Physics driven scaling laws for fusion reactors

F P Orsitto[1], M Romanelli [2], Vinay Menon[3]

[1] *ENEA Fusion and Nuclear Safety Department , 00044Frascati, Italy*

[2] *TOKAMAK Energy Ltd., 173 Brook Drive, Milton Park, Oxfordshire, OX14 4SD, UK*

[3] *Institute for Plasma Research, Gandinaghar, Gujarat, India*

1.Introduction

The scaling laws for tokamak non-burning plasmas are obtained using the Kadomtsev[1] similarity scheme, where the alpha particle heating and atomic physics effects are neglected and the confinement is depending only from the dimensionless set of parameters (q,ϱ*T,ν*,βT), safety factor, normalized Larmor radius, collisionality and toroidal beta [see refs. 8,10]. Since the alpha particles heating is relevant in fusion reactor burning plasmas, the Kadomtsev scheme is NOT valid[2,3]. In this paper New scaling laws for 'similar devices' linking the fusion gain factor Q, the major radius R, the magnetic field B and aspect ratio A (ratio of major radius R and minor radius a of a tokamak A= R/a) , are obtained for fusion reactors operating in H-mode. In this context, the conditions are also analyzed where the reactor gain factor Q is held fixed, and the alpha power (Palpha) of the same order of the plasma radiation (Pradiation , Bremsstrahlung and synchrotron radiation), while the net power (Palpha –Pradiation) is still higher than the power threshold for the transition to H-mode. This scheme is considered the basis for DEMO operation[7]. Sets of parameters can be obtained to determine reactor plasma scaling laws, when high magnetic field compact machines are considered[2]: for these devices small space is left for heating systems, so low power heating systems are envisaged. On these conditions the ohmic or L-mode plasma operation with pellet is studied. The energy confinement time used for these devices is the so-called SOC (saturated ohmic confinement) or L-mode scaling[4]. The paper is organized as follows : in sec.2 the physics plasma conditions at the basis of the scaling laws are summarized ; in sec.3 the scaling laws corresponding to the physics conditions are reported and examples of device parameters are derived from the scaling laws ; in sec.4 the conclusions and future work are presented.

2.Physics Conditions.

We can consider the following sets of conditions :

I.Q= Q0 fixed , τSD.~ΛSD τE (ΛSD<=1) , Pα=Λth PLH (Λth>~1.5)

where τE is the confinement time, τSD alpha slowing down time, Pα alpha power, PLH the L-H threshold power and Λ numbers, Q fusion gain factor . The plasma is heated by alpha particles , in time scales less than the energy confinement time, and the alpha power is enough to bring the plasma into the H-mode.

II.Q=Q0 fixed , Pα ~Prad plasma radiation power(bremsstrahlung + impurity seeding line radiation) , and (Pα -Prad)>Λth PLH (Λth>~1.5). The plasma is impurity seeded (by Xenon for example) to radiate most of the power , the net power is still enough to keep the plasma into the H-mode.

III.Q=Q0 fixed , τSD.~ΛSD τE (ΛSD<=1) , Pα=Λth PLH (Λth<1) L-mode. The plasma is heated by alpha particles , but it is working into the L-mode confinement. This scenario could be typical of high field plasmas with pellet injection where an improved L-mode characterizes the plasma behaviour.

3.Scaling laws for Fusion reactors.

3.1.First set:Fusion Reactor H-mode

The scaling law for the first set of conditions is represented by the scaling parameter :

$$S_{FR} = R\ B^{4/3}\ A^{-1}\ Q_0^{1/3}$$

Similar fusion reactors have the same scaling parameter. In Fig.1 major radius vs aspect ratio is given for similar devices taking as reference JET pulse# 42976 DT high performance at gain factor Q0=0.56 [see ref.5 , Tables 1 and 2]. From Fig.1 a Q0=0.55 device with major radius R=1.5m and A=3 will have a magnetic field B=5.5T , while a ‘similar device’ at low aspect ratio A=1.7 will have a magnetic field B= 3.6T and major radius R=1.6m.

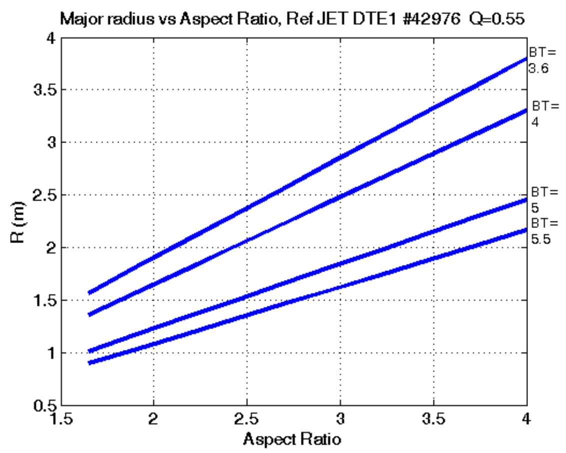

Fig.1 Major Radius vs Aspect ratio for similar devices

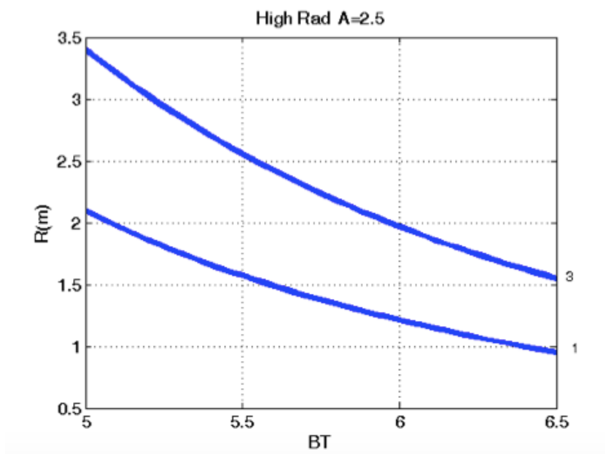

Fig.2 Major radius vs BT (magnetic field on axis) for Tokamak parameters at fusion gains Q0=1 and 3 ,

The scaling parameter S_{FR} is obtained taking into account that the ITER IPBy2 scaling law[8] is used for the confinement time and the Martin scaling for the L-H power threshold[9].

3.2.Second set:High radiation

The scaling law for the second set of conditions is represented by the scaling parameter :

$$S_{HR} = R\ B^{3} A^{-2}\ Q_0^{-3/5}$$

This scaling law has been obtained supposing (in addition to the point II sec.2) that the scaling is done at fixed beta , and taking the functional form of the emitted radiation a bremsstrahlung like formula in terms of dependence on the plasma density and temperature. In Fig.2 a plot of the dependence of the major radius versus the magnetic field is given for the values of the gain factors Q0=1 and 3, the plot is done taking as reference the parameters for ITER scenario at Q=10, and device aspect ratio A=2.5. For example a Q0=1 machine with major radius R=1.5m can have a magnetic field on axis BT=5.5T.

3.3.Third set :SOC/L-mode

The scaling law for the third set of conditions is represented by the scaling parameter :

$$S_{FR-L} = R\ B^{3/2}\ A^{-3/4}\ Q_0^{-3/4}$$

Parameters	Value
H_{97}	1.2
A	2.5
Q0	1
R_0 (m)	1.66
a (m)	0.66
Kappa	1.8
I_p (MA)	7.26
B_T (T)	8.0
Pfus (MW)	8.0
n_{avg} (10^{20})	1.43
$\langle T_e \rangle$	3.9
tauE (s)	0.56

Table I Plasma parameters evaluated by SPECTRE system code

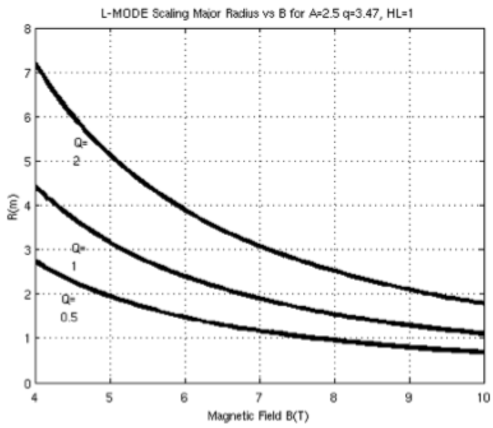

Fig.3 Major radius vs the magnetic field on axis, for Gain factors Q0=0.5,1 and 2 , at Aspect ratio A=2.5, qcyl=3.47.

The Fig.3 shows a plot of the major radius versus the magnetic field on axis at gain factors Q0=0.5,1,2, for aspect ratio A=2.5 and q_{cyl}=3.47, corresponding to the family of tokamaks having the scaling factor S_{FR-L}. and following the L-mode ITER 97P confinement scaling[8].

In the figure the parameter HL=1 is the value of improvement confinement factor over the L-mode scaling. Following this scaling parameters of devices working at high magnetic field can have the following parameters : i) Q0=1 , R=1.5m , BT=8T; ii) Q0=2 , R=2.5m , BT=8T. To check the validity of the scalings, the SPECTRE [6] code was used to generate a self consistent design for the Q=1 device , working at B=8T, consistent with Pfus=8MW. Table 1 shows the plasma parameters of such a device where a neutron yield of the order of 10^{18}n/s is reported.

4.Conclusions and future work.

The paper presents scaling laws for fusion reactors working in a variety of operational scenarios like H-mode , H-mode with high radiation and L-mode High field (BT=8T) with pellet injection. Following the scaling laws, relatively compact, low gain factor machine device parameters are derived as examples . The calculations presented are based on physics conditions defined in sec.2. The engineering constraints, like the effects on the radial build of the machine due to the shieldings needed to protect the central solenoid, are not taken into account at the present stage and will be examined in a subsequent phase of the work.

Acknowledgements-The EPS Organizing Committee is warmly acknowledged for the support given for the participation to the conference of one of the authors (FPO).

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