Electrical manipulation of Antiferromagnets by spin-orbit torque

(inverse spin galvanic effect and spin Hall effect (if time))

Jörg Wunderlich

Hitachi Cambridge Laboratory, (Cambridge, UK)
Institute of Physics, Academy of Sciences of the Czech Republic, Prague. CR

Institute of Physics ASCR, Prague

Tomas Jungwirth
Vit Novák
Kamil Olejník
Xavi Marti
V. Schuler
Helena Reichlová
Dominik Kriegner
Jakub Šeleznð
Libor Ł mejkal
Frantił ek Máca
Jan Mał ek
Alexander Shick

Forschungzentrum Jülich

Frank Freimuth
Yuriy Mokrousov

University of Mainz

Helen Gomonay
Jairo Sinova

University of Nottingham

Pete Wadley
Bryan Gallagher
Richard Campion
Tom Foxon
Kevin Edmonds
Andrew Rushforth
Bryn Howells
Victoria Hills
Michal Grzybowski

Hitachi & Cavendish Laboratories in Cambridge

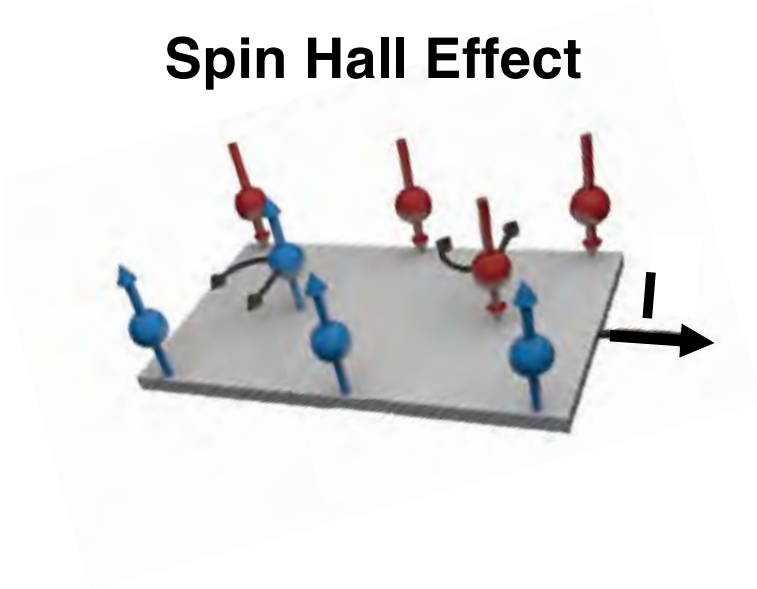
Pierre Roy
Ruben Otxoa
Thomas Wagner

Chiara Ciccarelli
Andrew Ferguson
Vahe Tshitoyan
Andrew Irvine

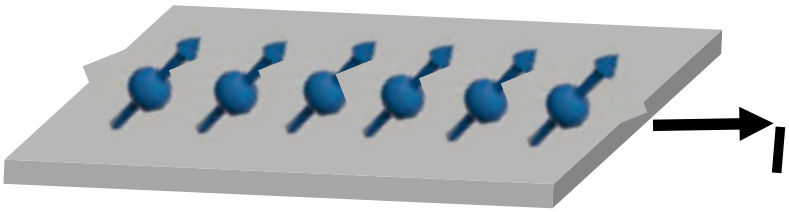
European Research Council

Transfer from linear momentum to spin angular momentum

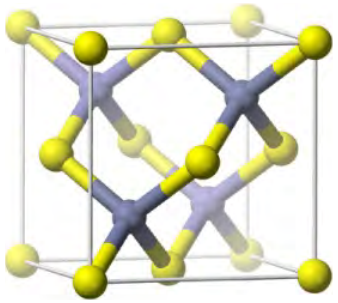
Spin Hall Effect



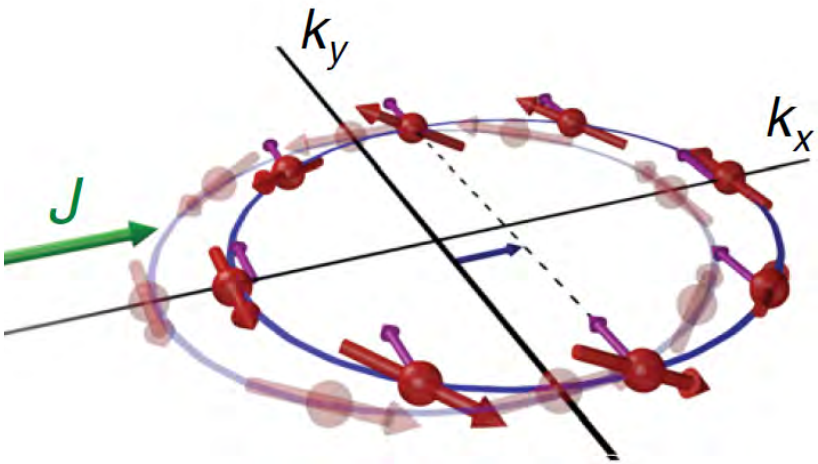
inverse spin-galvanic Effect (Edelstein Effect)



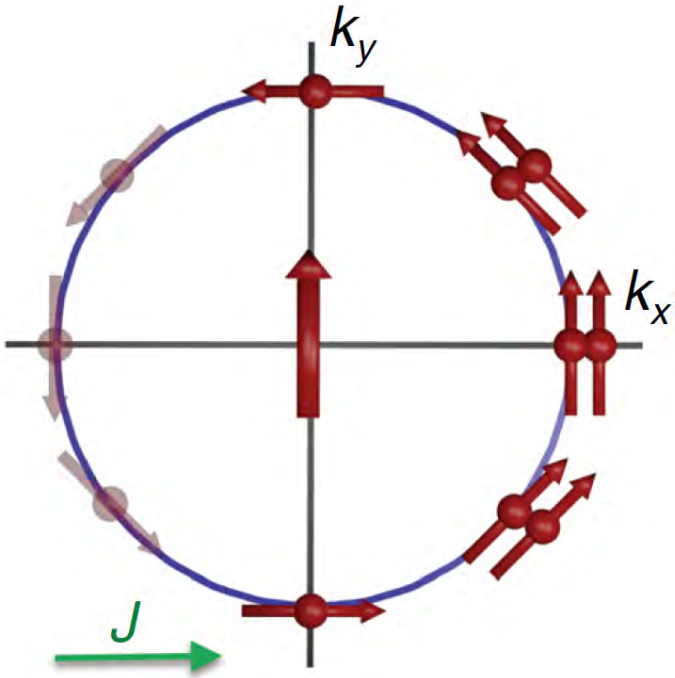
$\hat{H} = c\vec{p} \cdot \vec{\sigma}$



Inversion asymmetry



(intuitive picture for intrinsic SHE)



(intuitive picture for iSGE)

Electrical manipulation of antiferromagnets

Interfacial SHE Torque in Antiferromagnets

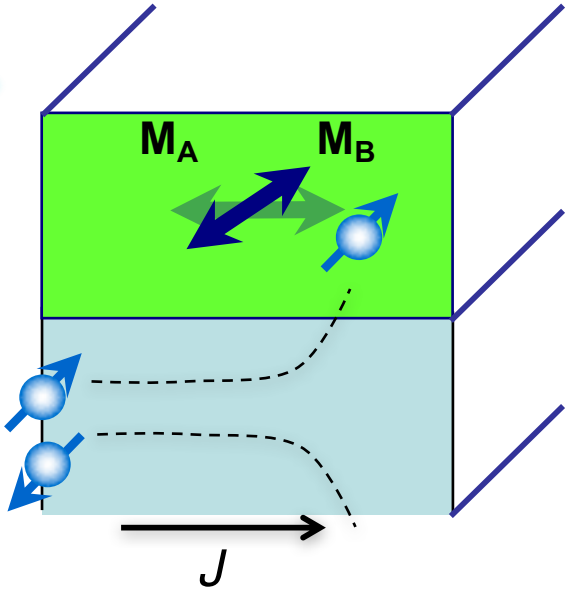
Gomonay & Loktev, Low Temp. Phys. '14, MacDonald & Tsoi, Philos. Trans. A PRL '11

Requires thin AFM (spin absorption at interface)

Field like torque

$$\vec{T}_A^{FIELD} \sim \vec{M}_A \times \vec{\sigma}_\perp$$

$$\vec{T}_B^{FIELD} \sim \vec{M}_B \times \vec{\sigma}_\perp$$



Antidamping like torque

$$\vec{T}_A^{AD} \sim \vec{M}_A \times (\vec{\sigma}_\perp \times \vec{M}_A)$$

$$\vec{T}_B^{AD} \sim \vec{M}_B \times (\vec{\sigma}_\perp \times \vec{M}_B)$$

Very inefficient!!!

Staggered field

Efficient to couple to the staggered AF order of the AFM !

Electrical manipulation of antiferromagnets

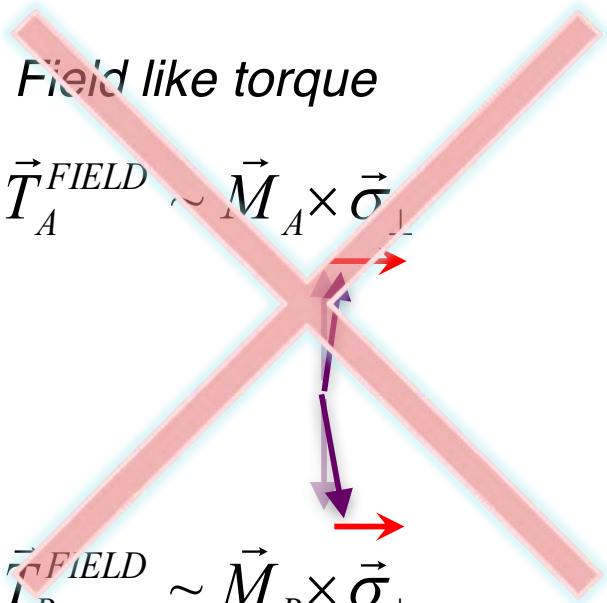
Interfacial SHE Torque in Antiferromagnets

Gomonay & Loktev, Low Temp. Phys. '14, MacDonald & Tsoi, Philos. Trans. A PRL '11

Olena Gomonay's 2nd lecture
(Monday afternoon)

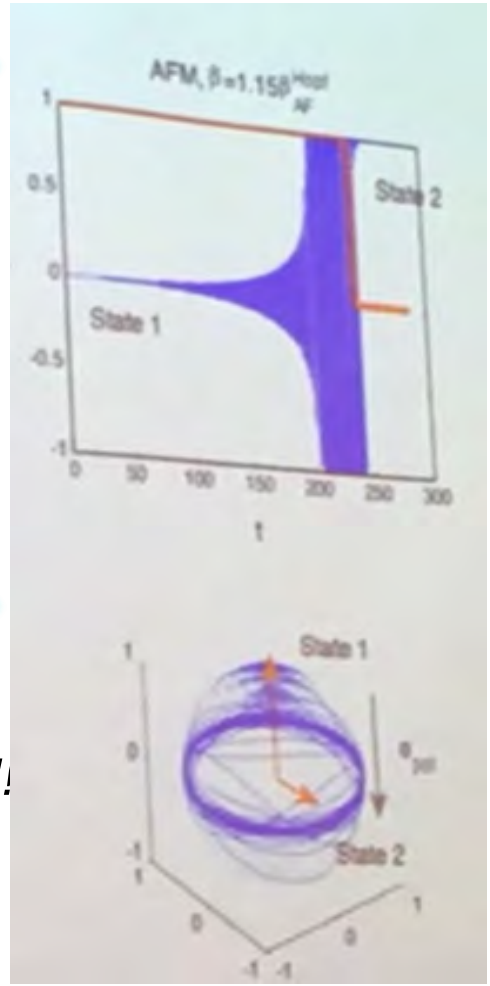
Field like torque

$$\vec{T}_A^{FIELD} \sim \vec{M}_A \times \vec{\sigma}_\perp$$



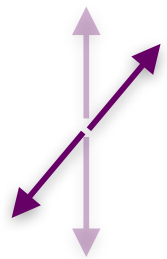
$$\vec{T}_B^{FIELD} \sim \vec{M}_B \times \vec{\sigma}_\perp$$

Very inefficient!!



Antidamping like torque

$$\vec{T}_A^{AD} \sim \vec{M}_A \times (\vec{\sigma}_\perp \times \vec{M}_A)$$

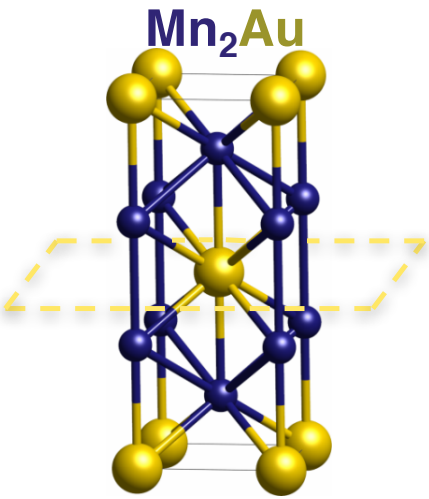


$$\vec{T}_B^{AD} \sim \vec{M}_B \times (\vec{\sigma}_\perp \times \vec{M}_B)$$

Electrical manipulation of antiferromagnets

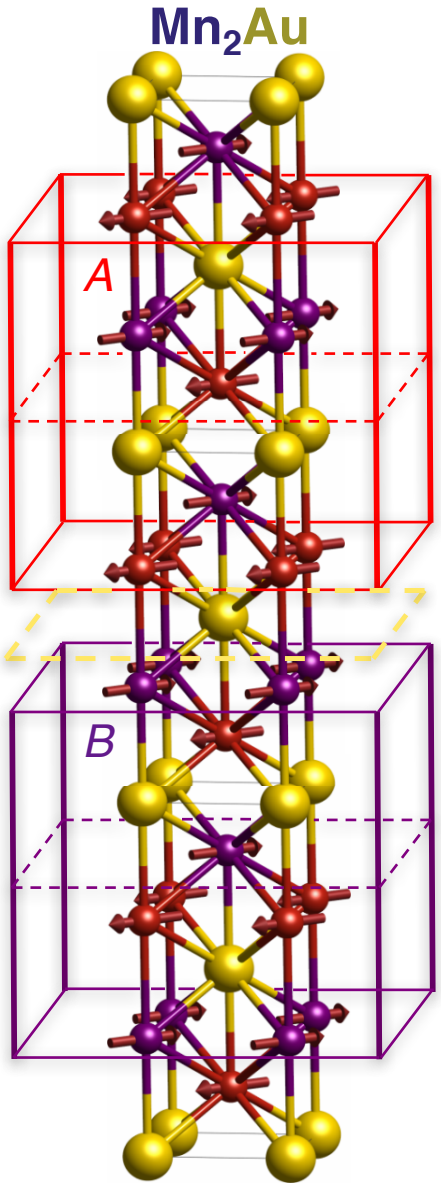
Field-like **iSGE torque** in antiferromagnets with local IA

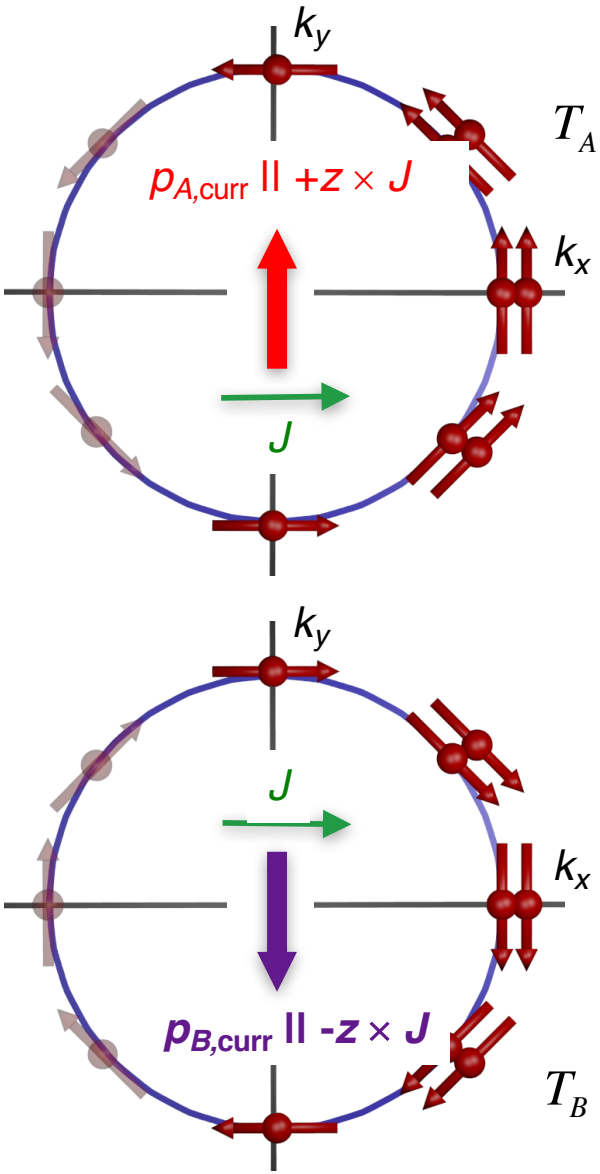
J. Zelezny, et al. PRL '14



Centro-symmetric lattice → no net iSGE

Staggered Field-like SOT in Mn_2Au





J. Zelezny, et al. PRL '14

$$T_A \sim M_A \times p_{A,curr}$$

H_A

→ effective fields are **staggered**

H_B

M_A M_B

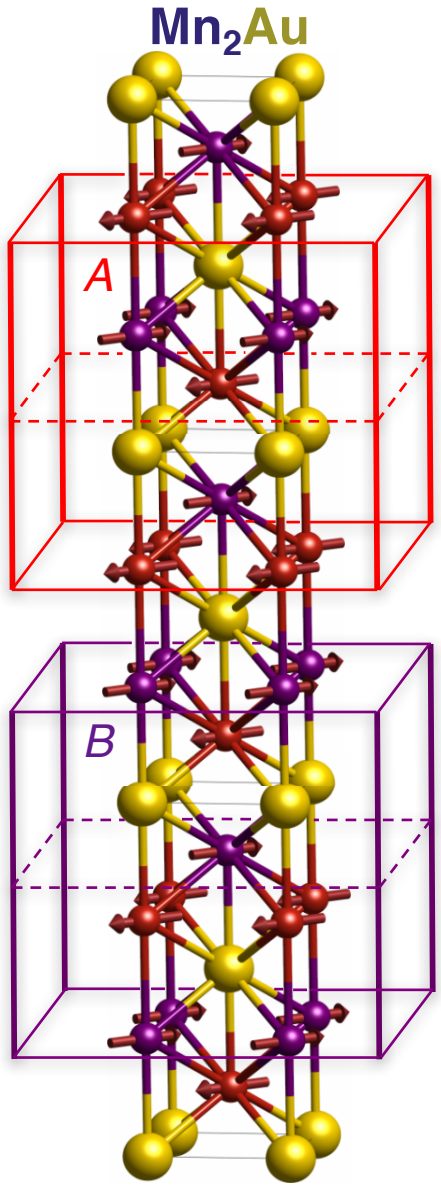
$\vec{T}_A$ $\vec{T}_B$

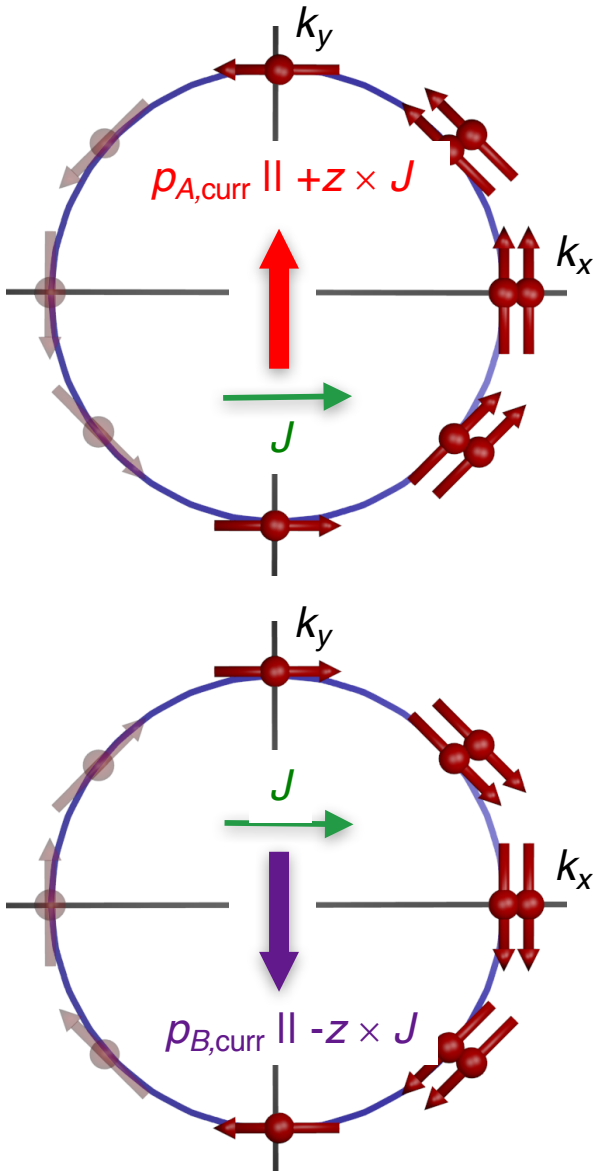
→torques are equal

$$T_B \sim M_B \times p_{B,curr}$$

Non-centro-symmetric sublattices → Néel-order (alternating-sign) $p_{A/B,curr}$

Field-like iSGE torque in Antiferromagnets



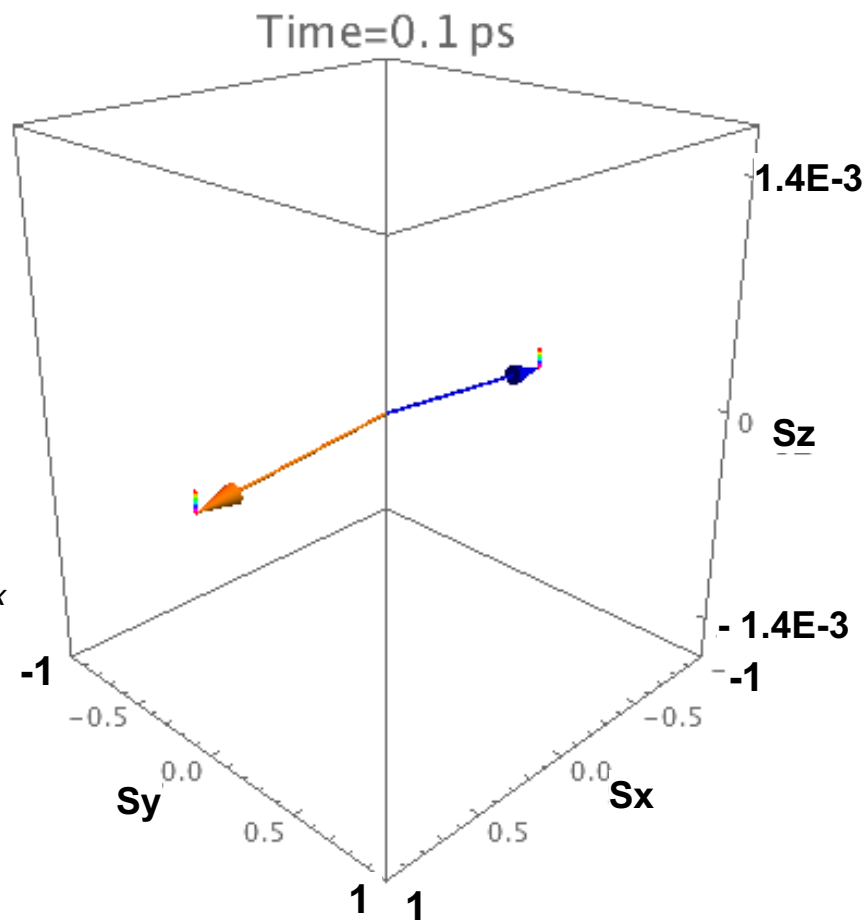


J. Zelezny, T. Jungwirth, J. W., et al. PRL '14

Fast in-plane AFM dynamics

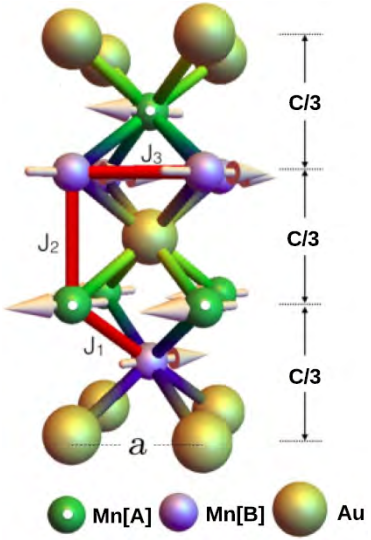
$$\mu_0 \vec{H}^{so}_{A/B} = +/-7\,\text{mT}\ \hat{y} \quad \mu_0 H^{an.}_{biax.} = 10\,\text{mT}$$

α=0.001



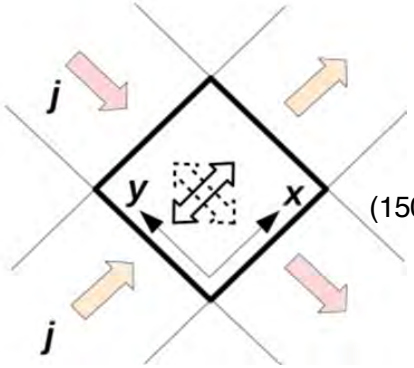
Non-centro-symmetric sublattices ➔ Néel-order (alternating-sign) $p_{A/B,curr}$

Staggered Field induced switching in bi-axial Mn_2Au



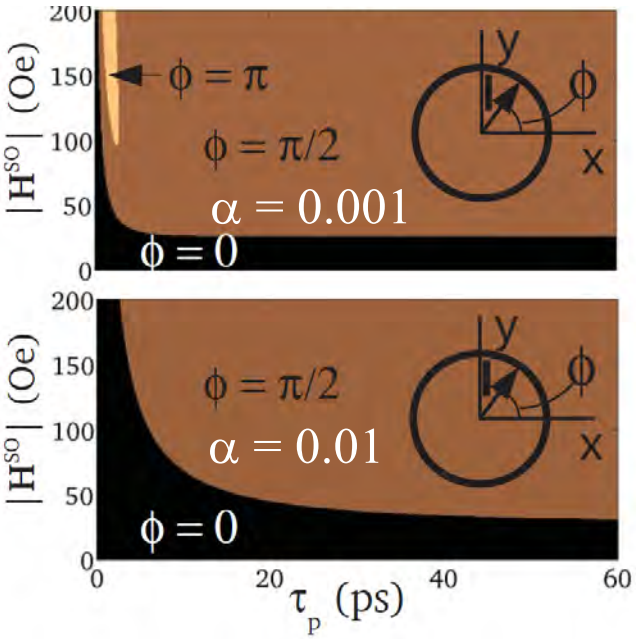
P. E. Roy, R. M. Otxoa, and J. Wunderlich, PRB '16

atomistic spin dynamics calculation

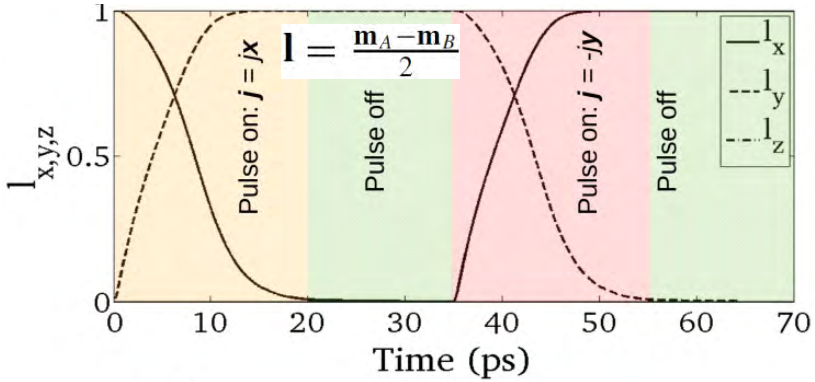


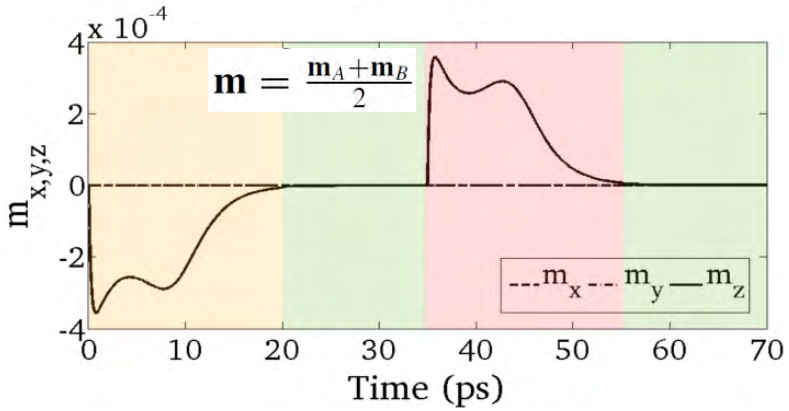
(150 x 150 x 5 unit cells)

Little chance of overshooting

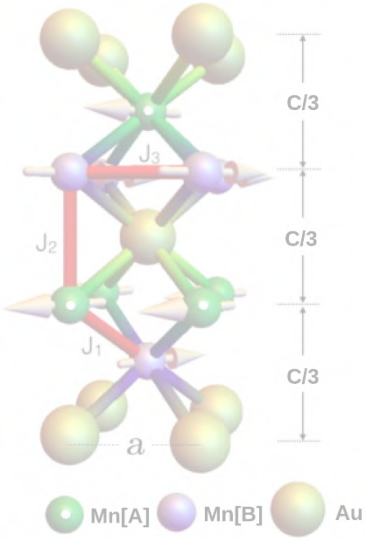


$\mu_0 H^{so}_{A/B} = +/-10$ mT (j = 5E7 A/cm^2), α=0.001





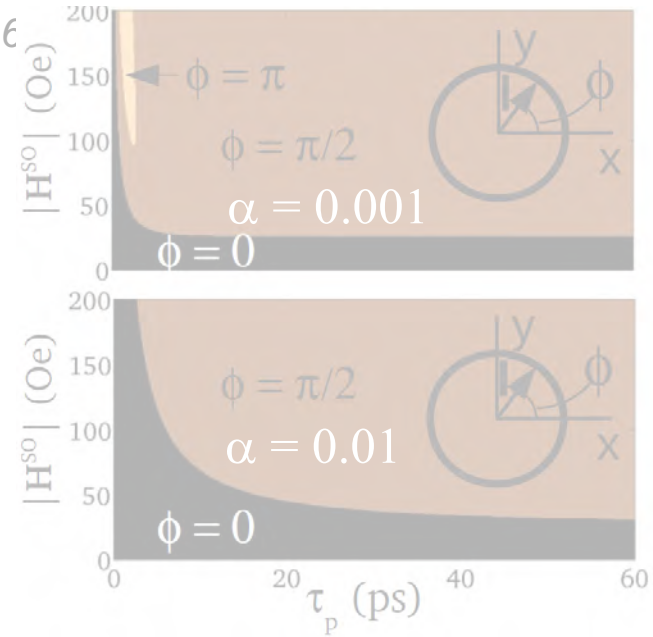
Staggered Field induced switching in bi-axial Mn_2Au



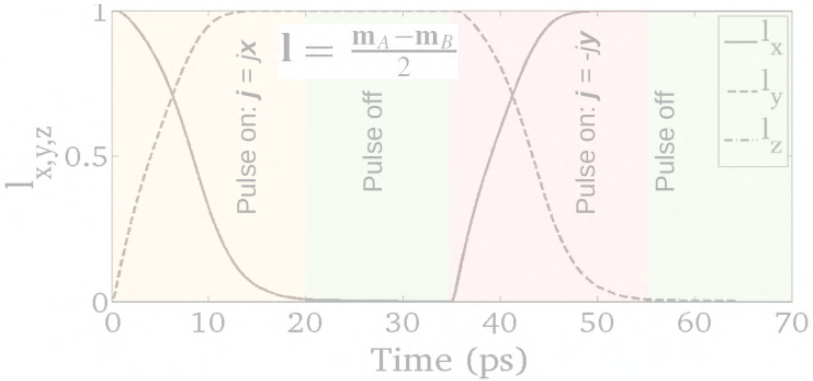
P. E. Roy, R. M. Otxoa, and J. Wunderlich, PRB '16

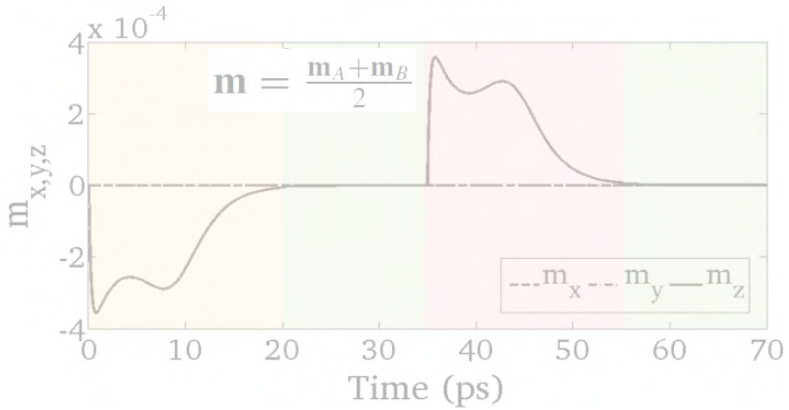
(atomistic spin dynamics calculation)

Little chance of overshooting



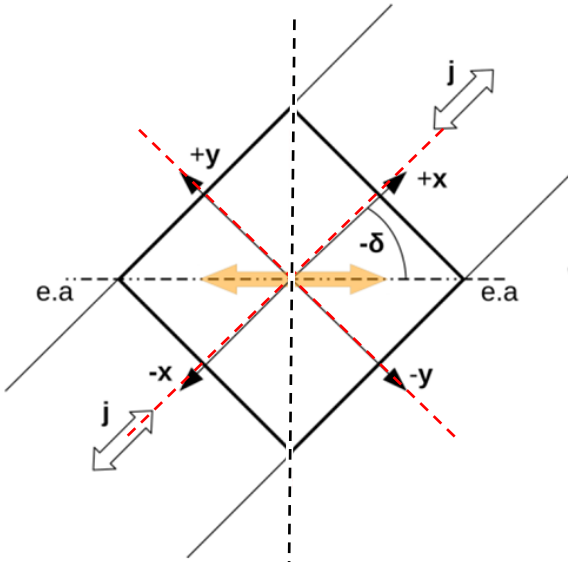
$\mu_0 H^{so}_{A/B} = +/-10$ mT (j = 5E7 A/cm^2), α=0.001



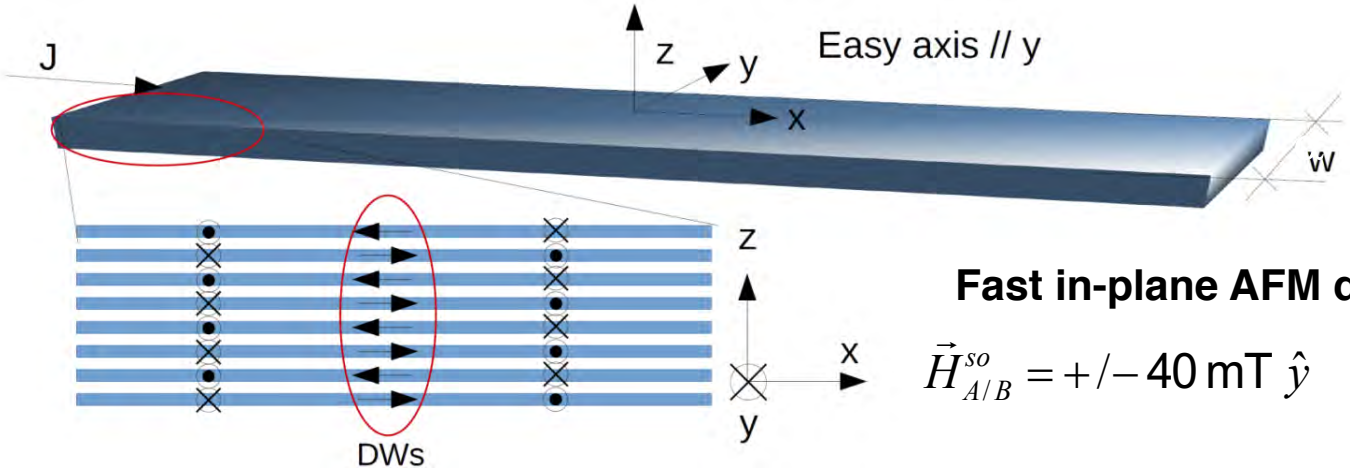


2 terminal device (current polarity dependent)

- bi-axial anisotropy (tuned pulses – overshooting)
- **uni-axial anisotropy at arbitrary long pulses**

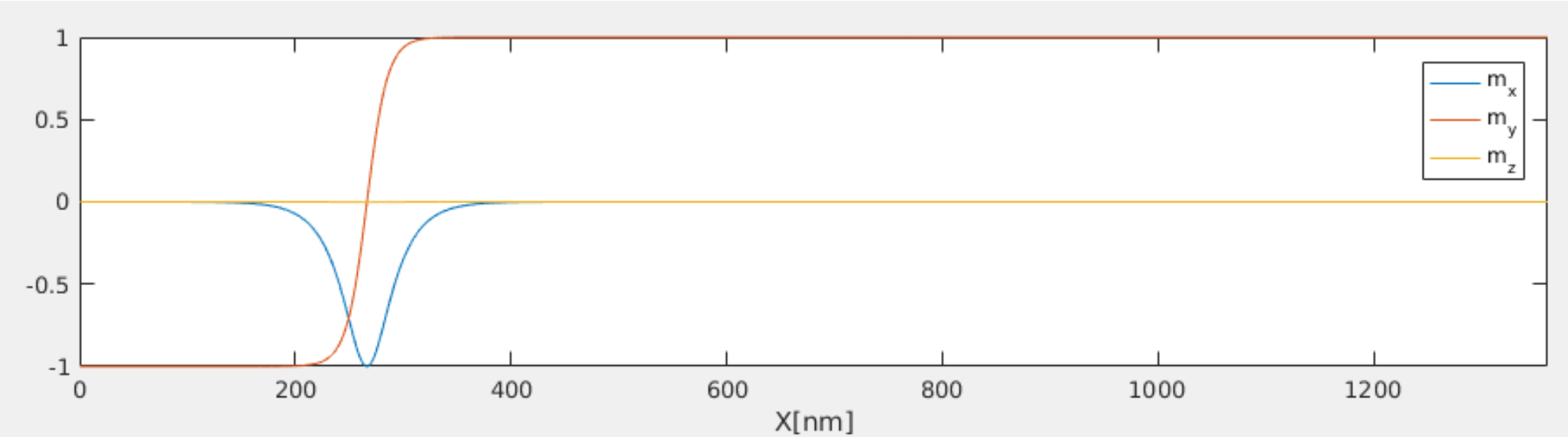


Staggered Field induced domain wall motion in the basal plane of uni-axial Mn_2Au



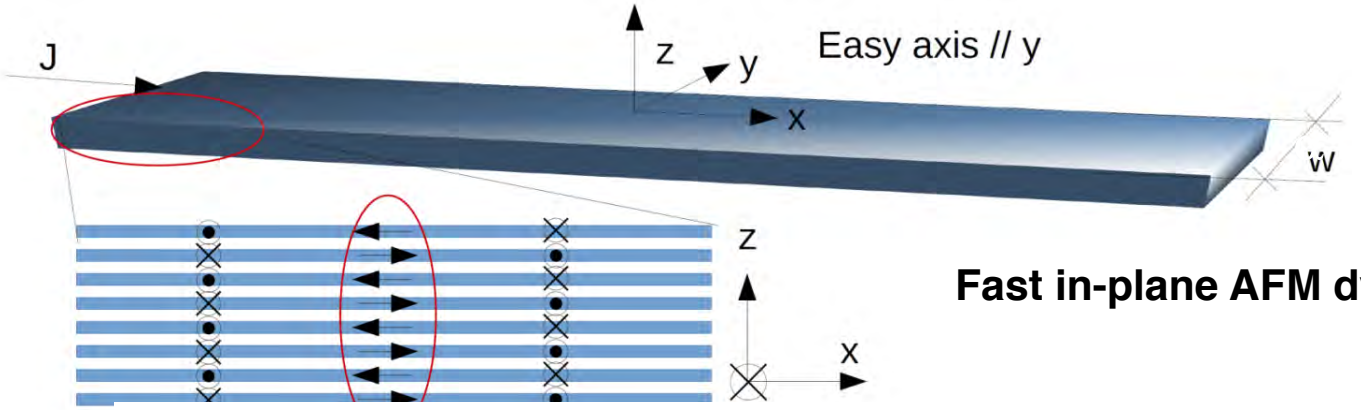
Fast in-plane AFM dynamics

$$\vec{H}^{so}_{A/B} = +/-40\,\text{mT}\ \hat{y} \quad \vec{H}^{an.}_{uniax.} = 70\,\text{mT}$$

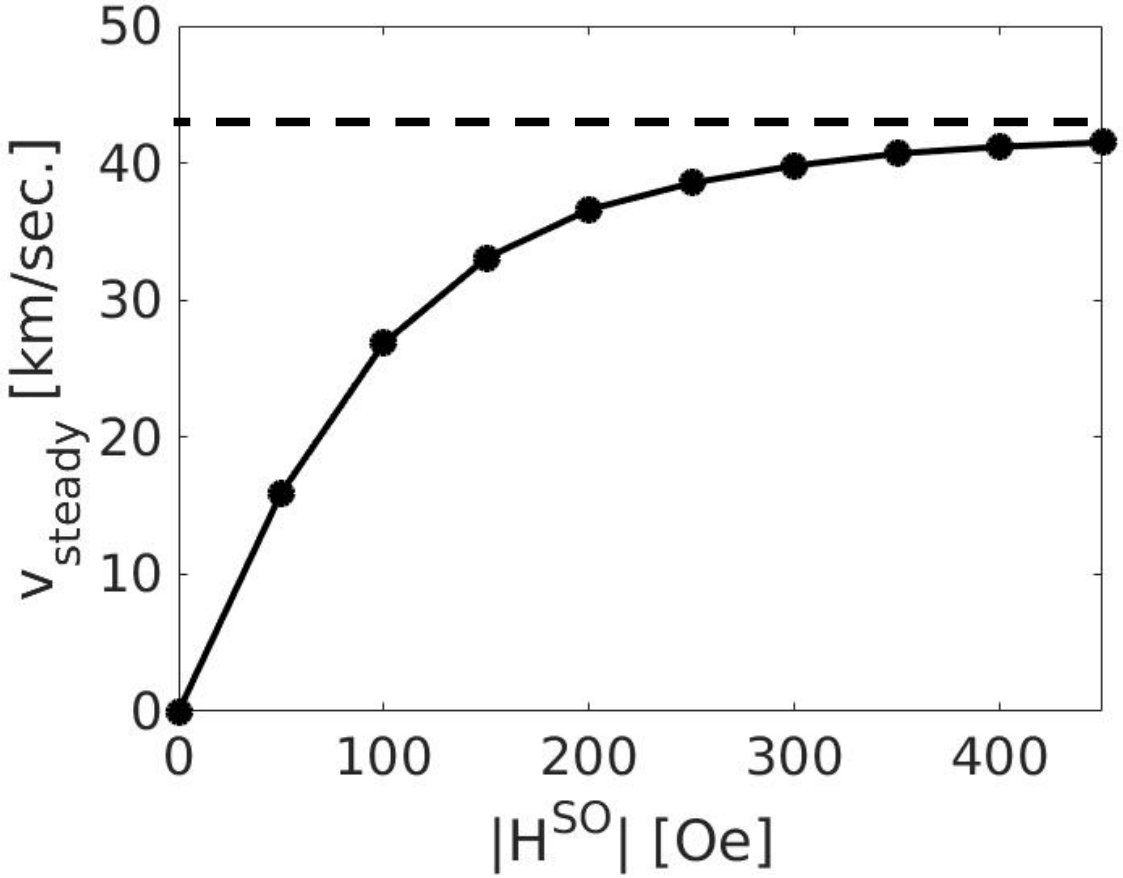


V_{DW} ~ 41 km/s

Staggered Field induced domain wall motion in the basal plane of uni-axial Mn_2Au



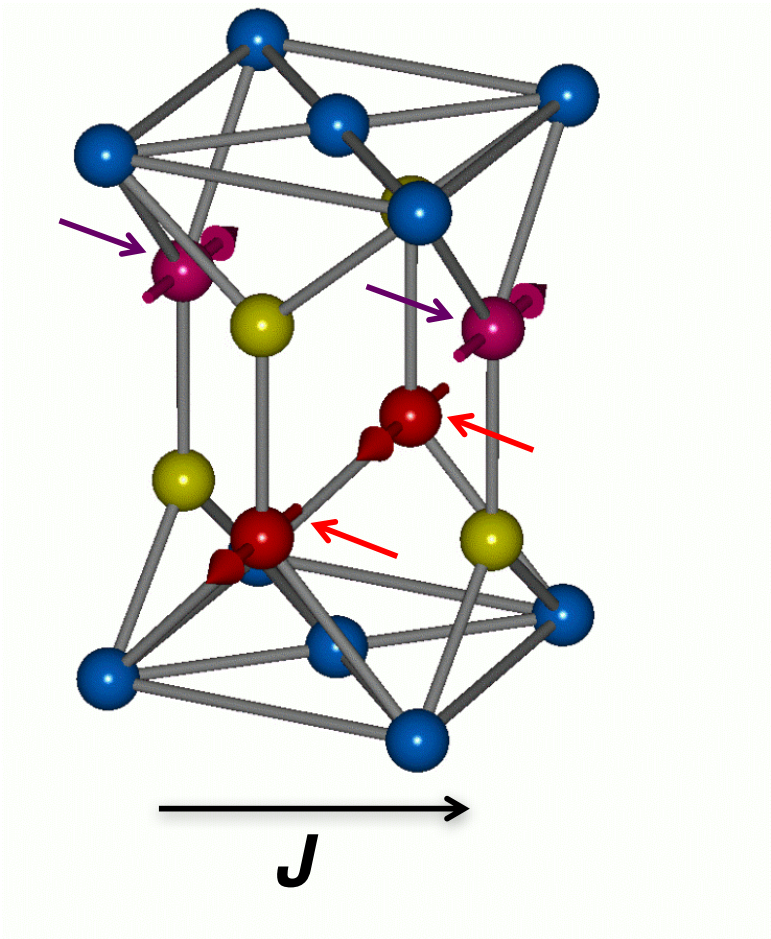
Fast in-plane AFM dynamics



Staggered field-like iSGE torque in CuMnAs

P. Wadley, et al. Science '16

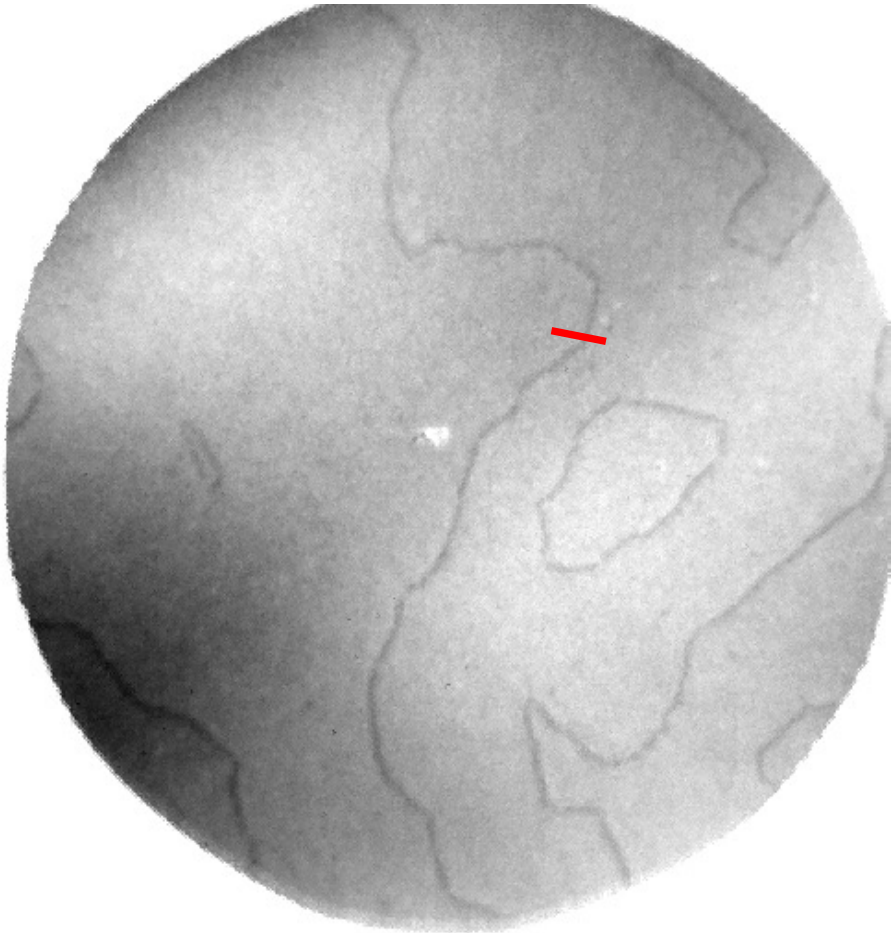
Local inversion asymmetry in CuMnAs:



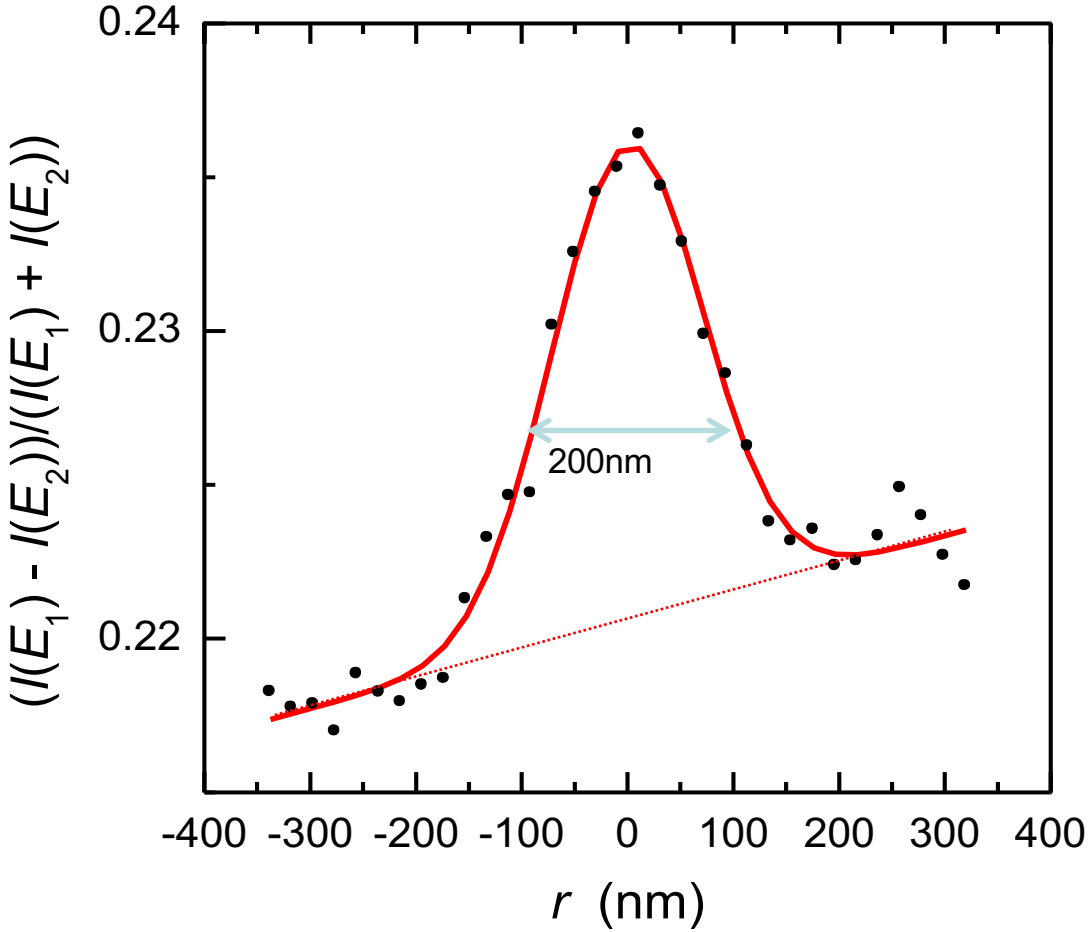
PEEM X-MLD measurements (Pete Wadley)

on thin CuMnAs (50nm) with uniaxial anisotropy with 180° domain walls

40 μm field-of-view



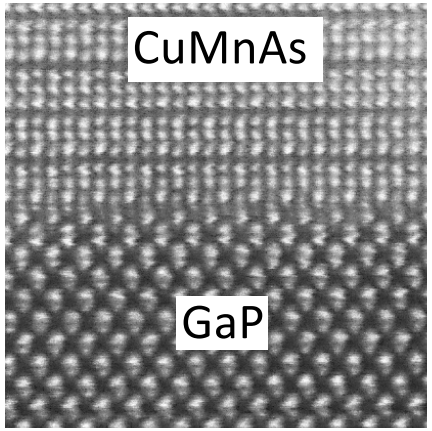
Uniaxial Domains

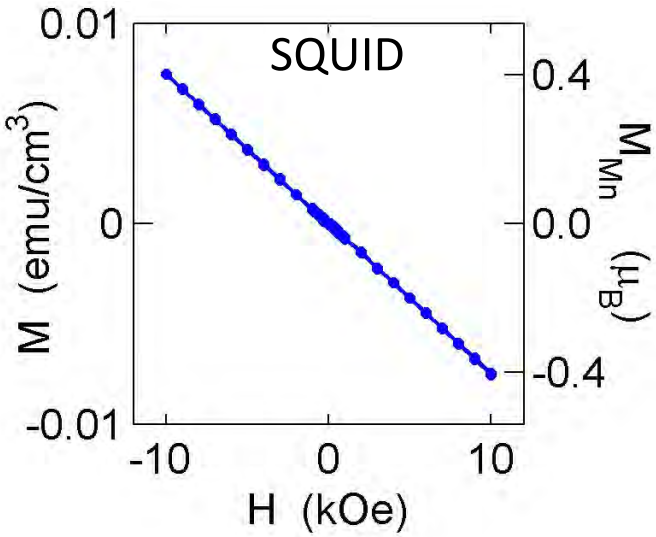


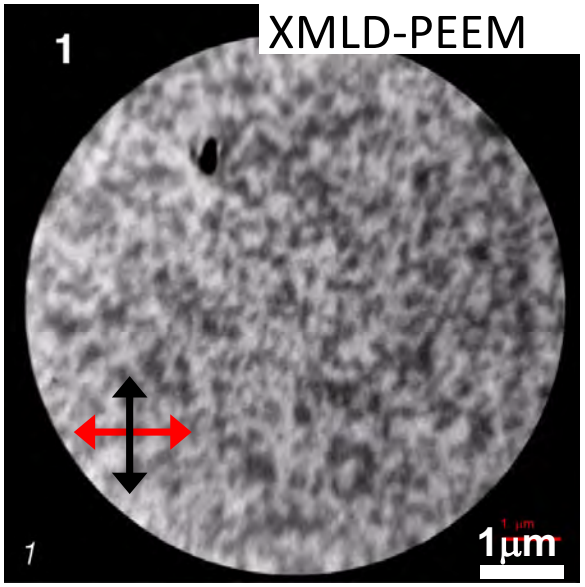
Domain Wall Profile

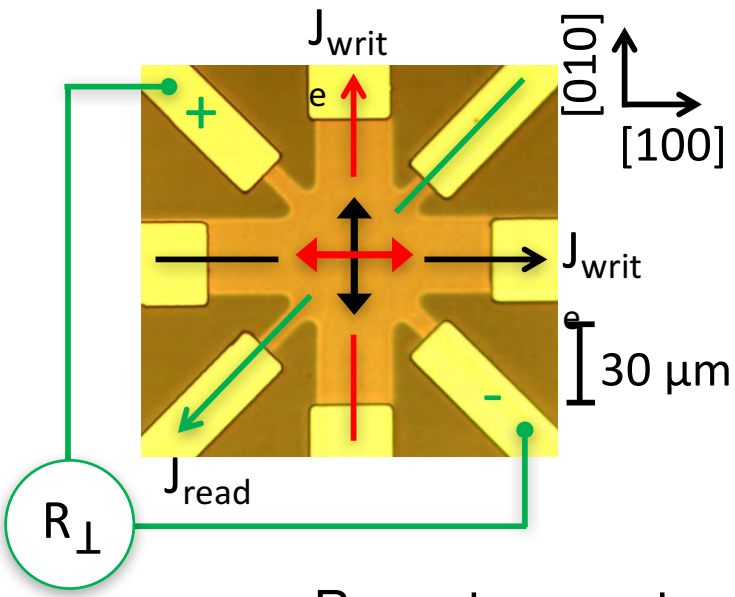
Electrical switching of antiferromagnetic CuMnAs

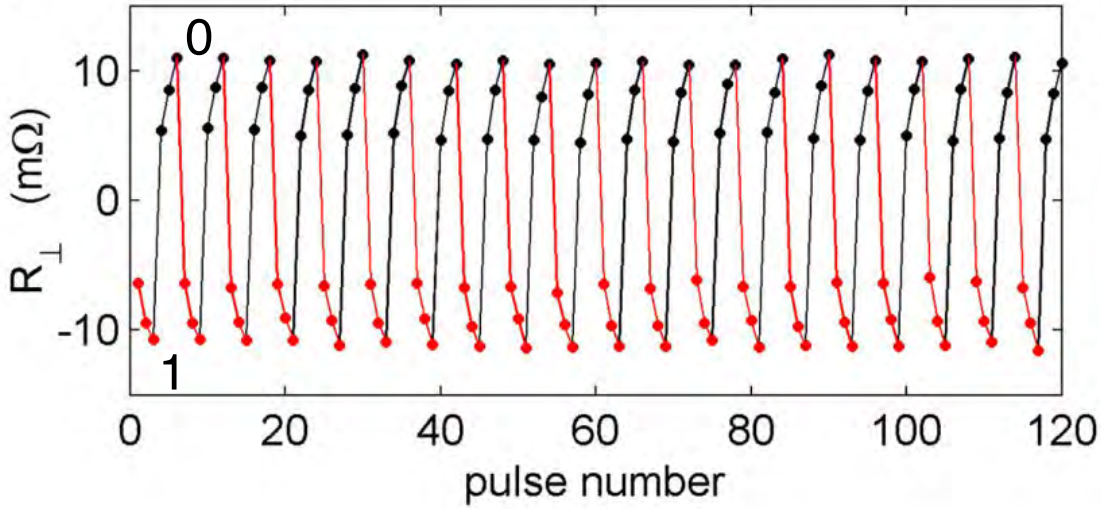
P. Wadley, et al. Science '16











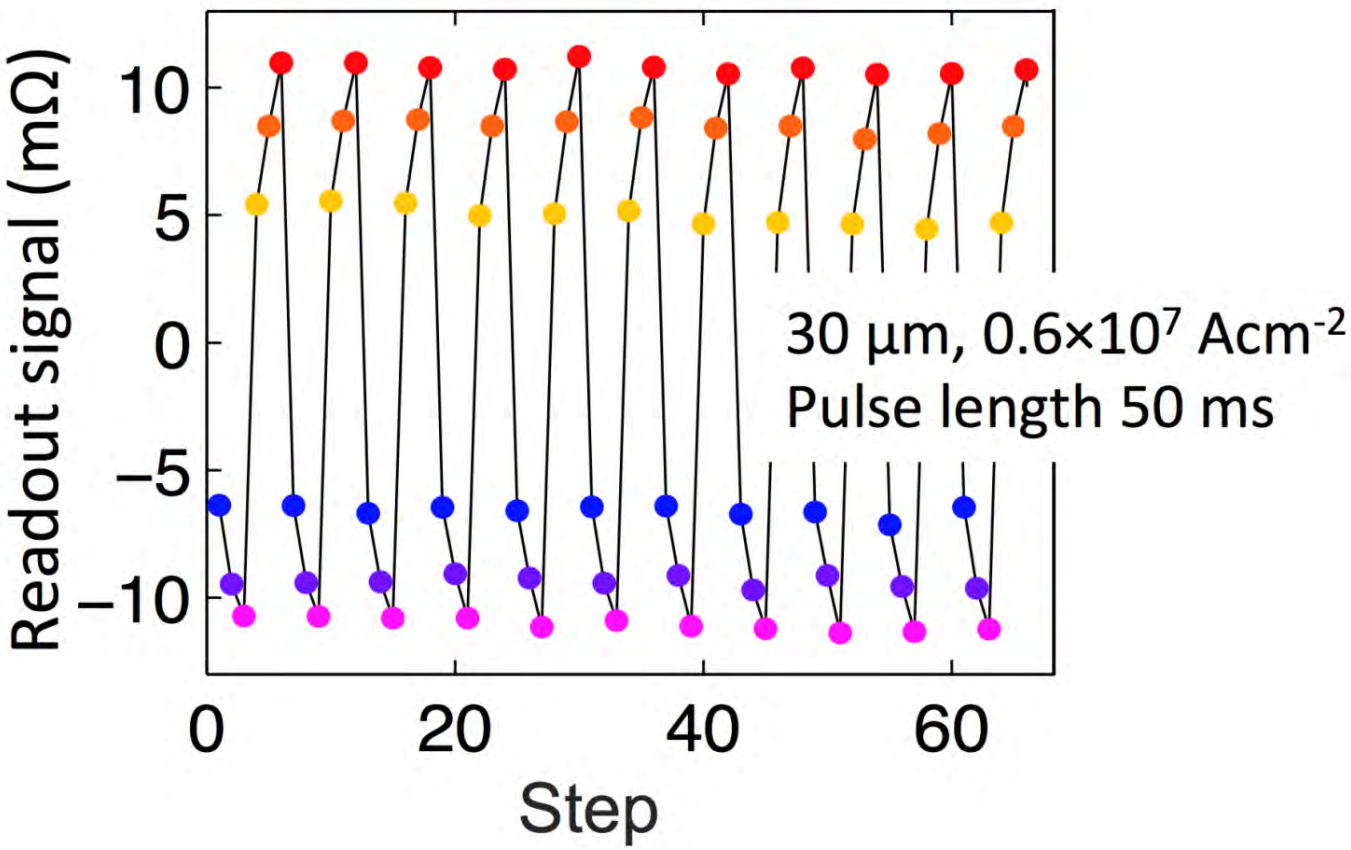
-Room-temperature

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

Electrical switching of antiferromagnetic CuMnAs

V. Schuler, et al. arXiv: '16

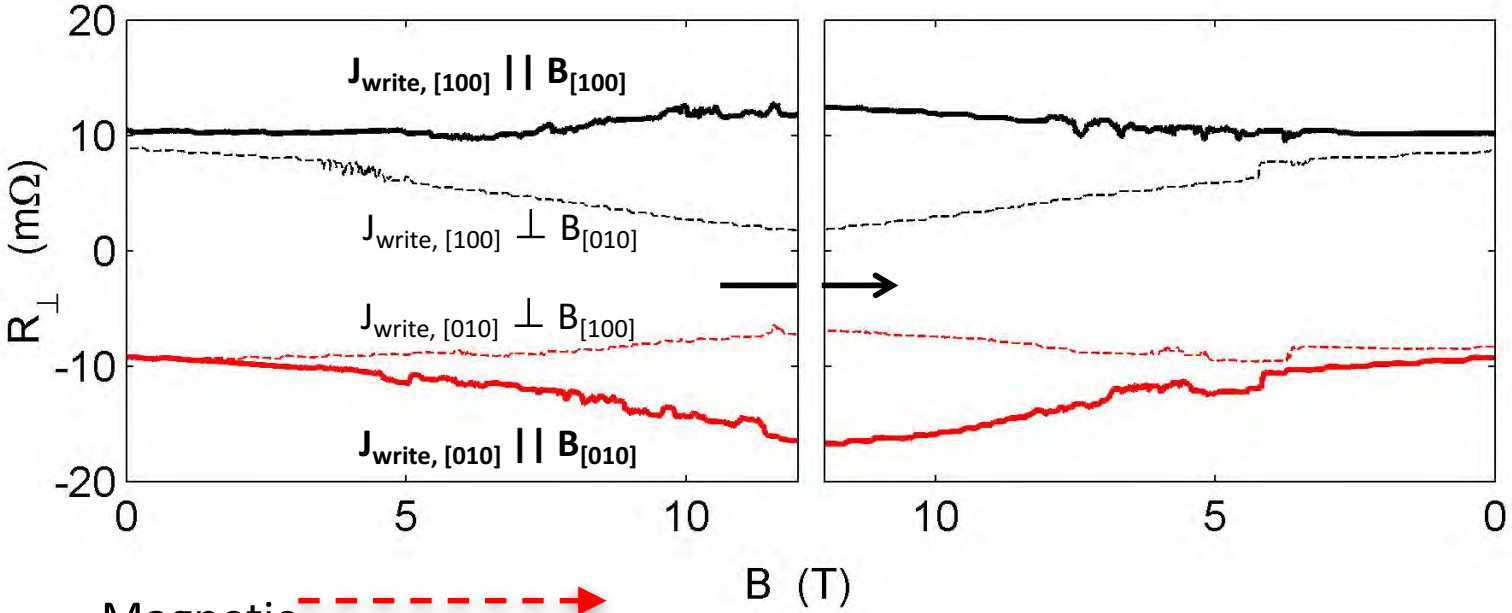
Incomplete switching → MEMRISTOR functionality

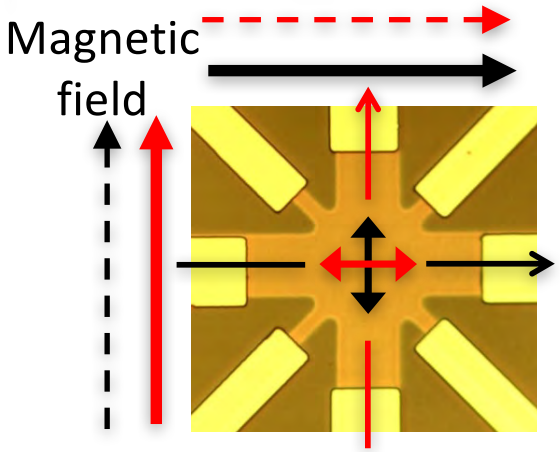


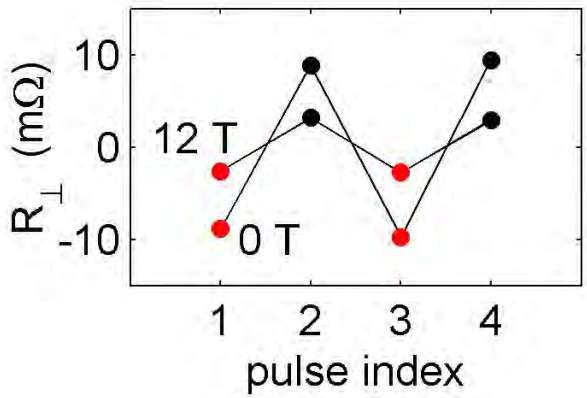
→ Talk by Xavi Marti (Thursday afternoon)

Electrical switching of antiferromagnetic CuMnAs

Behavior in strong magnetic field (electrical switching up to 12T)

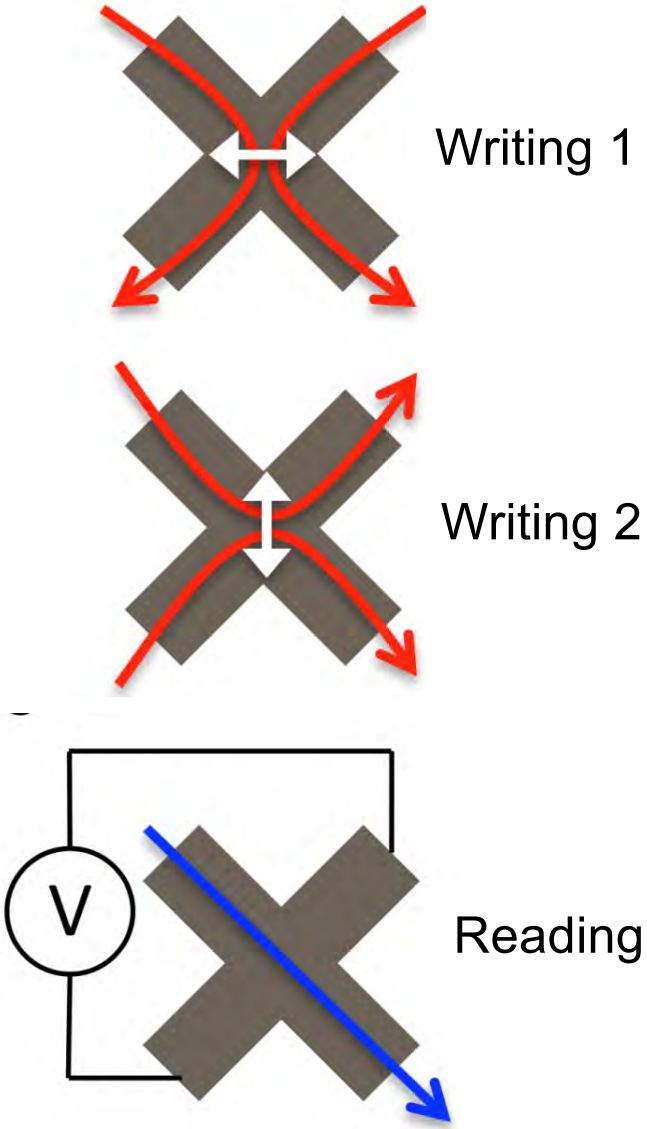


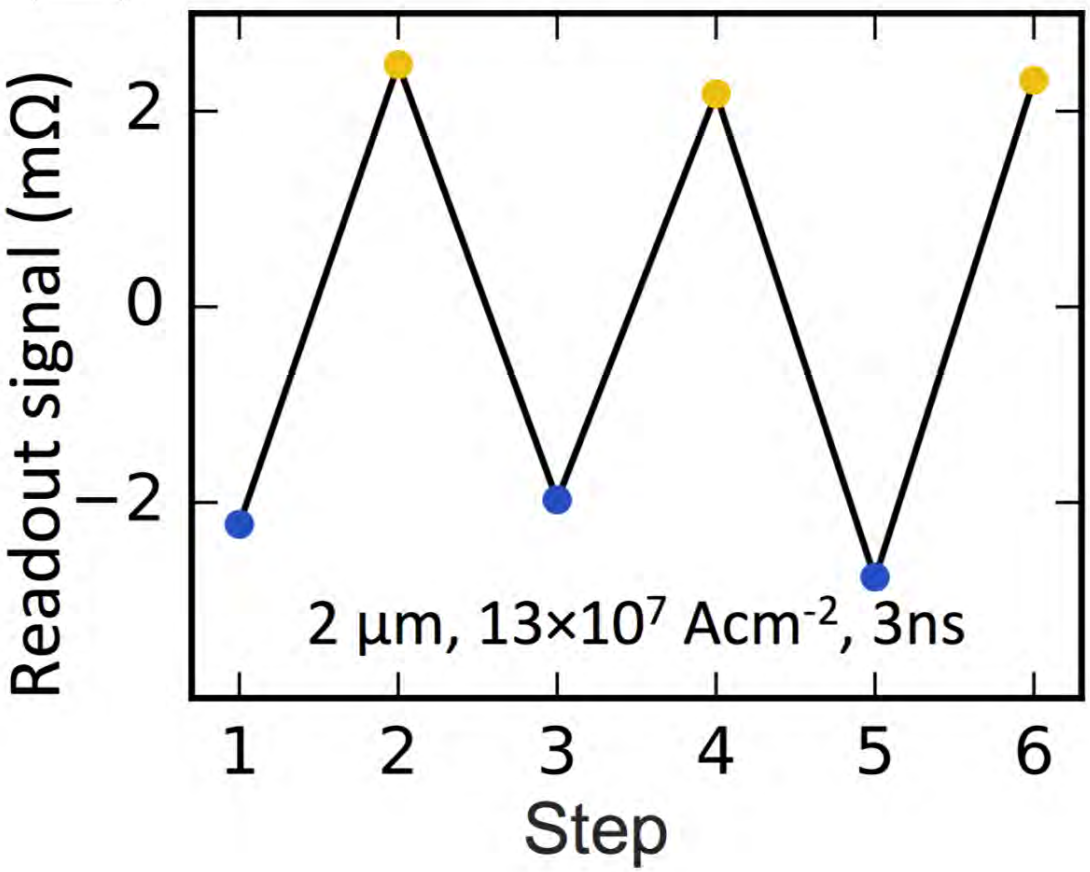




Electrical switching of antiferromagnetic CuMnAs

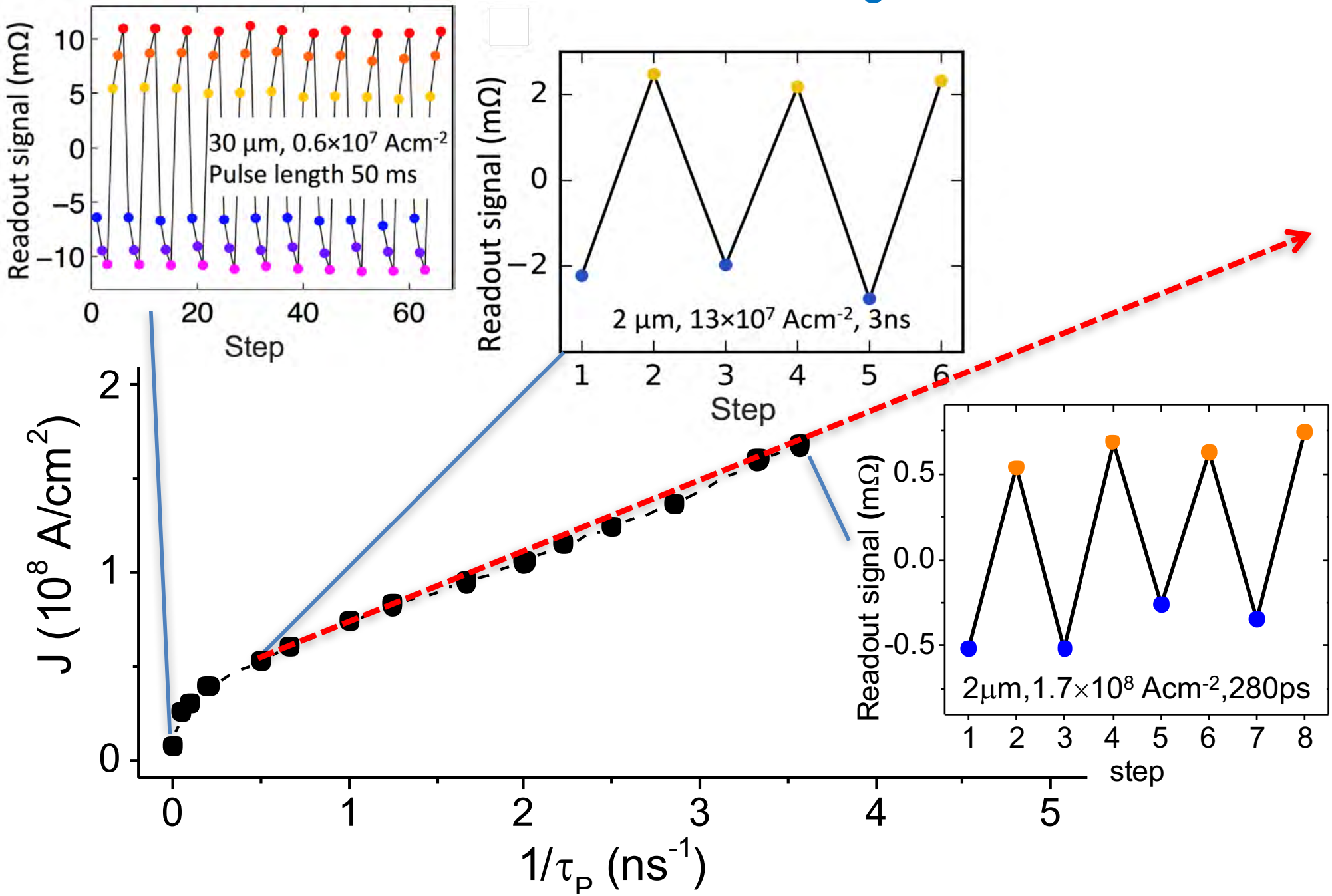
Towards Fast Switching





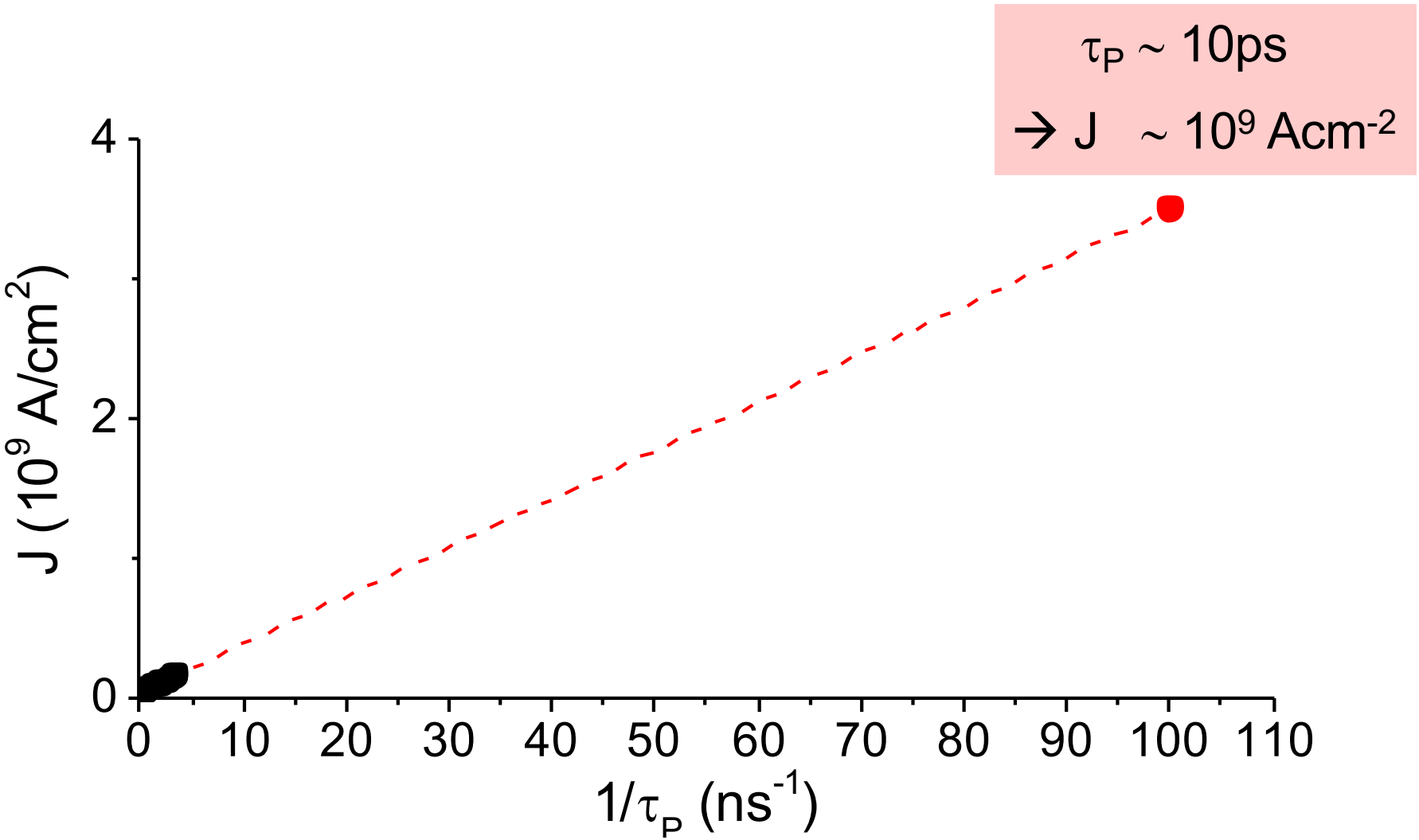
Electrical switching of antiferromagnetic CuMnAs

Towards Fast Switching



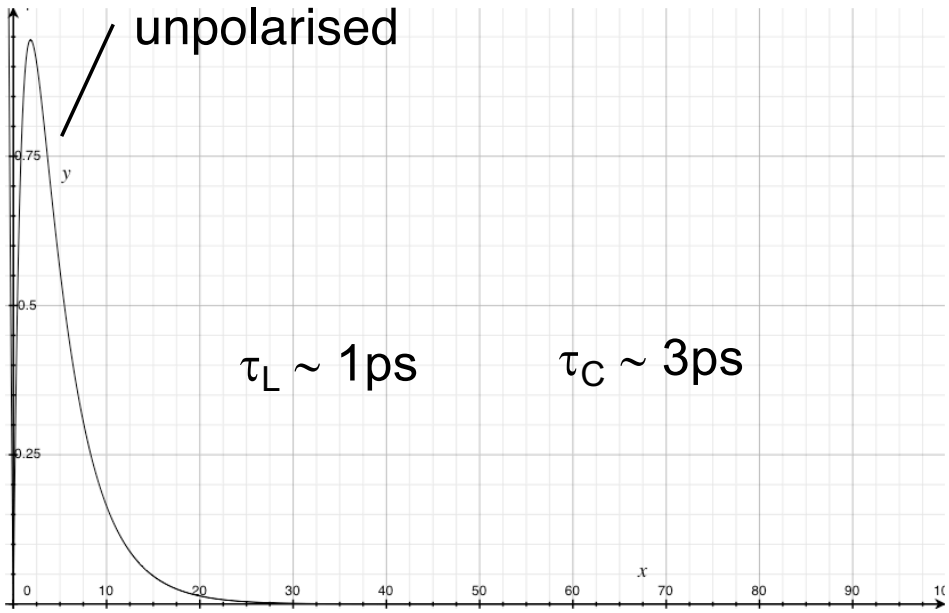
Electrical switching of antiferromagnetic CuMnAs

Towards Fast Switching

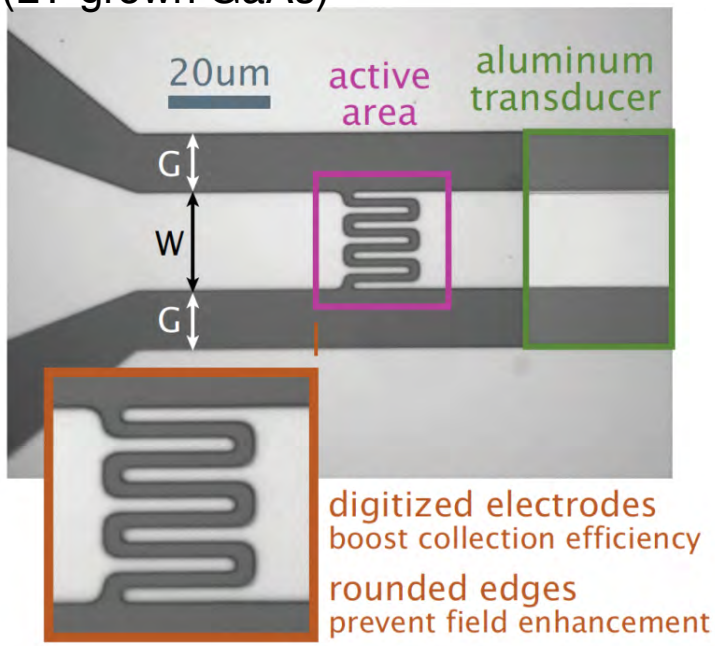


Electrical switching of antiferromagnetic CuMnAs

Towards Fast Switching



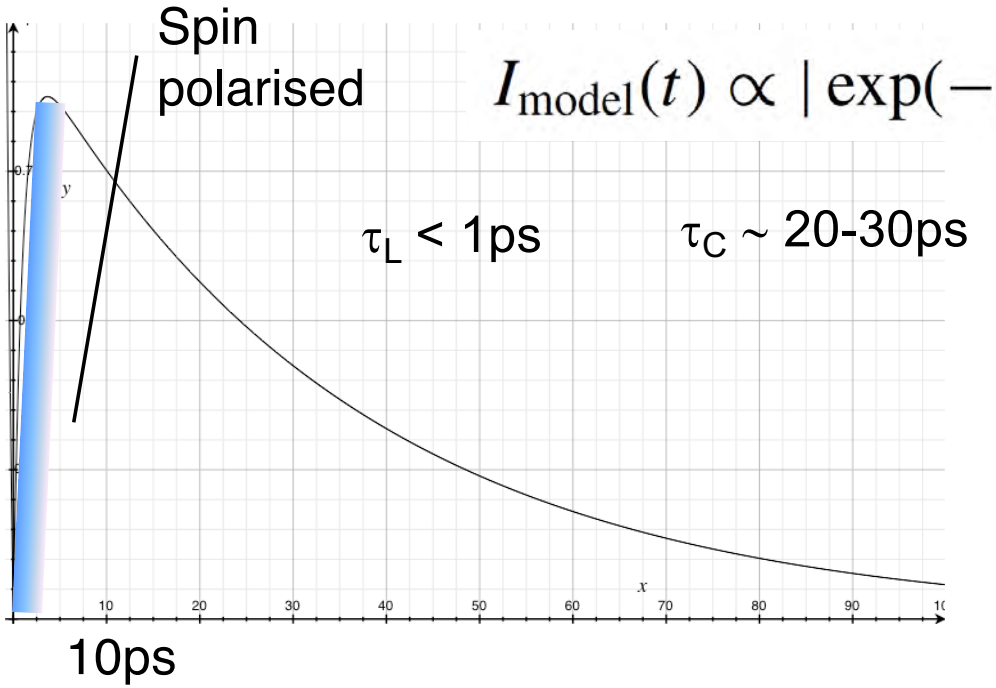
B. Vermeersch, PRB 88, 214302 (2013)
(LT-grown GaAs)



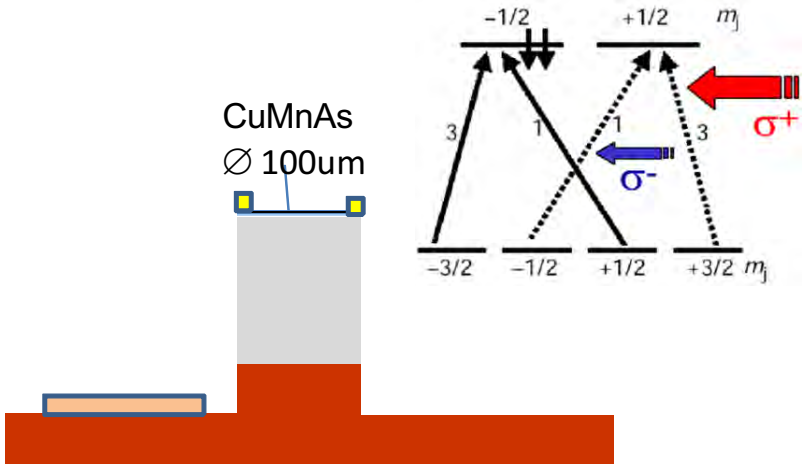
Conventional Auston switches

Electrical switching of antiferromagnetic CuMnAs

Towards Fast Switching



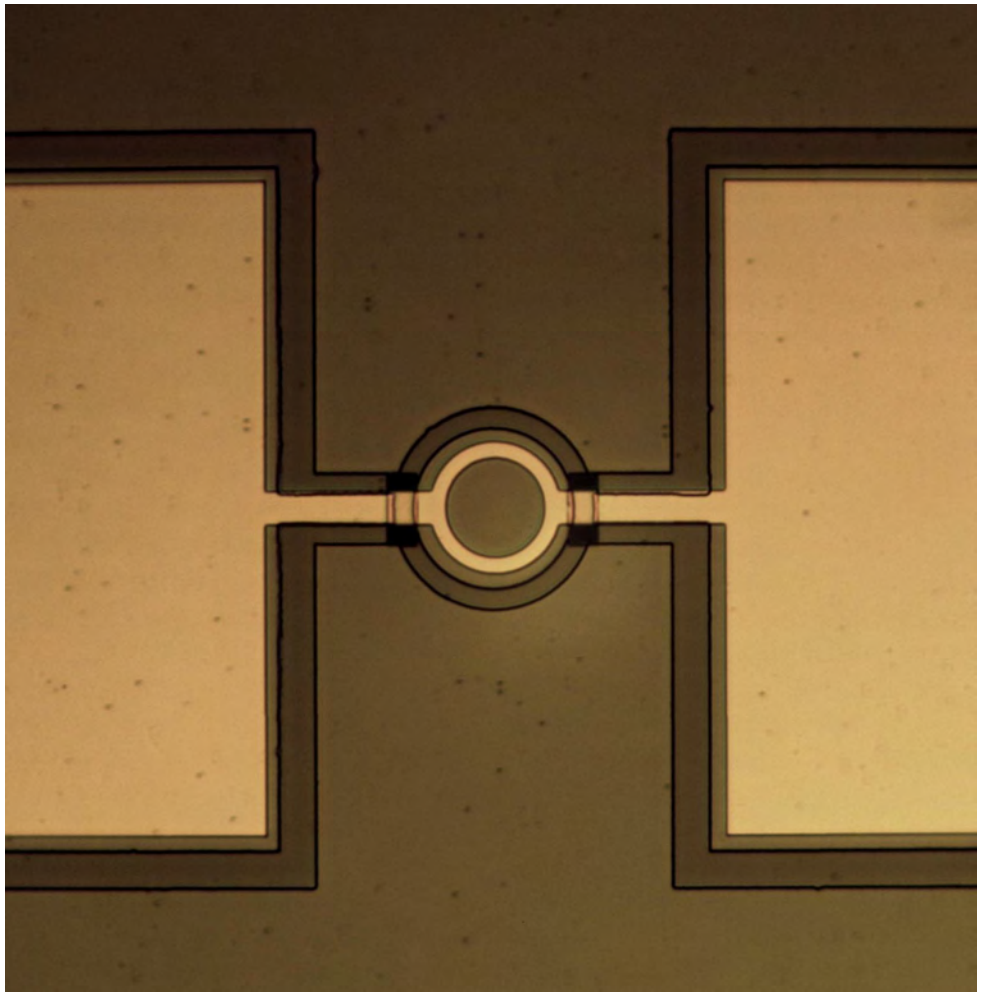
$$I_{\text{model}}(t) \propto |\exp(-t/\tau_L) - \exp(-t/\tau_C)|$$

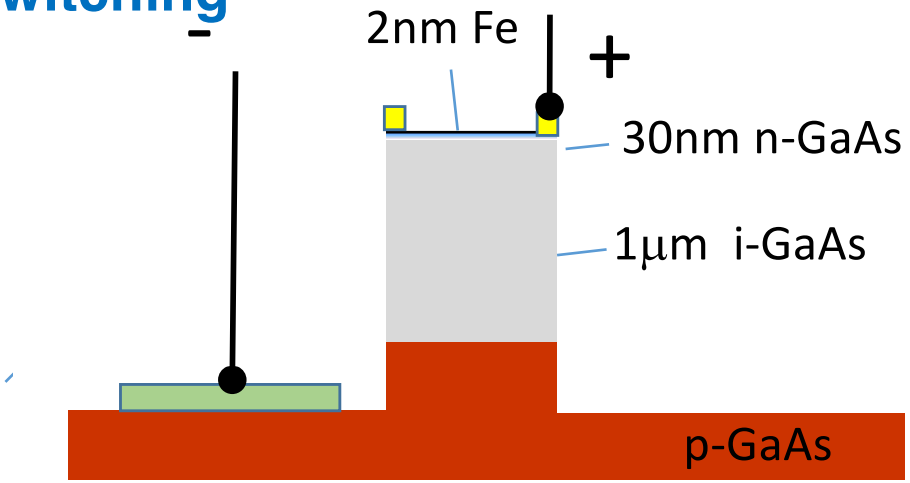


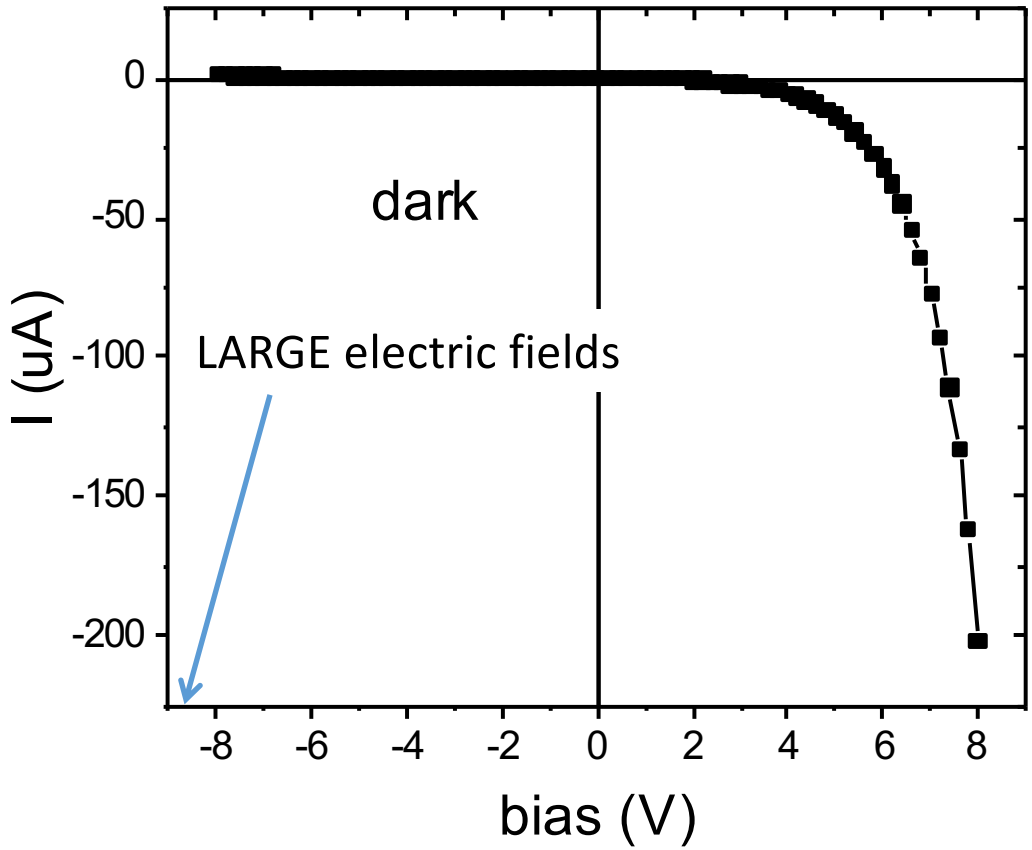
Substrate embedded photodiodes

Electrical switching of antiferromagnetic CuMnAs

Towards Fast Switching

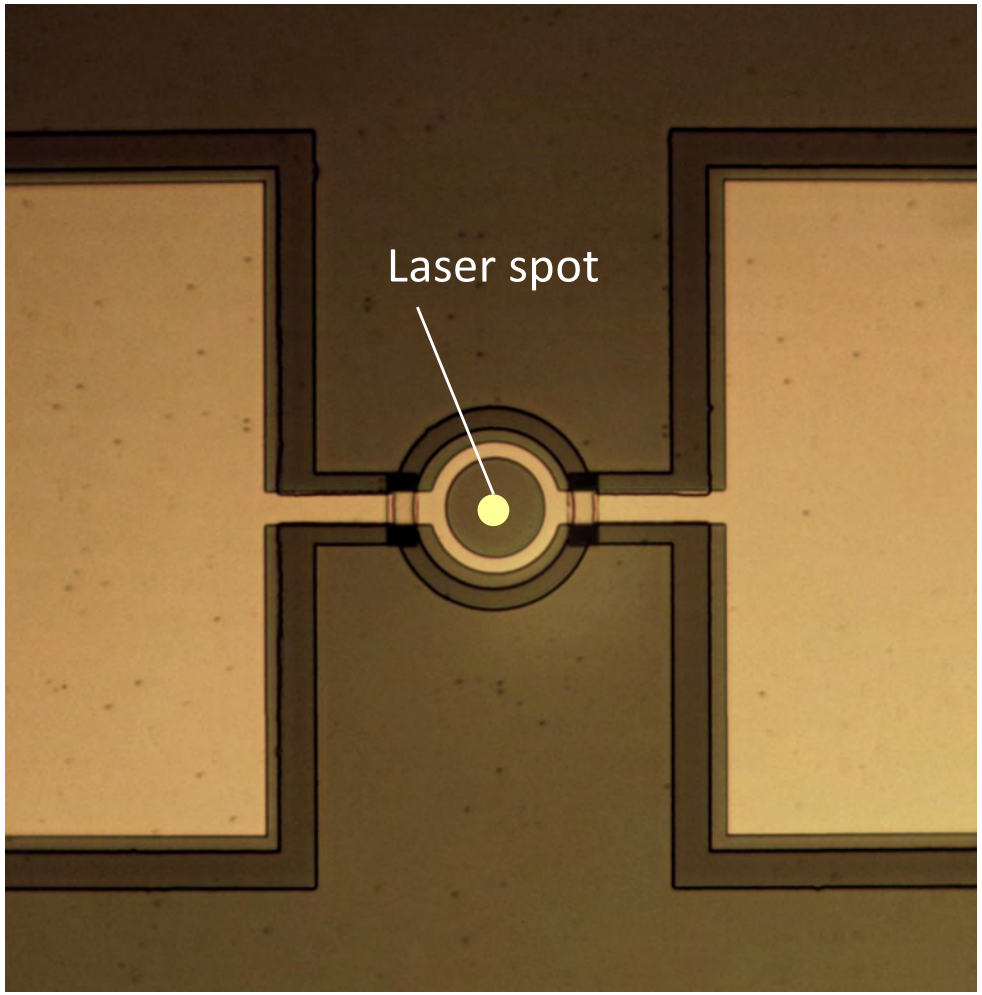


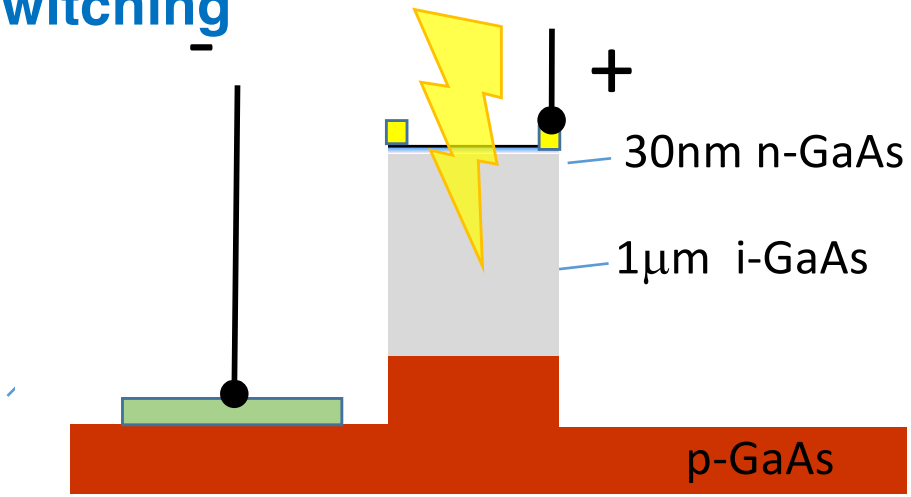


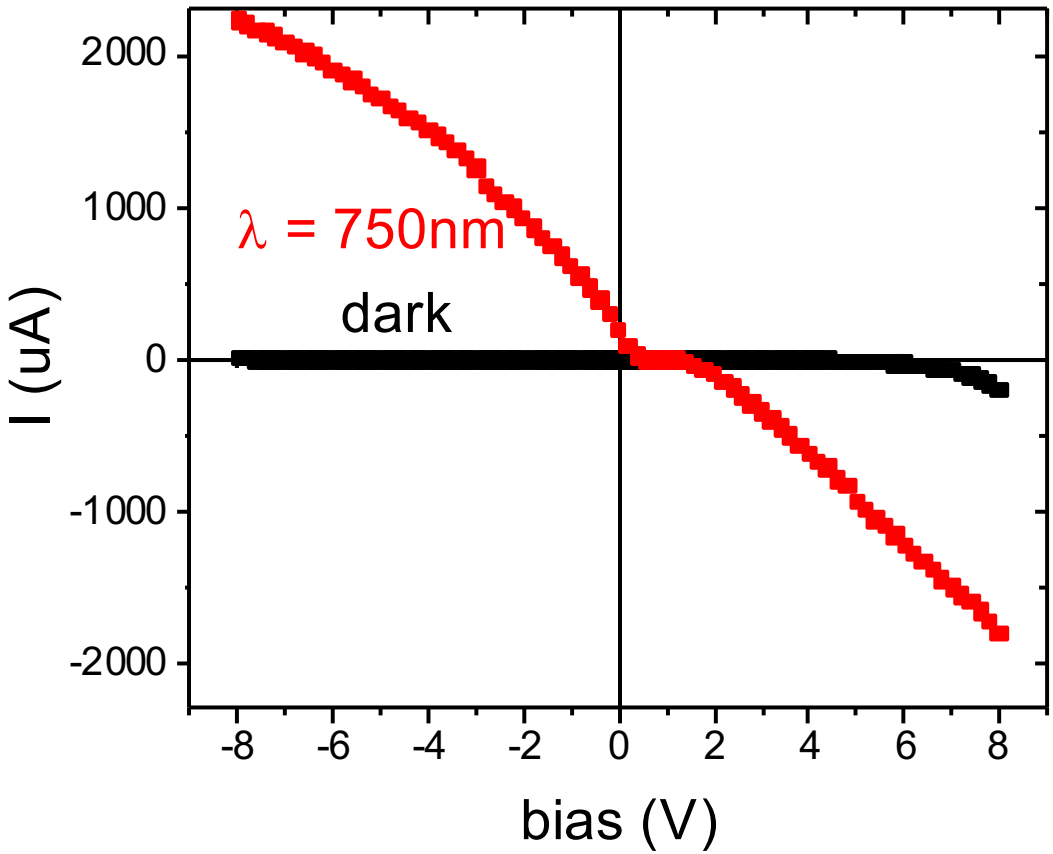


Electrical switching of antiferromagnetic CuMnAs

Towards Fast Switching

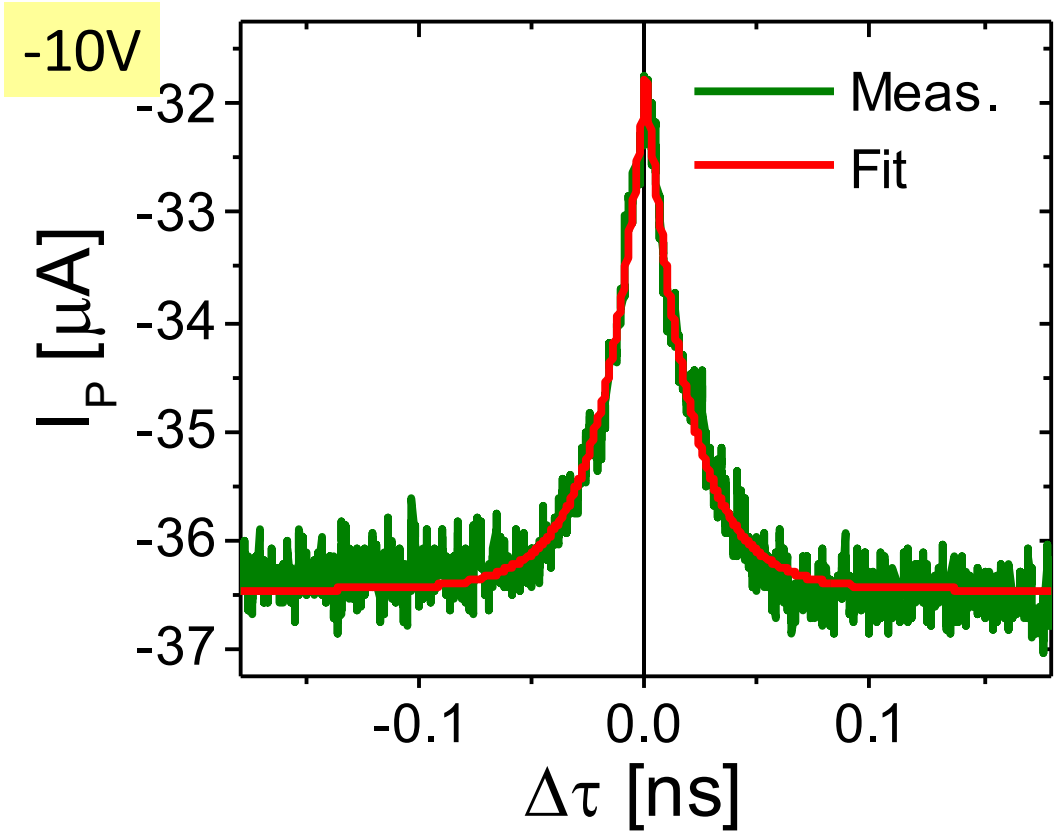


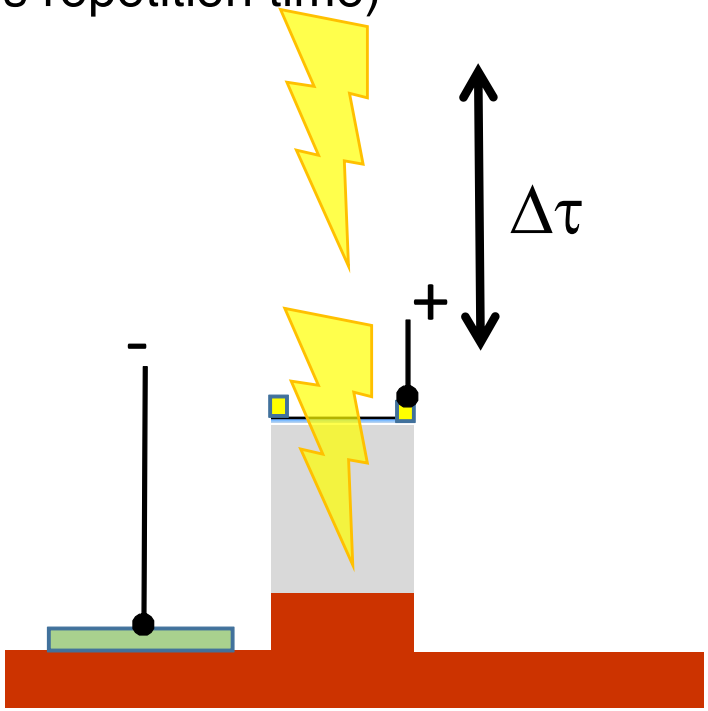




Towards Fast Switching

pulse – pulse correlation measurement (120 ns repetition time)



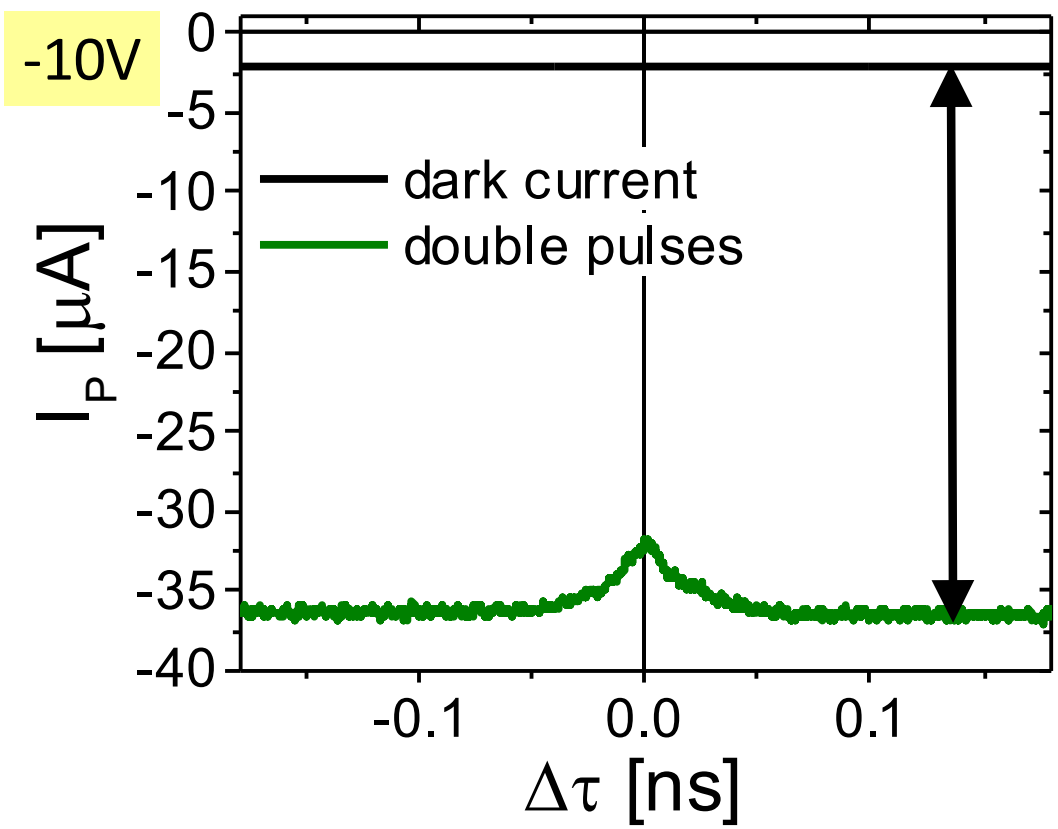


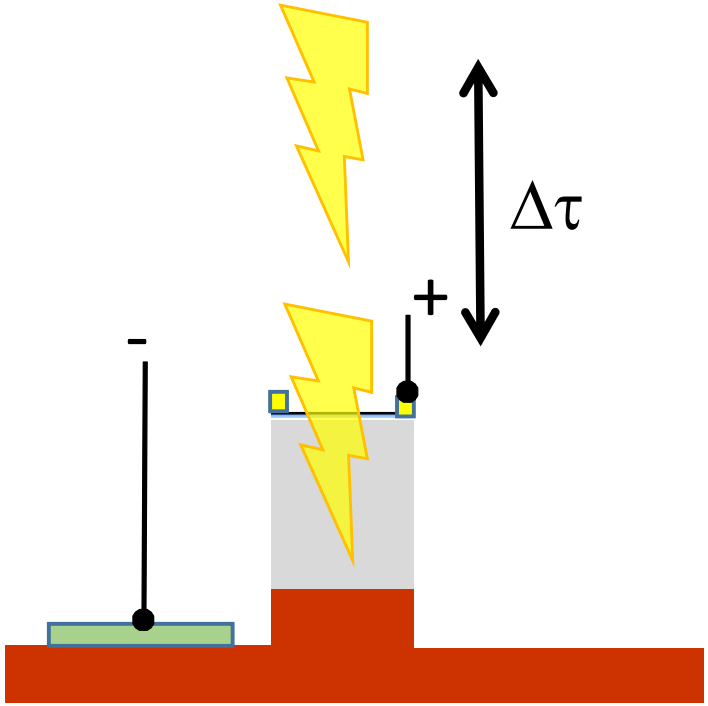
From the Fit we get: τ_R **<1ps**

τ_F **= 19.1±0.2 ps**

Generation of fast current pulses

Pulse – Pulse correlation measurement (120 ns repetition time)





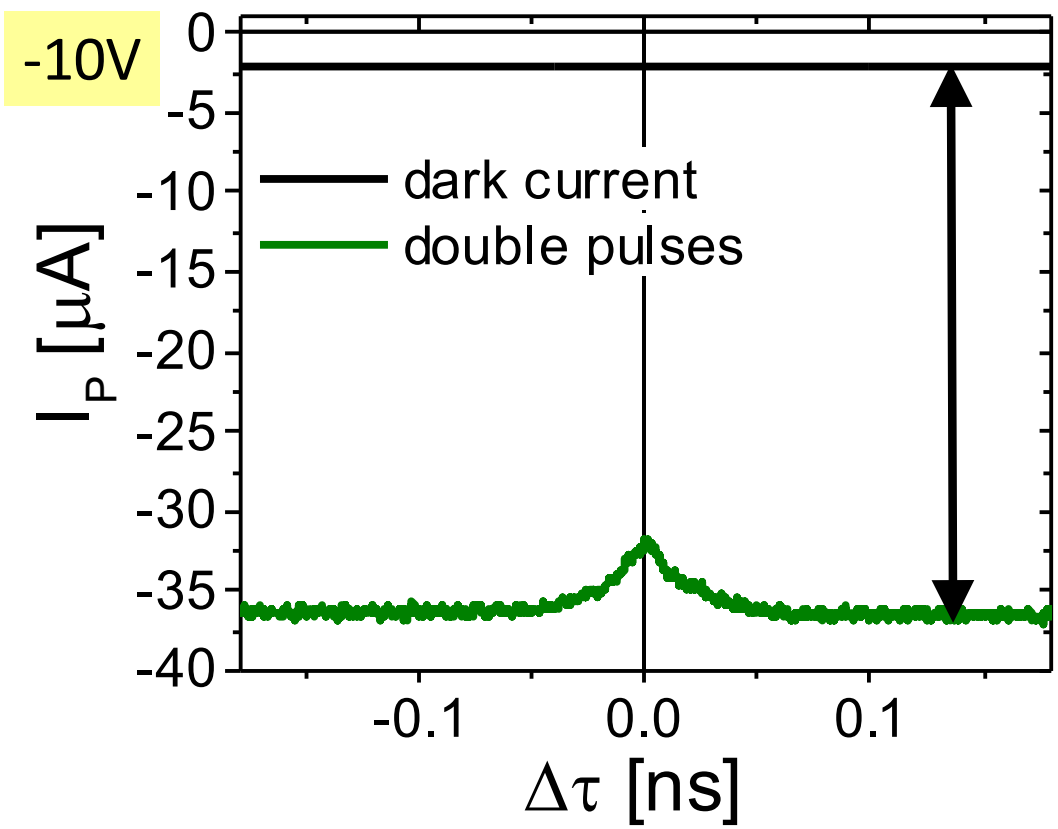
τ_R **<1ps** , τ_F **= 19.1±0.2 ps**

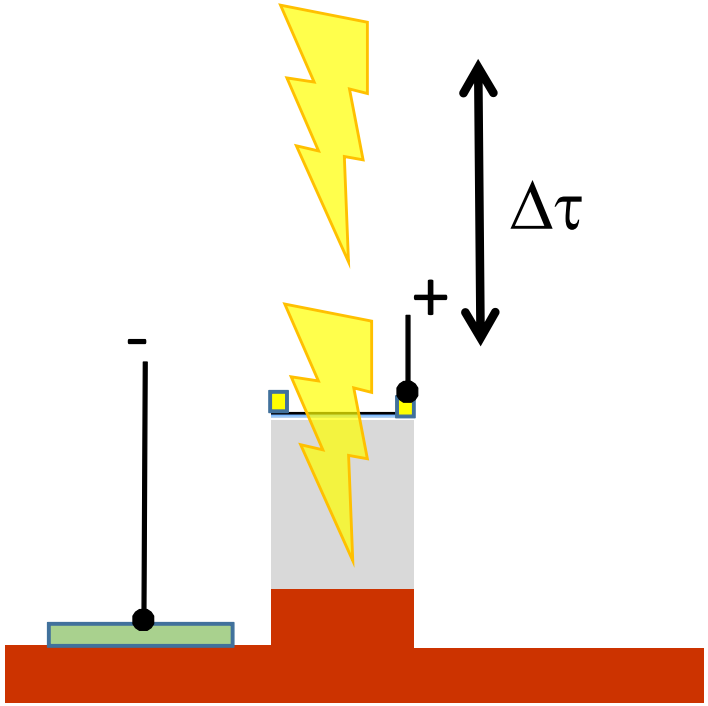
$I_0 \approx ½ \times (- 34\ \mu A \times 120\ ns/19\ ps) \approx$ - **100 mA**

(**j ~ 10^9 A/cm²** in 1μm x 10 nm wire)

Generation of fast current pulses

Pulse – Pulse correlation measurement (120 ns repetition time)





τ_R **<1ps** , τ_F **= 19.1±0.2 ps**

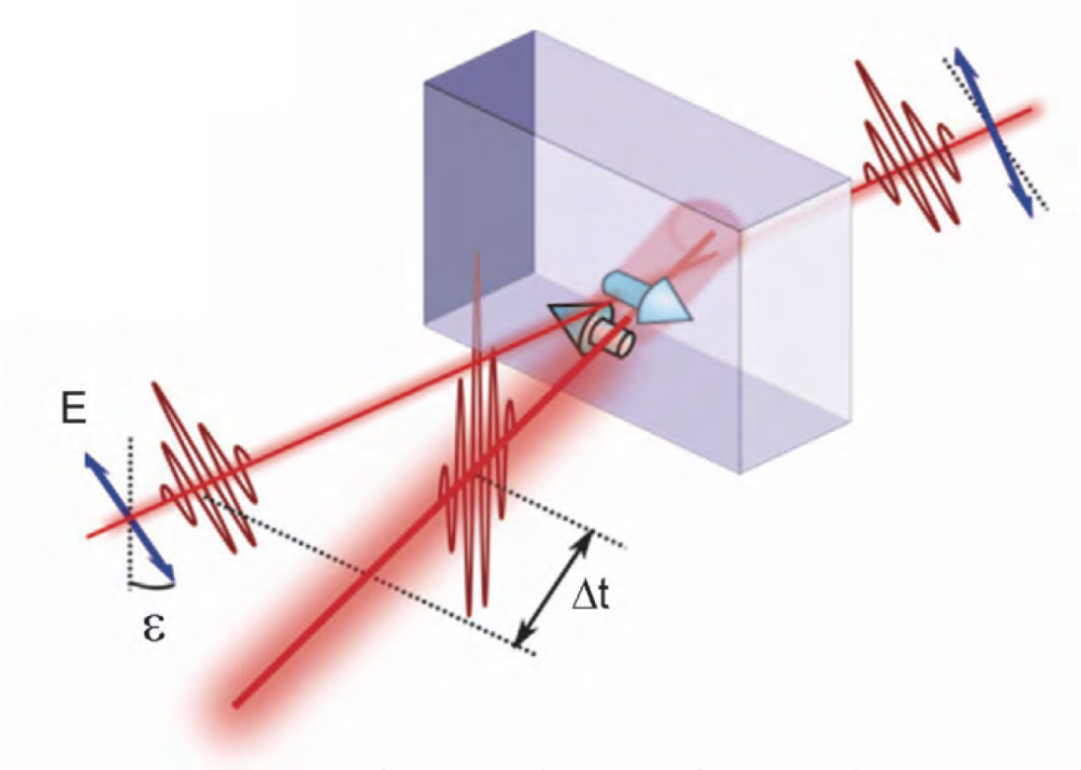
$I_0 \approx ½ \times (- 34\ \mu A \times 120\ ns/19\ ps) \approx$ - **100 mA**

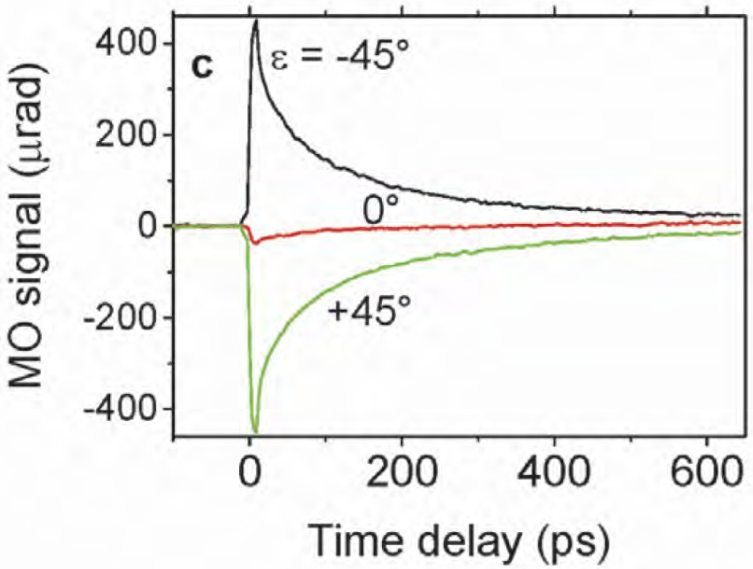
(**j ~ 10^9 A/cm²** in 1μm x 10 nm wire)

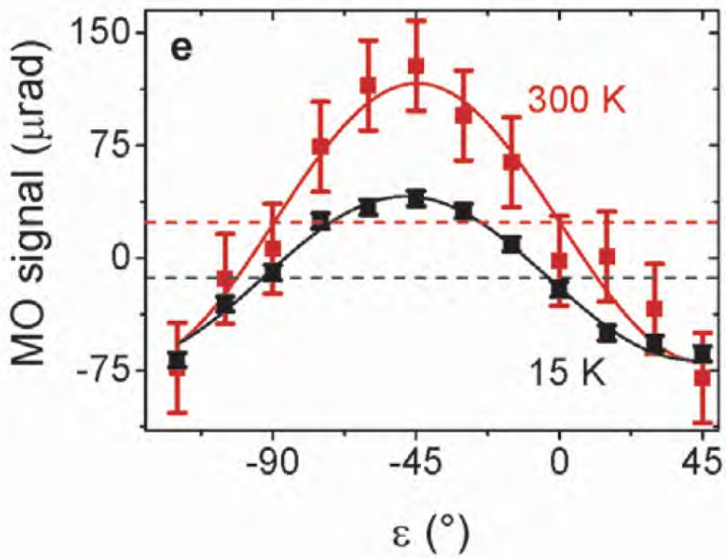
pump (fast photogenerated electric pulse) – probe **(MLD)**

Time resolved MO response on uniaxial CuMnAs

Vit Saidl, Petr Nemec, et al., arXiv:1608.01941(2016)



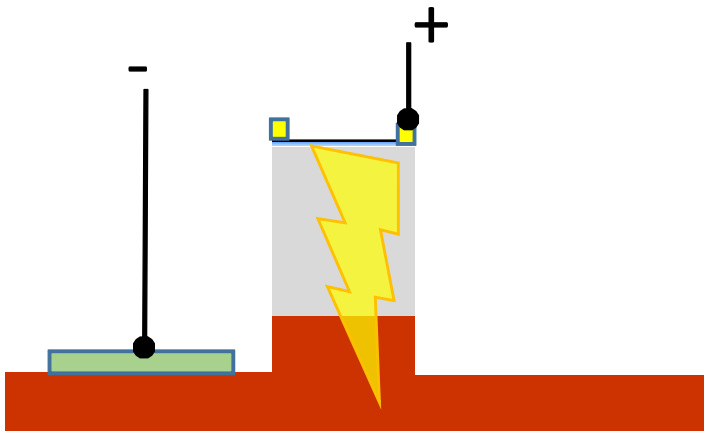


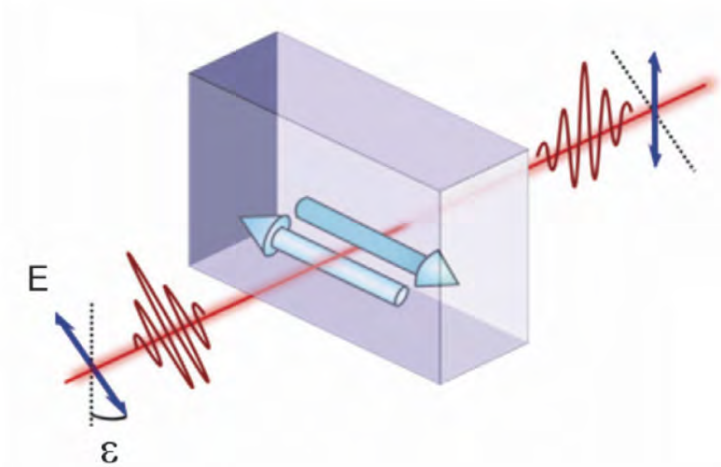


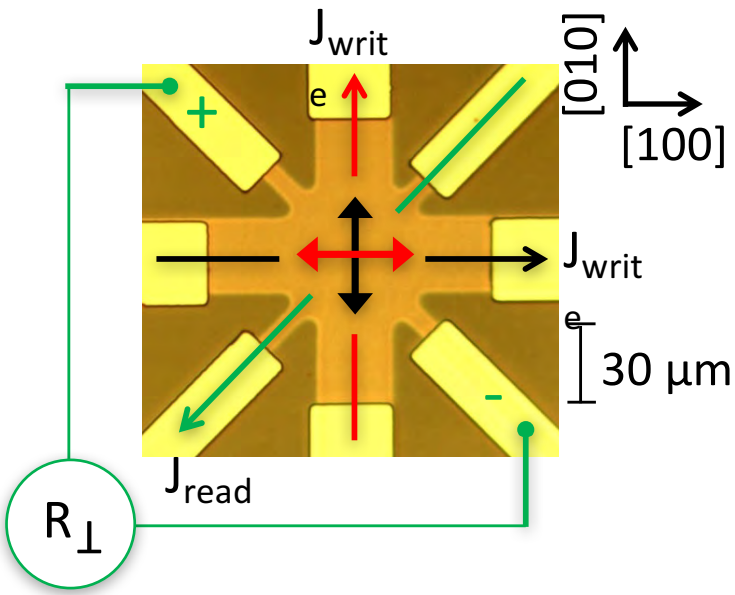
pump (fast photo-generated **electric pulse**) – probe (time-depend. **MLD**)

Time resolved MO response on uniaxial CuMnAs

Vit Saidl, Petr Nemec, et al., arXiv:1608.01941(2016)

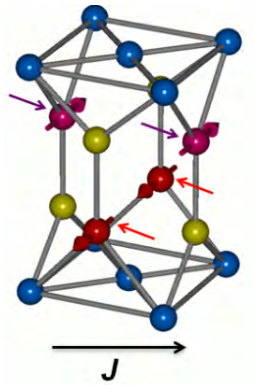


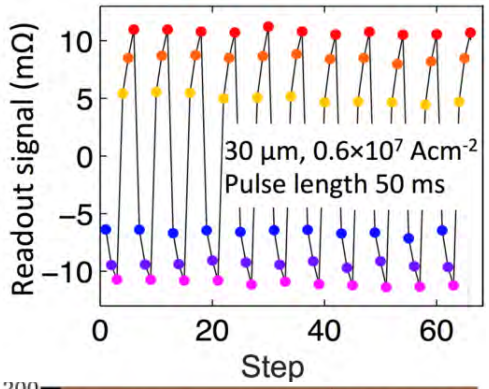




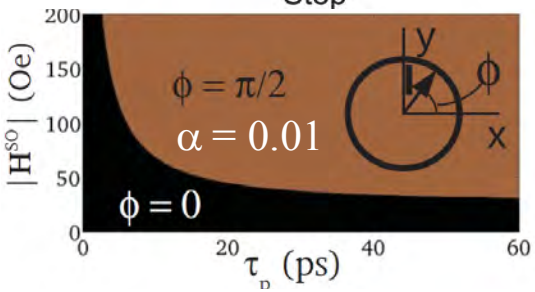
Conclusion

- efficient electrical switching with staggered SOT field ($H_{SO} \sim H_A$)

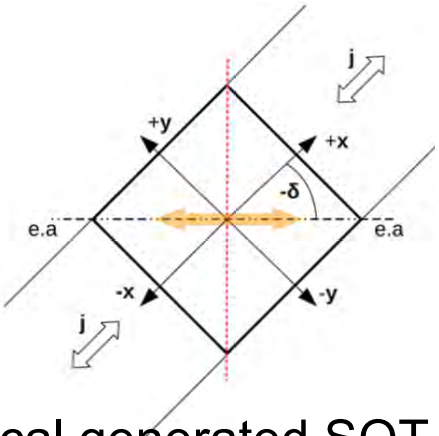


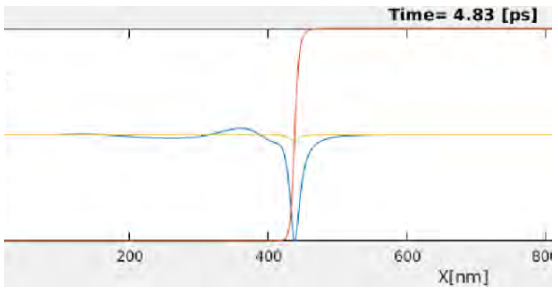


- <u>deterministic</u> and <u>robust</u> (no overshooting)

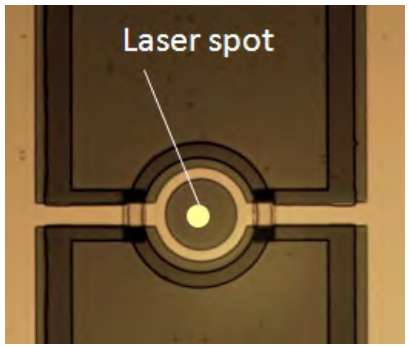


- <u>unidirectional</u> reading and writing

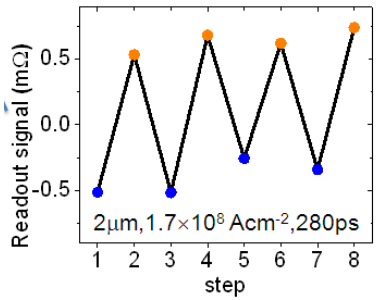




- <u>ultrafast switching</u> via electro-optical generated SOT field

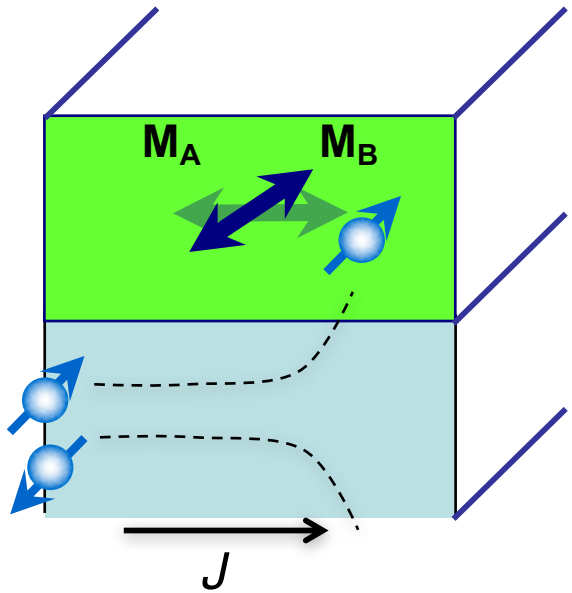


- small signals (AMR)



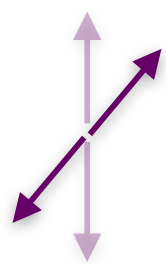
If I have still some time:

Interfacial SHE Torque in Antiferromagnets



Antidamping like torque

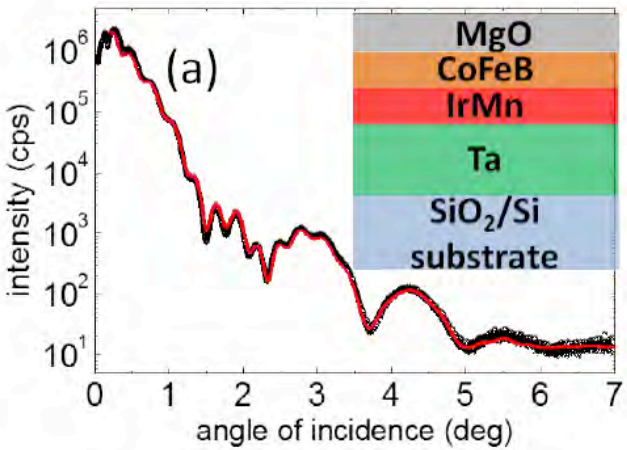
$$\vec{T}_A^{AD} \sim \vec{M}_A \times (\vec{\sigma}_\perp \times \vec{M}_A)$$



$$\vec{T}_B^{AD} \sim \vec{M}_B \times (\vec{\sigma}_\perp \times \vec{M}_B)$$

Interfacial SHE torque in ultrathin IrMn antiferromagnet

H. Reichlova, et al., Phys. Rev. B 92, 16, 165424 (2015)



Compare

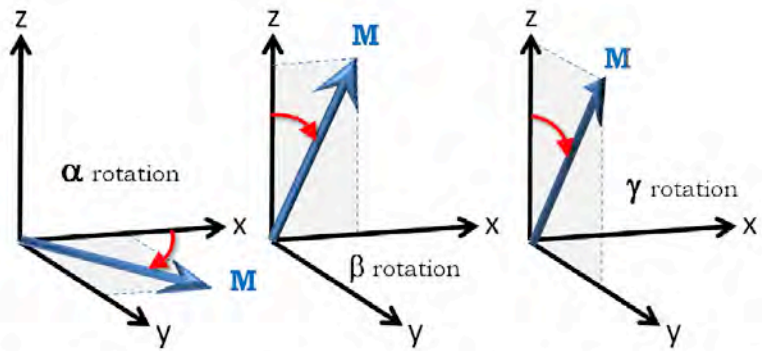
- Ta/**IrMn(1nm)**/CoFeB
- Ta/CoFeB
- Ta /**IrMn(1nm)**

at 300K: IrMn is paramagn

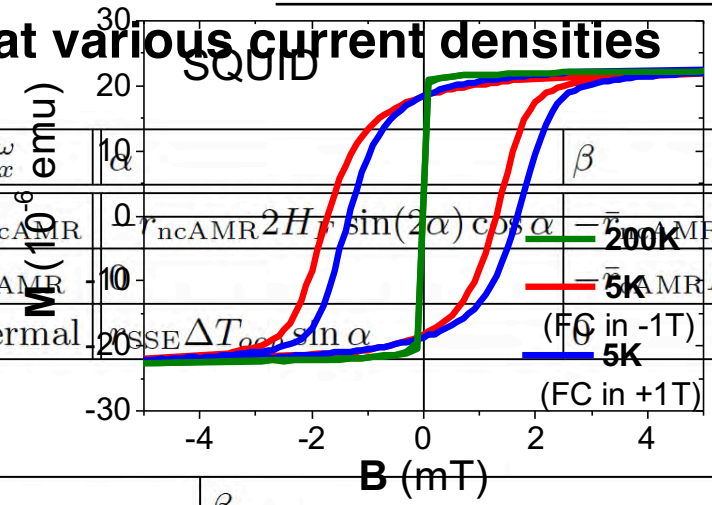
at 5K: IrMn is antiferromagn.

- exchange coupling between FM and AFM

Rotate Magnetization



Detection of first and second harmonics signal at various current densities

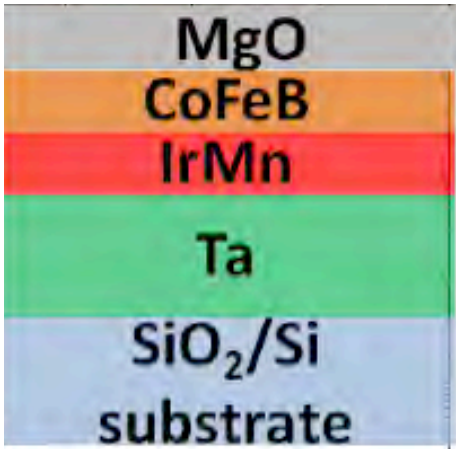


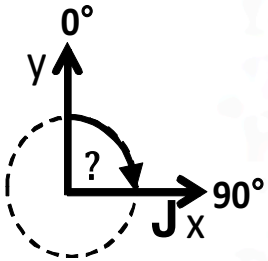
$R_{xx}^{2\omega}$	α	β	γ
R_{ncAMR}	$r_{\mathrm{ncAMR}} 2H_F \sin(2\alpha)\cos\alpha$	$-\bar{r}_{\mathrm{ncAMR}} 2H_{AD} \sin(2\beta)$	0
R_{cAMR}	0	$-\bar{r}_{\mathrm{cAMR}} H_{AD} \sin(2\beta)$	$2\bar{r}_{\mathrm{cAMR}} H_F \sin(2\gamma)\cos\gamma$
thermal	$r_{\mathrm{SSE}} \Delta T_{oop} \sin\alpha$	0	$r_{\mathrm{SSE}} \Delta T_{oop} \sin\gamma$

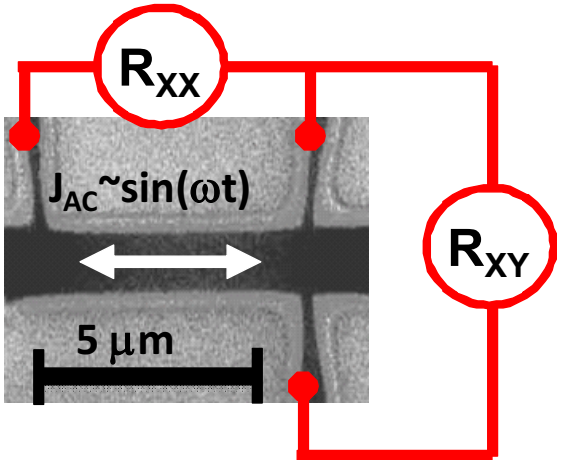
$R_{xy}^{2\omega}$	α	β	γ
R_{AHE}	$r_{\mathrm{AHE}} H_{AD} \cos\alpha$	$\bar{r}_{\mathrm{AHE}} H_{AD} \sin\beta$	$-\bar{r}_{\mathrm{AHE}} H_F \sin\gamma\cos\gamma$
R_{tAMR}	$r_{\mathrm{ncAMR}} 2H_F \cos(2\alpha)\cos\alpha$	$\bar{r}_{\mathrm{ncAMR}} 2H_F \,\mathrm{sgn}(\sin\beta)$	$\bar{r}_{\mathrm{ncAMR}} 2H_{AD} \,\mathrm{sgn}(\sin\gamma)\cos\gamma$
thermal	$r_{\mathrm{SSE}} \Delta T_{oop} \cos\alpha$	$r_{\mathrm{SSE}} \Delta T_{oop} \sin\beta + r_{\mathrm{ANE}} \Delta T_{ip} \cos\beta$	$r_{\mathrm{ANE}} \Delta T_{ip} \cos\gamma$

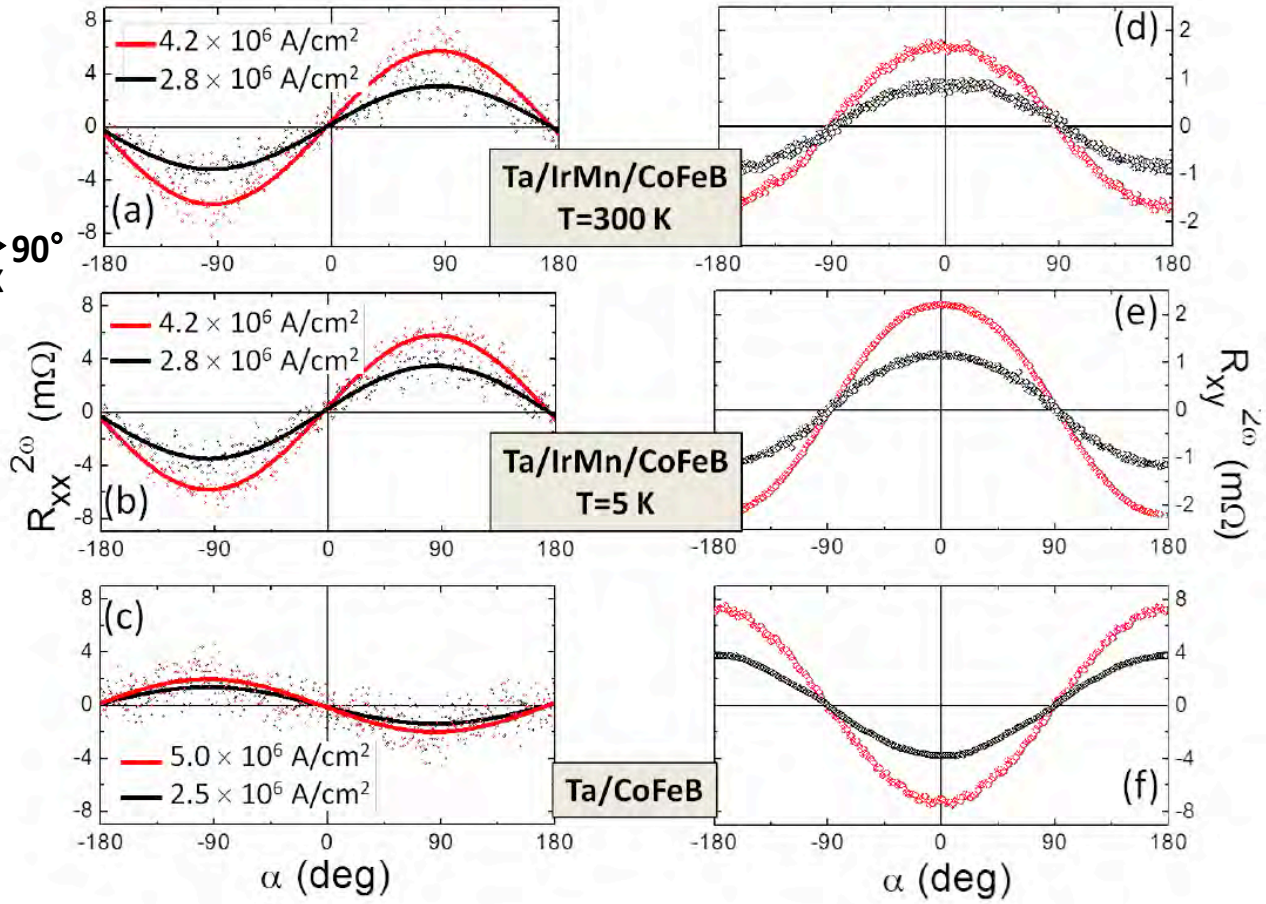
Interfacial SHE torque in ultrathin IrMn antiferromagnet

H. Reichlova, et al., Phys. Rev. B 92, 16, 165424 (2015)







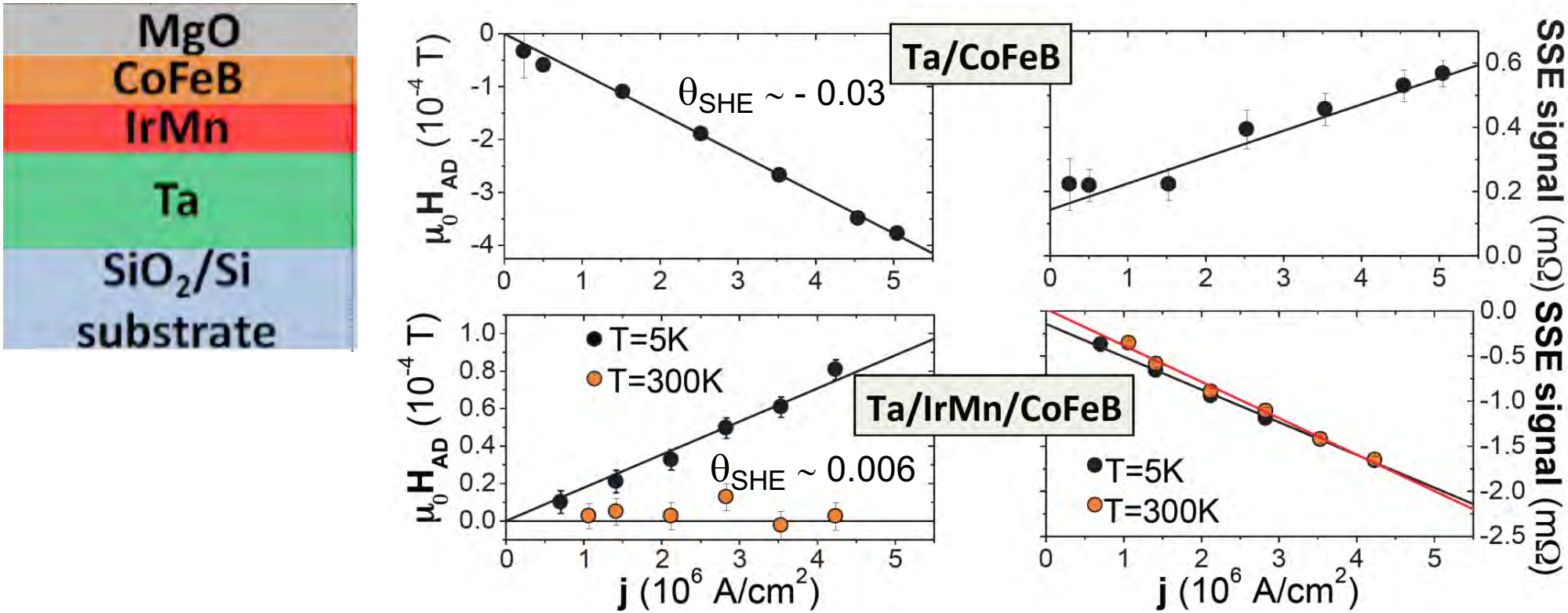


→ **$R^{2\omega}$ xx** - signal arises from $\sim\partial T_z$ (SSE)

→ **$R^{2\omega}$ xy** - signal arises from $\sim\partial T_z$ (SSE) and **<u>antidamping-like SOT field</u>**: $\mathbf{H_{AD}} \sim \mathbf{M} \times (\mathbf{j_X} \times \mathbf{z})$ (SHE origin)

Interfacial SHE torque in ultrathin IrMn antiferromagnet

H. Reichlova, et al., Phys. Rev. B 92, 16, 165424 (2015)

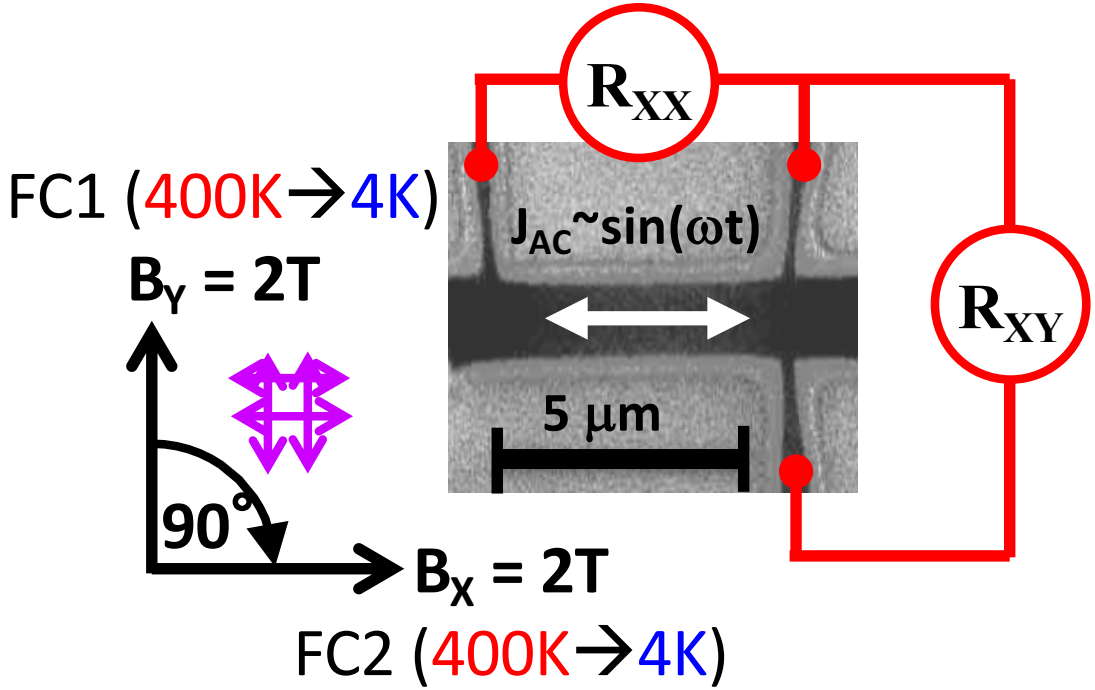


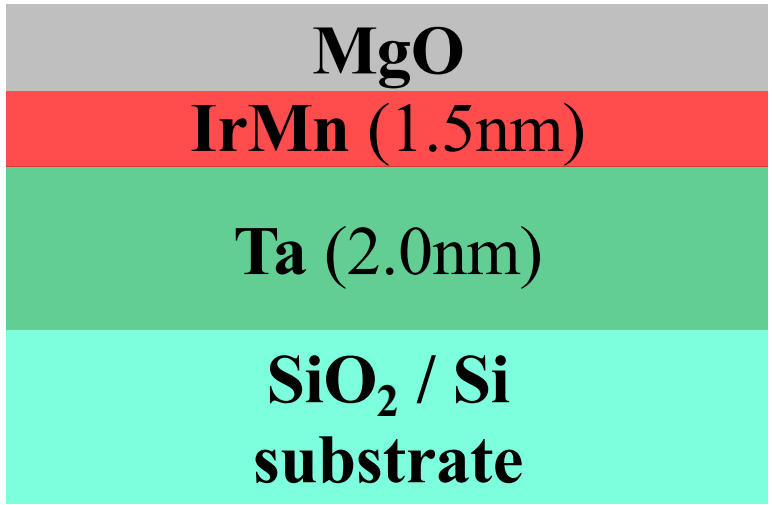
→ **$R^{2\omega}$ xx** - signal arises from $\sim\partial T_z$ (SSE)

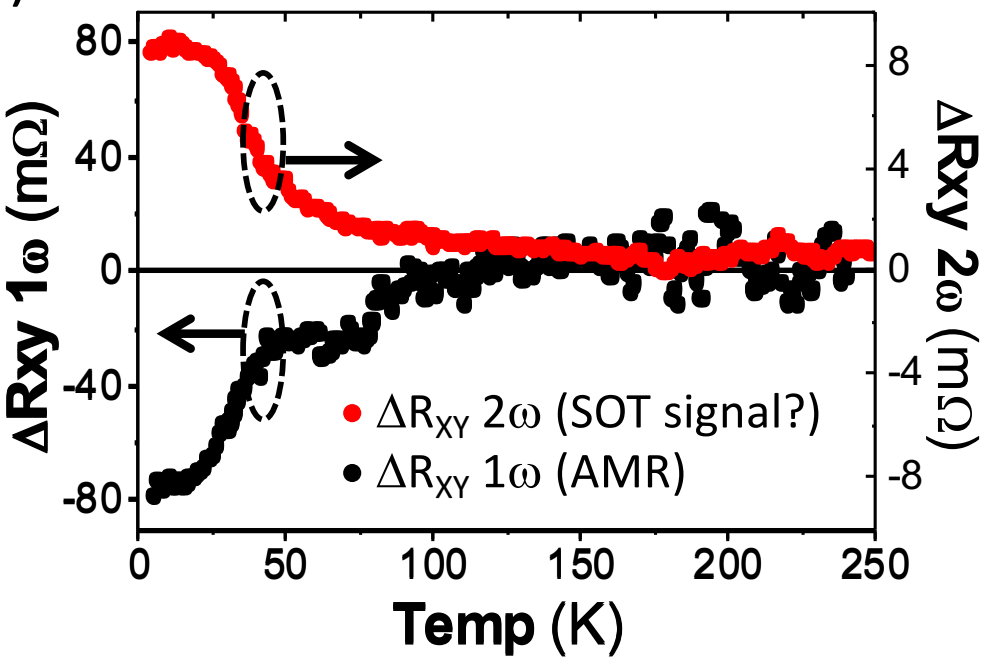
→ **$R^{2\omega}$ xy** - signal arises from $\sim\partial T_z$ (SSE) and **<u>antidamping-like SOT field</u>**: $\mathbf{H_{AD}} \sim \mathbf{M} \times (\mathbf{j_x} \times \mathbf{z})$ (SHE origin)

Interfacial SHE torques in ultrathin IrMn antiferromagnet

H. Reichlova, et al., Phys. Rev. B 92, 16, 165424 (2015)







Conclusion

- only indication of torque on AF coupled moments in IrMn thin film