Fusion Engineering and Design 112 (2016) 47–52

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Evaluation of CFETR key parameters with different scenarios using system analysis code

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ARTICLE INFO

Article history:
Received 26 January 2016
Received in revised form 13 July 2016
Accepted 22 July 2016

Keywords:
CFETR
Scenario
System code
Steady-state

ABSTRACT

This paper presents a system analysis on both phases of China Fusion Engineering Test Reactor (CFETR) under the same structure of toroidal field coil with a magnetic field on axis of 6–7 T and device size of major radius of $R\sim6$ m. Phase I is designed with moderate gain aimed at exploring steady-state scenarios with DEMO relevant plasmas. One operating mode with higher magnetic field and conservative physics is presented, which could serve as a backup CFETR baseline in case of shortfall in physics performance. Phase II targets high gain with power plant relevant requirements and objectives, including more than 1 GW of fusion power, high fusion gain for DEMO validation and more ambitious assumptions based on advanced physics. A system analysis code, General Atomics System Code (GASC) [R. Stambaugh, V. Chan, et al., Fusion nuclear science facility candidates, Fusion Sci. Technol., 59 (2001) 279–307] is used to evaluate key parameters of scenarios for both phases.

1. Introduction

It is well known that energy shortage and environmental pollution are two critical issues we have to confront with in this century. In solving these issues, it is necessary to replace fossil-based energy with carbon-free renewable energy that is capable of producing thousands of gigawatts of sustained base load [1]. Fusion power has the potential to provide sufficient energy to satisfy mounting demand sustainably, with a relatively small impact on the environment. With the approval of International Thermonuclear Experimental Reactor (ITER, which is an international nuclear fusion research and engineering megaproject), the magnetic fusion program has entered an exciting new era. However, it is understood that ITER will not resolve all the issues needed to proceed to a net electric power plant. Before making possible a fusion demonstration power plant (DEMO) [2], a facility addressing the technology and physics gaps that complements ITER would be necessary, such as Fusion Development Facility (FDF) [3,4] proposed in US. CFETR has recently been proposed as a next step fusion facility to bridge gaps between ITER and DEMO and realize the fusion energy application in China. The primary mission elements are demonstrating fusion energy production; tritium self-sustainment with TBR $\geq$ 1.0; steady-state operation with a duty cycle of 0.3–0.5; exploring options for DEMO blankets and divertor solutions; and exploring the technical solution for licensing DEMO. Since some mission elements are more readily achievable than others, two phases of CFETR have been proposed [5,6]. Phase I focuses on fusion power $P_{fusion}=50\sim200$ MW, fusion power gain $Q_{plasma}=1$–5, $TBR>1.0$, Neutron dpa requirement $\sim$10 dpa with a small size of major radius $R=5.7$ m and lower toroidal field $B_0\sim5.0$ T. Phase II emphasizes DEMO validation, which means $Q_{plasma}>10$, $P_{fusion}>1$ GW and $\sim$50 dpa requirement with an upgrade to $R\sim6$ m and higher toroidal field B_0 about 6.0–7.0 T.

Phase I has been studied extensively and the physics and engineering conceptual designs have been published [7,8]. A comprehensive set of physics performance predictions for CFETR was carried out with a system code described in [7], and a benchmarking study using different system codes has been done to corroborate the findings [9]. As a unique characteristic of CFETR, both of the phases can be operated in the same toroidal field structure. This means Phase I might be operated at same size and toroidal field as Phase II, providing the magnet technology is available to meet the requirements. Based on this assumption, one set of scenarios with conservative physics and technology has been calculated and will be shown here. This can be considered as backup baseline to achieve the desired fusion performance by higher toroidal field and larger plasma volume, i.e. using engineering to make up for the physics shortfall. As a follow-up, a system analysis of possible scenarios

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http://dx.doi.org/10.1016/j.fusengdes.2016.07.017
0920-3796/

for Phase II based on its mission has been done. Four scenarios are considered. They are generating more than 1 GW of fusion power, achieving a fusion gain within 25–50 for DEMO validation, operating at more advanced physics point, and testing advanced magnetic technology. The detailed results will be shown in this paper. All the evaluations employed General Atomics System Code (GASC) and are based on a steady-state H-mode with fully non-inductive current drive.

This paper is organized as follows. A simple introduction of system code of GASC is described in Section 2. Options of Phase I with conservative assumption are discussed in Section 3. Evaluation of CFETR phase II with different objectives are shown in Section 4. Finally, a brief summary is given in Section 5.

2. System analysis code and general parameters of CFETR

A system analysis based on zero-dimensional (0-D) models could be effectively used to scope out a large number of possible operating scenarios, which satisfy physics and engineering constraints, to provide an initial assessment. The system optimizer GASC [10,11] based on Microsoft Excel spreadsheet is used for the evaluation of CFETR parameters in this paper. It can treat both copper and superconducting tokamaks, but only superconducting case is considered here. GASC contains an extensive suite of 0-D physics and engineering models required for optimizing fusion performance within constrains to inform the engineering design. The physics and engineering models, as well as the optimization capability, have been described in [3,10] in details. Only a brief introduction, which combines with corresponding parameters we used, is shown below. As we said, CFETR plays a role of bridging the gap between ITER and DEMO; the fusion power of 50–200 MW in Phase I is lower than ITER, but the required burning duty is longer. Principally, it is reasonable to apply ITER physics as the physics basis at the beginning of CFETR design with appropriate extrapolation taking into account the specific requirements.

The density and temperature profiles are assumed by using parabolic exponents, i.e. a power of $(1-\rho^2)^S$ (where ρ is the normalized radial location r/a, and S is respectively S_n or S_T of the exponents of density or temperature expression), in combination with an approximate treatment of the H-mode pedestal. The elongation κ and triangularity δ can be set to represent two-dimensional equilibrium shape effects. The elongation κ is taken as a fraction of the maximum stable elongation, which is a function of aspect ration, i.e. $\kappa_{\max} = 2.4 + 65e^{-A/0.376}$. The fraction of 82% is chosen to give $\kappa \sim 2$, in which feedback stabilization is achievable using an EAST-like control system, i.e. the vertical instability is controllable by the active coils with passive plates in vacuum vessel. Concept design and analysis of CFETR vertical instability [12] has shown the necessity of passive plates. CFETR conceptual design selects a single null configuration to satisfy the space requirement for sufficient tritium breeding, which fixes the triangularity at 0.4. This value is close to that of the ITER baseline case, and many existing experiments have shown that adequate confinement factor can be achieved with triangularity in this range (δ = 0.35–0.45) [13]. Potential means of heating and current drive for CFETR include combinations of lower hybrid (LH), electron cyclotron (EC), Ion cyclotron (IC) and Neutral beam (NB). In the present study, only EC and NB are considered, with 40% of the plasma current driven by EC and 60% driven by NB. Other means will be examined in the future. The power required to drive the current by various ways is based on the formulas originally published in [14] but calibrated by additional supplemental calculations with ONETWO, NFREYA, TORAY-GA and GENRAY [3,15–17], since it is known that the system analysis code, i.e. GASC, desires to use simple expressions to scale the driven current over a range of parameters. These calibrated calculations are based on the parameters of FDF, which has similar temperatures and densities as CFETR. The calculation given by TORAY-GA indicated that the present expression of $g_{EC} = 0.09 < T_e > / \left(5 + Z_{eff}\right)$ used for ECCD in the spreadsheet is about right, though it does omit some physics related to the value of launched refractive index $n_{||}$ or the launch location; these effects may be captured only by other ray tracing calculations. For NBCD, comparing with NFREYA calculation, the expression used in the spreadsheet $g_{NB} = 0.025 < T_e >$ may be a factor 2 optimistic. The possible reason of the difference may be the beam ions lost on the first orbit due to the large minor radius of the birth location in the calculations and these calculations should be repeated using NUBEAM. The calibrated calculation for CFETR employing TORAY-GA and NUBEAM are now in process and the expression of current drive efficiency in the spreadsheet will be modified according to the results. Specifically, the current drive efficiency of 0.27–0.36 m^{-2}MA/MW for NNBCD and 0.13–0.18 m^{-2}MA/MW for ECCD are used. The core bremsstrahlung and cyclotron radiations are calculated using appropriated core/edge density, temperature and ionic charges. The line radiation is assumed as a certain fraction of the core heat, which is radiated at the plasma edge by heavy impurities. External heavy impurity puffing to enhance the radiation in the plasma boundary is included in the system code by this way. Neon is assumed as a seeding impurity with Zimp = 10. The helium and impurity dilution of the majority ion density is included. The total core heating power is the sum of the auxiliary power and the alpha power. The electrical efficiency from wall plug to antenna for the RF system is based on information from ITER specifications. For example, 50% electrical efficiency for gyrotron would be considered near the limit of today's technology, and the upper limit for microwave transmission efficiency from source to antenna is about 90%. Because only EC is examined for now, so the electrical efficiency is taken as 0.4.The general house power to run the physics plant is taken as 7% of the gross electric power. The total power to run the plant is the sum of the electric power for the auxiliary system and the house power. The net electric power is gross electric power minus the power to run the plant.

The Excel nonlinear solver allows a chosen function to be maximized or minimized by iterating a set of free parameters under a set of constraints, to achieve the optimization. The optimization performed for CFETR is set to minimize the size of the machine, i.e. CFETR is the smallest device that can give the indicated performance. With the different goals of the design consideration, the function can be set accordingly. The set of free parameters contains: the aspect ratio, radial build of the TF and OH coils, current density in the TF and OH coils, filling fraction of TF and OH, ion temperature, the ratio of auxiliary power to current drive power. The set of constraints generally includes: the confinement factor, the Greenwald ratio, neutron wall load, divertor heat load, TF and OH coil stress set by engineering limits, fraction of the OH coil flux provided for start-up and et al. Meanwhile, the special requirements can be taken as additional constraints, e.g. in Phase II predication, fusion power and net electric power are added as constraints. The next two sections discuss the findings employing GASC for CFETR Phase I and Phase II, respectively.

3. Phase I with more conservative considerations

One of the missions of CFETR Phase I is demonstrating the fusion energy production with at moderate gain, fusion power P_{fusion} = 50–200 MW [18]. The initial physics design, which is envisioned to produce ~200 MW of fusion power, has been determined [7] and multi-system codes benchmarking study has been published [9] by using GASC and TESC (Tokamak Energy System Code [19]). Both of them chose a small device size of $R \sim 5.7$ m, $a \sim 1.6$ m