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SCONE code: Superconducting TF coils design code for tokamak fusion reactor

Hiroyasu UTOH, Takaaki ISONO, Mitsuru HASEGAWA[1)], Kenji TOBITA and Nobuyuki ASAKURA

Japan Atomic Energy Agency, Naka, Ibaraki 311-0193 Japan

[1)] Mitsubishi Electric Cooperation, Chiyoda, Tokyo 100-8310 Japan

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For fusion reactor design study, a maneuverable design tool of superconductor (SC) TF coils, SCONE code, has been developed. The code was originally developed to apply reactor conceptual design where a baseline design of TF coils is required rather than the detailed one. The code consistently solves heat balance, electromagnetic stress and magnetic field at the TF coil system, and eventually provides the maximum field of the coil system and the optimal material composition of the conductor consisting of SC strand, stabilizing copper, support structure, etc. It was confirmed that the calculated result was reasonable in comparison with existing coil design.

Keywords: Superconducting coil, TF coil design, reactor design

1. Introduction

In tokamak fusion reactor, the TF coils are one of the most important components affecting the power density of reactor. In addition, since the TF coil system accounts for a significant fraction of the total mass of the reactor, the design of the TF coil system has a large impact on the construction cost of the reactor. This means that the TF coil design is one of the most important processes in the conceptual design of fusion reactors. However, the conceptual design requires only a rough picture of the TF coils. This is why we have developed a concise and versatile design code of the TF coils, named SCONE (**S**uper**con**ducting coil **e**valuation).

The SC material used in the existing or abuilding tokamaks are NbTi and Nb_3Sn as shown in Table 1. In fusion reactors beyond ITER, candidate SC materials will be Nb_3Sn, Nb_3Al and high temperature SC (HTS) from a point of view of critical current density in the high magnetic field regime as shown in Fig.1. In the figure, Bi-2212 is a HTS with the chemical composition of $Bi_2Sr_2CaCu_2O_x$, and Nb_3Al (RHQT) represents the Nb_3Al wire processed by rapid-heating, quenching and transformation (RHQT), which is high J_c (~1000A/mm^2) at 16T and 4.2K [5]. Nb_3Al can employ react and wind (R&W) method. In the R&W method, a furnace size is compact, suitable for large coil fabrication. Bi-2212 wire has high critical current density of more than 1000A/mm^2 at 20T and 4.2K [6]. The conductor design by HTS has been reported [7,8].

Considering these situations, the SCONE code encompasses the physical and electromagnetic property data of Nb_3Sn, Nb_3Al and Bi-2122, and find an optimal coil design along the same design methodology.

Tab. 1 Superconducting strand and B_{max} on existing or a building machines and fusion reactor designs.

	SC strand	B_{max}
KSTAR	Nb_3Sn	7.4T
JT-60SA	NbTi	5.65T
ITER	Nb_3Sn	11.8T
PPCS model A [1]	Nb_3Sn	~13T
Demo-CREST [2]	Nb_3Al	~16T
SlimCS [3,4]	Nb_3Al	~16T

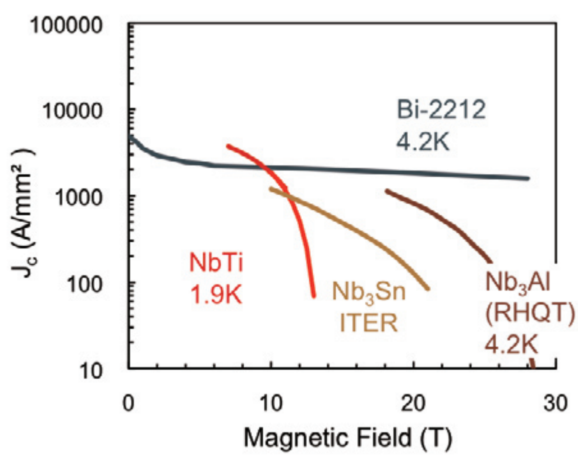

Fig. 1 Critical current density versus magnetic field

author's e-mail: uto.hiroyasu@jaea.go.jp

3. Description on SCONE code

3.1 Basic concept

The main input parameters of the code are:

(i) choice of SC strand material

(ii) coil size

(iii) operation conditions of SC

Choice of superconducting strand are NbTi, Nb_3Sn, Nb_3Al and Bi-2212. The coil size parameters are the height (H), the width (D), the number of TF coils (N_t), the conductor thickness (t_c), the outer radius of central solenoid (CS) coils (R_{cs}) and the thickness of coil case (d_{in} & d_{out}), as shown fig.2. The conductor area is given by t_c, R_{cs} and d_{out}. The magnetic field in TF coils is determined at the TF coil inner leg R_{TF} (=R_{cs} + d_{out} + t_c). The operation conditions include the conductor current (I_0), the operation temperature T_o, the strain (ε), the terminal voltage (V_{term}), temperature limit up on a quench (T_a) and the design stress (S_m).

Figure 3 shows the flowchart of the SCONE code. Using input parameters, the operation current density of superconducting wire (J_{op}) and the number of turns (N) are calculated. The amount of stabilizer is given by solving the heat balance at the conductor area. From the amount of structure material, the von Mises stress caused by electromagnetic force is calculated. When the stress given by calculation does not meet the design conditions, the calculation starts over N-1. When the code finds a consistent solution satisfying all the conditions, key design parameters, such as B_{max}, J_{op} and N are output.

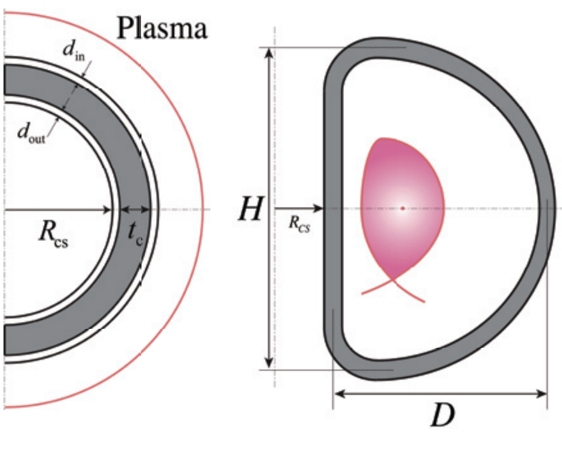

Fig. 2 Input data regarding TF coil geometry in SCONE code

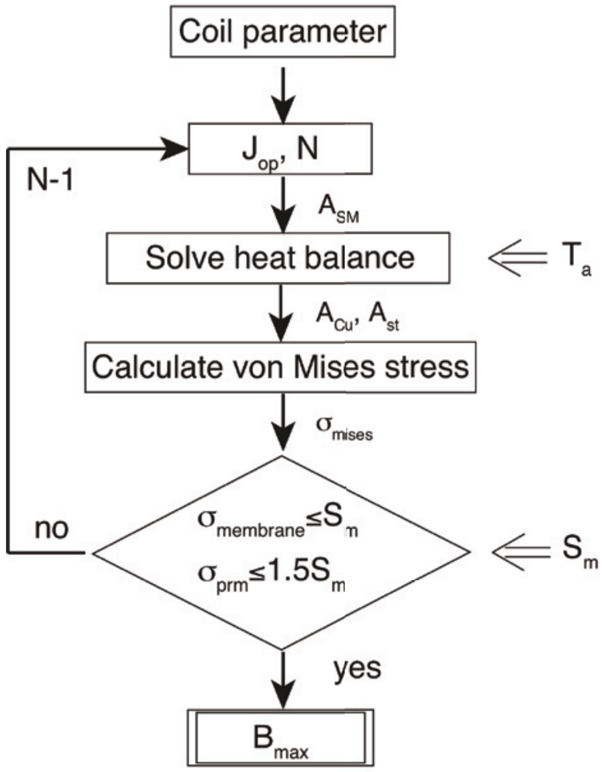

Fig. 3 Flowchart of SCONE code

3.2 Calculation of operation current density

The critical current density (J_c) of the superconducting wires is given by the magnetic field (B), the temperature (T) and the strain-state (ε). J_c of the superconducting wires is calculated by using the scaling law for these parameters dependence of J_c [9].

$$J_c(B,T,\varepsilon) = A(\varepsilon)\left[T_c(\varepsilon)(1-t^2)\right]^2 \times\left[B_c(T,\varepsilon)\right]^{n-3} b^{p-1}(1-b)^q \tag{1}$$

where, A (ε) is single strain-dependent parameter, and $b = B/B_c(T,\varepsilon)$ and B_c (T, ε) is the upper critical field, which is parameterized by

$$B_c(T,\varepsilon) = B_c(0,\varepsilon)(1-t^v) \tag{2}$$

Here, $t = T/T_c(\varepsilon)$ and T_c (ε) is the critical temperature. These parameters A (ε), B_c (T, ε) and T_c (ε) are dependent on the strain, and have the following relationship:

$$\left(\frac{A(\varepsilon)}{A(0)}\right)^{1/u} = \left(\frac{B_c(0,\varepsilon)}{B_c(0,0)}\right)^{1/w} = \frac{T_c(\varepsilon)}{T_c(0)}$$
$$\frac{B_c(0,\varepsilon)}{B_c(0,0)} = 1 + c_2\varepsilon^2 + c_3\varepsilon^3 + c_4\varepsilon^4 \tag{3}$$

A (0), B_c (0, 0), T_c (0), c_2, c_3 and c_4 depend on not only type of superconducting strand, but also the fabrication process and the manufacture. In the code, the suitable values for reactor design employed the present database.

On ITER TF coil design, J_{op} is determined in consideration of temperature margin ΔT (T_{op}=5.2K, ΔT

=0.5K). Figure 4 shows the temperature dependence of J_c on Nb_3Sn. When ΔT is considered as operation temperature margin, J_c (T_{op} + ΔT) becomes less than J_c (T_{op}), and the difference is also understood to be a J_{op} margin.

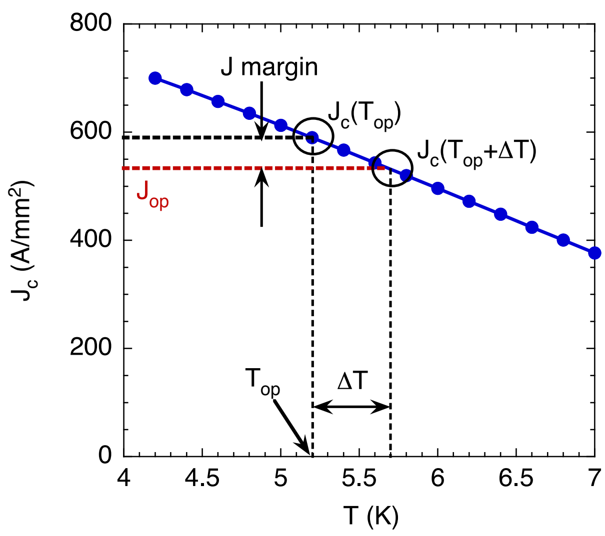

Fig. 4 Temperature dependence of J_c on Nb_3Sn.

3.3 Heat balance calculation

In superconducting coils, a stabilizer are required for the quench protection. In the SCONE code, the area of stabilizing copper is determined by the balance of Joule heating and heat capacity of materials in the conductor, as the follows

Nb;

$$\int_0^\infty I^2 dt = \int_{T_{op}}^{T_a} \frac{A_{Cu}}{\rho_{Cu}} \left(\gamma_{SM} C_{SM} A_{SM} + \gamma_{Cu} C_{Cu} A_{Cu} \right) dT \qquad (4)$$

Bi;

$$\int_0^\infty I^2 dt = \int_{T_{op}}^{T_a} \left(\frac{A_{Ag}}{\rho_{Ag}} + \frac{A_{SM}}{\rho_{SM}} \right) \cdot \left(\gamma_{SM} C_{SM} A_{SM} + \gamma_{Ag} C_{Ag} A_{Ag} + \gamma_{Pb} C_{Pb} A_{Pb} \right) dT \qquad (5)$$

where ρ_{Cu}, ρ_{Ag} and ρ_{SM} are the resistivity of copper, silver and superconducting material, A_{SM}, A_{Cu}, A_{Ag}, γ_{SM}, γ_{Cu}, γ_{Ag}, γ_{Pb}, C_{SM}, C_{Cu}, C_{Ag} and C_{Pb} are the area, the density and the specific heat capacity of superconducting material, stabilizing copper, silver and lead, respectively. Each of these parameters has a dependence of temperature. I is the conductor current, T_{op} is the operation temperature and T_a is the maximum allowable temperature at conductor area. Although γ_{Cu} is dependent on T and B, the data at B=16T is assumed in the code. The dependence on B is little at the considered temperature range. At very low temperature, γ_{Cu} reduces to one-eighth, but the effect on heat calculation at the quench is little. A_{SM} is determined by the quotient of total magneto motive I_t and operation current density J_{op}. I_t is the product of the number of TF coils N_t, number of turns N and conductor current I_0.

The heat balance calculation considers the detection delay time. The Joule heating term of equation (4) and (5) is written as follows.

$$\int_0^\infty I^2 dt = \int_0^{t_d} I_0^{\,2} dt + \int_{t_d}^\infty \left(I_0 \exp\left(-\frac{t - t_d}{\tau} \right) \right)^2 dt = I_0^{\,2} \left(t_d + \frac{\tau}{2} \right) \qquad (6)$$

where, t_d is the detection delay time and τ is equivalent discharge time constant given by

$$\tau = \frac{L_t}{N \cdot \dfrac{V_{term}}{I_0}} \qquad (7)$$

Here, L_t is the inductance in the TF coil system and V_{term} is the terminal voltage.

3.4 Stress calculation

To calculate the stress of the TF coil inboard leg, the following simple method is adopted in the conducting area. The amount of structure material in the conductor is determined by the area of structure material A_{st}.

$$A_{st} = A - A_{SM} - A_{Cu} - A_{in} - A_{cl} \qquad (8)$$

where, A_{in} is the area of insulator given by $0.1A$, and A_{cl} is the area of cooling channel given by $0.49(A_{SM}+A_{Cu})$. From the area of structural materials, the von Mises stress of TF coils at a cylinder formed by inboard legs are calculated by the following equation:

$$\sigma_{mises} = \sqrt{\frac{(\sigma_t - \sigma_r)^2 + (\sigma_r - \sigma_z)^2 + (\sigma_z - \sigma_t)^2}{2}} \qquad (9)$$

where, σ_t, σ_r and σ_z are the toroidal, radial and axial stresses, respectively. These are approximately determined using the ratio η_{st} of A_{st} to conductor area A ($= \pi(R_{out}^{\ 2} - R_{in}^{\ 2})$) and the area of coil case A_{case} ($= \pi(R_{out} + d_{in})^2 - A - \pi R_{cs}^{\ 2}$), as follows.

$$\begin{aligned}
\sigma_t &= \frac{\sigma_t^*}{1 - \sqrt{1 - \eta_{st}}} \frac{2A}{2A + A_{case}} \\
\sigma_r &= \frac{\sigma_r^*}{1 - \sqrt{1 - \eta_{st}}} \frac{2A}{2A + A_{case}} \\
\sigma_z &= \frac{\mu_0}{8\pi} \frac{I_t^{\,2}}{\eta_{st} A + A_{case}} \ell n \frac{R_2}{R_1} \\
\eta_{st} &= A_{st} / A \\
R_{in} &= R_{cs} + d_{out} \\
R_{out} &= R_{cs} + d_{out} + t_c \\
R_1 &= R_{in} + t_c / 2 \\
R_2 &= R_1 + D
\end{aligned} \qquad (10)$$

where, σ_t* and σ_r* indicate the average stress in the conductor area.

$$\sigma_r^* = -\frac{pR_{out}^2}{R_{out}^2 - R_{in}^2}\left(1 - \frac{R_{in}^2}{r^2}\right)$$
$$\sigma_t^* = -\frac{pR_{out}^2}{R_{out}^2 - R_{in}^2}\left(1 + \frac{R_{in}^2}{r^2}\right) \qquad (11)$$
$$p = \frac{\mu_0 j_0^2 t_c^2}{6} = \frac{\mu_0 I_t^2}{6\pi^2 R_{out}^2}$$

Here, p is the equivalent pressure of pinch strength at inner leg of TF coils. The membrane stress $\sigma_{membrane}$ is defined as an arithmetic average of the von Mises stresses of TF coils at the six radial positions (Fig.5).

$$\sigma_{membrane} = \frac{\sum_{k=1}^{6} \sigma_{rk,mises}}{6} \qquad (12)$$

where,

$$r_k = R_{cs} + d_{out} + \frac{(k-1)t_c}{5} \qquad (13)$$
$$k = 1,\cdots,6$$

The maximum primary stress σ_{prm} is defined as a maximum the von Mises stresses.

$$\sigma_{prm} = \max\{\sigma_{rk,mises}, k = 1 \to 6\} \qquad (14)$$

The allowable stress criteria are:

$$\sigma_{membrane} \le S_m \text{ and } \sigma_{prm} \le 1.5 S_m \qquad (15)$$

The design stress S_m is determined by two-third yield stress ($=2/3S_y$). Incidentally, the structural material of ITER is JJ1, and the designed S_m is 667 MPa. At present, S_m of about 750 MPa is achieved [10].

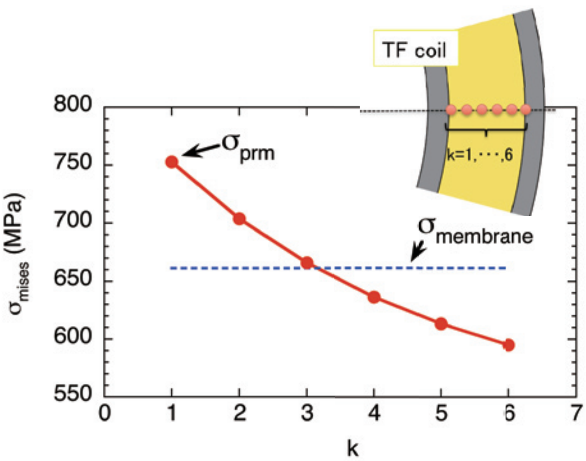

Fig. 5 Distribution of the von Mises stresses of the conductor area.

4. Application to ITER-like TF coils

To validate the calculation result obtained from the SCONE code, the result was compared with the design

Tab. 2 ITER TF coil parameters

Number of TF coils	18
SC strand	Nb_3Sn
Maximum field in TF coils	11.8T
Operation current in TF coils	68kA
Operation temperature in TF coils	5.2K
Operation strain	~0.77%
Width of TF coils	9m
Height of TF coils	14m
Magnetic energy in TF coils	41GJ
Number of turns	134
Terminal voltage	3.55kV
Allowable stress	667MPa
Equivalent discharge time const.	15s

parameters of ITER TF coils. A comparison on the coil parameters [11] are shown in Table 2. ITER consists of 18 TF coils, a CS, six poloidal field (PF) coils and 18 correction coils (CCs). The TF coils are operated at the maximum field of 11.8T. The conductor is a circular Nb_3Sn cable-in-conduit with a central cooling channel, cooled by supercritical helium. The winding uses one-in-hand conductor with a double pancake configuration.

The ITER-TF coil parameters and the calculation result from SCONE code are shown in Table 3. A reasonable agreement is seen between the SCONE result and the design parameters of ITER. Both "total magneto motive force" and "number of turns" have a little deviation compared to ITER parameters. The difference of "magnetic energy in TF coils" E_t and "equivalent discharge time const." τ are caused by the difference of coil shape definition. In SCONE code, the coil D-shape is approximated by,

Tab. 3 Comparison between ITER TFC and SCONE code

	ITER	SCONE code
Maximum field in TF coils	11.8T	11T
Total magneto motive force	164MA	166MA
Magnetic energy in TF coils	41GJ	43GJ
Number of turns	134	136
Equivalent discharge time const.	15s	20s
Operation current density (J_{op}/J_c)	0.765	0.80

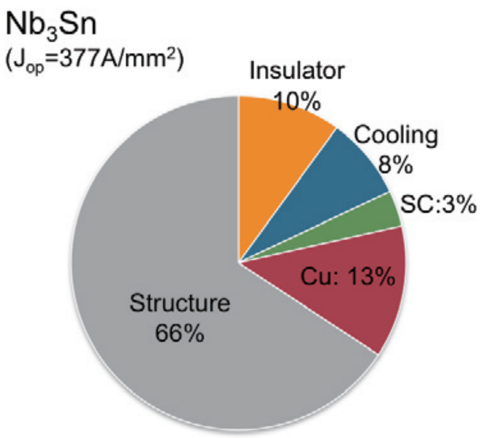

Fig. 6 Material composition ratio of conductor on Nb_3Sn

$$E_t = \frac{\mu_0 I_t^2 H}{4\pi}\int_0^{\pi}\frac{\sin(\theta)^2}{\frac{R_2+R_1}{R_2-R_1}+\cos(\theta)}d\theta \tag{16}$$

where, H is the height of TF coils and τ is calculated by E_t,

$$\tau = \frac{L_t}{N\cdot\frac{V_{term}}{I_0}} = \frac{2E_t}{N\cdot V_{term}\cdot I_0} \tag{17}$$

$$\because E_t = \frac{1}{2}L_t I_0^2$$

Figure 6 shows the composition ratio of conductor material in the conductor area A, such as SC material, stabilizing copper and structure material. As shown in this figure, the structure material dominates in the SC coil.

There is the difference of 1T on “maximum field in TF coils” between ITER TF coils and the SCONE result. To evaluate the magnetic field distribution, the magnetic field distribution on ITER was calculated by a TOROIND code. The TOROIND is a magnetic field calculation code based on coil shape and current. B_{max} obtained by the SCONE code is extrapolated using $B \propto 1/R$. Figure 7 shows the magnetic field distribution on ITER from TOROIND and an extrapolation of B_{max} of the SCONE result. As shown in this figure, both magnetic field distributions are good agreement. On ITER design, the magnetic field at R_p=6.2m is 5.3T. The magnetic field distribution on SCONE code at axis (R_p=6.2m) is equal to ITER design value. A difference in calculation models is responsible for the difference between the ITER design values and the SCONE result. B_{max} of ITER is calculated with a detailed model taking account of actual coil structure. On the other hand, the SCONE code calculates B_{max} using imaginary conductors over the entire coil cross section. The imaginary conductors are assumed to be a uniform mixture with superconductor, stabilizing copper and structural material and so on. This means that the

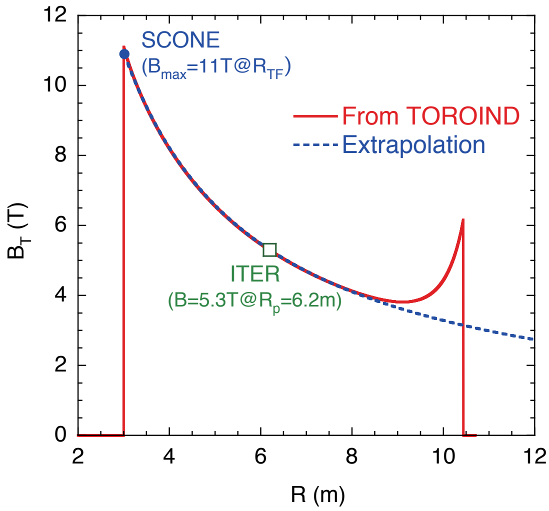

Fig. 7 Magnetic field distribution on ITER from TOROIND and the SCONE extrapolation

conductors are widely distributed over the coil cross section and thus B_{max} tends to be lower than the actual coil. It should be noted that such an underestimation of B_{max} tends to impose strenuous requirements for plasma parameters and thus leads to a safety side design from the point of view of reactor system design. Apart from this small disagreement, it should be stressed that this approach is useful in the baseline design study of fusion reactors where one is interested in dependences of B_{max} on different parameters such as coil size, shape, conductor current, operation temperature, etc., rather than an exact B_{max} for a specific TF coil design. By using the SCONE code, the calculation time becomes longer than existing TF coil design module, but the difference is a few seconds by a personal computer. Integration of the SCONE code into the existing system code can be useful in the demo conceptual design.

5. Summary

The SCONE code has been developed to survey reactor concept widely. The SCONE code consistently solves heat balance, electromagnetic stress and maximum magnetic field generated by the TF coils. It was confirmed that the calculated result from SCONE code was reasonable in comparison with existing coil design. These result suggests that by using SCONE code, the rough evaluation of B_{max} generated TFC system is available. The SCONE code seems invaluable in design study of the TF coil for tokamak fusion reactor.

Acknowledgment

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