International Workshop on
Quantum Magnets in Extreme Conditions
2021. 3. 22-26 online

Metastable magnetization plateau states observed in an $S = 1$ two-leg spin ladder by fast sweeping of a magnetic field up to 150 T

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Spin ladder

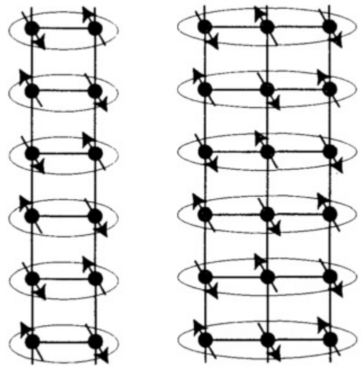
Physics in between 1D and 2D spin systems

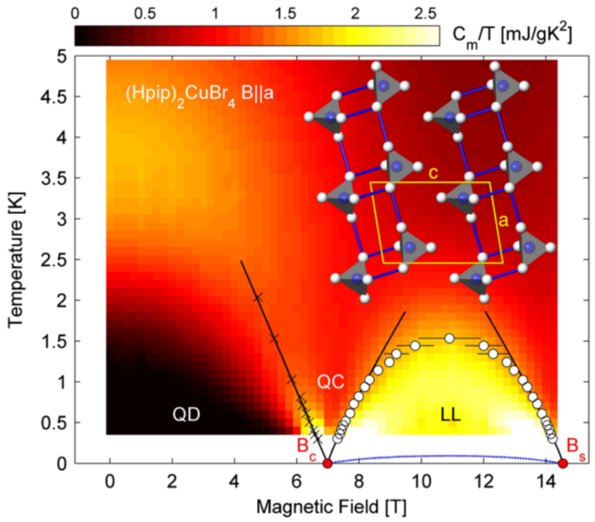
Properties of S = 1/2 AF spin ladder

Legs	Even	Odd
Energy gap	Gap	Gapless
Correlation function	Exponential Decay	Power Decay

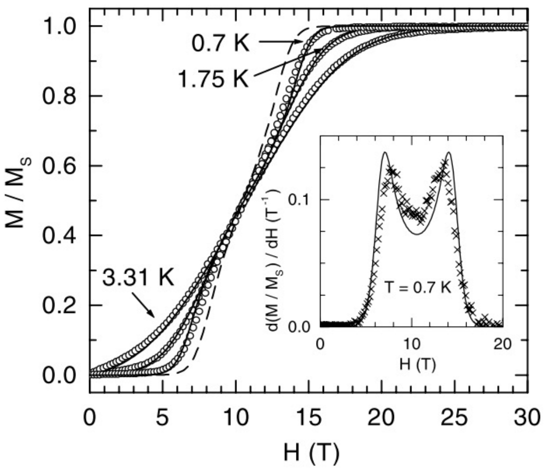
E. Dagotto and T. M. Rice, Science, **271**, 681 (1996).

Even-leg ladder Odd-leg ladder





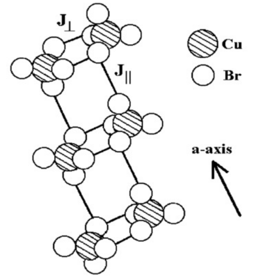
Ch. Ruegg *et al.*, Phys. Rev. Lett. **101**, 247202 (2008)



B. C. Watson, *et al.*, Phys. Rev. Lett **86**, 5168 (2001)

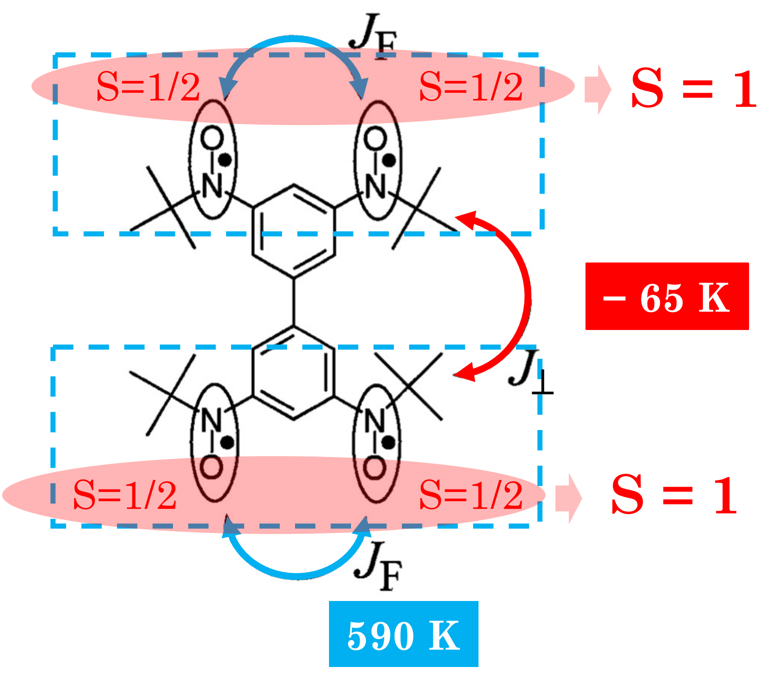
S=1/2 two-leg spin ladder

$(C_5H_{12}N)_2CuBr_4$

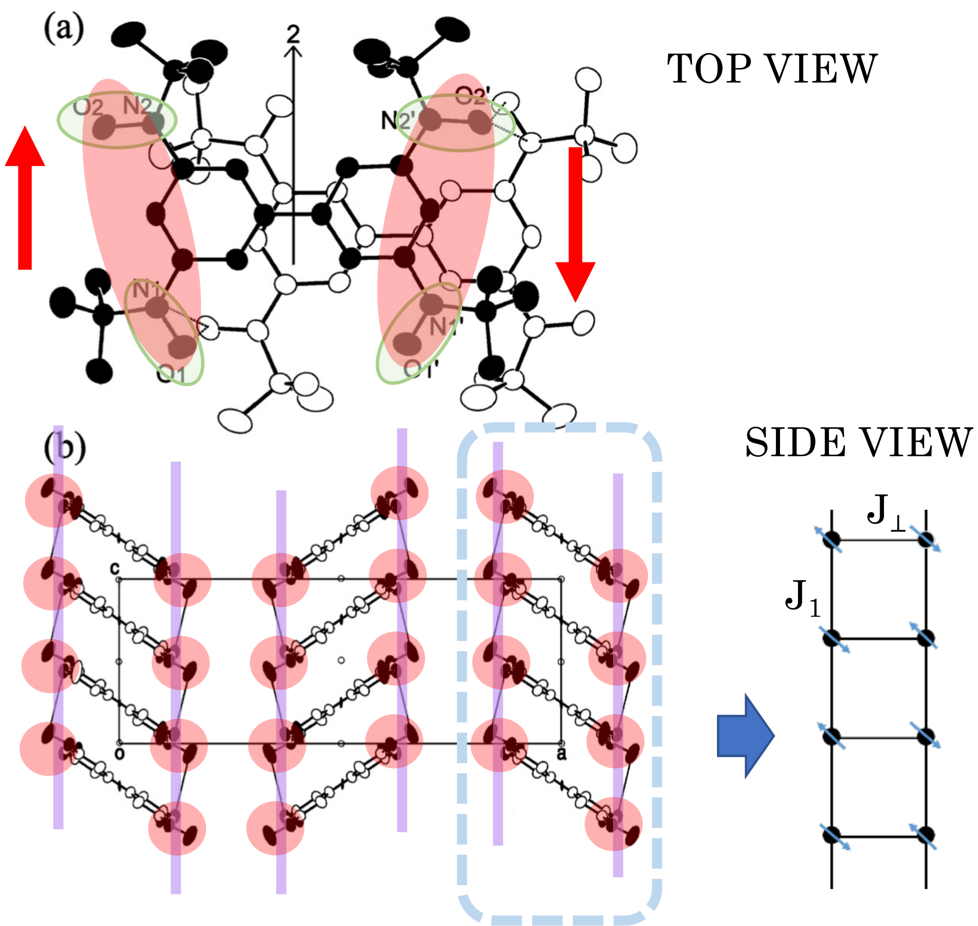


Organic S =1 two-leg spin ladder

BIP-TENO 3, 3’, 5, 5’-tetrakis(*N*- *tert*-butylaminoxyl)biphenyl ($C_{28}H_{42}N_4O_4$)

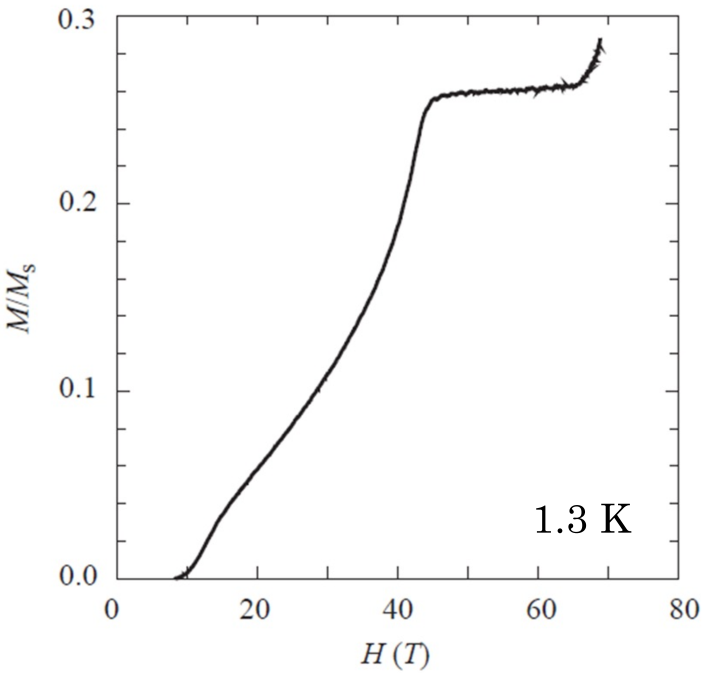


K. Kato *et al.*, J. Phys. Soc. Jpn. **69**, 1008 (2000)

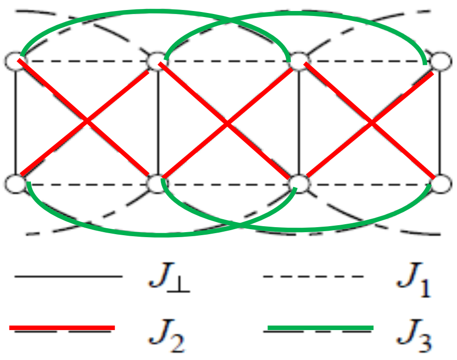


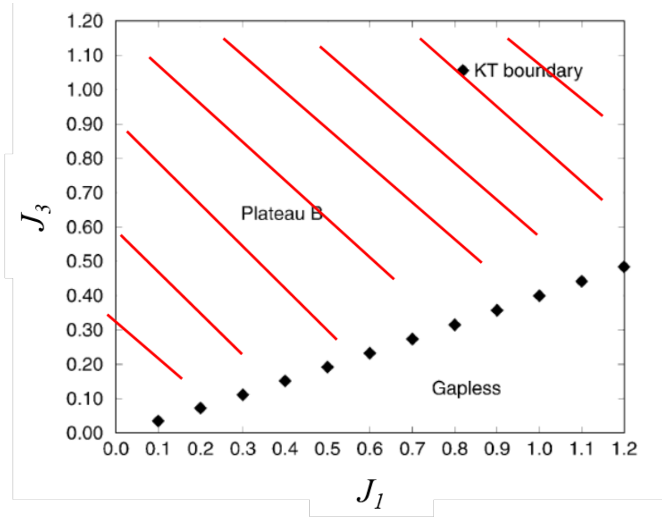
High-magnetic-field magnetization process in BIP-TENO

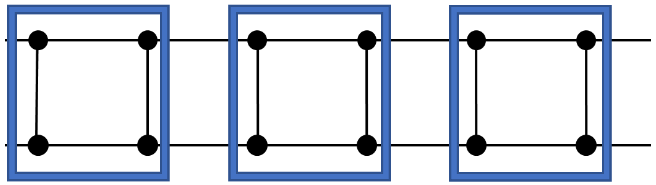
Unusual 1/4 plateau appears

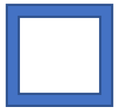


T. Sakai, *et al.*, Physica B **346-347** (2004) 34-37.









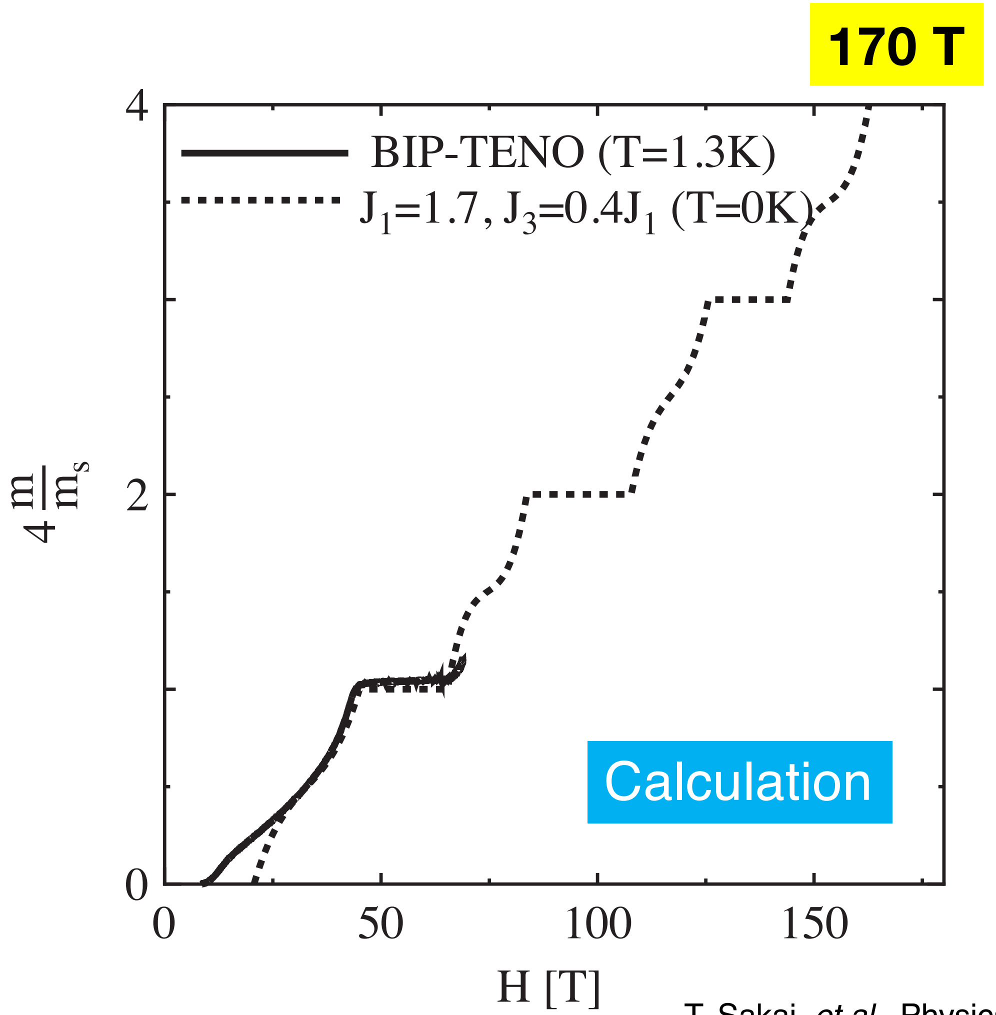
$$= {}^{1}\!/\!{}_{\sqrt{2}}\,(\phi_{0,0}\ \phi_{1,-1} - \phi_{1,-1}\phi_{0,0})$$

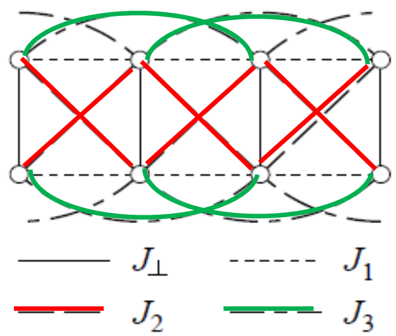
$$S = 1 \quad \phi_{1,-1} = {}^{1}\!/\!{}_{\sqrt{2}}\,(|0\downarrow\rangle - |\downarrow 0\rangle)$$

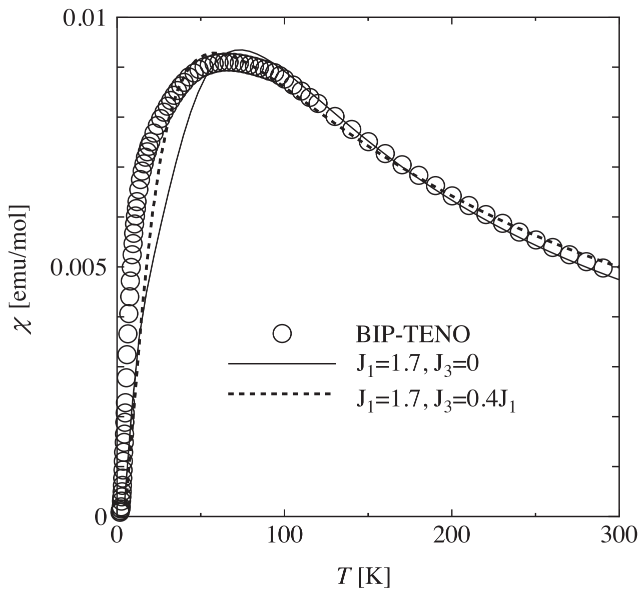
$$S = 0 \quad \phi_{0,0} = {}^{1}\!/\!{}_{\sqrt{3}}\,(|\downarrow\uparrow\rangle - |00\rangle + |\uparrow\downarrow\rangle)$$

K. Okamoto, N. Okazaki, T. Sakai, J. Phys. Soc. Jpn. **70**, 636, 2001

Higher magnetic field magnetization process should be uncovered







T. Sakai, *et al.*, Physica B **329–333** (2003) 1203–1204

Generation of ultrahigh magnetic fields

Non-destructive or Destructive ?

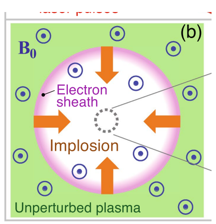
Non-destructive	Destructive
Wire-wound coil (1 mH)	Low-inductance coil (10 nH)
1 ~ 100 **ms**	1 – 100 **μs**
20 -70 T (B_{max} =101 T)	100 – 1000 T
10 kV, 10 mF ; 500 kJ (a middle class capacitor bank)	50 kV, 160 μF ; 200 kJ (single-turn) 50 kV, 4 mF ; 5 MJ (flux compression)

Very long 1-10 s 45 -60 T
generator (210 MJ, 600 MJ)

DC (10 – 45 T) min. – day
30 MW (45 T)

Laser driven methods 1000 T – 1000 kT
ns –fs 0.0001- 100 μm^2

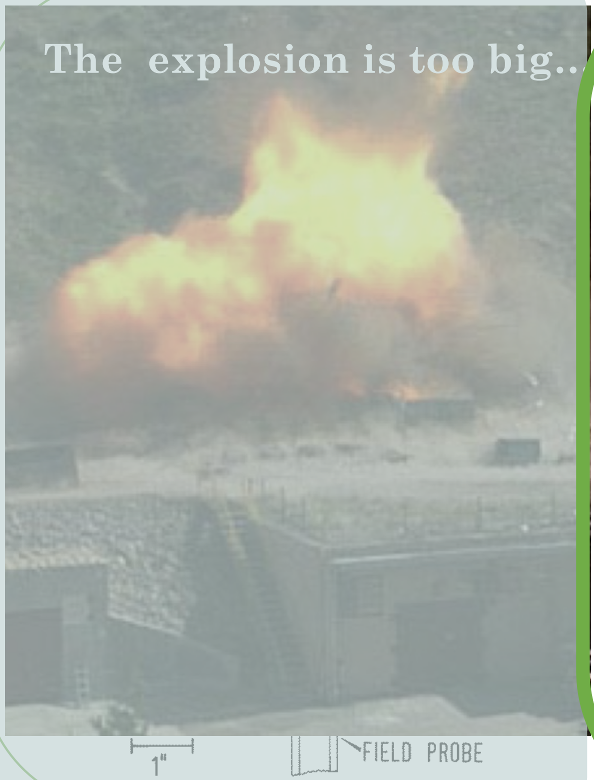
Not suitable for condensed matter physics



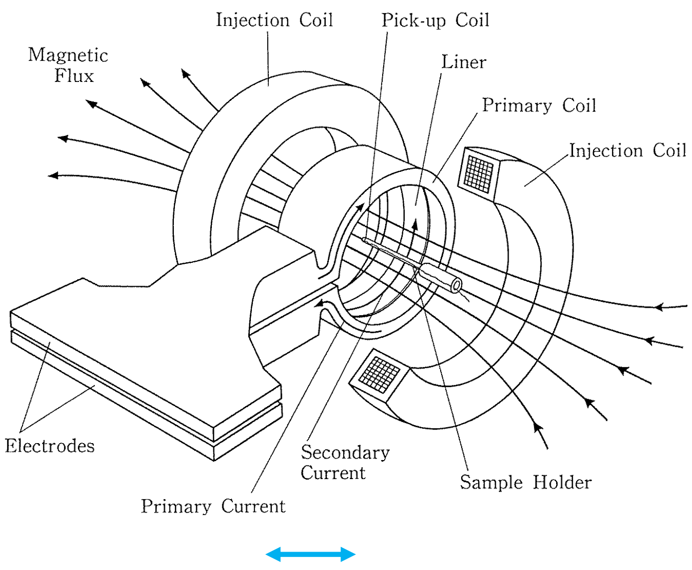
M. Murakami, et al., Sci. Rep. **10**, 16653 (2020)

Destructive means for generation of a strong B exceeding 100 T

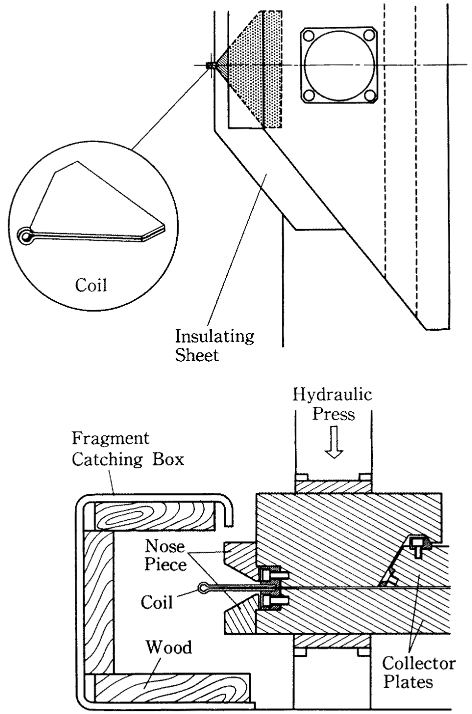
For condensed matter physics



Electromagnetic flux compression (EMFC)

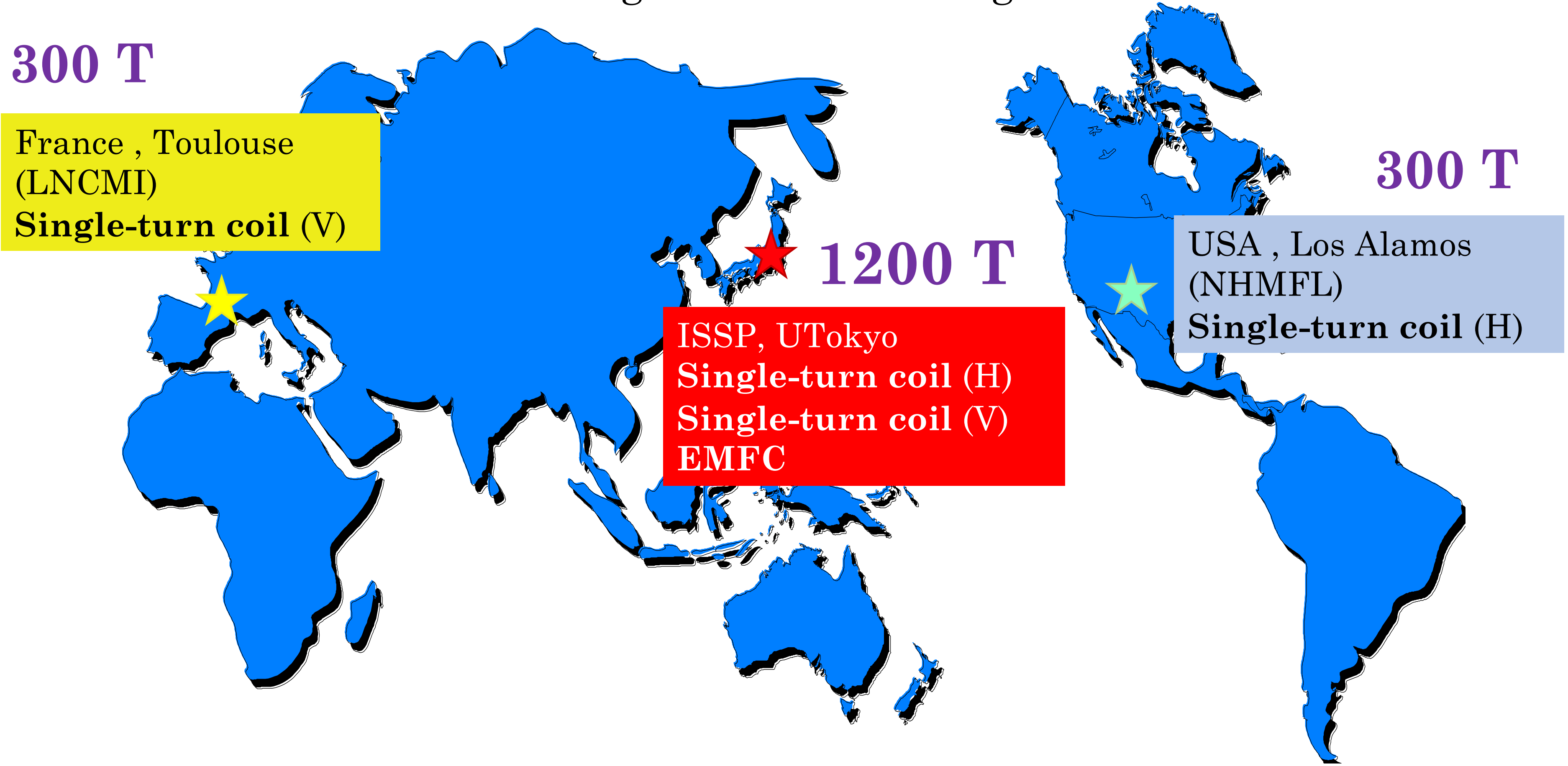


Single-turn coil (STC)

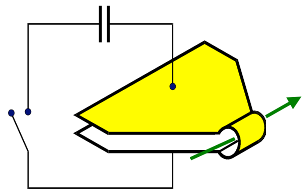


Fritz Herlach, Rep. Prog. Phys. **62** (1999) 859

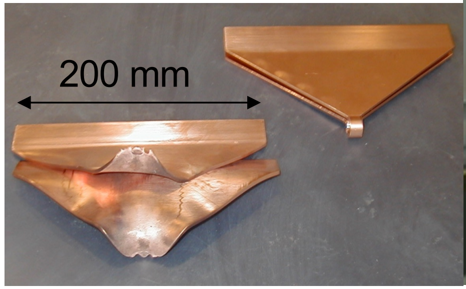
One electromagnetic flux compression system
Four single-turn coil field generators

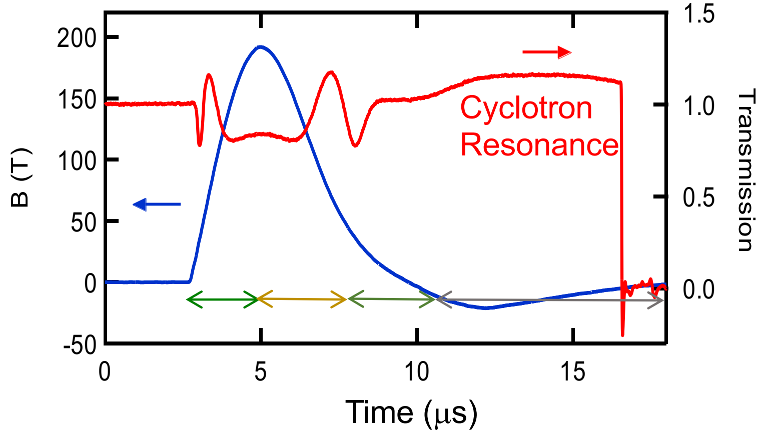


Single-Turn Coil (STC) at ISSP

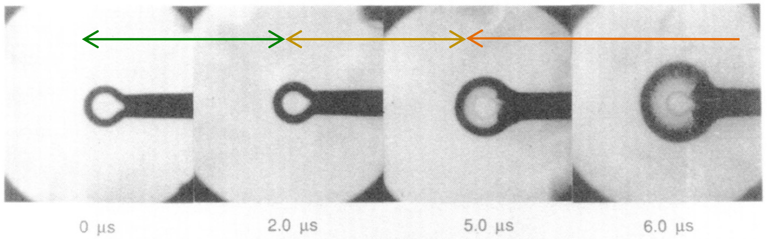


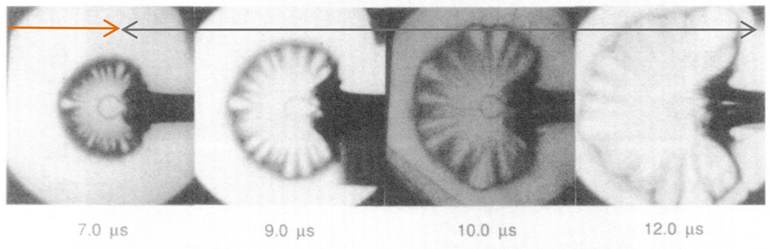
I_{max} = 4MA   160 / 263.5 mF
50 / 40 kV





Relatively compact system
Things inside are intact (only coil is broken)





Magneto-optical spectroscopies
Magnetization
Electrical transport
Magnetostriction
Sound velocity

The Electromagnetic Flux Compression (EMFC)

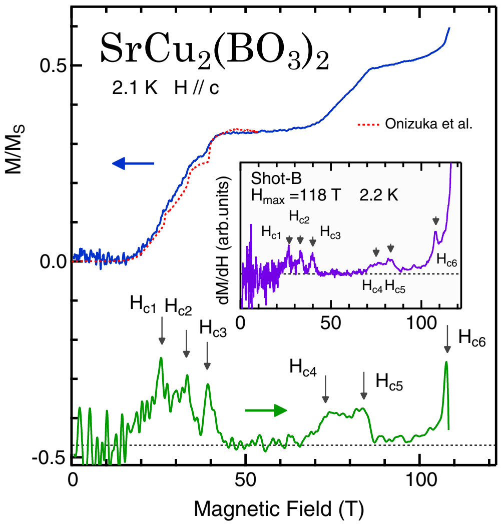
Indoor Strongest Magnetic Field Worldwide

$$B_{\max} \sim \text{Flux (Seed Coil)} \times \frac{\text{Initial diameter (Liner)}}{\text{Final diameter (Liner)}}$$

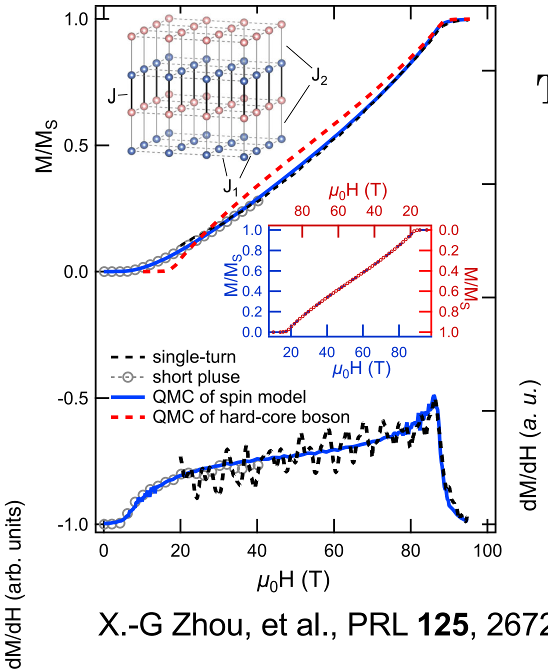
1200 T !!

D. Nakamura et al., Rev. Sci. Instrum. **89**, 095106 (2018)

Magnetization

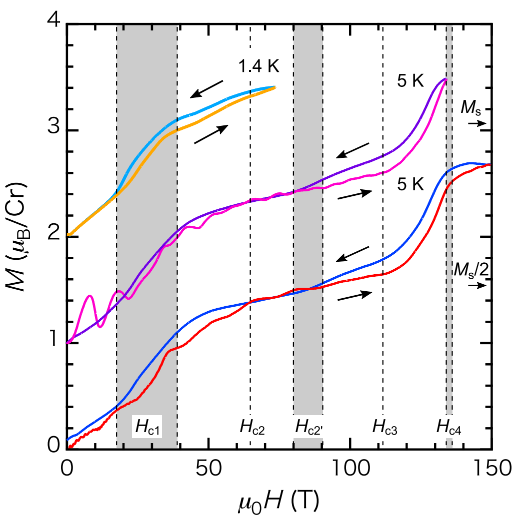


Y. H. Matsuda, et al.,
PRL **111**, 137204 (2013)



$TlCuCl_3$

X.-G Zhou, et al., PRL **125**, 267207 (2020)

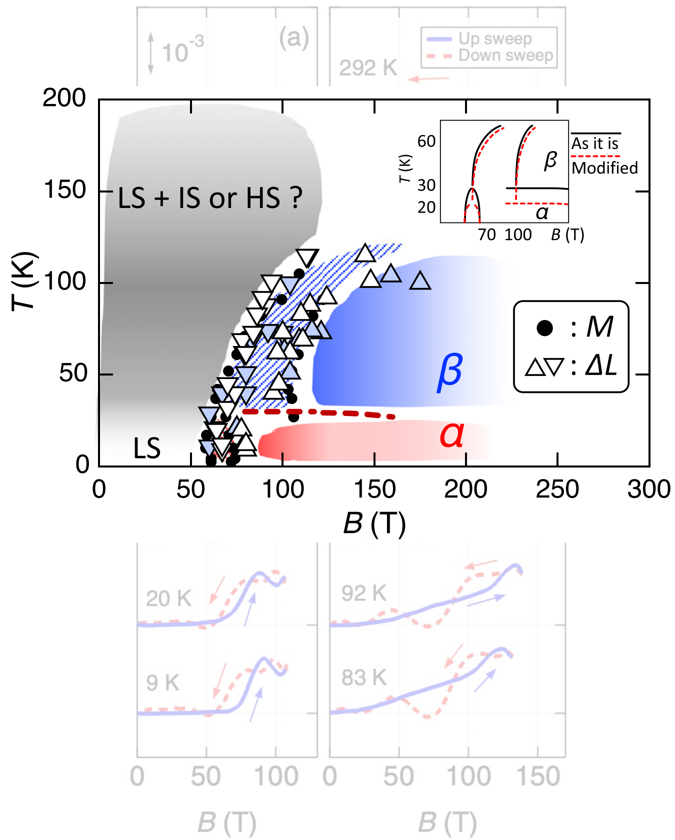


$CuInCr_4S_8$

M. Gen, et al.,
PRB **101**, 054434 (2020)

Magnetostriction

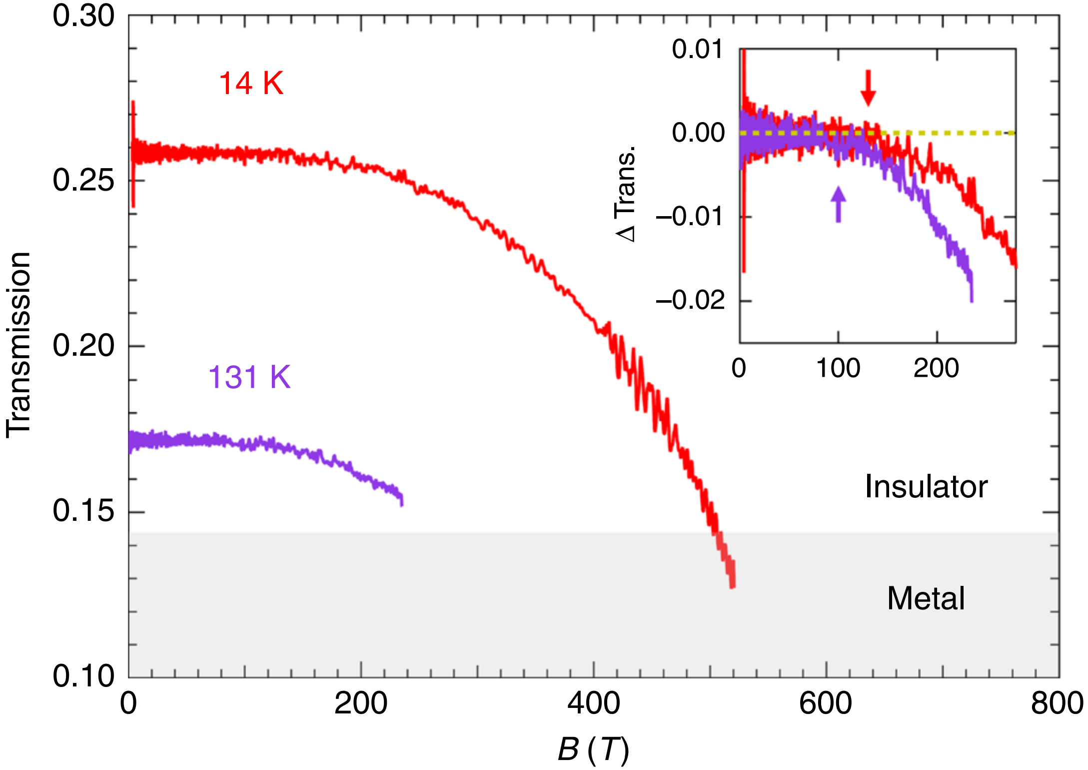
$LaCoO_3$



A. Ikeda, et al.,
PRL **125**, 177202 (2020)

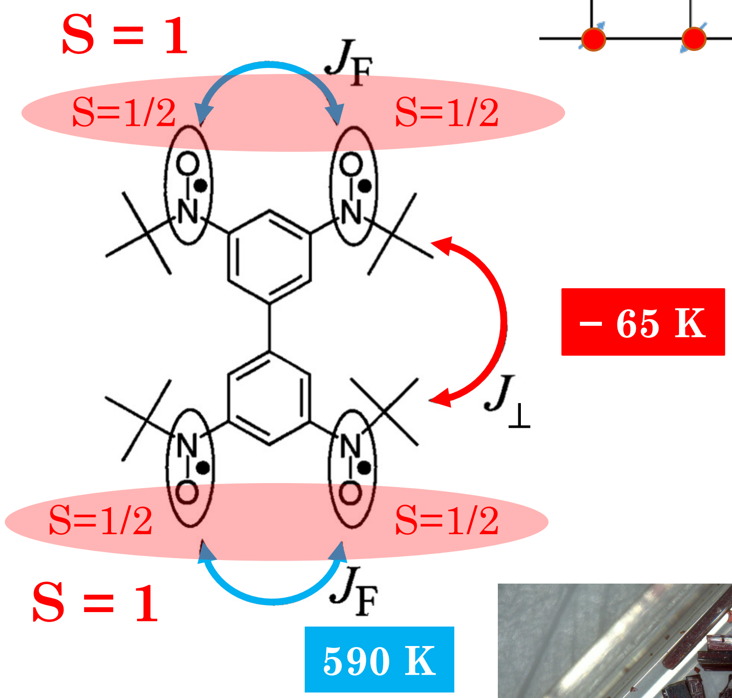
Insulator-metal transition

$V_{0.94}W_{0.06}O_2$

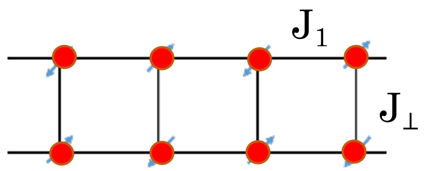


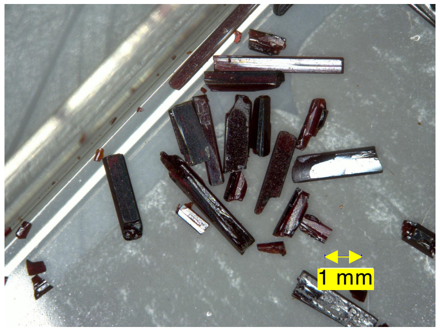
Y. H. Matsuda et al,
Nat. Commun. **11**, 3591 (2020)

BIP-TENO



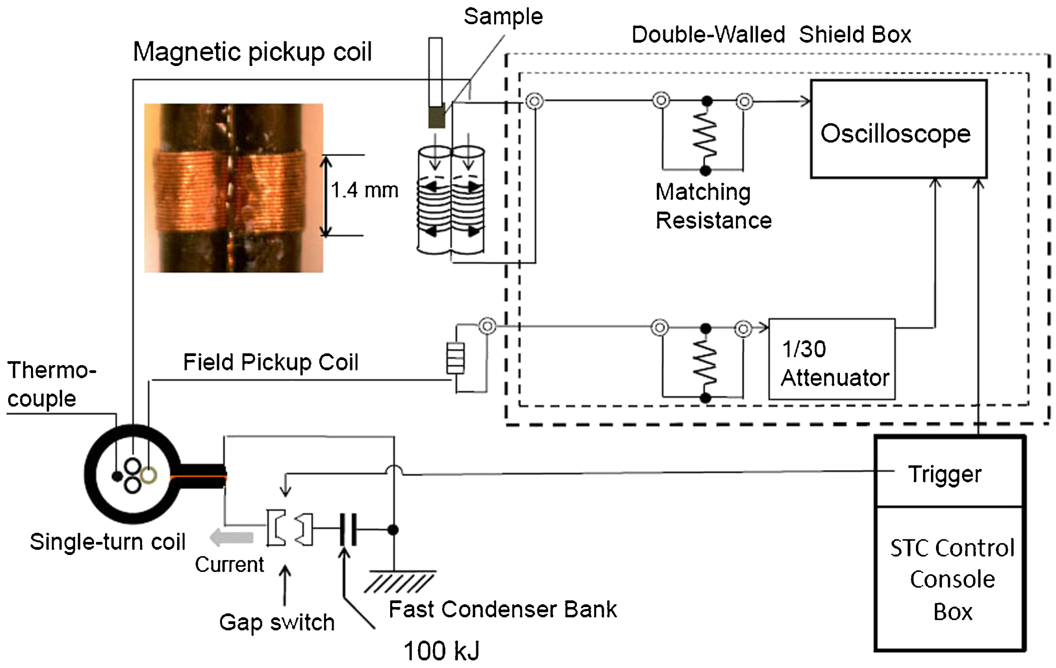
S =1





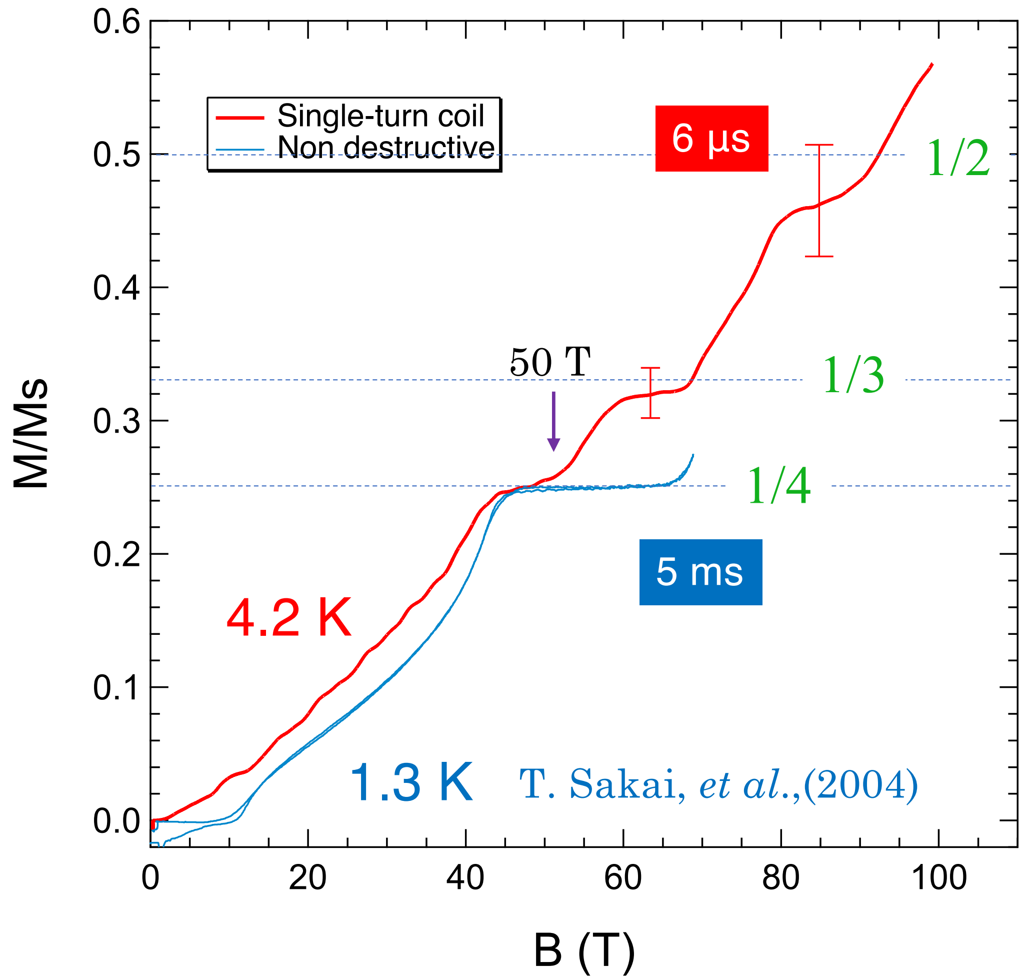
Magnetization measurement

$$\frac{dM}{dt} \propto \frac{d\{(B_1 + M)A_1\}}{dt} - \frac{d\{(B_2)A_2\}}{dt} \quad : \quad B_1A_1 \approx B_2A_2$$



S. Takeyama, et al., J. Phys. Soc. Jpn. **81**, 014702 (2012)

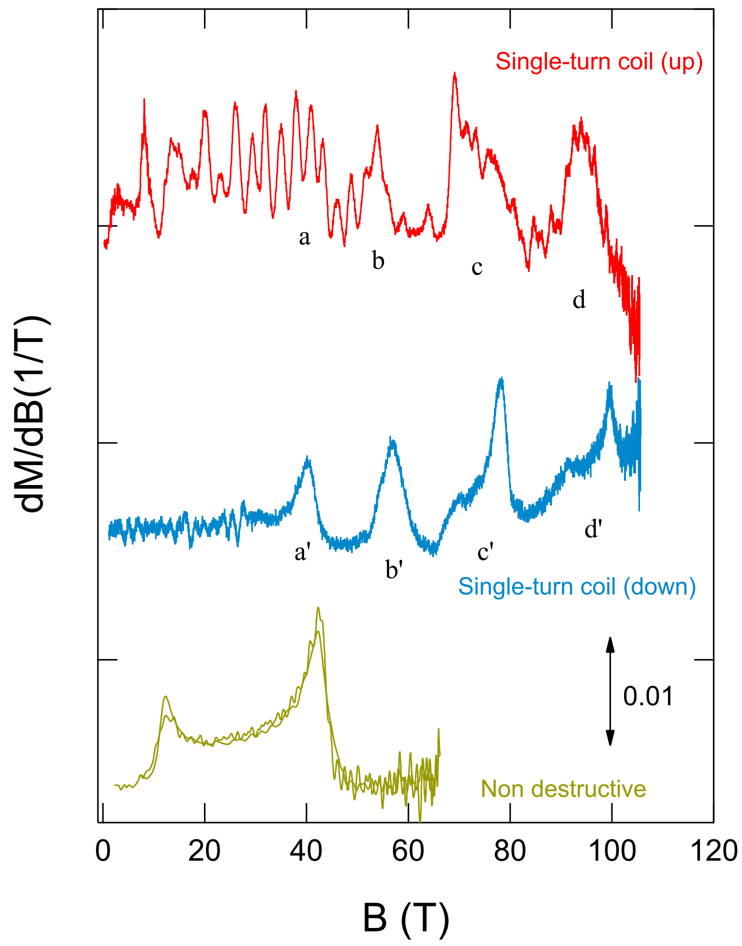
Magnetization curve measured up to 100 T



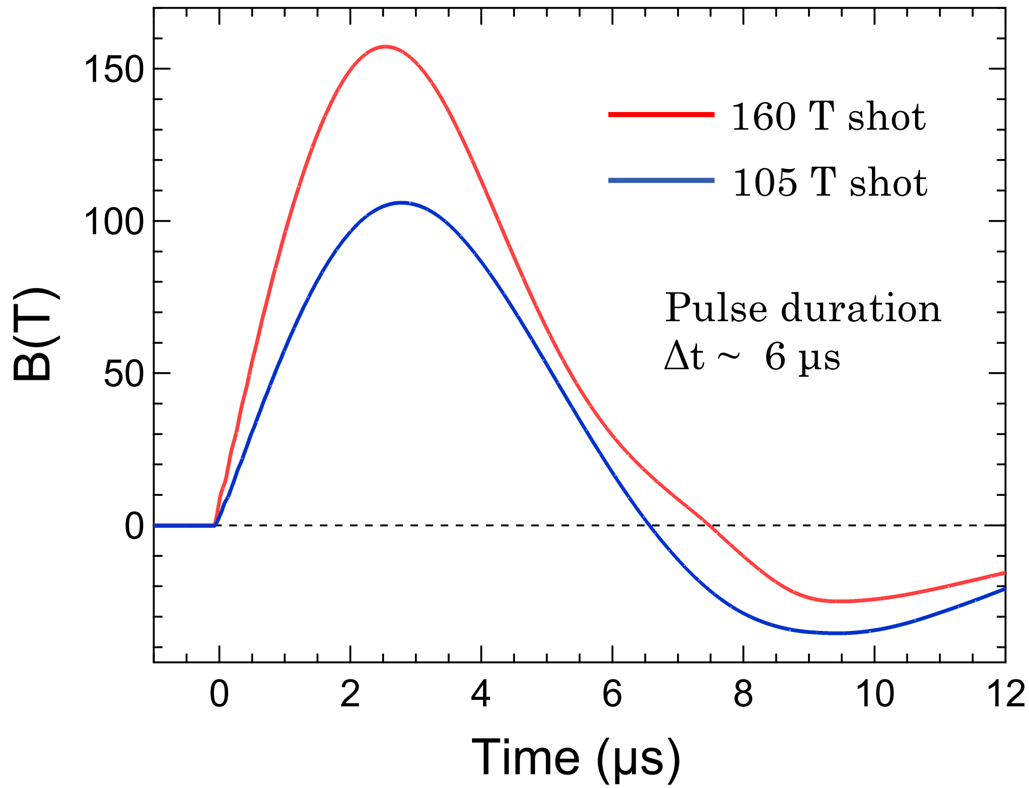
1/4 plateau is terminated at around 50 T.

1/3 and 1/2 plateaus are possibly observed at around 60 T and 85 T.

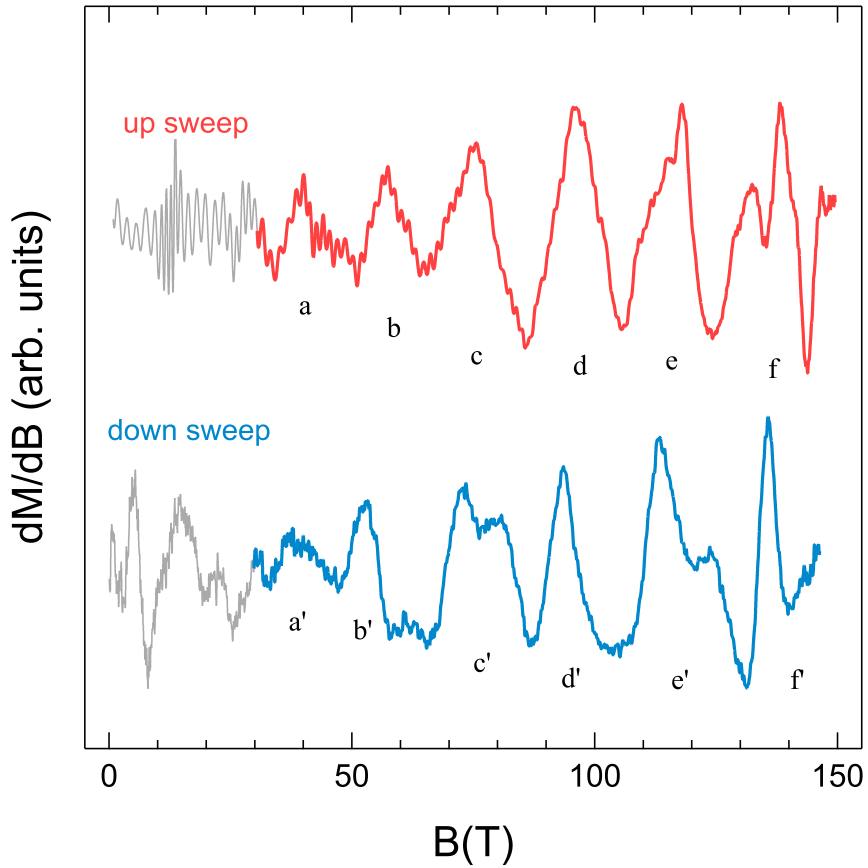
Raw data of d*M*/d*B*

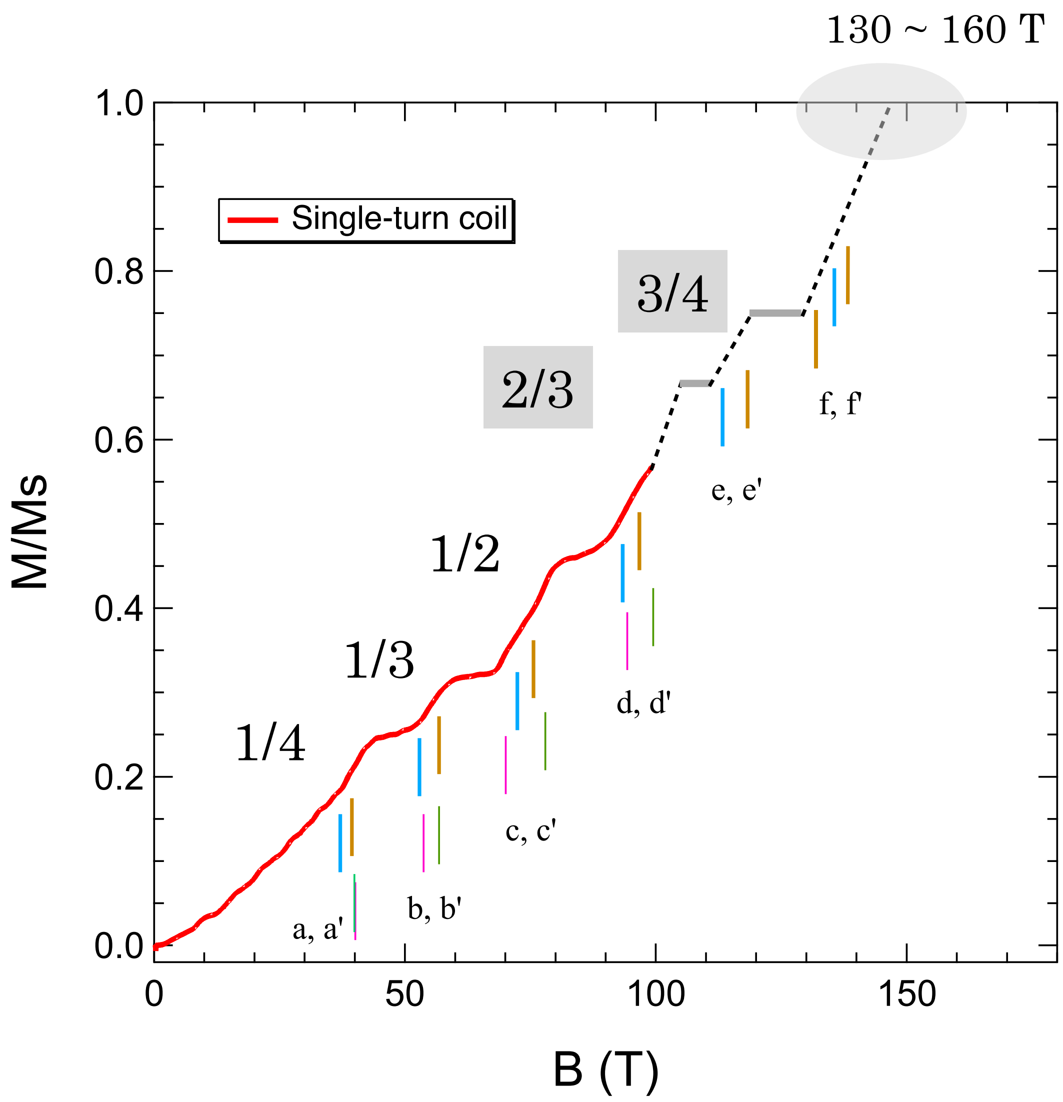


Time profile of the magnetic field

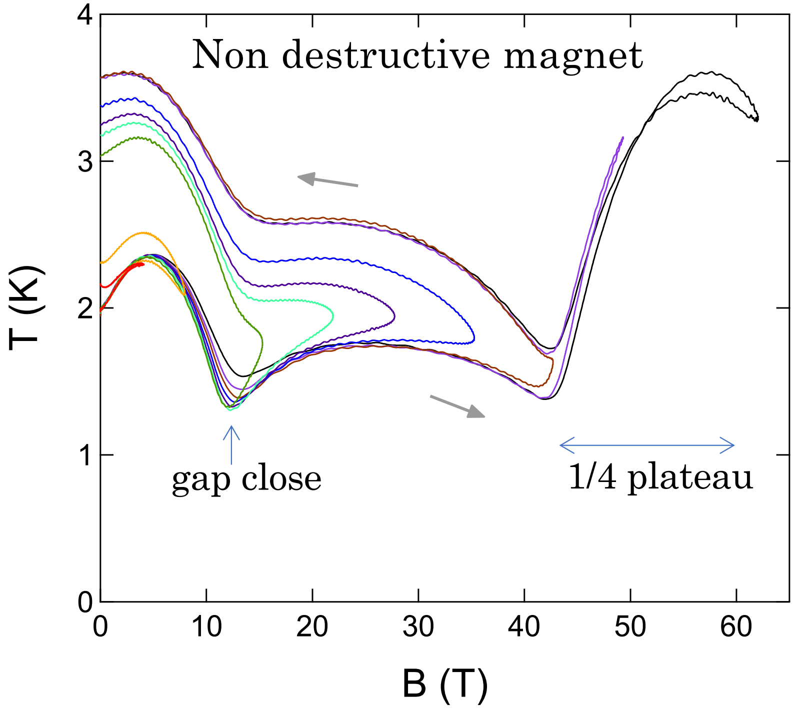


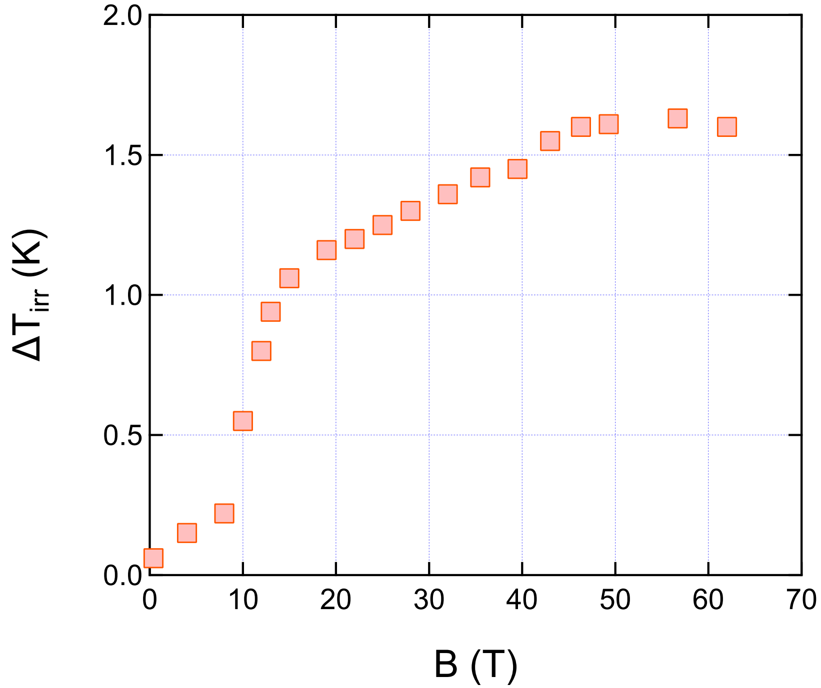
Non destructive coil (short pulse) : Δt ~ 5 ms dM/dB peaks observed in the 160 T-magnetic field





Magnetocaloric Effect (MCE) ?





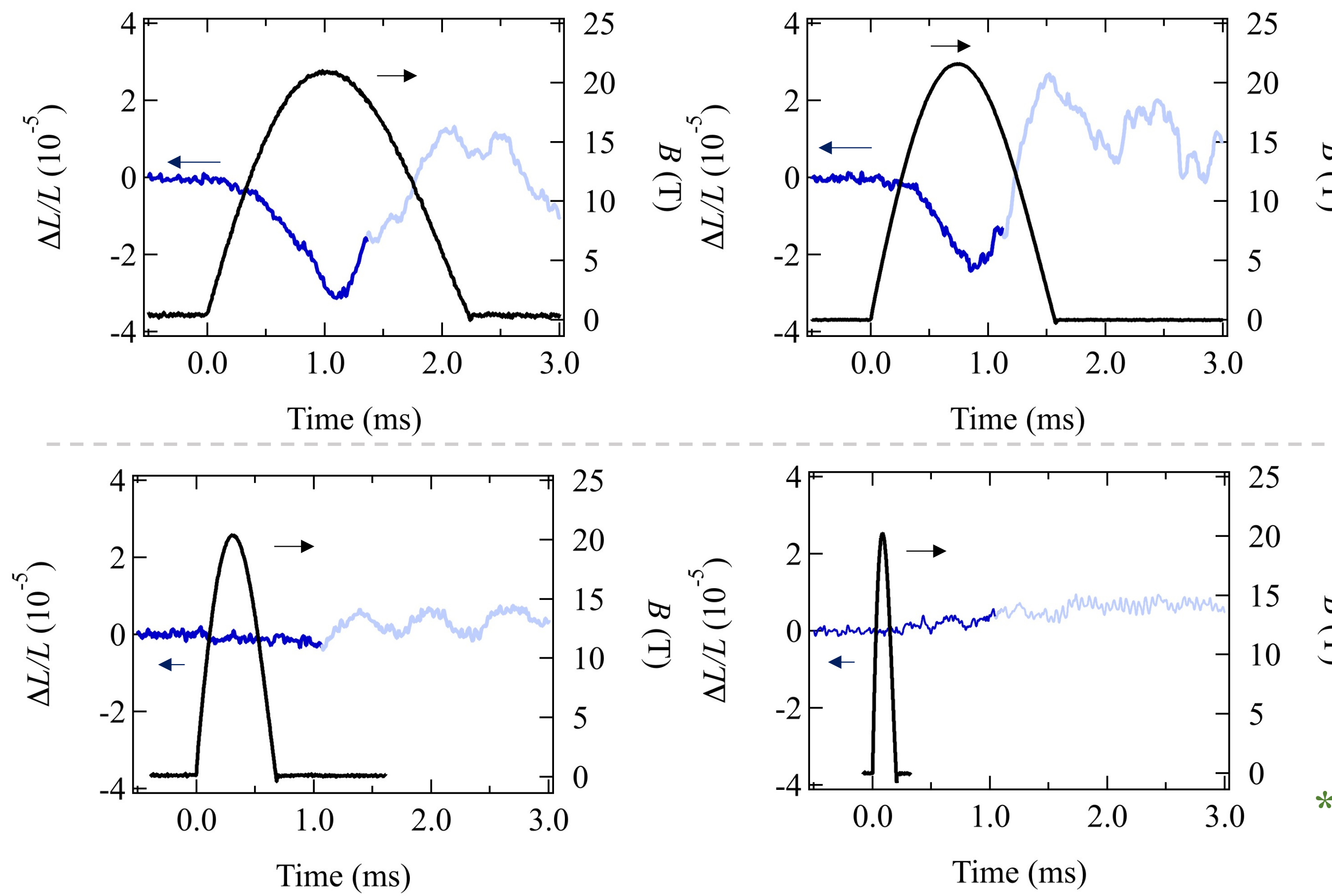
Adiabatic condition (6 μs) can make temperature lower.

However, we have no indication of any phase boundaries at around 50 T.

Irreversible heating becomes large after the gap closes. (B > 10 T)

Magnetostriction ??

Magnetostriction can be an origin for the discrepancy between the magnetization curves in different-pulse-duration magnetic fields



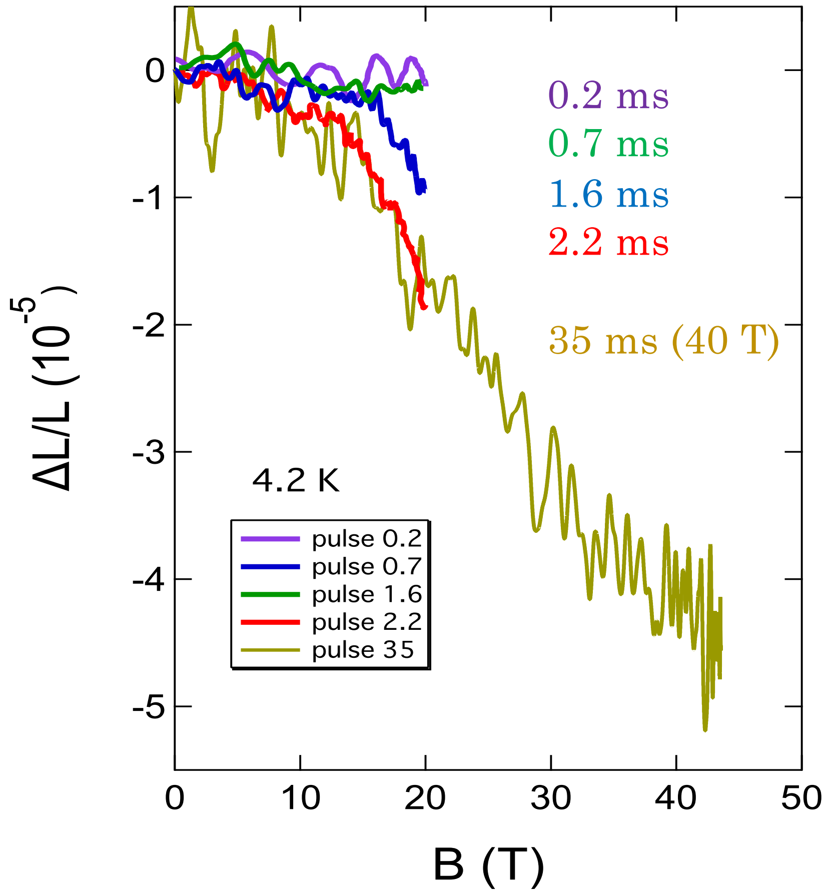
Fiber Bragg Grating (FBG) was used as a strain-gauge

Long pulse (> 1 ms)

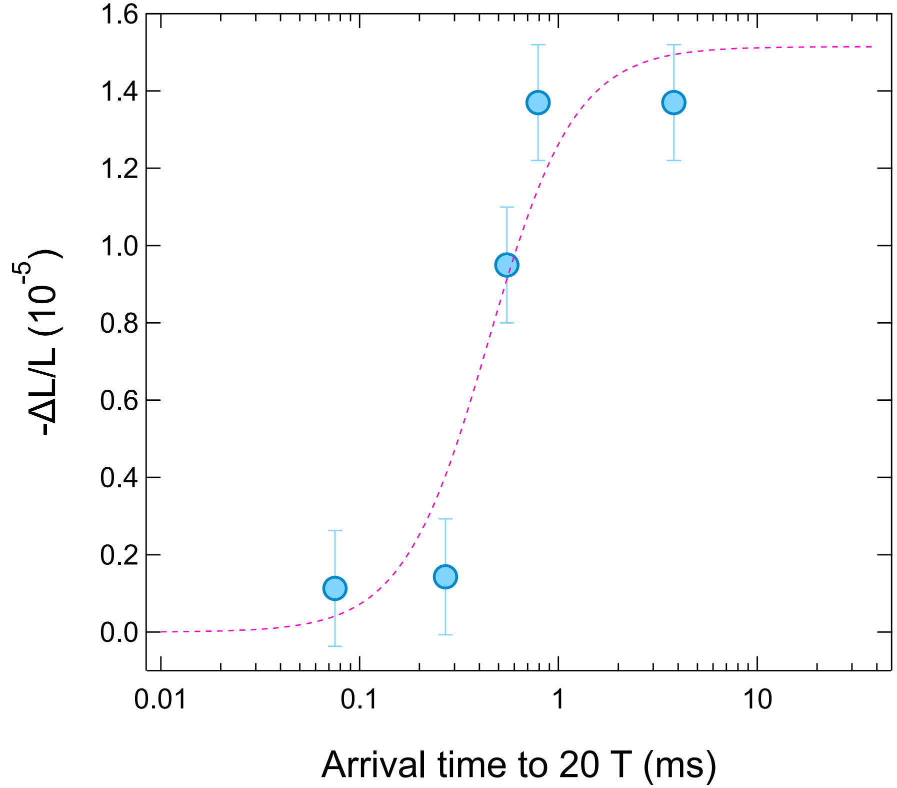
Short pulse (< 1 ms)

* ***B*** // leg direction // striction direction

Magnetostriction of BIP-TENO

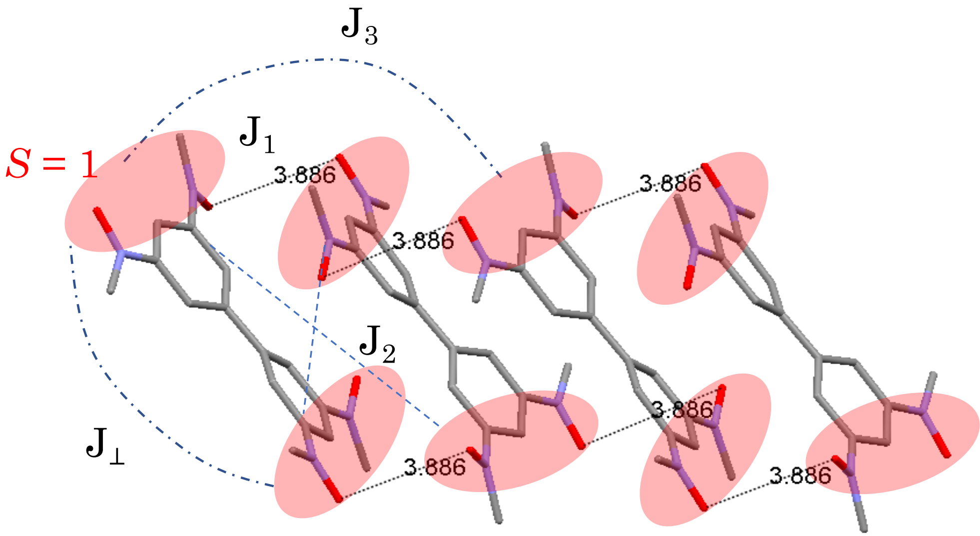


Magnetostriction at 20 T with different speed of the magnetic field



Characteristic time is ~ 0.5 ms

Molecular arrangement of BIP-TENO



N. Hasegawa
Master thesis (Osaka Pref. Univ. 2011)

The biphenyl torsion angle may change through the magnetic interactions when magnetic field is applied.

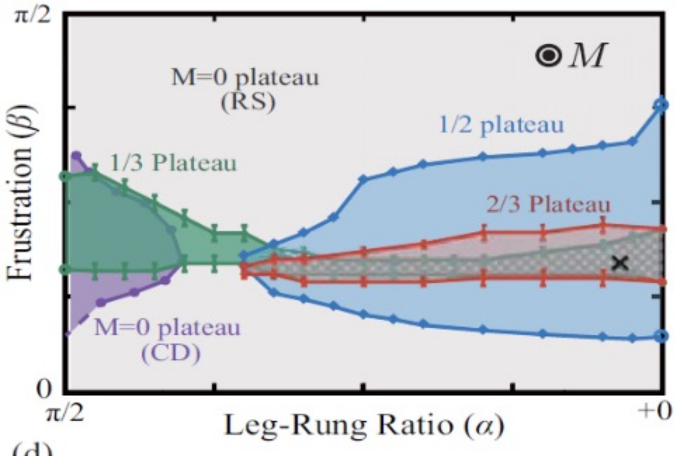
Exchange striction can occur.

➡ Can stabilize the 1/4 plateau

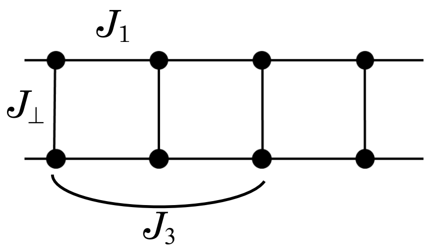
Symmetry breaking with nontrivial periodicity

S=1/2

Renormalization-group method



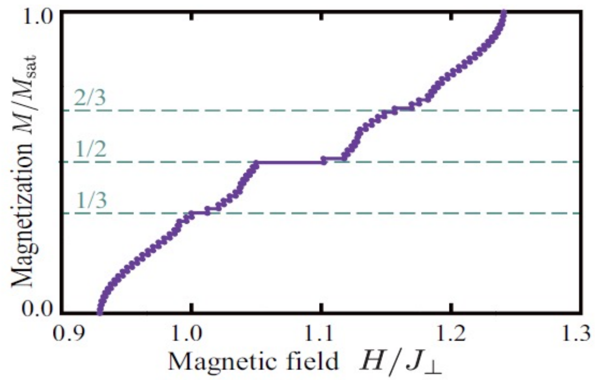
$\alpha = \tan^{-1}(J/J_{\perp})$ $\beta = \tan^{-1}(J_2/J_1)$



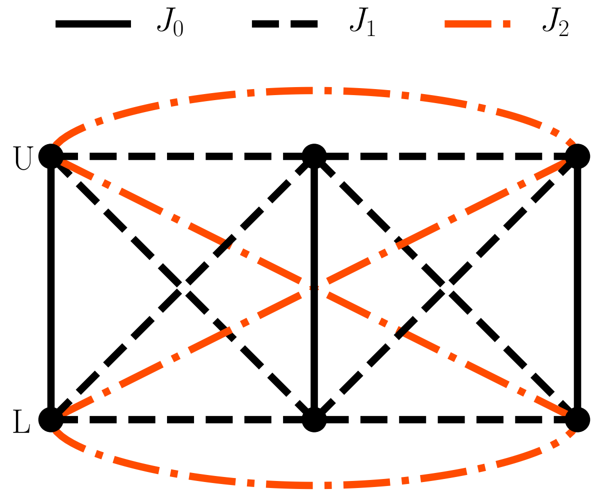
$J_{\perp} = 1$

$J_1 = 0.1$

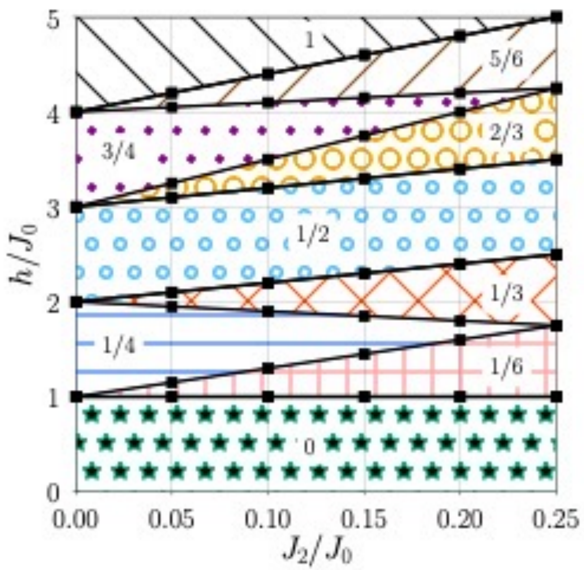
$J_3 = 0.06$



T. Sugimoto, *et al.*, Phys. Rev. B, **92**, 125114 (2015).

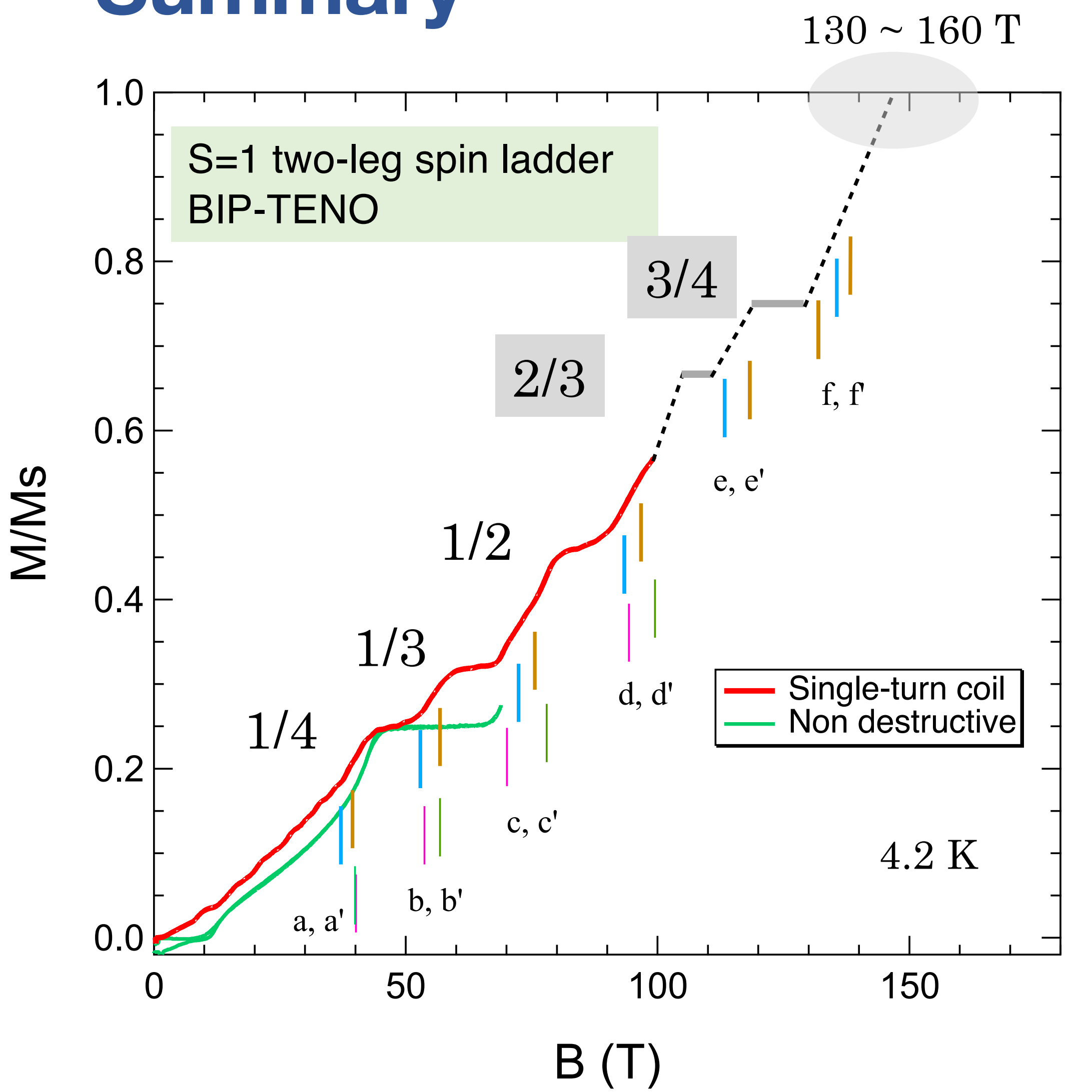


S=1



H. Kohshiro, *et al.*, arXiv 2102.07473 (2021).

Summary



1. The novel 1/3 plateau is found to only appear when B is swept in µs time scale.

2. In a slow B sweep, 1/4 plateau (green curve) is stabilized probably due to the contraction of the lattice.

3. The measured intriguing magnetization process (red one) is due to metastable quantum phases with spin-lattice separation.

4. The characteristic time scale for the lattice deformation would approximately be 0.5 ms.