Spin-triplet supercurrent and controllable phase states in Josephson junctions containing ferromagnetic materials

Norman Birge, Michigan State University

in collaboration with Northrop Grumman Corporation

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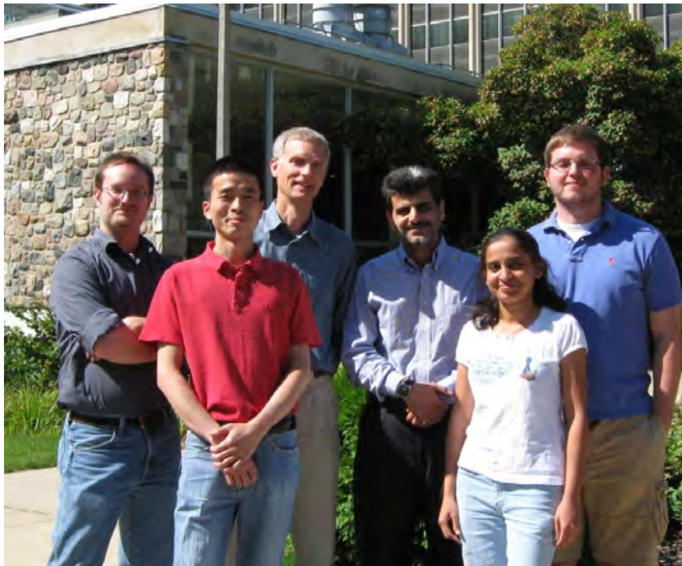
I A R P A

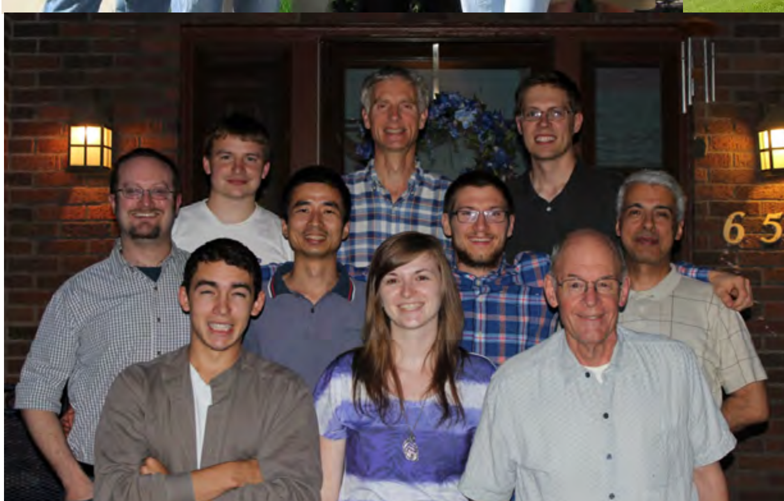
BE THE FUTURE

Collaborators: Trupti Khaire, Mazin Khasawneh, Caroline Klose, Patrick Quarterman, Hamood Arham, Kurt Boden, Yixing Wang, Eric Gingrich, Simon Diesch, Kevin Werner, Alex Cramer, Bill Martinez, Joseph Glick, Bethany Niedzielski, Victor Aguilar, Josh Willard, Sam Edwards, Bob Klaes, Alex Madden, Thomas Bertus, Anna Osella, Reza Loloee, William P. Pratt, Jr.

2010



2017

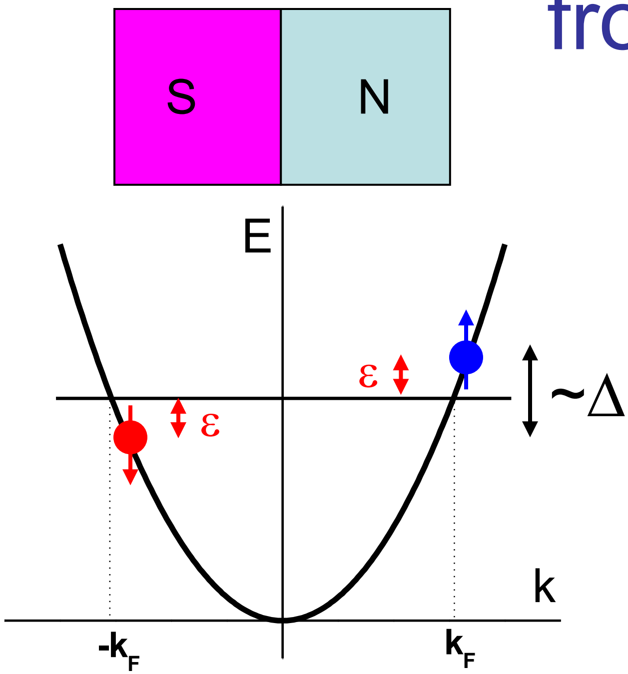


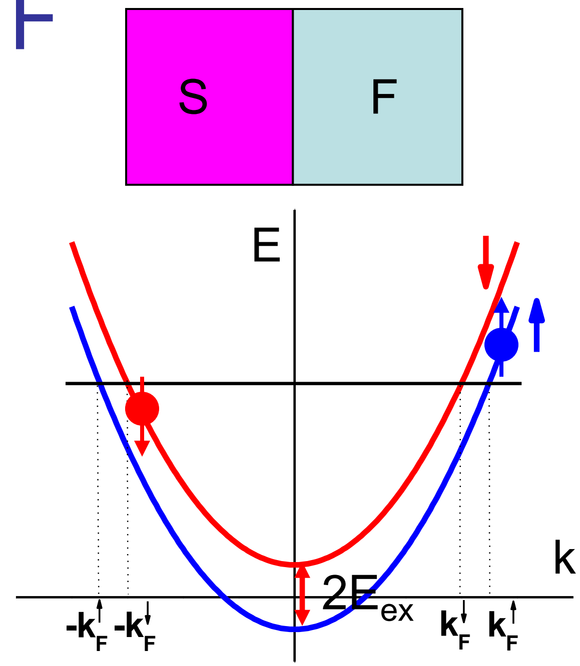
2013

Outline

- Introduction: Proximity effect in S/N and S/F systems
- Theoretical prediction: spin-triplet pair correlations
- Experimental verification using S/F/S Josephson junctions
- Amplitude and phase control of spin-triplet supercurrent
- Work toward a superconducting magnetic memory
  - Phase control in a simpler system
- Summary and Future Prospects

Proximity effect: "leakage of Cooper pairs" from S to N or F





Electron wavefunctions dephase over time $\tau \approx \dfrac{\hbar}{2\varepsilon}$

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

Average over thermal distribution:

$$\xi_N = v_F \tau = \frac{\hbar v_F}{2\pi k_B T} \quad \text{ballistic}$$

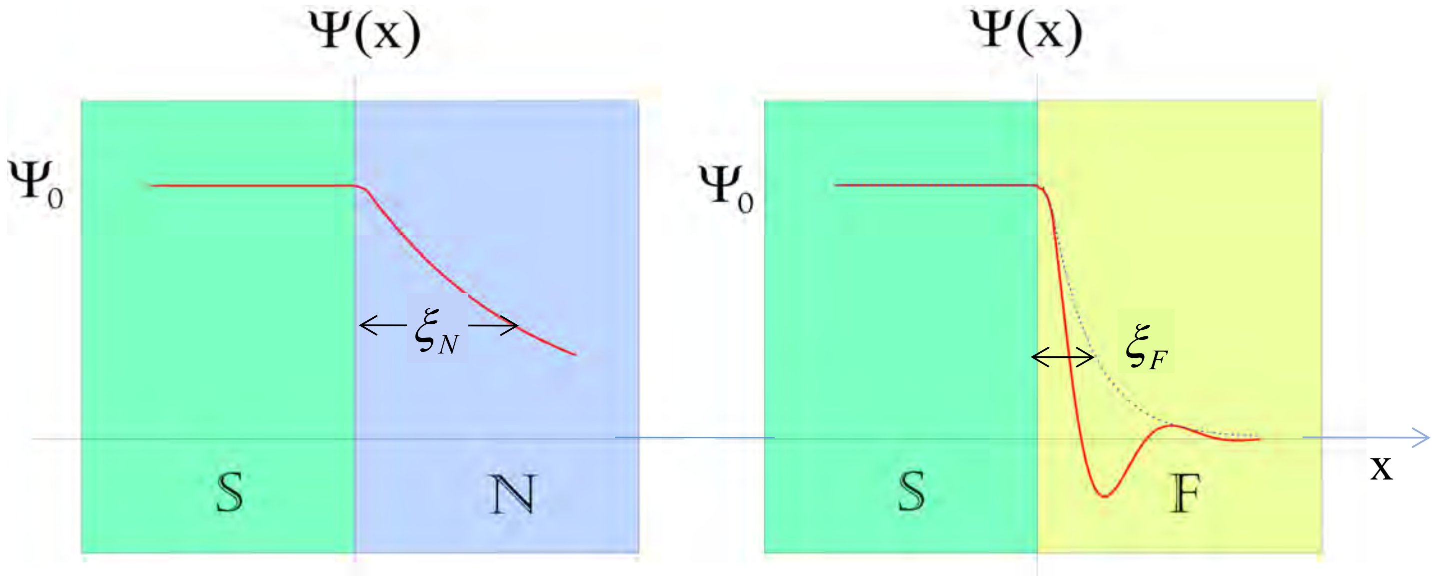
$$\xi_F = Q^{-1} = \frac{\hbar v_F}{2E_{ex}} \quad \text{ballistic}$$

$$\xi_N = \sqrt{D_N \tau} = \sqrt{\frac{\hbar D_N}{2\pi k_B T}} \quad \text{diffusive}$$

D = diffusion constant

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

Proximity effect: S/N vs. S/F



$$\xi_N = \sqrt{\frac{\hbar D_N}{2\pi k_B T}} \approx 0.1 - 1\mu m$$

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

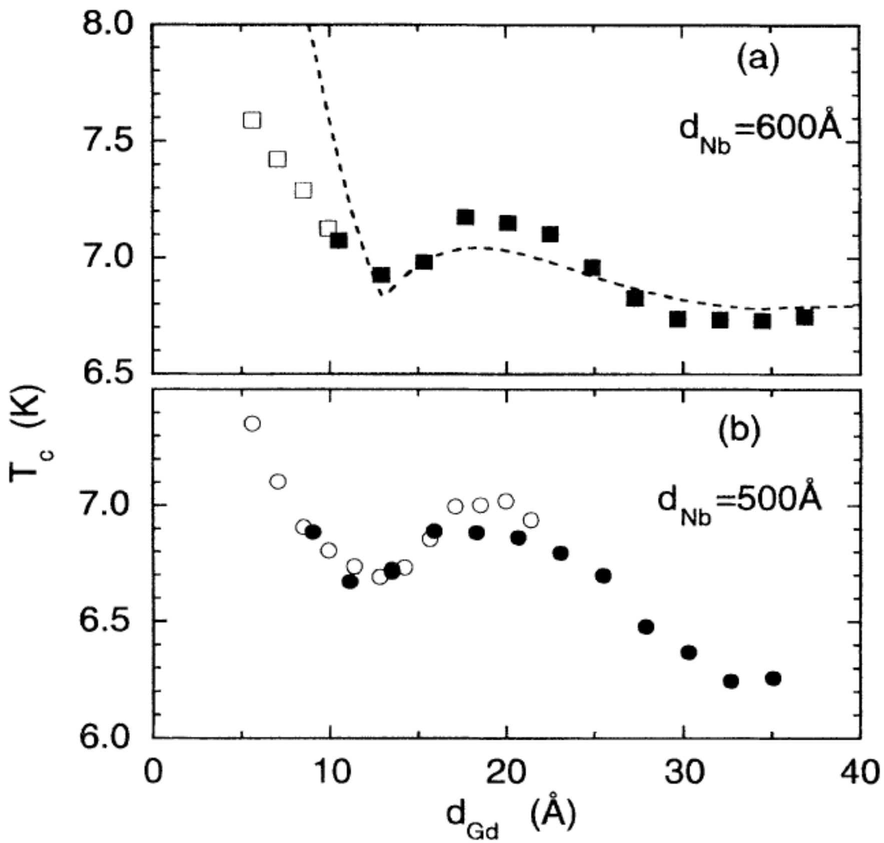
$$\Psi(x) = \Psi_0 \exp(-x/\xi_N)$$

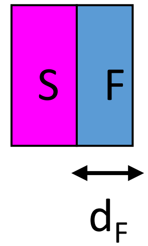
$$\Psi(x) = \Psi_0 \cos(x/\xi_F) \exp(-x/\xi_F)$$

How to detect the oscillating pair correlation function?

1. Measure Tc of S/F bilayers as a function of d_F

Jiang, Davidovic, Reich, Chien, PRL 74, 314 (1995).



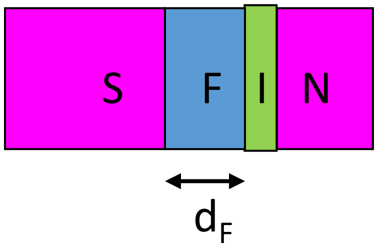


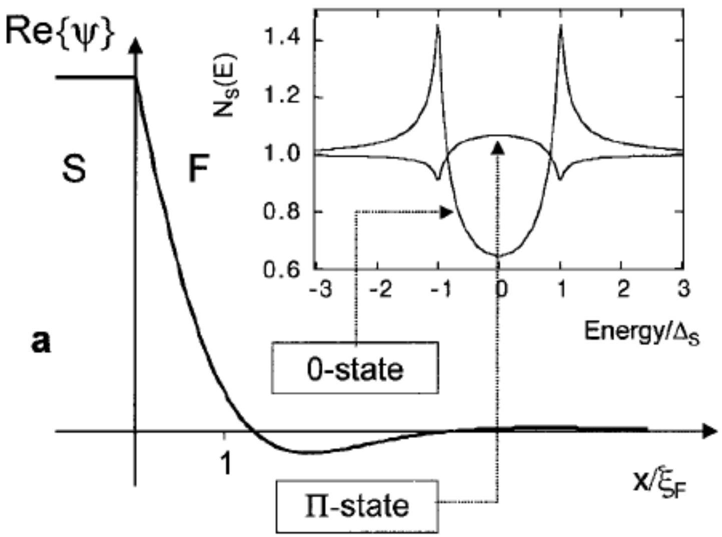
Problem: interpretation controversial due to magnetic dead layers.

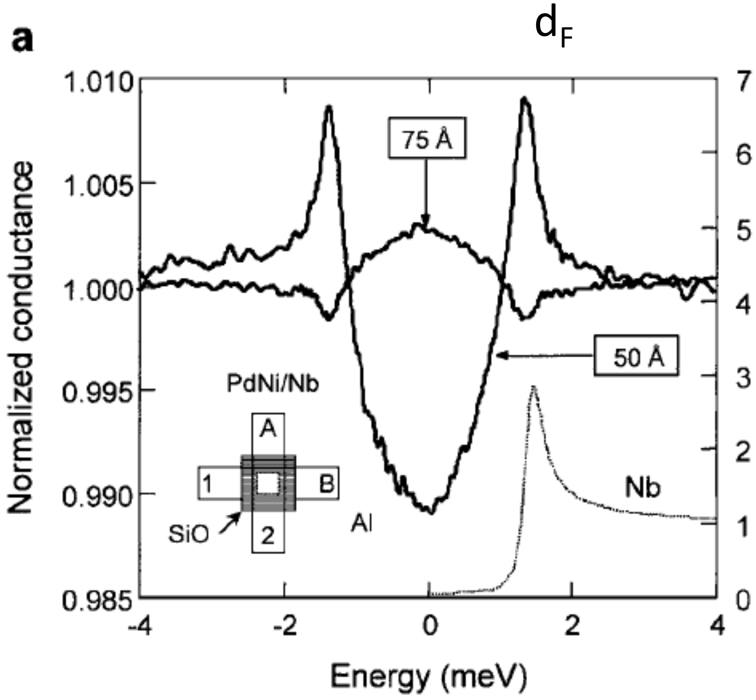
How to detect the oscillating pair correlation function?

2. Measure tunneling density of states in S/F/I/N structure, as function of d_F

Kontos, Aprili, Lesueur, Grison, PRL 86, 304 (2001)





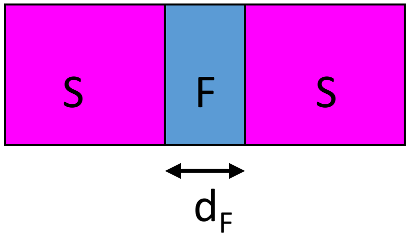


How to detect the oscillating pair correlation function?

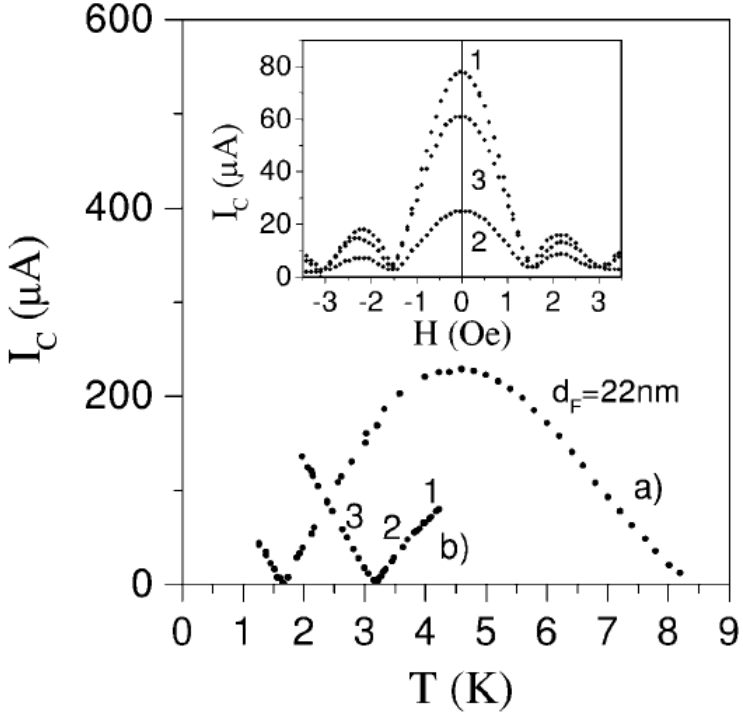
3. Measure critical current of S/F/S Josephson junction, as function of d_F

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

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

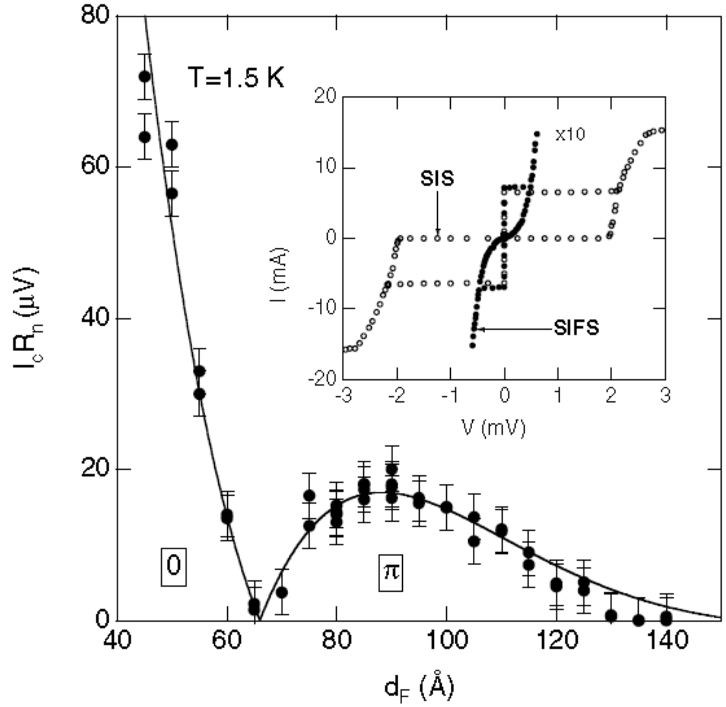


Weak F: $Cu_{48}Ni_{52}$ alloy, vary T



Ryazanov *et al.*, PRL **86**, 2427 (2001).

Weak F: $Pd_{88}Ni_{12}$, vary d_F



Kontos, Aprili … **89**, 137007 (2002)

How to detect the oscillating pair correlation function?

3. Measure critical current of S/F/S Josephson junction, as function of d_F

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

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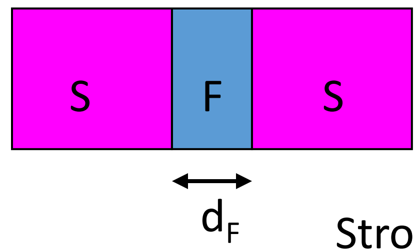
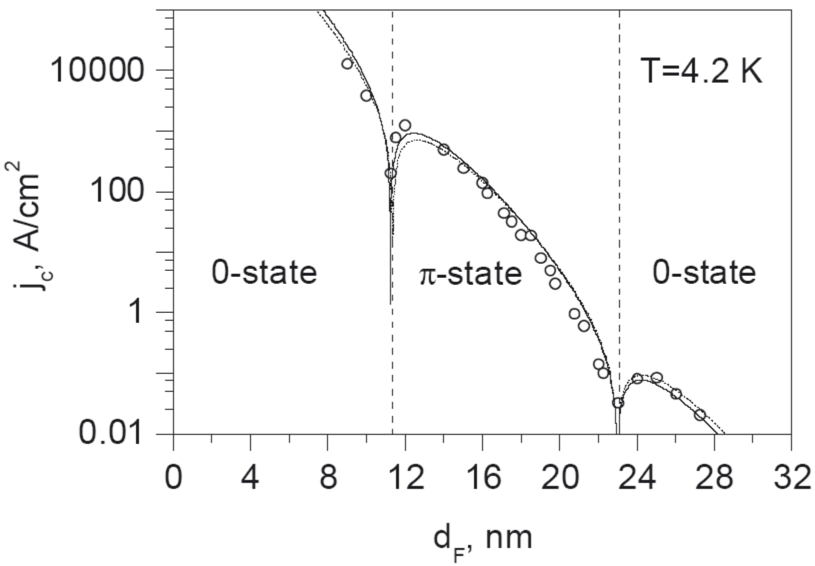
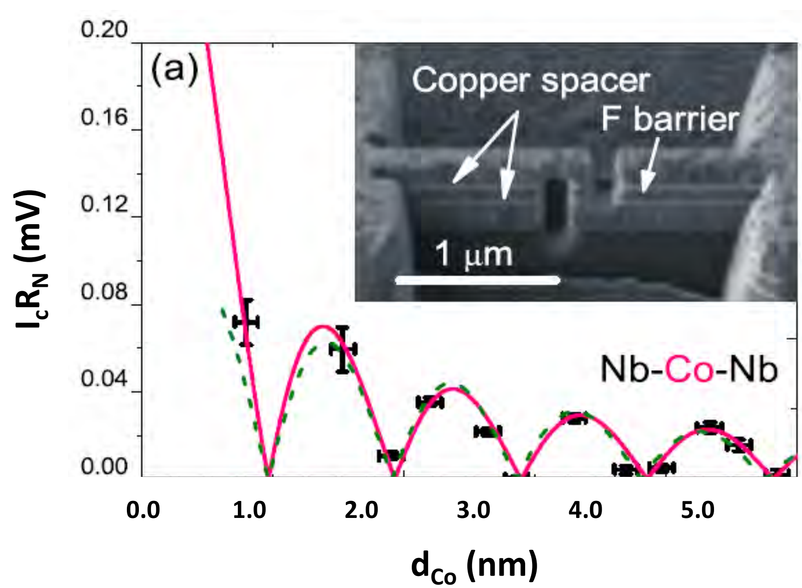


More $Cu_{48}Ni_{52}$ alloy

Strong F: Co





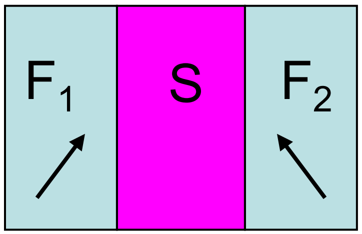
Oboznov *et al.,* PRL **96**, 197003 (2006).

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

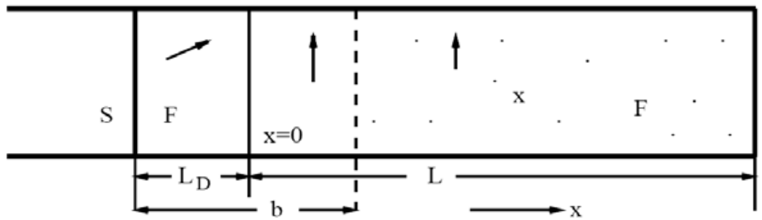
2001 Prediction: *spin-triplet* pair correlations

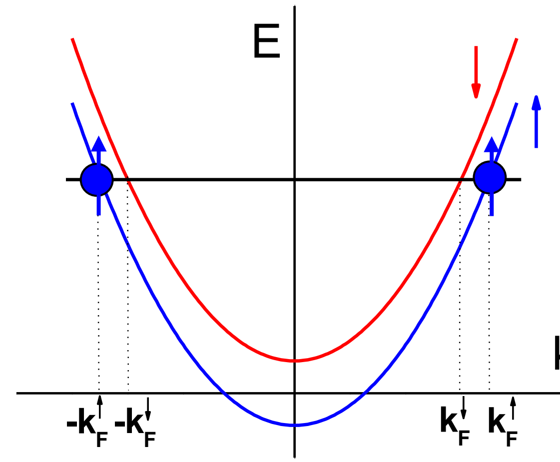
i) are long-ranged in F

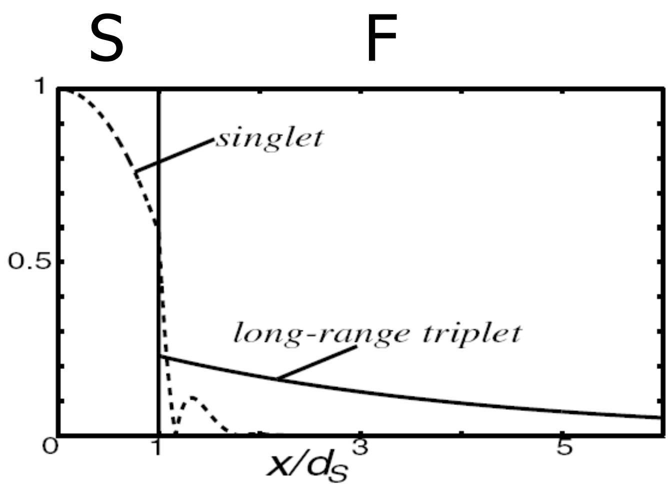
ii) can be induced by noncollinear magnetization



or







Singlet

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

Triplet

$$\xi_F^{\ T} = \sqrt{\frac{\hbar D_F}{2\pi k_B T}}$$

$$\boxed{\xi_F^{\ S} << \xi_F^{\ T}}$$

Bergeret, Volkov & Efetov, PRL **86**, 4096 (2001); PRL **90**, 117006 (2003)

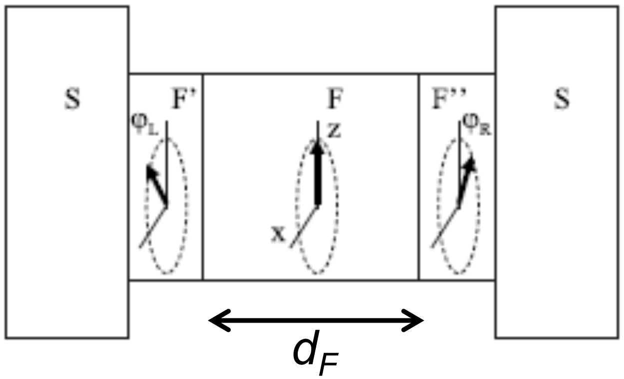
Kadrigrobov, Shekhter & Jonson, Europhys. Lett. **54**, 394 (2001)

S/F/S Josephson junction can carry spin-triplet supercurrent

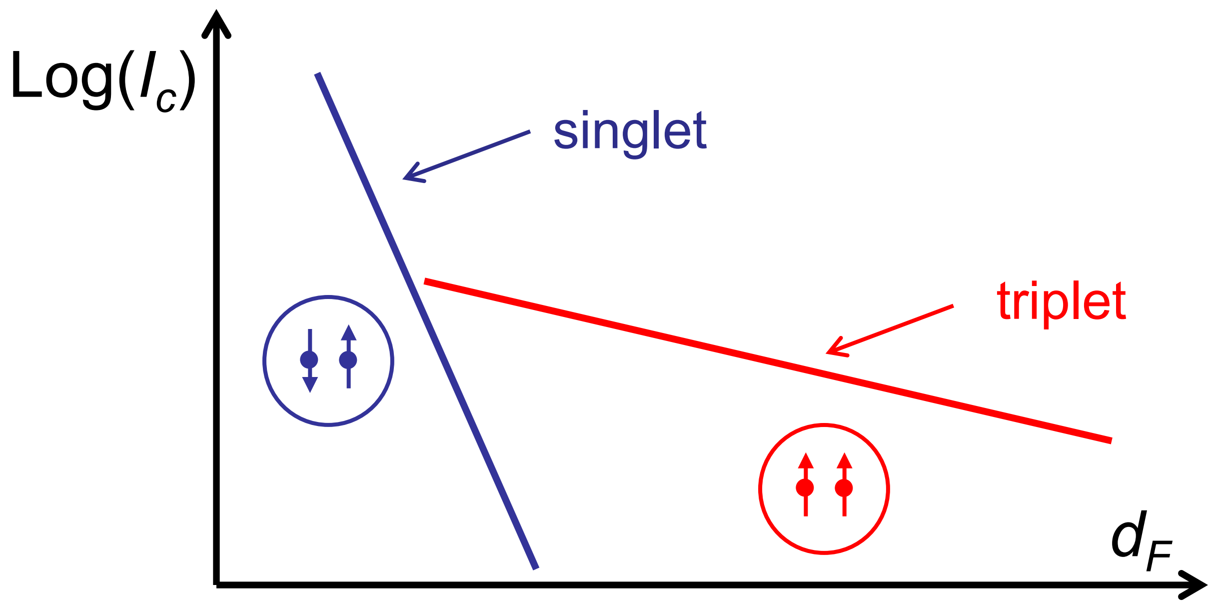
Bergeret, Volkov & Efetov, PRL **86**, 4096 (2001)

Houzet & Buzdin, PRB **76**, 060504(R) (2007):

Non-collinear magnetizations convert pairs from spin-singlet to spin-triplet



Signature of spin-triplet supercurrent:

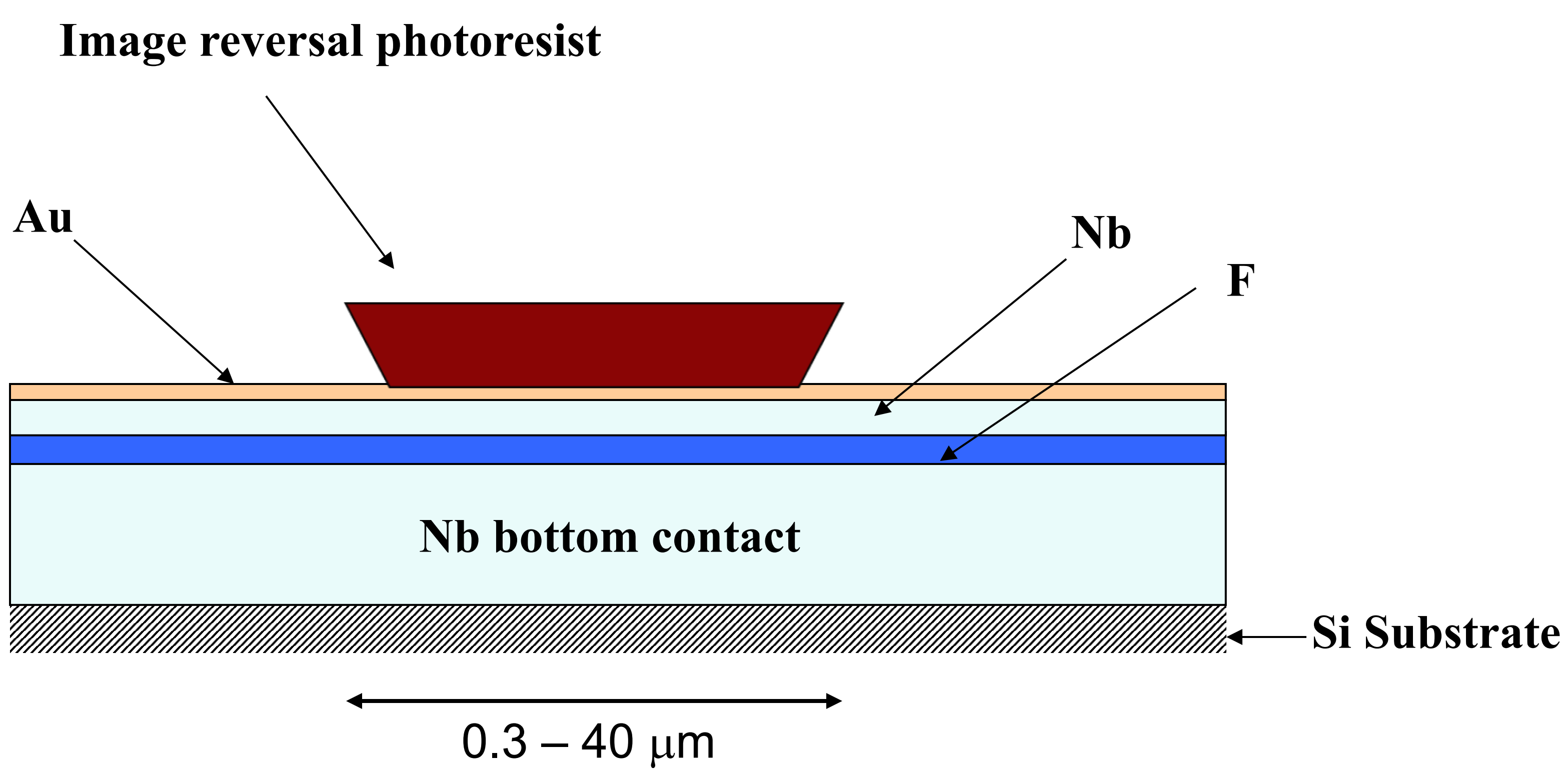


$$\xi_F^{\;S} = \sqrt{\frac{\hbar D_F}{E_{ex}}}$$

$$\xi_F^{\;T} = \sqrt{\frac{\hbar D_F}{2\pi k_B T}}$$

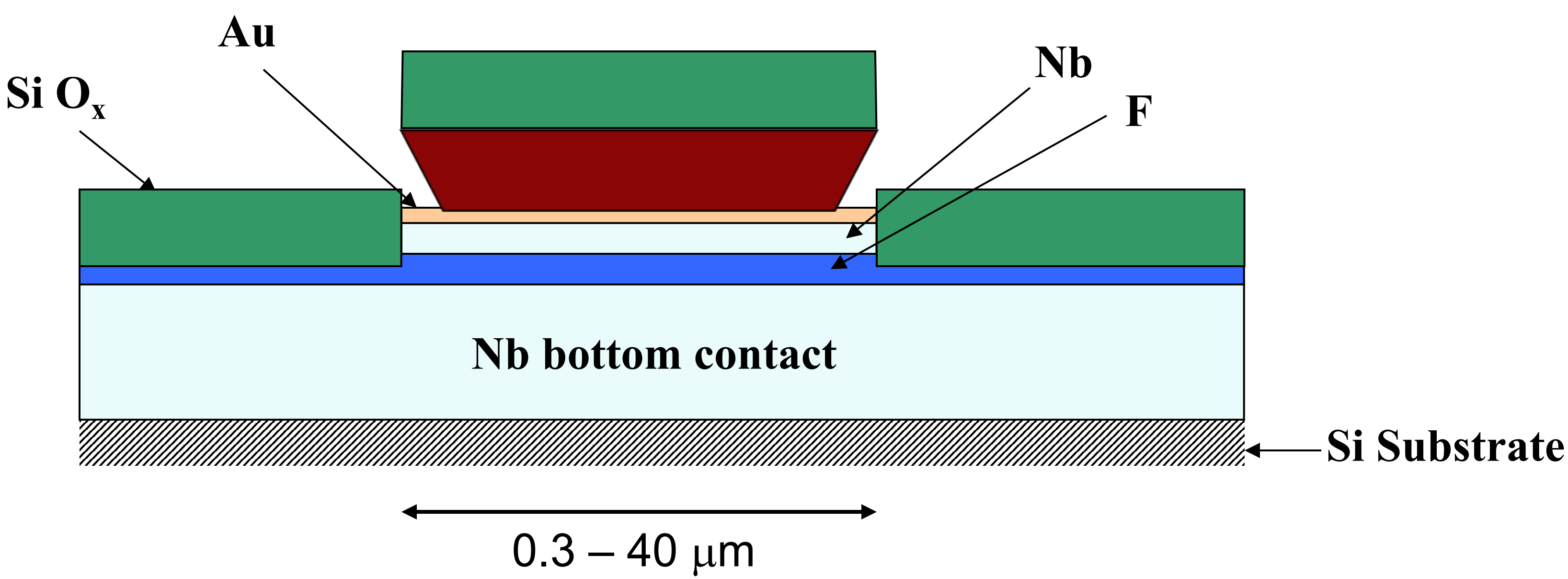
Sample Fabrication

1. Sputter S/F/S
2. Pattern pillars with photo or e-beam lithography



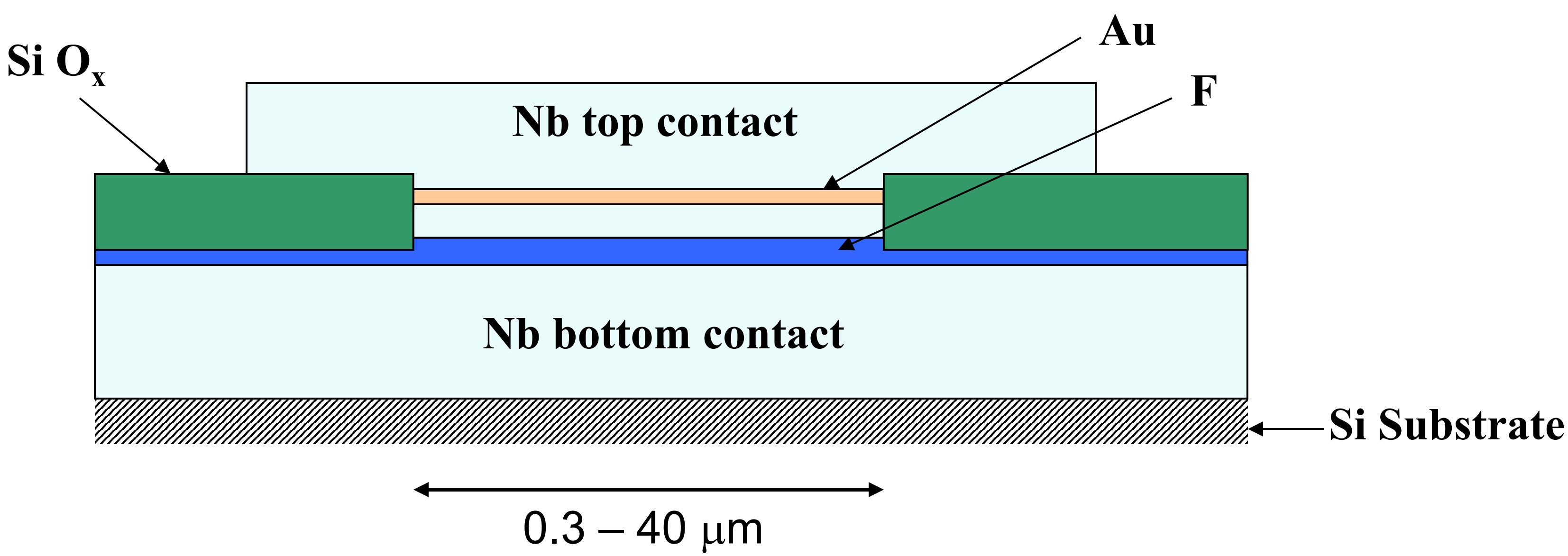
Sample Fabrication

1. Sputter S/F/S
2. Pattern pillars with photo or e-beam lithography
3. Ion mill
4. Deposit SiOx



Sample Fabrication

1. Sputter S/F/S
2. Pattern pillars with photo or e-beam lithography
3. Ion mill
4. Deposit SiOx
5. Liftoff
6. Deposit top Nb contact

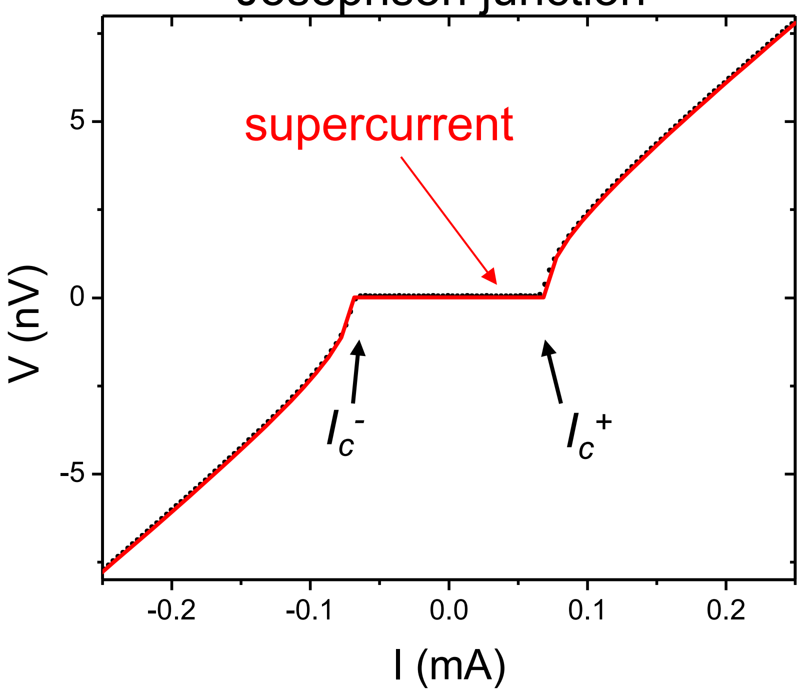


Measurement

Low sample resistance: 100 $\mu\Omega$ – 10 mΩ

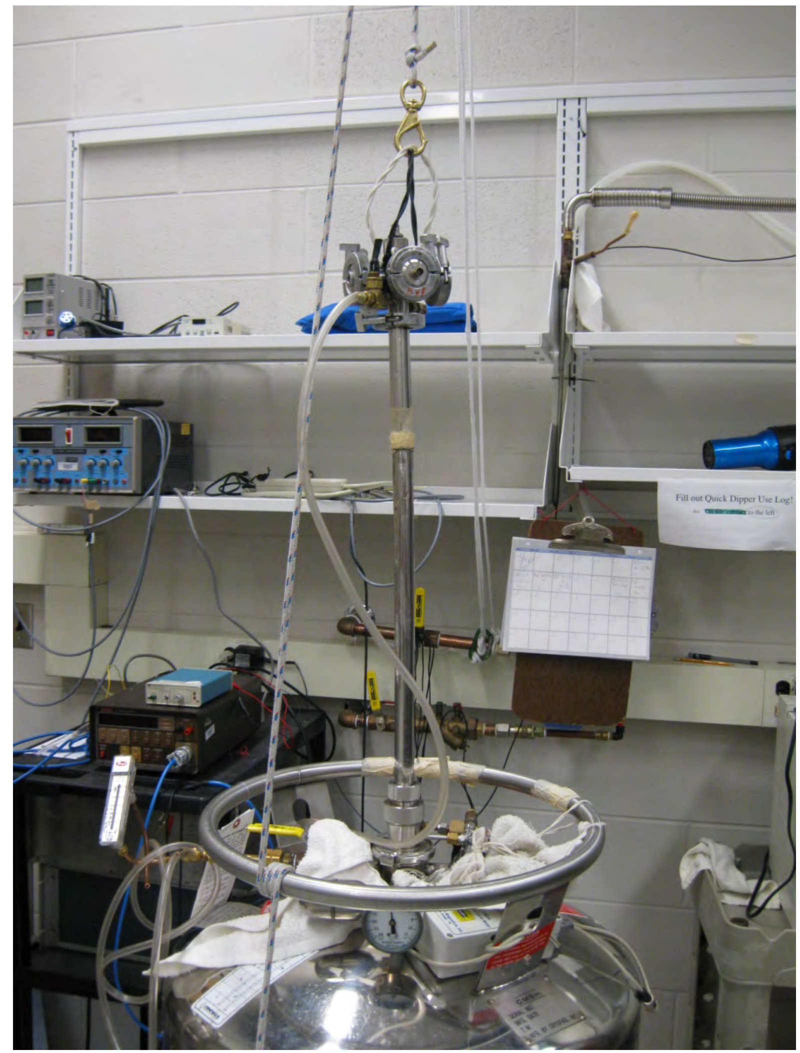
$\rightarrow$ Measure with SQUID-based potentiometer

I-V characteristic of overdamped Josephson junction

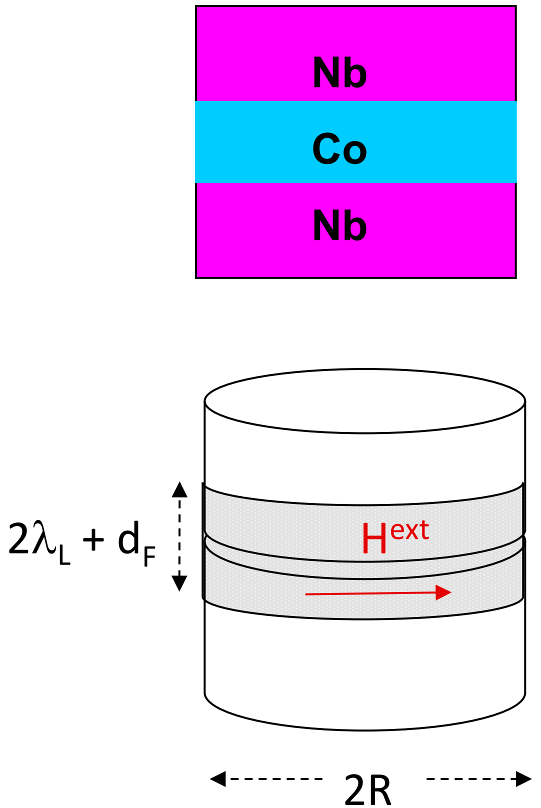


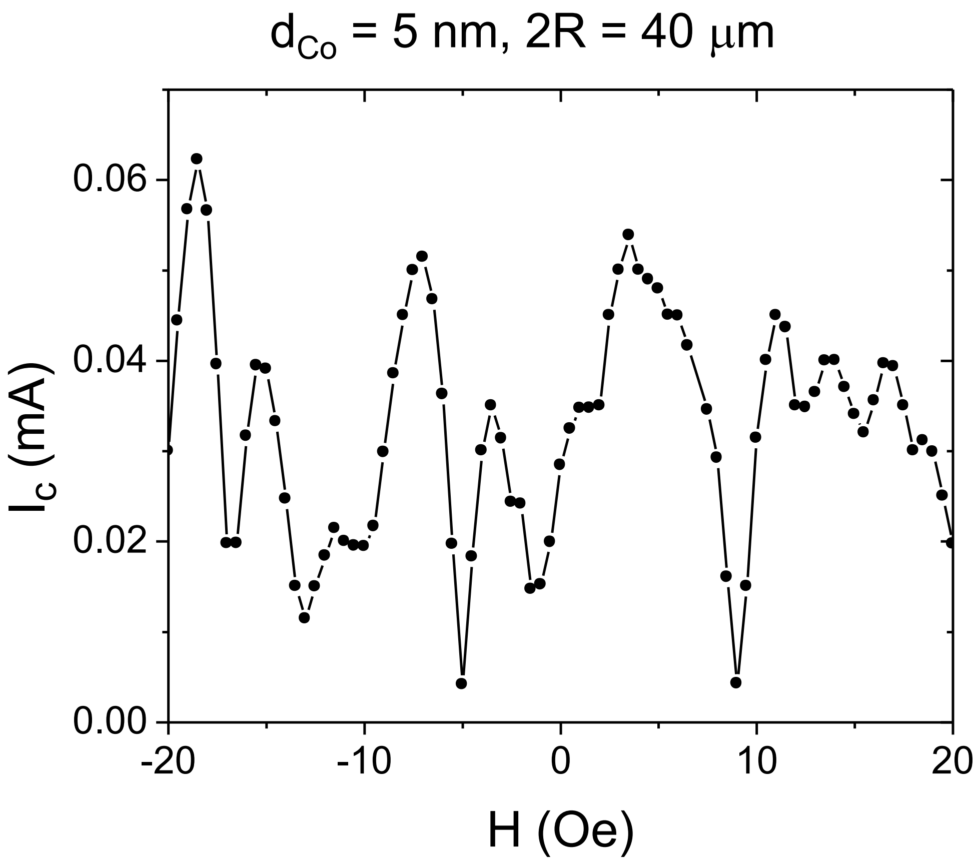
$I_c \equiv$ critical current

Measure at T = 4.2 K in “quick-dipper” cryostat in helium storage dewar



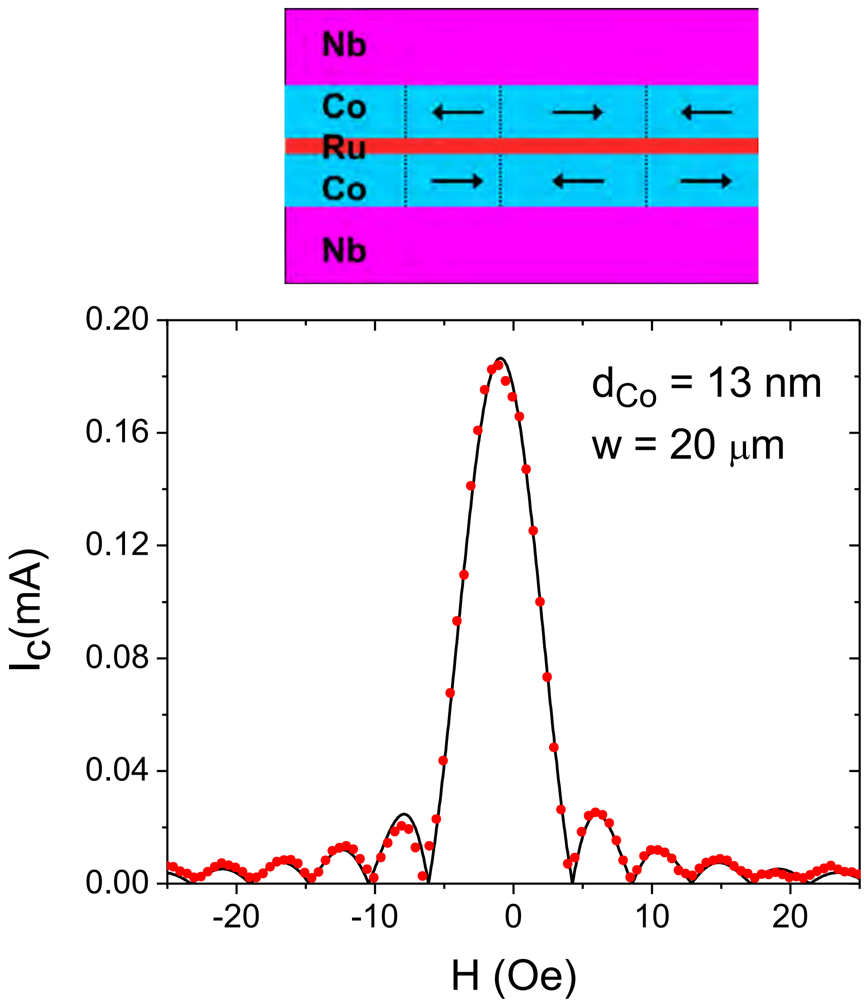
Problem: Large-area S/F/S junctions with strong ferromagnets $\Rightarrow$ distorted Fraunhofer patterns

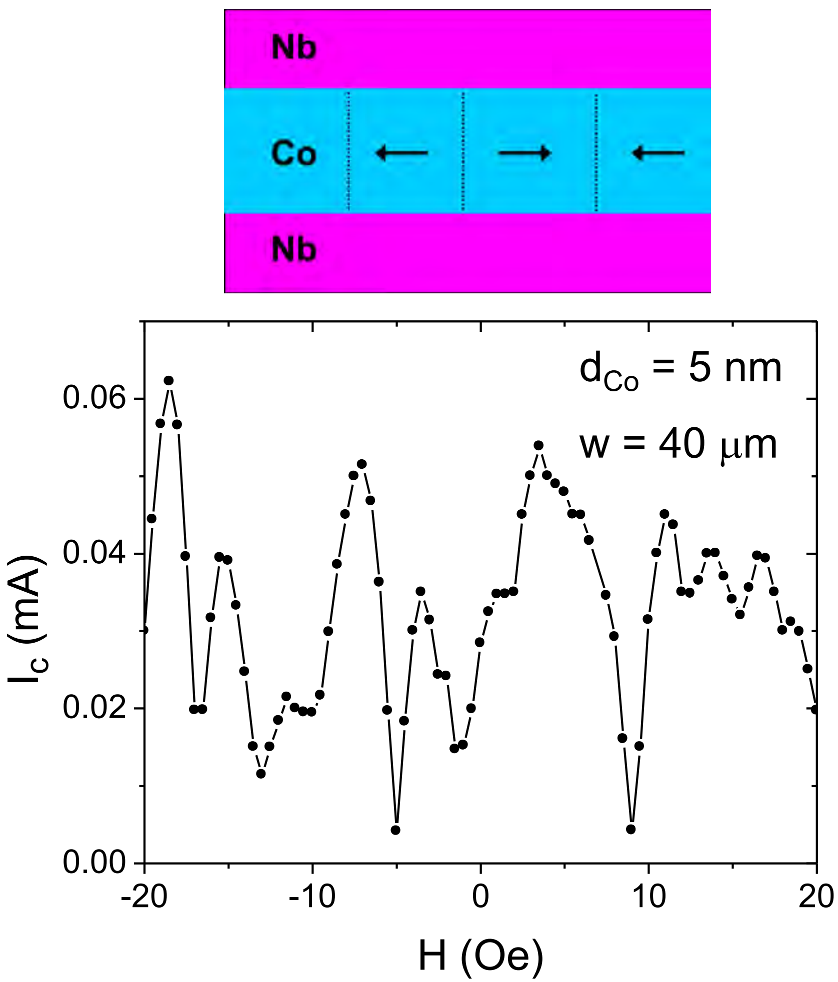




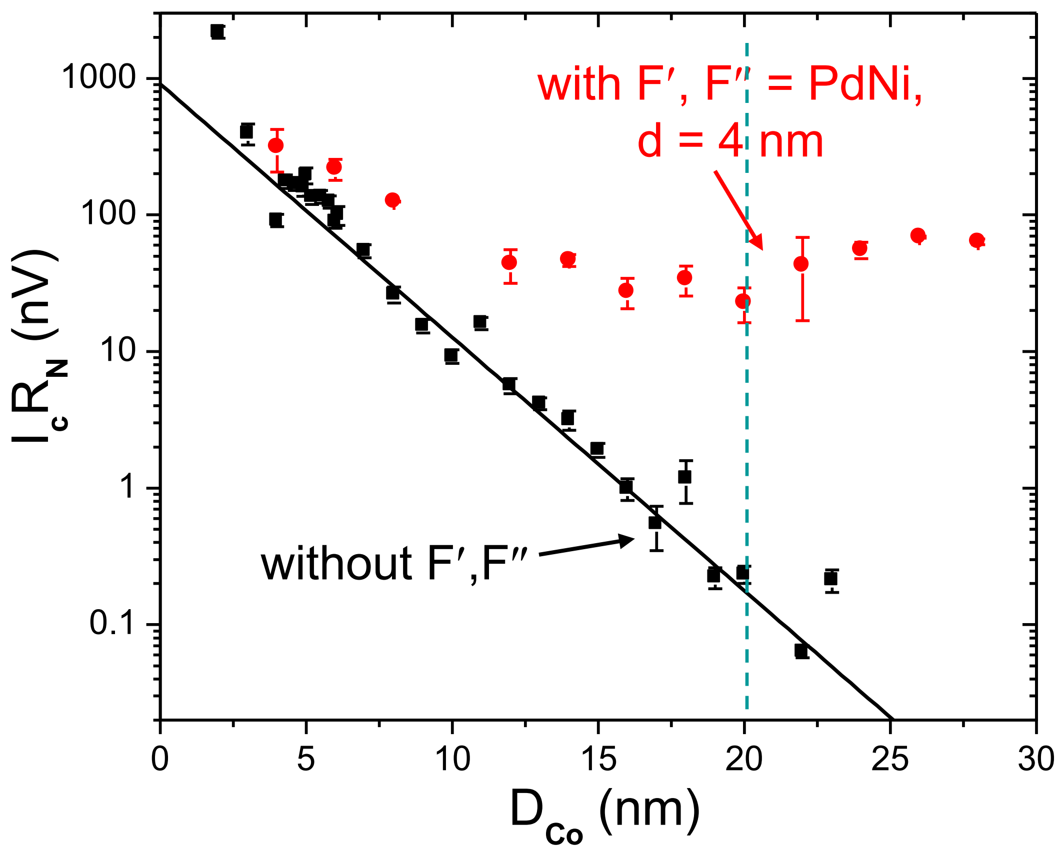
Random Fraunhofer pattern due to complex domain configuration

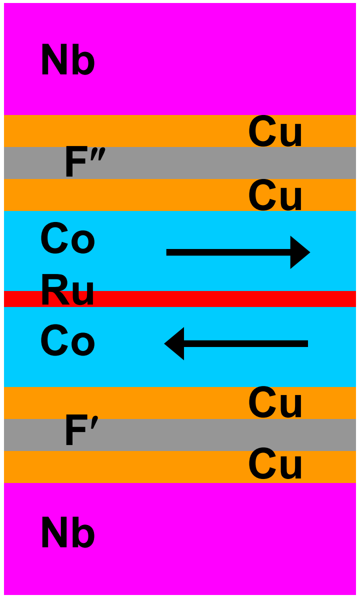
Solution: Co/Ru/Co synthetic antiferromagnet cancels flux and restores Fraunhofer pattern

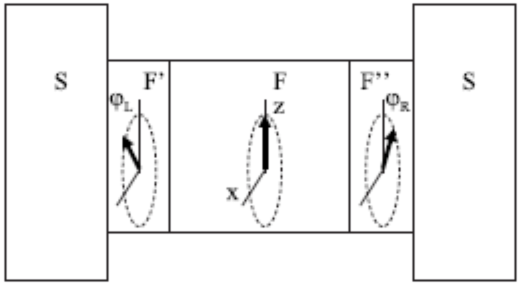




How to generate spin-triplet supercurrent



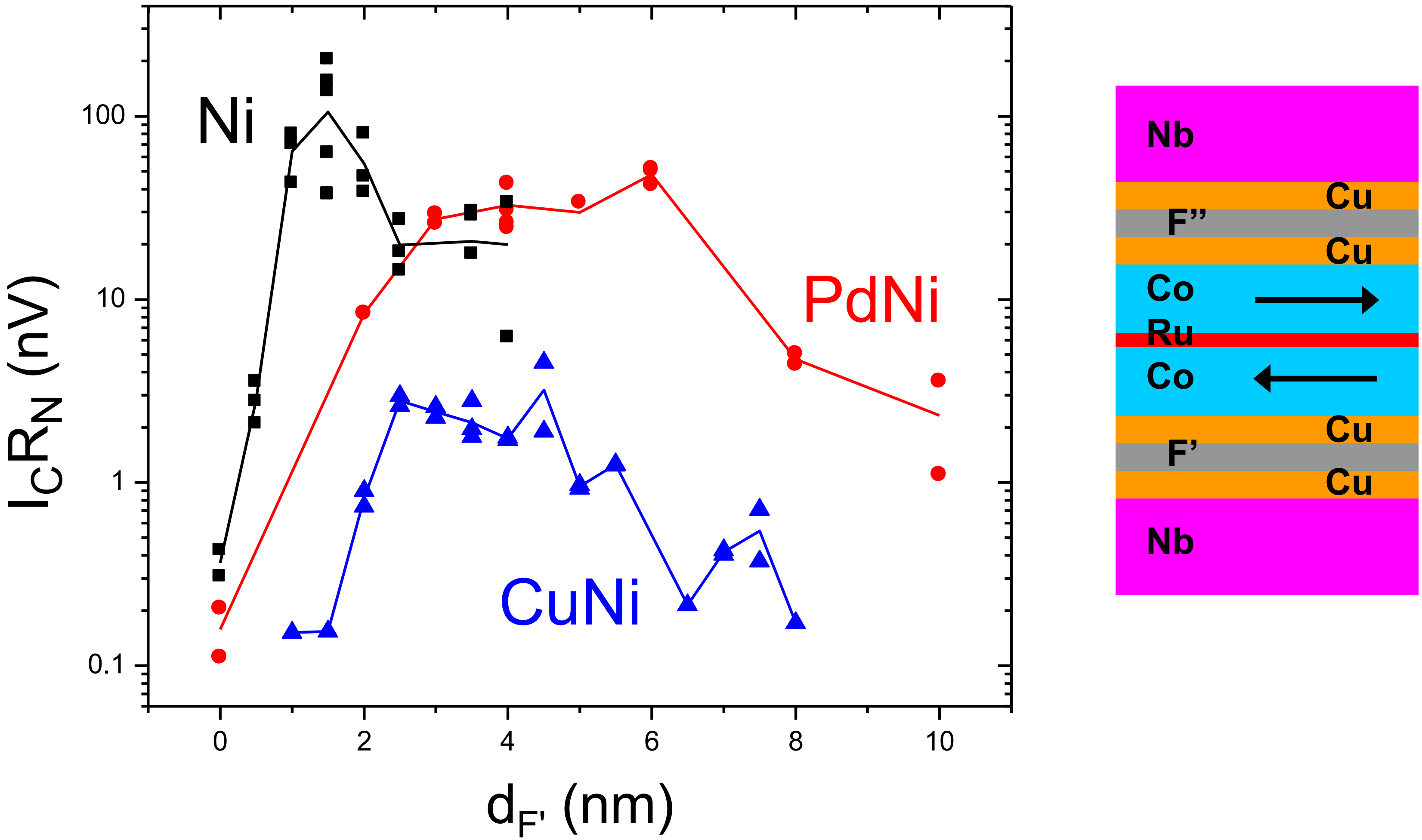




Fix D_{Co} = 20 nm and vary $d_{F'}$

Khaire, Khasawneh, Pratt, & NOB, Phys. Rev. Lett. **104**, 137002 (2010)

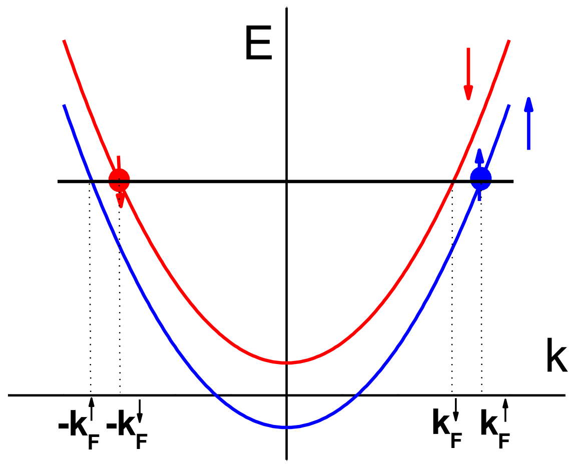
Control amplitude of triplet with $d_{F'}$, $d_{F''}$

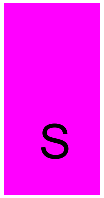


Khasawneh, Khaire, Klose, Pratt & NOB, Supercond. Sci. Technol. **24**, 024005 (2011).

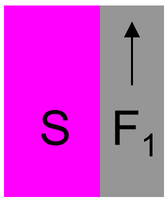
Microscopic mechanism for triplet generation

(M. Eschrig)





$$|0,0\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$



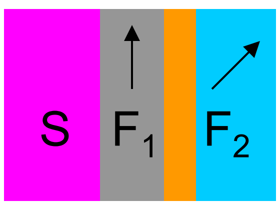
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle e^{iQx} - |\downarrow\uparrow\rangle e^{-iQx}\right)$$

$$= \frac{1}{\sqrt{2}}\left[\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)\cos(Qx) + i\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)\sin(Qx)\right]$$

$$Q = k_F^{\uparrow} - k_F^{\downarrow}$$

$$= |0,0\rangle_z \cos(Qx) + |1,0\rangle_z \sin(Qx)$$

short-range triplet component



rotate basis:

$$|1,0\rangle_z = \frac{\sin(\theta)}{\sqrt{2}}|1,1\rangle_\theta + \cos(\theta)|1,0\rangle_\theta - \frac{\sin(\theta)}{\sqrt{2}}|1,-1\rangle_\theta$$

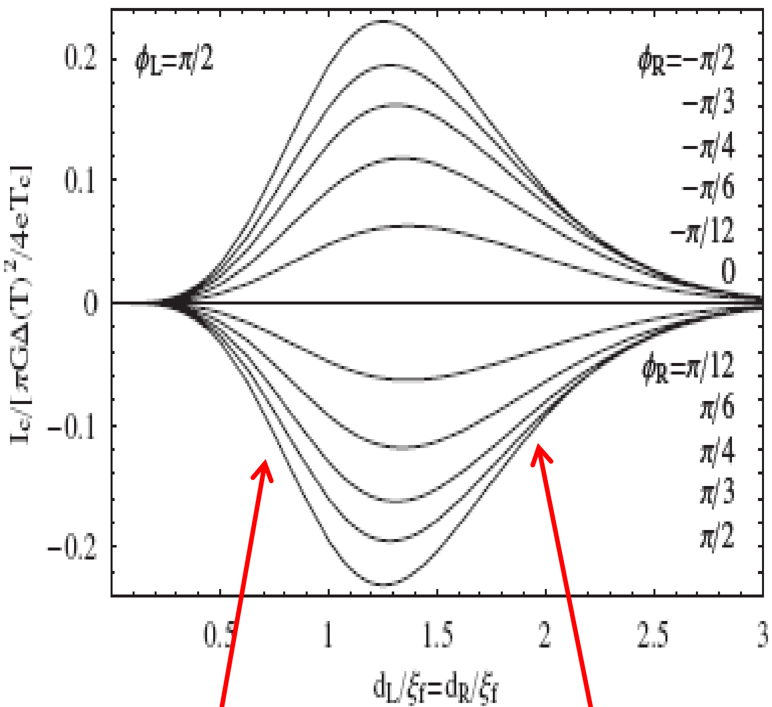
long-range triplet components in F_2

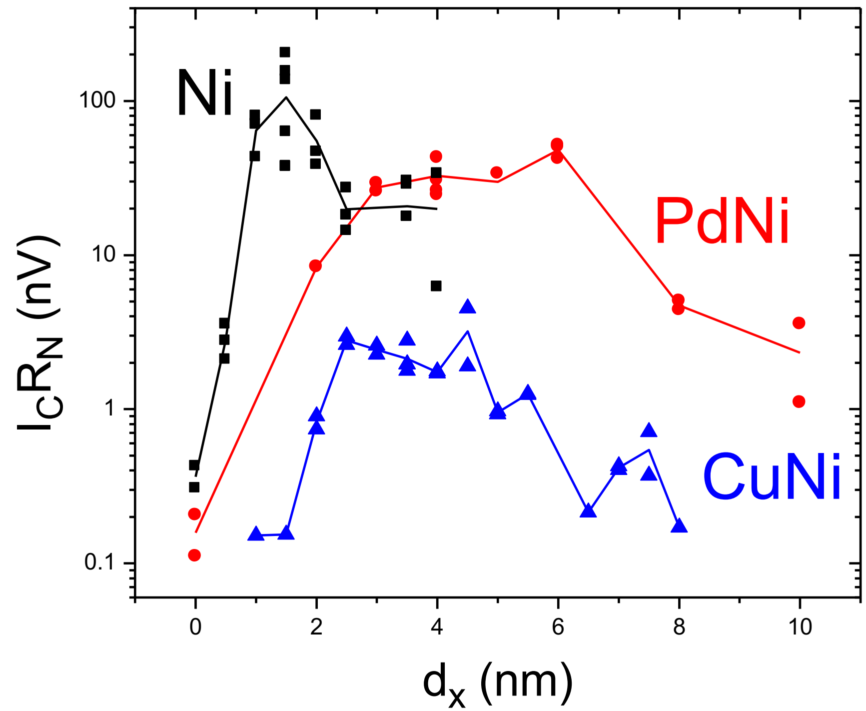
$$|1,1\rangle_\theta = |\uparrow\uparrow\rangle_\theta$$

$$|1,-1\rangle_\theta = |\downarrow\downarrow\rangle_\theta$$

Optimization of triplet generation

M. Houzet and A. I. Buzdin, PRB **76**, 060504R 2007





Triplet contribution to the critical current is observed only for $d_X \approx (0.5\text{–}2.5)\xi_F$

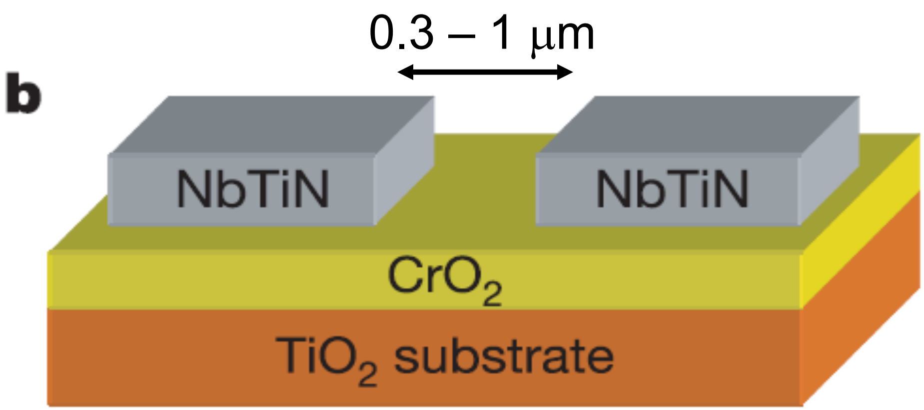
increase ~ $\sin^2(Qx)$; decrease ~ e^{-x/ξ_F}

$$E_{ex}^{Ni} > E_{ex}^{PdNi} > E_{ex}^{CuNi}$$

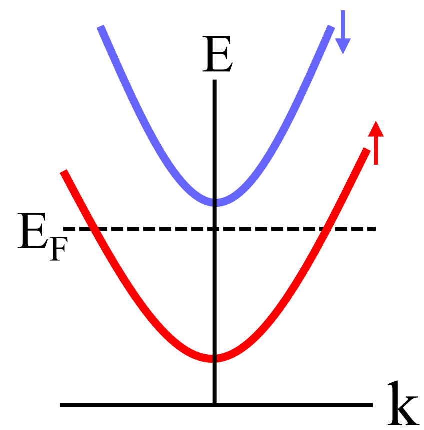
$$\xi_F^{Ni} < \xi_F^{PdNi} < \xi_F^{CuNi}$$

Earlier observation of triplet:

Keizer, Goennenwein, Klapwijk, Miao, Xiao, Gupta, Nature **439**, 825 (2006)



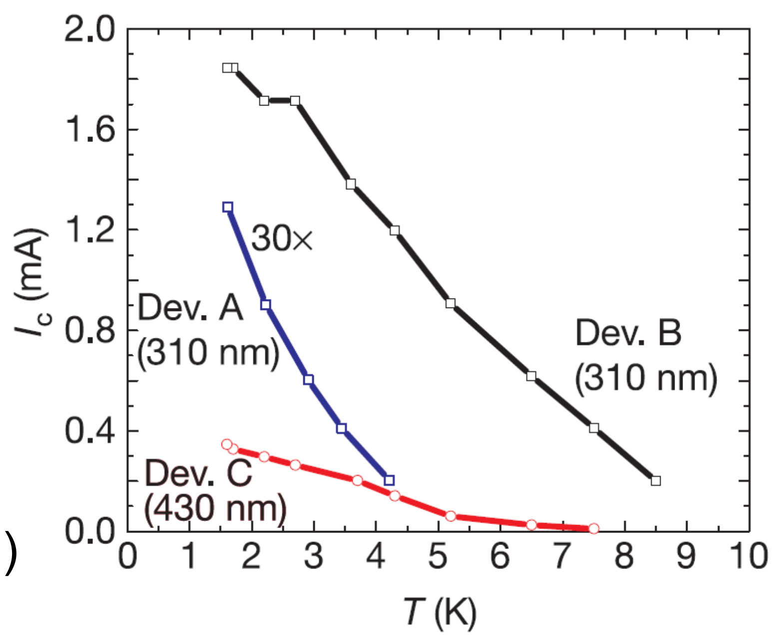
CrO_2 is a "half metal"



Long-range propagation of supercurrent, but large sample-to-sample variations in I_c.

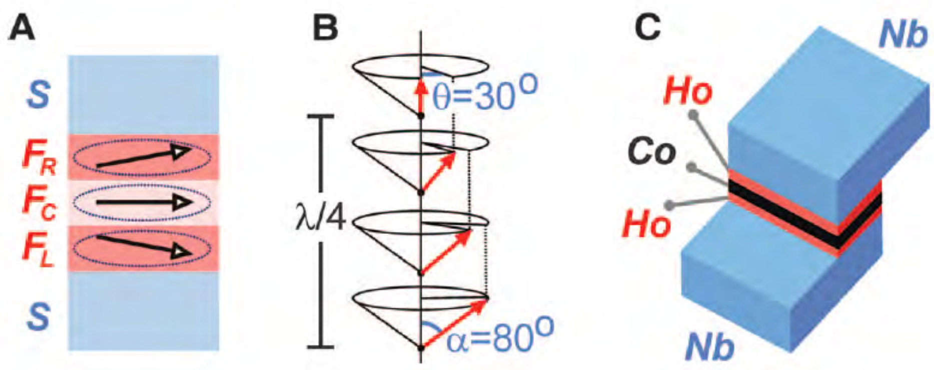
Reproduced in 2010 by J. Aarts:

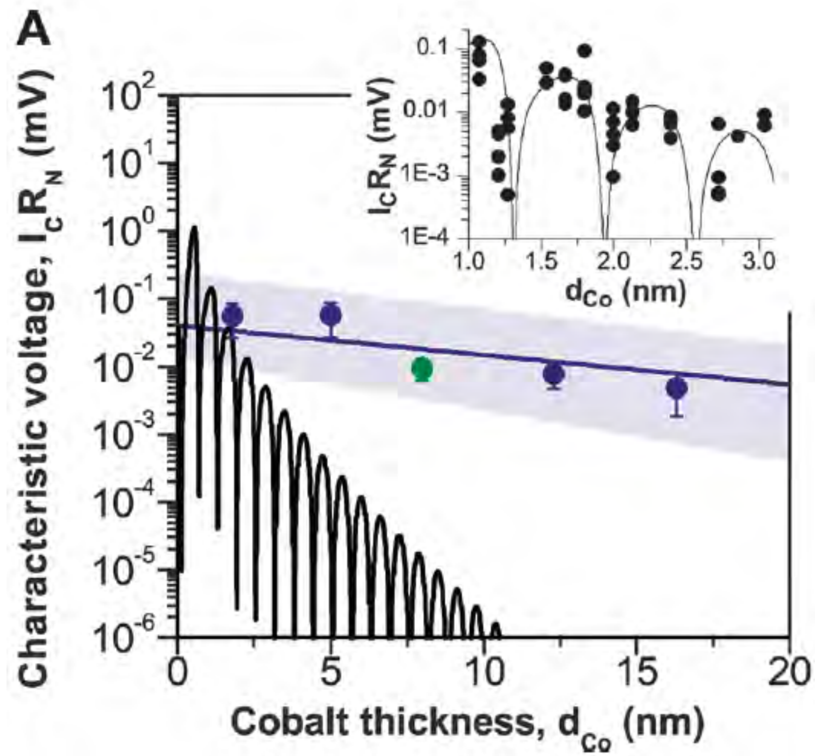
M. S. Anwar et al., Phys. Rev. B **82**, 100501 (2010)

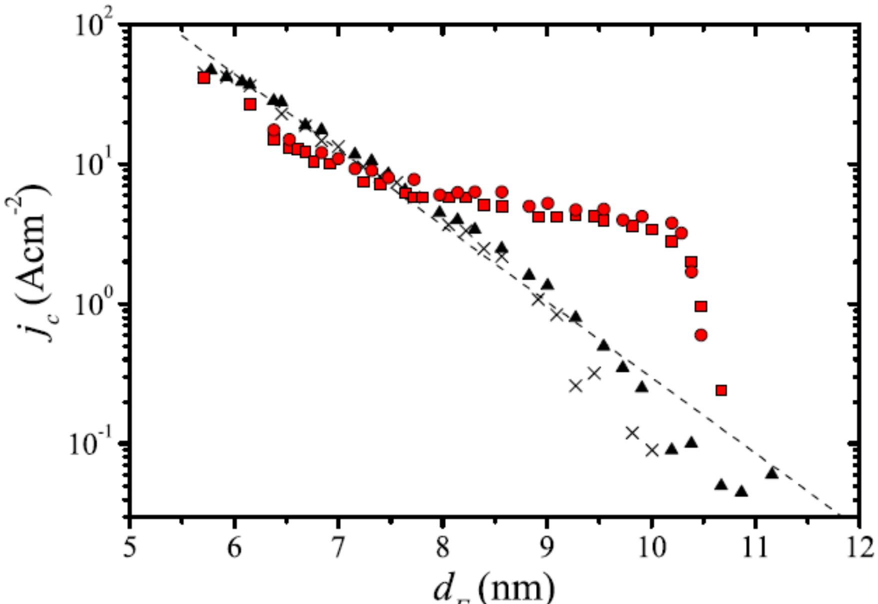


Spin-triplet supercurrents observed by others in 2010

1. Robinson et al., Science 329, 59 (2010)





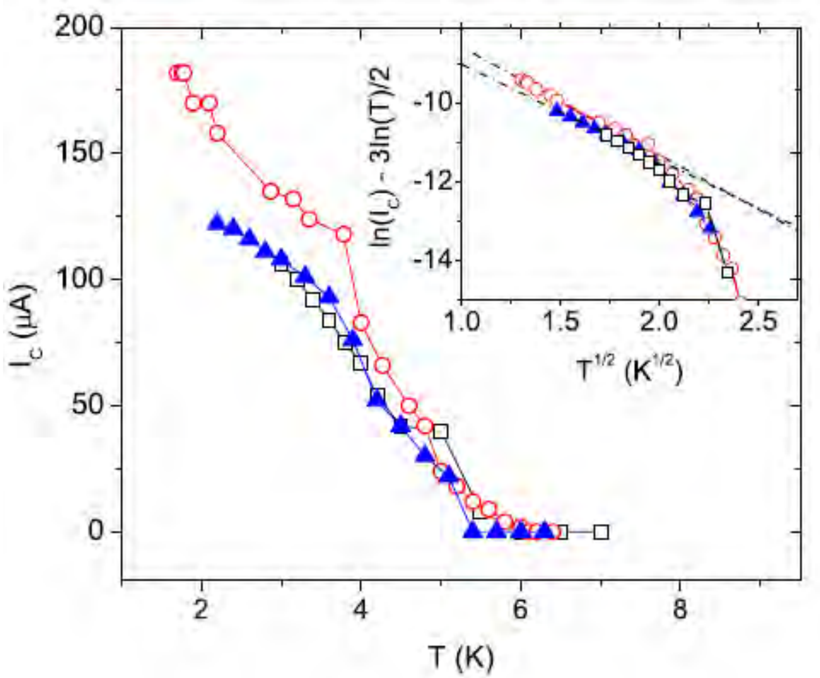


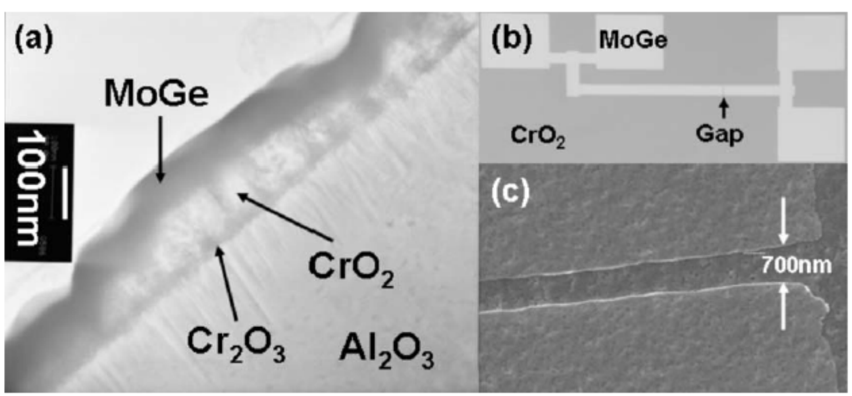
2. Sprungmann et al., PRB 82, 060505 (2010)

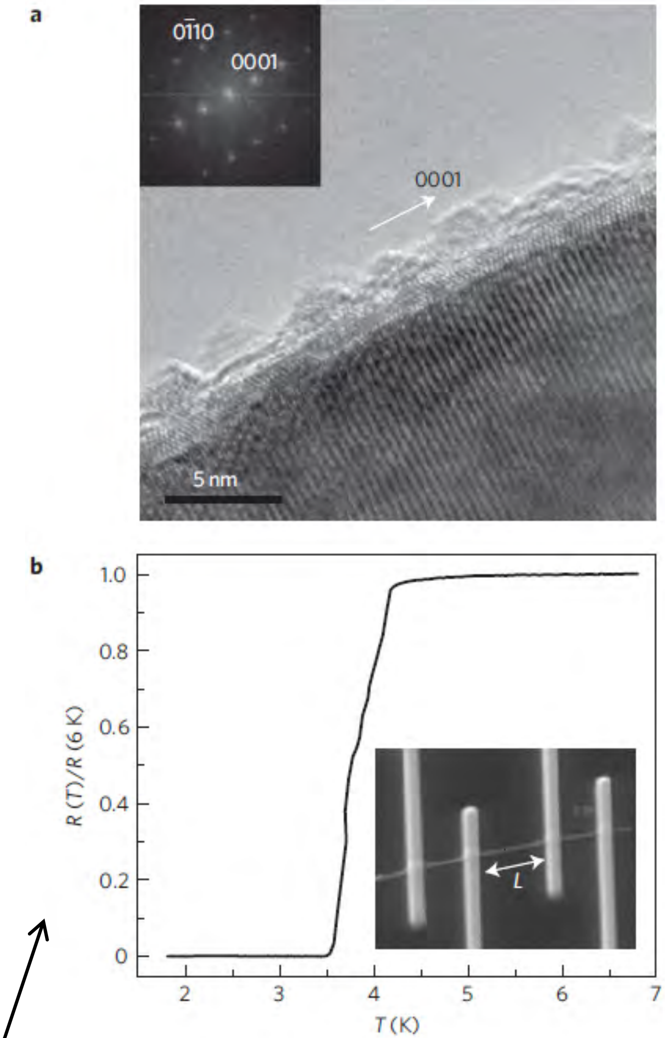
Heusler alloy Cu_2MnAl

Spin-triplet supercurrents observed by others in 2010

3. Anwar et al., PRB 82, 100501 (2010)



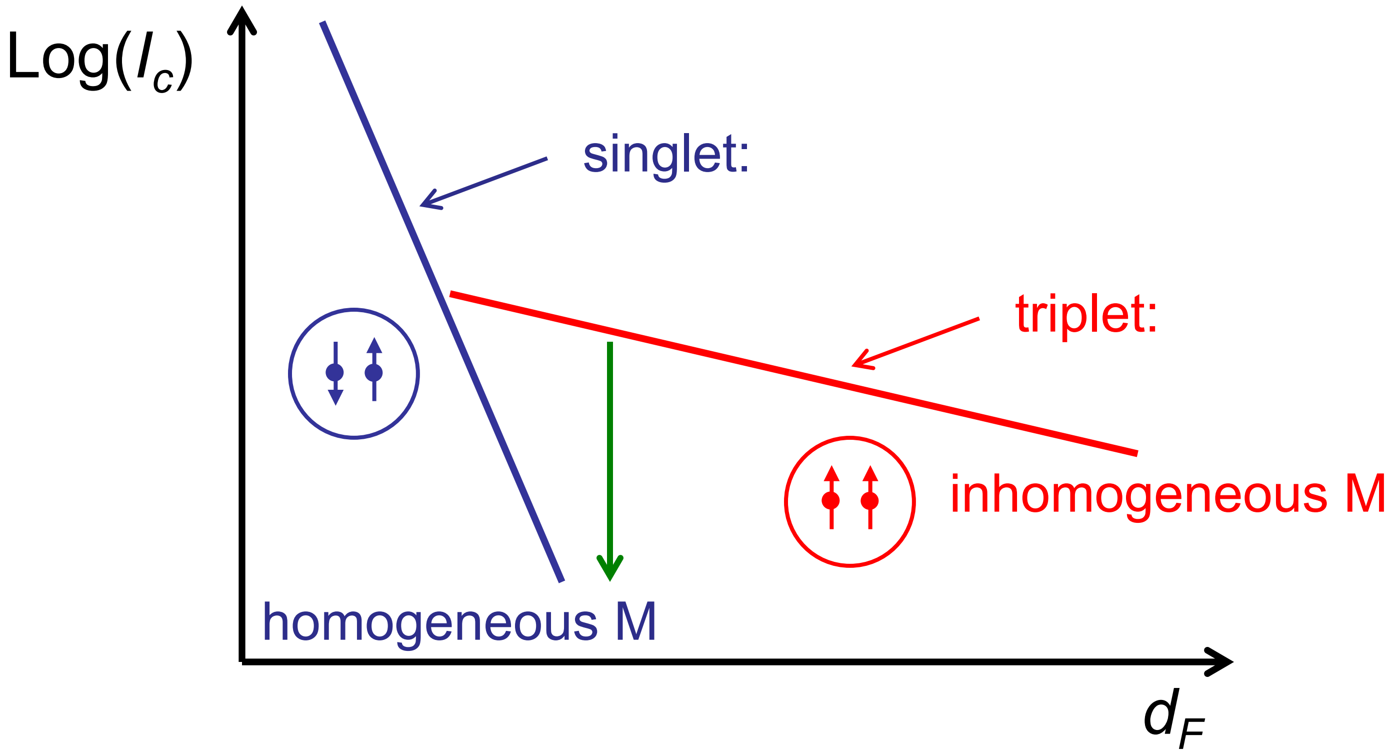


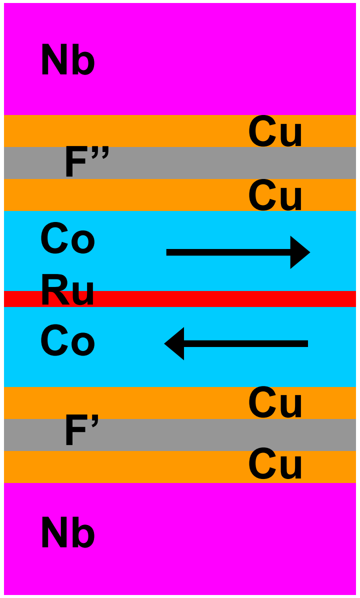


4. Wang et al., Nature Phys. **6**, 389 (2010)

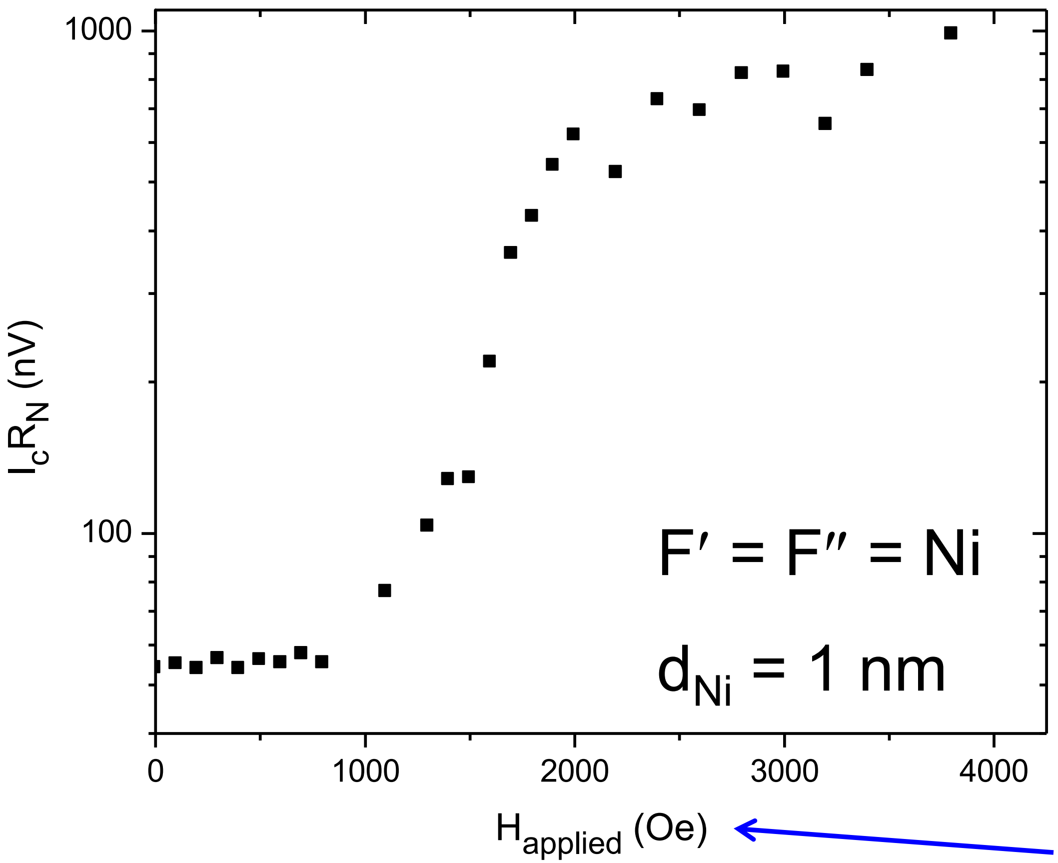
First step toward control of supercurrent: magnetize the samples

(Expect I_c to drop by reducing non-collinear magnetization?)





I_c increases!

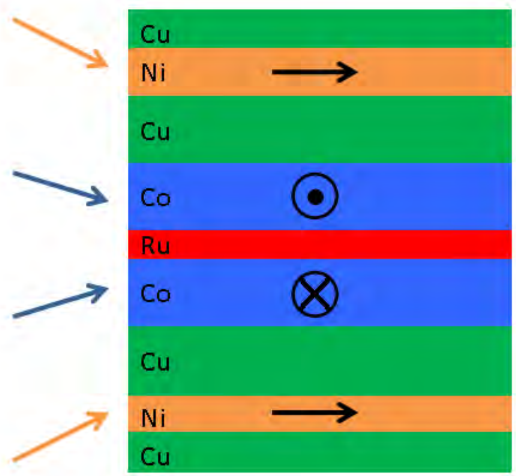


Magnetizing field

Why does I_c increase?

Klose *et al.*, Phys.Rev. Lett. **108**, 127002 (2012)

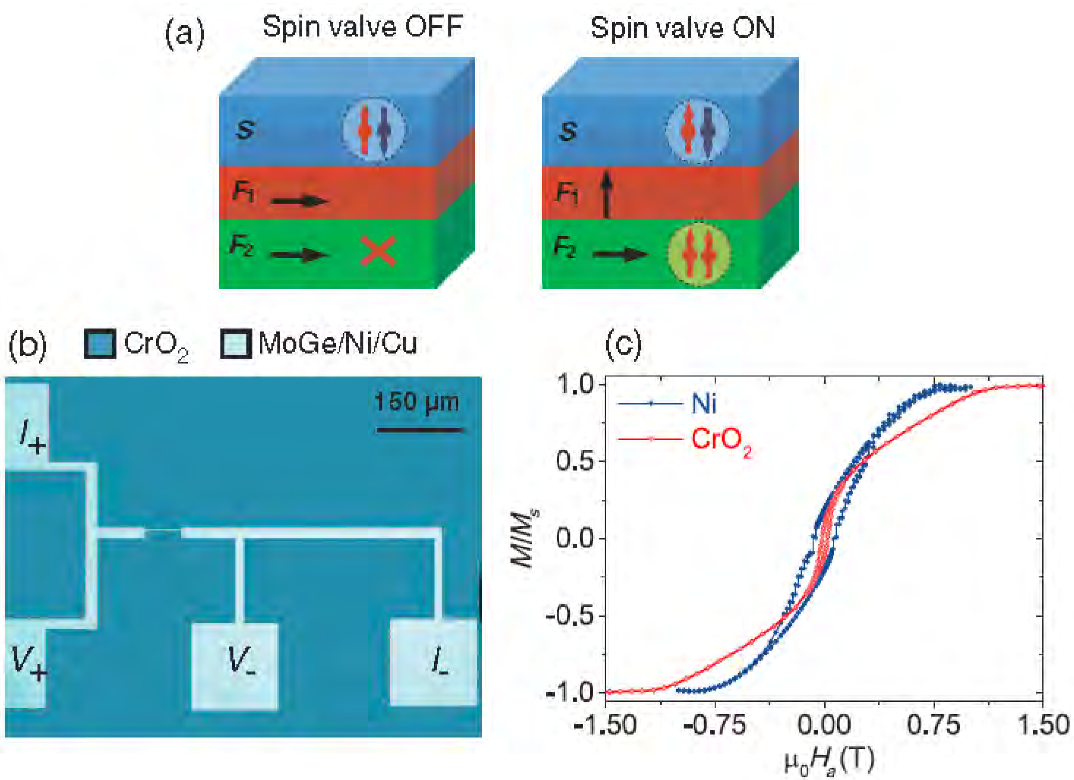
Co/Ru/Co undergoes "spin-flop transition"

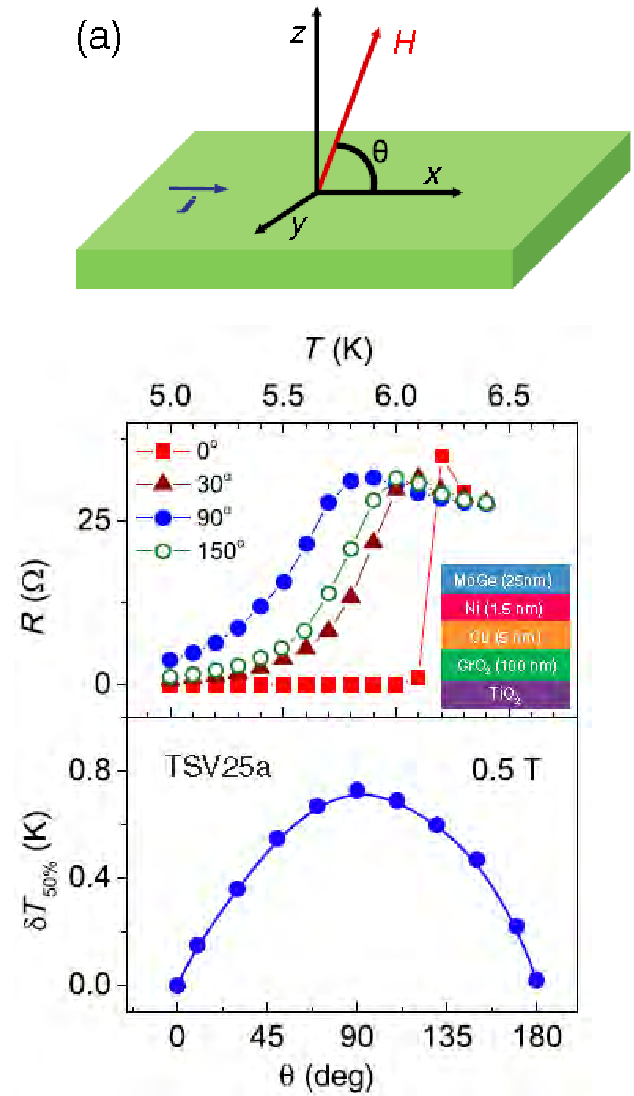


Spin-flop transition optimizes 90° angle between $\mathbf{M}_{Co}$ and $\mathbf{M}_{Ni}$ and aligns Ni magnetizations

Magnetic configuration confirmed at NIST by SEMPA (McMorran & Unguris) and PNR (Ginley & Borchers); see Klose *et al*., Phys.Rev. Lett. **108**, 127002 (2012)

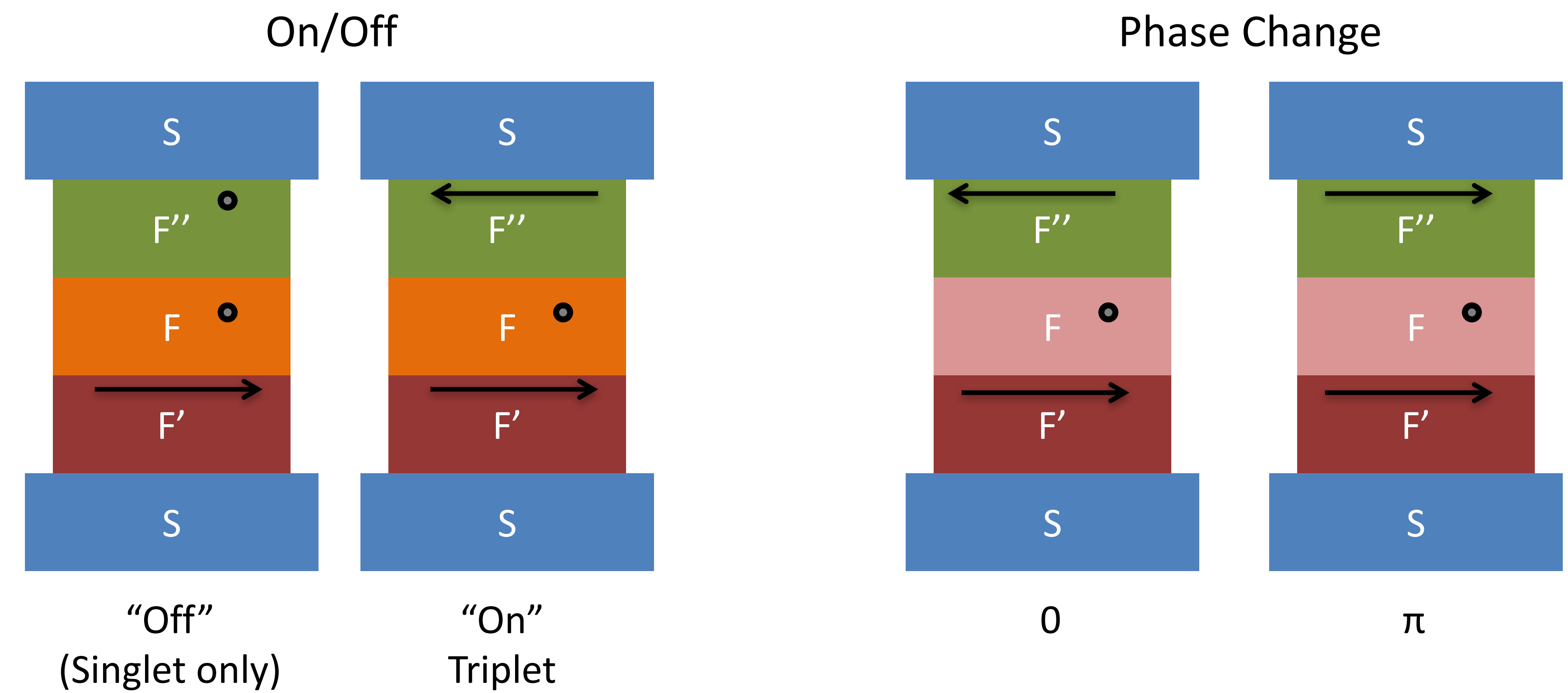
Other probes of spin-triplet correlations: T_c of S/F/F' trilayers





Singh, Voltan, Lahabi, Aarts,
PRX 5, 021019 (2015).

Next step: Control spin-triplet supercurrent by controlling magnetic states

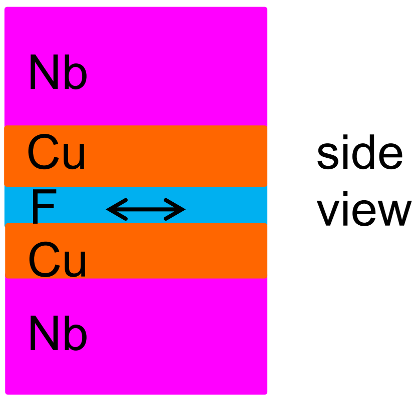


- Rotate **M** by 90°
- Requires only one junction
- Need two external field coils

- Rotate **M** by 180°
- Measure with SQUID (interference)
- Need one external field coil

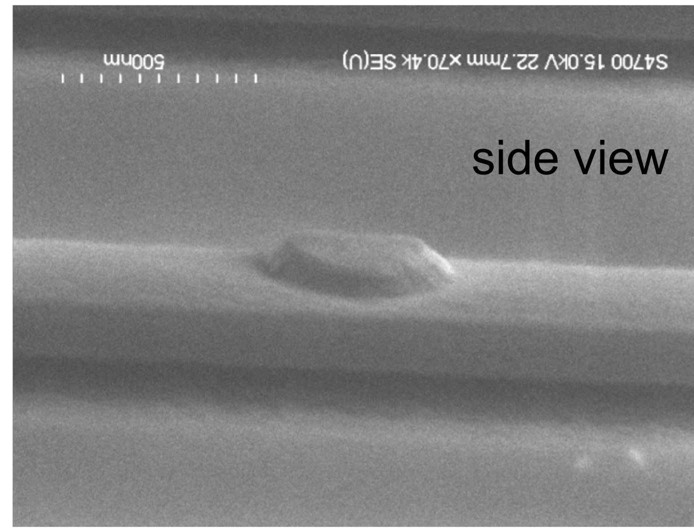
Desire single-domain magnets:

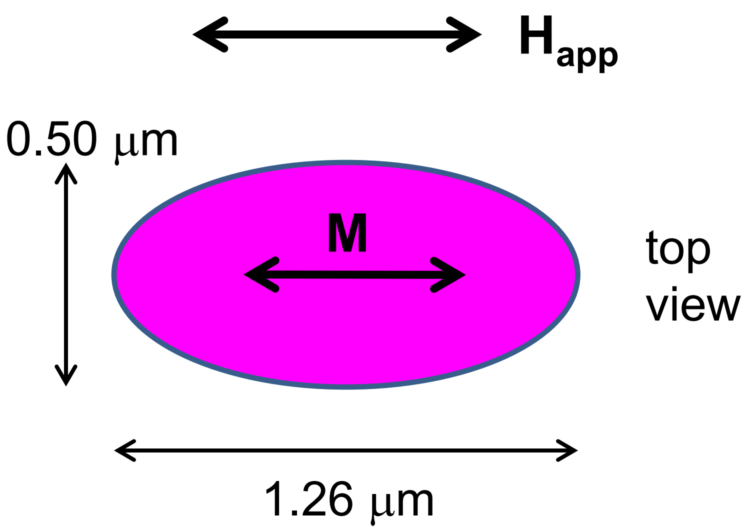
Fabricate submicron S/F/S Josephson junctions

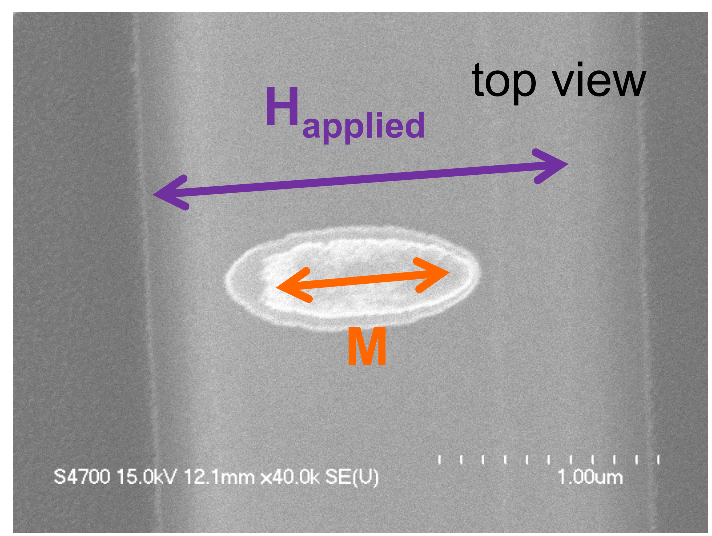


ma-N 2401 negative e-beam resist

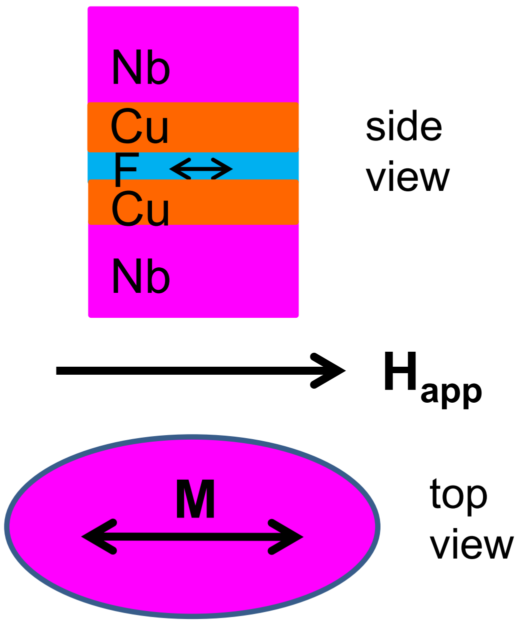
Junctions patterned by Ar ion milling

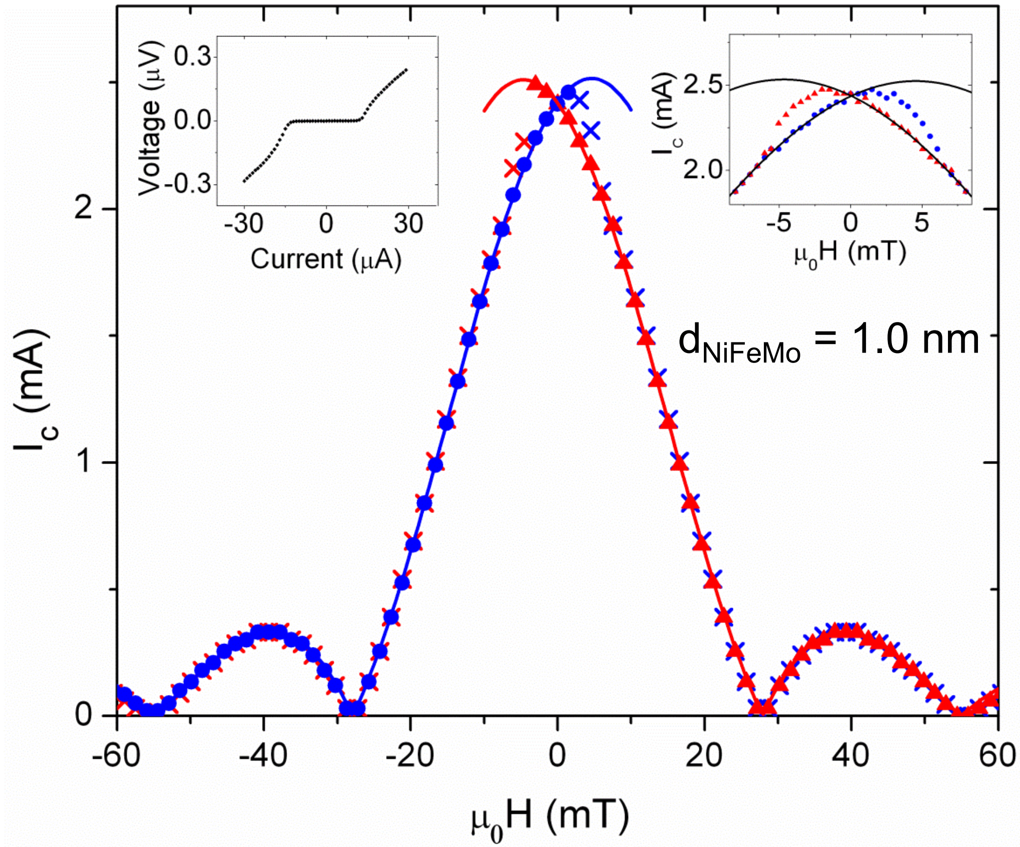






Fraunhofer pattern for junction with F = $Ni_{73}Fe_{21}Mo_6$

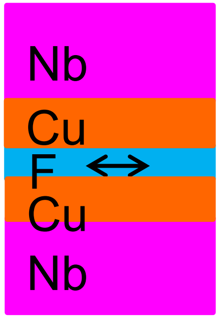




Airy pattern is shifted in opposite direction of **M**

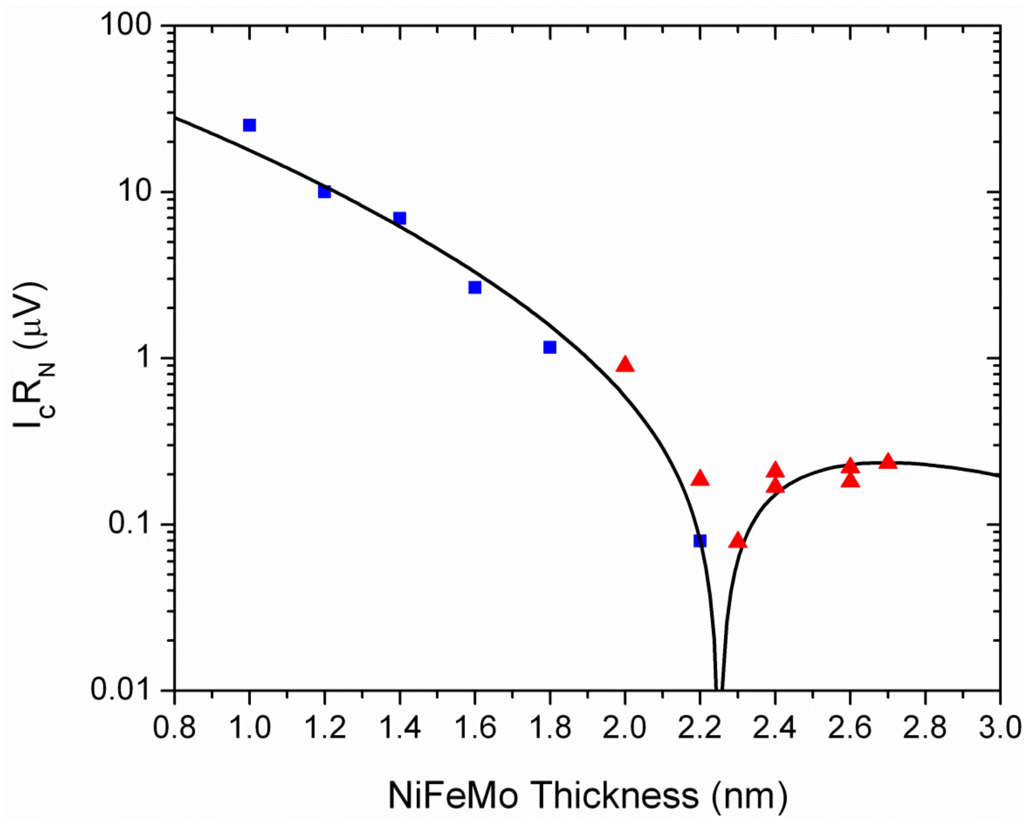
F layer is single-domain in remnant state

Niedzielski, Gingrich, Loloee, Pratt, & Birge, SuST 28, 085012 (2015).



F = NiFeMo

I_c vs NiFeMo thickness



Data fit to:

$$I_c R_N = V_0 * e^{-\frac{d_F}{\xi_{F1}}} * \cos\left(\frac{d_F}{\xi_{F2}} - \phi\right)$$

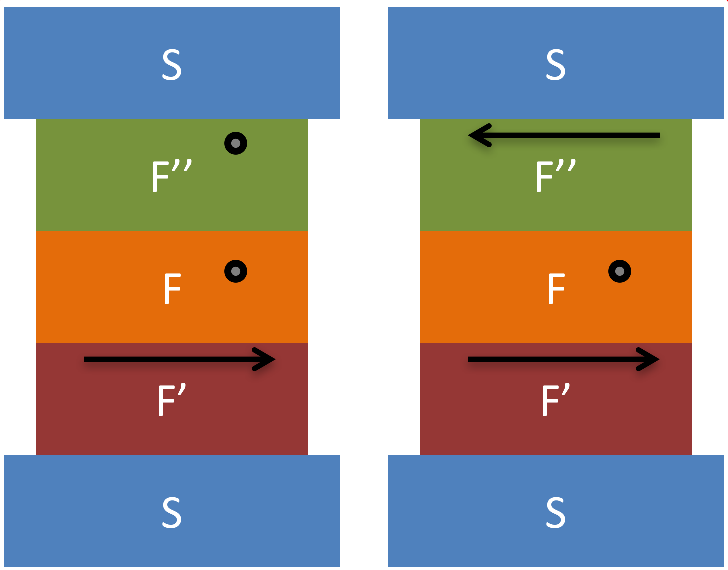
0 - π transition occurs at d_{NiFeMo} = 2.25 nm

I_c decays rapidly with d_{NiFeMo}: ξ_{F1} = 0.48 nm

Niedzielski, Gingrich, Loloee, Pratt, & Birge, SuST 28, 085012 (2015).

Next step: Control spin-triplet supercurrent by controlling magnetic states

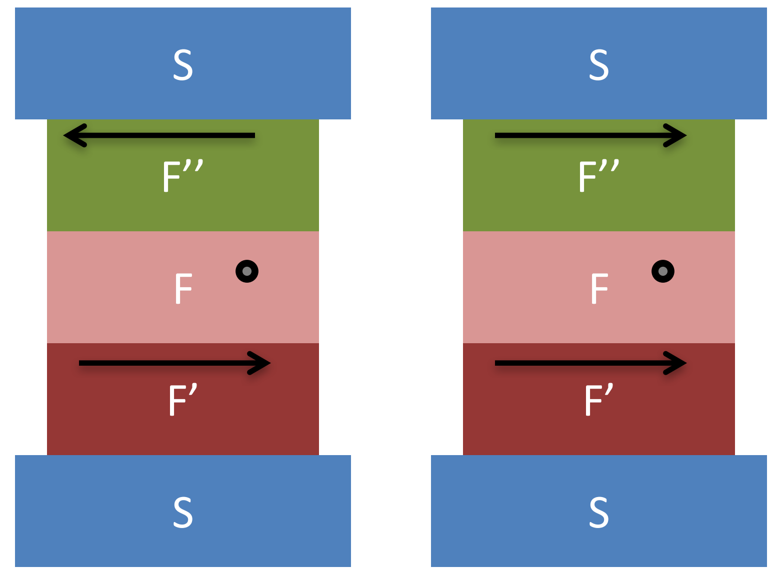
On/Off



“Off”
(Singlet only)

“On”
Triplet

Phase Change



0

π

- Rotate **M** by 90°
- Requires only one junction
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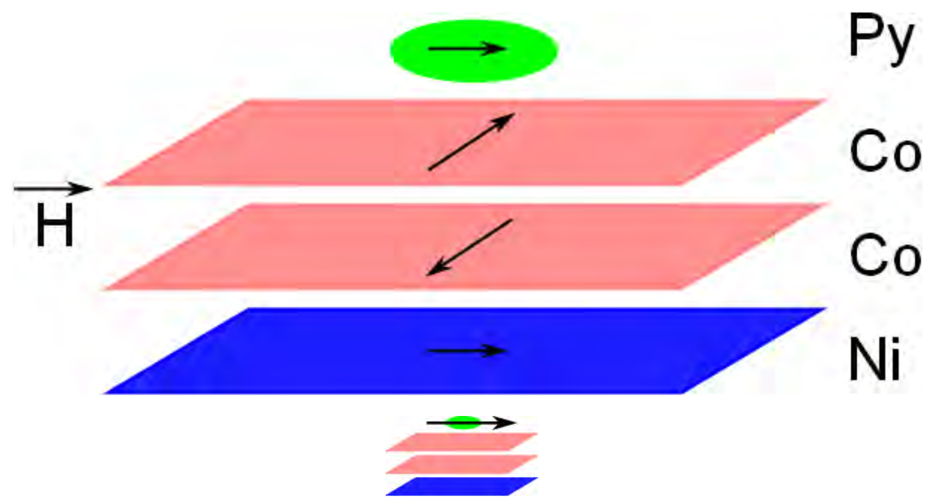
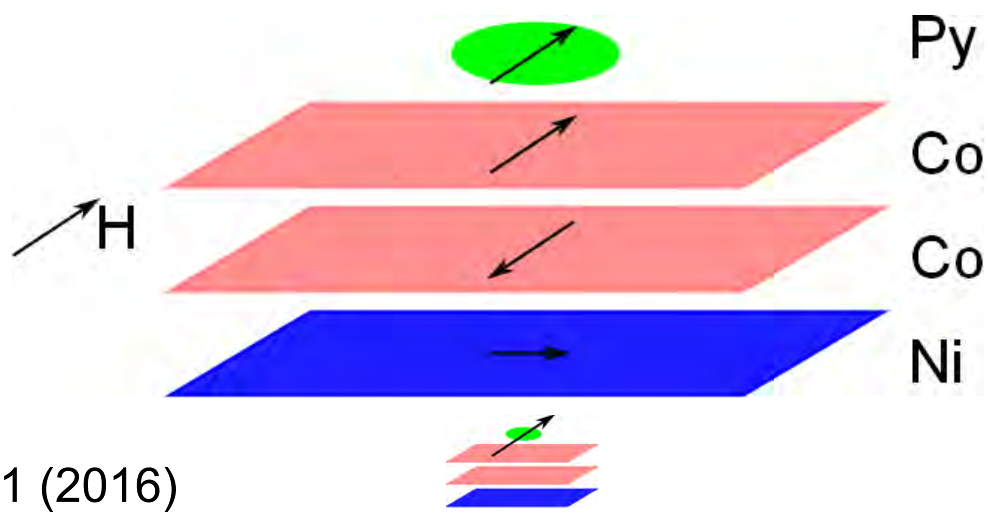
- Rotate **M** by 180°
- Measure with SQUID (interference)
- Need one external field coil

Cartoon Representation ("Py" = NiFe)

- Orthogonal magnetizations – "High" state

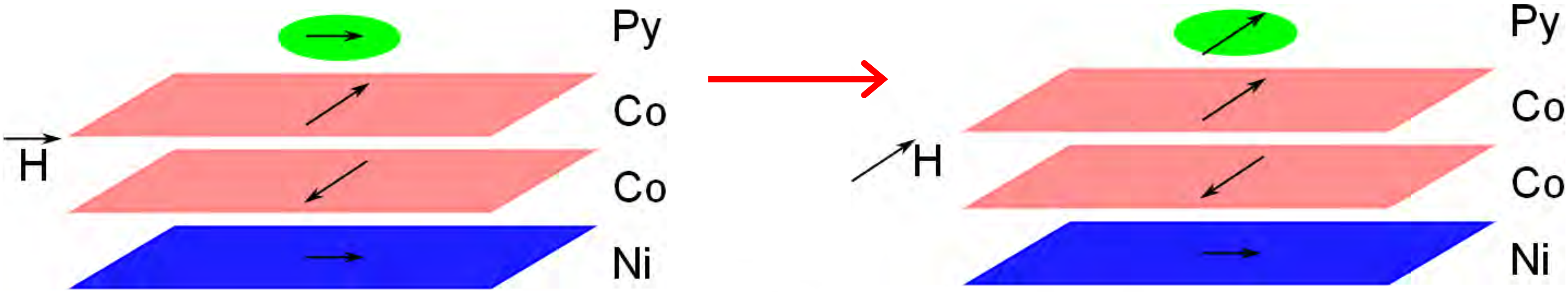


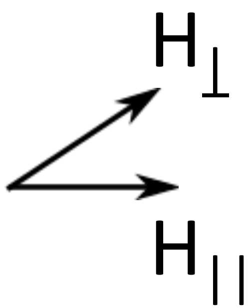
- Non-orthogonal magnetizations – "Low" state

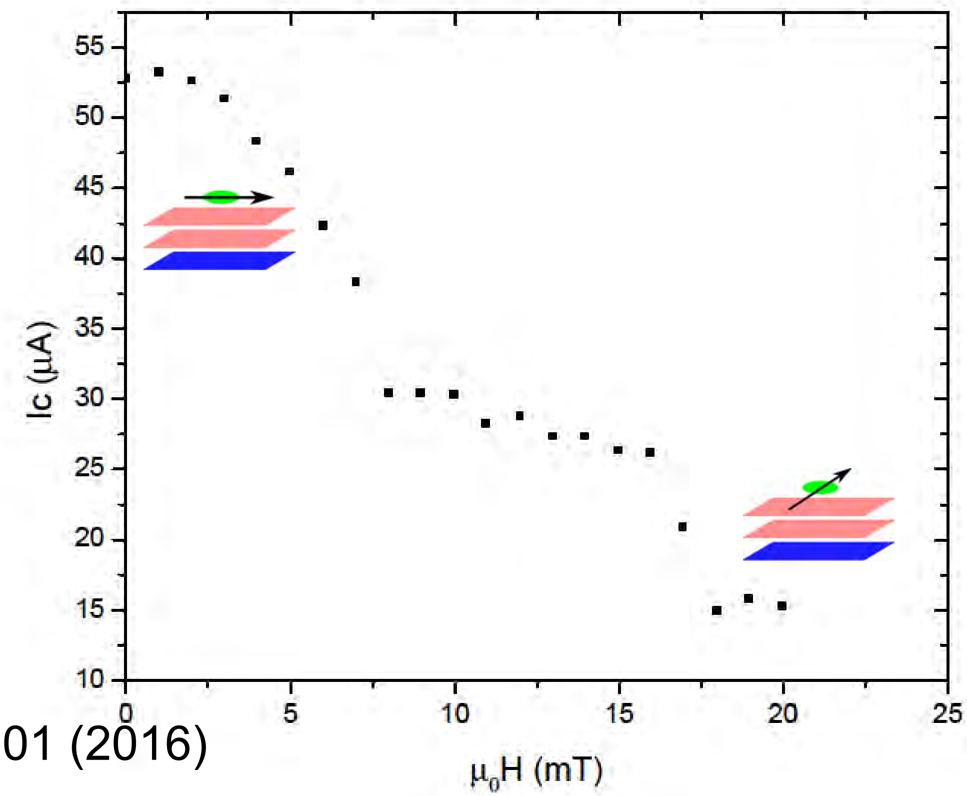


Martinez, Pratt & Birge, PRL 116, 077001 (2016)

Rotate Py Magnetization to turn “off”





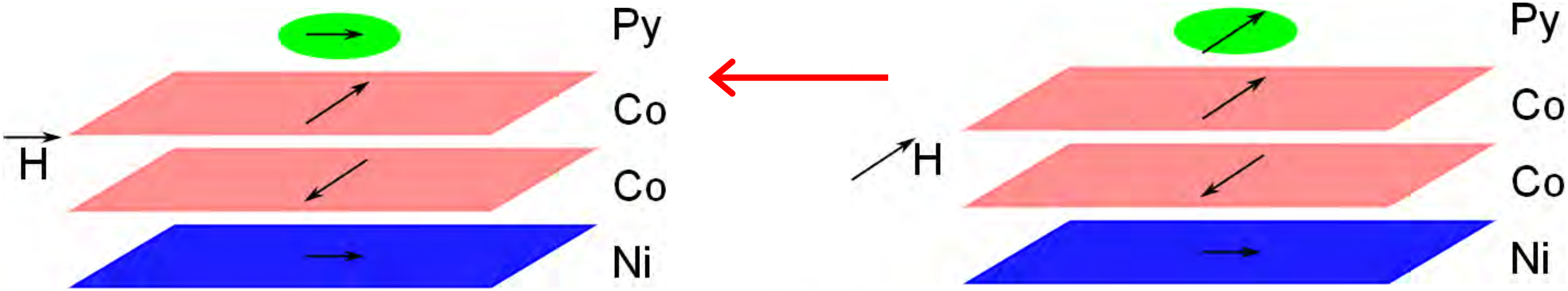


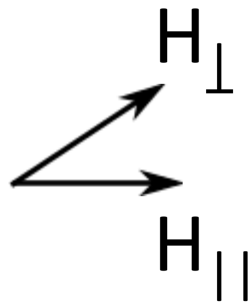
Slowly increase $H_{\perp}$ to rotate M_{Py}

Measure at 0-field

Martinez, Pratt & Birge, PRL 116, 077001 (2016)

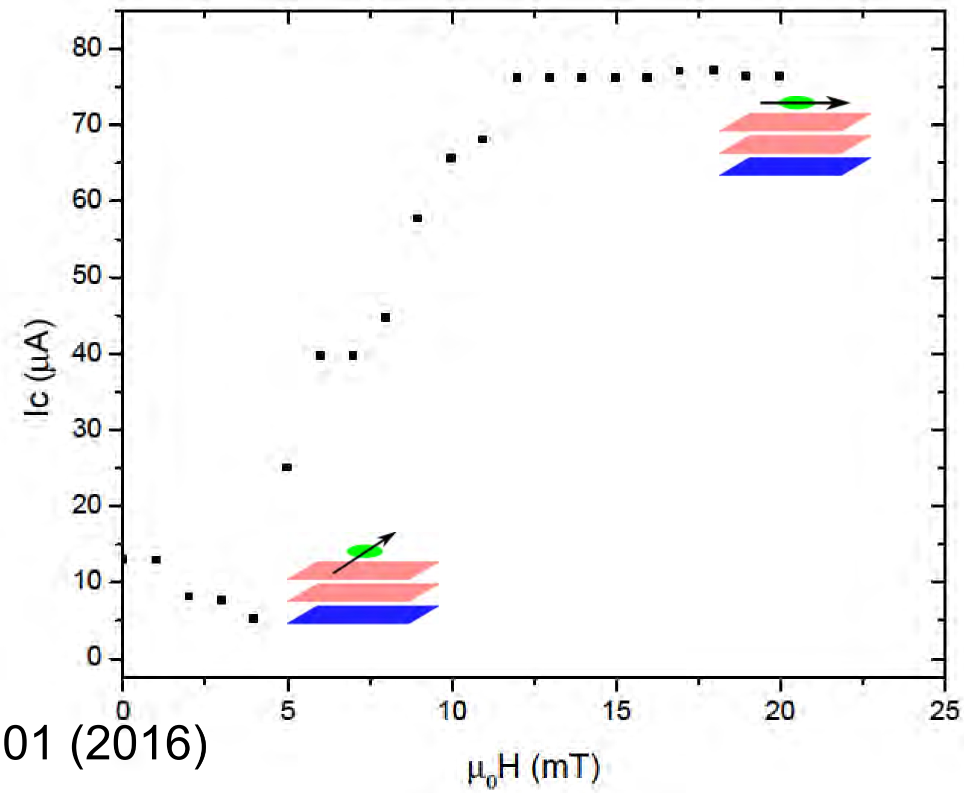
Rotate Py back to turn “on”





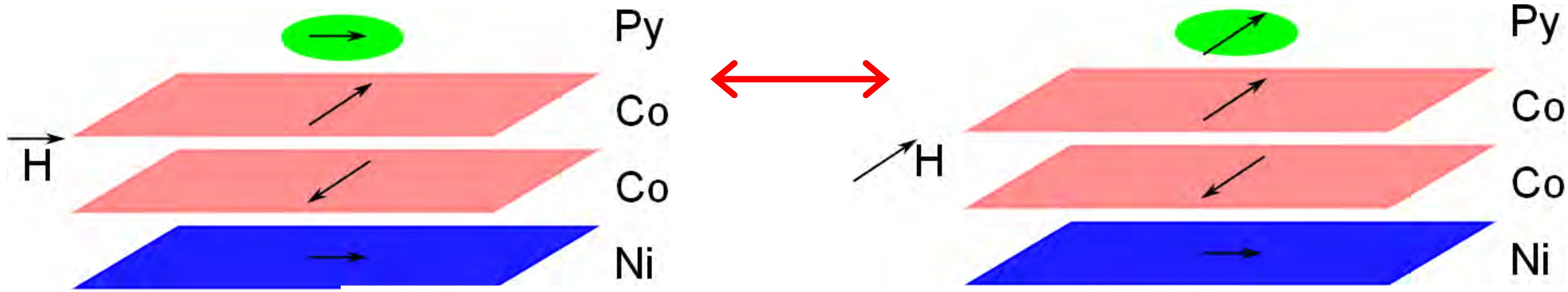
Slowly increase $H_{||}$ to rotate M_{py} back again

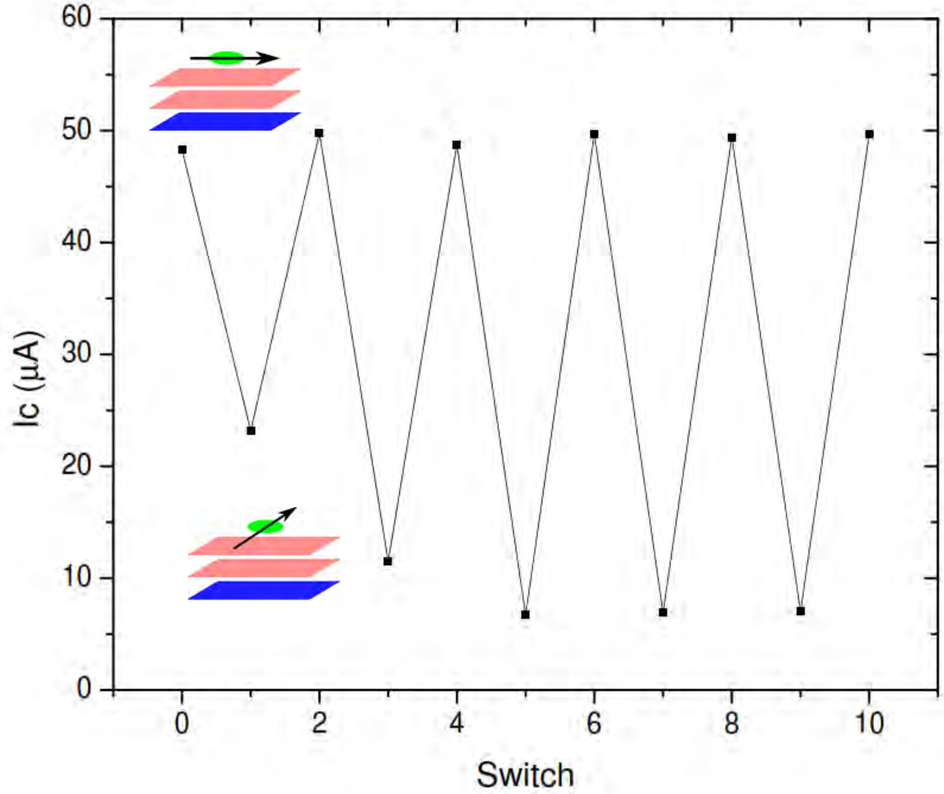
Measure at 0-field



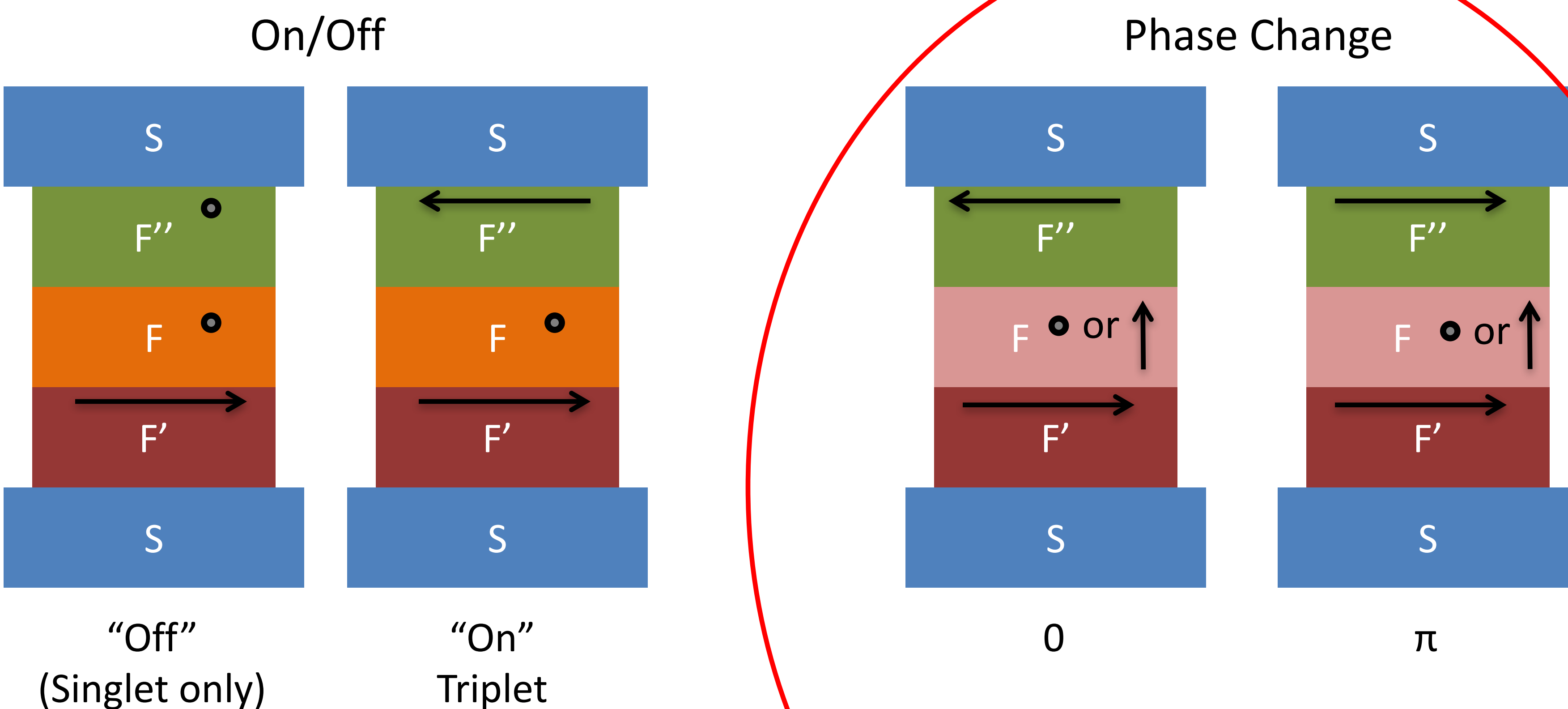
Martinez, Pratt & Birge, PRL 116, 077001 (2016)

Turn on and off repeatedly





Next step: Control spin-triplet supercurrent by controlling magnetic states



- Rotate **M** by 90°
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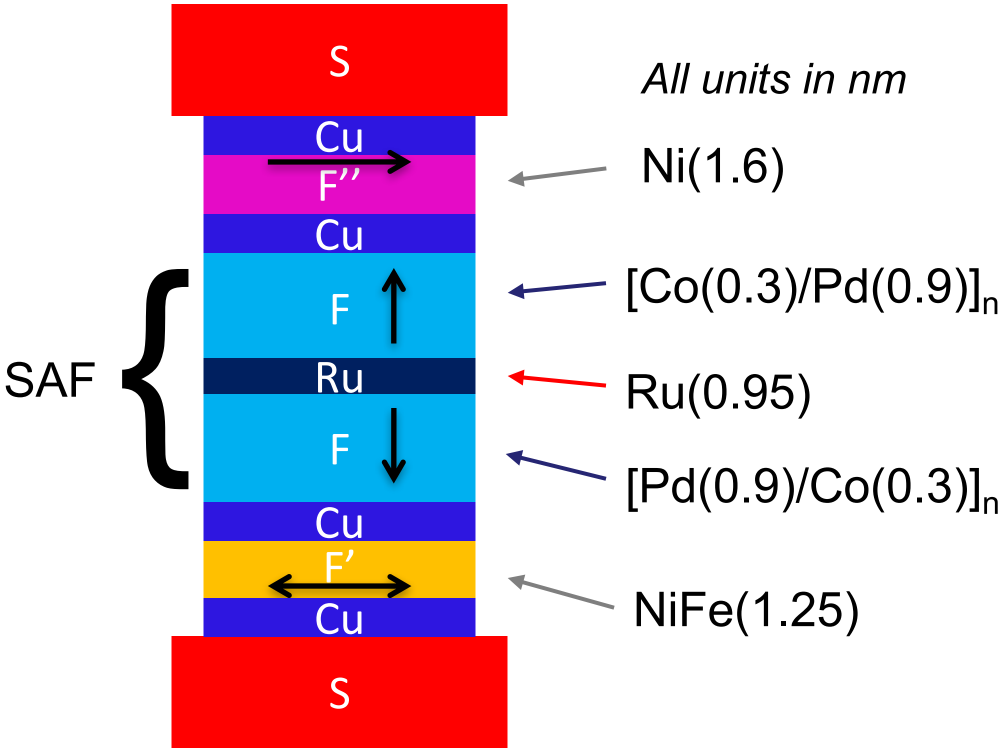
Controllable 0-π switching with spin-triplet supercurrent



[Co/Pd] multilayers have strong perpendicular magnetic anisotropy.

Central Ru layer creates a synthetic antiferromagnet, to reduce stray field at domain walls

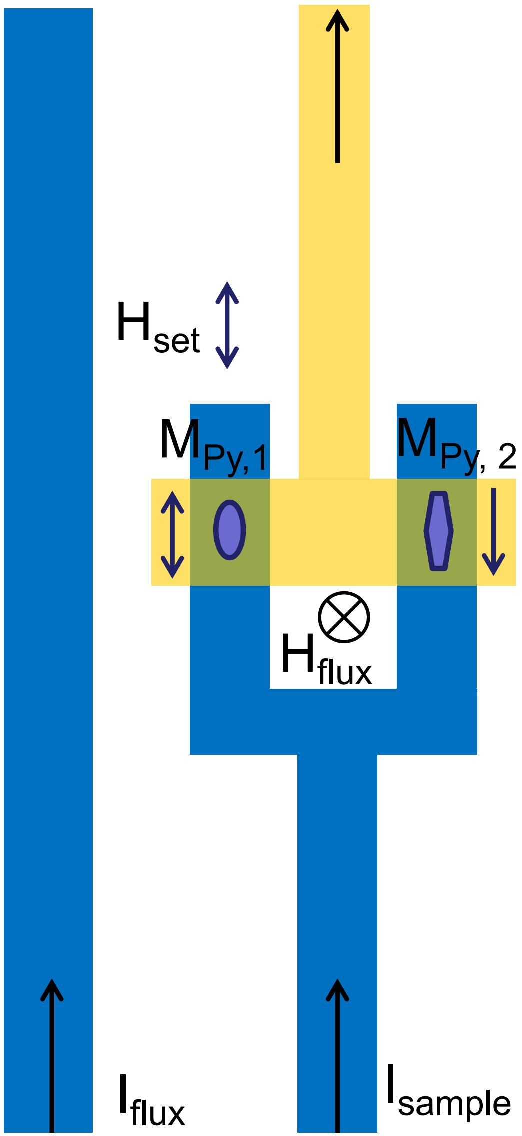
Ni(1.6) has fixed in-plane magnetization direction

NiFe(1.25) is in-plane free layer

Glick *et al.* (in preparation)

SQUID design & measurement protocol

- SQUIDs have one ellipse with aspect ratio = 2 and one hex bit with aspect ratio = 3, both have area = 0.5 μm^2.
- Measurement protocol:
  - Initialize bits at -1500 Oe, then remove trapped flux
  - Apply set fields H_{set} = +5 Oe, +10 Oe, +15 Oe, etc. until magnetic state switches
  - After each set field, measure $I_c(I_{flux})$
  - Apply set fields H_{set} = -5 Oe, -10 Oe, etc. to return to initial state
  - All measurements are performed at H_{set} = 0.
  - Keep $|H_{set}|$ small enough so that only the elliptical bit switches (minor loop).



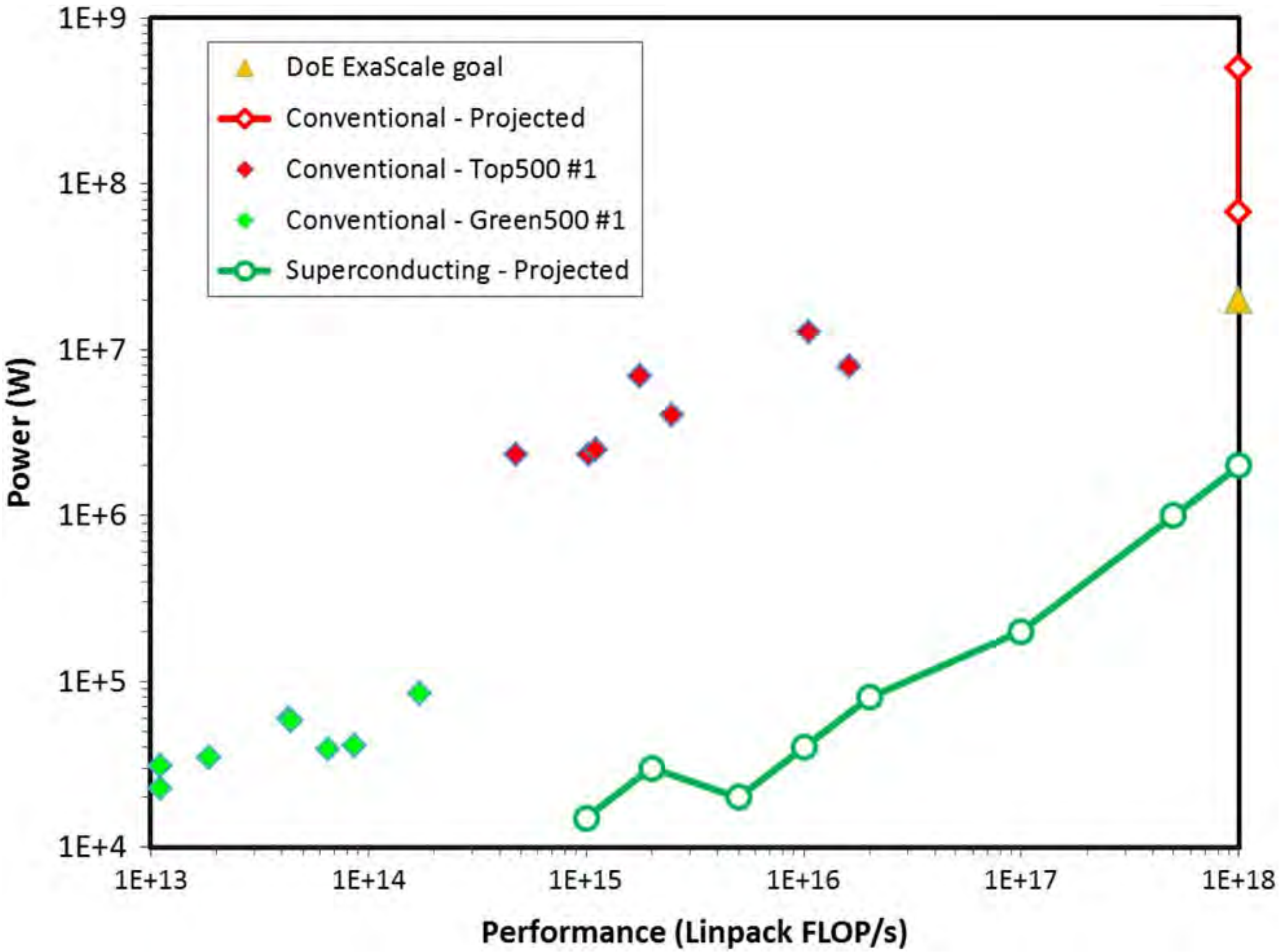
Controllable 0-π switching with spin-triplet supercurrent

Data will be re-inserted after publication (Glick *et al.* in preparation)

This work is not just of academic interest!

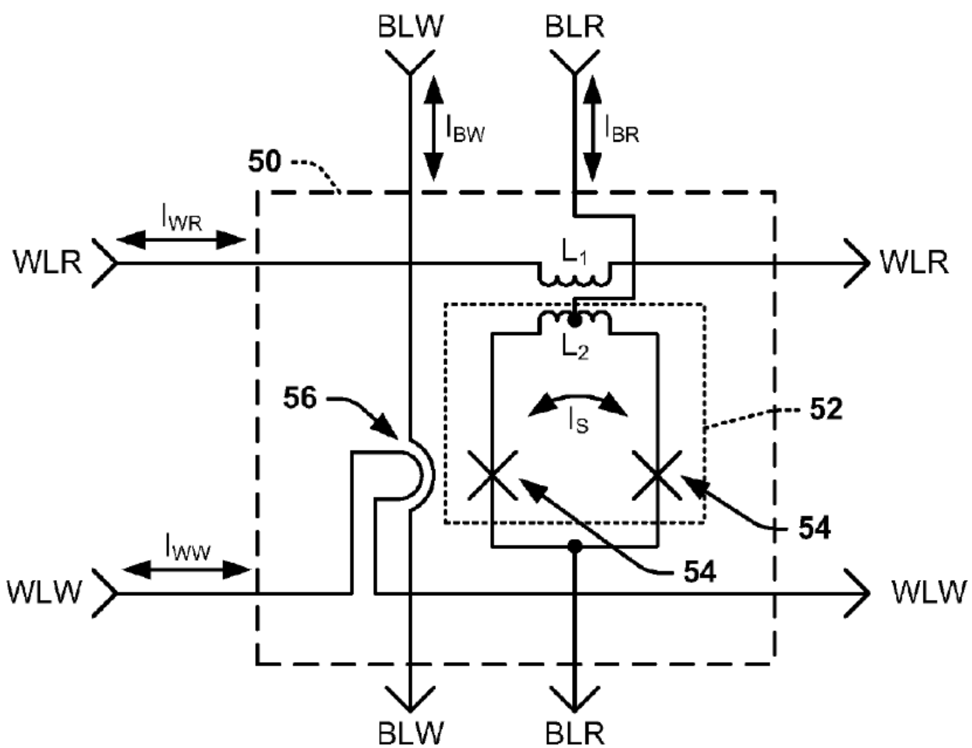
Energy-Efficient Superconducting Computing—Power Budgets and Requirements

D. Scott Holmes, *Senior Member, IEEE*, Andrew L. Ripple, and Marc A. Manheimer



A superconducting computer needs memory…

Josephson Magnetic Random Access Memory (JMRAM)
Anna Y. Herr & Quentin P. Herr, US Patent 8,270,209 (2012)
Northrop Grumman Corporation



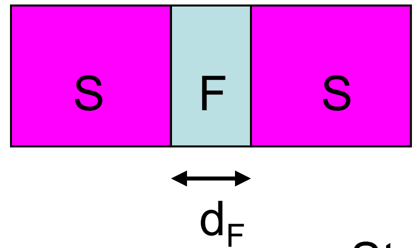
Memory cell is SQUID loop

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

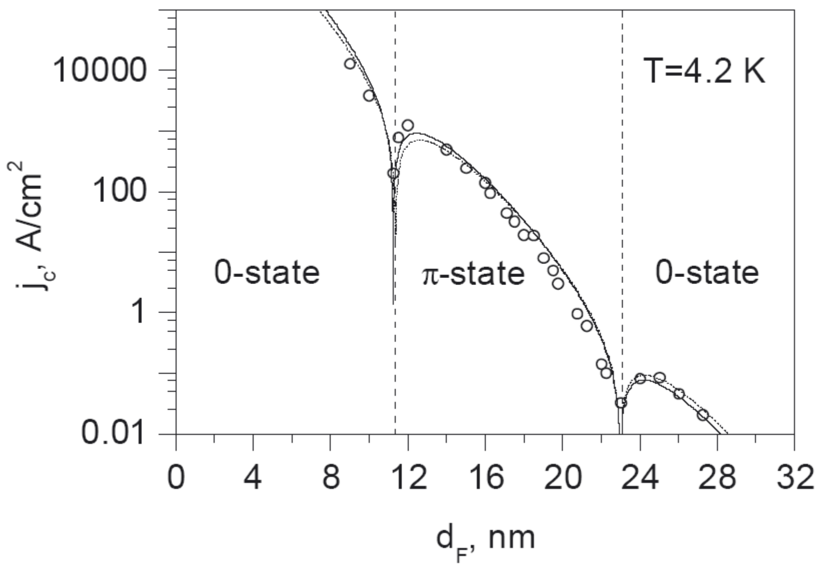
Magnetic states are written using standard MRAM techniques

Recall: I_c of S/F/S Josephson junction oscillates with d_F

0-state: $I_s = I_c \sin(\phi)$
π-state: $I_s = I_c \sin(\phi+\pi)$

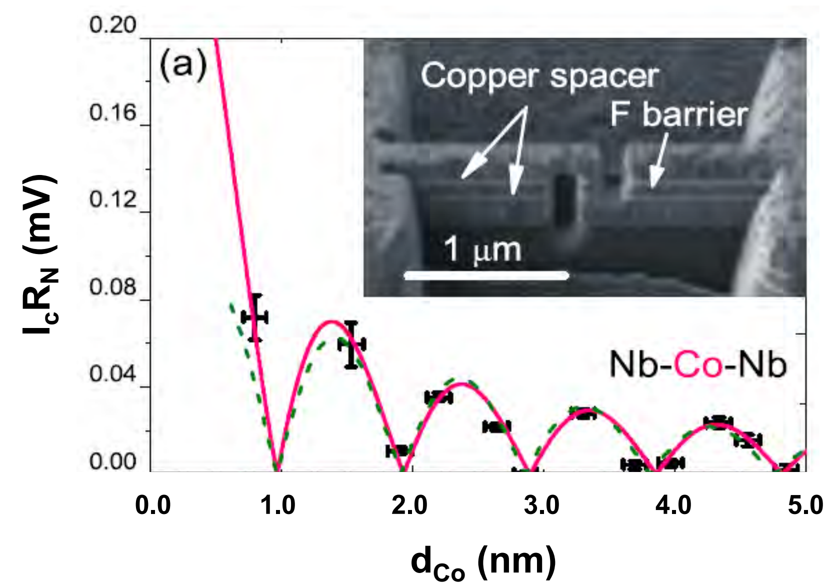


Weak F: $Cu_{48}Ni_{52}$ alloy



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

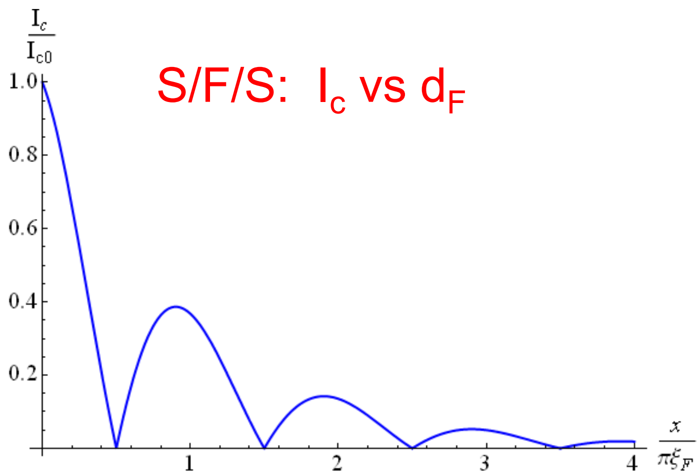
Strong F: Co



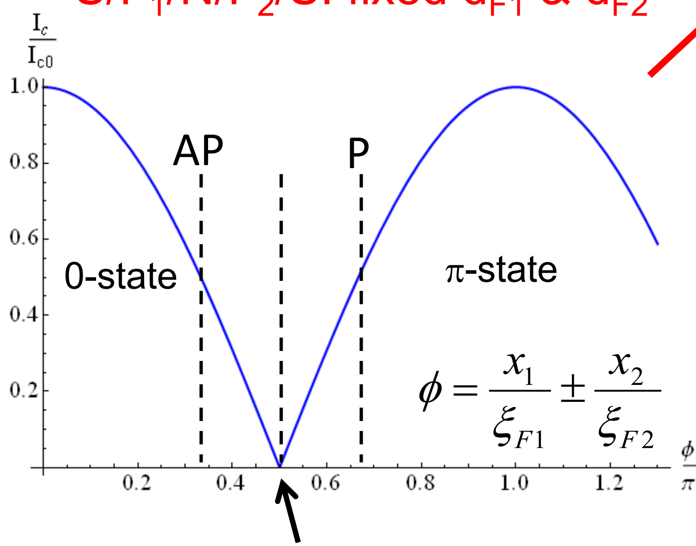
Robinson, Piano, Burnell, Bell, Blamire,
PRL **97**, 177003 (2005)

JMRAM memory cell junction

S/F/S: I_c vs d_F

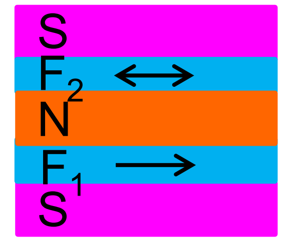


S/F_1/N/F_2/S: fixed d_{F1} & d_{F2}



ϕ for fixed F_1 layer

Spin-valve memory element



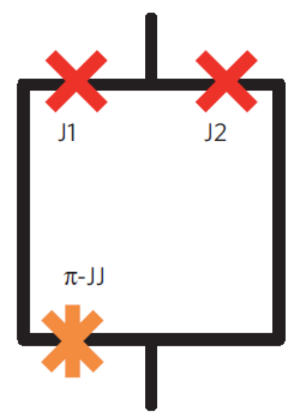
P state: Cooper pair phase shifts add $\Rightarrow$ π state

AP state: Cooper pair phase shifts subtract $\Rightarrow$ 0 state

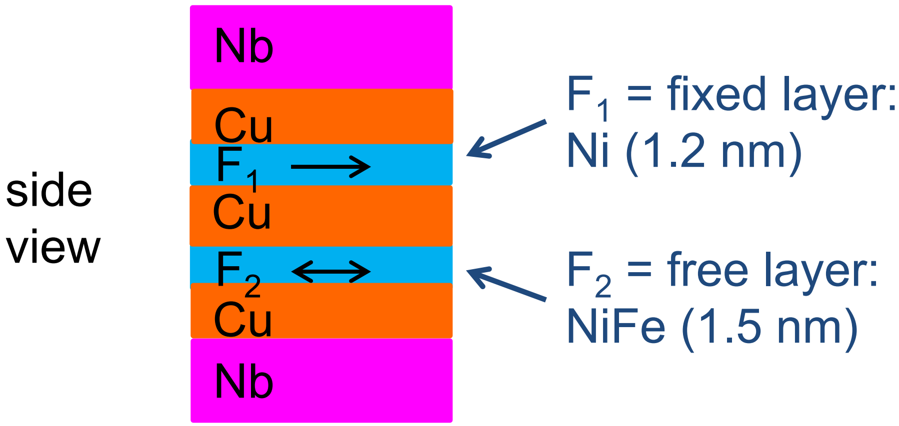
Control phase rather than amplitude:

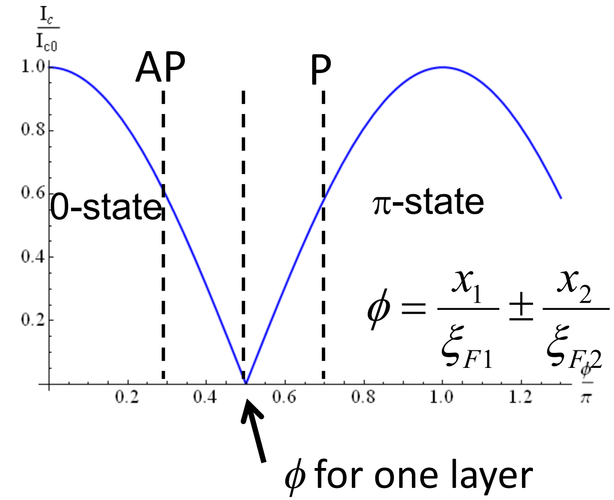
JJ acts as passive phase shifter; no need for large $I_c R_N$

Example: Feofanov et al., Nature Phys. 6, 593 (2010)

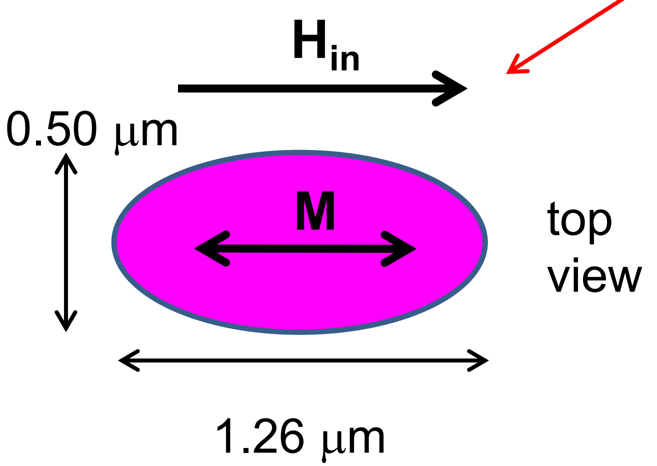


Demonstration of 0 - π switching of $S/F_1/N/F_2/S$ spin-valve Josephson junctions

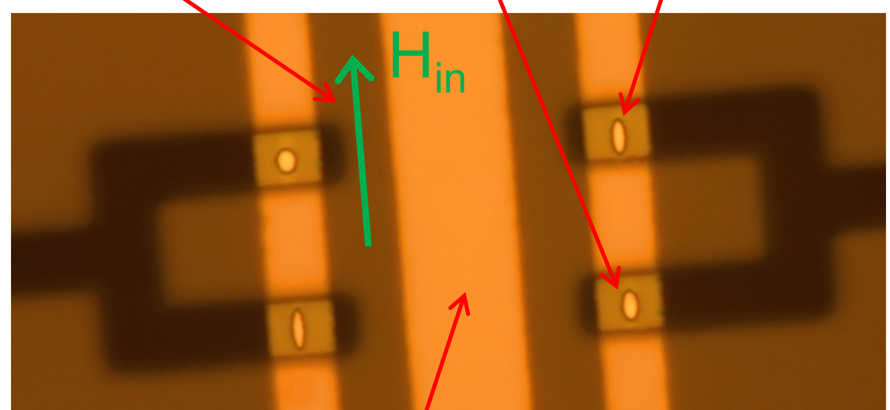




Switch magnetization with in-plane field

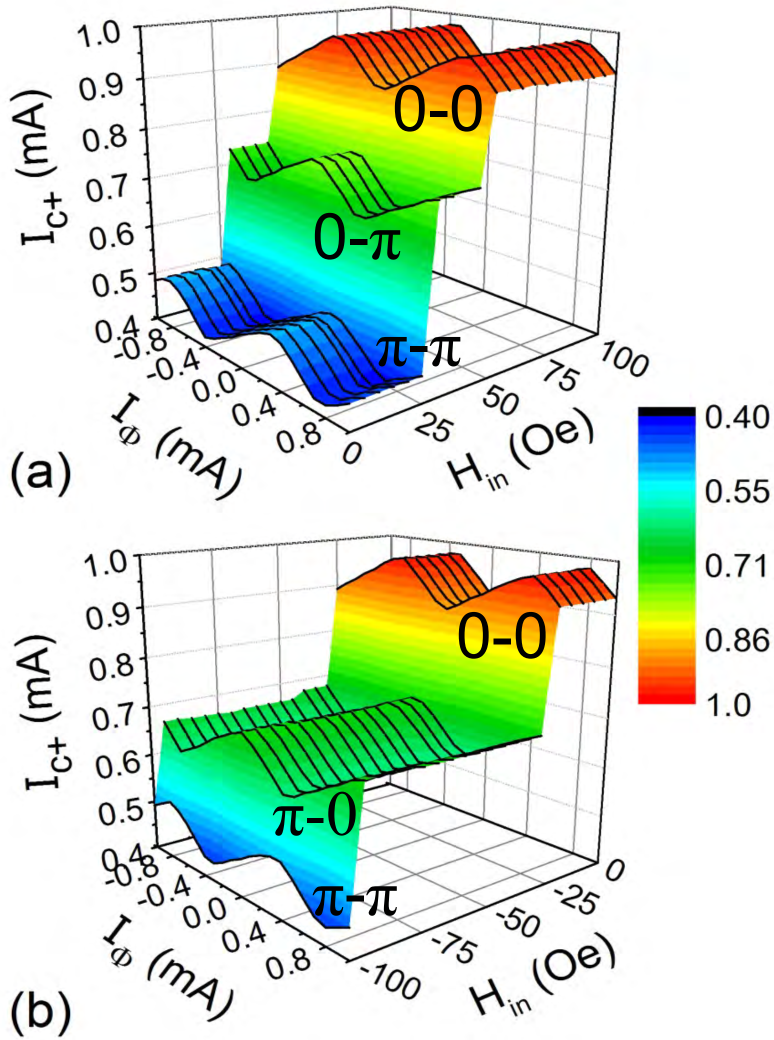


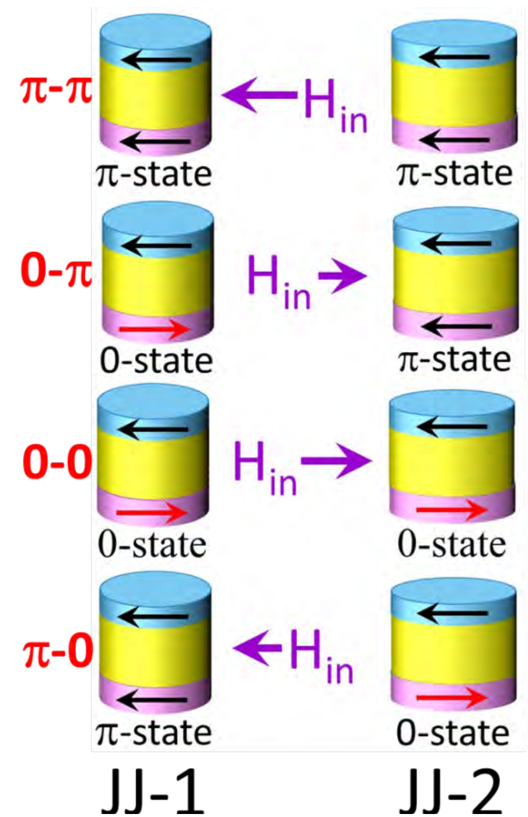
JJ's with different aspect ratios switch at different applied magnetic fields



On-chip current line couples magnetic flux into SQUIDs

Major loop data show switching of both JJs

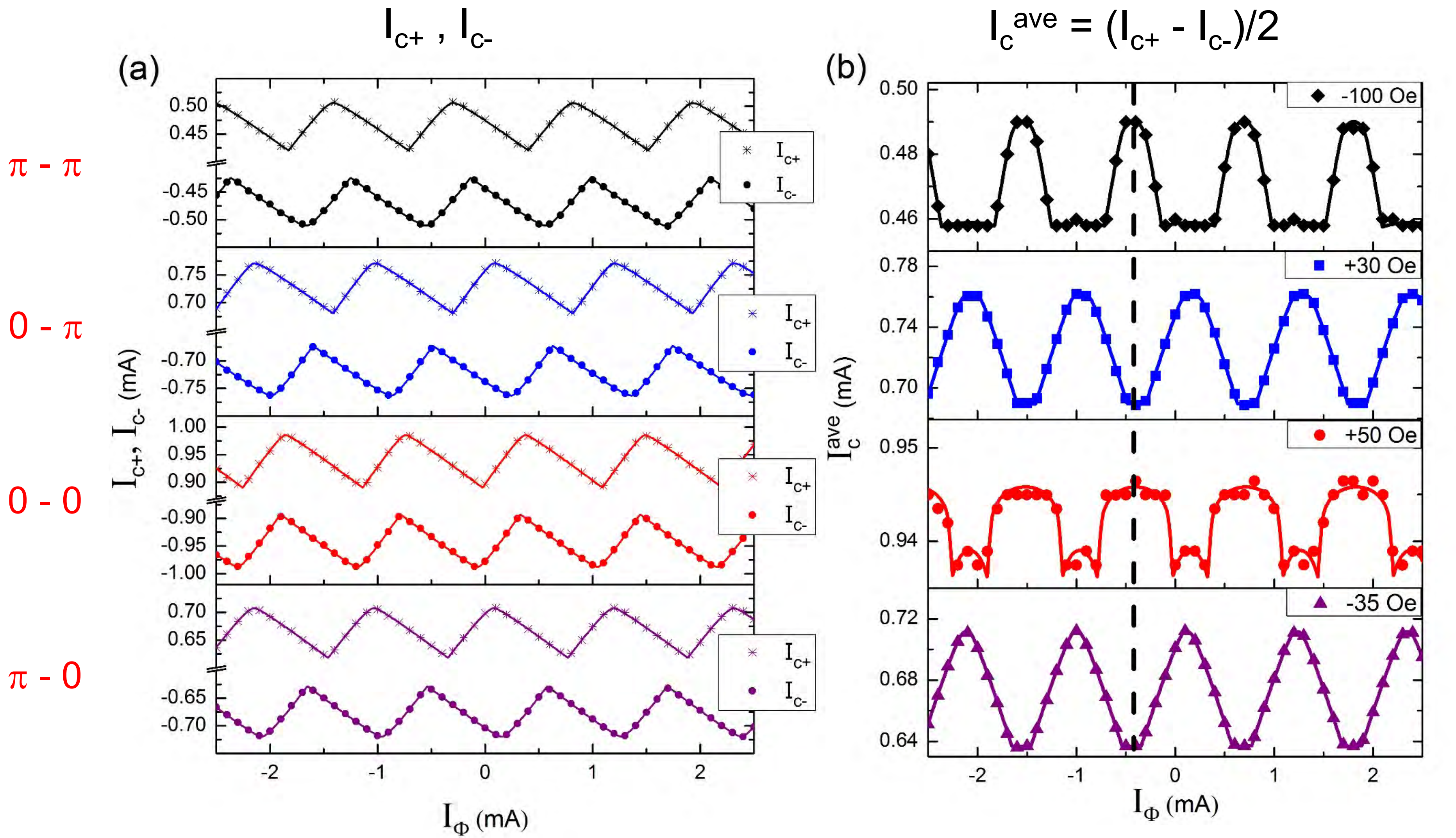




Switching Fields: +30 Oe, +50 Oe, -35 Oe, -100 Oe

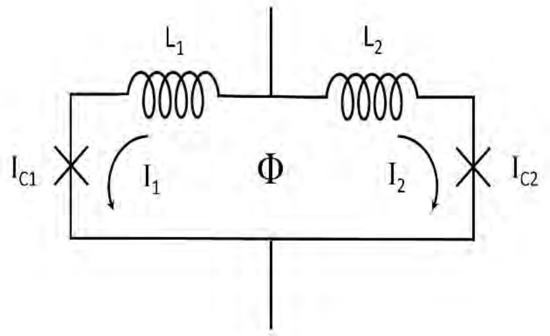
Gingrich, Niedzielski, Glick, *et al.*, Nat. Phys. **12**, 564 (2016)

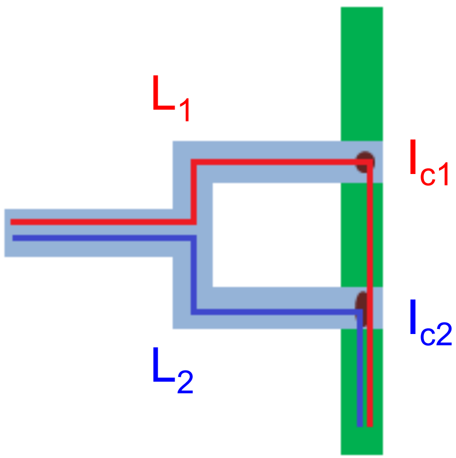
Data cuts for the four magnetic states

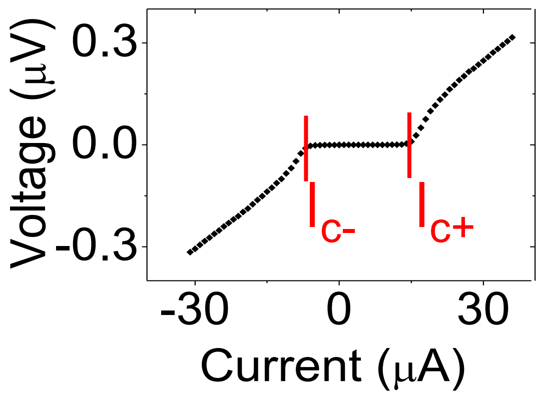


Gingrich, Niedzielski, Glick, *et al.*, Nat. Phys. **12**, 564 (2016)

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



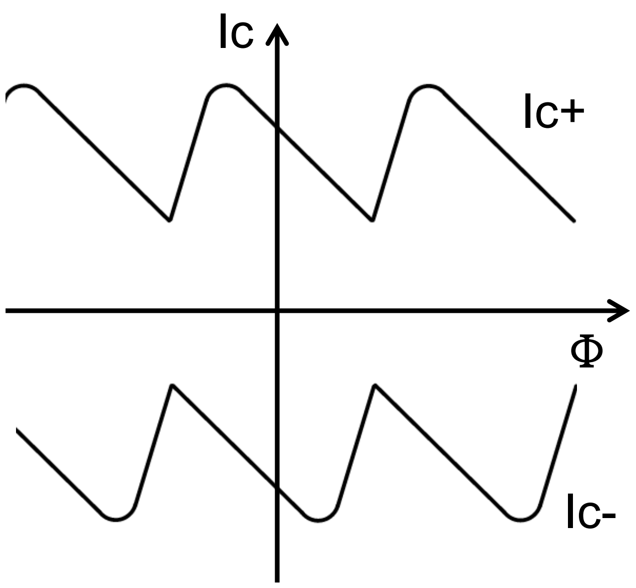




$I_c^+(\Phi)$ and $I_c^-(\Phi)$ oscillations are asymmetric when $L_1 \neq L_2$ & $I_{c1} \neq I_{c2}$

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-}

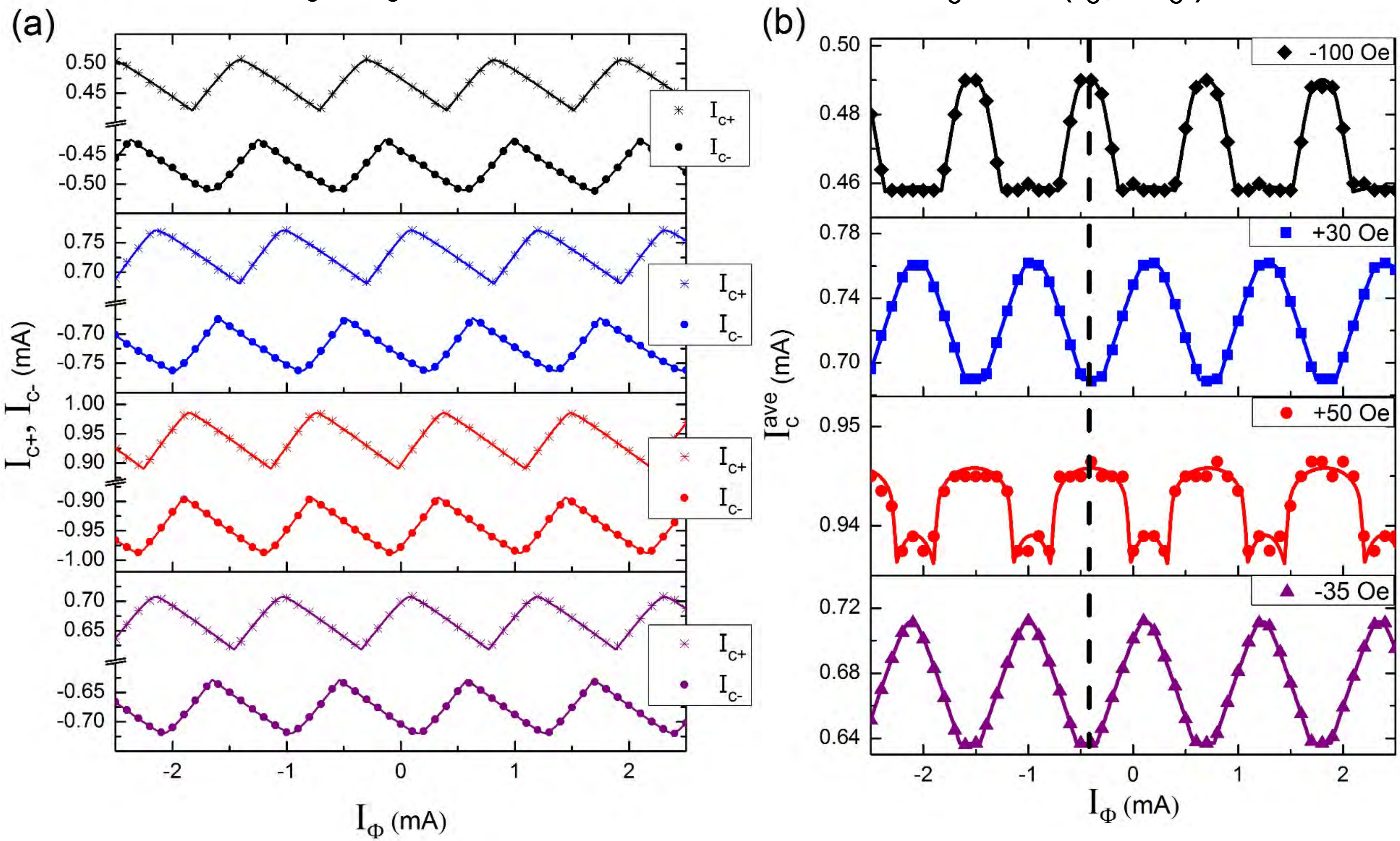
$I_c^{ave} = (I_{c+} - I_{c-})/2$

π - π

0 - π

0 - 0

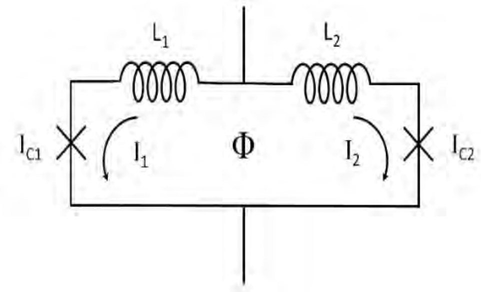
π - 0



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)

What needs to be done

- Memory
  - 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
- Make the rest of the computer!

Summary

- Experimental observation of long-range supercurrent in S/F/S Josephson junctions:
  - requires three F layers
  - can control either supercurrent amplitude or junction ground-state phase by changing the magnetic state
- Magnetic Josephson junctions may be useful for ultra-low-power cryogenic memory
  - phase control achieved with a spin-valve JJ