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

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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 start-up, plasma burn and ramp-down phases. This paper presents the recently updated 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 coolant pumping requirements. The intermittent power requirements range from -125 to 300 MW. The time between pulses is shown to strongly influence the average plant 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 power to meet the machine's aims given the current burn time, time between pulses and power requirements.

Keywords: Fusion; Systems Codes; Power Requirements; Pulsed DEMO

## 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 and efficiency.

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 information is useful for determining the recirculating power of the reactor.

Current EUROfusion DEMO baseline designs are based on output from the fusion reactor systems code PROCESS [1, 2] [3]. The code currently outputs values for the reactor at a single point in time and doesn't capture power requirement information outside of the flat-top. The update to the model separates the power requirements into pulsed and steady-state (similarly done for ITER in [4], in EUROfusion [5] and power plants in [6]) and includes this in the recirculating power model in PROCESS. The EUROfusion baseline DEMO machine has a burn time of 7200s, a time between pulses of 1800s and produces roughly 500 MW net electric during the burn phase.

The power requirement data in this paper is based on the systems code PROCESS. The power requirement assumptions in PROCESS will be updated in line with the ongoing EUROfusion work during the current work programme.

## 2 Intermittent power requirements

The main two components of the intermittent power requirements are the heating and current drive systems and the poloidal field magnet system (including the central solenoid). Electrical power needed for unexpected control or emergencies as well as power that might be required for disruption prevention is not considered in this work.

### Heating and Current Drive

The heating and current drive (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 flat-top (burn) phase as there is no $\alpha$-particle heating during start up.

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

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requirements as 50 MW during the burn phase and the HCD power during the heating, ramp-up and ramp-down is taken to be equal to the L-H power threshold, which is 120 MW [3]. A HCD wall-plug efficiency of 40% is used in the baseline design and here.

### Poloidal Field Magnets

The poloidal field (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 magnet system vary the most outside of the plasma burn phase. The power required is both positive and negative, losses account for net energy usage. Negative power being when stored energy is taken out of the coil when the current is reduced during the plasma current ramp up. The code assumes that any negative power could be used elsewhere on the plant and is included in the power balance. Active power requirements vary for each coil, range is -125 to 105 MW.

## 3 Continuous power requirements

This electrical network will need to provide constant power over the pulse cycle. The systems that require constant steady-state power are systems that are deemed to be *always-on* during operational periods, in reality they might fluctuate around these values but this is not considered here.

### Cooling system

The primary cooling in a reactor transports heat out of the first-wall, blanket and shield and to the secondary cycle. Power is required to pump the coolant round (in this case He for a HCPB or HCLL blanket). The DEMO baseline has a value of 155 MW of primary cooling pumping power [3]. This is for a helium-cooled blanket and water-cooled first wall and divertor.

### Cryoplant

The cryoplant in a reactor maintains the low temperatures required for multiple systems, such as the superconducting magnets and cryopumps used for neutral beams and possibly in the reactor. Shielding the TF coils from neutron heating also influences the cryogenic power requirement. The cryoplant has a power usage value of 30 MW from PROCESS in the baseline design. This is given in PROCESS by the following:

$$P_{cryo} = 1 \times 10^6 \frac{(293 - T_{cryo})}{0.13 T_{cryo}} P_{removed} \qquad (1)$$

Where $P_{removed}$ is the heat removal at cryogenic temperatures in Watts and $T_{cryo}$ is the cryogenic temperature in Kelvin (in this case 4.5K). PROCESS uses 13% of the ideal Carnot efficiency in its calculation.

### Vacuum System

The vacuum system in a reactor provides the vacuum conditions that allow the plasma to be formed and maintained. PROCESS lists a power requirement of $< 1$ MW. It is small but will be included in case the power requirement assumption is changed in future.

### Tritium System

The tritium systems remove tritium from the breeding blanket, purify and store it, and maintain the correct isotopic balance in the fuel. They also remove tritium from the primary coolant, and from the ventilation systems. The tritium system in PROCESS and the baseline design has a power requirement of 15 MW. It is assumed that the fuel does not need to be isotopically separated.

| Description | Value | Unit |
|---|---|---|
| Fusion power | 2037 | MW |
| Primary (high-grade) heat | 2436 | MW |
| Thermal efficiency | 37.5 | % |
| Gross electric power | 915 | MW |
| Continuous power | 290 | MW |
| Intermittent power(flat-top) | 125 | MW |
| Net electric power | 500 | MW |

**Table 1:** *Summary table of plant power information during flat-top in current EUROfusion baseline design.*

| Continuous | Intermittent |
|---|---|
| TF Magnets | PF Magnets |
| Cryoplant | Heating & Current Drive |
| Vacuum System | |
| Tritium system | |
| Facilities | |
| Remaining systems | |
| Cooling system | |

**Table 2:** *Split of plant systems into intermittent and continuous power usage for this paper.*

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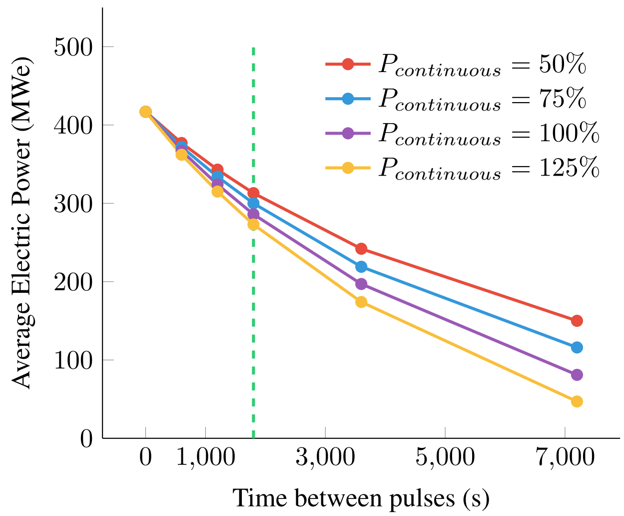


**Figure 1:** *Time-average net electric power output from plant vs. time between pulses for a range of continuous power requirements. $P_{continuous}$ = 100% is equal to the 290 MW of the EUROfusion DEMO baseline design. The dashed line is the dwell time for the baseline design.*

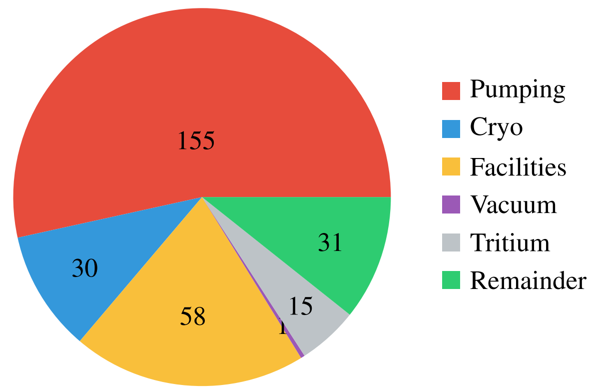


**Figure 2:** *Continuous electrical power requirements in MWe for EUROfusion baseline design. Total continuous electric power required is 290 MW.*

### Toroidal Field Magnets

In ITER (and likely in DEMO) the TF coils will not be operated in persistent mode, but will be connected to a power supply at all times. This means that there will be power losses in the power supplies as well as in the busbars and feedthroughs. The baseline does not include this in the continuous power.

### Facilities

The facilities power is an estimate of the general power requirements of a plant/site consisting of nuclear grade buildings. The estimate of the facilities power is calculated by using a reference power per unit building floor space which is 150 $W/m^2$. This gives the facilities power in PROCESS to be 58 MW for the baseline DEMO case.

### Remaining systems

All plant systems that are not listed above are accounted for in the remaining systems part of the power requirements. For DEMO this collection covers systems such as CODAC and diagnostics. In PROCESS this is given a value equal to $\sim 3\%$ of the gross electric power, which equals 31 MW.

## 4 Results

Given the net electrical power shown in figure 3 the DEMO case produces a total of 2.8 GJ of net electric energy output over the entire 9760 s operational cycle. This equates to an average power production over the whole cycle of 286 MW. The power usage during the time between pulses lowers the power production average from ∼425 MW (over 7960 s, i.e. no gap between pulses) to 286 MW (over 9760 s). Reducing the time between pulses or the power consumption during this time will be essential in a power plant and desirable for DEMO.

The time between pulses is required to pump down the vessel after the pulse and to recharge the central solenoid and reset the PF magnets. A time of 1800 s is an estimate and work is ongoing to determine the time between pulses for DEMO.

Power supplies with a fast response to enable rapid plasma control and potential disruption prevention are not considered here or inside the scope of PROCESS. The EUROfusion baseline uses 2015 PROCESS models but the planned baseline in 2017 will have revised pulse timings and power usage, most notably the PF coil power usage and CS charge time. The TF coils are not included in the power requirements as it is assumed that they will continue to be operating between pulses. The power from TF losses (from the bus bar and joints not the coils

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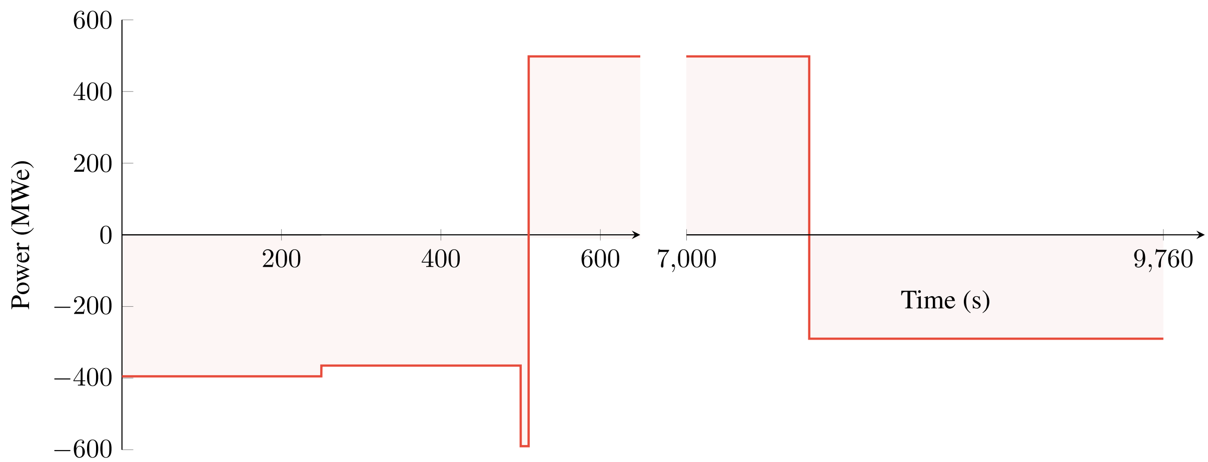


**Figure 3:** *Net electrical power in MWe over entire pulse cycle including the time between pulses.*

themselves) is not currently included but is not thought to be significant.

## 5 Summary

Previously PROCESS only considered the power requirements during the burn phase, after the update it outputs the power requirements over the entire pulse cycle and outputs the total energy generated and average power. It is clear from figure 1 that the length of the time between pulses strongly influences the mean power production of a power plant. By including this information in PROCESS we can allow the user in future to constrain the average power production to be over a certain value and then optimise the machine to meet this.

The remote handling system power requirements are not included and the power usage during maintenance isn't taken into account in the cost of electricity or the total energy production over the lifetime of the machine and the average power production over 40 years. The operation of plant facilities during maintenance could require significant power and impact machine optimisation greatly.

Updates of the power requirements will take place as more detailed designs, being undertaken by EUROFusion, become available for the various plant systems and their power requirement estimates become more certain.

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