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On The Motional Stark Effect Diagnostic for ITER

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Introduction.

The Motional Stark Effect diagnostic [1] is now considered as an essential diagnostic for an accurate determination of current profiles in tokamak discharges. For this reason, this diagnostic is implemented on most of the existing machines. It mainly allows 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.
In line with the original proposal by F. Levinton [2], here we evaluate the use one of the heating beams as the source for this diagnostic, the main advantages of these beams being the deep penetration and the long pulse duration.

I. Principle of the diagnostic and feasibility at higher Lorentz Electric Field.

The MSE diagnostic observes the line radiation, usually the H_α, emitted by a fast beam of neutrals propagating (with velocity v) through the plasma discharge. In the presence, in the atom's rest frame, of the Lorentz electric field F, which is due to the local magnetic field B (F= v x B), the radiation is split into several components (mainly 9) equally separated in frequency (first order Stark effect). These components have a polarisation either parallel (π components) or perpendicular (σ components) to the Lorentz field when observed transversally. The spectrum is also Doppler-shifted due to the beam velocity, which allows a separation of the lines emitted by the neutral beam, from the intense edge $H\alpha$ lines. Two methods are mainly used for the determination of the direction of B:

- The spectroscopy method in which the measurement of the intensity ratio of σ and π lines gives the angle between B and the diagnostic line of sight. This method is also being considered for ITER (M. von Hellermann et al. [*presentation at this conference*]), but using the diagnostic neutral beam as source.
- The polarimetry method in which the measurement of the polarisation direction of the σ or π lines directly gives the direction of B. Here we shall concentrate on this method and, as we mentioned above, we will adopt, as our first choice, one of the heating beams as source.

The first question addressed concerns the feasibility of the method for the higher value of the Lorentz electric field. For the present day beam energies (*100 keV*), the Lorentz electric fields are moderate, and only the linear Stark effect needs to be considered. For ITER, as the magnetic field and the velocity of the beams increase (*1 MeV*), the electric field is almost one order of magnitude higher (F ~7 10^7 V/m). At these values of F the quadratic terms need be added in the calculation of the ground states of the hydrogen atom [3]:

$$E_n = -1/(2n^2) + 3/2\ F\ n\,(n1-n2) - 1/16\,F^2 n^4\,(17n^2 - 3(n1-n2)^2 - 9m^2 + 19) \quad \text{(atomic units)}$$

Here n= 1,2,3,… is principal quantum number, n1=0,… n-1 and n2=0,… n-1 are parabolic quantum numbers and m= -n+1, …, n-1 is the magnetic quantum number; they must satisfy the relation: n= n1+n2+/m/+1.

The application of the transition quantum rules between levels n=3 and n=2 allows the determination of the emitted spectrum. The result is very similar to the one with the linear Stark effect only, except a slight shift towards the negative energies, and a separation of the central 0-σ line, due to a removal of a degeneracy by the quadratic term. But since there is no mixing between the σ and π components at this level of the electric field, **the conventional method can still be applied**.

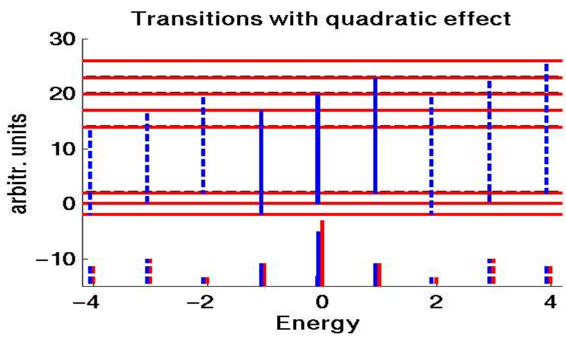


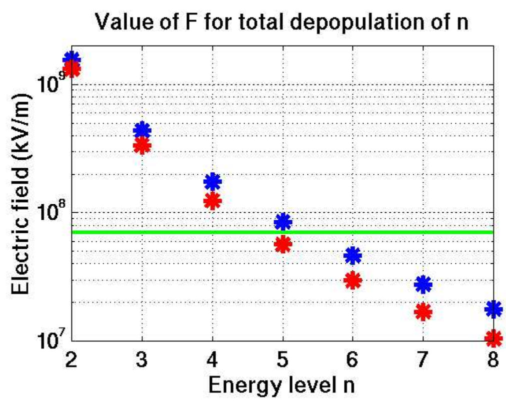
Figure 1 *Energy levels n= 3 and n=2 with linear (dashed lines) and quadratic (solid lines) Stark effect, and the corresponding transitions (sigma in solid and pi in dashed lines), for E_L= 7.10^7 V/m. . The distance between the n=2 and n=3 systems is not in scale. The bottom of the figure shows the energy position of the lines, with the red lines corresponding to the first order Stark effect.*

Ionisation of H^0 by high electric fields.

Another phenomenon must be considered, since it becomes important as the electric field increases: the possible ionisation of the excited hydrogen atoms, and thus the quenching of the corresponding emitted lines.

The potential energy of the hydrogen atom's electron in an external electric field F can be expressed as: $V= -1/r + F z$

Which means that the electron can find lower potential energies at high distances from the atom, in the direction of the anode. To reach these regions, the electron must pass the potential barrier, and once it has passed the barrier, it will be accelerated and freed from the nucleus. This phenomenon becomes significant quite abruptly over a certain value of the electric field, which is smaller than the value classically needed to overcome the barrier, because of the quantum tunnelling.



This effect is stronger for the electrons located at higher distances from the nucleus, that is levels with higher principal quantum number *n*. For a given *n*, the electrons on the anode side (*n1* < *n2*) will be more strongly affected, which means that the red components of the spectrum will disappear first.

To obtain numerical values for the total depopulation of F, approximated analytic calculations [4] were used, and the result is plotted in *fig 2*.

Fig2*. Value of electric field for total depopulation of Hydrogen energy levels.*

For Hα transition (n=3), the quenching of the line appears at a value of F, equal about 5 times the maximum value expected on ITER, which means that no direct attenuation of the emitted line is expected.

Nevertheless, a slight indirect decrease of the line emission could be due to the beam attenuation, since all the electron being excited to levels n> 4 will escape from the nucleus, leading to the atom's ionisation.

II. Spatial Resolution of the diagnostic.

An important question concerning the accuracy of the diagnostic is its performance in terms of spatial resolution. The requirements expressed by the ITER expert groups can be found in ITER reports [5] : a precision of 5cm is required between r/a = 0.3 and 0.9 for the spatial resolution.

The diagnostic has for the moment a provisional location in equatorial port 3 and possibly 9 (heating beams are on port 4, 5 and eventually 6). The calculation of the spatial resolution that can be obtained from these ports, shows that no correct solution can be obtained for central MSE, and that port 3, allows edge MSE with the required resolution *(fig.3)*.

Better solutions were searched for, but the only possibility to fulfil the requirement would have been to install MSE diagnostic in port 6. However, port 6 is devoted to the implementation of a third heating beam during a subsequent operation phase, and is not a possibility (Port 7 is occupied by a limiter).

We are driven to the fallback solution to use port 2 for central MSE and port 3 for edge MSE. This choice, however, would result in poorer resolution (about 10 cm or higher) especially in the mid minor-radius region where the transport barriers are likely to be located with the *advanced-scenario* plasmas, i.e. where good space resolution is going to be required most. It would also involve the extra complications of doubling up the entire diagnostic and of a major re-distribution of port spaces between diagnostics and other equipment (port 2 is presently allocated to a test blanket module, its reallocation is seen as a possibility, albeit with significant implications for other ITER systems.).

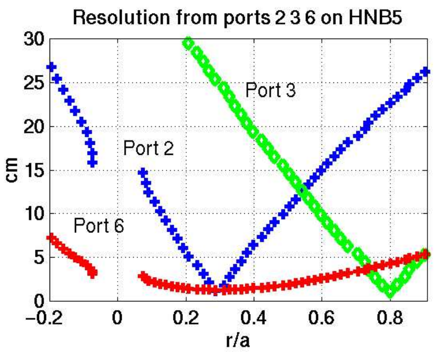


Fig 3. *Views from equatorial ports giving the best spatial resolutions*

The observation of the beam from the upper ports, although never used on the existing tokamaks (because of the decrease of the polarisation fraction), is seen as a possibility, and is now evaluated.

III. Design of the light collection system.

A preliminary study of the light collection system has been done for port 3 using ray-tracing to define the optical components. Four mirrors at least are necessary, with a W-shape of the light path, to reduce sufficiently the neutrons flux escaping from the machine through the optical channel [6]. Because of the thermal load and neutrons flux in the machine, the first two mirrors will probably be metallic, while the other ones are likely to be dielectric mirrors.

Unfortunately, the mirrors will alter the direction of the initial polarisation, which is the most important parameter to be measured. This effect, that is usually taken into account by the system's calibration is one of the most important sources of uncertainty in the measured magnetic pitch-angles. On ITER the expected effect would necessarily be larger unless extra precautions will be taken. Indeed, it appears necessary to minimise it by an optimised optical design. This is why another design has been done, using 6 mirrors to keep all the incidence angles low (below 30°), and maintaining the neutron shielding. The best solution for the modification of the initial polarisation is under calculation.

To obtain a more realistic estimation of the polarisation modification, the fact that the first mirror will probably be coated by impurity depositions was taken into account, simulating the effect on the first mirror of Be deposition in layers of increasing thickness [7]. When the layer thickness reaches one micron, the polarisation direction begins to change strongly for incidence angles even lower than 30°. The qualification of mirrors effects on polarisation modification is a continuing activity.
Nevertheless, due to this rapid variation of the mirrors reflectivity, it is necessary to develop *in-situ* or *real-time* calibrations of the diagnostic. On this line, we are evaluating a method that consists of the measurement of both the σ and π line. It can be shown that the initial polarisation angle, as well as the de-phasing introduced by the mirrors between parallel and perpendicular components can be deduced by analytic calculation, and therefore also reconstructed in real time, from the measurement of the 8 Stokes parameters [8]. The method appears also useful as an "unbiased" means to reject or validate data points on the basis of the consistency or not of the two polarisation measurement. The full implications of this method have not yet been analysed and a verification on one existing experimental device is envisaged as a way to validate it.

Conclusions

Several important issues concerning the diagnostic feasibility have been examined:

Even at ITER high values of the electric field the measurement principle is not in question, and the conventional methods can still be applied. No severe attenuation of the signal is expected since the quenching of the lines appears at much higher values of the electric field. The attenuation of the neutral beam due to ionisation of the high energy levels of the atom should be a moderate effect.

A possible location of the diagnostic in equatorial port 3 will allow edge measurements. For central measurements no solution is readily available from equatorial ports, and views from upper ports are now studied.

The first design of the light collection system shows that a light path can be devised through the machine port, keeping a good neutron shielding. Unfortunately, four mirrors at least are necessary for that. But incidence angles on mirrors can be minimised, and modification of the initial polarisation can be evaluated, the impurity coating on the first mirrors even being considered.
A real time calibration method is being developed to cope with effects of rapid modification of polarisation due to mirrors coating.

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