Understanding of the Fundamental Differences in JET and JT-60U AT Discharges
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ABSTRACT
Plasma current density simulations of JET and JT–60U shots in reverse–q advanced scenarios based on the previous data analysis of the identity plasma experiments have been performed. The effects of the main differences between the shots (neutral beam current density ($j_{\text{nbi}}$), electron density and geometry) have been studied. The reversed q–profile (which was the target in this identity experiment is observed at the beginning of each shot) was sustained in JT–60U while it became flat in JET towards the end of shot. In JET, $j_{\text{nbi}}$ is peaked on–axis whereas in JT–60U it is peaked off–axis (at $\rho = 0.5$) while NBI fraction of the selected shots is the same (22–24%). A strong density ITB appeared (at $\rho = 0.5$) in JT–60U but not in JET. The plasma geometry was mainly set to match but it was not identical. In addition, the extrapolation to JET steady–state operation has been done by testing the sensitivity of $q$ to different externally driven currents, electron density and geometry in predictive current diffusion simulations. Moreover, critical bootstrap current density has been analysed.

The reasons for the different time evolution of q–profile have been studied with predictive current simulations with the 1.5–dimensional transport code JETTO. The current diffusion model was validated against reverse–q shots, and simulations were performed with experimental data profiles, $j_{\text{nbi}}$ given by ASCOT and neoclassical resistivity and bootstrap current calculated by NCLASS.

Bootstrap current density was the most efficient way to sustain the beneficial reverse shape of q–profile. Replacing the JET $n_e$ profile with one from JT–60U leads to an increase of 0.2–0.3MA in the bootstrap current ($f_{\text{bs}}$ increases from 15% to 30%). However, sustaining the stationary reverse $q$ is not achieved in JET with bootstrap current induced by the density gradient of JT–60U. Even 10 times larger gradient than in JT–60U helps to sustain the shape of the q–profile longer than the experimentally observed density profile in JET but the minimum value of $q$ moves closer to central plasma and the shape of $q$ is not stationary in a 10–second simulation. The effect of different shape of NBI current density profile is negligible due to quite small fraction. Sustaining the reverse $q$ requires 45% or larger added off–axis fraction. However, increasing the inverse aspect ratio increases bootstrap current and decreases the critical bootstrap current more effectively than increasing the density gradient: two times larger inverse aspect ratio produces almost three times larger bootstrap fraction but ten times larger density gradient only two times larger bootstrap fraction. The conclusions based on these simulations indicate that the need of bootstrap current is larger in JET and the same conditions cause smaller bootstrap fraction, which suggests that achieving steady–state operation in JET under these conditions is unlikely.

1. INTRODUCTION
The advanced tokamak (AT) scenario (defined by high fusion efficiency with operation close to steady–state conditions [1]) is the most promising ways to achieve steady–state operation in the forthcoming fusion power plants. The goals for the ITER AT scenarios include the requirement for high beta and non–inductive current fraction (self–generated bootstrap fraction >50% and the rest replaced by external current) [2]. Strong pressure gradients are necessary to make better confinement
and higher non–inductive fraction by driving sufficiently large bootstrap current \[3\] linked to the transport barriers \[4\].

The most promising results in AT scenarios have been achieved in JT–60U in early 2000’s. In those experiments, high poloidal beta, bootstrap fraction and H factor exceeded the ITER target values \[5\]. In contrast, the fuel purity was the farthest from the ITER goal – only 2/3 of the target value \[6\]. Fuel purity and impurity accumulation will be problematic issues in developing of the AT scenarios with transport barriers. In addition, there are no studies on the AT scenarios foreseen during the first operational years of ITER \[7\]. However, AT scenarios can provide a feasible solution for steady–state operated fusion reactors and will be exploited in ITER in 2030s. \[8, 9\]

dentity plasma experiments were done in 2008 at JET and JT–60U to study different confinement properties and current profile time evolution in advanced tokamak scenarios \[10, 11\]. These experiments were the first experiments where the global plasma parameters and profiles were matched between two similar–size tokamaks in advanced scenarios (especially with reverse q and high bootstrap fraction).

Previous data analysis based on these experiments has been done and presented in \[11\]. From the experiments, one discharge from JET (Pulse No: 74740) and one discharge from JT–60U (Pulse No: 49469), which are the most comparable for the reverse–q–scenario simulations, were selected for more extensive analysis which is presented in this paper. Accurate comparison of experimental data between JET and JT–60U is important to find the major reasons for the most significant differences in the time evolution of plasma properties. The most important parameters are dimensionless ones, i.e. safety factor q, collisionality $\nu^*$, normalized Larmor radius $\rho^*$, beta $\beta$ and temperature ratio $T_i/T_e$ \[12\]. The aim of this data analysis and the following simulations is to find the cause for these differences and also to study the consequences of specific features, temperature and density gradients, external current and equilibrium.

In section 2, the motivating differences between the advanced discharges are analysed based on the previous publication \[11\]. Different behaviour in the time evolution of the electron density and plasma current density components was observed. Bootstrap current density is noticeably higher in JT–60U and bootstrap fraction nearly three times larger than in JET due to a density ITB. In addition, the reverse q was sustained in JT–60U throughout the discharge, but in JET it has been lost after three seconds.

Predictive current diffusion simulations have been performed with the 1.5–dimensional JETTO \[13\] code (part of the JET integrated transport code suite JINTRACK \[14\]) coupled with neoclassical effects (resistivity, bootstrap current density) given by NCLASS \[15\] and Monte–Carlo–based fast–particle following code ASCOT (NBI current density) \[16, 17\]. In section 3, the approach of the critical bootstrap current density \[18\] is connected with the analysis of the current diffusion simulations, and its utility and limitations in this analysis are discussed in subsequent sections. The validation of the JETTO simulation model with advanced and baseline shots is described in section 4, and the most interesting simulations cases, as well as the effect of the electron density
and neutral beam current density, are presented in section 5. In addition, extended analysis of a JET discharge with different density or temperature gradient scans and added externally driven current components is performed. In section 6, the results are clarified and the main reasons for the different time evolution of the plasma current concluded.

Identity experiments in JET and JT–60U with the reversed q;

Motivation the modelling work

The best agreement of the reverse q–profile (at the beginning of shots) in these identity experiments was detected between Pulse No: 74740 JET (bottom) and Pulse No: 49469 JT–60U (top) in the time interval which is presented in Figure 1. Hence, these shots have been selected for more extensive analysis. The durations of the high–power phase of the shots were 3.8 seconds for Pulse No: 74740 and 2.2 seconds for Pulse No: 49469.

Matching of the plasma parameters (presented in Figures 2 and 3), which was achieved in these identity experiments with the selected shots, was reasonably successful with most of the parameters. Ion temperature at $t = 3.5s$ in JET and $t = 2.0s$ in JT–60U was the same within 2keV, but in JT–60U a weak ion temperature ITB was forming. The electron temperature and q were similar within errorbars (based on experimental errors time averaged over 0.5–seconds in temperature and 10% errors weighted by radial position in q profile), and, and with acceptable 15% errors (differences outside the half radius were smaller than 10% and in the central plasma 15%). The Electron density profile was flat in both devices (same level but a little different pedestal which was assumed between different devices [19]). In JT–60U, the minimum of q and a density ITB are localised at the same position at , whereas in JET a strong density gradient at the same position could not be observed. Parameters sustained the matching with the exception of the q–profile (Figure 5a) and electron density (Figure 5b). Also beta (Figure 6d) was different in later phase, which is caused by the different electron density and the forming of the stronger ITB. Normalised Larmor radius is the same. In the maximum difference in the central plasma is approximately 25% and in 35% due to the weak ion temperature ITB. Beta, electron density, q and temperature profiles matched outside half radius. Maximum differences (inside the half radius) in temperature are 1keV. Density gradient in JT–60U in ITB region ($0.2<\rho<0.5$) is larger by a factor of 3 than in JET at beginning, but later it increases to even 10 times larger (Figure 4a). In JET, a density ITB is not formed, and the reverse–q shape was totally lost after 3 seconds.

The most significant differences between the shots of JET and JT–60U are the density gradient and the shape of the q–profile which were observed later in the flat top phase. The density gradient is presented in Figure 4a, where it can be noticed that a transport barrier is not observed in the density profile time evolution in JET. Instead, the shot Pulse No: 49469 in JT–60U has a rather strong density gradient at $\rho = 0.15–0.5$, which produces a considerable peak in the bootstrap current density profile. Consequently, the bootstrap fraction (presented in Figure 4b) in JET is less than 30%, whereas in JT–60U the fraction is even 80 % and as high as 40 % also in the later phase. These are significant contributions in the total plasma current and its time evolution, when neutral beam fraction and possible other externally induced current components are taken into account.
This denotes that achieving steady–state requires 50% more non–inductive current capacity.

Neutral beam fractions in both devices are approximately the same: in JET with the time–averaged NBI current density (given by ASCOT), the fraction is 22%, and for JT–60U 24%. On the contrary, the main difference between the NBI–current properties is the shape of the NBI current density profiles which are illustrated in Figure 7. The current component given by NBI is larger by a factor of 2 in JET inside the half radius. In JT–60U, the maximum values are located in the half–major–radius area instead of the central plasma at ρ = 0−0.2 which is the peak position in JET. This kind of a flat NBI alignment is possible in JT–60U due to the off–axis beams of the NBI system [10]. Commonly, it has been thought that a JT–60U–like profile is more favourable for steady–state operation because it advances to sustain a hollow current profile in the center of plasma. Approximately 50% of the total NBI current is localized inside of ρ = 0.4 in JET, but in JT–60U the same fraction was only 30%.

The plasma geometry was matched as well as possible, but the inverse aspect ratio is different in JET and JT–60U. That causes the effect especially outside of ρ> 0.5 (10% and at the boundary 15−20%) and leads to differences in the plasma equilibrium (magnetic and current flux functions ψ and F). The time evolution of diamagnetic flux function which is also named the current flux function F in tokamak physics basis and this text (presented in Figure 8) is connected to effect of the pressure gradient in producing of the bootstrap current and to a higher fraction of non–ohmic current. In addition, the most significant dissimilarities in the fixed parameter values of the selected shots (based on the identity experiments) were different inverse aspect ratio and plasma current (approximately 30% larger total current in JET) which affects the different ratio of current components, especially the amount of ohmic current, and larger critical bootstrap current. These differences were necessary due to matching q95 with different dimensions (JET R=3.3m, a=0.8m, JT–60U R=3.1m, a = 0.9m).

3. CRITICAL BOOTSRAP CURRENT DENSITY

The role of critical bootstrap current density in achieving stationary state is presented in publication [18]. In this section, the results with the critical bootstrap current density condition are analysed. Plasma current flux function F describes how the toroidal magnetic field (or poloidal current density) has been generated on the radial position. Current flux function is defined by formula

\[ F = -RB\varphi, \]  

(1)

where F is usually defined positive. As poloidal (magnetic) flux, also F is constant in the magnetic surface and connected to the plasma equilibrium properties by using Grad–Shafranov equation

\[ \frac{\partial}{\partial R} \left( \frac{1}{R} \frac{\partial \varphi}{\partial R} \right) + \frac{1}{R} \frac{\partial^2 \varphi}{\partial z^2} = \left( \mu_0 R \frac{\partial}{\partial \varphi} \varphi - F \frac{\partial F}{\partial \varphi} \right). \]  

(2)
which gives equations for poloidal and toroidal current density

\[ j_\theta = -\frac{dF B_\theta}{d\psi} \mu_0 \]
\[ j_\phi = R \frac{dp}{d\psi} - \frac{F}{\mu_0 R} \frac{dF}{d\psi} \]

(3)

(4)

Pressure gradient is also connected plasma equilibrium properties, stable flux functions and the condition of zero poloidal current density. Transition-like effect from a basic inductive Elmy H-mode to a non-inductive advanced scenario can be characterised by the following condition of flux function derivative respect to poloidal flux

\[ \frac{dF}{d\psi} = F' = \frac{\mu_0 R (-j_\phi + Rp')}{F} = 0 \]

(5)

which is equal to zero poloidal current density. More demonstrative form of the same effect is the following condition

\[ j_{bs}^{crit} = \frac{\varepsilon^2 \left( E_\phi \frac{1}{\eta} + j_{cd} \right)}{1 - \varepsilon^2} \leq j_{bs}, \]

(6)

where \( \varepsilon \) is the inverse aspect ratio, \( \eta \) neoclassical resistivity and \( E_\phi \) toroidal electric field (induced by ohmic plasma current). This form uses the approximation of bootstrap current density with total pressure gradient, which does not take into account the different contributions of temperature and density gradient. A rough approximation can be replaced with the better approach (here from NCLASS) in the deriving the equation of critical bootstrap current density. Now, the equation gets a form

\[ j_{bs}^{crit} = \frac{\xi \left( 1 - \frac{\xi}{j_{bs} - \xi} \right) \left( E_\phi \frac{1}{\eta} + j_{cd} \right)}{1 - \varepsilon^2 \left( 1 - \frac{\xi}{j_{bs} - \xi} \right)} \leq j_{bs}, \]

(7)

where \( \xi = j_{bs} - \varepsilon^{1/2} RP' \) which describes the error of a rough approximation or difference between analytic simple form and bootstrap current density given by neoclassical code.

The need for the critical bootstrap current is very sensitive for small variations in the temperature and density profiles, which can be seen in time derivatives of critical bootstrap current density condition. This has to be noticed when calculating the critical bootstrap current alignment and explaining the results. By doing these two rough approximations (cylindrical geometry and \( j_{bs} \sim \frac{dp}{d\psi} \)) a simple analytical condition for critical bootstrap current density could be derived. In this paper, the transition to the non-inductive state is studied with critical bootstrap density due to more intuitive understanding than in the case of zero (or negative) poloidal current density. Analysis of poloidal current density or defining diamagnetic current flux function requires a large accuracy from the
equilibrium calculation method, so the approximate view can be noticed when interpreting these results. On the other hand, description of the critical bootstrap current density includes two significant approximations whose impact is difficult to estimate. For this reason, one has to be careful when drawing conclusions based on the critical bootstrap current condition and take into account the estimated margin of error.

By checking the correction term, the lower limit of the error of the critical bootstrap current can be estimated, if the ideal accuracy of the calculated \( j_{bs} \) assumed. The analysis presented in this paper NCLASS has been used to define bootstrap current density. Comparison between NCLASS and approximate form (based on total pressure gradient \( \frac{dp}{d\psi} \)) is difficult due to accuracy of NCLASS and agreement with approximation is challenging to conclude in these cases. In the analysis of this paper, equation 7 is mainly used. The pressure gradient approximation (includes ion and electron pressure) is not valid if the bootstrap current is produced by a strong electron pressure gradient but the ion pressure gradient is rather large. Due to this reason, Equation 7 (includes the bootstrap current from NCLASS) has been used in the comparison.

4. JETTO CURRENT DIFFUSION MODEL, VALIDATION AND TESTING DIFFERENT OPTIONS

Current diffusion analysis [20, 21] is based on the solving of the toroidal current diffusion equation

\[
\frac{\partial j_\psi}{\partial t} = \nabla^2 \left( \eta \left( j_\psi - j_{bs} - j_{ext} \right) \right),
\]

in the simplified 1D–geometry in poloidal flux surfaces \( \psi \) which are defined in Grad–Shafranov equation (2). In addition, current diffusion modelling includes the solving of the plasma equilibrium, internal and external produced source terms (neoclassical bootstrap current and NBI current density) and neoclassical resistivity in this case. Theoretical or semi–empirical transport models for temperature and density have not been used but the experimental data profiles have been taken.

In the validation of the current diffusion model a set of experimental data profiles from several shots (reverse and monotonic q) was used. The validation and testing procedure includes the following cases:

1. comparing the equilibrium given by EFIT–MSE [22, 23] and ESCO in JET
2. comparing the NBI current densities given by ASCOT (time–dependent, time–averaged) and PENCIL [24] options in JET
3. validation of JETTO model with several different AT shots in JET [25]
4. validation of JETTO model with the AT shots from JET and JT–60U in identity experiments [11]

The role of the plasma equilibrium (defined by flux functions \( \psi \) and \( F \)) is not only to provide the geometry for the current diffusion solution, but \( F \) has also been used directly to define poloidal
current density. In addition, F has to be noticed in the analysis of the critical current density condition, which is based on the effect of pressure gradient on producing the bootstrap current density as described in Section 3.

In the validation, the ESCO equilibrium code was used to achieve the best comparability between JET and JT–60U current–diffusion simulations, since the possible need to calculate the flux functions \( F \) requires the same method of determination of the equilibrium. ESCO is the only applicable equilibrium code in JT–60U with JETTO simulations. In JET, ESCO equilibrium results were compared with the EFIT equilibrium in the MSE measurements which is the most reliable experimental–based safety factor \( q \) data which is available. Differences based on this comparison are not significant and ESCO equilibrium was close to MSE–EFIT.

Different options to define the NBI current density have been tested before the JETTO model validation, and, based on that, the time–averaged ASCOT NBI current density was used in the current density analysis. The biggest problem in using the ASCOT code, especially coupled to JETTO, is that it requires much additional data (for instance EFIT calculation) which is not generally available from all tokamaks. In addition, ASCOT is not suitable for quick analysis due to the time–consuming nature of Monte Carlo orbit following. Hence, it is needful to review other alternative NBI codes to take into account possible need in the future. Time–depended NBI current density data was not available from JT–60U case. Due to the better comparability, time–independent NBI current density profile was wanted to use in the both cases. The sensitivity of \( q \) profile due to different (time–depended and time–independent profile given by ASCOT, time–depended profile given by PENCIL) NBI current density has been tested. Differences in NBI current density and power deposition profiles were mainly smaller than 10% and this did not affect to the time evolution of current density.

Neoclassical resistivity and bootstrap current density have been defined by NCLASS (coupled to JETTO) which takes the experimental temperature and density profile as input. Estimated experimental error level of these quantities is mainly within 20% (maximum error in JT–60U electron temperature data, shown in Figures 2 and 5). Multiplying a temperature gradient by factor two, bootstrap current density increases 20%. In that case, the difference in \( q \)–profile is smaller than 10% in central plasma (\( \rho < 0.15 \)) and smaller than 0.5% at \( \rho > 0.5 \); within the modifications applied here the effects on the current diffusion are small so varying of temperature does not significantly affect current diffusion in these studies. 10%–change in bootstrap current density does not have any effect on \( q \)–profile time evolution (after three–second simulation the difference in bootstrap current density is smaller than 10% in the central plasma and smaller than 1% at \( \rho > 0.15 \)). Based on that, the results from NCLASS can be considered acceptable in this current diffusion analysis.

The validity of JETTO model was studied and the feasibility proved by running several predictive current diffusion simulations based on the data from different JET shots (mainly cases with the reverse \( q \)–profile). The following general validation parameters have been calculated and the representative subset of that is presented in Table 1.

The model offset for the \( q \) profile is defined by equation
\[ m_{q}^{off} = \left( \sum_{t=1}^{T} \frac{\sum_{j=1}^{X} \left( q_{\text{exp}}(x_j) - q_{\text{model}}(x_j) \right)}{X} \right) / T, \]

where \( T(t) \) is the length of time vector, \( X(j) \) is the length of the space vector, is \( q \)-profile from MSE and \( q \)-profile from JETTO.

The variance between experimental \( q \) and result given by JETTO is

\[ \Delta_{q}^{2} = \left( \sum_{t=1}^{T} \frac{\sum_{j=1}^{X} \left( \left( q_{\text{exp}}(x_j) - q_{\text{model}}(x_j) \right) / q_{\text{model}}(x_j) \right)^{2}}{X} \right) / T. \]

Generally, the largest differences between experimental (magnetic–MSE) and simulated values are located in the central plasma where the experimental error estimates are quite significant (20–50%). In low shear shots (magnetic shear \( \approx 0 \)) the problems to define the equilibrium and separatrix have been observed, which are indicated in large values of offset parameter and different scaling of initial \( q \)-profile (by using equilibrium from MSE–EFIT or ESCO). That problem is illustrated in Figure 9 and large values of the modelling offset parameter in Table 1 and it points that in low shear shots the agreement of the initial state (experimental and JETTO initial \( q \)) has to be checked before analysis.

The simulated \( q \)-profile is compared with the experimental one with estimated errors (the radially weighted statistical errors of 10%, presented for the first time in Section 2) are presented in Figure 10. With the time evolution of \( q \) in the model validation, it can be noticed that the agreement between the experimental data and the JETTO simulation model is quite reasonable: the largest deviations between the simulated and experimental values are observed at \( t = 6.0 \) s in JET and at \( t = 3.5 \) s in JT–60U in the reverse–\( q \) phase. Larger deviations from the estimated errors in the center of plasma can be considered acceptable, since the error bars including systematic errors in the \( q \)-profile are difficult to estimate due to the challenging measurement conditions, especially in the center of plasma.

5. CURRENT DENSITY SIMULATIONS BASED ON THE IDENTITY EXPERIMENTS: EFFECT OF DIFFERENT SOURCE TERMS

The main objective of the two following simulation cases was to compare and understand the reason for the different time evolution of the \( q \)-profile which is connected to generating ITBs and non–inductive current in steady–state scenarios. In these simulations, the same experimental data as in the validation was used (described in section 4) with 10–second extrapolated simulations (time interval in JET Pulse No: 74740 3.0–13.0 s and in JT–60U Pulse No: 49469 2.0–12.0 s) which are considered more extensively in Section 6.

Extrapolation to long simulations and different source terms (external current density, bootstrap current density driven by different electron density gradients) are used to increase the understanding
of the different behaviour of the plasma current density especially in JET. In this section, the effect of external and internal current density terms and, additionally, the sensitivity of q to different non–ohmic current fractions (induced by internal bootstrap with density ITB or external current drive) are analysed in JET AT discharges.

5.1 EFFECT OF NBI CURRENT DENSITY

Studying the impact of different NBI current density profiles has been implemented with simulation cases, where the NBI current density in JET was replaced with a corresponding profile from JT–60U and vice versa in JET. The results in the figures indicate that the shape of the profile did not have an influence on controlling the current density time evolution. Maximum differences with the reference case are 10% (at $\rho = 0.25–0.40$) which are smaller than the estimated errors in the experimentally defined $q$. As mentioned, the differences between the NBI current density profiles were sufficiently large only at $\rho < 0.5$, and the NBI current fraction was approximately same. Simulations with larger differences, for instance different NBI current fractions, could be implemented, but this way does not give answers for the different time evolution in these identity experiments with fixed properties (temperature, density, geometry).

5.2 BS AND ELECTRON DENSITY GRADIENT

Neoclassical self–generated bootstrap current density can be presented approximately by the equation [26]

$$ j_{bs} = -\sqrt{b} \frac{RB_0}{B_0} \left(2.44(T_e + T_v) \frac{dn_e}{d\psi} + 0.69n_e \frac{dT_e}{d\psi} - 0.42n_e \frac{dT_t}{d\psi}\right), $$

(11)

where $b = (B_{max} - B_{min})/(B_{max} + B_{min})$ and the most significant contribution is driven by electron density gradient. As mentioned before, the density gradient is the most important difference between the shots of JET and JT–60U AT shots. In the shot Pulse No: 49469 in JT–60U the contributions of different terms of pressure gradient are approximately $j_{bs}^{vne} \sim 5j_{bs}^{VT_e} \sim -10j_{bs}^{VT_t}$, which also shows that the role of a weak ion temperature ITB is negligible in this current diffusion case. In these sets of simulations which are described in this section, the effects of density gradient on the bootstrap fraction are analysed. By comparing the shots Pulse No: 74740 and Pulse No: 49469 to the following predictive current simulations, the most important role of electron density profile was established. This can be noted in a case where the electron density profile in JET was replaced with the profile from JT–60U (Pulse No: 49469 at $t = 4.0s$ with the largest density gradient at $\rho = 0.25–0.5$ described on red in Figure 12a) and in JT–60U with profile from JET (Pulse No: 74740 at $t = 3.5s$). The replaced electron density profiles which have been used in the simulations were constant in time and include the cases with the strongest (in JT–60U) and the smallest (in JET) gradients during the identity shots. The reference cases and other data which were used were the same as in the validation case in the previous section.
The time evolution of the $q$ profile has been studied with a 10.0–second simulation whose results have been presented in Figure 12 b–d. The reverse shape can be noticed for a few seconds longer than in the reference case, but the stable $q$–profile is flat. In the reference case, the reverse shape has disappeared at $t = 8.5s$, whereas with the replaced density profile it stayed until $t = 11.0s$. After 7.0 seconds’ simulation, differences between the simulated and reference cases are negligible.

The electron density profile in JET was quite stable, and the profile from time point $t = 6.0s$ was used for replacing the electron density profile in JT–60U at $t = 2.2s$. In the JT–60U simulation, the electron density profile was replaced at time point $t = 2.2s$, in which case the density transport barrier cannot be observed with the used data during the simulation. The $q$ profile gets a flat shape after a 5.0–second simulation, and the minimum value of $q$ located at the half–radius area cannot be observed which can be seen in the results in time evolution of $q$ in Figure 12 b–d.

Impact of the density gradient on bootstrap current varies between the tokamaks due to different inverse aspect ratio and required bootstrap fraction. In JT–60U, the same density gradient is more effective to increase the bootstrap current than in JET. In addition, the strong density gradients are not often observed in JET. This makes it challenging to create good conditions for steady–state operation, so in such case a larger fraction of the total current has to be produced with the external current drive methods. In JT–60U, the bootstrap fraction is 50% or larger at every time point (at least 1.5 times larger than in JET). This fraction does not appear to be achievable in all tokamaks, which can be also seen in the following simulation results when testing different electron density profiles and stronger gradients in the next section.

Interpretation of the steady–state properties is done by studying the critical bootstrap current condition. Bootstrap currents and critical bootstrap currents calculated by Equation 7 have been presented with the experimental cases in Figure 13. Satisfying of the critical bootstrap condition compared with the experimental cases shows that the same density gradient gives a larger effect on the bootstrap current, which can be seen in Table 2. The bootstrap fraction in JET with the replaced density profile is smaller by approximately a factor of two than in JT–60U, which means 0.13MA less bootstrap current in JET. Since the difference in temperature is minor, electron density is the most significant property in increasing the bootstrap current.

Another issue, which affects the bootstrap fraction and the critical bootstrap current, is the inverse aspect ratio, where the maximum local difference given by $\varepsilon$ is 15–18% ($j_{bs} \sim \varepsilon^{1/2}$). The results and bootstrap fractions in table 3 show that the critical bootstrap condition is satisfied only in JT–60U with these density profiles. The bootstrap fractions in JT–60U are larger than in JET with smaller electron density gradients, so it can be assumed that the same gradient produces a larger bootstrap fraction and better bootstrap alignment in JT–60U. These assumed and produced sufficient bootstrap fractions have also been discussed with studying bootstrap fractions when different electron density gradients.
6. EXTRAPOLATION TOWARDS JET STEADY–STATE OPERATION

6.1 EXTRAPOLATION WITH THE DIFFERENT EXTERNAL CURRENT COMPONENTS

6.1.1 Effect of different density gradients

A set of 10–second simulations which has been implemented using four different density gradient tests for shot Pulse No: 74740 in JET and comparing the different cases with each other and the reference case (same as in validation case in Section 4) are described. The same experimental data than in validation case was used with these simulations with the exception of replaced density profiles (three different density profiles and gradients are presented in Figure 14a). The experimental electron density profiles were replaced at t = 3.5s with different density gradient cases. Otherwise experimental data was used by input of these simulations (same than reference case which has been described before).

The equivalent predictive current density simulations are shown in Figure 14 b–d in which it can be seen that even very steep density gradients (the gradient in the case 1 is more than 10 times larger than experimental gradient in discharge Pulse No: 74740 at t = 3.5s) cannot sustain the reverse shape of the \(q\)–profile in JET for 10 seconds. Shifting the gradient to outer in radius (case 3) increases the non–inductive current fraction but the critical bootstrap current density is 50% larger than real bootstrap current density at \(\rho > 0.4\). In experimentally, the reverse shape of \(q\) sustains 3.0 seconds and with case the steepest gradient (blue, red) the reverse shape can be observed still after 5 seconds but the shape becomes flat before 7 seconds. In JT–60U lower density gradient can give rise to a larger bootstrap fraction and reverse shape of \(q\)–profile remained until 5.0 s at least which can be seen in experimental results (in simulations reverse shape is observed still after 15 seconds). Bootstrap fractions in JET with different density gradients have been presented in table 3 (smaller fraction than in JT–60U in every cases), so with these observations it can be noticed that any density gradient cannot sustain the reverse shape of \(q\)–profile and bootstrap current density remains below the critical bootstrap condition in every case since the produced bootstrap current is localized inside \(\rho = 0.5\), which is the same position with the density gradient.

6.1.2 Effect of external current

Generating the strong and stable density gradient on the half radius in JET is very challenging, so the residue of plasma current is replaced with the external methods. In JET, the high beta non–inductive scenarios can be realised with off–axis LH current drive [27, 28] but generally, ECCD is a potential method to produce sufficiently large and well–aligned off–axis current components. Due to nonlinearity, the impact of different (externally or internally generated) current components should be unequal, in which case, by increasing the fraction of the external current components, a beneficial result is not achieved. This can be seen also in generated bootstrap fractions in Table 4, where case 2 gives the largest fraction regardless of the same density and temperature gradient. For instance, bootstrap fraction is connected to temperature or density transport phenomena and different plasma profiles (gradients) which cause different confinement and equilibrium (see different flux functions in JET and JT–60U in Figure 7).
By this set of simulations, effects of several different added (on–axis and off–axis) current density profiles on the $q$–profile time evolution in JET have been studied. The experimental data of shot Pulse No: 74740 is used as input in these several current diffusion simulations (reference case without added current components in black dash line in Figures 15 and 16). The most significant observations of four different externally produced current densities which correspond to different current fractions (listed in Table 4 and current density profiles in Figures 15a and 16a) can be made. During the 7–second simulation, the reverse $q$–profile has remained only in high off–axis current in case 4 (Figure 11 d). In cases 1 and 2, reverse shape disappears after 5 seconds and the behaviour of the $q$–profile is approximately identical to the reference. With lower off–axis current in case 3, the reverse shape can be sustained for a few seconds longer than in the reference case (compared in Figure 15c and 16c), but here current fraction above 20% is required, and after 10 seconds the $q$–profile is flat also in this case. The fully non–inductive current has been achieved in cases 2 and 3 but the current alignment is not beneficial and critical bootstrap current density condition is not fulfilled.

The critical bootstrap current condition gives the same results as the cases with stronger density gradient. The bootstrap–current density remains below the critical bootstrap condition in every case. The critical bootstrap current density is 2 – 3 times larger than the obtained bootstrap current density which is not sufficiently large. The need for non–ohmic current is the largest at $\rho > 0.5$ but the non–ohmic components $j_{\text{abi}}$ and mostly added $j_{\text{ext}}$ of these simulations are localized closer to the centre of the plasma.

6.2. GEOMETRY

Plasma geometry is connected to confinement by the standard confinement scaling law. The effect of different values of triangularity, elongation and aspect ratio to normalised beta has been reported in [29]. In addition the geometrical features affect poloidal beta and non–inductive current fraction (presented in [18]). As it is seen in equation (4), the positive derivative of $F$ increases the effect of negative pressure gradient (or self–generated) term on the total toroidal current density. This dependence connects the plasma equilibrium (mainly characterised by flux functions $\psi$ and $F$) to the effect of the pressure gradient or ITB. The effect of a high (positive) pressure gradient is not sufficient if the flux function term repeals the contribution to the current density.

In this section, three sets of simulations with different equilibrium are presented: one set with different elongation (from 1.00 to 2.00), one set with different inverse aspect ratio (from 0.2 to 0.4) and one set with different triangularity (from 0.1 to 0.4). Plasma equilibrium can be changed by changing elongation (or ellipticity), triangularity and inverse aspect ratio, if the total plasma volume has been fixed to a constant value which retains the comparability of the current fractions. The dependence of varying the plasma geometry on the bootstrap current fraction is presented in Figure 17 and the profiles of bootstrap current density, critical bootstrap current density, bootstrap current and the flux function $F$ are presented in Figures 18–20.
Inverse aspect ratio affects directly the critical bootstrap current density (as seen in Equation 6 or 7). Also, the effect of a real bootstrap current density can be seen in the flux function (directly in Equation 11) or simply in the analytical approximation which is used to derive the condition of the critical current density. Other geometrical features, mainly elongation and triangularity affect the bootstrap current density through the flux functions. The effect of elongation is negligible on the bootstrap current density profile, fraction or the derivative of the flux function. Small variations at \( \rho = 0.3–0.9 \) can be seen in the critical bootstrap current density profile, but this does not have the effect on fulfilling the condition. Increasing the triangularity multiplies the bootstrap current density profile with a small factor, but it does not change the current alignment. Three times larger triangularity increases bootstrap current less than 0.01MA, and elongation does not have an effect on the flux function.

As expected, increasing the inverse aspect ratio affects generating bootstrap current the most. The inverse aspect ratio multiplied by a factor two (from 0.2 to 0.4) generates almost three times larger bootstrap fraction. Changing the inverse aspect ratio does not change the shape of the bootstrap current density profile, but it has a strong effect on the derivative of the flux function. These results show that changing the inverse aspect ratio is a more efficient way to increase the non-inductive current fraction than a strong density ITB. By using an almost 10 times larger density gradient, as large a bootstrap fraction as can be achieved in machines with a larger inverse aspect ratio cannot be generated. The simulated case with the largest inverse aspect ratio (0.4) is close to fulfilling the steady-state condition based on the critical bootstrap current density and closer to a JT–60U-like flux function (shown in Figure 7). Inverse aspect ratio (or plasma geometry in general) is a fundamental difference between JET and JT–60U, and it was not perfectly compensated in the identity experiments.

CONCLUSIONS

The results of identity plasma experiments between two same-sized tokamaks JET and JT–60U, have been analysed and compared. Current-diffusion modelling with the 1.5-dimensional transport code JETTO has been performed based on the experimental data. Differences in the time evolution of the current components and the q-profile have been studied and the approach of the critical bootstrap current has been applied to drawing conclusions on the steady-state properties.

Experimentally, the parameters in the identity shots Pulse No: 74740 (JET) and Pulse No: 49469 (JT–60U) were successfully matched in the initial state, but after a few seconds the time evolution of \( q \) and electron density \( n_e \) take a different trend. Notwithstanding the good matching of the dimensionless parameters and temperature profiles, the fractions for the ohmic current are different. In JT–60U the need for the ohmic current is considerably smaller, but in JET the ohmic current is the most significant component of the total plasma current.

The effects of the non-inductive current components have been studied by simulations where the NBI–current density profile or the electron density was replaced with different profiles. These...
results say that sustaining the reverse–shaped q is very difficult in JET; even an almost six times larger density gradient is not able to sustain it for longer than 5 seconds. In JT–60U, the reverse shape \( q_{MIN} \) is localized at \( 0.3 < \rho < 0.4 \) is kept for over a 15–second simulation with the experimental electron density profile, so it can be assumed that the reverse q is steady state.

The steady–state conditions with the critical bootstrap current density have been compared between the selected discharges. The need for the critical bootstrap current depends on the ohmic current density as shown in equation 6 where a time–independent \( j_{nbi} \) has been assumed. This shows that even small variations (small time variations which can be observed for example in the temperature profile or gradient) in the bootstrap–current density cause non–stationary behaviour of the need for bootstrap current. Hence, a completely stationary state can be achieved only by satisfying the condition of stationarity defined by the critical bootstrap–current density. This can be seen in the connection between the ohmic and the bootstrap–current time evolution. The need for the critical bootstrap current decreases during first few seconds whereas in JET it increases.

Probably, the most significant error source in the analysis of the critical bootstrap current density is the rough approximation of the bootstrap current which does not take into account the different contributions from electron and ion temperature or density gradients. The sign of the bootstrap current driven by ion temperature gradient is negative but the approximate form gives positive current and it cannot see different gains in the terms of the total pressure gradient either. The form with the correction term can give more reliable results if only a computing method with better accuracy is used to define the bootstrap current density profile. In this analysis, NCLASS code was used and its error sources were not clarified in these cases. Extended and more reliable analysis with the critical current density condition requires studying the cases by codes with better accuracy and different approach; kinetic neoclassical computing, for example. The differences between the approximate and corrected form of the critical current density condition varied from 1—2% to over 100% (noise–like effect only at few time points), averaging around 20%, but further studies are required to draw any quantitative conclusions based on the scale of errors.

The reasons which cause forming of the steep density gradient in JT–60U are not clearly clarified in the previous analysis [11]. The large density ITB has not been observed experimentally in JET with this kind of conditions, and on the basis of these simulations, steep density gradients in the region \( 0.25 < \rho < 0.6 \) would not help to sustain the reverse shape of q for longer than 5—10 seconds. Moreover, adding external current does not lead to fulfilling of the steady–state condition in these cases.

The role of the plasma geometry is significant to achieve the steady–state as shown in these studies. Changing geometrical features (elongation, triangularity, inverse aspect ratio) is more efficient way to increase the bootstrap fraction and decrease the level of critical bootstrap current density. Bootstrap current has a significant role in AT scenarios and in these studies the important impact of plasma geometry has been shown. Beneficial geometry (high inverse aspect ratio and triangularity) is more efficient way to increase the bootstrap current density than electron density...
ITBs. In JT–60U both, density ITB and favourable geometry have been obtained which affect the achieved bootstrap current and critical bootstrap current density profile and they are connected to the sustainability of the reverse $q$–profile.

The cause for the electron density peaking which was one of the most significant differences between discharges Pulse No: 74740 and Pulse No: 49469 was not clarified by this analysis. For this, predictive temperature and density simulations are required and will be the focus of further studies in future.

ACKNOWLEDGMENT
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REFERENCES

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Table 1: Parameters (offset, variance) from the comparison of the agreement of JETTO model and experimental q values in AT (reverse q, low shear) discharges.

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<td>16</td>
<td>33</td>
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<td>JT-60U</td>
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<td>80</td>
<td>7.7</td>
<td>27</td>
<td>-11</td>
<td>3.0</td>
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Table 2: Current fraction components in Pulse No: 74740 JET ($t = 6.0s$) and Pulse No: 49469 JT–60U ($t = 3.5s$) in normalised radius $\rho = 0.4$ and $\rho = 1.0$. 
<table>
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<th>bs fraction t = 10.0s</th>
<th>nbi fraction</th>
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<td>22</td>
<td>&lt;60</td>
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<tr>
<td>2 (cyan)</td>
<td>32</td>
<td>25</td>
<td>22</td>
<td>&lt;57</td>
</tr>
<tr>
<td>3 (red)</td>
<td>43</td>
<td>34</td>
<td>22</td>
<td>&lt;65</td>
</tr>
<tr>
<td>ref</td>
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<td>11</td>
<td>22</td>
<td>&lt;31</td>
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Table 3: Current fraction components in Pulse No: 74740 JET with different density gradients.

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<th>bs fraction t = 7.0s</th>
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<th>nbi fraction (time independent)</th>
<th>added external current fraction</th>
<th>non-inductive current fraction</th>
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<td>14.4</td>
<td>11.2</td>
<td>22</td>
<td>18</td>
<td>&lt; 64.1</td>
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<tr>
<td>2 (high on-axis)</td>
<td>24.1</td>
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<td>11.1</td>
<td>22</td>
<td>53</td>
<td>&lt; 99.1</td>
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<tr>
<td>3 (low off-axis)</td>
<td>24.1</td>
<td>15.4</td>
<td>11.8</td>
<td>22</td>
<td>24</td>
<td>&lt; 93.1</td>
</tr>
<tr>
<td>4 (high off-axis)</td>
<td>24.1</td>
<td>17.0</td>
<td>12.8</td>
<td>22</td>
<td>47</td>
<td>&lt; 70.1</td>
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Table 4: Current fractions in the sensitivity tests with different external current components.

Figure 1: The time window (red: total NBI power, black: plasma current) and the initial $q$ of the discharges JT–60U Pulse No: 49469 (top) JET Pulse No: 74740 (bottom). Time axis has been shifted such that the starting point at $t = 0s$ is the start of the current ramp up.
Figure 2: Safety factor (a), electron density (b) and temperature profiles (c,d) of Pulse No: 74740 (JET) at t = 3.5s (blue) and Pulse No: 49469 (JT–60U) at t = 2.0s (red).
Figure 3: Dimensionless parameters of Pulse No: 74740 (JET) at $t = 3.5s$ (blue) and Pulse No: 49469 (JT–60U) at $t = 2.0s$ (red): a) collisionality, b) normalized Larmor radius, c) temperature ratio, d) beta in the time point of the best agreement at the start of the current flat top phase.
Figure 4: Density gradient (a) and bootstrap fraction (b) in JET Pulse No: 74740 (blue) and JT–60U Pulse No: 49469 (red). Time point $t_0$ is defined to same as beginning point in Figure 1.

Figure 5: Safety factor (a), electron density (b) and temperature profiles (c,d) of Pulse No: 74740 (JET) at $t = 6.0s$ (blue) and Pulse No: 49469 (JT–60U) at $t = 3.5s$ (red).
Figure 6: Dimensionless parameters of Pulse No: 74740 (JET) at $t = 6.0s$ (blue) and Pulse No: 49469 (JT–60U) at $t = 3.5s$ (red): a) collisionality, b) normalized Larmor radius, c) temperature ratio, d) beta in the time point of the best agreement at the start of the current flat top phase.
Figure 7: NBI current density profile in JET Pulse No: 74740, JT–60U Pulse No: 49469 calculated by ASCOT.

Figure 8: Flux functions in JET and JT–60U.
Figure 9: Experimental (magnetic–MSE) and simulated (JETTO) $q$–profiles from JET Pulse No: 72836 and Pulse No: 74527 AT discharges.
Figure 10: Experimental (magnetic–MSE) and simulated (JETTO) $q$–profiles from JET Pulse No: 74740 and JT–60U Pulse No: 49469 reverse–$q$ AT discharges.
Figure 11: Simulation with replaced neutral beam current density profile in JET and JT–60U: a) used NBI profiles (constant in time blue JET, red JT–60U)b–d) q–profile time evolution. Dash: reference case in JT–60U, solid: NBI current density profile from JET/JT–60U.
Figure 12: Simulation with replaced electron density profile in JET and JT–60U: a) used electron density profiles (constant in time, blue JET, red JT–60U) b)–d) $q$–profile time evolution. Dash: reference case in JT–60U, solid: electron density profile from JET/JT–60U.
Figure 13: Bootstrap current density (solid line) and critical bootstrap current density (dashed line) in the experimental reference case (black) and in replaced electron density profile simulation: JET left side (black–blue), JT–60U right side (black–red).
Figure 14: Simulation with three different electron density gradients in JET: a) electron density at t = 3.5s b) $q$-profile in the initial state 3.0s c) $q$ profile at t = 7.0s d) $q$ profile at t = 10.0s.
Figure 15: $q$–profile time evolution (b–d) in predictive current diffusion simulation with added external on–axis current (a) density components in JET.
Figure 16: $q$-profile time evolution (b–d) in predictive current diffusion simulation with added external off-axis current (a) density components in JET.

Figure 17: Bootstrap fraction (a) and plasma boundary (b) with different geometric parameters (I elongation, II inverse aspect ratio, III triangularity).
Figure 18: Bootstrap current density (a), critical bootstrap current density (b), bootstrap current (c) and current flux function (d) with three different values (black 1.00, blue 1.60, cyan 2.00) of plasma elongation.
Figure 19: Bootstrap current density (a), critical bootstrap current density (b), bootstrap current (c) and current flux function (d) with three different inverse aspect ratios (black 0.20, blue 0.30, cyan 0.40).
Figure 20: Bootstrap current density (a), critical bootstrap current density (b), bootstrap current (c) and current flux function (d) with three different values (black 0.10, blue 0.30, cyan 0.40) of plasma triangularity.