Overview of High beta experiments on JET in preparation of JT60SA

F P Orsitto[1,3], L Garzotti [2], G Pucella[1], S Gabriellini[6], F Auriemma[7], M Baruzzo[1], A Burckhart[4], J Bernardo[5], N Hawkes[2], D Keeling[2], D King[2], J Mailloux[2], L Senni[3], V K Zotta[6], JET Contributors(*) and EUROfusion Tokamak Exploitation Team(**)
[1]ENEA Nuclear Department, Frascati, Italy,[2]UKAEA Culham Campus, Abingdon,UK,[3]CNR-IAC, Roma, Italy,[4]IPP,Garching,Germany,[5]IST,Lisboa,Portugal,[6]Universita di Roma La Sapienza, Italy, [7]Consorzio RFX and CNR ISTP, Padova,Italy , JET Contributors(*), and EUROfusion Tokamak Exploitation Team(**)

Corresponding author Email:Francesco.orsitto@consorziocreate.it ; fporsitto@gmail.com

1.Introduction

High beta discharges with normalized Larmor radius (ρ*), and normalized beta (β_N) relatively close to JT-60SA scenarios hybrid and advanced were realized in a new series of experiments on JET-ILW[1]. The strategy of these experiments was to explore high normalized beta (β_N) values, MHD effects at different B_T (Toroidal Magnetic field on axis) and find discharges with mild MHD. JET/JT-60SA 'similarity experiments' can be done with plasma parameters on JT-60SA, at BT/Ip=1.45T/1.4MA and heating power less than 10MW. Deuterium plasmas were realized in hybrid scenario at B_T = 1.7, 2, 2.4 T, Ip = 1.4 MA, elongation k = 1.7, triangularity $\delta \approx 0.4$, q95=4-6, and central safety factor q0>1 at NBI (Neutral Beam Injection) start, with NBI power P_{NBI} = 16-25 MW. The preliminary results of the JET high beta experiments were presented in [1]. Here an overview is presented on the following topics : i) confinement properties of high beta discharges versus input power and scaling of confinement improvement with beta; ii) dynamics of formation of the Internal Transport Barriers(ITB) while approaching high beta; iii) pedestal structure and its evolution at high beta ; iv) current profile evolution. It is found that the maximum normalized beta (β_N) obtainable, increases with input power and depends (decreases with) on the magnetic field . These effects are compatible with a small dependence of the confinement time on the input power. Looking into the electron kinetic spatial profiles , the progress toward the high beta is characterized by the formation of an ITB. The confinement dynamics can be related to the critical gradient scale length of the ITG turbulence, which depends on Ti/Te and magnetic shear. These discharges indicate that H98Y (the improvement confinement factor) has a linear dependence on the β_N, changing with the magnetic field.

2. Confinement properties of high beta discharges

It is interesting to analyze the dependences of the maximum β_N versus the P_{NBI} at different magnetic field . The Fig. 1 shows these behaviours . Inspecting the Fig.1 and comparing the slopes of the linear fits of β_N vs P_{NBI} a weak dependence on the magnetic field can be noted .

The linear dependence of β_N vs P_{NBI} for the BT=1.7T (Fig.1) is consistent with the result reported in ref.2,(see [2] Fig.28) corresponding to the medium gas injection (used also in experiments reported in this paper), and confirmed at BT=2.0T , and BT=2.4T. These results confirm the importance of the gas pressure on the confinement , presumably through the improvement of the pedestal confinement. The approximate linear dependence of β_N on P_{NBI} and a decrease with the magnetic field can be deduced also theoretically, under the hypothesis that the confinement time depends weakly on P_{NBI} and magnetic field. The definition of normalized beta , i.e. β_N is as follows:

$$\beta = \beta_N \frac{I_P}{a\,BT} = \frac{3nT}{BT^2 / 2\mu 0} \qquad (1)$$

Where n is the plasma density, T the plasma temperature , I_P the plasma current, BT the magnetic field and 'a' the torus minor radius. On the other side the definition of the confinement time (τE) is given by the following expresssion (where the plasma power loss is set equal to the external input power P_{NBI}) :

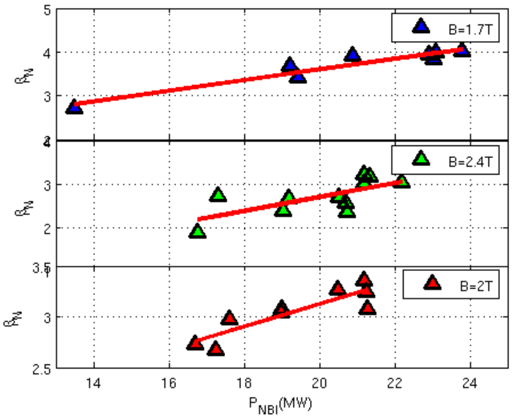
$$P_{loss} = \frac{n\,T\,V}{\tau_E} = P_{NBI} \qquad (2)$$

Merging together (1) and (2), we get : $$\beta_N \propto \frac{P_{NBI}\ \tau_E}{V} \frac{a}{I_P\,BT} \qquad (3)$$

At fixed plasma current and geometry the nomalized beta (eq.3) can be rewritten as follows:

$$\beta_N = \left(\frac{6\mu_0}{Ip}\frac{a}{V}\right)\left(\frac{P_{NBI}\ \tau_E}{BT}\right) \propto \left(\frac{P_{NBI}\ \tau_E}{BT}\right) \qquad (4)$$

where Ip is the plasma current in units of MA , V the plasma volume.
Therefore , the results shown in Fig.1 are consistent with the formula (4) , i.e. β_N proportional to P_{NBI} at fixed magnetic field, provided the confinement time has a small dependence on the P_{NBI} and magnetic field. It is interesting to plot β_N/P_{NBI} versus P_{NBI} to get some information on the residual dependence of confinement time on the input NBI power : the Fig.2 shows that for BT=1.7T, 2.0T and 2.4T, this residual dependence is very small: for example at BT=1.7T the slope of the linear fit is $3.6\ 10^{-3}$. Following the expression (4) the dependence of the confinement time versus the P_{NBI} can be evaluated: The parameter $BT^*\beta_N/P_{NBI}$ (which is proportional to the confinement time) and its linear fit versus P_{NBI} shows a weak dependence on the P_{NBI} power being the slope $3.4\ 10^{-3}$.



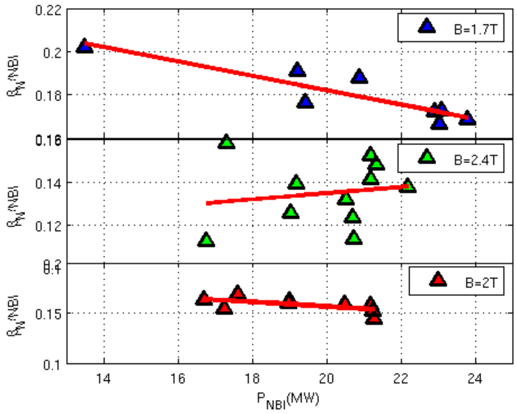


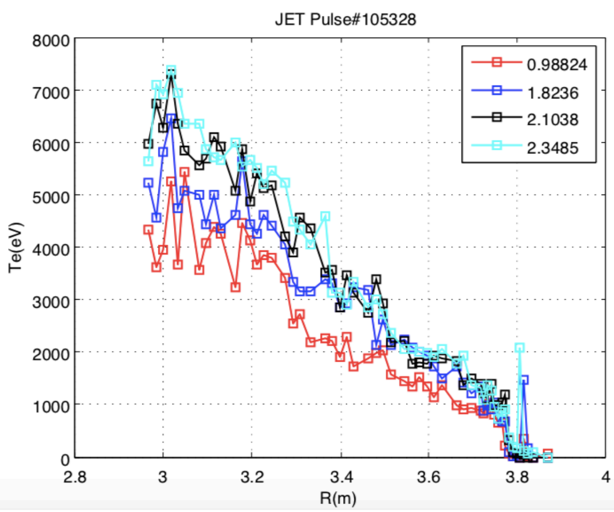
Fig.1. β_N vs P_{NBI} for BT=1.7T , 2.0T , 2.4T
(linear fits in red)

Fig.2 . β_N/P_{NBI} vs P_{NBI} (MW) for B=1.7T, 2.0T , 2.4T
(red lines linear fits)

Another aspect of this behaviour is the H98Y (the confinement improvement factor with respect to ITER Confinement Scaling) increasing with normalized beta.

3.Dynamics of kinetic profiles including pedestal.

It is interesting to observe the evolution of the temperature and density profiles (as measured by HRTS, High Resolution Thomson Scattering) while the high beta phase in a discharge is reached .



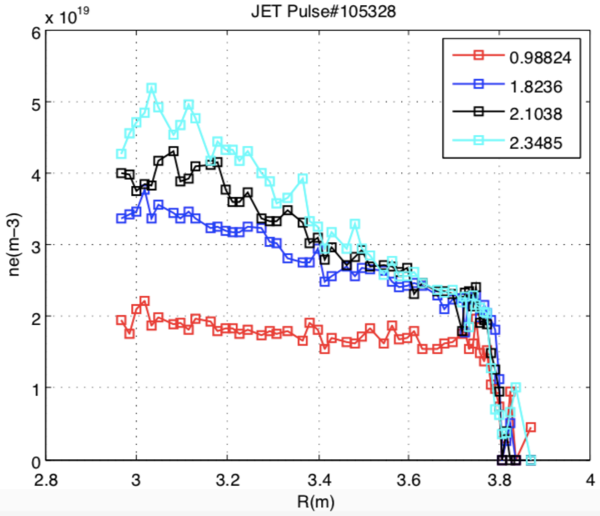


Fig.3. JPN105328 Formation of Te (R) ITB

Fig.4.JPN105328 formation of ne(R) ITB

The dynamics of formation of the ITB can be observed in Fig.3 which reports the Te spatial profiles versus the major radius at β_N =1.8,2.1,2.3 for JPN 105328 (BT/Ip= 2.4T/1.4MA) . The ITB is formed at β_N=2.34 in the radial position R=3.3m: once the pedestal reaches the maximum height (compatible with MHD stability the ITB is formed . This means that the improvement of confinement of bulk plasma is consequent to the establishment of the pedestal stability. As a consequence of ITB formation, a temperature peaking can be observed : Te(R=3)/Te(3.6)= 5/2 =2.5 (at β_N=1.8) increases to 7/2=3.5 (corresponding to β_N=2.34) , see Fig.3. The time evolution of the density profile is reported in Fig.4 : the change of density profile starts from the pedestal and the ITB forms at R≈3.4m. The density peaking appears as one of the consequences of the ITB formation : ne(R=3)/ne(R=3.6) increases from 3.5/2.5=1.4 to 5/2.5=2. The ion-ITB is formed as well : the ion temperature radial profiles (as measured by the CXRS, Charge Exchange Recombination Spectroscopy) for times when $\beta = \beta_{MAX}$, show that the formation of an ITB is done at R=3.4m.

4.Current profile evolution

The time evolution of the q_0 (the safety factor on axis) and β_N at the start and during the heating phase for JPN #103116 (BT=2.4T), shows that q0>1 while approaching the maximum beta. The q0 versus time was evaluated using EFIT constrained by polarimetry measurements (EFTF) and also by MSE polarimetry (EFTM , polarimetry channels in addition to MSE , motional Stark effect measurements) and $q_0>1$ for most of the discharge. The q-profile evolution was evaluated by EFTF for time close to β_{NMAX} where there is a change in the shear of q-profile at mid radius .

5.Conclusions

The confinement property of the high beta discharges show a linear dependence of the maximum beta obtained on the input power : this can be compatible with a weak dependence of the confinement time on the input power . This explains also the linear dependence of the H98Y (the confinement improvement factor) with normalized beta. The formation of an Internal Transport Barrier is part of the dynamics of the high beta phase. In high performances discharges the safety factor (as measured by EFIT constrained by polarimetry and MSE) at the plasma centre remains $q_0>1$ during the high beta phase. It must be noted that the similarity experiments enable the investigation of JT-60SA scenarios already in OP2 with limited auxiliary heating power.

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(*) See author list in C F Maggi et al., Nuclear Fusion 64(2024)112012

(**) See author list in E Joffrin et al , Nuclear Fusion 64(2024)112019

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