give a variation in mirror properties which we would measure with the new set-up. The materials are not the first choice for ITER but represent a variety of coatings with which the accuracy and reliability of our measurements could be determined. Gold in particular is interesting since it is inert and will have little or no surface layer, even though surface roughness and voids in the material may still be of importance. Measurement on gold confirmed the measurement procedure and also gave an idea of the accuracy we could expect from other materials.

Differences between the input and output polarisation angle are shown in figure 2. The fitted angle difference is also shown and the expected variation with polarisation shows a minimum at 0° and 90°. The precise form of the angle change as a function of polarisation is different for each kind of mirror and is also strongly affected by the incidence angle of the light. General features are a smoothly varying function with none or a single zero-crossing between 0° and 90° and an amplitude that increases strongly with incidence angle. The circular polarisation fraction which is also shown in fig 2 shows a similar behaviour but never has extra zero-crossings between 0° and 90°.

A comparison between different materials can therefore be done based on the peak angle difference introduced by the mirror. Such a comparison is shown in fig 3. Mirrors of Rh, Au or SS could readily be fitted with the single interface model but Ag and Al, which indeed have a protective coating of unknown composition applied by

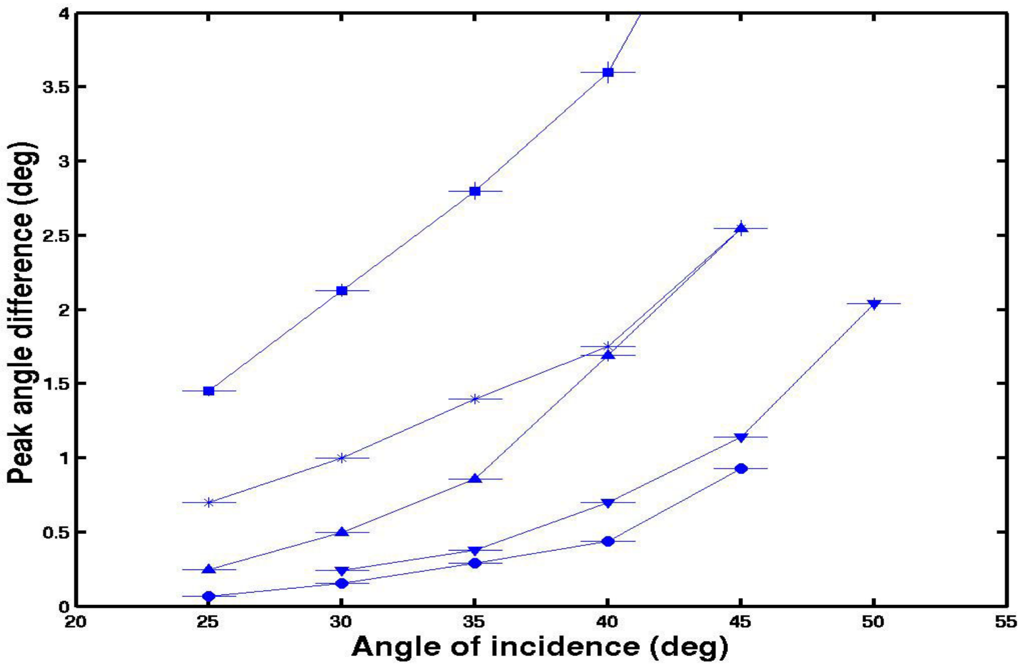

Fig 3. Measurement of peak angle difference of unexposed single mirrors, Au (▼), Rh (✱), SS (■), Ag (●), Al(▲).

the manufarturer, had to be fitted with the two-interface model.

There were in total four mirrors supplied by CEA after exposure in Tore Supra. One glass mirror with an Al coating (I), one SS mirror with an Al coating (II), one SS mirror without coating (III) and one unexposed reference SS mirror with Al coating (IV). The reference mirror probably had a surface oxide or protection for the Al but it was nevertheless possible to determine the optical properties using the single interface model. With that knowledge it was possible to measure the refractive index and thickness of the layers on mirror I and II. For mirror III the single interface model was adequate.

Mirror I had a 171 nm thick layer with refractive index 1.29 whereas mirror II had a 130 nm thick layer with refractive index 1.49. These results were an average of measurements taken over different angles of incidence. The results showed a small increase in thickness with increasing incidence angle indicating a slight inadequacy of the two-interface model. Mirror III had a refractive index $n_c = 1.87 - i \cdot 2.11$ but without a reference mirror (i.e. a non-exposed identical mirror) it could not give further information.

The maximum angle change introduced by the mirrors is shown in figure 4. Both mirror I and II affect the polarisation less after exposure than the reference mirror (IV). The amount of change in mirror properties is undoubtedly related to differences in the exposure history of the two samples.

Figure 2 also shows the result of a 4 Rh-mirror labyrinth with incidence angles as proposed in the present ITER MSE labyrinth design. Their respective incidence angles were 17°, 32°, 24.5°, 21.5°. In the Stokes formalism several objects can easily be described by multiplying their Mueller matrices; the measurements show very close agreement with theory. The single mirror refractive index was measured to be $n_c = 1.85 - i \cdot 5.15$ with a standard deviation of 0.12 in n, and 0.25 in k. Fitting to the labyrinth yields $n_c = 1.76 - i \cdot 5.08$ which is within the uncertainty of the measurement. Predictions were also in line with measurements for labyrinths constructed using gold or silver mirrors although the peak angle differences introduced were less, 1.2° and 0.63° respectively.

It was not possible to measure absolute reflectivities in this set-up but they are nevertheless important. For example, after 4 SS-mirrors the signal was so attenuated that it was impossible to get good data. Although not the prime concern of this investigation, it may become important if signal levels are low (like in the center of the plasma).

In these experiments we used fully polarised light but in ITER and other tokamaks the light is only partially polarised. This can have a serious impact on the polarisation preserving properties of a labyrinth. Simulation with the two-interface model shows that the angle difference introduced by the mirrors are approximately tripled if the polarisation fraction is 10% instead of 100%.

IV. DISCUSSION

The measurements shown in figure 4 clearly point out that even after exposure times of only 12 hours the effect of coating layers is already too large to neglect. This emphasises the need for an in-situ calibration system for the plasma facing mirror on ITER. It is possible that even the second mirror must have a monitor since the flux of particles may be non-negligible. Further investigation into this will be required.

An in-situ calibration system could monitor the first mirror either at the same incidence angle but in an orthogonal plane or at a different angle but the same plane. Using a different angle requires a good model for the mirror or the extrapolated data will be inaccurate. Experimental results show that such a model will need to be more complex than the two-interface model. The reason may be attributed to voids or substrate imperfections but more likely it is due to non-transparency or non-uniformity (as function of thickness) or surface coordinate) of the eroded/deposited layer.

All experiments with several mirrors show very close agreement with the Stokes formalism, therefore making prediction from simulation reliable for the labyrinth effect on

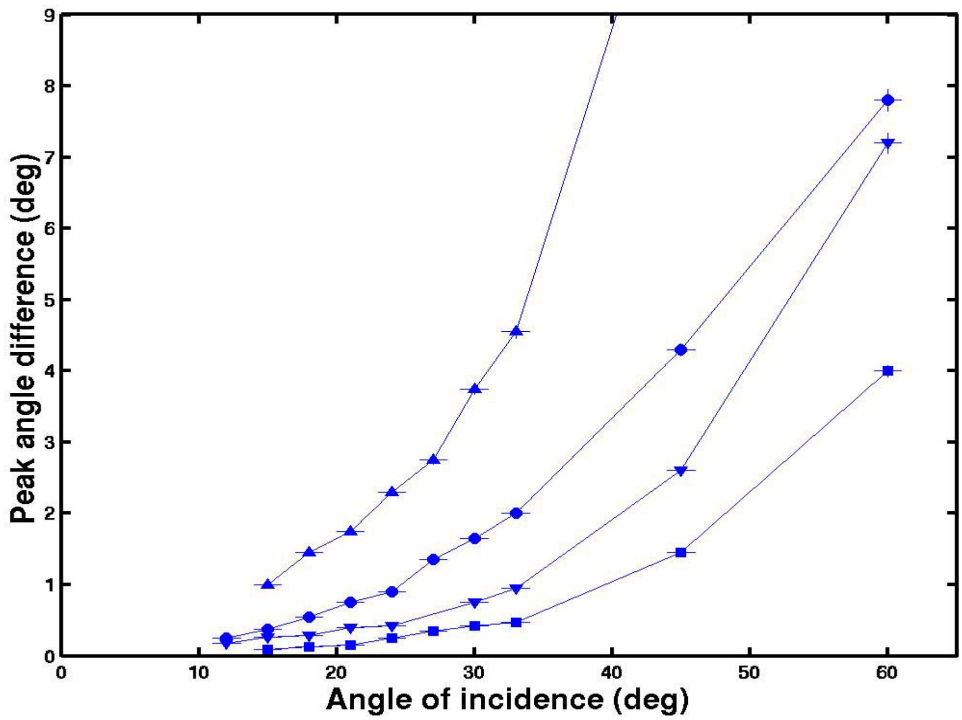

Fig 4. Measurement of peak angle difference of exposed mirrors, SS (▲), Al on Glass (▼), Al on SS (■) and Al on SS reference (●).

polarisation.
The choice of mirror material for the inner labyrinth mirrors is not so restricted as the first mirror and the choice should be a material with good polarisation preserving properties as well as high reflectivity. Both Ag and Au perform well in this aspect, whereas the only dielectric mirror tested showed high reflectivity but also high distortion of the polarisation.

Whatever material is chosen for the inner labyrinth and first mirror, the incidence angles should be kept as small as possible. A single mirror with 45° incidence angle will alone generate larger distortion than a labyrinth of 4 mirrors at 20°. It should also be possible to reduce the problem by aligning the entire labyrinth in such a way that the π and σ polarisation will lie close to the mirror P or S planes.

A better way to reduce the problems may be to use symmetry effects that can appear in 3D labyrinths. This is a very promising alternative that will be experimentally investigated further in the future.

V. SUMMARY

We have experimentally investigated the effect of single plasma exposed mirrors and mirror labyrinths on polarisation and concluded that it is an important issue when determining mirror materials and labyrinth design. The optical properties of the first mirror evolve so quickly under exposure that an in-situ first mirror calibration system is a necessity for ITER. The measured properties of the labyrinth closely follow the Mueller matrix formalism. With a correct choice of material the angle change introduced by the 4 mirrors furthest away from the plasma will be below 1°.

ACKNOWLEDGMENTS

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2. Influence of ELM's on the MSE spectroscopy

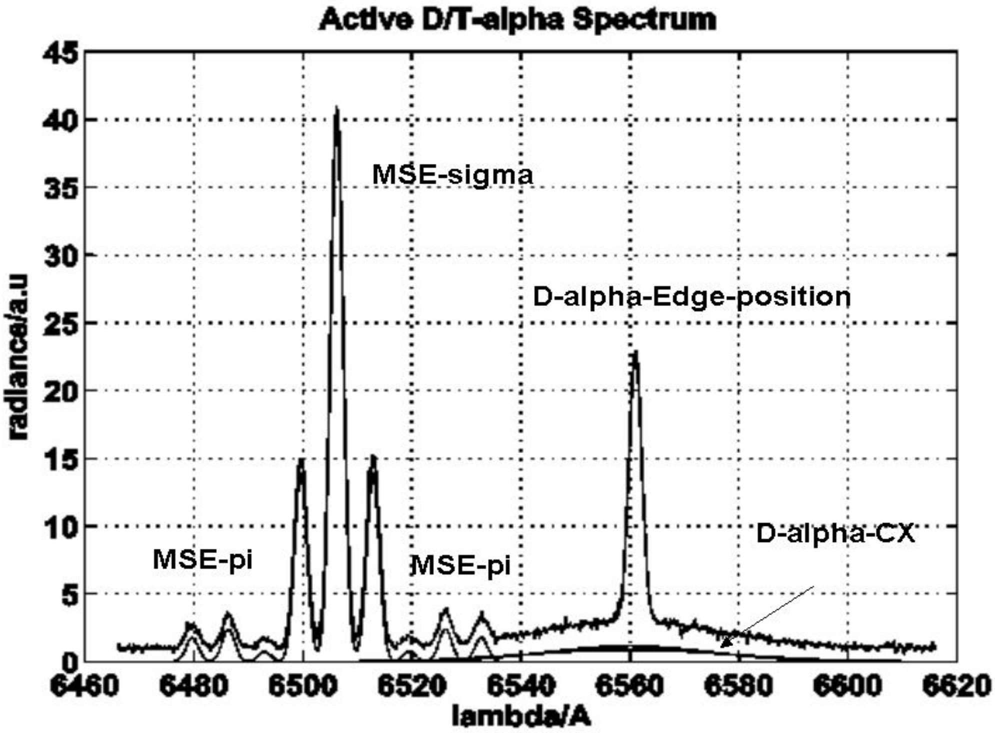
The occurrence of ELMs has been found difficult to handle in any automatic fashion. An automatic program to delete the MSE data, whenever ELMs are adding appreciable disturbance to the MSE data, has been constructed by R Giannella, CEA [2] and tested on several cases for JET.

However, for the EFIT analysis constrained with the MSE data it has been found relevant to only delete the short time slice before and after the ELM to get the most data out of the MSE diagnostic. This means, however, a rather tedious and manual procedure has to be performed for many different scenarios of the JET operation to best use the acquired MSE data and to get the best time evolution of the q-profile.

To study the influence of large ELMs we analysed the MSE data with high time resolution (1ms) and found that the EFIT analysis converged nicely up to the one time-slice of the sharp rise (as seen in the H_α emission) of the ELM. One hypothesis (Solano, EPS 2003) has been that the outer current layer is lost due to the ELM and that a new equilibrium is found by the plasma. We could, however, not disclaim or verify this hypothesis taking into account the uncertainty in the reconstructed current profiles from the MSE data.

An approach to increase the sensitivity of the MSE data that has been tested at JET is to measure simultaneously the σ and π polarisations and thus detect the onset of interfering signals [3]. In these tests the adjacent channels of the JET MSE system were tuned to σ and π during density ramps which gave encouraging results (Fig. 9, ref. 12, final report contract EFDA 02-1005, N. Hawkes)

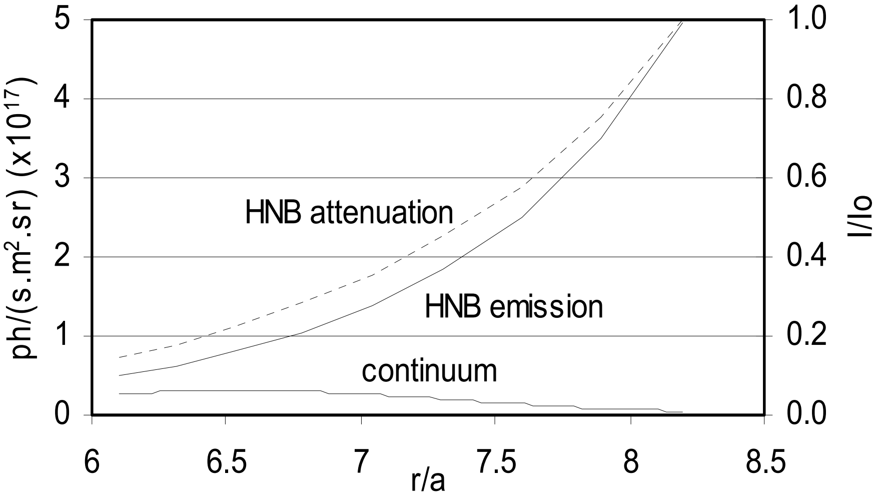
3. Influence of electric fields on the intensity distribution of the π and σ components of the MSE spectrum



The calculated spectra for the Doppler-shifted BES and CXRS Dα line for the central top-port view on the DNB for ITER (from Ref. 13, Fig.10, and Ref.1, Fig. 7). Beam modulation for background suppression is assumed. The Signal-to-Noise-Ratio for bulk ion CX is 24, and for BES(π)>60 corresponding to 4% and 1.5% errors respectively (from Ref. 1). As can be seen from the simulations the high Lorentz electric field induces a clear separation between the σ and the π lines of the Dα spectrum.

The first comparisons of the ITER radial electric field and the Lorentz electric field show that the influence of E_r on the MSE angles is negligible in most ITER scenarios [11,12].

4. Validate the beam attenuation atomic physics input and where possible verify with comparisons with JET data



Heating Neutral Beam attenuation (right scale) and beam emission rate (left scale) for ITER. The contribution due to bremsstrahlung in the spectral range of the measurements is also plotted (from Ref.1).

Calculations [1,11,12,13] of the beam emissivity, compared to the plasma bremsstrahlung (considered as the major source of noise for MSE) indicate that a temporal resolution of 20 ms might be feasible.

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