IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2017.
This invited oral presentation Tu-I-SSP-04 was given at ISEC 2017.

Tu-I-SSP-04

Ferromagnetic Josephson Junctions for Cryogenic Memory

Norman Birge, Michigan State University

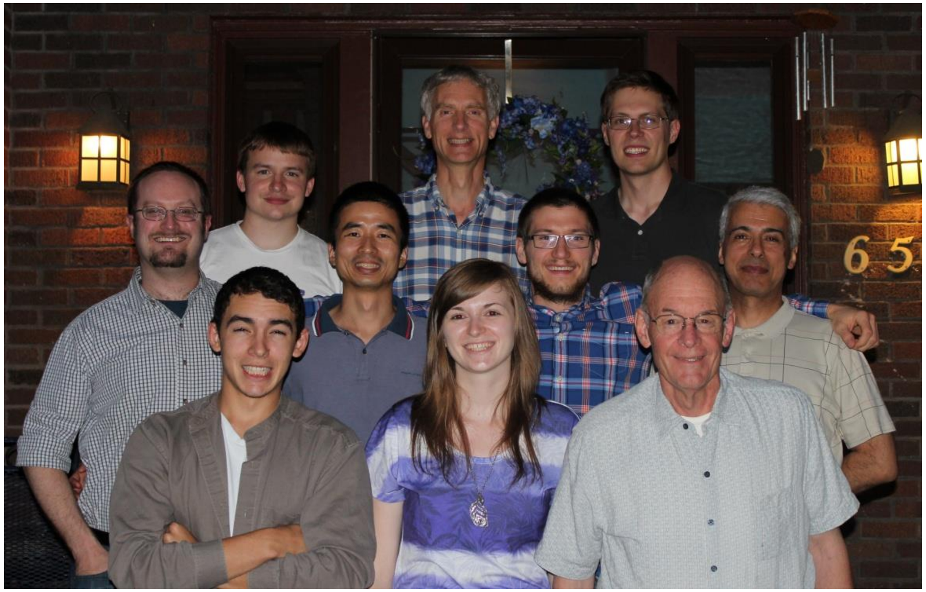
in collaboration with Northrop Grumman Corporation
and Arizona State University

(with thanks to D. Scott Holmes, Booz Allen Hamilton & IARPA)

The project depicted was or is supported in part by the U.S. Army Research Office and/or the Department of Energy. The information depicted does not necessarily reflect the position or the policy of the Government, and no official endorsement should be construed.

The group

Eric Gingrich, Bethany Niedzielski, Joseph Glick, Yixing Wang, Bill Martinez,
Josh Willard, Sam Edwards, Reza Loloee, William P. Pratt, Jr.,
plus many earlier students!

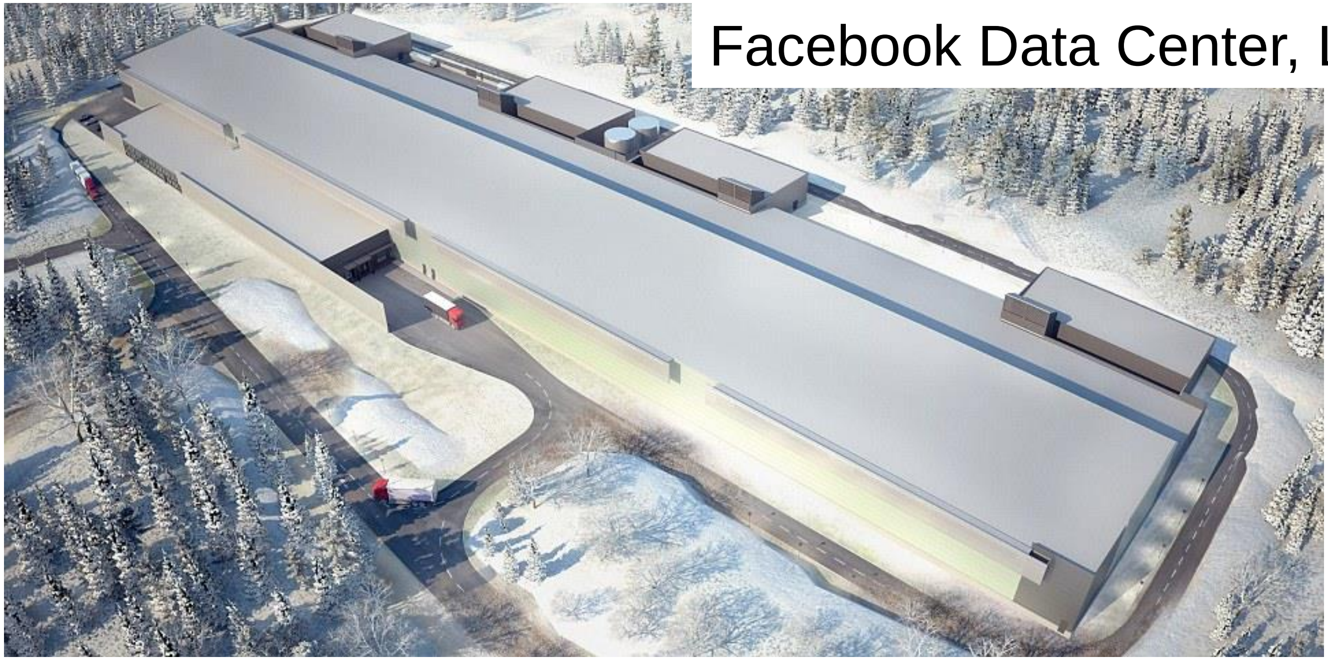


An old picture…

Outline

- The need for energy-efficient computing
- Superconducting memory: JMRAM
- Superconducting/ferromagnetic hybrid systems
- Demonstration of phase control of an S/F/S Josephson junction – the basic memory device
- Future prospects

The need for energy-efficient computing



Facebook Data Center, Luleå, Sweden

Copyright
Facebook

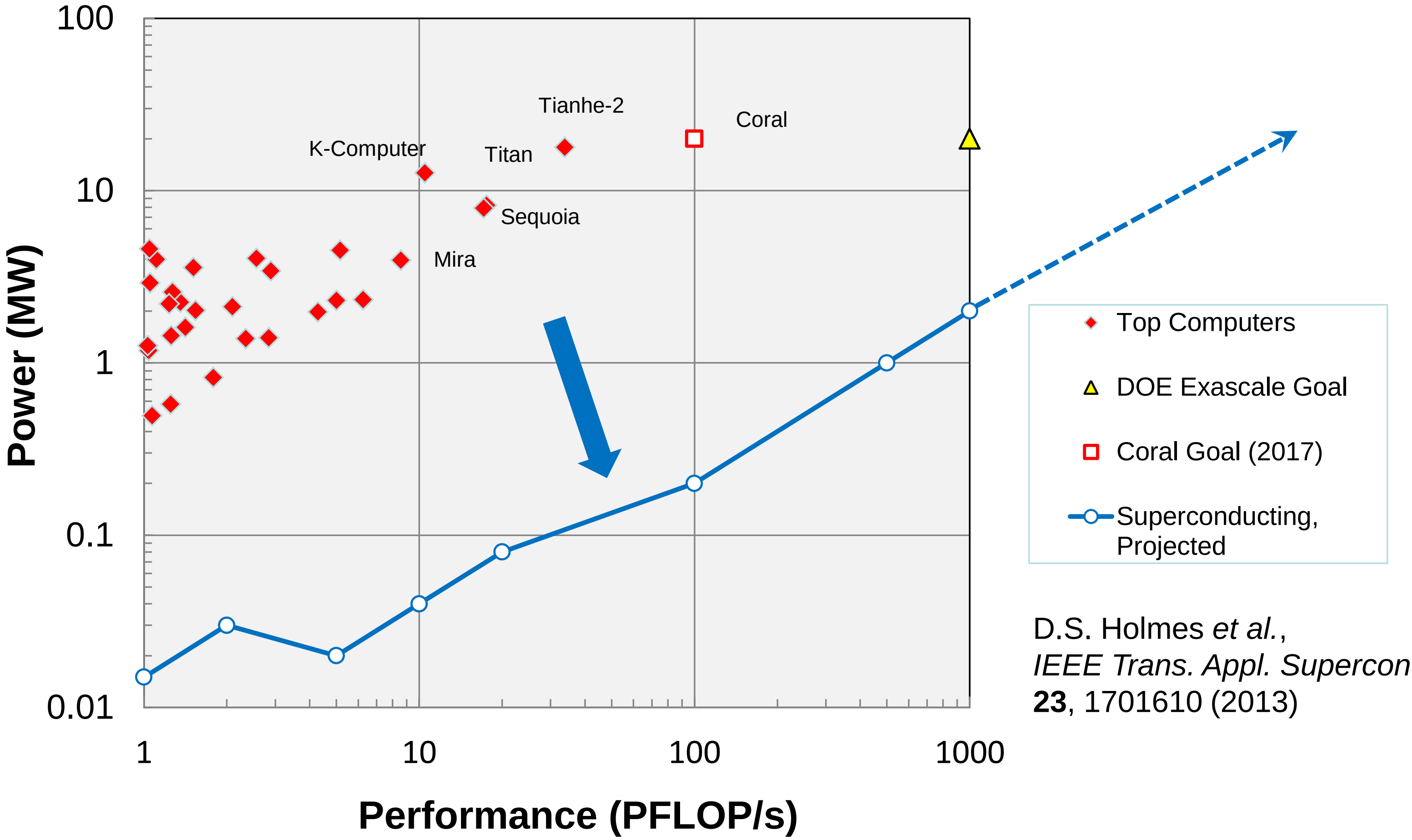
- Opened in 2013
- Cost: ~760 M$
- Nearby Lule River generates
  9% of Sweden's electricity (~4.23 GW)
- Average annual temperature: 1.3 °C

	Specifications
Performance*	**27-51 PFLOP/s**
Memory*	**21-27** PB RAM **1900-6800** PB disk
Power	**84** MW avg* (120 MW max)
Space	**290,000** ft^2 (27,000 m^2)
Cooling*	~1.07 PUE

* estimated

Slide courtesy of Scott Holmes

Superconducting computing looks promising



D.S. Holmes *et al.*,
IEEE Trans. Appl. Supercond.
23, 1701610 (2013)

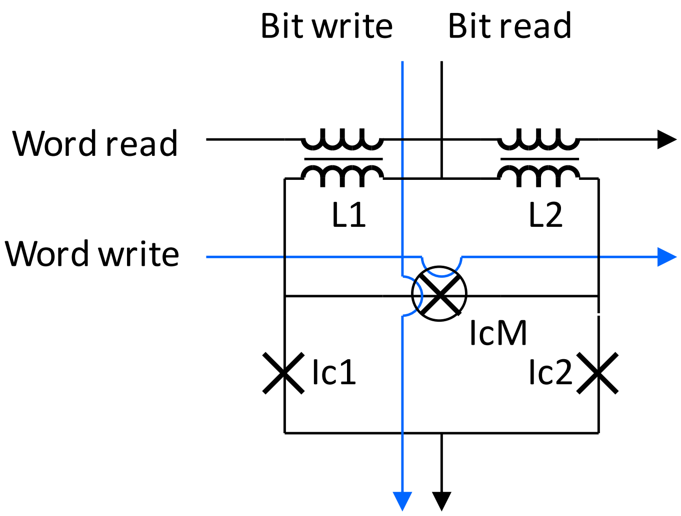
Slide courtesy of Scott Holmes

Our approach to superconducting memory:

Josephson Magnetic Random Access Memory (JMRAM)

Anna Y. Herr & Quentin P. Herr, US Patent 8,270,209 (2012)
A.Y. Herr, Q.P. Herr & Ofer Naaman, US Patent 9,208,861 (2015)

Northrop Grumman Corporation



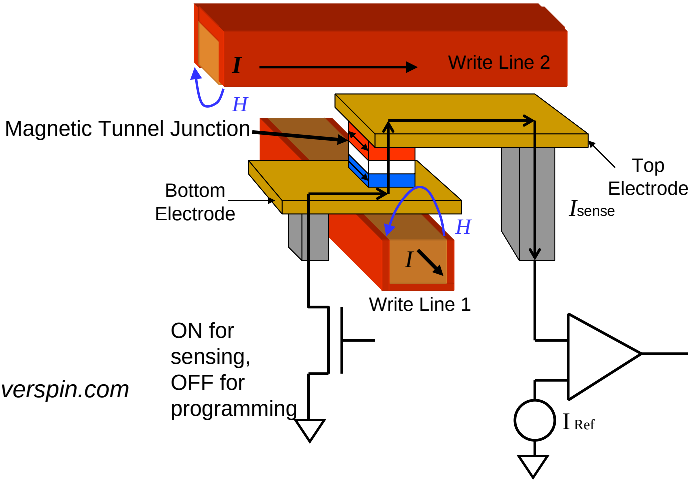
Memory cell is a SQUID loop

One junction has two stable phase states for “0” and “1”

Magnetic states are written using standard MRAM techniques

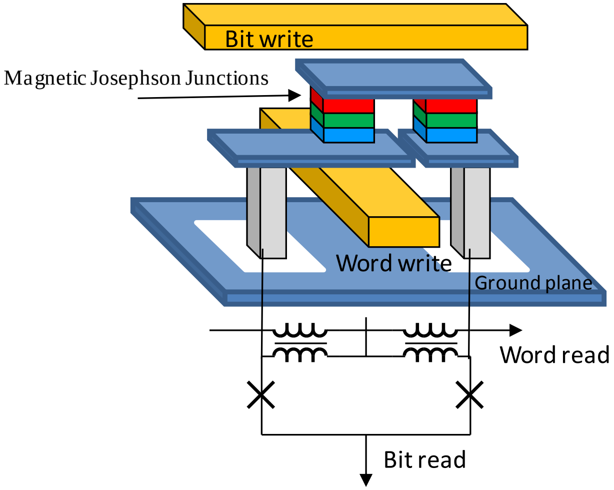
JMRAM is a Superconducting MRAM

MRAM (Everspin)



www.everspin.com

JMRAM (Northrop Grumman)



Memory cell is a Josephson junction containing a magnetic spin valve

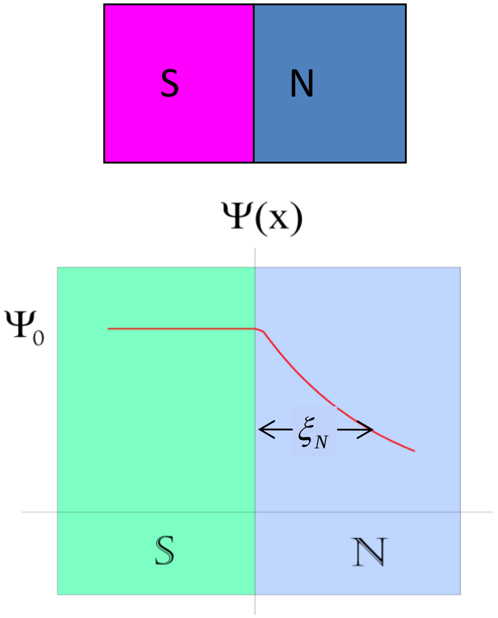
memory state – spin-valve state sets junction phase

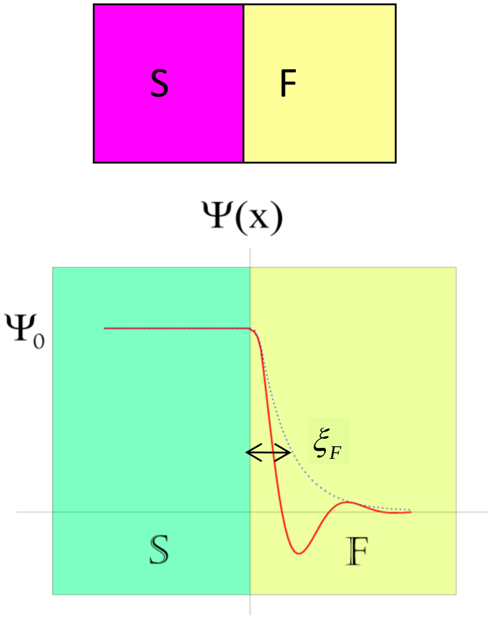
write – magnetization reversal

read – Josephson effect

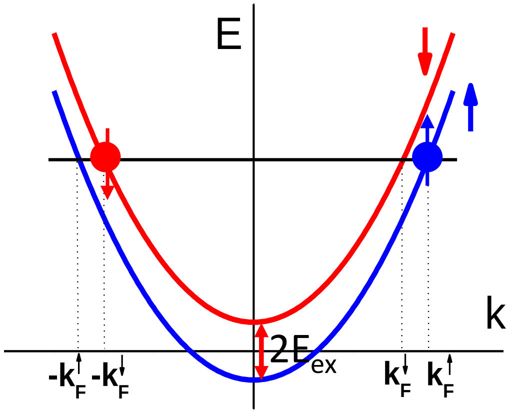
No idle/static power dissipation, read energy is dissipated only for logical “1”

Superconductor/Ferromagnet proximity effect





“FFLO-type” physics



$$k_F^\uparrow - k_F^\downarrow \equiv Q \approx 2E_{ex}/\hbar v_F$$

$$\xi_N = \sqrt{\frac{\hbar D_N}{2\pi k_B T}} \approx 1\,\mu m$$

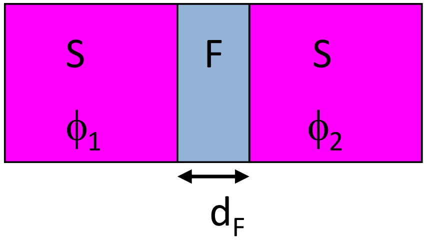
$$\xi_F \sim \sqrt{\frac{\hbar D_F}{E_{ex}}} \approx 1\,nm$$

$$\xi_F = Q^{-1} = \frac{\hbar v_F}{2E_{ex}}$$ ballistic

$$\xi_F = \sqrt{\frac{\hbar D_F}{E_{ex}}}$$ diffusive

D = diffusion constant

Consequence: S/F/S Josephson junctions oscillate between 0 and π junctions as d_F increases:



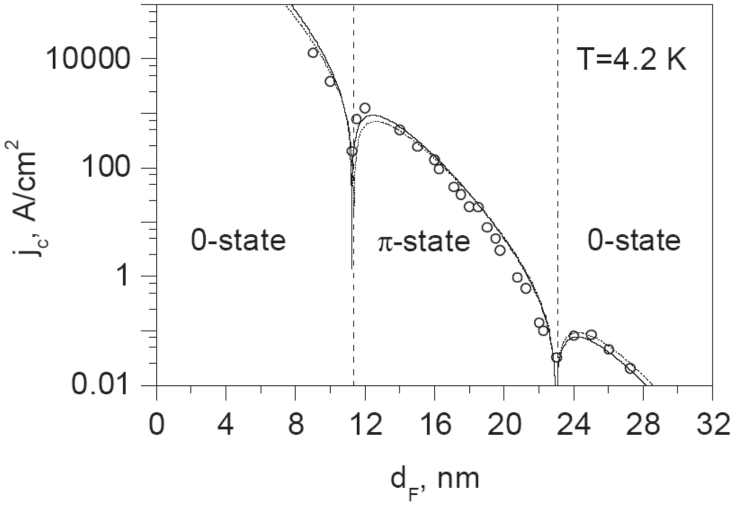
Buzdin, Bulaevskii, & Panyukov (1982).

$$\xi_F = \sqrt{\frac{\hbar D_F}{E_{ex}}}$$

0-state: $I_s = I_c \sin(\phi_2 - \phi_1)$

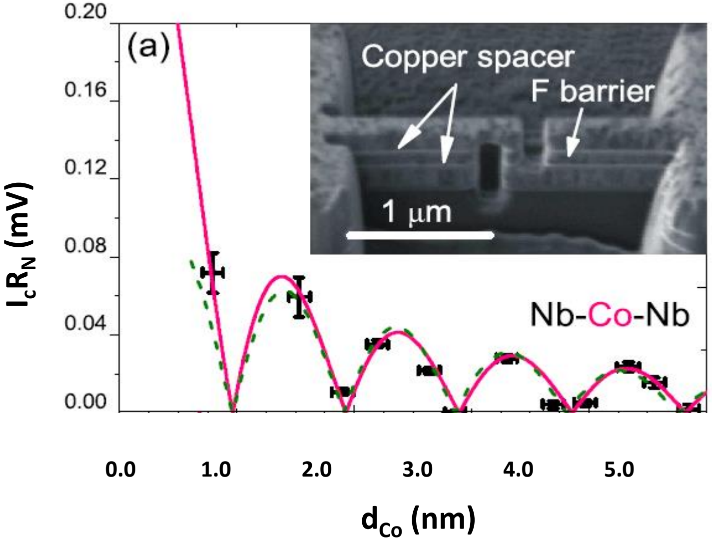
π-state: $I_s = I_c \sin(\phi_2 - \phi_1 + \pi)$

Weak F: $Cu_{48}Ni_{52}$ alloy



Ryazanov *et al.*, PRL **86**, 2427 (2001); PRL **96**, 197003 (2006).

Strong F: Co



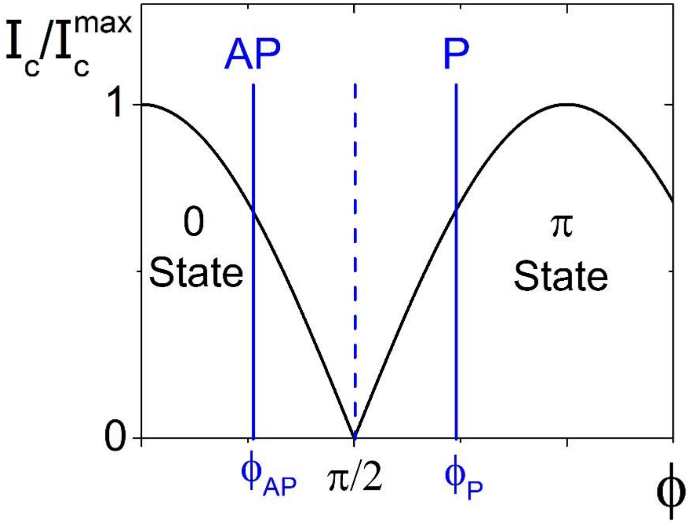
Robinson, Piano, Burnell, Bell, Blamire, PRL **97**, 177003 (2005)

Can we control I_c or phase state of a single Josephson junction?

Add a second ferromagnetic layer: $S/F_1/F_2/S$

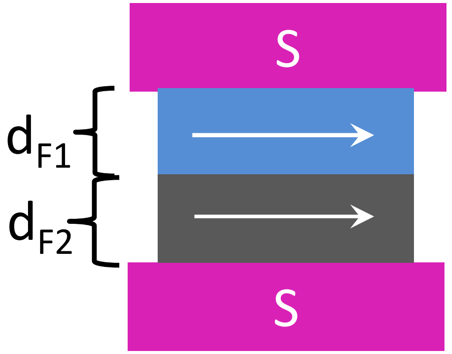
I_c and phase depend on relative magnetization direction

Electron pair accumulates phase ϕ while traversing junction

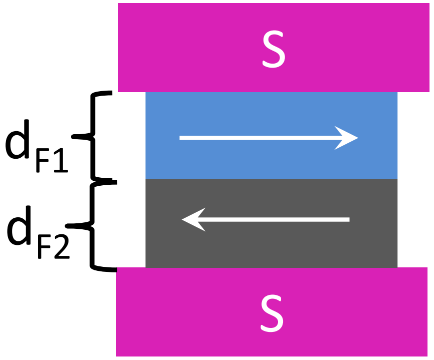


$$I_c \propto \exp[-(d_{F1}/\xi_{F1} + d_{F2}/\xi_{F2})] \left|\cos(d_{F1}/\xi_{F1} \pm d_{F2}/\xi_{F2})\right|$$

Parallel state: $\phi = \dfrac{d_{F1}}{\xi_{F1}} + \dfrac{d_{F2}}{\xi_{F2}}$



Antiparallel state: $\phi = \dfrac{d_{F1}}{\xi_{F1}} - \dfrac{d_{F2}}{\xi_{F2}}$

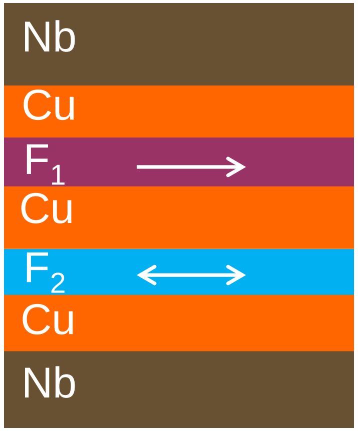


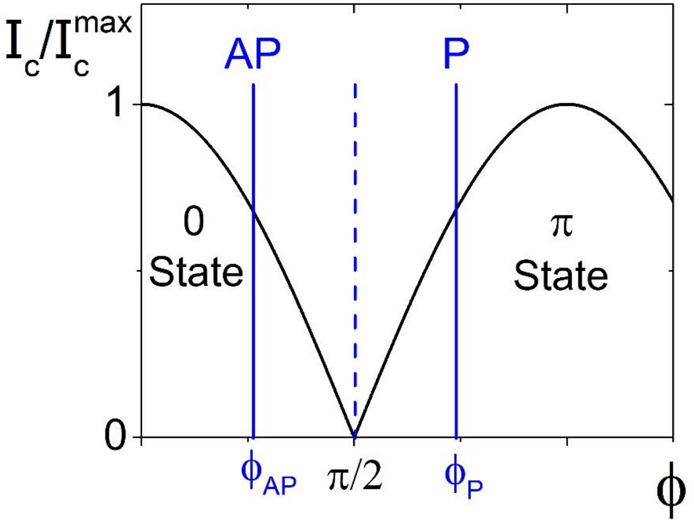
S/F$_1$/N/F$_2$/S Josephson Junction Composition

Nb(100)/Cu(5)/NiFe(1.5)/Cu(10)/Ni(1.2)/Cu(5)/Nb(150)

F$_1$ = Ni (1.2 nm)
fixed layer

F$_2$ = NiFe (1.5 nm)
free layer



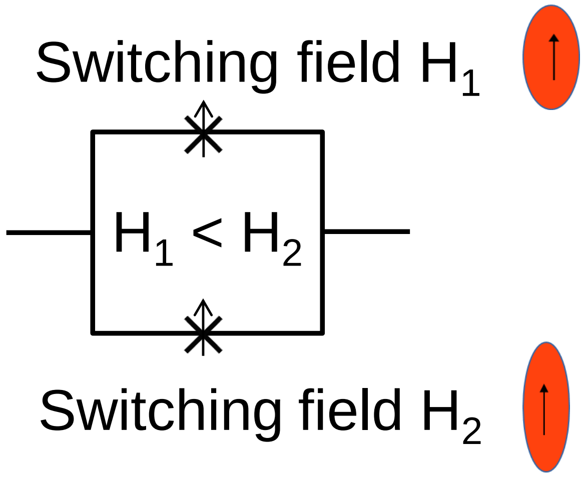


Choose NiFe thickness to put F$_2$ close to 0 - π transition.

Ni provides additional small push to right or left.

Two junctions in a SQUID loop used to measure relative junction phase

Schematic:



Switching field H_1

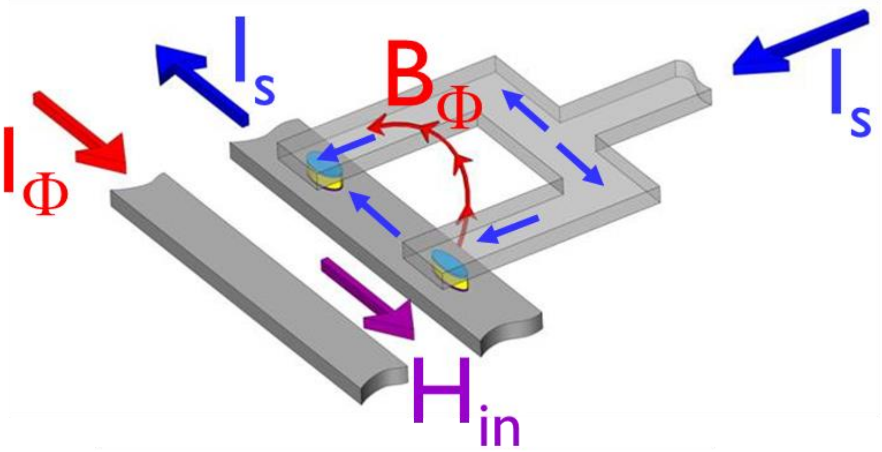
$H_1 < H_2$

Switching field H_2

Junction sizes:
Both have Area = 0.5 μm^2
Aspect Ratios = 2.2 and 2.8

Cartoon of Actual Device:

On-chip current line couples magnetic flux into SQUIDs

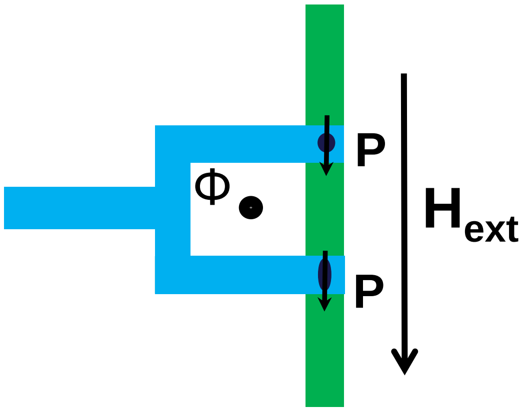


Switch magnetization with in-plane field

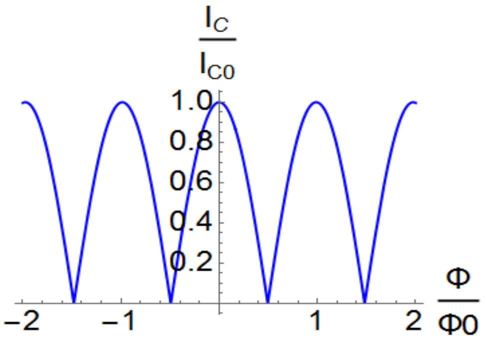
Different aspect ratio pillars have different switching fields

At Relatively Low External Fields, Two Phase Changes Should Be Observable

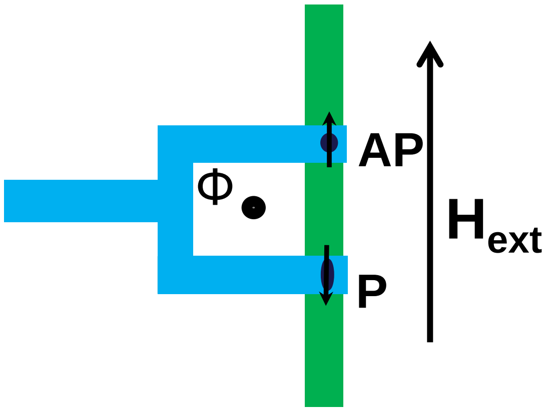
Initialize with large field in -z direction, then slowly increase H_{ext} in +z direction



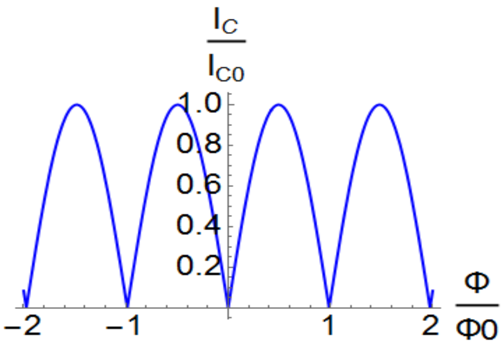
Constructive Interference



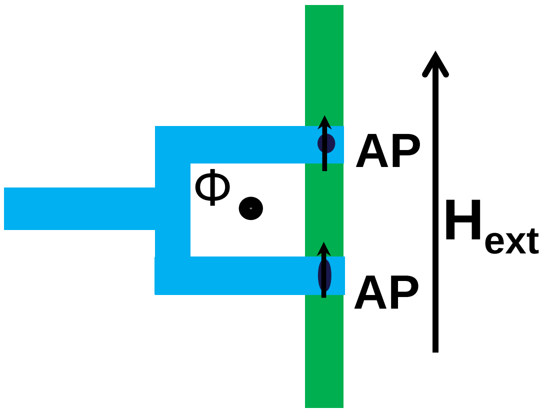
$H_1 < H_{ext} < H_2$



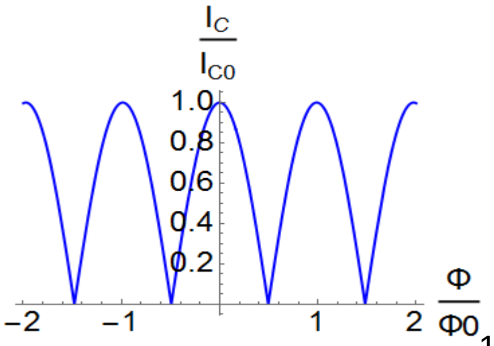
Destructive Interference



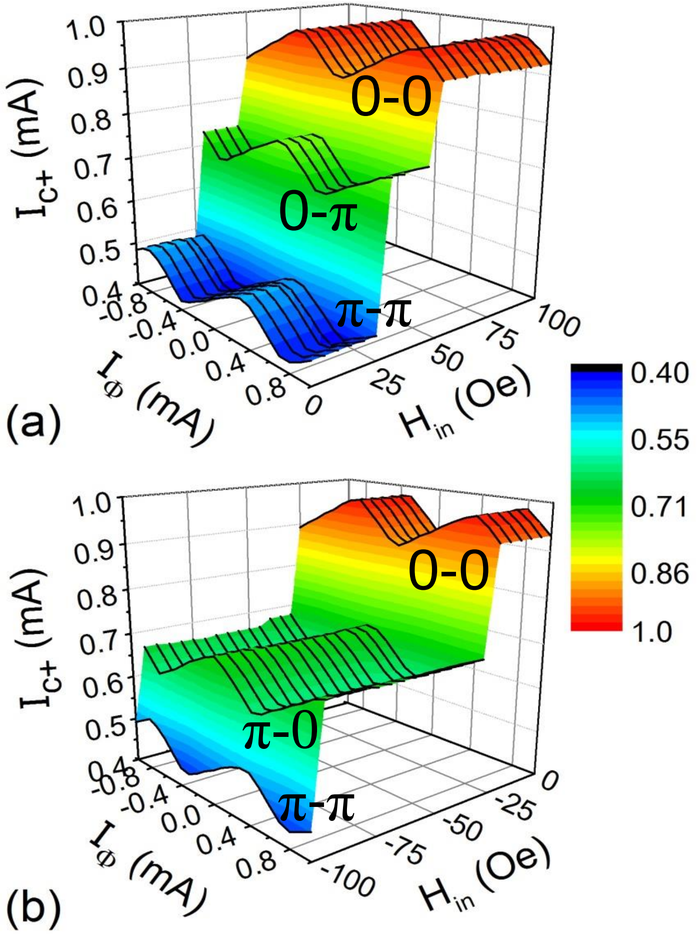
$H_{ext} > H_2$

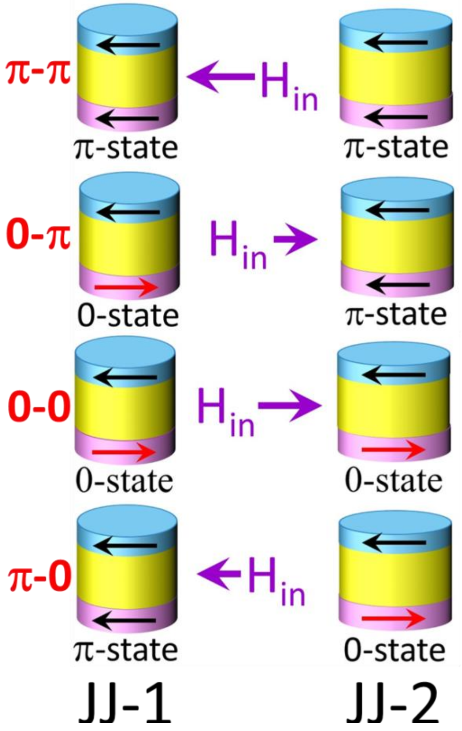


Constructive Interference



Data show clean switching between the four expected states





Switching Fields: +30 Oe, +50 Oe, -35 Oe, -100 Oe

Gingrich, Niedzielski, Glick, *et al.*, Nat. Phys. **12**, 564 (2016)

Data cuts for the four magnetic states

I_{c+} , I_{c-}

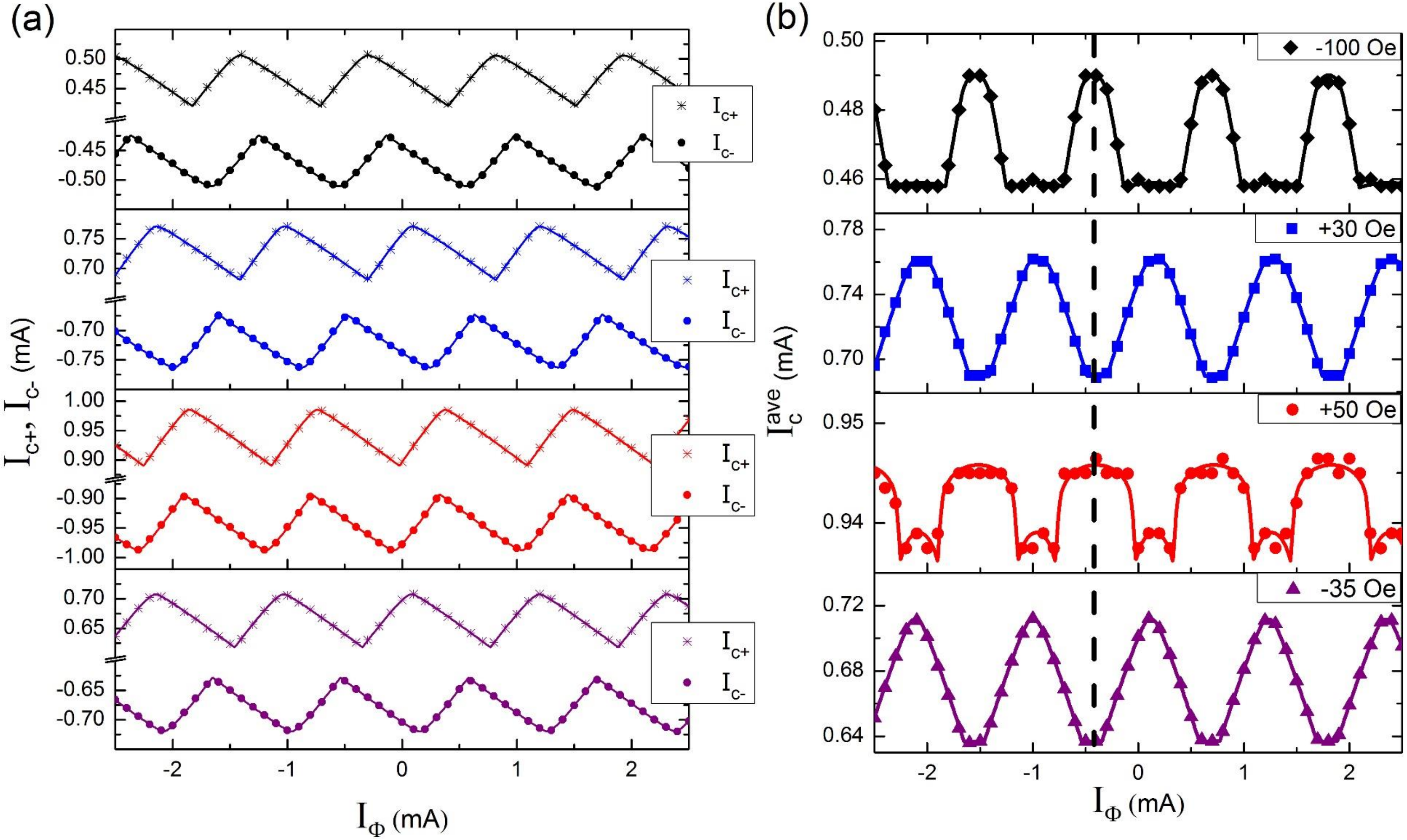
$I_c^{ave} = (I_{c+} - I_{c-})/2$

π - π

0 - π

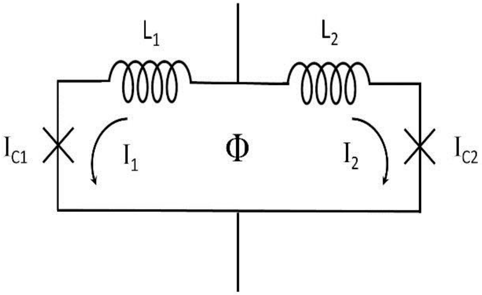
0 - 0

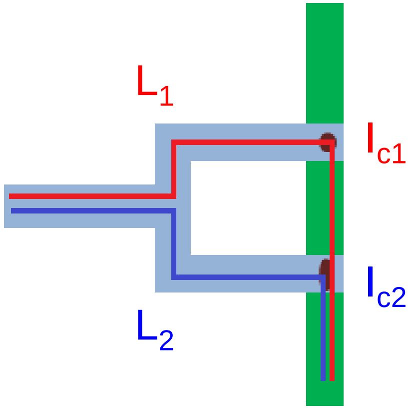
π - 0

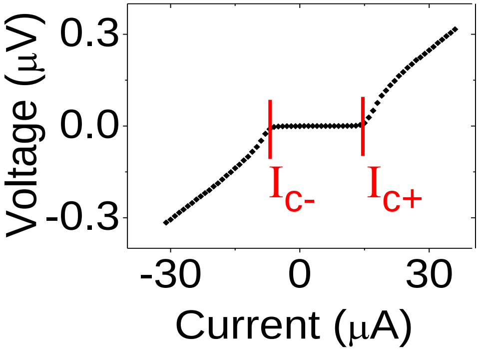


Gingrich, Niedzielski, Glick, *et al.*, Nat. Phys. **12**, 564 (2016)

$I_c(\Phi)$ curves have tilted ratchet shape when loop inductances and/or critical currents are asymmetric



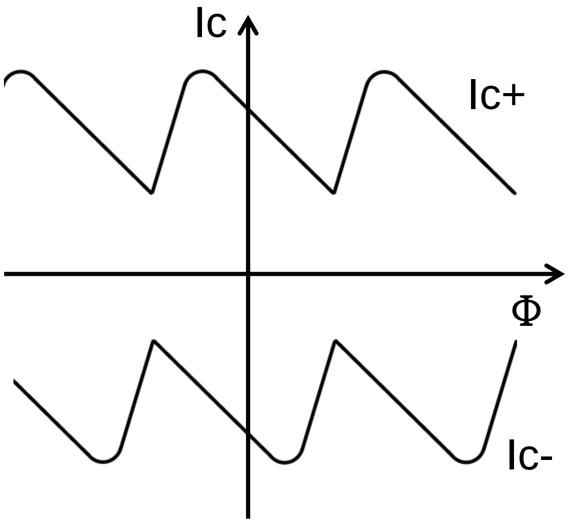




$I_c^+(\Phi)$ and $I_c^-(\Phi)$ oscillations are asymmetric when $L_1 \neq L_2$ & $I_{c1} \neq I_{c2}$

I_c^+ and I_c^- shift by equal amounts and in opposite directions along the Φ axis

Analyze I_c^+ and I_c^- peak shifts to extract JJ phase shifts



Quantitative fits to SQUID modulation data for the four magnetic states

I_{c+} , I_{c-}

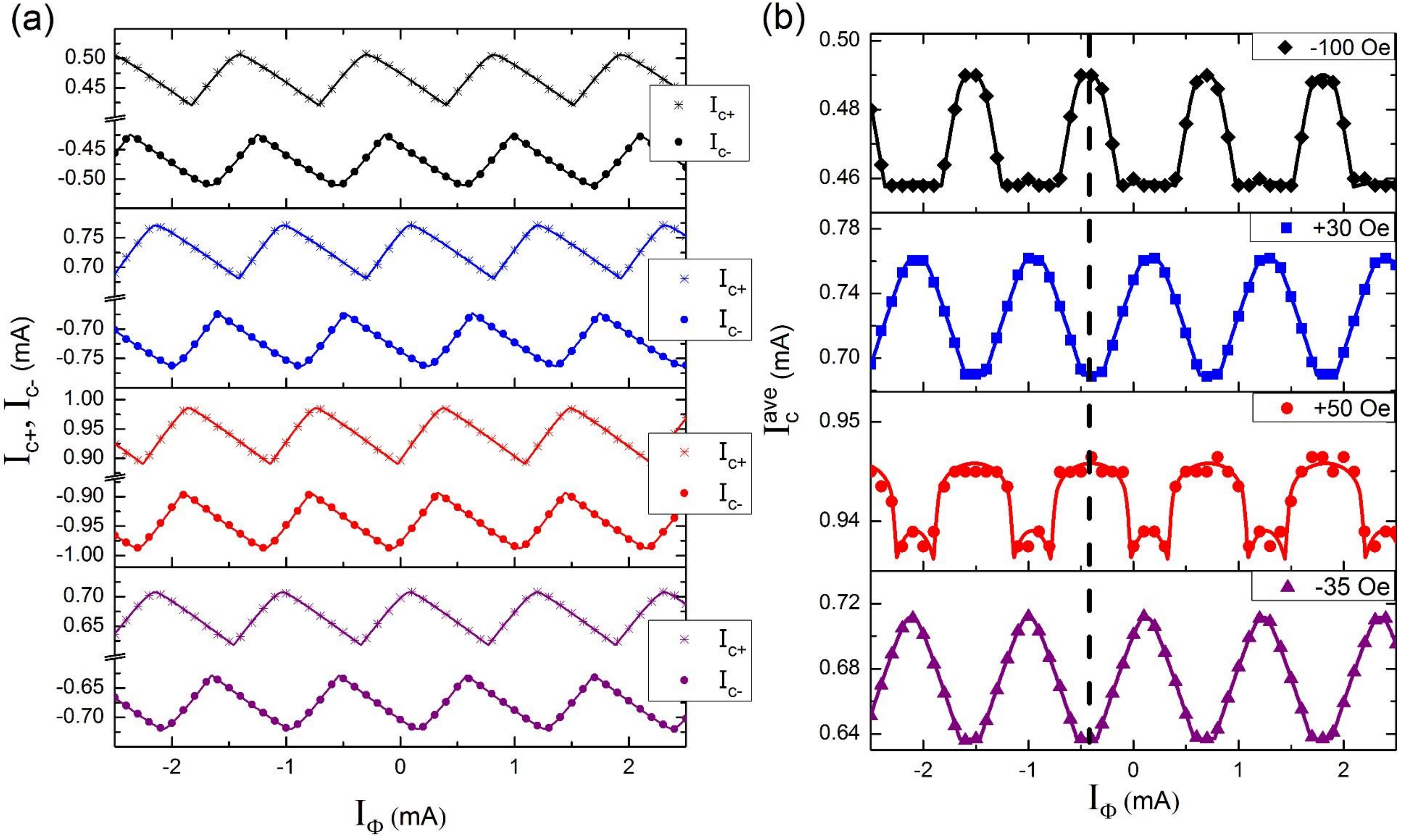
$I_c^{ave} = (I_{c+} - I_{c-})/2$

π - π

0 - π

0 - 0

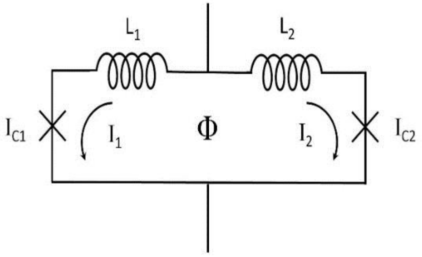
π - 0



Gingrich, Niedzielski, Glick, *et al.*, Nat. Phys. **12**, 564 (2016)

Quantitative Analysis Consistently Assigns the Inductance and Critical Currents of Each State

state	I_{c1} (mA)	I_{c2} (mA)	L_1 (pH)	L_2 (pH)
π - π	0.292	0.217	5.73	11.38
0 - π	0.565	0.203	5.64	11.33
0 - 0	0.567	0.419	5.63	11.55
π - 0	0.294	0.420	5.71	11.56
		ave	5.68	11.46
		σ	0.05	0.12



FastHenry simulations:

$L_1 \approx 7$ pH, $L_2 \approx 13$ pH

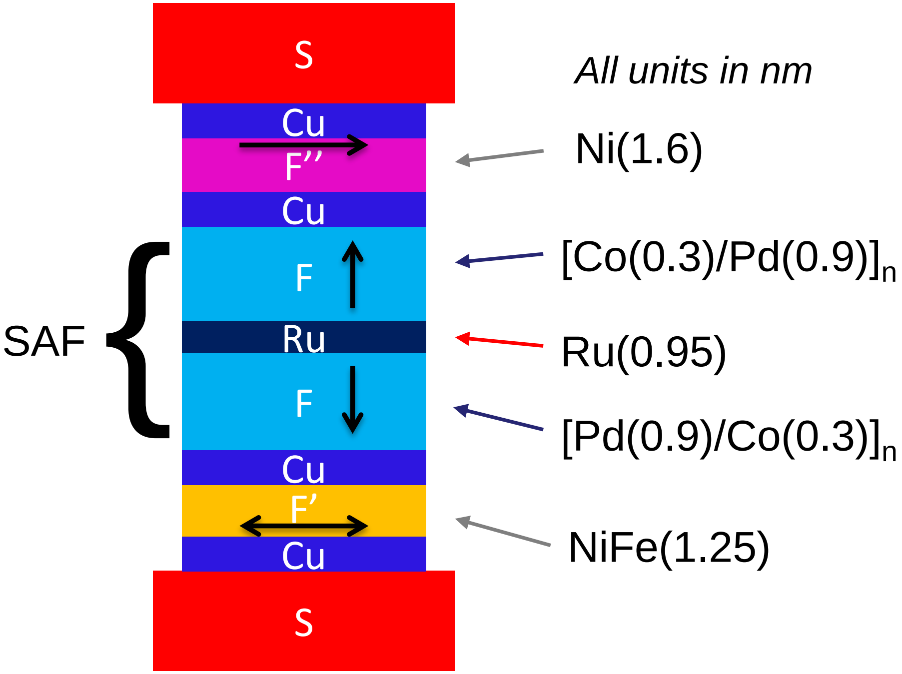
Fitting parameters from independent fits of 4 magnetic states are highly consistent

- Exception: critical current of JJ #2 changes slightly in π state when JJ #1 switches from π to 0 state

Gingrich, Niedzielski, Glick, *et al.*, Nat. Phys. **12**, 564 (2016)

New result!

Controllable 0-π switching with spin-triplet supercurrent



Spin-triplet supercurrent decays very slowly in F

0 - π switching occurs by spin rotation rather than accumulated pair phase

Spin-triplet JJ requires three F layers with non-collinear magnetizations between adjacent layers

Data are not yet available for public dissemination, but we plan to submit them for publication soon: J.A. Glick et al. (2017)

What needs to be done

- Memory (see talk Fr-C-DIG-03 by Ofer Naaman)
  - Optimize performance of magnetic materials
    - Lower $M_{sat} \Rightarrow$ lower E_{switch}
    - Reduce extrinsic sources of anisotropy in thin films
    - Find better material for fixed layer (Ni has issues)
    - Minimize underlayer roughness
  - Develop read/write electronics & interface to SFQ logic
    - (see poster We-SDM-08 by Quentin Herr)
- Make the rest of the computer! (see talk Fr-I-DIG-02 by Anna Herr)

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2017.
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Conclusions

- Magnetic Josephson junctions have demonstrated potential for ultra-low-power cryogenic memory
- Much more work needs to be done!

Bibliography

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