Data retention extraction methodology for perpendicular STT-MRAM

Luc Tillie[1,2], E. Nowak[1], R. C. Sousa[2], M.-C. Cyrille[1], B. Delaet[1],
T. Magis[1], A. Persico[1], J. Langer[3], B. Ocker[3], I-L Prejbeanu[2] and L. Perniola[1]

[1]CEA-LETI, Minatec Campus, Grenoble, France, email: luc.tillie@cea.fr
[2]SPINTEC, Univ. Grenoble Alpes / CEA / CNRS, Grenoble, France
[3]Singulus Technologies AG, Kahl am Main, Germany

Introduction

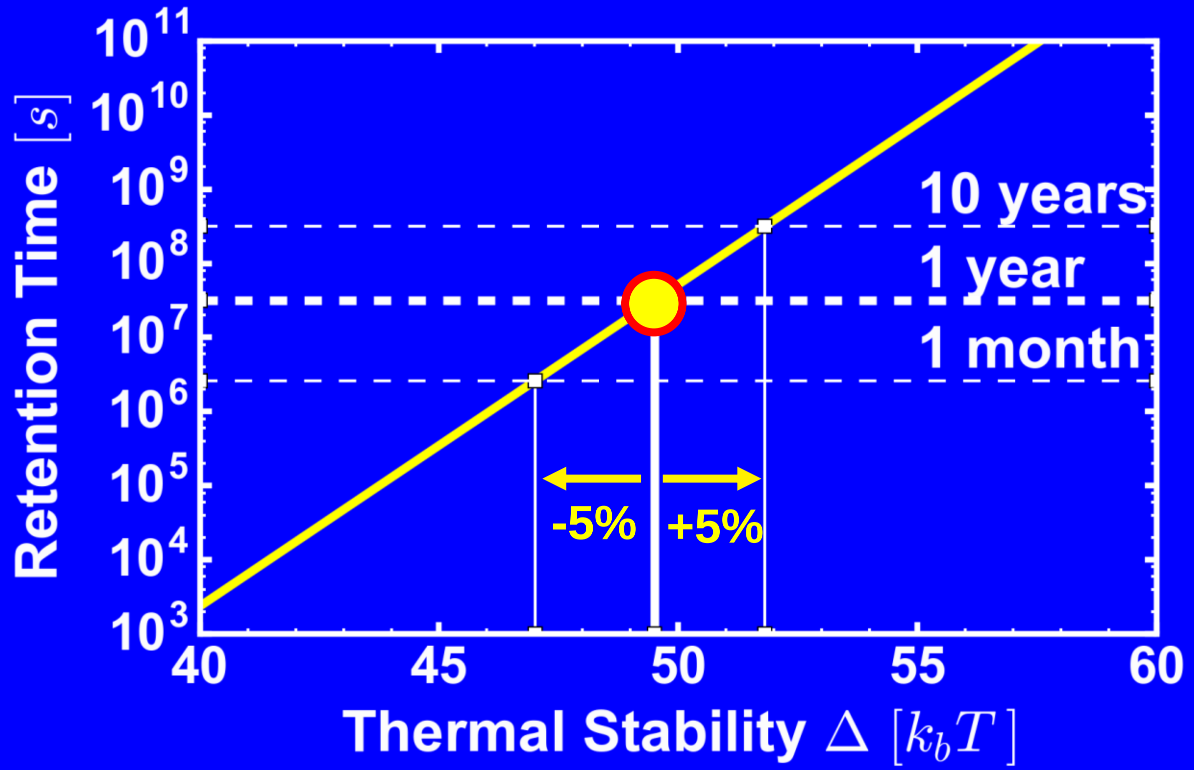
In Perp STT-MRAM, retention time τ at a given temperature is related to the Thermal Stability factor Δ [Feng et al. JAP 95] :

$$\tau = \tau_0 exp(\Delta) \qquad \Delta = \log\left(-\frac{\tau_0}{N\tau} log(1 - BER)\right)$$

Application	Retention Time τ	Bit Error Rate (N=1)	Thermal Stability Δ $[k_b T]$
Cache	10 ms	10^{-9}	36 @85°C
Soldering	~9 min	10^{-5}	38 @260°C
Storage (SCM)	1 month	10^{-9}	56 @85°C
Automotive	10 years	10^{-5}	51 @150°C
Consumer	10 years	10^{-5}	51 @85°C

Each application has a different temperature and retention target

Introduction



5% error ~ factor 10 in retention time

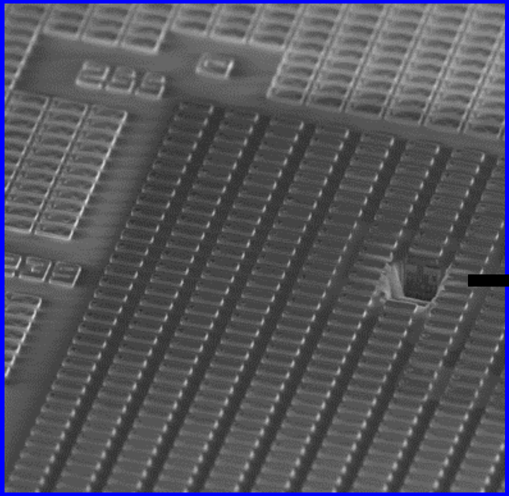
→ Thermal Stability must be extracted with high precision

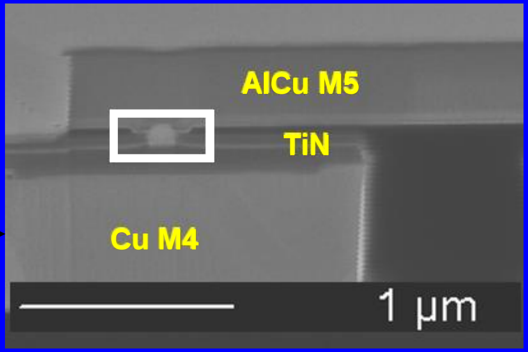
Outline

- Perp-STT description
- Direct retention time measurement
- Delta extraction methods
- Accuracy and precision
- Delta dependence
- Conclusion

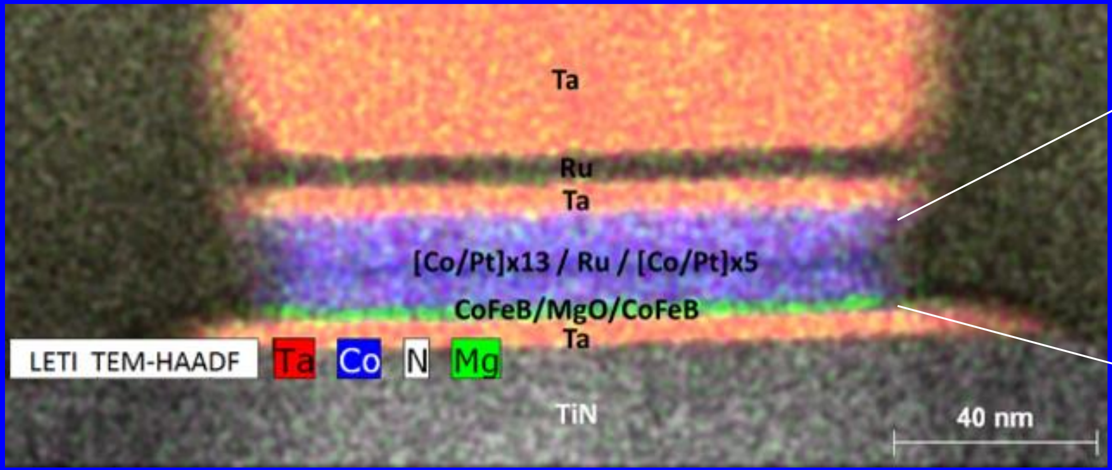
MAD Leti test chip

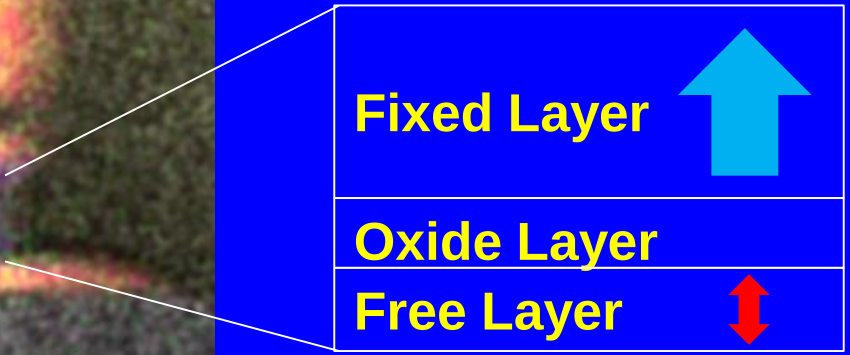
- Standard Foundry Wafer CMOS 130nm + 4 Cu Metal
- TiN Bottom Electrode Definition
- CMP touch (RMS ~ 2Å)
- Perpendicular magnetic stack deposition by Singulus Ta/FeCoB/MgO/FeCoB/Ta/Co /5x[Pt/Co]/Ru/Co/13x[Pt/Co]/Pt/Ta
- Ø100nm Mesa Patterning
- Encapsulation and CMP
- M5



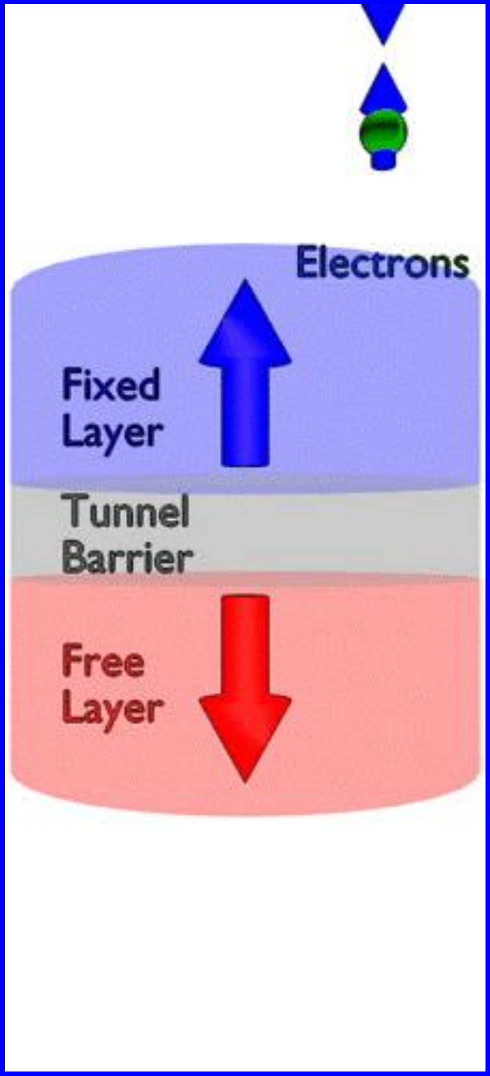


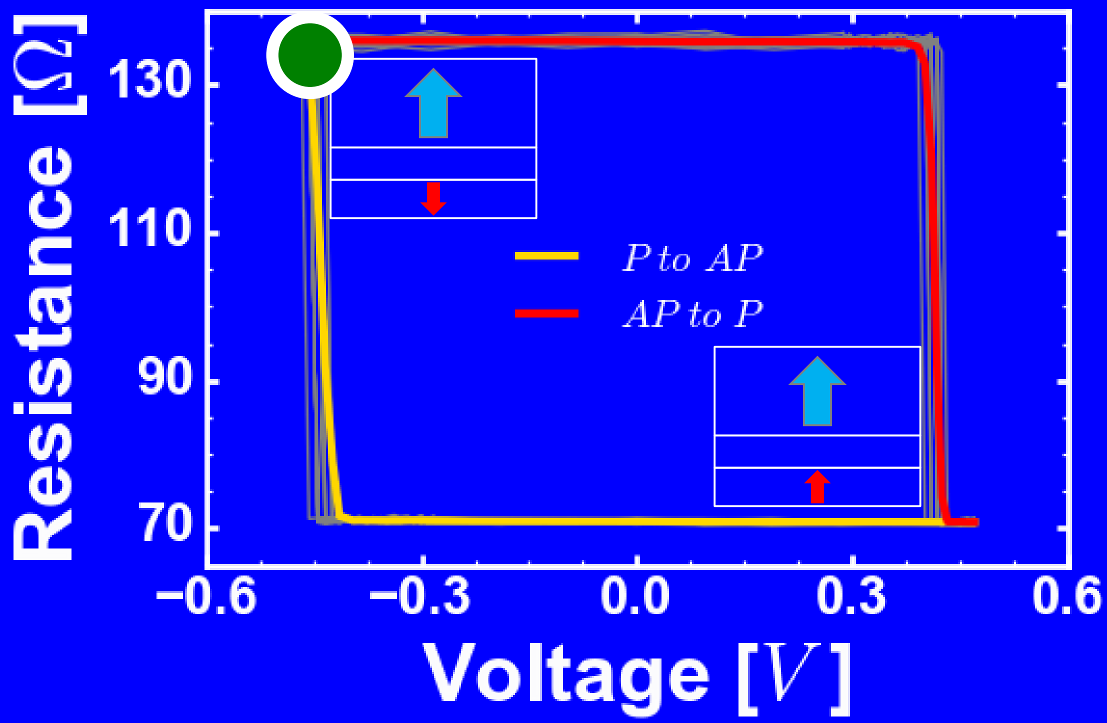
MAD Leti test chip : Multi back-end memory platform





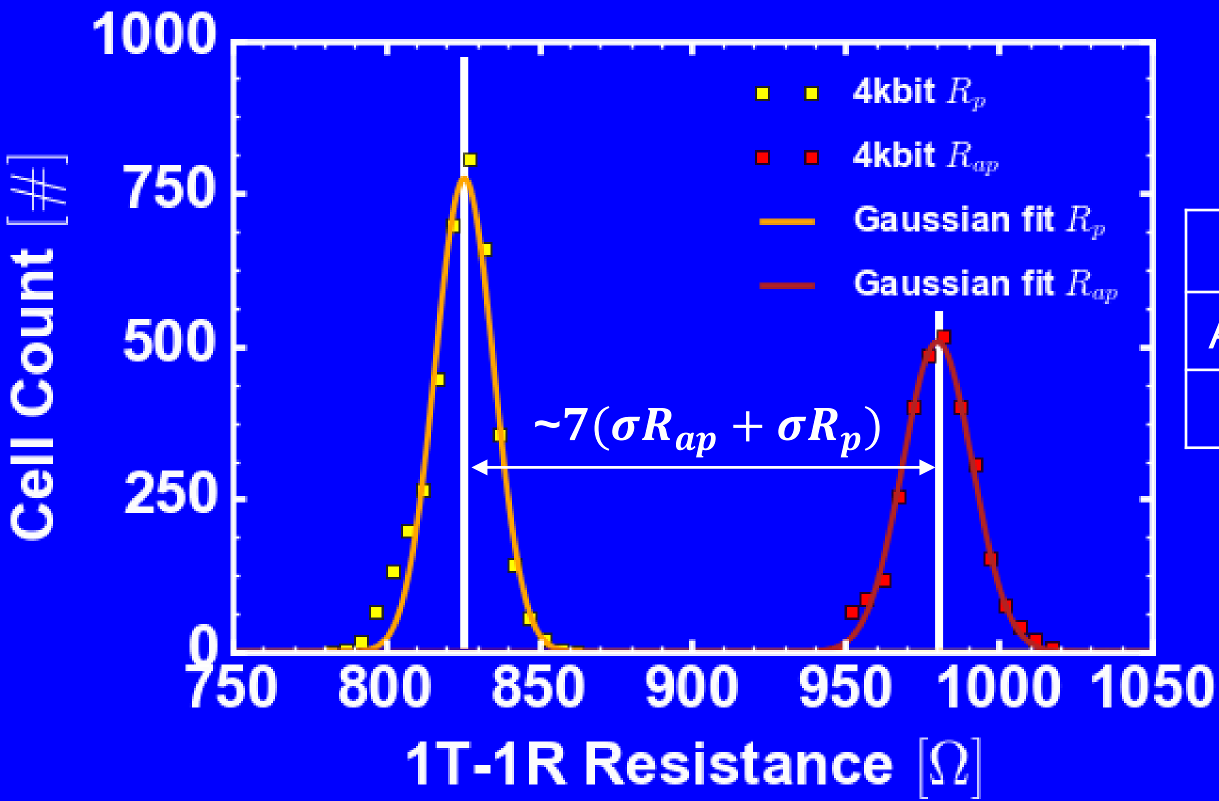
Resistance Hysteresis Cycle





Switching by current polarity
Parallel state : Low Resistance State
Anti-Parallel state : High Resistance State

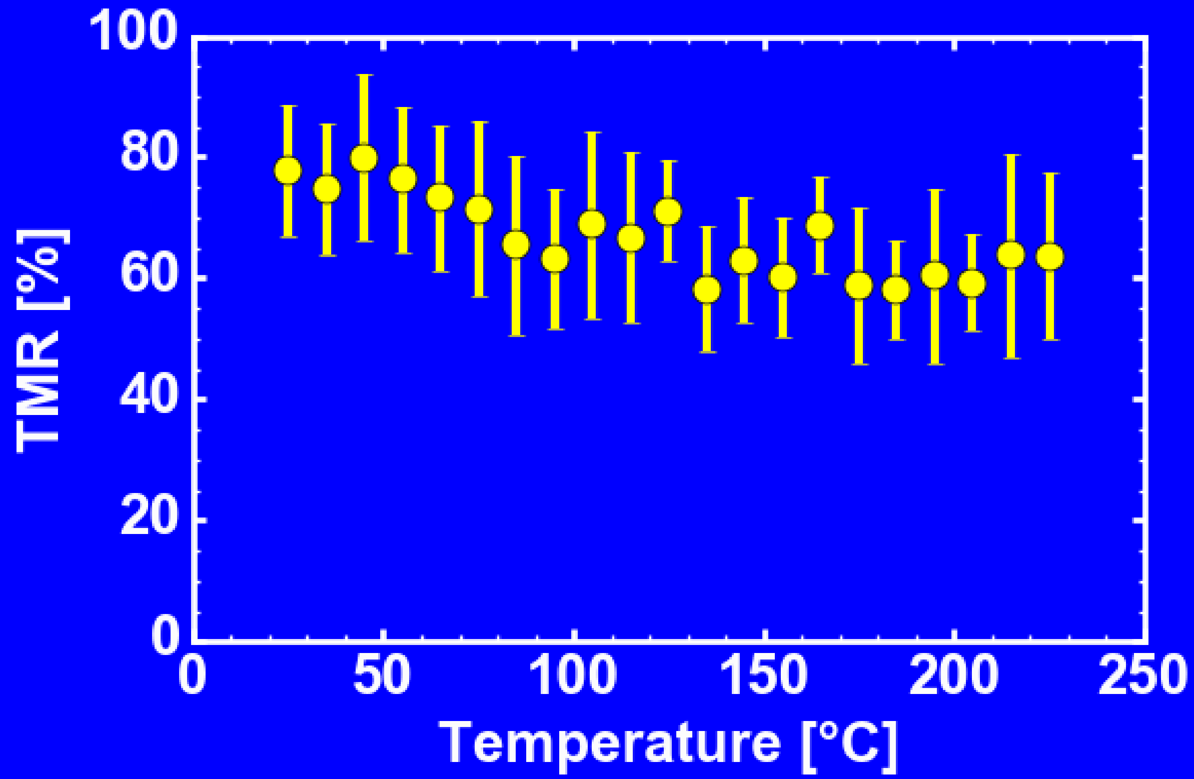
Resistance Distribution



	R_p [Ω]	R_{ap}[Ω]
Average	825	980
σ	9.53	11.37

4kbit matrix shows fully separated distributions

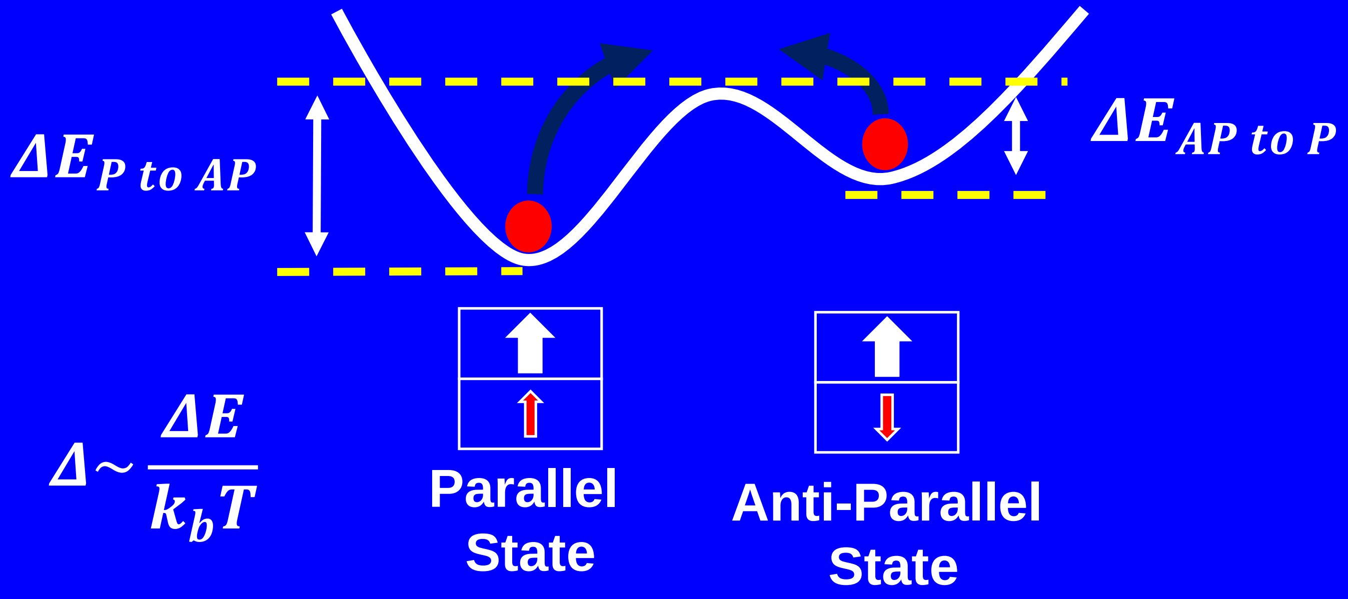
TMR Temperature dependence



$$TMR = \frac{R_{ap} - R_p}{R_p}$$

The resistance window stays stable up to 235°C
→ Good state differentiation

Sharrock's Model



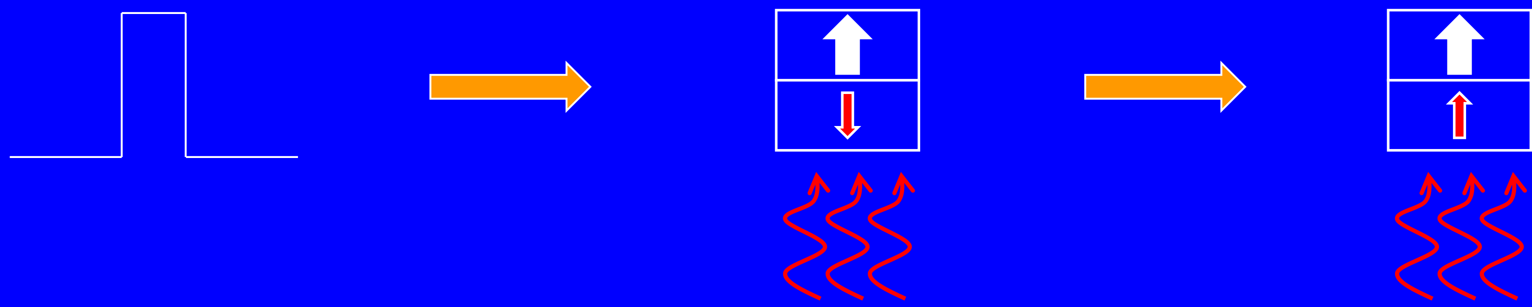
$$\Delta \sim \frac{\Delta E}{k_b T}$$

Sharrock's model [Sharrock, IEE Trans. On Magnetism, 35 ,1999] :
→ Two stable states, Parallel (P) and Anti-Parallel (AP), separated by an energy barrier ΔE

Outline

- Perp-STT description
- **Direct retention time measurement**
  - On single devices
  - On matrices
- Delta extraction methods
- Accuracy and precision
- Delta dependence
- Conclusion

Switching Time Probability (STP) on single device

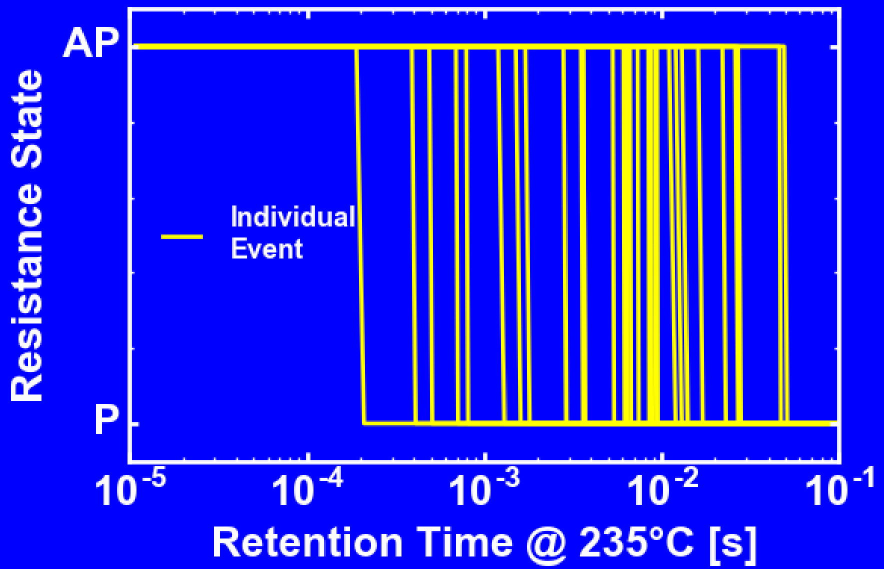


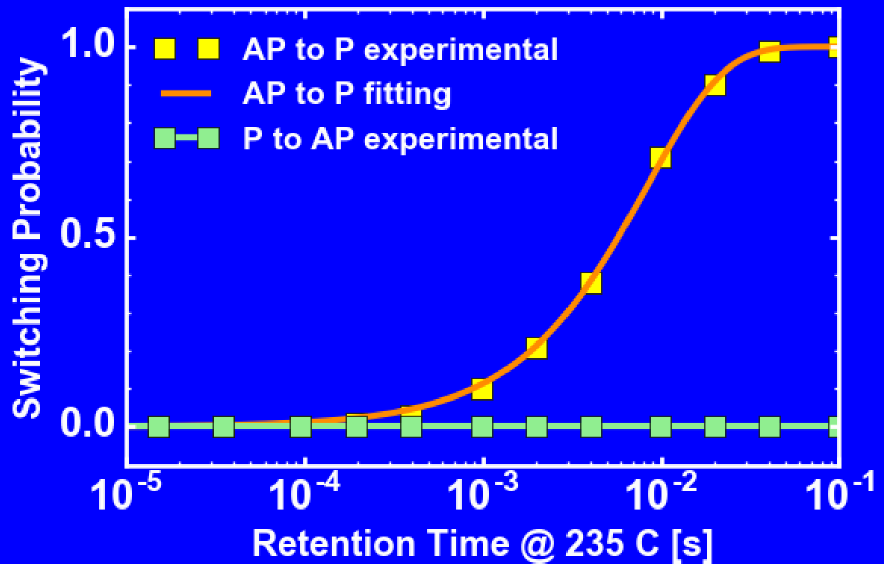
Voltage pulse **AP state** **P state**

Objective : How much time before it switches thermally?

Switching Time Probability (STP) on single device

$$P(\tau) = 1 - exp\left(\frac{\tau}{\tau_0 exp(\Delta)}\right)$$

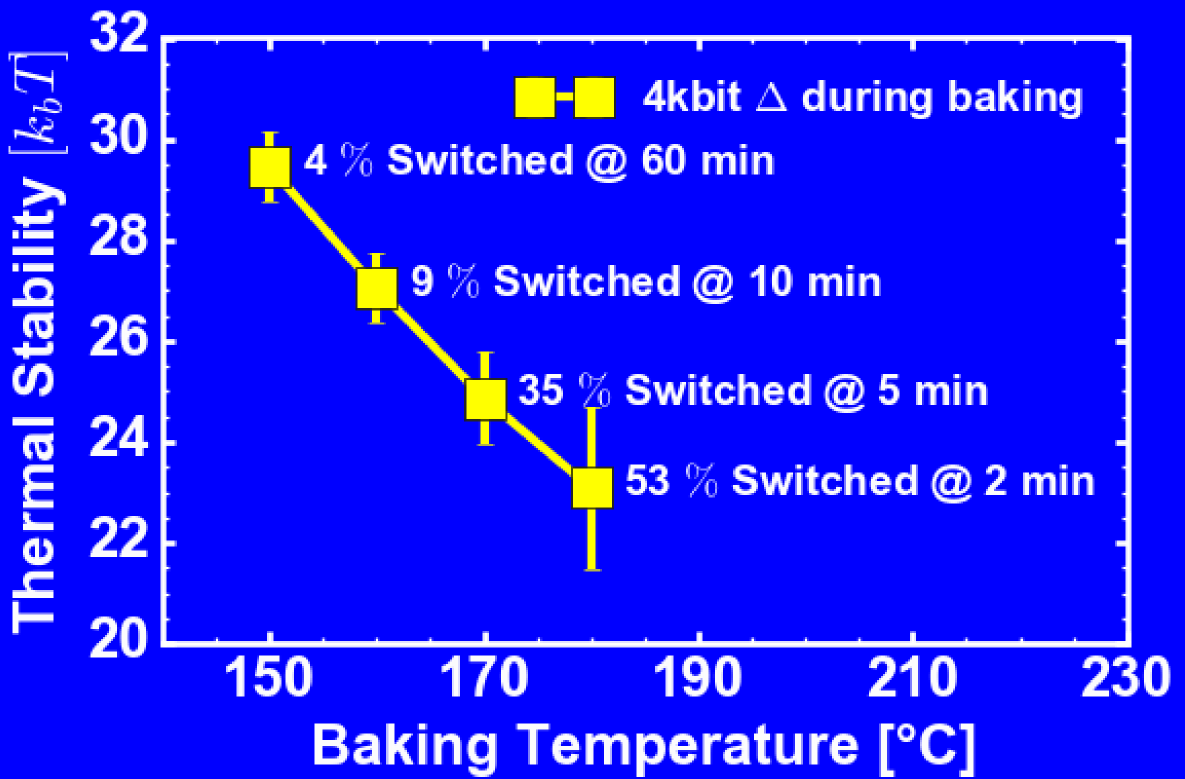




1000 events

- \+ Simple Method
- \+ Exact value of Retention time
- \- Impractical for long retention time
- \- Extrapolation for low temperature

Switching Time Probability (STP) on matrix



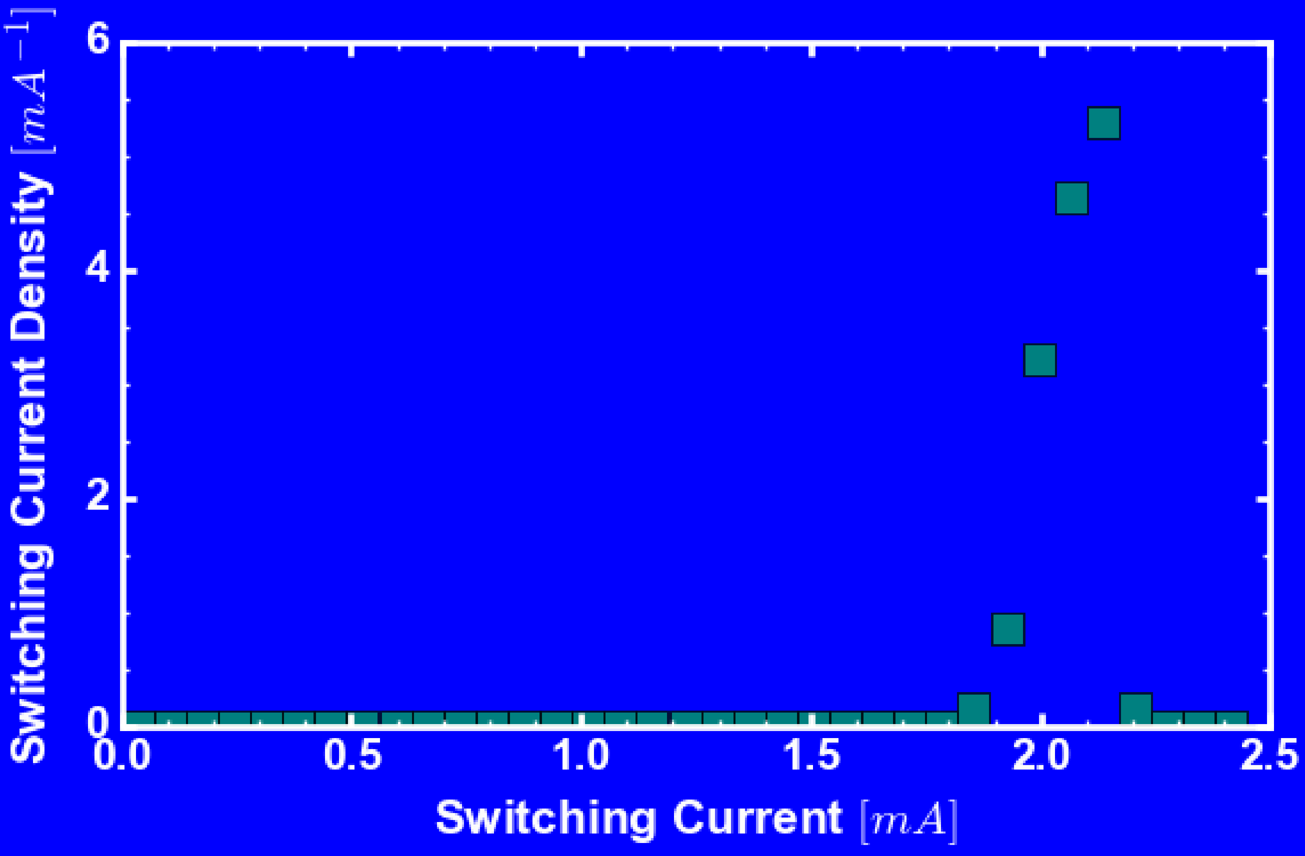
+ Simple Method
+ Exact value of Retention time
- Impractical for long retention time
- Extrapolation for low temperature

Outline

- Perp-STT description
- Direct retention time measurement
- Delta extraction methods
  1. Switching Current Density
  2. Switching Pulse Width
  3. Switching Field Density
- Accuracy and precision
- Delta dependence
- Conclusion

(1/3) Switching Current Density (SCD)

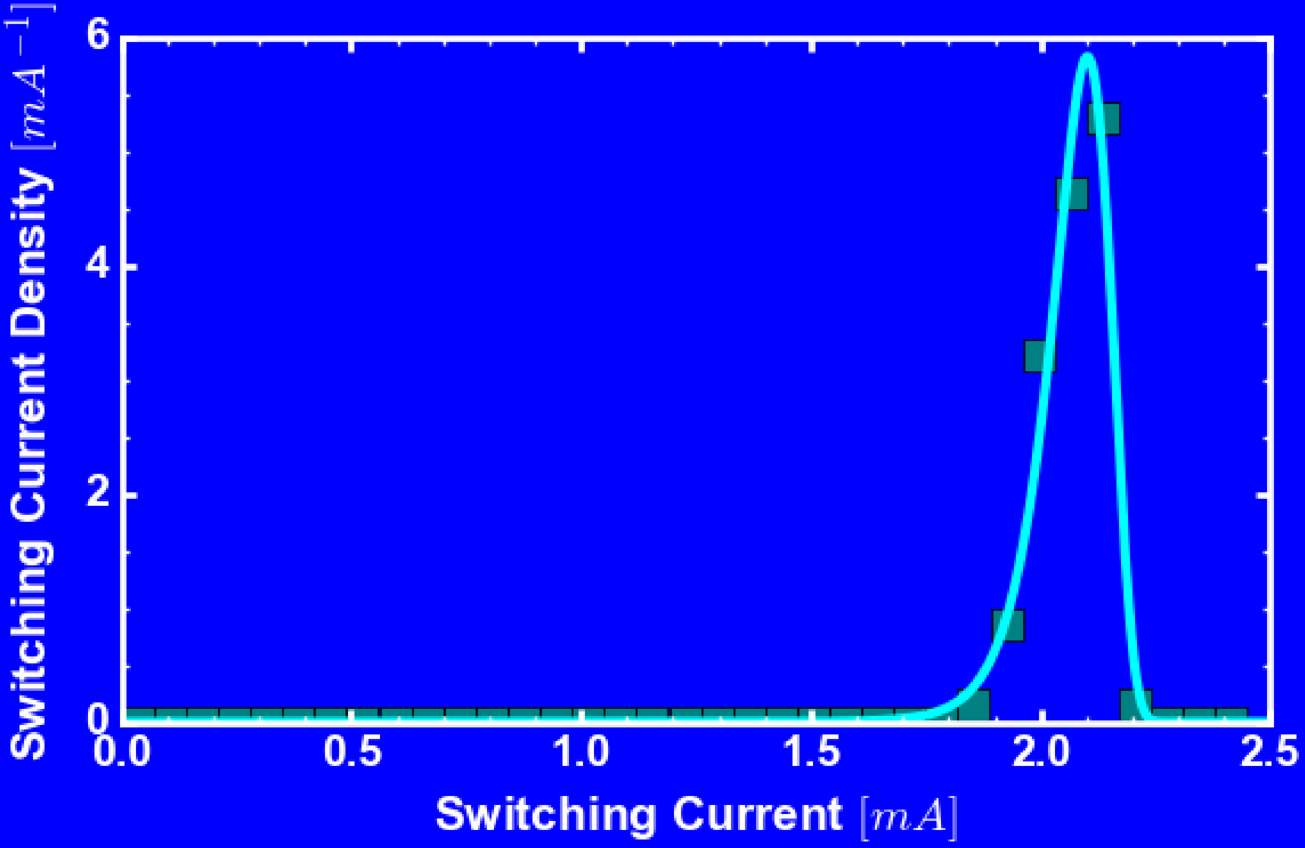
$$SCD(I) = \frac{\Delta}{I_c \tau(\Delta)} t_p \exp\left(-\frac{t_p}{\tau(\Delta)}\right)$$ [Huai et al, JAP 98, 2005]



T	Δ [k_bT]	I_c [mA]
25°C		

(1/3) Switching Current Density (SCD)

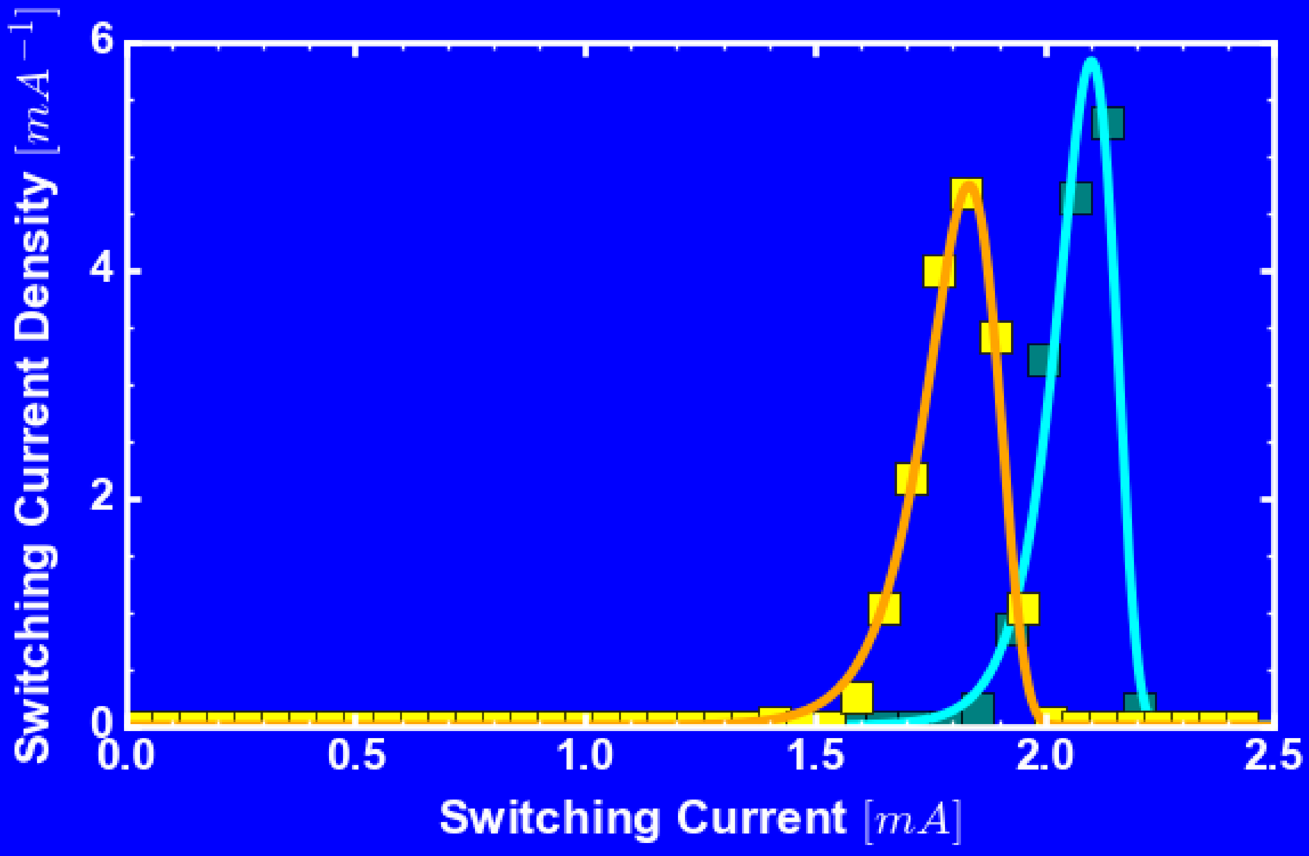
$$SCD(I) = \frac{\Delta}{I_c \tau(\Delta)} t_p \exp\left(-\frac{t_p}{\tau(\Delta)}\right)$$ [Huai et al, JAP 98, 2005]



T	Δ [k_bT]	I_c [mA]
25°C	37	2.4

(1/3) Switching Current Density (SCD)

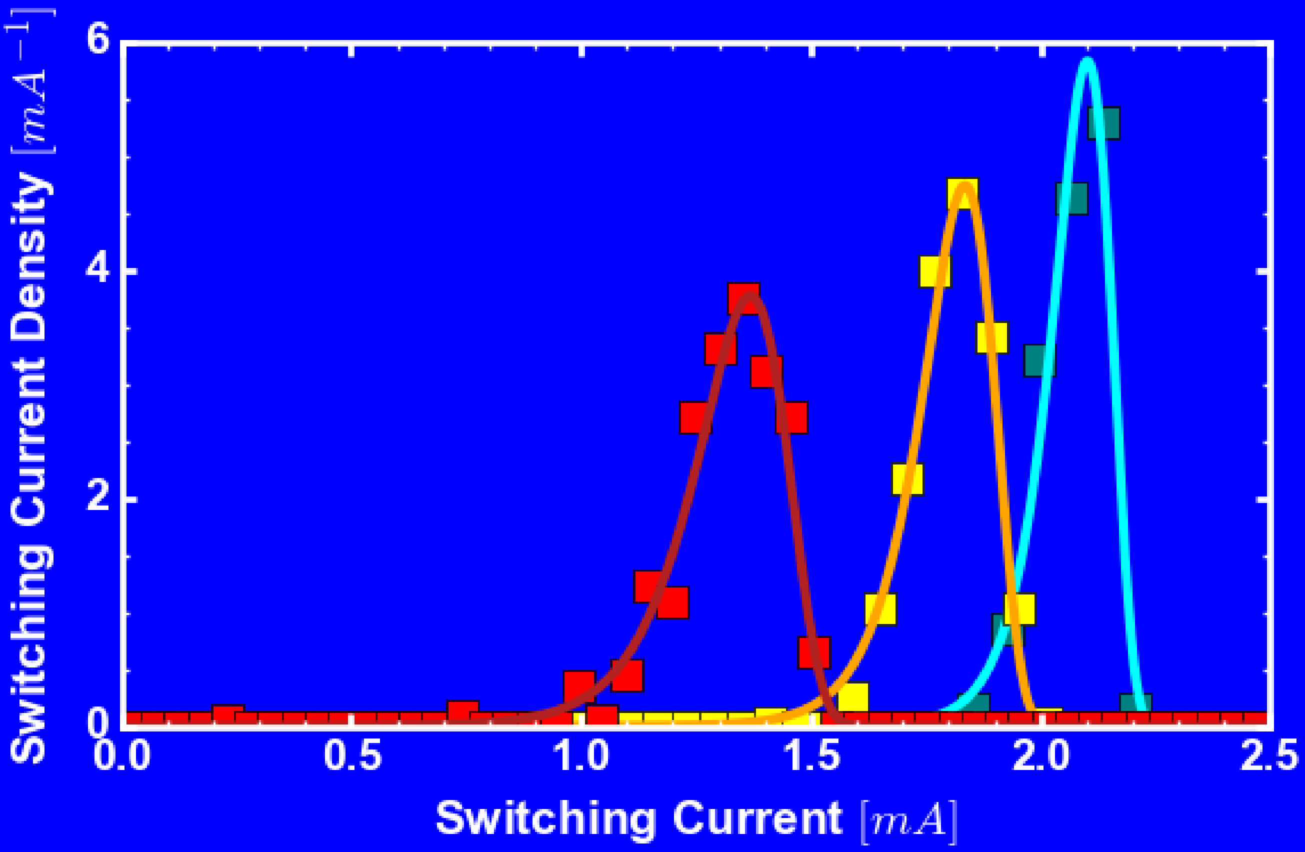
$$SCD(I) = \frac{\Delta}{I_c \tau(\Delta)} t_p \exp\left(-\frac{t_p}{\tau(\Delta)}\right)$$ **[Huai et al, JAP 98, 2005]**



T	Δ [k_bT]	I_c [mA]
25°C	37	2.4
125°C	28	2.2

(1/3) Switching Current Density (SCD)

$$SCD(I) = \frac{\Delta}{I_c \tau(\Delta)} t_p \exp\left(-\frac{t_p}{\tau(\Delta)}\right)$$ [Huai et al, JAP 98, 2005]

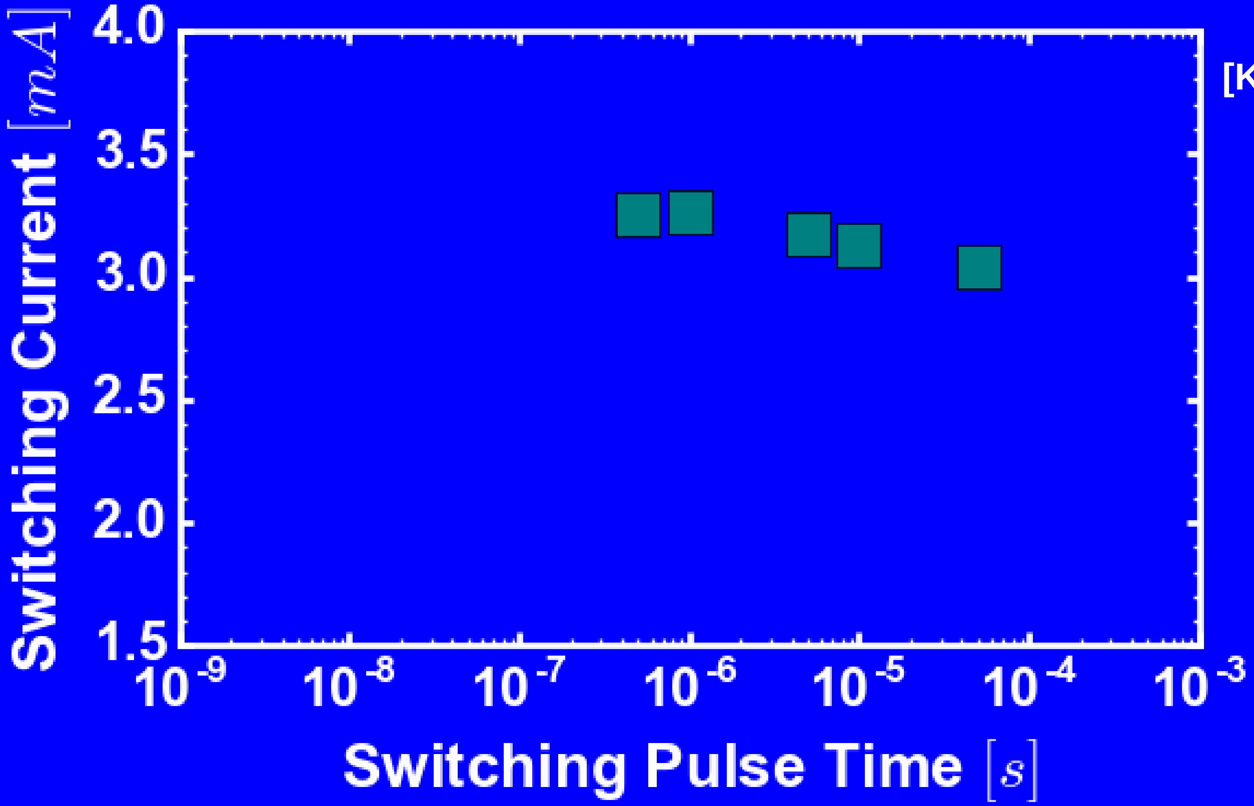


T	Δ [k_bT]	I_c [mA]
25°C	37	2.4
125°C	28	2.2
215°C	18	1.8

+ Fast Method
+ Standard measurement

(2/3) Switching Pulse Width (SPW)

In thermally activated regime : $SPW(t_p) = I_c\left[1 - \frac{1}{\Delta} log\left(\frac{t_p}{\tau_0}\right)\right]$

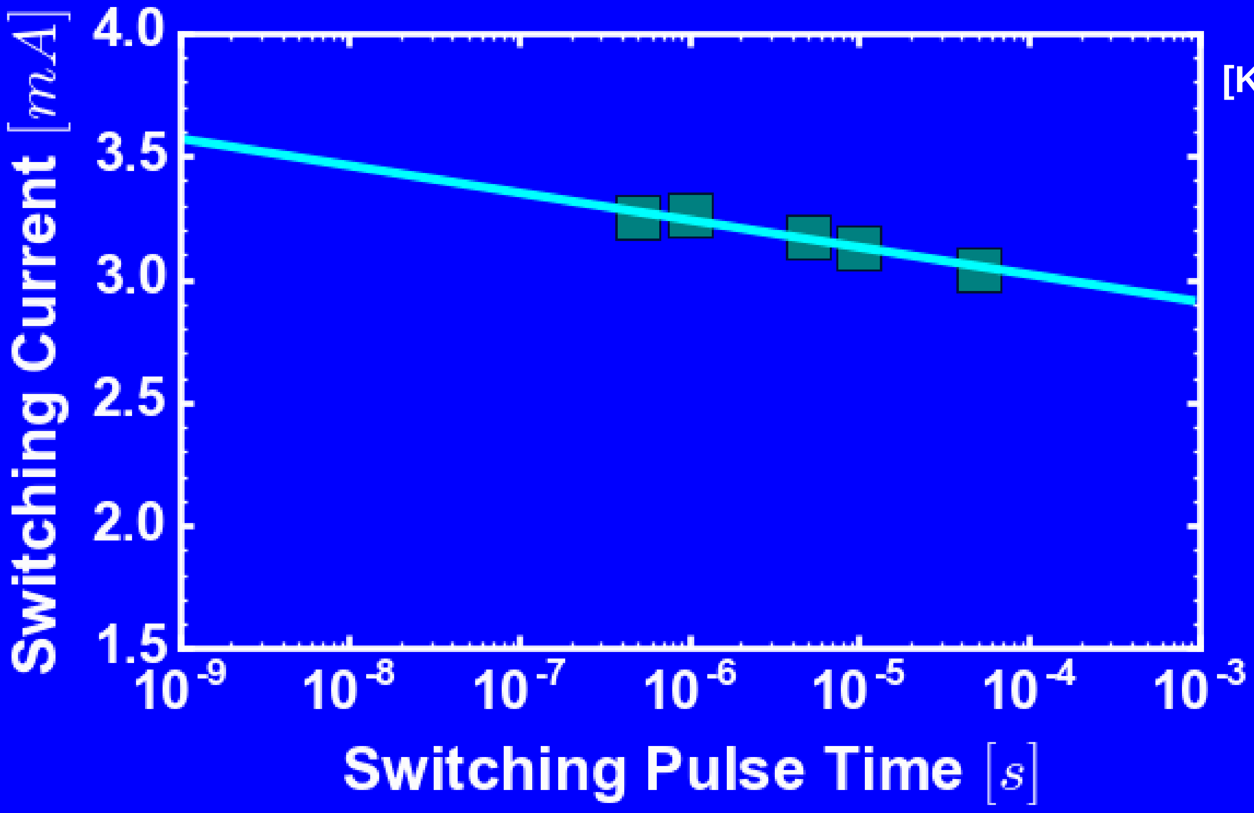


[Koch et al, Phys. Rev. Lett. 92, 2004]

T	Δ [k_bT]	I_c [mA]
85°C		

(2/3) Switching Pulse Width (SPW)

In thermally activated regime : $SPW(t_p) = I_c\left[1 - \frac{1}{\Delta} log\left(\frac{t_p}{\tau_0}\right)\right]$

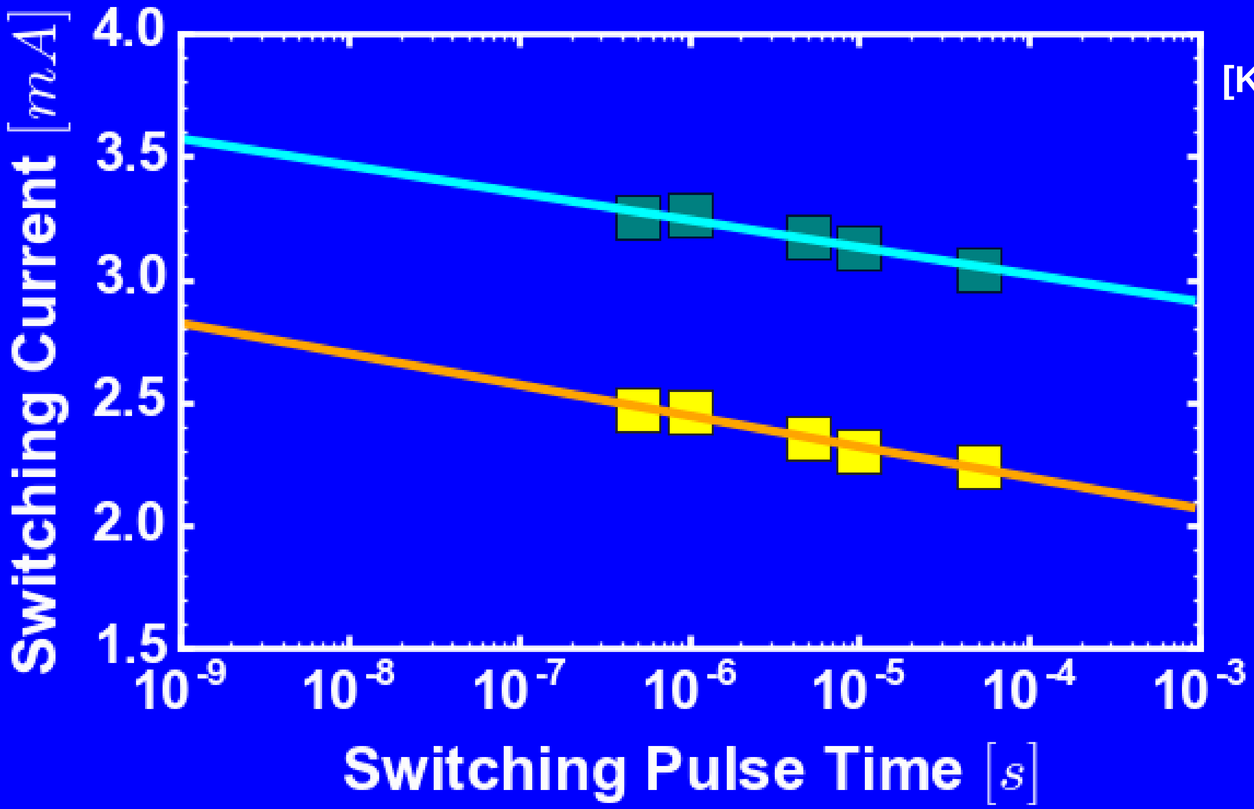


[Koch et al, Phys. Rev. Lett. 92, 2004]

T	Δ [k_bT]	I_c [mA]
85°C	**74**	**3.57**

(2/3) Switching Pulse Width (SPW)

In thermally activated regime : $SPW(t_p) = I_c\left[1 - \frac{1}{\Delta} log\left(\frac{t_p}{\tau_0}\right)\right]$

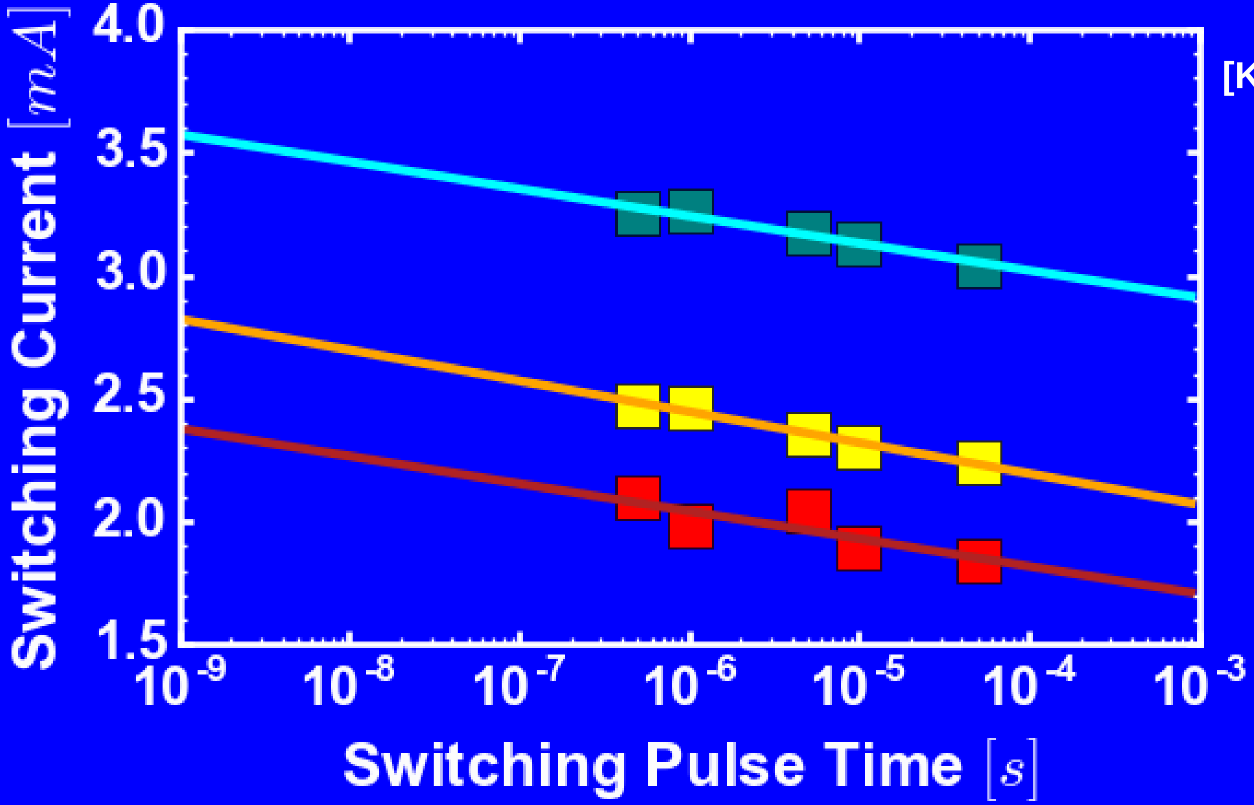


[Koch et al, Phys. Rev. Lett. 92, 2004]

T	Δ $[k_b T]$	I_c [mA]
85°C	**74**	**3.57**
175°C	**51**	**2.82**

(2/3) Switching Pulse Width (SPW)

In thermally activated regime : $SPW(t_p) = I_c\left[1 - \frac{1}{\Delta} log\left(\frac{t_p}{\tau_0}\right)\right]$



[Koch et al, Phys. Rev. Lett. 92, 2004]

T	Δ [k_bT]	I_c [mA]
85°C	74	3.57
175°C	51	2.82
235°C	48	2.38

+ Fast Method

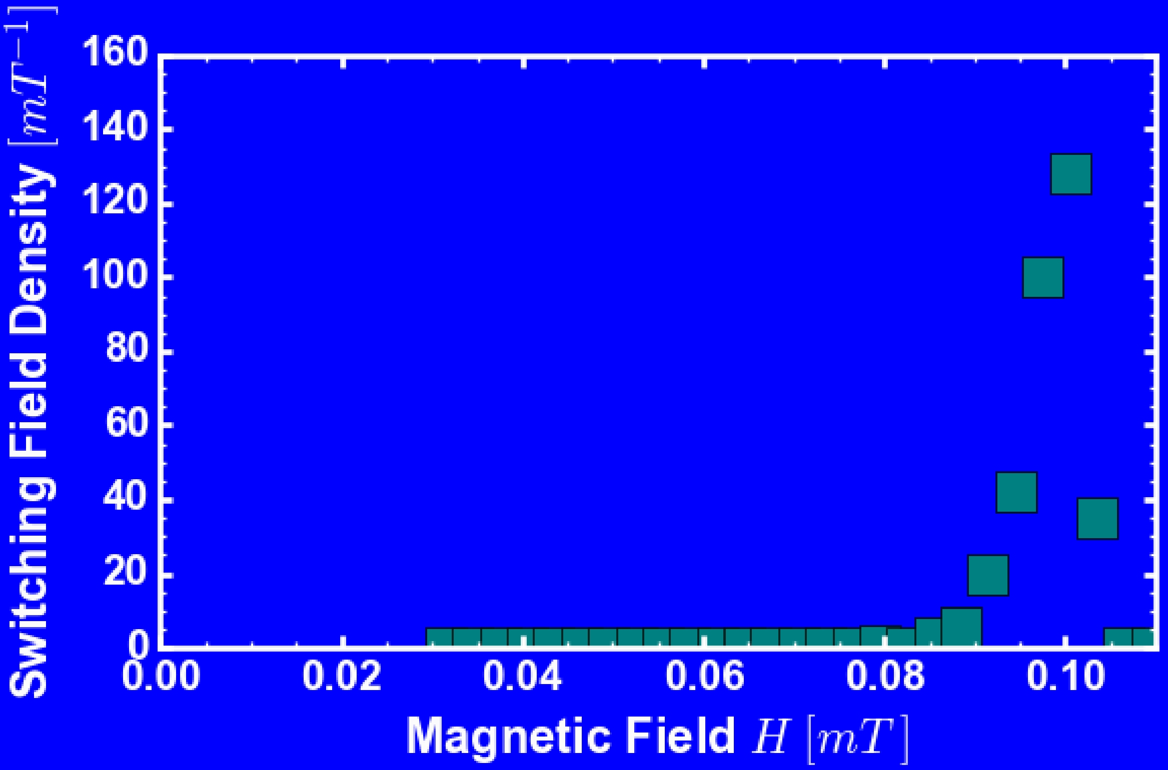
+ Requires to be in thermally activated regime

- Degradation due to long pulses

(3/3) Switching Field Density (SFD)

$$SFD(H) = \frac{1}{R_H \tau_0} exp\left\{-\frac{H_k}{2\tau_0 R_H}\sqrt{\frac{\pi}{\Delta}} erfc\left[\sqrt{\Delta}\left(1-\frac{H}{H_k}\right)\right]\right\} exp\left[-\Delta\left(1-\frac{H}{H_k}\right)^2\right]$$

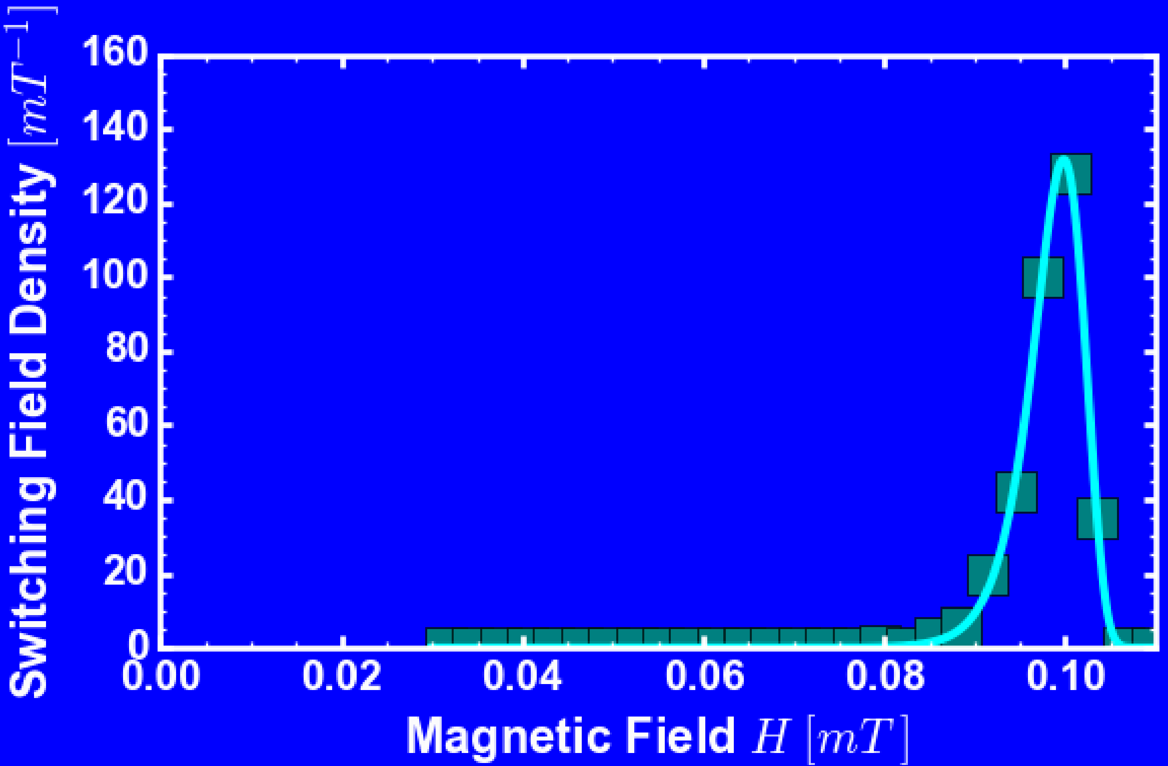
[Feng et al. *J.A.P 95*, 2004]



T	Δ [k_bT]	H_k [mT]
$30°C$		

(3/3) Switching Field Density (SFD)

$$SFD(H) = \frac{1}{R_H \tau_0} exp\left\{-\frac{H_k}{2\tau_0 R_H}\sqrt{\frac{\pi}{\Delta}} erfc\left[\sqrt{\Delta}\left(1-\frac{H}{H_k}\right)\right]\right\} exp\left[-\Delta\left(1-\frac{\mathrm{H}}{\mathrm{H_k}}\right)^2\right]$$

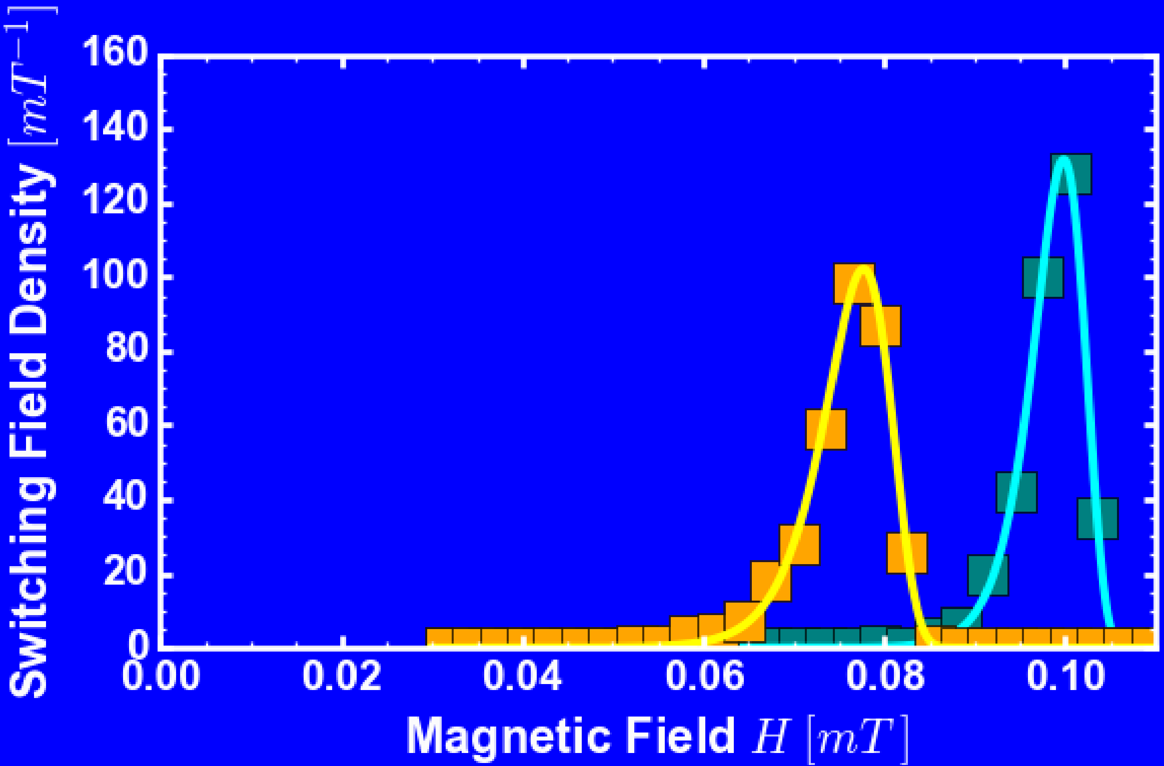


[Feng et al. *J.A.P 95*, 2004]

T	Δ $[k_b T]$	H_k [mT]
$30°C$	69	0.18

(3/3) Switching Field Density (SFD)

$$SFD(H) = \frac{1}{R_H \tau_0} exp\left\{ -\frac{H_k}{2\tau_0 R_H}\sqrt{\frac{\pi}{\Delta}} erfc\left[\sqrt{\Delta}\left(1-\frac{H}{H_k}\right)\right]\right\} exp\left[-\Delta\left(1-\frac{H}{H_k}\right)^2\right]$$



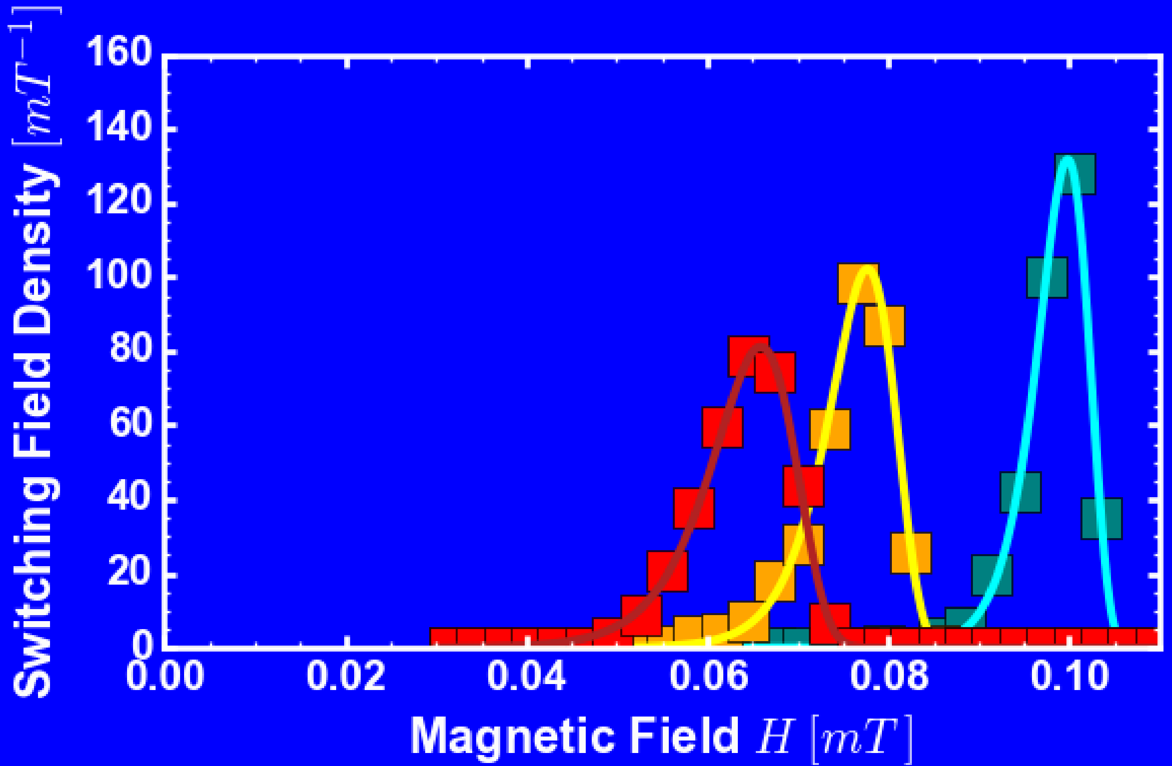
[Feng et al. *J.A.P 95*, 2004]

T	Δ $[k_b T]$	H_k [mT]
$30°C$	69	0.18
$50°C$	43	0.19

(3/3) Switching Field Density (SFD)

$$SFD(H) = \frac{1}{R_H \tau_0} exp\left\{-\frac{H_k}{2\tau_0 R_H}\sqrt{\frac{\pi}{\Delta}} erfc\left[\sqrt{\Delta}\left(1-\frac{H}{H_k}\right)\right]\right\} exp\left[-\Delta\left(1-\frac{H}{H_k}\right)^2\right]$$

[Feng et al. *J.A.P 95*, 2004]



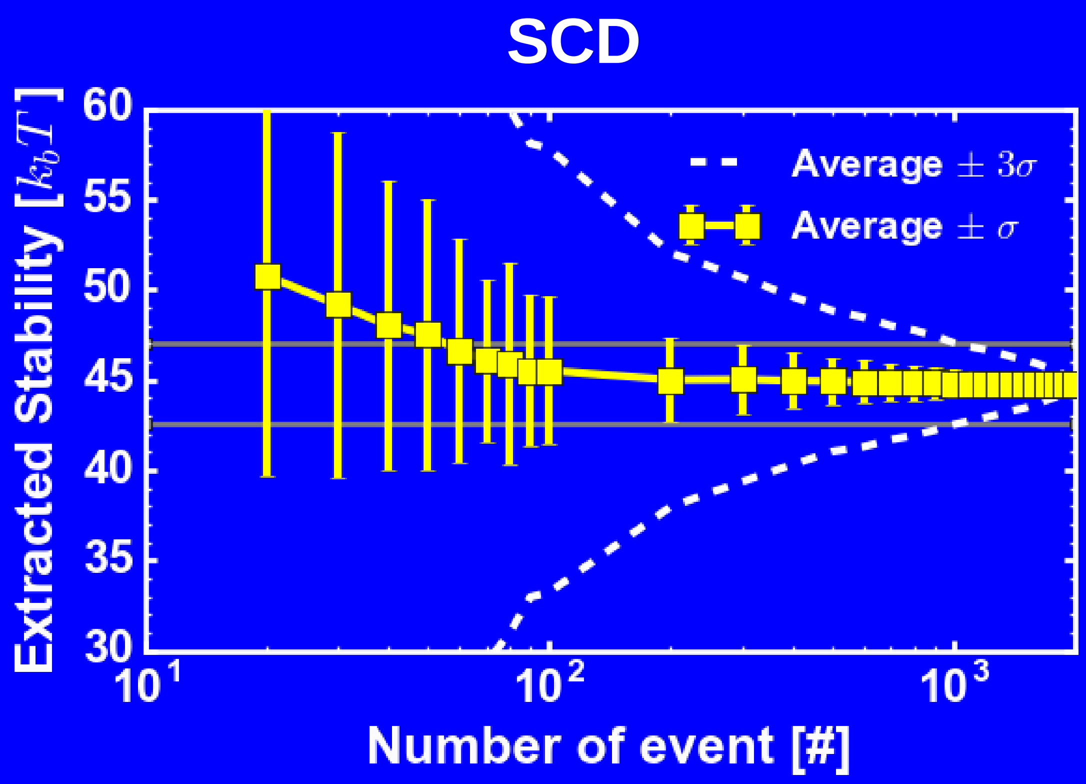
T	Δ $[k_b T]$	H_k $[mT]$
$30°C$	69	0.18
$50°C$	43	0.19
$70°C$	32	0.21

+ No degradation (only for reading)
- Involves magnetic field (Setup compatibility)

Outline

- Perp-STT description
- Direct retention time measurement
- Delta extraction methods
- **Accuracy and precision**
- Delta dependence
- Conclusion

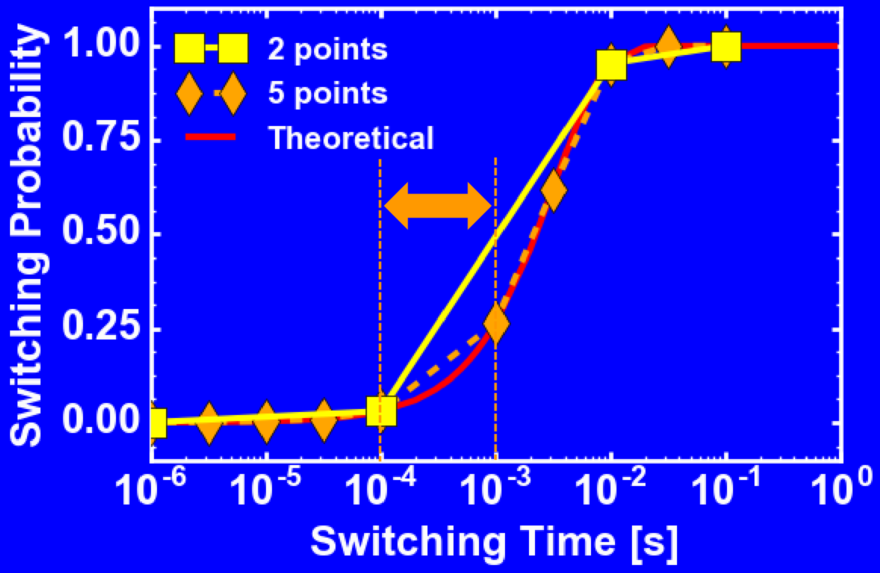
Precision Measurement

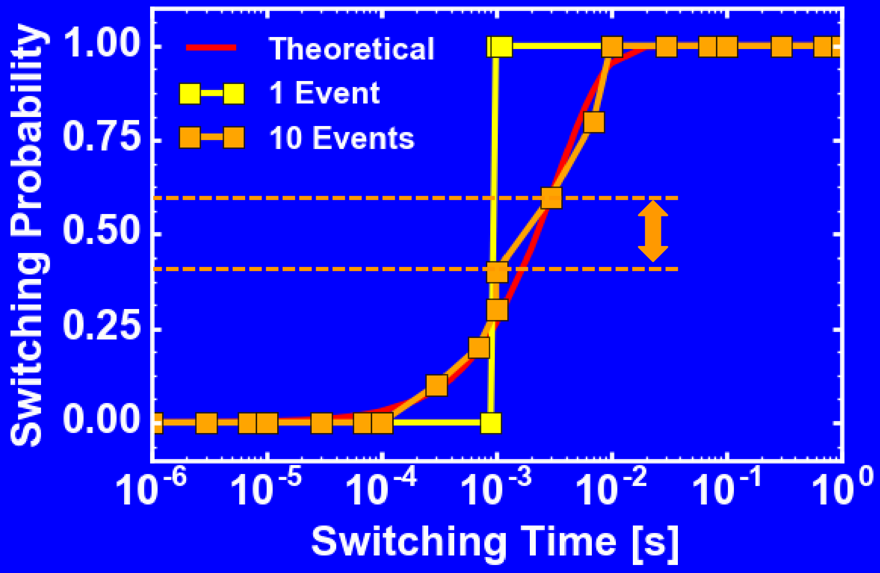


Low cycle number induces optimistic Δ extraction and high variability

→ High number of cycles needed

Measurement parameters

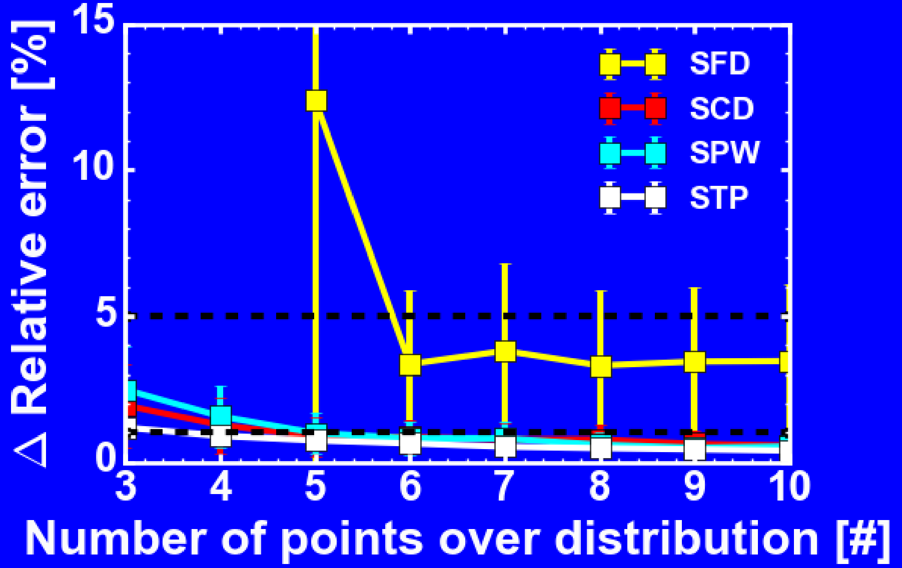


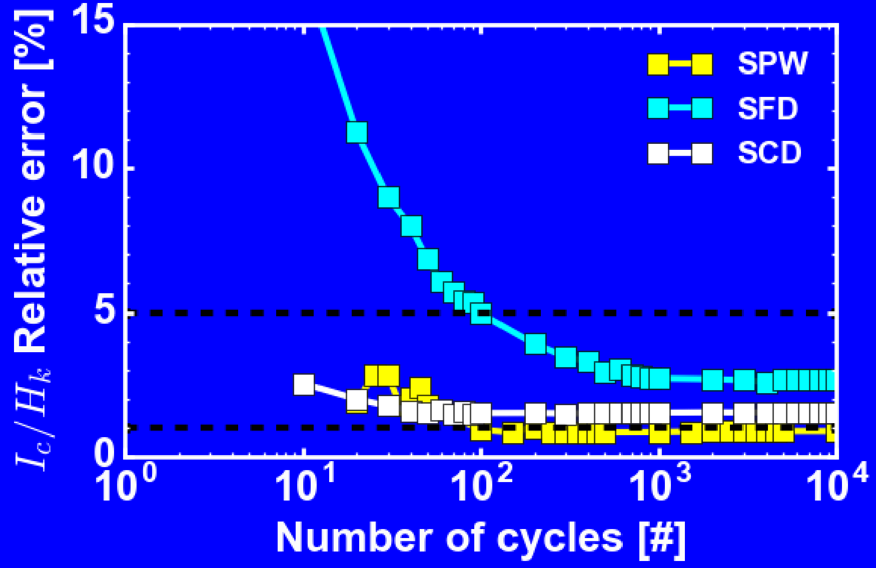


Two main measurement conditions :

- **Number of significant points for curve fitting**
- **Number of events measured**

Delta – accuracy and precision





Delta extraction requires :

→ At least 5 points over the distribution

→ A high number of events measured

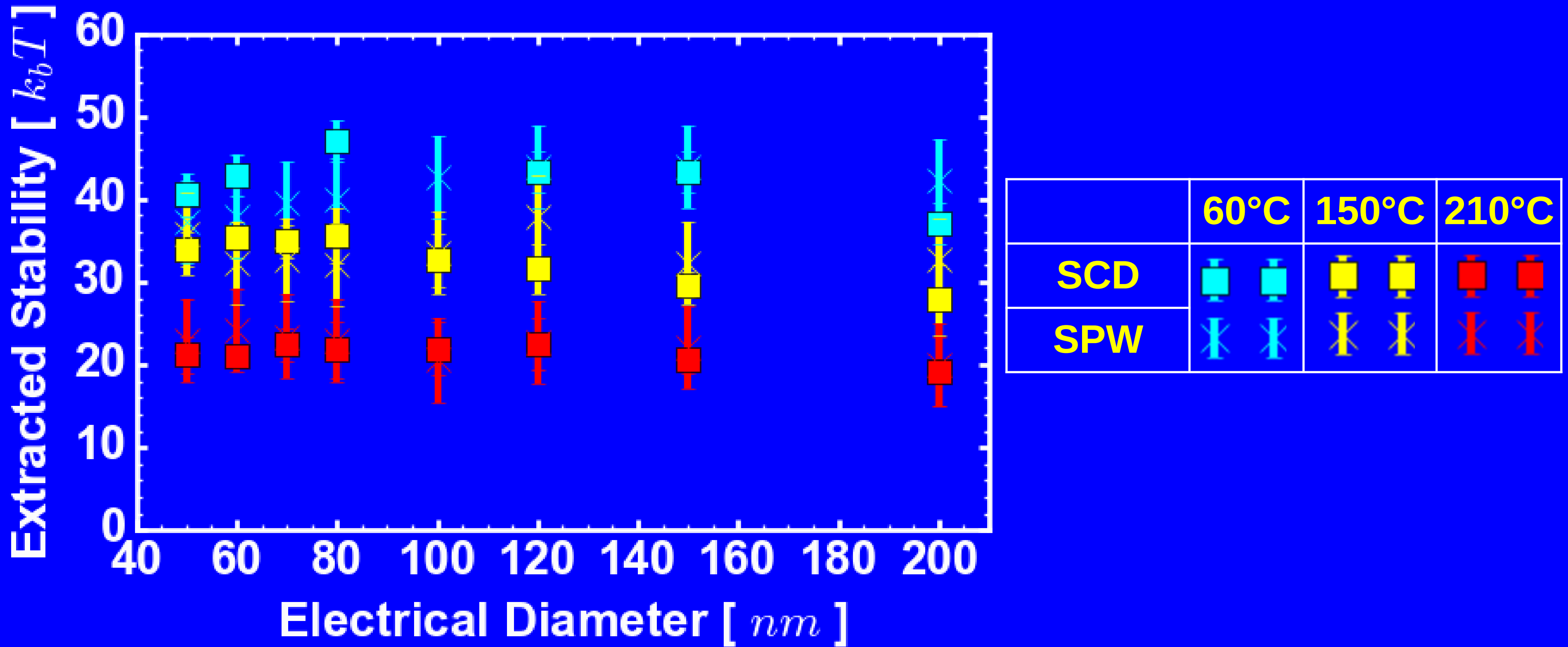
Summary Table

	Switching Mechanism	Significant points # Accuracy 5%	Significant points # Accuracy 1%	Events # Precision 5%	Events # Precision 1%	Step speed	Comments
STP	Retention (thermal)	-	-	≥10	≥20	1s – 1 yr	+ Simple method + Most precise - Impractical for long retention time
SCD	Current pulse (amplitude)	≥3	≥6	≥200	$\geq 10^4$	ns	+ Fast method + Typically no degradation
SPW	Current pulse width (length)	≥3 (per pts)	≥5 (per pts)	≥10	≥100	ns – ms	+ Fast method - Requires to be in thermally activated regime - Degradation due to long pulses
SFD	Magnetic Field	≥6	-	≥300	$\geq 10^5$	µs – ms	+ No degredation - Involves magnetic field

Outline

- Perp-STT description
- Direct retention time measurement
- Delta extraction methods
- Accuracy and precision
- **Delta dependence**
  - **Diameter dependence**
  - **Temperature dependence**
- Conclusion

Stability dependence with diameter

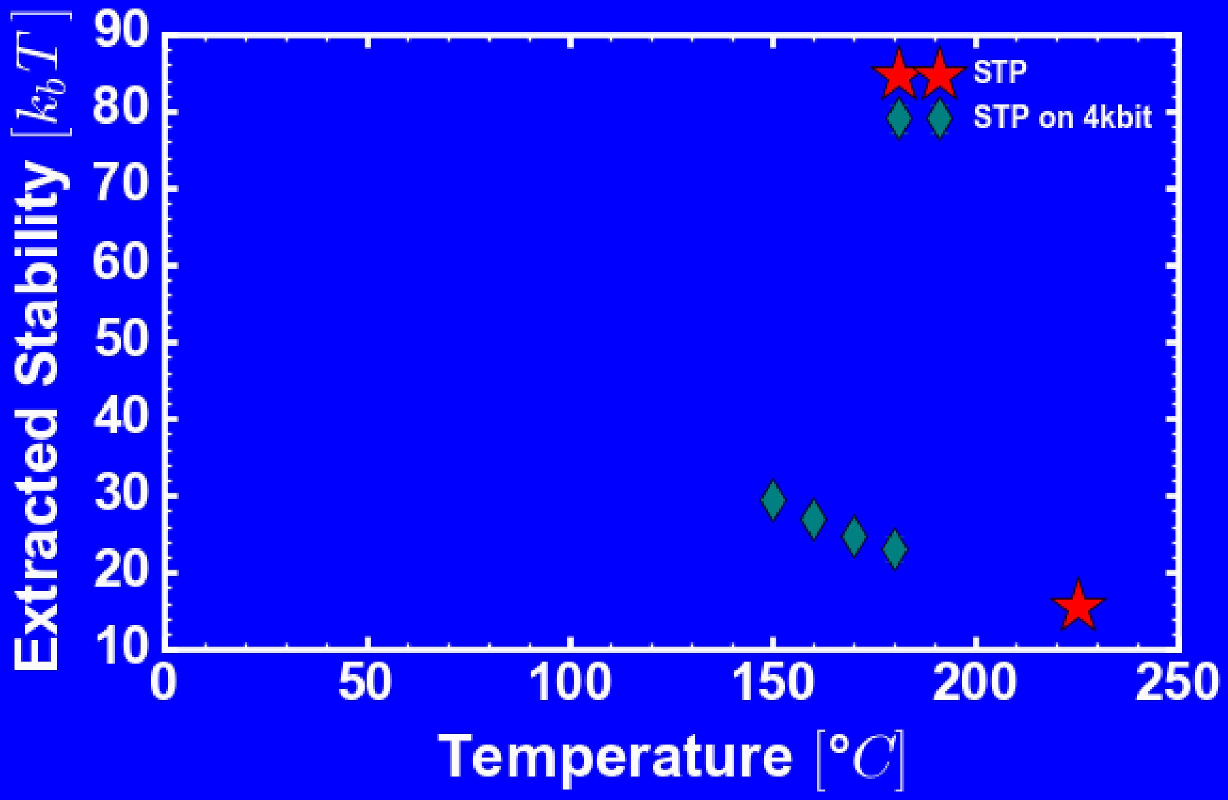


Non-quadratic behavior

→ Coherent with a constant sub-volume nucleation.

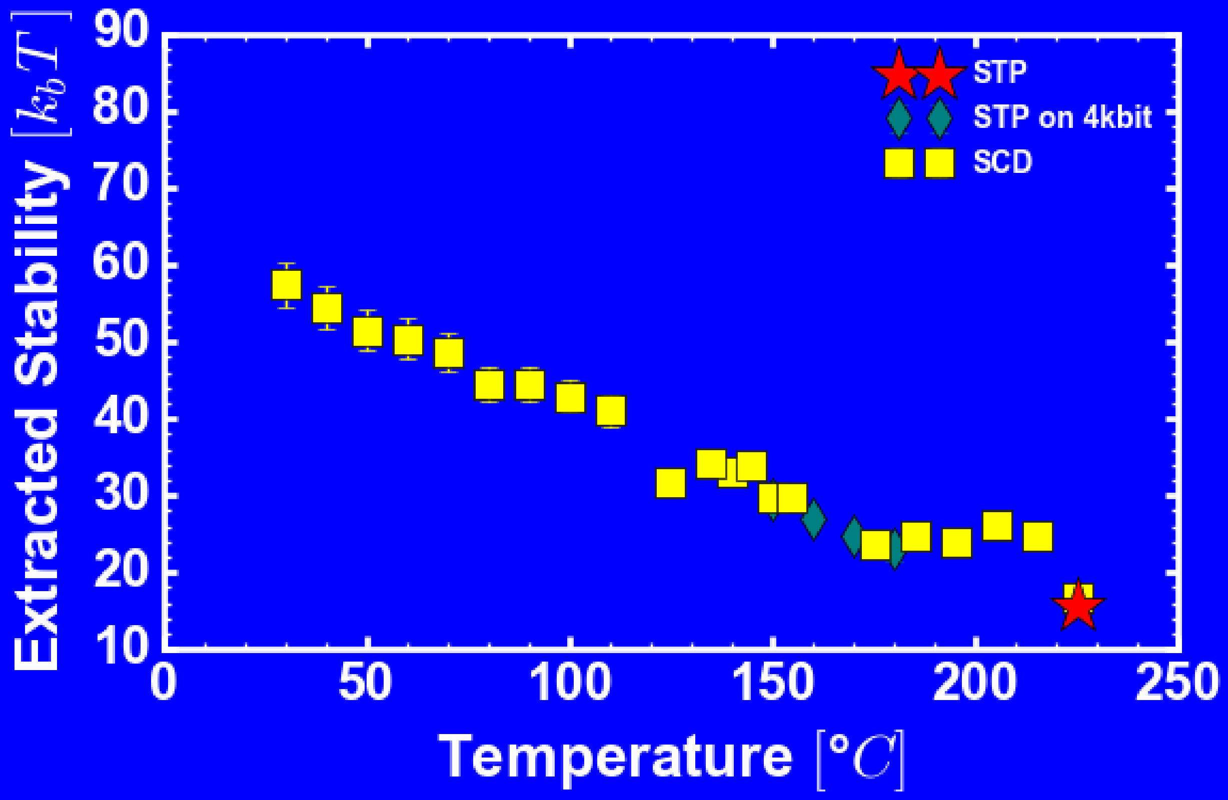
[Sun et al, Phys. Rev. B 84’]

Stability dependence with temperature



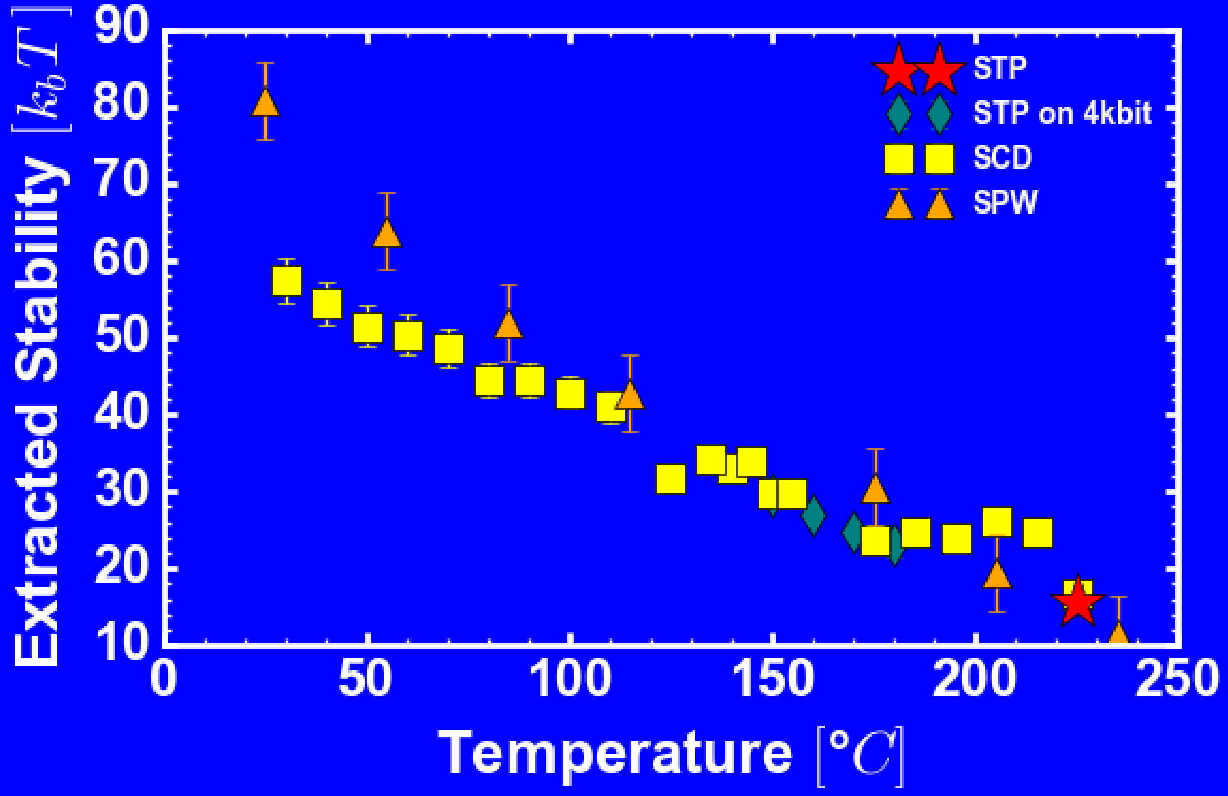
STP at high temperature : Reference values

Stability dependence with temperature



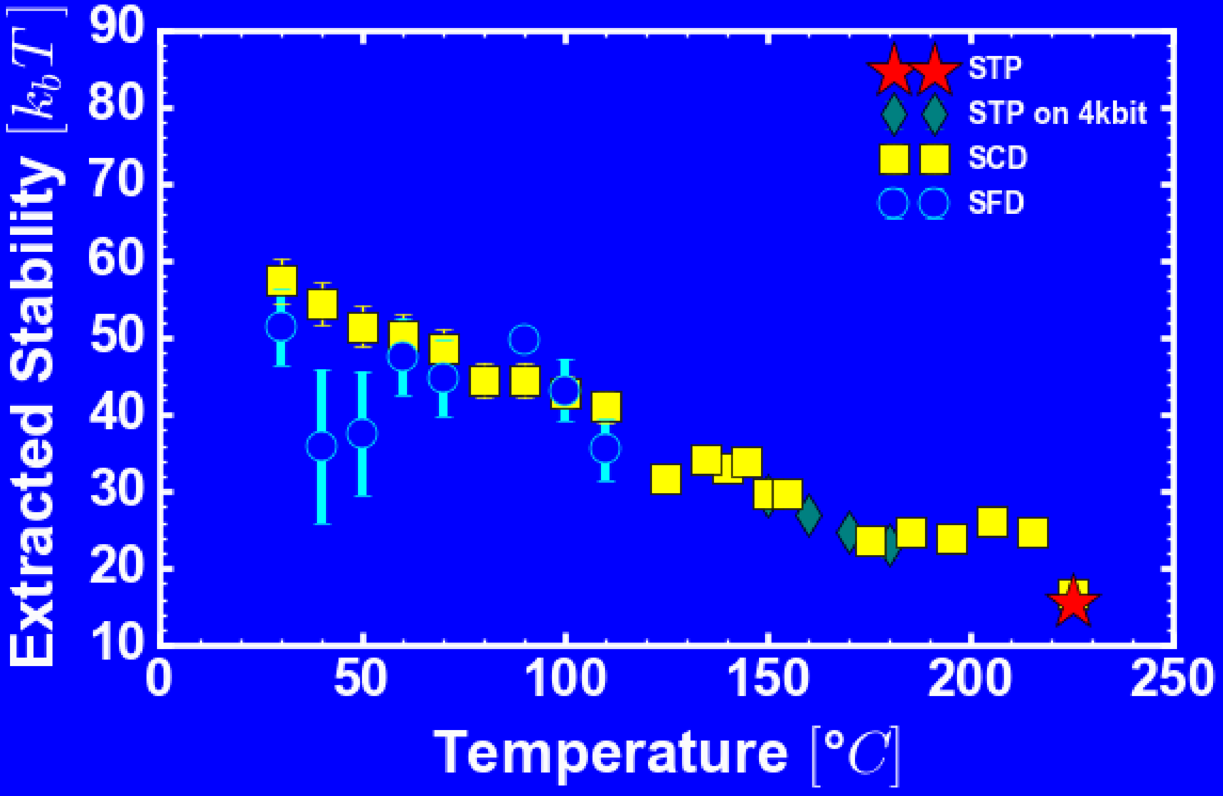
SCD on all range : Coherent with reference values

Stability dependence with temperature



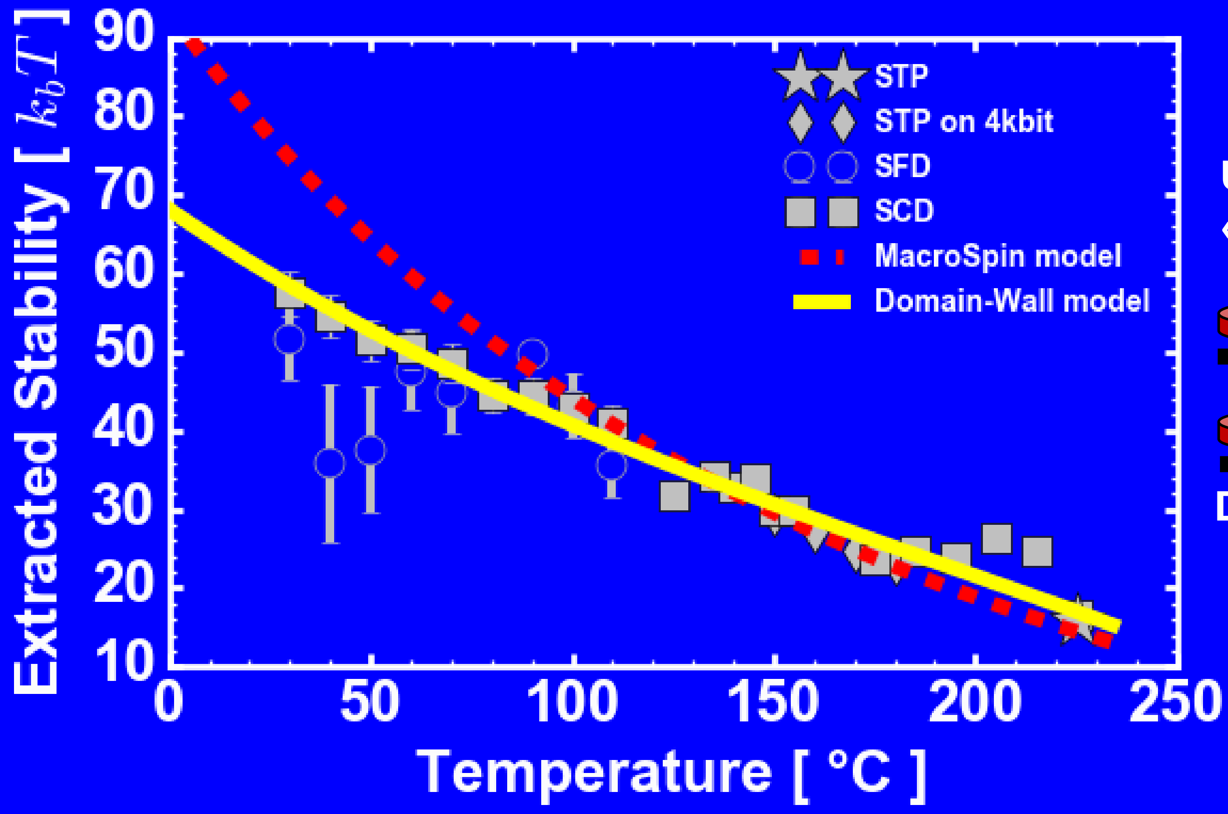
SPW Measurements : Coherent at high temperature, deviates from SCD below 100°C

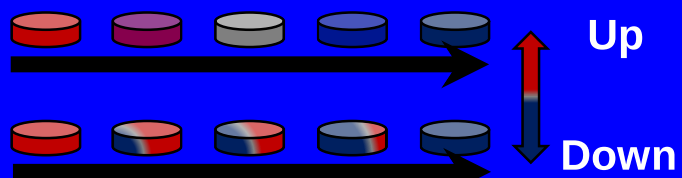
Stability dependence with temperature



SFD at low temperature : noisy but coherent with SCD

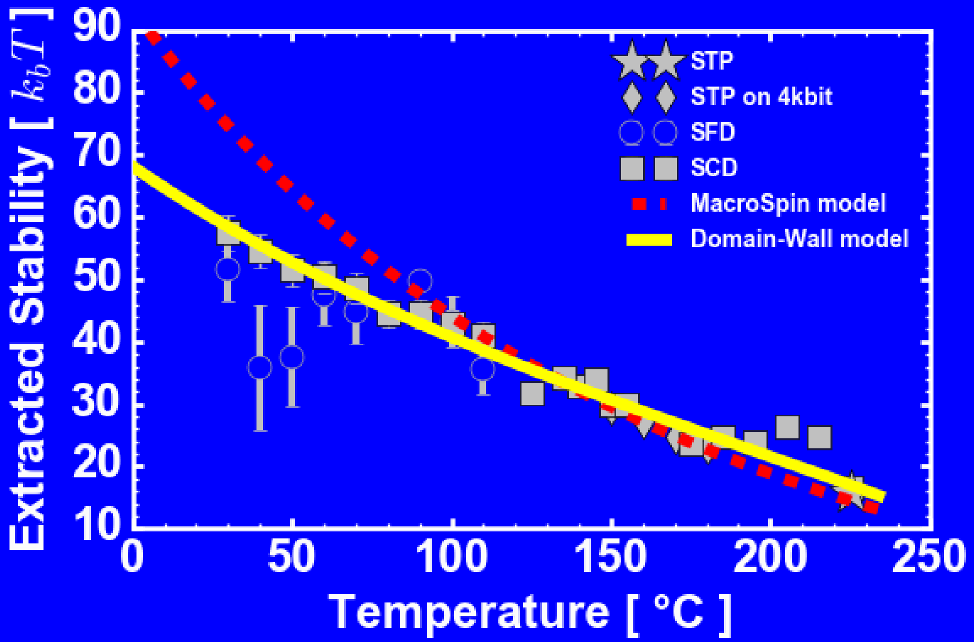
Thermal stability modeling





- MacroSpin and Domain-Wall models coherent at high temperature
- MacroSpin deviates below 100°C
- Domain-Wall close to SCD on all range

Stability dependence with temperature



Application	Retention Time τ	Bit Error Rate (N=1)	Thermal Stability Δ $[k_b T]$
Cache	10 ms	10^{-9}	36 @85°C
Soldering	~9 min	10^{-5}	38 @260°C
Storage (SCM)	1 month	10^{-9}	56 @85°C
Automotive	10 years	10^{-5}	51 @150°C
Consumer	10 years	10^{-5}	51 @85°C

Conclusion

- **4 retention time methods have been compared in diameter and temperature**
- **Accuracy and precision study showed the need of measuring enough events with a minimum number of significant points**
- **The 4 extractions gave similar results except the SPW which deviates significantly below 100°C**
- **Extrapolating from high temperature to a certain value has to be done with care**

Thank you for your attention

Luc.tillie@cea.fr