High beta experiments on JET in preparation of JT60SA

F P Orsitto[1], L Garzotti [2], G Pucella[1], S Gabriellini[6] , F Auriemma[7], M Baruzzo[1],A Burckhart[4], J Bernardo[5], C Challis[2],R Dumont[3], N Hawkes[2], D Keeling[2], D King[2], J Mailloux[2] , A Patel[2], C Piron[1], C Sozzi[8], V K Zotta[6], L Senni[9], JET Contributors(*) and EUROfusion Tokamak Exploitation Team(**)

[1]ENEA Dep. FSN, Frascati, Italy,[2]UKAEA Culham Campus, Abingdon,UK,[3]CEA Cadarache, France,[4]IPP,Garching, Germany,[5]IST,Lisboa, Portugal, [6]Universita di Roma La Sapienza, Italy, [7]Consorzio RFX and CNR ISTP, Padova,Italy , [8]CNR ISTP, Milano, Italy. [9] CNR-IAC, Roma, Italy. Email:Francesco.orsitto@enea.it

1.Introduction

High beta discharges with dimensionless parameters collisionality (ν^*) and normalized Larmor radius (ϱ^*), and also normalized beta (β_N) relatively close to the JT-60SA scenarios hybrid and advanced were realized on JET. In particular the JET poloidal Larmor radius $\varrho_P^*=0.036$ and bootstrap fraction $f_{BS}=0.6$ were close to JT60-SA values. So the discharges realized on JET are expected having similar confinement properties as in JT60SA[1]. Since the maximum normalized beta $\beta_N MAX \approx A^{-1/2}$, is dependent on the aspect ratio A, the equilibrium properties at high beta on JET (A=3.2) would be similar as in JT-60SA(A=2.7). Strategy of the experiments was to explore high normalized beta (β_N) values, MHD effects at different BT (Toroidal Magnetic field on axis) and find an optimal set of parameters for discharges with mild MHD. Deuterium plasmas were realized in a **variant of the hybrid-advanced scenario** at BT = 1.7, 2, 2.4 T, Ip = 1.4 MA, elongation k = 1.6, and high triangularity $\delta \approx 0.4$, q95=4-6, and central safety factor q0>1.2 at NBI (Neutral Beam Injection) start, with NBI power P_{NBI} = 16-25 MW, no ICRH (Ion Cyclotron Resonant Heating). Shots at BT=2.4T were realized in third Deuterium-Tritium (DTE3) campaign. The deuterium dataset is new: the pulses at BT=1.7/Ip=1.4MA have the same charateristics of 2014 Hybrid power scan at high δ[2], but there is an extension in the range of NBI power to P_{NBI} =25MW. While pulses at BT=2.4T are executed at higher q95 (q95>5) with respect to the yr 2014 advanced pulses[3]. Two scans were carried out : i) a NBI power scan, affecting

β_N and ii) a NBI start time scan, affecting the central safety factor q0 at the time of NBI onset, which is a key ingredient for MHD stability of the high beta phase. Main results of the experiments are: i) Good confinement properties and relatively high β_N values; the normalized beta achievable increases with input power, $\beta_N \approx 3.7\text{-}4$ for BT/Ip=1.7T/1.4MA(JPN 102422) ; ii) Good control of q0 at the beginning of the main heating phase with NBI starting time t0_NBI depending on the toroidal magnetic field value, as investigated in JET hybrid[2] and advanced scenarios; iii) Maximum $\beta_N \approx 2.5\text{-}2.7$ with relatively mild/stable MHD in the hybrid-advanced scenario at BT = 2.4 T and q0 > 1 (pulse#103116 and 103117). Preliminary transport analysis has been done using Bohm-gyroBohm , QuaLiKiz , CDBM. The measured ion and electron temperature profiles and neutron fluxes are reproduced by CDBM code at all the magnetic fields. The paper is organized as follows : in sec.2 the experiment is described and the usefulness of the JET experiment for preparing the high beta scenarios in JT-60SA is discussed ; in sec.3 The main experimental results are presented : i) the max β_N versus the NBI heating power ii) the MHD characteristics ; iii) the confinement improvement factor and the plasma energy content versus β_N ; in sec .4 the conclusions are drawn.

2.JET experiment and similarity with JT-60SA

The 'similarity' principle states that tokamak plasmas are equivalent from the point of view of confinement if they share the same values of the dimensionless parameters (β, ϱ^*, ν^*, q) [1]. From the point of view of confinement, in 'similar' Tokamak plasmas the plasma parameters are linked by the following scalings (A = aspect ratio, R = major radius, M = main ion mass, B = magnetic field on axis, Ip = plasma current [1]) see Table I .

$n=M R^{-2} A^{2}$
$T=M^{1/2} R^{-1/2} A^{7/4}$
$Ip=M^{3/4} R^{-1/4} A^{-1/8}$
$B=M^{3/4} R^{-5/4} A^{15/8}$

Table I

In case of similarity of JT-60SA/JET (which share the same major radius, and at a fixed ion mass) the magnetic field and current of similar discharges is depending on the aspect ratio following the scaling: $B \approx A^{15/8}$ and $Ip \approx A^{-1/8}$. This means that to get similar discharges (between JET (A = 3.2) and JT-60SA (A = 2.7)) we must choose the magnetic field B and the current Ip as follows: B_JET/B_SA = $(\text{A\_JET}/\text{A\_SA})^{15/8}$ = 1.37;Ip_JET/Ip_SA =$(\text{A\_JET}/\text{A\_SA})^{-1/8}$ = 1.02. The present JET experiment at (BT/Ip) = (2.4T/1.4MA) can be used for studying the confinement (and the MHD stability) of the JT-

60SA experiments at (BT/Ip) = (1.7T/1.4MA), auxiliary heating power PAUX_JT-60SA<≈10MW. JET experiments are useful to give the basis for the high beta experiments on JT-60SA at low power , for the study of current drive optimization and transport model validation. A comparison between the dimensionless parameters of JT-60SA high beta scenario 5-1 [4] and reference discharges of JET experiments (see Table II and [4]) shows a reasonable agreement .

3. Results of JET experiments

Table II	ϱ*Poloidal X100	ν* X100
SA#5-1	3.9	1.2
JET B=2.4T 103117(@45.7s)	3.7	1.7
JET B=2T 102706(@45.4s)	3.4	1.3
JET B=1.7T 102442(@44.6s)	3.6	1.98

The main traces of the plasma parameters of a reference discharge #103117 (B=2.4T) are given in fig.1: from top Neutral Beam power and radiation , β_N, plasma diamagnetic energy, electron/ion maximum (TeMax) temperature and Ti , ne central density , neutron flux. The dependence of maximum β_N (β_NMAX evaluated by EFIT equilibrium) on the NBI power is given in fig.2 : β_NMAX increases with the injected power.

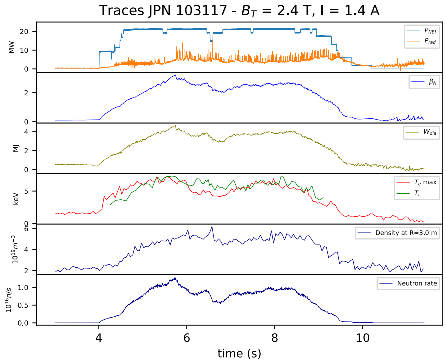

Fig .1 .Plasma parameters of the JET #103117

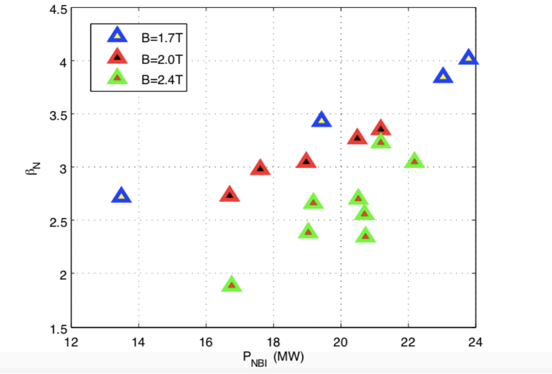

Fig.2 . Max β_N . vs NBI Power (MW)

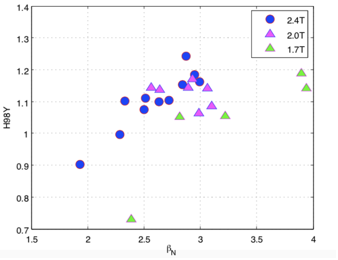

Fig.3 H98Y vs β_N

Moving to the confinement properties of the reference discharges the fig.3 shows the H98Y confinement improvement (with respect to the ITER scaling, see the Nuc Fus Ref in [4]) vs the β_N : H98Y =1.25 at BT=2.4T is evaluated. The confinement properties of the high beta discharges can be described also by the dependence of the energy content upon the NBI power and ϱ* toroidal. Fig.4 shows the energy content has an improvement as P_{NBI} is increased. Fig.5

shows the energy content (W_{DIA}) has a dependence upon the ϱ*toroidal close to linear.

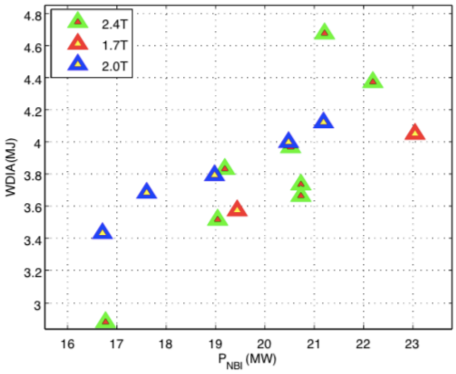

Fig.4 WDIA vs PNBI

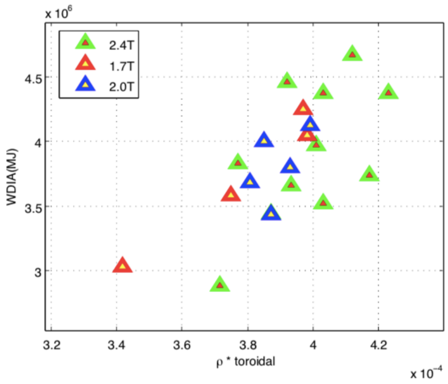

Fig.5 WDIA vs ϱ* toroidal

The MHD behaviour of the discharges is linked to a critical β for the onset of the m=3/n=2 NTM (Neoclassical Tearing Mode) around P_{NBI}=20MW. As the current profile evolves the m=2/n=1 mode can be destabilized. Pulses with lower power showed no strong MHD modes.

4. Conclusions

Deuterium plasmas were realized in hybrid-advanced scenario at BT = 1.7, 2, 2.4 T, Ip = 1.4 MA, elongation k = 1.6, triangularity δ ≈ 0.4, q95=4-6, and centre safety factor q0>1.2 at NBI start, power PNBI = 16-25 MW. Pulses at BT=2.4T were realized in third Deuterium-Tritium (DTE3) campaign. JET pulses at BT/Ip=2.4T/1.4MA are ‘similar’[1] to JT-60SA scenario 5-1 with BT/Ip=1.66T/1.44MA, and auxiliary power PAUX_JT-60SA< ≈10MW. Maximum normalized β≥2.5 with relatively mild/stable MHD at BT = 2.4 T and q0 > 1 (pulse#103116). Transport analysis and modelling is in progress and will be presented in the future.

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References

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[3] J Mailloux et al , 43rd EPS Berlin 2014 , paper O4.127

[4] JT-60SA Research Plan Version 4.0,yr 2018 , Table 1-3. The definitions of ρ* and ν* are in Chapter 5 p 75. In the definition of ν* : i) the q used is the cylindrical safety factor as defined in Nuc Fusion 39(1999) 2203; ii) ne density and Te used are from JET High Resolution Thomson Scattering. The evaluation of <Ti> for ρ* is carried out using the CXRS measurement of Ti radial profile fitted with a formula $Ti=Ti0*(1-(r/a)^{0.5})$, where Ti0 is taken as the average of TiCXRS(@R=3.11m) and the value measured by the X-ray crystal spectroscopy.