Effects of alloying the magnetic shape memory material Ni-Mn-Ga with Cobalt

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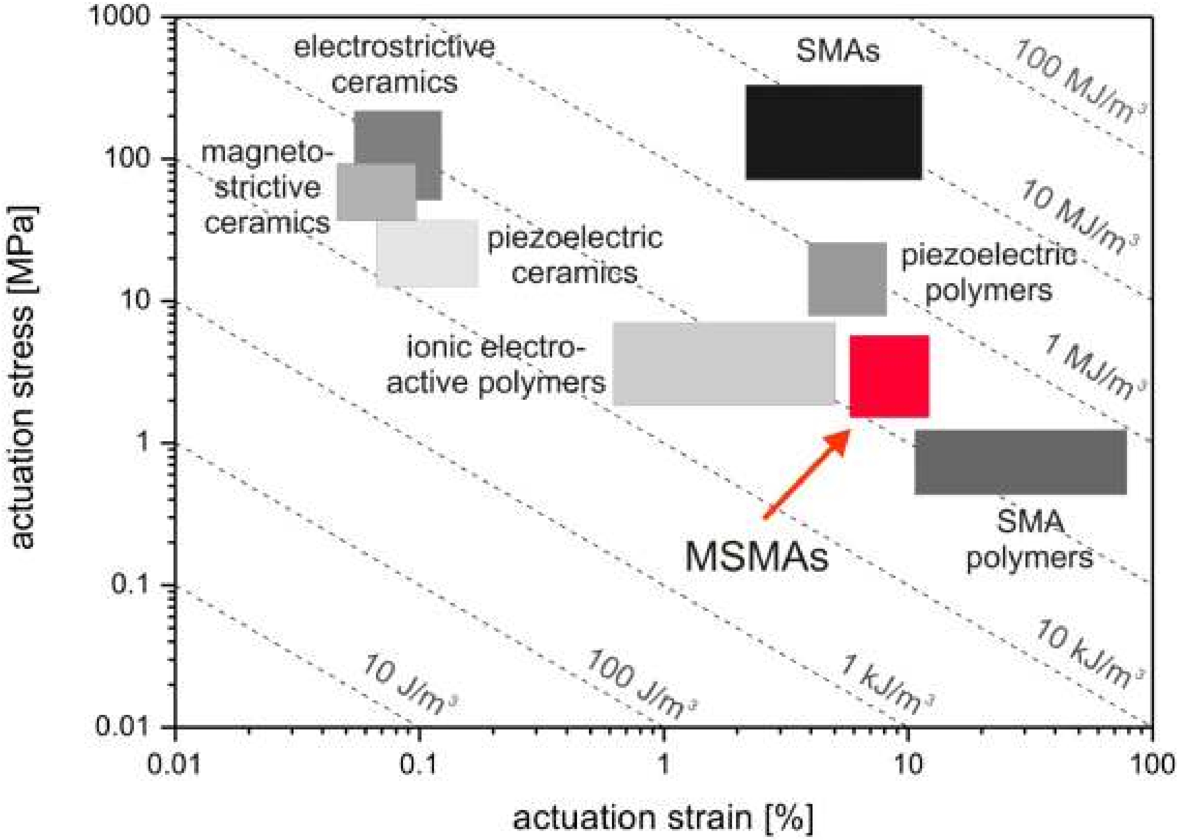
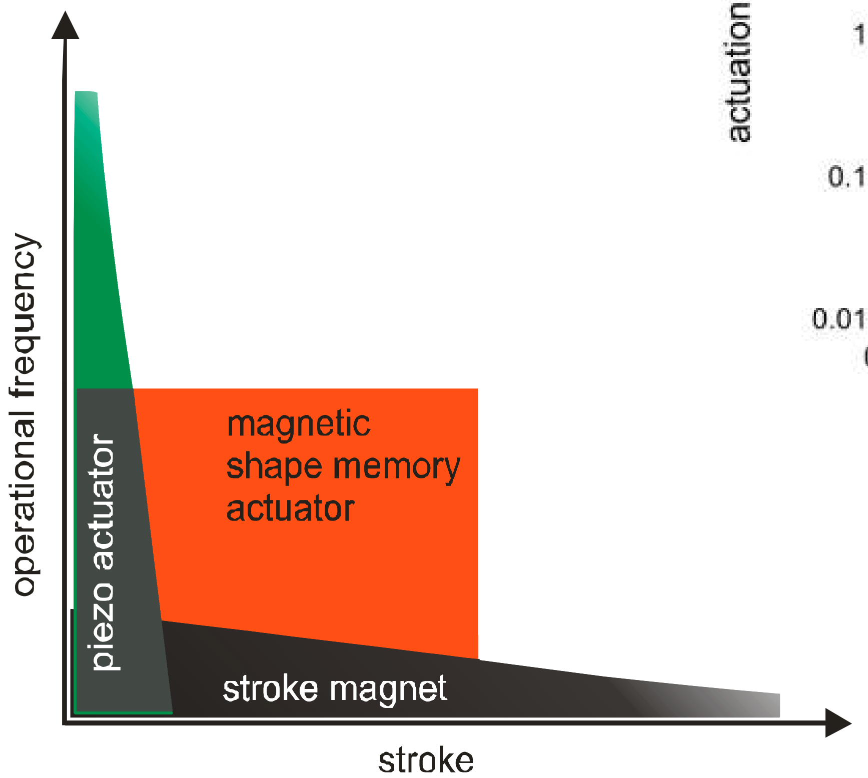
Outlook

- Motivation
- (Magnetic) Shape Memory Effect
- Sample Preparation – SLARE
- Sample Characterization

Motivation



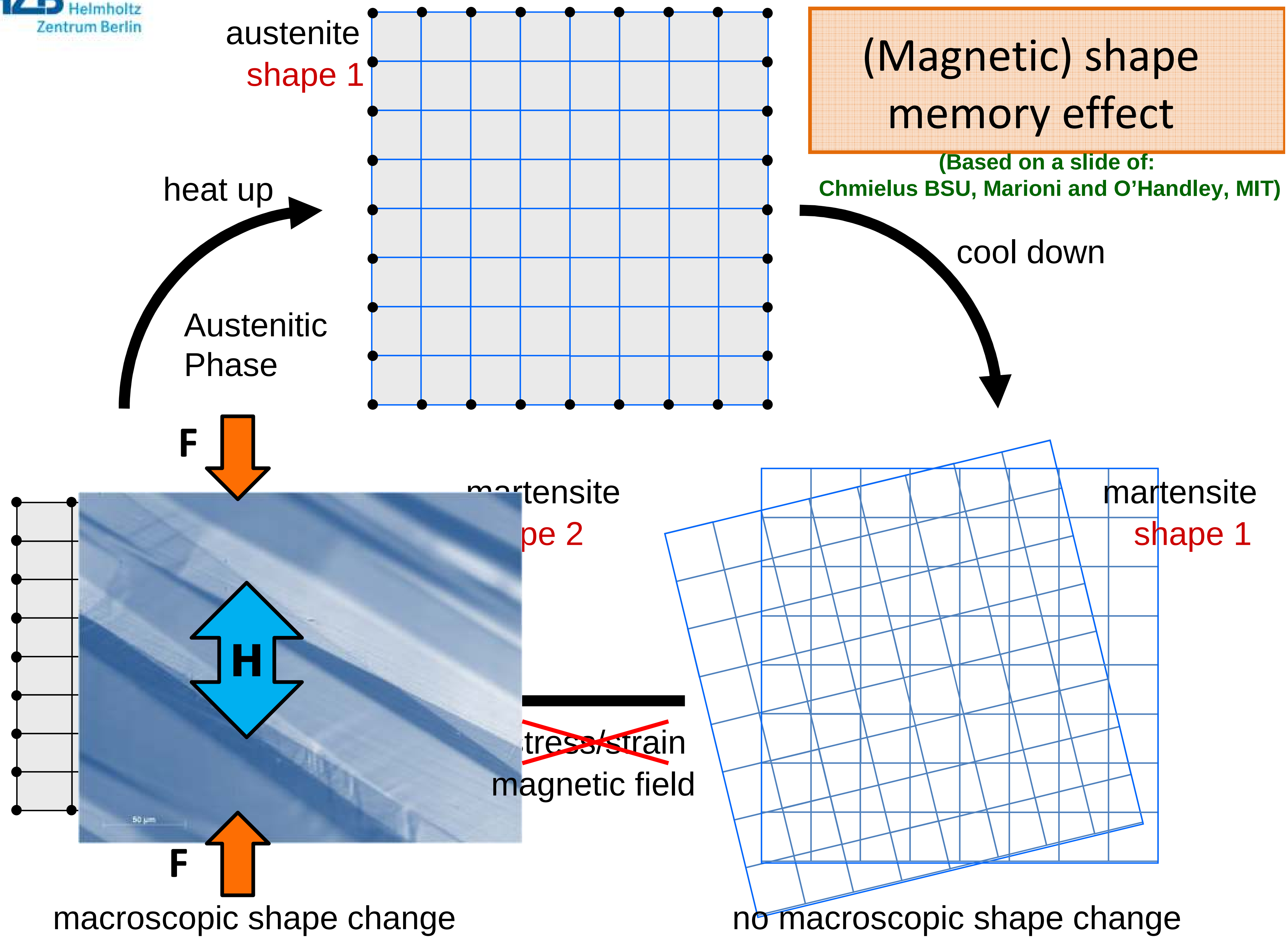
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
actuation stress [MPa]
actuation strain [%]
electrostrictive ceramics
SMAs
magneto-strictive ceramics
piezoelectric ceramics
piezoelectric polymers
ionic electro-active polymers
MSMAs
SMA polymers
100 MJ/m³
10 MJ/m³
1 MJ/m³
10 kJ/m³
1 kJ/m³
100 J/m³
10 J/m³



operational frequency
piezo actuator
magnetic shape memory actuator
stroke magnet
stroke

(Magnetic) shape memory effect

(Based on a slide of: Chmielus BSU, Marioni and O'Handley, MIT)

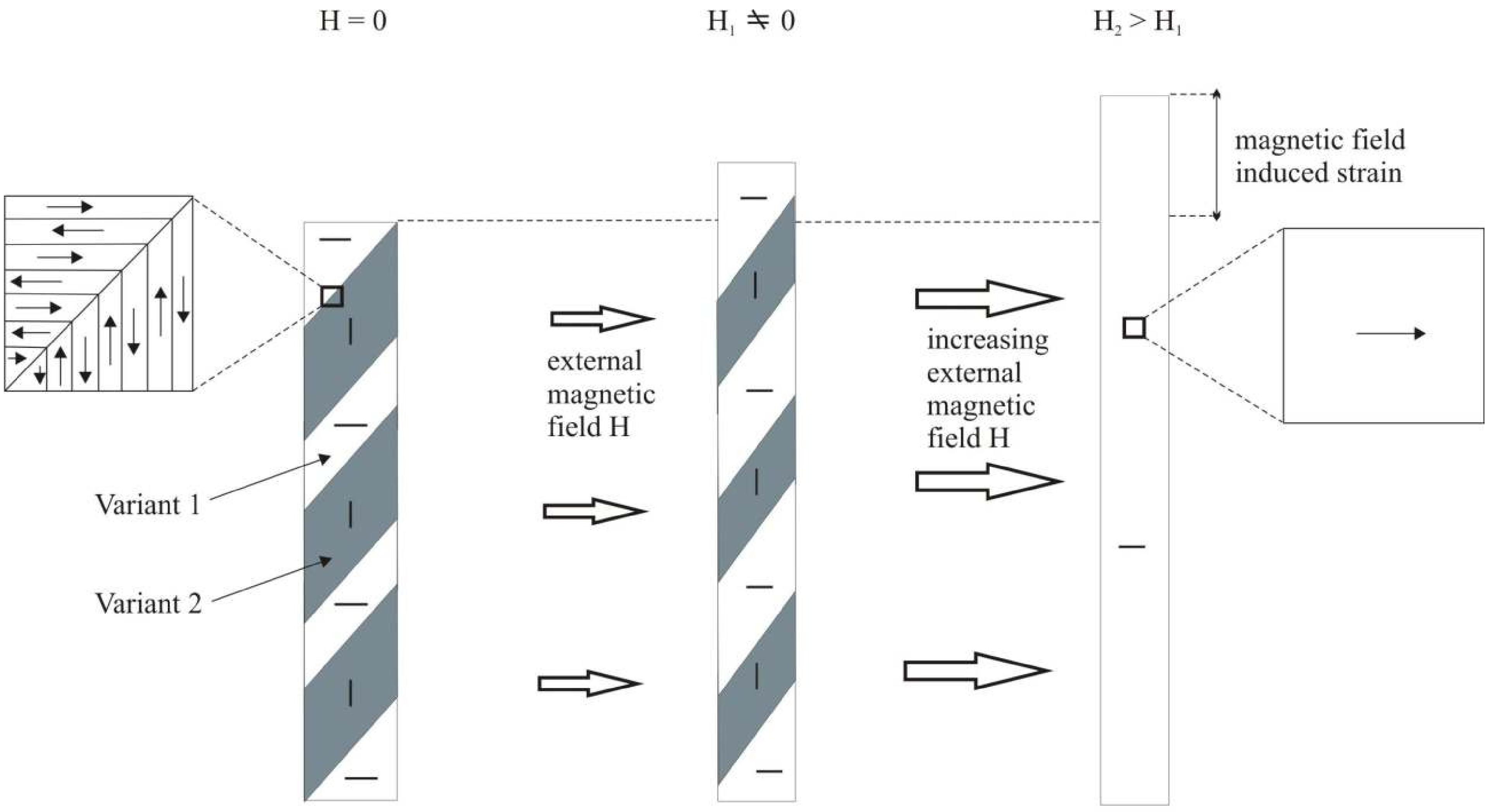


Magnetic shape memory effect

[illegible] magnetic field:

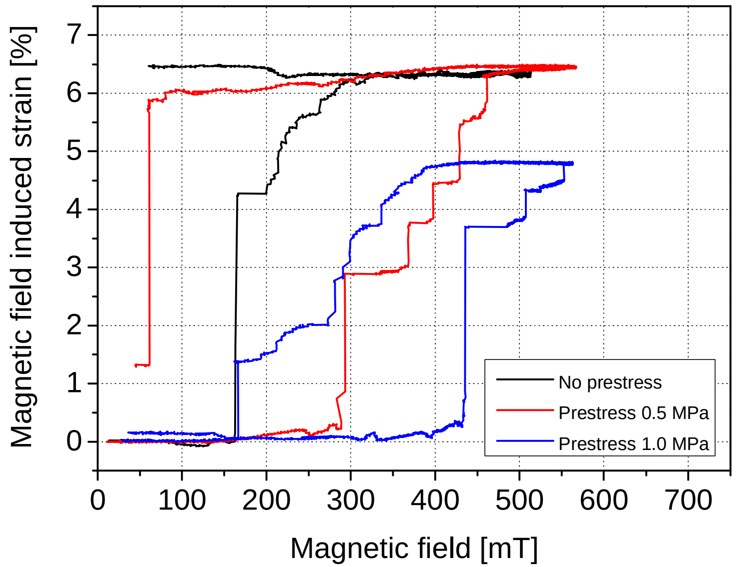
[illegible] stress

⇒ movement of the twinboundaries



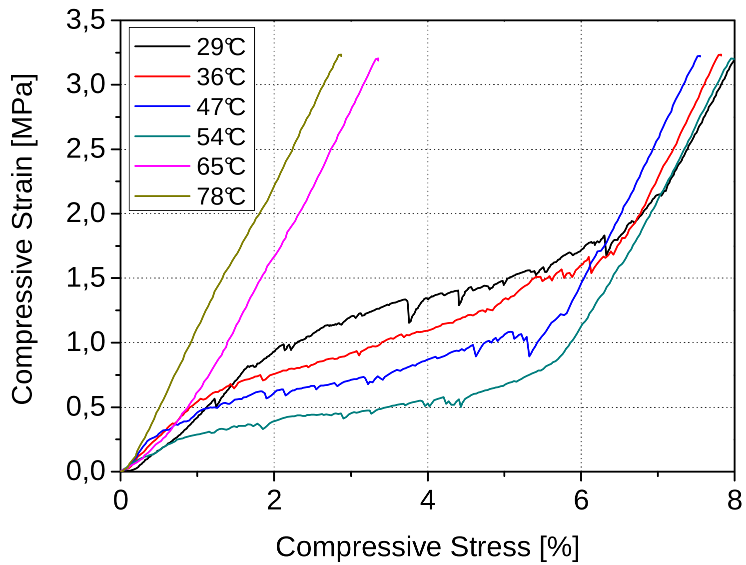
Magnetic shape memory effect in Ni-Mn-Ga

- Without prestress and less than 170 mT, 5M-crystal shows a strain of ~4 % and exhibits max. strain below 340 mT.

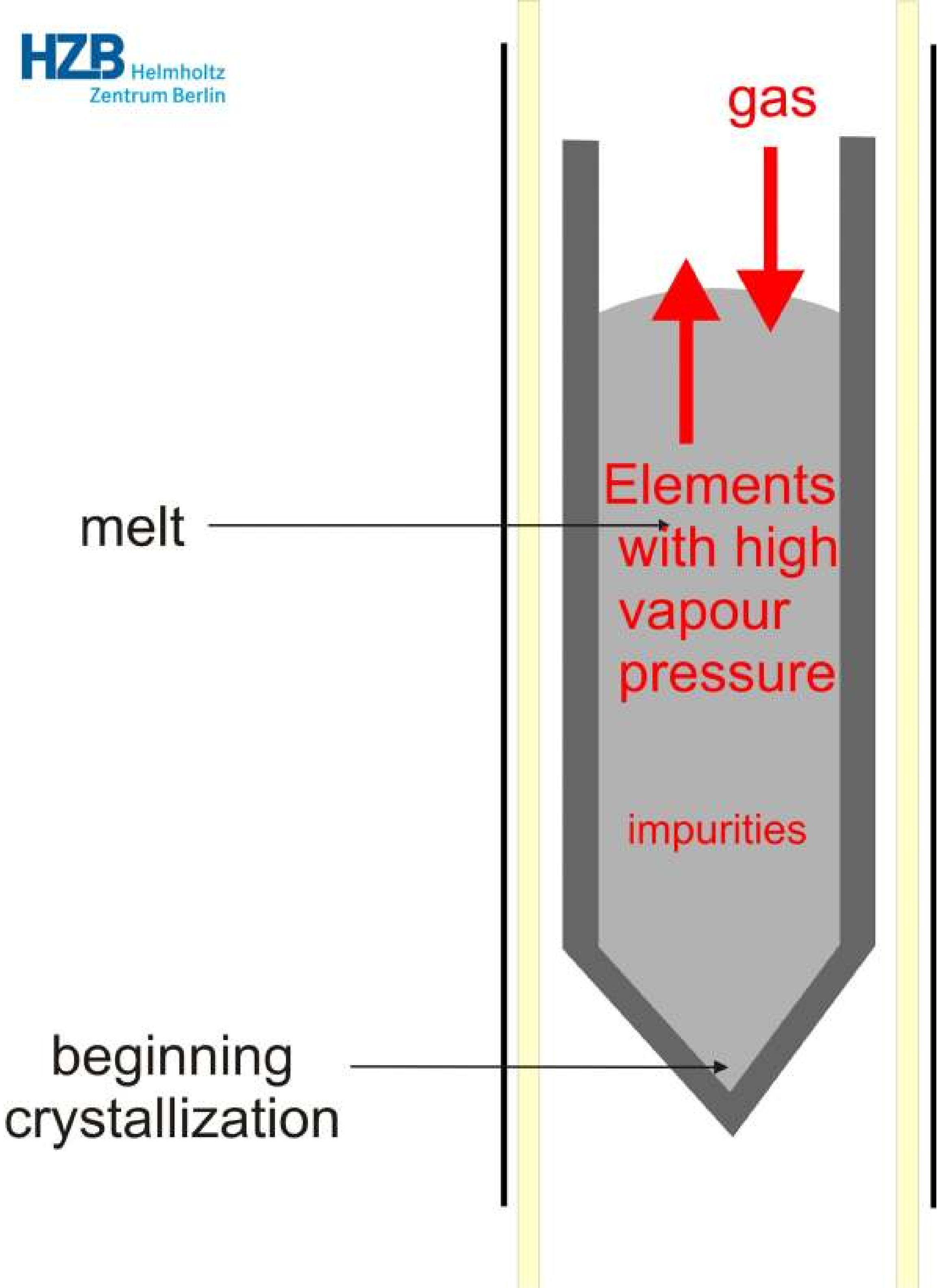


- Limitation in operational temperature

- Brittleness of material



K.Rolfs et al. JMMM, 2008

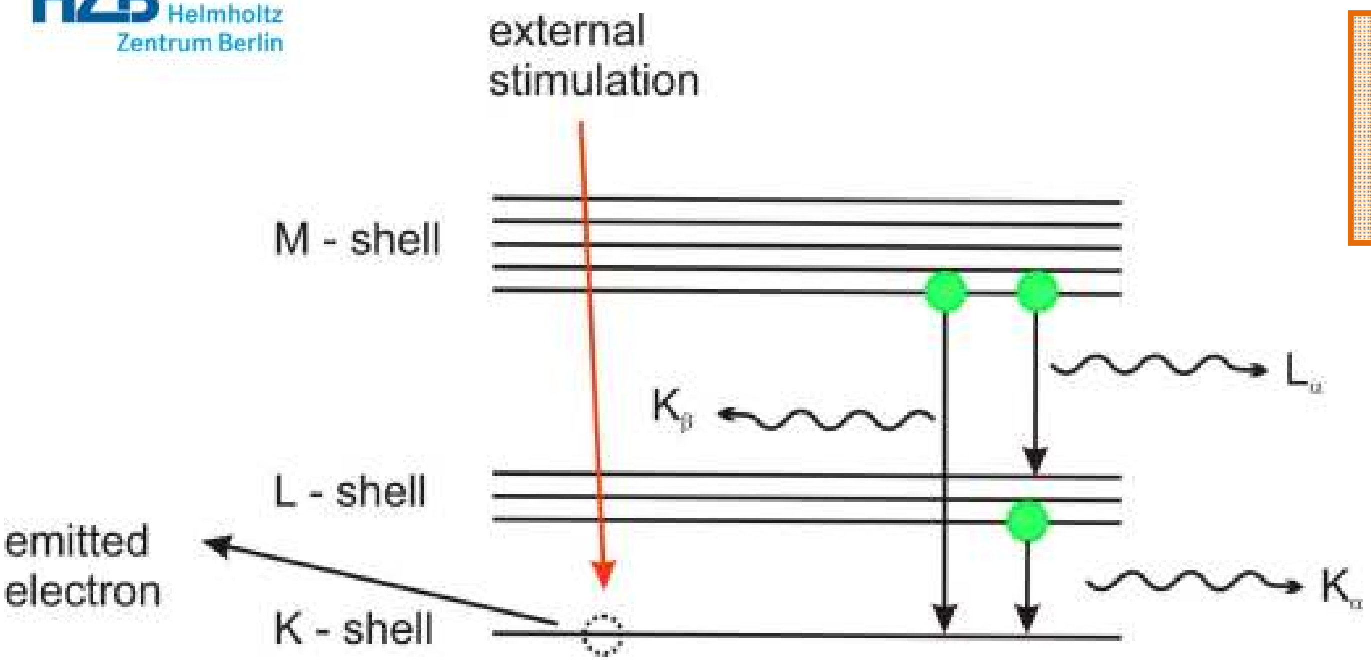


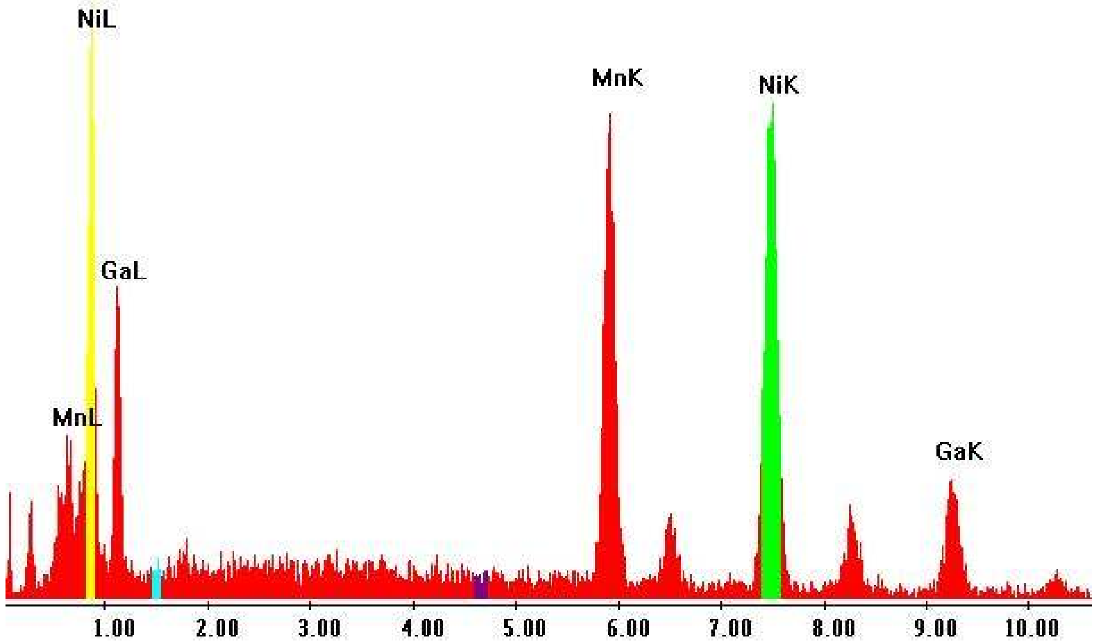
Sample Preparation

- **SL**Ag **R**emelting and **E**ncapsulation technique
- Encapsulation of alloy avoids manganese loss
- Slag reacts with inclusions and dissolve ionic impurities as oxides and sulfides
- No reaction between alloy and crucible

A.Mecklenburg et al. DE 102004018664A1, 2005

Determination of composition



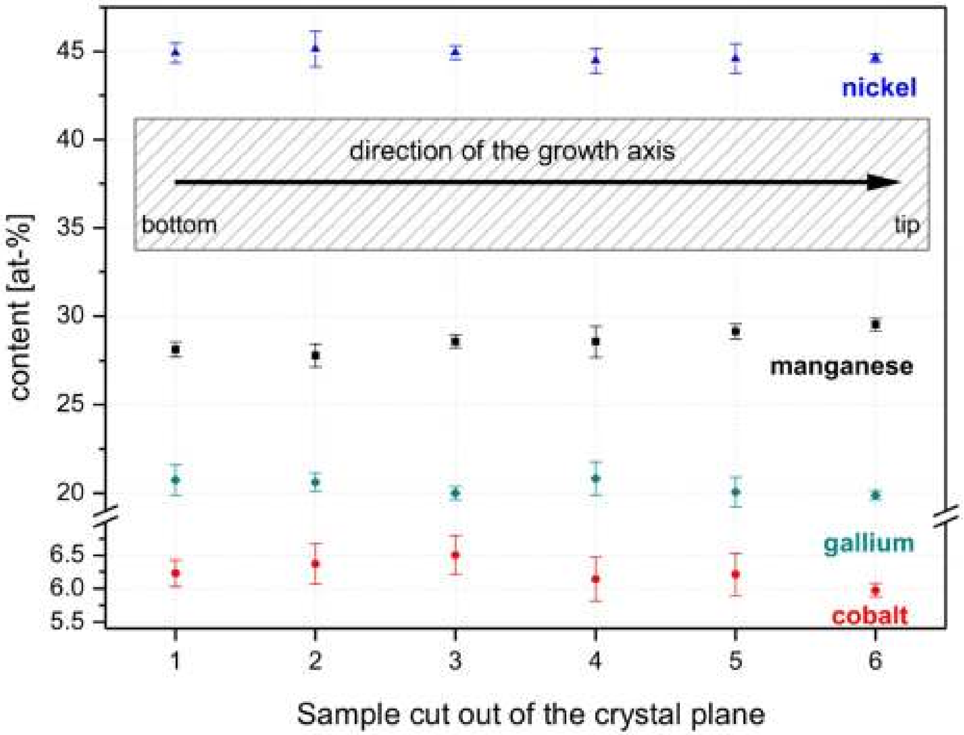


- Energy Dispersive X-Ray Spectrometry
- Deviation of several percent if no standard is given
- Preparing of standards
- Quantitative analyses by ICP-OES

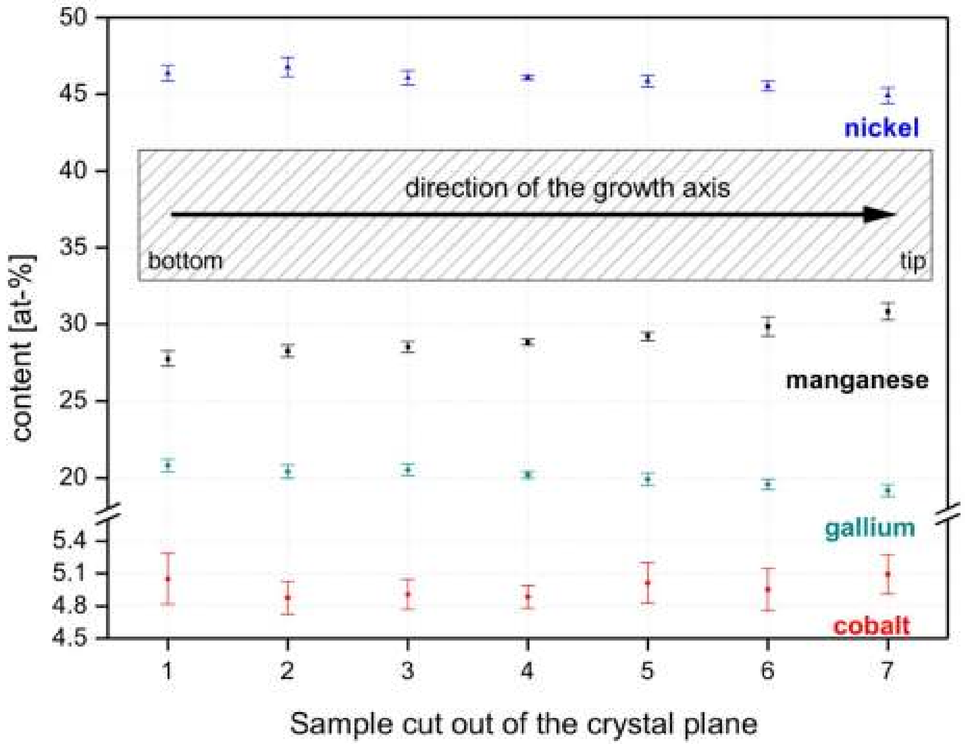
Composition gradient in Ni-Mn-Ga-Co rods

- homogeneous Co-Content, different Mn/Ga – ratio

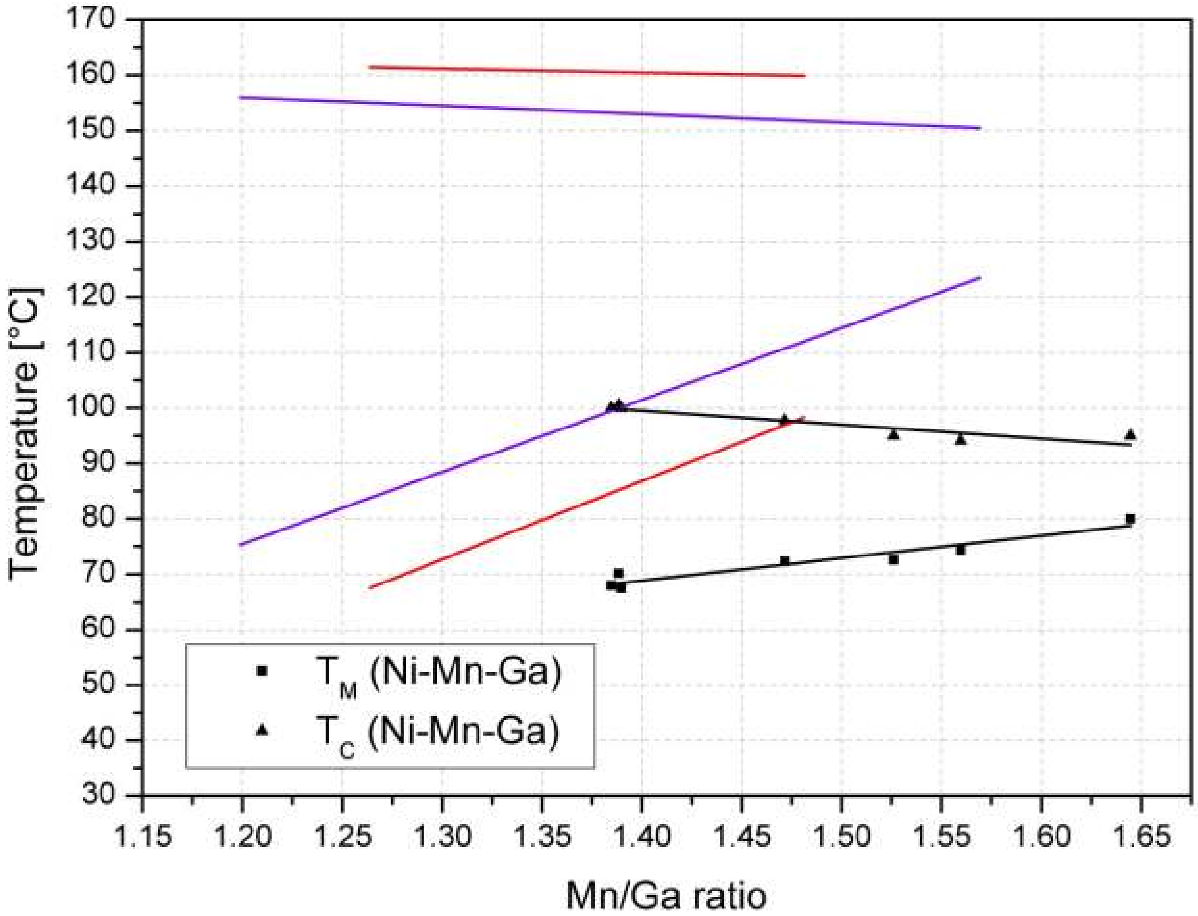
$Ni_{44}Co_6Mn_{31}Ga_{19}$



$Ni_{44.6}Co_{5.4}Mn_{30.7}Ga_{19.3}$

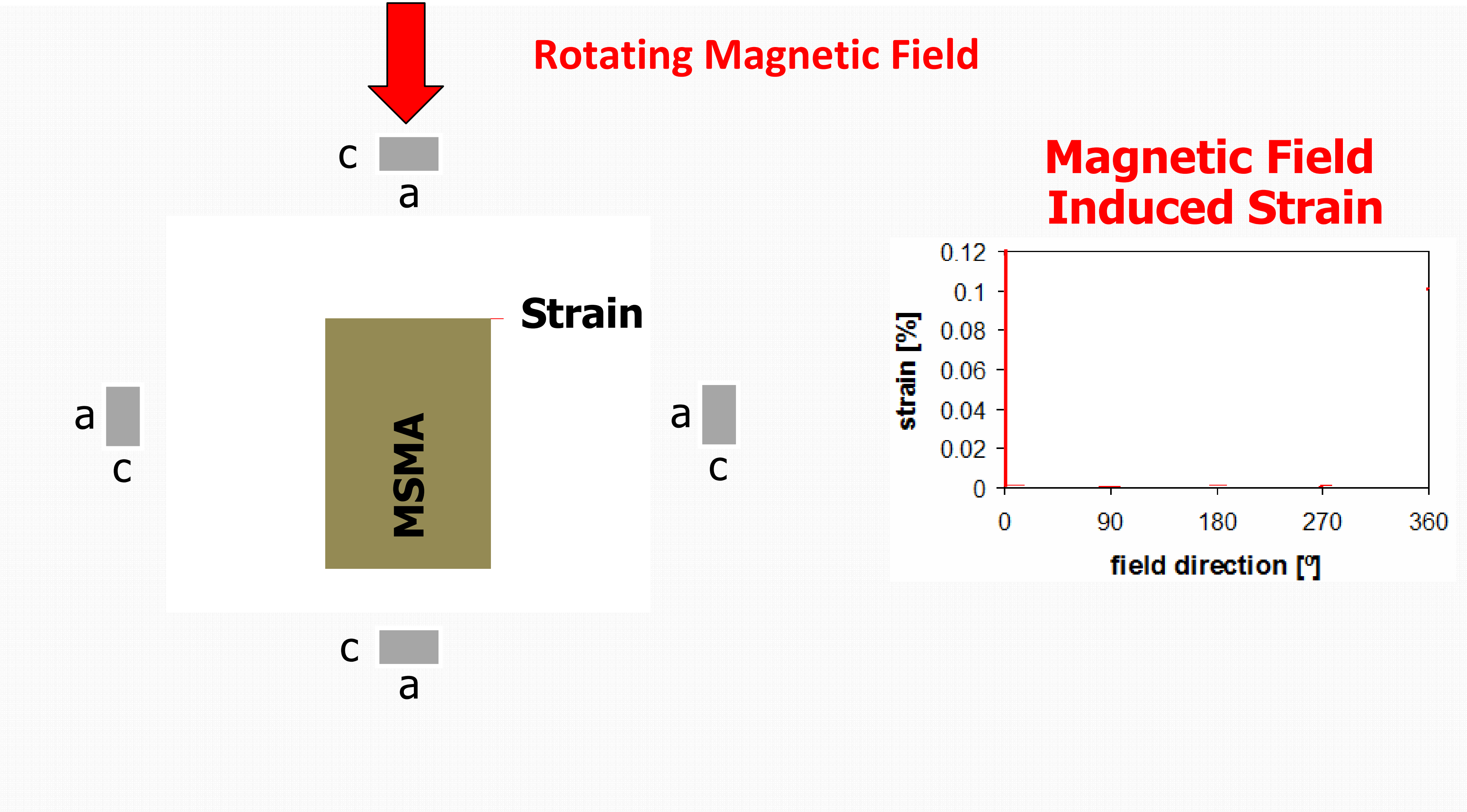


Phase transition temperatures in Ni-Mn-Ga-Co

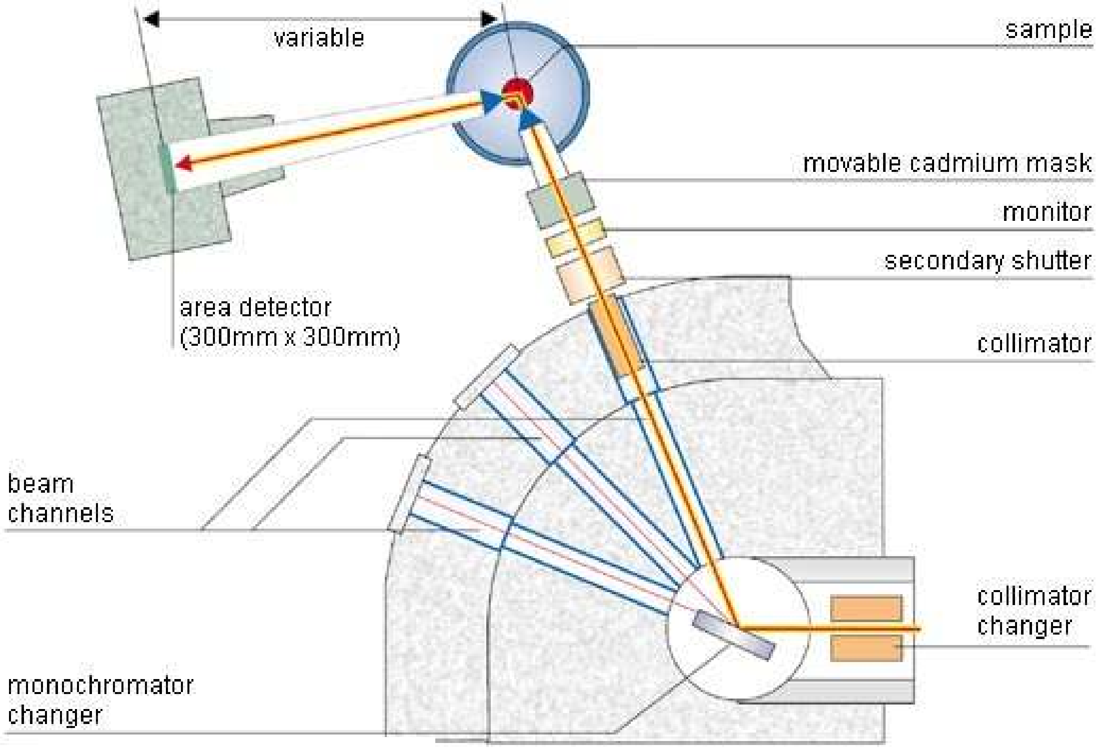


- Structural phase transition temperature increases with increasing Mn/Ga ratio
- Curie-temperature increases with increasing Co-content
- T_M and T_C increase by substituting Ni with Co

Schematic of magneto-mechanical testing principle



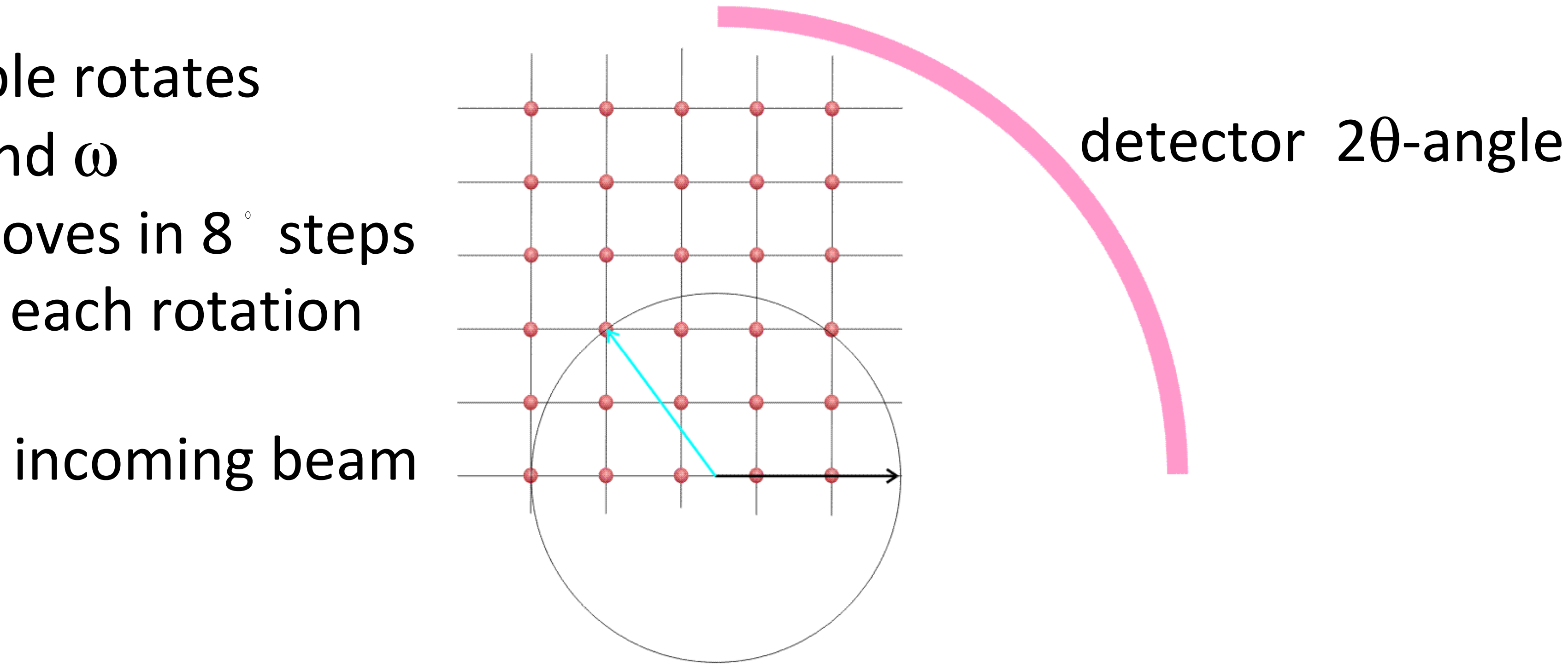
Schematic Diagram of E3 (Angular Dispersive Technique)



Take off angle of monochromator [°]	65
Wavelength [nm]	0.1486
Collimation [′]	open
FWHM standard powder [°]	~ 0.3 (at 2theta = 90°)
Resolution	Δd/d ≈ 1.4 x 10-3
Flux [n/cm2/s]	~ 5 x 10^6
Detector	PSD 30 x 30 cm^2
Monochromator	Si (400), Double Focussing
XYZ Table	~ Max 300 Kg

Measurement technique

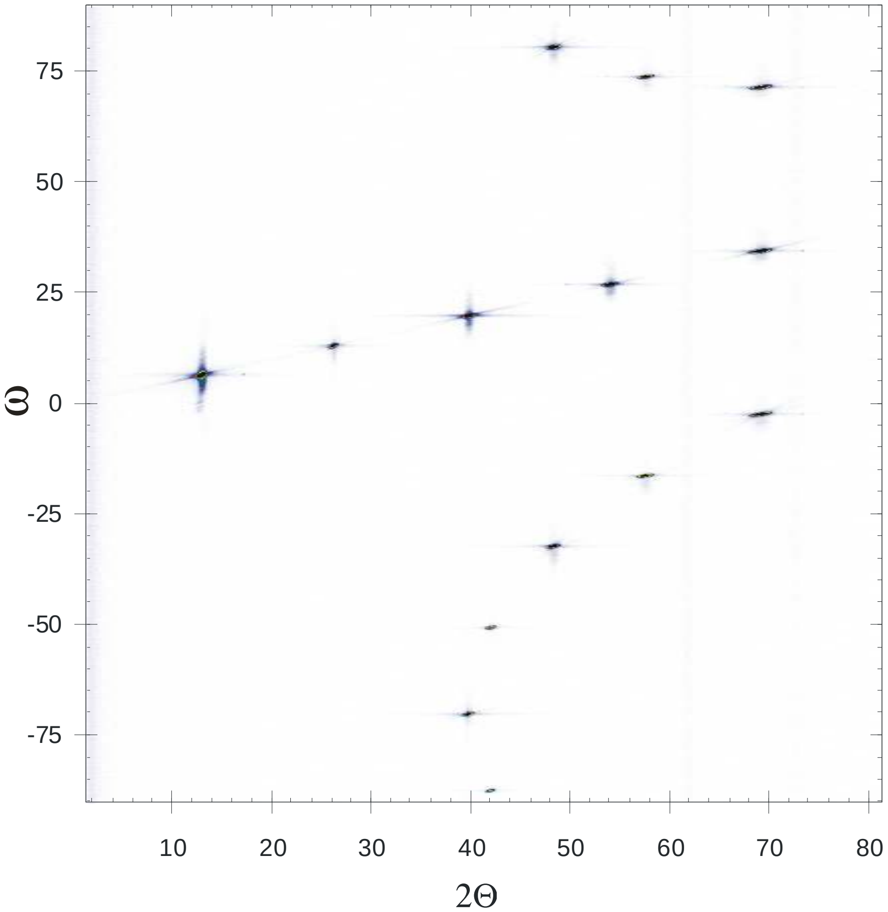
- sample rotates around ω
- 2θ moves in 8° steps after each rotation

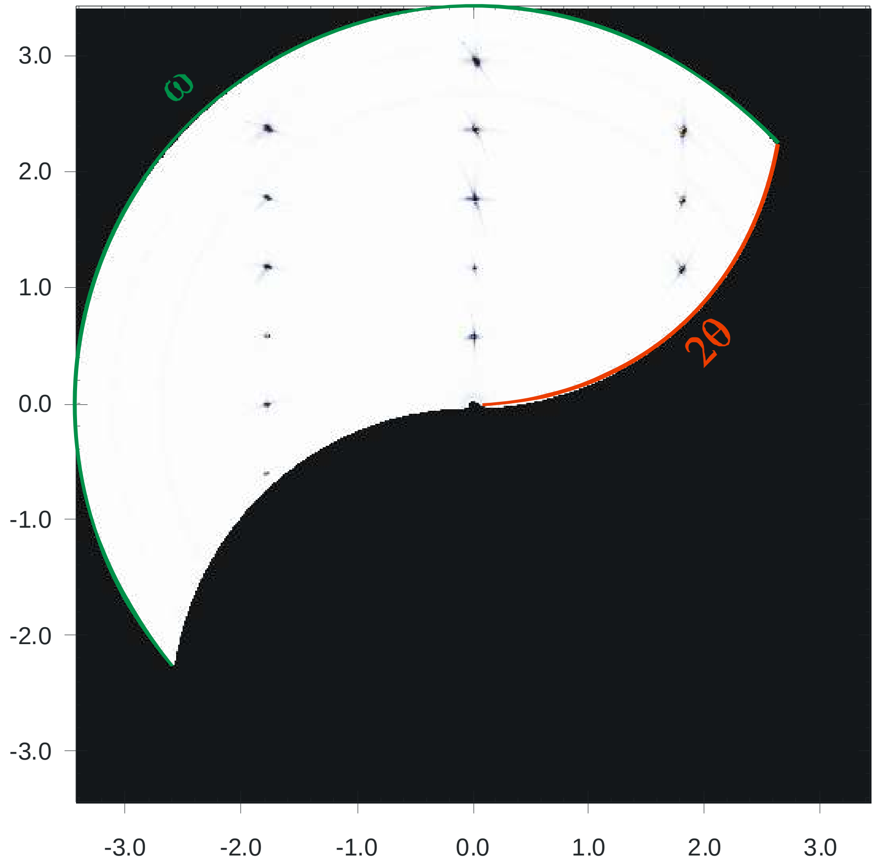


Ewald sphere (radius $r = 2\pi / \lambda$)

Measurement technique

Simple Transformation to the Reciprocal Space.





Low temperature structures in Ni-Mn-Ga-Co

Ni-Mn-Ga-Co with Co 1.2 - 6 at-%

tetragonal structure

$Ni_{45.7}Co_5Mn_{29.4}Ga_{19.9}$
a = b = 5.53 Å
c = 6.51 Å

c/a = 1.18

Theoretical

strain 18%

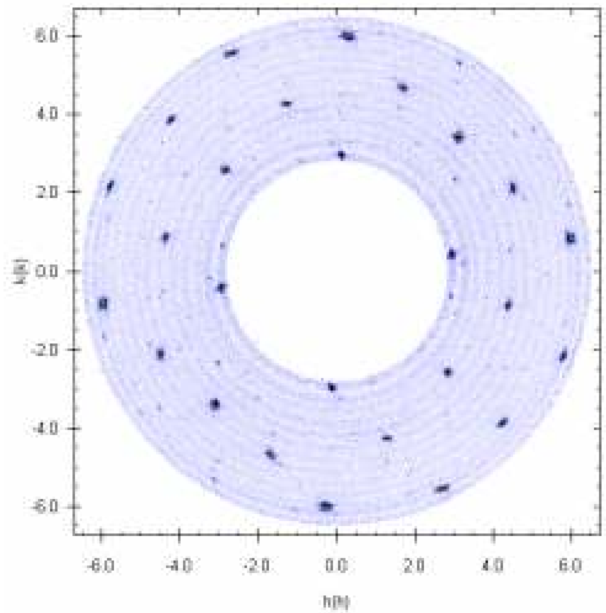
orthorhombic structure

$Ni_{44.7}Co_{4.9}Mn_{31.7}Ga_{18.7}$
a = 6.62 Å
b = 5.85 Å
c = 5.48 Å

c/a= 0.83

Theoretical

strain 17%



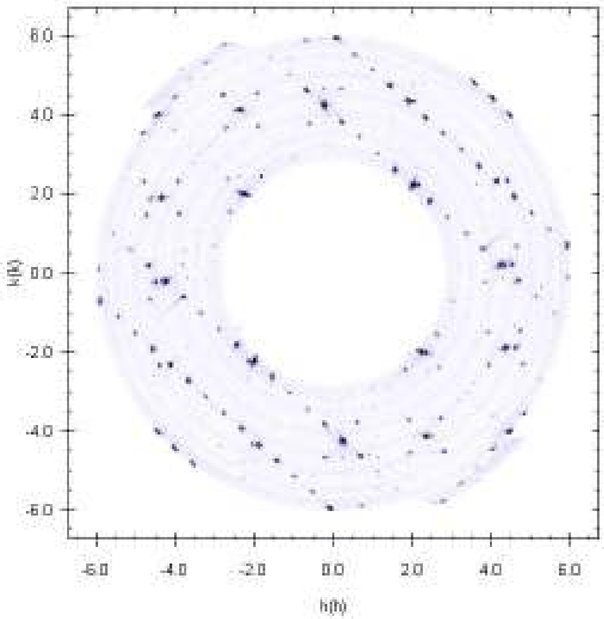
Ni-Mn-Ga-Co with Co 0.8 at-%

tetragonal modulated structure

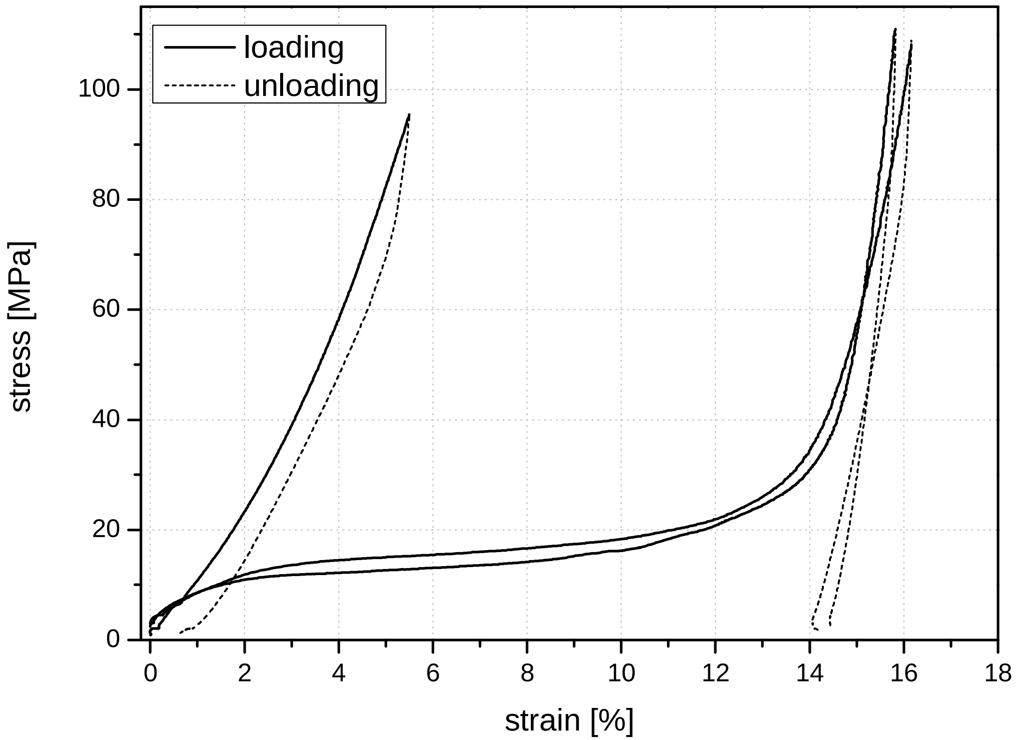
$Ni_{44.7}Co_{4.9}Mn_{31.7}Ga_{18.7}$
a = b = 5.93 Å

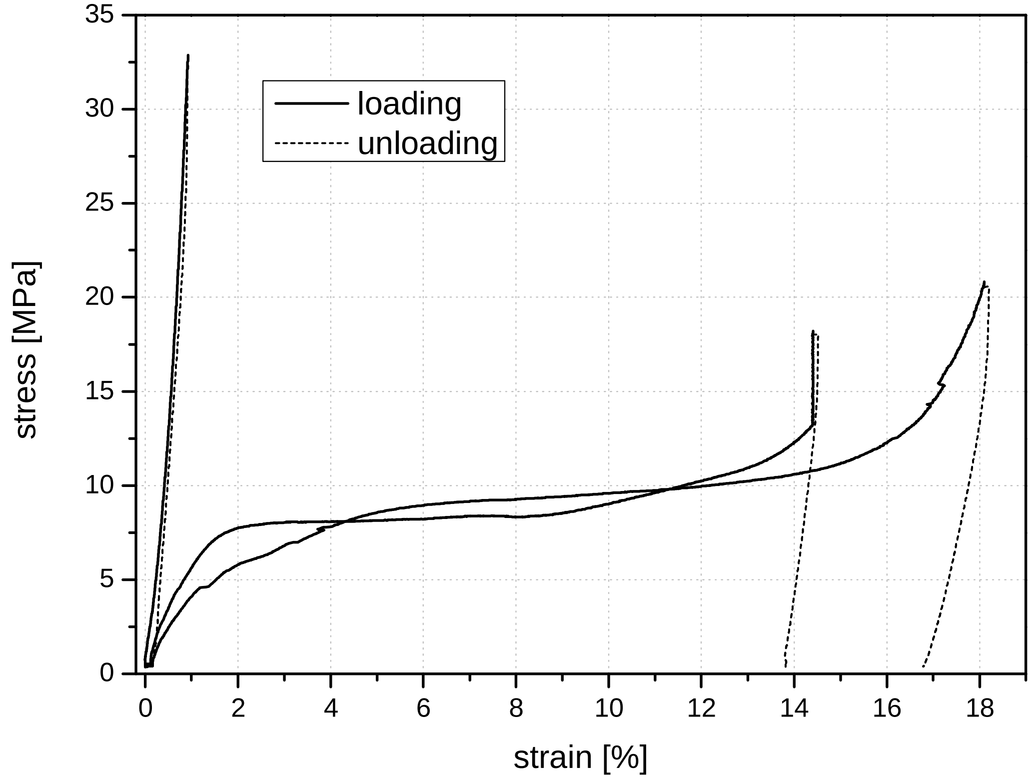
c= 5.59 Å

c/a= 0.94



Stress – Strain – Behaviour in tetragonal Martensite

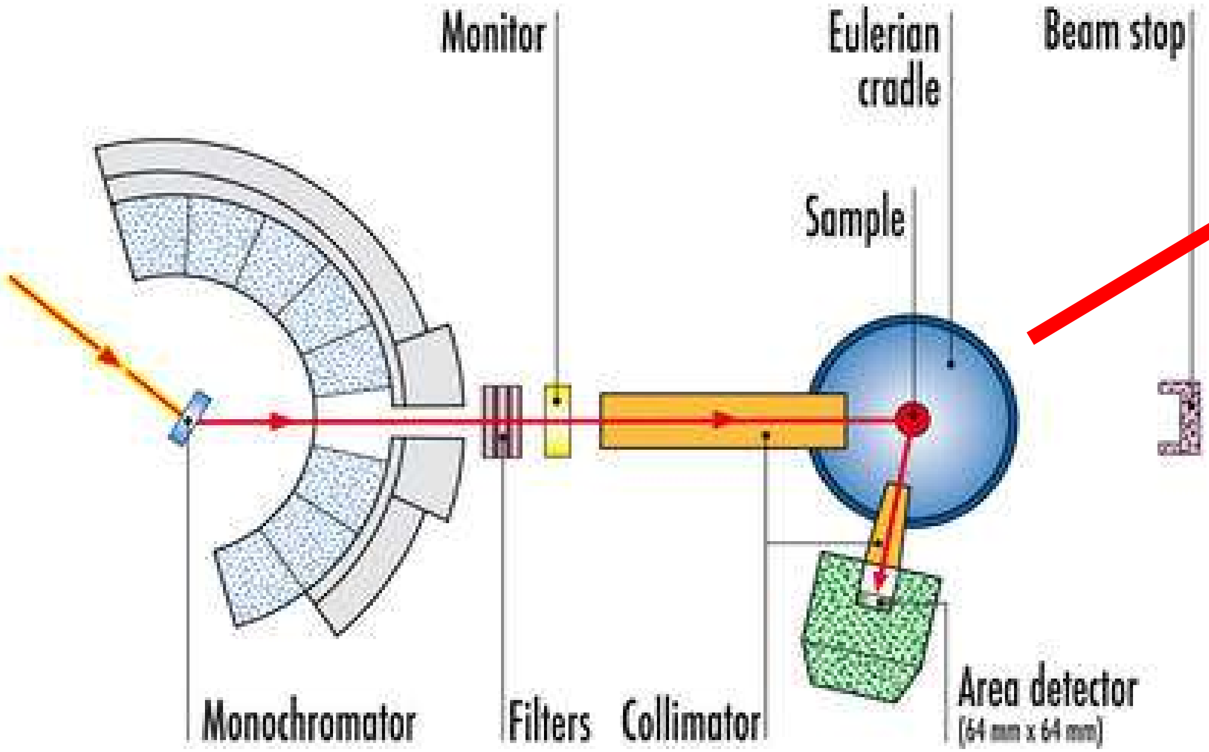


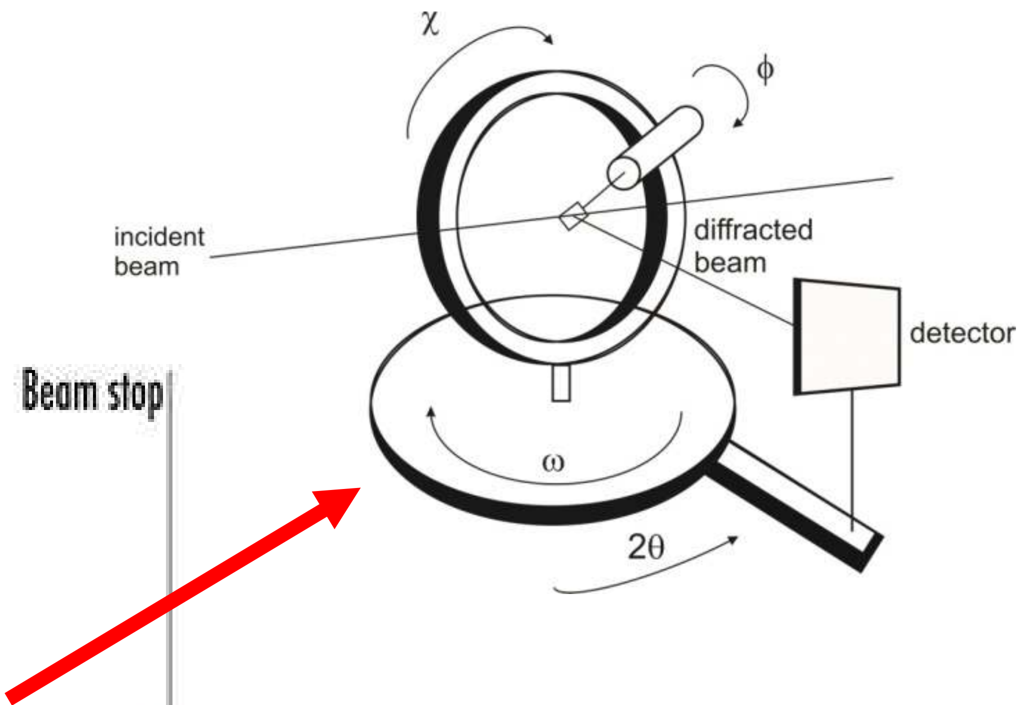


6% Co → 1% Co

- twinning stress decreases with decreasing amount of Co
- reachable strain increases with decreasing Co - content

Schematic Diagram of four cirlcle diffractometer D9 using hot neutrons





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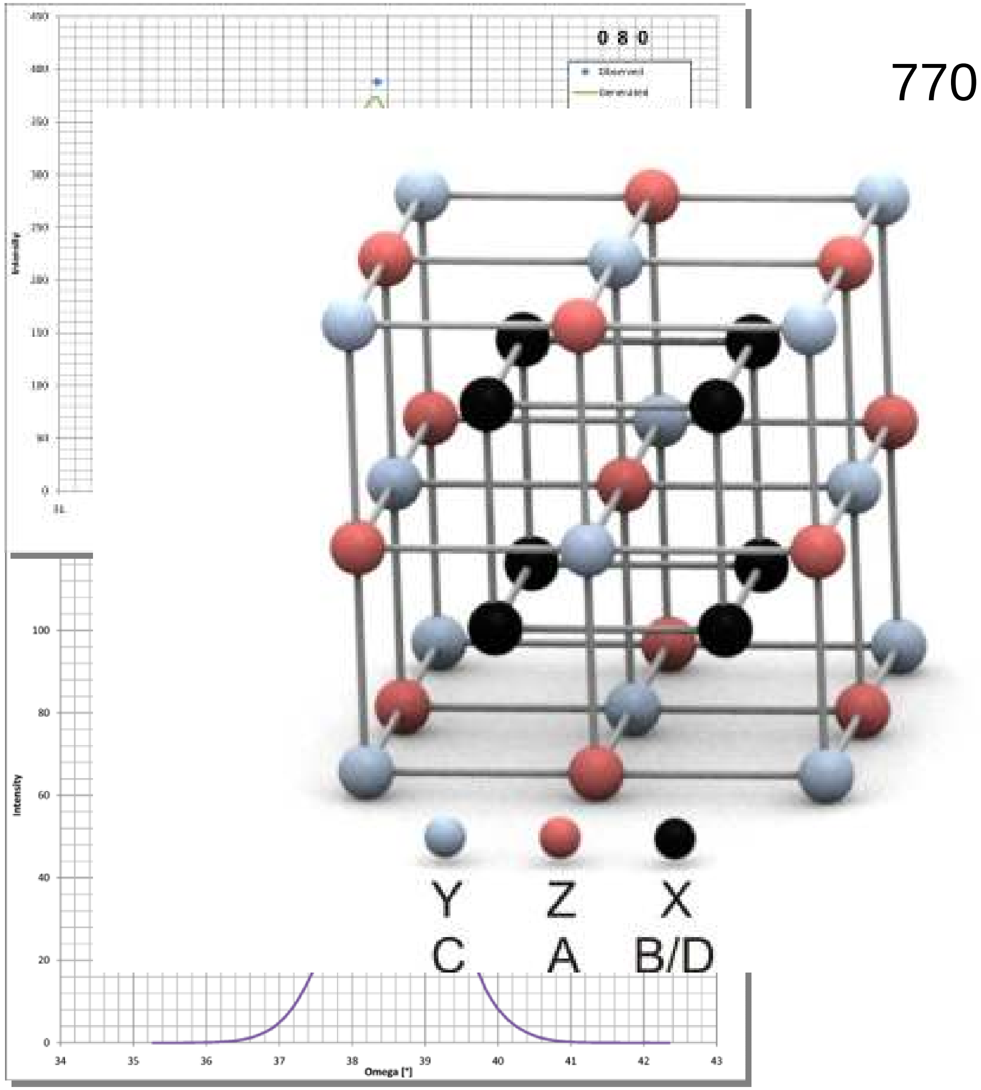
Distribution of cobalt in Ni-Mn-Ga lattice



770 Bragg reflections have been measured in
mperature phase

$$= \sum_{j,\alpha} b_j \cdot e^{2\pi i (h\cdot u_\alpha + k\cdot v_\alpha + l\cdot w_\alpha)}$$

Fm-3m

- ≈ 80% of Co on Ni-places (¼ ¼ ¼)
- ≈ 20% of Co on Mn-places (½ ½ ½)

Double Twinning in nonmodulated orthorhombic Martensite

Sequence of loading:

x . y . z

Stress plateau in x direction: **30MPa**

Stress plateau in y direction: **95MPa**

Stress plateau in z direction: **-**

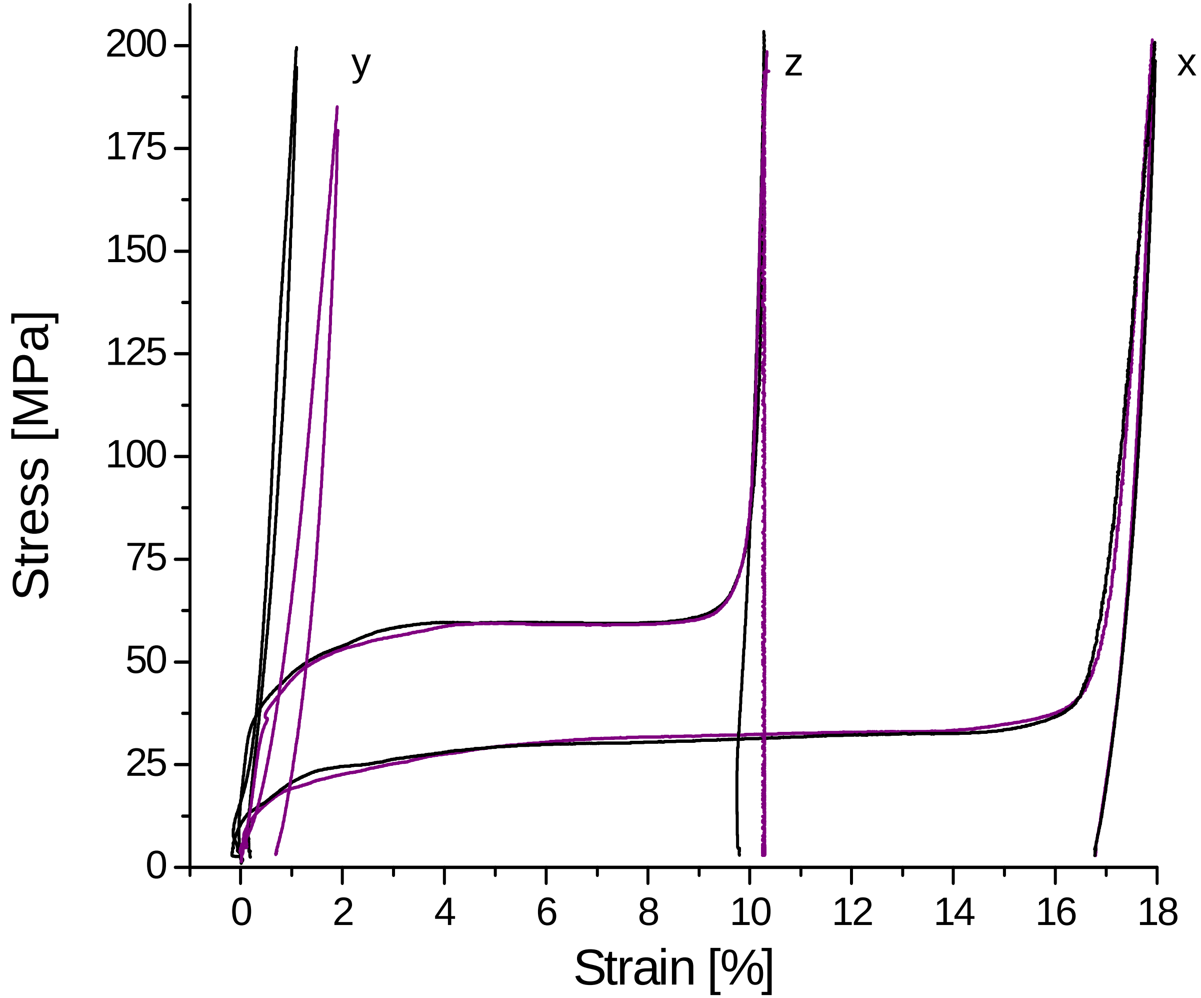
Sequence of loading:

x . z . y

Stress plateau in x direction: **30MPa**

Stress plateau in z direction: **60MPa**

Stress plateau in y direction: **-**



K.Rolfs et al. Acta Mat., 2009

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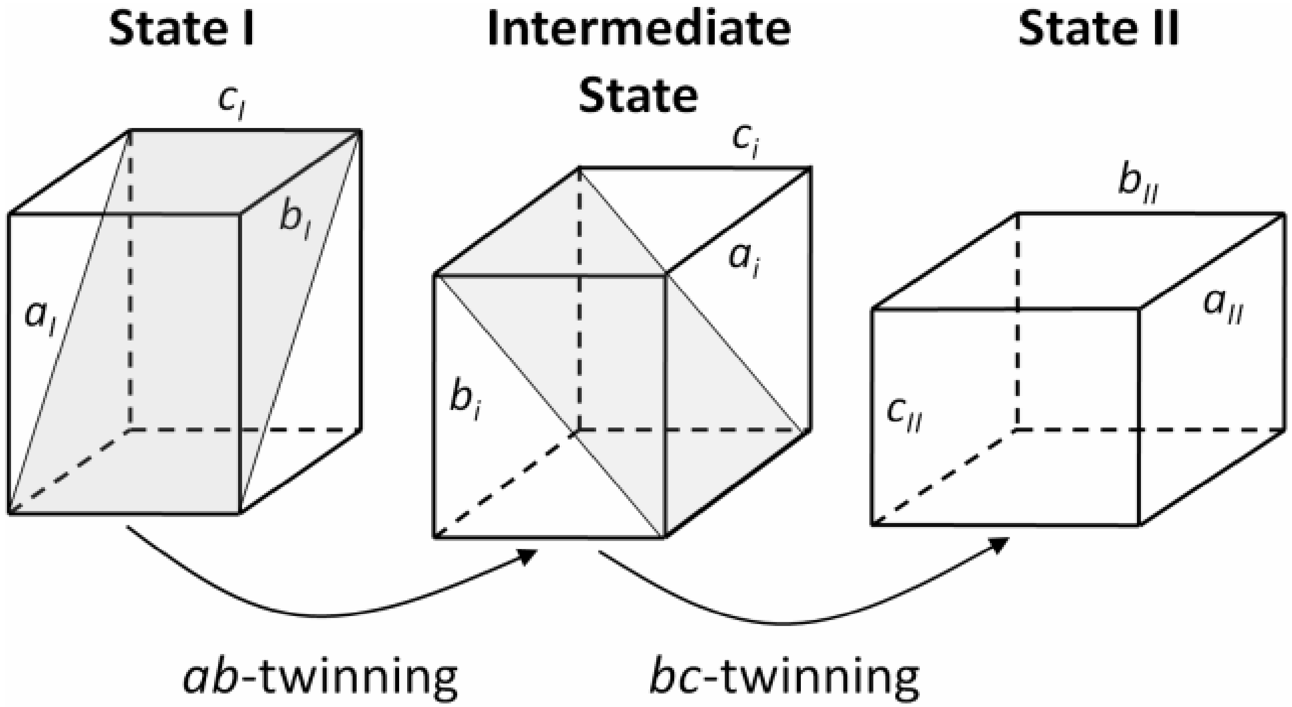
Double Twinning in nonmodulated orthorhombic Martensite

Example

• *ab*-twinning followed by *bc*-twinning

a . b , b . c , c . a



• grey planes indicate twin planes of each twinning event

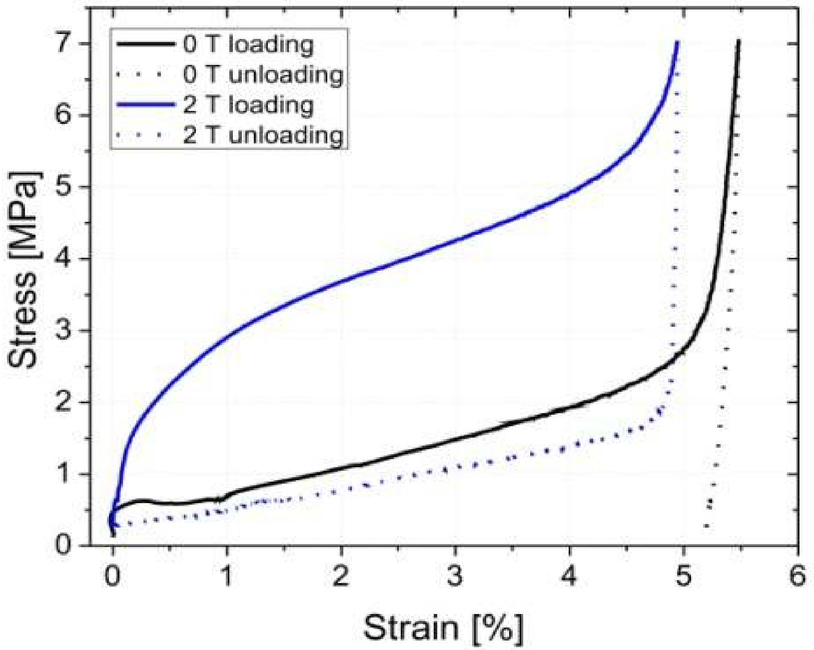
• *ab*-twinning: *a* and *b* axes interchange, *c* axis stays constant

• followed by *bc*-twinning: *b* and *c* axes interchange, *a* axis stays constant

. **crystallographic axes permute cyclically**

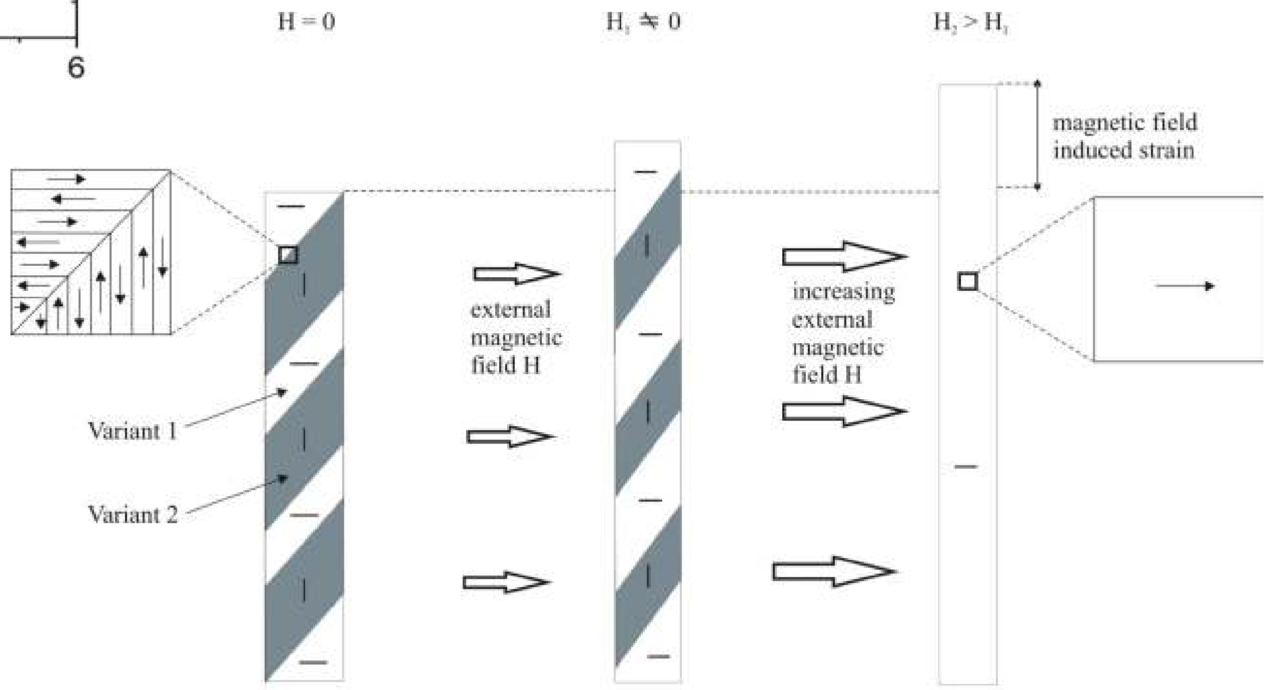
K.Rolfs et al. Acta Mat., 2009

Magnetic field induced strain in modulated tetragonal Martensite



Ni-Mn-Ga alloyed with 0.8% Co

- T_M from 50 °C to 65 °C
- high T_C (100 °C)
- Mechanical induced strain: 5%



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Application in actuators

Acknowledgment

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Thank you for your attention