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DEMO design using the SYCOMORE system code: conservative assumptions and pathways towards the reactor

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Abstract:
Demonstration fusion power plants (DEMO) are the next step for fusion electricity after ITER. DEMO design is currently studied worldwide but critical design choices are still to be made. The SYCOMORE system code developed at CEA-IRFM was used to propose a specific approach to DEMO design. Instead of assuming reasonable assumptions on how much the main performance parameters of a tokamak are likely to evolve until DEMO is built, it was chosen to start from a very conservative set of assumptions, close to what achievable on present machines, with the objective of a 325 MW net electric power, 2 hours burn duration reactor. Constraints were then relaxed towards more optimistic values to determine which yields the biggest gain in terms of reactor size. It was found that the main plasma performance parameters tend to play the major role starting from the conservative design point. However, technological limits such as the maximum heat flux on the divertor become more critical than the plasma performance as soon as smaller machines or higher net electric powers are reached.

1 Introduction

A demonstration power plant is the next step for fusion energy following ITER. The design of such reactors is currently ongoing and still requires solving a number of issues regarding the models used for the different subsystems of the plant. System codes are able to address these questions as they model every major element of the fusion power plant and their interactions. This ensures that appropriate compromises between the different subsystems

*See the Appendix to G. Falchetto et al., Nucl. Fusion 54 (2014) 043018 are handled correctly and enforces the global consistency of the design. Models used in system codes are simplified and often assume rather optimistic improvements on some of the key performance-related parameters compared to present machines. The modular system code SYCOMORE [8] has been used to propose a novel approach to DEMO design by starting the design process from present performance parameters and assessing the key variables to improve performances up to a reactor of reasonable size. Sensitivity analyses were also carried out to estimate the width of the operational domain around the design points.

2 SYCOMORE physics and technology content

SYCOMORE is a modular system code developed for DEMO reactor design. Most of the major subsystems of a fusion power plant are handled by an independent code module:

- Plasma geometry and physics. This module is derived from the HELIOS 0D code [1]. It computes the plasma main parameters from scaling laws (confinement time, pedestal temperature...) and plasma power balance using integrals over 1D profiles.
- Scrape-off layer and divertor physics. This module uses a two-point model derived from [2]. It computes the impurity seeding fraction required to match the user-defined heat flux on the divertor plates.
- Neutronics, breeding blanket and shields (Helium-cooled lithium lead). The neutronic module uses neural networks derived from more advanced 2D/3D neutronic calculations to compute the tritium breeding ratio, energy multiplication factor and neutron flux on the toroifal field coil inner leg [3]. The required breeding zone thickness and shield thickness are computed accordingly.
- Toroidal field coil. This module computes the dimensions of the TF coil winding pack, casing and vault following the prescribed toroidal field on axis and the maximum stress allowed in the steel casing. Hoop stresses and centering stresses are taken into account.
- Central solenoid coil. This module computes the size of the central solenoid by maximizing the available flux according to the mechanical constraints in the coil steel.
- Power conversion. This module computes the pumping power needed for the primary circuit (blankets and divertor). Helium or water circuits are possible options.
- Pulse duration. This module computes the flat-top duration using simple 0D calculations derived in [1]
- Balance of plant. This is the final step of a Sycomore calculation. It calculates the global power balance of the reactor and gives the net eletricity output to the grid.

This caculation chain is wrapped in an optimization loop which allows specyfying figures of merit on any of the inputs or outputs, with an arbitrary number of constraints on the outputs. The optimization is performed through genetic algorithms [5]

3 Performance evolution from conservative assumptions

Instead of trying to start the design from extrapolations of best performances obtained on present-day machines, the present paper proposes to start from very conservative assumptions and assess which parameters are most critical to improve the performance (or decrease the size) of a future reactor.

3.1 Starting point

Figure of merit	Minimize R
Optimization variables	R, a, B_0, $\langle T_e \rangle_{n_e}$
Constraints	
P_{net}	>325 MW
Flat-top dur.	>7200 s
δ_{95}, κ_{95}	0.333, 1.40
safety factor at 95% flux	4.0
Greenwald fraction	0.9
H-factor	0.9
P_{line} mantle radius	0.8
NBI current drive efficiency	$0.02 \times 10^{20} \times \langle T_e \rangle$
Max. heat flux on divertor	5 MW.m^{-2}
Tritium breeding ratio	1.12
Neutron flux on TF coil	10^{13} n.m^2.s^{-1}
Number of TF coils	18
Max. stress on TF coil jacket	500 MPa
Max. stress on TF coil vault	500 MPa
Max. stress on CS coil	500 MPa

Results	
R/a	13.58 m/5.91 m
I_p	32.51 MA
B_t	4.52 T
Boostrap fraction	12.7 %
τ_E	11.9s
W_{th}	1999 MJ
β_N	1.1
Z_{eff}	1.23
Helium fraction	6.6 %
Argon fraction	0.031 %
$\langle n_e \rangle$	2.55×10^{19} m^{-3}
$\langle T_e \rangle$	11.7 keV
$n_{e,max}$	2.90×10^{19} m^{-3}
$T_{e,max}$	28.6 keV
P_{fus}	1105 MW
P_{brem}	20 MW
P_{synch}	37 MW
P_{line}	5 MW
P_{con}	164 MW
P_{NBI}(flatttop)	≈ 0 MW
$P_{L-Hthresh.}$	125 MW
Q	∞
$P_{Hepumping}$	86 MW
$P_{net,elec}$	333 MW
Flux from CS	1105 Wb
Burn duration	7300 s

TABLE I: Conservative assumptions - starting point

Sycomore was used to find the smallest machine fulfilling the constraints summarized in table I. Although some higher values have been obtained for most of these parameters taken independently, high performance for all of them are seldom obtained simultaneously. For example confinement enhancement factors of more than 1.4 have been obtained, but rarely with high Greenwald fractions and high plasma pressures at the same time. Please note the design result given below should not be taken as a viable design proposal, but merely a starting point for the rest of the parameter space exploration. The net electric power and pulse durations constraints are typical of DEMO1-like constraints used in European designs [6]. Plasma elongation is downgraded from a DEMO1-like typical design to allow more margin with respect to vertical stabilization. H-factor and Greenwald fractions are representative of present day's large machines high performance baseline scenarios (for example JET [7]. A value of 4.0 is taken for the safety factor at 95% flux instead of the usual 3.0 in order to keep some margin with respect to disruptions [9]. The normalized radius for line radiation is a parameter specific to Sycomore which defines the fraction of the plasma where line radiation is considered as a loss for the plasma power balance [8]. Maximum stresses on magnets have been reduced from the usual 600-650 MPa down to 500 MPa.

Results of the design are given in table I. As expected, the machine is very large with a major radius of more than 13 m. Additional power needed in such a large machine is very low due to the long confinement time merely due to the size of the plasma, even if the validity of the confinement time scaling law is subject to caution in such a plasma regime. Note that only the steady-state power during the burn phase is considered; additional power to initiate the burn is not taken into account. The density is very low in this design due to the low Greenwald fraction and its unfavorable scaling with the size of the machine. From this point, constraints will be relaxed to assess which of them bring the most benefits to the reduction of the reactor size.

3.2 Scans towards size reduction

Starting from the point described above, assumptions are relaxed to assess their impact on the global design. Each point in the scans is the smallest machine that satisfies the constraints described in table I with the exception of the one which is relaxed. The effect of an increase of the Greenwald fraction is shown on figure 2(a). It leads to a reduction of the size of the machine due to higher density and therefore higher fusion power for a constant size. One can also notice that the size reduction tends to slow down for fractions higher than 1.5, so increasing the Greenwald fraction cannot be the only means to reduce the size of a reactor. The additional heating power increases with the Greenwald fraction; this is due to the size reduction leading to higher energy densities in the reactor together with a smaller divertor surface available to spread the power. As a consequence, the argon seeding fraction increases to keep heat loads on the targets low enough. This calls for higher additional heating to compensate for extra radiation losses.

Increasing the confinement enhancement factor leads to a similar behaviour in terms of sizer reduction as shown on figure 2(b), but slows down around 12.5m. Unlike the Greenwald fraction, this does not come with an increasing additional heating power due to the higher confinement. Fusion power remains approximately the same along the scan (around 1100 MW). This is due to a trade-off between the size of the reactor and the

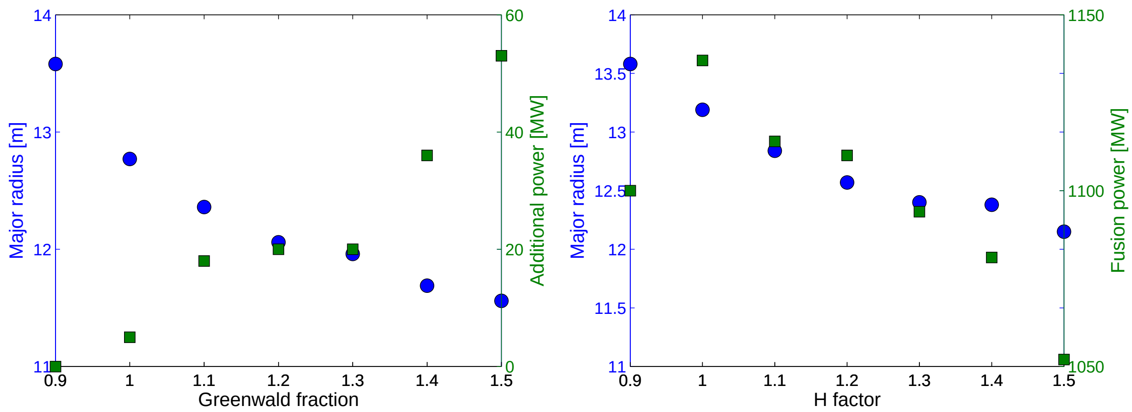

FIG. 1: Scan towards size reduction. (a) Effect of the increase of Greenwald fraction on the minimum size of the reactor and the associated NBI power needed (b) Effect of the increase of the confinement enhancement factor on the minimum size of the reactor.

confinement enhancement factor, which is automatically found by the Sycomore optimizer.

The maximum heat flux allowed on the divertor was also increased from the conservative 5 MW^{-2}, but this has little influence on the reactor size. This is due to the fact that with only 325 MW of net electric power requested, the fusion power is low enough to keep the power to the divertor at bay. The low additional heating power needed (leading to lower power through the separatrix) together with the large major radius (leading to a large divertor area) also tend to relax the constraint on the divertor heat loads. As a consequence, the machine size does not decrease with increasing maximum heat flux on the targets beyond 6-7 $MW.m^2$. Note that the situation may be different when starting from smaller machines.

A scan of elongation was also done starting from the conservative point. The size reduction as the elongation increases is larger than with the Greenwald fraction or the H-factor (in line with [10] and shows no sign of saturation (albeit diminishing returns) for values higher than 1.6 as shown on figure 1(a). Of course, the maximum elongation allowed for a particular design depends heavily on the vertical stabilization capabilities, which would need to be assessed externally to be able to set a real limit. But unlike the increase of Greenwald fraction or the H-factor, the size reduction with increasing elongation does not come with either increasing additional power or saturation after a certain level.

The maximum stresses allowed in the toroidal field coil jacket and vault was increased from the starting value of 500 Mpa up to a fictional value of 850 MPa. The result is presented on figure 1(b) and shows that increasing the maximum stress does not yield a large gain in the machine size. In such large designs, the toroidal field is not actually limited by the stress in the TF steel but rather by the maximum field on the conductor. Therefore the size reduction saturates after a 1.2 meter gain. The maximum field on the conductor cannot be increased in the present version of the magnet module of Sycomore. The development of a simple high-temperature superconductor module is foreseen in the next future to be able to explore this parameter space.

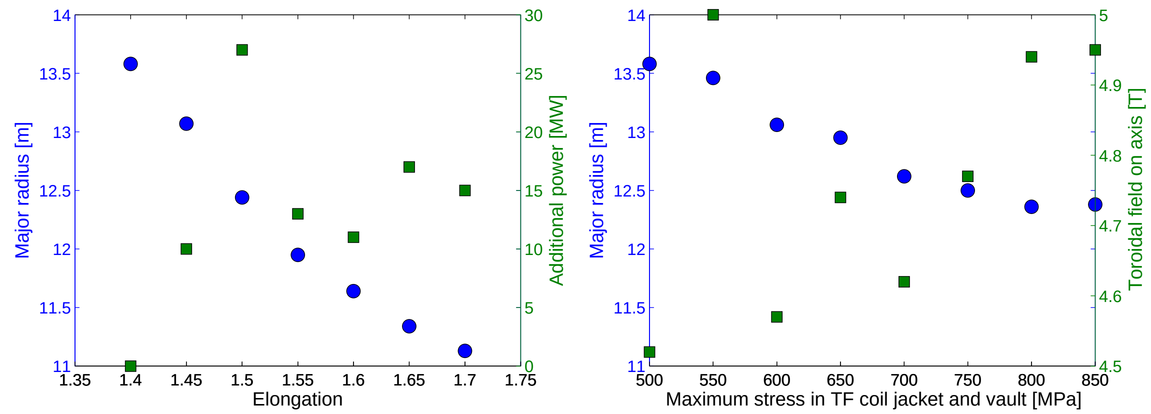

FIG. 2: Scan towards size reduction. (a) Effect of the increase of plasma elongation on the minimum size of the reactor and the associated NBI power needed (b) Effect of the increase of the maximum allowed stress in the toroidal field coil and the associated magnetic field values

Relaxation of conservative constraints can also be combined to investigate synergies between parameters. For instance, relaxing the Greenwald fraction and the H-factor simultaneously decreases the major radius by almost 3.0 meters whereas the size reduction for each parameter taken independently only yields 0.7 m for the H-factor and 1.5 m for the Greenwald fraction.

4 Scoping and sensitivity studies

A number of sensitivity and scoping studies can be carried out around the different design points presented above. In particular, all of them were obtained by setting a minimum net electric power (325 MW) to be reached together with a 2 hours pulse duration. It might be of interest, for example, to see how the minimum size of the reactor evolves when the minimum net electric power is changed. The result of such a study for various combinations of the conservative constraints is presented on figure 3. Five situations have been selected: starting from the point described in section 3 then a step-by-step relaxation of the conservative constraints up to a more typical level for a DEMO1-class reactor. For each case, a multi-criterion optimization problem is solved: minimization of the size of the machine and maximization of the net electric power under the 2-hours burn duration constraint. The result is a Pareto front as described in [5]. One can see that no design solution exists with the most pessimistic constraints for net electric powers above 350 MW. When the plasma parameters (H factor and Greenwald fraction) are relaxed, net powers close to 500 MW can be reached, at the expense of large machines (more than 12 m). For a given power below 500 MW, the minimum size is of course smaller than for the conservative starting point. It is worth noting that the slope of the curves for each problem changes for net electric powers above a certain value. This value is around 400-500 MW for all the optimization problems except the one where the constraint on the maximum heat flux on he divertor Q_{peak} is relaxed for which the threshold is around 900 MW. This suggests that Q_{peak} becomes a design-driving constraint only for reactors above a certain power. It is also consistent with the weak effect of this constraint on the size described in the previous section for net electric powers around 300 MW. Note though that the five situations presented in figure 3 still contain some conservative assumptions ($q_{95} = 4.0$, TBR=1.12). The value of the power threshold may therefore change if all the constraints were to be relaxed and is subject in any case to large uncertainties.

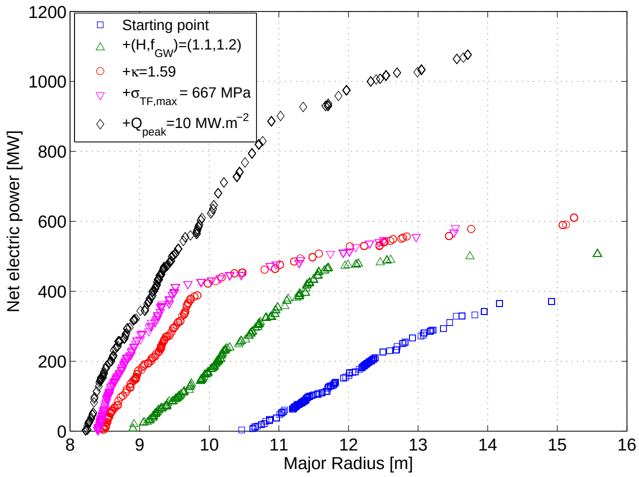

FIG. 3: Multi-criterion optimization studies (minimize major radius and maximize net electric power). The four cases relax constraints cumulatively. Blue squares: starting point defined in section 3.1. Green triangles: add H-factor and f_{GW}. Red circles: add elongation. Purple triangles: add maximum stress on TF coils. Black diamonds: add the maximum allowed heat flux on the divertor to 10 $MW.m^{-2}$.

Instead of setting the burn duration and the net electric power, one can also scan the size of the machine around a design point and estimate the consequences of such size changes on the performances. This is represented on figure 4 for a reasonably optimistic starting point (H-factor 1.1, Greenwald fraction 1.2, max heat flux on the divertor 10 $MW.m^{-2}$, maximum TF stress 600 MPa, target net electric power 500 MW), which corresponds approximately to the most optimistic situation on figure 3. One can see that for such class of designs (reasonable compact devices with net electric power around 500 MW), the addtional power needed increases quickly when the size is reduced (figure 4(a). This is due to the shrinking of the divertor area and the additional power needed to compensate for the decreasing confinement time, also leading to higher heat flux to the divertor. One can also see that the burn duration becomes very sensitive to small changes in size when the design is very compact (lower corner of figure 4(b), whereas the net electric power seems less sensitive, although already quite low due to the plant balance being constrained by the high additional heating power.

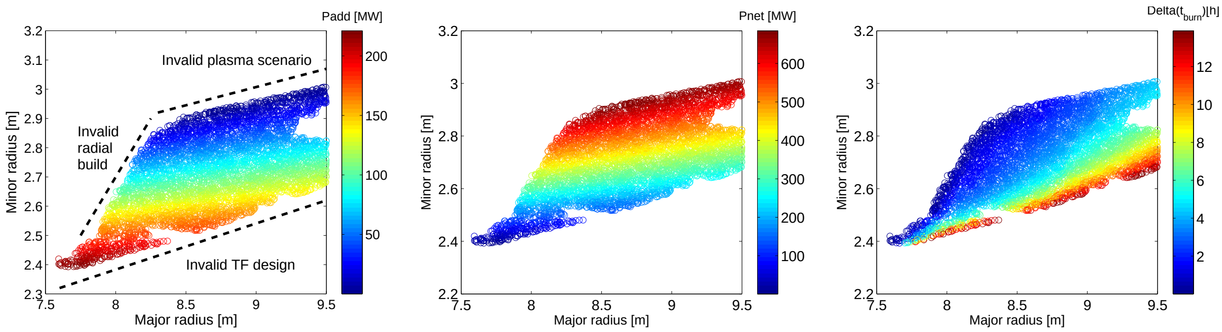

FIG. 4: Sampling around a DEMO1-like design point. Major and minor radius are the sampled variables. Other parameters (toroidal field, kinetic profile parameters) are kept constant. The operational space is given in terms of additional heating power (a), net electric output (b) and burn duration (c). Notches in the lower right corner of the operational space are due to the discrete design of the TF winding pack.

5 Conclusions

An exploration of the influence of a number of physics and technology assumptions for DEMO reactors was made using the Sycomore system code. Starting from an conservative point trying to reflect present day simultaneously achievable performance parameters, design constraints are relaxed. It is found that for the design objective considered (325 MW net electric power and 2 hours burn duration), plasma elongation, confinement enhancement factor and Greenwald fraction are the most critical parameters. Relaxing only one of these constraints is however not sufficient to bring the reactor down to reasonable sizes. In the reactor class considered in this study, stress limits on the magnets or maximum allowed heat flux on the divertor are found to be less critical. A larger scoping study show that this situation changes for higher net electric powers: the maximum heat flux on the divertor then becomes a design driving constraint. More generally, performances become very sensitive to small changes in physics and technology assumptions when the designs are smaller in size.

Acknowledgments

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