Magnetically induced transitions in Heusler alloy $Ni_2MnGa_{1-x}In_x$ single crystals in high magnetic field

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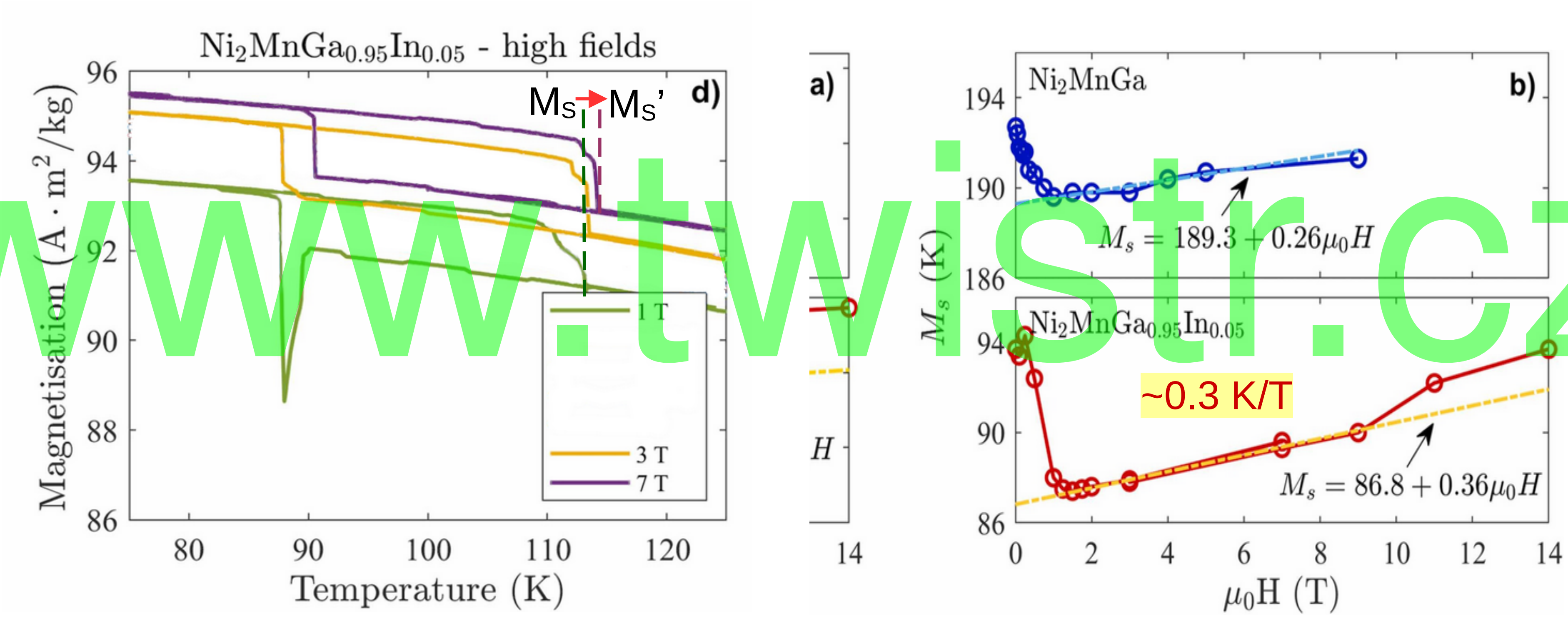
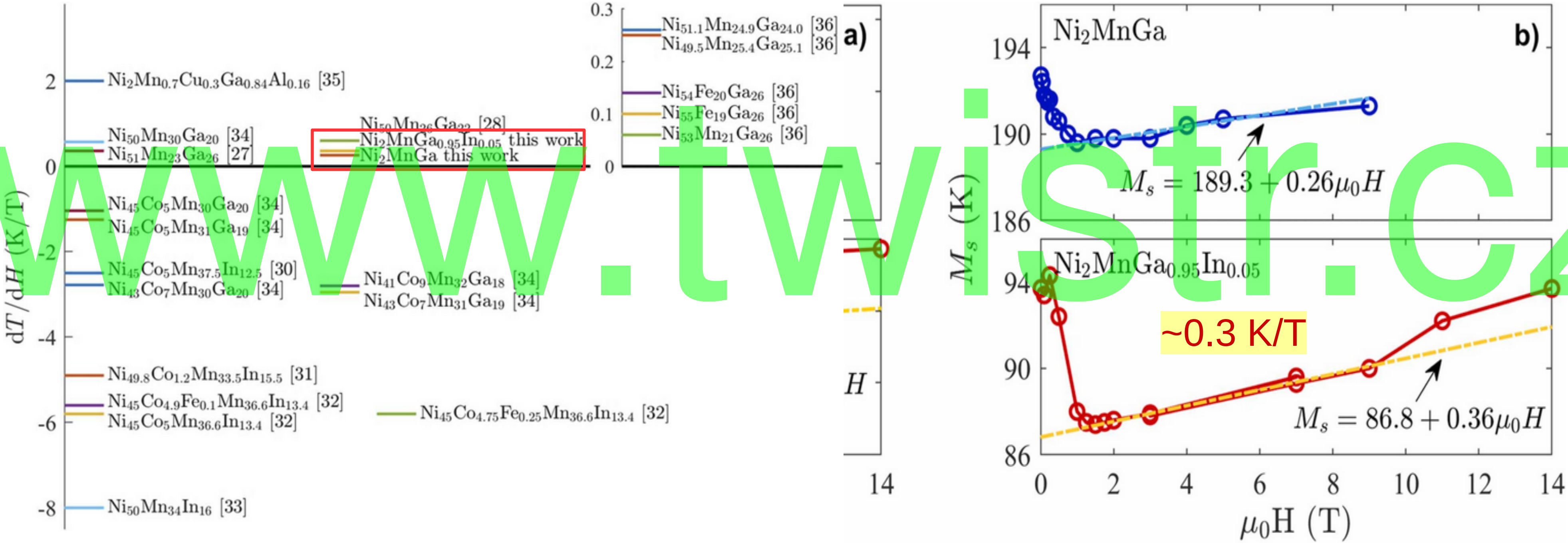
We acknowledge the support of the HLD-HZDR,
member of the European Magnetic Field Laboratory (EMFL)

Motivation: Ni-Mn-Ga-In as one of the magnetocaloric materials



Cejpek, P., Proschek, P., Straka, L., & Heczko, O. (2022). J. Alloys Compounds, 908, 164514.

Motivation: Ni-Mn-Ga-In as one of the magnetocaloric materials



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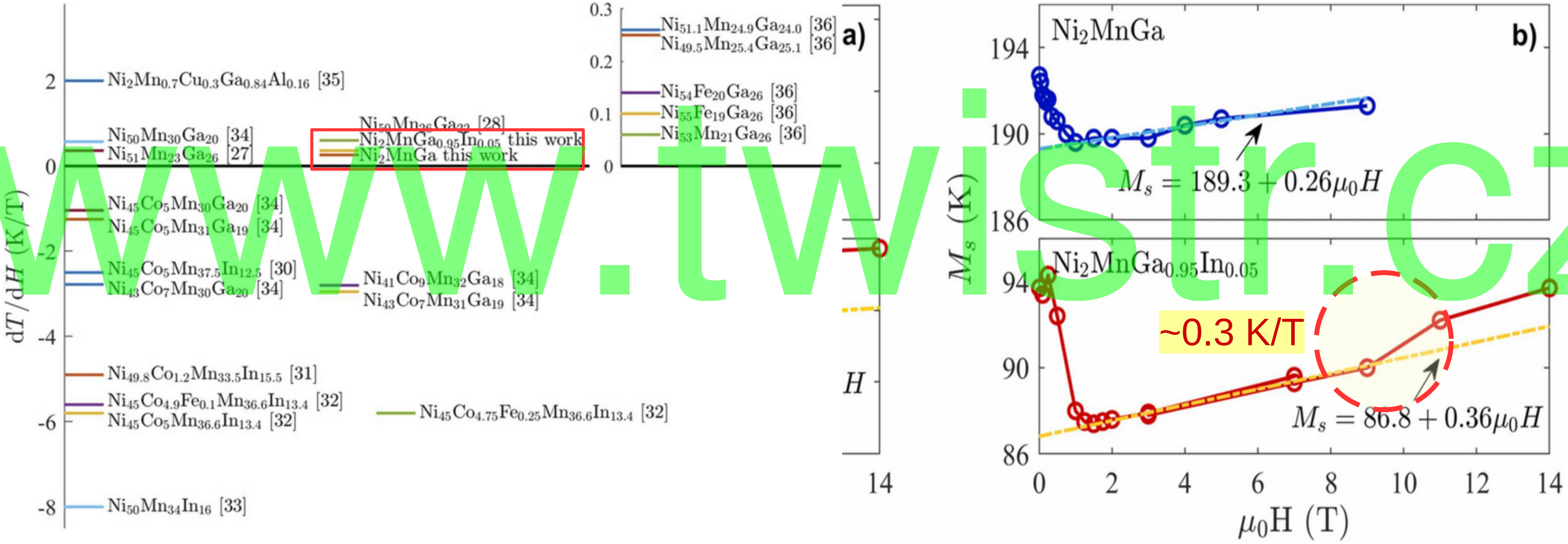

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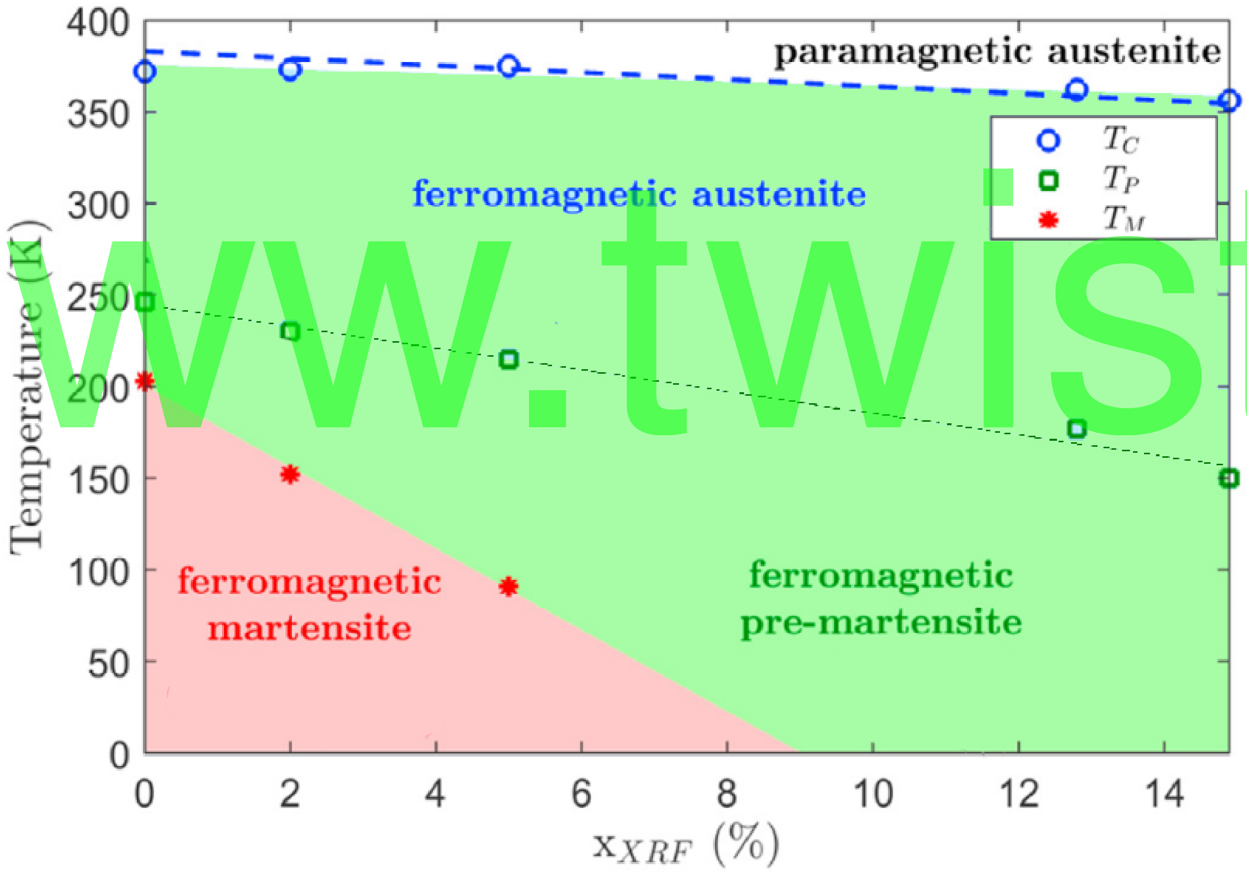
Phase diagram

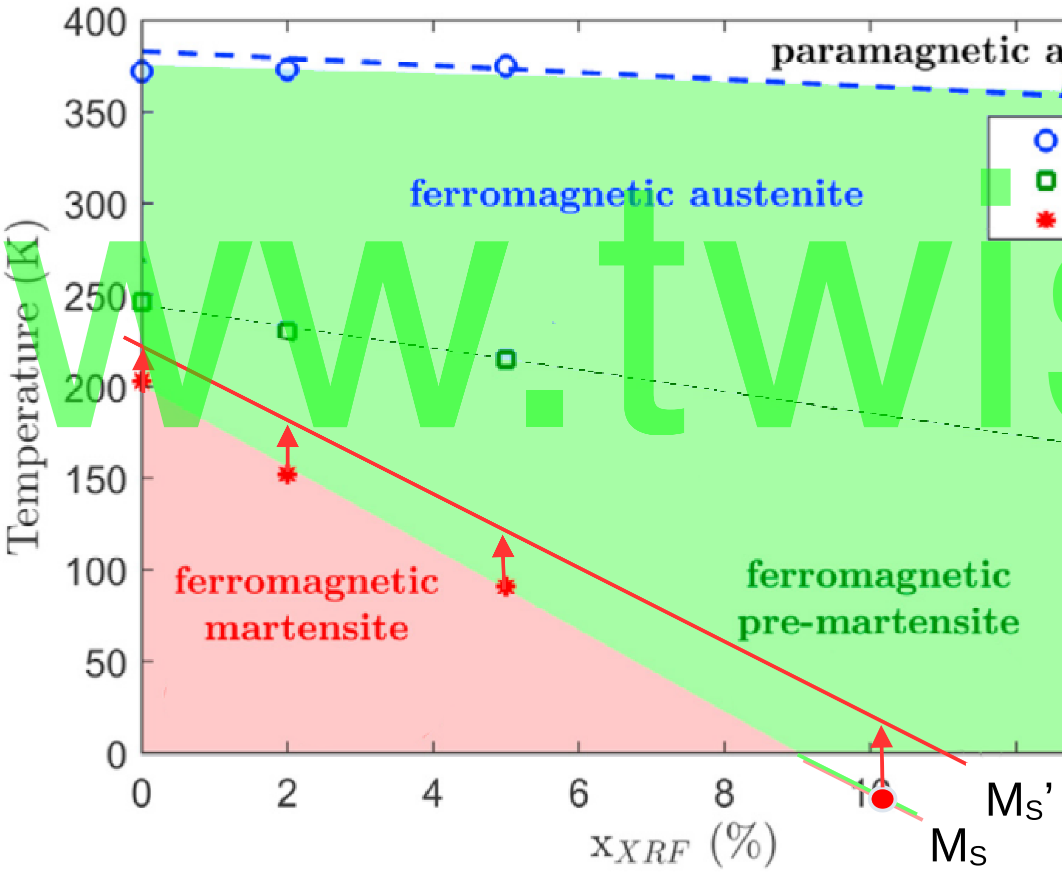


$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

Phase diagram



$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

~0.3 K/T -> ~20K/60T

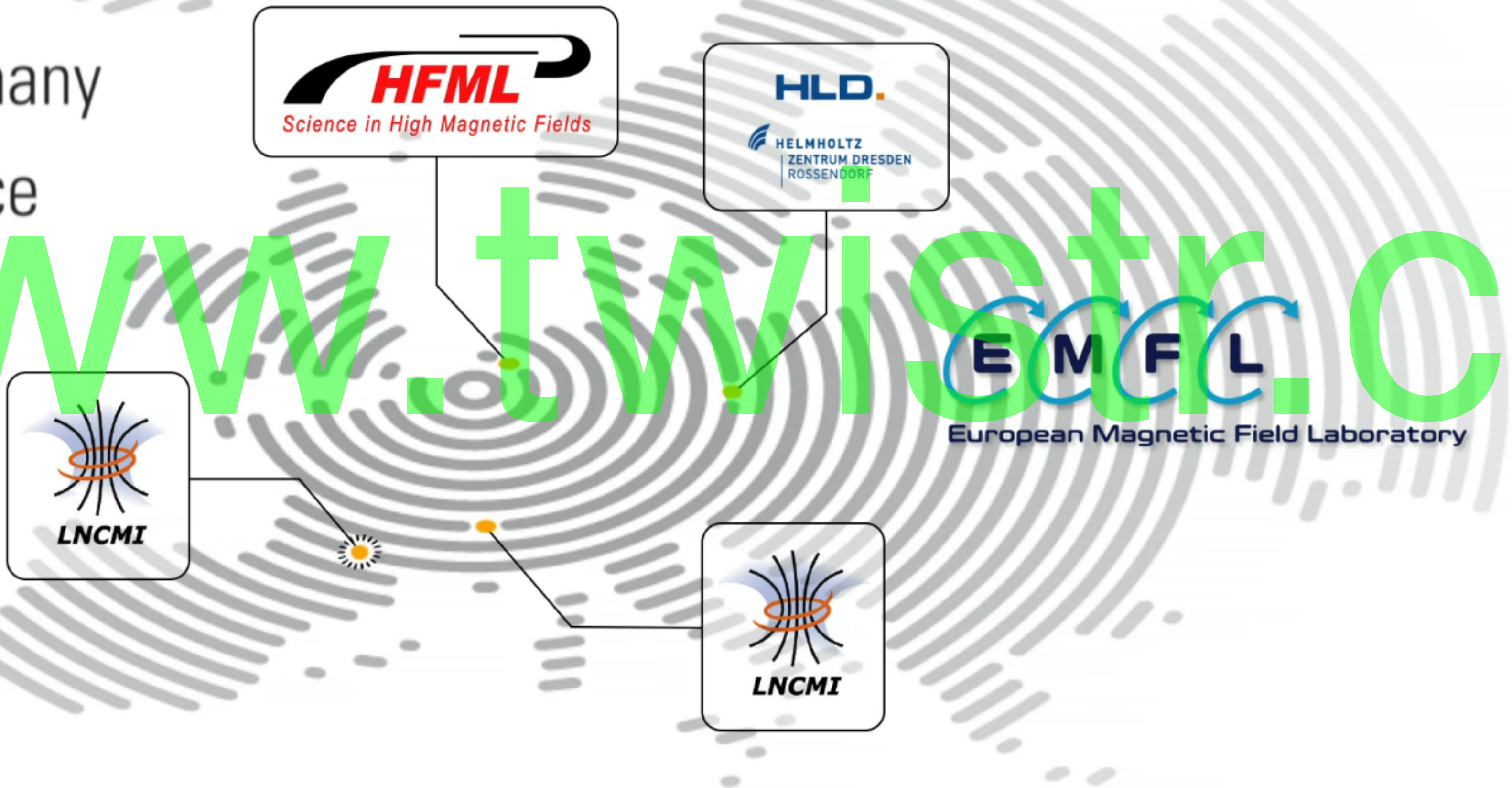
Strength of magnetic field

Order of magnitude for magnetic field	Example
10^{-12} T	Human brain magnetic field
10^{-5} T	Earth's magnetic field
10^{-3} T	Strength of a typical refrigerator magnet
10^{0} T	Strength of a modern neodymium–iron–boron rare earth magnet
10^{1} T	16 T Strength used to levitate a frog
	40 T Strength needed to levitate a person
	32 T/45 T *Strongest continuous* mag. field yet produced in a lab.
	56 T This talk (pulsed field)
10^{2} T	100 T Strongest *pulsed non-destructive* magnetic field
	J. Appl. Phys., Vol. 87, No. 9, 1 May 2000 & wikipedia.org

The Netherlands

Germany

France



HZDR

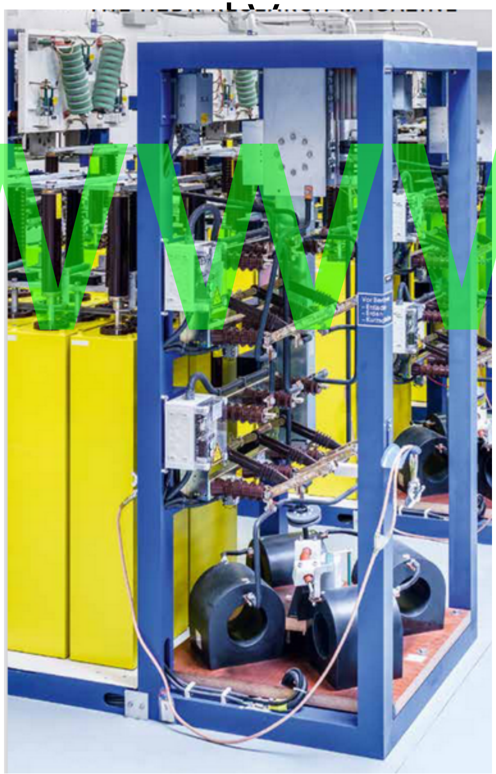
High Field Laboratory

https://en.wikipedia.org/wiki/Helmholtz-Zentrum_Dresden-Rossendorf

High Magnetic Field Laboratory / HZDR (up to ~100 T)

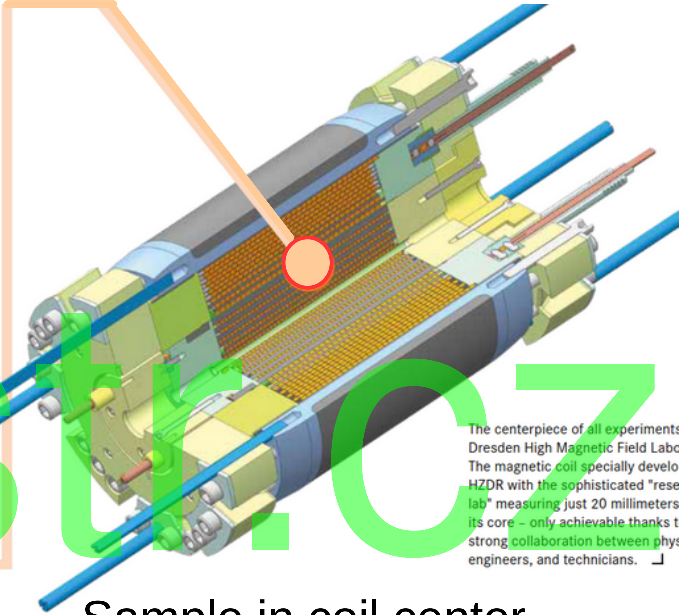
Capacitor modules ~21

~3 m



https://www.hzdr.de/

Coil ~20 mOhm, core 20 mm



Sample in coil center
~1 mm, ~2-300 K

High Magnetic Field Laboratory / HZDR (up to ~100 T)

https://
www.hzdr.de/

Field up to 95.6 T (~1 ms)

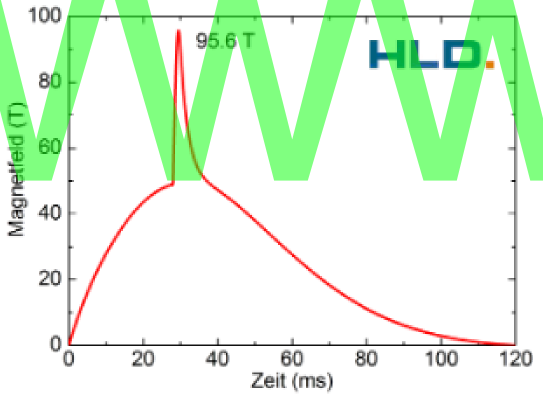
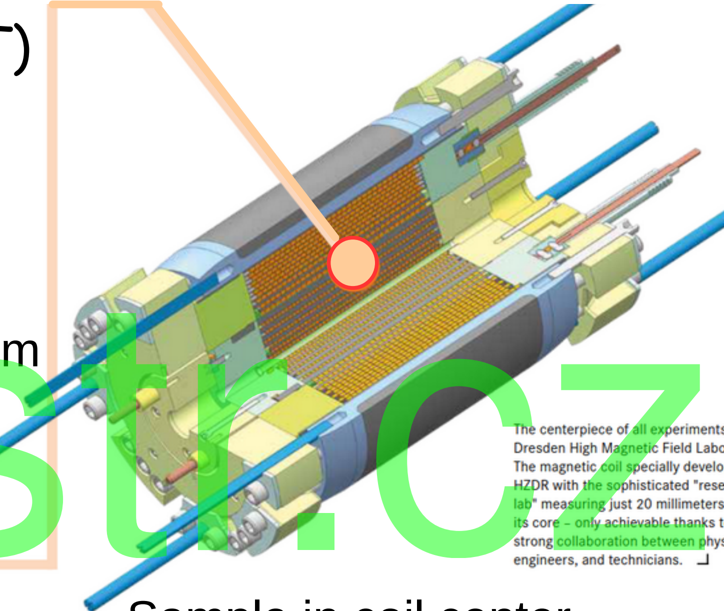


Fig. 4: Zeitlicher Verlauf des Magnetfelds in einer HLD-Spule, die Felder jenseits von 95 T erzeugen kann. // Magnetic field as a function of time, observed in an HLD coil that can generate fields beyond 95 T. (© HLD)

Coil ~20 mOhm, core 20 mm



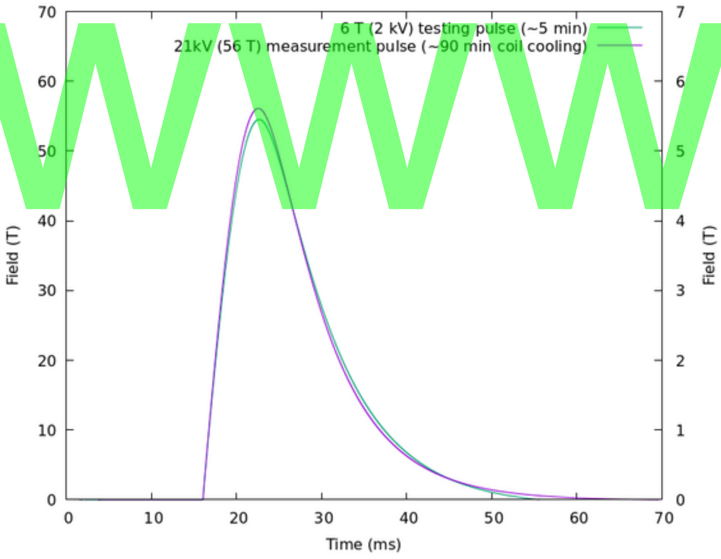
The centerpiece of all experiments
Dresden High Magnetic Field Labo
The magnetic coil specially develo
HZDR with the sophisticated "rese
lab" measuring just 20 millimeters
its core – only achievable thanks t
strong collaboration between phys
engineers, and technicians.

Sample in coil center
~1 mm, ~2-300 K

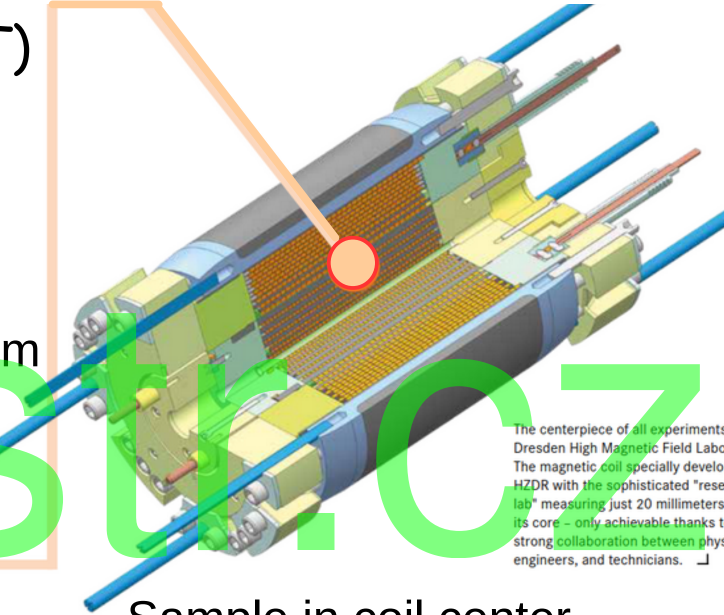
High Magnetic Field Laboratory / HZDR (up to ~100 T)

https://www.hzdr.de/

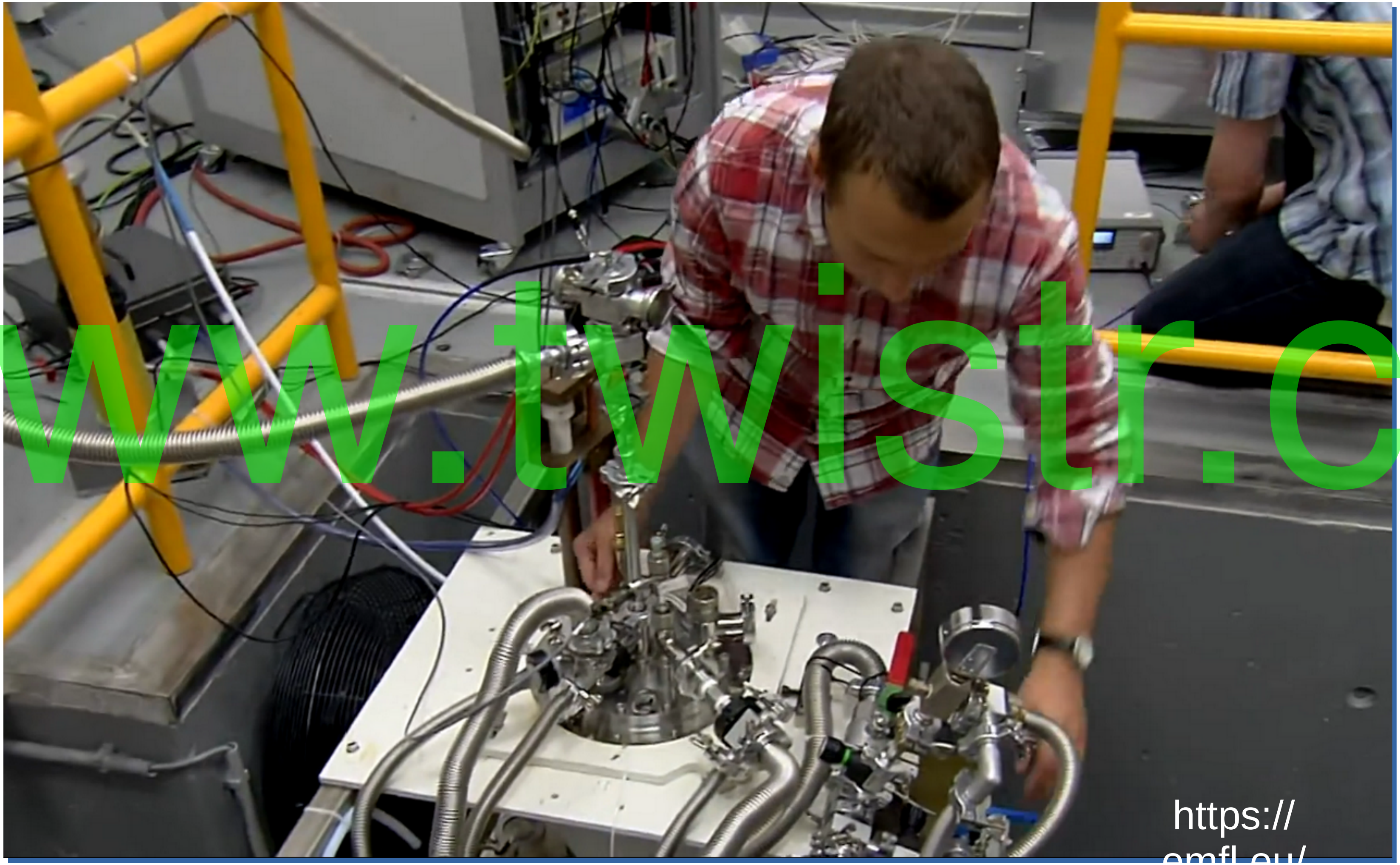
Usual pulse 56 T (~10 ms)



Coil ~20 mOhm, core 20 mm

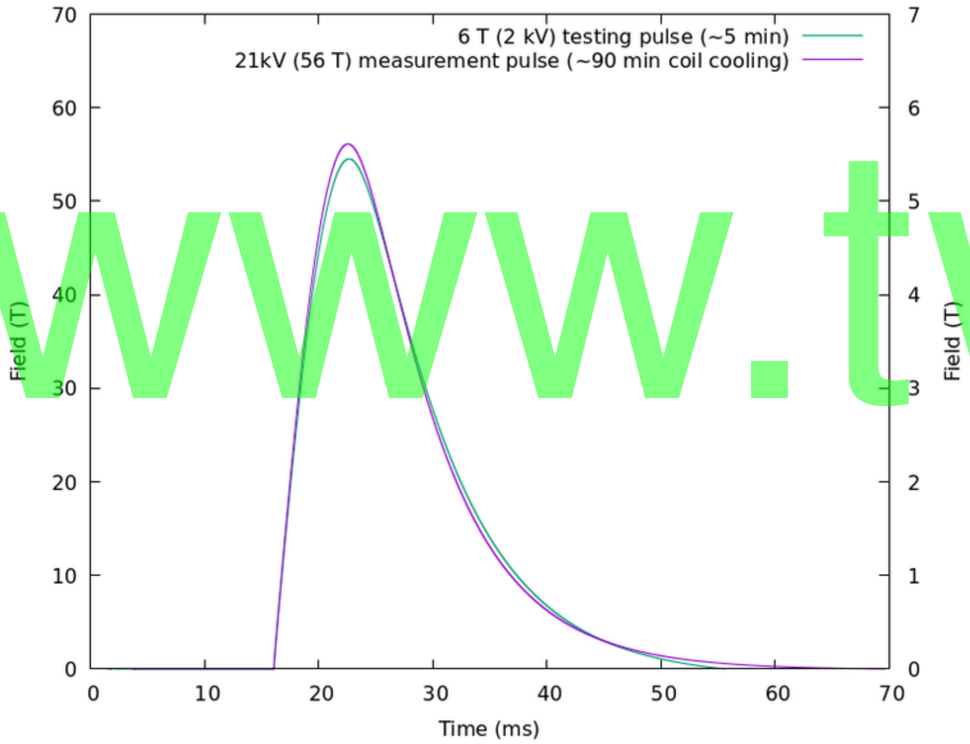


Sample in coil center
~1 mm, ~2-300 K



https://emfl.eu/

High Magnetic Field Laboratory / HZDR (up to ~100 T)



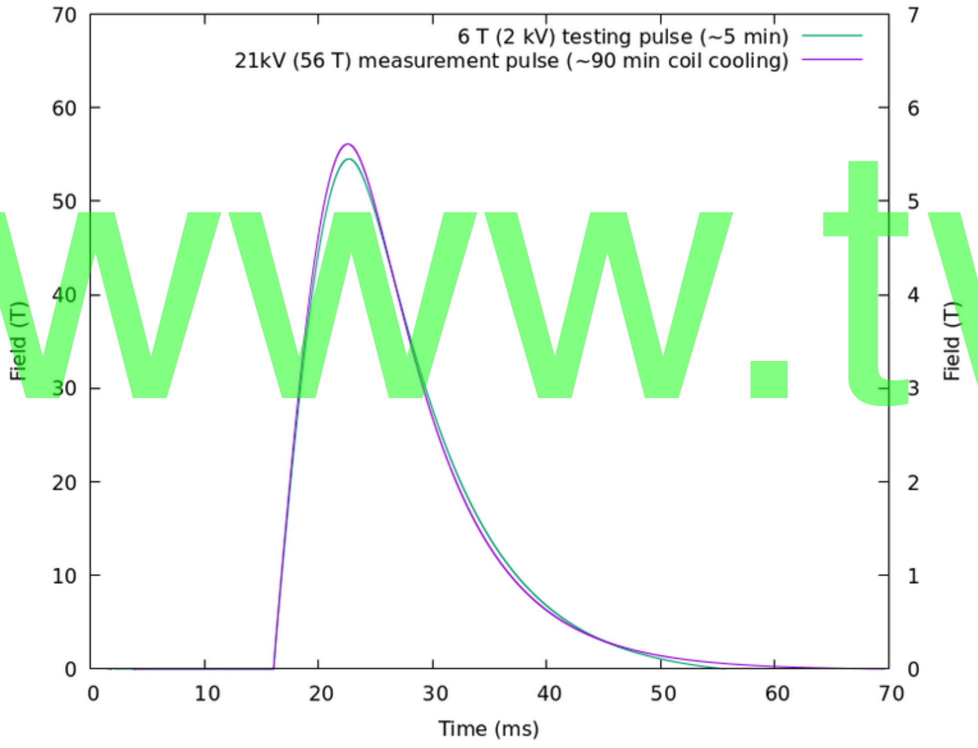
Testing ~6 T (2 kV):

Uprise: ~10 ms i.e. ~**600 T/s**
Downrise: ~30 ms
No waiting time

Scientific 56 T (21 kV)

Uprise: ~10 ms i.e. ~**6000 T/s**
Downrise: ~30 ms
90 min. waiting time

High Magnetic Field Laboratory / HZDR (up to ~100 T)



Energy efficient:

20 kV/20 mOhm ~ million Amps

Power ~ 2 GW
Energy "only" ~ 2 MJ

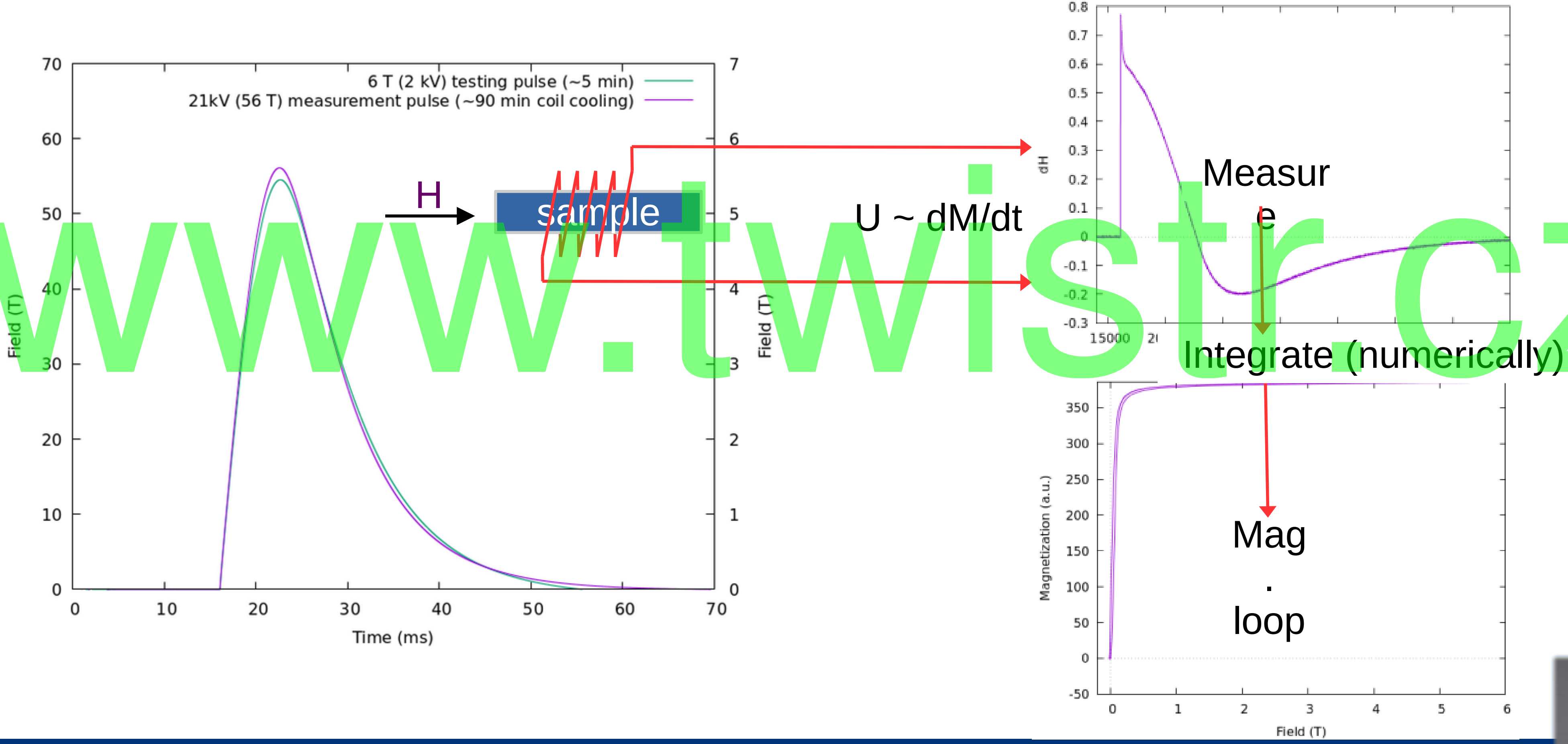
2 GW / 1 ms

2 MW / 1 s

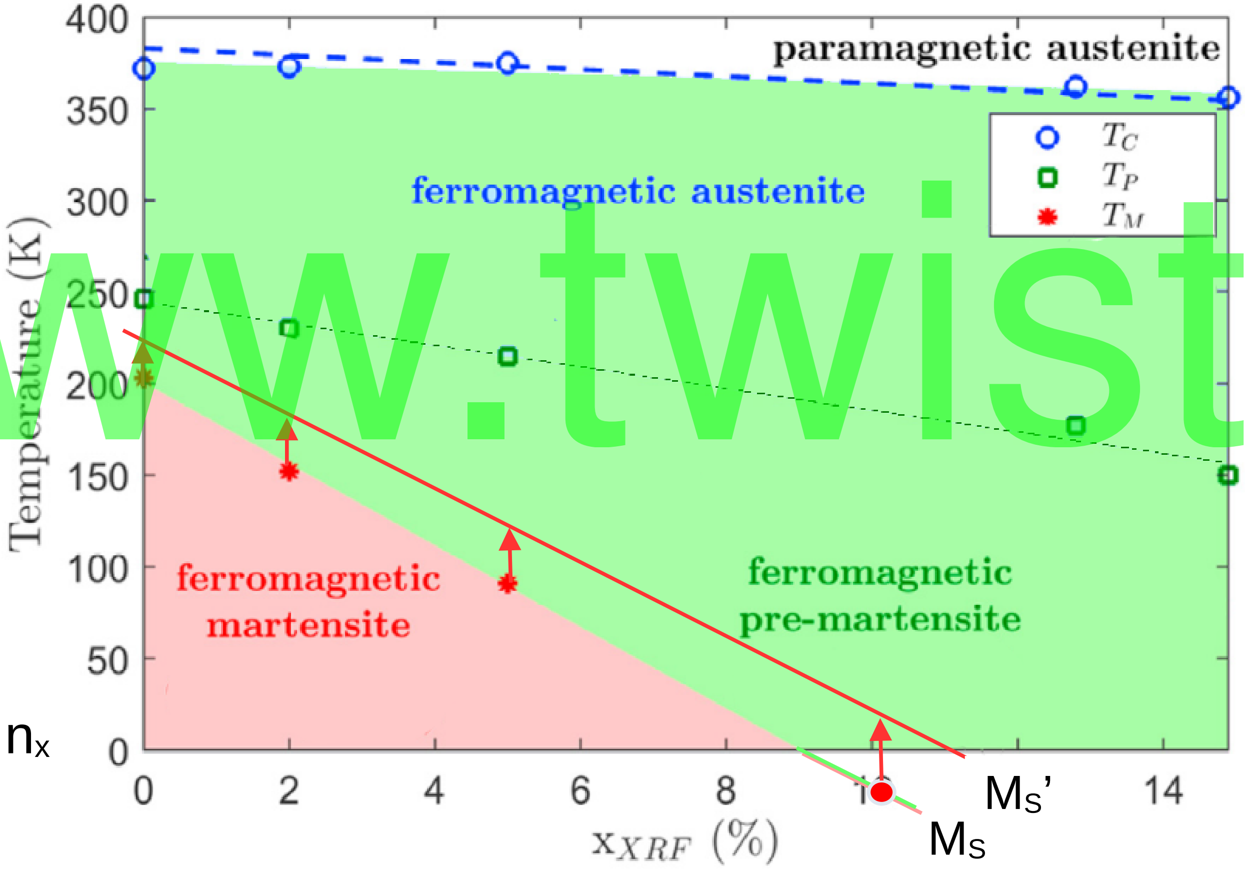
2 kV / 1 ks

~15 mins

High Magnetic Field Laboratory / HZDR (up to ~100 T)



Phase diagram

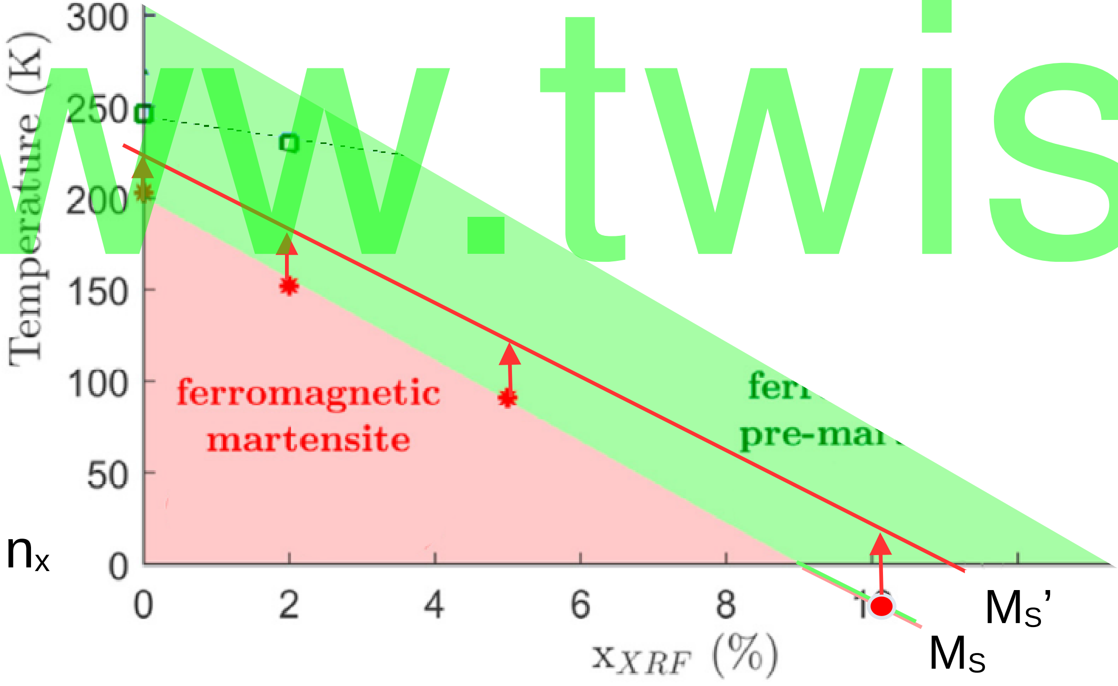


$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

Phase diagram



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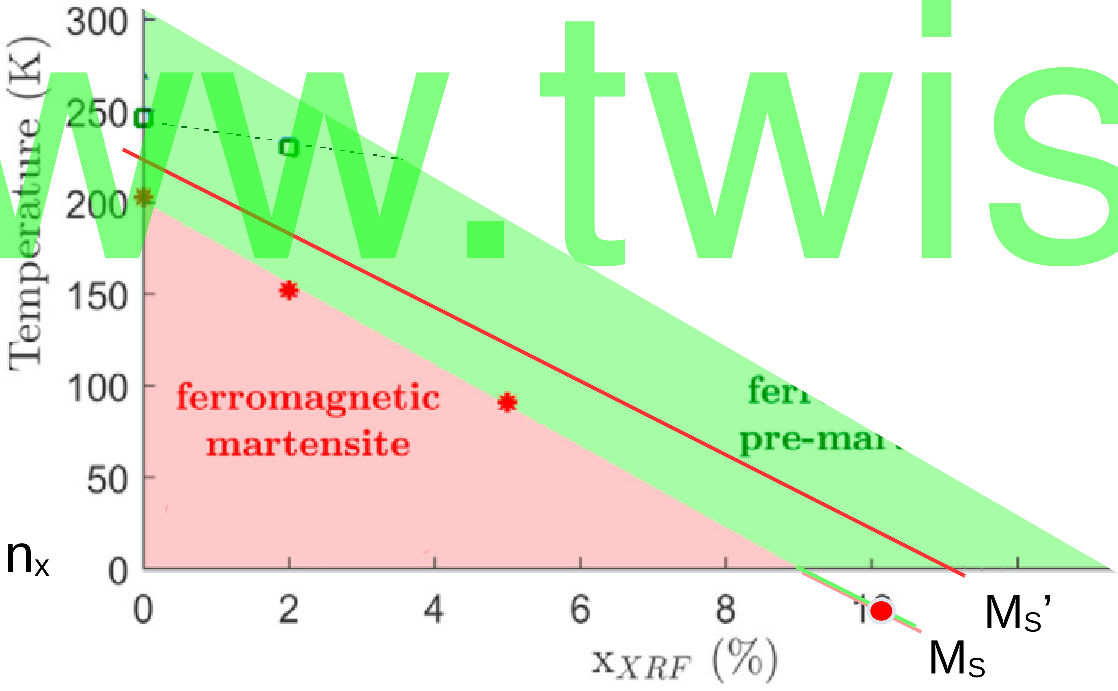
(*e/a* constant)

x=0.1, 0.05, 0.02, 0

Phase diagram

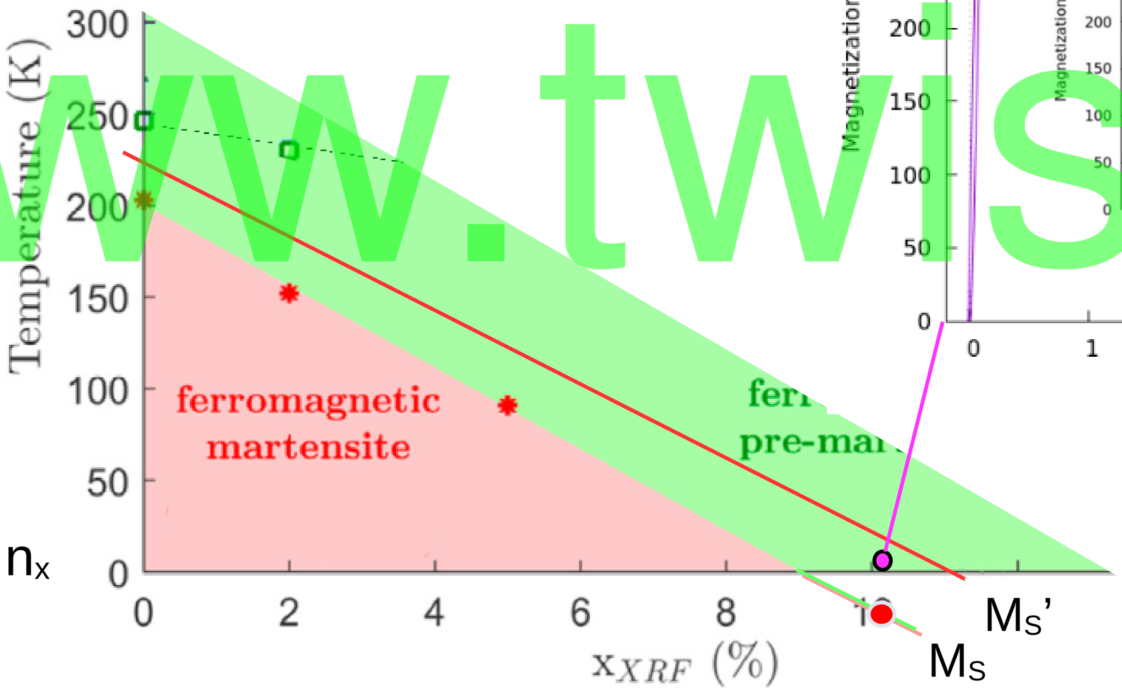


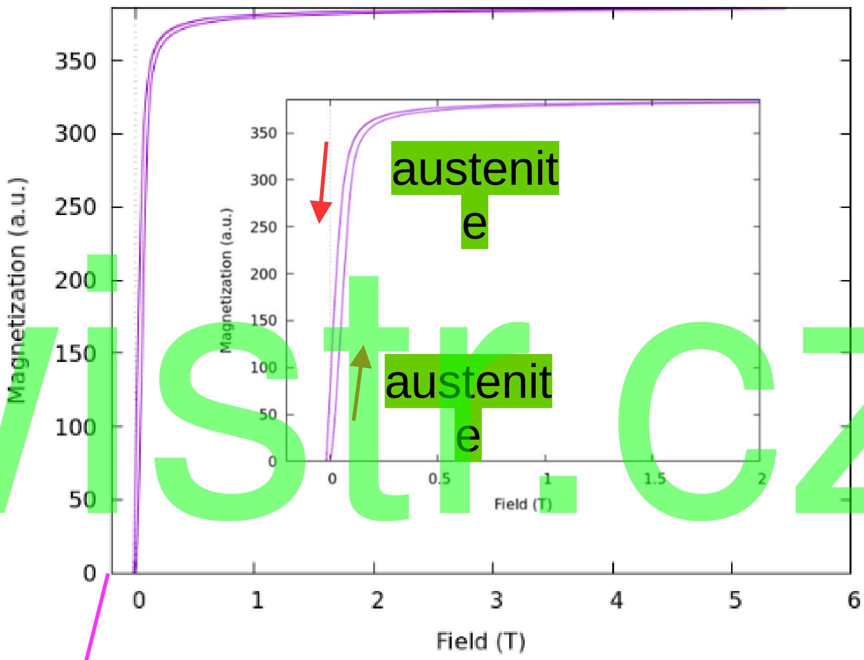
$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.1





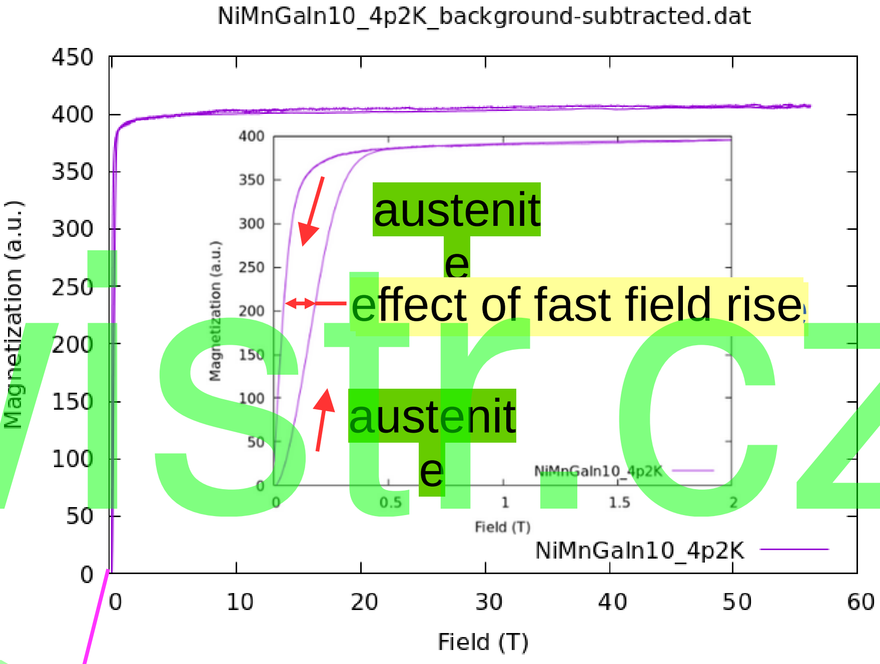
4 K
TEST (6 T)

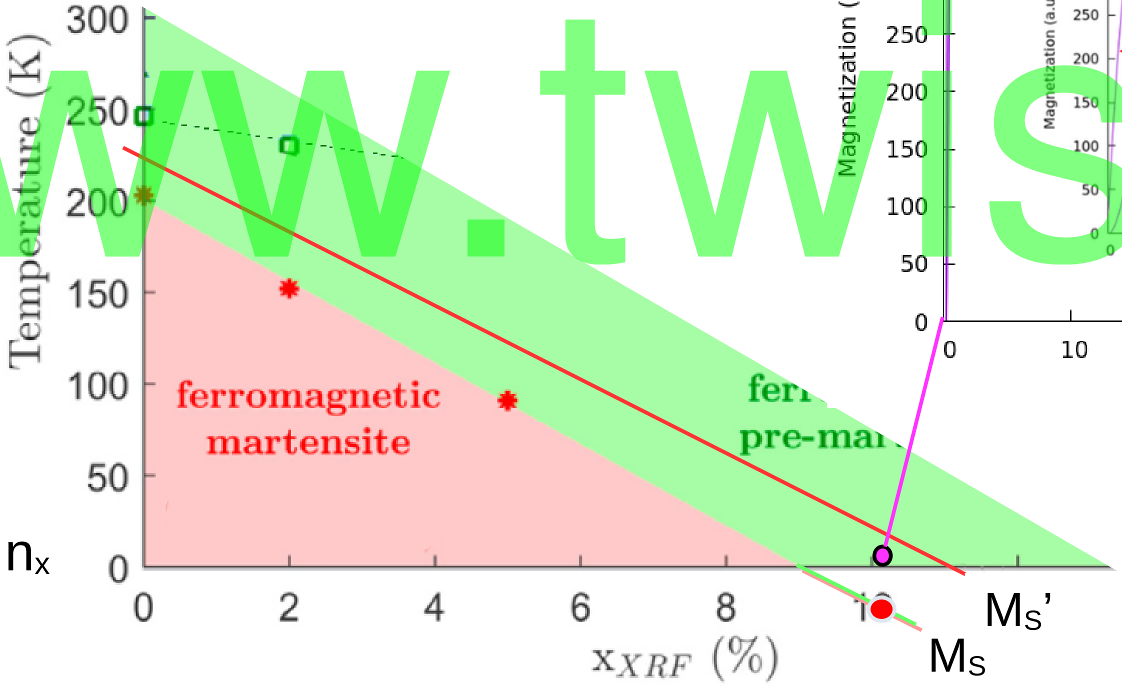
$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.1





$Ni_2MnGa_{1-x}In_x$

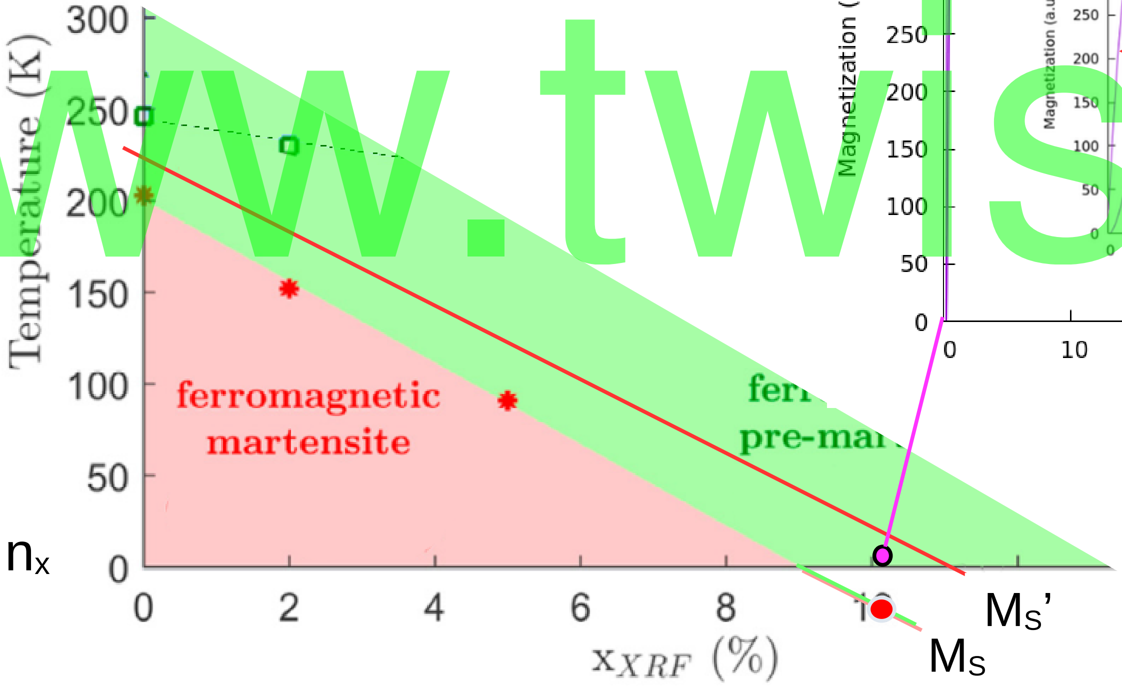
(*e/a* constant)

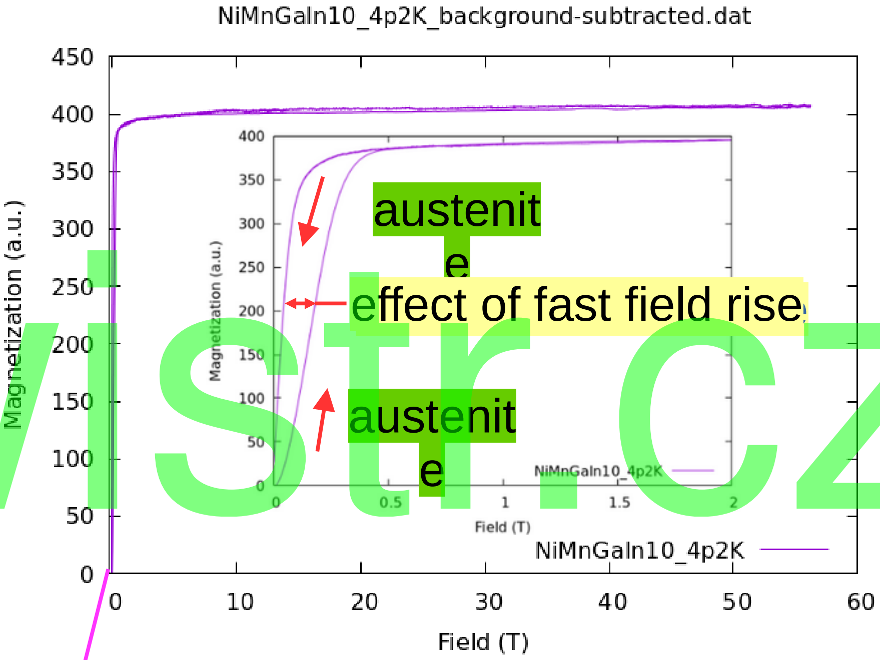
x=0.1, 0.05, 0.02, 0

4 K

PULSE (56 T)

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.1





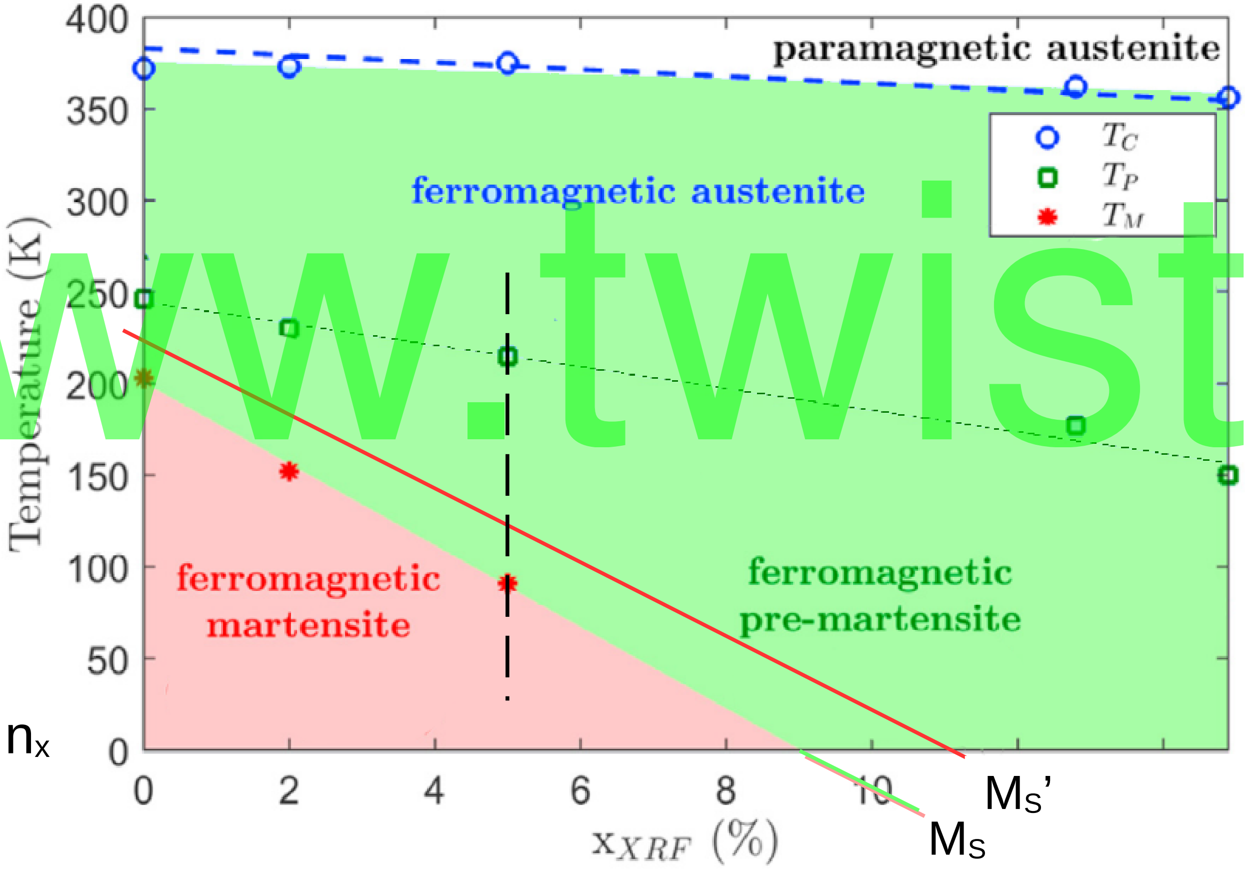
$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

4 K
PULSE (56 T)
ALL
AUSTENITE

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.05

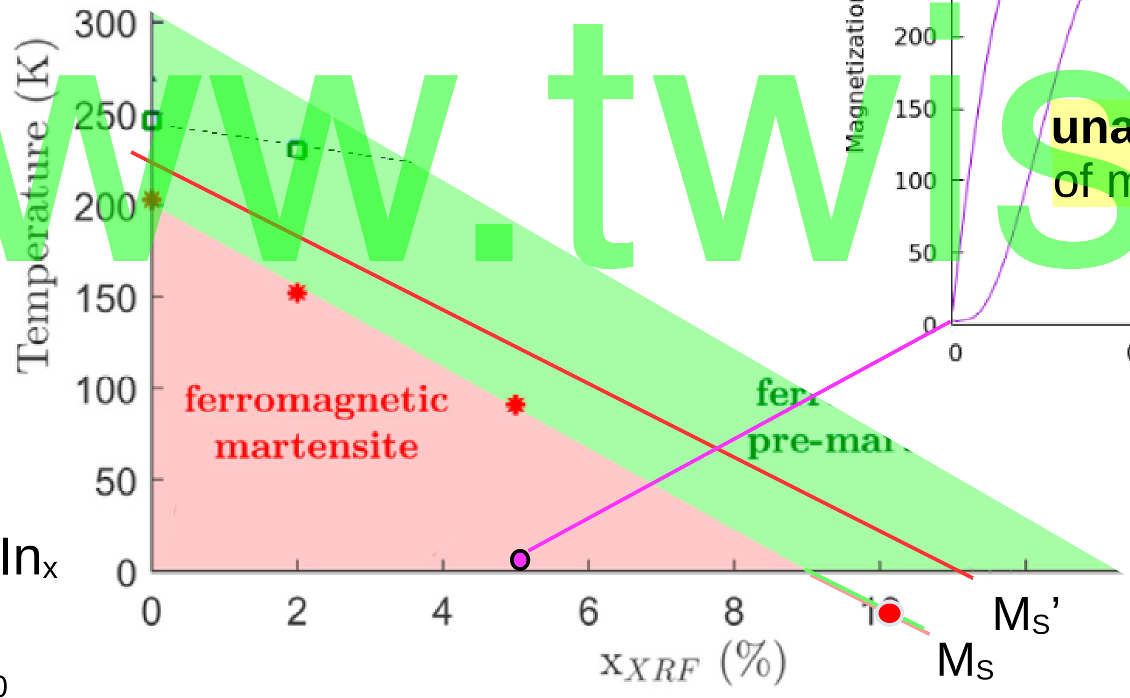


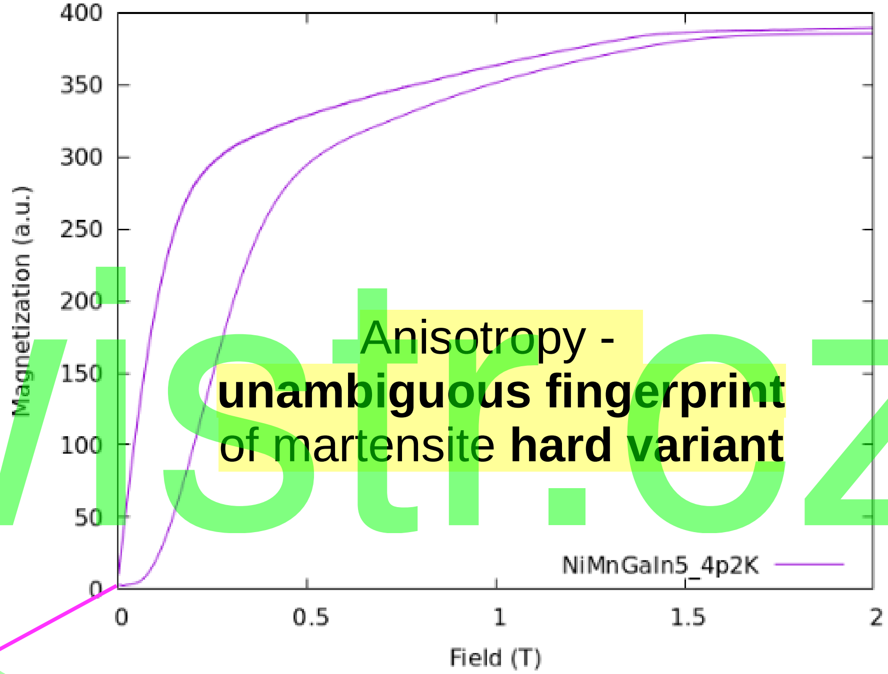
$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.05





Anisotropy - **unambiguous fingerprint** of martensite **hard variant**

4 K

TEST (6 T)

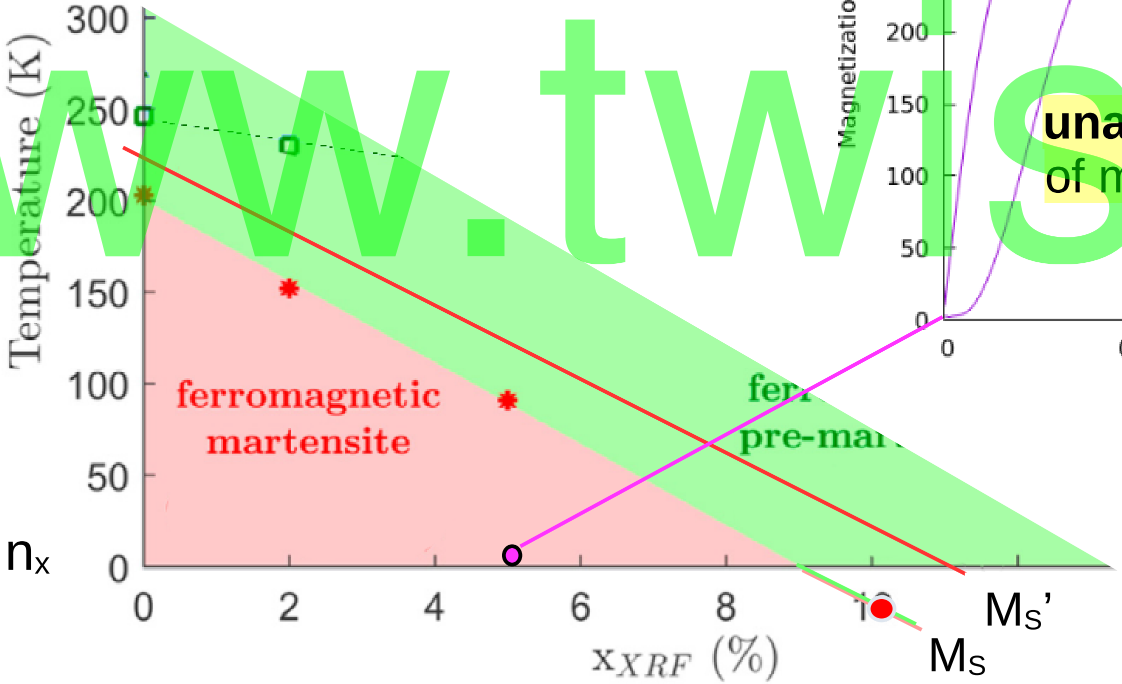
martensite

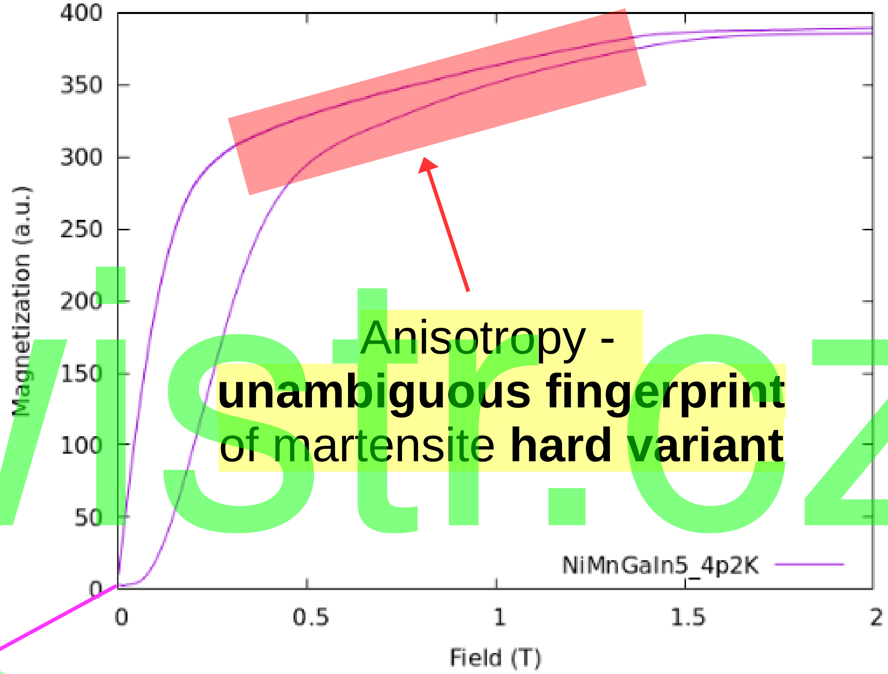
$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.05





$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

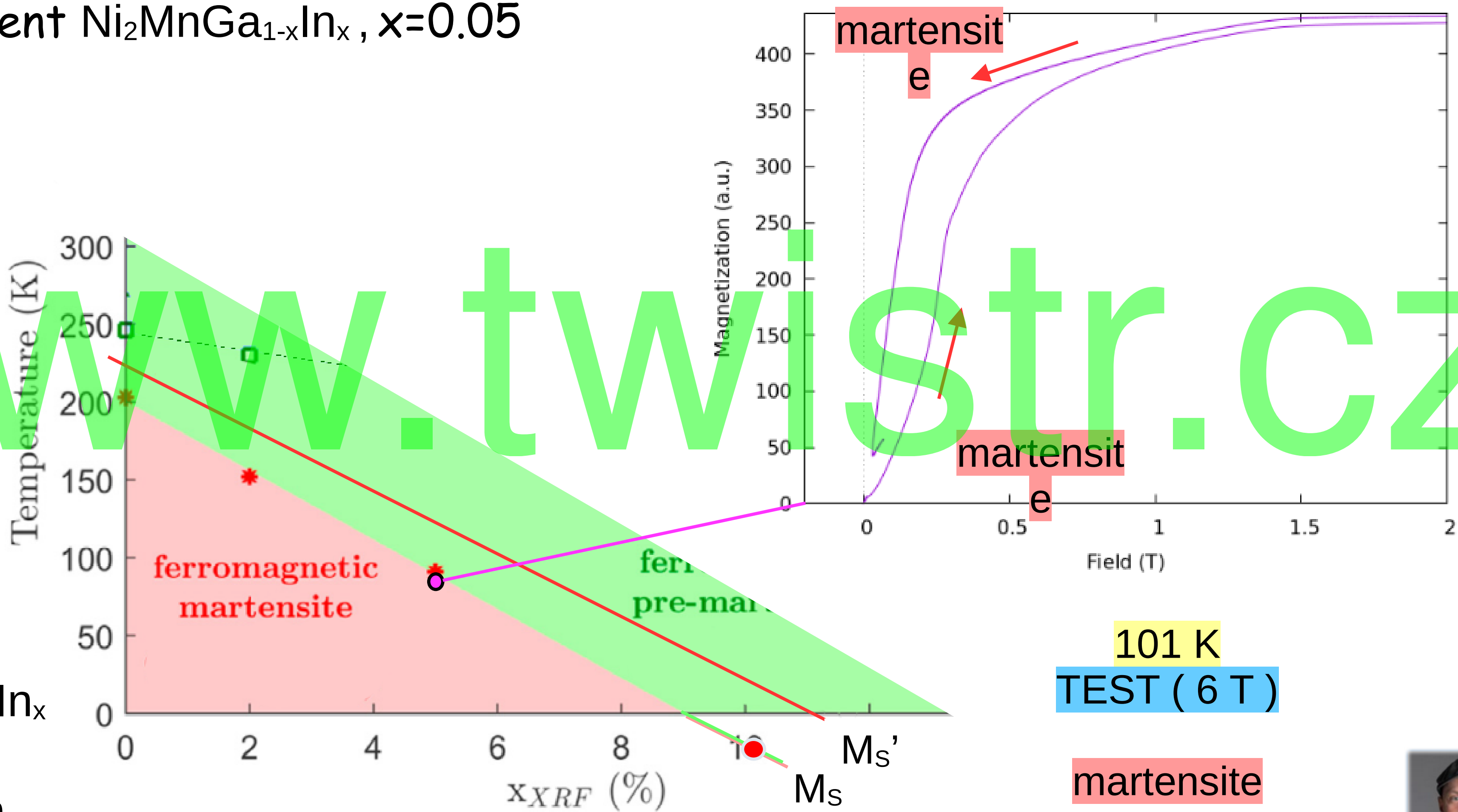
x=0.1, 0.05, 0.02, 0

4 K

TEST (6 T)

martensite

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.05

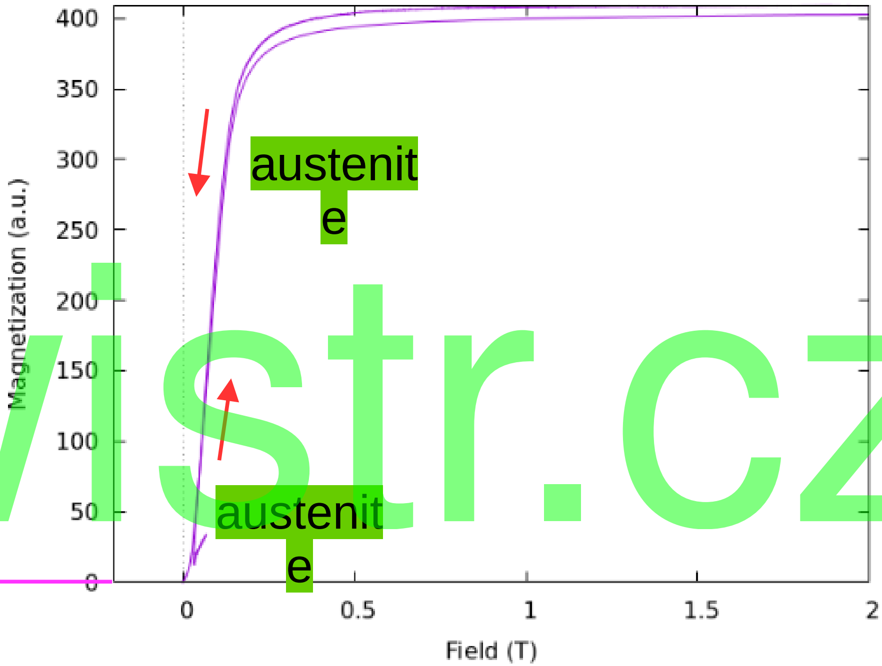


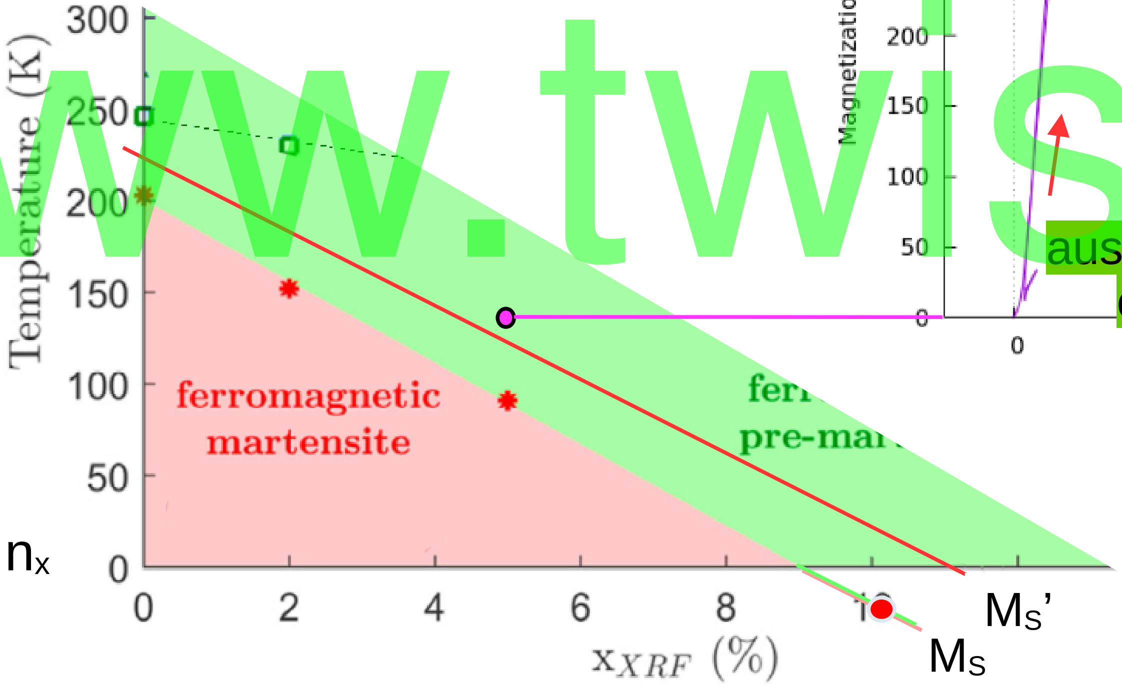
$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.05





$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

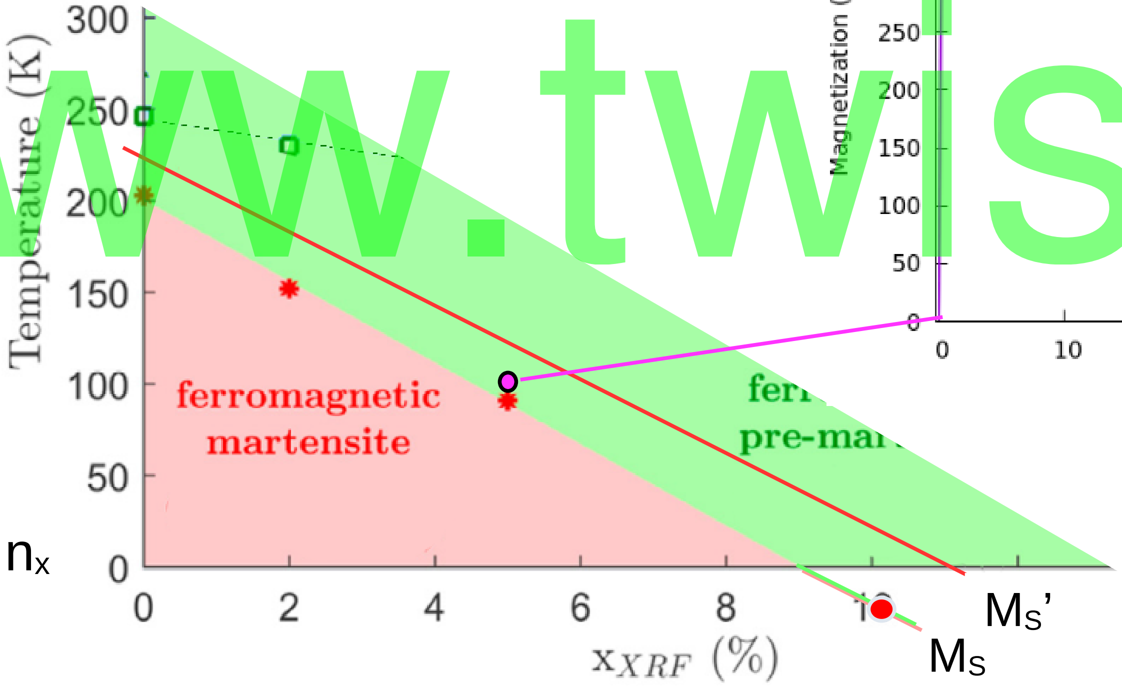
x=0.1, 0.05, 0.02, 0

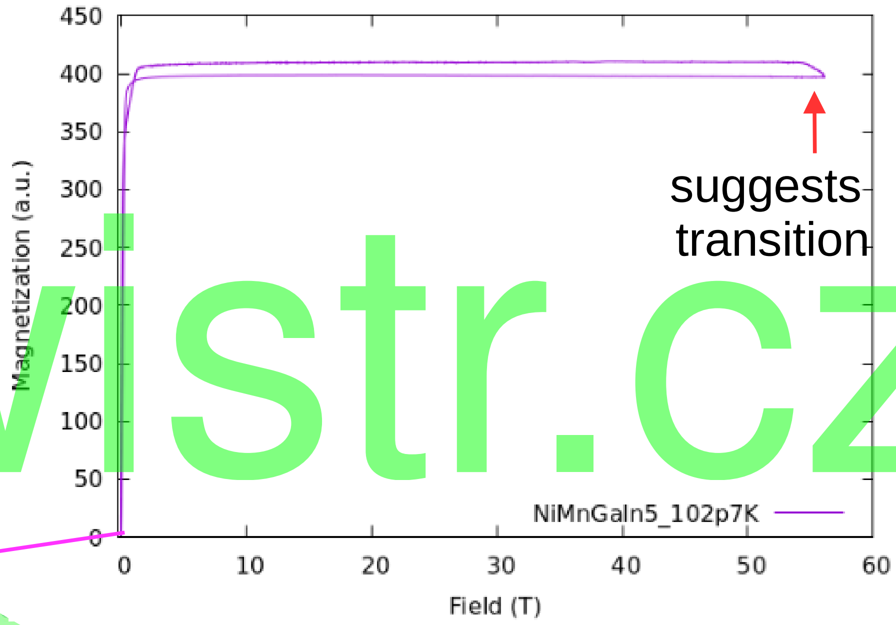
155 K

TEST (6 T)

austenite

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.05





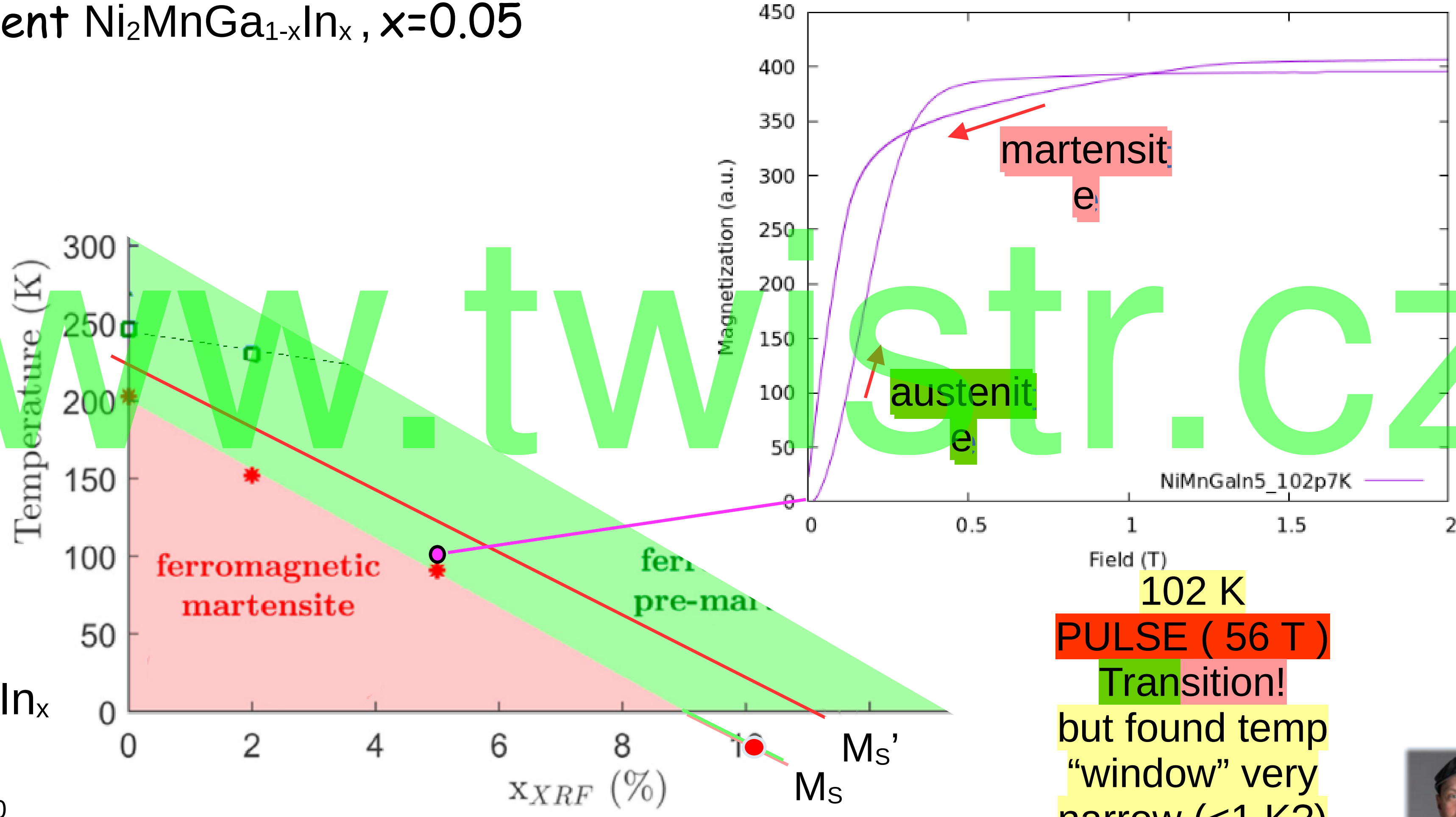
102 K
PULSE (56 T)

$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.05



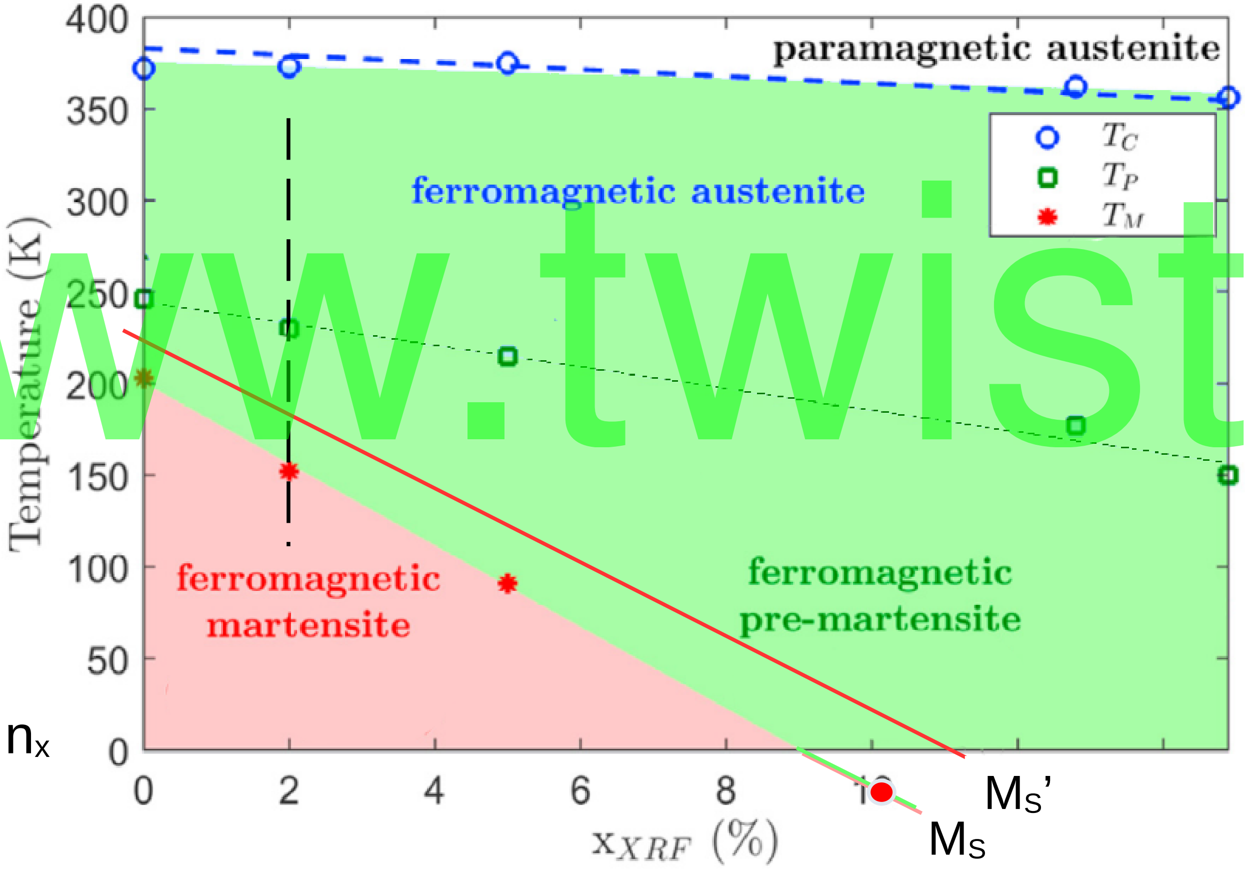
102 K
PULSE (56 T)
Transition!
but found temp "window" very narrow (<1 K?)

$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.02

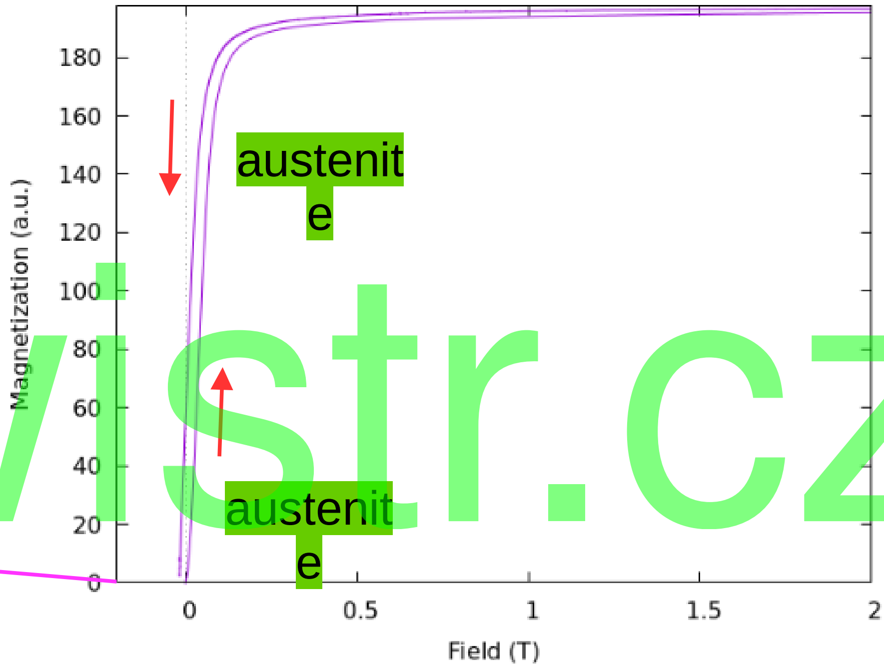


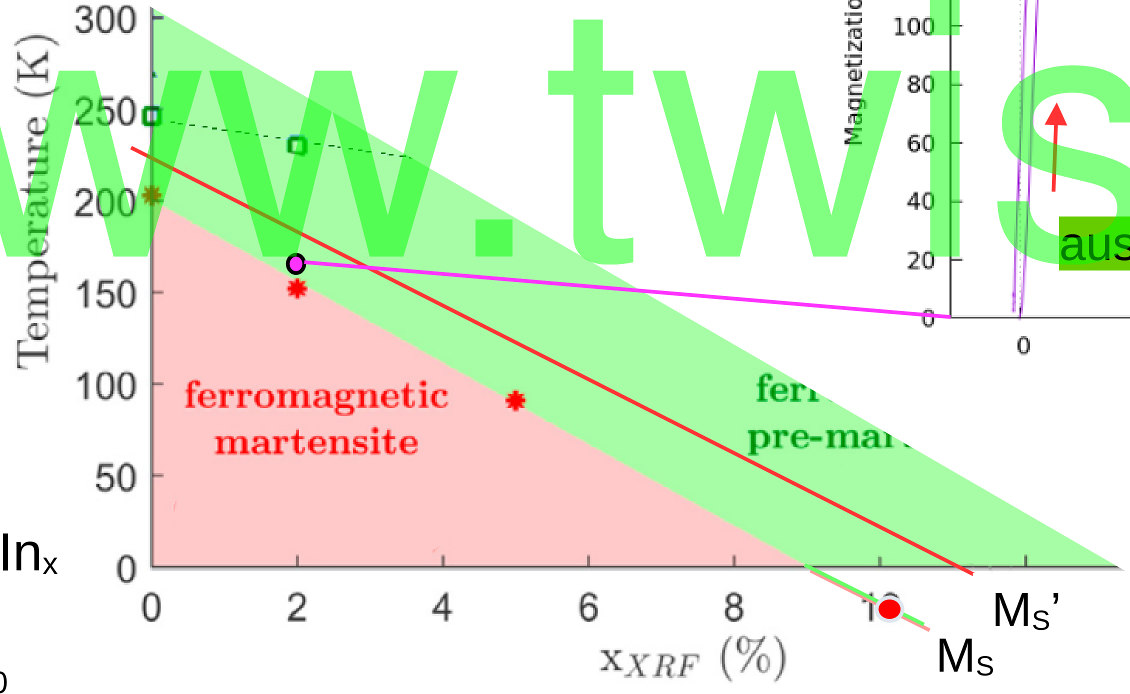
$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.02





$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

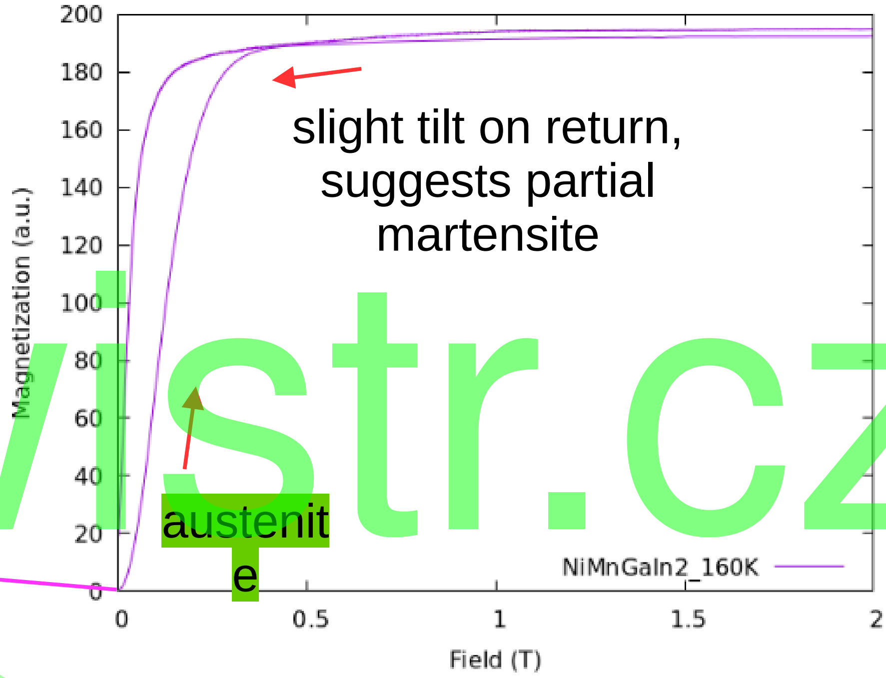
x=0.1, 0.05, 0.02, 0

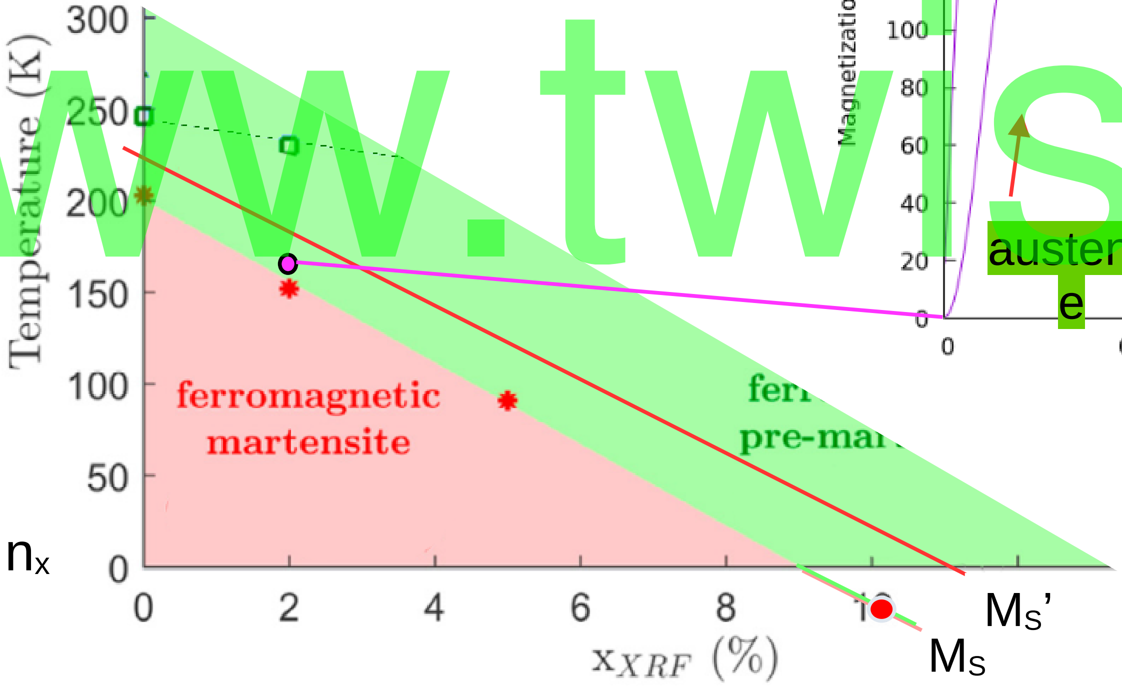
165 K

TEST (6 T)

(no transition)

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.02





$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

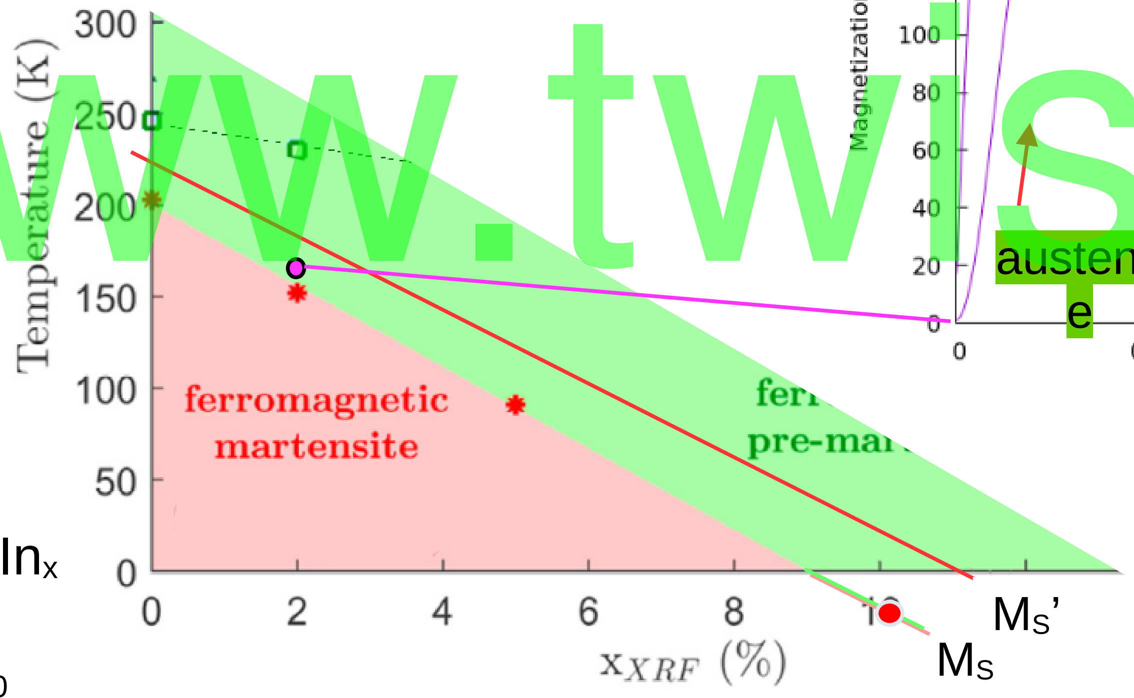
x=0.1, 0.05, 0.02, 0

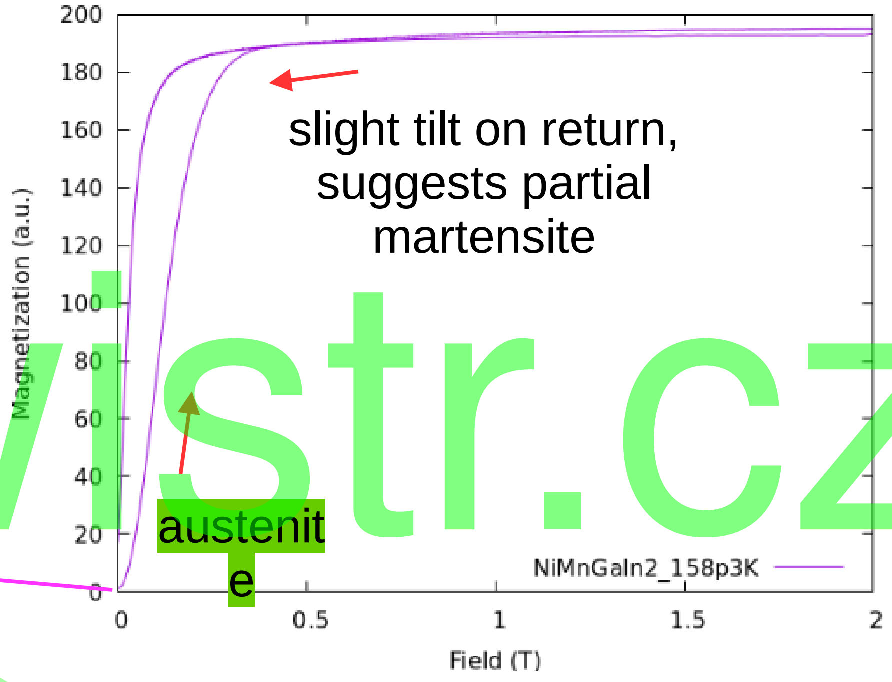
160 K

PULSE (56 T)

partial trans.?

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.02





$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

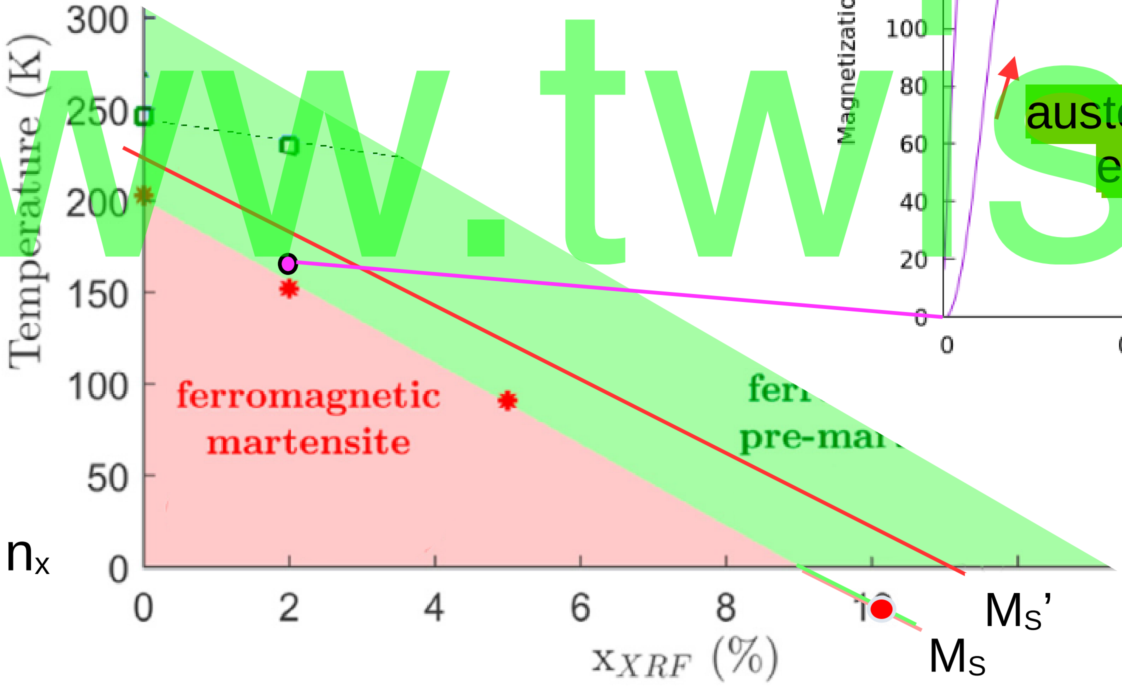
x=0.1, 0.05, 0.02, 0

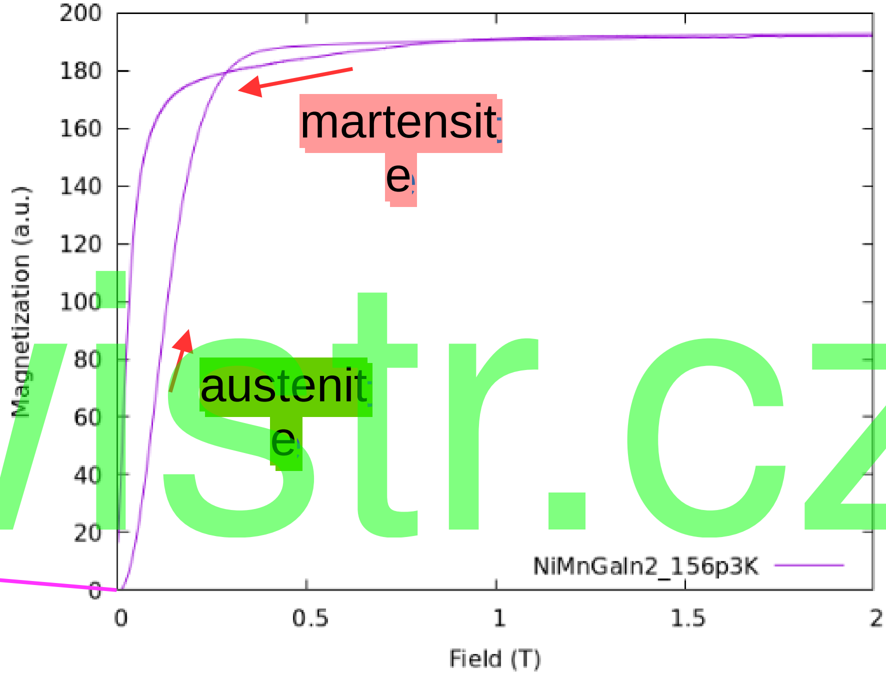
158 K

PULSE (56 T)

partial transf.?

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.02





$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

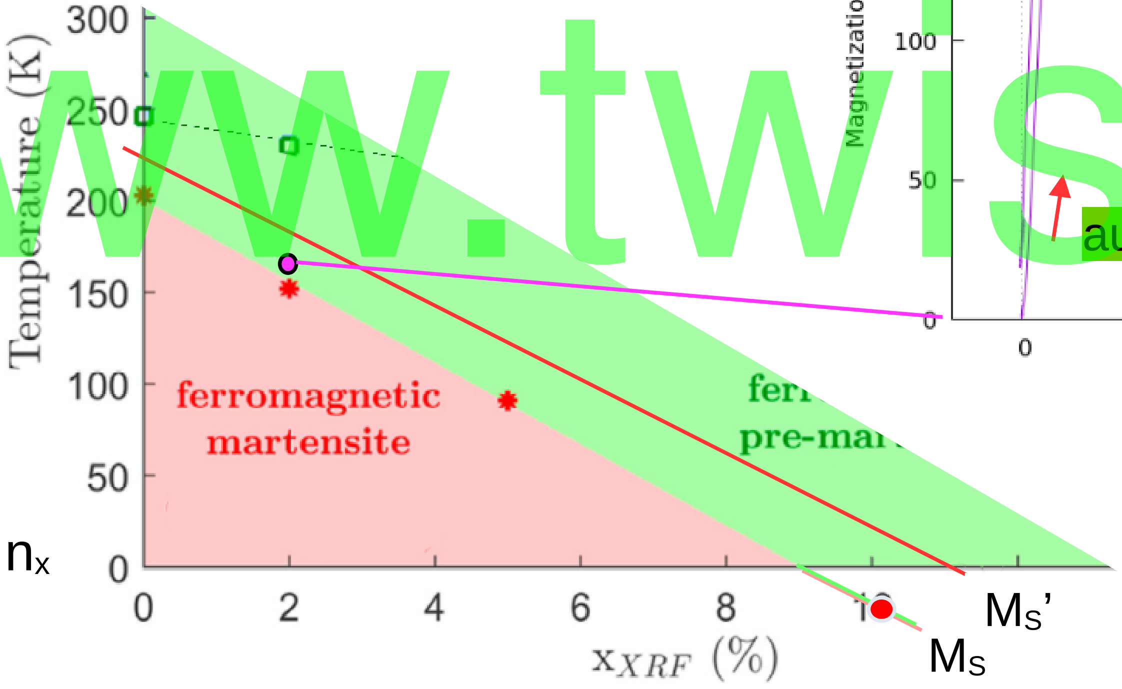
x=0.1, 0.05, 0.02, 0

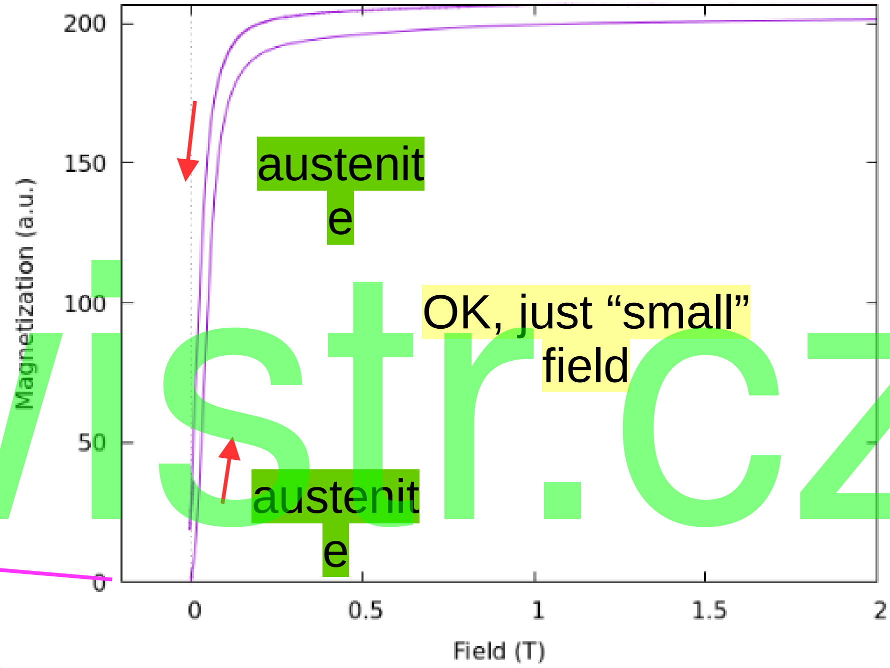
156 K

PULSE (56 T)

Transition!

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.02





$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

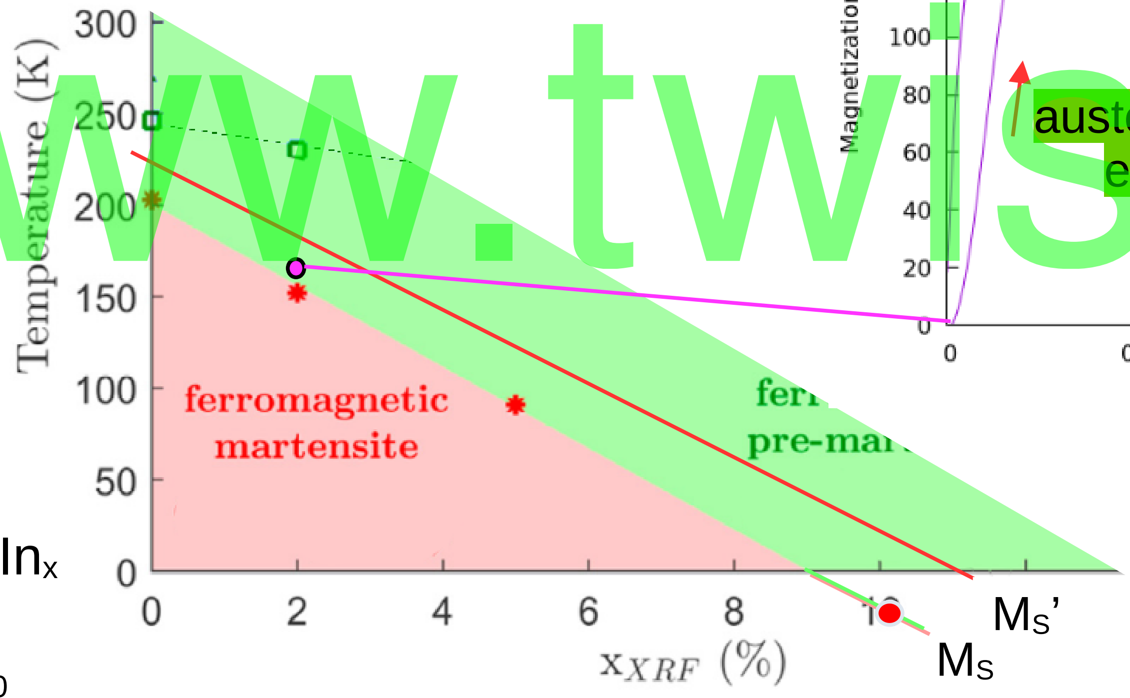
x=0.1, 0.05, 0.02, 0

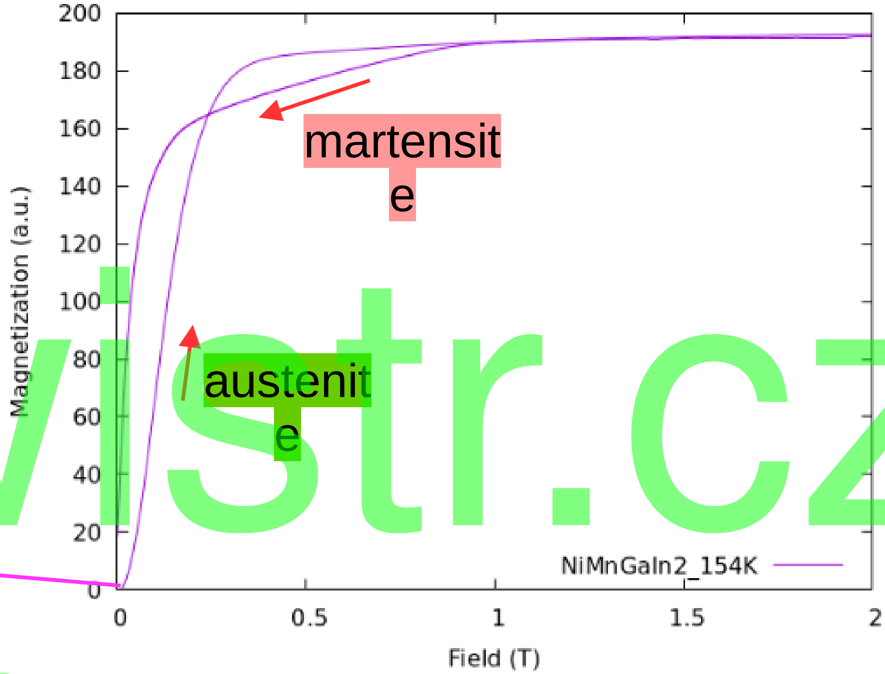
154 K

TEST (6 T)

no transition, OK

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.02





154 K

PULSE (56 T)

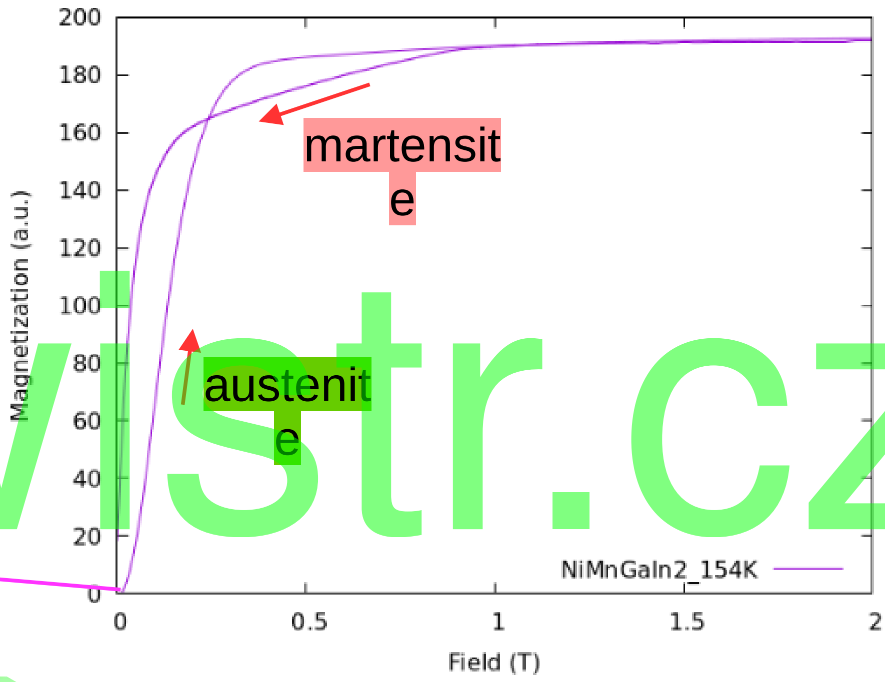
Transition!

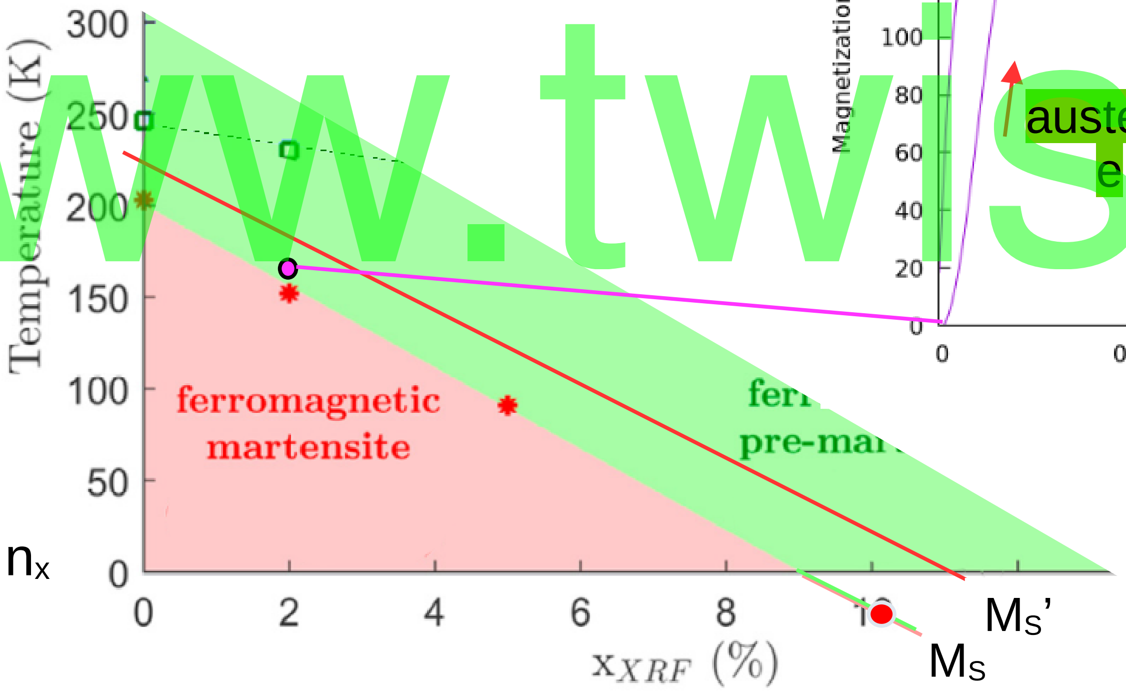
$Ni_2MnGa_{1-x}In_x$

(*e*/*a* constant)

x=0.1, 0.05, 0.02, 0

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.02





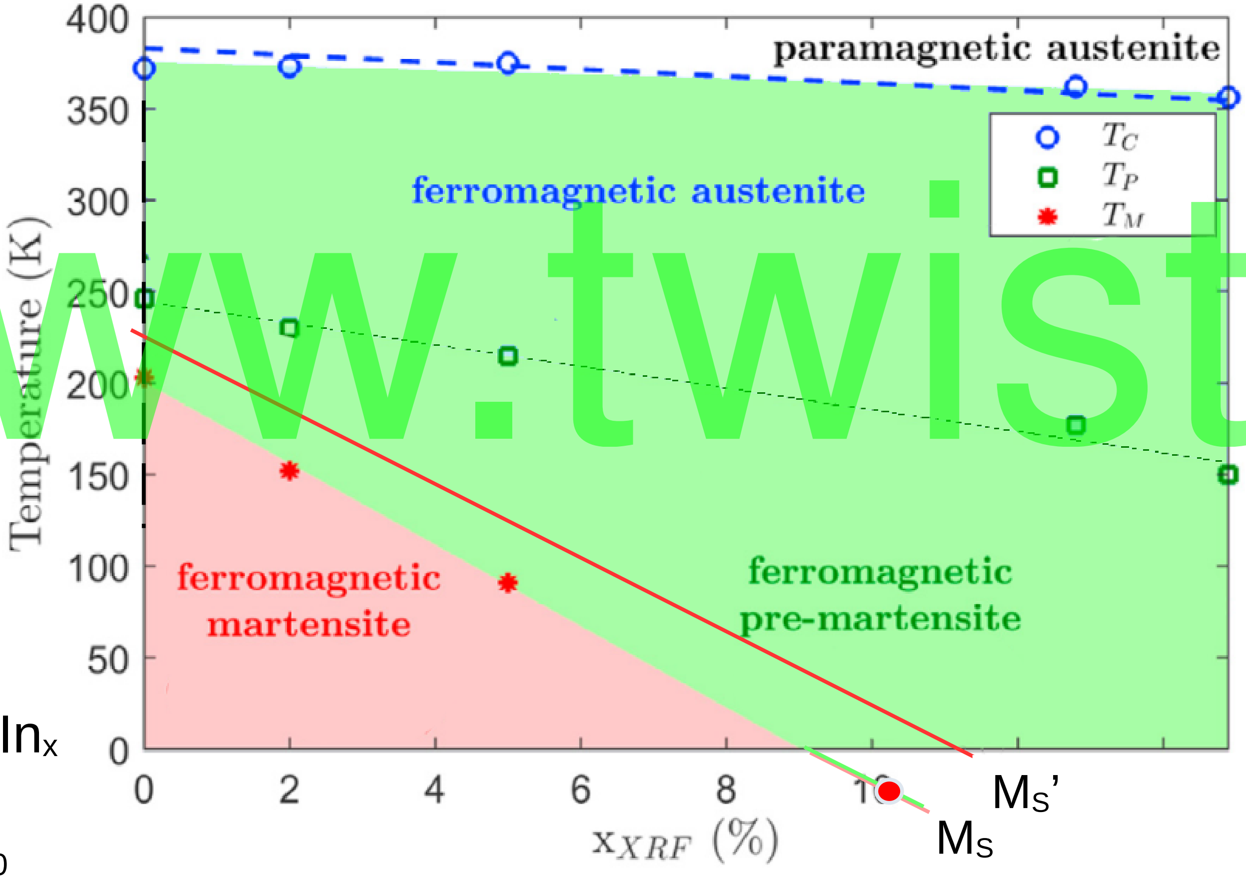
$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

154 K
PULSE (56 T)
Transition!
but transition "window"
only 2-6 K

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.00

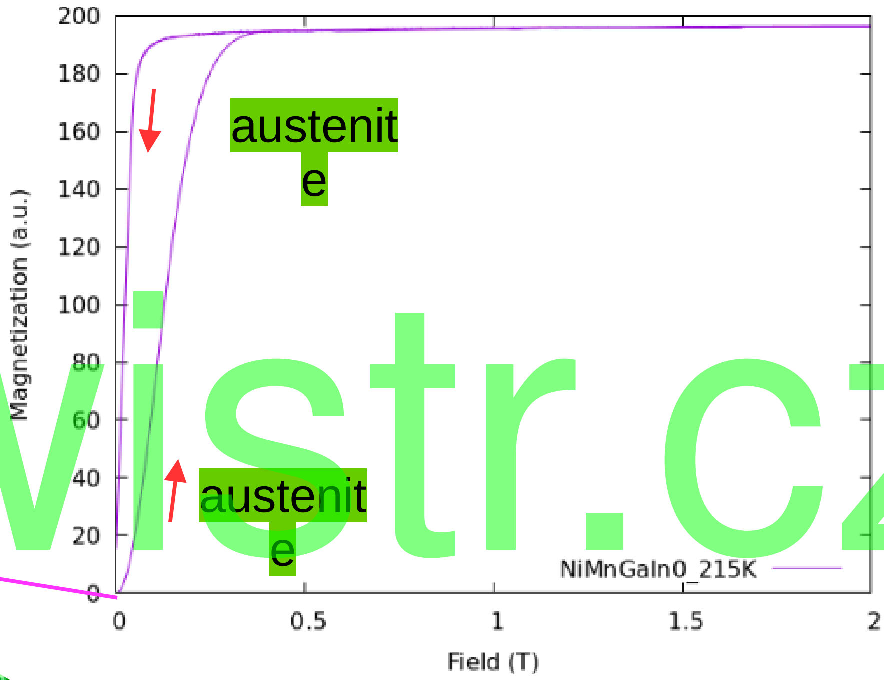


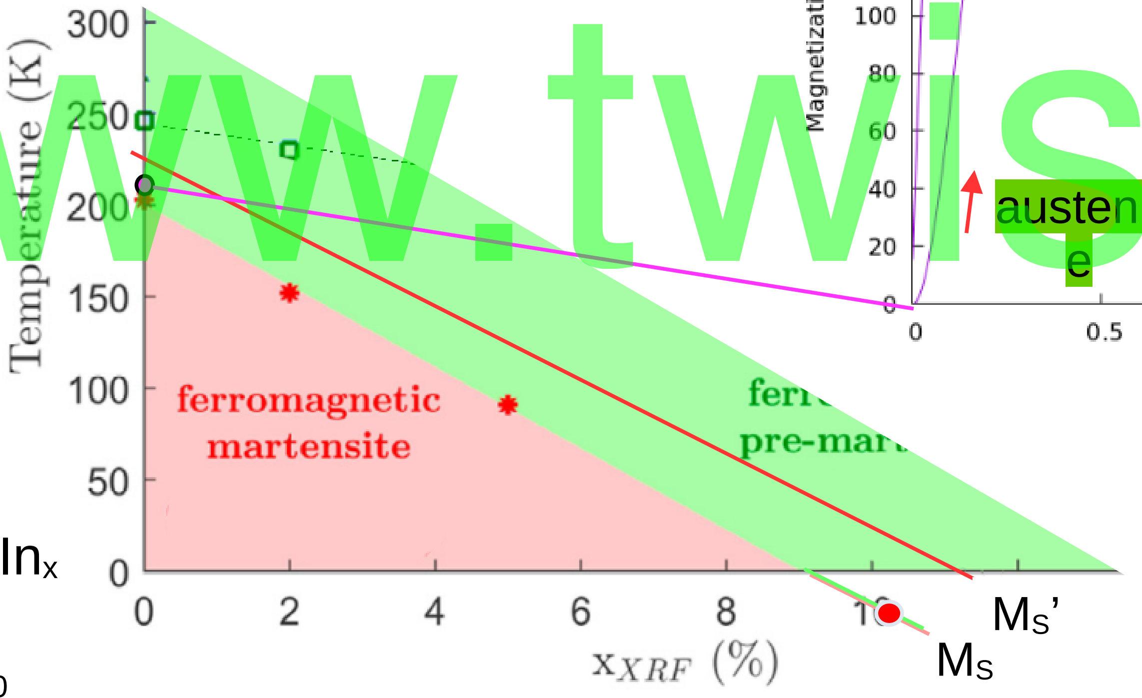
$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.00





$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

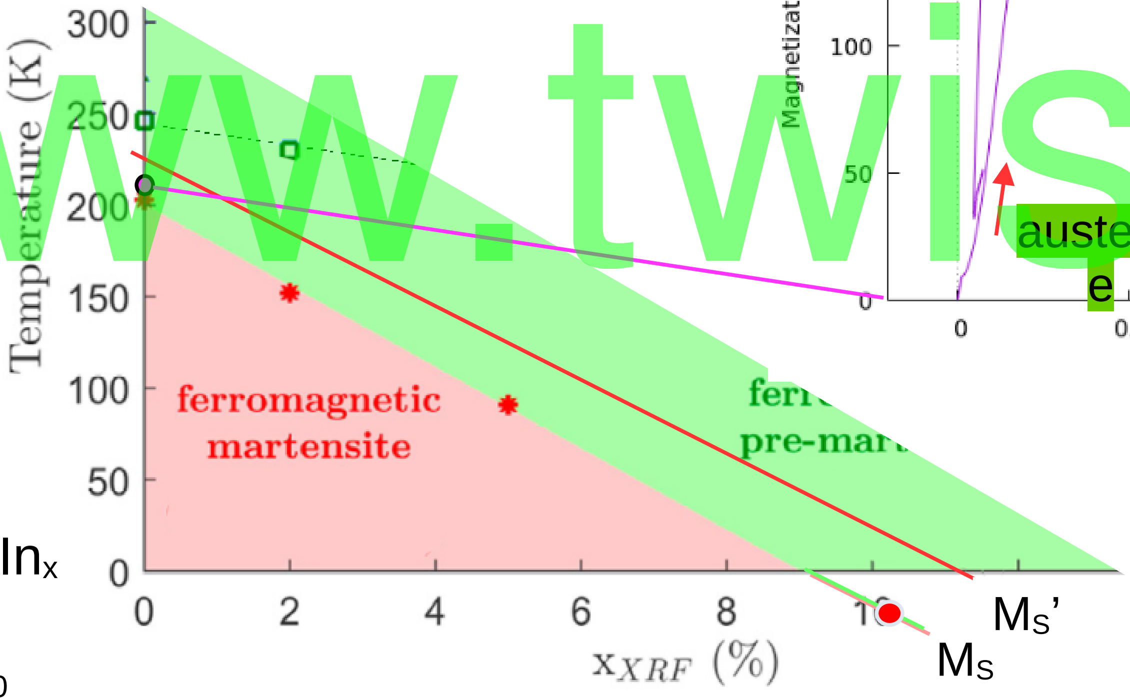
x=0.1, 0.05, 0.02, 0

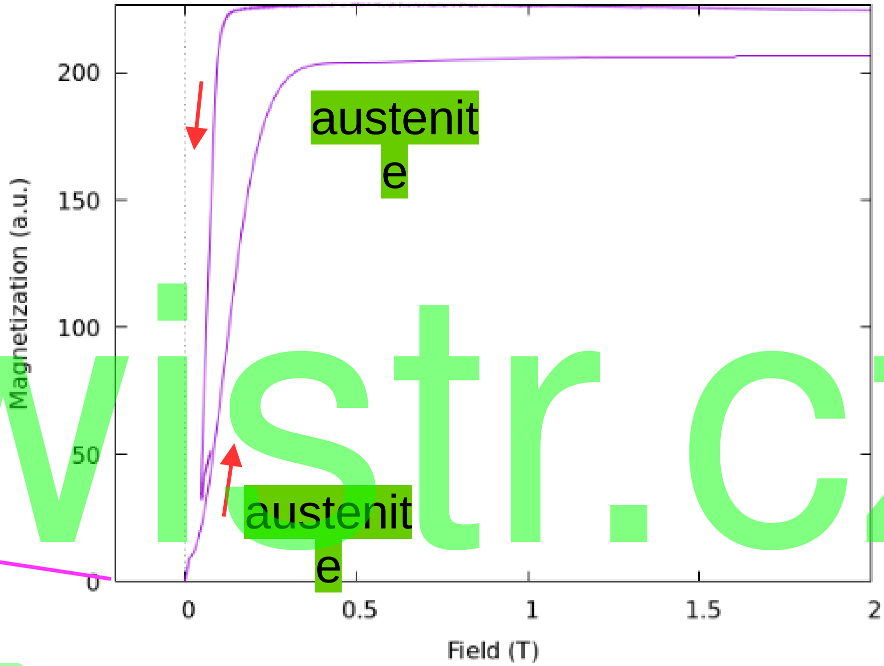
215 K

PULSE (56 T)

austenite

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.00





$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

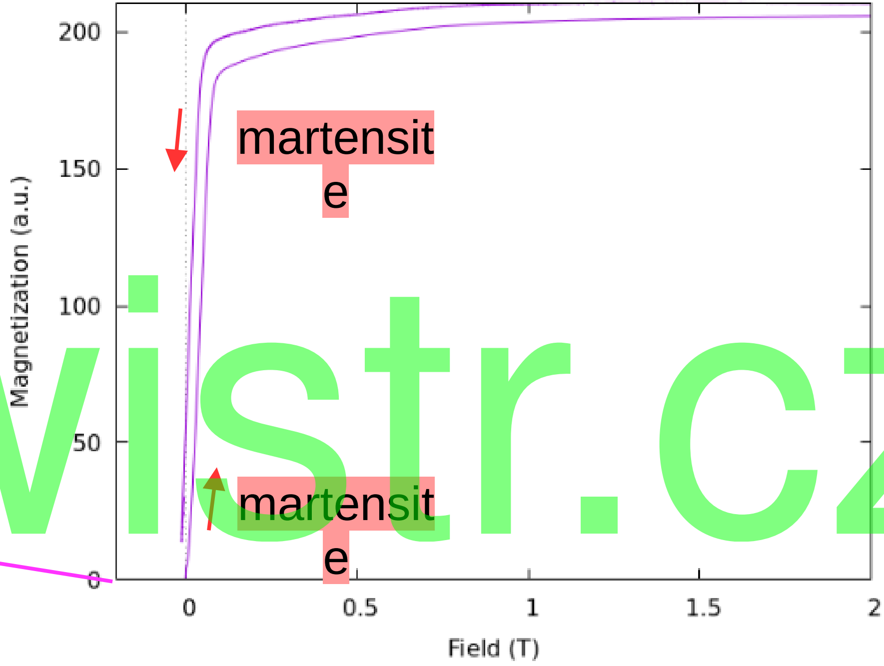
x=0.1, 0.05, 0.02, 0

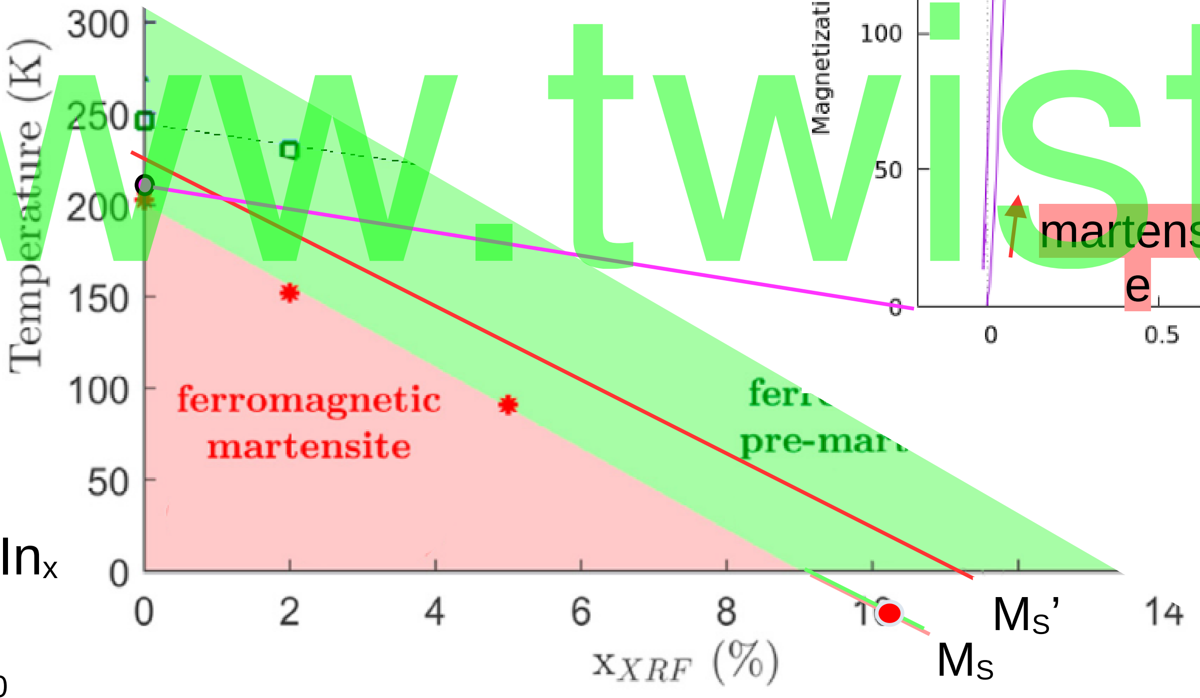
212 K

PULSE (56 T)

austenite

Measurement $Ni_2MnGa_{1-x}In_x$, x=0.00





$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

210 K

TEST (6 T)

martensite

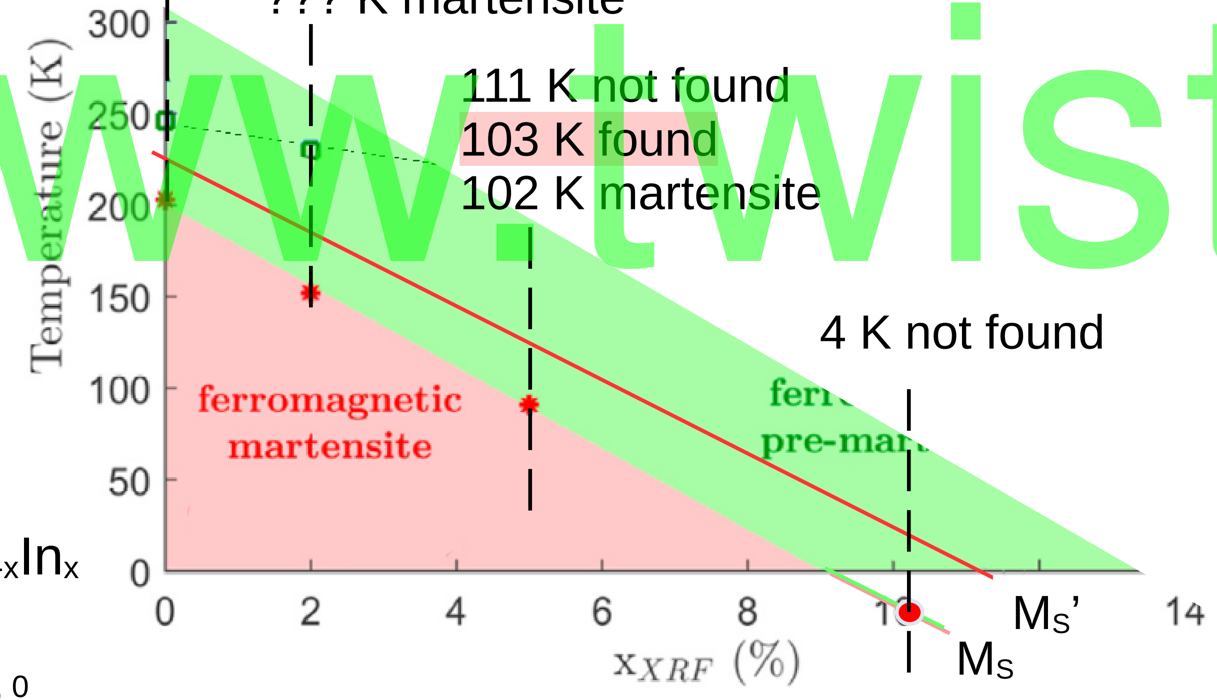
Summary on transition under 56 T

212 K not found
210 K martensite

165 K not found
160 K, 158 K partial
156 K, 154 K found
??? K martensite

111 K not found
103 K found
102 K martensite

4 K not found



$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

x=0.1, 0.05, 0.02, 0

Summary on transition under 56 T

212 K not found
210 K martensite

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160 K, 158 K partial
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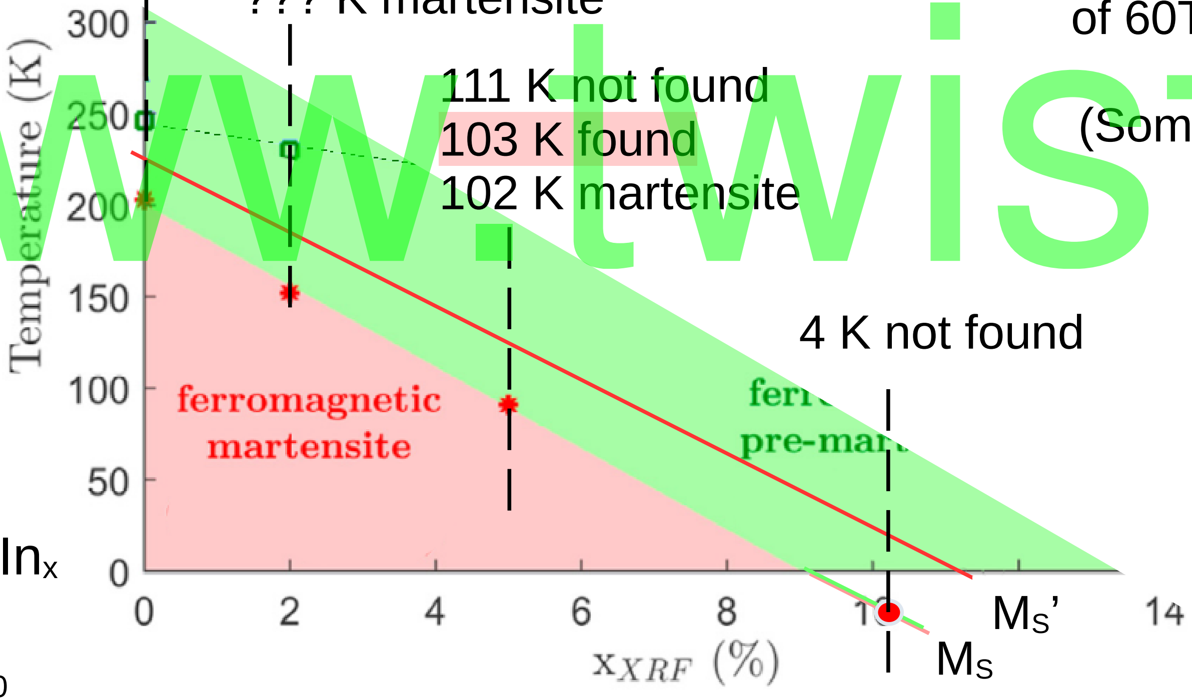


$Ni_2MnGa_{1-x}In_x$

(*e/a* constant)

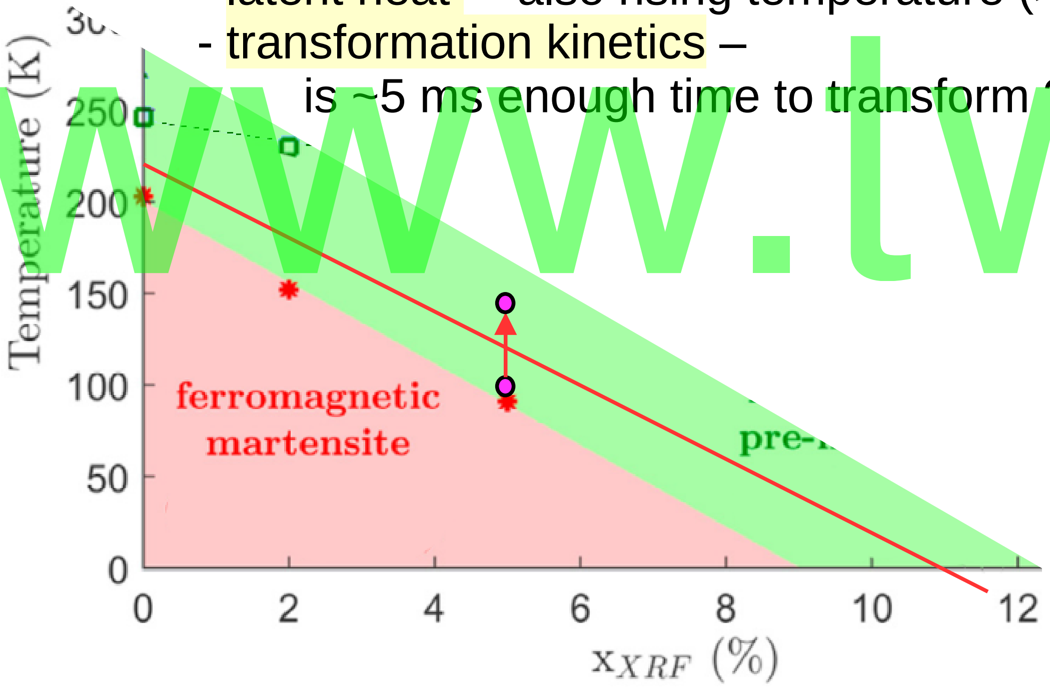
x=0.1, 0.05, 0.02, 0

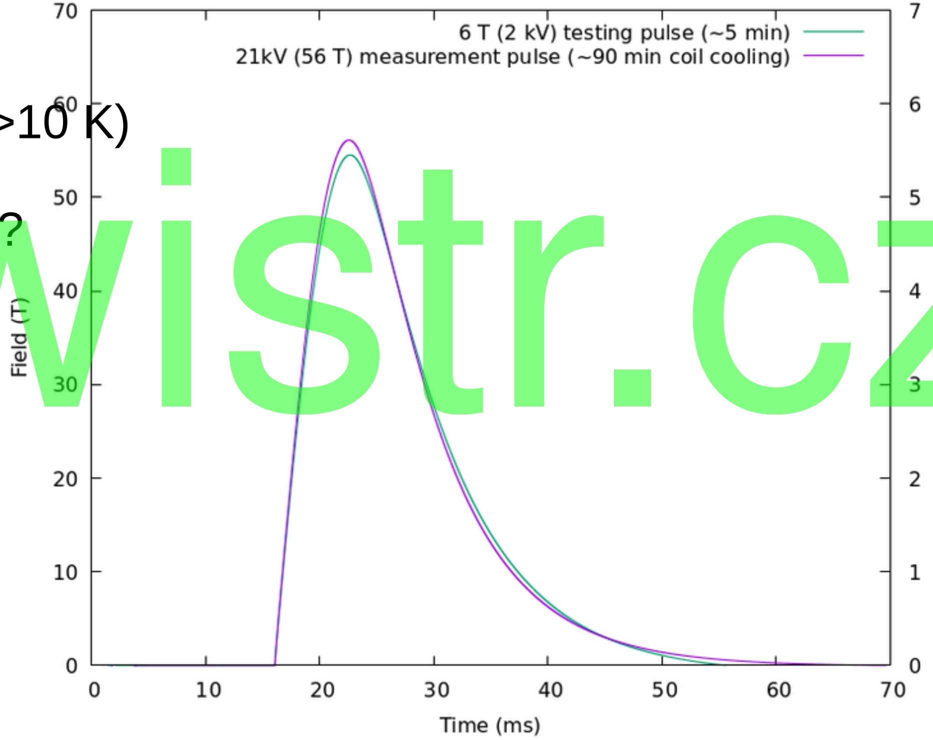
The missing or very narrow temperature windows are far from the expectation of 60T*0.3K/T ~ 20 K windows.

(Some explanation next slide.)

Issues to think about

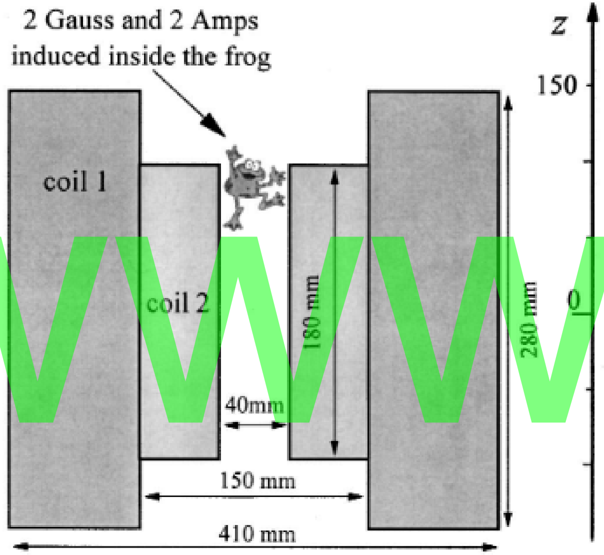
- eddy currents – rising temperature (adiabatic process) – how much ?
- latent heat – also rising temperature (>10 K)
- transformation kinetics –
  is ~5 ms enough time to transform ?






End of presentation
Thank you!
&
Merry Christmas !

Levitating a frog (not at HZDR) -- in 16 T field



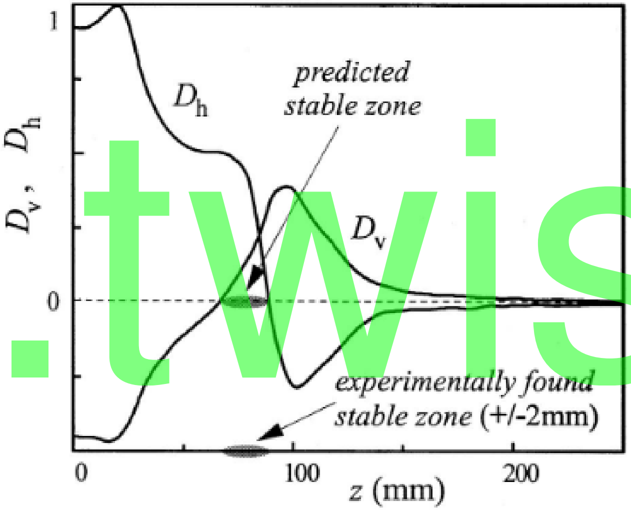


FIG. 1. Frog levitated in stable zone of a 16 T magnet.

"Levitation of a person would require a new magnet design with a field of about 40 T and energy consumption of about GW."

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