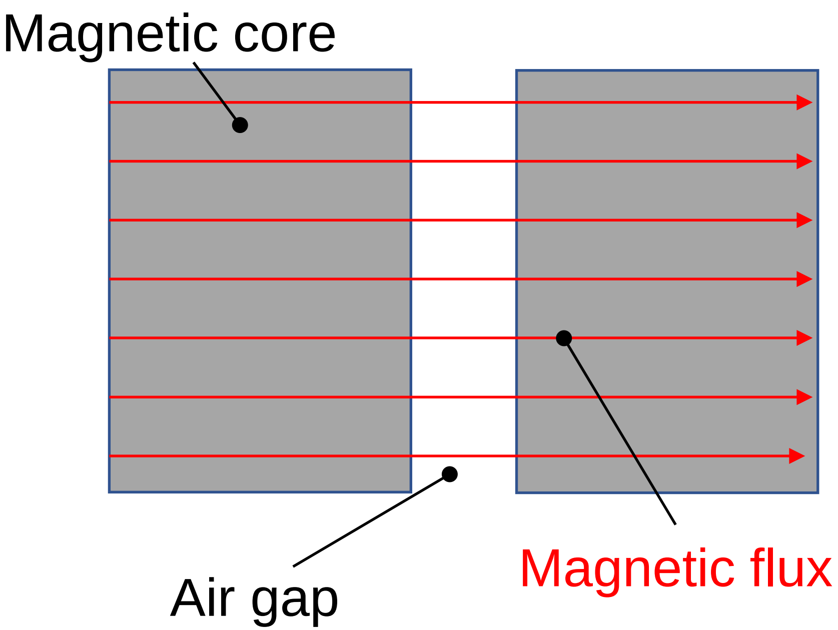
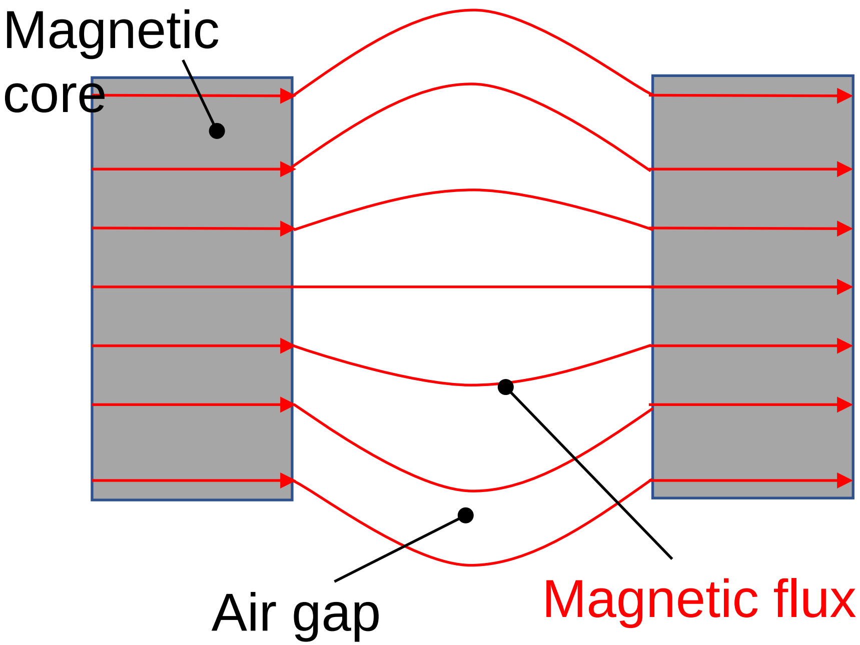
Formulation for the reluctance of the wide air gap

Magnetic flux in a narrow air gap



No magnetic flux spread in the air gap,
➡the reluctance can be calculated using air gap space volume.

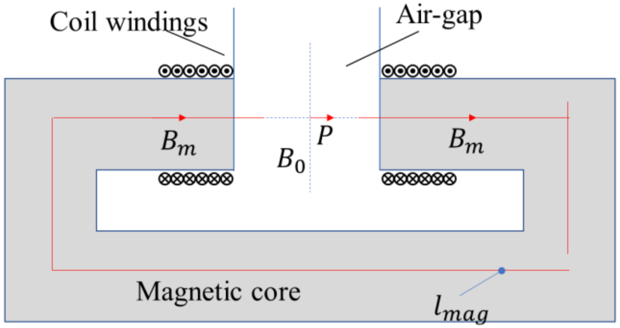
Magnetic flux in a wide air gap



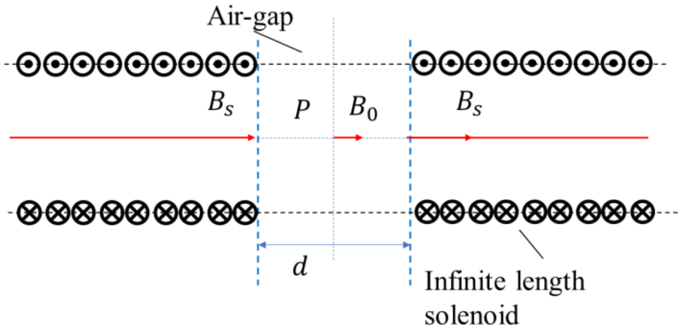
Magnetic flux will spread in the wide air gap,
➡the reluctance calculation becomes difficult.

A simple equivalent model of the electromagnet

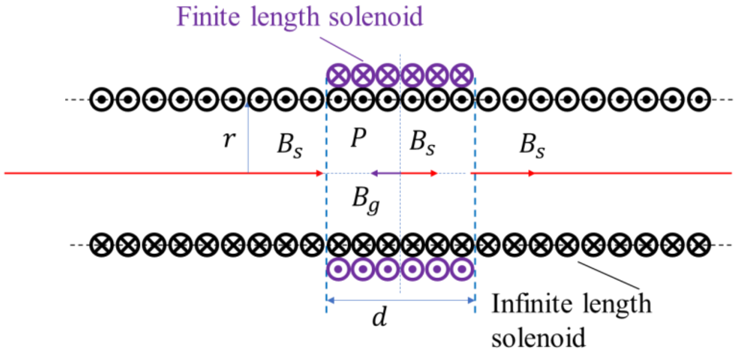
Electromagnet with a wide air gap



A infinite length solenoid with a wide air gap

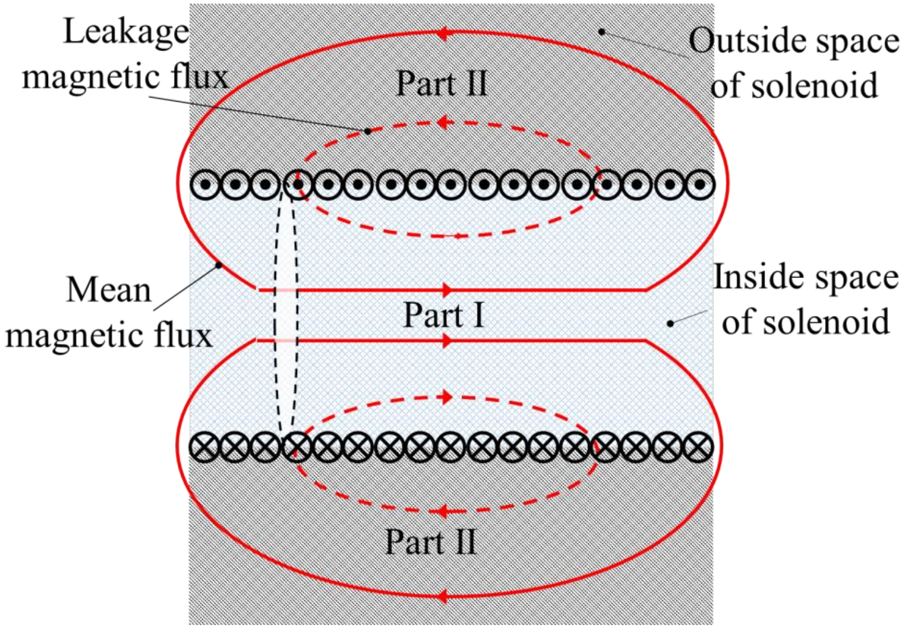


A infinite length solenoid with a reverse direction finite length solenoid

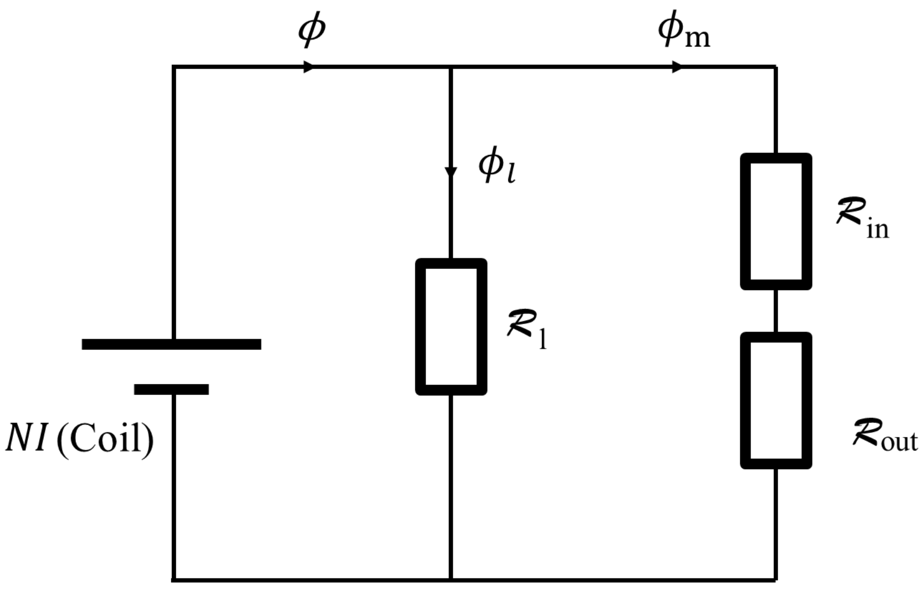


Magnetic flus distribution of the finite solenoid

Magnetic flux distribution



Equivalent magnetic circuit



Self-inductance of the finite solenoid can be calculated using the Nagaoka coefficient K_n

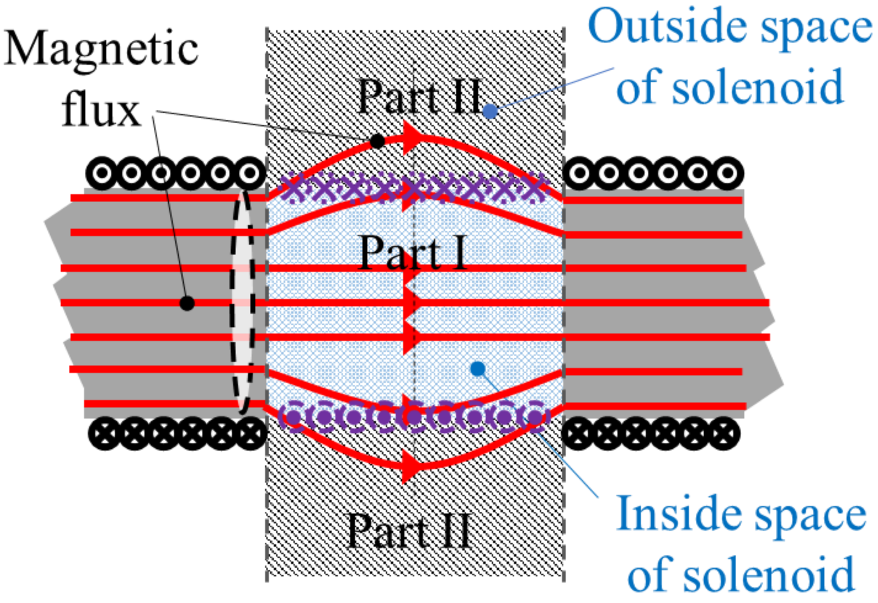
Assuming the leakage flux can be neglected

$$\Rightarrow \quad L = \frac{N^2}{\mathcal{R}_{in} + \mathcal{R}_{out}}$$

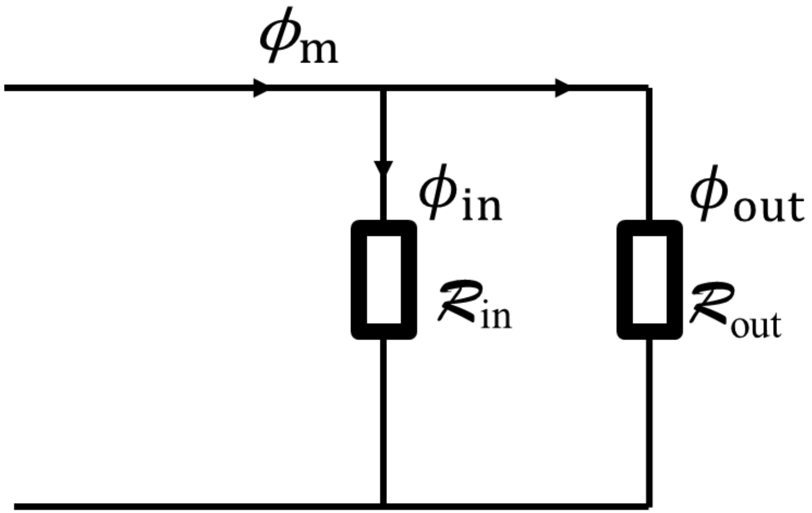
$$L = K_n \frac{\mu_0 S}{d} N^2 = K_n \frac{1}{\mathcal{R}_{in}} N^2 = \frac{N^2}{\mathcal{R}_{in} + \mathcal{R}_{out}} \Rightarrow \mathcal{R}_{out} = \frac{1 - K_n}{K_n} \mathcal{R}_{in}$$

Magnetic Flux distribution in a Wide air gap

Wide air gap



Equivalent magnetic circuit



The magnetic flux are the same direction in part I and part II

Parallel connection

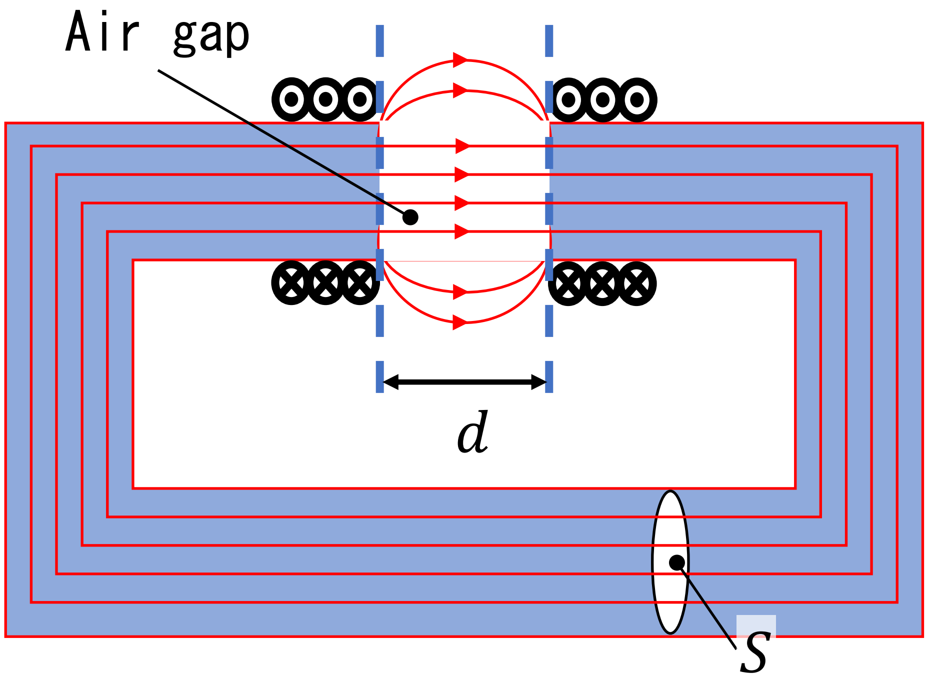
$$\frac{1}{\mathcal{R}_{air}} = \frac{1}{\mathcal{R}_{in}} + \frac{1}{\mathcal{R}_{out}}$$

The reluctance of the wide air gap

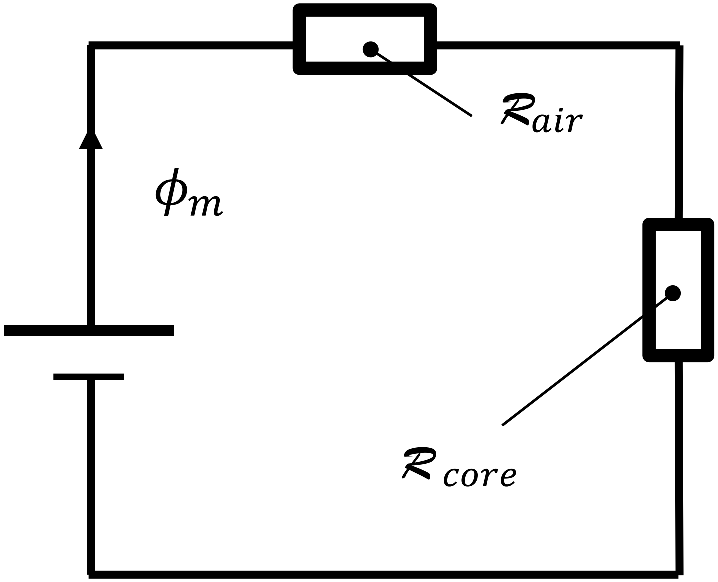
$$\mathcal{R}_{air} = (1 - K_n)\mathcal{R}_{in} = (1 - K_n)\frac{d}{\mu_0 S}$$

Self-inductance of electromagnet

Electromagnet with a wide air gap



Equivalent magnetic circuit



$$\mathcal{R}_{air} = (1 - K_n)\frac{d}{\mu_0 S} \qquad (5)$$

$$L = \frac{N^2}{\mathcal{R}_{core} + \mathcal{R}_{air}} \qquad (6)$$

Cooling system design for real-scale electromagnet

Base on the thermal equilibrium equation :

$$U = (P_C + P_m) \cdot t_{\mathrm{op}} = U_c + U_m + U_r$$

$$= \int_{T_0}^{T_{\max}} m_{\mathrm{c}} C_{\mathrm{c}} + m_{\mathrm{m}} C_{\mathrm{m}} \, dT + \int_{T_o}^{T_{\mathrm{r}}} Q t_{\mathrm{op}} \rho_{\mathrm{r}} C_r \, dT$$

U_c : specific heat capacity of coil windings
U_m: specific heat capacity of magnetic core
U_r:endothermic energy of coolant

$m_C C_{\mathrm{C}}$: mass and specific heat capacity of coil winding
$m_{\mathrm{m}} C_{\mathrm{m}}$: mass and specific heat capacity of magnetic core
$T_{\max} - T_o$: temp. rise of electromagnet

Q: coolant volumetric flow rate
$\rho_r C_r$: liquid density and specific heat capacity of coolant
$T_{\mathrm{r}} - T_0$: temp. rise of coolant

➡

$$Q = \frac{(P_{\mathrm{C}} + P_{\mathrm{m}}) t_{\mathrm{op}} - (m_{\mathrm{c}} C_{\mathrm{c}} + m_{\mathrm{m}} C_{\mathrm{m}})(T_{\max} - T_0)}{t_{\mathrm{op}} \rho C_{\mathrm{r}} (T_r - T_0)}$$

Coolant

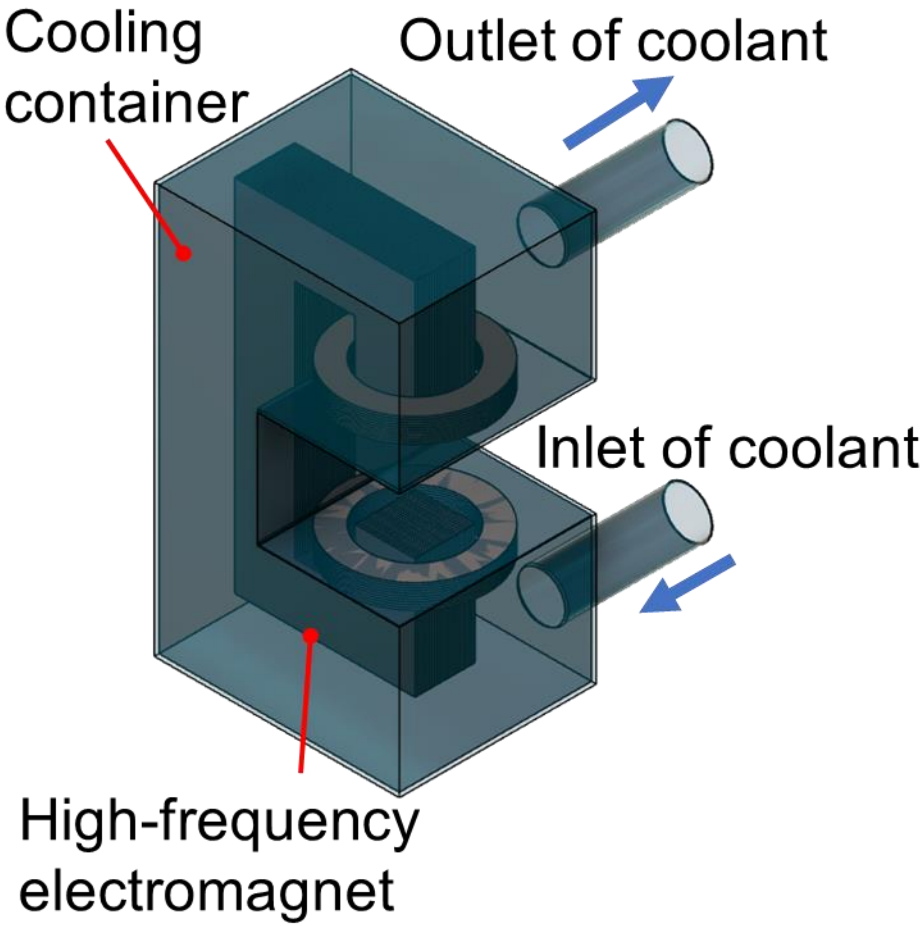
3M Fluorinert Electronic Liquid FC-40

It is necessary that use a low dielectric constant coolant to reduce the effect on the self-inductance of the electromagnet because the electromagnet is operated at high-frequency.

	FC-40 Flrorinert	Pure water
Boiling point	165 ℃	100 ℃
Liquid density	1870 kg/m^3	1000 kg/m^3
Liquid specific heat	1050 J/kg・K	4217 J/kg・K
Dielectric constant	1.9	80

URL:https://www.3mae.ae/3M/en_AE/p/d/v000586117/#variation1

Cooling system design for real-scale electromagnet



t_{op}	360 s
ρ_{r}	$1855\ \mathrm{kg}\ /\mathrm{m}^3$
ρ_{c}	$8960\ \mathrm{kg/m}^3$
ρ_{m}	$4800\ \mathrm{kg/m}^3$
C_r	$1100\ \mathrm{J/kg}\cdot\mathrm{K}$
C_{C}	$386\ \mathrm{J/kg}\cdot\mathrm{K}$
C_{m}	$600\ \mathrm{J/kg}\cdot\mathrm{K}$
T_0	25℃
$T_{\max}$	75℃
T_{r}	50℃
Q	21.5 L/s
$Q\cdot t_{\mathrm{op}}$	7731 L