Fusion Engineering and Design xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Optimal design of a toroidal field magnet system and cost of electricity implications for a tokamak using high temperature superconductors

T.S. Lee [a,b], I. Jenkins [b], E. Surrey [b], D.P. Hampshire [a,*]

[a] Superconductivity Group, Centre for Material Physics, Durham University, DH1 3LE Durham, UK
[b] EURATOM/CCFE, Culham Science Centre, Abingdon OX14 3DB, UK

ARTICLE INFO

Article history:
Received 29 September 2014
Received in revised form 26 April 2015
Accepted 24 June 2015
Available online xxx

Keywords:
High temperature superconductors
PROCESS
Cost electricity
Toroidal field magnets

ABSTRACT

The potential for reducing the Cost of Electricity (CoE) by using High Temperature Superconductors (HTS) in the Toroidal Field (TF) coils of a fusion tokamak power plant has been investigated using a new HTS module in the PROCESS systems code. We report the CoE and the design of HTS tokamaks that have been optimised by minimising the major radius of the plasma. Potential future improvements in both the superconducting properties and the structural materials for TF coils operating at 4.8 K and 30 K are considered. Increasing the critical current density by a factor of 10 (with a commensurate reduction in costs $kA^{-1}\,m^{-1}$) results in a CoE 4.4% less than equivalent tokamaks using current low temperature superconductors (LTS). If the yield strength of the TF casing material is increased by 40% to 1400 MPa, the CoE is further reduced by 3.4%. Implementing both improvements and operating the TF coils at 4.8 K leads to CoE of 19.1 (10.1) €cent $kW^{-1}\,h^{-1}$ for a 500 MW (1.5 GW) HTS reactor compared to 20.7 (11.1) €cent $kW^{-1}\,h^{-1}$ for an LTS reactor (2013 costs). Operating the HTS TF coils at 30 K with both improvements, gives a similar CoE for HTS and LTS tokamaks.

1. Introduction

It is well established from the fusion power scaling law, $P_F \propto \beta^2 B^4$, that in order to realise economic fusion power, it is necessary either to improve plasma performance significantly (to increase β) or to increase the toroidal magnetic field (B) [1]. High-temperature superconductors (HTS) offer one way to increase the magnetic field, with upper critical fields in excess of 50 T. $REBa_2Cu_3O_7$ (RE: Rare-Earth, REBCO) 2nd generation (2G) HTS tapes already have critical current densities in the superconducting layer alone, one or two orders of magnitude higher than in Nb_3Sn and are improving rapidly as manufacturing techniques develop. HTS also have the benefit of having high critical temperatures (T_c) that allow the possibility of increased operating temperatures and a reduction in our reliance on helium as a coolant. Furthermore these tapes are far from a mature technology: currently REBCO tape is manufactured with only ~1% of the cross sectional area made of the superconductor, so we can expect significant improvements in cost and performance of HTS fusion conductors.

Many institutes have already investigated building tokamaks using HTS technology, with peak magnetic fields as high as 22 T [2]. However most of the more broadly based conceptual system studies have focused mainly on using established Nb_3Sn technology, operating at more modest fields (up to 13.6 T). In this paper, we report the results from adding generic critical current density (J_c) equations as part of a new HTS module added to the PROCESS systems code developed in CCFE, in order to assess both the economic impact of using HTS, and to investigate how key tokamak parameters such as the major radius and operating temperature will change when switching from low temperature superconductors (LTS) to HTS. Parameter scans are carried out that not only consider the superconducting properties of today's materials but also potential improvements that are likely on the timescale of DEMO being built.

In this paper we focus on the results for a 500 MW net electric power plant as this is a possible size for DEMO. We also summarise results for larger power plants.

2. Power plant systems code—PROCESS

Designing a tokamak is demanding, since hundreds of constraints have to be met whilst simultaneously trying to optimise critical figures of merit. The Power Reactor Optimisation Code for Environmental and Safety Studies (PROCESS), developed in CCFE, is a systems code that uses scaling laws to model all aspects of a tokamak, including the plasma characteristics, magnet design,

* Corresponding author. Tel.: +44 1913343520.
E-mail address: d.p.hampshire@durham.ac.uk (D.P. Hampshire).

http://dx.doi.org/10.1016/j.fusengdes.2015.06.125
0920-3796/

balance of plant etc. In doing so, it is possible to find an optimal design for a nuclear fusion power plant. PROCESS is a powerful tool as the simple scaling laws require very little computational power allowing parameter scans of key tokamak parameters with 16 processor clusters in a few minutes.

Previous work (e.g. the PPCS study [3]) using PROCESS included investigations into the constraints on the plasma and technology performance and analysis of relatively near term increases in the plasma and technology performance as compared with ITER. We have been guided by that previous work to set key parameters as follows: $\beta_N \sim 3.0$, the plant availability set at 0.75, the calculated bootstrap current fraction ~35%, the efficiency of converting the thermal power into electrical power of 40% and a peak divertor heat load of 10 MW m^{-2}. Further details of the technological assumptions made in this paper can be found in the PPCS study and in a recent PROCESS update [4]. We have also assumed a learning factor of 0.65, equivalent to a 10th of a kind reactor. For the superconductors we used costs of 6.1 and 80.6 $ kA^{-1} m^{-1} at 12 T, 4.2 K for Nb_3Sn and REBCO respectively, which are 1990 ¢ costs calculated retrospectively for use in the 1990 cost module in PROCESS. In principle, increases in J_c and reductions in cost of HTS tapes occur separately. Influenced by the low cross sectional area of superconductor in HTS tapes compared to LTS strands and to simplify our analysis, we have chosen to consider increases in J_c at constant cost per unit length (i.e. when J_c doubles, the cost kA^{-1} m^{-1} halves). We also convert 1990 ¢ costs to 2013 €cent costs using CPI inflation where 1 ¢ (1990) = 1.32 €cent (2013).

3. Critical currents in superconductors

PROCESS describes the reduced field $\left(b = B/B_{c2}\right)$, reduced temperature $\left(t = T/T_c\right)$ and strain (ε) dependence of the critical current density (J_c), more strictly the engineering (or whole strand) critical current density, of Nb_3Sn strand using [5]:

$$J_c = \frac{C}{B} s(\varepsilon)\left(1 - t^{1.52}\right)\left(1 - t^2\right) b^p (1 - b)^q \quad (1)$$

where all symbols have their usual meanings.

In the new HTS module, J_c of tapes is described as a function of field (B), temperature (T), angle of the field with respect to the tape $\left(\theta\right)$ and strain, using:

$$J_c \approx \alpha(T)\left(1 - c(T)(\varepsilon - \varepsilon_0(T))^d\right) \times \left(1 - \frac{B}{B_{c2}}\right) \exp\left(-\frac{B\cos\theta}{\beta_W(T)}\right) \quad (2)$$

The form of the field and temperature dependencies follow those reported for flux flow along channels [6,7]. We also include an empirical strain dependence in Eq. (2) to provide a generic parameterisation of J_c. The free parameters $\alpha(T)$, $c(T)$, $\varepsilon_0(T)$, and $\beta_W(T)$ are taken as functions of temperature alone and fitted using variable strain J_c data from Sunwong [7] and Sugano [8] in the form:

$$f(T) = U\left(1 - \frac{T}{T_c}\right)^V, \quad (3)$$

where T_c is independent of strain. The values of the constants U and V for REBCO tape are shown in Table 1. The constant d was found to be ~2. The (strain independent) upper critical field (B_{c2}) was taken to be:

$$B_{c2} = B_{c2}(0)\left(1 - \left(\frac{T}{T_c}\right)^{0.61}\right) \quad (4)$$

where T_c is 87.6 K and $B_{c2}(0)$ is 68.5 T for HTS [7]. Current values of J_c were taken to be 7.8 and 3.2 × 10^8 A m^{-2} at 12 T and 4.2 K for LTS strands and HTS tapes respectively. Improvements in J_c are implemented by changing the values of C (LTS materials) and U (HTS materials) associated with $\alpha(T)$. In PROCESS, we set the maximum operating current to 50% of J_c. The heat loads in the cryogenic system, are scaled from ITER values, whilst assuming no additional AC losses as we are investigating steady state tokamak devices.

Table 1
The values of U and V for REBCO derived from experimental data [7,8] for $\alpha(T)$, $c(T)$, $\varepsilon_0(T)$, and $\beta_W(T)$ using Eq. (3).

	U	V
$\alpha(T)$	$(1.08 \pm 0.03) \times 10^{11}$ A m^{-2}	2.0 ± 0.1
$c(T)$	0.025 ± 0.003	−1.200 ± 0.005
$\varepsilon_0(T)$	−0.51 ± 0.04%	1.09 ± 0.08
$\beta_W(T)$	13.8 ± 0.2 T	0.42 ± 0.03

4. Results

4.1. Optimum operating temperature for TF coils

Fig. 1 shows the Cost of Electricity (CoE) that has been found by minimising the major radius of the plasma torus for a 500 MW net electricity tokamak operating at a given coolant temperature—using either Nb_3Sn or REBCO as the superconductor in the TF coils. For Nb_3Sn, the optimum operating temperature is in the liquid helium range (~2.5 K) with a corresponding CoE of 15.3 ¢ kW^{-1} h^{-1} and peak operating magnetic field of ~13.5 T. Although the assumptions made about cryoplant efficiency at very low temperatures do affect the optimum operating temperature itself, because the cost of electricity is only weakly dependent on operating temperature as shown in Fig. 1, the important conclusions of the paper are unaffected. ITER will operate at 4.8 K so that it can use supercritical helium as the coolant. If present-day REBCO were to be used as the superconductor in the TF coils, the opti-

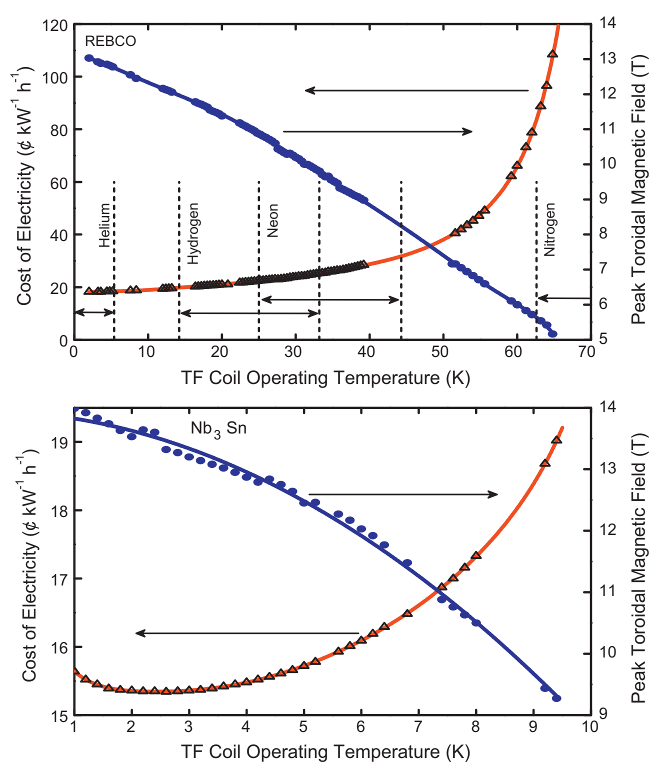

Fig. 1. The cost of electricity in 1990 $ that has been found by minimising the major radius of a 500 MW net electricity tokamak operating at a given coolant temperature. The equivalent peak toroidal magnetic field is also shown. The TF coils are constructed using the superconductors (a) REBCO and (b) Nb_3Sn. For (a) the temperature range over which some cryogens are liquid is shown.