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AC Loss Analysis on the KSTAR PF1L Coil Based on the Long-Term Commissioning Data

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Abstract – Typical tokamak fusion device uses CS (Central Solenoid) coil to initiate plasma heating by ramping up the coil with steadily increasing current which induces the plasma inside the vacuum vessel. For the case of the KSTAR (Korea Superconducting Tokamak Advanced Research) which uses superconductor for all of its magnets, this operation brings various AC losses to the magnets including hysteresis loss, coupling current loss, and eddy current loss. Thus it is important to analyze AC losses of the superconducting magnet for its reliable operation in two main perspectives: short term quench prevention and long term steady-operation. With 10 years of operation, KSTAR has provided many invaluable data in superconducting magnet operation regarding AC loss issues. This paper focuses on the AC loss of the KSATR PF (Poloidal Field) coil based on the long term operation data. Among the components of the PF coils, PF1L coil contributes to CS coil operation from which it experiences the highest field, and consequently the largest loss. First, numerical approach will be taken to analyze quantitatively each AC loss. Then the losses will be compared with the total loss measured by the calorimetric method. Finally, the results will be interpreted in qualitative manner to investigate the possible relation between the AC loss and the magnet's performance.

◆ Introduction: For Reliable Operation of KSTAR Magnet

- **Background**
  - 10th anniversary in 2018
  - Extended period of duties as the ITER pilot machine.
  - Steady and persistent plasma operation mission.
- **Significance**
  - First to analyze the long-term operation data of the superconducting coils.
  - Critical for a reliable operation of the tokamak.
- **Objective:** To investigate the possible method to analyze the superconducting magnet's performance for a safe and steady operation in the future.

◆ Coil Specification and Analysis Method: Calorimetric + Analytic Method

Table 1. Specification of the KSTAR PF1L

Parameters		Values
Strand		
Superconductor		Nb_3Sn
Strand diameter	[mm]	0.78
Filament diameter	[μm]	4.5
Effective filament diameter, D_{eff}	[μm]	12.5
Number of filaments		3477
Cu/non-Cu ratio		1.5
Critical current density (@ 4.2 K, 12 T)	[A/mm^2]	836
Average AC loss ($\pm$ 3 T, @ 4.2 K)	[mJ/cc]	214
n-value (index number)		20
Residual Resistivity Ratio (RRR)		167
Conductor		
Conduit material		Incoloy 908
Conduit dimension, $width; height; thickness$	[mm]	22.1; 22.4; 2.41
Length per cooling channel	[m]	64.5
Number of strands, SC; Cu		240; 120
Cabling pattern		3×4×5×6
Cable twist pitch, $1^{st}; 2^{nd}; 3^{rd}; 4^{th}$	[mm]	40; 80; 145; 237
Void fraction	[%]	33.5
Coil		
Inner diameter; Outer diameter	[mm]	455; 685
Number of turns		180 (9×20)
Maximum magnetic field (@ I_{op} = 15 kA)	[T]	5.01

- **Poloidal Field 1 Lower (PF1L) Coil**
  - Experiences the largest magnetic field → largest AC loss
  - Experienced quench in 2011 → meaningful effects from the quench is expected

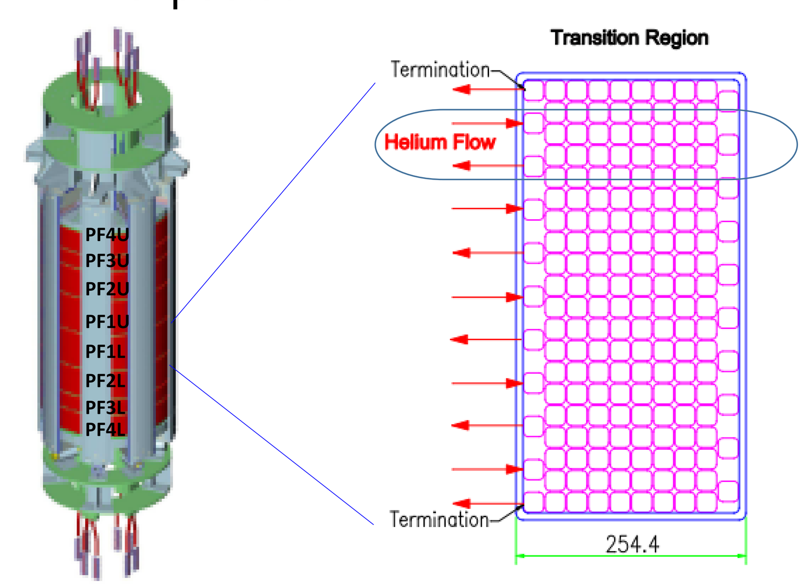


Fig. 1. Graphical drawing of the KSTAR CS coils (left). Courtesy of Dr. Choi, C.H. Cross section view of PF1L coil (right), Courtesy of Dr. Oh, Y.K., Property of NFRI

- **AC Loss Evaluation Method**

- Total loss (measured by calorimetric method, J)

$$Q_{tot} \approx \int_{t_{init}}^{t_{end}} \dot{m}\,[h_{out}(T_{out}, P_{out}) - h_{in}(T_{in}, P_{in})]dt$$

t_{init}, t_{end} : initiation and end of elapsed time of cooling path (s)
$\dot{m}$: mass flow rate of SHe at the inlet (g/s)
$h_{out}(T_{out}, P_{out})$: enthalpy of SHe at the outlet (J/kg)
$h_{in}(T_{in}, P_{in})$: enthalpy of SHe at the inlet (J/kg)

- Hysteresis loss (J)[1]

$$Q_{hy} \approx \frac{4}{3\pi} D_{eff} \int_{B_{min}}^{B_{max}} J_c(B)dB \times A_{fil} \times \ell$$

D_{eff} : effective filament diameter (m)
B_{max}, B_{min} : maximum, minimum magnetic field (T)
$J_c(B)$: B dependent critical current density (A/m²)
A_{fil} : area of a single filament (m²)
ℓ : conductor length (m)

<u>Assumption</u>

$$Q_{tot} = Q_{hy} + Q_{cp}$$

Other losses (eddy current, wire motion, flux jumping, heat leaks, particle showers, nuclear heats) are negligible[2]

- Coupling current loss (J) and coupling time constant (s)[3]

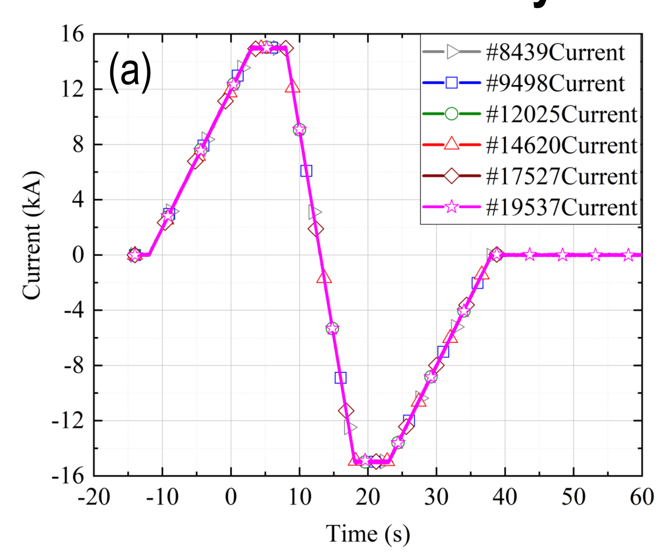
$$Q_{cp} = Q_{tot} - Q_{hy}$$

$$n\tau_{cp} = \frac{\mu_0 t_m}{2B_{max}^2} \cdot \frac{Q_{cp}}{A_{non\_sc} \cdot \ell}$$

n : 2, shape factor (null)
ℓ : conductor length (m)
τ_{cp} : coupling time constant (s)
t_m : elapsed time to the target magnetic field (s)
A_{non_sc} : non-superconducting area (m²)

◆ Commissioning Shot Data and Loss Evaluation Results

- **Data Plots of the Analyzed Commissioning Shots**



Parameter	Sensor	DAQ	Accuracy
Temperature	Cernox® 1050-CU-HT	SCXI-1125 / PXI-6280 / PXI-8196	0.088 K
Pressure	APT3200	Simatic S7-300 (PLC) / EPICS Soft-IOC	0.031 bar
Mass Flow Rate	Cernox® 1050-CU-HT APT3200 APT3100	LakeShore Temperature Monitor Simatic S7-300 (PLC) EPICS Soft-IOC (calculated here)	0.097 g/s

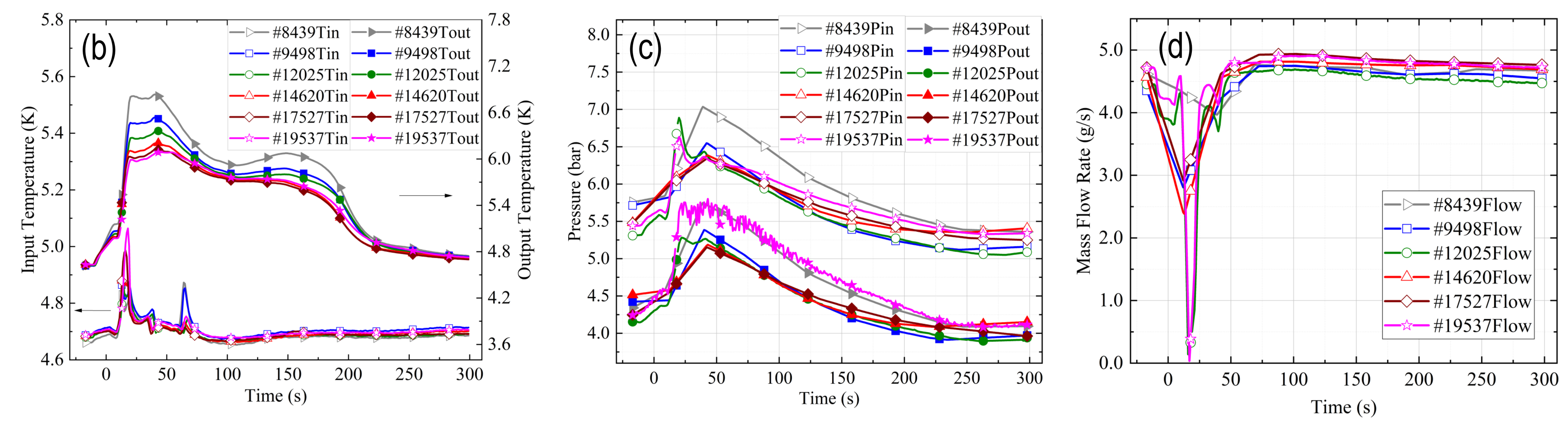


Fig. 2. (a) Current profiles of the analyzed shots (I_{peak} = 15 kA, up, down: di/dt = 1, −3 kA/s); (b) Temperature at the inlet and outlet showing decreasing trend in the peaks; (c) Pressure at the inlet and outlet; and (d) Mass flow rate of supercritical helium (SHe) at the inlet of the cooling channel. Measurement accuracies (absolute accuracies) were obtained using the conventional method with key parameters provided by the manual of the each device. The accuracies show reasonable values relative to the measurement range.

- **Major Source in the Total Loss Change: Change in Coupling Current Loss**

$$Q_{tot}^{Y} = Q_{hy}^{Y} + Q_{cp}^{Y} \qquad Y: \text{year of interest}$$
$$Q_{tot}^{Y-1} = Q_{hy}^{Y-1} + Q_{cp}^{Y-1}$$
$$\Delta Q_{tot} = Q_{tot}^{Y} - Q_{tot}^{Y-1} \approx (Q_{hy}^{Y} - Q_{hy}^{Y-1}) + (Q_{cp}^{Y} - Q_{cp}^{Y-1})$$

$\because \Delta Q_{tot} > Q_{hy} \Rightarrow \Delta Q_{hy}$ minor $\therefore \Delta Q_{cp}$ major

Table 2. AC Loss Evaluation Results

Year	Shot No.	Measurement Q_{tot} (J)	Calculation Q_{hy} (J)	Calculation Q_{cp} (J)
2013	#8439	8433.9	469.4	7964.5
2014	#9498	6926.1	469.8	6456.3
2015	#12025	6134.0	470.3	5663.7
2016	#14620	5454.8	469.4	4985.4
2017	#17527	5276.5	469.7	4806.8
2018	#19537	5114.4	470.4	4644.0

◆ Discussion: Total Loss Change and Aspects of Coupling Time Constant

- **Calculation of $n\tau_{cp}$ in Different Ramping Rate**

Q_{cp} separated by empirical ratio:

Loss at ramp up $$Q_{cp,up} = \frac{2B_{max}^2 n\tau_{cp,up}}{\mu_0 t_m} \times A_{non\_sc} \times \ell$$

Loss at Ramp down $$Q_{cp,dn} = \frac{2B_{max}^2 n\tau_{cp,dn}}{\mu_0 t_m} \times A_{non\_sc} \times \ell$$

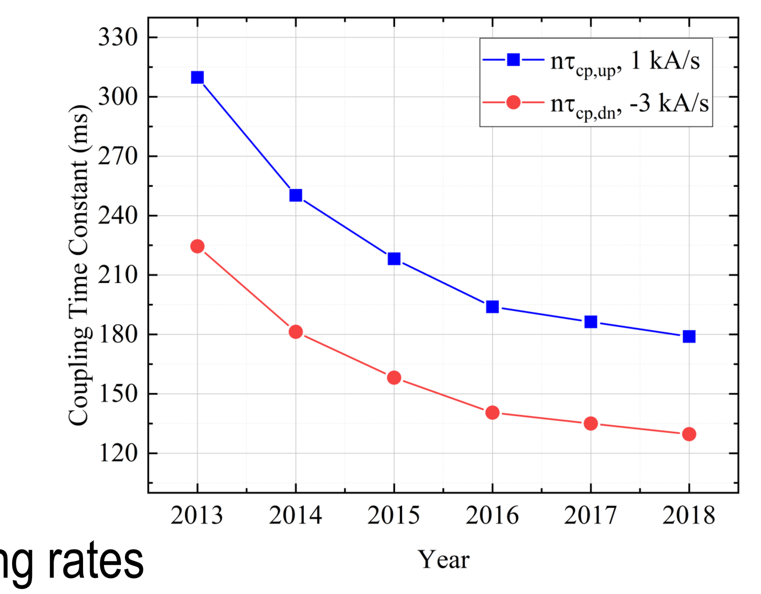


Fig. 3. Coupling time constant of different ramping rates

- **Yearly Decreasing Trend of $n\tau_{cp}$**
  - Fig. 3 shows yearly decreasing $n\tau_{cp}$ for both ramping rates
  - From Eq. 1, effective resistivity may have changed due to some changes in the mechanical contacts between the strands
  - Results of transverse cyclic loading experiments on the ITER model CICC show similar tendencies[4]

$$\tau_{cp} = \frac{\mu_0 \ell_p^2}{8\pi^2 \rho_{eff}}$$

ℓ_p^2 : twist pitch length [m]
ρ_{eff} : effective transverse resistivity [Ω·m]

Eq. 1. Analytic equation of coupling time constant[2]

- **Ramping Rate Dependency of $n\tau_{cp}$**
  - Fig. 3 shows a lower $n\tau_{cp}$ for higher ramping rate
  - When $n\tau_{cp} \ll t_m$, inter-strand coupling current flows through a dominant current path → $n\tau_{cp}$ is determined by the dominant path of the current
  - In Fig. 3, $n\tau_{cp} \approx 0.3$ s is comparable to $t_m = 15$ s (ramp up) or $t_m = 5$ s (ramp down)
    → dominant path of the current may change → $n\tau_{cp}$ is not determinate
    → current ramping rate dependency

◆ Conclusion: Total Loss Variation is Highly Relevant to $n\tau_{cp}$ Variation

- Commissioning shots for the KSTAR PF1L coil were plotted and analyzed.
- The total loss measured by calorimetric method shows a decreasing trend by the year.
- By AC loss analysis, $n\tau_{cp}$ seem to be dominant in the total loss change.
- It showed yearly decreasing trend and difference between different ramping rate.

References
[1] C. Gung, M. Takayasu, and J. Minervini, "Experimental estimation of energy dissipation in ITER central solenoid superconductor," in *15th IEEE/NPSS Symposium. Fusion Engineering*, vol. 2. IEEE, 1993, pp. 692-695.
[2] Y. Iwasa, *Case Studies in Superconducting Magnets: Design and Operational Issues*. Springer Science & Business Media, 2009.
[3] M. N. Wilson, *Superconducting Magnets*, Clarendon Press Oxford, 1983.
[4] A. Nijhuis, Y. Ilyin, W. Abbas, B. ten Haken, and H. H. ten Kate, "Performance of an ITER CS1 model coil conductor under transverse cyclic loading up to 40,000 cycles," *IEEE Trans, Appl. Supercond.*, vol. 14, no. 2, pp. 1489-1494, 2004

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