# Current induced switching of an antiferromagnet

Peter Wadley

***Univ. of Nottingham United Kingdom*** (P Wadley, K Edmonds, R Campion, B Gallagher *et al.*)

***Inst. of Physics ASCR Prague, Czech Republic***
(T Jungwirth, V Novak, K Olejnik, X.Marti, V. Schuler)

***Institute of Physics, Warsaw, Poland***
(M Grzybowski, M Sawicki, T Dietl)

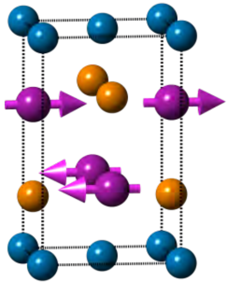
***Hitachi Cambridge Lab. United Kingdom*** (J Wunderlich, P. Roy)

***Diamond Light Source, United Kingdom*** (S Dhesi, F Maccherozzi)

***Univ. of Mainz, Forschungs-zentrum Julich, Germany*** (J Sinova, H Gomonay, F Freimuth

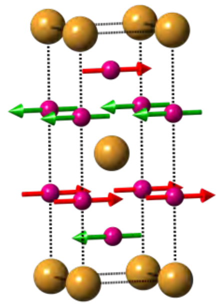
The University of Nottingham

School of Physics & Astronomy



# Outline

- Motivation
- Spintronics with antiferromagnets
- CuMnAs system
- Current induced switching of the spin axis
- Imaging of domain structure
- Imaging the switching
- Conclusions and outlook



# Motivation

- Wide range of antiferromagnetic systems :
  oxides, semiconductors, semimetals, half metals, metals etc

- Some spin-orbit based magnetotransport effects are equally strong in AF systems (AMR, TAMR…..) (Shick *et al Phys. Rev. B 81, 212409 (2010)*) demonstration (Marti, PW *et al* Nat. Mat. (‘14), Park *et al*. Nature Mat. ’11, PRL ’12), Wang *et al*. PRL ’12:)

- No stray fringing fields. Robust against external magnetic fields (like charge based memory) and against radiation (like magnetic memory)

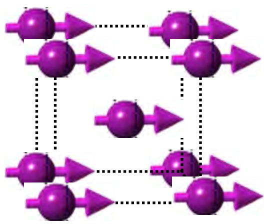
- Ultrafast dynamics (*Kimel,Rasing et al Nature ‘04, P. Roy, Wunderlich PRB 16, Gomonay, Jungwirth, Sinova PRL 16)*

- Topologically interesting systems : predictions of magnetically switchable Dirac semimetals (L. Smejkal-Thursday morning) and AF skyrmionic compounds

# Spintronics with antiferromagnets

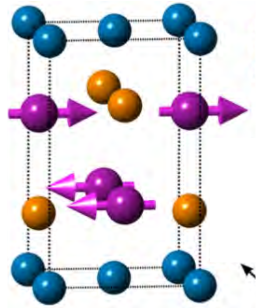
**Ferromagnet (FM):**

**global** uniform molecular field



**Antiferromagnet (AF):**

**local** alternating molecular field



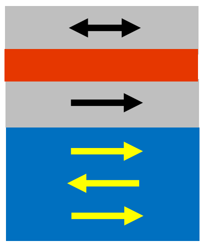
*Nobel Lecture, December 11, 1970*

LOUIS NÉEL

**“Interesting, but without application”**

**Exchange bias**

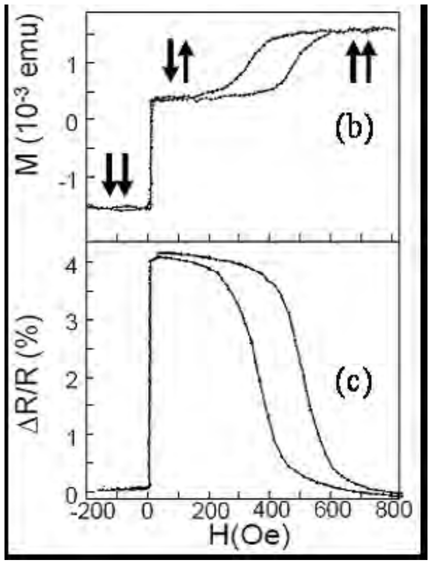
spin valve

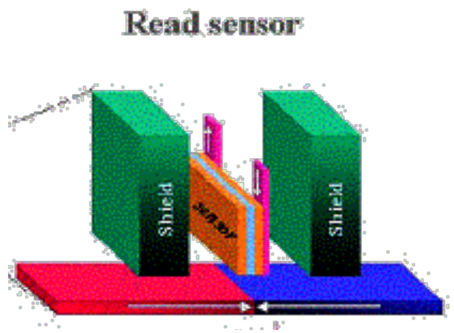


free FM

pinned FM

AF

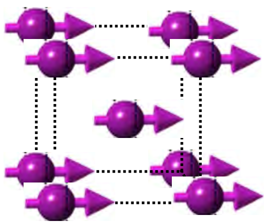


# Spintronics with antiferromagnets

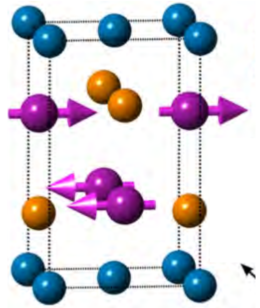
**Ferromagnet (FM):**

**global** uniform
molecular field



**Antiferromagnet (AF):**

**local** alternating
molecular field



*Nobel Lecture, December 11, 1970*

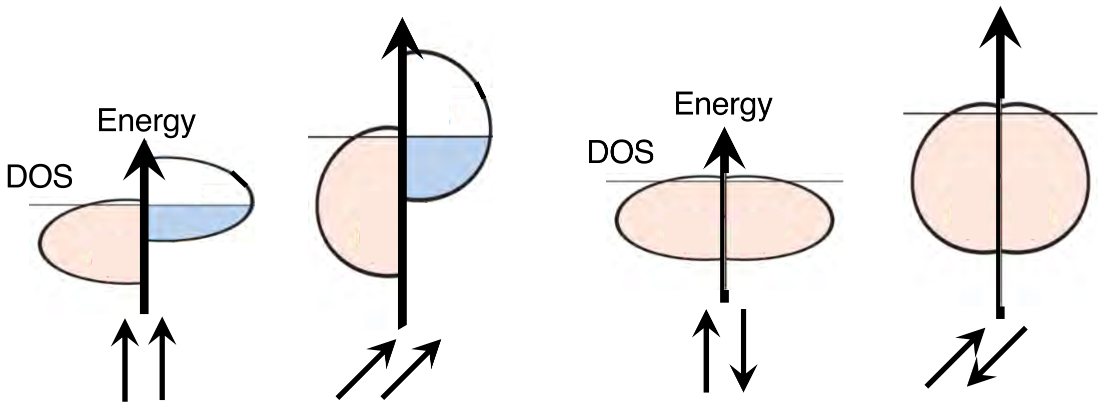
LOUIS NÉEL

**"Interesting, but without application"**

Effects even in magnetization should be equally present in FM and AF

Example:

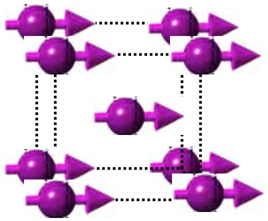
Magnetic anisotropy energy due to coupling between spin and lattice orbitals ⟶ **magnetic memory**



# Spintronics with antiferromagnets

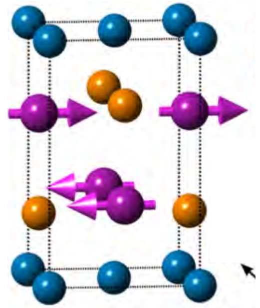
**Ferromagnet (FM):**

**global** uniform molecular field



**Antiferromagnet (AF):**

**local** alternating molecular field



*Nobel Lecture, December 11, 1970*

LOUIS NÉEL

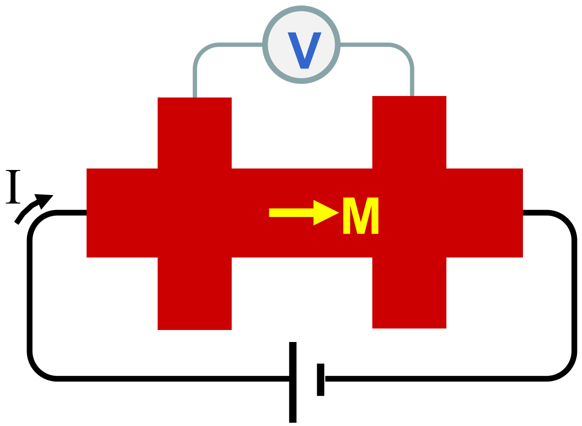
**"Interesting, but without application"**

Effects even in magnetization should be equally present in FM and AF

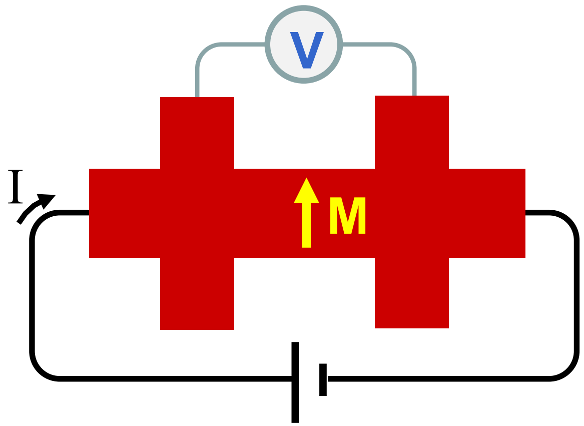
To make them more widely applicable we need the ability to efficiently control and measure the spin state…

# Reading the antiferromagnetic state:
# **Anisotropic Magnetoresistance (AMR)**

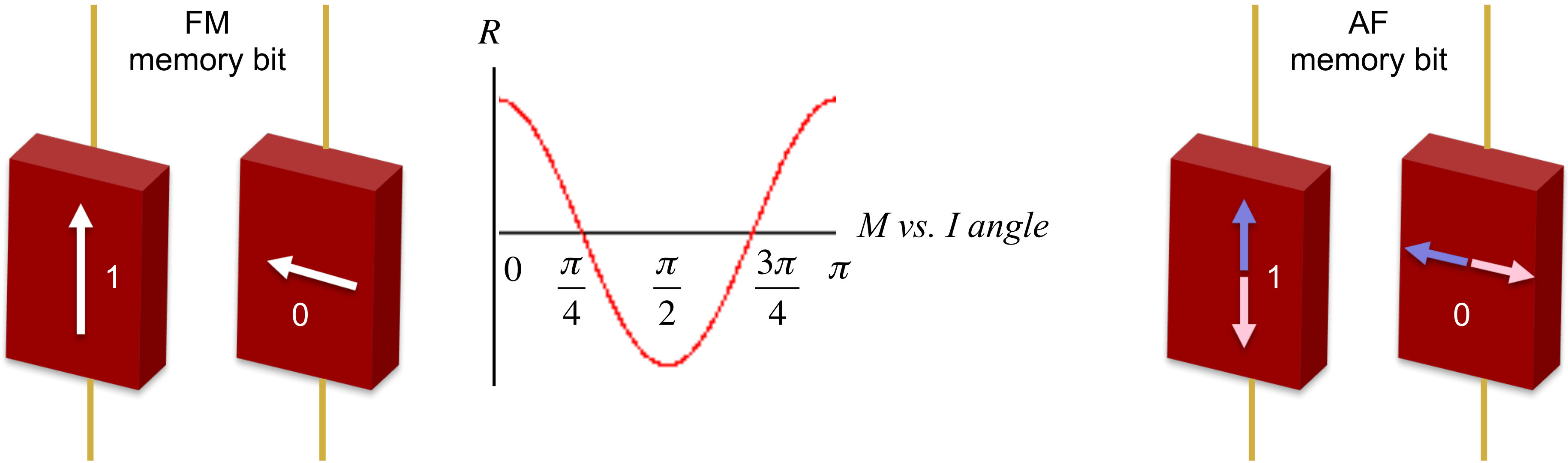
W Thomson , Proc. Roy. Soc. (1856)



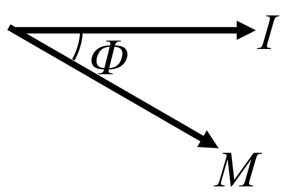

**high resistance state**

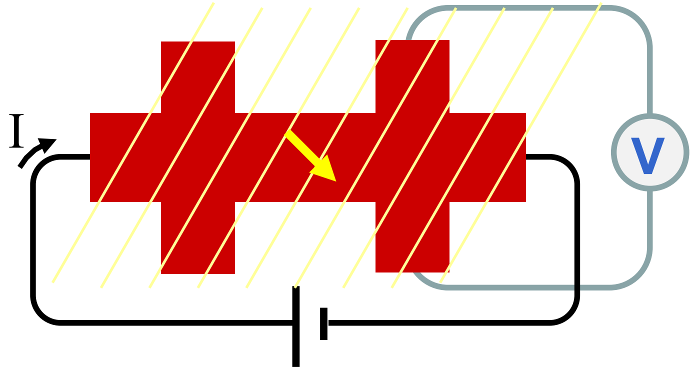



**low resistance state**



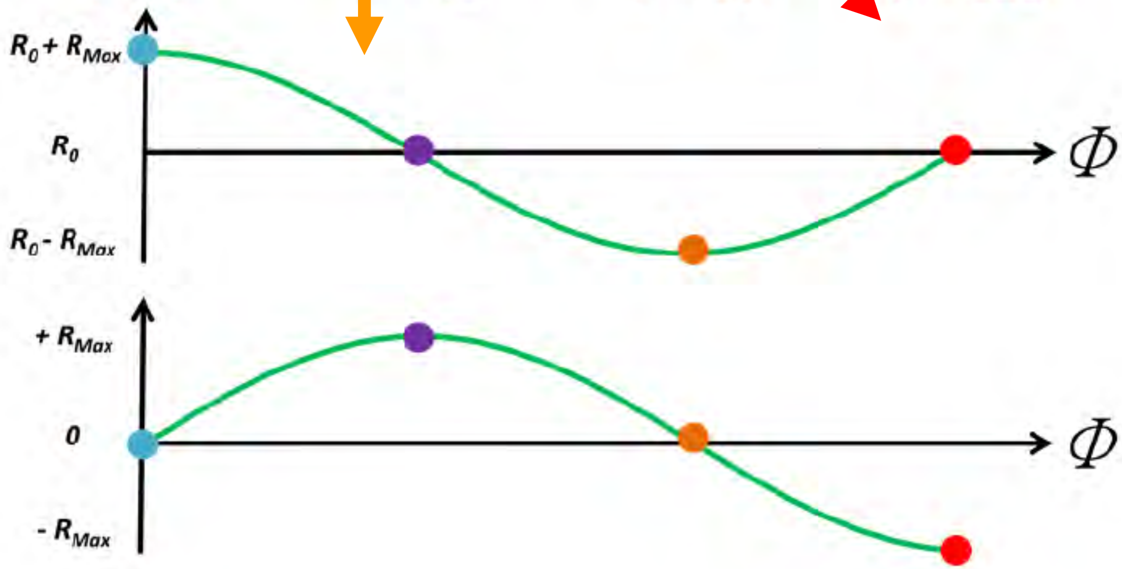
# Reading the antiferromagnetic state:
# **Anisotropic Magnetoresistance (AMR)**
# (transverse geometry)



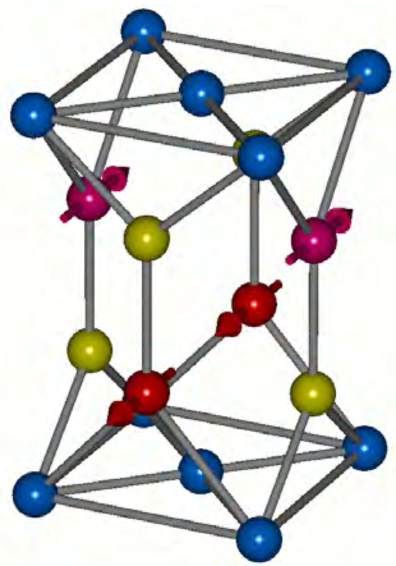




longitudinal $R_{xx} = R_0 + R_1\cos 2\Phi$

transverse $R_{xy} = R_1\sin 2\Phi$



# Switching an antiferromagnet



F. Freimuth

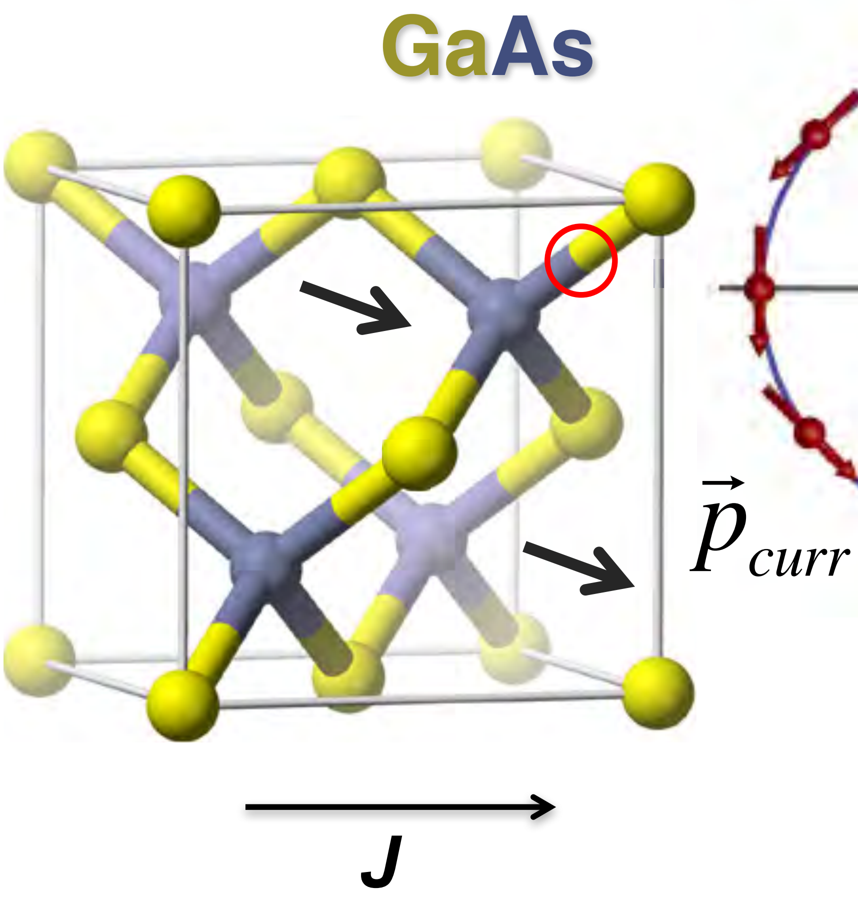
Need to generate an alternating local field on a sub unit cell resolution!

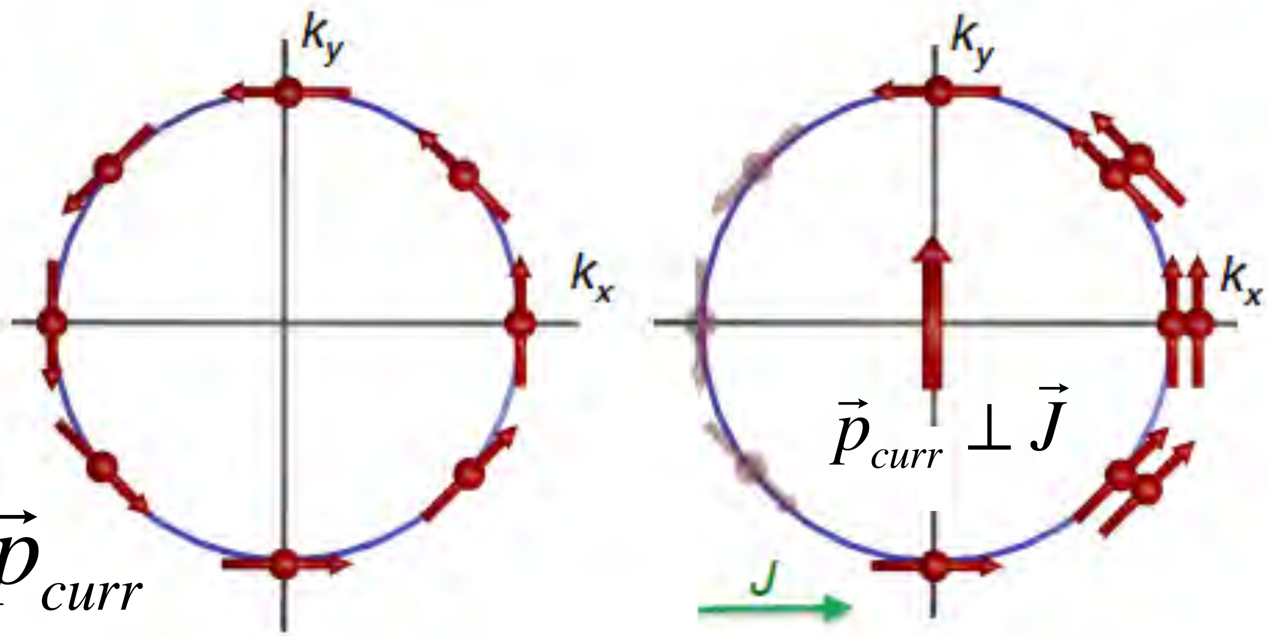
Zelezny, Jungwirth *et al* PRL 2014 predict a way to accomplish this based on *current–induced spin polarization*

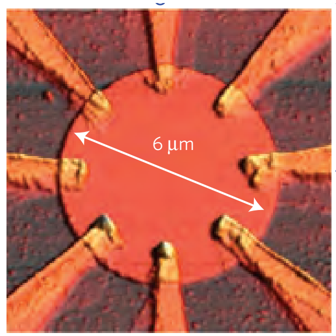
# Current-induced spin polarization

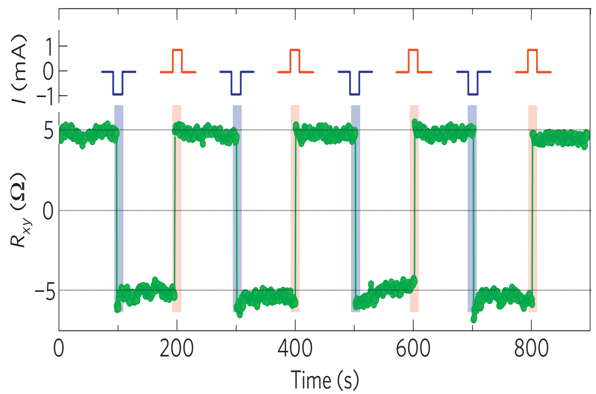
**Inverse spin galvanic (Edelstein) effect**

Global inversion asymmetry - -> **non-equilibrium spin polarization**



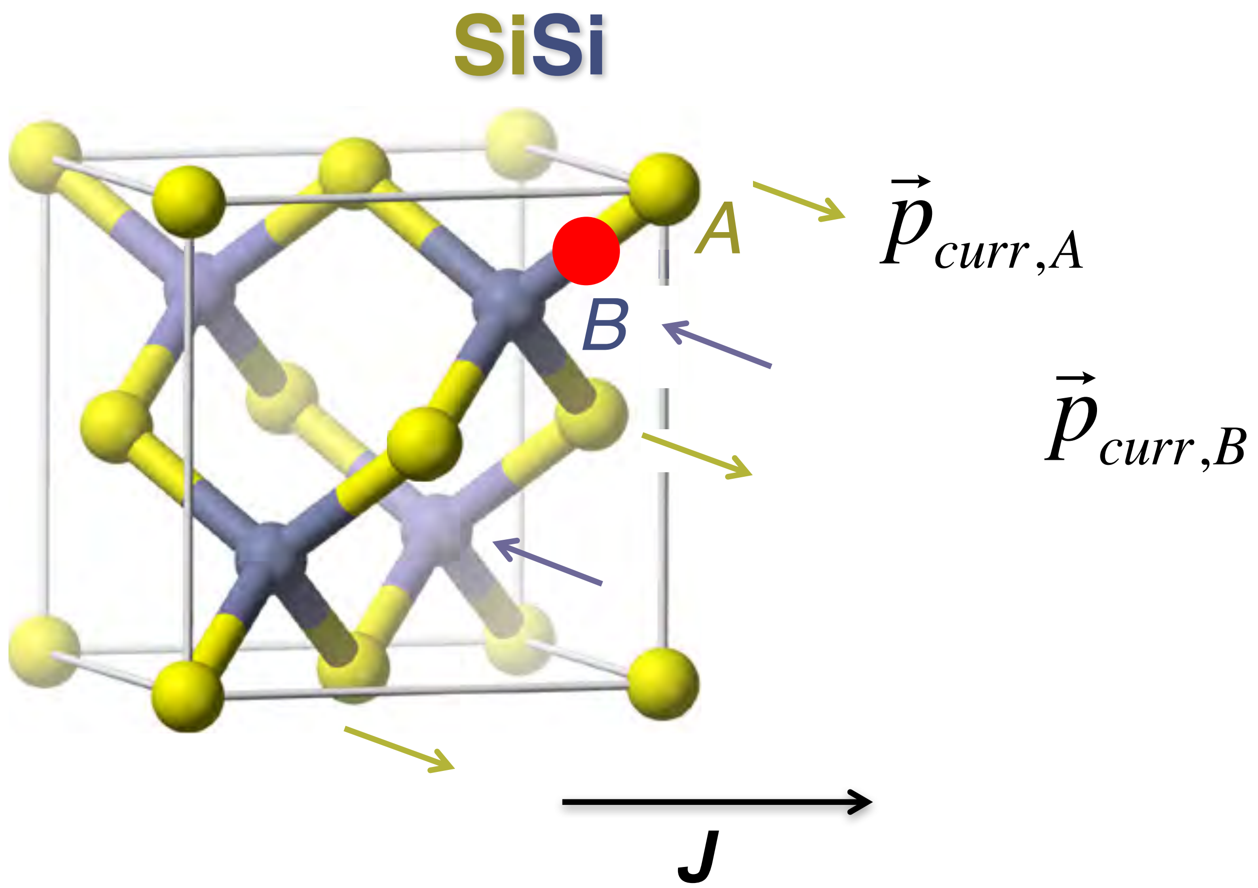




*Chernyshov et al. Nature Phys. '09*

# Writing by spin-orbit torque in antiferromagnets

**Inverse spin galvanic (Edelstein) effect**

Local inversion asymmetry



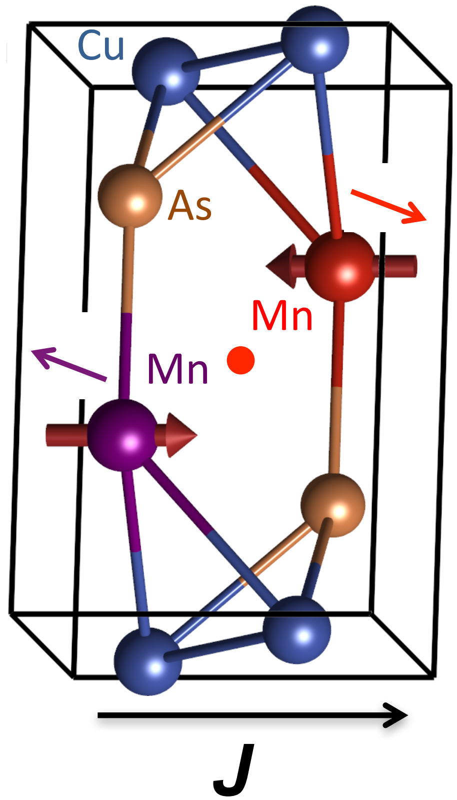

**“Hidden” spin polarization**

*Zhang et al. Nature Phys. 2014*
*Zelezny, et al. PRL2014*

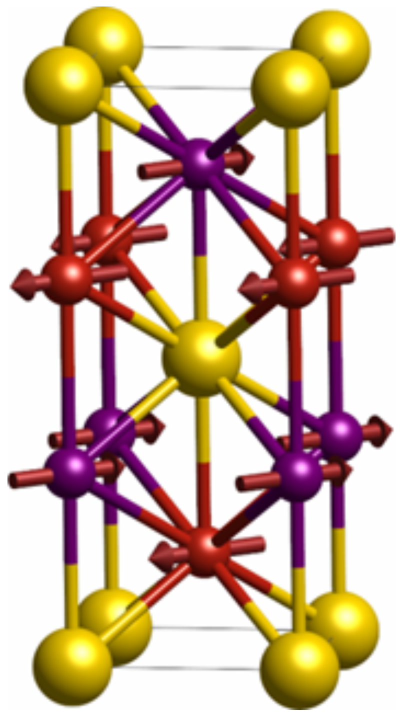
# Switching an antiferromagnet

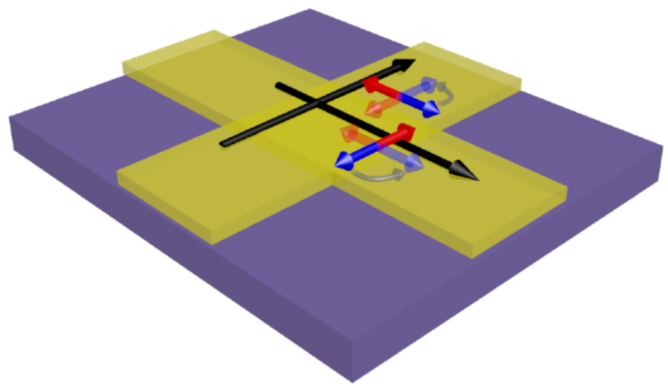
All we have to do is find a system where the local spin accumulation matches the spin sub-lattices

**Tetragonal CuMnAs**




**$Mn_2Au$**

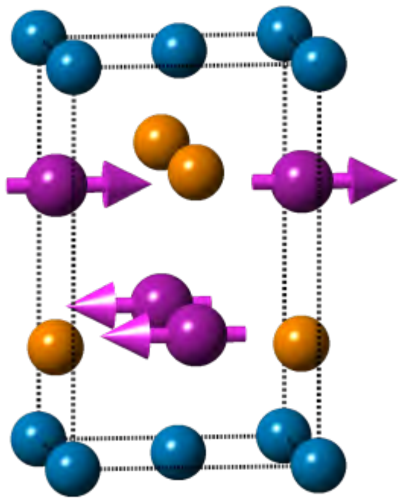


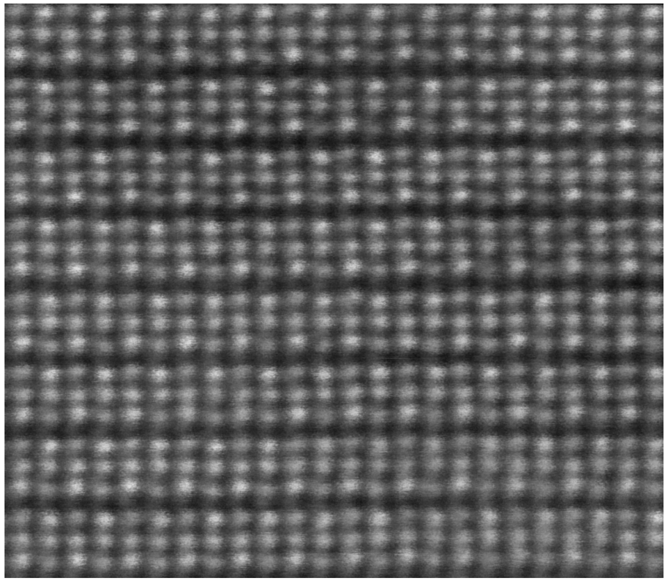


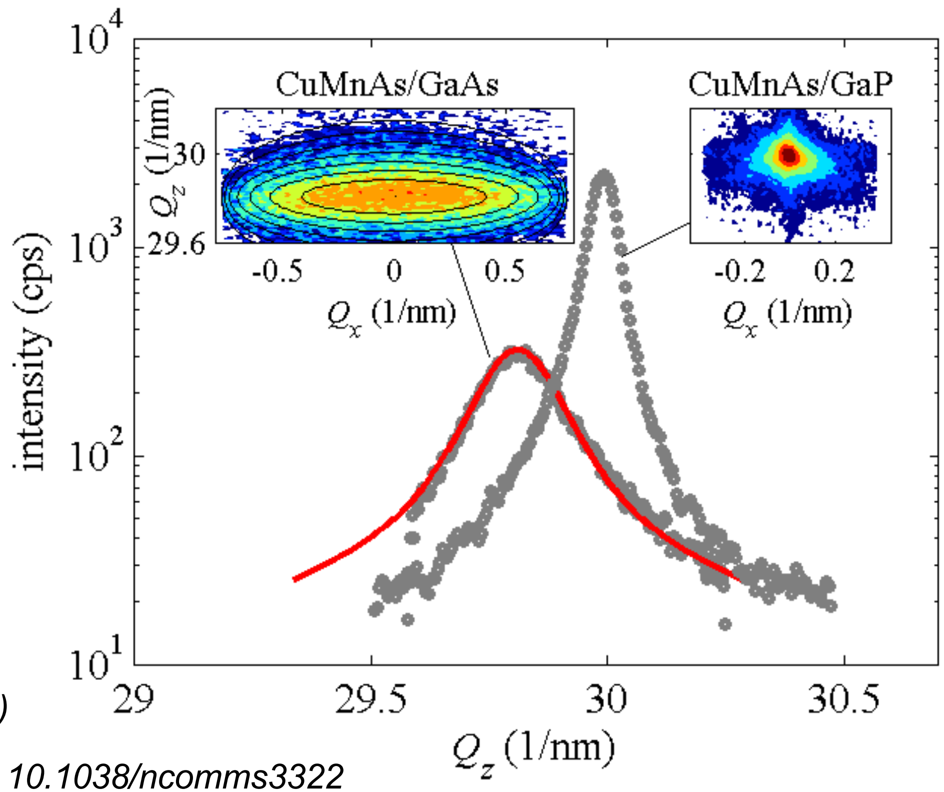
# CuMnAs material system

- Grown using molecular beam epitaxy on GaAs and GaP substrates
- Tetragonal $Cu_2Sb$ structure
- Single crystal growth
- Relaxed mosaic block structure on GaAs
- Strained and more coherent on GaP

Richard Campion – 9:30am Friday





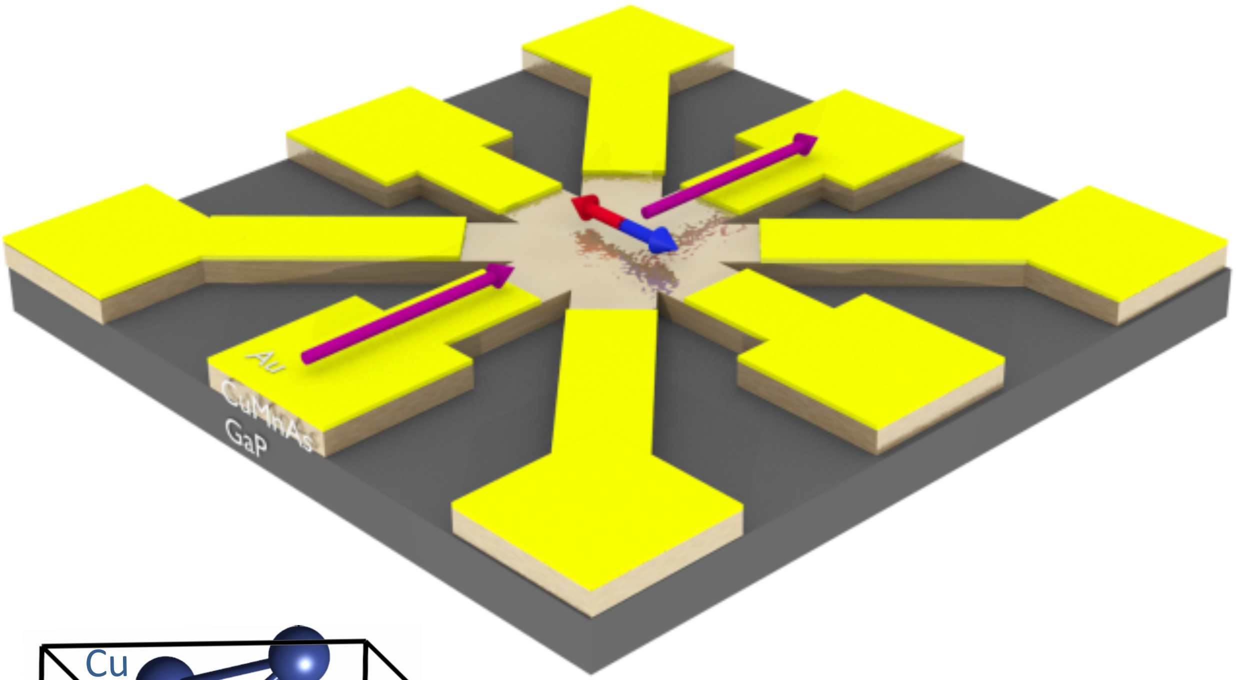


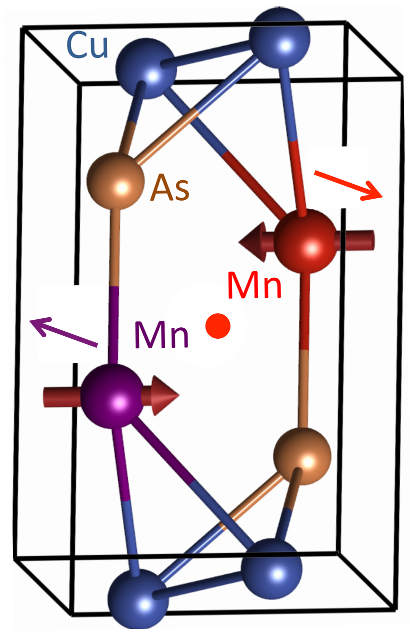

Wadley, Campion, Jungwirth, Gallagher *et al Sci. Rep. (5), 17079 (15)*

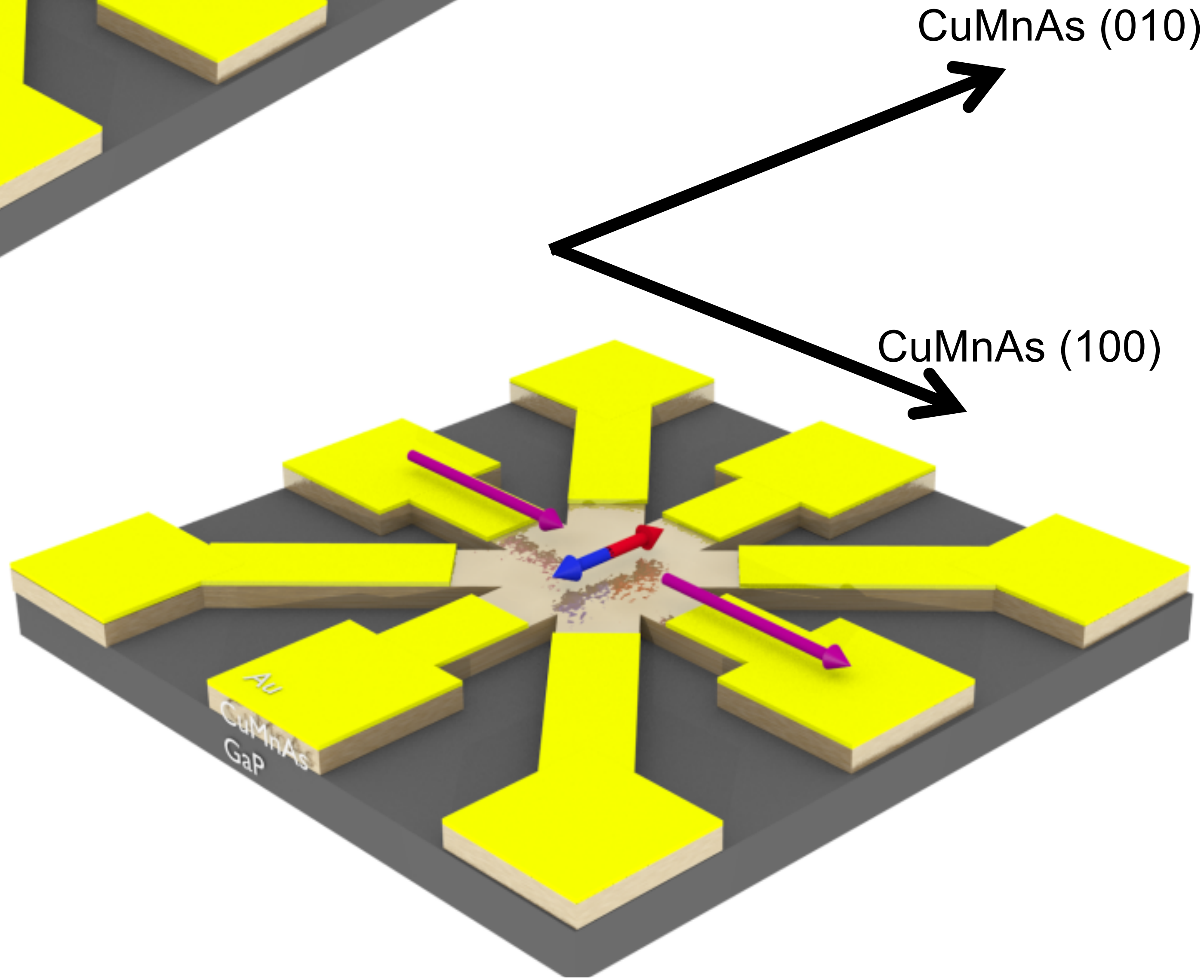
Wadley, Campion, Gallagher, Jungwirth *et al Nat. Commun. (13) DOI: 10.1038/ncomms3322*

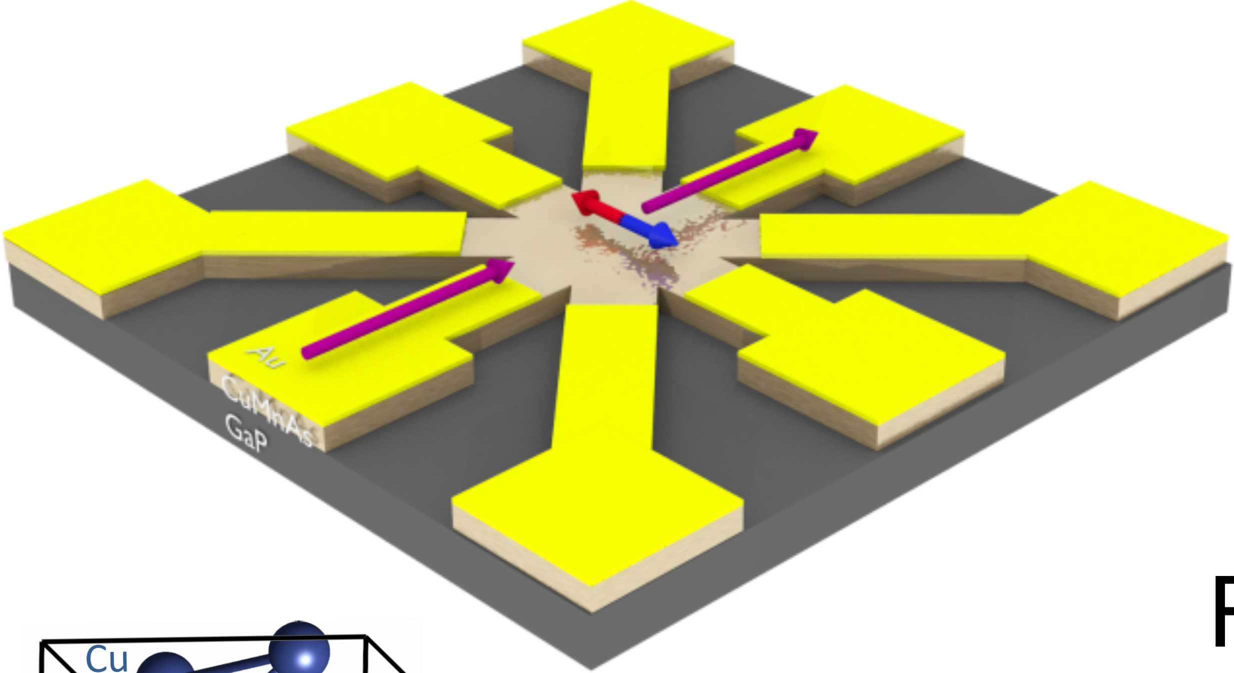
# Writing the state

$J_{write} \sim 10^7$ A/cm$^2$



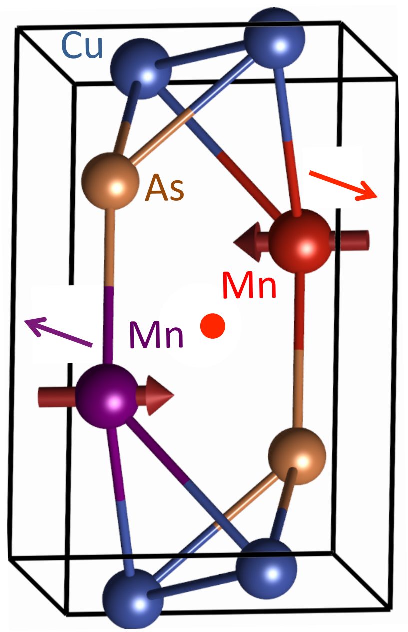





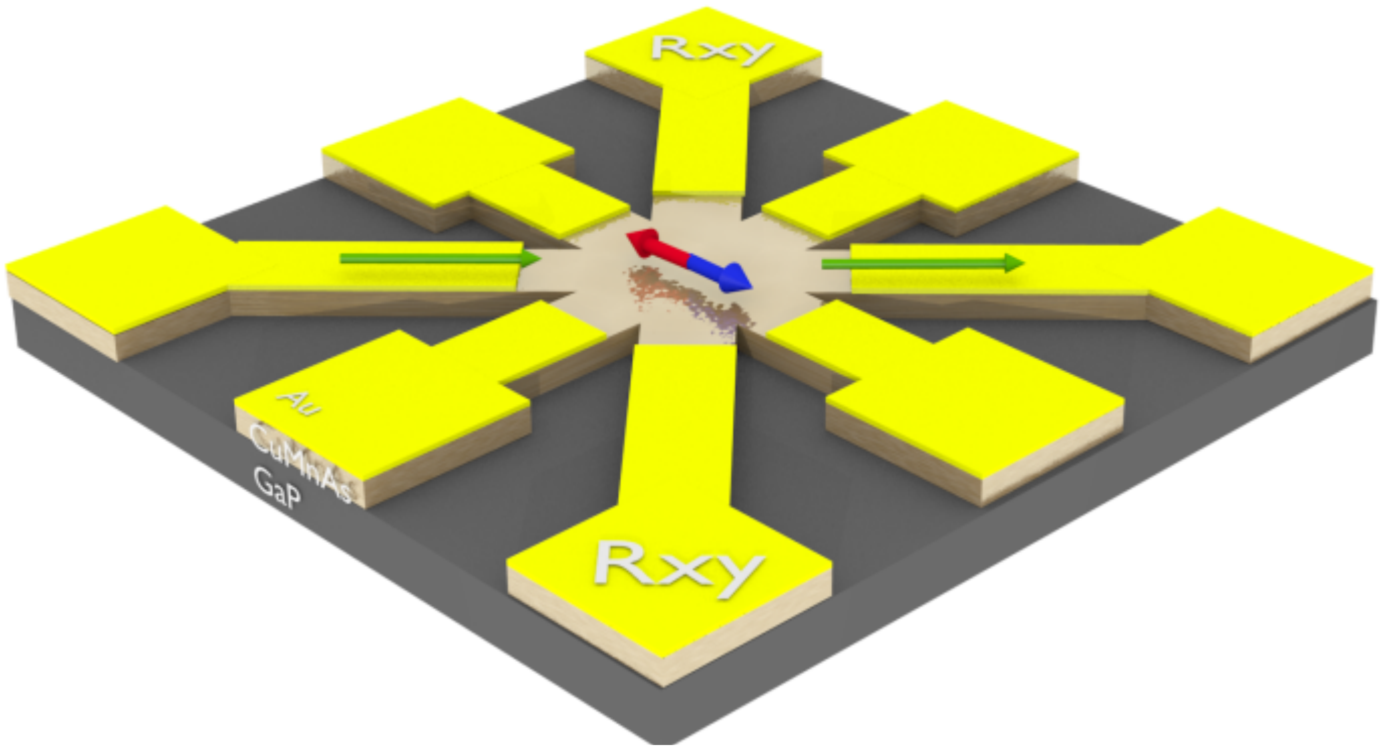

# Writing the state

$J_{write} \sim 10^7$ A/cm$^2$

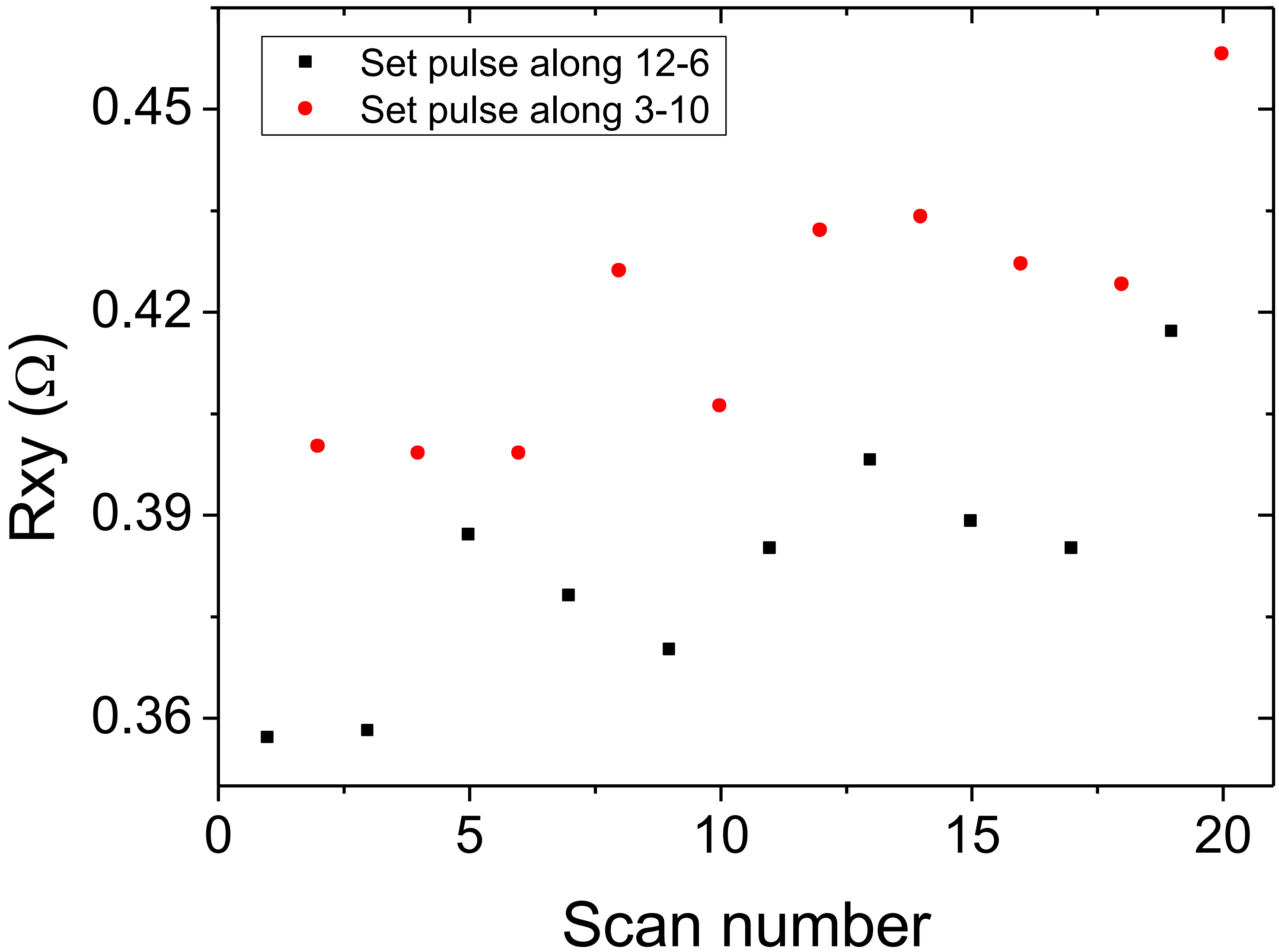



# Reading the state

$J_{read} \sim 10^4$ A/cm$^2$



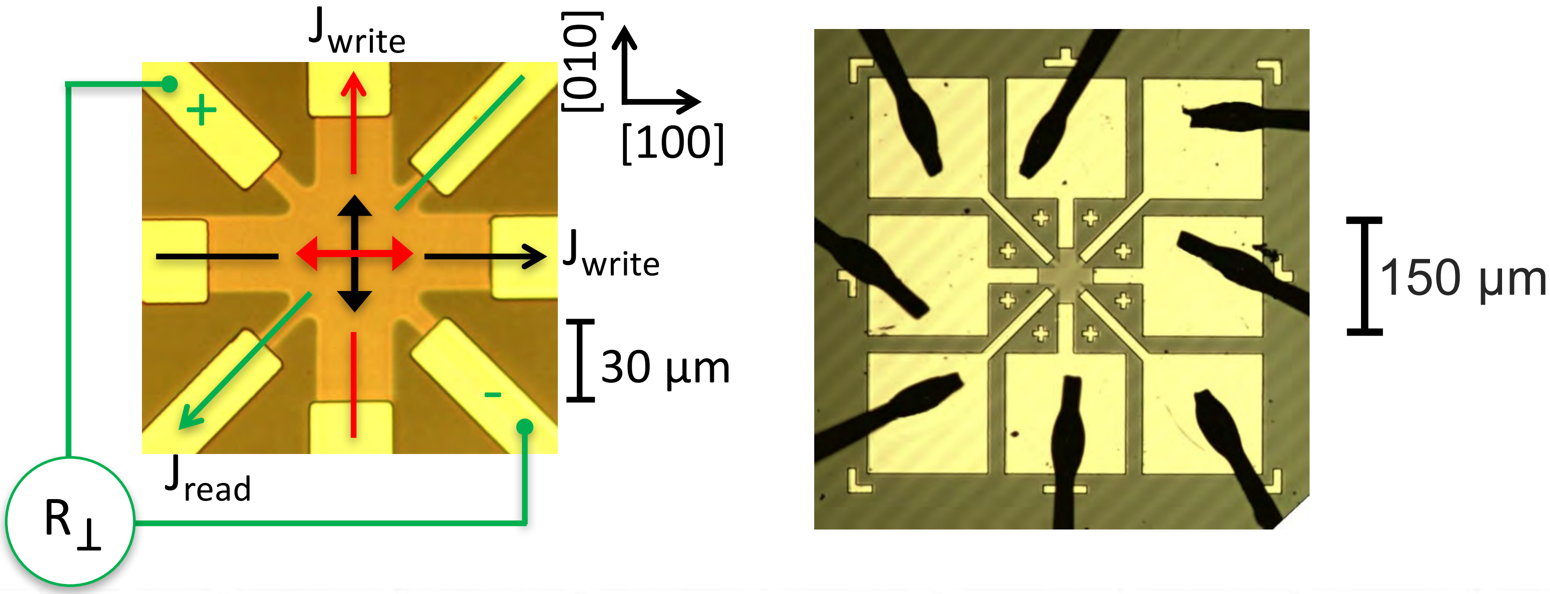
December 2014 – Very first measurements

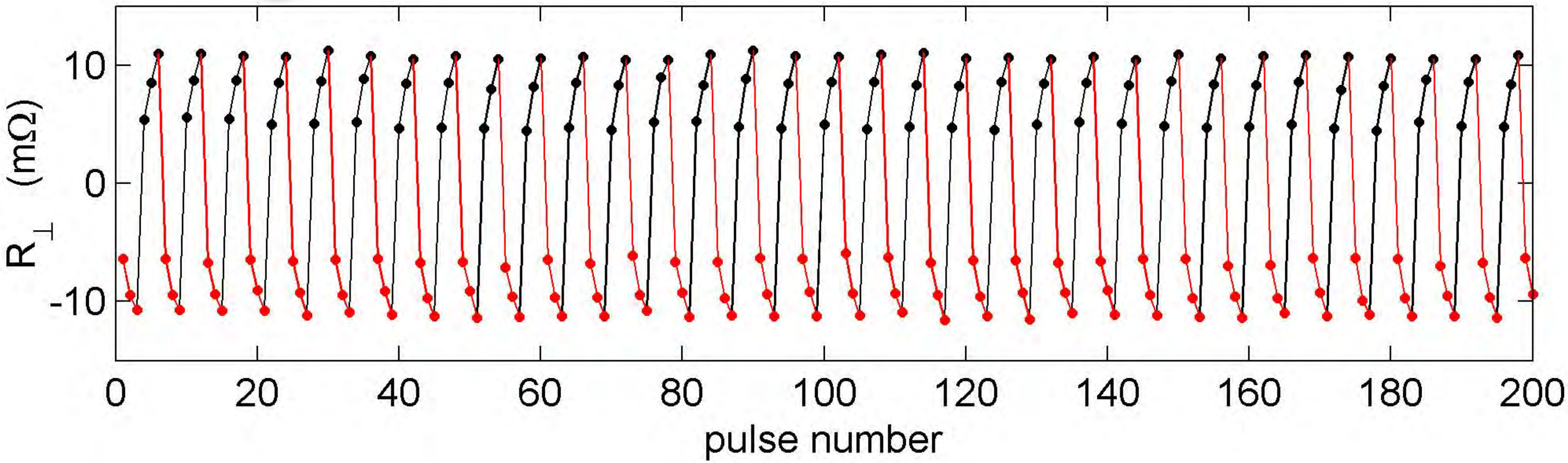



Wadley, Howells

# Electrical switching of antiferromagnetic CuMnAs

*Wadley, Olejnik, Jungwirth et al. Science 2016*

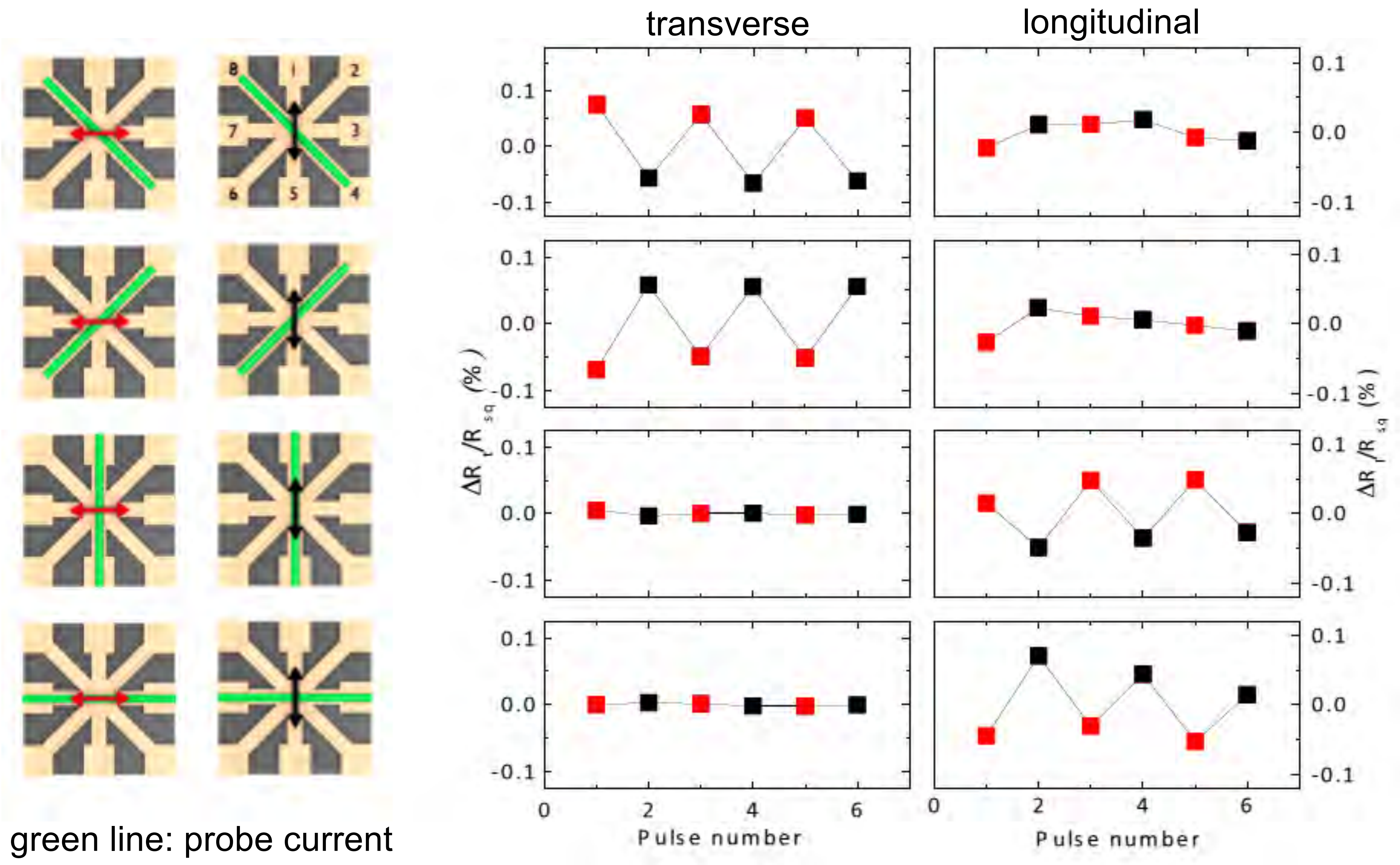



- Room-temperature

-- Switching current density ~$10^6$ A cm$^{-2}$ comparable to FM STT-MRAM devices

# AMR symmetry of the electrical read-out

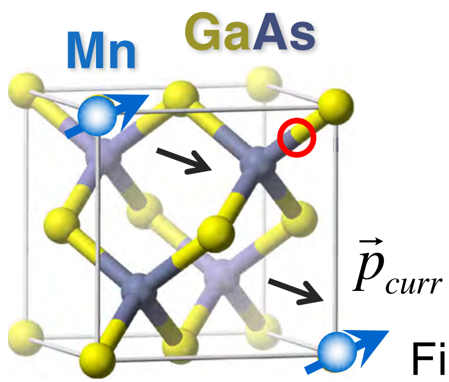



green line: probe current

# Writing by spin-orbit torques

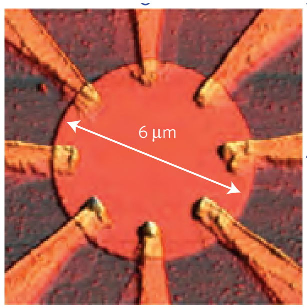
**Inverse spin galvanic (Edelstein) effect**

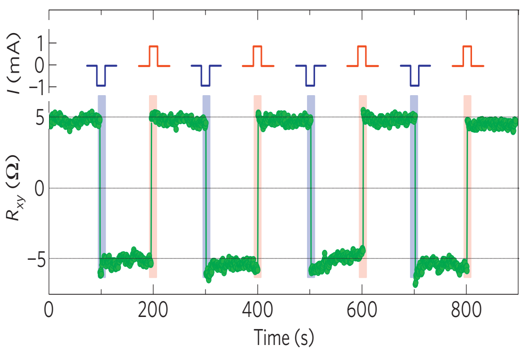
## Global inversion asymmetry & FM




Field-like torque

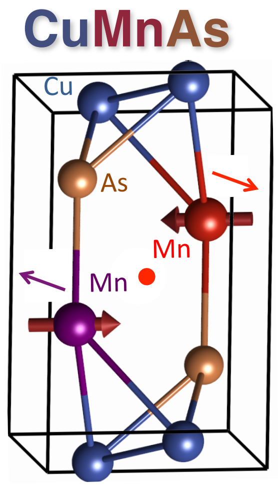
$$\vec{T} \sim \vec{M} \times \vec{p}_{curr}$$



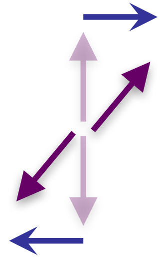

*Chernyshov et al. Nature Phys. '09*

## Local inversion asymmetry & AF

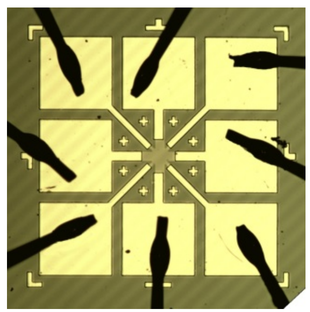


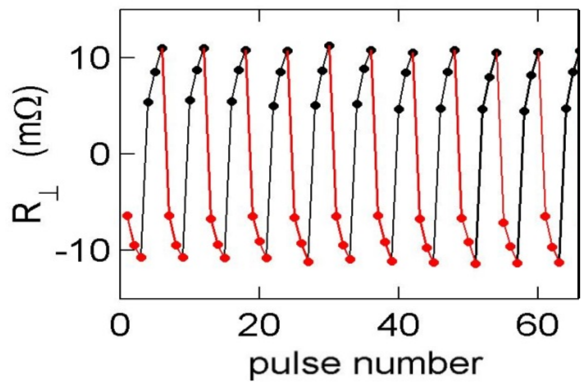

Field-like torque

$$\vec{T}_A \sim \vec{M}_A \times \vec{p}_{curr,A}$$



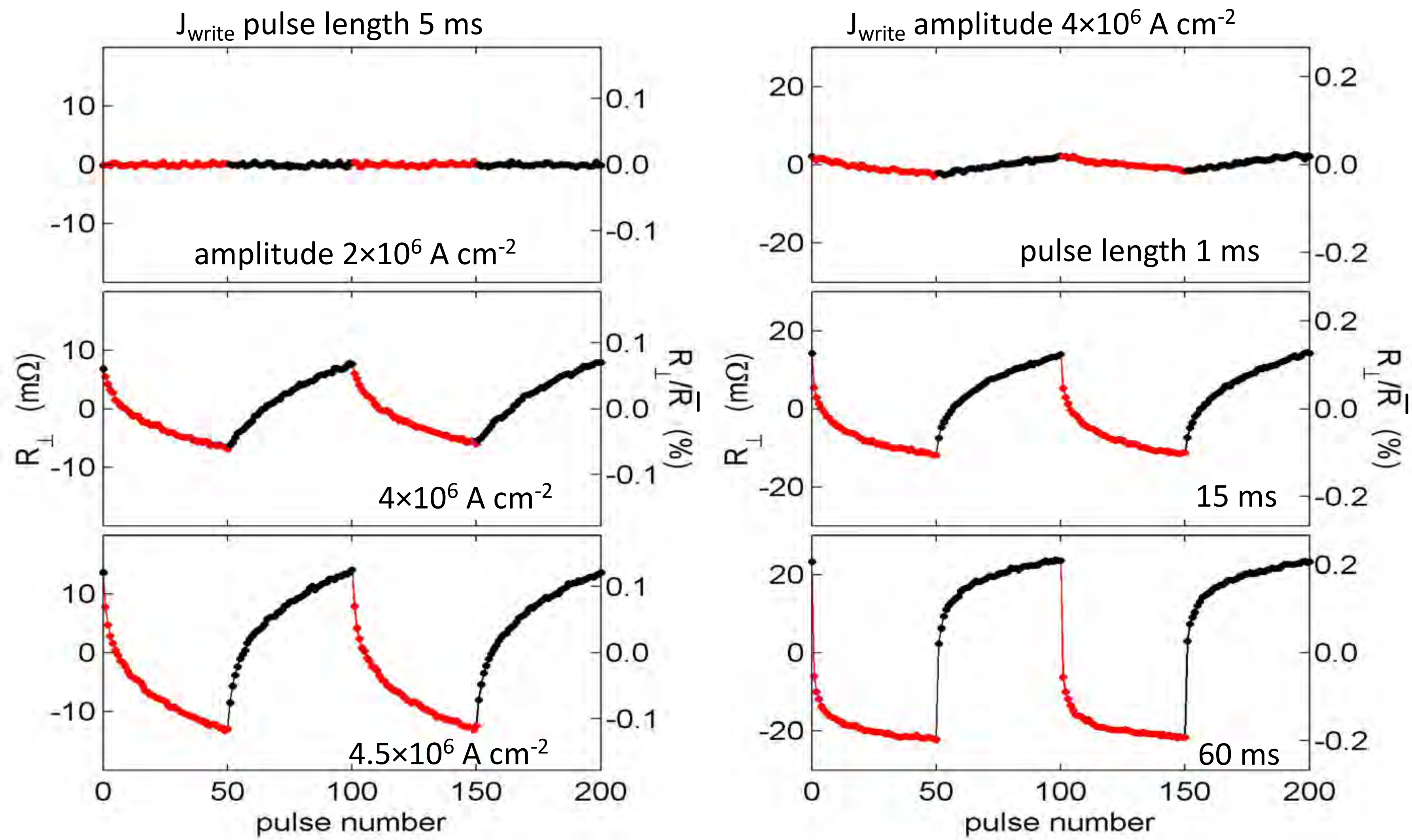
$$\vec{T}_B \sim \vec{M}_B \times \vec{p}_{curr,B}$$






*Wadley, Jungwirth et al. Science '16*

# Variation of writing pulse length and amplitude



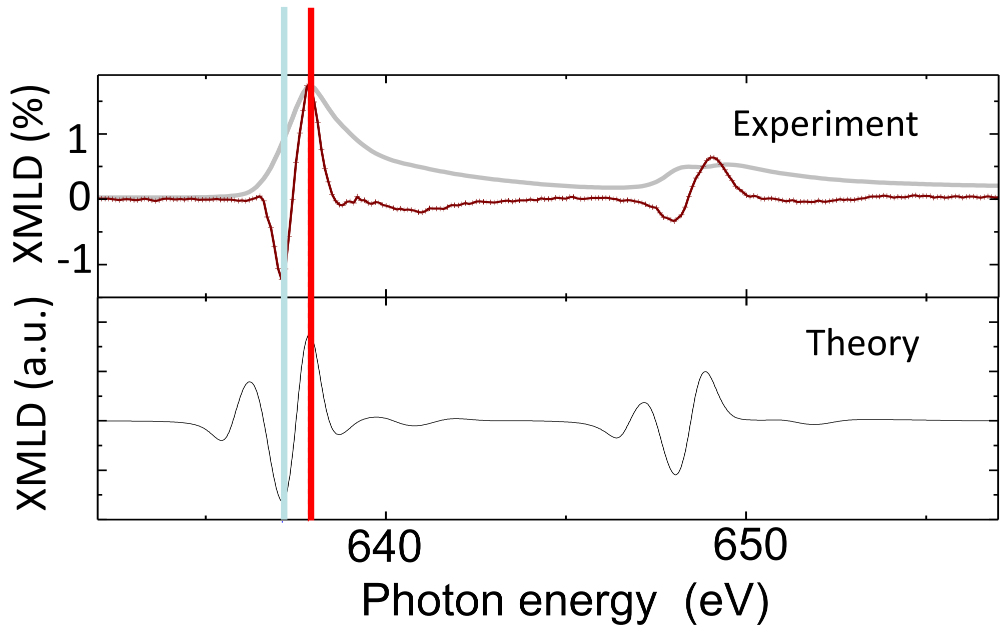

Domain-like saturation behaviour

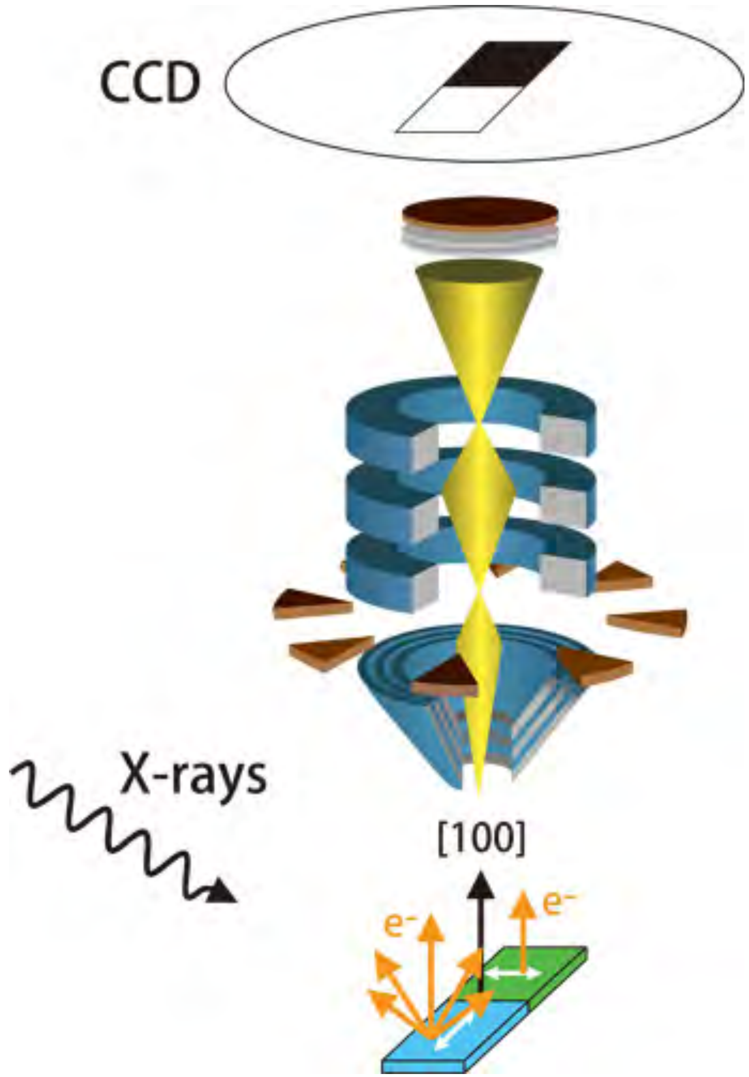
See talk by J. Wunderlich and X. Marti – Thursday

Schuler, Olejnik, Marti, PW, Jungwirth et al arxiv 16

Would like independent evidence of magnetic switching

# X-ray photoelectron emission microscopy (XPEEM)

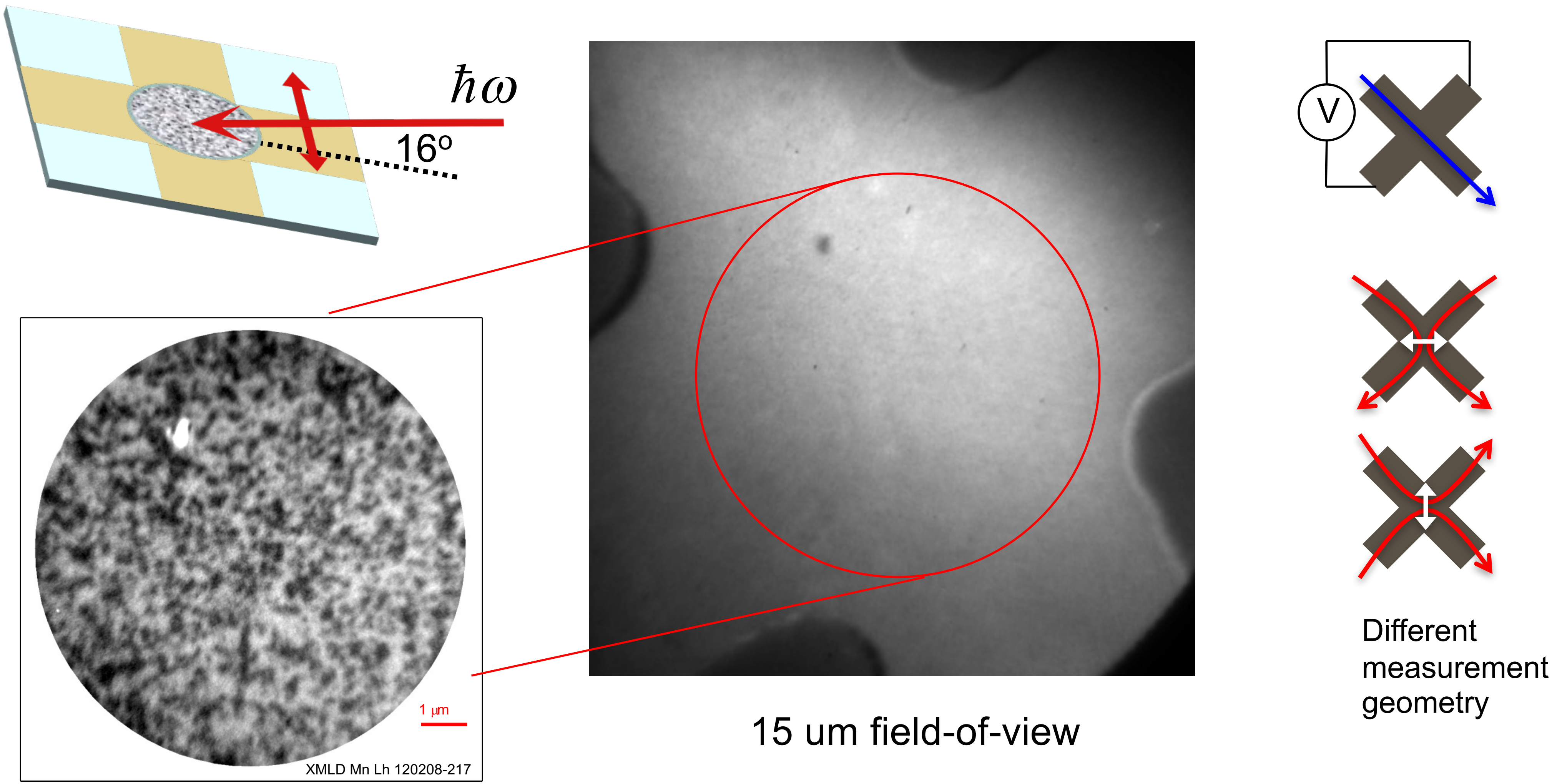


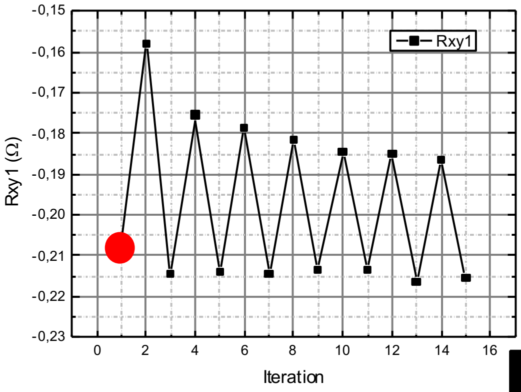



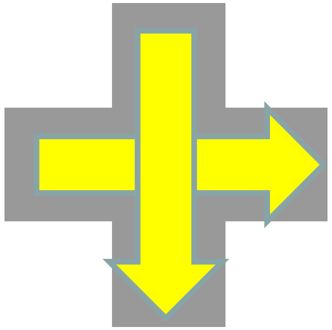

http://www.spring8.or.jp

# X-ray photoelectron emission microscopy (XPEEM)

Beamline I06,
Diamond Light Source

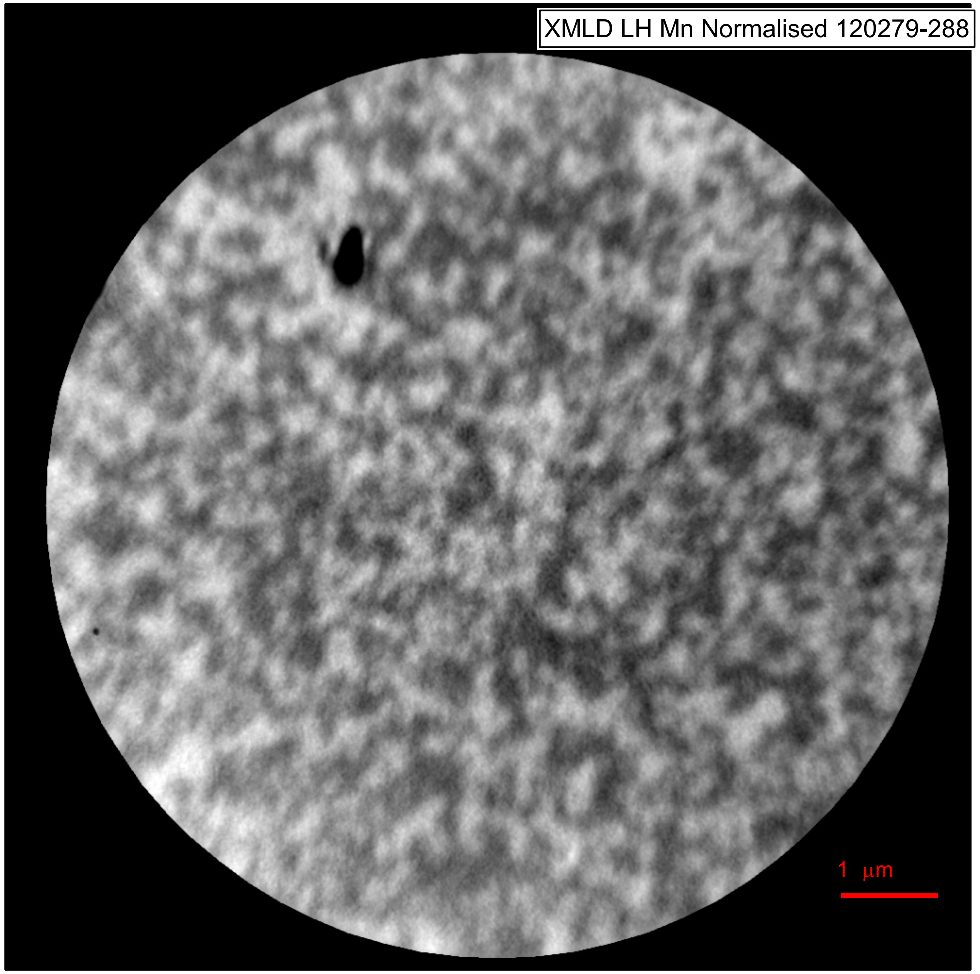


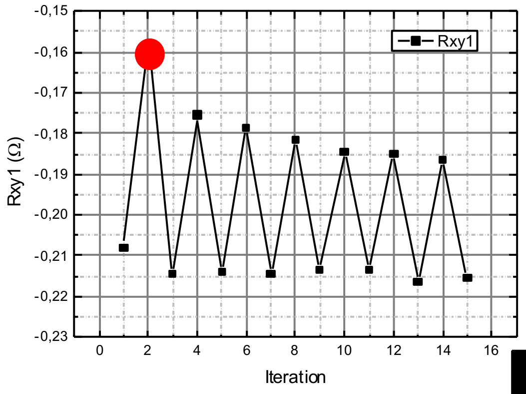


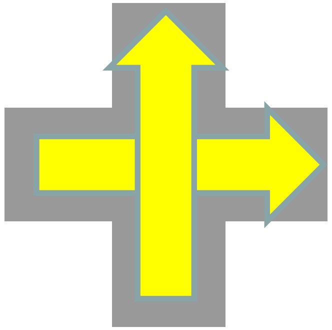



69mA current pulse

($6.1 MA/cm^2$)

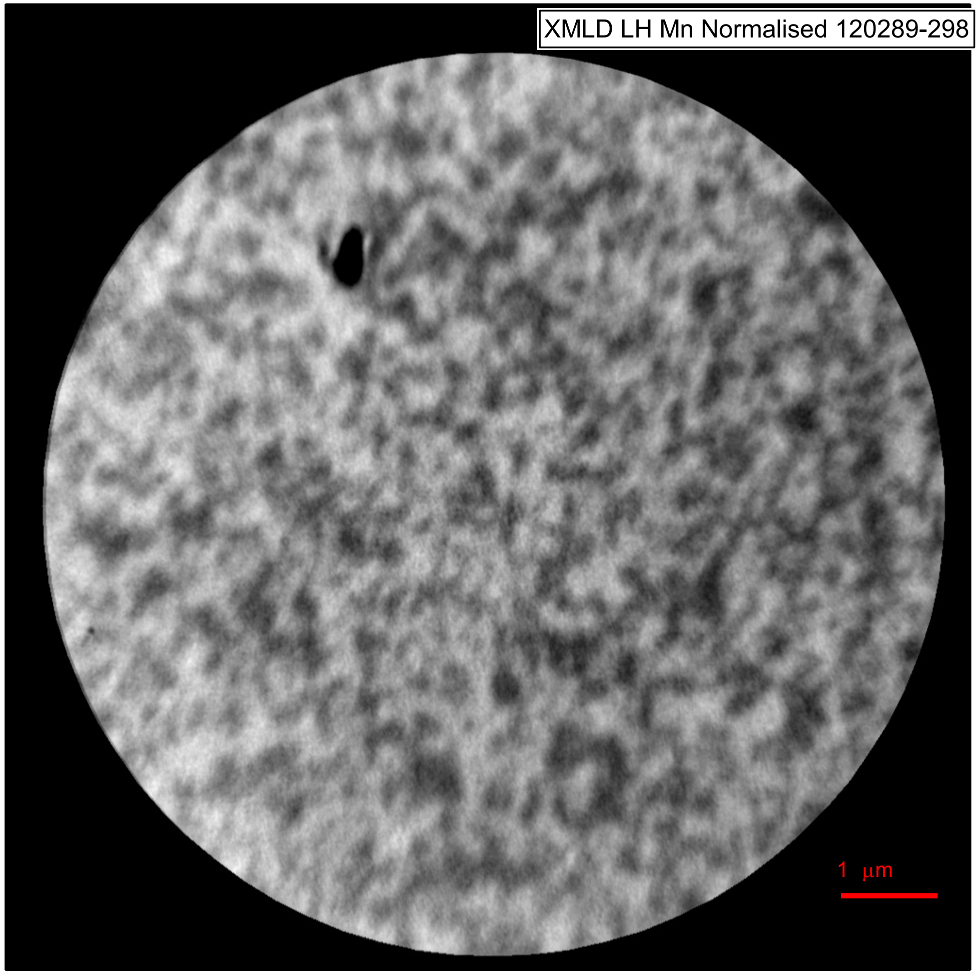


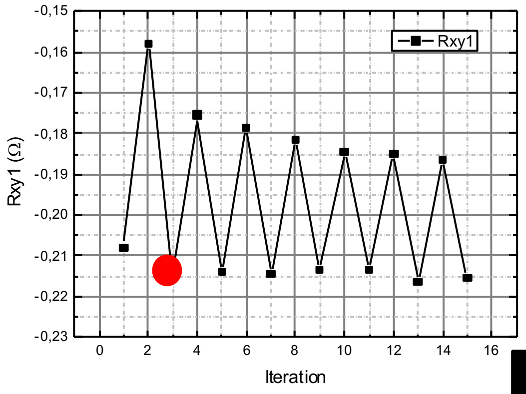


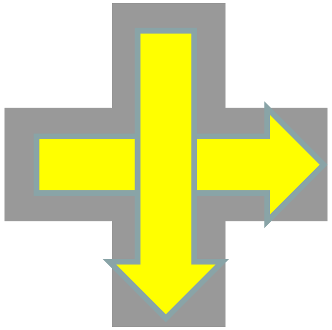



69mA current pulse

(6.1MA/cm$^2$)

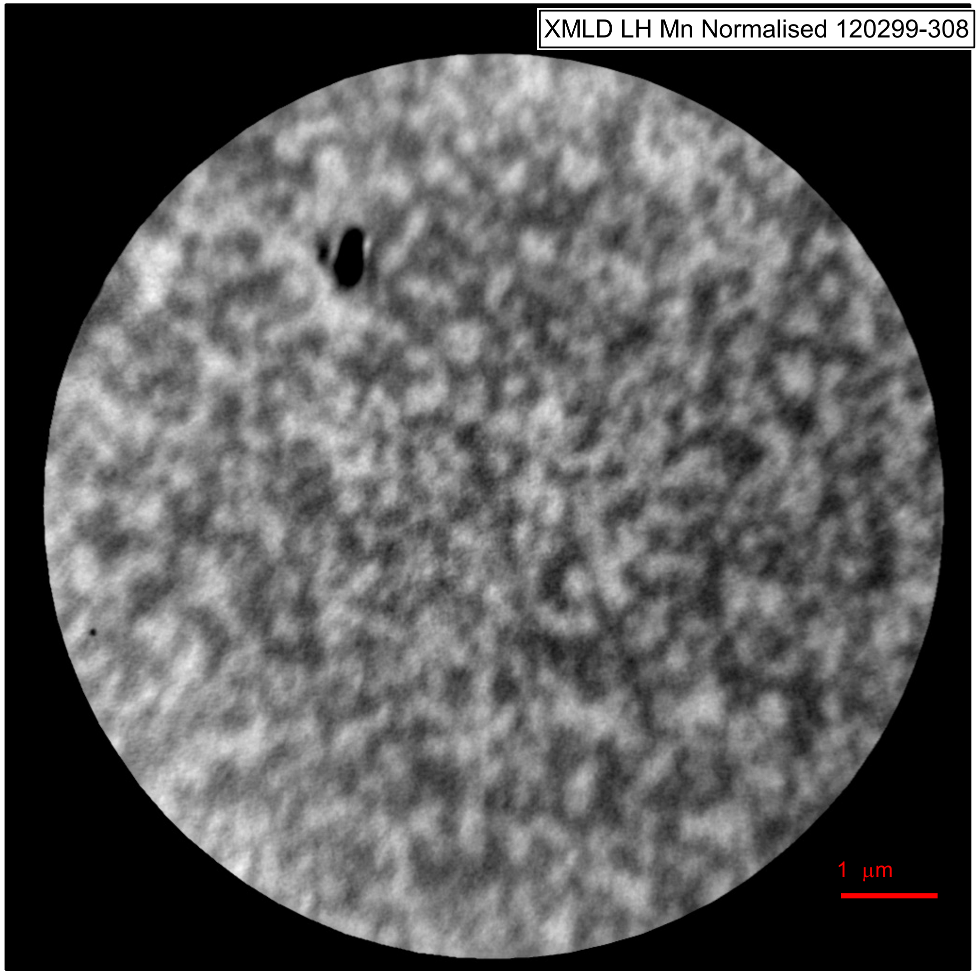


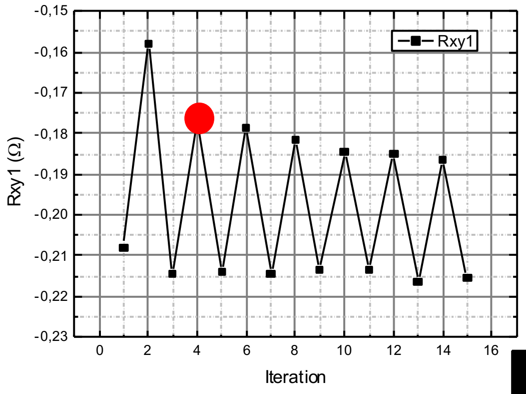


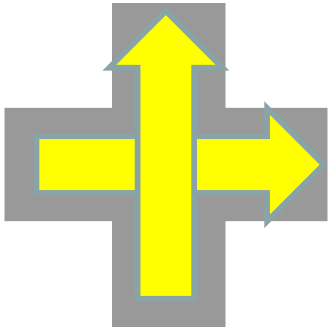



69mA current pulse

($6.1 MA/cm^2$)

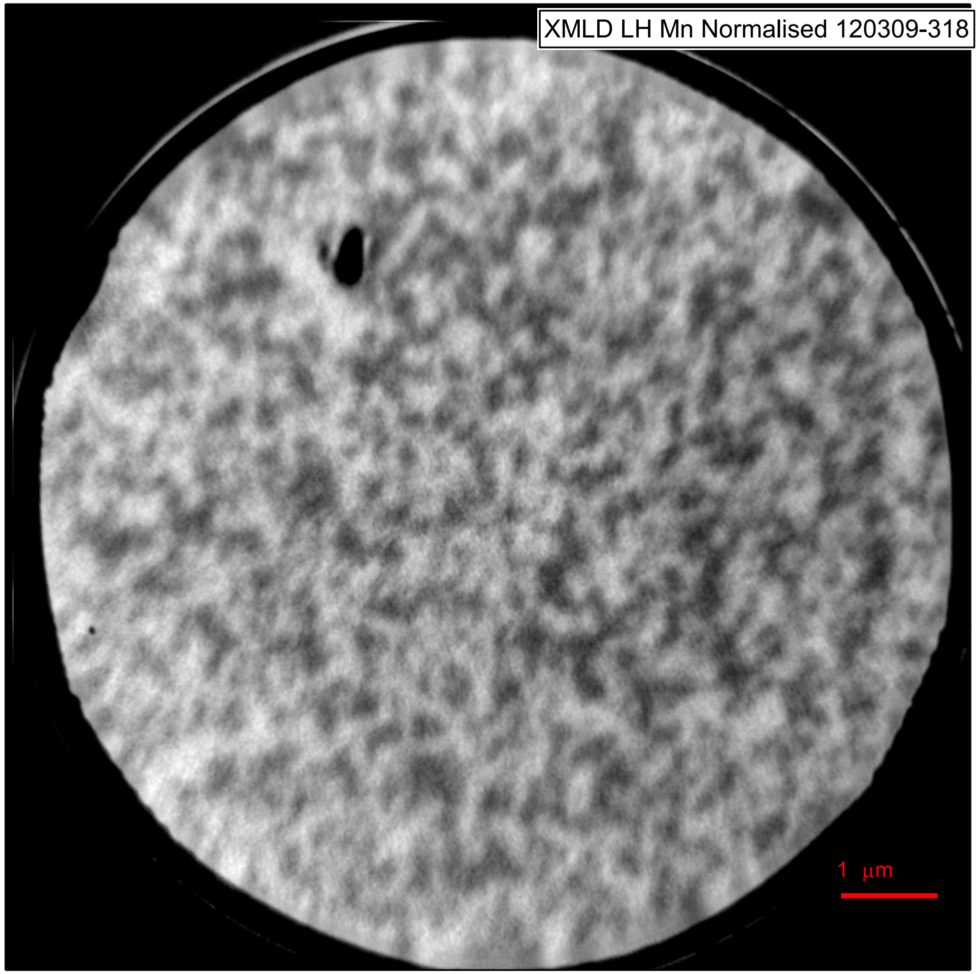


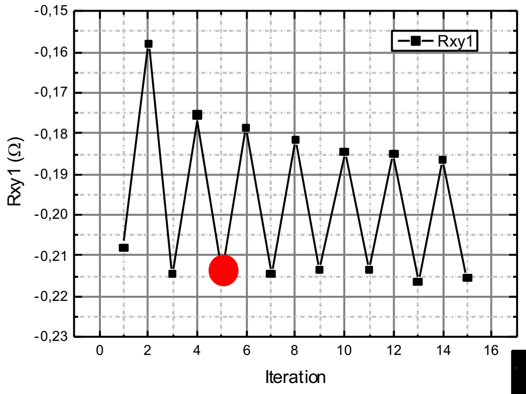


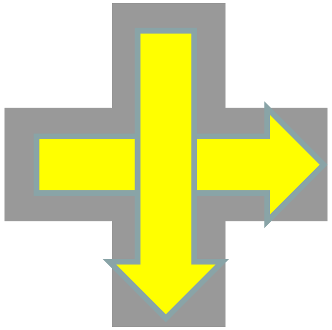



69mA current pulse

(6.1MA/$cm^2$)

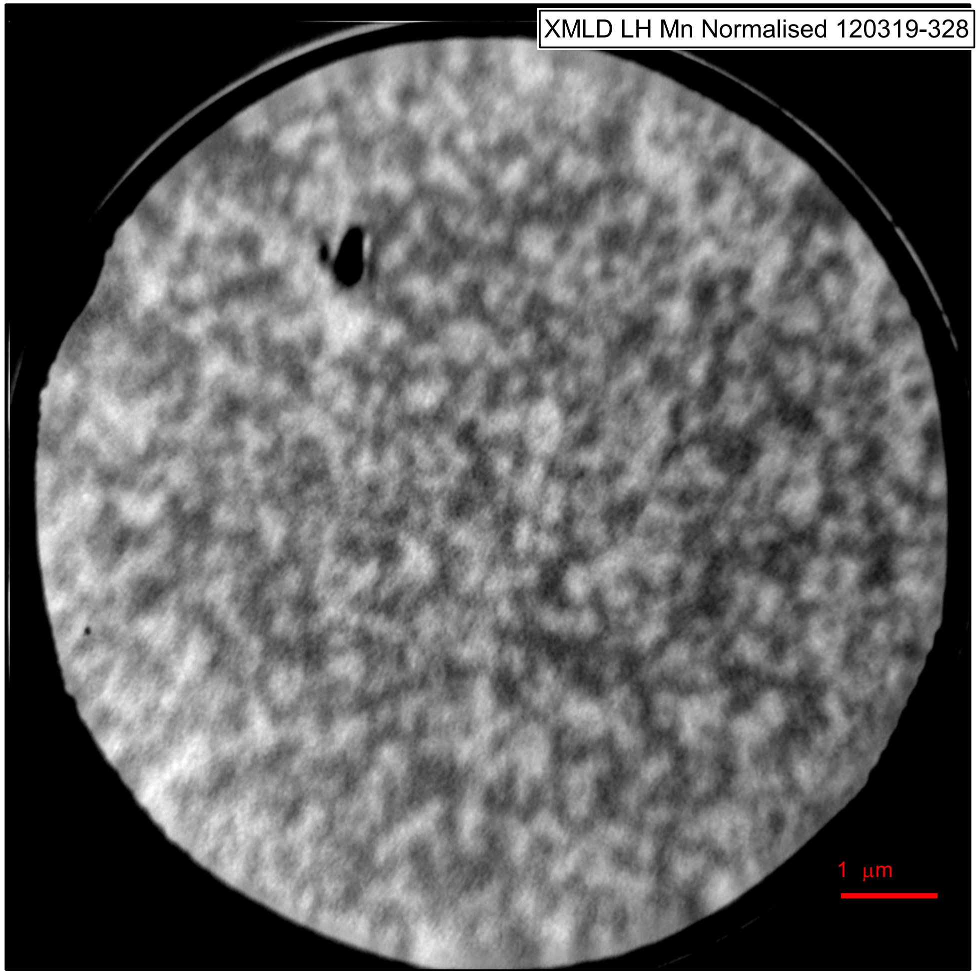


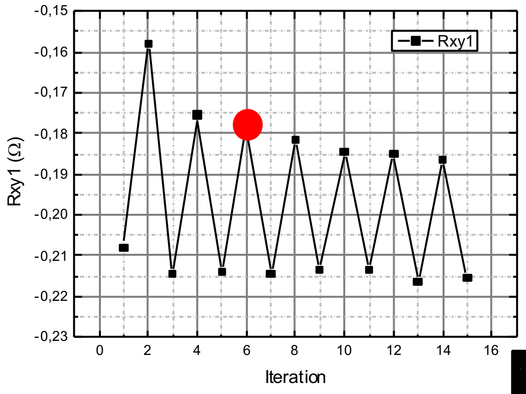


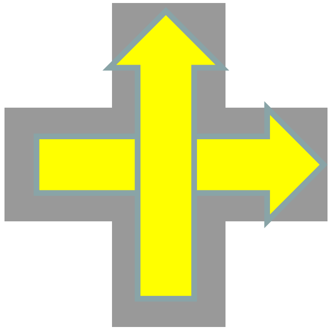



69mA current pulse

(6.1MA/cm$^2$)

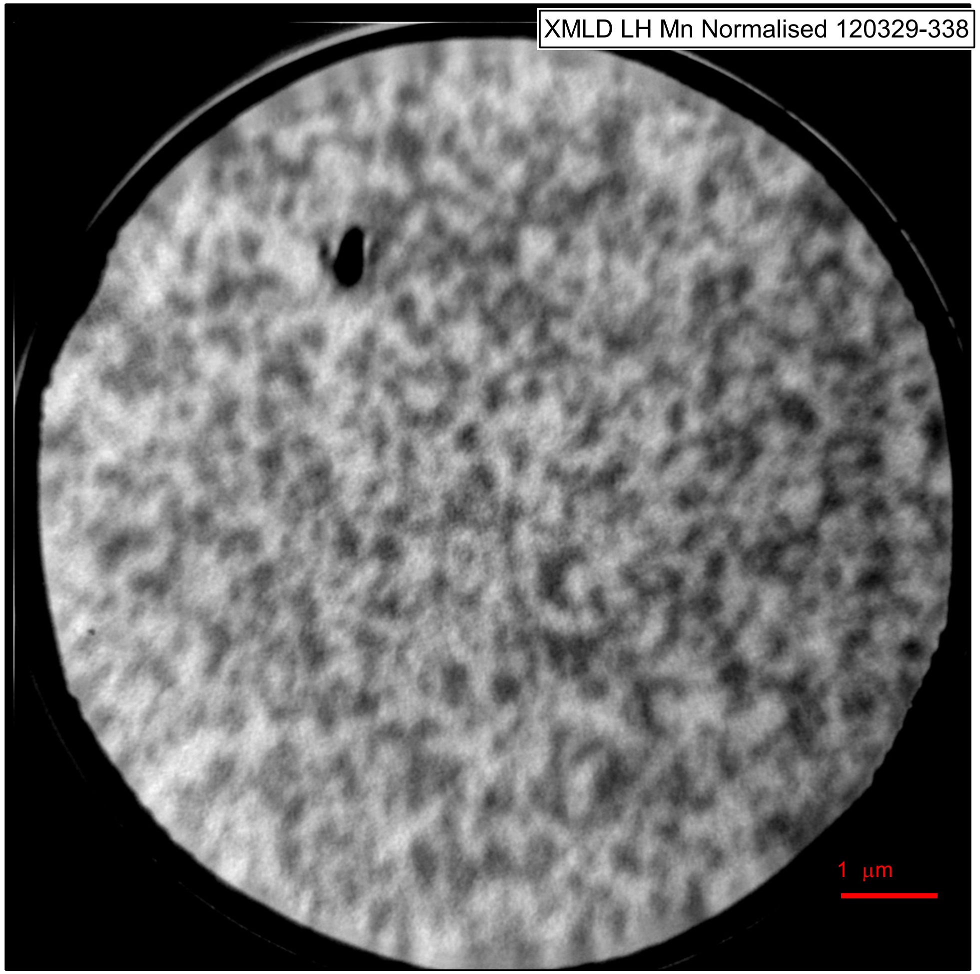


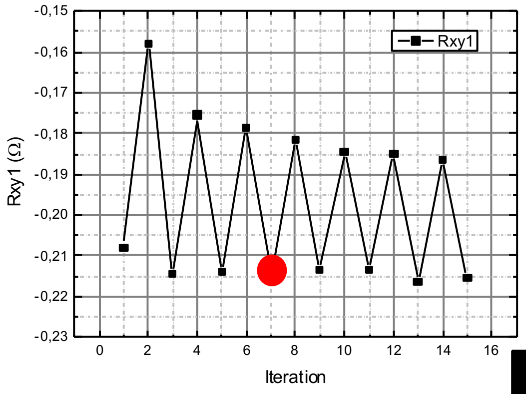


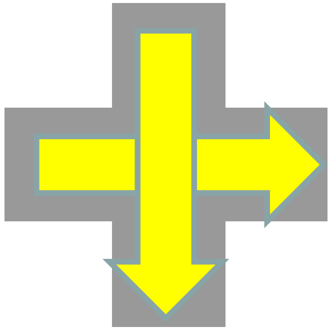



69mA current pulse

(6.1MA/$cm^2$)

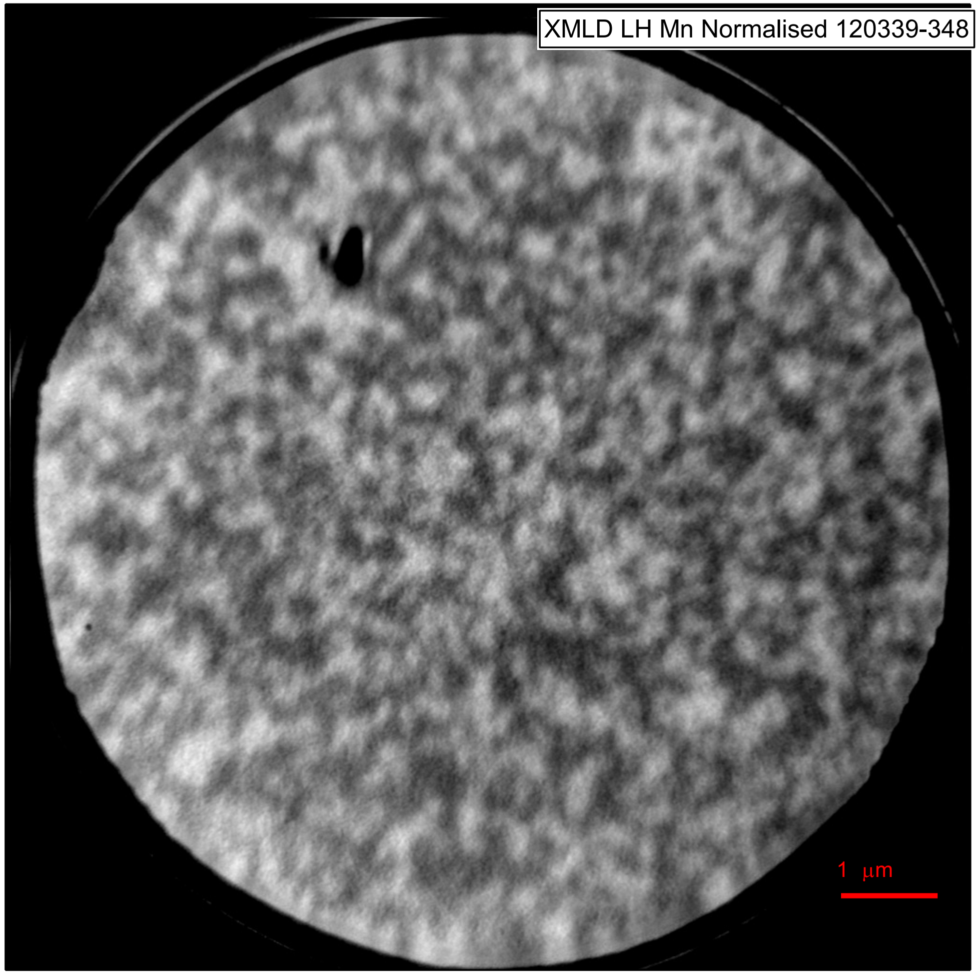


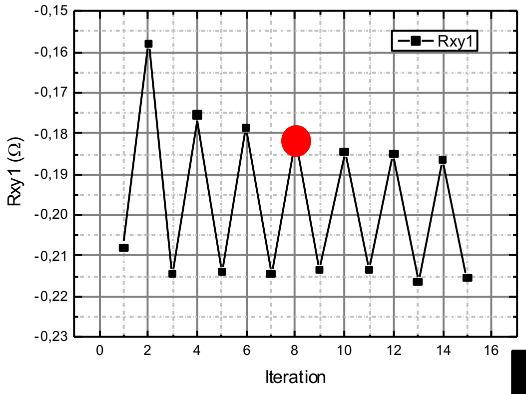


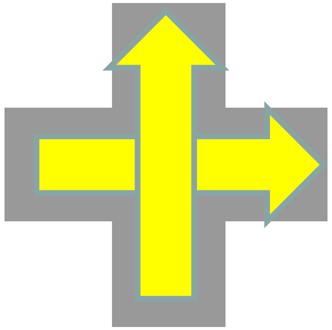



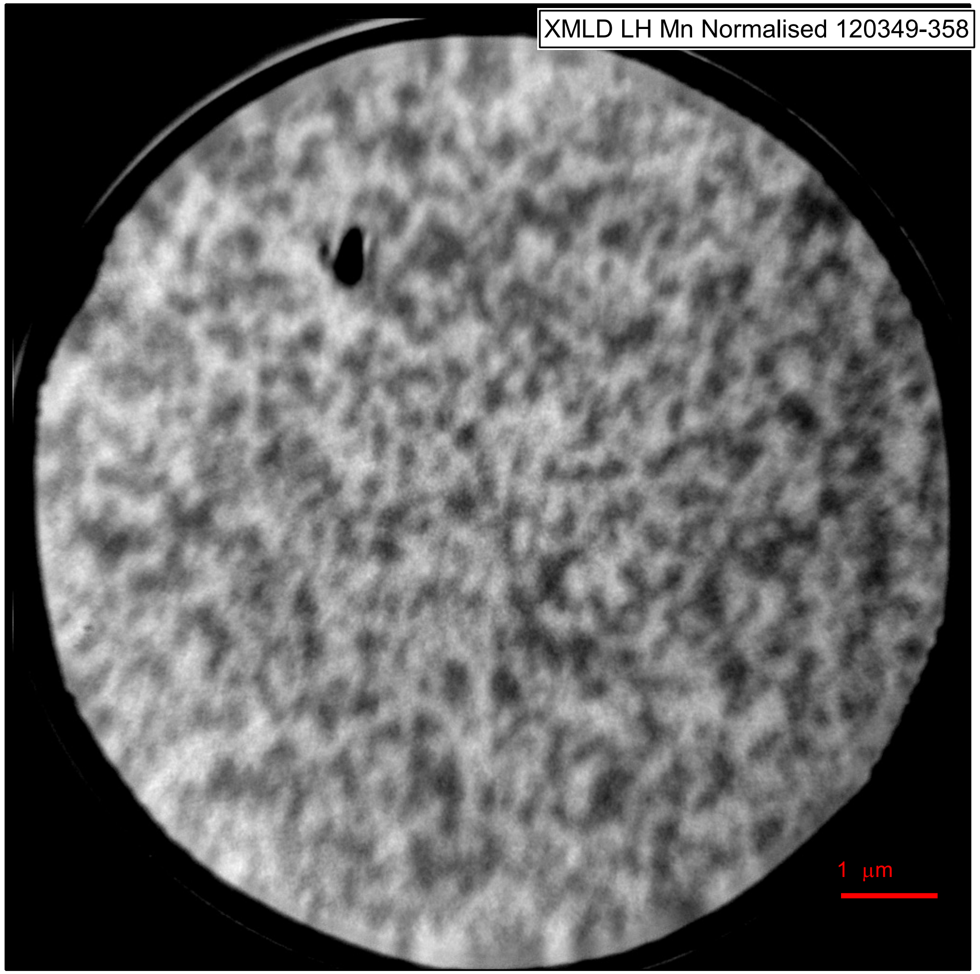
69mA current pulse

(6.1MA/cm$^2$)



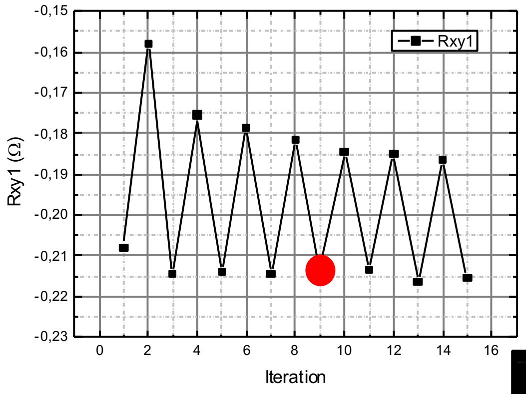


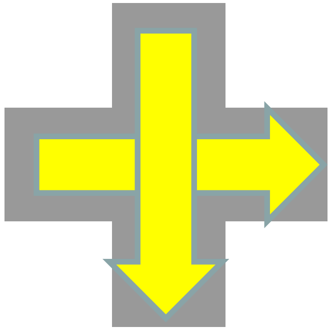






69mA current pulse

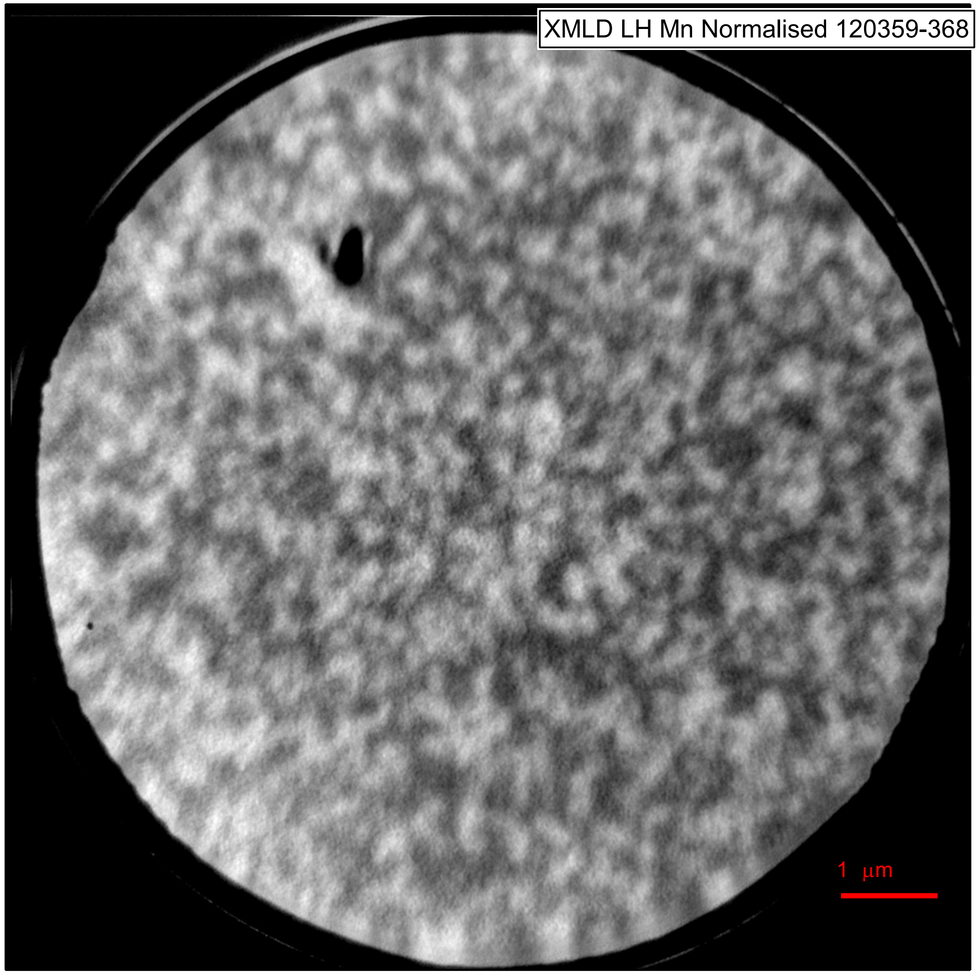
(6.1MA/cm$^2$)

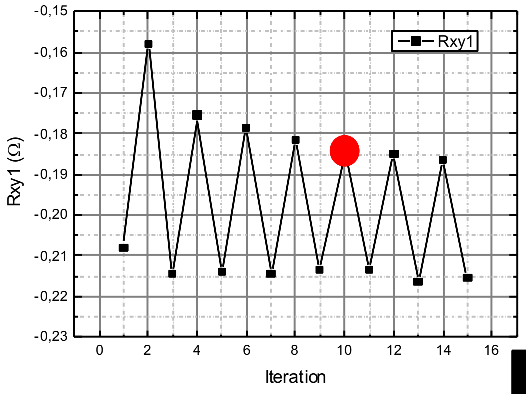


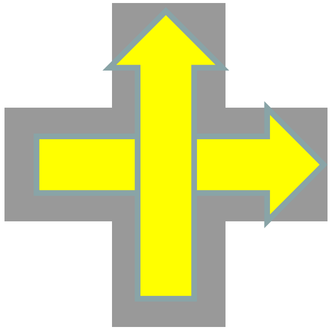



69mA current pulse

(6.1MA/cm$^2$)

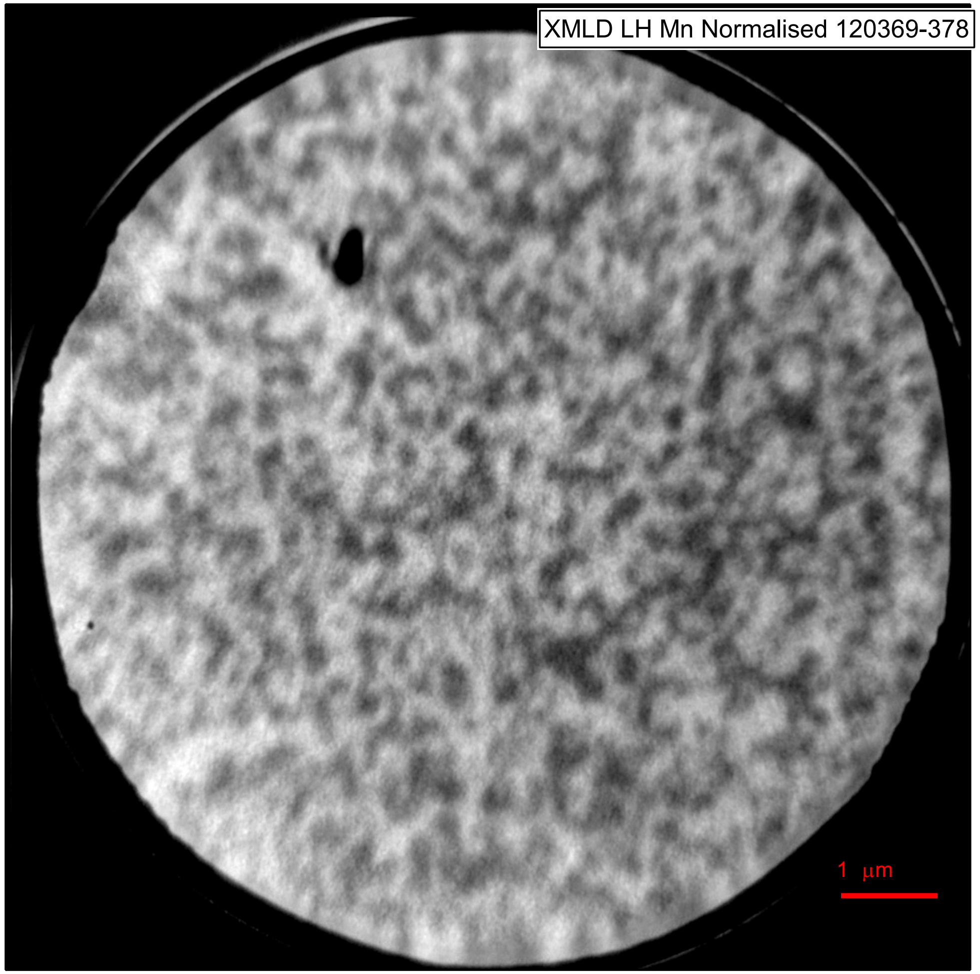


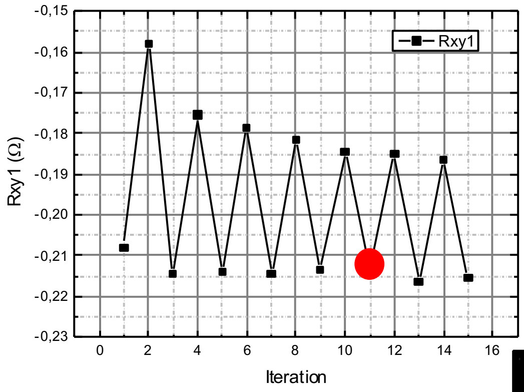


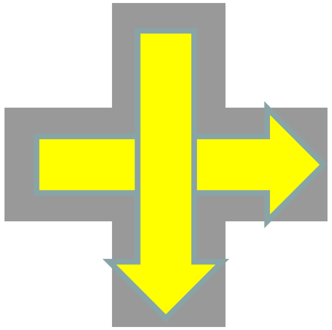



69mA current pulse

(6.1MA/cm$^2$)

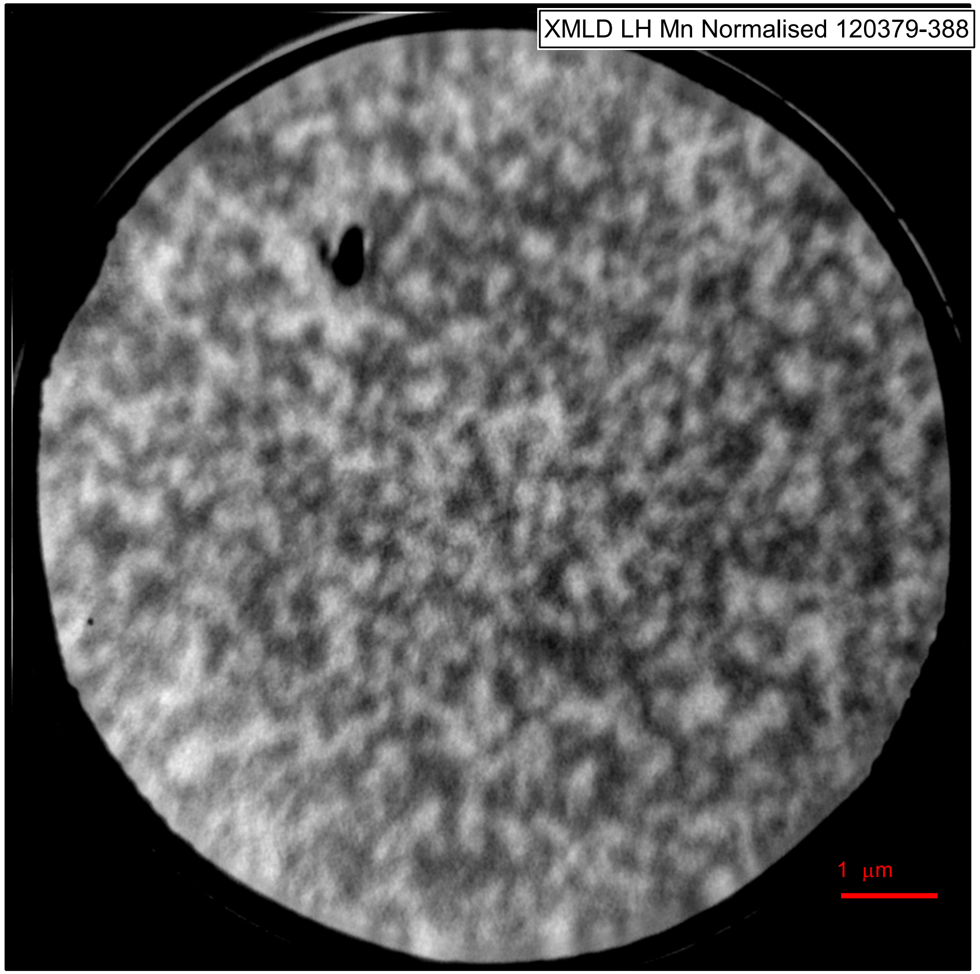


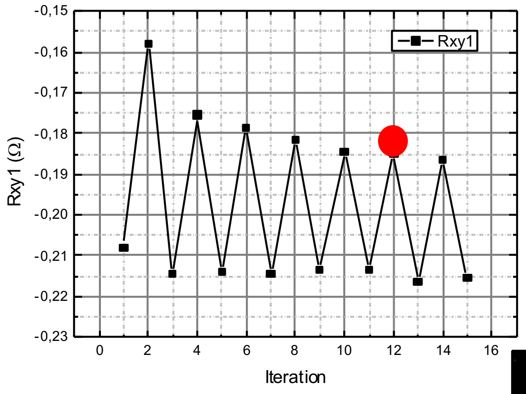


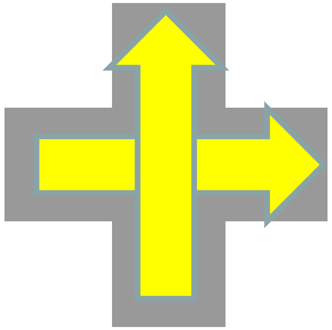



69mA current pulse

(6.1MA/cm$^2$)

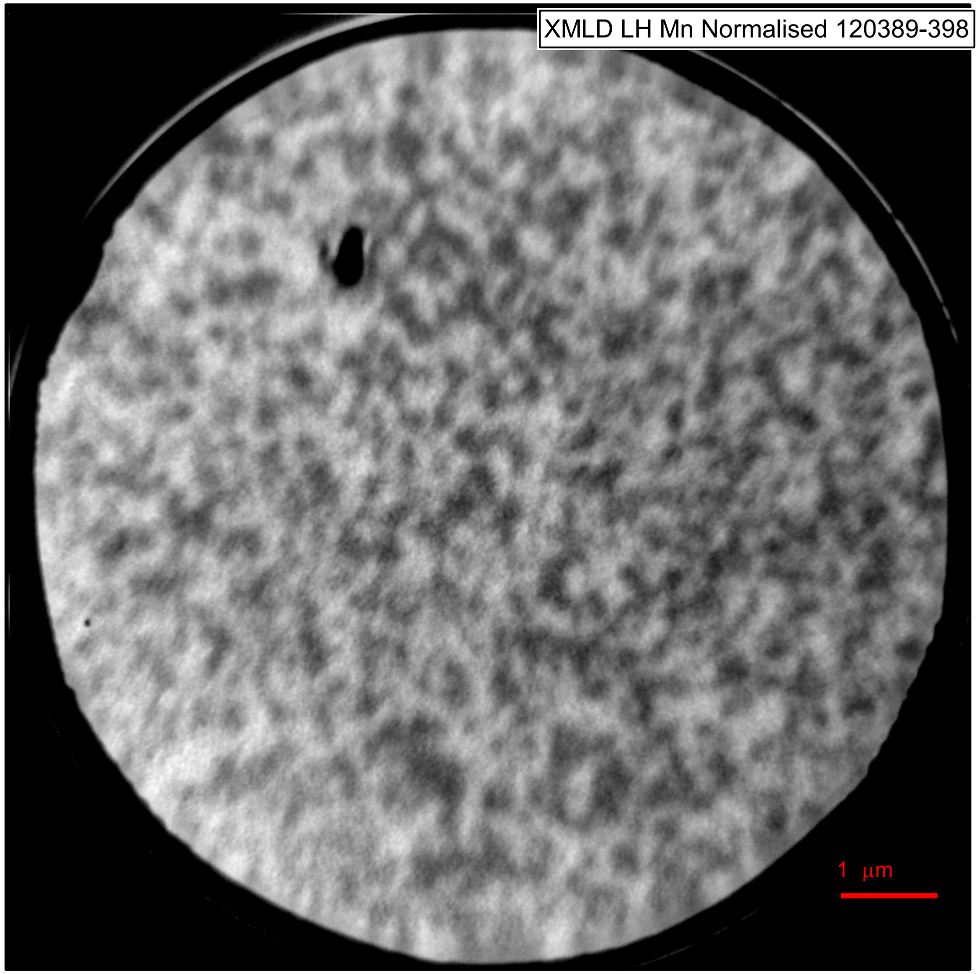


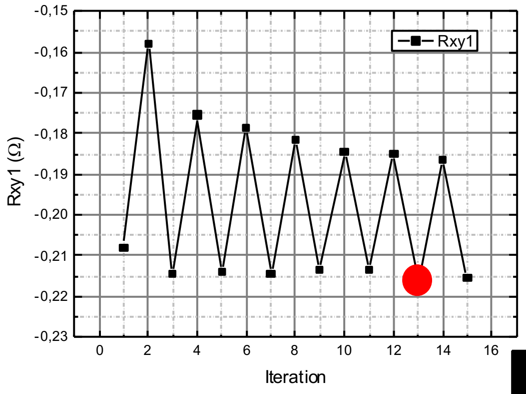


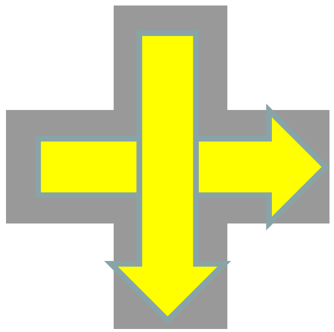



69mA current pulse

(6.1MA/cm$^2$)

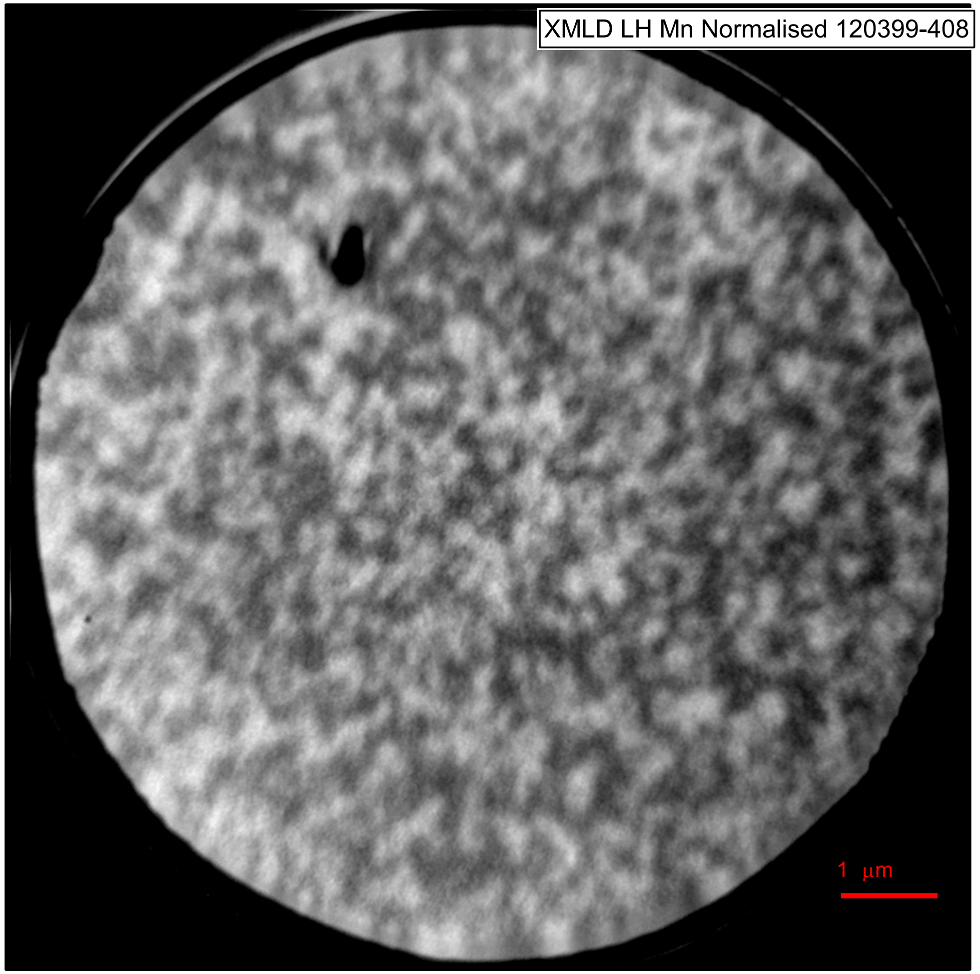


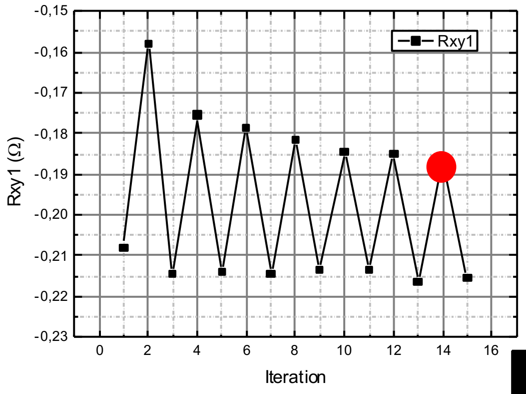


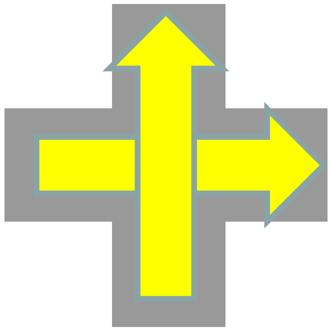



69mA current pulse

(6.1MA/cm$^2$)

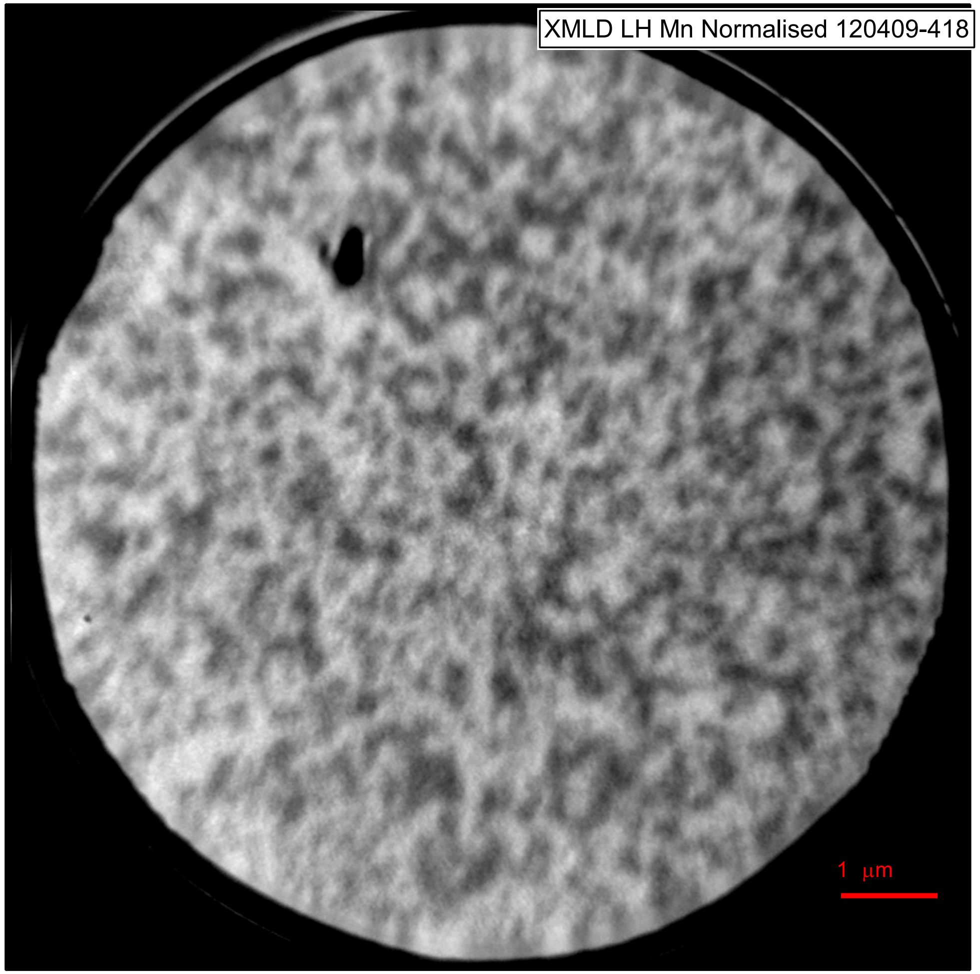


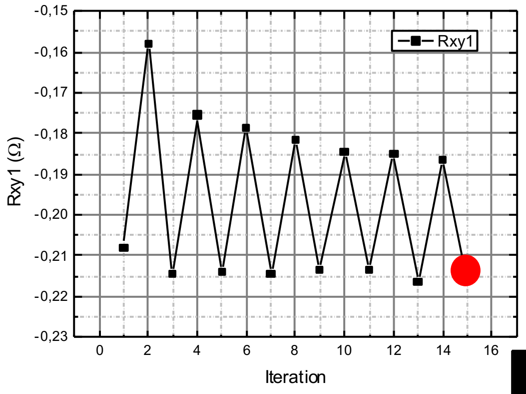


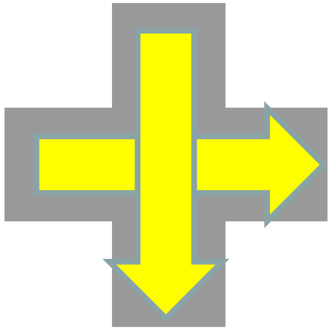



69mA current pulse

(6.1MA/cm$^2$)

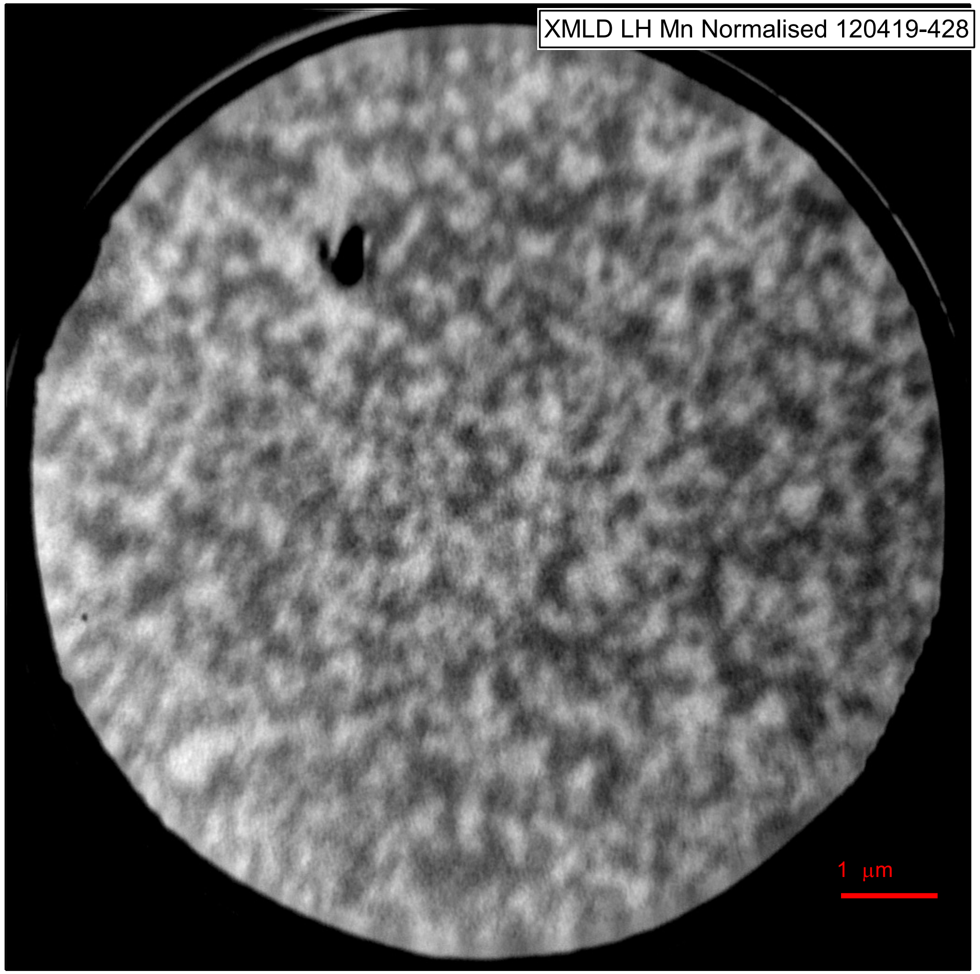




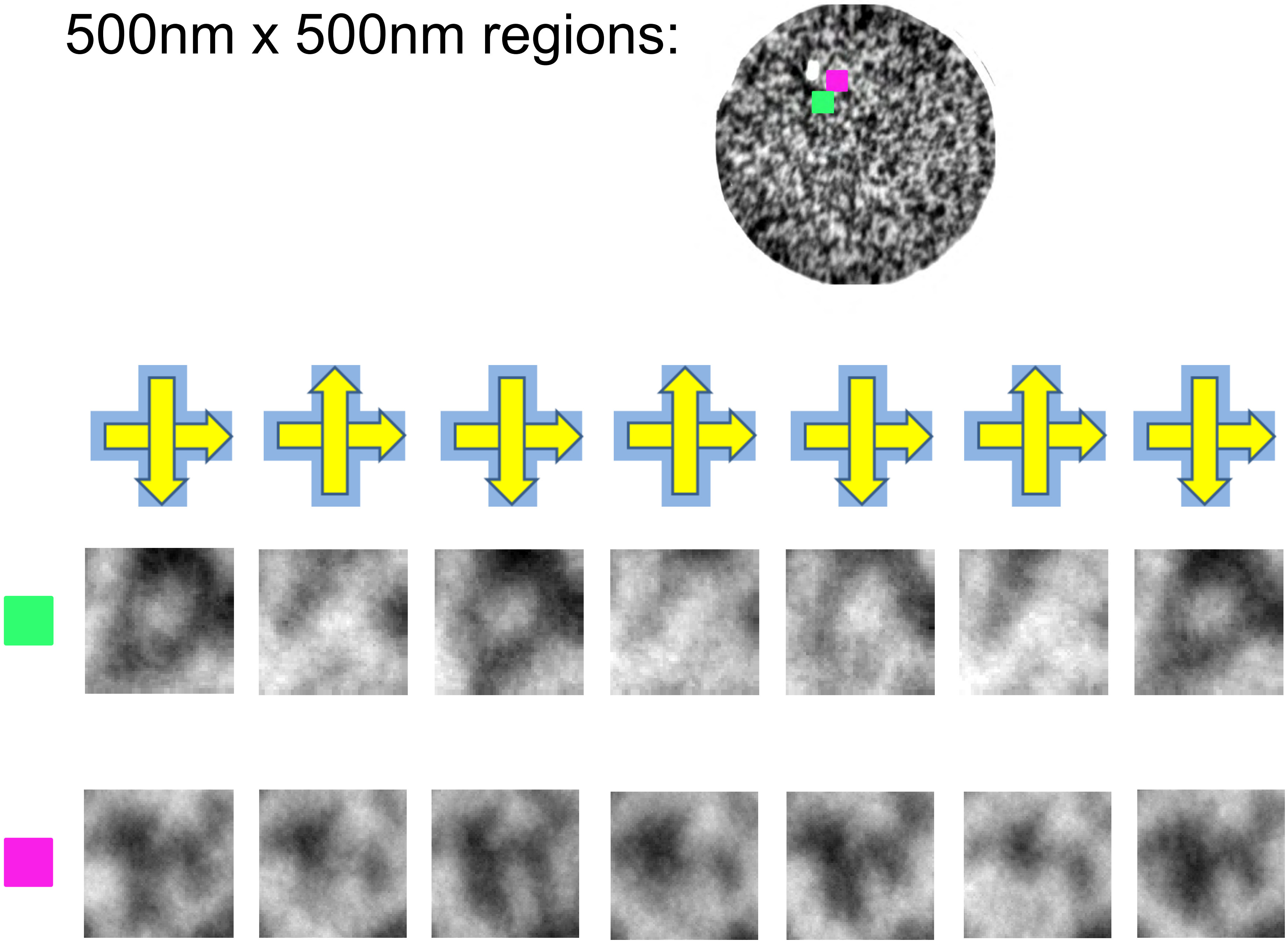



69mA current pulse

(6.1MA/cm$^2$)

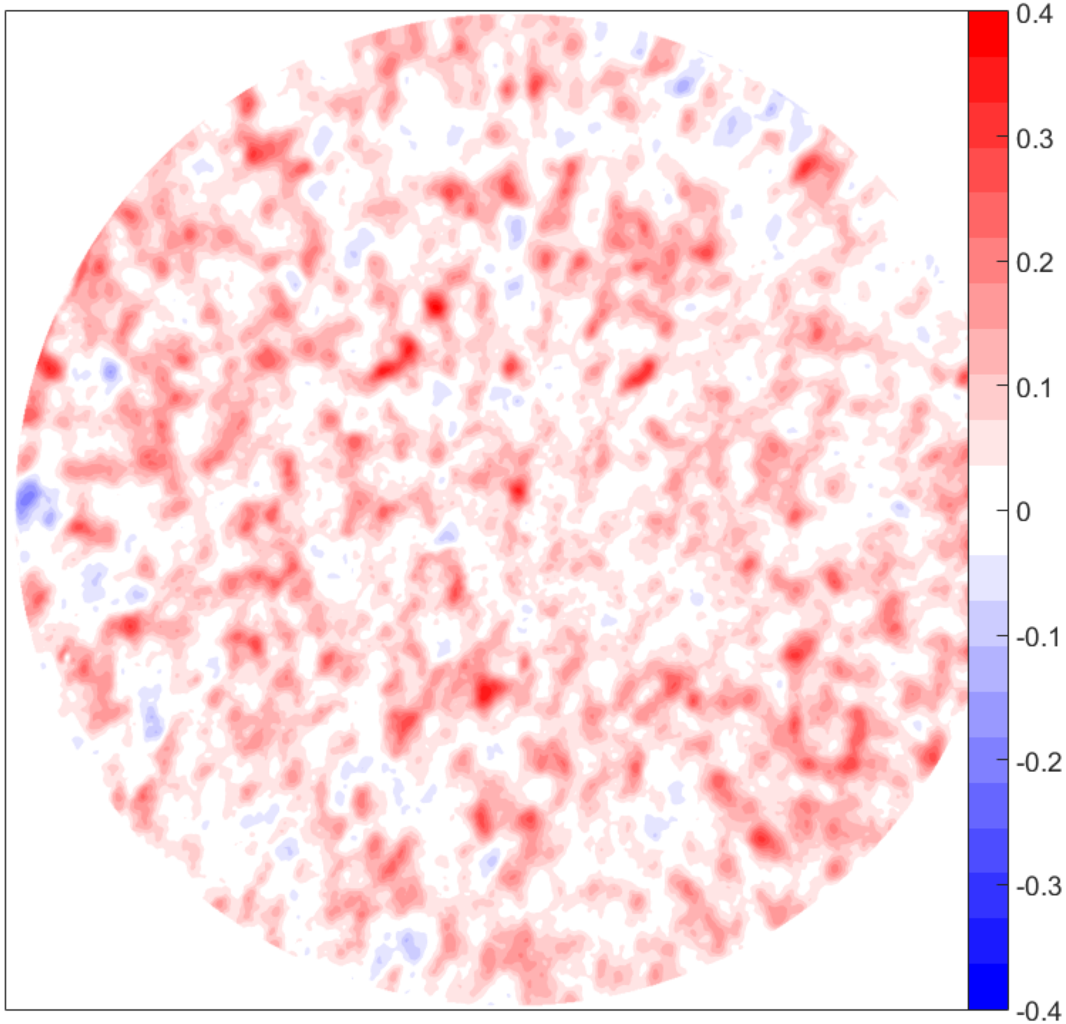


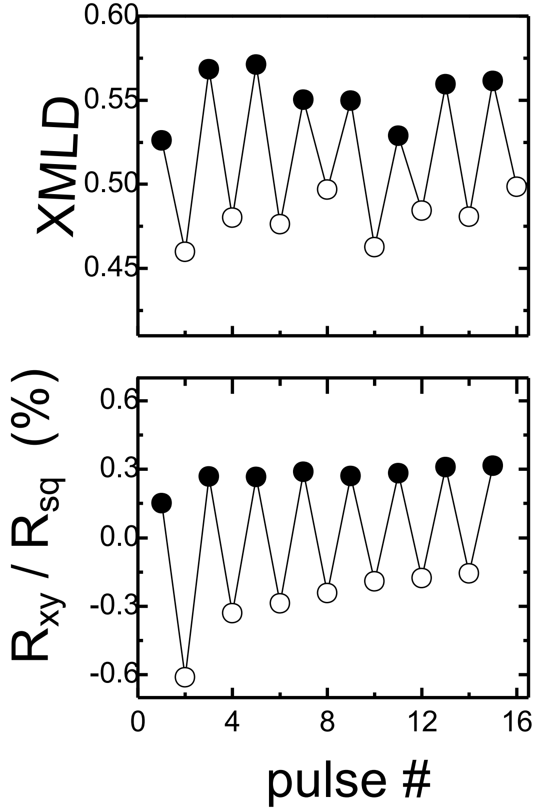
500nm x 500nm regions:



# Average difference

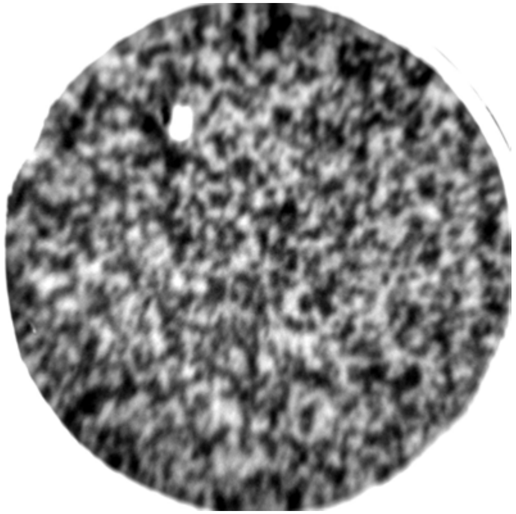
"1" = full switch from "black" to "white"

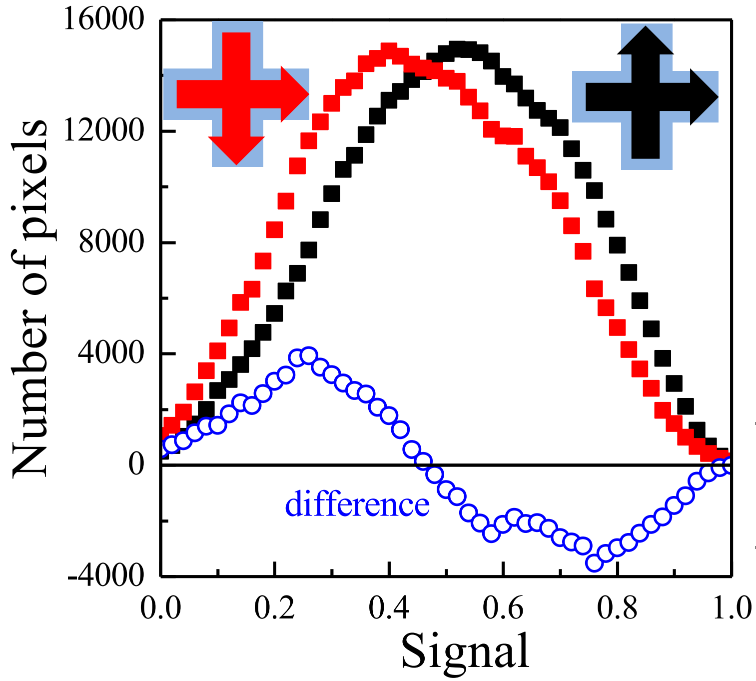


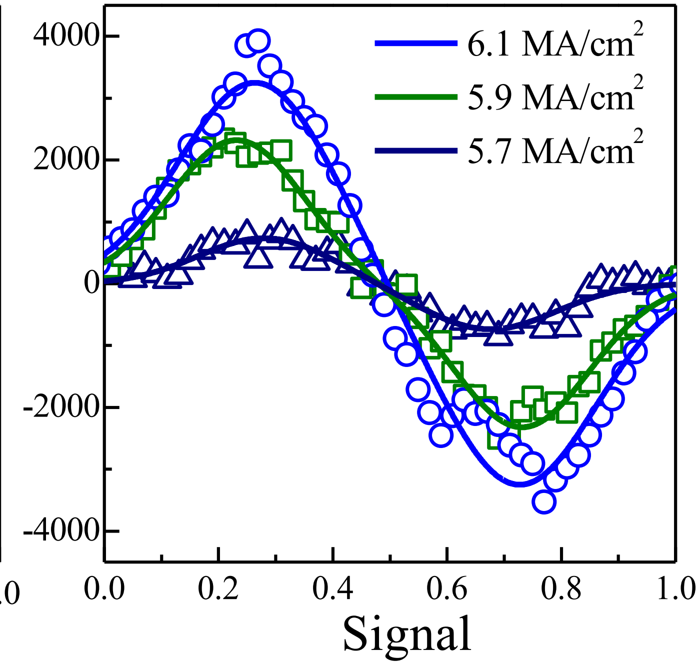




Grzybowski, Wadley, Edmonds, Gallagher, Jungwirth et al
http://arxiv.org/abs/1607.08478

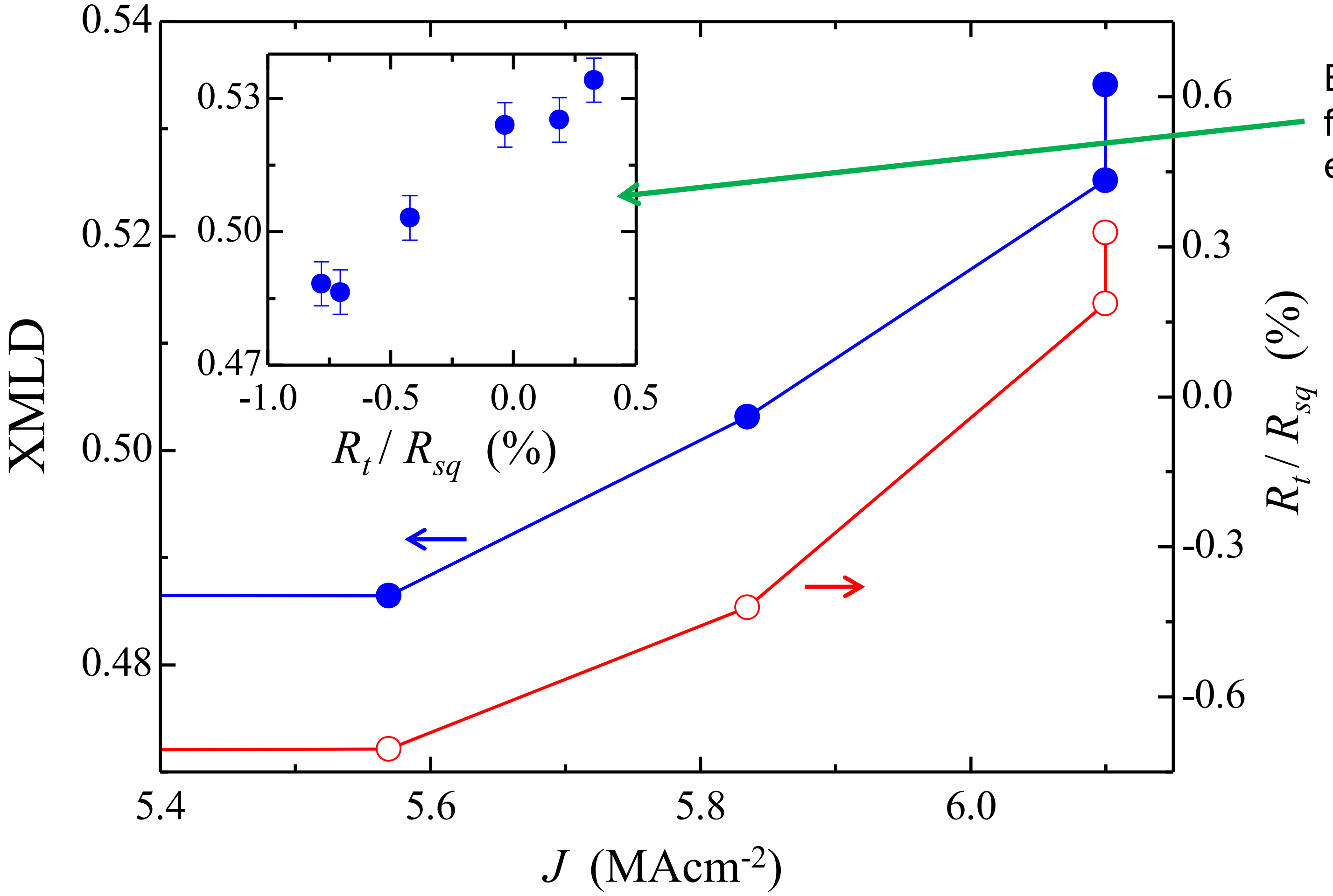
# Distribution functions





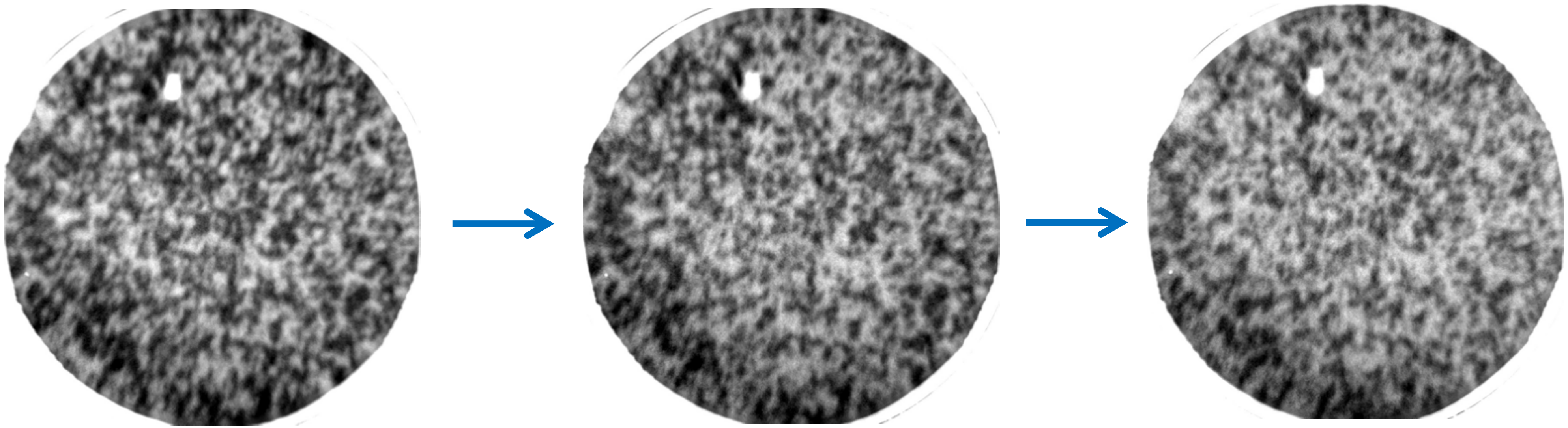




Grzybowski, Wadley, Edmonds,
Gallagher, Jungwirth et al
http://arxiv.org/abs/1607.08478

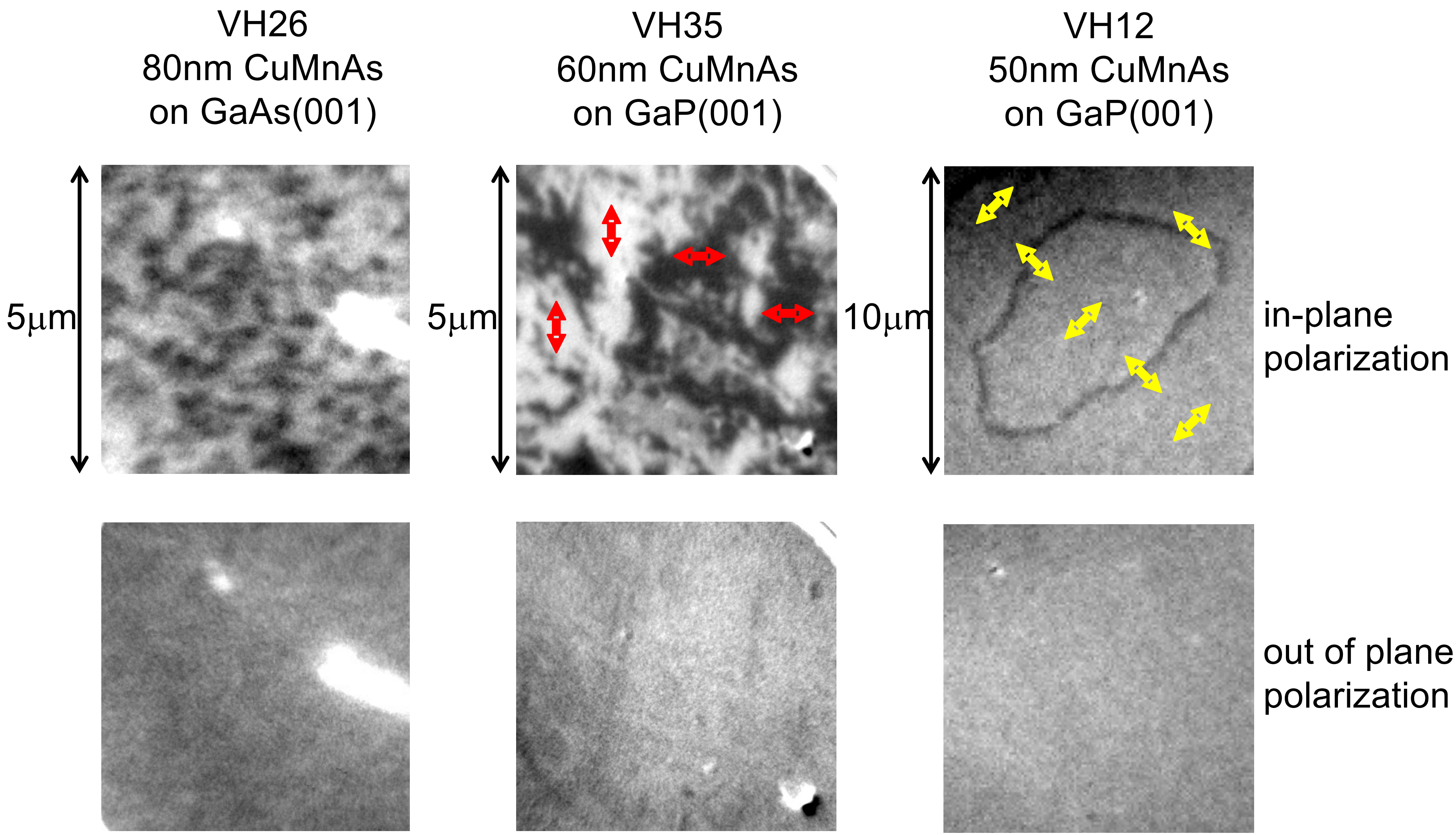



Extrapolating this relationship to full switching yields an expected AMR of 3.0 +/- 1%

Grzybowski, Wadley, Edmonds, Gallagher, Jungwirth et al
http://arxiv.org/abs/1607.08478



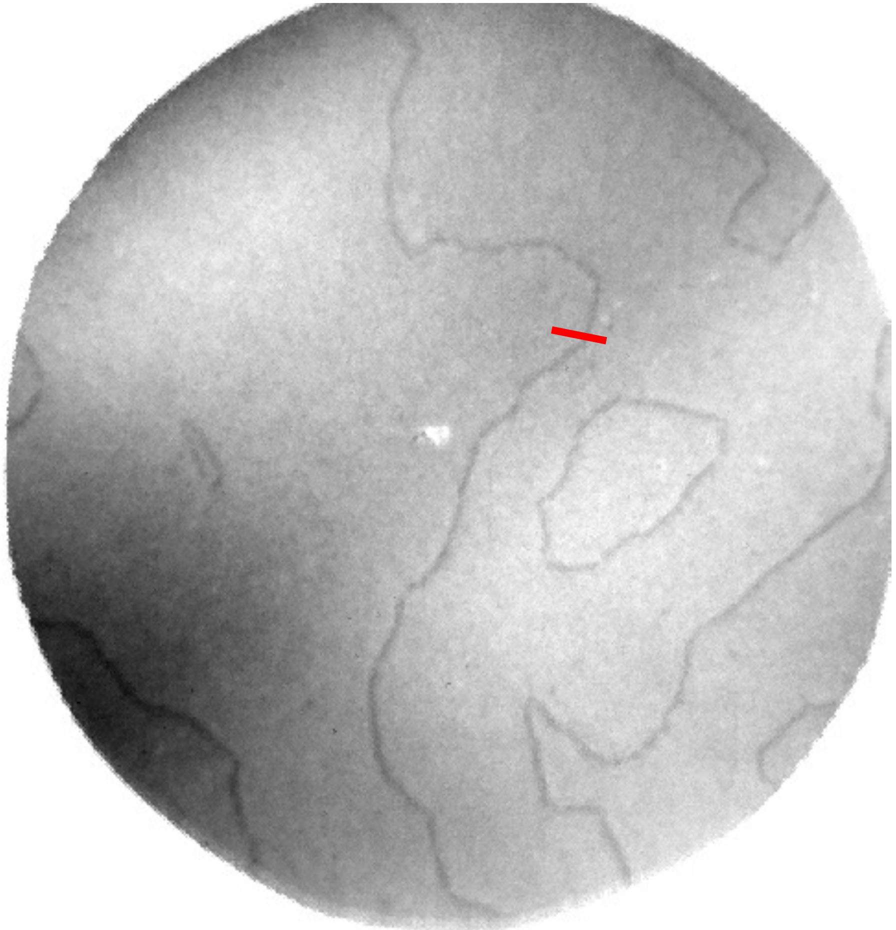
# CuMnAs antiferromagnetic domain structures

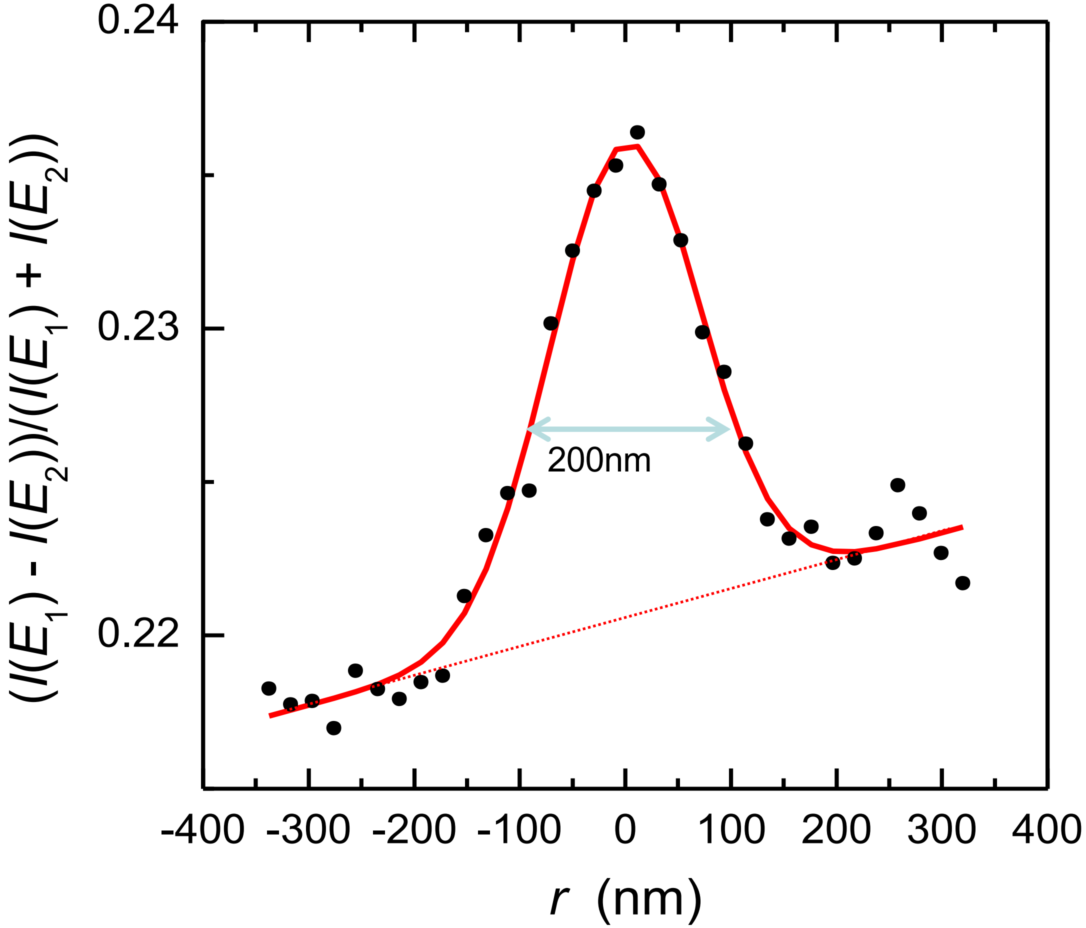


# CuMnAs domain structures

**Thin CuMnAs ( 50nm): uniaxial anisotropy with 180° domain walls**

**40 μm field-of-view**

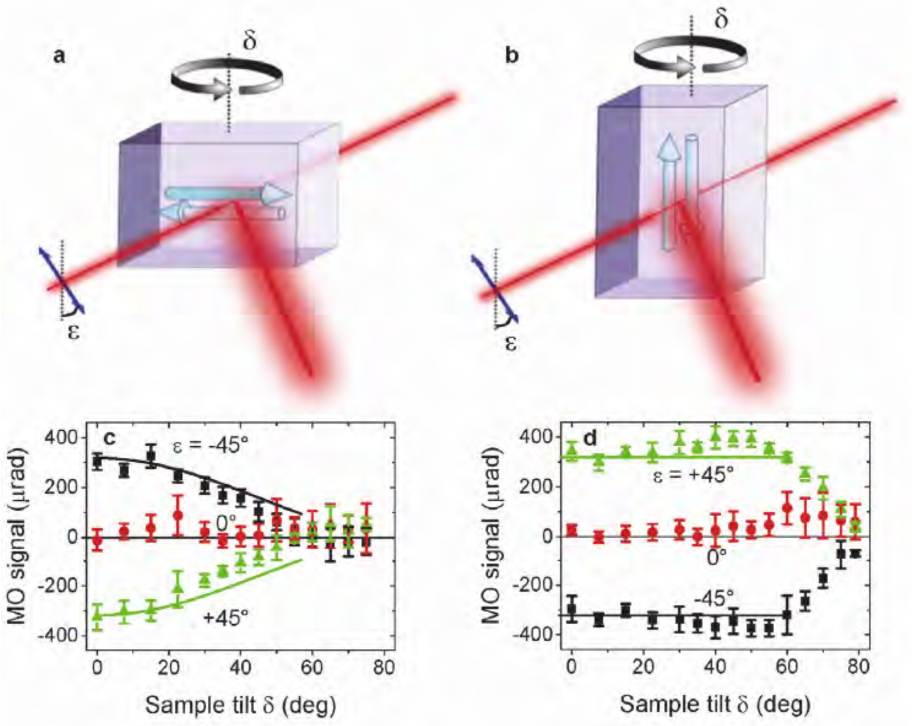


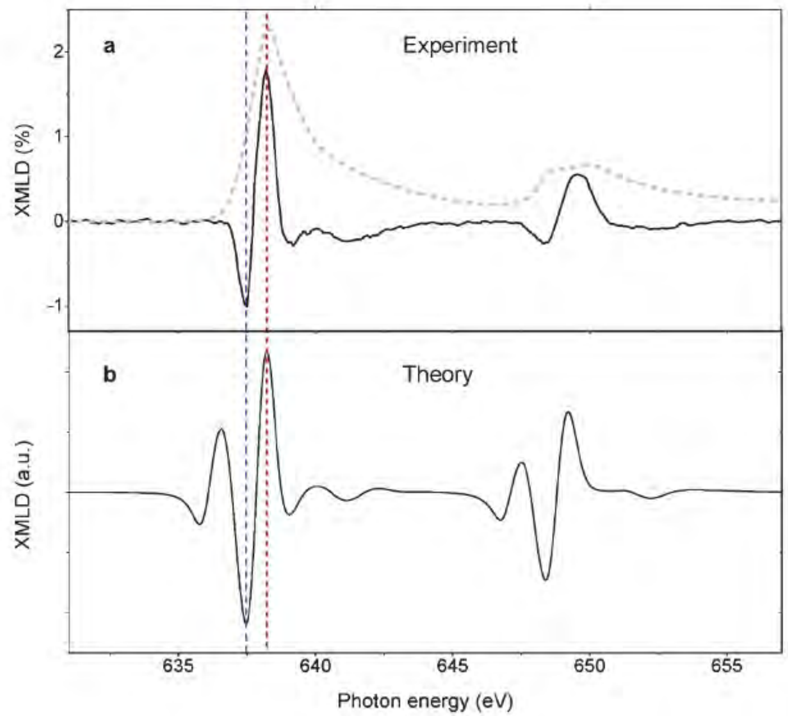



**Uniaxial Domains** **Domain Wall Profile**

*Domain wall velocities limited only by magnon velocity (Gomonay, Jungwirth, Sinova PRL 16)*

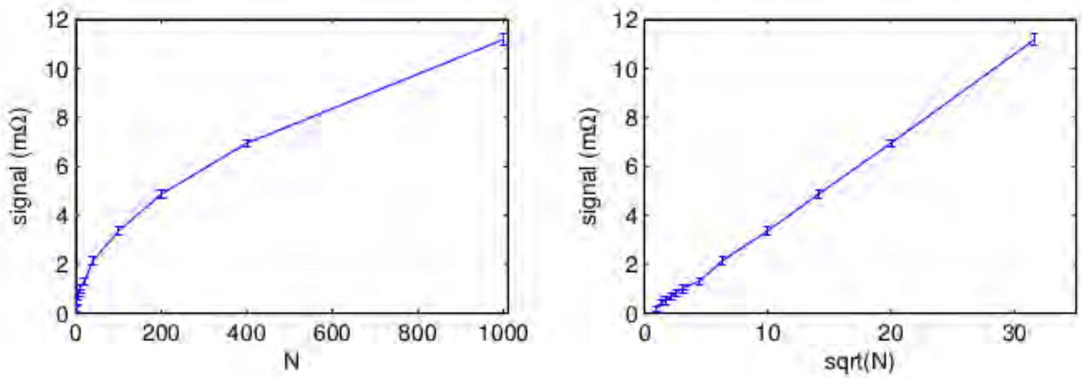
# Optical detection of the spin axis (Poster T5)

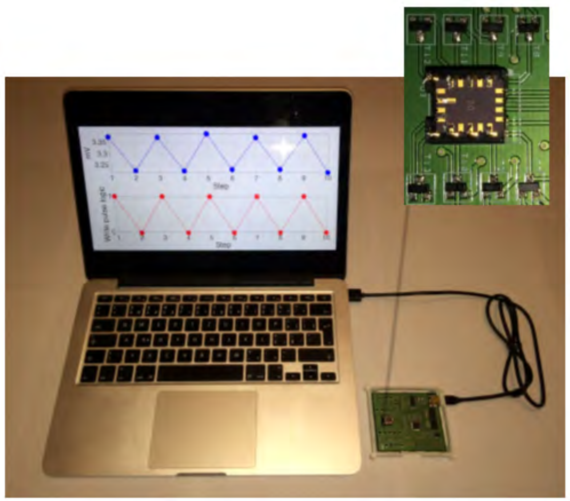



Saidl, Nemec, PW et arxiv 16

Switching using 250ps pulses (Olejnik, Schuler, Marti et al - ETH)



Talks by X. Marti and J. Wunderlich Thursday

*Marti, Olejnik, Schuler , et al.*

# Outlook

- Incredible tool to study the domain behaviour and dynamics of antiferromagnets
- Switching with 250ps pulses achieved with very little optimisation
- Multi-level memory cell demonstrated
- Picosecond switching expected for coherent reorientation and domain wall motion
- Optical reading of the Neel vector demonstrated (Saidl, Nemec, PW et al)
- Insensitive to external fields