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RADIAL ELECTRIC FIELD MODIFICATION BY PERPENDICULAR NEUTRAL BEAM INJECTION IN THE STELLARATOR W7-AS

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Introduction

The radial electric field E_r is of crucial importance for the confinement properties of a stellarator plasma. In general, large values of E_r can reduce the neoclassical transport coefficients, thus improving the global discharge confinement [1]. In addition, the resulting $E \times B$ drift motion could reduce the anomalous transport by a decorrelation of turbulences and fluctuations due to the enhanced shear flow [2]. The value of E_r is determined by the ambipolarity condition for the thermal particle fluxes. In W7-AS, recently a new perpendicular neutral beam injector PNBI had been installed. The purpose is to drive nonambipolar radial fast ion orbit losses in order to enhance E_r towards more negative values, and to improve thus the global discharge confinement. In parallel, a numerical computer program had been written to calculate the expected fast ion losses and the temporal change of E_r as a function of the plasma parameters and the magnetic configuration quantitatively.

The new perpendicular injector PNBI consists of two beamlines with a nominal input power of 275 kW, each. The injection energy is 50 keV for H and 55 keV for D injection. Two spectroscopic systems are installed with viewing chords into the interaction volume between the neutral beam and the plasma to allow for charge exchange spectroscopy measurements CXRS of both the poloidal and toroidal rotation component, in order to evaluate the change of E_r during PNBI. In addition, passive line integrated spectroscopy is performed on *B VI* in the near UV to measure the poloidal rotation in vicinity of the plasma edge, and actice CXRS is performed in another low power diagnostic beam.

Numerical

In a first step, the birth profile of the fast ions from PNBI is calculated. CX, proton and electron ionisation are taken into account for the calculation, using the background plasma profiles $n_e(r)$ and $T_e(r)$, and impurity densities $n_I(r)$. The CXRS measurement on He in the PNBI beam delivers the radial profile of the He++ density. The numerically calculated beam attenuation profile (fast ion birth profile) can thus be benchmarked towards the spectroscopic measurement. Then the fast ions are followed in real geometry around the torus in a guiding center approximation. The Biot-Savart law is used to calculate $\vec{B}(\vec{r})$ and $\vec{\nabla}(B(\vec{r}))$ anywhere in the torus. Slowing down of the fast ions is calculated by a Monte-Carlo procedure [3], taking into account diffusion spreading in velocity space and heat transfer to the background ions. The fast ions are followed until they disappear either in the thermal bulk, or until they are lost from the plasma volume. Thus, for a set of nested flux surfaces, the radial electric currents carried by the fast ions are obtained. From this, the temporal change of the radial electric field $\Delta E_r(r,t)/\Delta t$ is calculated by:

$$\frac{1}{\mu_0}\left\{\frac{1}{c^2}\dot{E}_r - m_i n_i \mu_0 \frac{\dot{E}_r}{B^2}\right\} = \left\langle \hat{e}_p \cdot \nabla \vec{\Pi} \right\rangle - m_i n_i \frac{1}{|B|}\frac{d}{dt}\left(\frac{\nabla P_i \times \vec{B}}{B^2} + \hat{e}_p \cdot \left(V_{\parallel} \cdot \frac{\vec{B}}{B}\right)\right) \quad (1)$$

Here, m is the particle mass, n the density, V the fluid velocity, P the fluid pressure, e the electric charge, $\nabla \vec{\Pi}$ the total viscous force, c the light speed, ε_0 the dielectric constant, μ_0 the vacuum permeability, $\vec{j}$ the electric current, $\hat{e}_p \cdot V_{\parallel}$ is the poloidal component of the parallel ion flow velocity, $\hat{e}_p$ a poloidal Hamada vector.

The first (very small) term on the left-hand side describes Maxwell's displacement current going with $1/c^2$. The second (much larger and dominating) term is the plasma polarisation current going with $1/V_A^2$, with $V_A^2 = B^2/\mu_0 n_i m_i$ being the Alfven velocity. The first small term can thus be neglected. Further we assume constant background plasma parameters: thus the second and third term on the right-hand side are dropped. The temporal evolution of the radial electric field is thus calculated in the numerical program by [4]:

$$\varepsilon_0 \frac{c^2}{V_{A,p}^2} \cdot \left\{\frac{l \cdot \iota}{m}\right\} \cdot \dot{E}_r = e \cdot \Gamma_{loss} \quad (2)$$

This formula contains a correction term for the stellarator magnetic field topology including the poloidal Alfven velocity. $l = 2$ and $m = 5$ are assumed as the dominating magnetic field mode numbers for W7-AS, ι is the magnetic field iota. Note the B^2 dependence in eq. (2). The value of the magnetic field influences the temporal change of E_r drastically: The larger B, the larger is $\Delta E_r(r,t)/\Delta t$ even at constant ion loss fluxes.

Results

The temporal development $\Delta E_r(r,t)/\Delta t$ is calculated for a variety of discharge conditions and magnetic configurations to figure out, which of them are most appropriate for a variation of E_r by PNBI. Focus was on the possibility of different locations of magnetic minima around W7-AS, which strongly affect the ion losses by trapping the ions locally. The calculations provide only a starting value of $\Delta E_r(r,t)/\Delta t$ directly after switching on the PNBI, with otherwise constant background plasma parameters. It is not possible to calculate the transient change of $\Delta E_r(r,t)/\Delta t$ during a longer phase of PNBI injection self-consistently, because in this case the background plasma parameters will change in a (still) unknown manner. In general the calculations show a rather large shine-through for the PNBI power (20%-50%). The calculated values for $\Delta E_r(r,t)/\Delta t$ range typically between ≈ -100 V/m· msec to - 300 V/m· msec. Thus, PNBI injection time intervals T ≈ 100 msec are experimentally required to influence E_r considerably, because then $T \cdot \Delta E_r(r,t)/\Delta t$ comes to the order of magnitude of the ambipolar E_r for W7-AS. The calculated $\Delta E_r(r,t)/\Delta t$ depends only weakly on n_e or the heating power. Discharges with combined NBI and ECRH heating

show slightly larger values than with NBI alone for $\Delta E_r(r,t)/\Delta t$ because of the longer slowing time. Some results for $\Delta E_r(r,t)/\Delta t$ versus minor radius as a function of the PNBI accelerating voltage are shown on the left side in the figure 1, demonstrating the increase for larger voltages. The error bars result from the Monte Carlo procedure.
The effective toroidal magnetic field ripple is changed by a modification of the currents in

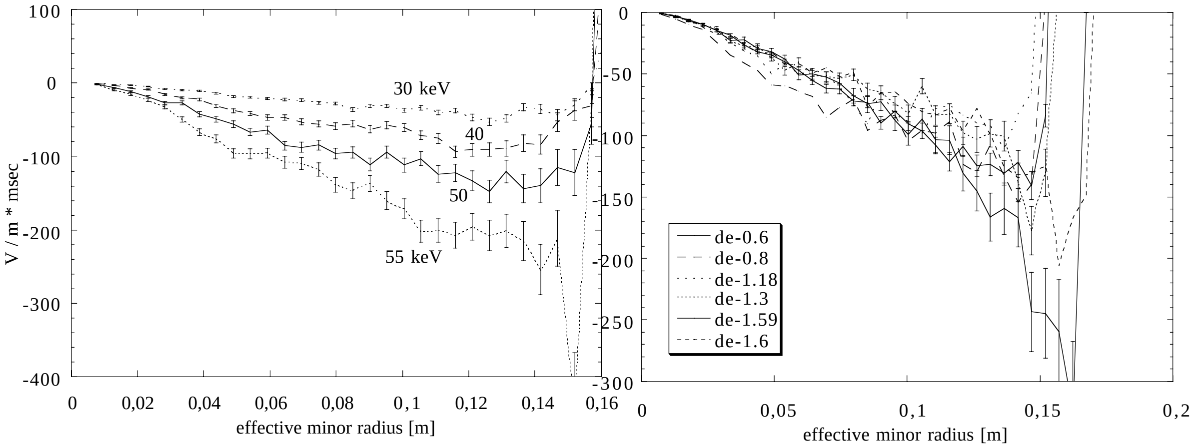

Figure 1: Radial profiles for the calculated values of $\Delta E_r(r,t)/\Delta t$.

the modular magnetic field coils of W7-AS. This provides either a magnetic field maximum (configuration de-1.6) or a minimum (de-0.6) at the location of the PNBI device, or values between. The results for those cases are shown in fig. 1 on the right side. The variation between all the results remains, however, small. For the case of the minimum configuration (de-0.6) very large ion loss fluxes are calculated because of the local ion trapping; however the mean B is rather small, resulting only in moderate $\Delta E_r(r,t)/\Delta t$. This is the consequence of the B^2 dependence in eq. (2): the application of the local minimum reduces also the mean B. For the case of the maximum the fast ions are trapped in the neighbouring minima and are also lost rapidly; but the reduction of the mean B is now slightly smaller than in the first case, resulting in slightly larger $\Delta E_r(r,t)/\Delta t$. Therefore experiments with the magnetic maximum configuration de-1.6, high n_e and combined NBI and ECRH are the most promising candidates for experiments with PNBI.
First experiments with the PNBI system show values of $\Delta E_r(r,t)/\Delta t$ which are well consistent to the calculated ones. Directly after switching PNBI on, an transient increase of E_r is observed comparable to the calculated one, which saturates however after ≈ 20 - 60 msec, thus resulting only in marginal net changes of $\Delta E_r \approx$ - 6000 V/m, despite longer PNBI injection times (up to 200 msec). The reason for that effect is still unknown. The improvement of the global energy confinement time τ_E is only marginal (≈ 5%), so far. The experiments are performed by applying a sequence of one PNBI pulse followed by one tangential NBI pulse of the same duration and roughly the same heating power, with

otherwise constant background plasma parameters. Thus, pure heating effects can be distinguished from driven ion loss effects. This is important, because pure heating without driven ion losses can affect the density and temperature profiles and therefore the ampipolarity condition for the thermal fluxes, thus also leading to an (undesired) change of E_r.

Figure 2 shows time traces of the measured E_r and T_i from passive spectroscopy for three effective minor radii during the PNBI pulse. During the tangential NBI phase, the change of E_r remains negligible. After switching the PNBI system on, E_r is enhanced from ≈ - 10000 V/m (right y-axis) to ≈ - 25000 V/m during about 100 msec, then the effect saturates. During the same time interval, all other plasma parameters experience only negligible changes, including the T_i values (left y-axis) indicating small heating effects by PNBI. The values shown here are the most pronounced observed so far with $\Delta E_r(r,t)/\Delta t$ ≈ - 300 V/m· msec. Despite the large net change of E_r ≈ - 15000 V/m, which is comparable to the ambipolar E_r , no considerable improvement of the global discharge properties are observed during these first experimental tests. Systematic variations of heating scenarios and magnetic configurations during PNBI will be performed in the near future to optimise the impact of the PNBI device.

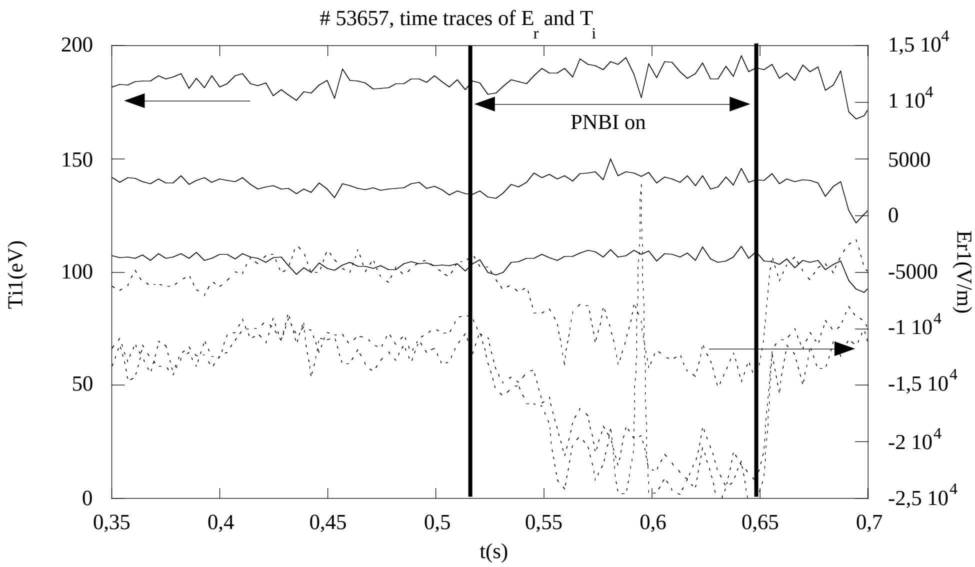

Fig. 2: Time traces of measured T_i (solid) and E_r (dotted) for r = 11.5; 12.7; 13.9 cm, respectively. The plasma minor radius is ≈ 15.5 cm.

[1] H. Maassberg et al, *Phys. Fluids* B **5** (1993), page 3627

[2] H. Biglari et al, *Phys. Fluids* B **2** (1990), page 1

[3] S. Spitzer *Physics of Fully Ionized Gases*, Interscience, (1962)
A. Boozer et al, *Phys. Fluids* **24** (1981), page 851

[4] D.E. Hastings et al, *Nucl. Fusion* **25** (1985), page 445