Fusion Engineering and Design xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Time-dependent power requirements for pulsed fusion reactors in systems codes

J. Morris*, M. Kovari

Culham Centre for Fusion Energy, Abingdon OX14 3DB, UK

HIGHLIGHTS

- Outline what systems codes are and what they are used for.
- Describe the steady-state and intermittent power requirements for a fusion reactor.
- Show plant total power output and values for the 2015 EU DEMO 1 baseline design.
- Discuss how time between pulses is important for fusion plant power output.
- What sections of the plant dominate the power requirements.

ARTICLE INFO

Article history:
Received 29 September 2016
Received in revised form 7 April 2017
Accepted 8 April 2017
Available online xxx

Keywords:
Fusion
Systems codes
Power requirements
Pulsed DEMO

ABSTRACT

The investigation of time-dependent power requirements for a future nuclear fusion reactor is part of the systems integration task for the European Fusion Programme. A pulsed DEMO will require intermittent and continuous electrical power to operate the various plant systems. For example, the heating and current drive system will require power during I_p start-up, heating, plasma burn and I_p ramp-down phases. This paper presents the modelling of these power requirements over the whole pulse cycle for all plant systems in the systems code PROCESS. In the EUROfusion baseline case the continuous power requirements are −290 MW and are dominated by the primary coolant pumping requirements. The total intermittent power requirements range from −50 to −375 MW. The time between pulses strongly influences the average plant net electrical power production and for a power plant would have to be minimised to stay commercially viable. The EUROfusion DEMO baseline is estimated to produce enough electrical power to meet the machine's aims given the current burn time, time between pulses and power requirements.

1. Introduction

The purpose of the proposed European Demonstration (DEMO) reactor is to validate the physics and technology required for a commercial fusion power plant. Whilst DEMO needs to demonstrate these technologies and produce a reasonable amount of power for a reasonable amount of time, a commercial power plant will need to optimise its design for power output, reliability, efficiency and cost (capital and operational).

A fusion power plant can be designed to operate in steady-state (pulse length tends to infinity) or pulsed (a finite pulse length limited by the available magnetic flux and current drive). The definition of the pulse timings used for this work is given in Table 1 and are described in Section 2.

The recirculating power required for a fusion power plant has a large impact on the net electrical power output. DEMO will have a number of systems that require power during operations. Some systems will require power continuously and some will be powered only during certain operational phases. Capturing this power usage is required for determining the recirculating power of the reactor and therefore must be included in a systems code to correctly calculate the power balance. The power requirements impact plant parameters such as the cost of electricity, power supply size/cost and plant capital/operational cost.

Current EUROfusion DEMO baseline designs are based on output from the fusion reactor systems code PROCESS [1–3]. The code outputs values for the power requirements during the whole operational cycle. The model separates the recirculating power requirements into intermittent and steady-state (similarly done for

* Corresponding author.
E-mail address: james.morris2@ukaea.uk (J. Morris).

http://dx.doi.org/10.1016/j.fusengdes.2017.04.033
0920-3796/© 2017 Published by Elsevier B.V.

Table 1
Table listing the various pulse phases and their duration in PROCESS.

Name	Definition	Time [s]
CS pre-mag	Time to pre-charge the CS	500
Ip up	Time to ramp-up plasma current	$I_p/0.1$
Heating	Heating phase before the burn	10
Burn	Time there is a burning plasma	7200
Ip down	Time to ramp-down plasma current	$I_p/0.1$
Dwell time	Time between pulses	0

Table 2
Summary table of plant power information during the burning phase for EU DEMO. Thermal power in blanket is higher than fusion power due to energy multiplication in blanket from the exothermic n-^{6}Li reaction.

Description	Value	Unit
Fusion power	2037	MW
Thermal power in blanket	2436	MW
Thermal efficiency	37.5	%
Gross electric power	915	MW
Recirculating power	−415	MW
Net electric power	500	MW

ITER in [4], in EUROfusion [5] and power plants in [6]) and uses these values in the recirculating power model in PROCESS.

The EUROfusion baseline DEMO machine's goal is to have a burn time of 2 h and to produce roughly 500 MW_e net electric power during the burning phase [7,8]. Table 2 lists power information from the 2015 European DEMO 1 baseline (DEMO 1 is the pulsed reactor and DEMO 2 is the steady-state reactor in [3], this paper only concerned with DEMO 1).

The power requirement data in this paper is based on the systems code PROCESS. The code is used for investigating large parameter spaces for feasible plant designs using parameterised models. It is used as the first step in DEMO reference designs for EUROfusion. PROCESS is also able to model tokamaks different to the EUROfusion baseline such as spherical tokamaks, provided those machines are pulsed then the model described in this paper would still apply. For the values given in this paper a positive power requirement is power produced and a negative power requirement is power required (see Table 3 for details).

A number of the power requirements are based on user input and expert opinion from the EUROfusion projects, and therefore the assumptions in PROCESS will be updated in line with the ongoing EUROfusion work during the current work programme.

2. Pulse timings

In the PROCESS code the pulse is split into a number of phases. These are listed in Table 1. The definition of the times is also given. The burn time can be allowed to vary in PROCESS and maximising it is often the priority for optimisation (along with minimising the major radius). For the EU DEMO runs the minimum burn time is set to 2 h to fulfil the machine requirements. The plasma current ramp-up and ramp-down time are limited by allowing the plasma current to change by a maximum of 0.1 MA s^{-1}. The 500 s for the CS recharge is a user input that is currently guided by advice from the EUROfusion balance of plant project. The 10 s heating phase is also a user input and will be subject to further review during the DEMO design programme.

3. Intermittent power requirements

The two main components of the intermittent power requirements are the heating and current drive system (HCD) and the poloidal field (PF) magnet system including the central solenoid (CS). Electrical power supplies with a fast response needed to enable rapid plasma control and potential disruption prevention are not considered here or inside the scope of PROCESS.

3.1. Heating and current drive

The HCD system on a pulsed plant would operate at different powers during the pulse [3]. More power would be required during the heating phase than the burn phase as there is no α-particle heating during start-up. Additionally no HCD power is required during the CS pre-magnetisation (see Table 3).

The exact HCD mixture in DEMO is not yet fully defined so the powers listed below could be from a mixture of HCD methods (NBI, EC, IC). The current EUROfusion DEMO baseline has the HCD power requirements as −50 MW during the burn phase and the HCD power during the heating, ramp-up and ramp-down is taken to be −150 MW [9]. These values are the power coupled to the plasma after which a wall-plug efficiency is used to give a value for the electrical power required. A HCD wall-plug efficiency of 40% is used in the baseline design and here (the current work assumes 40% for both NBI and EC, but can be changed by the user if necessary).

3.2. Poloidal field magnets

The PF magnet system provides positioning and shaping control of the plasma and the central solenoid is required to induce the plasma current by transformer action. The currents in the PF

Table 3
Summary of the power requirements for the pulse phases and the net electric power output including the average over the whole pulse cycle.

	Units	CS ramp	I_p ramp-up	Heating	Burn	I_p ramp-down	Dwell	Total
Duration	s	500	194	10	7200	194	0	8098
Continuous								
Cooling	MWe	−155	−155	−155	155	155	155	
Cryoplant	MWe	−44	−44	−44	−44	−44	−44	
Vacuum	MWe	−1	−1	1	−1	−1	−1	
TF	MWe	−11	−11	−11	−11	−11	−11	
Tritium	MWe	−15	−15	−15	−15	−15	−15	
Facilities	MWe	−63	−63	−63	−63	−63	−63	
Total	MWe	−290	−290	−290	−290	−290	−290	
Intermittent								
H &CD	MWe	0	−375	−375	−125	−375	0	
PF	MWe	−50	44	0	−2	175	0	
Total	MWe	−50	−331	−375	−127	−200	0	
								Average
Net output	MWe	−340	−621	−665	500	−490	−290	395

Please cite this article in press as: J. Morris, M. Kovari, Time-dependent power requirements for pulsed fusion reactors in systems codes, Fusion Eng. Des. (2017), http://dx.doi.org/10.1016/j.fusengdes.2017.04.033