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Role of Core Radiation Losses From Plasma and Its Impact on ST Reactor Design Parameter Choices

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Spherical Tokamak reactor (STR) is attractive due to its inherent capabilities such as disruption avoidance, natural elongation, natural divertor and high beta capability, apart from a smaller size, with presumably lower costs [1, 2]. There has been an extraordinary evolution from the early concepts like SMARTOR [3] with devices like START, NSTX, MAST, GLOBUS-M and a number of others with the HTS based future devices like STEP [4]. Given the pace of development of the new superconducting materials [5,6] and the new divertor concepts [7,8,9], the STRs represent a rapidly developing front and may very well be realized not far in the future. Following an elegant paper by Peng et al. in 1986, a range of compact reactor designs (R and P_f) has emerged, e.g. FNS-ST (0.5m, 10 MW), DTST (1.1m, 30-60 MW), ARC (3.3m, 525 MW), SlimCS (5.5m, 2950 MW), ARIES-ST (3m, 2980 MW) with a variety of objectives like, neutron source, component-test-facility (CTF) and power plant [10,11,12,13,14]. However, while the high neutron loads are welcome for reactor economics, the size reduction comes at a penalty of extreme heat loads on the divertor with concomitant engineering challenges [15]. Several designs of STRs are currently being developed around the world with scoping studies and available data from currently operating tokamaks as well as other experimental/dedicated test facilities and insights from experts [16]. This paper brings out the role of constraints arising from steady-state power balance and core-radiation. It is argued that the core-radiation plays a crucial role in the reactor design, as it not only restricts the accessible parameter-space but also determines the limits on impurity accumulation [17]. A comprehensive physics-design study [18] shows that about 50% of the heating power needs to be lost by core-radiation. Such considerations can impact stability as well [19]. In the following, the ST-parameter space ($R - B_t$) is analyzed to elucidate the limits posed by the various constraints. For T_i from 6 to 20 keV, the fusion power (MW) may be approximated for analytic purposes as:

$$\mathrm{P}_F = 0.026\frac{(S_n+S_T+1)^2}{(2S_n+2S_T+1)}\frac{\kappa{\beta_N}^2{S_\kappa}^2}{q^2A^4}R^3{B_t}^4$$

where $q = 5RB_tS_k/(A^2I_p)$ is the safety factor, I_p is the plasma current in MA, A is the aspect ratio and S_k is the shape factor. $\beta_N = \beta aB_t/I_p$ and S_n, S_T are the exponents for the parabolic profile of the density and temperature respectively. The stored energy in MJ can be expressed as:

$$\mathrm{W}_\beta = \frac{\pi}{8}\frac{\kappa S_\kappa}{qA^3}\beta_N R^3{B_t}^2$$

In steady-state, where the power from α-particles and the externally injected power are balanced by the transport losses, the power-balance is given by $W_\beta = P_L\tau_E$, where P_L (defined as $P_H(1-f)$) is the power reaching the edge, after a fraction f of the power deposited

$$\mathrm{P}_H = P_\alpha + P_{ext} = P_F(1/5 + 1/Q)$$

is radiatively lost from the core region. It is assumed that the ITER-IPB(98,y2) scaling holds good, although it is likely to be more favorable in reality [20]:

$$\tau_E = 0.0562H_h{I_p}^{0.93}{B_t}^{0.15}{n_{19}}^{0.41}R^{1.97}\kappa^{0.78}\epsilon^{0.58}M^{0.19}P_L^{-0.69}$$

The power-balance can then be written as: $\mathrm{Q}_{LF} = (f_\alpha/5 + 1/Q)(1-f)$

where f_α is the fraction of α-particles which transfer their energy to the plasma. The Q_{LF} is actually the ratio P_L/P_F and is an involved expression with fractional powers of plasma parameters. To understand its dependencies, it is best approximated as:

$$\beta_N\ A^{14/5}\ q^{6/5}\frac{}{{B_t}^{92/35}\ H_h^3\ f_G^{6/5}\ S_k^{16/5}\ M^{3/5}\kappa^{2/5}\ R^{9/5}}$$

where, the nearest integer ratios are used to approximate the exponents in the expression for τ_E. The radiated power fraction f can be expressed in terms of Q_{LF}. Its role in accessibility constraints in the R-B_t space has been shown in Fig.1, where, the contours of constant P_f are shown along with the limits on achievable B_t assuming either copper or HTS peak current-density in the center-stack. The constant fusion contours intersect increasingly high divertor load curves as one makes the reactor more compact. The dotted curves (f=0, 0.5 and 0.94) correspond to the power balance constraint. The $f = 0$ curve shows the limit of 'no core-radiation' and thus represents the lower boundary of physically acceptable solutions. Thus, for a given set of parameters as an example (q=3, $\kappa = 2.5$, $\delta = 0.3$, $\beta_N = 5$, $Q = 5$), there exists an upper limit on the value of R (3m). The two Q_{LF} curves that 'bracket'the fusion power curve, define the accessible space until the limit on achievable B_t is encountered. An example of a design point (R=1.25 m, Bt=2.8 T, Pf = 200 MW) has been shown (red dot). It may not be possible to meet it unless almost 60$\%$ of the heating-power is radiated from the core. Such constraints make it necessary to examine how much core concentration of impurities would be acceptable.

Fig.2 shows impact of Q in the parameter space – higher values reduce the available space in the lower left-hand corner.

This has implications for the reactors which may operate at modest values of Q (CTF or fusion-fission hybrid, fissile material converters or radioactive waste processing, or just fusion-science devices). At the same time, the higher Q demand from power reactors (to remain cost-competitive and investment-attractive), eliminates a large space and pushes accessibility points further up. An important consequence of the power balance constraint is that the divertor heat load (transported power) $P_{div} \approx B_t^{3/2}/R^{4/5}$. The gradients of $P_{div} \approx$ constant are in dramatic contrast to those of constant neutron load contours, so while the neutron load per unit area varies slowly as one moves towards the top left-hand corner, the divertor load builds up rapidly. Three case studies will be presented (R=1.75, 1.25 and 2.25m for P_f=100, 200 and 900 MW respectively) in detail. Fig.3 shows how the power balance constrains the $\kappa - \beta$ space for the case R=1.25m, P_F = 200 MW. It can be seen that higher β cases will need a higher κ.

The sensitivity to different τ_E scaling, as well as impurity transport, the effects of neutron and particle loads on the center-stack, first-wall and divertor will be presented in detail.

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