Validation Technique of High Frequency Magnetics, Standard & Practice

JC Sun · Bs & T

IEEE · 5. Nov 26 Long Island, New York

Outline

1 Introduction

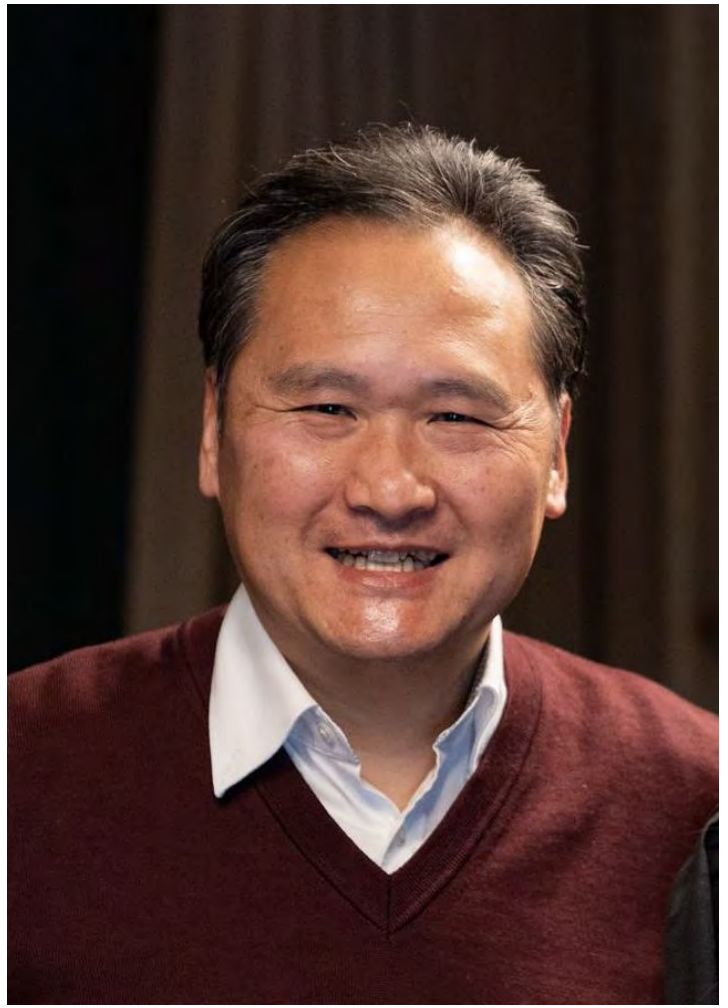
2 *hf* Magnetics

3 AC Magnetization & Pulsation Conditions

4 Conclusion

About JC

1. Physicist and Process Engineer
2. Make and design Ferrite 3 & 4 C/D/E/F/H
3. Sales Amorphous Metals MAGNAPERM® 2714AF Core
4. Marketing Vitroperm® Components
5. Bs&T Frankfurt am Main GmbH



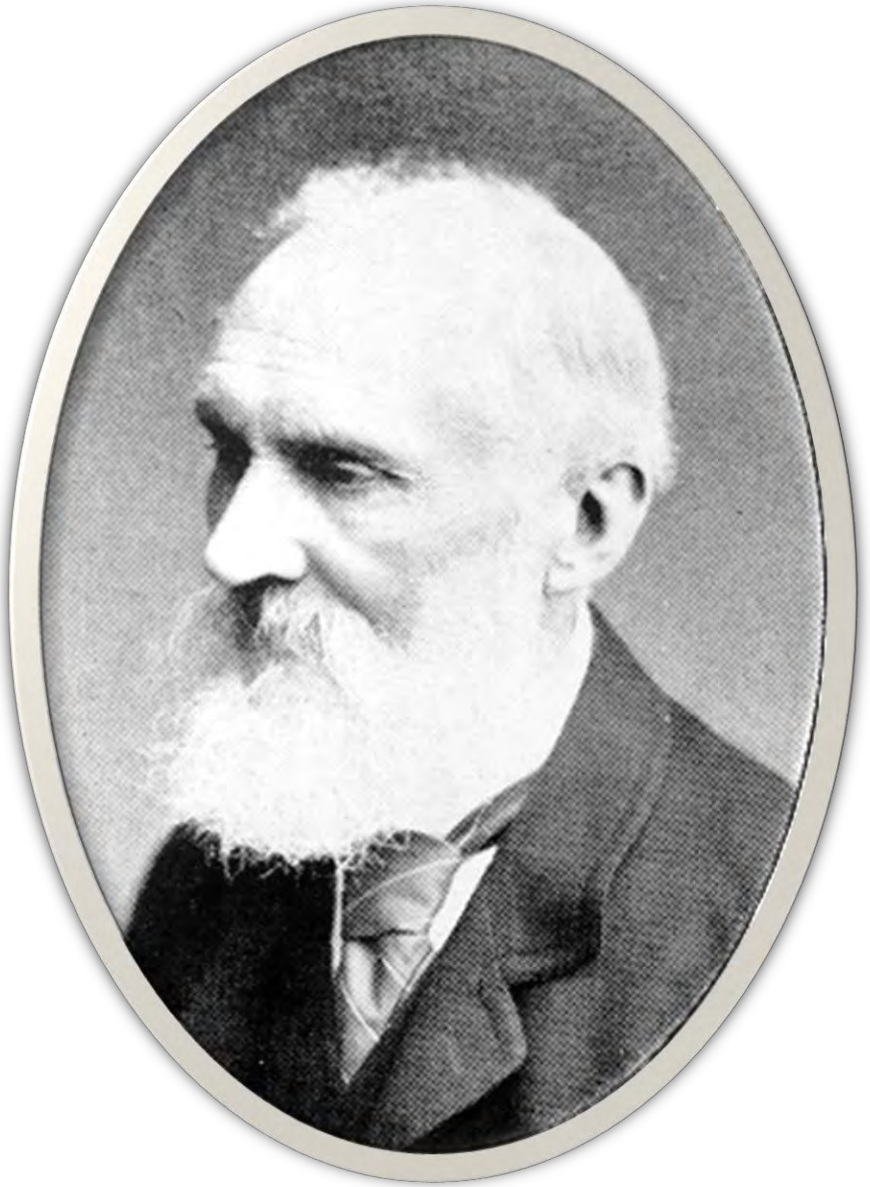
JC Sun

Measurement is Indispensible

Quote from Lord Kelvin

"When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge”

- Lord Kelvin



Background Information

Importance of Validation Technique

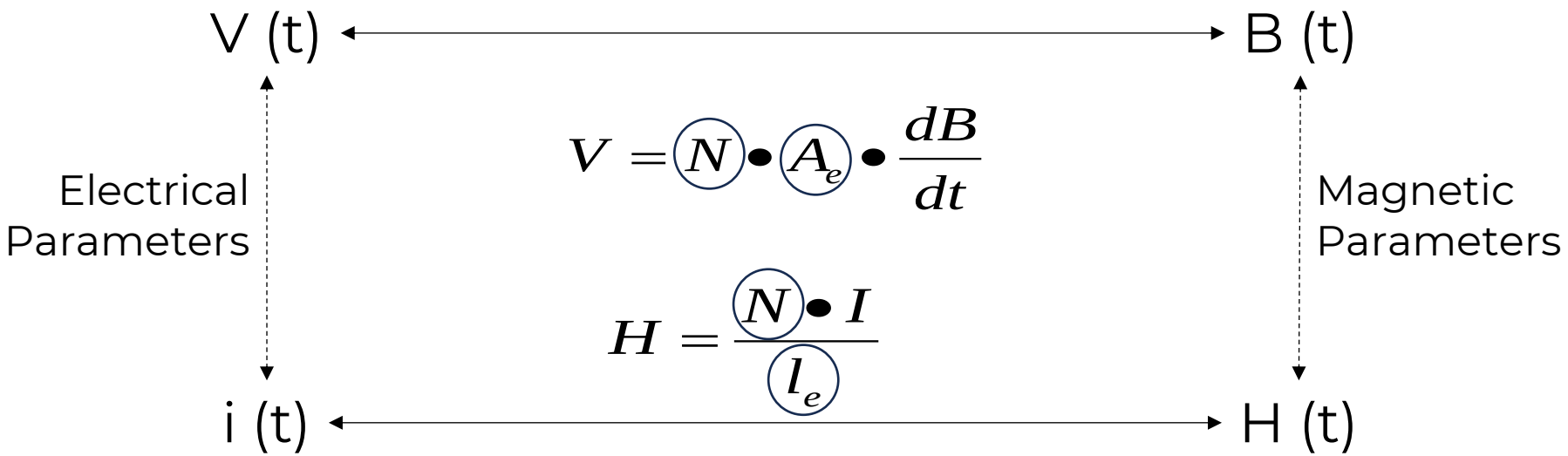
- Power Electronics is enabling technology, like power magnetics key technical performance factors are: **Power Density** and **Efficiency**

- Mag. Materials (Permeability /Losses @ *hf*) identified as barrier need to sensitize magnetic ***material***, ***core, component, part, group and system*** distinguish core vs. coil loss

- Loss mechanism of magnetic material and shaped core is **Not trivial, Not intuitive, No analytic way**
  consequence: measurement is indispensible

Oberservation:
Power Electronics -> Energy Electronics relativize power density
Efficiency -> Inefficiency, e.g. loss (switching loss + magnetic loss)
Material requirement: *hf, high flux swing (for linkage)*

Permeability vs. inductance



$$V = L \bullet \frac{dI}{dt}$$

$$V \bullet \Delta t = \mu_0 \bullet \frac{A \bullet \Delta I \bullet N^2}{l} = L \bullet \Delta I$$

$$L = \frac{\mu_0 \bullet A \bullet N^2}{l}$$

1 Henry = 10^9 cm

$$B = \mu_0 \bullet \mu_r \bullet H$$

Permeability

Term

- initial permeability — IEC 62044-2 small signal
- amplitude permeability — IEC 62044-3 large signal
- peak permeability
- Impedance permeability
- Incremental permeability — small AC biased with DC
- reversible permeability — small enough AC biased with DC, reversibility granted
- differential permeability — slot @ magnetization curve (infinitely small)
  sum of reversible and irreversible permeability

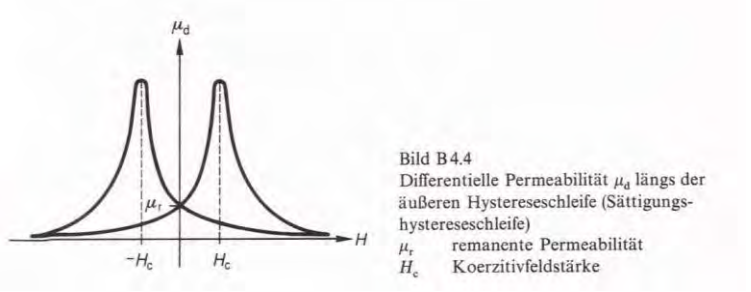


Bild B4.4
Differentielle Permeabilität μ_d längs der äußeren Hystereseschleife (Sättigungs-hystereseschleife)
μ_r remanente Permeabilität
H_c Koerzitivfeldstärke

- apparent permeability

$$\mu_{app} = \frac{L_{jig_{with\ core}}}{L_{jig_{without\ core}}}$$

  regardless energizing amplitude, effectiveness of geometry, with fixed number of turns
- effective permeability

Inductance

Term

IEC 60076-6

$$L_s(i) = \frac{N \cdot \Phi}{i} = \frac{\Psi}{i}$$

Differential L

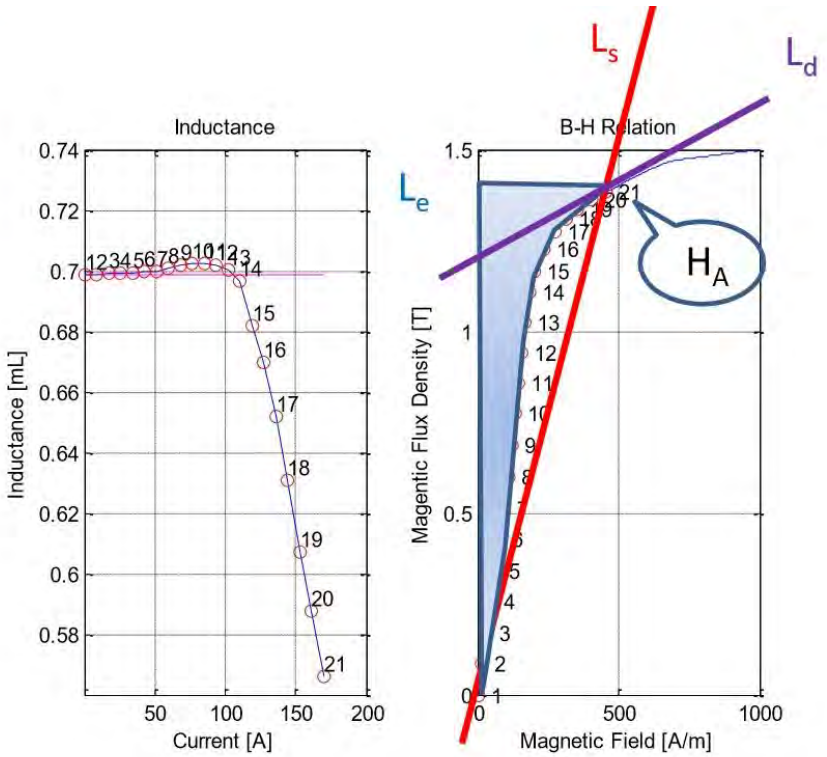
$$L_d(i) = \frac{\mathrm{d}(N \cdot \Phi)}{\mathrm{d}i} = \frac{\mathrm{d}\Psi}{\mathrm{d}i}$$

$$v(t) = L_d(i) \cdot \frac{\mathrm{d}i}{\mathrm{d}t} = \frac{\mathrm{d}\Psi}{\mathrm{d}i} \cdot \frac{\mathrm{d}i}{\mathrm{d}t} = \frac{\mathrm{d}\Psi}{\mathrm{d}t} =$$

$$\frac{\mathrm{d}\left[i \cdot L_s(i)\right]}{\mathrm{d}t} = L_s(i) \cdot \frac{\mathrm{d}i}{\mathrm{d}t} + i \cdot \frac{\mathrm{d}L_s(i)}{\mathrm{d}t}$$

Amplitude L → $$L_s(i) = \frac{1}{i} \int_0^i L_s(i')\, di'$$

Energetic L $$L_e(i) = \frac{2}{i^2} \int_0^i i \cdot L_s(i')\, di'$$



Alex van den Bossche

ac Magnetization

Sinusoidal Magnetization

High excitation: IEC 62044-3

Loss, μ_a driven by B mode

B_{peak} , loop driven by H mode

Low excitation: IEC 62044-2

DC superposition

BsT - Pro

loss map (f, B, T, H_{DC}) μ_{inc}

Major and biased minor loop

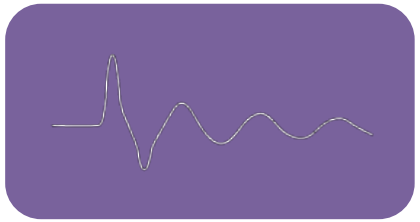


Pulse Magnetization

Fast transit of Magnetic state

dB/dt

BsT - Pulse

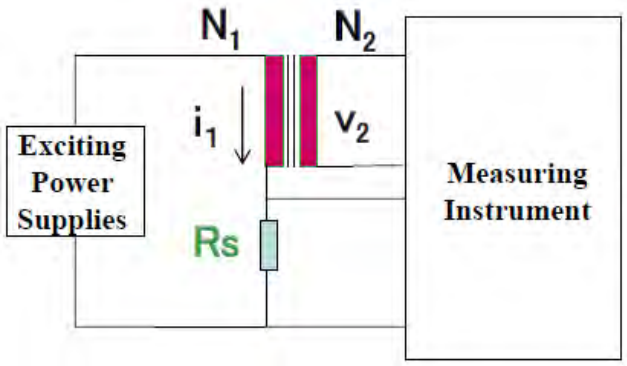


Differential and **Amplitude L,**

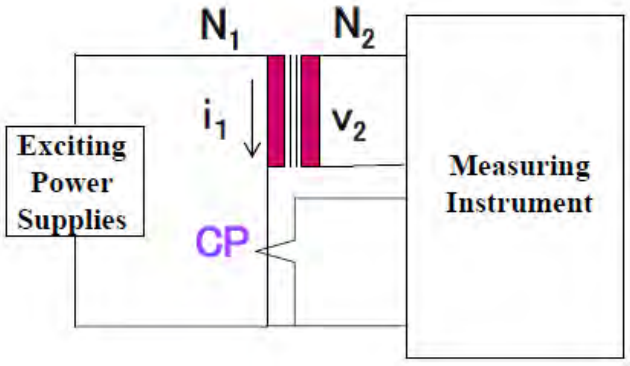
Energetic L, power loss

Overview of Electrical Testing Circuit IEC 62044-3

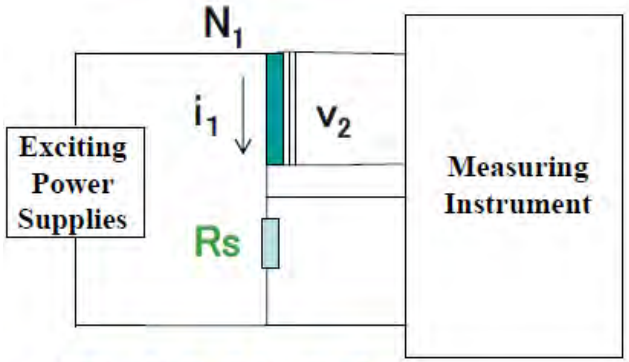
The 4-Type Basic Measuring Circuit for Multiplying Methods



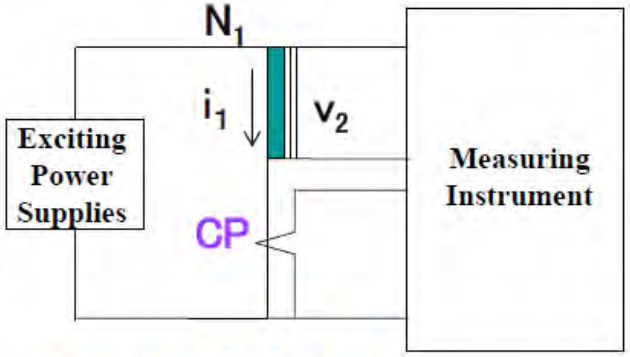
(1) Double Coil Method + Non-Inductive Resistor



(2) Double Coil Method + Current Probe



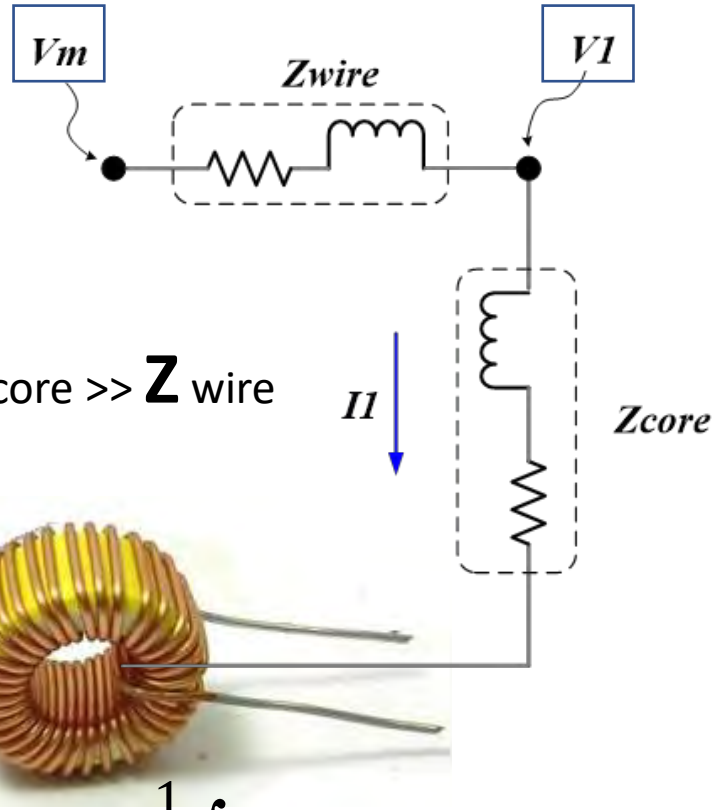
(3) Single Coil Method + Non-Inductive Resistor



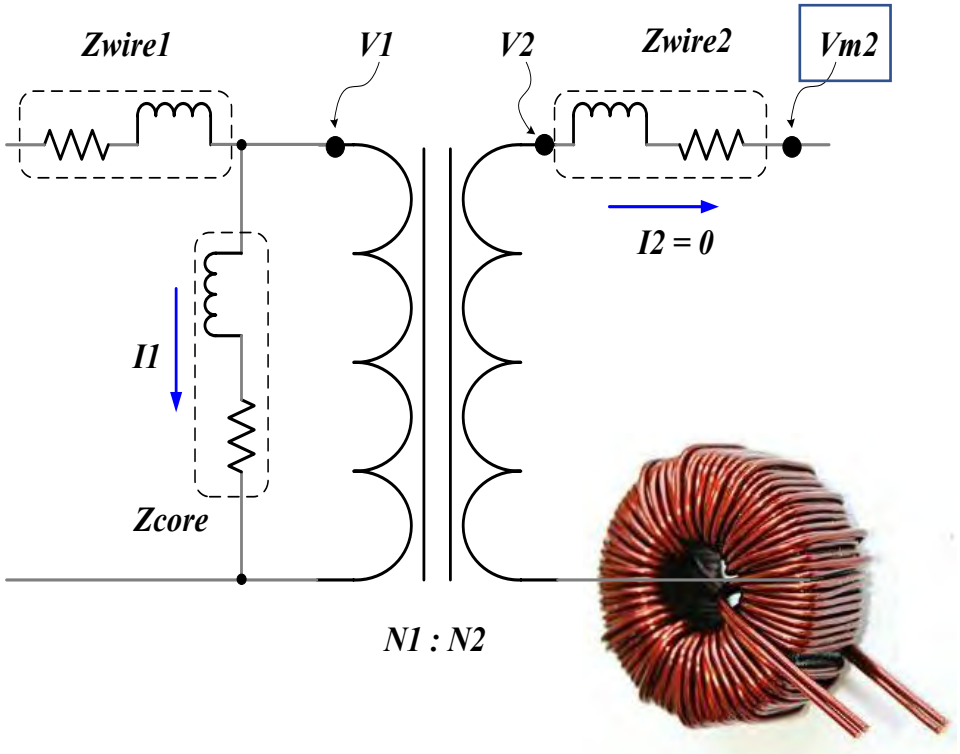
(4) Single Coil Method + Current Probe

D.U.T.

Single vs. Double Coil



Z core >> **Z** wire



$$\mathrm{Pv} = \frac{1}{T}\int Vm(t) * I1(t)dt$$

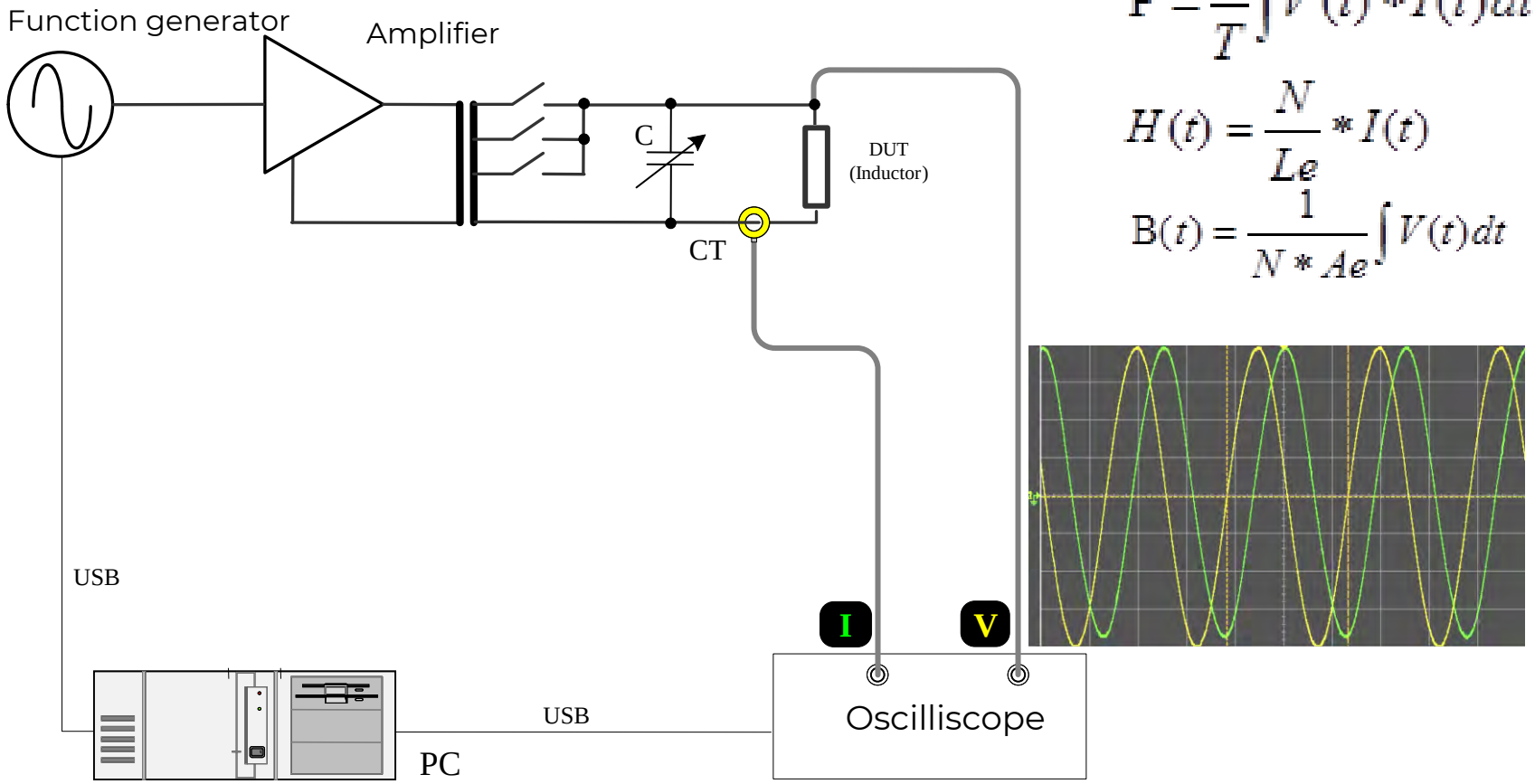
Assumption: accurate voltage drop

$$\mathrm{Pv} = \frac{1}{T}\int (\tfrac{N1}{N2})Vm2(t) * I1(t)dt$$

Assumption: perfect coupling

Configuration

Example as Single Coil Measurement



$$P = \frac{1}{T}\int V(t) * I(t)dt$$

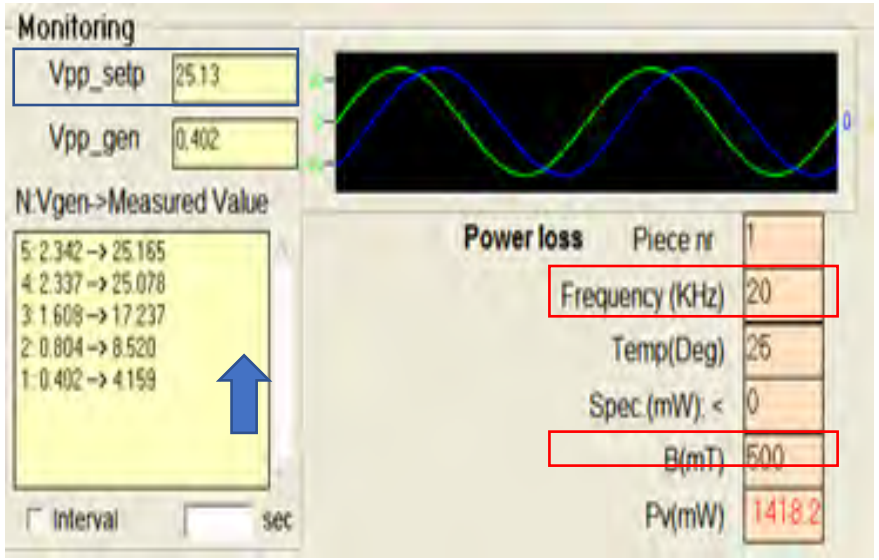
$$H(t) = \frac{N}{Le} * I(t)$$

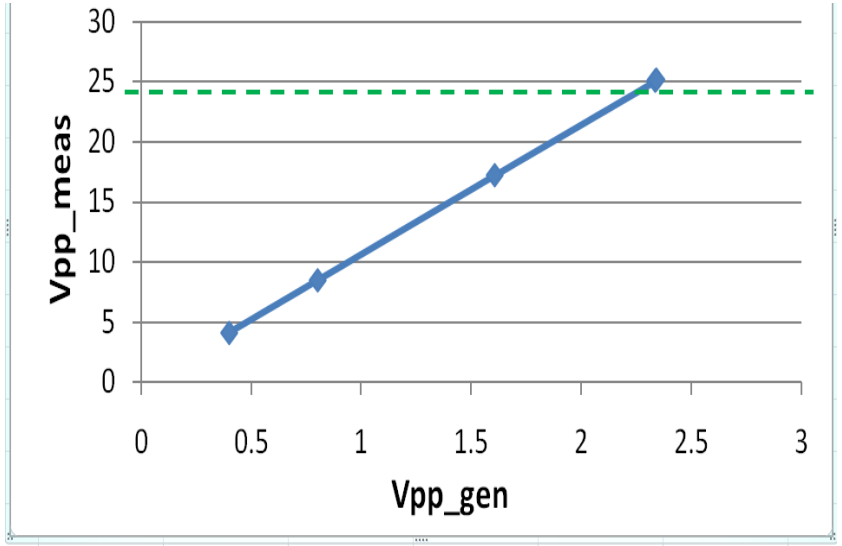
$$B(t) = \frac{1}{N * Ae}\int V(t)dt$$

Loss Measurement

Voltage Source Driven

- Desired $V_{pp} = 2 \times (2\pi f) \times N_s \times A_e \times B_p$



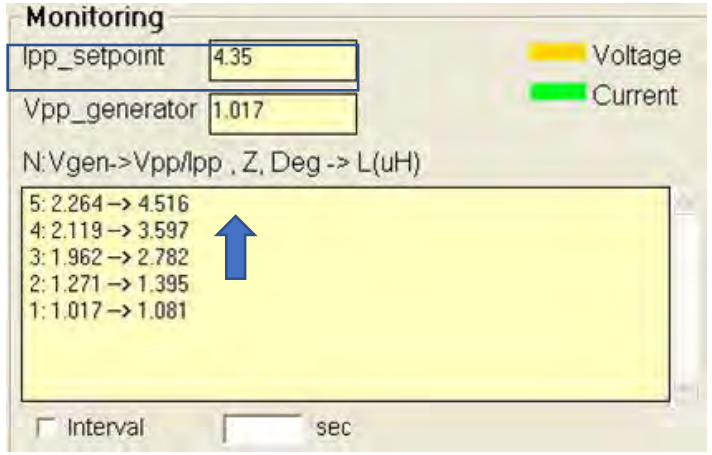


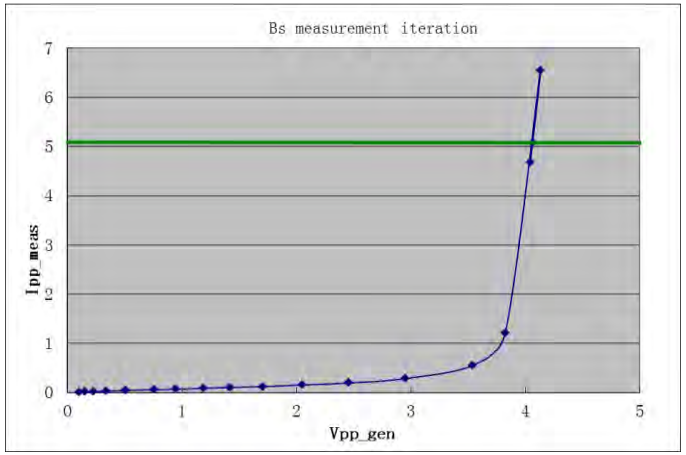
Iteration steps

Flux Density

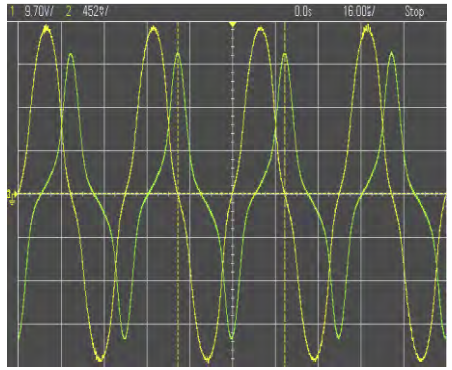
Current Source Driven

- Desired $I_{pp} = 2 \times H_p \times L_e / N_p$





Iteration steps



Data Processing

Example on a Data-Log File

Batch Nr :								
Date & Time :	02-01-01, 00:13							
Piece Nr	Code Nr	Temp(℃)	Freq(kHz)	Vpp_Sp(V)	Vpp_Mv	Vrms_Mv	V_CF	V_DC
1	0000 000 00001	25	25	11,517	11,511	4,004	1,438	-0,584
1	0000 000 00001	25	25	23,034	23,414	8,076	1,450	-0,509
1	0000 000 00001	25	25	34,551	34,992	12,007	1,457	-0,360
1	0000 000 00001	25	25	46,068	46,922	15,859	1,479	-0,315
1	0000 000 00001	25	25	57,585	58,176	19,380	1,501	-0,281
1	0000 000 00001	25	25	69,102	70,065	22,433	1,562	-0,156

Ipp_Mv(A)	Irms_Mv	I_CF	I_DC
0,212	0,073	1,451	-0,001
0,385	0,133	1,450	0,001
0,537	0,184	1,460	0,002
0,722	0,240	1,501	0,004
0,979	0,313	1,570	-0,019
1,380	0,421	1,645	-0,013

PhaseShift	Phi_Cal	Phi_Corrected	CosQ
1,457	76,503	75,062	0,258
1,457	74,435	72,978	0,293
1,457	72,654	71,196	0,322
1,457	71,622	70,177	0,339
1,457	71,965	70,558	0,333
1,457	73,774	72,456	0,301

Pv_Cal(mW)	Pv_Corrected	Pv_Final	Pv_FinalOffset
68,357	75,501	79,910	78,504
287,997	314,175	318,410	316,329
658,207	711,587	734,394	729,695
1201,240	1292,009	1366,165	1358,309
1879,682	2020,949	2263,251	2243,208
2636,412	2844,095	3488,736	3465,131

Critical 1 System for Test

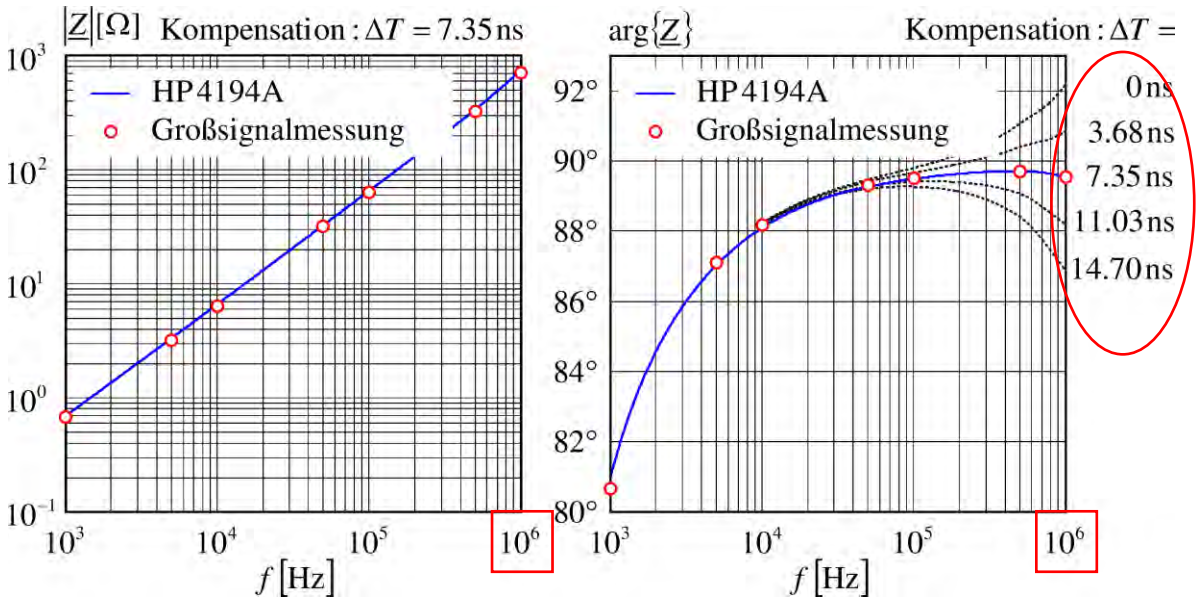
Current Signal

- CP: galvanic isolation, ***no*** interference
- CP: signal ***delay*** about ~5 ns, can be compensated through phase angle drift till +/-1 ns, which corresponding 0.3° @ 1 MHz
- Rs coaxial shunt, being part of circuit, always having parasitic leakage inductance

$$|\varphi_{\Delta T}| = \omega \bullet {L_{sh}}/{R_{sh}}$$

Compensation: Reason and its Limitation

Phase Measurement is Challenging



- No Error at Absolute Value of the Impedance
- But visible at the Phase Measurement
- It must be compensated

Figure: Absolute Value of Impedance and Phase Measurement of Air Core

Limitation of Digitalization Method is around 1 MHz

How to Compensate?

how to Compensate Signal Propagation error

Compensate with Capacitor:

Advantages

- High impedance at low Frequencies
- High Phase angle near 90°

Disadvantages

- Very small Frequency range of one capacitor
- Much capacitors needed to compensate a wide frequency range (up to 1MHz)

Compensate with Inductor:

Advantages

- High impedance at high frequencies
- High phase angle near 90° for high frequencies
- Very big frequency range
- Linear course of the absolute value of the impedance

Disadvantages

- Very small impedance for low frequencies

Phase Error

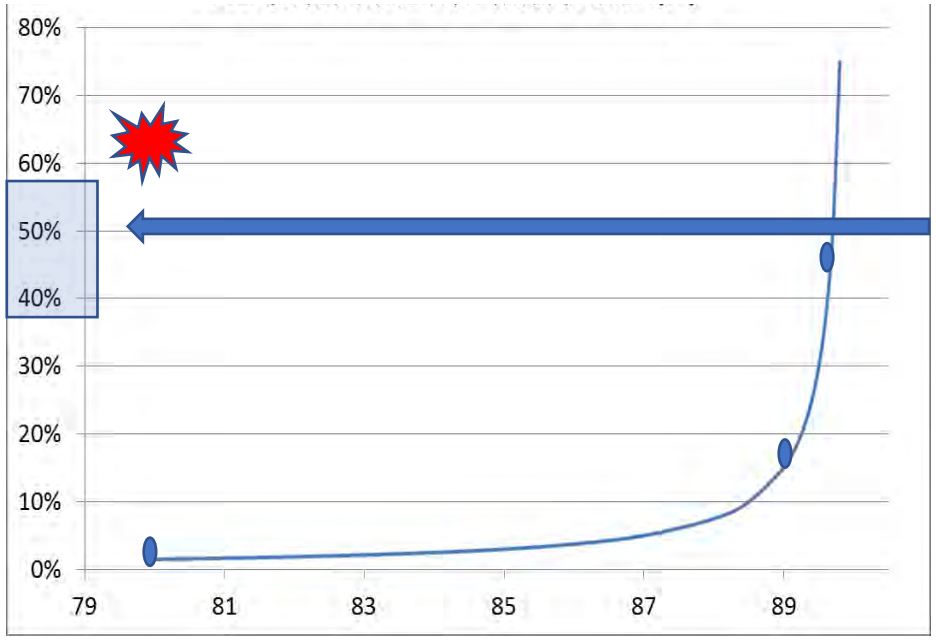
Critical 2 Material under Test

- Systemic drawback
- Phase 80 °

  → 1.5%
- Phase 89 °

  → 15%
- Phase 89.5 °

  → 30%



Mess(ungenauigkeit) bei Verlustmessung [%]
verursacht mit Phasenfehler von +/- 0.15°

The less lossy,
The higher inaccuracy

Further Uncertainty Sources

--- and more

- Temperature as major impacting parameter is a must for ferrite material loss measurment, due to crystalline anisotropy is temperature dependent
- Mechanical conditioning before measurement, due to magnetostriction
  like conditioning during winding & potting before, and under defined pressure during measuring operation
- Uncertainty with effective geometry and number of turns
- Harmonics of higher orders impact results
- Intermediate connections (wiring and connectors) have parasitics, which further limiting frequency and amplitude response

Incremental Permeability

ac Biased with DC

- Application of soft magnetic materials for high frequency application nowadays mostly biased with DC
- The ac ripple tends to go up, however always with biased DC, and the ratio of AC peak / DC differently from application to application, buck and boost, different as PFC
- Loss dependence extends with a fourth dimension, namely H_{DC}

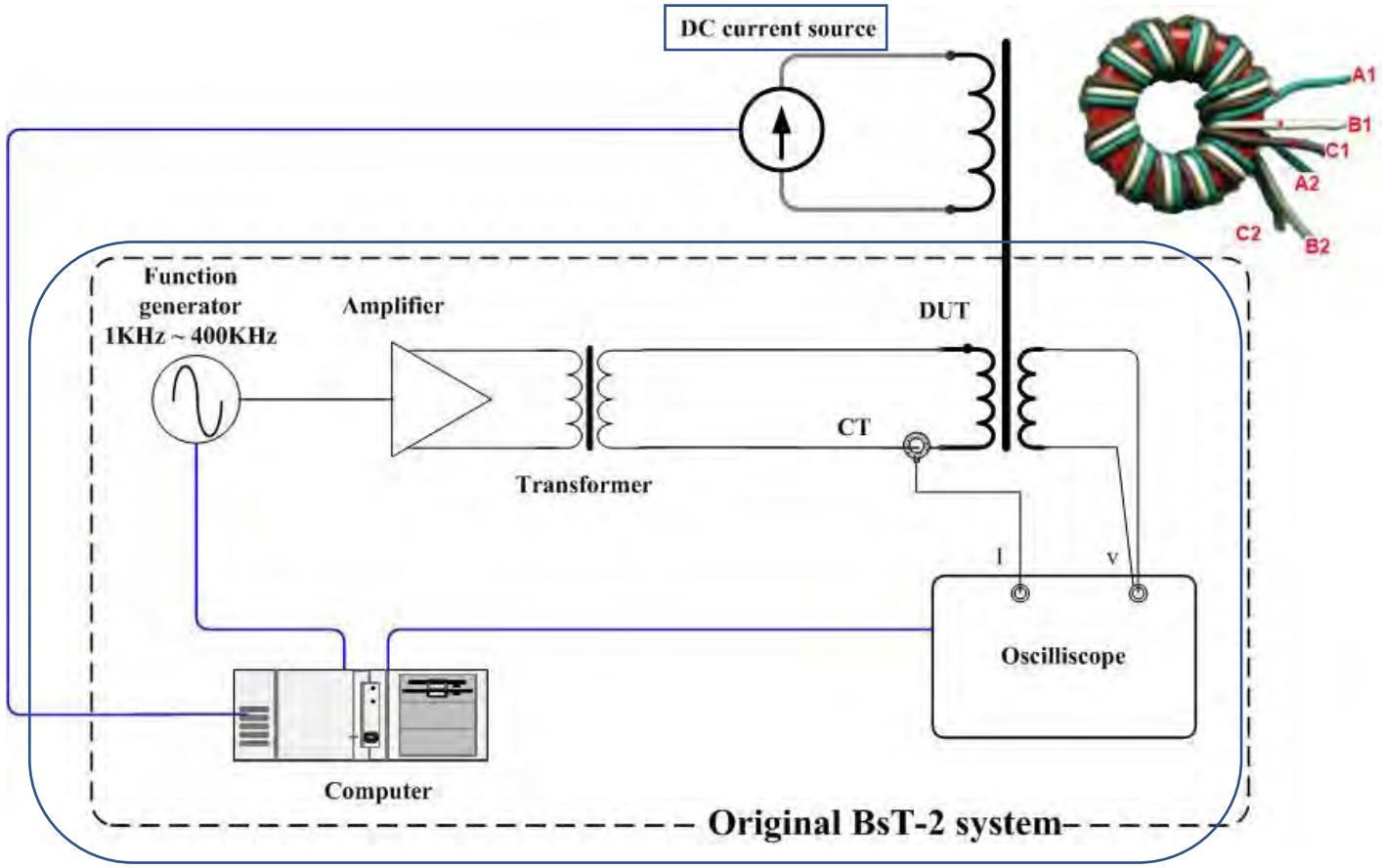
Questions (raised in 2015) are:

how much DC is DC, DC quality? and
how to bias the DC into testing circuit?

Answer delivered in literatures

Configuration of BsT-Pro

BsT-Pro windings scheme

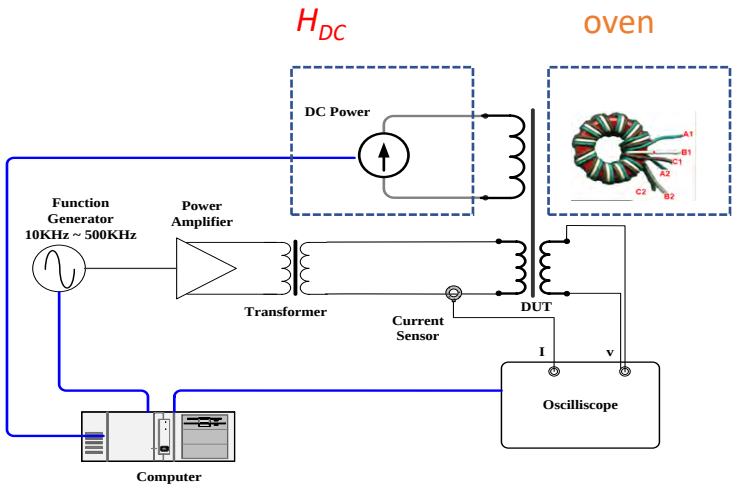


BsT-Pro Proposal

Hardware presented in 2015







loss map (f, ***B***, T, H_{DC}) ← μ_{inc}

Pulse Excitation Mode

Several ways to Compensate Signal Propagation error

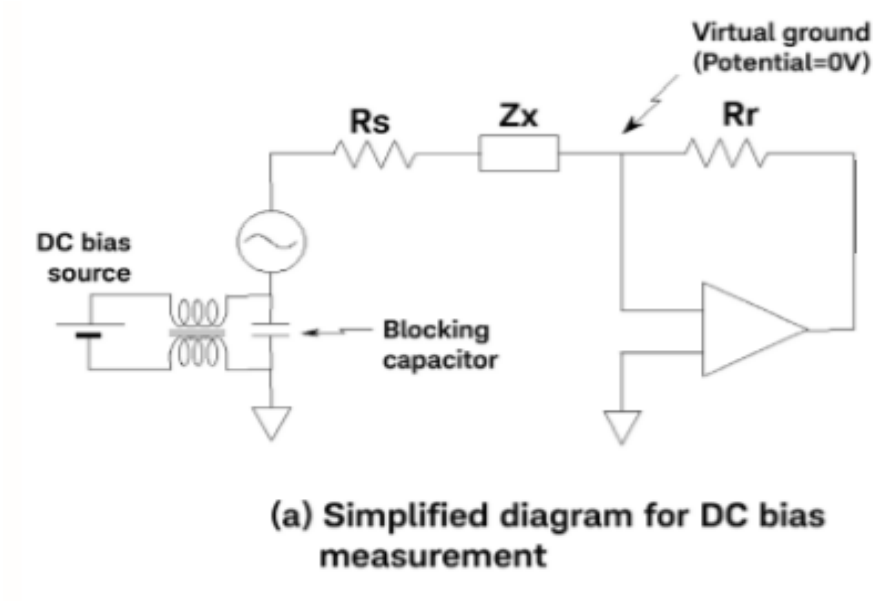
- Core maker provides material characteristics i.e. permeability under low excitation; and indicates only TYPICAL value @ operation condition, sometimes with fitting parameters
- Coil maker supposed to be demanded by his clients with LIMIT value, and…

… There is a GAP

Incremental Inductance Measurement

Auto Balance Bridge with external DC bias

- Generally, the internal bias output current is not enough to bias the inductor at the required current levels. To apply a high DC bias current to the DUT, external current bias units needed (expensive).

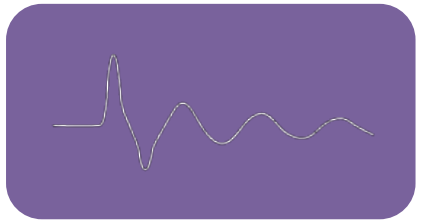


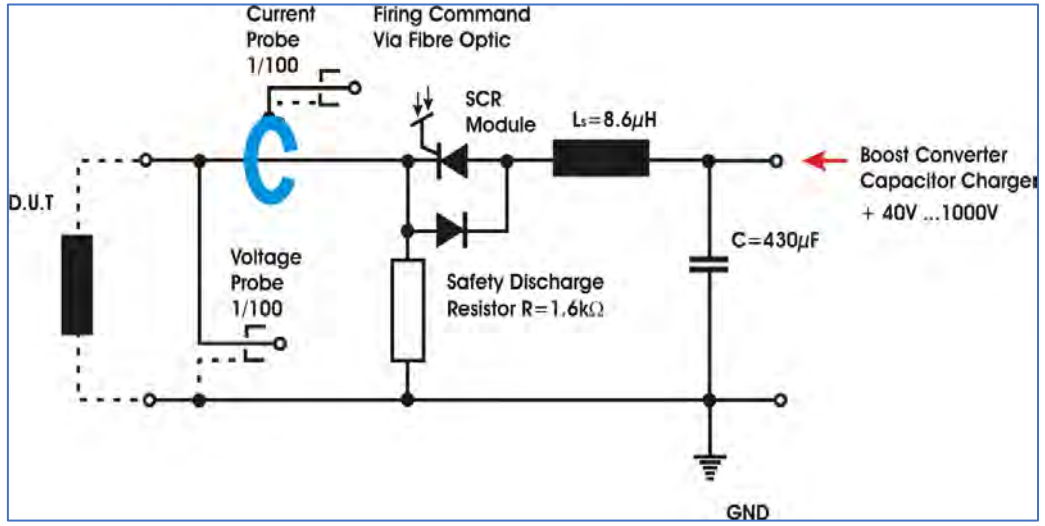
(a) Simplified diagram for DC bias measurement



Damped Oscillation

Principle and Device

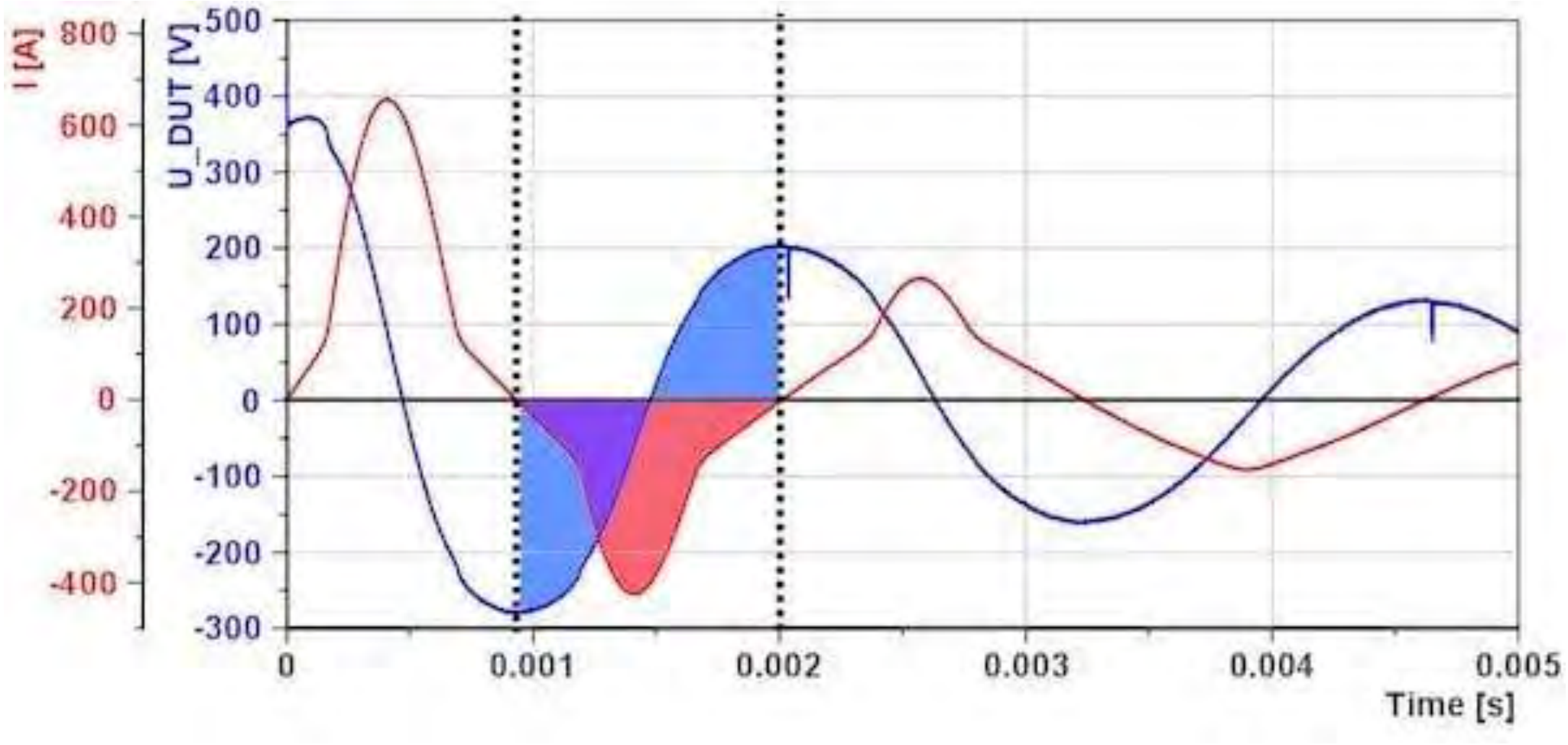






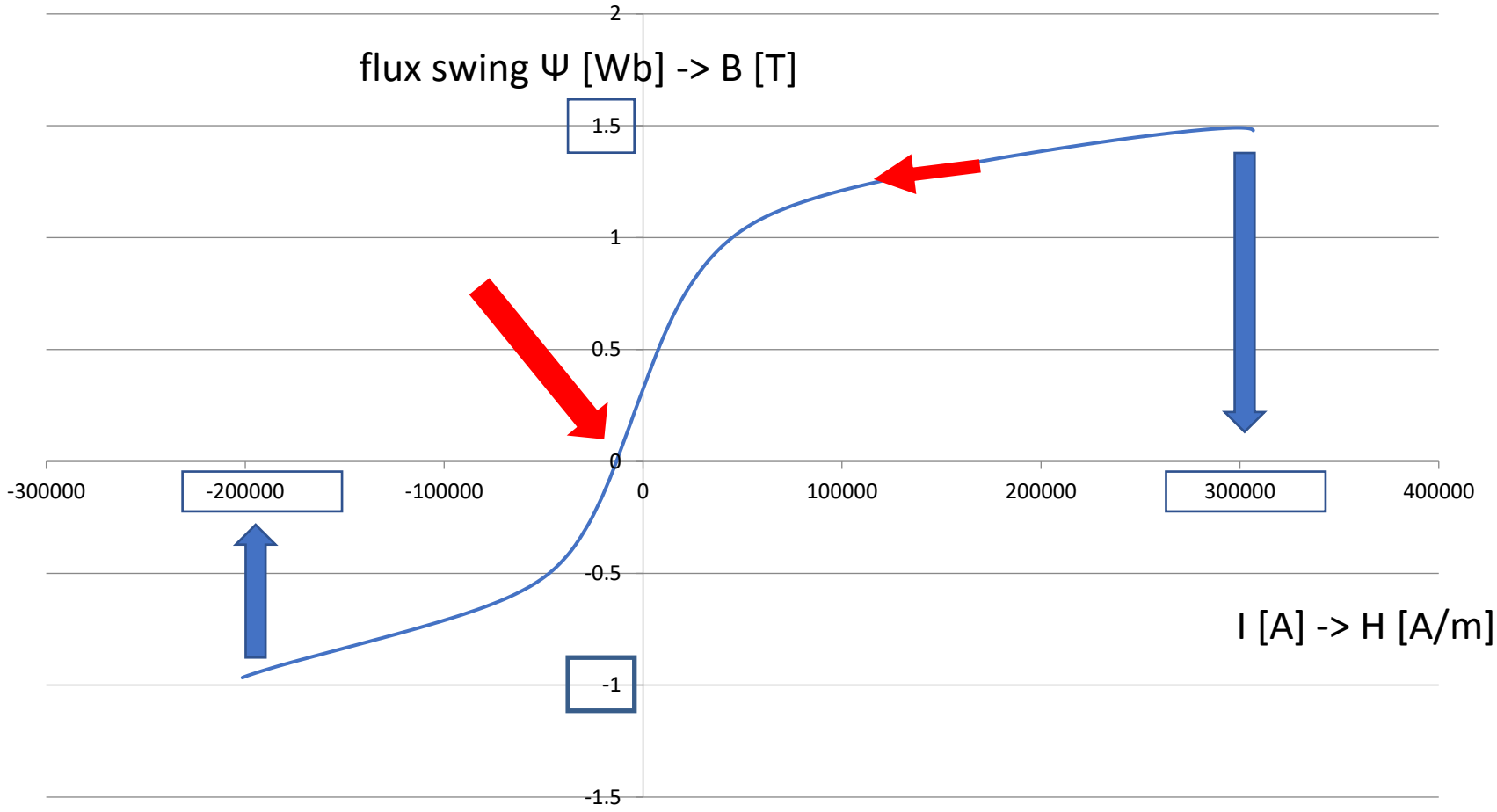
Voltage Current Decay of Typical Damped Oscillation Test

Up to 10kV macro BsT-Pulse



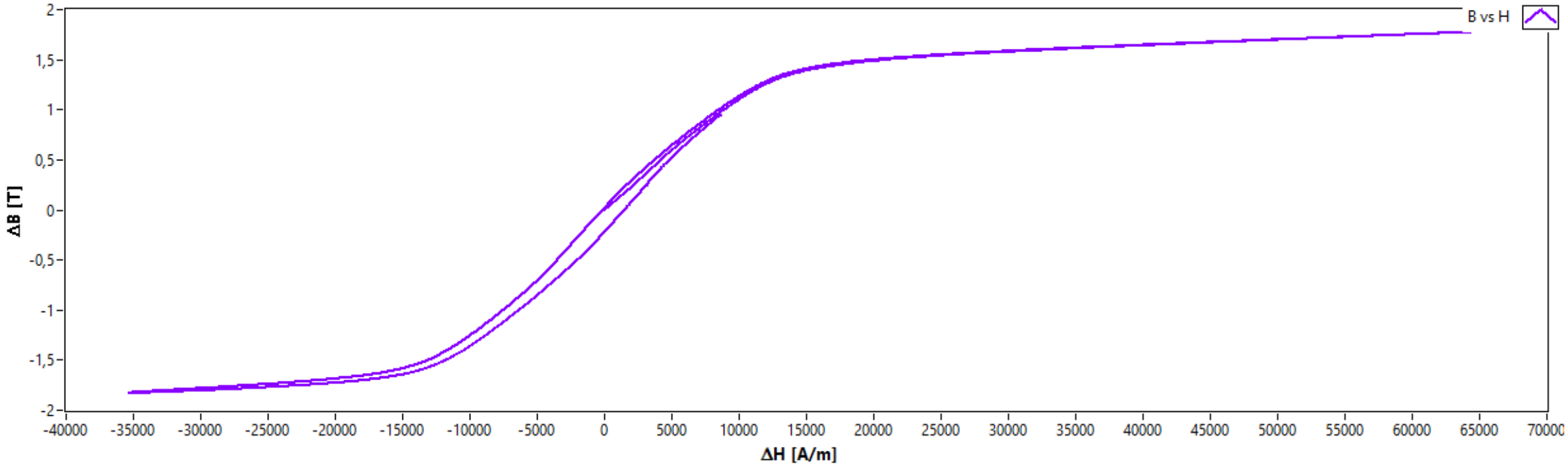
Demagnetization

With full reversed Current Cross Zero



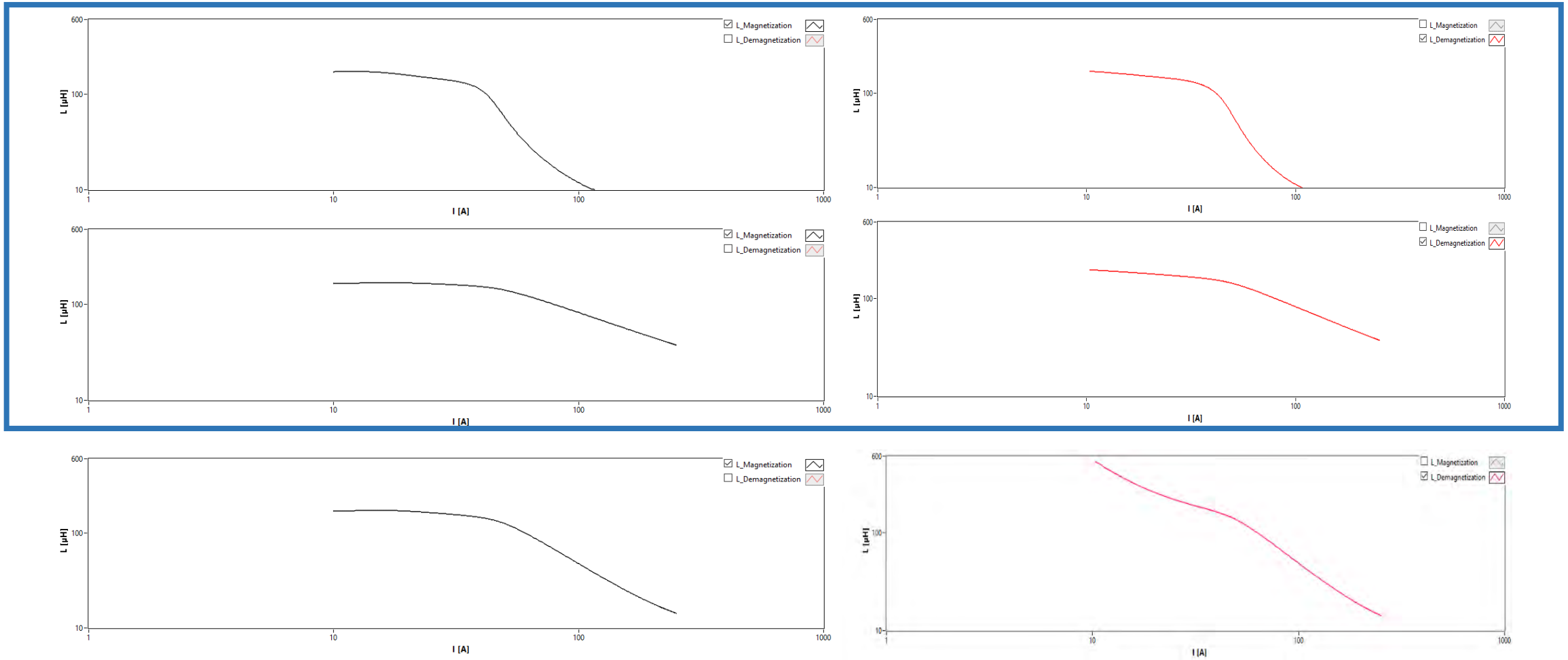
Magnetic and Electrical Parameter Characterization

One Cycle



Magnetic and Electrical Parameter Characterization

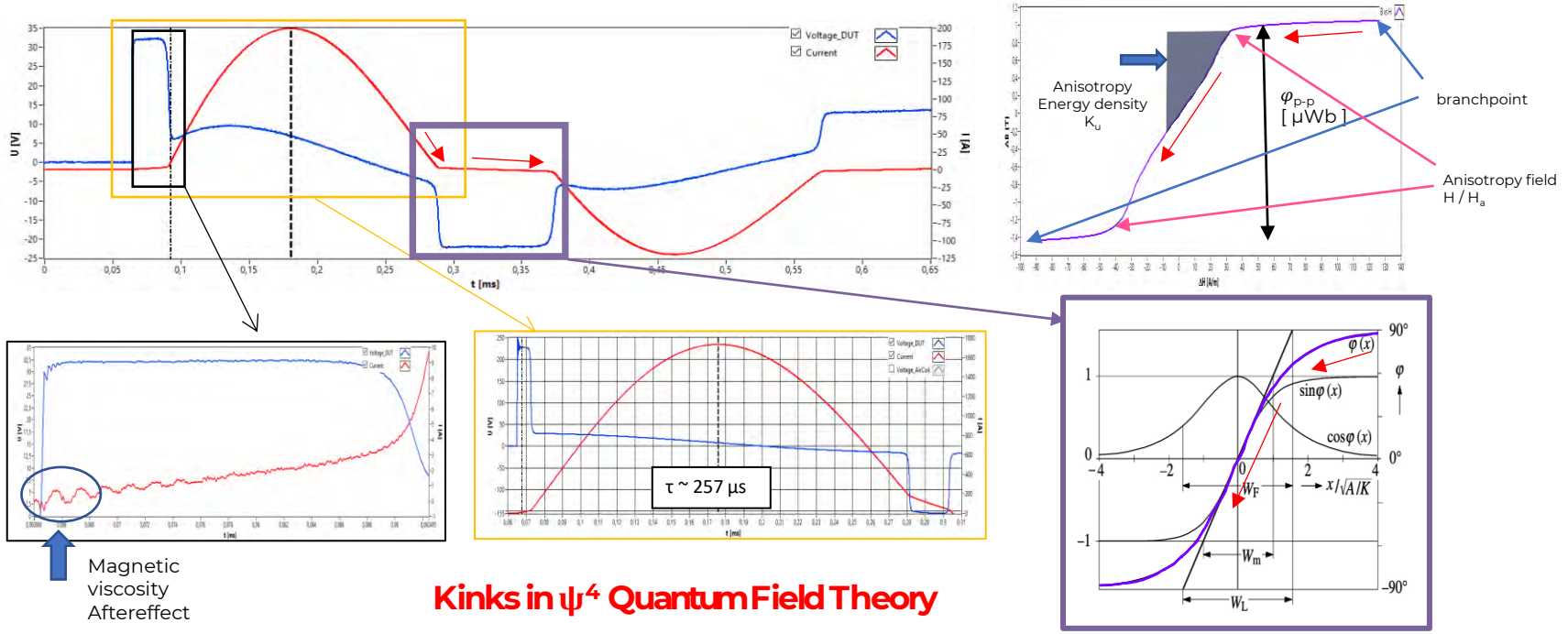
One Cycle



Reloaded Data Processing PSMA Workshop 2022

Portrays Nonlinear Attributes of Magnetic Components

- Micromagnetic parameters, like wall energy, thickness even mobility, can be provided by demagnetization path, with full reversal current cross zero, adiabatically



Kinks in ψ⁴ Quantum Field Theory

Single Pulse vs. Multiple Pulses

Comparison

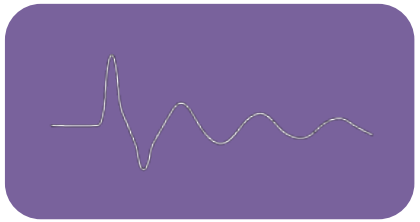
Pulse Magnetization

Fast Transit of Magnetic State
dB/ dt

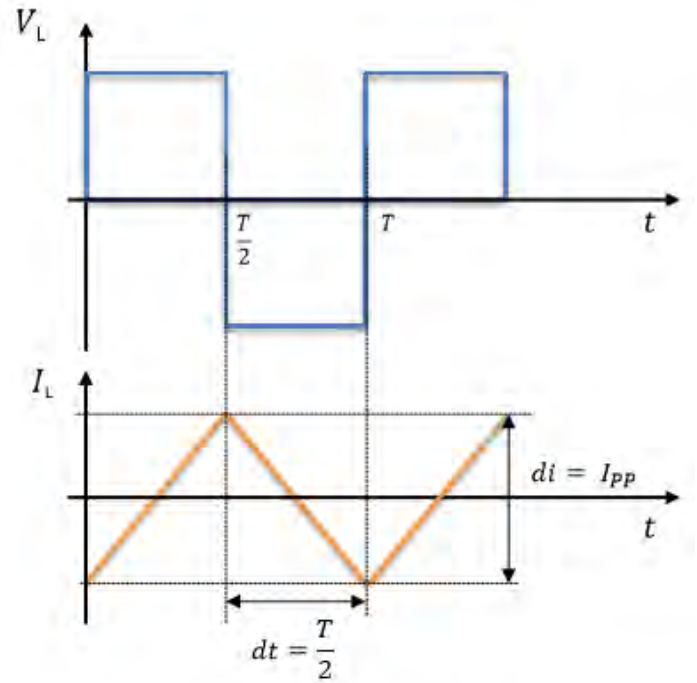
Single Pulse

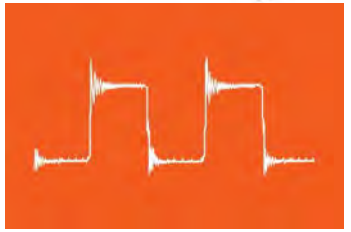
BsT- Pulse

Differential Amplitude L
Energetic L, Power Loss



Square Wave

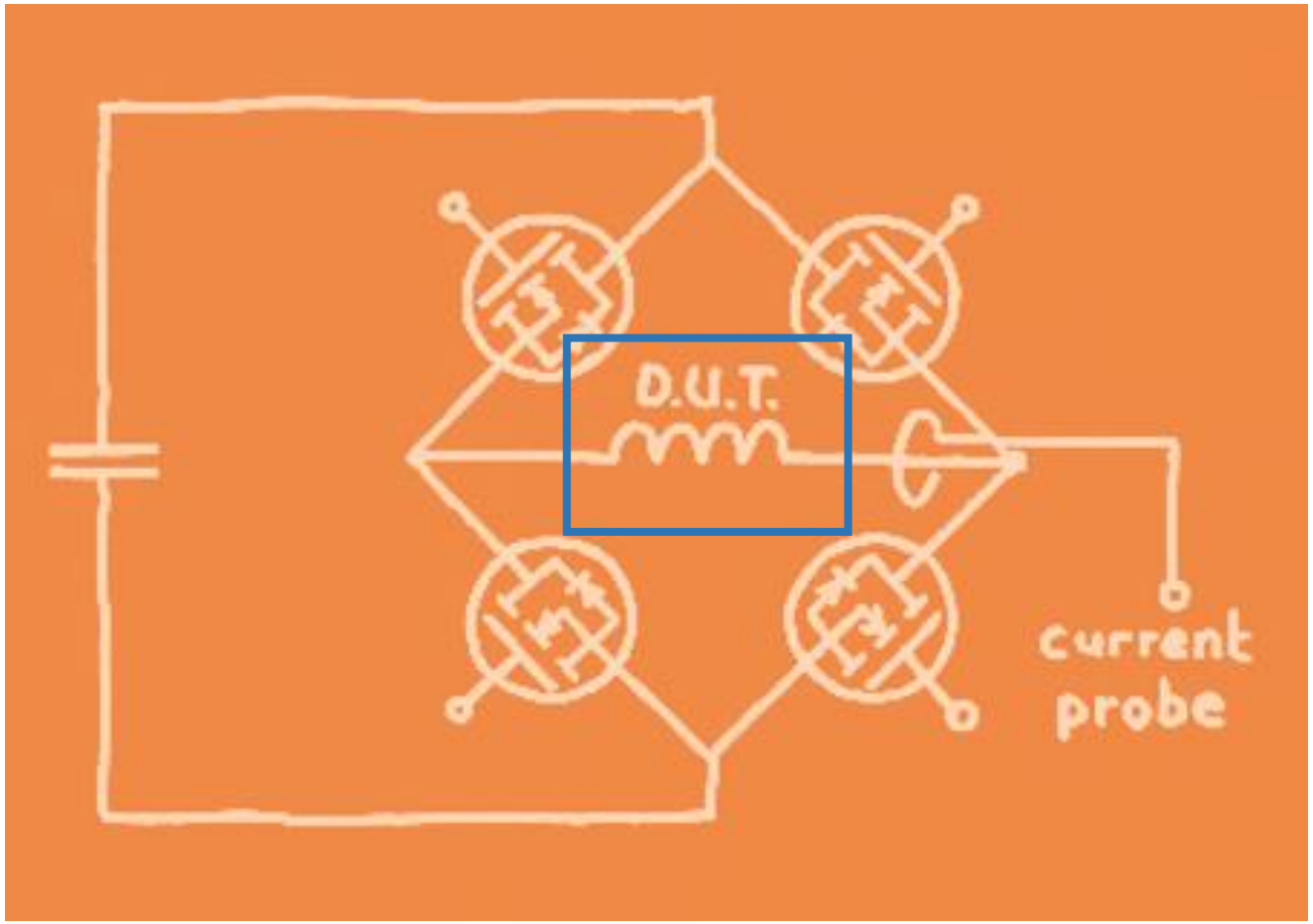




PCIM 2018

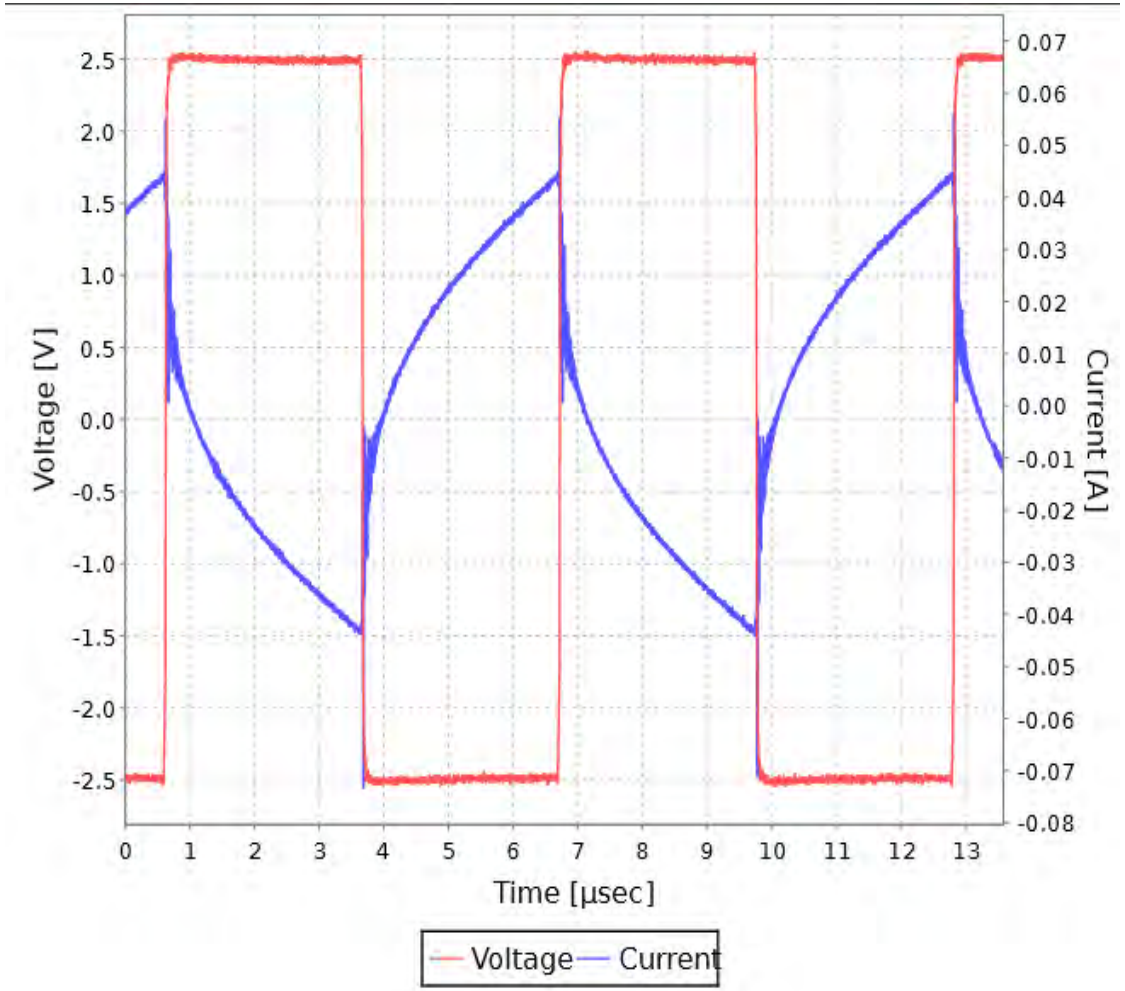
Circuit (half / full bridge)

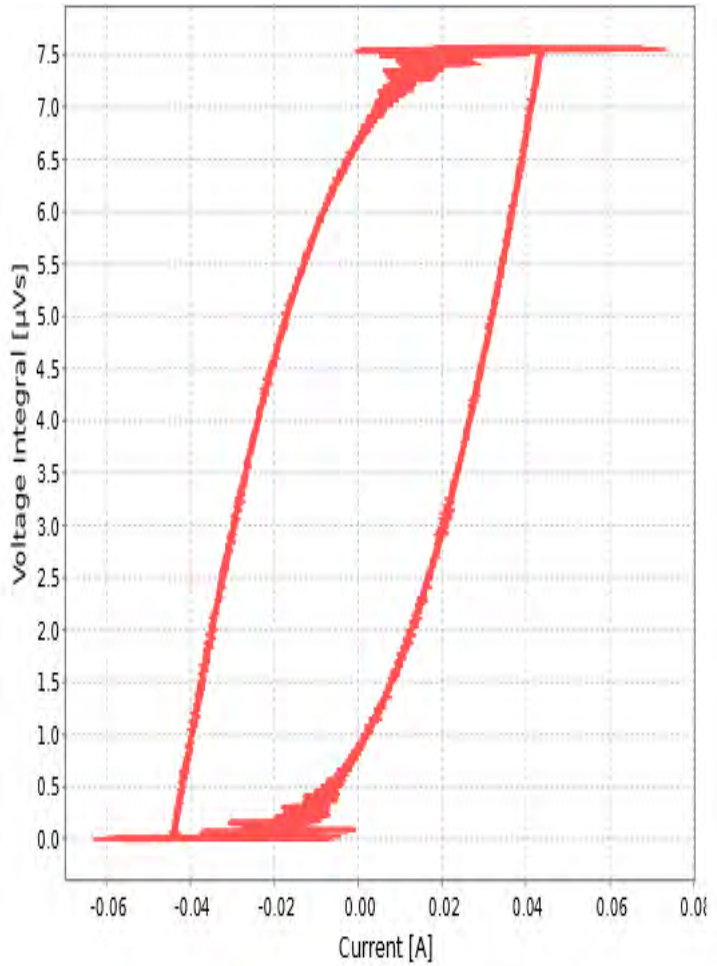
Pulse width flexible, Callibration feasible and intuitive



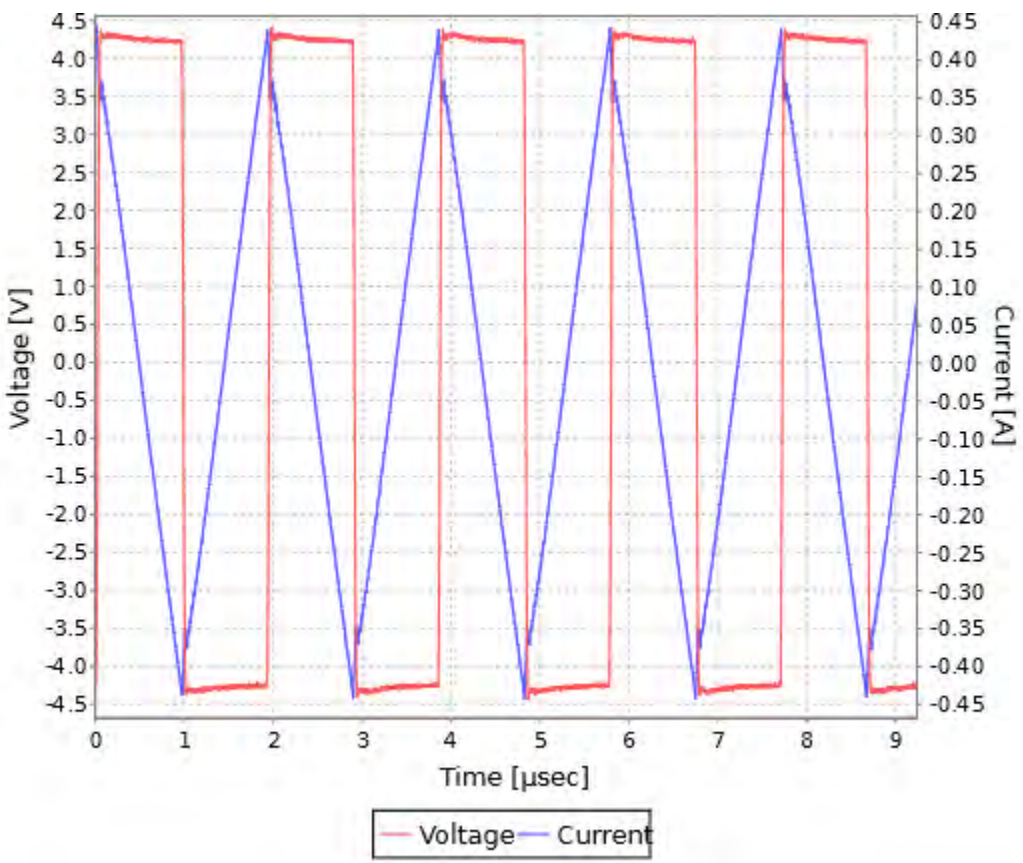
Voltage Current Time Domain vs. Power Loop (~3µs)

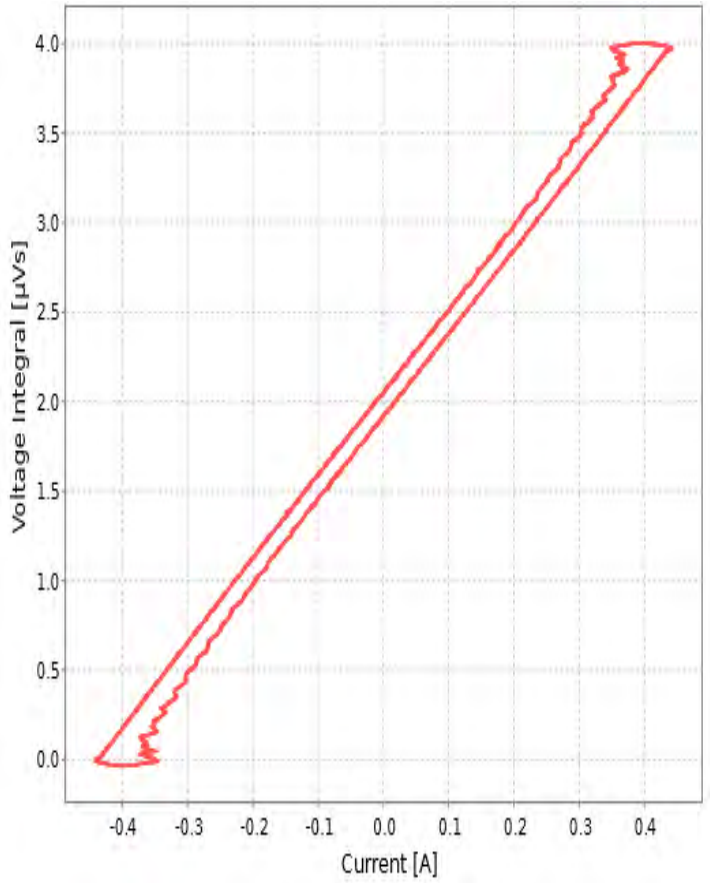
Up to 690V macro BsTSQ





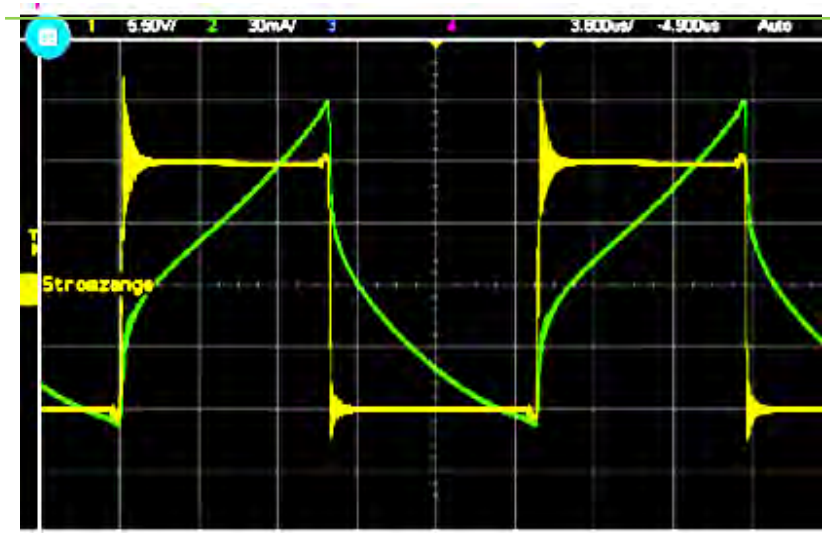
Voltage Current Time Domain vs. Power Loop (1µs)

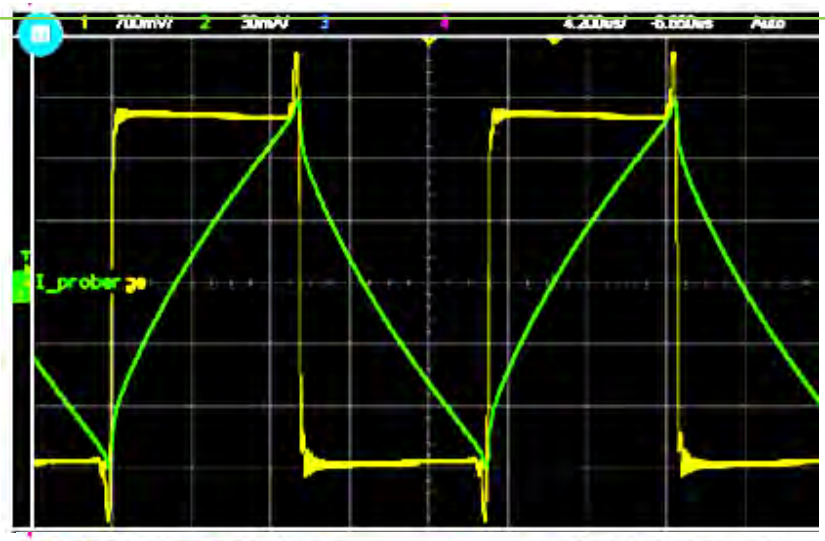




Diverse Coils under Test

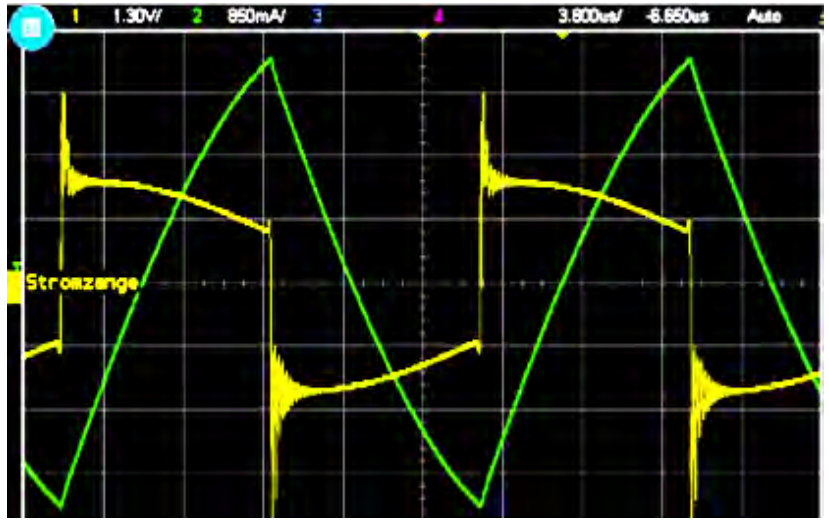
Power ferrite

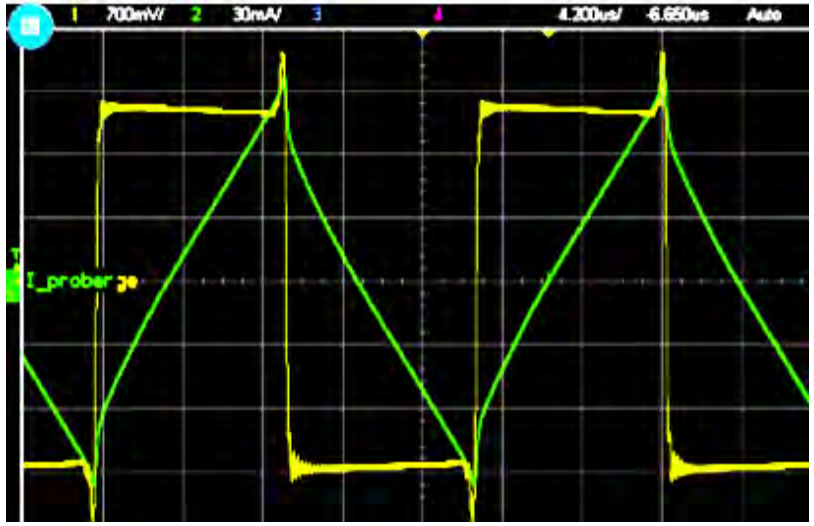




Fe amorphous

Metal Alloyed Powder



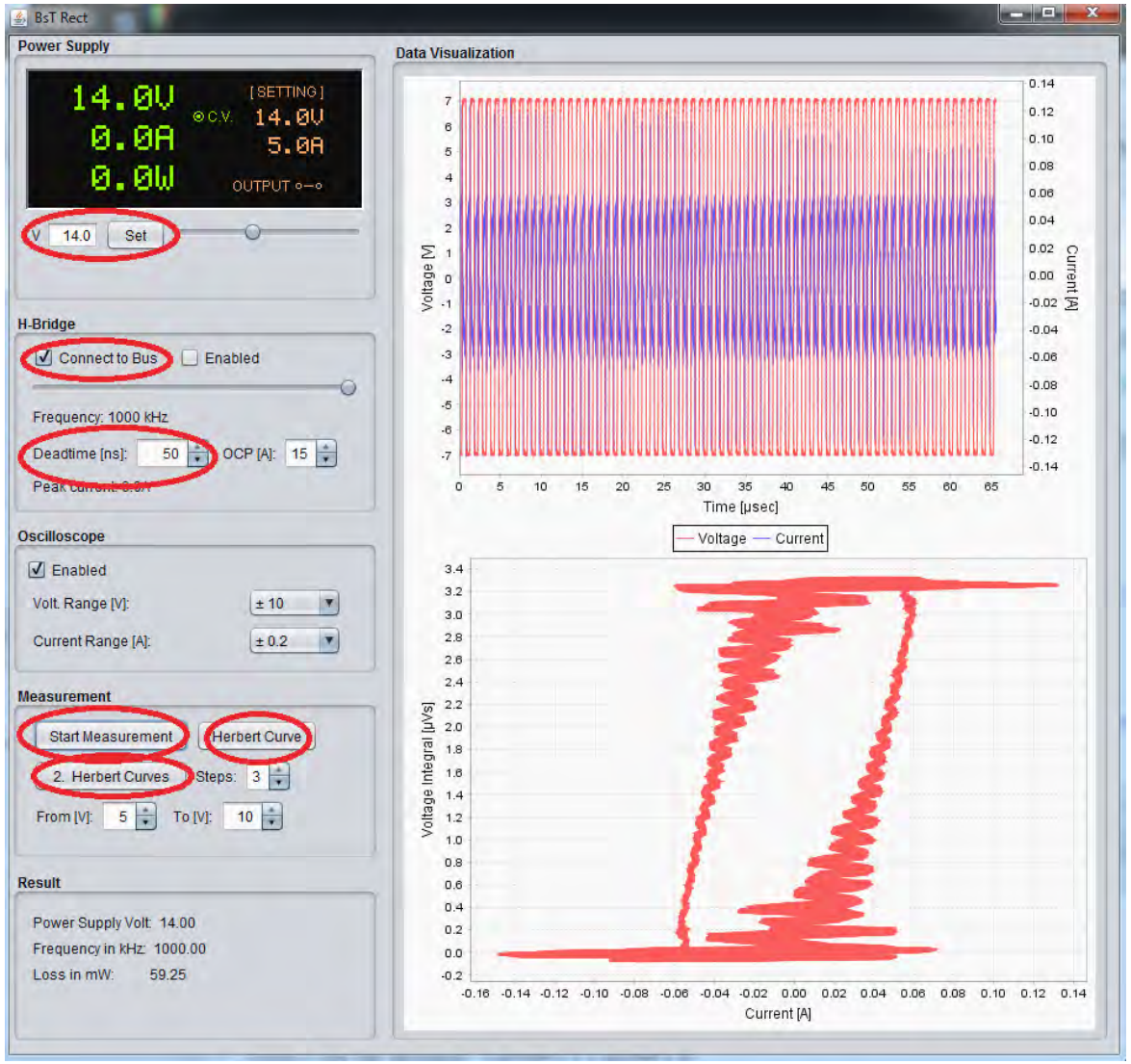


“HF” ferrite

Output BsT – SQ Power Loop

DC voltage

sw. frequency
pulse width
dead time



time domain

µVs vs. I

Arbitrary vs. sinusoidal wave

Differental vs. Incremental Inductance

Arbitrary wave form can be defined by:

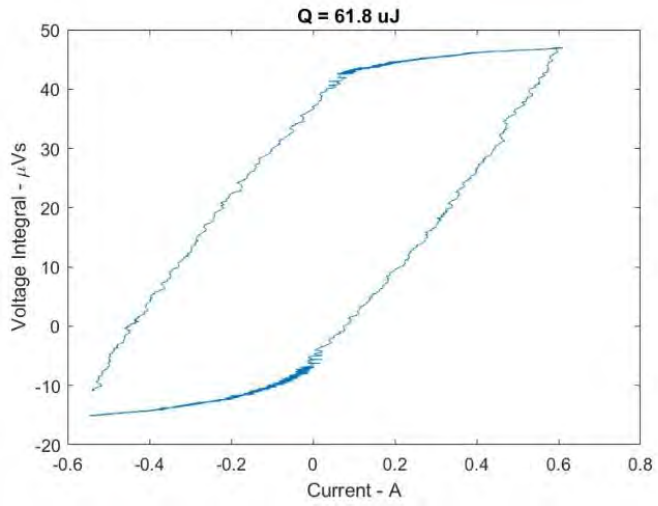
any number of time, amplitude points needed;
a set of time intervals with varying amplitude with necessary resolution

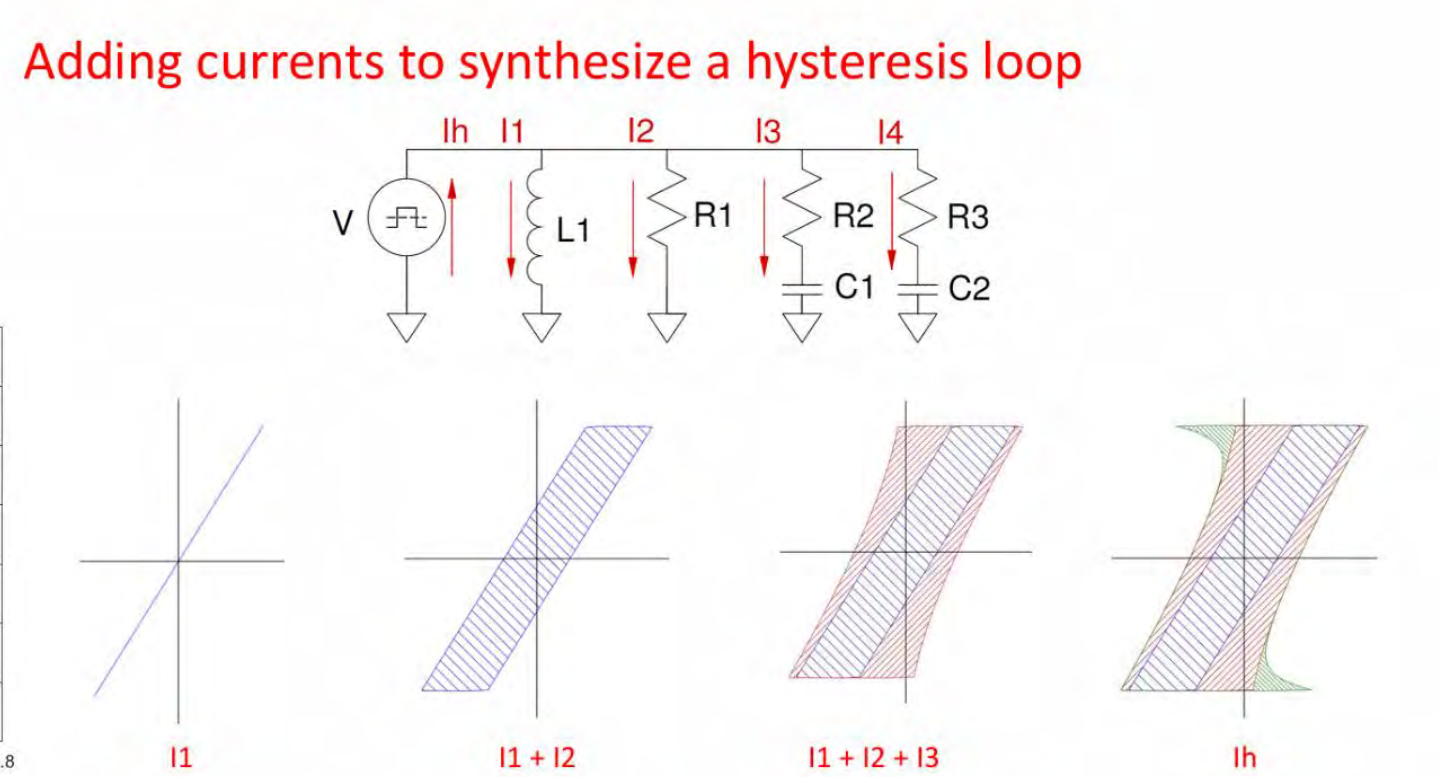
- Periodic bipolar rectangular voltage excitation in rms, peak amplitude and average rectified value

- Bipolar with reversal current through zero and overcome exchange bias effect, if when periodically

Pulse Width modulation in time domain

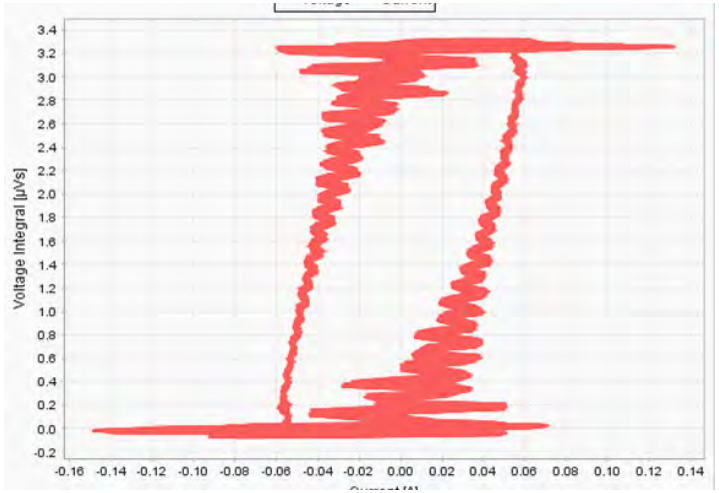
From data to simulation LTspice





Coil loss under square wave $10^{-1\sim3}$ V $10^{-6\sim-3}$s

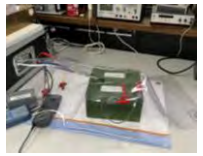
µWb PSMA 2018



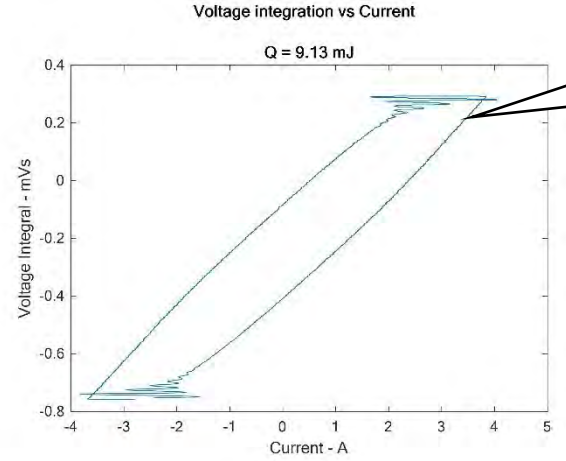
- **Object Name:**
  Drahtbüro DUT
- **Test Date:**
  January 2025
- **Photo of BsT SQ macro Testing System:**



- **Photo of Object:**

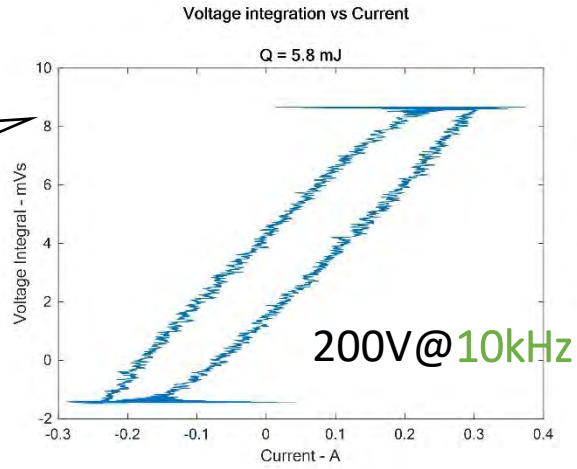


mWb PSMA 2025



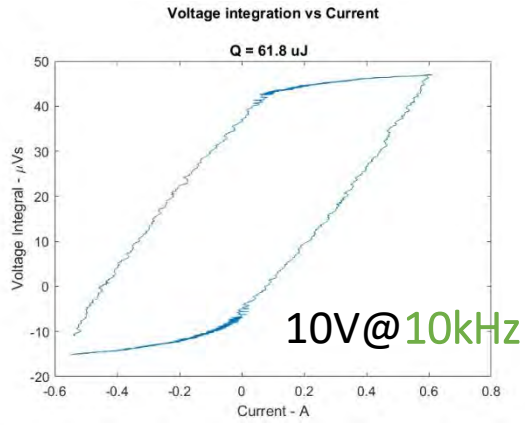
123 µH

20V@**10kHz**



18 mH

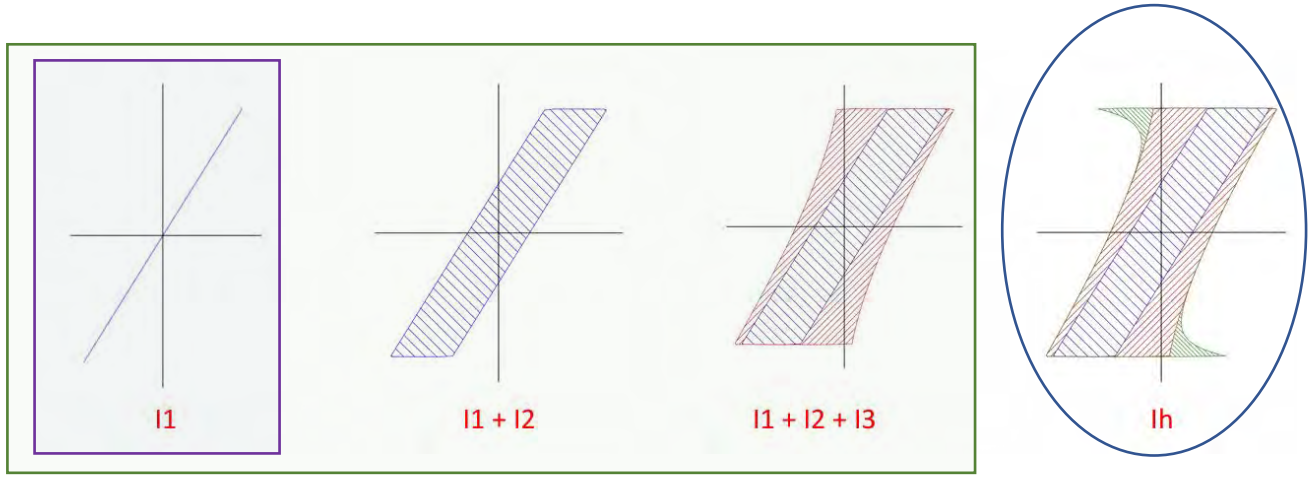
200V@10kHz

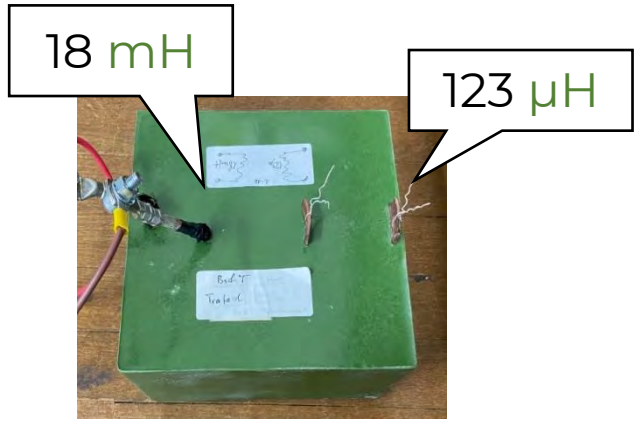


10V@10kHz

private communiqué with Jin UB

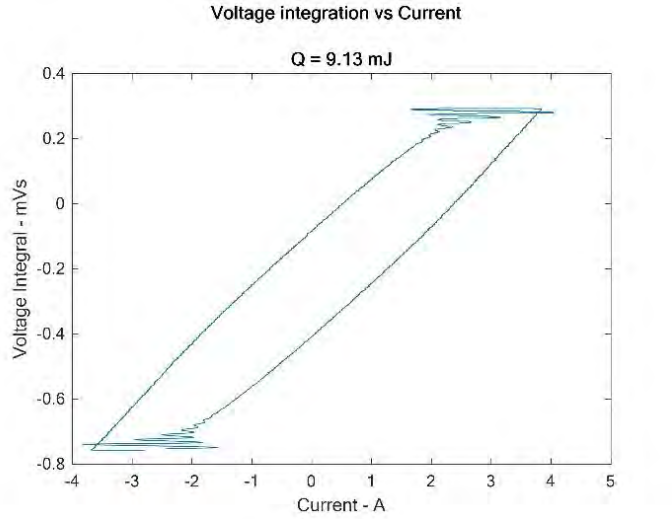
Coil loss Map vs. Model Parameterization





Core Loss Modeling page 14

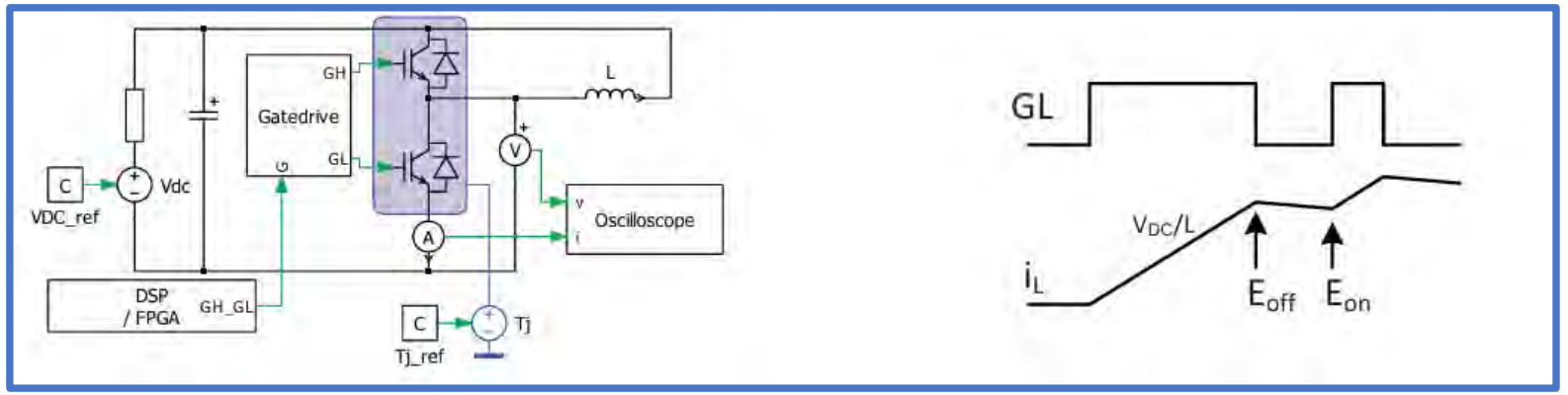
1. L: Inductance value* is slot from Vs vs I diagram
2. R and C**:
   primary N=1 ~12 µΩ
   secondary N=12 ~1,3 mΩ
3. Switching loss



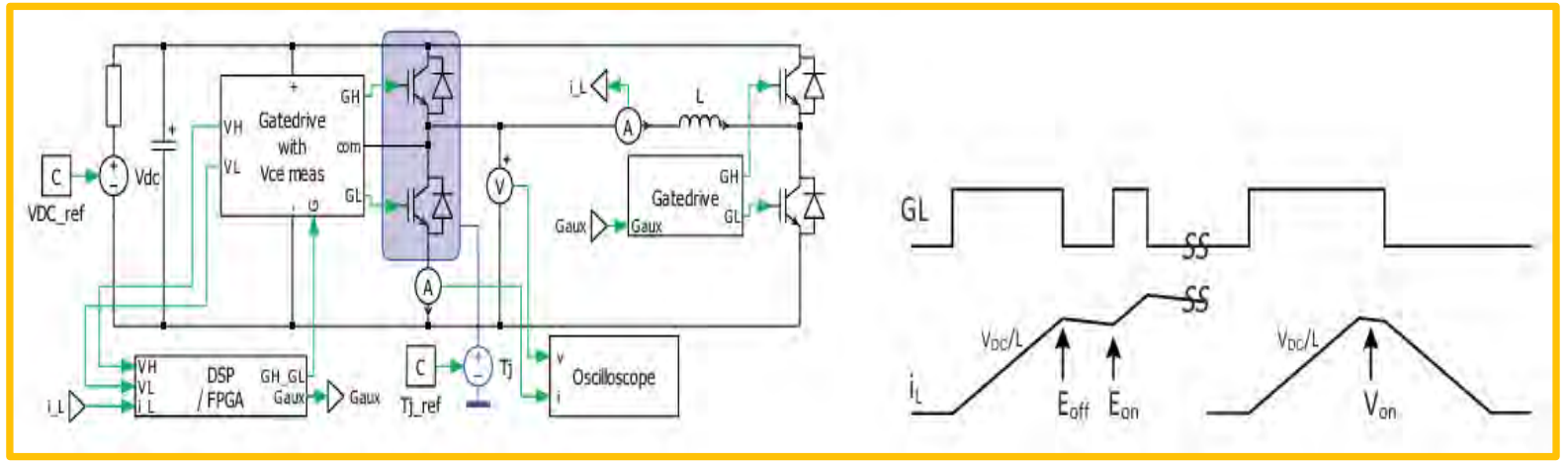
*linear, differential, amplitude and energetic equivalent overlap each other
** C wire capacitance and capacitance from source to DUT

Triple vs. Double Pulse Test

switching (On, Off) loss IEC60747 TC10

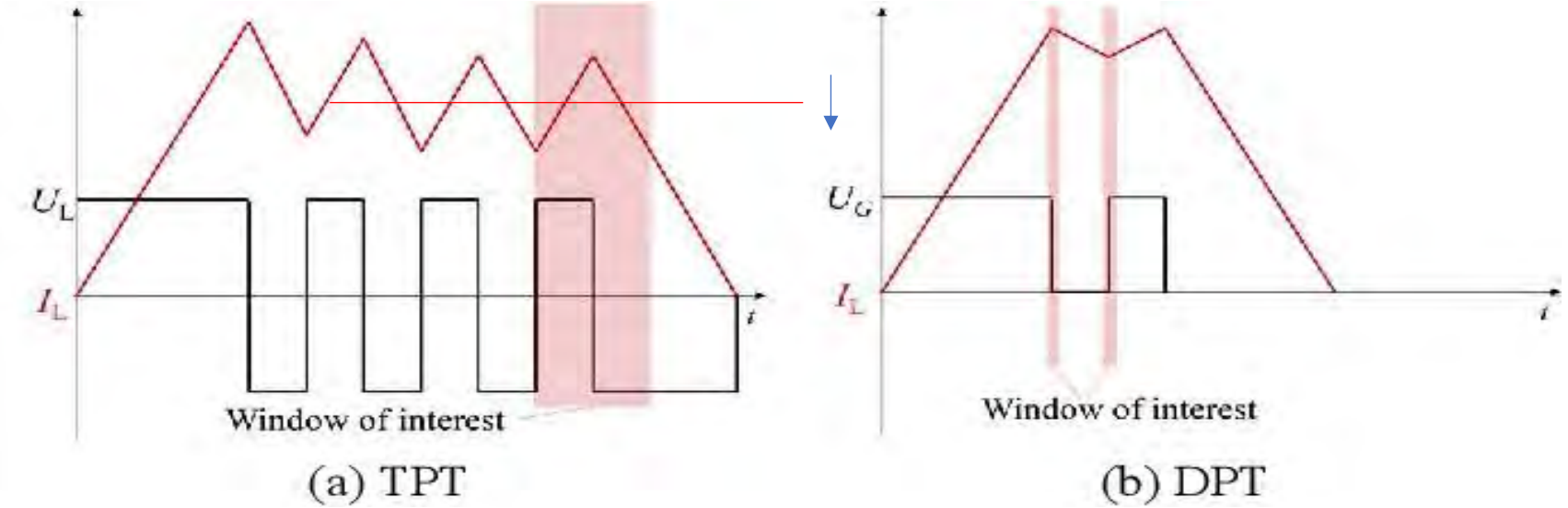


+ conduction (+ recovery) loss IEC60287



Triple Pulse Test Reload

Full bridge: characterize sw. Loss + conduction



Extend conduction loss with full bridge to include induction loss

Conclusion

Summary

1. Review standard of loss measuring techique
2. Contemporary DC biased ac loss via BsT-Pro -> core loss map with more dimension H_{DC}
3. Progress in parametrization via BsT-Pulse
4. Loss characterization including switching loss

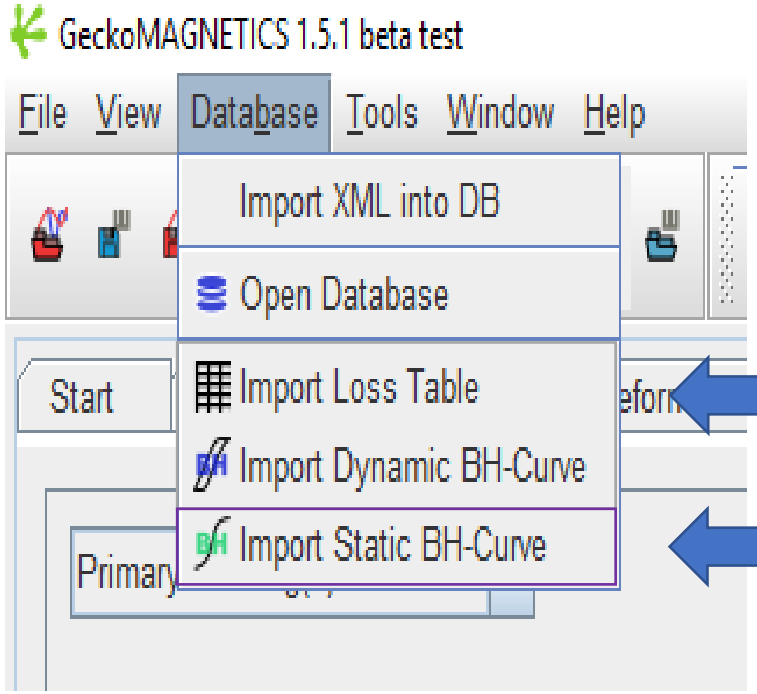
Annex 1 Simulation of Inductive Component

With Core Loss Map under Sinusoidal Wave

Video import loss map as an example FeSiAl powder material:

Step 1: rename particular material

Step 2: mark frequency, flux density, and bias, and import



import_loss_table.mp4

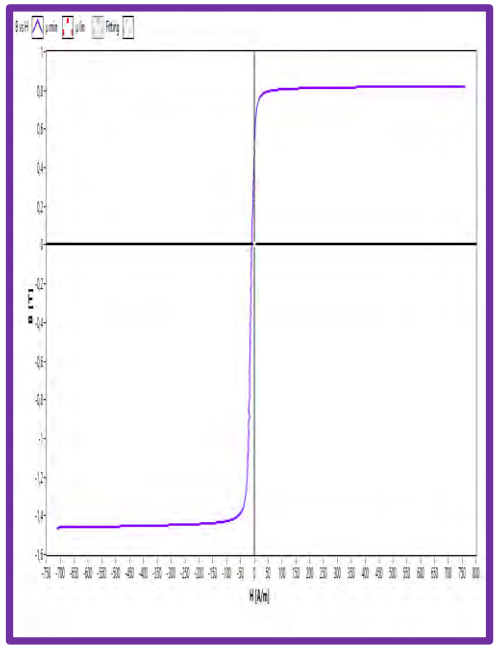
BsT-Pro 2016

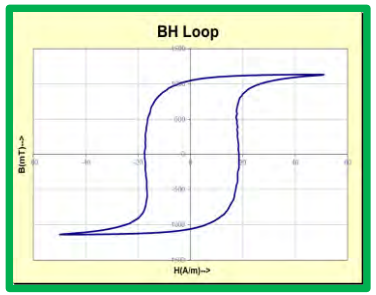
BsT-Pulse 2017

Annex 2 Coil Loss: Voltage Bipolar

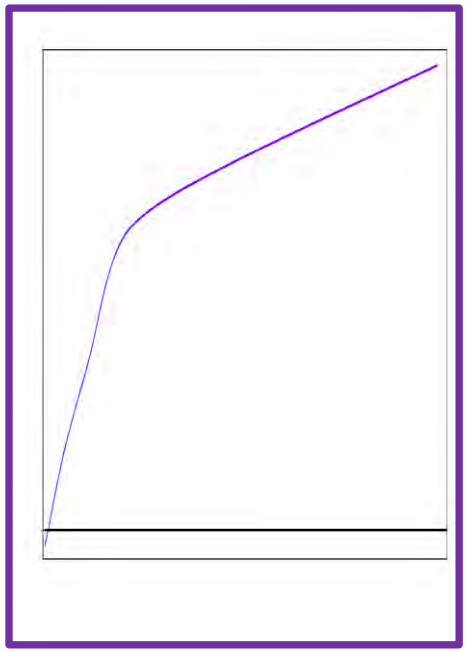
Reversal Current Cross Zero

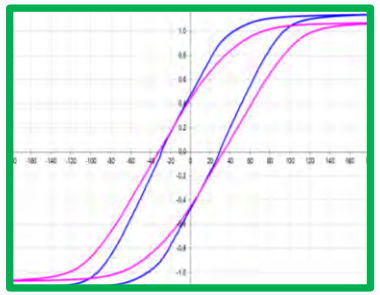
Magnetic Switch



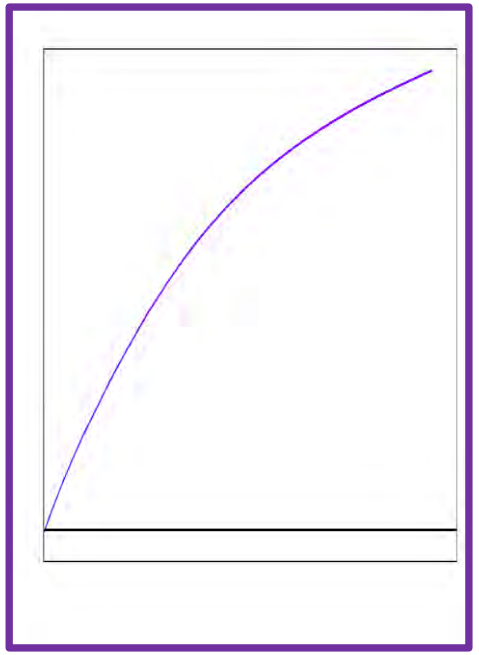


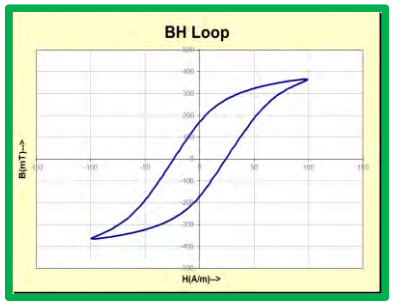
Hard Saturation





Soft Saturation







Bs&T Frankfurt am Main GmbH
b-stone.de · sun@b-stone.de