Inductive Adder for FCC Injection Kicker Systems

Requirements for the FCC injection Inductive Adder

Parameter	Unit	Value
Pulse flat top length	[µs]	2.00
Flat top tolerance	[%]	±0.50
Field rise time	[µs]	0.425
Voltage	[kV]	15.70
Current	[kA]	2.50
System impedance	[Ω]	6.25
Pulse frequency	[Hz]	115

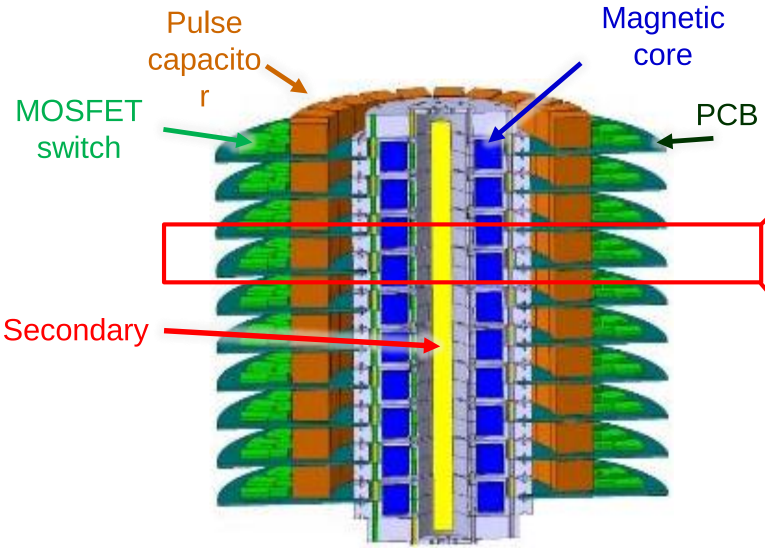
Challenges of the inductive adder design:

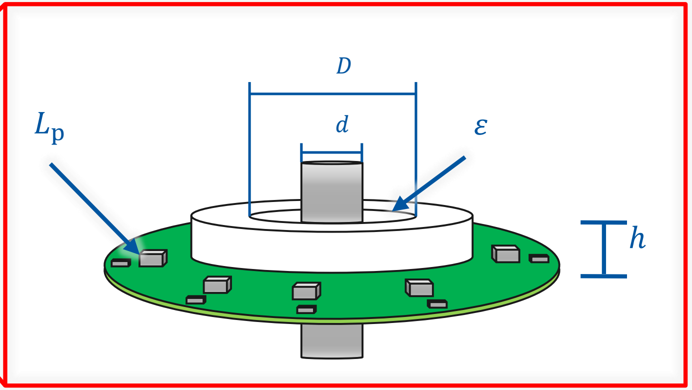
Field rise time:
- → 0.350 µs of **kicker magnet fill time**
- → 0.075 µs remain for **pulse current rise time**

Current: Relatively high current

System impedance: Low impedance

One layer of the Inductive Adder





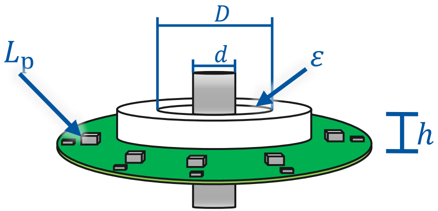
Content

- Impedance matching of the stack
- Layer design for fast rise times
- Biasing of magnetic cores

Impedance matching of the stack

Factors influencing the layer impedance:

- Ratio of primary inner diameter (D) and stalk diameter (d)
- Insulation material between primary and secondary (ε)
- Layer height (h)
- Inductance of primary winding (L_p)



Impedance of IA:

$$C_{layer} = \frac{2\pi\varepsilon h}{\ln\frac{D}{d}} \qquad L_{layer} = \frac{\mu \cdot h \cdot \ln\frac{D}{d}}{2\pi}$$

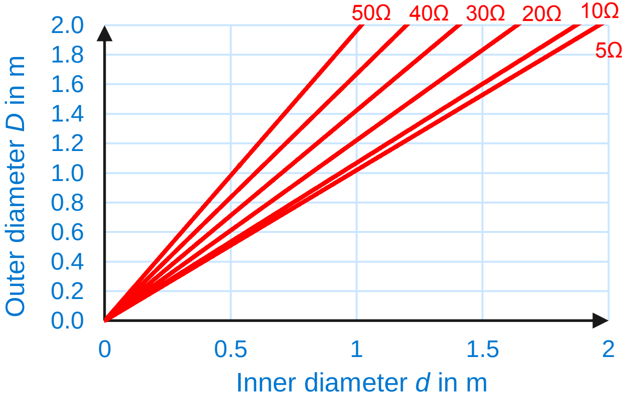
$$Z_{IA} = \sqrt{\frac{L_p + L_{cell}}{C_{cell}}} = \sqrt{\frac{L_p}{2\pi\varepsilon h}\ln\frac{D}{d} + \frac{\mu}{4\pi^2\varepsilon}\ln^2\frac{D}{d}}$$

Examples for insulation materials:

- Air
- **Oil**
- Water
- Epoxy
- FC-77
- SF6
- Vacuum

Outer diameter D over inner diameter d for different Z_{IA}

$$D(d) = d \cdot e^{-\frac{L_{p1}\cdot\pi}{h\mu} + \sqrt{\left(\frac{L_{p1}\cdot\pi}{h\mu}\right)^2 + Z_{IA}^2 \cdot \frac{4\pi^2\varepsilon_0\varepsilon_r}{\mu}}}$$

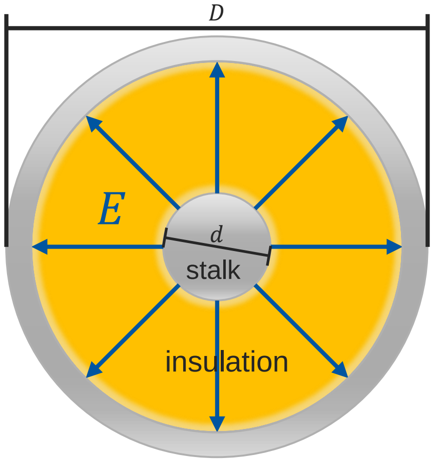


Low impedance -> small insulation gap

Electric field in insulation:

$$E(r) = \frac{V_{out}}{r \cdot \ln\frac{D}{d}}$$

$$E_{max} = \frac{V_{out}}{\frac{d}{2} \cdot \ln\frac{D}{d}}$$



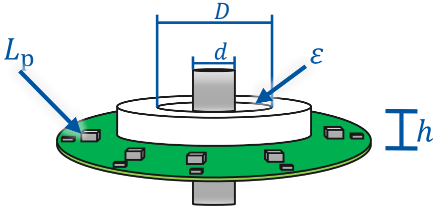
inner primary winding

Layer design for fast rise time

Propagation time of IA layer: $t_{\mathrm{p,layer}} = \sqrt{(L_{\mathrm{p}} + L_{\mathrm{cell}}) \cdot C_{\mathrm{cell}}} = \sqrt{\left(L_{\mathrm{p}} + \frac{\mu \cdot h \cdot \ln\frac{D}{d}}{2\pi}\right) \cdot \frac{2\pi\varepsilon h}{\ln\frac{D}{d}}} = \sqrt{L_{\mathrm{p}} \cdot \frac{2\pi\varepsilon h}{\ln\frac{D}{d}} + \mu\varepsilon h^2}$

Propagation time of IA stack (n layers): $t_{\mathrm{p,stack}} = 2n \cdot t_{\mathrm{p,layer}} = 2n \cdot \sqrt{L_{\mathrm{p}} \cdot \frac{2\pi\varepsilon h}{\ln\frac{D}{d}} + \mu\varepsilon h^2}$

$C_{\mathrm{cell}} = \frac{2\pi\varepsilon h}{\ln\frac{D}{d}}$ $\quad L_{\mathrm{cell}} = \frac{\mu \cdot h \cdot \ln\frac{D}{d}}{2\pi}$

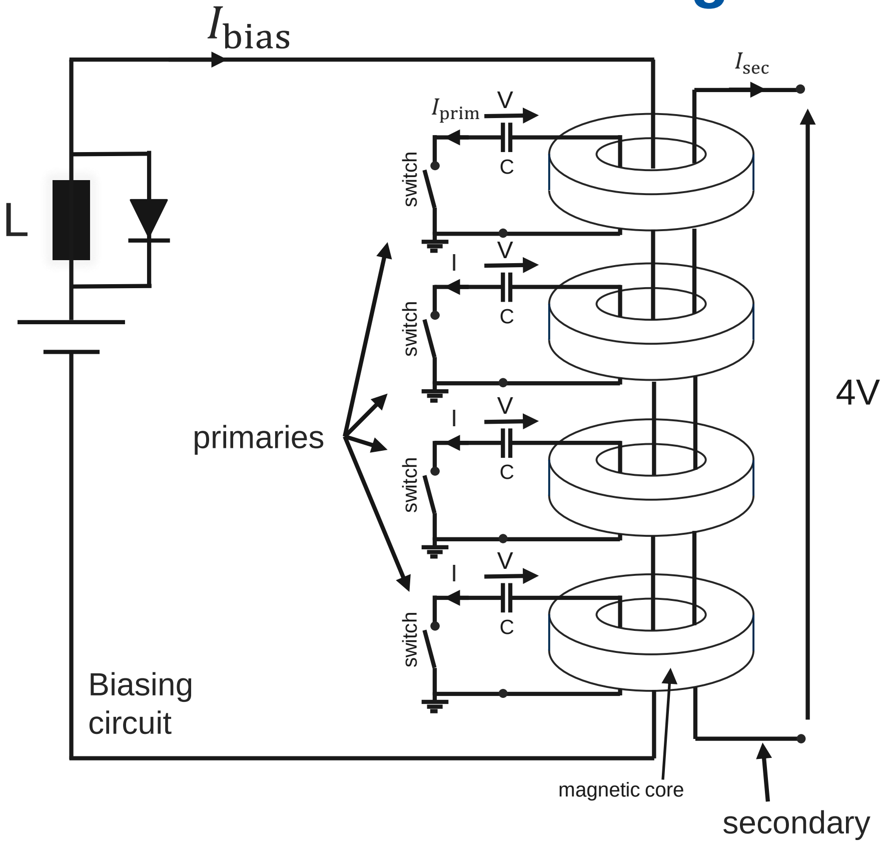


Factors influencing the rise time:

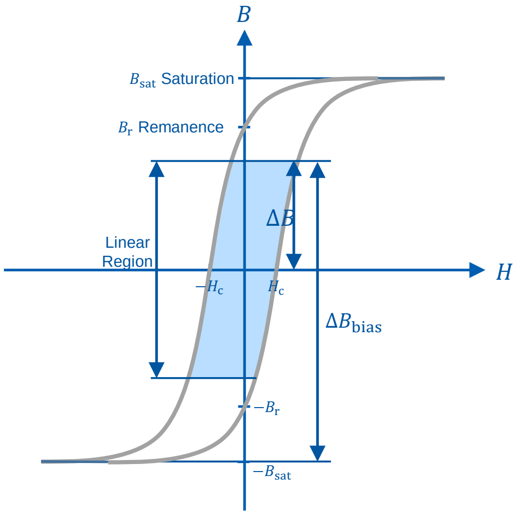
- Layer height
- Insulation material
- Primary inductance
- Output voltage, layer voltage
- Switching time of switching device (SiC MOSFET)

The inductance of the secondary circuit should be low to not limit the rise time!

Biasing of magnetic core

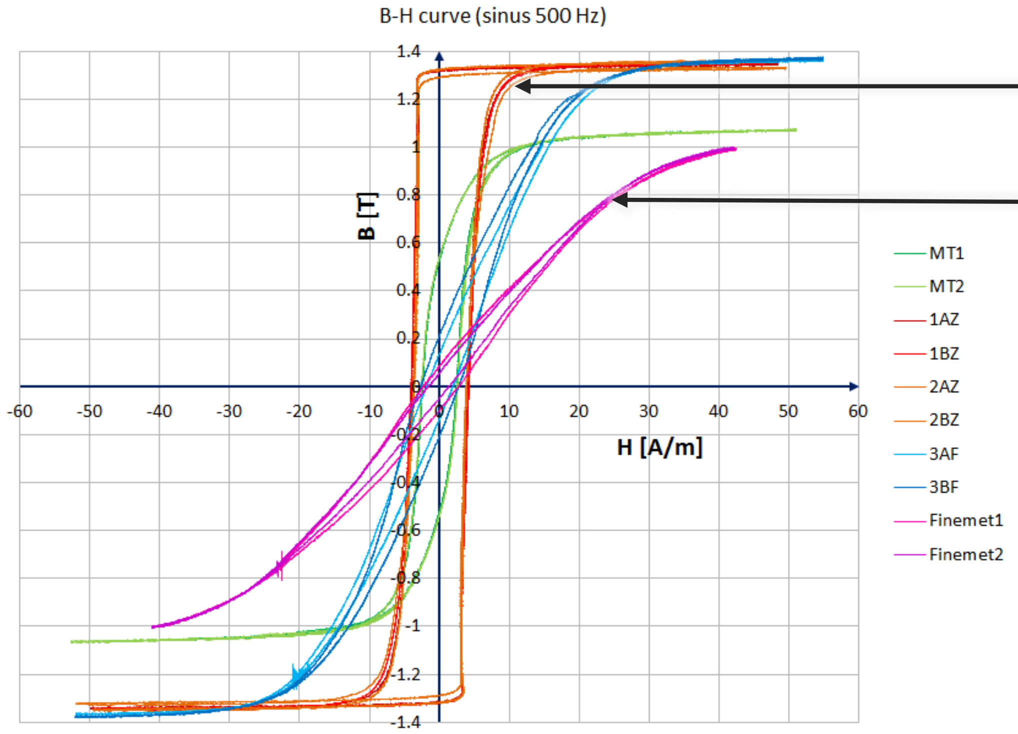


$$A_c = \frac{\int V_c\,dt}{\Delta B} \qquad \Delta t = \frac{A_c \cdot \Delta B}{V_c} \qquad \oint H\,ds = I_{prim} + I_{sec} + I_{bias}$$



Biasing of the magnetic core can reduce the required core material and therefore **reduce the layer height**.

Biasing of magnetic core

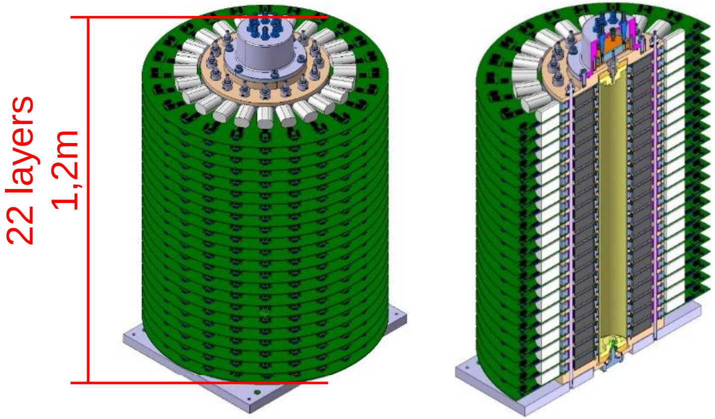


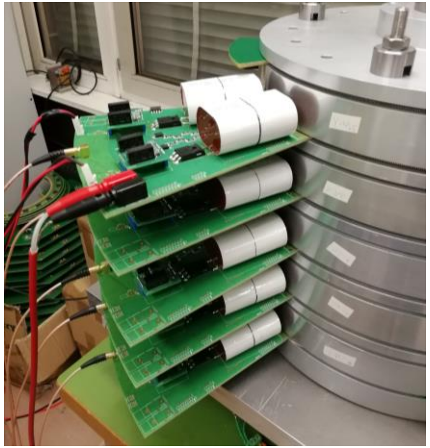
Square shaped

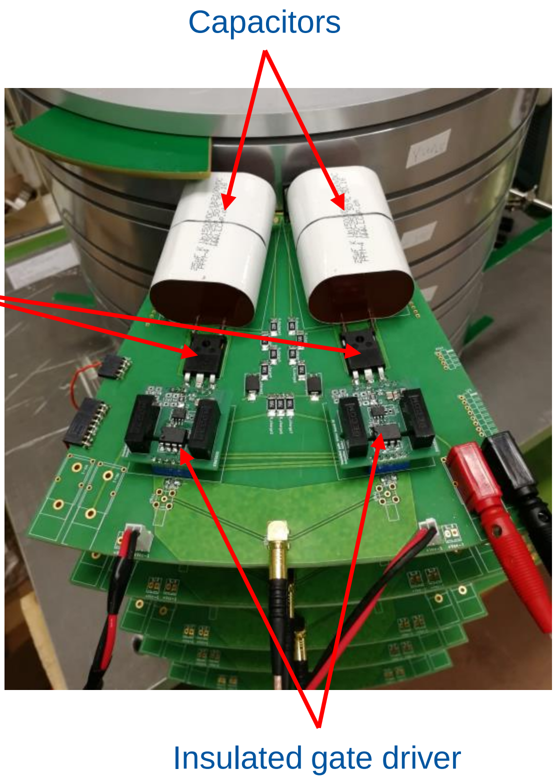
linear

Summary

- System impedance of 6.25 Ohm (2.5 kA, 15.7 kV)
- Oil insulation required
- Use of a biasing circuit
  - reduce magnetic material
  - Shorter layer height possible
  - ➢ Faster rise time achievable







Thank you
for your attention!

Questions?

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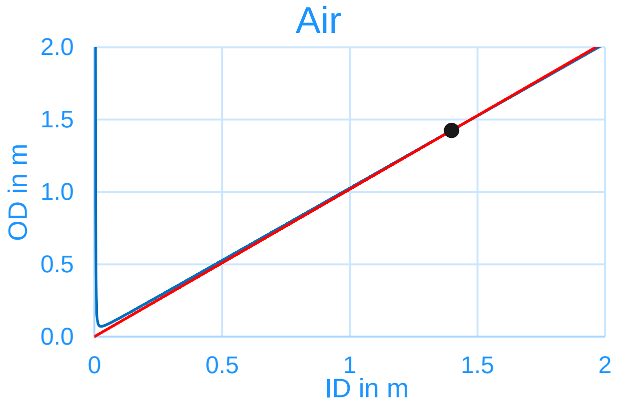
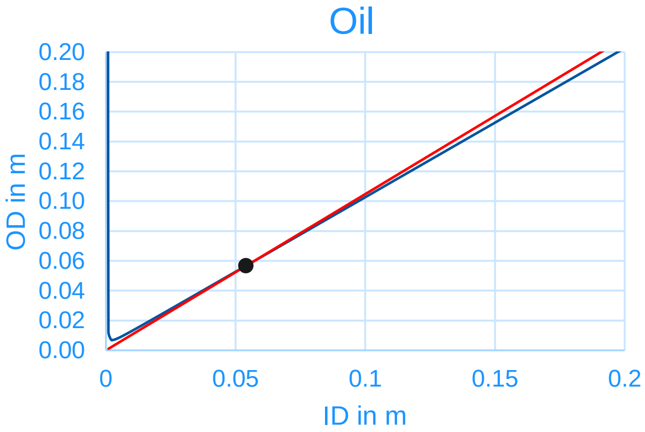
Evaluation of Dielectricum



$$Z_{\text{out}} = 5\ \Omega$$
$$d = 1.405\ \text{m}$$
$$D = 1.431\ \text{m}$$
$$\delta = 18.7\ \text{mm}$$

$$E_{\text{max,Air}} = 0.4 \cdot 2.5\ \frac{\text{kV}}{\text{mm}}$$
$$\varepsilon_{\text{r,Air}} = 1$$



$$Z_{\text{out}} = 5\ \Omega$$
$$d = 5.44\ \text{cm}$$
$$D = 5.7\ \text{cm}$$
$$\delta = 1.3\ \text{mm}$$

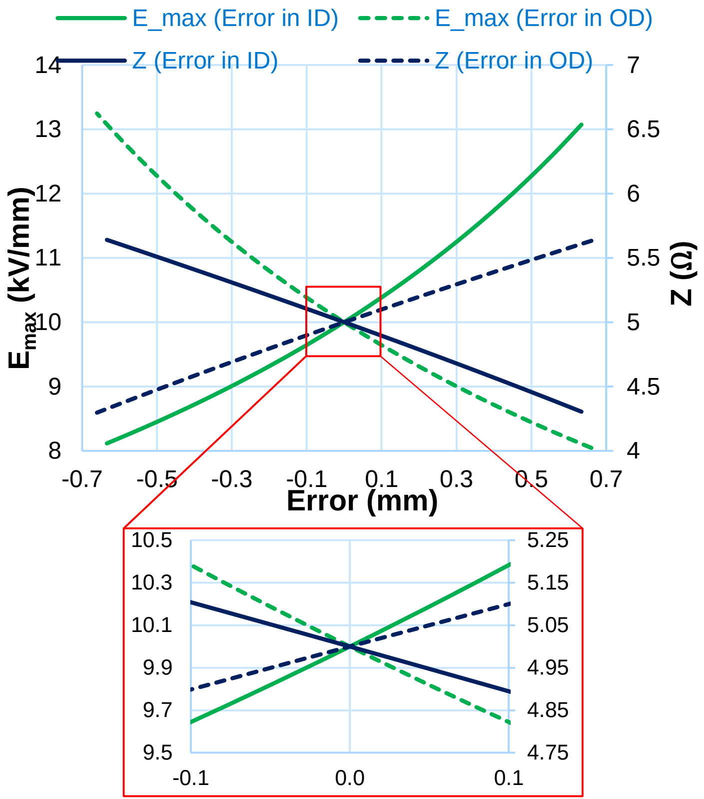
$$E_{\text{max,Oil}} = 0.4 \cdot 25.7\ \frac{\text{kV}}{\text{mm}}$$
$$\varepsilon_{\text{r,Oil}} = 2.7$$

Big diameters result in high costs for the magnetic cores.

Small insulation gaps are difficult to manufacture.

Example for insulation materials:
- Air
- Oil
- Water
- Epoxy
- FC-77
- SF6
- Vacuum

Tolerances in stalk



Precise manufacturing and adjustment of stalk and core is necessary!

- E_{max} can be reduced by using bigger diameters
- Impedance mismatch caused by an unprecise stalk is influencing the output pulse

PSpice simulations showed that the error needs to be <0.06 mm, what is a reasonable value.

However, very precise production and alignment of the primary and secondary windings is necessary.

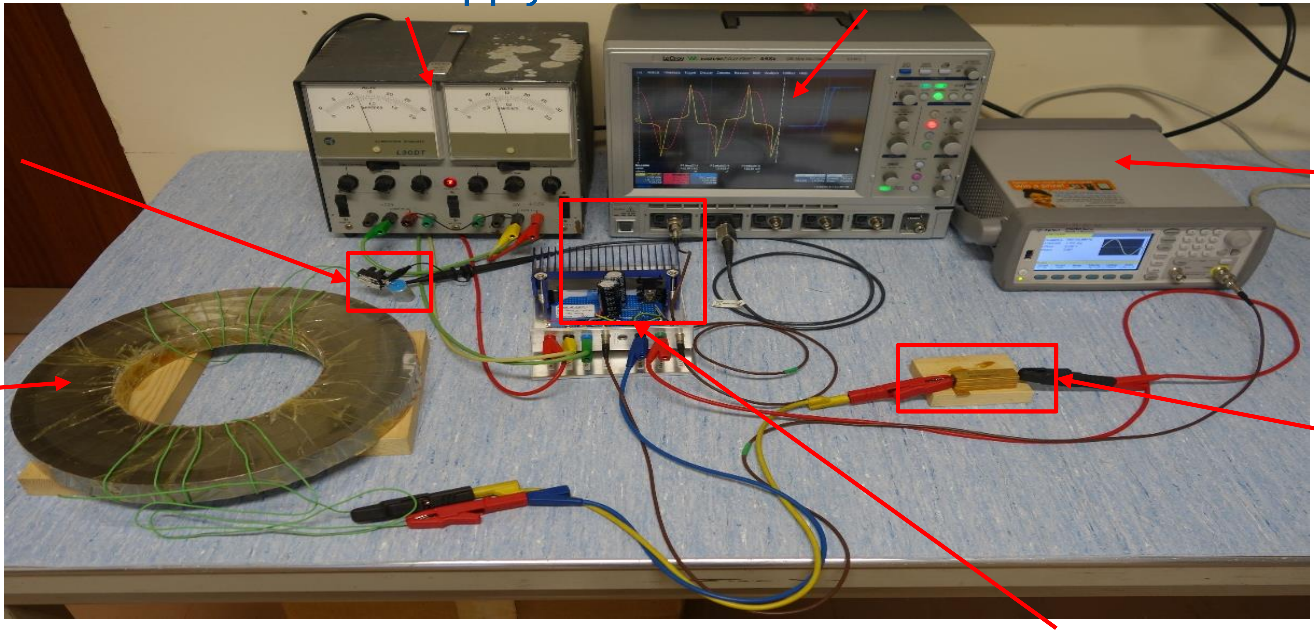
BH curve measurement test setup from BE-BI-PI

Power supply

Oscilloscope

RC integrator to measure $\int U_{sec}\, dt \sim B$

Function generator



Test core

Current limiting resistor

Other required parameters:
Core dimensions, weight, fill factor, no of windings

Amplifier, incl. 1 Ω Shunt to measure $I_{prim} \sim H$

Thanks to S. Aguilera and M. Krupa