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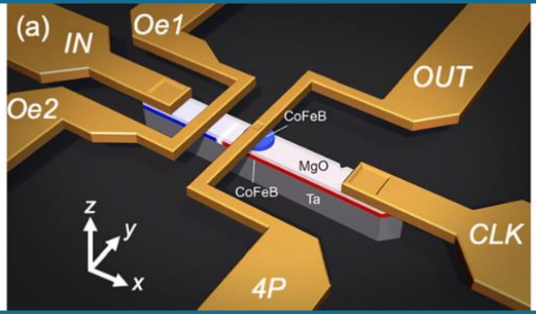
Sandia National Laboratories

Investigation of Total Ionizing Dose on Domain-wall Magnetic Tunnel Junction Logic Devices



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Session C - RADIATION EFFECTS IN DEVICES AND INTEGRATED CIRCUITS

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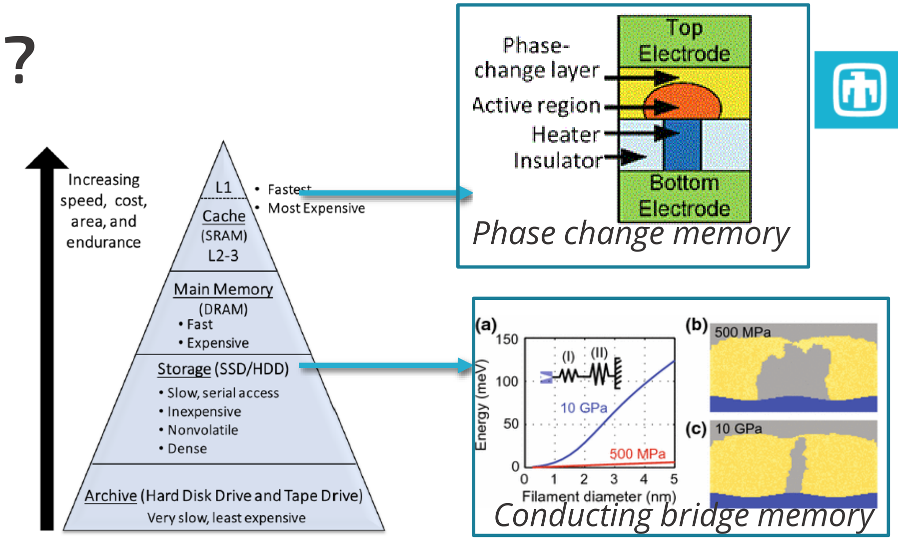
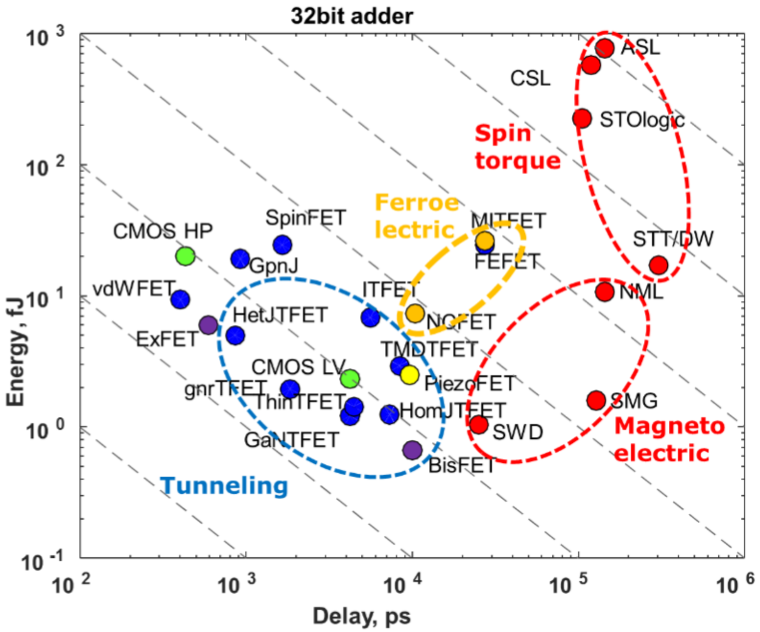
Why Non-volatile memory and future logic ?

- Pathways to post-CMOS computer architecture
  - Hybrid systems where emerging devices integrated alongside new ones: *e.g.* , NVM caches alongside storage class memory [SCM]
    - Different devices compete on different levels of memory /compute hierarchy
- Enabling components for on-chip matrix algebra in neural accelerators
  - Goal : perform machine-learning (ML) tasks e.g. regression, classification, and anomaly detection in embedded, low power hardware systems
- Advantages :
  - *Memory:* tunable programmable resistors
    - Have non-volatility (unlike SRAM arrays)
  - *Logic:* new frontiers in basic energy efficiency and speed
    - Potential radiation resilience v. charge-based approaches
  - Post-CMOS devices need high endurance ,low latency
    - Memory ideal device behavior: <10ns read/write, 10^{10+} cycles, highly resistive, with many internal states
    - Logic ideal behavior: <5 fJ elementary switching cost; <10ns speed



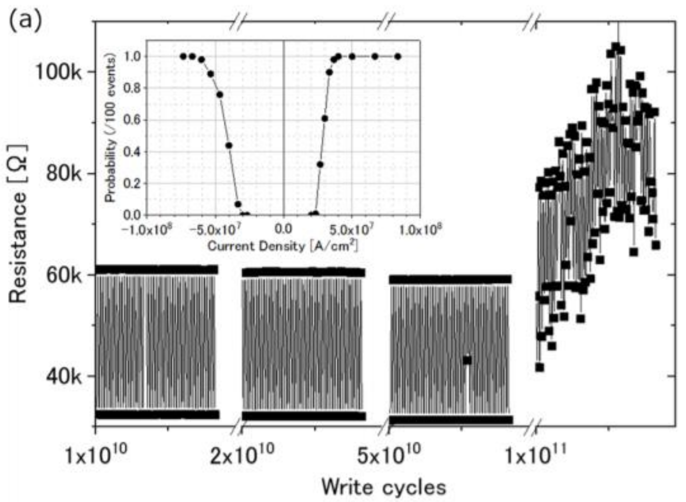
Source: **Marinella, et al**. "Radiation Effects in Advanced and Emerging Nonvolatile Memories."



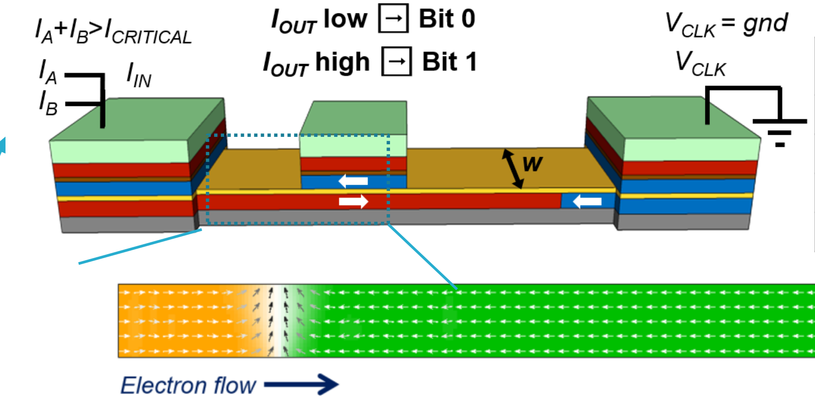
Source: **Nikonov, et al** https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7076743

Why use spintronic junctions for memory/ logic?

- Extreme endurance
  - Not charge based (spin reflectance at interface modulates resistance)
- Very low latency
  - Typically <10nanoseconds, academic work shows <1 nanosecond operation
- Readily compatible with CMOS processes
  - Thin film deposition completed on back-end-of-the-line (BEOL) after CMOS layers
- Variants of spintronic memory/logic devices:
  - Perpendicular anisotropy for lower switching current
    - Spin-transfer torque (STT): current passes through tunnel junction
    - Spin-orbit torque (SOT): current is orthogonal to free layer
    - Hybrid SOT/STT operations, e.g. composite spintronic devices
  - Domain-wall magnetic tunnel junction: racetrack along underlayer; switching MTJ bit
    - Can readily implement a NAND gate
    - Moving domain wall (DW-MTJ ON state, DW-MTJ OFF state) , lead to multifunctional spin switches (inverter, buffer…)



Source: **Shiokawa et al**, AIP Advances 2029

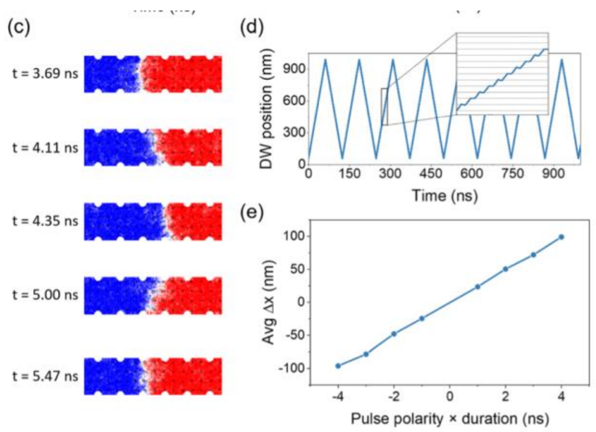


I_A	I_B	I_{OUT}
0	0	1
0	1	1
1	0	1
1	1	0

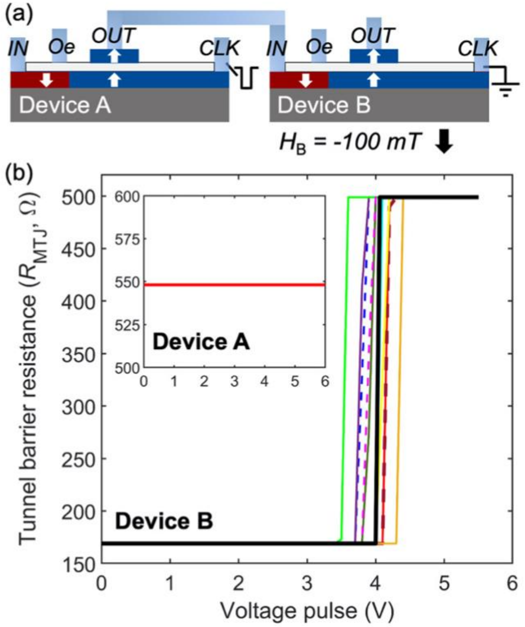
Courtesy: J. Incorvia

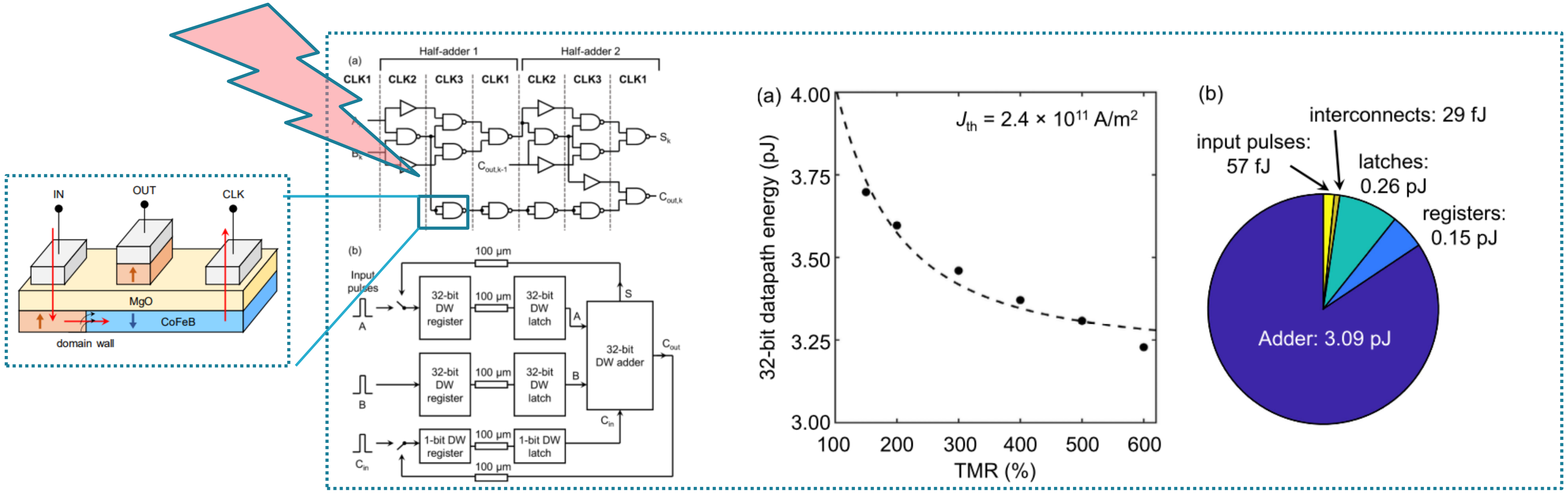
Application of Domain wall magnetic tunnel junctions

- Promising post-CMOS memory devices
  - Demonstration of multi-state , fast, analog DW-MTJ synapse/memories have recently been made
- Promising post-CMOS logic devices
  - DW devices implement NAND cascaded logic with DW buffers
  - Energy efficiency , speed of system driven critically by tunneling magnetoresistance (TMR), required tunneling current
  - Question: how resilient will such a system be as compared to CMOS baseline?
    - Radiation resilience including gamma/electron, proton, and heavy ion sources must be benchmarked



Source: **Liu et al, 2021,** APL



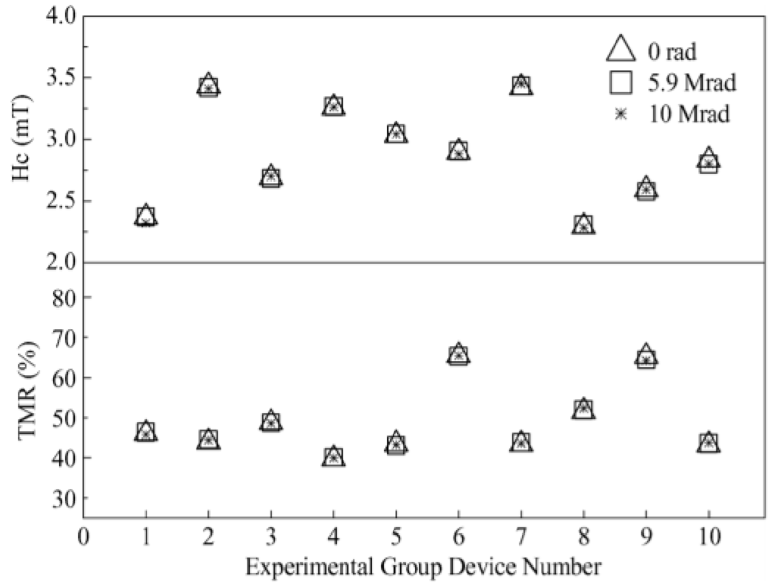


Source: **Xiao, Bennett, et al,** IEEE, JxDC, 2019

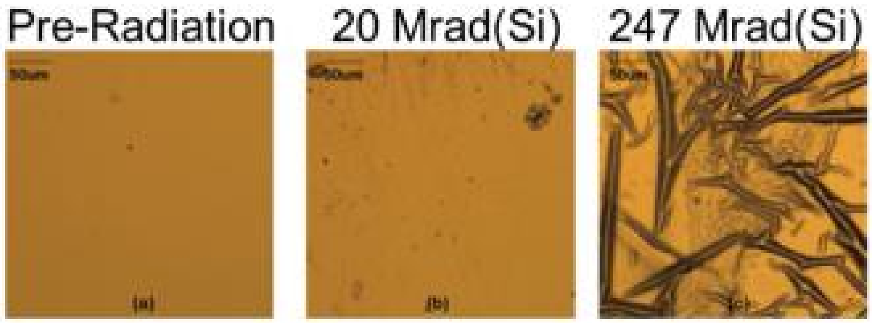
Source: **Alamdar et al,** APL, 2021 https://aip.scitation.org/doi/full/10.1063/5.0038521

Spintronic junctions putatively resilient to proton/gamma irradiation

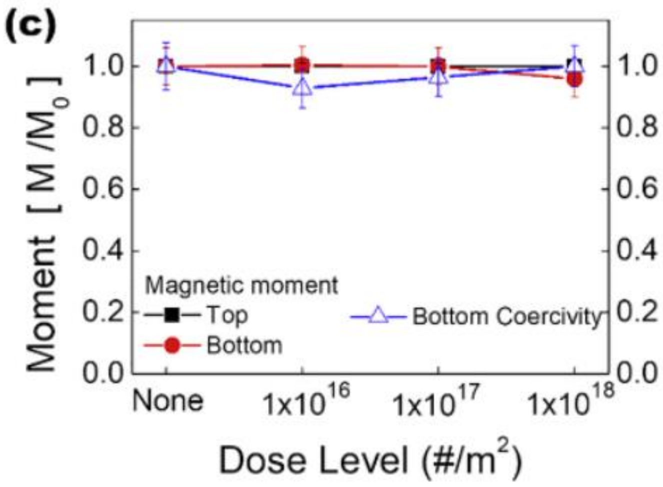
- MTJs are very robust against total ionizing dose (TID)
  - 10Mrad shows no effect on critical field for switching bits or TMR (effectively On/Off ratio)
  - > 100 Mrad causes breaking and visible damages
- MTJs are relatively robust against proton irradiation
  - Magnetic moments are unaffected and very slight effect in coercivity
  - Proton beam energy 20MeV up to 1e18 fluence
- However, impacts of TID in working devices are often more significant than in films/solo junctions



Source: **Ren, et al** IEEE 2012



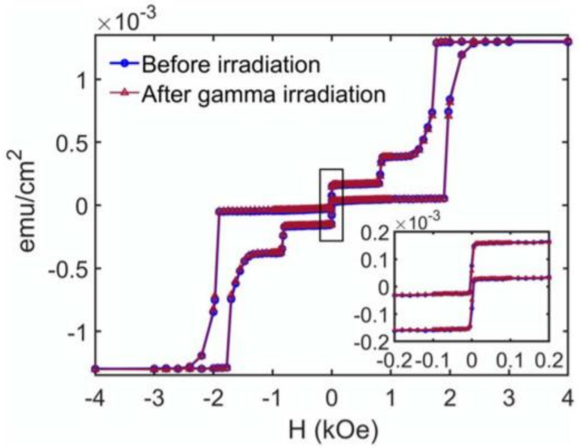
Source: **Wang, et al,** IEEE, 2019



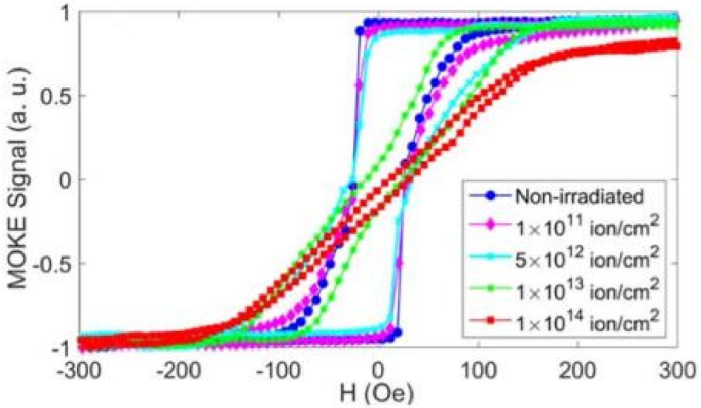
Source: **Park , et al,** Thin Solid Films, 2019

Earlier DW-MTJ results & research hypothesis

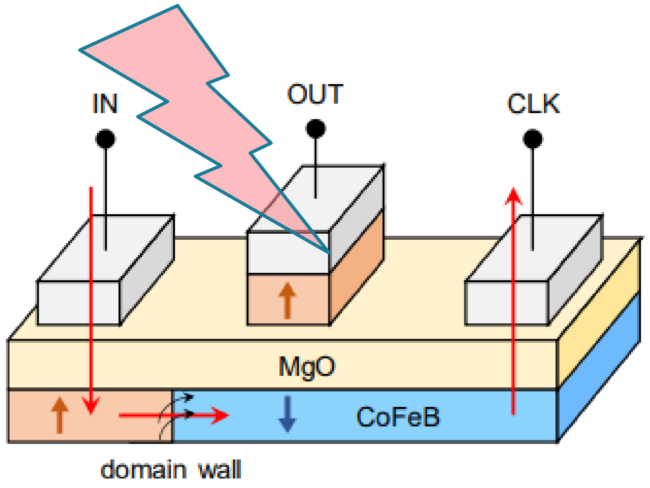
- Immediate predecessor to this work analyzed impact of a) gamma irradiation and b) heavy ion (Ta) on Spin-orbit-torque (SOT) DW device thin films
  - High resilience to TID (1Mrad), but are susceptible to displacement damage
  - Magnetic coercivity was used as proxy , but these were not fully functioning devices
- Hypothesis: high dose may cause additional issues in fully functioning DW-MTJ devices due to thermal and/or diffusion effects.
  - Sub-study 1: re-confirming TID resilience in switching DW-MTJ devices
  - Sub-study 2: exposing working DW-MTJ bits to more aggressive dose environments



Relative resilience to TID



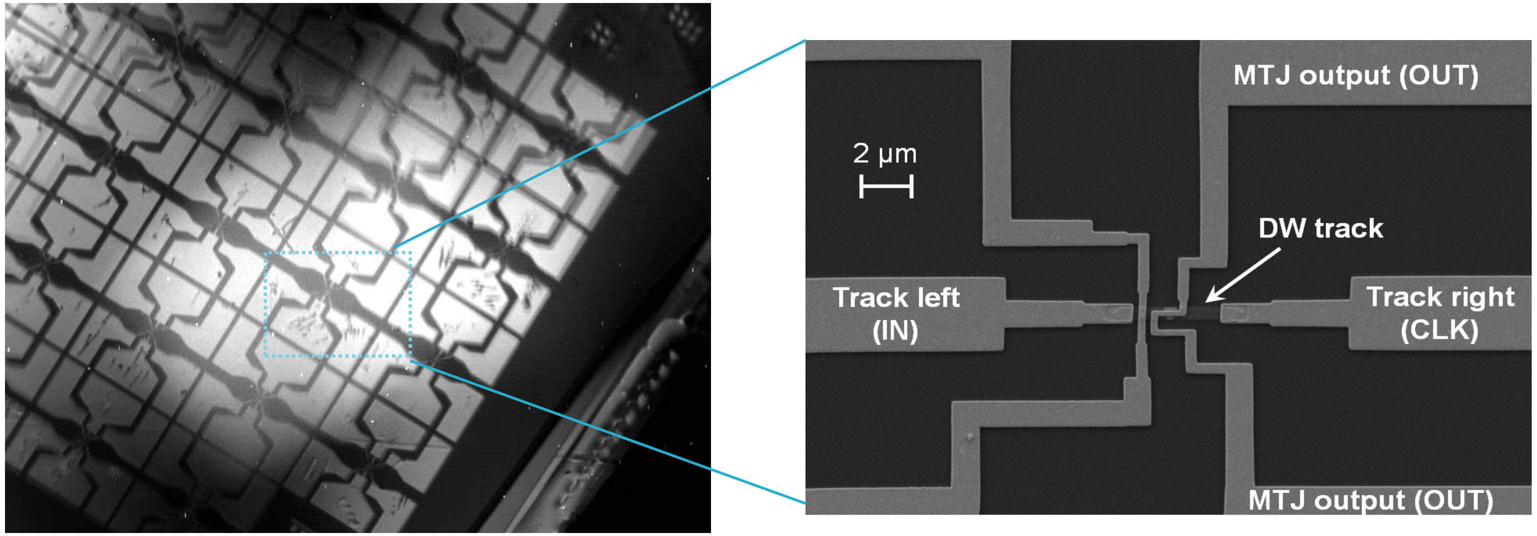
Strong impacts from heavy ions

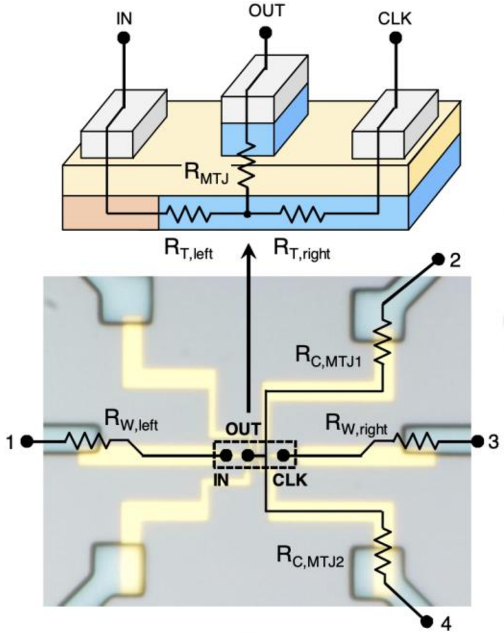


Source: **Alamdar et al,** NSREC 2020, (Published 2021), https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9378556

Methods: STT Logic bits exposed to gamma radiation

- Studied chip consists of thin films fabricated at Applied materials, with primary STT DW-MTJ device stack fabricated at UT-Austin, and final processing step at Sandia
- 32 devices on chip total, with 17/32 devices initially switching
  - Lithography mismatch issue in y dimension created a pad contacting issue in many devices.
- H-loops conducted on all switching devices, with 11 devices total profiled with high tunneling magneto resistance (TMR) >50% .
- Pad structure of all devices on chip allows for both 2 point measures (emulating use in logic circuit) and 4 point (allowing us to electrically infer the TMR values via Kelvin measures
  - For speed /reliability of switching, following pre/post measures used 2 point measures

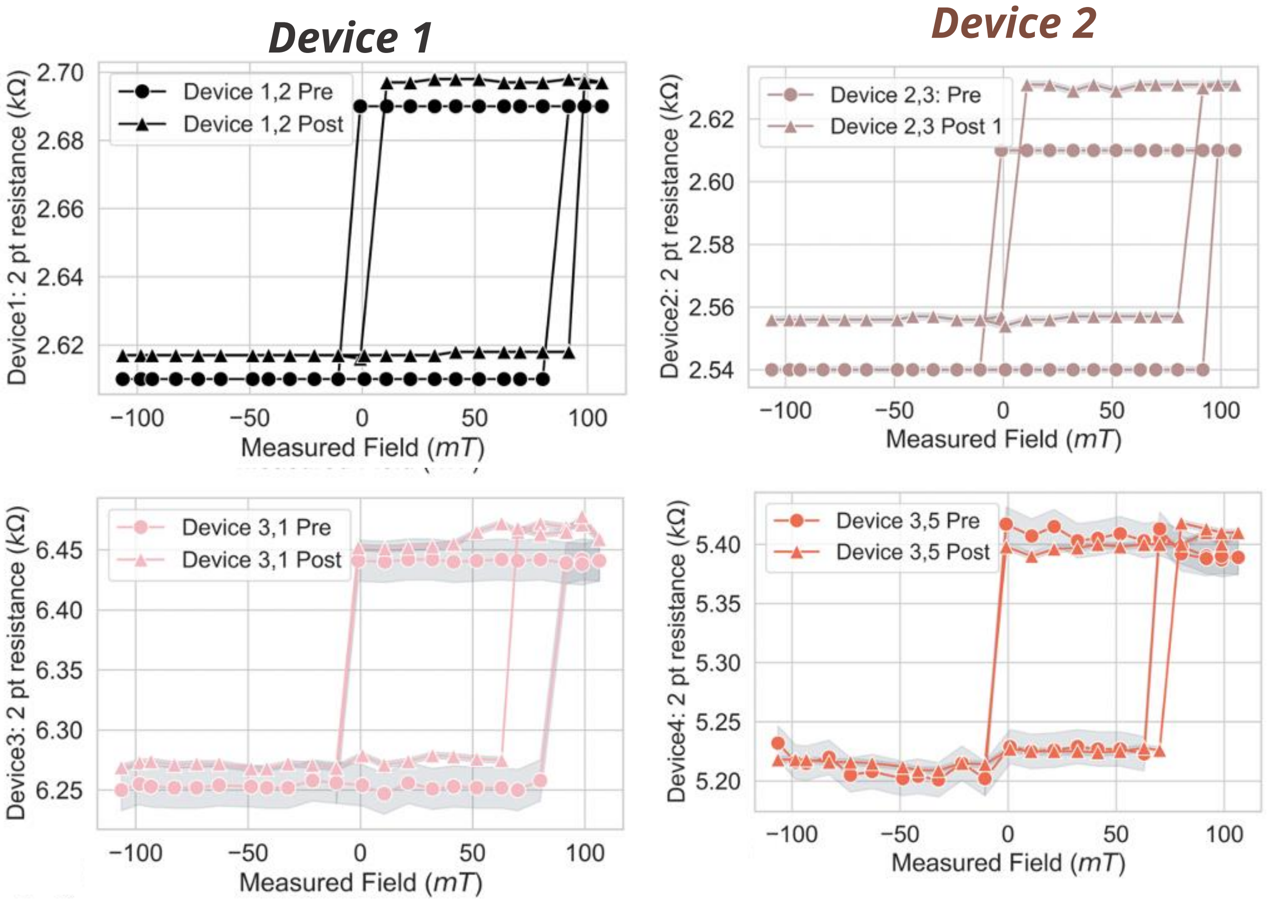




Results: 1Mrad Gamma irradiation

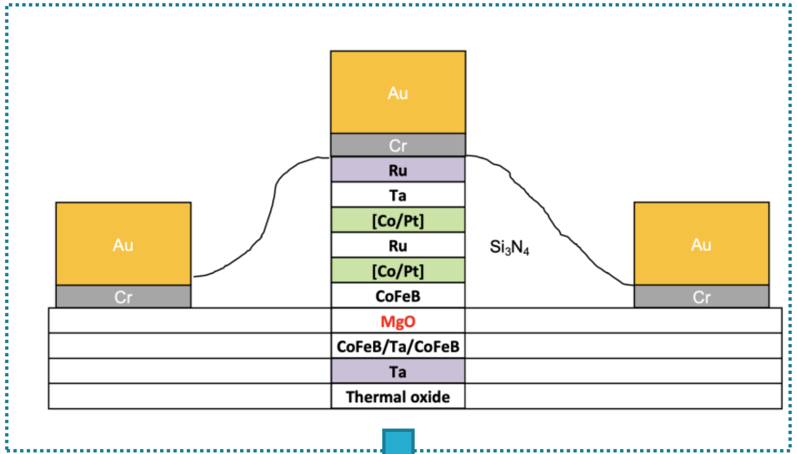
- Functioning STT DW devices profiled (5) are overall, resilient to TID (1Mrad) using a Co60 gammacell
  - No profiled devices cease to shift or show an H-loop collapse
- Some devices show slight changes in R_p ,R_{ap} in changes that exceed standard cycle-to-cycle variability
  - Most (3/5 devices), shown as **pink** and **orange** series below, are within statistical estimates normal variability
  - 2 of 5 devices (**black**, **light brown**) show statistically different values in On/Off resistance
    - May relate to accumulated charge in the composite device from TID

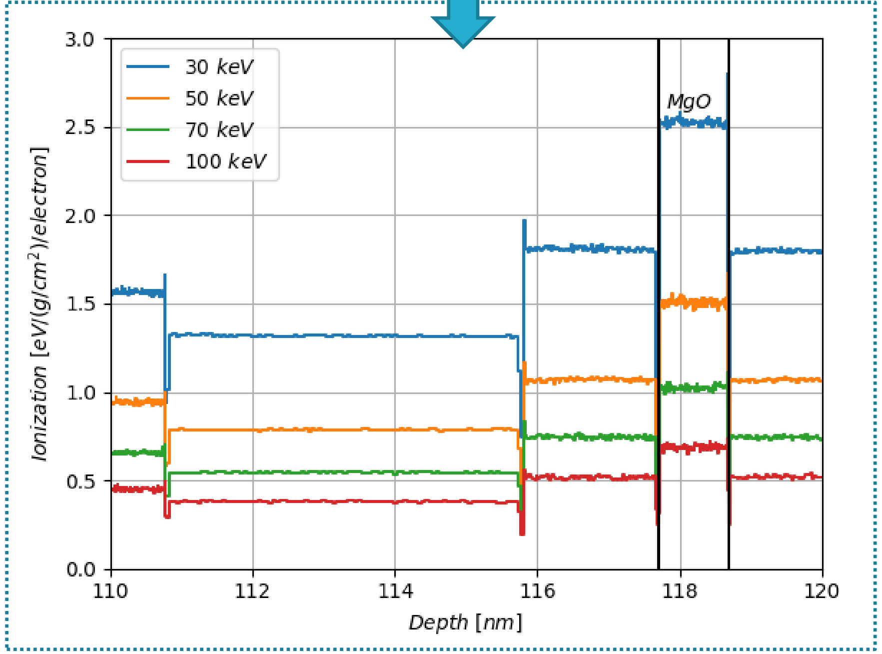
DW-MTJ device		ΔR (Ω)	TMR (%)
1	Pre:	80.0 ± 0.0	--
	Post:	20.1 ± 0.5	55.3 ± 2.1
2	Pre:	74.3 ± 1.0	--
	Post:	14.3 ± 1.1	49.7 ± 4.9
3	Pre:	199.9 ± 17.1	--
	Post:	169.9 ± 2.6	76.3 ± 1.8
4	Pre:	183.7 ± 14.5	--
	Post:	165.8 ± 2.8	199.0 ± 9.6
5	Pre:	190.2 ± 12.2	--
	Post:	173.0 ± 0.8	187.2 ± 1.8



Methods: Electron beam irradiation

- Motivation:
  - E-beam is capable of targeting particular layers of interest (in our case (MgO) and not entire stack
  - E-beam can put more dose in less time
  - The effect of total dose changes at high rate
- Calibration
  - Penelope calculations estimate electron impact energy given actual DW-MTJ spin-transfer torque stack
  - Ion beam energy is calibrated to peak ionization in structure, yielding beam energy of 30 keV
- Experimental execution
  - Pre, post and 2 intermediate H-loop measures made during progressive e-beam irradiation of devices <u>(4 total measures)</u>
  - 6 initial devices targeted for profiling, with only 3 /6 surviving all tests (electrostatic and/or fragile pad events, *e.g.* shorting)
  - 2 point measurements made in semi-automated H-loops for speed and accuracy at 4 checkpoints





Results: Electron beam irradiation 1/2

- Devices were individually targeted using electron beam at Sandia's Ion Beam Lab (IBL)
- Cumulative changes were observed throughout the ongoing e-beam irradiation , with substantial changes in R_p ,R_{ap} visible but without device failure (bit flip/H collapse)
  - Greater than gamma ΔR consistent with estimated total dose from e-beam using Penelope:
    - Post 1: < 1Mrad(MgO)
    - Post2: ~8 Mrad(MgO)
    - Post3: ~30 Mrad(MgO)

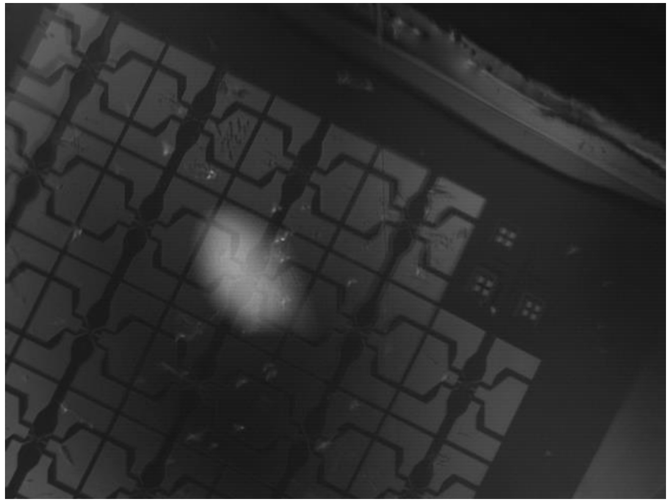
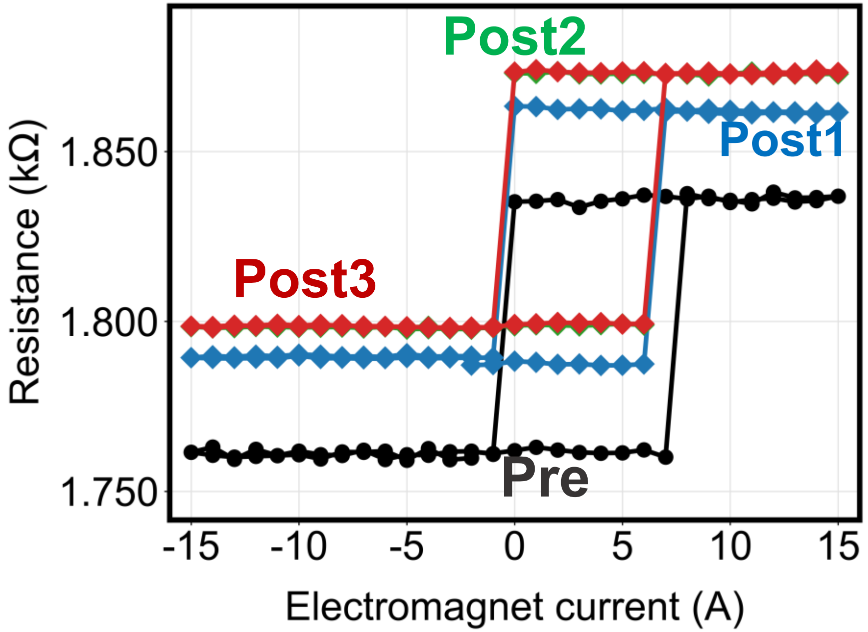
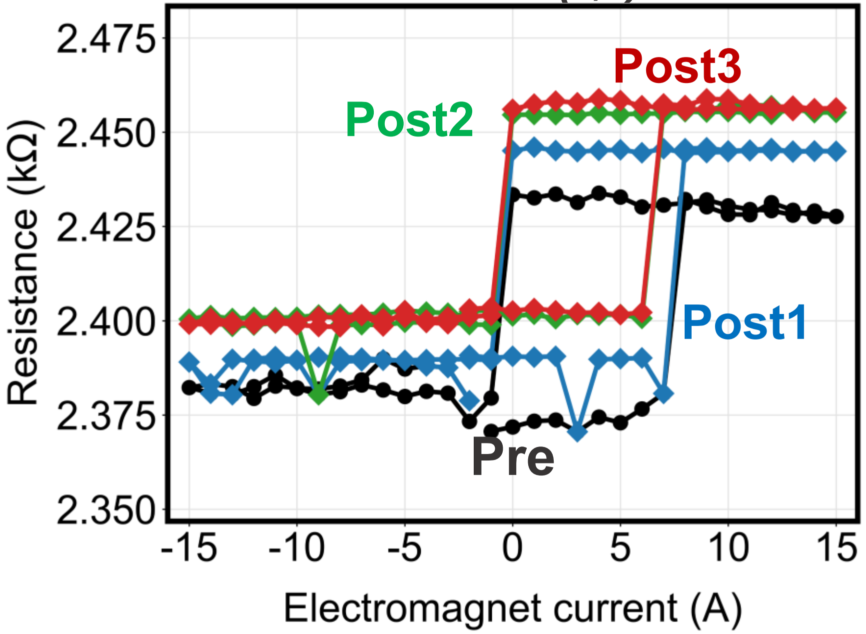


Image of focused electron beam on 1 device

Device 1 (4,5)



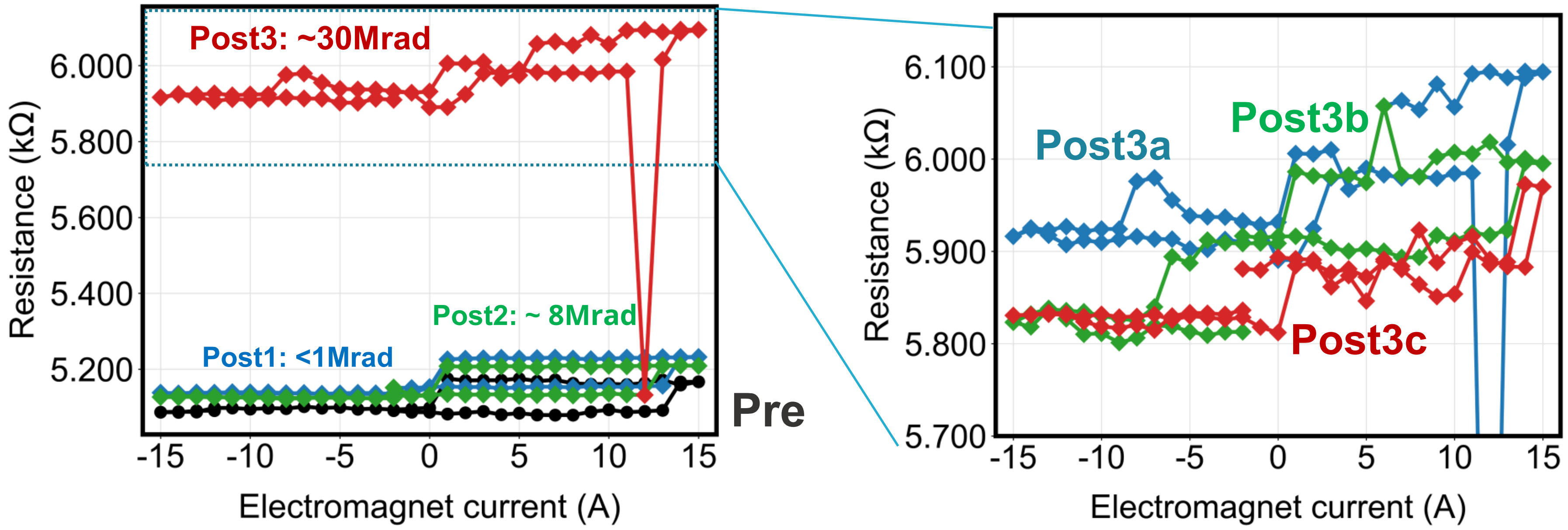
Device 2 (4,0)



Electromagnet Current (A)	Perpendicular Magnetic Field
-10	~ -75mT
-5	~ -37.5 mT
0	~0.2 mT
5	37.5 mT
10	~75 mT
15	~ 108 mT

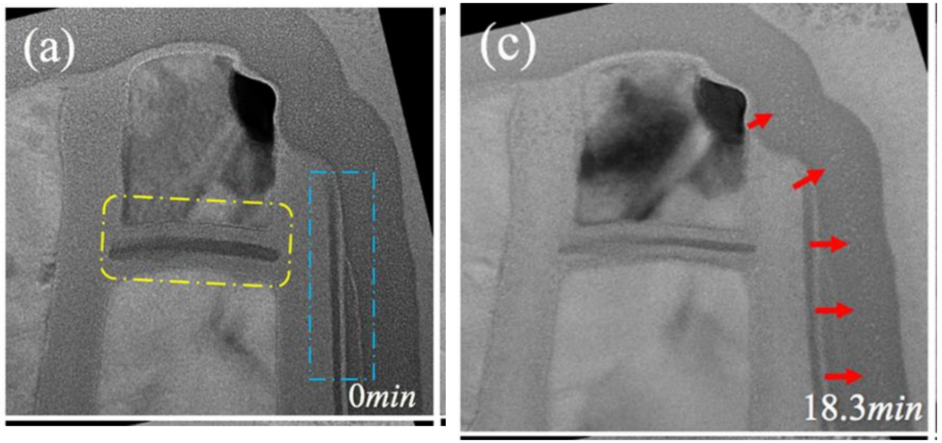
Results: Electron beam irradiation 2/2

- One of three devices showed not only characteristic /slight change in resistance, but a dramatic resistance change at the last irradiation level
- More significantly, H-loop shape and structure also changed in this device, implying a potential interface/structural change due to irradiation
- Several post-3 cycles were taken to confirm this was not an artefact of the electrical measures



Discussion on physical origin of observed effects

- Since e-beam was targeted for maximum impact at critical junction for switching (MgO), this is primary site of further analysis
- Past literature on radiolysis damage in MgO exists and can shed light on results
  - Irradiation of MgO crystal samples with 5kEV electron beam showed large prototypical response
- 1) Fast-electron irradiation might result in hot holes and possibly drive diffusion along MgO interface
  - Minor diffusion could drive increases in resistances observed in most devices
- 2) Thermal effects may be possible and result in degraded interfaces
  - Thermal intermixing at MgO interface is possible and would degrade perpendicular anisotropy
  - May have contributed to collapsed H-loop visible in 1/3 e-beam device
  - Profiling of thermal effects well established in ONO stacks, <u>but may be needed for DW-MTJs</u>



Source: **Liu et al,** AIP, https://aip.scitation.org/doi/pdf/10.1063/1.5051813

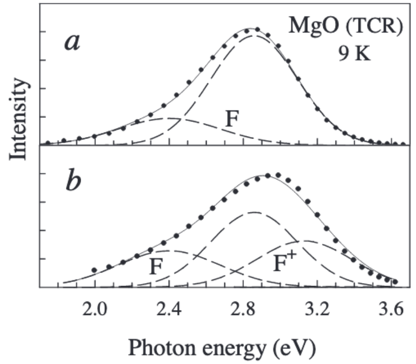


Fig. 2. Cathodoluminescence spectra (••) for a MgO(TCR) crystal measured in 3 (a) or 30 min (b) after irradiation by 5 keV electrons at 9 K was started. Components of decomposition (dashed lines) and their sum (solid line).

Source: **Luschick et al, ,** Nuclear Instruments and Methods in Physics Research B

Conclusions & Future work

- DW-MTJ logic devices are a promising post-CMOS candidate but need to be more thoroughly analyzed for susceptibility to full suite of radiation effects
- Composite DW-MTJ logic devices were subjected to both gamma dose and electron beam, resulting in perceptible effects following total ionizing dose
  - Characteristic On/Off logic states (R_p ,R_{ap}) showed gradual increase with irradiation
  - Electron beam interactions were more significant, and for one profiled device, showed significant change in actual bit switching
- Next steps for analysis
  - Existing devices will be exposed to combination of in-plane and out-of-plane fields to better understand potential changes in anisotropy
  - EELS or imaging (e.g. TEM) techniques may be necessary to better understand intermixing or thermal events that contributed to radiation induced changes in these devices

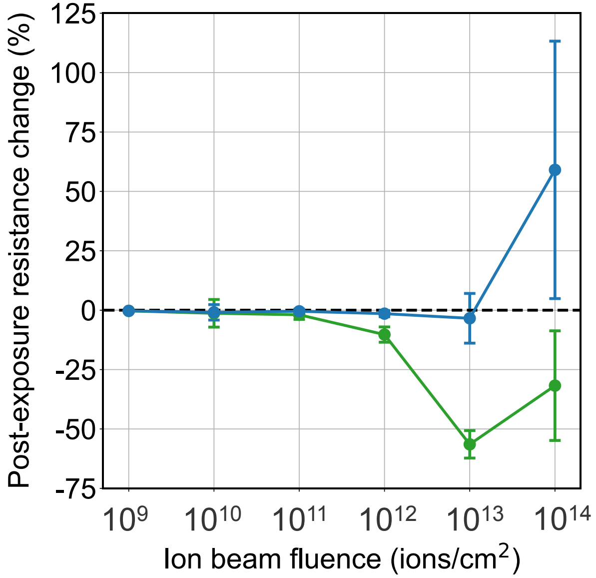
Questions?

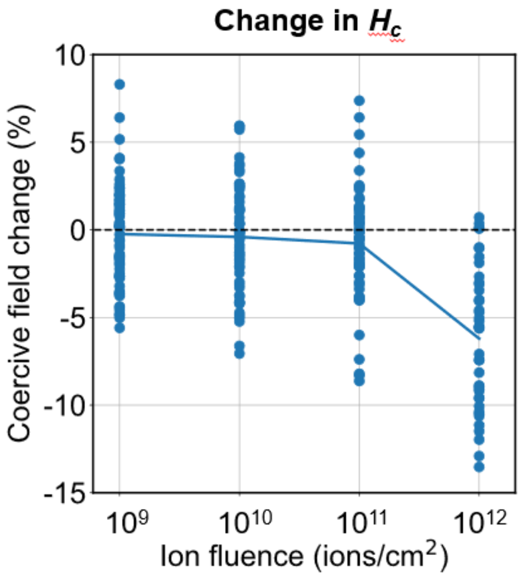
Feel free to contact me at cbennet@sandia.gov with questions asynchronously.

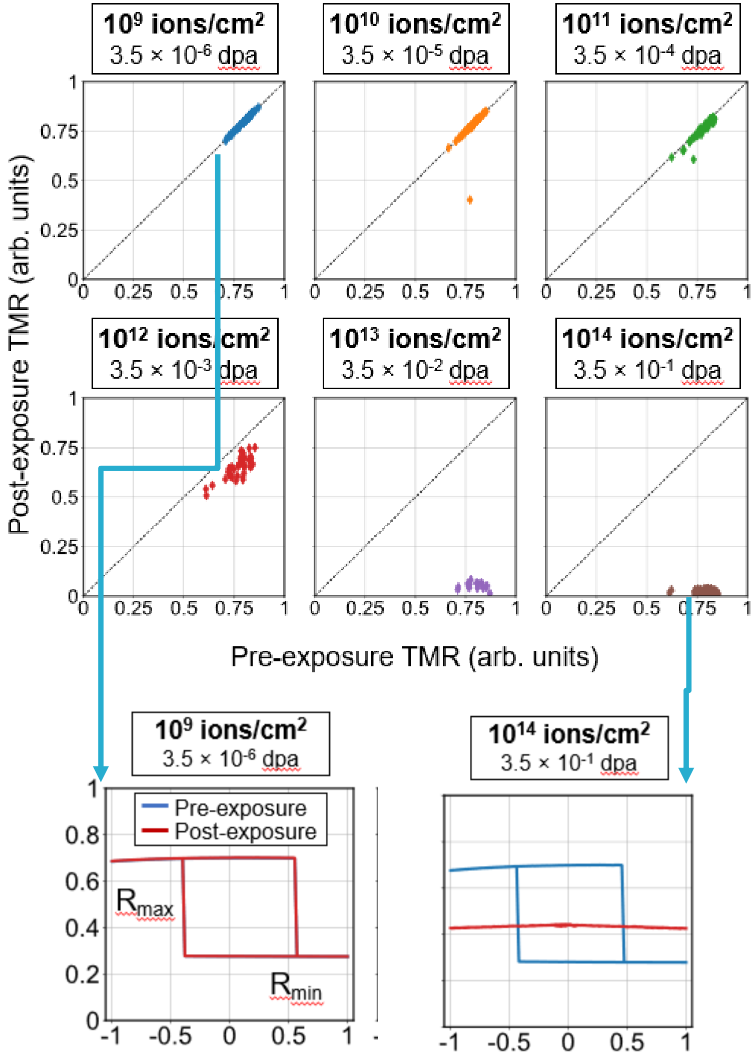
Appendix slides

Spintronic junctions are affected by heavy ion damage

- Industrial quality (Everspin) MTJ parts using perpendicular anisotropy (pMJTs) bombarded with a Ta beam over a variety of fluences
- Ensemble statistics demonstrate that large heavy ion fluences totally degrade switching performance
  - At > 10e12 fluences, magnetic H loops begin to collapse
- Electron spin polarization is reduced as interface is structurally damaged, resulting in a lower coercive field
- Structural damage affects perpendicular magnetic anisotropy







Single device examples