Calculation of the radial electric field change during radial neutral beam injection into the stellarator W7-AS

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Motivation

The radial electric field E_r is of crucial importance for the confinement in a stellarator [1]. Large values of E_r are in general accompanied by good confinement, as for instance for H-mode. There exist other improved confinement regimes with strong negative E_r in the gradient region, in W7-AS with record ion temperatures up to 1.6 keV in the plasma center [2]. The measured energy confinement times are here more than a factor of two larger than those predicted by the International Stellarator Scaling Database ISS95 [3]. The possible solutions for the value of E_r are given by the ambipolarity condition for the thermal particle fluxes [4]. One possibility to modify the ambipolar E_r experimentally be external means is the use of auxiliary heating devices, driving non-ambipolar particle fluxes in excess to the thermal ones. This has been demonstrated at W7-AS successfully during Electron Cyclotron Resonance ECRH heating. Toroidally trapped outward drifting suprathermal electrons in a toroidal magnetic field minimum can drive E_r here positive [5]. Record central electron temperatures of more than 6 keV are then observed, resulting from the strongly reduced central electron heat conductivity. Recently, a radial Neutral Beam Injector device RNBI had been installed on W7-AS. By the injection of neutrals with beam energies $\approx$ 50 keV roughly perpendicular to the magnetic field, fast ion orbit losses should be driven in addition to the thermal ion fluxes. Thus, E_r should be driven more negative, with a subsequent improvement of the confinement. In this contribution, the numerical Monte-Carlo procedure is described which is used to calculate the expected change of E_r as a function of the minor radius and time during RNBI operation. Those calculations are performed for different plasma parameters and magnetic configurations. Thus, it is investigated which type of discharge is most appropriate for maximum changes of. And it is investigated which amplitude for $\Delta E_r(r)$ can be expected as a function of the injection time length.

Numerical procedure

To support the numerical calculations, Active Charge eXchange Recombination Spectroscopy CXRS is performed in the beam of the RNBI device on the fully stripped ions of He, C or N on W7-AS [6]. This spectroscopic signal provides the experimental impurity concentration profile. In parallel, the neutral beam attenuation profile in the plasma is calculated, taking into account charge exchange, proton and electron ionization. Because impurities also contribute to the beam attenuation, the impurity concentration profile is calculated iteratively, including the impurity species, which is subject to the CXRS measurement (with a yet unknown concentration profile shape at first iteration). This calculated impurity concentration profile is

then compared to the CXRS measurement, providing a benchmark test for the outcome of the beam attenuation calculation. Thus, the reliability for the calculations described next is enhanced. Then test particles are started numerically by means of a Monte Carlo procedure, taking into account the RNBI parameters like the injection geometry, energetic beam composition, beam divergence, background plasma parameters and of course the calculated and benchmarked beam attenuation profile. The born fast ions then are followed on their orbits in real geometry for W7-AS, considering the background density and temperature. The procedure is based on a Monte Carlo finite step approach to take into account the slowing down process, in accordance to a solution of the Fokker-Planck equation [7]. A guiding center approach is employed to follow the orbits in small time steps: typically 10^{-3} of the 90-degrees deflection time. Thus, a radial profile is gained for the local fast ion deposition and losses, i.e. for the radial ion fluxes. In a final step, the temporal change of E_r is calculated as a function of time and minor radius including the following consideration: due to the radial charged particle fluxes, the electrostatic space potential experiences a temporal change. This leads to Maxwell's vacuum displacement current, and a polarisation current inside the plasma dominating the temporal change of E_r. This polarisation current due to an ion polarisation drift motion, being proportional to $\partial E_r / \partial t$, screens the local change of E_r. That screening is described by the plasma internal dielectric constant $\varepsilon_\perp \approx c^2 / V_A^2$ with the Alven velocity $V_A^2 = B^2 / \mu_0 n_i m_i$ [8]. Here B is the magnetic field, μ_0 the vacuum permeability, n_i and m_i the ion density and mass, respectively. Note the B^2 dependence of $\varepsilon_\perp$: the mean magnetic field determines the speed of the E_r change drastically: a higher B field causes a much faster change of E_r for the same ion fluxes.

Radial neutral beam injector and spectroscopic equipment

The radial neutral beam injector RNBI device [9] consists of two roughly parallel beamlines, with an acceleration voltage of 50 keV for H and 55 keV for D beams, with a nominal power for each beamline of 275 kW for hydrogen injection. The energetic beam power composition into full, 1/2 and 1/3 component is about 50%, 30% and 20%, respectively, with a beam divergence of 1.2 degrees mean half angle. The total beam diameter at the plasma edge for each beamline is about 270 mm. The mean angle between the beamlines and the direction of the magnetic axis is nominally 68.5 degrees, with both beams lying roughly horizontally. This angle had been the optimum between a maximum power transmission through the modified W7-AS port, and an injection angle as close as possible to the perpendicular. The CXRS spectroscopic system on W7-AS consists of 3 different spectrometers, one of which looks into the interaction volume between the RNBI device and the plasma, the two others into the beam of a diagnostic neutral beam injector. Thus, CXRS measurements independent from RNBI are possible. Additionally, one system with good temporal and spatial resolution is available, observing the B IV spectral line emission after electron excitation. By a numerical fit procedure the spectral line shapes are evaluated, delivering thus the local impurity concentration for the fully stripped ion species under consideration, the local ion temperature

and the poloidal impurity rotation velocity. From the force balance equation, the experimental E_r profile can thus be determined.

Results and discussion

Radial profiles of $\Delta E_r / \Delta t\ (r)$ are calculated for a variety of plasma parameters and magnetic configurations, using measured density and temperature profiles from W7-AS as input data. From the calculations it is found, that the ion orbit loss fluxes are typically in the range of 10^{-3} of the thermal particle fluxes. The maximum values for $\Delta E_r / \Delta t\ (r)$ are $\approx$ - 400 V/m · msec for 55 keV D_2 injection, and $\approx$ - 250 V/m · msec for 50 keV with H_2. Those highest values are located in vicinity to the plasma edge, where the ion losses are maximum. The ambipolar E_r is typically $\approx$ - 30.000 V/m in W7-AS: if one were to double that value by RNBI, therefore an injection time interval of at least $\approx$ 75 msec is required. In general, discharges with so-called Optimised Energy Confinement [10] are most appropriate for a further enhancement of E_r. They are characterised by low recycling fluxes with high ion temperatures, good energy confinement and high E_r in the gradient region, resembling to some extent to H-mode. The major difference to H-mode is the very slow transition into the improved confinement, taking typically $\approx$ 100 msec. The magnetic configuration is tailored for these discharges showing low effective magnetic ripple in conjunction with thorough wall conditioning, supported by application of a vertical magnetic field. The calculations for those discharges show a maximum for the attainment of $\Delta E_r / \Delta t\ (r) \approx$ - 250 V/m · msec for $n_e(0) \approx 10^{20}\,m^{-3}$ at 50 keV, with only a weak n_e dependence. Even higher densities might be preferable because of technical reasons. The calculations predict a RNBI power deposition in the range of 40%-70 % only. The rest of the power hits the inner vessel wall (which is, however, protected by graphite tiles). Therefore a release of carbon is expected during RNBI phases, an aspect which requires attention during the experiments. Thus, the unfavourable enhanced impurity radiation resulting from the carbon influx might overcompensate the favourable gain in $\Delta E_r / \Delta t\ (r)$, leading after too long RNBI phases to a degradation in the global discharge confinement. A variation of Z_{eff}, resulting for instance from that carbon sputtering, for the calculations predicts an increase of $\Delta E_r / \Delta t\ (r)$ from - 150 to -200 V/m · msec, if Z_{eff} is increased from 1.4 to 6.0 (and otherwise constant plasma parameters), in particular close the the plasma edge. This effect is explained by enhanced angle scattering rather than energy scattering for the fast ions with the increased number of background impurity ions. It is found that the maximum $\Delta E_r / \Delta t\ (r)$ is rather independent from the heating power level, or the type of the heating devices (ECRH or NBI). The dependence from the electron density is also rather weak: if $n_e(0)$ is increased for the calculation in steps from $2 \cdot 10^{19}$ to $2 \cdot 10^{20}\ m^{-3}$, $\Delta E_r / \Delta t\ (r)$ increases only from -200 to - 250 V/m · msec. This is shown in fig. 1 on the right plot. A very strong $\Delta E_r / \Delta t\ (r)$ variation is found as a function of the injector accelerating voltage: if the voltage is increased from 30 to 55 keV, the calculated $\Delta E_r / \Delta t\ (r)$ increases from -40 to - 400 V/m · msec, see fig. 1, left plot. However, the injector voltage is limited by the power supply to 55

keV, and by the beam perveance, which causes a strongly increasing beam divergence for higher voltages. This might result in hazardous consequences for in-vessel installations.

Variations of the magnetic configuration with different effective toroidal ripple values are investigated, too. The local B at the toroidal location of the RNBI device is varied, to modify the toroidally trapped fast ion population with resulting variations in the trapped fast ion orbit loss fluxes. Application of a local B minimum enhances locally the ion loss fluxes, but the total mean B around W7-AS is then reduced this way. The net resulting $\Delta E_r / \Delta t\ (r)$ is therefore smaller than for a standard configuration with low ripple as a consequence of the $\langle B^2 \rangle$ dependence, as pointed out above. To conclude: RNB Injection at maximum voltages and high n_e is preferred. Care has to be taken for sputtered carbon from the wall. Application of toroidal magnetic minima at the location of the RNBI device are helpful for the production of ripple trapped fast ions, but the reduced mean magnetic field might overcompensate the desired increase of E_r.
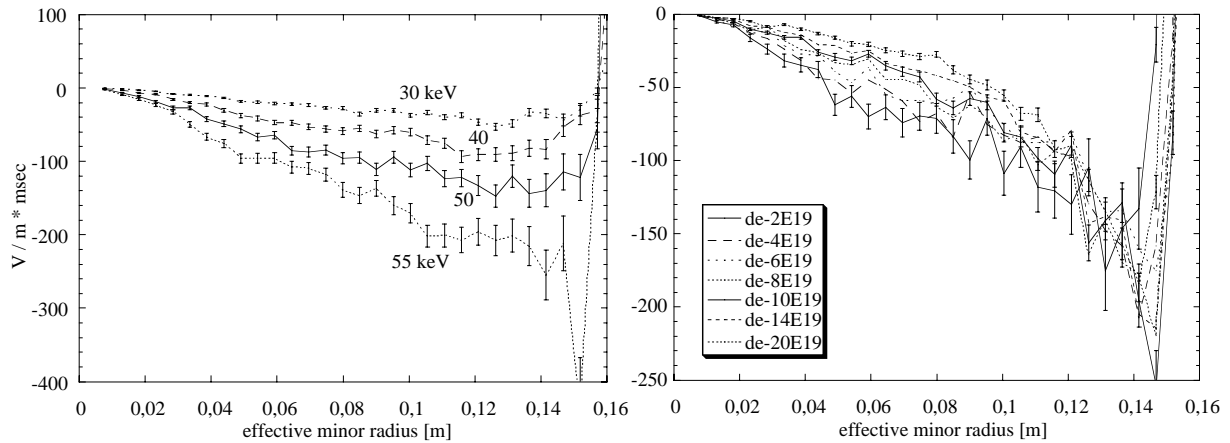

Fig.1: Calculations of radial profiles for $\Delta E_r / \Delta t\ (r)$ in V/m · msec. Left plot: variation of the injection energy (30 keV to 55 keV), right plot: variation of the electron density. Statistical error bars arising from the Monte Carlo procedure are given.

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