The structure, evolution and role of the radial edge electric field in H-mode and L-mode on MAST

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Abstract. The first measurements of the structure of the edge radial electric field, $E_r$, in a spherical tokamak (MAST) are presented. Using active Doppler spectroscopy on He$^+$ with 120 lines of sight $E_r$ profiles are calculated from the leading terms of the radial momentum balance. A spatial resolution up to $\Delta r \approx 1.5$ mm with a typical time resolution of $\Delta t = 5$ ms can be achieved. In L-mode the field is largely determined by the diamagnetic term of the force balance, and fields of only a few kV/m are observed. The measured impurity flow is mostly parallel to $B$, and is greatly affected by MHD, such as sawteeth or mode locking of tearing modes, or error fields. In H-mode a strong perpendicular flow evolves with poloidal and toroidal velocities up to $v_{\theta, \phi} \approx -20$ km/s, and a deep negative electric field well $E_{r, \min} \gtrsim -15$ kV/m develops. The profile form is dominated by the diamagnetic term.

1. Introduction
Plasmas confined by a toroidal magnetic field configuration exhibit a regime with a sudden improvement of confinement, the so called H-mode [1–6]. In this regime a transport barrier develops at the plasma edge (ETB), where the turbulent (anomalous) transport perpendicular to the magnetic field is largely suppressed. The physics of the formation of the ETB is still not fully understood.

It was soon recognised that strong perpendicular flows develop during H-mode [2], and that a negative radial electric field is generated [2, 7–9], causing a sheared $E \times B$ flow. The common theoretical picture is that this sheared flow is responsible for the suppression of the turbulent transport [10, 11]. The mechanisms leading to the generation of the electric field in H-mode, however, are less clear. One theoretical picture is that macroscopic flows generated by the turbulence itself, zonal flows, lead to the strong $E_r$ [12], and indeed evidence for such flows has been found experimentally [13]. Other theoretical work and experimental evidence points towards the flow in the scrape-off-layer (SOL) as an important factor in establishing $E_r$ [14, 15]. Here, the field is generated by viscous transport of momentum from the SOL into the edge region, and the field is mainly neoclassical [15].

Only on a few devices is the electric field in the edge measured to allow comparison with theory [7, 9, 16]. Here, usually the edge flows are measured either by active or passive Doppler spectroscopy [7, 9, 17] or by Doppler reflectometry [18]. In smaller devices sometimes also reciprocating Langmuir probes are used. The time resolution of these measurements, however, is seldom high enough to resolve the L/H transition, and the spatial resolution is often too coarse to resolve the detailed field structure.

In this paper we present the first profile measurements of $E_r$ in a spherical tokamak, using active Doppler spectroscopy on He$^+$. On the Mega-Ampère-Spherical-Tokamak (MAST) an existing system
for measuring the toroidal velocity at the plasma edge at 17 spatial points ($\Delta R = 6 \text{ mm}$) was recently upgraded to a higher spatial resolution up-to $\Delta R \gtrsim 1.5 \text{ mm}$. In addition, poloidal chords were added. In section 2 we will introduce the new diagnostic (ECELESTE) and discuss the main sources of errors in the evaluation of $E_r$. The structure of the field in L-mode is treated in section 3 and in H-mode in section 4. Finally we will discuss and summarise the results (section 5).

2. Edge Doppler spectroscopy on MAST (ECELESTE)

The radial electric field in a magnetically confined plasma can be calculated from the force balance of any charged species $\alpha$

$$m_\alpha n_\alpha \left\{ \frac{\partial u_\alpha}{\partial t} + (u \cdot \nabla) u \right\} = -\nabla \cdot \vec{P}_\alpha + n_\alpha q_\alpha (E + u_\alpha \times B) + F_\alpha - m_\alpha u_\alpha S_\alpha$$

(1)

Here, $m_\alpha$ is the mass, $n_\alpha$ the density, $u_\alpha$ is the fluid velocity, $\vec{P}_\alpha = p_\alpha \vec{I} + \vec{\tau}_\alpha$ the pressure tensor ($p_\alpha$: scalar pressure, $\vec{\tau}_\alpha$: viscosity tensor), $q_\alpha$ the charge, $F_\alpha$ the friction, and $S_\alpha$ the sources. Neglecting inertia, viscosity, friction, and sources [9] $E_r$ is approximated by the leading terms in equation (1)

$$E_r \approx \frac{k_B T_\alpha}{q_\alpha} \left( \frac{1}{L_{T_\alpha}} + \frac{1}{L_{n_\alpha}} \right) + u_{\theta_\alpha} B_\theta - u_{\theta_\alpha} B_\theta,$$

(2)

with $L_f = \partial \ln f / \partial r$ the gradient length of $f$, and $k_B \approx 1.38 \cdot 10^{-23}$ the Boltzmann constant. The first term on the right side is the diamagnetic contribution to $E_r$, and the two other terms are the contribution from the Lorentz force.

Using Doppler spectroscopy on He$^+$, atomic data with the electron temperature, $T_e$, and density, $n_e$, and the magnetic equilibrium reconstruction all of the terms on the right hand side of equation (2) can be calculated. It is also worth noting that in the diamagnetic term only the density gradient length is not directly measured, but has to be calculated from the measured intensity with the help of the atomic excitation data using $T_e$ and $n_e$ profiles measured by a different diagnostic.

In a conventional aspect ratio tokamak it is usually enough to measure the poloidal velocity, since the toroidal magnetic field is much higher than the poloidal field, and the poloidal and toroidal flows are similar [9]. In the low-field-side (LFS) edge of a spherical tokamak, however, both field components are of similar magnitude, and hence, both velocity components have to be measured.

Until recently only toroidal measurements in 17 spatial locations with a radial resolution of $\Delta R = 6 \text{ mm}$ (The spot size of the optics in the plasma was $\Delta R = 12 \text{ mm}$, with a hexagonal packing of the fibres leading to a nominal resolution of $\Delta R = 6 \text{ mm}$ due to the imaging properties) were available on MAST and only differences in $E_r$ could be estimated with the help of neoclassical theory [19]. This system has now been upgraded to 120 lines of sight. The 120 slits are connected to a patch panel where they can be connected to an individual selection out of 64 toroidal chords, 64 poloidal chords, one radial chord, and one chord illuminated by a Zn-lamp. The latter two chords are used to determine the absolute velocity. Details of the spectrometer can be found in [17]. The data are stored on the storage part of the frame transfer CCD throughout the discharge and only read-out after the shot. This allows a fast time resolution of up to $\Delta t \approx 110 \mu s$ if the measurement is restricted to 10 chords to avoid smearing between chords (see section 2.2). Here, we concentrate on measurements with high spatial resolution. In the normal chord layout, used for the measurements throughout the paper, 58 toroidal chords and 59 poloidal chords as well as the Zn-lamp and the radial chord were connected. In this set-up a time resolution of $\Delta t = 4.85 \text{ ms}$ has to be used.

The toroidal and poloidal view optics have a spot size of $d_t = 3 \text{ mm}$, and $d_p = 2.8 \text{ mm}$ respectively. The fibres at the image plane have a hexagonal packing in 6 rows and 64 columns of $180 \mu m$ fibres for the toroidal system, and 2 rows and 64 columns of $400 \mu m$ fibres for the poloidal system. The overlap between the 64 radial points due to the hexagonal packing allows for a maximum spatial resolution of
\( \Delta r \approx 1.5 \text{ mm} \) after spatial deconvolution to be done in future. Both optics have a narrow field of view of about 10 cm. The poloidal in-vessel optic is fixed, whereas the field of view of the toroidal ex-vessel optics can be moved manually between 1.2 m \( \leq R_{\text{mid}} \leq 1.5 \text{ m} \). For the measurement of \( E_r \) both systems have to cover the same radial range. The poloidal and toroidal views are orthogonal to each other, but tilted by 6° with respect to the horizontal mid-plane. Note, that the field line angle at the LFS mid-plane is about 30° on MAST, hence about 36° with respect to the toroidal axis of the diagnostic.

The lines of sight of both systems pass through the plume of a thermal He jet usually injected within 10 cm of the plasma edge at the LFS mid-plane. This non-perturbing He jet not only provides about 10 times higher signal levels than the background emission of He\(^+\), but also a good localisation. In the most simple way this localisation can be estimated by the \( \cos^3 \gamma \) angular distribution (\( \gamma \) angle) of the plume, and the curvature radius of the plasma \( R_c \). The length of the chord at the distance \( x \) from the nozzle containing about 90% of the density of the plume is \( g(x) = 8|x|e/15 \) (\( e \approx 2.71 \ldots \)), giving a height of the segment of a circle with radius \( R \) and base \( g \) is \( \Delta R(x) = R_c - \sqrt{R_c^2 - g^2(x)/4} \). For the geometry on MAST this gives a spatial resolution of 2 mm \( \lesssim \Delta R \lesssim 6 \text{ mm} \) for the toroidal views (\( R_c = 1.4 \text{ m} \)) and 5 mm \( \lesssim \Delta R \lesssim 17 \text{ mm} \) for the poloidal views \( R_c \approx 0.5 \text{ m} \) over the 10 cm field of view. Again a full spatial deconvolution can be used to increase the spatial resolution to \( \Delta R \approx 1.5 \text{ mm} \). More work is underway to characterise the He plume experimentally and theoretically, and to deconvolve the data.

![Example of (a) toroidal and (b) poloidal He\(^+\) flow profiles in H-mode for discharges with different plasma current #18571 (black, \( \bigtriangleup \), \( I_p = 0.7 \text{ MA} \)) and #18617 (blue, \( \blacklozenges \), \( I_p = 1.1 \text{ MA} \)). The minor radius \( r \), poloidal angle \( \theta \) and toroidal angle \( \phi \) define a right handed coordinate system with \( \phi \) in the co-current direction, and \( r \) outward from the plasma centre.](image)

Example profiles of (a) the toroidal and (b) the poloidal He\(^+\) flow in ELM free H-mode are shown in figure 1 as function of normalised poloidal flux \( \psi_N = (\psi - \psi_s)/(\psi_0 - \psi_s) \), with \( \psi = \psi_{\text{pol}}/2\pi \) the poloidal flux function, and \( \psi_0 \), \( \psi_s \) the flux at the magnetic axis and the last closed flux surface (LCFS) respectively. The error bar of the velocity comes from the uncertainty of the fit (see section 2.1) and the wavelength calibration. The error bar on the radial position comes from the calculation above in the absence of a deconvolution. The resulting \( E_r \) from these measurements will be discussed in section 4.

### 2.1. Data analysis

The data presented in this paper are restricted to measurements with the He puffing. Each of the 120 line shapes are fitted by a Gaussian convoluted with the detector pixel size for each time slice. The apparatus function measured with the spectral line of a cold, low pressure Zn spectral lamp is also very close to a Gaussian shape. Therefore, the Doppler width is simply \( \Delta \lambda_D = \sqrt{(\Delta \lambda_{\text{fit}})^2 - (\Delta \lambda_{\text{fit}})^2} \), where \( \Delta \lambda_{\text{fit}} \) and \( \Delta \lambda_{\text{fit}} \) are the fitted line width of the He\(^+\) line and the fitted width from the apparatus function respectively. From the fits we get the He\(^+\) intensity, the relative He\(^+\) velocity, and the He\(^+\) temperature values for each chord. The absolute velocity is calculated using the recorded Zn spectrum at \( \lambda_{\text{ZnI}} = 468.1034 \text{ nm} \) close to the measured He\(^+\) line at \( \lambda_{\text{HeI}} = 468.5673 \text{ nm} \) with its known spectral offset, and the relative positions from the spectral calibration of each chord also with the Zn lamp. The data are checked for consistency against the data from radial chord assuming a negligible radial velocity.
relative He discussed in section 2.2 and possibly reflections. On the innermost chords the intrinsic He currently rejected. The intensity of the outermost chords is too low and suffers from smearing as used to determine the bulk ion temperature.

\[ \Delta R \]

the TS and the ECELESTE diagnostic. A relative shift between the two measurements of the order of the TS profile, however, is of the order of \( \sigma_R \approx 3 \text{ mm} \). The uncertainty of the position of the TS profile, however, is of the order of \( \sigma_R^{TS} \approx 5 \text{ mm} \). An outward shift of the ECELESTE measurement with respect to the TS measurement leads to a reduction of the diamagnetic contribution by several km/s, whereas an inward shift increases the diamagnetic contribution. However, an outward shift leads also to a relative He\(^+\) density profile which peaks outside the LCFS, which is unlikely at electron temperatures of typically 20 eV \(< T_e^{LCFS} \approx 30 \text{ eV} \). No relative shifts between the two measurements were employed. A further error source comes from the lack of an optical shutter. Therefore, the CCD is exposed to the radial calibration of both diagnostics, by back-illuminating the fibres and measuring their position inside the vessel. The data of ECELESTE was also compared to other diagnostics with high accuracy since the ionisation into He\(^+\) is faster than the thermalisation time, hence the He\(^+\) temperature can’t be used to determine the bulk ion temperature.

Without a sophisticated inversion algorithm, data from the innermost and the outermost chords are currently rejected. The intensity of the outermost chords is too low and suffers from smearing as discussed in section 2.2 and possibly reflections. On the innermost chords the intrinsic He\(^+\) emission becomes comparable to the emission from the local gas puff and therefore requires careful inversion. The relative He\(^+\) density is calculated from ADAS data [22] using the fitted \( T_e \) and \( n_e \) profiles. The Lorentz term, \( E_r^{Lor} = u_{\phi, \text{He}^+} B_\theta - u_{\theta, \text{He}^+} B_\phi \) is calculated without a fit to the profile of the experimental velocity data. The components of the magnetic field are taken from an equilibrium reconstruction (EFIT).

2.2. Sources of systematic errors

The main source of errors is the relative uncertainty between the radial calibrations of the profiles from the TS and the ECELESTE diagnostic. A relative shift between the two measurements of the order of \( \Delta R \approx 1 \text{ cm} \) is enough to change the profiles significantly in strong H-mode. Great care was taken in the radial calibration of both diagnostics, by back-illuminating the fibres and measuring their position inside the vessel. The data of ECELESTE was also compared to other diagnostics with high accuracy of the radial calibration, giving an uncertainty of \( \sigma_R \approx 3 \text{ mm} \). The uncertainty of the position of the TS profile, however, is of the order of \( \sigma_R^{TS} \approx 5 \text{ mm} \). An outward shift of the ECELESTE measurement with respect to the TS measurement leads to a reduction of the diamagnetic contribution by several km/s, whereas an inward shift increases the diamagnetic contribution. However, an outward shift leads also to a relative He\(^+\) density profile which peaks outside the LCFS, which is unlikely at electron temperatures of typically 20 eV \(< T_e^{LCFS} \approx 30 \text{ eV} \). No relative shifts between the two measurements were employed.

A further error source comes from the lack of an optical shutter. Therefore, the CCD is exposed to light whilst it is clocked vertically. Since the 120 slits are arranged as an array of 12 rows and 10 columns, a given measurement picks up a fraction of light from all the 12 measurements vertically stacked on the CCD. This unwanted pick-up may amount to 22% due to the ratio of vertical transfer time \( \tau_v \approx 0.3 \mu s \), exposure time \( \Delta t_{exp} = 4.9 \text{ ms} \), and binning on the CCD. The chord positions on the CCD were chosen in a way to reduce this pick-up, and the strong chords usually only have a pick-up of 2%. In the absence of transient events the data can be corrected.

A problem, however, arises for the radial chord, which doesn’t pass through the He puff, and hence has a much reduced intensity. Analysis of this chord has to be restricted to time slices before the He puff, and preferably during L-mode phases of the discharge, which have low rotation speeds. A wrongly calculated velocity offset leads to a shift of the \( E_r \) profile by roughly \( 0.3 \times \Delta \text{v}_{\text{offset}} \). The error on \( E_r \) was
calculated by using a relative shift between the TS profiles and the ECELESTE profiles of $\Delta R = \pm 2.5$ mm to show the uncertainty and using the statistical errors of the velocity measurement. No error was added for the fitting error of the profiles.

3. The radial electric field in L-mode and during the L/H transition

The radial electric field in L-mode on MAST is very shallow and close to zero. An example of an L-mode $E_r$ field at a single time point ($\delta t = 5$ ms, $t = 0.208$ s) is shown in figure 2 (black, ——) for a beam heated double null (DN) discharge immediately before a relatively sharp L/H transition (#18571, $I_p = 0.7$ MA, $n_e = 2 \times 10^{19}$ m$^{-3}$, $P_{\text{NBI}} = 1.8$ MW). There are some unavoidable H-mode dithers during the measurement period, which may lead to slightly deeper profile than in an L-mode further away from H-mode. The TS profile, however, was measured during a true L-mode phase. The radial force balance of He$^+$ (equation (2)) is dominated by the diamagnetic term (red, - - - -), which determines $E_r$ almost entirely. Any He$^+$ flow measured in L-mode is mainly parallel to $B$. Measurements in L-mode are particularly influenced by MHD affecting the edge plasma flow. Changes to mainly $u_{\phi}^\text{He}^+$ of the order of a few km/s have been observed during internal reconnection events, sawtooth crashes, and mode locking or growth of locked modes. These effects can even lead to positive $E_r$ and will be the subject of further investigations. In the data presented here such MHD is absent.

Changes in the flow perpendicular to $B$, however, do occur, for example when the magnetic configuration is changed from DN to single null (SN) [16, 19, 23]. A comparison of the fields in similar Ohmic discharges with different magnetic configurations is shown in figure 3. The profiles are plotted against the normalised poloidal radius $\rho_{\text{pol}} = \sqrt{\psi_r}$. A problem in these set of discharges was the different behaviour of low frequency MHD ($f < 5$ kHz) susceptible to mode locking. The data are averaged between $0.2 \text{ s} \leq t \leq 0.233 \text{ s}$ where the MHD was believed to be absent. The TS profiles were assembled from the individual time slices and fitted as one, because of the considerable fluctuation of the edge

Figure 2. Typical radial electric field in L-mode (black, ——). The contributions from the diamagnetic term (red, - - - -), and the individual components from the Lorentz term of $u_\phi$ (cyan, - - - - -) and $u_\theta$ (blue, — — —), as well as the intensity profile for reference (green, ·····) are also shown.

Figure 3. Comparison of the electric field in Ohmic discharges in DN ($\Delta R_{\text{sep}}^{\text{pol}} = 0$ mm, black, ——), U-SN ($\Delta R_{\text{sep}}^{\text{pol}} = 10$ mm, red, - - - -) and L-SN ($\Delta R_{\text{sep}}^{\text{pol}} = - 10$ mm blue, — — —). $\delta R_{\text{sep}}^{\text{pol}} = R_{X}^{\text{li}} - R_{X}^{\text{ui}}$, with $R_{X}^{\text{li}}$ the outer radius of the flux surface passing through the lower and upper X-point respectively.
plasma. In previous experiments on MAST and ASDEX Upgrade a $\Delta E_r \approx -1$ kV/m more negative $E_r$ was observed in the DN compared to L-SN [19, 23]. The negative shear region of $E_r$, however, was very similar. In this data set the field in L-SN is the most negative with a broad $E_r$ well, but the negative $E_r$ shear seems to be strongest in DN with the narrowest $E_r$ well. Furthermore, the strong change in $\partial E_r/\partial R$ observed on ASDEX Upgrade between upper SN (U-SN) and L-SN is not present in these discharges [23]. This difference between MAST and ASDEX Upgrade was also seen in B2SOLPS5.0 modelling [15]. Further experiments in more MHD stable plasmas are planned to investigate the subtle differences of $E_r$ in the different configurations and compare them with theoretical predictions.

Of particular interest is the evolution of the radial electric field through an L/H transition. In figure 4 the evolution of $E_r$ and its components through a relatively sharp L/H transition is shown. As the L/H transition is approached, the electric field well becomes deeper (figure 4a). Initially, during the dithery phase, the field is mainly determined by the diamagnetic term (figure 4b), and the Lorentz part is small and slightly positive (figure 4c). After the L/H transition at $t_{L/H} = 0.208$ s the Lorentz part becomes negative as a perpendicular He$^+$ flow develops, and a deep $E_r$ well forms. The shear of $E_r$, however, dominated by the diamagnetic term of the He$^+$ force balance. The contribution of the Lorentz term to the minimum of $E_r^{\text{min}} \approx -14$ kV/m is in this case $E_r^{\text{Lor}} \approx -3$ kV/m.

Contour plots of (a) $E_r$, (b) $E_r^{\text{dia}}$, and (c) $E_r^{\text{Lor}}$ through a very slow L/H transition are shown in figure 5.
Interestingly no strong shear is observed in the Lorentz part of the TS profile is an instantaneous snap shot of perpendicular velocity of the He⁺ flow becomes increasingly more important, although the well is formed by the diamagnetic part. Care has to be taken when interpreting the diamagnetic part though, since the TS profile is an instantaneous snapshot (ΔTS = 7 ns which sometimes is exactly on an ELM, whilst the ECELESTE data is averaged over Δt = 5 ms. This is the case at the times where the diamagnetic part is reduced around t = 0.280 s and t = 0.315 s. The ECELESTE measurement averages over several ELMs. Interestingly no strong shear is observed in the Lorentz part of the Eₚ on MAST.

4. The radial electric field in H-mode
As already shown in figure 4 a deep negative electric field well evolves in H-mode. The structure is mostly given by the diamagnetic part, as can be seen from figure 6, showing a low current Iₚ = 0.7 MA H-mode (#18571), and figure 7, showing a high current Iₚ = 1.1 MA H-mode (#18617). The Lorentz part contributes strongly to the minimum. The FWHM of the field well is only between 1 cm to 2 cm, and is narrower in the high current case (see also figure 8a). Also the pedestal width is narrower in the high current case than in the low current case. Both, the low and high current discharges have similar injected power of Pₙbi = 1.8 MW (The initial input power in the high current discharge is Pₙbi = 3.2 MW until t = 0.215 s), but different line averaged densities of \( \bar{n}_e = 3.6 \times 10^{19} \text{ m}^{-3} \) and \( \bar{n}_e = 4.6 \times 10^{19} \text{ m}^{-3} \) respectively at the time of the measurements. The densities in the low current discharge reaches \( \bar{n}_e = 4.3 \times 10^{19} \text{ m}^{-3} \) at the end of the H-mode and the \( E_r \) well broadens and deepens in time. Obviously, there is a difference between the two discharges in the power flowing over the LCFS, \( P_{\text{loss}} \), due to the difference in \( I_p \). In the \( I_p = 1.1 \text{ MA discharge} P_{\text{loss}} = 2.6 \text{ MW}, whereas in the \( I_p = 0.7 \text{ MA discharge} P_{\text{loss}} = 1.9 \text{ MW.} \)
Figure 6. Typical radial electric field in a low current H-mode #18571 (black, ———). The contributions from the diamagnetic term (red, - - -), and the individual components from the Lorentz term of \( u_\phi \) (cyan, — — —) and \( u_\theta \) (blue, ---), as well as the intensity profile for reference (green, · · ··) are also shown.

Figure 7. Typical radial electric field in a high current H-mode #18617 (black, ———). The contributions from the diamagnetic term (red, - - -), and the individual components from the Lorentz term of \( u_\phi \) (cyan, — — —) and \( u_\theta \) (blue, ---), as well as the intensity profile for reference (green, · · ··) are also shown.

Figure 8. Comparison of (a) \( E_r \), (b) \( T_e \), and (c) \( n_e \) between the low current (#18571, black ———) and the high current discharge (#18617, red - - - -).

A further difference between the discharges is the fuelling location. The \( I_p = 0.7 \) MA discharge is fuelled from the high-field-side (HFS) with controllable valves at the top and bottom of the centre column, and the \( I_p = 1.1 \) MA discharge is continuously fuelled from the HFS mid-plane. These different fuelling locations generally lead to a different distribution of the pedestal pressure between \( T_e \) and \( n_e \) as can be seen from figure 8 (b,c). Nevertheless, pedestal pressure itself is relatively similar in both discharges. It is also noteworthy that the difference in \( T_e \) is not caused by a steeper temperature gradient, but rather by the wider transport barrier. The electron pressure gradient is larger in the low current discharge (see figure 9), although the negative electric field shear \( \nabla E_r \approx -800 \) kV/m² is 2 times smaller.
than in the high current discharge (\(\nabla E_r \approx -2000 \text{ kV/m}^2\)) (see figure 9).

Because of the uncertainty in the absolute separatrix position by about \(\Delta R \approx 1 \text{ cm}\) all the profiles have been shifted with respect to each other so that \(E_r = 0 \text{ kV/m}\) at the separatrix, \(\rho_{\text{pol}} = 1\). In the SOL the plasma potential is usually positive \(\phi_{\text{pl}} \propto T_e\) and increases from the outside, due to the requirement of a constant potential, \(\phi_{\text{target}} = 0 \text{ V}\) along the earthed conducting target plates. Inside the LCFS the potential drops to give a negative electric field confining the ions. Therefore, \(\phi_{\text{pl}}\) usually has a maximum at the LCFS, thus motivating the shift of the profiles. To arrive at a firm conclusion, whether the differences in \(E_r\) are due to the different plasma current, or the different fuelling location, will be the subject of future work.

![Figure 9](image-url)

**Figure 9.** Electron pressure gradient against the radial electric field gradient for the low current (#18571, black ——) and the high current discharge (#18617, red - - - -) as in figure 8.

The transport barrier seems to be related to the negative shear region of the \(E_r\) well rather than the strong positive shear approaching the LCFS as demonstrated in figure 9. Here, the pressure gradient is plotted against the electric field gradient. Both are derived from fits to the data using the functions given in equation 3 for the pressure, and equation 4 for \(E_r\). Clearly the strongest gradient is in the region of the negative shear. In figure 10 the contributions of the force balance for the bulk ions are shown. Here, \(T_e = T_i\) is assumed. The strong diamagnetic contribution (figure 10a) leads to an mostly positive Lorentz contribution (figure 10b). This is consistent with a co-current toroidal rotation of the bulk ions. Note, that the position of the strongest pressure gradient of the bulk ions is further inward than the strongest pressure gradient for the He\(^+\) ions.

![Figure 10](image-url)

**Figure 10.** Contributions to the radial force balance for the bulk ions (a) diamagnetic part, and (b) Lorentz part for the low current (#18571, black ——) and the high current discharge (#18617, red - - - -) as in figure 8. Also shown in (a) is the measured \(E_r\) (\(\bigcirc, \triangle\)).

5. Summary and conclusions

For the first time in a spherical tokamak the edge radial electric field structure has been measured. Using a new active edge Doppler spectroscopy diagnostic, the field inside the first 10 cm of the plasma is calculated from the impurity ion momentum balance on up to 60 points with a spatial resolution of a few mm.

The L-mode field on MAST is rather shallow and the impurity flow which is mostly parallel to \(B\) plays a small role in the force balance. At the L/H transition the plasma spins up perpendicular to \(B\) and a strong negative electric field well develops in H-mode. The depths of the \(E_r\) well is of the order of \(-15 \text{ kV/m} \lesssim E_r\) and has a width of \(1 \text{ cm} \lesssim \Delta R \lesssim 2 \text{ cm}\) amounting to a negative shear up to
$\nabla E_r \approx -2 \text{ MV/m}^2$. The He$^+$ flow, though important for the absolute value of $E_r$, contributes little to the overall shear of $E_r$. For the bulk ions the diamagnetic term (estimated from the electron profiles) is even larger than for He$^+$, and exceeds the values of $E_r$. Hence, the perpendicular bulk ion flow is likely to be in the opposite direction compared to He$^+$ flow consistent with a toroidal rotation generated by co-current neutral beam injection rotation. It is not surprising that due to the strong gradients in fully developed H-mode the diamagnetic term of the force balance is important. At the L/H transition this might be different as experimental evidence suggests [7]. The perpendicular flow could build up on a faster time scale than the pressure gradient, and therefore become more important for the transition physics. Faster measurements using the new diagnostic will be used in future to investigate this aspect on MAST.

The width of the H-mode $E_r$ well reflects roughly the width of the transport barrier. The inner region of negative shear of the $E_r$ well coincides with the position of the strongest pressure gradient, although the positive shear across the last closed flux surface is higher. This suggests that the negative shear is more important for the suppression of the turbulence. The pedestal temperature gradient and indeed the pressure gradient of the electrons on MAST is independent of the strong shear of the electric field, showing that once the shear is high enough, and the turbulence is largely suppressed other effects seem to govern $\nabla p_e$. Insight into this threshold behaviour might be gained in future by investigations using the new ELM control coils on MAST, and turbulence measurements using a new beam emission spectroscopy system.

These first results show, that the new instrument is well suited to investigate the intimate relationship between the edge transport barrier and the radial electric field. Detailed comparison of the field structure with theory will allow a deeper understanding of what physics generates $E_r$, and what leads to the L/H transition. In particular the question what determines the width of the $E_r$ well is important, because it may lead to better confinement regimes on MAST, and an understanding of the width of the pedestal.

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References
[1] Wagner F, Becker G, Behringer K et al. 1982 Phys. Rev. Lett. 49 1408
[2] ASDEX-Team 1989 Nucl. Fusion 29 1959–2040
[3] Burrell K H, Carlstrom T N, Doyle E J et al. 1992 Plasma Phys. Control. Fusion 34 1859–1869
[4] Akers R J, Counsell G F, Sykes A, Appel L C, Arends E R, Byrom C, Carolan P G, Conway N J, Cunningham G, Dnestrowskij Y N, Field A R, Fielding S J, Gryaznevich M, Helander P, Kirk A, Korsholm S, Martin R, Meyer H, Nightingale M P S, Roach C M, Shevchenko V, Tournianski M R, Walsh M J, Warrick C D, Team T M and Team T N 2002 Phys. Rev. Lett. 88 035002
[5] Maingi R et al. 2002 Phys. Rev. Lett. 88 35003
[6] ITER-Team 1999 ITER Physics Basis vol 39 (Nucl. Fusion) chap 2, pp 2175–2249
[7] Burrell K H 1999 Phys. of Plasmas 6 4418–4435 invited contribution to the APS-meeting 1999 in Atlanta
[8] Ida K 1998 Plasma Phys. Control. Fusion 40 1429–1488
[9] Meyer H, Carolan P G, Conway N J, Field A R, Fielding S J and Helander P 2000 Czechoslovak Journal of Physics 50 1451
[10] Hahm T S and Burrell K H 1995 Physics of Plasmas 2 1648–1651
[11] Terry P W 2000 Rev. Mod. Phys. 72 109–165
[12] Diamond P H, Itoh S, Itoh K and Hahm T S 2005 Plasma Phys. Control. Fusion 46 R35–R161
[13] Burrell K H 2006 Plasma Phys. Control. Fusion 48 A347–A363
[14] LaBombard B et al. Poloidal transport asymmetries, edge plasma flows and toroidal rotation in Alcator C-MOD 16th Int. Conf. on Plasma Surface Interactions in Controlled Fusion Devices (Portland, USA 24–28 May 2004) P2-57, to be published in J. Nucl. Mat.
[15] Rozhansky V, Kaveeva E, Voskoboynikov S, Counsell G, Kirk A, Meyer H, Coster D, Conway D, Schirmer J, Schneider R and ASDEX Upgrade team 2006 Plasma Phys. Control. Fusion 48 1425–1435
[16] Schirmer J, Conway G D, Zohm H, Suttrop W and the ASDEX Upgrade Team 2006 Nucl. Fusion 46 S780–S791
[17] Carolan P G, Conway N J, Field A R, Jones P B and Meyer H 2001 Rev. Sci. Instr. 72 881–887
[18] Conway G D, Schirmer J, Klenge S, Suttrop W, Holzhauer E and the ASDEX Upgrade Team 2004 Plasma Phys. Control. Fusion 46 951–970
[19] Meyer H, Carolan P G, Conway N J, Counsell G F, Cunningham G, Field A R, Kirk A, McClements K G, Price M, Taylor D and the MAST team 2005 Plasma Phys. Control. Fusion 47 843–867
[20] Scannell R, Walsh M J, Carolan P G, Conway N J, Darke A C, Dunstan M R, Hare D and Prunty S L 2006 Rev. Sci. Instrum 77 10E510
[21] Groebner R J and Carlstrom T N 1998 Plasma Phys. Control. Fusion 40 673–677
[22] Summers H P and von Hellermann M 1993 Atomic and plasma-material interaction processes in controlled thermonuclear fusion ed Janev R K and Drawin H W (P. O. Box 103, 1000 AC Amsterdam, The Netherlands: Elsevier Science Publishers B. V.)
[23] Meyer H, Carolan P G, Conway G D, Cunningham G, Horton L D, Kirk A, Maingi R, Ryter F, Saarelma S, Schirmer J, Suttrop W, Wilson H R and the MAST, ASDEX Upgrade and NSTX teams 2006 Nucl. Fusion 46 64–72