Thermal and Electric Analysis of Flux Pump for Conduction Cooled Superconducting Magnet

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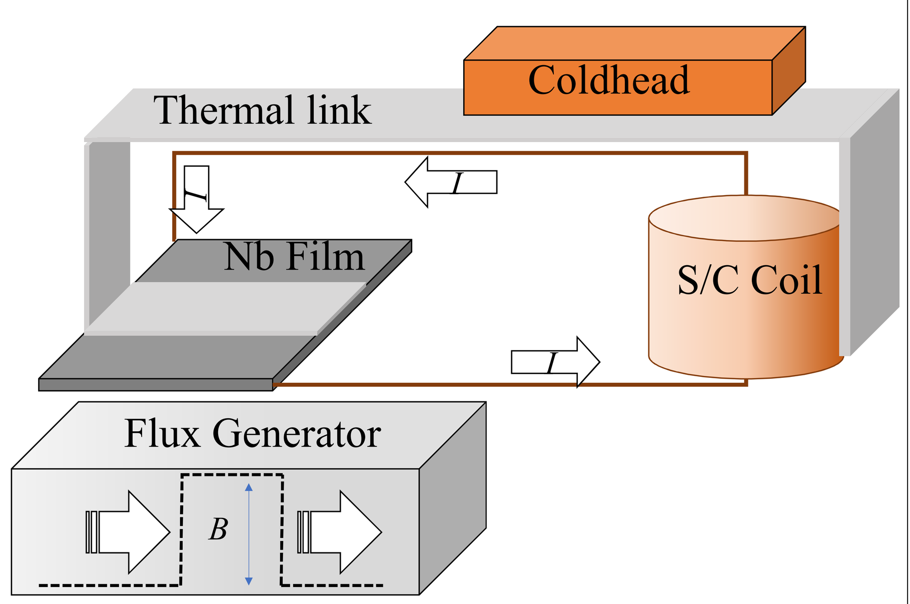
Introduction

- ❖ A superconducting magnet system requires a current feeder, usually using current leads which are one of the major heat load of the superconducting magnet system.
- ❖ **Flux pump can be a fascinating alternative of the current leads because it requires no mechanical contacts from feeder to the magnet system, thus, it can reduce the heat load from the outside system**.
- ❖ However, the flux pump generates small amount of heat which can be a critical load for conduction cooled magnet system.
- ❖ **A simple flux pump model is established and simulated** to investigate the thermodynamic behaviour of flux pump with conduction cooling system.

Flux Pump with Conduction Cooled Magnet System Schematics

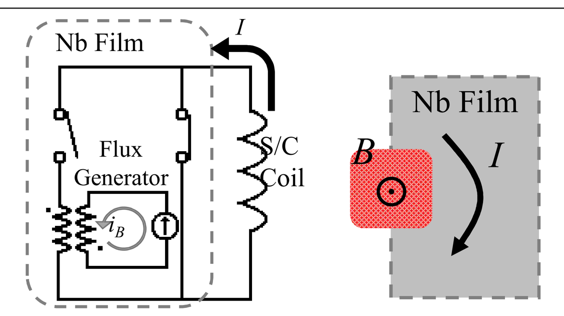


[Schematics of the flux pump system for conduction cooled magnet]

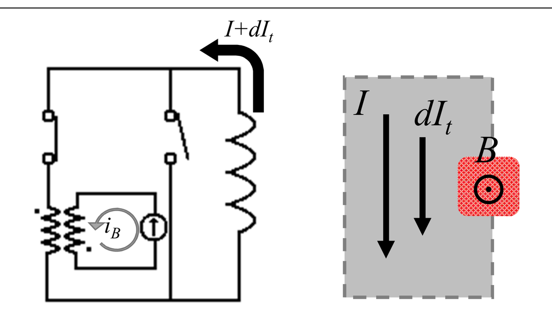
- ❖ A flux pump system is composed of
  - ➢ [Coldhead] : Terminal link of cryocooler.
  - ➢ [S/C coil] : Main superconducting coil.
  - ➢ [Thermal link] : Link for conduction cooling.
  - ➢ [Nb film] : Superconducting film for switching operation.
  - ➢ [Flux generator] : Generating moving flux.
- ❖ Based on this schematics, **Electrical Circuit, Flux Generator, Nb superconducting film** with **its thermodynamic behaviour** are modelled for simulation study.

Electrical Circuit Modelling with Nb Film Status

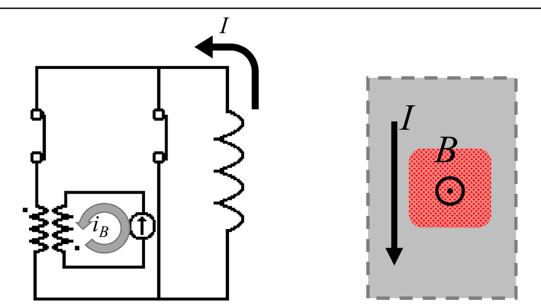
- ❖ Electrical circuit characteristic of the flux pump can be expressed as a transformer with two switches.



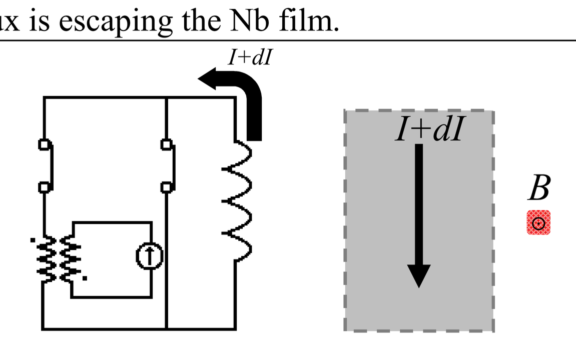
(a) The outside switch is opened and primary side is charged when the flux heats the outside of Nb film.



(c) The current start to be transferred to the coil while the flux is escaping the Nb film.

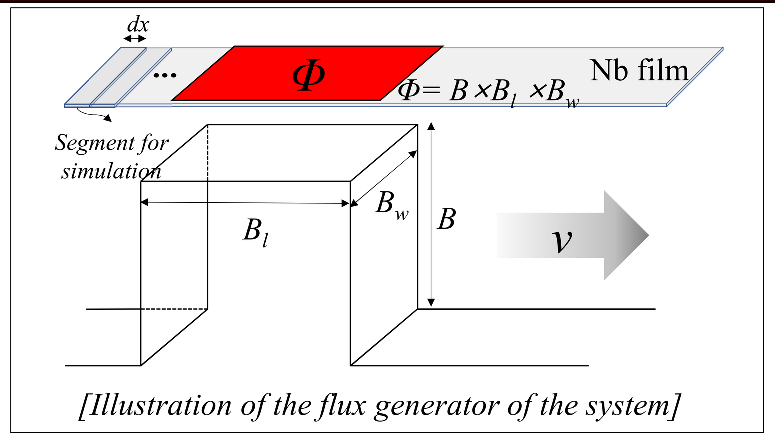


(b) Once the flux is fully trapped inside the Nb film, the transformer is fully charged and both of the switches are closed



(d) After the flux is diminished, the current is fully transferred into the S/C coil, and system waits for next pumping sequence.

Flux Generator & Nb Film Modelling



[Illustration of the flux generator of the system]

TABLE I
PHYSICAL PROPERTIES OF NB FILM

Physical Property	Chosen Value
Critical Temperature	9.2 K
Critical Current Density	2.40×10^8 A/m^2
Critical Magnetic Field(H_{c2})	410 mT
Heat Capacity	385 J/kg·K
Thermal Conductivity	400 W/m·K
Density	8700 kg/m^3

- ❖ Flux generator generates moving flux toward inside the system. The shape of the flux is rectangular wave which travels speed of *v*. Linear type flux pump is assumed for operation.
- ❖ Representative physical properties of Nb is chosen for the Nb film modelling. The Nb film is virtually split into small calculation segments for the simulation process.

Thermodynamic Modelling

- ❖ The major heat source of the flux pump operation is AC loss originated from the changing flux. Thin slab model is used for the AC loss calculation.

$$Q_{AC} = \frac{\Delta B^3 \cdot V}{12 \cdot \mu_0^2 \cdot j_c \cdot a}$$

V : volume of segment, j_c : critical current density, *a* : width of Nb film

- ❖ The heat generated in one segment spread to neighbour segments by conduction.

$$\dot{Q}_{cond} = k \cdot A_{seg} \cdot (T_{neighbor} - T_{segment}) \cdot dx$$

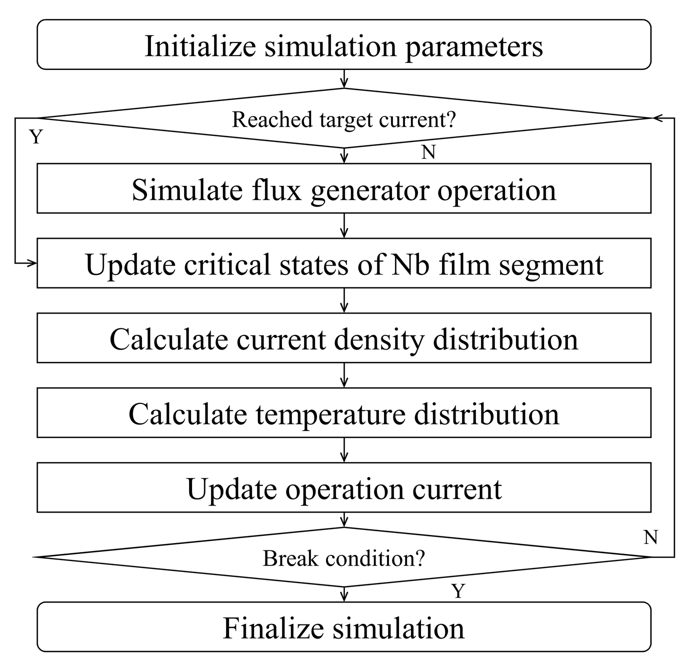
k : thermal conductivity of Nb, A_{seg} : contact area between segments

- ❖ The Nb film is cooled by the thermal link which has cooling coefficient ***c***.

$$\dot{Q}_{cool} = c \cdot A_{th} \cdot (T_{segment} - T_{base})$$

c : cooling coefficients of the thermal link, A_{seg} : contact area between segment and thermal link

Simulation Flow & Design Parameter



[Flowchart of the simulation]

- ❖ Simulation flow is shown in the left diagram.
- ❖ The simulation stops when it reached break conditions
  - ➢ End of simulation time.
  - ➢ Thermal runaway.
- ❖ Simulation target current is set to 10 A.

TABLE II
COMMON DESIGN PARAMETERS FOR EACH MODEL

Design Factor	Chosen Value
Superconducting coil inductance	50 mH
Target operation current	10 A
Target ramping rate	1 A/s
Base temperature	4.2 K
Field strength of the flux generator	1 T
Frequency of the flux generator	60 Hz
Thickness of Nb file	0.5 mm

Dependent Variables

- ❖ Some variables are dependent to the design parameters.
- ❖ Speed of flux can be calculated from width of the Nb film and frequency of generator.

$$v = a \cdot f$$

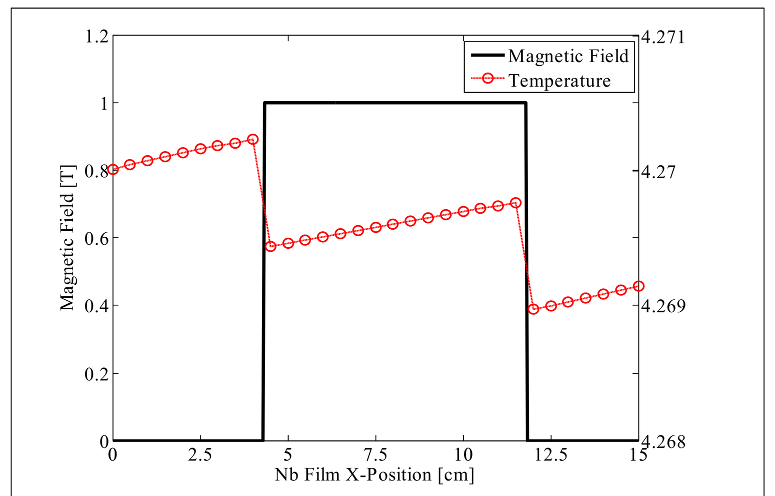
- ❖ If the length of flux B_l is set *a/2* for linear type, the period of one pumping sequence is

$$\tau = (a + 2B_l)/v = 3/f$$

- ❖ The width of the flux B_w with desired ramping rate can be calculated as follows.

$$B_w = \frac{\tau L}{B \cdot B_l} \cdot \frac{di}{dt}$$

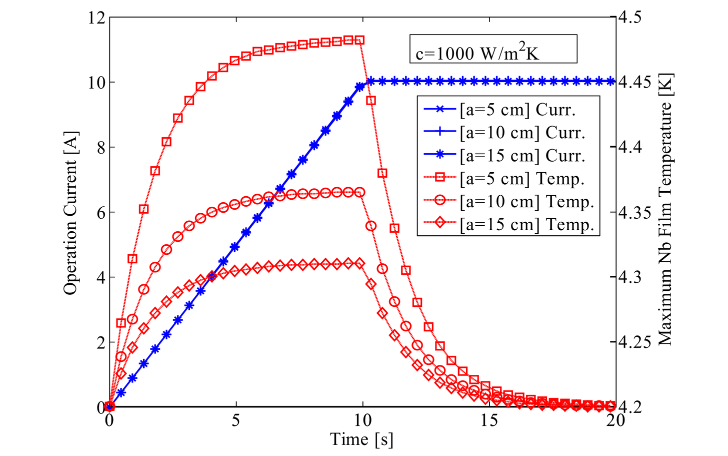
Heat Distribution During Pulse



[Temperature distribution of the Nb film]

- ❖ The temperature increases at the point of flux changing.
- ❖ The heat is spread and cooled by conduction.

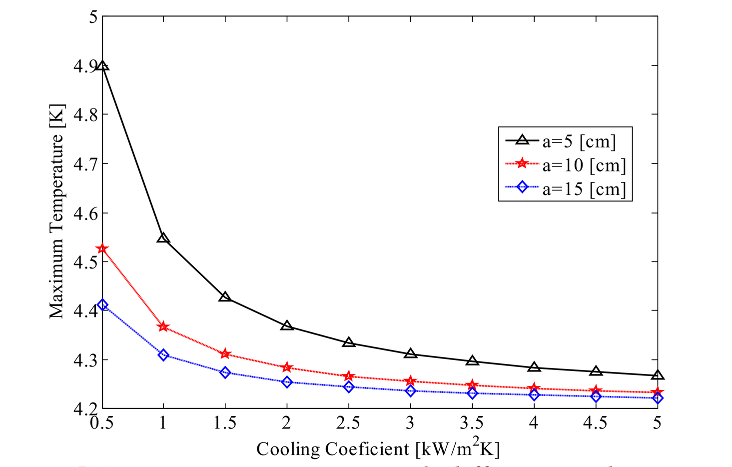
Temperature & Current



[Operation current and maximum temperature of the Nb film]

- ❖ The desired ramping rate 1 A/s is achieved for every Nb film width, 5, 10, and 15 cm.
- ❖ Narrower film gets higher temperature.

Effect of Cooling Coefficient



[Maximum temperature with different cooling coefficients and Nb film widths]

- ❖ The inversely proportional relation between the maximum temperature and cooling coefficient is checked by the simulation.

Conclusion

- ❖ A simple model of flux pump is established and simulated.
- ❖ **Some dependent relations of design parameters are derived. Based on the relation, desired ramping rate characteristic has been achieved in the simulation.**
- ❖ The relation between cooling coefficient and maximum temperature of the Nb film is derived. **The required cooling coefficient can be calculated for target temperature.**
- ❖ Yet, the simulation model should be improved with,
  - ➢ **More accurate AC loss model is needed.**
  - ➢ More precise Nb film model should be collected with experimental way.
- ❖ These features will be studied with experiment in future study.

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