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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:

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

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. $\beta_N = \beta a B_t/I_p$ 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:

$$W_{\beta} = \frac{\pi}{8} \frac{\kappa S_{\kappa}}{a A^3} \beta_N R^3 B_t^2$$

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

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

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]:

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

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

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:

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

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, κ = 2.5, δ = 0.3, β_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.

References:

- 1. Y-K.M Peng et al., Nucl. Fusion 26 769 (1986)
- 2. Gi et al., Nucl. Fusion 55 063036 (2015)
- 3. D. Jassaby et al., Plasma. Phys. Control. Fusion 3, 151, (1977)
- 4. L. A. El-Guebaly et al., Fusion Sci. and Tech., 74:4, 340-369 (2018)
- 5. A. Sykes et al., Nucl. Fusion 58 016039 (2018) and references therein
- 6. Dennis Whyte, Phil. Trans. R. Soc. A 377 20180354 (2018)
- 7. M. Kotschenreuther et al. Nucl. Fusion 50 35003 (2010)
- 8. R. J. Goldston et al., Phys. Scr. T167 014017 (2016)
- 9. V. A. Soukhanovskii, IEEE Trans. Plasma Sci. 44 3445 (2016)
- 10. B. V Kuteev et al., Nucl. Fusion 51 073013 (2011)
- 11. Y-K.M. Peng et al., Nucl. Fusion 40 583 (2000)
- 12. B.N. Sorbom et al., Fusion Eng. and Design 100, 378-405 (2015)
- 13. Tobita K. et al., Nucl. Fusion 49 075029 (2009)
- 14. Najmabadi F. et al., Fusion Eng. Des. 65 143 (2003)
- 15. E. Surrey, Phil. Trans. R. Soc. A 377: 20170442 (2019)
- 16. M. Tillack et al., Nucl. Fusion 53 027003 (2013)
- 17. H. Takenaga et al., Nucl. Fusion 45 1618 (2005)
- 18. S. C. Jardin et al., Fus. Eng. Des. 65 165 (2003)
- 19. P. Kaw et al., Phys. Rev. Lett. 65 2873 (1990)
- 20. P F Buxton et al., Plasma Phys. Control. Fusion 61 035006 (2019)

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