EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–CP(01)05-01

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**See Annex of J. Pamela et al., "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

Preprint of Paper to be submitted for publication in Proceedings of the
International Conference on Advanced Diagnostics,
(Varenna, Italy, 3-7 September 2001)

ABSTRACT
In magnetic connement devices the plasma connement and stability are determined by the magnetic field conguration consisting of toroidal and poloidaleld components. In tokamaks the poloidal magnetic field is determined by the toroidal current prole. In addition to the Faraday rotation polarimetry the Motional Stark Effect (MSE) has become a routine diagnostic technique to determine the current density distribution. The MSE diagnostic utilizes the Doppler shifted neutral beam emission spectrum which is dominated by the Stark effect due to the electrical field experienced by the fast atoms in their rest frame which is mainly the Lorentz electric field $\vec{v}_{beam} \times \vec{B}$. The orientation of this Lorentz electric field is measured, and incorporated in an equilibrium reconstruction, which yields proles of poloidal magnetic field, current density, safety factor q or poloidal flux. In this paper the diagnostic principle and its implementation on ASDEX Upgrade and JET will be presented; the obtained results and the experimental difficulties will be discussed. Since the MSE diagnostic is sensitive to electric fields in general this opens the possibility to measure also internal electric fields. The radial electriceld is considered to be important in transport physics due to the stabilizing effect of the $\vec{E} \times \vec{B}$ shearing rate on microinstabilities. If $E_r = v_{beam}$ becomes of the order of B_{pol} then E_r can no longer be neglected which is the case in particular for discharges with an internal transport barrier (ITB). This may also be applicable to stellarators where the magnetic field conguration derivates only slightly from the vacuum conguration, which is known. The Motional Stark Effect (MSE) diagnostic at ASDEX Upgrade has recently been extended to infer the radial electric field by detecting not only the polarization angle of the full energy but also that of the half energy component of the beam spectrum. First results of the measured radial electric field on ASDEX Upgrade will be shown and the possibilities for a similar extension on JET will be discussed.

1. INTRODUCTION
In magnetic connement devices the plasma connement and stability are determined by the magneticeld conguration consisting of toroidal and poloidal field components. In tokamaks the poloidal magnetic field is determined by the prole of the toroidal current. In addition to the Faraday rotation polarimetry [1, 2] the Motional Stark Effect (MSE) has become a routine diagnostic technique to determine the current density distribution [3, 4, 5, 6, 7, 8, 9, 10, 11]. The MSE diagnostic utilizes the Doppler shifted neutral beam emission spectrum which is dominated by the Stark effect due to the electricaleld experienced by the fast atoms in their rest frame which is mainly the Lorentz electric field $\vec{v}_{beam} \times \vec{B}$. The orientation of this Lorentz electric field is measured, and incorporated in an equilibrium reconstruction, which yields proles of poloidal magnetic field, current density, safety factor q or poloidal flux. In this paper the diagnostic principle and its implementation on ASDEX Upgrade and JET will be presented in sections two and three. The results of the diagnostic will be discussed in section 4 and the in uence of another beam source on the measurement in section 5. Since the MSE diagnostic is sensitive to electricelds in general this opens the possibility to measure also internal electric fields such as the radial electric field [12, 13]. If E_r / v_{beam} becomes of the order of B_{pol} then E_r can no longer be neglected which is the case in particular for discharges

with an internal transport barrier (ITB). The measurement of E_r may also be applicable to stellarators where the magnetic field conguration deviates only slightly from the known vacuum conguration. The stronger field line curvature could how ever increase the requirements regarding the spatial resolution of a MSE diagnostic. First measurements of the radial electric field will be presented in section 6 and a summary will follow in section 7.

2. PRINCIPLE OF THE MEASUREMENT

The MSE diagnostic is a kind of beam emmission spectroscopy (BES)[14]. But in contrast the BES it is not the intensity of the light but rather the polarisation that is analysed. The injected fast neutrals experience in their rest frame a strong Lorentz ($\vec{E} = \vec{v}_b \times \vec{B}(+ \vec{E}_{internal})$) electric field.

This gives rise to the Stark effect which dominates strongly over the Zeemann effect under usual experimental conditions in a tokamak ($E_b \approx 50 - 150keV, B_{tor} \approx 1-4T$). Due to the Stark effect the D_α or H_α beam emission lines split components perpendicular to the electric field linear polarized (σ) and parallel polarized (π).

An example of the spectrum for AS-DEX Upgrade (calculated, maesured in gure 4) is shown in Fig. 1. Three lines each are very close together so that the spectrum looks more like a 3 line spectrum, two are π lines and one is a s calculated emmission spectrum and polarisation fraction line. The spectrum presented in the upper part of Fig. 1 contains the 3 full energy component lines, the half, and the third energy component lines. The three beam components are doppler shifted corresponding to the energies of the accelerated D^+; D_2^+ ;D_3^+ particles in the neutral beam ion source. In the lower part of the figure the polarisation fraction is presented. +1 means only σ and the polarisation of the π lines is negative. The polarisation of the full energy σ line is the strongest strongest and the line is not much overlapped by others. For the half energy the polarisation is still comparible to the full energy π lines.

To use the information carried by the spectral lines a diagnostic needs to measure the direction of the electric field by measuring the direction of the polarisation of one of the spectral lines. This can be done in a static way [15, 16] by splitting the light to two linear polarizers and a circular polarizer to get the complete stokes vector or it can be done in a dynamic fashion used in most tokamak diagnostics by means of two photo elastic modulators (PEMs).

3. DIAGNOSTIC SETUP

The diagnostic setup will be described for the JET motional Stark effect diagnostic in the follwing section. The ASDEX Upgrade diagnostic is very similar except for the number of lines of sight, details of the monochromator and the data aquisition. The setup for JET is shown ingure 2. The optics has 25 lines of sight covering the whole minor radius on the loweld side with a distance of 5cm between the channels and a spatial averaging of 3-7cm in one channel. The beam emitted light is reflected by a prism trough a vacuum window into a tube with an integrated transfer optic. The window and the optics effect the polarisation of the transmitted light because in the optical components the Faraday rotation adds a magneticeld dependent oset to the measurement. This needs to be included in the calibration process. Behind the optics a set of two PEMs is placed followed by a linear polarizer which allows polarimetry by means of a lock-in technique. To collect the light only from the selected spectral line a small band width interferencelter is placed before an Avalanche diode.

4 EXPERIMENTAL RESULTS

The discussed setup of the MSE diagnostic results in a measurement of a polarisation angle γ_m. For interpretation of this angle the complete observation geometry needs to be taken into account. For an arbitrary viewing geometry it results in the following formula:

$$tan\,\gamma_m = \frac{A_1 B_R + A_2 B_T + A_3 B_Z + A_4 E_R / v_b}{A_5 B_R + A_6 B_T + A_7 B_Z + A_8 E_R / v_b + A_9 E_Z / v_b} \quad (1)$$

Equation 1 contains geometric coefficients A_n which are composed of the sin and cos of the observation angles and the inclination of the neutral beam against the midplane. Furthermore all magneticeld components (B_R, B_Z and B_T) and the components of a radial electriceld (E_R and E_Z) are contained where R; Z, and T denote the radial, vertical and toroidal direction respectively. For a very simple viewing geometry in which beam and viewing lines lie in the magnetic midplane ($B_R = 0; E_Z = 0$) the equation 1 reduces to tan $g_m = \gamma_m = \frac{A_3 B_Z + A_4 E_R}{A_6 B_T}$. This measurement is used as an additional constraint to the plasma equilibrium reconstructed by and equilibrium codes like EFIT on JET or CLISTE on ASDEX Upgrade. This code makes a fit to the measurement and minimizes the fit error. Additionally the magnetic data from the edge is included which gives mainly information about integrals (like plasma current) and a boundary condition (plasma shape). Without internal information from the MSE system the codes freely extrapolates the internal field structure. In Fig. 3 profiles for two different kinds of discharges from AS-DEX Upgrade are shown. On the left an L-mode prole during sawtooth oscillations taken in a stationary phase is given. In the upper part the measured MSE angles and the corresponding fit are plotted. For a help also the zero line (equivalent to poloidal field zero) is shown. In ASDEX Upgrade the MSE usually and unfortunately does not cover the plasma centre. In this example thet is very good and the q-profile in the lower part of thegure represents the MHD (Magneto Hydro Dynamic) features of the discharge quite well. The discrepancy in the $q = 1$ radius is well inside the measurement errors. On the right an early time point ($t = 0{:}7$s) in a discharge with an internal transport barrier is presented. Already the measured angle profile shows that the poloidal field has dierent features. Already the smaller difference between g_m and zero line. Roughly the representing the poloidal magnetic field, shows that the poloidal field in the interior of the plasma is much smaller then in the other discharge. This results in reversed shear prole shown in the lower part. The measurement and the equilibrium reconstruction here also fit very well to the information from the MHD. In this reconstruction also the effect of the radial electric field has been included.

5 INFLUENCE OF ANOTHER BEAM SOURCE ON MEASUREMENT

One main dierence between the JET and ASDEX Upgrade MSE diagnostic is the spectral line which is used for the measurement. ASDEX Upgrade uses the σ line because it has a much higher polarisation degree and a higher intensity, whereas the most Doppler shifted line is utilized in the JET diagnostic. The reason for this is the influence of other beam lines (from the same beam box, overlaying in the plasma) to the measured polarisation angle. In Fig. 4 two ASDEX Upgrade spectra are shown. On the left the unperturbed spectrum with only the beam line which is used for the measurement is given. On the right the spectrum perturbed by additional beam is shown. The nicely separated lines in the unperturbed spectrum have smeared out by overlaying the spectrum of the other beam source which exhibits a slightly dierent Doppler shift. The σ line of the full energy component is still visible, but but the degree of polarisation is drastically reduced. The conclusion is that here π (and σ) lines from the second beam line overlay with the σ line from first source. The consequence is a jump in the γ_m which dependents on various plasma parameters. If the polarisation direction from one σ line changes, the polarisation from the other beam line changes also but dierently because it corresponds to a different position in the plasma. The only conclusion which can be drawn is that the measurement is not useful if any other beam line is active in ASDEX Upgrade. For JET with 8 beam sources in one box this is a more serious problem. One possibility to prevent the disturbance is to use a spectral line which is not perturbed, ideally a different (higher) beam energy should be used for the measurement. A partly successful solution to the problem has been found at JET using the outermost π line from the beam source which has the largest Doppler shift. Ideally there should be no overlay between the spectra any more but the lines are very broad beam and viewing line divergence[17]. The goal achieved, is that the overlay now is mostly only between π and π components which can be included into the equilibrium reconstruction by a weighting function which resolves partly the problem.

6 FIRST RESULTS OF RADIAL ELECTRICELD MEASUREMENTS

The radial electric field plays an important role in tokamak transport theory as it determines the $\vec{E} \times \vec{B}$ shear flow which is one of the processes responsible for the suppression of micro turbulence [18]. To verify these theories various measurements of E_r have been developed in recent years: (A) From charge exchange recombination spectroscopy (CXRS) the dierent terms of the radial force balance are inferred and subsequently E_r is calculated [19]. (B) The change of the edge radial electric field in the H-mode transition has been derived by charge exchange measurements of high energy neutrals [20].(C) The measurement of the poloidal magnetic field by means of the motional Stark effect (MSE) is also sensitive to E_r [12], because the neutral beam atoms experience not only the Lorentz field, but also the radial electric field.

If two independent measurements of $\vec{E} = vecE_{Lorenz} + \vec{E}_r$ are employed, this facilitates not only the deduction of B_{pol} but also of E_r. One possibility to measure E_r by means of MSE is to use two different lines of sight at the same radial position [12]. Another one is to use the same line of sight and to measure two different energy components of the neutral beam [13]. In ASDEX Upgrade the latter method is employed, which for machines with limited spatial access is easier to implement.

Neglecting the terms A_5B_R, A_7B_Z, A_8E_R / v_b, and A_9E_Z / v_b in the denominator of (1), which are small compared to A_6B_T, E_r can be approximated by

$$E_r = (\tan \gamma_m - \tan \gamma_{m/2})\, B_T v_b \frac{A_6}{A_4(1 - \hat{}2)} \tag{2}$$

In Fig. 5 this method has been used to derive E_r from the measured γ_m's at $\rho_{pol} \approx 0.6$.

This is the only radial position at which the diagnostic has been upgraded so far. As the small difference ($\tan \gamma_m - \gamma_{m/2}$) is multiplied by the large values of beam velocity and toroidal magnetic field, a large noise level is produced in the resulting E_r. Another problem is the absolute value of γ_m. The calibration procedure results in a minimum error of about 0.2 deg, corresponding to an uncertainty of 40kV/m in E_r. To improve the absolute accuracy, the calibration factors of the half energy channels are adjusted to produce $E_r = 0$ in the presence of locked modes. This assumption is justified, as the plasma toroidal rotation stops and the pressure gradient is balanced by the diamagnetic drift. In the example discharge of Fig. 5 a locked mode occurs at $t = 4$s.

ASDEX Upgrade is equipped with a CXRS diagnostic [19] which by means of poloidal and toroidal views measures the respective rotation velocities v_{pol}, v_{tor} and the radial pressure gradient $\nabla_r p$ of the impurity ion species C^{5+}. Substituted into the radial force balance equation, E_r is calculated:

$$E_r = \frac{1}{Zen_z} \nabla_r p_z - v_{pol} B_{tor} + v_{tor} B_{pol} \tag{3}$$

where B_{pol} and B_{tor} are the poloidal and toroidal magnetic field components, n_Z the density, and $_Z$ the charge number of ion species used. In Fig. 5 the different E_r measurements are compared. The time evolution of E_r is qualitatively the same for both methods. While E_r from MSE measurement is calibrated to be zero when a locked mode is present, the CXRS value drops to zero independently. Considering that the E_r value calculated from the MSE polarisation angles directly is only an approximation, also the quantitative agreement is acceptable.

To study the influence of E_r on the q-profile evaluated by CLISTE using the MSE data, the radial electric field components in equation 1 are taken from the CXRS measurements. In Fig. 6 q-profiles without considering E_r and with the correction by CXRS are compared. In the first case, a discharge with reversed magnetic shear and an ITB is shown [21]. Including E_r the whole q-profile drops, but most prominently the central q-value (q_0). The minimum value of q (q_{min}) decreases less, but nevertheless improves the agreement between the appearance of a ($m = 2$, $n = 1$) double tearing mode and the time when q_{min} reaches 2. The same trend in the q-profile can be observed in the second case, which shows the monotonic q-profile of an improved confinement

H-mode and is characterized by an extended low shear region in the plasma core. Here the central magnetic shear is not affected, but rather the absolute values of q in the core region of the plasma.

7 SUMMARY

The MSE diagnostic is after some years of development a routinely used diagnostic on many tokamaks. It gives reliable results on the plasma current profile and is an important ingredient in the equilibrium reconstruction. For discharges with high radial electric fields it is important to include also the radial electric field into the equilibrium reconstruction. On the other hand the MSE diagnostic can also be used to measure the radial electric field directly giving crucial informations on the physics of internal transport barriers.

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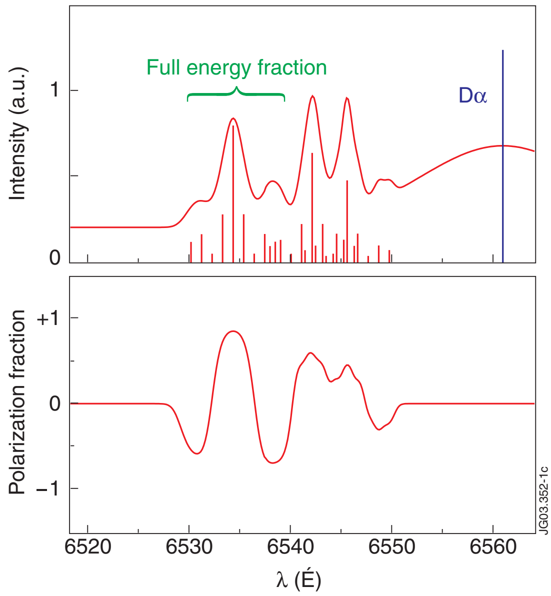

Figure 1: ASDEX Upgrade beam calculated emmission spectrum and polarisation fraction

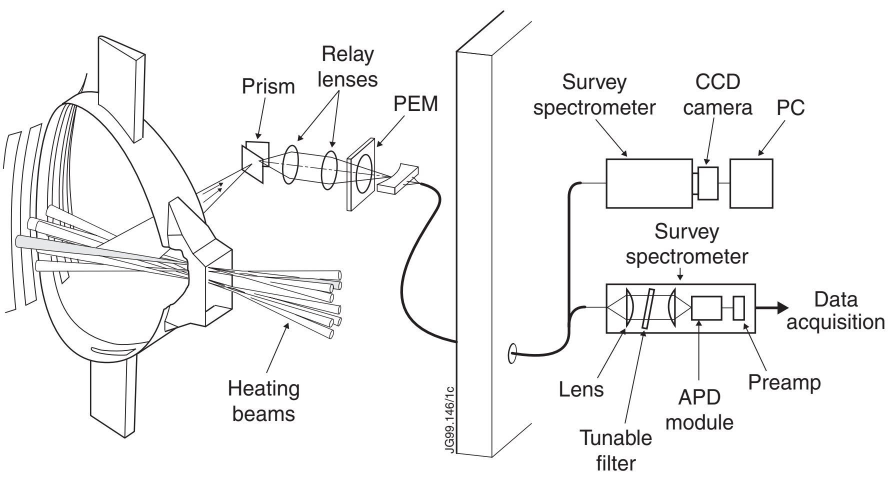

Figure 2: Diagnostic setup implemented at JET

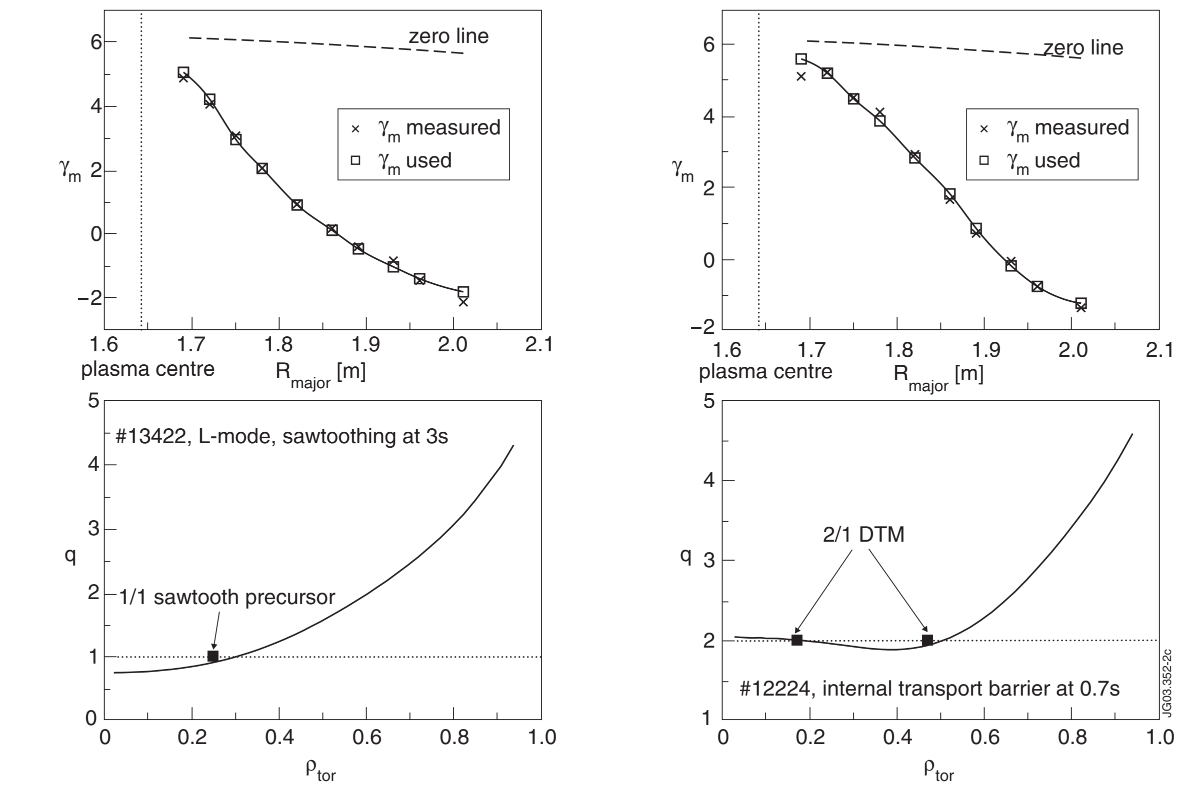

Figure 3: Measured and fitted polarisation angle profiles and corresponding q-proles for ASDEX Upgrade discharges

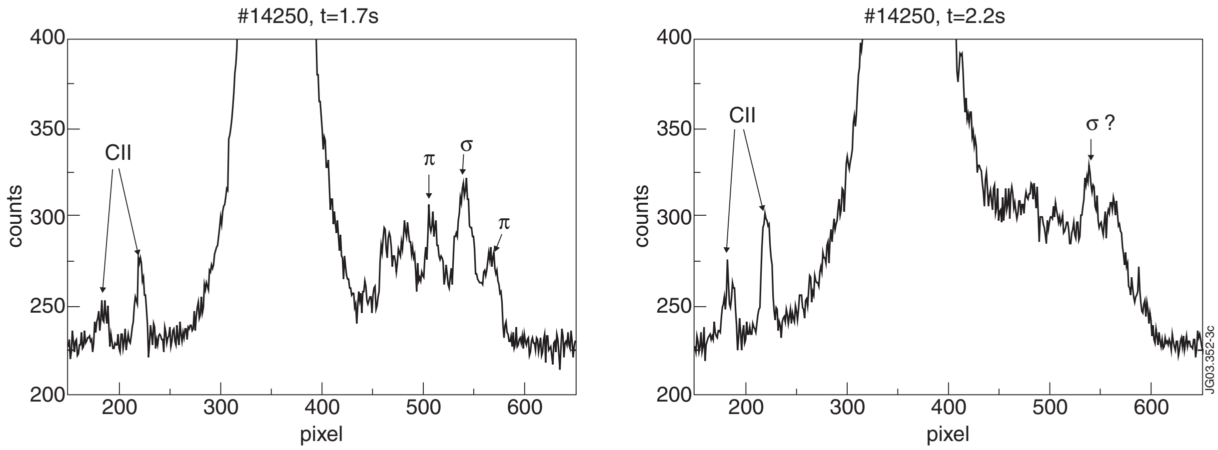

Figure 4: Beam emission spectra from ASDEX Upgrade. Left Figure spectrum with only the measurement beam line and right spectrum with two beam lines.

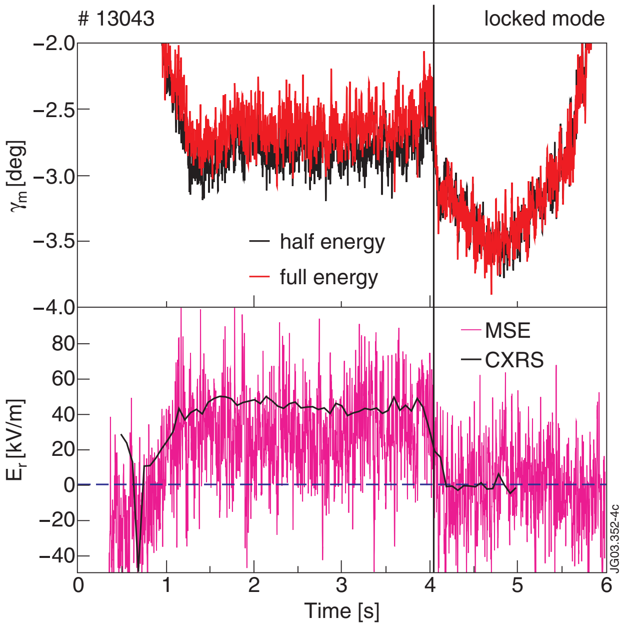

Figure 5: Time traces of γ_m, $\gamma_{m/}^{2}$ (upper trace) and calculated E_r (not averaged, lower trace) together with CXRS E_r for comparison. After reaching the β-limit, a locked mode occurs approximately at 4s.

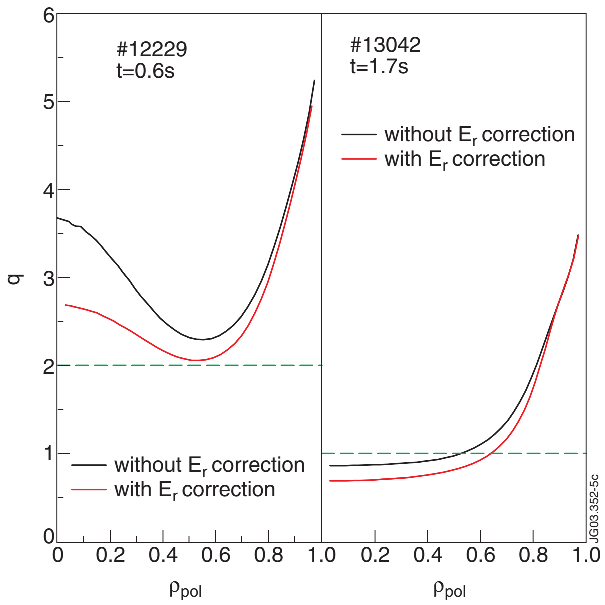

Figure 6: q-profiles without and with E_r correction, ITB and H-mode with improved confinement