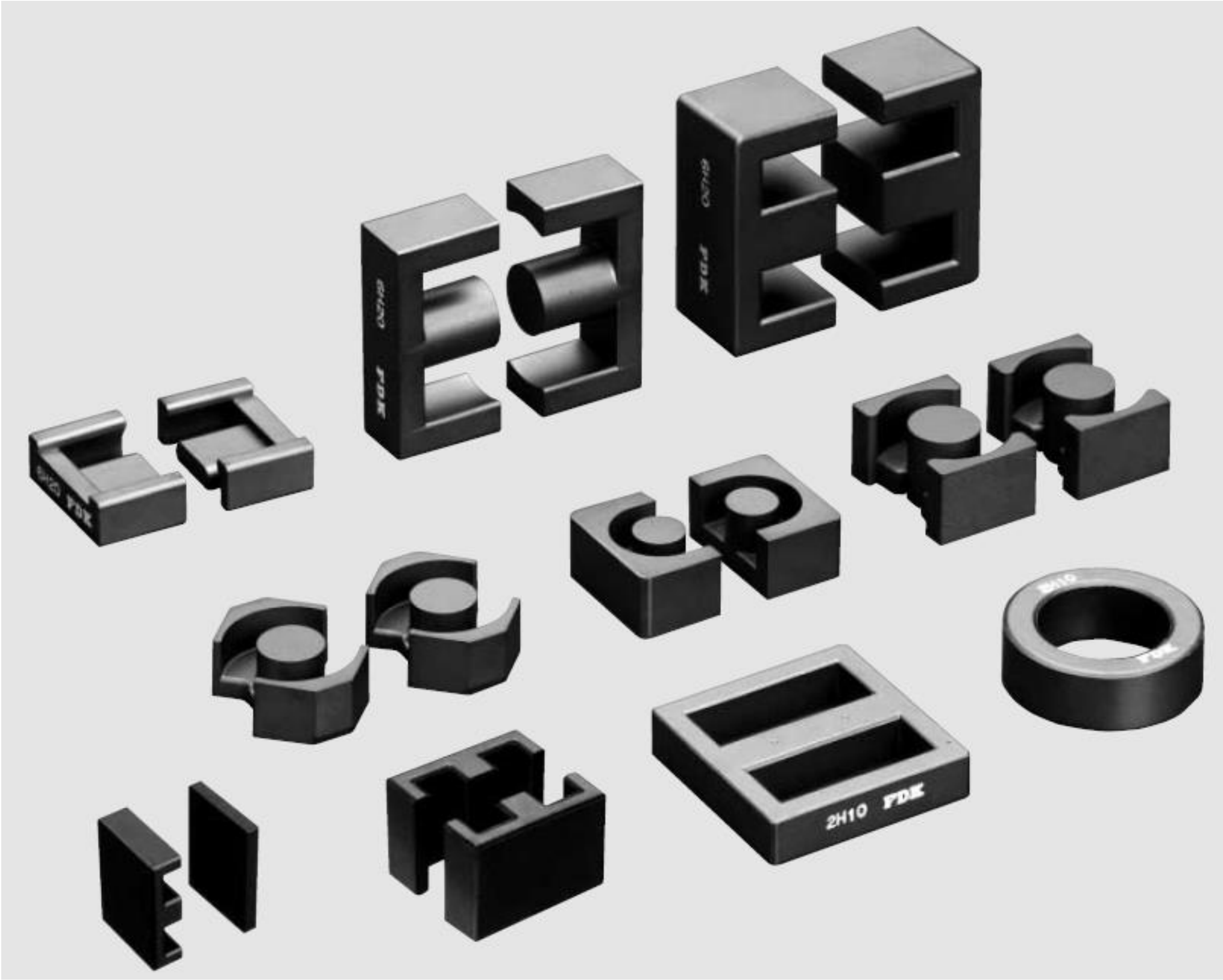
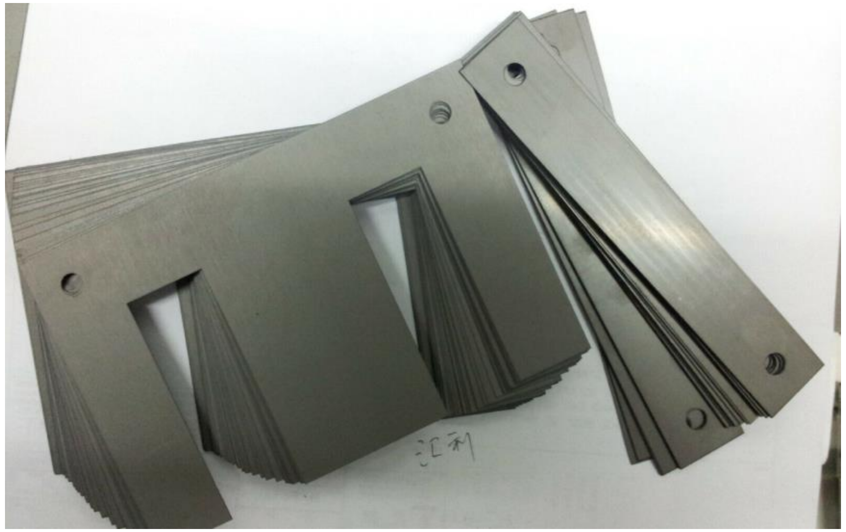
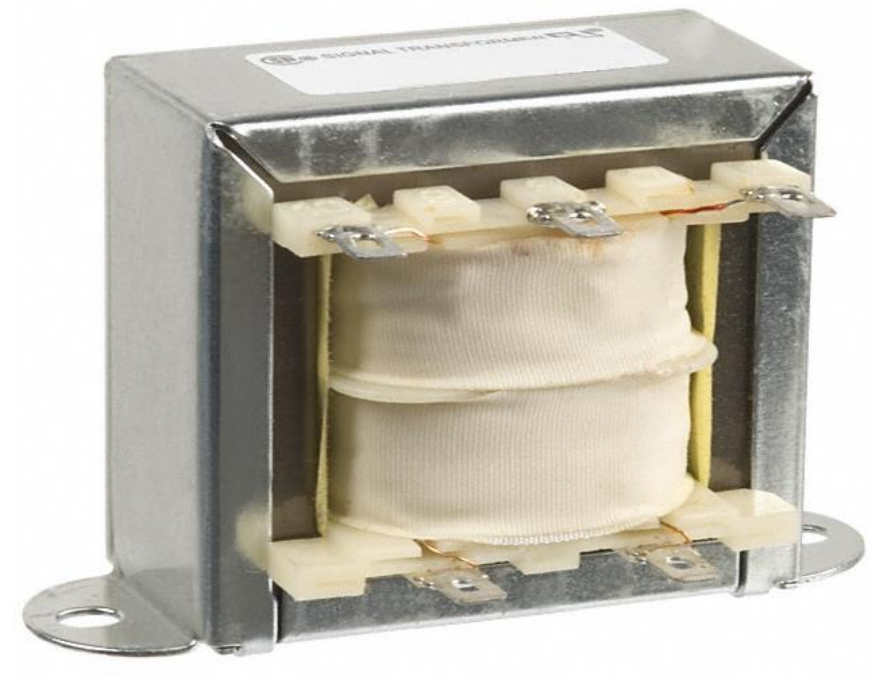
Ferrite cores



Laminated steel cores



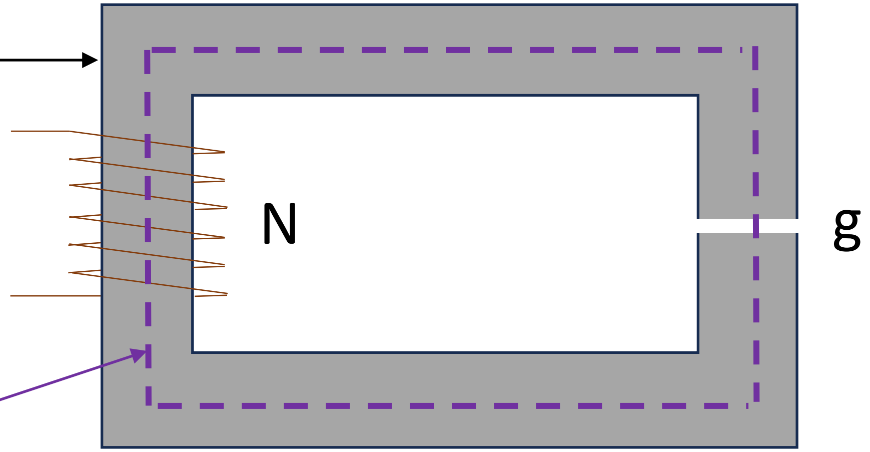


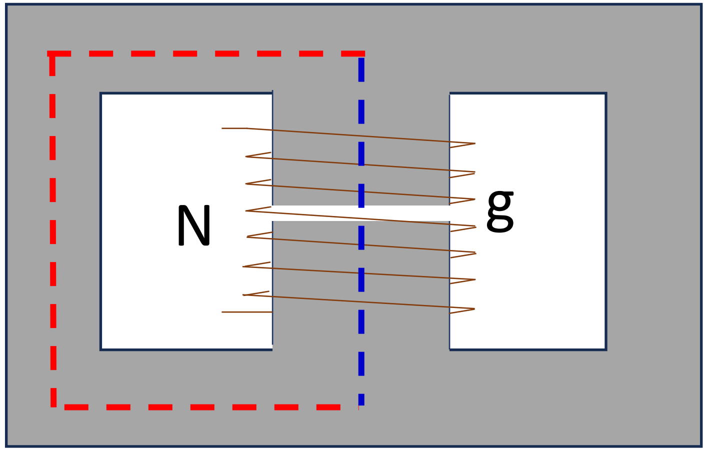
Within this educational project, we delve into the calculation methodologies for magnetic cores in coils and transformers, employing the classical framework rooted in principles of reluctance, magnetic flux, induction, magnetomotive force (MMF), and inductance. This classical model, by design, operates under the assumption of constant magnetic permeability throughout the entirety of the magnetizing field, thus simplifying analysis. Notably, it does not account for hysteresis effects.

This simplified approach serves as an excellent entry point for students, providing a foundational understanding of magnetic core behaviour without overwhelming complexities. Nonetheless, it's imperative to acknowledge the limitations inherent in this model. Specifically, the absence of hysteresis consideration and the assumption of linear permeability overlook real-world nuances. Introducing students to these simplified models while elucidating their constraints paves the way for a more comprehensive grasp of magnetic phenomena. Such an approach cultivates a solid foundation for future exploration into advanced studies or practical applications where accounting for hysteresis and nonlinearity becomes indispensable.

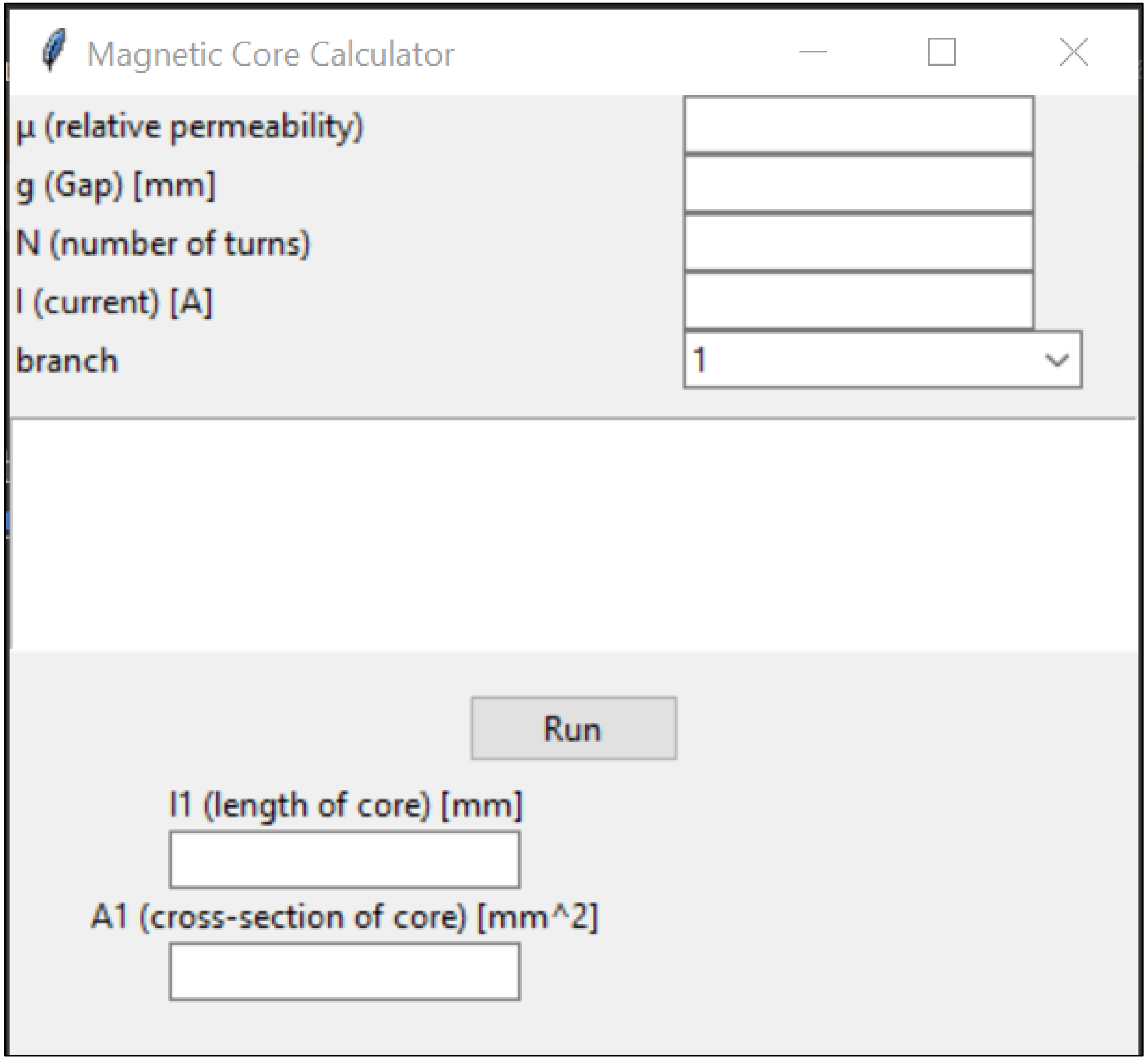
Console application: main.py

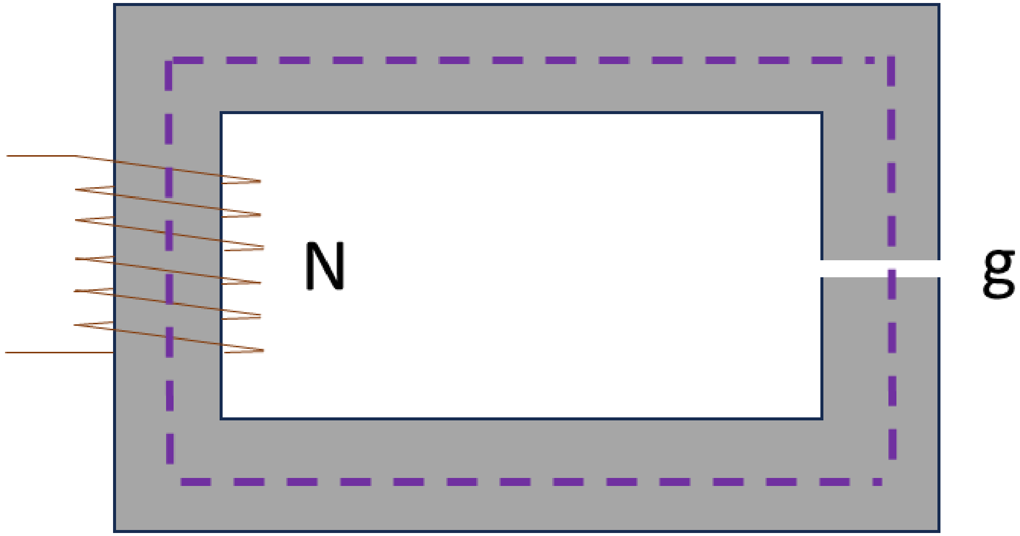
```
# Input parameters
mu = 1540.0  # core relative magnetic permeability
g = 0.2  # gap (mm) in the single loop or central part
N = 50  # number of turns of the coil
I = 0.5  # current (A) through the coil
branch = 2  # single loop core (1) or branched core (2)

# If the single loop core (otherwise ignore):
l1 = 0.0  # length of the core in mm
A1 = 0.0  # cross-section of the core in mm^2

# If the branched core (otherwise ignore):
lc = 29.3  # length of the central part in mm
Ac = 123.21  # cross-section of the central part in mm^2
lb = 59.1  # length of each branch part in mm
Ab = 61.605  # cross-section of the branch part in mm^2
```



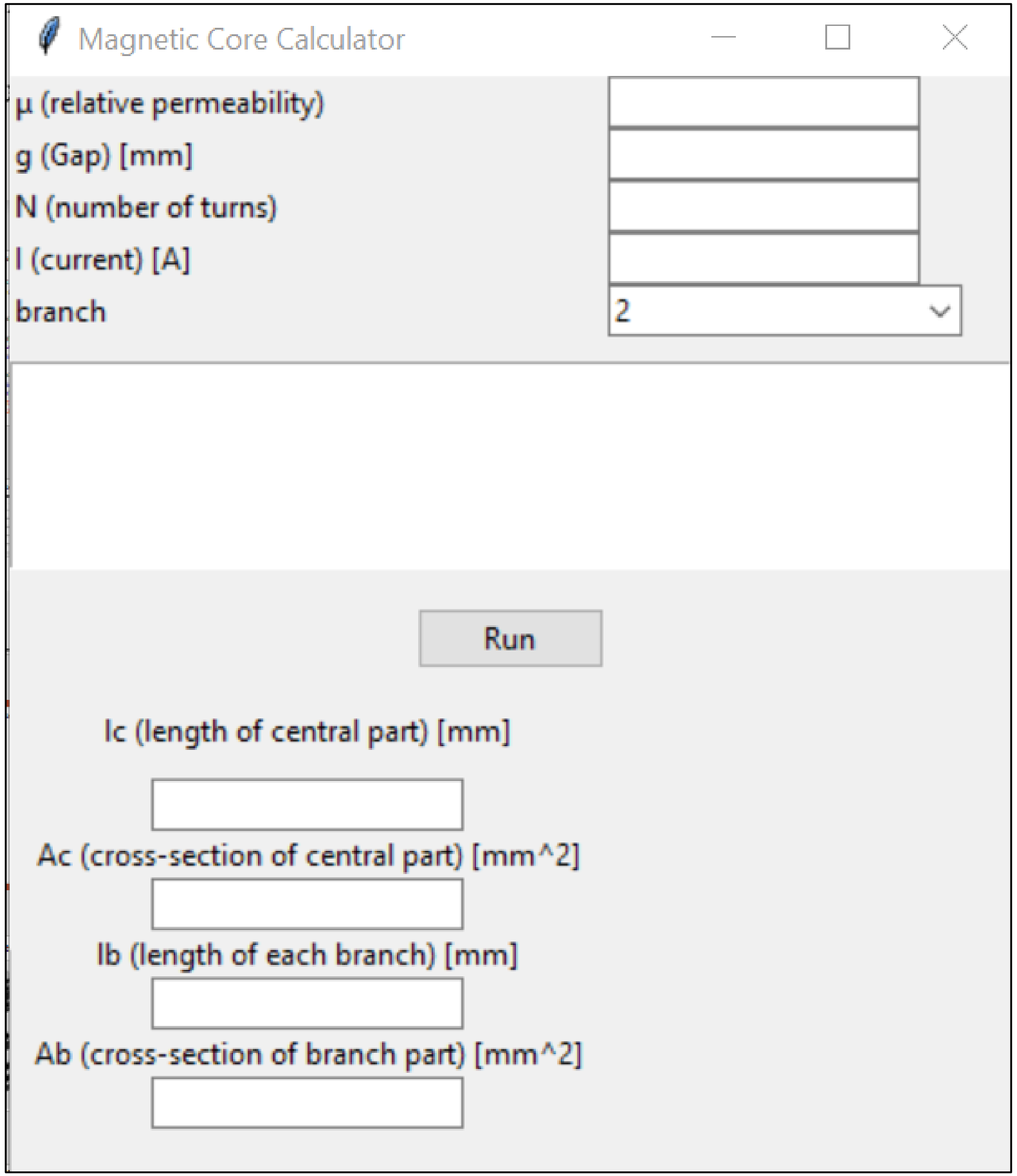


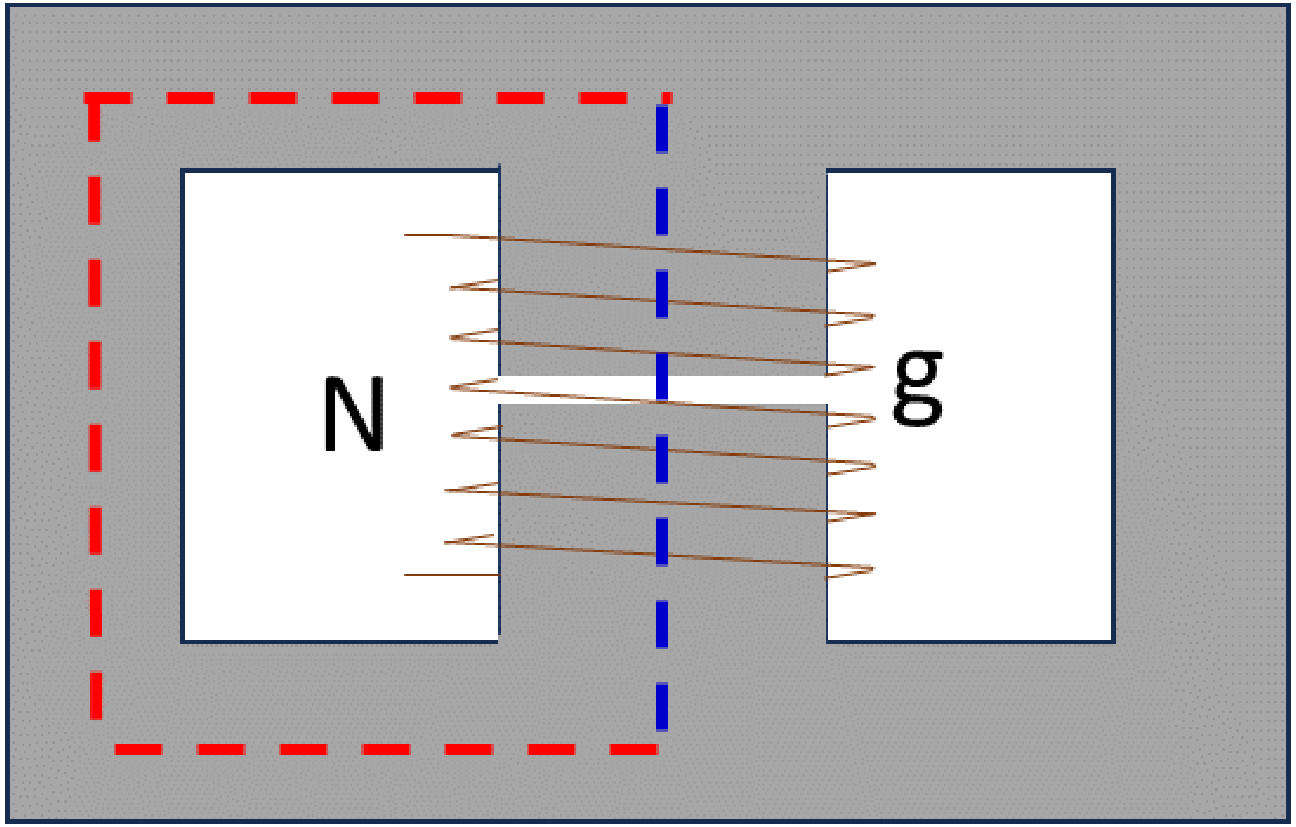
User interface: GUI.py



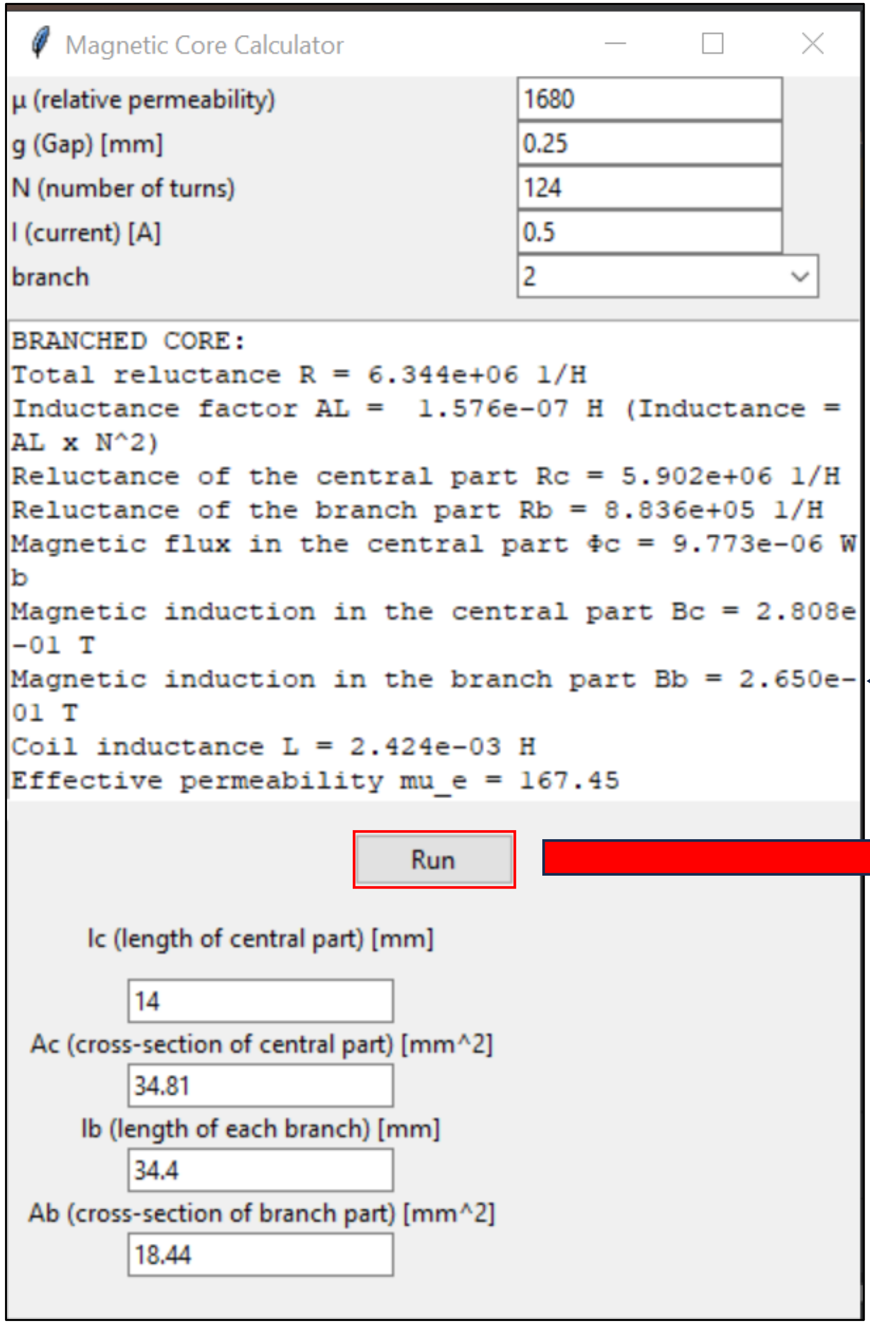


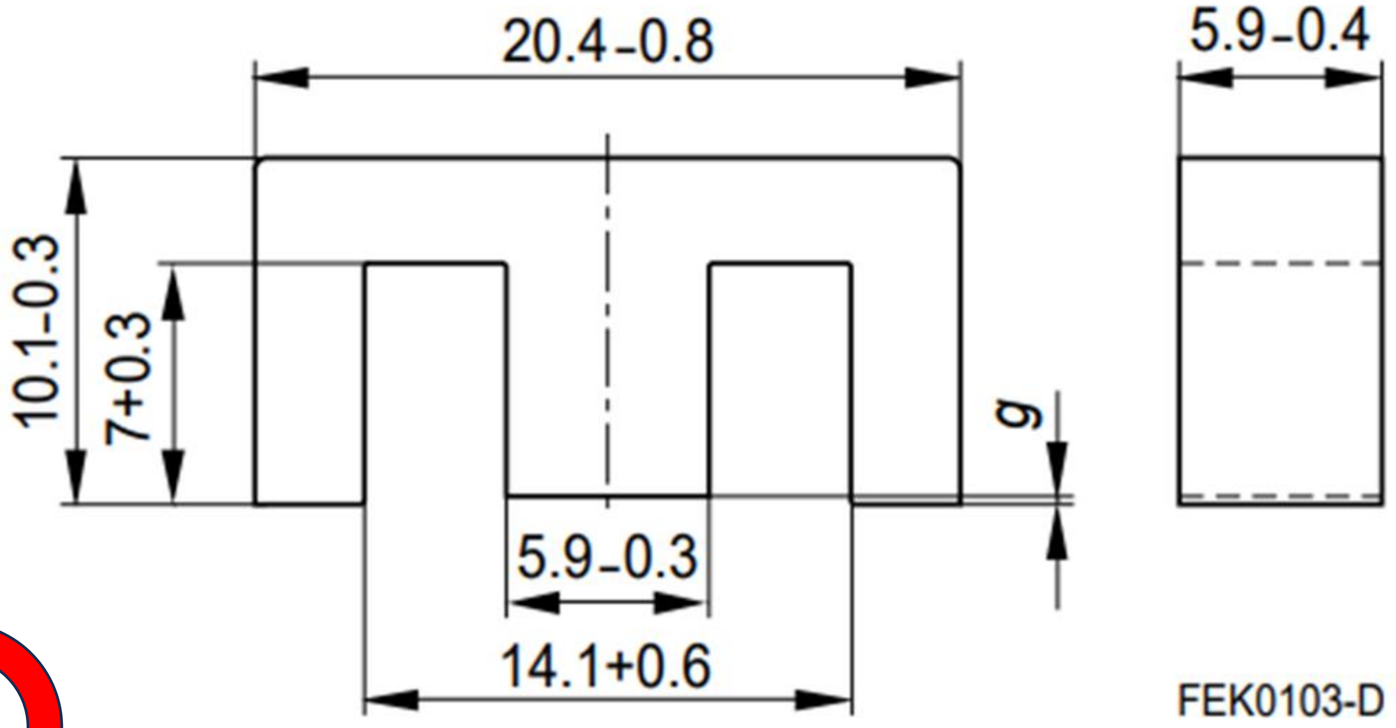
User interface: GUI.py

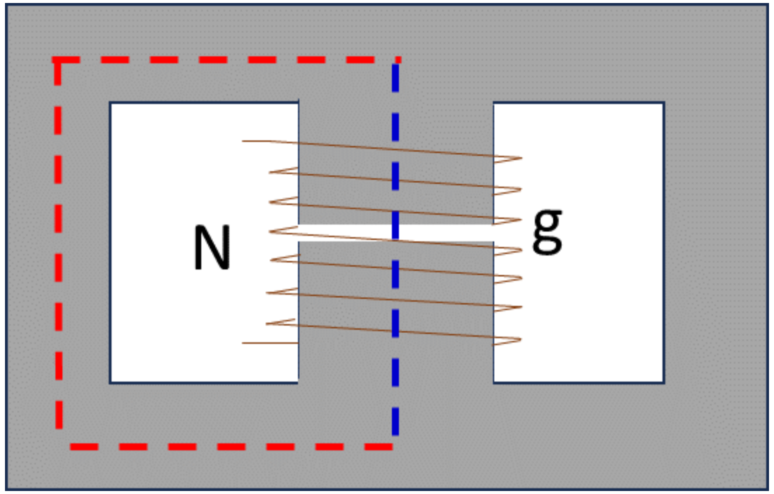




Calculation example: GUI.py

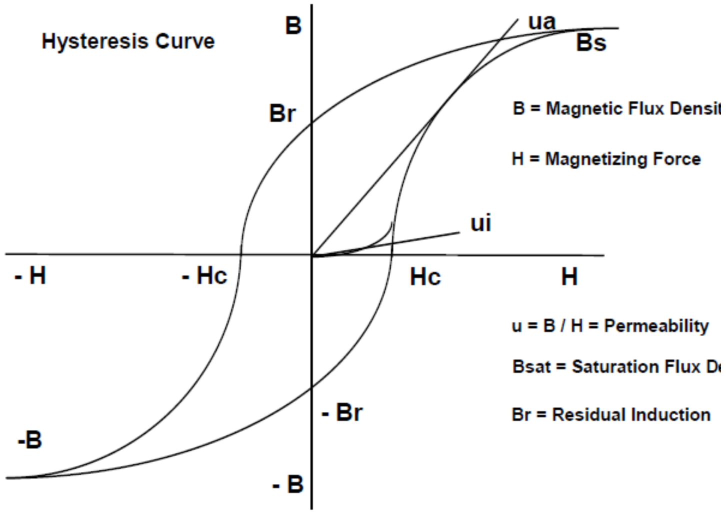






Ferrite cores

Magnetic saturation is an asymptotic state. Therefore, it is indicated for which **H** (1000 A/m) the induction (flux density) **B** was measured when approaching its saturation value.



Materials are only ferromagnetic below their corresponding **Curie temperatures**.

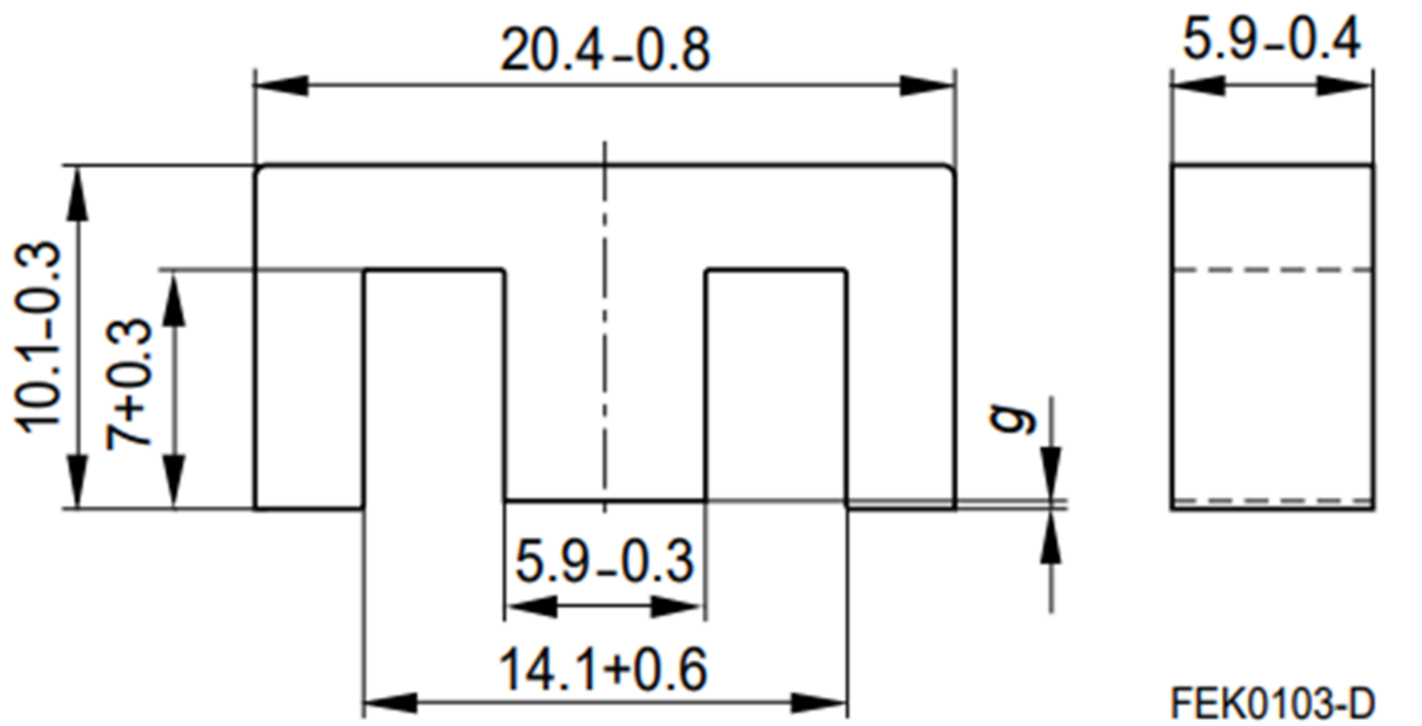
Standard material characteristics (Power material)

Property	Symbol		Condition	Unit	6H10	6H20	6H40	6H41	6H42	7H10	7H20
AC initial permeability	μi		0.1 MHz	—	2500	2300	2400	2500	3400	1500	1000
Saturation magnetic flux density	Bs (1000 A/m)		23 °C	mT	510	510	530	530	530	480	480
			100 °C		390	390	430	430	430	380	380
Residual magnetic flux density	Br		23 °C	mT	110	130	110	110	110	150	130
Coercivity	Hc		23 °C	A/m	13	13	10	10	10	30	25
Relative loss factor	tanδ/μi		0.1 MHz	$\times 10^{-6}$	<5	<5	<3	<3	<3	<5	<4
Core loss	200 mT	25 kHz	23 °C	kW/m^3	—	—	90	75	60	—	—
			40 °C		—	—	75	60	50	—	—
			60 °C		65	80	60	50	40	—	—
			80 °C		55	65	50	40	45	—	—
			100 °C		80	55	40	45	55	—	—
		100 kHz	23 °C	kW/m^3	—	—	650	550	450	—	—
			40 °C		—	—	550	450	350	—	—
			60 °C		450	550	450	350	300	—	—
			80 °C		400	450	350	300	325	—	—
			100 °C		500	400	300	325	375	—	—
	50 mT	500 kHz	60 °C	kW/m^3	—	—	—	—	—	100	50
			80 °C		—	—	—	—	—	80	40
			100 °C		—	—	—	—	—	100	50
		1 MHz	60 °C	kW/m^3	—	—	—	—	—	400	200
			80 °C		—	—	—	—	—	400	200
			100 °C		—	—	—	—	—	500	250
Temperature coefficient	αμr		20 °C~80 °C	$\times 10^{-6}$	8	8	8	8	8	8	8
Curie temperature	Tc		—	°C	>200	>200	>200	>200	>200	>200	>200
Resistivity	ρ		—	Ω · m	3	3	2	2	2	5	5
Apparent density	d		—	$\times 10^3$ kg/m^3	4.8	4.8	4.9	4.9	4.9	4.8	4.8

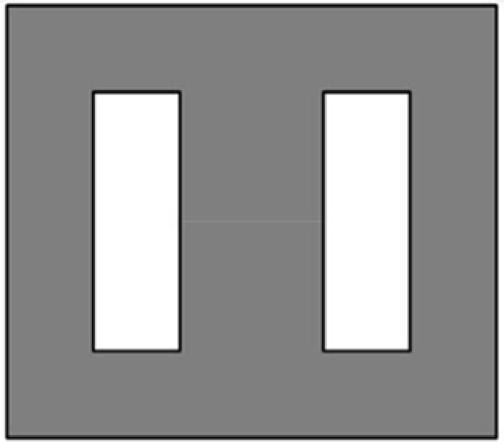
Note: 1) The values were obtained with toroidal cores (FR25/15/5).
2) The values were obtained at 23±2 °C unless otherwise specified.
3) Initial permeability was measured at 10kHz, 0.8A/m.

Ferrite E-core used in this case study

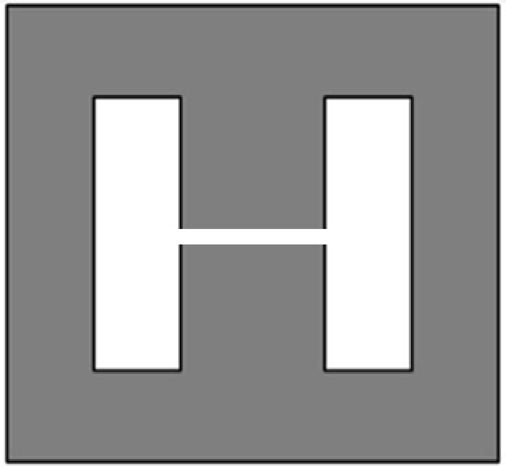
https://www.farnell.com/datasheets/1756165.pdf



Ungapped core



Gapped core



Design equations and magnetic circuit segments

$$R_i = \frac{l_i}{\mu_0 \mu_i S_i}$$ – reluctance (H^{-1}) of a magnetic segment with a length l_i and cross-section S_i

MMF – magnetomotive force (Amperes × turns)

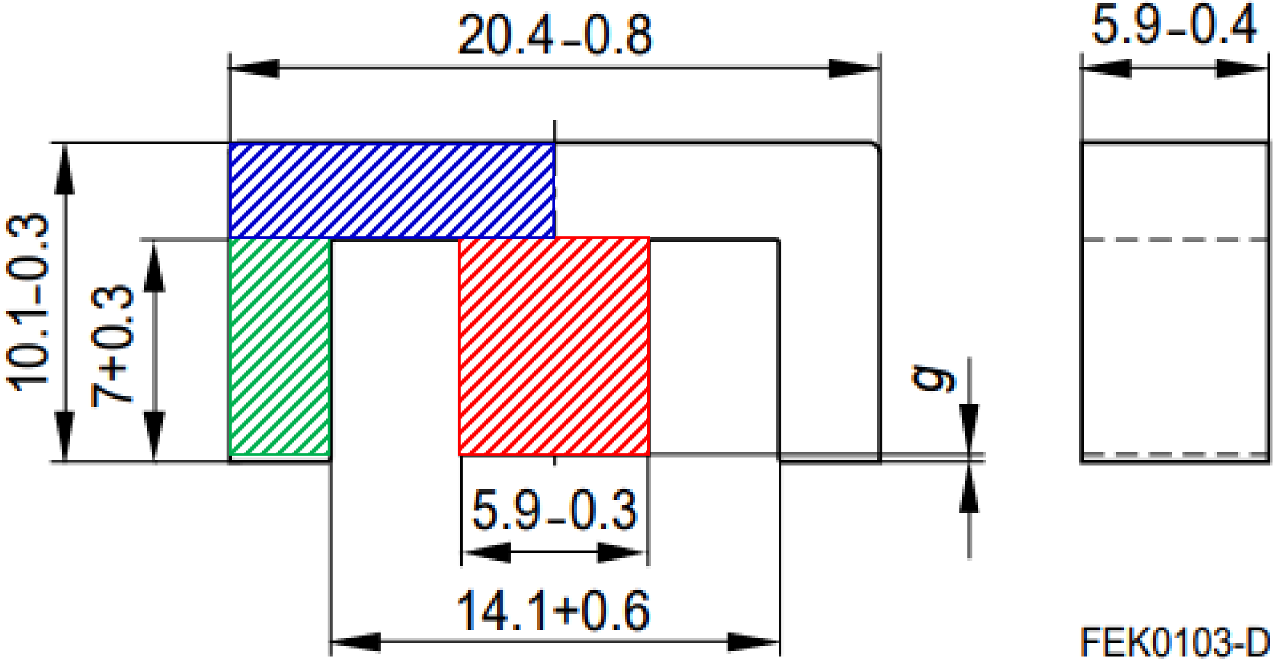
$$\Phi = \frac{\sum_j I_j \times N_j}{\sum_i \frac{l_i}{\mu_0 \mu_i S_i}} = \frac{\sum_j \mathrm{MMF}_j}{\sum_i R_i}$$ – magnetic flux (Weber, Wb) calculated in a single loop core

In a branched core, Φ is calculated using KVL & KCL

$$B_i = \frac{\Phi}{S_i}$$ – induction or flux density (Tesla, T)

$$H_i = \frac{\Phi}{\mu_0 \mu_i S_i}$$ – magnetising force (A/m)

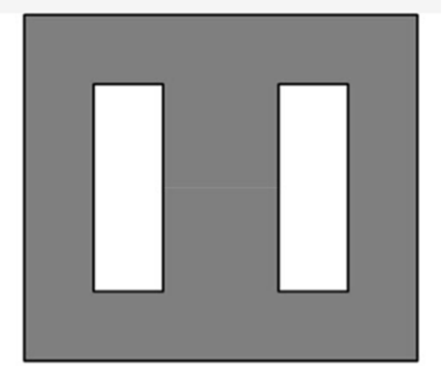
$$L = \frac{N^2}{R_{total}}$$ – inductance (Henry, H)



https://www.farnell.com/datasheets/1756165.pdf

Ungapped

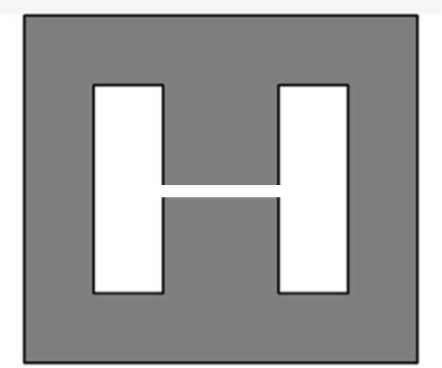
Material	A_L value nH	μ_e	P_V W/set	Ordering code
N30	2150 +30/–20%	2460		B66311G0000X130
N27	1300 +30/–20%	1490	< 0.27 (200 mT, 25 kHz, 100 °C)	B66311G0000X127
N87	1470 +30/–20%	1680	< 0.75 (200 mT, 100 kHz, 100 °C)	B66311G0000X187



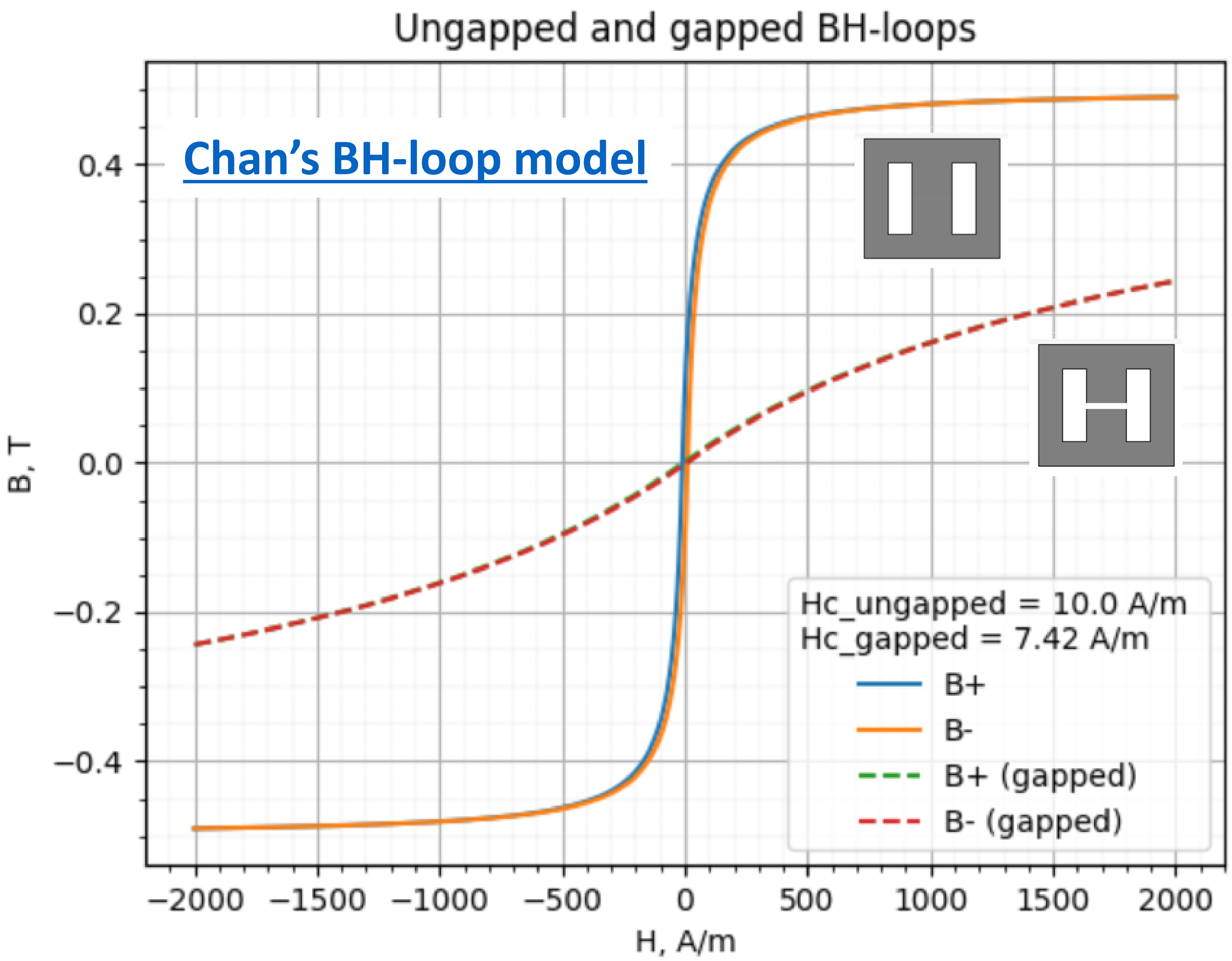
A_L	Inductance factor; $A_L = L/N^2$	nH

Gapped

Material	g (Total gap!) mm	A_L value approx. nH	μ_e	Ordering code ** = 27 (N27) = 87 (N87)
N27, N87	0.09 ±0.01	363	415	B66311G0090X1**
	0.17 ±0.02	227	259	B66311G0170X1**
	0.25 ±0.02	171	195	B66311G0250X1**
	0.50 ±0.05	103	118	B66311G0500X1**



The A_L value in the table applies to a core set comprising one ungapped core (dimension g = 0) and one gapped core (dimension g > 0).



The saturation properties of a magnetic core are equally if not more important than dimensions, $\mathbf{A_L}$ value (see the previous slide) and core loss and should also be specified measured and monitored. In many applications if the core saturates, the inductance and impedance of the component decreases and causes the circuit currents to escalate. Excessive currents can cause other circuit components (semiconductor switches, diodes, capacitors) to fail. The saturated core is hard to determine as the root cause since this failure mode typically exhibits no permanent damage to the ferrite core and the magnetic component.

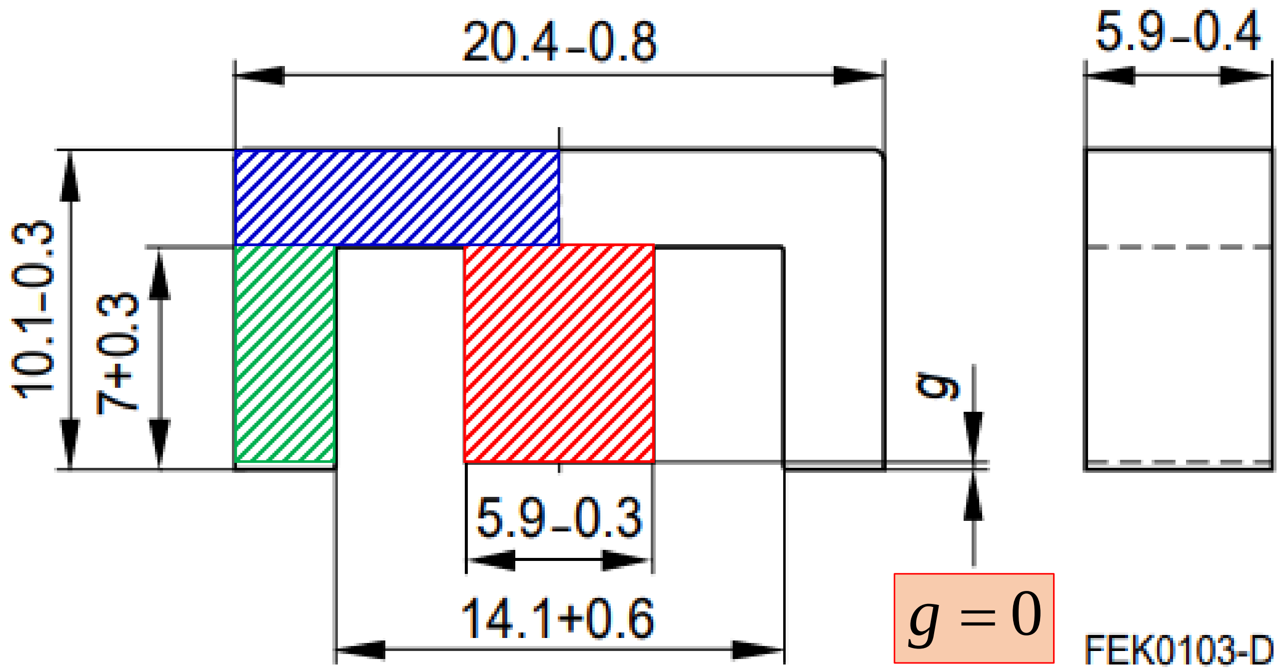
The slope of flux density (B) divided by magnetizing force (H) is the effective permeability. Permeability is a material's ability to conduct magnetic flux relative to air and is proportional to a component's inductance. Note that as the material saturates the slope of B/H decreases, thus the inductance of a component decreases. Introducing an air gap in the magnetic flux path sheers the hysteresis loop so that it requires more magnetizing force to saturate the core. The more air gap introduced into the flux path the lower the permeability (ratio of B/H). Note that the saturation flux density is unchanged even though a gapped core requires more magnetizing force before reaching saturation.

Estimated cross-sections

18.59 mm²

18.29 mm²

34.81 mm²



Reluctances of three segments in the magnetic E-core

$$R_{red} = \frac{7\times10^3}{\mu_0\times\mu\times34.81} \approx 9.53\times10^4$$

$$R_{blue} = \frac{10.2\times10^3}{\mu_0\times\mu\times18.29} \approx 2.64\times10^5$$

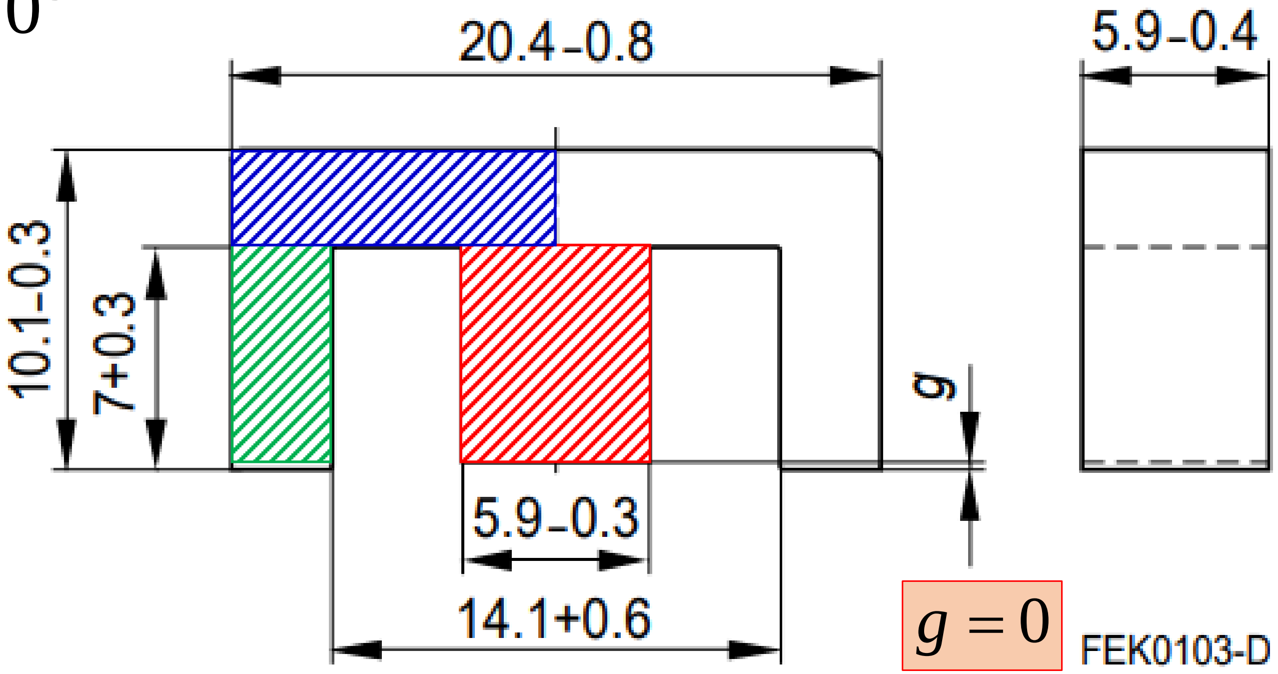
$$R_{green} = \frac{7\times10^3}{\mu_0\times\mu\times18.59} \approx 1.78\times10^5$$

$$\mu_0 = 1.25663706212\times10^{-6}\ \text{H/m}$$
$$\mu = 1680$$

18.59 mm²

18.29 mm²

34.81 mm²

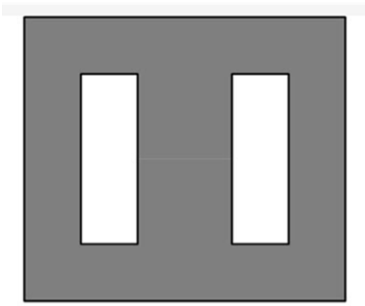


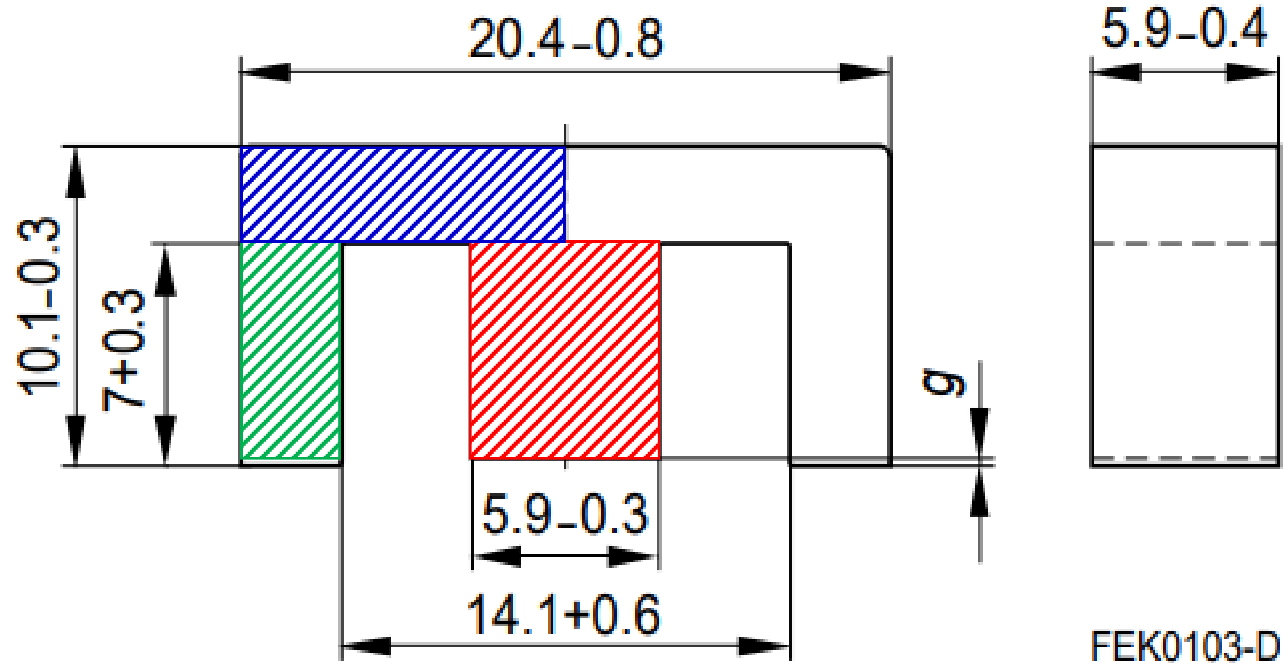
$$R_{red} = \frac{7 \times 10^3}{\mu_0 \times \mu \times 34.81} \approx 9.53 \times 10^4$$

$$R_{blue} = \frac{10.2 \times 10^3}{\mu_0 \times \mu \times 18.29} \approx 2.64 \times 10^5$$

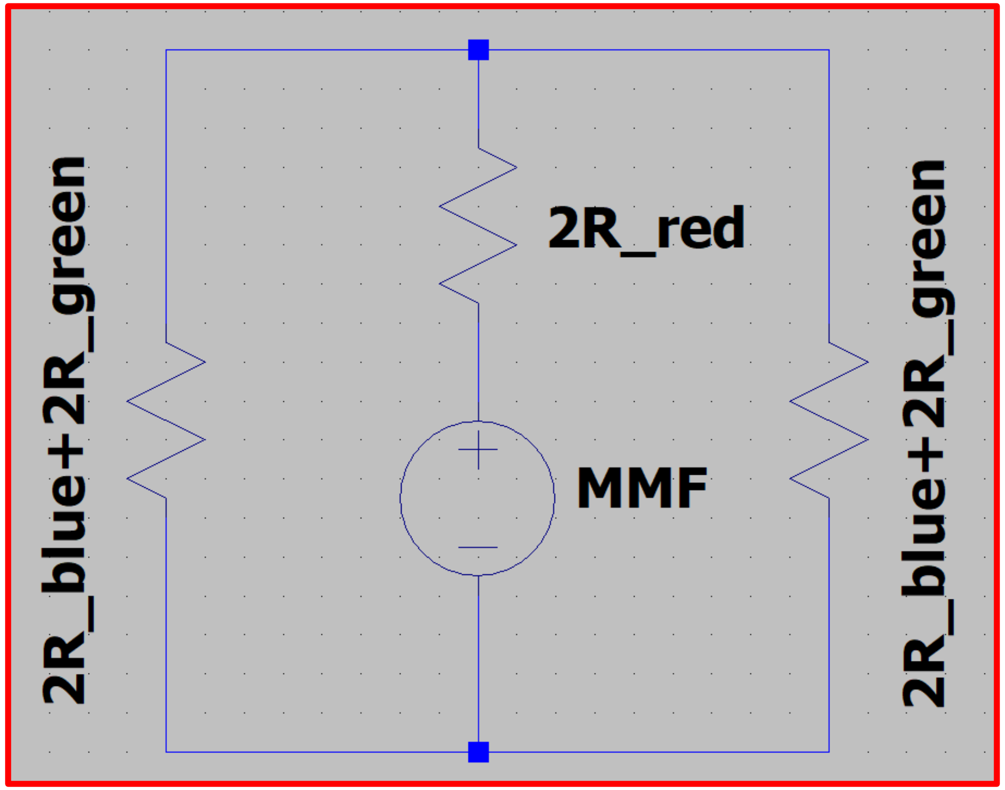
$$R_{green} = \frac{7 \times 10^3}{\mu_0 \times \mu \times 18.59} \approx 1.78 \times 10^5$$

$$\boxed{R_{total} = 2R_{red} + R_{blue} + R_{green} \approx 6.33 \times 10^5}$$





FEK0103-D

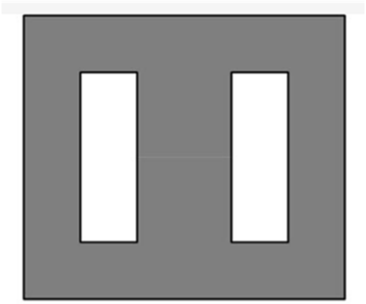


Equivalent electrical circuit

$$\boxed{g = 0}$$

$$\boxed{L = \left. \frac{N^2}{R_{total}} \right|_{N=124} \approx 24.3 \text{ mH}}$$

Ungapped



Material	A_L value nH	μ_e	P_V W/set	Ordering code
N30	2150 +30/–20%	2460		B66311G0000X130
N27	1300 +30/–20%	1490	< 0.27 (200 mT, 25 kHz, 100 °C)	B66311G0000X127
N87	1470 +30/–20%	1680	< 0.75 (200 mT, 100 kHz, 100 °C)	B66311G0000X187

A_L	Inductance factor; $A_L = L/N^2$	nH

For $N = 124$: $18.1\ \mathrm{mH} < L < 29.38\ \mathrm{mH}$

$\boxed{g = 0}$

$$\boxed{L = \left.\frac{N^2}{R_{total}}\right|_{N=124} \approx 24.3\ \mathrm{mH}}$$

The calculated value is in the middle of the tolerance interval

$$R_{red} = \frac{7\times10^3}{\mu_0\times\mu\times34.81} \approx 9.53\times10^4$$

$$\mu_0 = 1.25663706212\times10^{-6}\ \text{H/m}$$
$$\mu = 1680$$

$$R_{blue} = \frac{10.2\times10^3}{\mu_0\times\mu\times18.29} \approx 2.64\times10^5$$

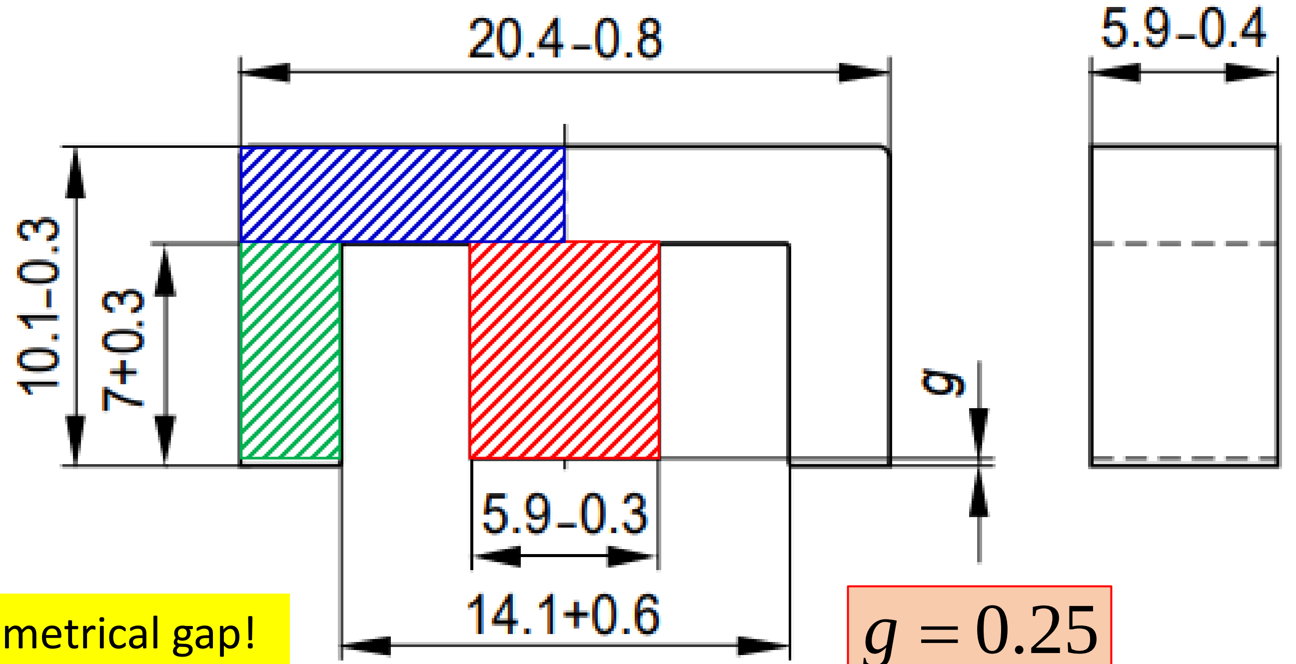
$$R_{gap} = \frac{0.25\times10^3}{\mu_0\times34.81} \approx 5.72\times10^6$$

$$R_{green} = \frac{7\times10^3}{\mu_0\times\mu\times18.59} \approx 1.78\times10^5$$

18.59 mm²

18.29 mm²

34.81 mm²



Total symmetrical gap!

$$g = 0.25$$

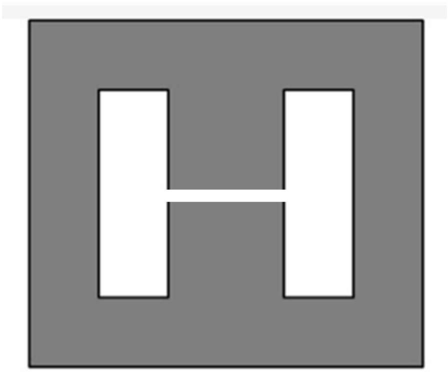
$$R_{red} = \frac{7\times10^3}{\mu_0\times\mu\times34.81} \approx 9.53\times10^4$$

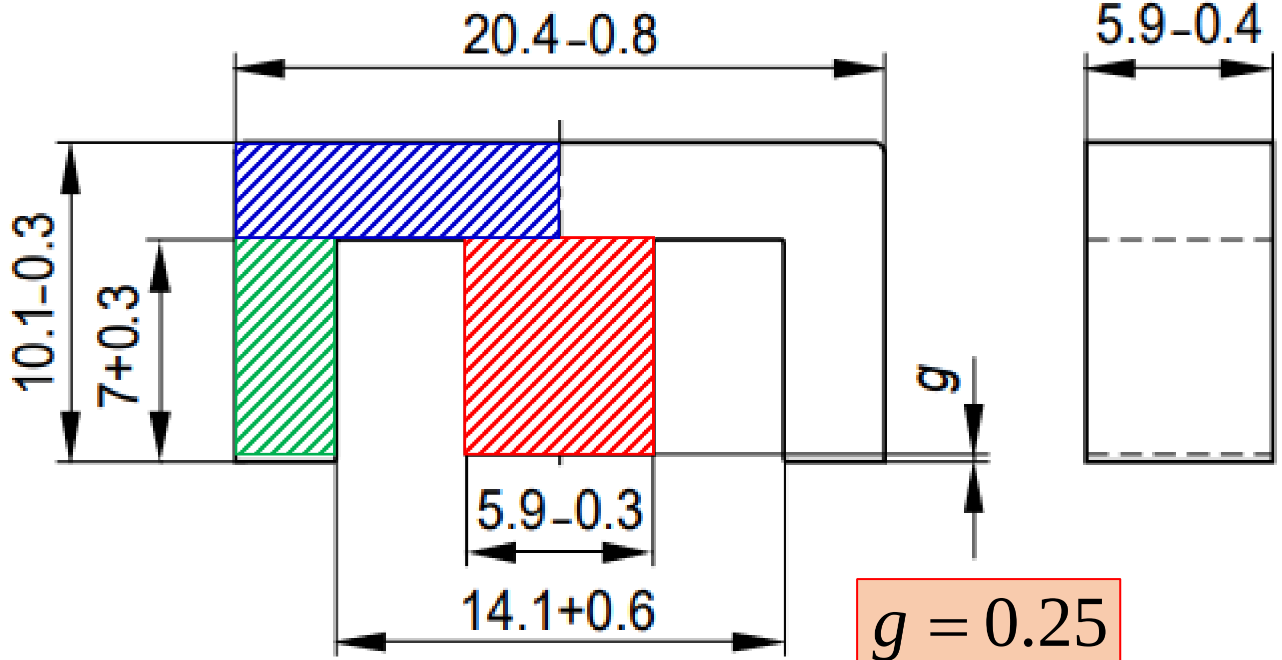
$$R_{blue} = \frac{10.2\times10^3}{\mu_0\times\mu\times18.29} \approx 2.64\times10^5$$

$$R_{green} = \frac{7\times10^3}{\mu_0\times\mu\times18.59} \approx 1.78\times10^5$$

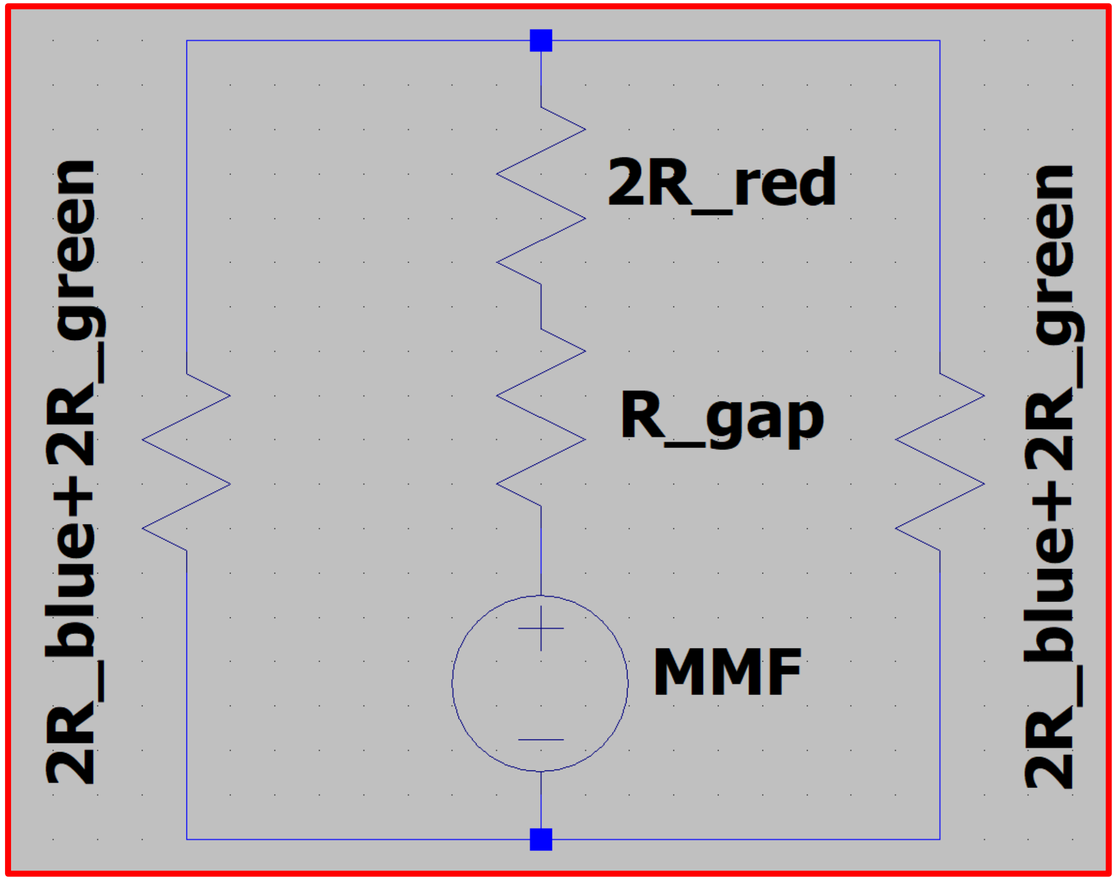
$$R_{gap} = \frac{0.25\times10^3}{\mu_0\times34.81} \approx 5.72\times10^6$$

$$\boxed{R_{total} = 2R_{red} + R_{gap} + R_{blue} + R_{green} \approx 6.35\times10^6}$$



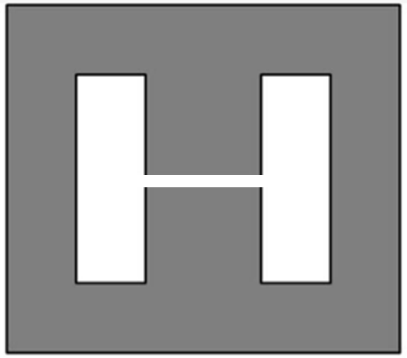


$$\boxed{g = 0.25}$$



Equivalent electrical circuit

$$\boxed{L = \left.\frac{N^2}{R_{total}}\right|_{N=124} \approx 2.4\ \text{mH}}$$



Gapped

Material	g mm	A_L value approx. nH	μ_e	Ordering code ** = 27 (N27) = 87 (N87)
N27, N87	0.09 ±0.01	363	415	B66311G0090X1**
	0.17 ±0.02	227	259	B66311G0170X1**
	0.25 ±0.02	171	195	B66311G0250X1**
	0.50 ±0.05	103	118	B66311G0500X1**

A_L	Inductance factor; $A_L = L/N^2$	nH

For $N = 124$: $L = 2.63$ mH

$\boxed{g = 0.25}$

$$\boxed{L = \left.\frac{N^2}{R_{total}}\right|_{N=124} \approx 2.4 \text{ mH}}$$

https://www.farnell.com/datasheets/1756165.pdf

Calculation factors (for formulas, see *“E cores: general information”*)

Material	Relationship between air gap – A_L value		Calculation of saturation current			
	K1 (25 °C)	K2 (25 °C)	K3 (25 °C)	K4 (25 °C)	K3 (100 °C)	K4 (100 °C)
N27	61.6	–0.737	88.1	–0.847	80.9	–0.865
N87	61.6	–0.737	88.5	–0.796	78.4	–0.873

Validity range: K1, K2: 0.05 mm < s < 1.50 mm
K3, K4: 50 nH < A_L < 430 nH

Calculation formulae a) and b) apply to the A_L value under the following measuring conditions:
Measuring flux density $\hat{B} \leq 0.25$ mT, measuring frequency f = 10 kHz,
measuring temperature T = 25 ±3 °C, measuring coil: N = 100 turns, fully wound

a) Air gap and A_L value

The typical A_L value tabulated in the individual data sheets refers to a core set comprising a gapped core with dimension „g“ and an ungapped core with „g“ approx. 0.

By inserting the core-specific constants K1 and K2, a nominal A_L value can be calculated for the materials N27 and N87 within the relevant quoted air-gap validity range:

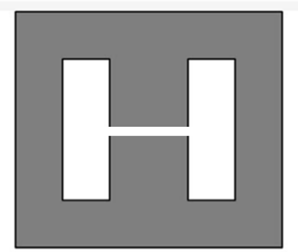
$$s = \left(\frac{A_L}{K1}\right)^{\frac{1}{K2}} \qquad s = [\mathrm{mm}] \quad A_L = [\mathrm{nH}]$$

https://www.farnell.com/datasheets/1756165.pdf

Calculation factors (for formulas, see *"E cores: general information"*)

Material	Relationship between air gap – A_L value		Calculation of saturation current			
	K1 (25 °C)	K2 (25 °C)	K3 (25 °C)	K4 (25 °C)	K3 (100 °C)	K4 (100 °C)
N27	61.6	–0.737	88.1	–0.847	80.9	–0.865
N87	61.6	–0.737	88.5	–0.796	78.4	–0.873

Validity range: K1, K2: 0.05 mm < s < 1.50 mm
K3, K4: 50 nH < A_L < 430 nH



b) DC magnetic bias I_{DC}

By using the core-shape-related factors K3 and K4, nominal values can be determined for the DC magnetic biasing characteristic of E, ETD and EFD cores made of N27 and N87 and ELP cores made of N87 at temperature 25 °C and 100 °C.

The direct current I_{DC} at which the A_L value drops by 10% compared to the A_L value without magnetic biasing (I_{DC} = 0 A) is determined for a coil with 100 turns.

For $A_L = 171$ (gapped) and $N = 100$: $I_{DC} \approx 0.5$ A

Calculation of I_{DC} at T = 25 °C:
The factors K3 and K4 for T = 25 °C and the A_L value without magnetic biasing are inserted into the equation for the calculation.

Calculation of I_{DC} at T = 100 °C:

The factors K3 and K4 for T = 100 °C are inserted into the equation for the calculation. The value for T = 25 °C without magnetic biasing should be used here as the A_L value.

$$I_{DC} = \left(\frac{0.9 \cdot A_L}{K3}\right)^{\frac{1}{K4}}$$

I_{DC} = [A]
A_L = [nH] (without magnetic biasing)

18.59 mm²

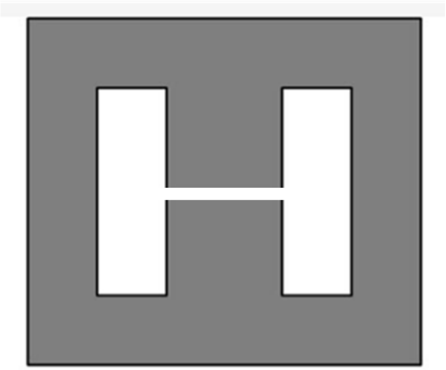
18.29 mm²

34.81 mm²

$g = 0.25$

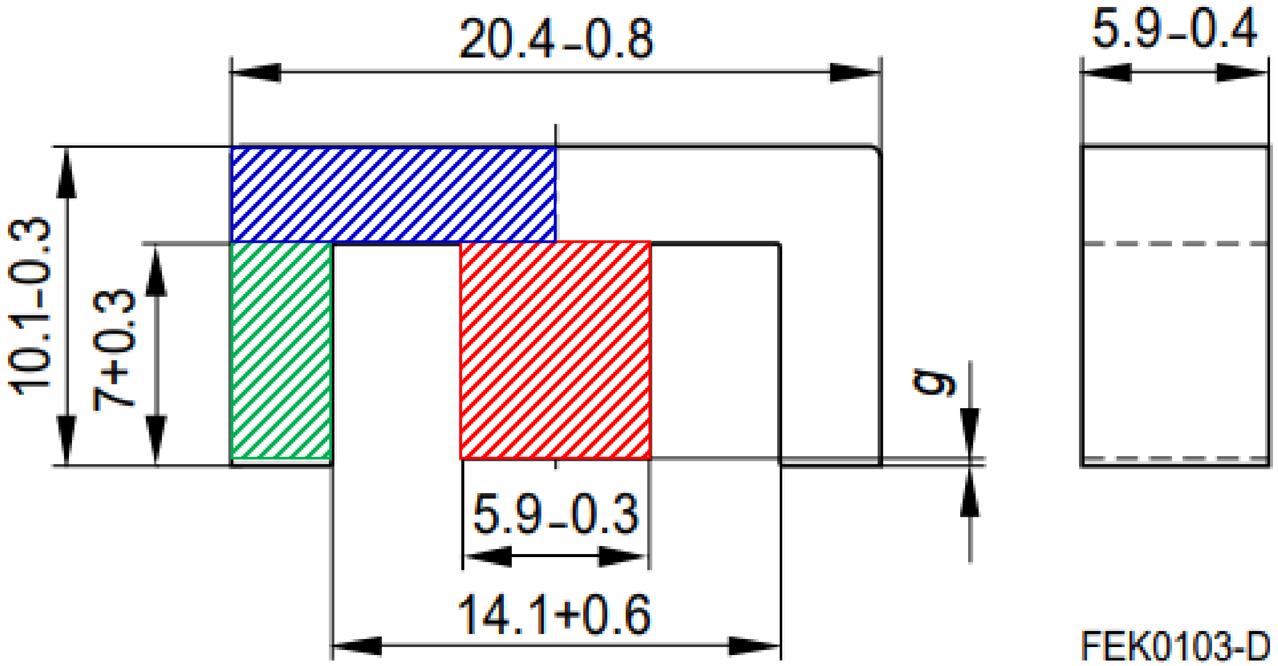
$$\boxed{R_{total} \approx 6.35\times10^{6}}$$

$$L = \frac{N^2}{R_{total}}$$



$I = 0.5$ A $-$ beggining of the saturation

$$\Phi_{red} = \frac{I \times N \times 10^{-6}}{6.35} = \frac{0.5\times100\times10^{-6}}{6.35} \approx 7.87\times10^{-6}\,\mathrm{Wb}$$



$$B_{red} = \frac{\Phi_{red}}{S_{red}} \approx 0.23\ \mathrm{T}$$

$$B_{blue} = \frac{(\Phi_{red}/2)}{S_{blue}} \approx 0.22\ \mathrm{T}$$

$$B_{green} = \frac{(\Phi_{red}/2)}{S_{green}} \approx 0.21\ \mathrm{T}$$

All parts are approximately at the same magnetic condition