Plasma Parameters of Compact Fusion Reactors using Similarity Scaling Laws of Spherical Tokamak Fusion Plasmas

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1.Introduction

Spherical tokamaks (ST) represent an attractive alternative to large aspect ratio tokamaks as they may provide a faster, more economical and compact solution on the path to a fusion reactor. Plasma studies carried out so far on compact, low aspect ratio tokamaks have been limited to small, low/ medium magnetic field and low plasma current therefore the information available for extrapolating to large scale ST plasmas are limited. The scaling law recently obtained [1] links the major radius (R_{ST}) to the fusion gain factor (Q_0) , the magnetic field on axis (B) , the aspect ratio (A), the isotopic mass (M) and the cylindrical safety factor (q):

$$R_{ST}=C_{ST}\,H_{ST}^{-1/2.23}\,Q_0^{0.46}\,B^{-1.13}\,A^{1.59}\,M^{0.22}\,q^{0.4} \qquad (1)$$

(where C_{ST} is a dimensional constant and H_{ST} is the confinement improvement factor with reference to the ST confinement scaling law) and it allows for the plasma design of compact spherical neutron sources with higher magnetic field compatible with the use of high temperature superconductors. A feature of the scaling for fusion-reactor plasmas is a stronger dependence on the magnetic field and aspect ratio than the one for ordinary sub-ignited plasmas[1]. The parameters of a spherical tokamak producing the same fusion gain Q (=10) of ITER under different confinement assumptions and for different aspect ratios are presented and discussed. An example of parameters of a Q=10 , ST device deduced using the previous scaling and the NSTX [2] confinement time scaling is : R=2.2m, A=1.8, B=4.0T, plasma current Ip=6.2MA, fusion power P_{fus}=26MW, auxiliary heating power P_{AUX}=2MW, confinement improvement factor with respect to the ITER IPBy2 confinement time scaling H_{ST} =1.8, qcyl=1.99. In addition, scaling laws for spherical tokamaks related to TFTR supershots and JET hot-ion scenarios are derived and discussed in the context of the operation of compact neutron fusion sources. The paper is organized as follows : in sec.2 the scaling laws for spherical tokamak (ST) fusion reactors are briefly recalled ; in sec.3 the plasma parameters of a ST with a fusion gain factor Q=10 are derived; in sec.4 the scaling laws for non-thermal plasmas are extrapolated from TFTR supershot confinement scaling law, and compared with the ST40 database of 'supershot-like' plasmas, the plasma parameters of a ST operating in this regime are derived and discussed; in sec.4 the conclusions are presented .

2.Scaling laws for spherical tokamak (ST) fusion reactors.

The following set of conditions can be considered as basis for a burning plasma similarity [1] :1.$Q=Q_0$ fixed ;2.$\tau_{SD} = \Lambda_{SD}\ \tau_E$.($\Lambda_{SD}$<<1) (slowing down time of alpha particles << energy confinement time) ; 3.$P_\alpha = \Lambda_{LH}\ P_{LH}$ (Λ_{LH} >1.5) the alpha heating is sufficient to keep the plasma in H-mode, τ_{SD} is the slowing down time of alpha particles, τ_E is the confinement time, P_{LH} the minimum heating power necessary to enter the H-mode (high confinement mode) , Q_0, Λ_{SD} , Λ_{LH} constants. The above set of conditions define a reactor plasma working in H-mode , with triple-product Q0, dominant alpha heating and alpha power above the L-H transition power threshold to sustain the high confinement mode. The previous set of conditions for a burning plasma need the specification of a confinement time scaling law, which for the case of spherical tokamak is the NSTX-improved scaling[2]. The previous set of conditions with the NSTX-improved scaling leeds to the scaling (1). The fig.1 shows the major radius vs the magnetic field of a fusion reactor with aspect ratio A=1.8, and fusion gain factor Q=1-10, with H_{ST}=1 and 1.8.

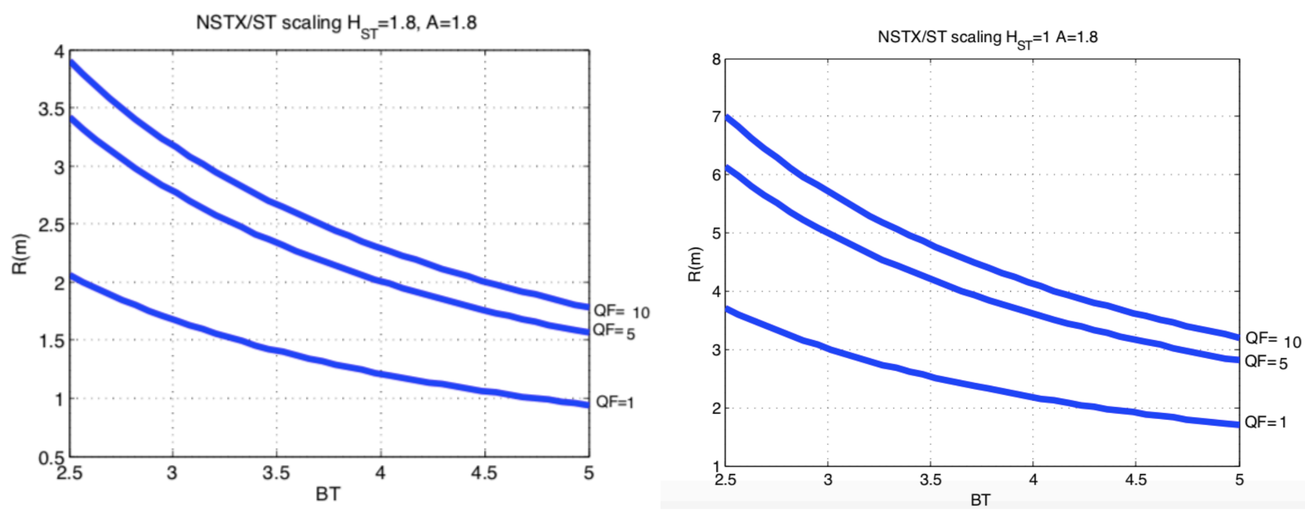

Fig.1.Major radius(m) vs magnetic field on axis B(T) For a spherical tokamak with NSTX confinement scaling : left H_{ST}=1.8 , right H_{ST}=1.

3. The plasma parameters of a ST with a fusion gain factor Q=10.

The figure 1 is evaluated using the scaling law(1) where the values H_{ST}=1.8 (left fig.) and 1. (right fig.) , and aspect ratio A=1.8 are used. The value of HST=1.8 is compatible with the results reported in [3], where NSTX confinement times are reported (see ref 3, fig.3a). The scaling obtained for a device similar to ITER Q=10 is : the plasma parameters are R=2.2 m, a=1.22m , B=4.0 T, qcyl=1.99 , elongation k=1.75 plasma current Ip=6.2 MA, n=1.3 $10^{20} m^{-3}$, n/nG=0.8 (Greenwald fraction, nG=Ip/π a^2) , fusion power Pfus=30MW.

4.The scaling laws for non-thermal plasmas extrapolated from TFTR supershot.

The scaling law of confinement time in TFTR supershots (τ_{TFTR}) was given in [4]:

$$\tau_{TFTR} \propto Ip^{0.22}\, Bt\ Wbeam^{-0.56} \qquad (2)$$

Where Ip is the plasma current , Bt the magnetic field on axis and Wbeam the energy of the heating neutral beam, additional dependence on the density peaking (not shown in (2)) was also reported. An extension of the scaling laws (2) to arbitrary geometry is proposed in the following form:

$$\tau_{TFTR} \propto Ip^{0.22}\, Bt\ Wbeam^{-0.56}\, R^{1.83}\ A^{0.06}\ k^{0.64} \left(\frac{n}{\langle n\rangle}\right)^{1.5} n^{0.4} \qquad (3)$$

Where the geometry (major radius R, eelongation k , aspect ratio A) , density dependence (n) and peaking (n/<n>) are added. The fig.2 report a plot of the measured confinement time on ST40[5] versus the scaling (3) : consistency of the scaling (3) with experimental data of ST40 is shown.

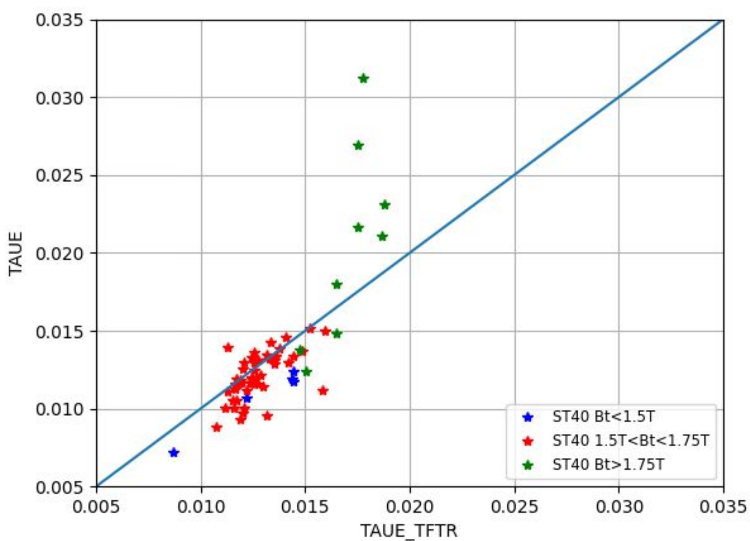

Fig.2 Measured confinement time on ST40 vs the TFTR scaling(3)
At various magnetic fields. Beam energy 35 keV and constant peaking factor 3.5 across all discharges, proportionality factor 0.024. Density variation within a factor 2. Current varies from 0.48MA to 0.54MA;

Now the possibility of using the TFTR scaling (3) to project the plasma parameters of a ST fusion reactor operating in the supershot scenario can be tested , using the method already applied in sec.2.

The fig.3 shows the results of the calculations of major radius versus the magnetic field to fusion gain factors Q=0.5-10, for devices working at a plasma current of Ip=7MA , with heating beam of energy W=80keV , density peaking n/<n>=3.5 . electron density n=10 $10^{19}m^{-3}$. Elongation K=2.8 , aspect ratio A=2. The parameters of a device operating in TFTR supershot scenario can be determined using the plot in fig.3: a Q=3 fusion gain factor can be obtained by a plasma with major radius R=1.4m and magnetic field B=4.2T , at aspect ratio A=2 , plasma elongation k=2.8 , plasma current Ip=7MA , electron plasma peaking n/<n>=3.5.

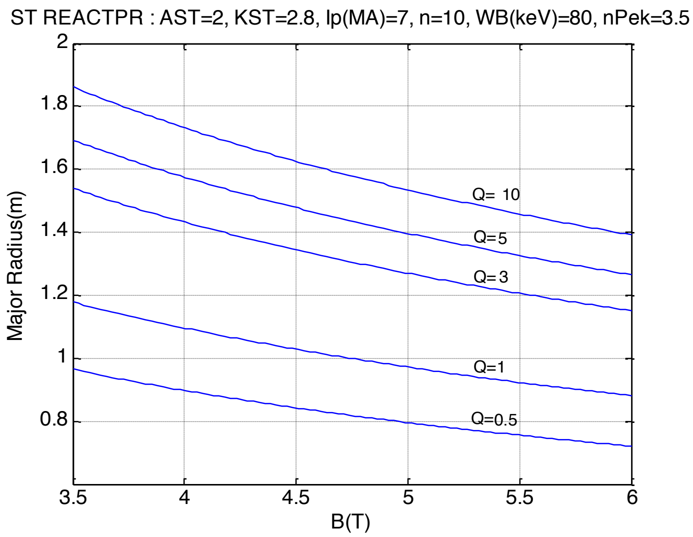

Fig.3. Major radius vs magnetic field evaluated using the TFTR scaling (3) and using the mehod outlined in sec.2.

4. Conclusions

The present paper shows that ST fusion reactors can be compact devices working in plasma regimes where the NSTX scaling law of confinement is valid. A new scaling law for TFTR supershot scenario applied to ST is shown consistent with ST40 data of confinement in a large range of magnetic fields. Extending a simple method introduced in [1] also to TFTR supershots, the scaling of plasma parameters of ST fusion reactors operating in supershot regime in deduced and shown in Fig.3.

References
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