Core Transport Reduction in Tokamak Plasmas with Modified Magnetic Shear

M.G. Bell, R.E. Bell, P.C. Efthimion, D.R. Ernst, E.D. Fredrickson,
F.M. Levinton[†], J. Manickam, E. Mazzucato, G.L. Schmidt, E.J. Synakowski,
M.C. Zarnstorff and the TFTR Group

*Plasma Physics Laboratory, Princeton University, Princeton, NJ, USA**
[†]Fusion Physics & Technology Inc., Torrance, CA, USA

Abstract

Spontaneous improvements of plasma confinement during auxiliary heating have been observed in many tokamaks when the q profile has been modified from its normal resistive equilibrium so that q > 1 and the magnetic shear is reduced or reversed in a region near the magnetic axis. The effects on the overall plasma confinement result from the formation in the plasma interior of transport barriers, regions where the thermal and particle transport coefficients are substantially reduced. These internal barriers are sometimes tied to unique magnetic surfaces, such as the surface where the shear reverses. The reduction in transport appears to result from the suppression of turbulence by sheared plasma flow, which has now been measured in TFTR. Extensions of the theory for turbulence suppression show that this underlying paradigm may also explain other regimes of improved core confinement. The excitement generated by these discoveries must be tempered by the realization that transport and stability to pressure-driven MHD instabilities are intimately linked in these plasmas through the bootstrap current and the effect of the resulting current profile on the transport. Thus the development of control tools and strategies is essential if these improved regimes of confinement are to be exploited to improve the prospects for fusion energy production.

PACS numbers: 52.55.Fa, 52.55.Dy, 52.55.-s, 52.35.Ra

* email contact: MBell@pppl.gov

Introduction

High-resolution plasma diagnostics have revealed the spontaneous development of regions in the interior of tokamak plasmas with markedly increased radial gradients in the temperature and density profiles during auxiliary heating. These regions are often referred to as “internal transport barriers” since they imply local reductions in the transport diffusivities. Similar transport barriers had previously been detected at the periphery of tokamak plasmas which underwent transitions to the so-called H-mode of confinement [1] and also in plasmas in which the edge was modified by the insertion of electrically biased probes [2]. In the H-mode, steep gradients form in the plasma temperature and density close to the last closed flux surface, leading to apparent “pedestals” in the profiles. The discovery of the H-mode, which was associated with improvements in overall plasma energy confinement by factors of about two compared with unimproved, or L-mode, plasmas in otherwise similar conditions, had a profound effect on the development of tokamak physics during the 1980s. The H-mode became the subject of intense study, both for its ability to improve tokamak performance and for the window it opened on the anomalous transport processes in tokamaks [3]. In similar fashion, internal transport barriers are now receiving much attention, both experimental and theoretical, not only because of their potential to improve plasma confinement but because they provide stringent tests of our ability to predict tokamak behavior.

The use of the term internal transport barrier (ITB) was introduced by Koide *et al.* [4] who observed regions of very high radial gradient in the ion temperature profile of neutral-beam heated plasmas in JT-60U. Transport barriers in the interior of tokamaks were, however, probably first seen in plasmas fueled by the injection of frozen deuterium pellets. The Pellet Enhanced Performance (PEP) mode was developed and studied on JET [5]. This mode was identified with the development of a region of elevated q, $q > 1$, and reversed magnetic shear, $s \equiv r/q \cdot \partial q/\partial r < 0$, near the magnetic axis following the pellet injection. These two conditions had been suggested by theory as being favorable both for macroscopic MHD stability to pressure-driven instabilities and also for stabilizing various micro-instabilities which were postulated to be the cause of the anomalous cross-field transport in tokamaks. The q-profile in the JET PEP plasmas was not directly measured but was inferred from calculations of the toroidal plasma current distribution which matched the location of rational q surfaces [6]. In TFTR, steep, localized density gradients in the plasma interior were also observed to persist for periods longer than the global particle and energy confinement times in ohmically heated plasmas fueled by deeply penetrating pellets [7]. These plasmas were calculated to have $q(0) > 1$ and a region of weak positive shear near the axis. In the “Core H-mode” observed in PBX-M [8], an ITB formed during heating of the plasma with ion-Bernstein waves. This type of ITB was believed to result from shear in the plasma flow generated directly by the waves in the vicinity of the absorption layer.

The tokamaks brought into operation in the 1980s incorporated extensive feedback systems which allowed the evolution of the plasmas to be carefully programmed and controlled. Experience in operating these devices had shown that producing a monotonic q profile with $q(0) < 1$, as evidenced by the onset of regular sawtooth oscillations, as early as possible in the plasma pulse was generally desirable from the standpoint of operational reliability. Attempts to produce plasmas with non-monotonic q-profiles were usually accompanied by deleterious MHD activity during the plasma startup and frequent discharge failure, so the study of plasmas with the shear deliberately reversed in the central region was accorded lower priority in the programs of these large facilities. However, in the early 1990s as the tokamak program began to consider the issues associated with steady-state operation, the realization occurred that plasmas with self-consistent pressure and current profiles and a high fraction of the self-generated bootstrap current naturally had reversed shear in the central region [9]. This realization, together with the development of diagnostics for the q-profile, paved the way for operating tokamaks with modified current profiles and, in particular, with the magnetic shear reversed, *i.e.* negative, in the central region.

Currently, the technique most frequently employed to modify the magnetic shear is to make use of the skin-effect in a highly conducting plasma. In a hot plasma with a cross-section typical of today’s large tokamaks, the timescale for resistive current penetration is many seconds. If the toroidal current is increased on a much shorter timescale, the current density will initially increase near the surface, resulting in a hollow radial profile of the current density and a region of reversed magnetic shear near the axis. Auxiliary heating during the current ramp-up is often employed to increase the electron temperature, and thereby the skin-time, and also, in some cases, to drive off-axis current directly. It should be noted that operation to produce reversed shear is generally not as reliable as the more traditional techniques which encourage rapid current penetration. Fortunately, however, the feedback systems now available for plasma control make it possible to reproduce reversed-shear discharges with reasonable reliability once a successful scenario has been developed.

Plasmas with modified magnetic shear have been observed to develop pronounced internal transport barriers in TFTR [10], DIII-D [11], JT-60U [12], JET [13] and a number of other tokamaks. Several common features have emerged from the study of these plasmas although there are differences in other respects. In the following sections, we shall examine the internal transport barriers occurring in TFTR particularly, highlighting similarities and differences between the phenomena observed on TFTR and other tokamaks.

Transport Barriers in TFTR Plasmas with Reversed Shear

Plasmas were produced in TFTR with the magnetic shear reversed within a normalized minor radius, r/a, up to about 0.45 by increasing the plasma current in full cross-section plasmas, $a \approx$

0.95m, while preheating the plasma with about 7MW of neutral beam injection (NBI) [14]. Final plasma currents of 1.6MA and 2.2MA have been used at high magnetic field, B_T = 4.6T, corresponding to edge q values, $q_a \approx 6.2$ and 4.4 respectively. Some plasmas were also run at reduced toroidal field and plasma current, preserving the value $q_a \approx 6.2$, to study the scaling of transport with field. Careful adjustment of the current ramp rate and the neutral beam heating were necessary to achieve reliable, reproducible conditions, particularly for high-current plasmas [15].

When an appropriate q-profile had been produced, the neutral beam power was increased to as much as 30MW to heat the plasma rapidly. During the high-power heating, some of the reversed-shear (RS) plasmas were observed to undergo a transition into a state of improved confinement, most obviously manifested by sudden increases in the rate of rise of the central plasma density and the global stored energy. This state is referred to as the Enhanced Reversed Shear (ERS) mode in TFTR. The corresponding states of improved confinement in other devices are known as the Negative Central Shear (NCS) mode in DIII-D, the Reversed Shear mode with Internal Transport Barrier (R/S-ITB) in JT-60U, and the Optimised Shear mode in JET. In the other tokamaks, the transition to enhanced confinement is sometimes not as clearly defined as in TFTR, but the profile and confinement characteristics of the final plasmas are quite similar. The transition to ERS in TFTR requires NBI heating above a threshold power level which increased with plasma current and the mass of the injected neutrals (T *vs.* D NBI) and also depended on the timing of the high-power heating and on the rates of influx of hydrogen and carbon from the limiter. The injection of a lithium pellet immediately prior to the high-power NBI was also found to reduce the power threshold for an ERS transition for reasons that are not well understood. In the 2.2MA RS plasmas in TFTR, ERS confinement was only obtained when lithium pellets were used to stimulate the transition.

A second type of confinement transition was sometimes observed in TFTR RS plasmas when the NBI power was below the threshold for the ERS transition [16]. These transitions, referred to as “Type II”, involved less change in the density profile evolution but produced localized regions of increased gradient in the ion and electron temperature profiles in the core of the plasma. These transitions were often found to occur when q_{min}, the value of q at the surface of shear reversal, crossed rational values, q = 3 and 5/2 in particular. These Type II transitions in TFTR produced changes in the profiles resembling those occurring in the DIII-D NCS and the JET optimised shear plasmas.

The confinement in the ERS mode is sufficiently good that if the NBI power is maintained at the level required to produce a transition, the plasma energy will rapidly increase to the β-limit, resulting in a disruption. However, by reducing the NBI power after the ERS mode had been established, quasi-steady-state ERS conditions could be maintained for several energy confinement times, depending on the external conditions. This provided the opportunity to study transport in the ERS plasmas and also back-transitions from the ERS state to the un-enhanced RS mode. In TFTR experiments, the period of lower power heating after the high power heating pulse was referred to as the neutral beam “postlude”.

The first profile analyses of the power and particle flows in RS plasmas without transitions showed that the transport was generally similar to that in the TFTR supershot mode of confinement [17]: the effective thermal diffusivities, χ_i and χ_e ($\chi = -q/n \quad T$) and electron diffusivity, $D_e = \Gamma_e/n_e$ were reduced relative to their levels in the L-mode [10]. In the ERS plasmas, χ_i and particularly D_e were further reduced in the interior of the plasma where the steep density gradient built up in the vicinity of the shear-reversal surface. However, in the original analysis, χ_e was not much changed from its profile in similar RS plasmas. Figure 1 shows the profiles of the calculated effective diffusivities for similar 1.6MA RS and ERS plasmas in TFTR.

The development of quasi-steady-state ERS conditions during the NBI postlude allowed us to apply perturbative methods to study ERS particle transport, as had previously been done in TFTR supershots and L-mode plasmas [18]. Brief puffs of both tritium and helium were introduced at the edge and the diffusion of the ions to the center was followed by measuring the profiles of either the 14MeV DT neutron emission or the charge-exchange recombination radiation of He-II respectively. Figure 2 shows the profiles of the measured T and He ion densities at successive times in ERS plasmas and the inferred diffusivity profiles in similar ERS and RS plasmas. There is a clear particle transport barrier, *i.e.* a region of reduced transport, extending from just outside the shear reversal radius into the reversed shear region. The analysis is subject to large uncertainties approaching the magnetic axis, but the flatness of the measured density profiles of the introduced ions at the center may indicate that the diffusivities rise again towards the center and that the transport barrier may be confined to a shell near the shear reversal surface.

In the final TFTR experiments highly detailed measurements were made of the electron temperature profile in ERS plasmas using a technique known as “jog” reconstruction of the profile. In these measurements, a plasma in a quasi-steady-state ERS phase is moved (jogged) rapidly in major radius (velocity ~ 2.4m/s) to sweep the internal flux surfaces past individual detector channels of the electron-cyclotron emission polychromator used to measure $T_e(R,t)$. Assuming that the relative movement of the flux surfaces is accurately calculable from the magnetic diagnostic data and that the temperature profile is unaffected, apart from known compressional effects, by the jog itself, the local temperature gradient can be measured on a single detector. Furthermore, channel to channel calibration uncertainties can be removed by matching the spatially overlapping data from adjacent channels on the forward and back strokes of the jog. This analysis revealed that the T_e profile in ERS plasmas was much flatter inside the shear reversal region than previously thought. Examples of the reconstructed profiles for an RS and an ERS plasma are shown in Fig. 3(a). The increased gradient in the confinement zone near the q_{min} surface and the absence of a gradient within, imply that the transport barrier is spatially localized for the electron channel and that, near the axis, the electron thermal transport is actually greatly increased with respect to both the particle and ion thermal transport in the same plasma and also the electron transport in companion RS plasmas, as seen in Fig. 3(b). Explanations for this anomaly are currently being investigated. Similar structure in the profile of χ_e has also been reported for JT-60U [12] where the profiles of the ion and electron temperature and electron density are all quite flat in the central region.

ERS plasmas provided the first clear example of a correlation between a change in transport properties in the interior of a tokamak plasma and a change in the level of turbulent plasma fluctuations. Correlations between the suppression of turbulence and reduced transport had previously been made near the edge in plasmas which underwent a transition to the H-mode, but such convincing evidence had not previously been available for changes in core confinement properties. The transition to ERS confinement in TFTR was accompanied by the cessation of repetitive bursts of density fluctuations detected in the preceding RS phase by a microwave reflectometer [19,20]. The bursts occurred with a repetition time of several milliseconds; each burst contained fluctuating components out to several hundred kilohertz in frequency. The region in which the fluctuations were suppressed coincided with the region of reversed shear and the fluctuations were observed to reappear when the plasma underwent a back-transition to RS confinement. Similar observations have been reported for NCS plasmas in DIII-D [21]

The suppression of turbulent transport observed in the formation of the H-mode edge barriers has been interpreted as resulting from sheared $\mathbf{E} \times \mathbf{B}/B^2$ flow between neighboring flux surfaces which decorrelates the turbulent structures [22]. The critical parameter for this effect is the shearing rate $\omega_{E\times B} = |(RB_\theta/B)\partial(E_r/RB_\theta)/\partial R|$ [23] which, for suppression to occur, must, roughly, exceed the linear growth rate γ_{max} of the most unstable mode contributing to the turbulence. The radial electric field E_r appearing in the expression for $\omega_{E\times B}$ may be determined either from the radial force balance equation, $E_r = \quad p_j/eZ_jn_j + v_{\varphi j}B_\theta - v_{\theta j}B_\varphi$, if all terms on the right hand side are available for a species j, or by direct measurement using the Stark effect, when this is possible. In experiments conducted in TFTR in 1996 [24], modifying the radial electric field by changing the toroidal flow driven by the neutral beam injection, while keeping the heating profile constant, provided strong evidence for the role of flow shear in suppressing turbulence and sustaining core transport barriers. Figure 4 shows examples of the particle diffusivity from the transport analysis and the density fluctuation measurements as a function of time in three plasmas with different amounts of toroidal flow driven by the neutral beams in the quasi-steady-state postlude phase. The plasma with the purely co-injected NBI, in which the toroidal flow opposes the p term in the expression for E_r, makes a back transition to higher transport as the fluctuations reappear after 2.3s. Interestingly, the decreasing contribution of the p term to the shearing rate as the transport worsens then allows the increasing toroidal flow term to dominate, so that the shearing rate increases (with E_r of opposite sign) and the fluctuations again become suppressed. In Fig. 4, the level of density fluctuations is derived from the phase of the probing wave using the reflectometer response function [25]. Because of the changing plasma density, the location of the measurements varies between r/a = 0.2 and 0.3, *i.e.* within the transport barrier. The breaks in the data of Fig. 4 occur when the amplitude of the fluctuations becomes very large, which renders the phase completely chaotic and makes quantitative measurements impossible. While these investigations appeared to be definitive with respect to the role of the toroidal flow in the transition process, they left open the role of poloidal flow, which was not measured but was assumed to be that predicted by neoclassical theory.

For its final experimental run from January through March 1997, a spectroscopic diagnostic for the poloidal flow was installed on TFTR [26]. In addition, the motional Stark effect (MSE) diagnostic for the poloidal magnetic field was expanded to measure the radial electric field directly [27]. With these new capabilities supplementing the existing diagnostics, measurements were ultimately made of all terms in the radial force balance for the carbon impurities. These revealed transient precursors to the ERS transition in the poloidal flow velocity and the radial electric field. These precursors, which are highly localized and appear to occupy a radial region smaller than the diagnostic channel separation of 3.5cm, occurred near the q_{min} surface in the region where steep gradients in the density evolve during the subsequent ERS phase [28]. An example of such a precursor is shown in Fig. 5. The agreement between the spectroscopic and Stark-effect measurements of E_r during the excursion is remarkable. The transient radial electric field is enormous, much larger than would be required for the shearing rate to exceed the characteristic growth rate of unstable drift modes, such as the ion temperature gradient (ITG) mode [29]. Interestingly, not every ERS transition was preceded by such a transient, although all such transients were followed by ERS transitions. Thus we speculate that the flow transient, while it can provide a trigger for the turbulence suppression, is itself an independent phenomenon. Various mechanisms are being investigated to explain the transient.

Suppression of Turbulent Transport in Other Regimes

The evidence obtained from reversed shear plasmas that reductions in at least some transport channels can be correlated with the suppression of microturbulence by flow shear, suggests that it would be appropriate to examine other regimes of improved core confinement in tokamaks for evidence of a similar mechanism. Prior to the interest in reversed shear plasmas, TFTR operated predominantly in its supershot mode of enhanced confinement, in which it had obtained its highest levels of fusion performance [30]. Supershots occur usually without a clear transition to improved confinement and are produced by applying strong NBI heating to a plasma in which the influxes of hydrogenic species and impurities from the limiter are reduced, either by removing adsorbed material with preconditioning discharges or by depositing thin surface coatings, particularly lithium, on the limiter surface.

In most supershots, q(0) < 1 and the q profile is monotonic, although for good confinement, sawteeth must become suppressed during the NBI heating. The sawtooth suppression is believed to result from a combination of diamagnetic drift (ω* effects) and energetic-particle stabilization of the n = 1 mode (n is the toroidal mode number) [31]. In these conditions, the edge density can be reduced so that the beam neutrals penetrate to the center where they ionize, building up the central density very rapidly. With strong ion heating from the NBI, the ions are preferentially heated, approaching the convection limit in temperature in the best cases, while the electrons remain at lower temperature. The global confinement time is enhanced by a factor typically about 2 over L-mode confinement [32] in average supershots and by more than 3 in the best cases.

Recently, a model has been developed for supershot confinement based on the behavior of anomalous transport from ITG mode turbulence in the presence of flow shear driven by the plasma pressure gradient itself and the external momentum source from the NBI heating [33]. This model is able to reproduce the ion temperature profiles of a representative ensemble of TFTR supershots for a wide range of operational conditions, including both equilibrium situations and the time-dependent response of the plasma to external perturbations [34]. In particular, the model is able to explain the apparent sensitivity of the central plasma temperature in supershots to relatively small changes at the plasma periphery, and the favorable scaling of supershot confinement with average ion mass in mixed D-T plasmas. This latter result is a challenge for traditional confinement scalings cast in terms of the dimensionless parameters normally thought to be important in tokamaks. Scalings based on inter-machine comparisons of plasmas matched in all dimensionless parameters save for the normalized gyro-radius, $\rho^* = \rho_i/a$, would suggest that confinement should be poorer in the plasmas with more massive ions. Figure 6 shows how the model with E_r shear applied to supershots leads to a non-linear dependence of the ion temperature at the center on its value at the half-radius, so that small increases in T_i near the edge, resulting, for example, from an isotopic dependence of the heating process or the edge confinement, causes a large improvement in the center. The model predicts that the profiles in the supershot plasmas are generally close to marginal stability for the turbulence responsible for the dominant transport. Thus, it is not surprising that measurements in this regime do not show significant reductions of the turbulent fluctuations as the confinement improves in response to the self-generated flow shear.

Stability of Plasmas with Internal Transport Barriers

One of the strong motivations for studying reversed-shear plasmas came originally from theoretical studies of the MHD stability of tokamak plasmas. In regions of reversed shear, tokamak plasmas are stable to high-n ideal pressure-driven ballooning modes [35] which were believed to impose a limit on the sustainable β. The systematic application of ideal-stability codes had shown that for optimized pressure profiles, plasmas with q(0) > 1 and a broad region of reversed shear had high limits for the Troyon-normalized-β [36], β_N ($\equiv 10^8 \beta_T a B_T / I_p$, where $\beta_T = 2\mu_0 \langle p\ \rangle / B_T^2$ and $\langle p\ \rangle$ is the volume-average plasma transverse pressure, a the plasma minor radius, I_p the plasma current and B_T the toroidal magnetic field on axis). In considering these predictions of improved stability relative to plasmas with positive shear, it must be borne in mind that ideal MHD theory is not able to cope with the situation $q(0) < 1$, which occurs in most tokamaks, because the n = 1 mode is predicted always to be unstable, contrary to experimental results.

With the exception of the results from DIII-D [37], the experience in large tokamaks with reversed-shear plasmas in enhanced confinement regimes has not fulfilled the original theoretical expectations for stability. This is because the transport barriers which form in these plasmas create extreme, localized pressure gradients, which exceed the stability limit of modes which destabilize the whole plasma leading to confinement collapses and sometimes major disruptions [38]. The problem reduces to the fact that in tokamaks, the profiles of the pressure and the current are closely linked: the current profile can modify the pressure profile through the creation of local transport barriers, while the pressure modifies the current through the bootstrap effect.

In ERS plasmas in TFTR, β_N was limited to less than 2 and disruptions often occurred at much lower β_N as the q-profile evolved during the ERS phase. However, it should be noted that as a result of the extremely peaked pressure profiles in these plasmas, the fusion-relevant β_N^*, defined in terms of the RMS plasma pressure, has reached 4.1 in a TFTR ERS plasma, comparable to what has been achieved in H-mode plasmas with broad pressure profiles. Calculations had shown that for pressure and q profiles with constant shape, the β_N-limit depended on q_{min}, decreasing markedly as q_{min} approached rational values, particularly $q_{min} = 2$ [39]. Furthermore, there appears to be a tendency for the transport barrier to expand in radius with time. This pushes the high pressure gradient into the region of weak shear around q_{min} which is vulnerable to pressure driven instabilities. The experience has been very similar in both JET Optimised Shear plasmas [13] and JT-60U R/S-ITB plasmas [12].

In a subset of the DIII-D NCS plasmas, a combination of plasma shaping and the timed triggering of an H-mode transition following development of the NCS phase has delayed the onset of instability and produced β_N values up to 4 [37]. This technique may be thought of as adding two transport barriers in series to reduce the gradient across each, thereby avoiding catastrophic instability. However, whether this technique is compatible with stability on the timescale of the resistive current penetration in hot, fusion-grade plasmas remains an open issue.

Summary and Conclusions

The initial excitement raised by the discovery of a new regime of enhanced confinement in tokamak plasmas with modified magnetic shear has encouraged a wide range of experiments to elucidate the underlying physics. The results of these experiments, coupled with advances in our ability to model plasma turbulence and the resulting transport, have suggested a paradigm for tokamak confinement in which self-consistent plasma flows, driven by external forces and intrinsic neoclassical effects, can describe confinement trends in several apparently disparate regimes. Diagnostics developed to study the phenomena associated with transitions to reduced transport have revealed a number of fascinating phenomena, which must now be explained and incorporated into our theoretical understanding and modeling capabilities for future generations of tokamaks. The results have suggested possible mechanisms for generating and controlling transport barriers through external means. One example of such a control mechanism is the generation of plasma flow by externally launched ion Bernstein waves which have been shown to generate localized poloidal flow in TFTR [40]. In these experiments the flow was, however, not sufficient to affect the turbulence and to trigger the formation of internal transport barriers.

The results obtained in plasmas without reversed shear raise the issue of its role in the production of localized transport barriers. Shear-reversal is neither sufficient for barrier formation (*q.v.* RS plasmas without transitions) nor necessary (*q.v.* the H-mode barriers at the edge of divertor plasmas where the shear is positive and large). It may be that reversed shear facilitates the creation of conditions necessary for the turbulent transport to become suppressed in some region. Once this occurs, the build up of the pressure gradient reinforces the shear stabilization and the process becomes entrenched. The facilitating role of shear reversal in the production of internal transport barriers may involve the larger flux surface shift resulting from the reduced poloidal field [29] or from changes in the contribution of $\partial B_\theta/\partial r$ to the shearing rate. One feature which is common to all these regimes of improved core confinement, including the various reversed-shear modes, supershots and PEP-like plasmas, is that the sawtooth instability, characteristic of the L-mode regime of confinement, is suppressed, either by the elevated central q or by non-ideal (finite Larmor radius) effects.

Acknowledgements

We wish to acknowledge the support and encouragement of Drs. R. Goldston, R. Hawryluk and J. Hosea for the current program of analysis for the TFTR data. These data were assembled over many years through the efforts of a dedicated and hardworking group of technicians, engineers and physicists. This work is supported by U.S. Department of Energy Contract DE-AC02-76CH03073

References

[1] Wagner F *et al.* 1982 *Phys. Rev. Lett.* **49** 1408

[2] Taylor R J *et al.* 1989 *Phys. Rev. Lett.* **63** 2365

[3] Burrell K H 1997 *Phys. Plasmas* **4** 1499

[4] Koide Y *et al.* 1994 *Phys. Rev. Lett.* **72** 3662

[5] Schmidt G L *et al.* 1989 *Plasma Physics and Controlled Nuclear Fusion Research 1988*, Proc. 12th Int. Conf., Nice (IAEA, Vienna) vol. 1, p. 215

[6] Hugon M *et al.* 1992 *Nucl. Fusion* **32** 33

[7] Milora S L *et al.* 1986 *Plasma Phys. Control. Fusion* **28** 1435

[8] LeBlanc B *et al.* 1995 *Phys. Plasmas* **2** 741

[9] Kessel C *et al.* 1994 *Phys. Rev. Lett.* **72** 1212

[10] Levinton F M *et al.* 1997 *Fusion Energy 1996*, Proc. 16th Int. Conf., Montreal (IAEA, Vienna) vol. 1, p. 211

[11] Lazarus E A *et al.* 1997 *Fusion Energy 1996*, Proc. 16th Int. Conf., Montreal (IAEA, Vienna) vol. 1, p. 199

[12] Fujita T *et al.* 1997 *Fusion Energy 1996*, Proc. 16th Int. Conf., Montreal (IAEA, Vienna) vol. 1, p. 227

[13] Gormezano C 1997 *Fusion Energy 1996*, Proc. 16th Int. Conf., Montreal (IAEA, Vienna) vol. 1, p. 487

[14] Levinton F M *et al.* 1995 *Phys. Rev. Lett.* **75** 4417

[15] Bell M G *et al.* 1997 *Phys. Plasmas* **4** 1714

[16] Bell R E *et al.* 1996 *Proc. 23rd EPS Conf. on Controlled Fusion and Plasma Physics* (Kiev) Part I **20C** 59

[17] Zarnstorff M C *et al.* 1989 *Plasma Physics and Controlled Nuclear Fusion Research 1988*, Proc. 12th Int. Conf., Nice (IAEA, Vienna) vol. 1, p. 183

[18] Efthimion P C *et al.* 1998 *Phys. Plasmas* **5** 1832

[19] Mazzucato E *et al.* 1996 *Phys. Rev. Lett.* **77** 3145

[20] Mazzucato E *et al.* 1997 *Fusion Energy 1996*, Proc. 16th Int. Conf., Montreal (IAEA, Vienna) vol. 1, p. 913

[21] Rettig C *et al.* 1997 *Phys. Plasmas* **4** 4009

[22] Biglari H, Diamond P H and Terry P W 1990 *Phys. Fluids B* **2** 1

[23] Hahm T S and Burrell K H 1995 *Phys. Plasmas* **2** 1648

[24] Synakowski E J *et al.* 1997 *Phys. Rev. Lett.* **78** 2972

Synakowski E J *et al.* 1997 *Phys. Plasmas* **4** 1736

[25] Mazzucato E 1998 *Rev. Sci. Instrum.* **69** 2201

[26] Bell R E 1997 *Rev. Sci. Instrum.* **68** 1273

[27] Levinton F M *et al.* 1998 *Phys. Rev. Lett.* **80** 4887

[28] Bell R E *et al.* 1998 *Phys. Rev. Lett.* **81** 1429

[29] Beer M 1997 *Phys. Plasmas* **4** 1792

Synakowski E J *et al.* 1998 *Plasma Phys. Control Fusion* **40** 581

[30] McGuire K M *et al.* 1997 *Fusion Energy 1996*, Proc. 16th Int. Conf., Montreal (IAEA, Vienna) vol. 1, p. 19

[31] Levinton F M *et al.* 1994 *Phys. Rev. Lett.* **72** 2895

[32] Yushmanov P N *et al.* 1990 *Nucl. Fusion* **30** 1999

[33] Ernst D R 1998 "*Momentum Transport, Radial Electric Field, and Ion Energy Confinement in Very High Temperature Plasmas*", Ph.D. Thesis, Massachusetts Institute of Technology

[34] Ernst D R *et al.* 1998 *Phys. Rev. Lett.* **81** 2454

[35] Greene J M and Chance M S 1981 *Nucl. Fusion* **21** 453

[36] Troyon F *et al.* 1984 *Plasma Phys. Control. Fusion* **26** 209

[37] Lao L L *et al.* 1996 *Phys. Plasmas* **3** 1951

[38] Manickam J *et al.* 1997 *Fusion Energy 1996*, Proc. 16th Int. Conf., Montreal (IAEA, Vienna) vol. 1, p. 453

[39] Phillips M W *et al.* 1996 *Phys. Plasmas* **3** 1673

[40] LeBlanc B *et al.* 1998 this conference.

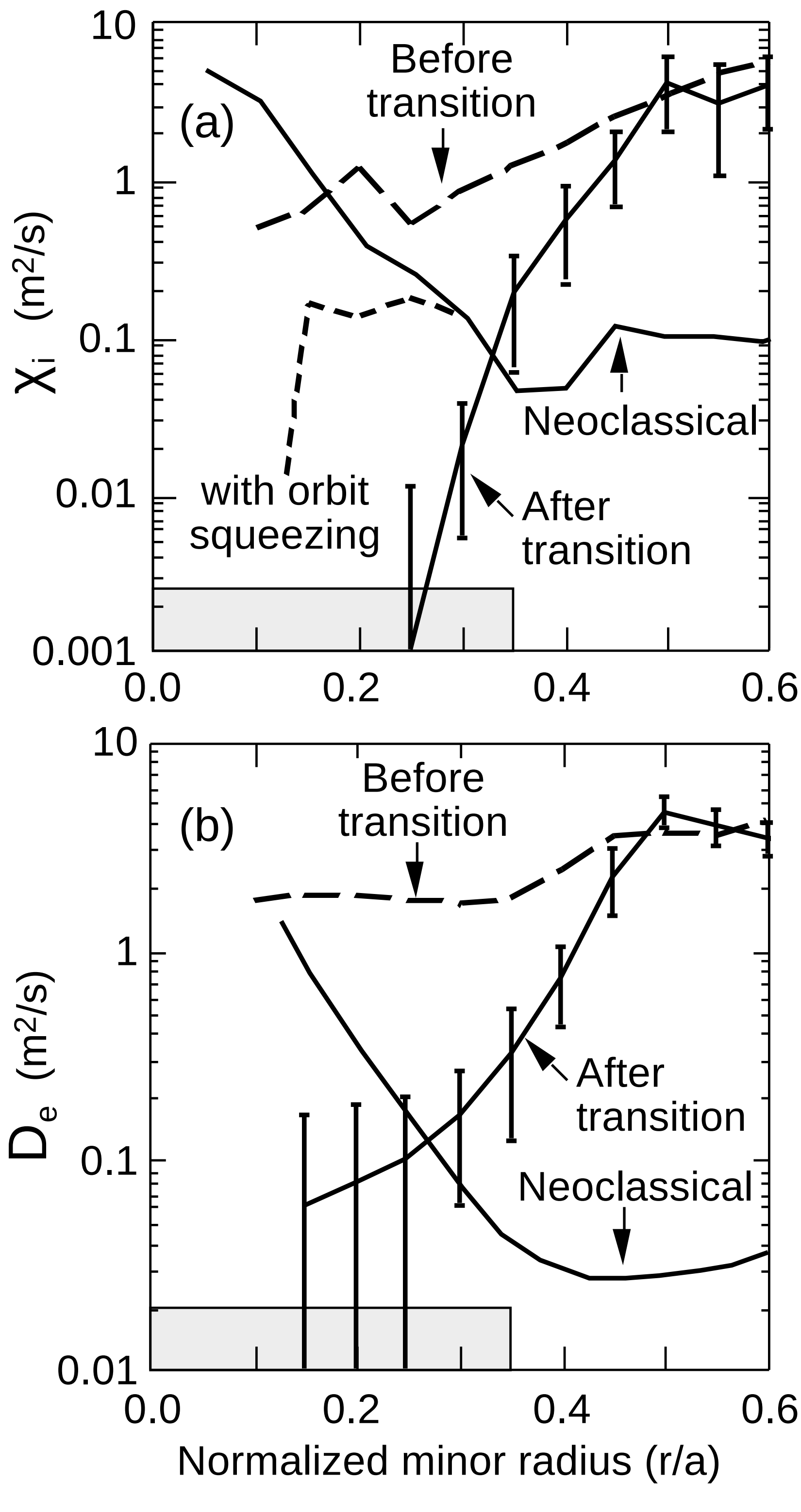


Fig. 1 Effective ion thermal diffusivity (a) and electron diffusivity (b) in the core of a plasma which undergoes an ERS transition. The radial extent of reversed shear is indicated by shading. The neoclassical calculations include off-diagonal contributions to the fluxes. The effect of "orbit squeezing" near the axis is taken from Shaing, Hsu, and Hazeltine 1994 [Phys. Plasmas 1 3365]

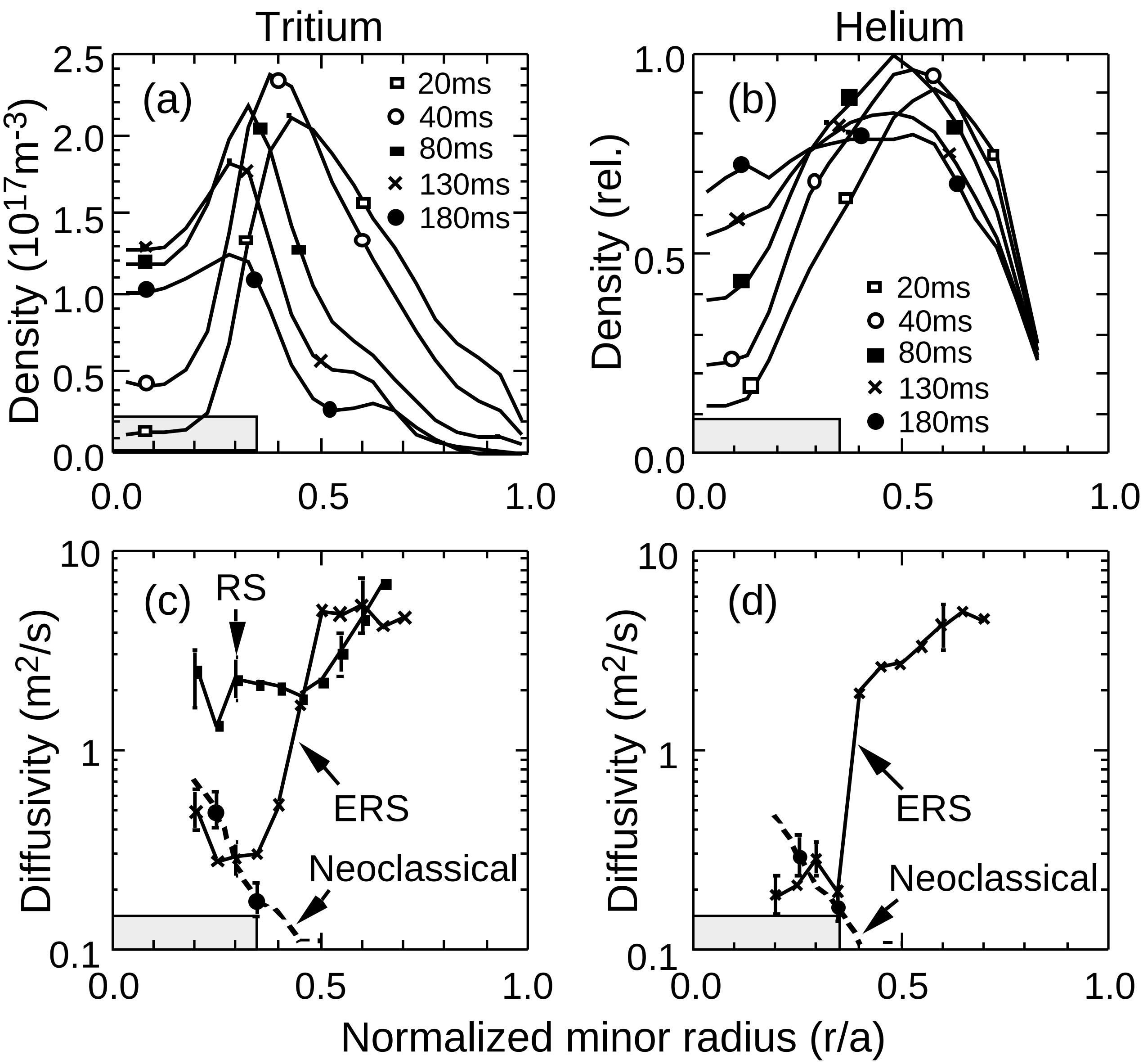
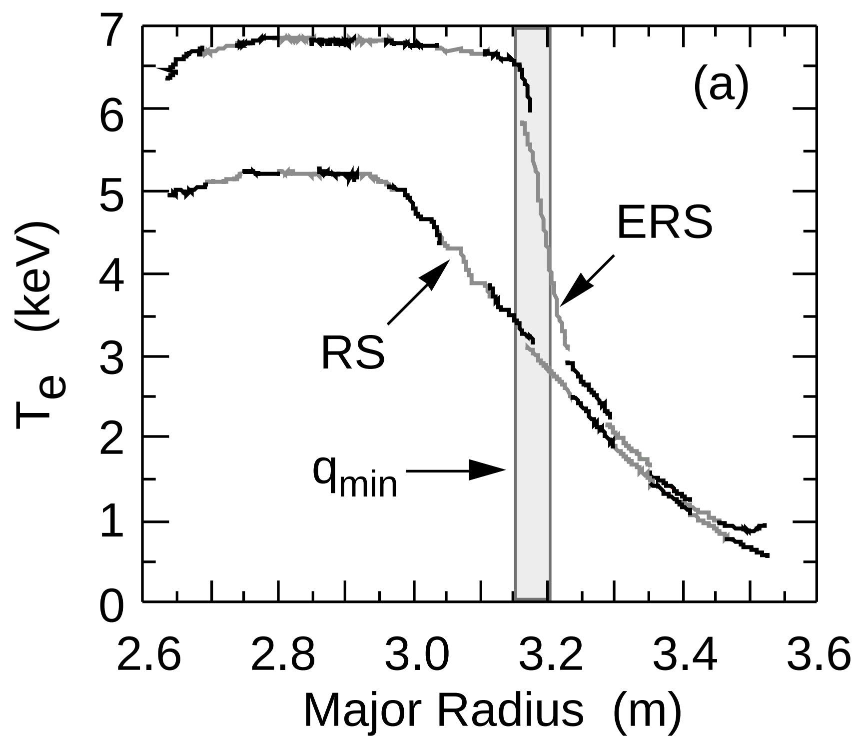


Fig. 2 Time evolutions of the radial profiles of the measured densities of (a) tritium and (b) helium following brief gas puffs at the edge during a steady-state ERS postlude phase. The times are shown from the start of the gas puff and the region of reversed magnetic shear is indicated by shading. A transport barrier is evident in the corresponding inferred particle diffusivities (c, d) for the two species respectively.



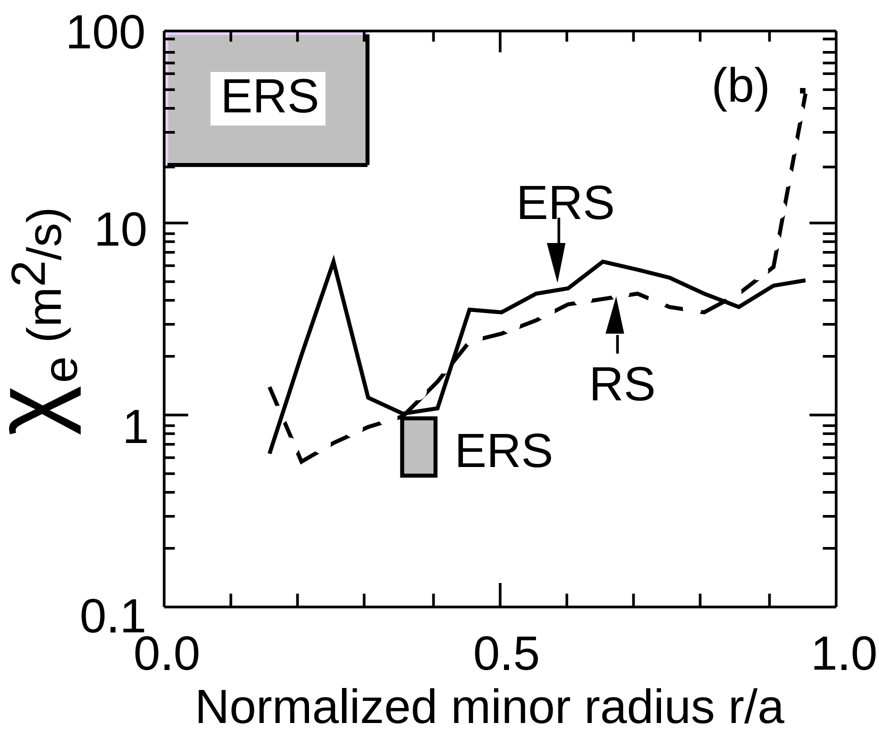


Fig. 3 (a) Radial profiles of the electron temperature in an ERS and an RS plasma measured by the plasma jog technique after correction for the channel-to-channel calibration uncertainties of the ECE grating polychromator diagnostic. (b) Lines show the electron thermal diffusivities based on the original point profiles. Shaded areas show the effects on the diffusivity inside the transport barrier of using the jog data for the RS plasma.

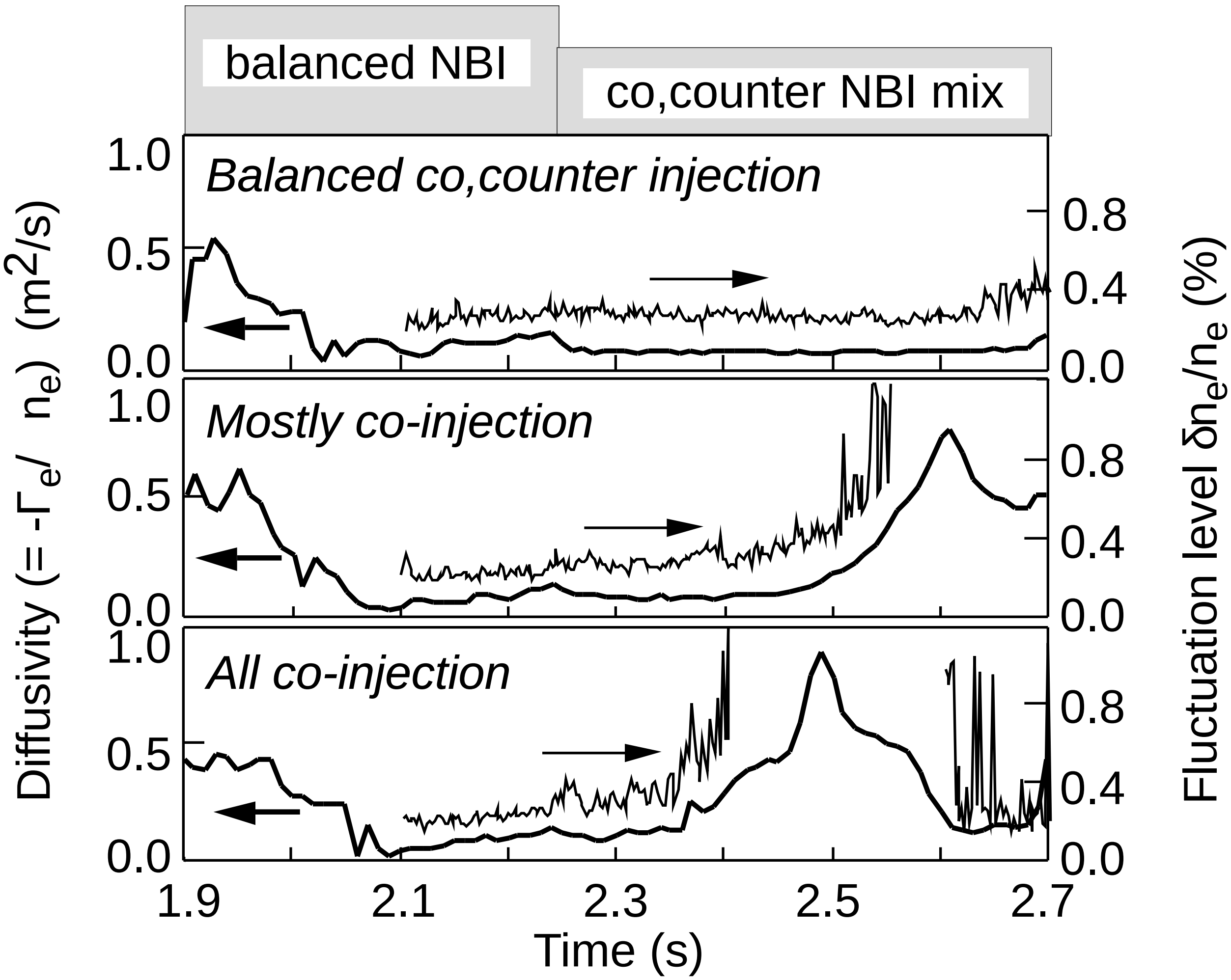


Fig. 4 Time evolution of the density fluctuation amplitude and the effective particle diffusivity D in the core of plasmas which enter the the ERS regime, marked by the reduction in the particle diffusivity, during high-power NBI. By varying the co-/counter- NBI mix in the subsequent lower power phase the plasma may be driven out of the ERS regime by the toroidal flow driven by co-injected NBI.

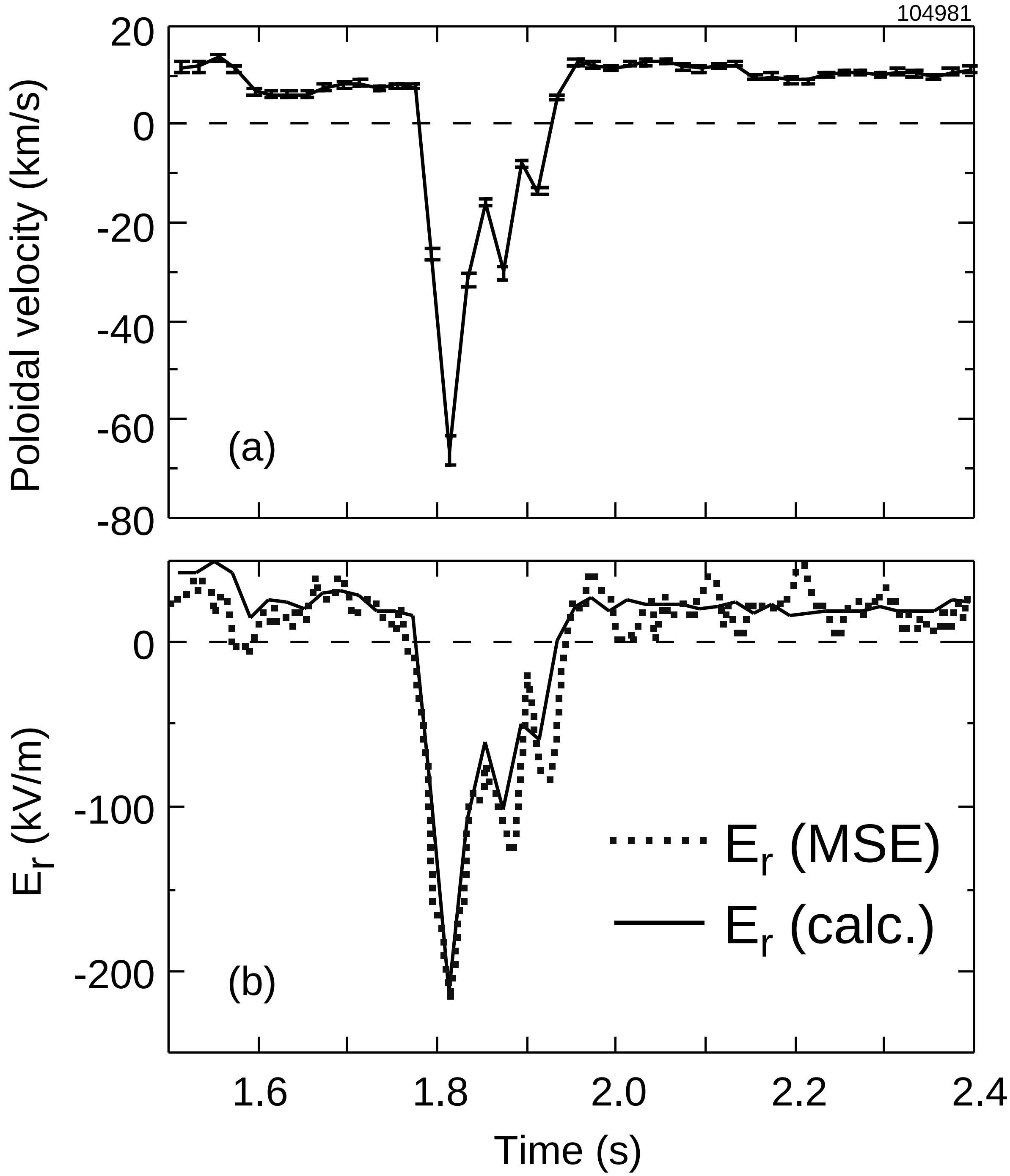


Fig. 5 Transient precursor to an ERS transition seen in (a) the poloidal flow of carbon impurities and (b) the radial electric field at R = 3.02m, corresponding to r/a ≈ 0.27. There is excellent agreement between the radial electric field calculated from the force balance equation for the carbon impurities (solid curve) and deduced from its Stark effect on the Doppler-shifted D_α emission from beam injected neutrals (dashed). The transient reversal of the poloidal flow and radial electric field occur in an extremely localized region (<3cm wide) near the shear-reversal surface where steep gradients in the density profile subsequently evolve.

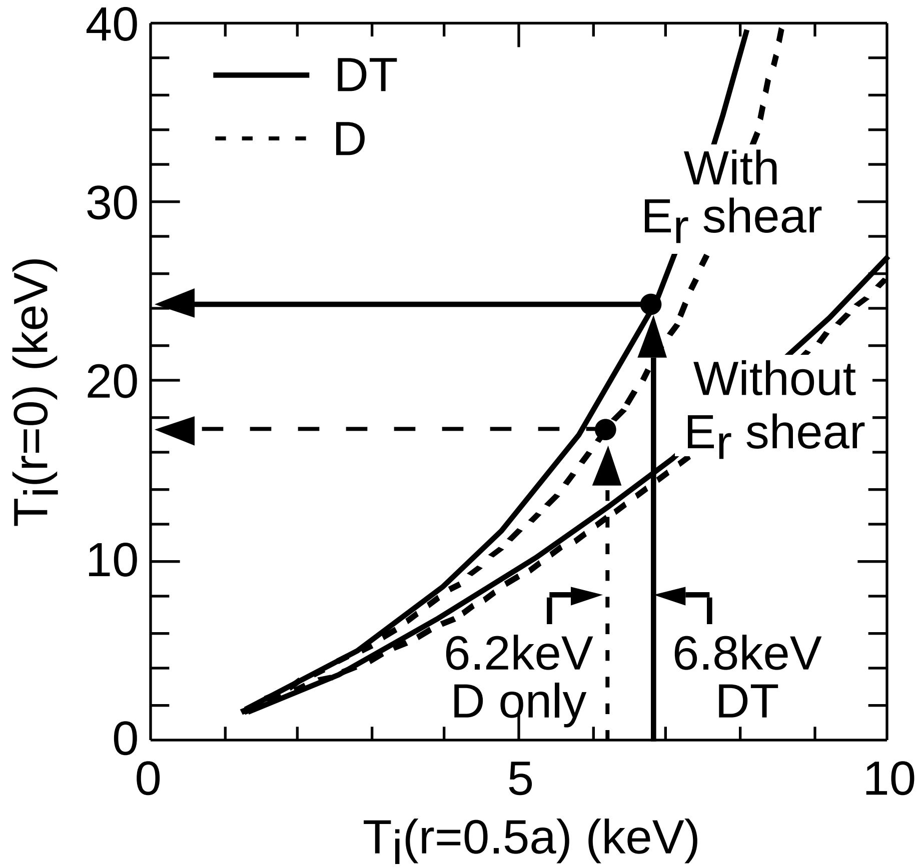


Fig. 6 Calculated dependence of the central ion temperature on its value at the half radius for transport resulting from ITG turbulence including a model for turbulence suppression by the self-consistent plasma flow. The inclusion of the intrinsic neoclassical flow causes a highly non-linear behavior of the central temperature. A measured increase of 0.6keV in the ion temperature at the half radius, changing from a D-only to a matched DT plasma, results in a predicted increase of 7keV at the center: an incease of 8keV was measured.