Superconducting diodes, surface barriers, and critical state of atomically thin superconductors

Filippo Gaggioli
V. B. G

ETH Zurich, Switzerland

Superconducting diodes, surface barriers, and critical state of atomically thin superconductors

Motivated by

K. S. Novoselov

NUS, Singapore

Superconducting diodes

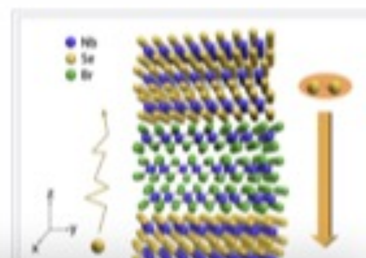
Josephson diode

Contents [hide]

A **Josephson diode** is an electronic device that superconducts electrical current in one direction and is resistive in the other direction. The device is a Josephson junction exhibiting a superconducting diode effect (SDE). It is an example of a quantum material Josephson junction (QMJJ), where the weak link in the junction is a quantum material.

Josephson diodes can be subdivided into two categories, those requiring an external (magnetic) field and those not requiring an external magnetic field; the so-called "field-free" Josephson diodes. In 2021, the field-free Josephson diode was realized.[1]

History [edit]



The Josephson diode is named after British physicist Brian David Josephson, who predicted the Josephson effect; and the resistive diode, since it has a similar function. In 2007 a "Josephson diode" was proposed with a design that was similar to conventional p-n junctions in semiconductor, but utilizing hole and electron doped superconductors.[2] This is different from the "Josephson fluxonic diode" that was introduced before the 2000s.[3][4][5][6] It is also different

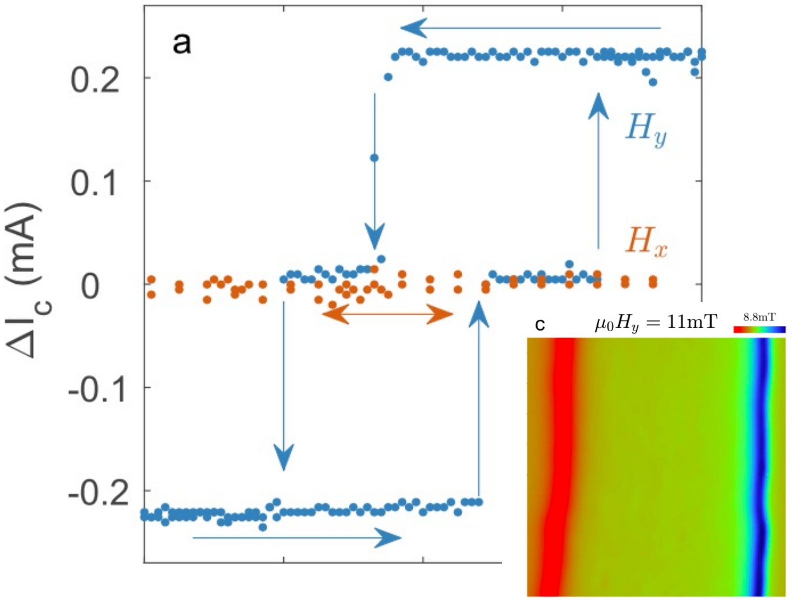
Motivation

Direct observation of a superconducting vortex diode

Received: 15 October 2022

Accepted: 9 March 2023

Alon Gutfreund[1], Hisakazu Matsuki[2], Vadim Plastovets[3], Avia Noah[1], Laura Gorzawski[2], Nofar Fridman[1], Guang Yang[2], Alexander Buzdin[3], Oded Millo[1], Jason W. A. Robinson[2] & Yonathan Anahory[1]



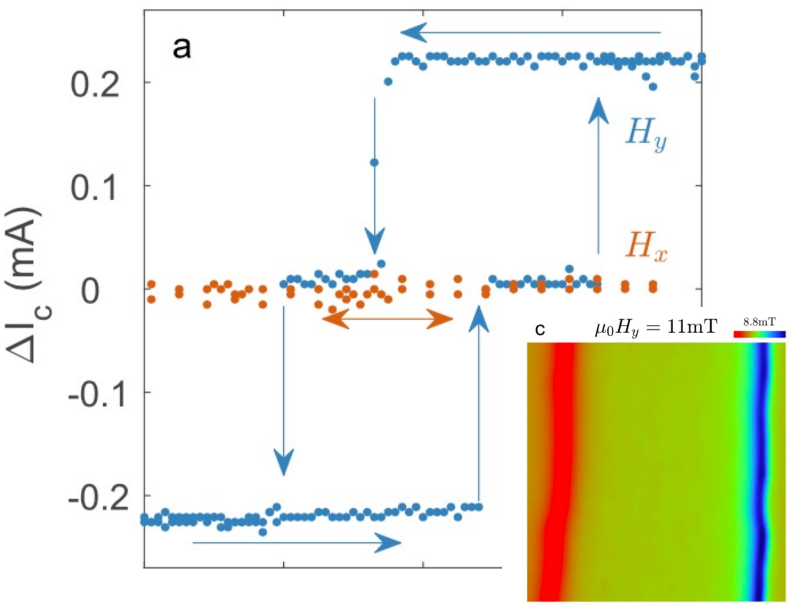
Motivation

Direct observation of a superco vortex diode

Received: 15 October 2022

Accepted: 9 March 2023

Alon Gutfreund[1], Hisakazu Matsuki[2], Vadim Plastovets[3], Avia Noah[1], Laura Gorzawski[2], Nofar Fridman[1], Guang Yang[2], Alexander Buzdin[3], Oded Millo[1], Jason W. A. Robinson[2] & Yonathan Anahory[1]

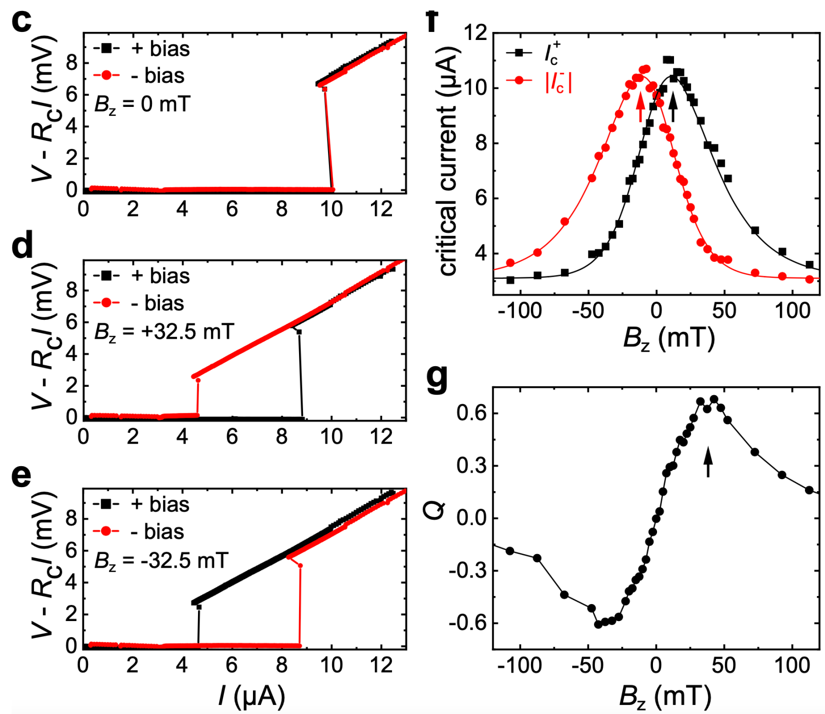


https://doi.org/10.1038/s41467-022-31954-5

OPEN

Supercurrent diode effect and magnetochiral anisotropy in few-layer $NbSe_2$

Lorenz Bauriedl[1], Christian Bäuml[1], Lorenz Fuchs[1], Christian Baumgartner[1], Nicolas Paulik[1], Jonas M. Bauer[1], Kai-Qiang Lin[1], John M. Lupton[1], Takashi Taniguchi[2], Kenji Watanabe[2], Christoph Strunk[1] & Nicola Paradiso[1]



Motivation

https://doi.org/10.1038/s41467-022-31954-5 OPEN

Supercurrent diode effect and magnetochiral

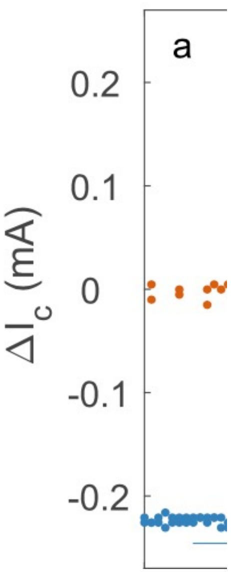
Ubiquitous Superconducting Diode Effect in Superconductor Thin Films

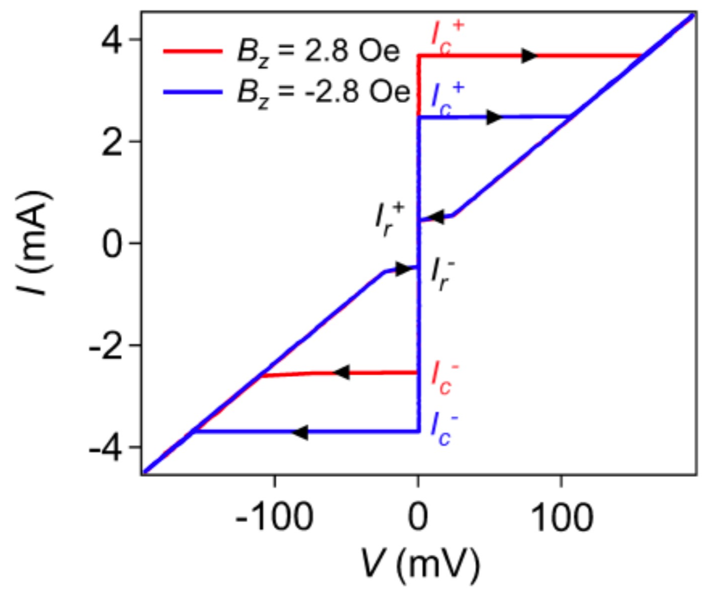
Direct ol
vortex d

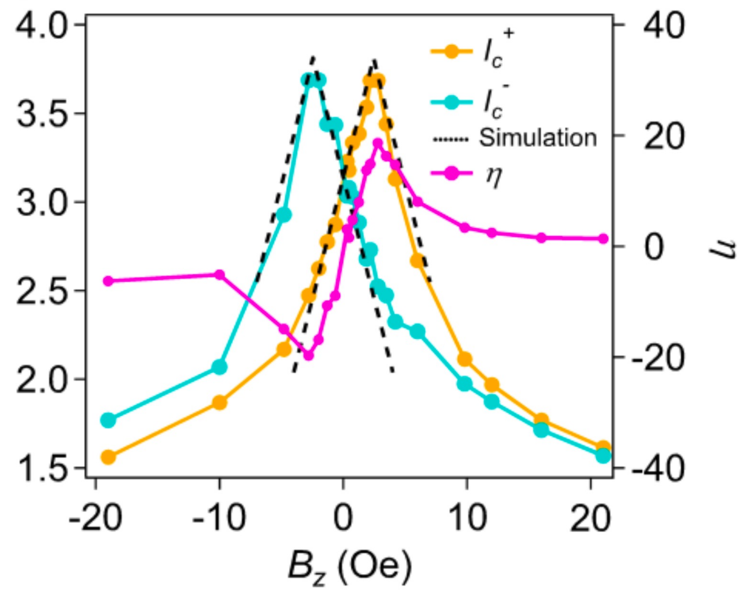
Yasen Hou[1*], Fabrizio Nichele[2], Hang Chi[1,3], Alessandro Lodesani[1], Yingying Wu[1], Markus F. Ritter[2], Daniel Z. Haxell[2], Margarita Davydova[4], Stefan Ilić[5], Ourania Glezakou-Elbert[6], Amith Varambally[7], F. Sebastian Bergeret[5,8], Akashdeep Kamra[9*], Liang Fu[4], Patrick A. Lee[4*], Jagadeesh S. Moodera[1,4*]

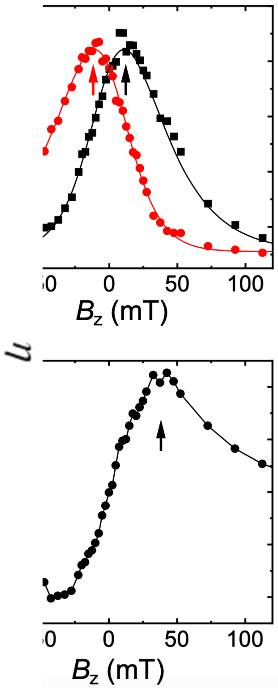
ik[1], Jonas M. Bauer[1], Strunk 1 &

Received: 15 October 202
Accepted: 9 March 2023









Larkin Award

The Anatoly Larkin Award in Theoretical Physics

Inaugural Award Recipients

The William I. Fine Theoretical Physics Institute (FTPI) at the University of Minnesota is proud to announce the recipients of the inaugural *Larkin Award in Theoretical Physics*

2022 Larkin Senior Researcher Award

Professor Patrick A. Lee
Massachusetts Institute of Technology (MIT) & California Institute of Technology (Caltech)

Professor Lee is being awarded the Larkin Senior Researcher Award for pioneering and wide reaching research in strongly correlated systems, in particular theories of the quantum transport phenomena in the mesoscopic and superconducting systems, and for his standing in the Physics community.

Award Ceremony Photos (https://photos.app.goo.gl/vKvCyzHnBt3fNheC6)

2022 Larkin Junior Researcher Award

Professor Liang Fu
Massachusetts Institute of Technology (MIT)

Professor Fu is being awarded the Larkin Junior Researcher Award for seminal works on 3D topological insulators and odd parity topological superconductors, crystalline topological insulators, Majorana zero modes, and for being an intellectual leader of his generation.

Award Ceremony Photos (https://photos.app.goo.gl/7ZT7h8wvcvZYCYUH9)

2022 Recipients

Senior Researcher: Patrick A. Lee
Massachusetts Institute of Technology
& California Institute of Technology


Junior Researcher: Liang Fu
Massachusetts Institute of Technology


4/23/23: 2022 Anatoly Larkin Junior Award

Professor Liang Fu from the Massachusetts Institute of Technology (MIT) was awarded the Junior Award for seminal works on 3D topological insulators and odd parity topological superconductors, crystalline topological insulators, Majorana zero modes, and for being an intellectual leader of his generation.

The title of his talk is, "Diodic Quantum Materials."

Abstract: The p-n junction is the key building block of modern microelectronics that underlies diodes and transistors. In recent years, it has been found that certain quantum materials can have a direction dependent electrical resistance and thus exhibit an intrinsic diode effect without any junction. In this talk, I will first describe diodic superconductors that exhibit zero (nonzero) resistance in the forward (backward) direction. Such superconducting diode effect generally appears when Cooper pairs in the ground state have finite center-of-mass momentum, as in the Larkin-Ovchinnikov-Fulde-Ferrell superconductor. Next, I will describe noncentrosymmetric conductors that exhibit a nonreciprocal Hall effect at zero magnetic field, with the transverse current quadratic in the applied voltage. This intrinsic nonreciprocity is a fundamental material property that originates from the quantum geometry of itinerant electron states in crystals. Potential applications of diodic quantum materials in high-frequency (THz) and low-power electronics will be discussed.

Motivation

https://doi.org/10.1038/s41467-022-31954-5 OPEN

Supercurrent diode effect and magnetochiral

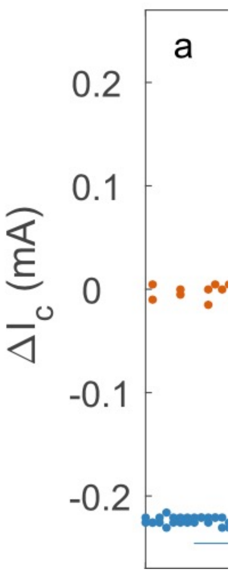
ik[1], Jonas M. Bauer[1],
Strunk [1] &

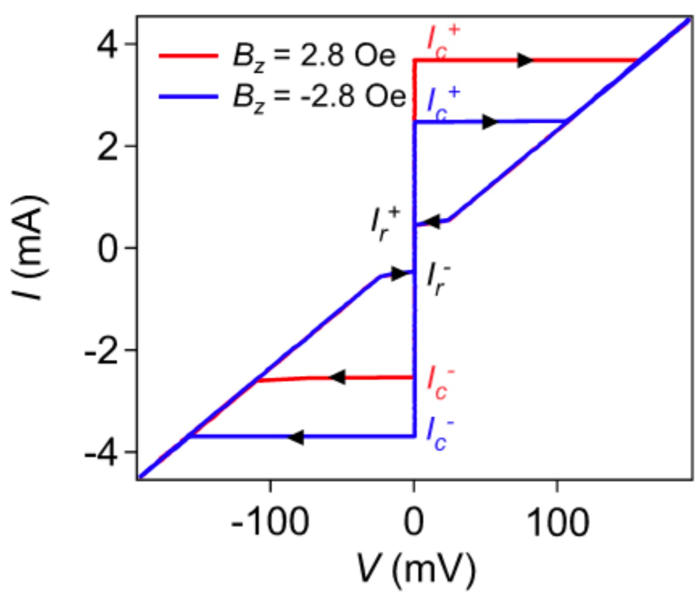
Direct ob
vortex d

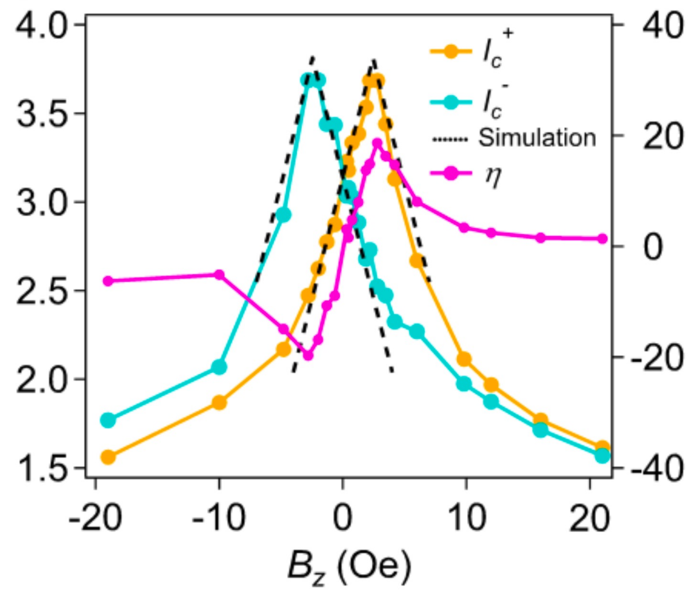
Received: 15 October 202
Accepted: 9 March 2023

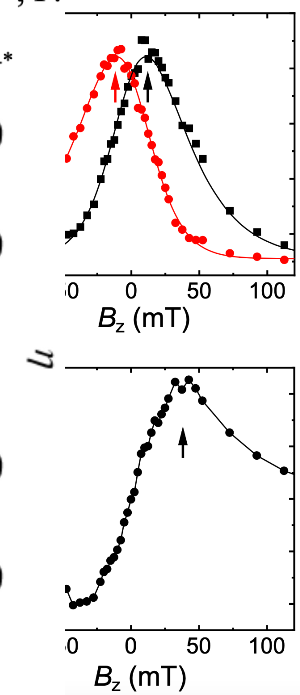
Ubiquitous Superconducting Diode Effect in Superconductor Thin Films

Yasen Hou[1*], Fabrizio Nichele[2], Hang Chi[1,3], Alessandro Lodesani[1], Yingying Wu[1], Markus F. Ritter[2], Daniel Z. Haxell[2], Margarita Davydova[4], Stefan Ilić[5], Ourania Glezakou-Elbert[6], Amith Varambally[7], F. Sebastian Bergeret[5,8], Akashdeep Kamra[9*], Liang Fu[4], Patrick A. Lee[4*], Jagadeesh S. Moodera[1,4*]





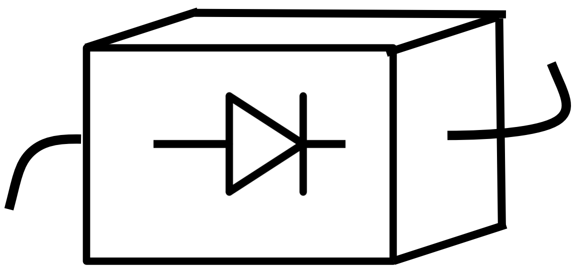


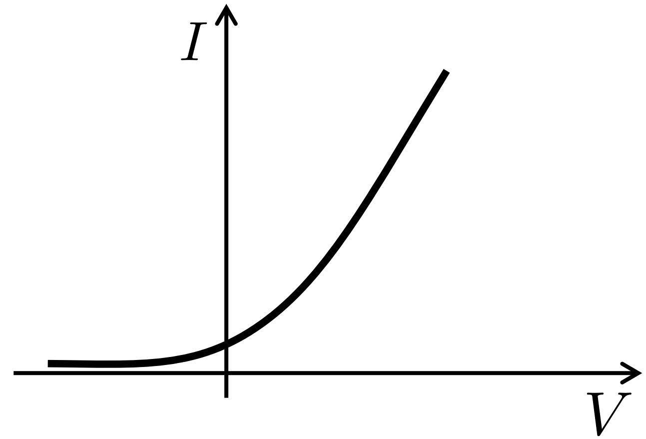


Time reversal symmetry

Time reversal symmetry

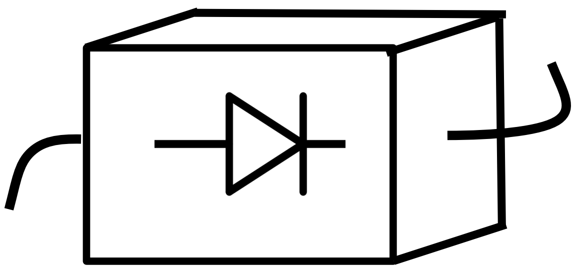
Usual diode



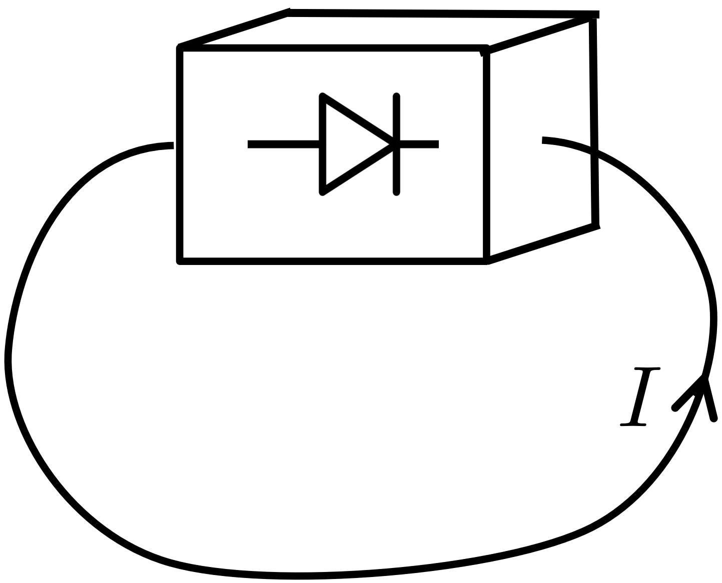


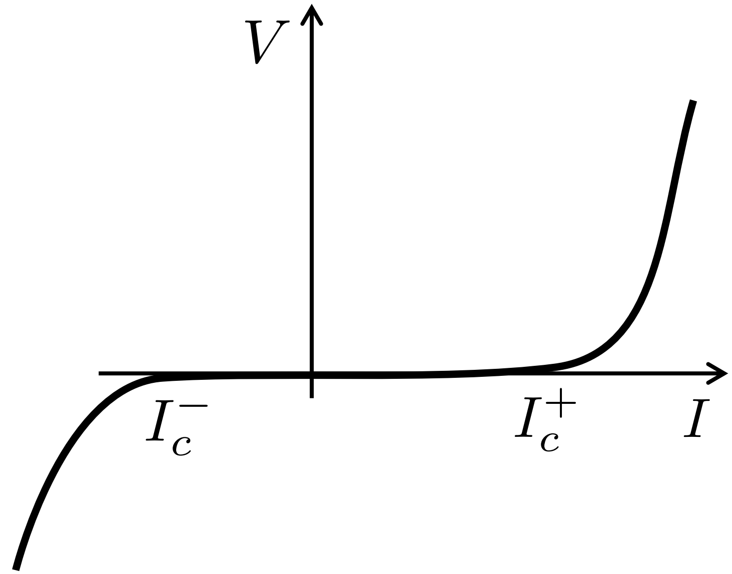
Time reversal symmetry

Usual diode



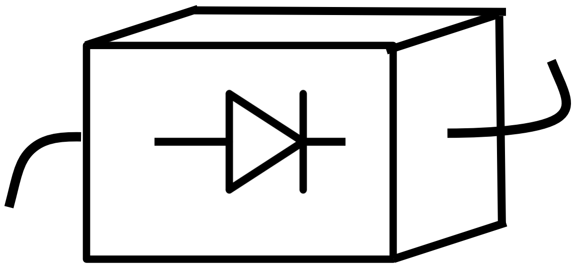
Superconducting diode

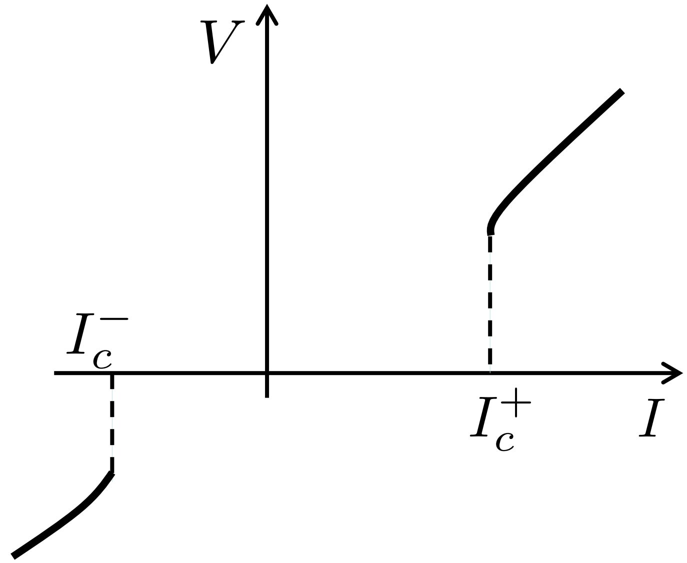




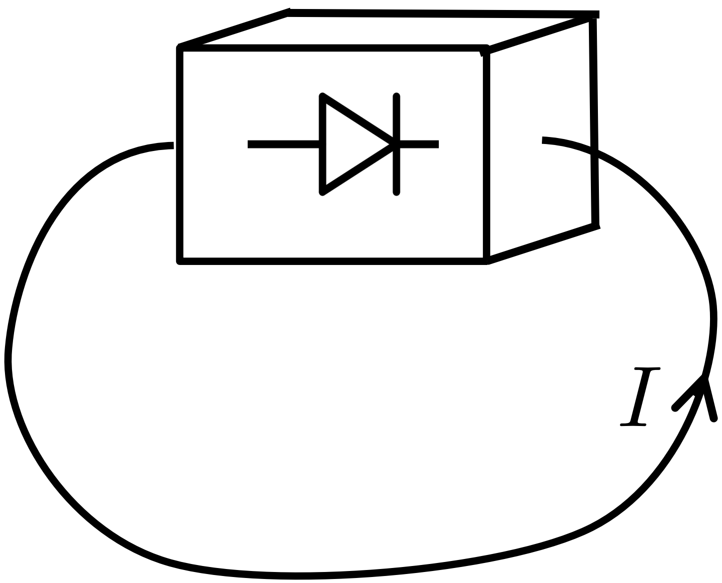
Time reversal symmetry

Usual diode





Superconducting diode

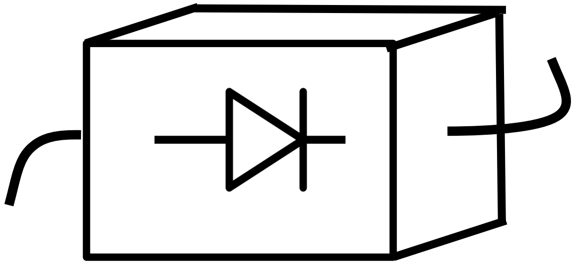


Supercurrent

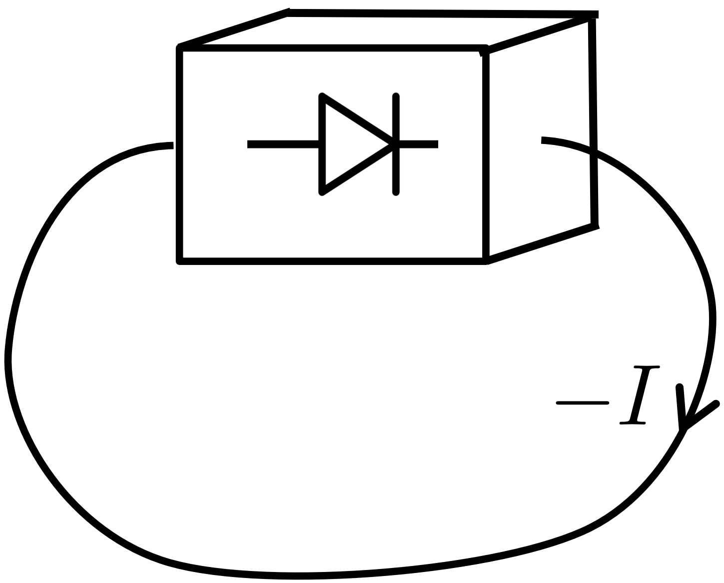
$t \to -t$ means $I \to -I$

Time reversal symmetry

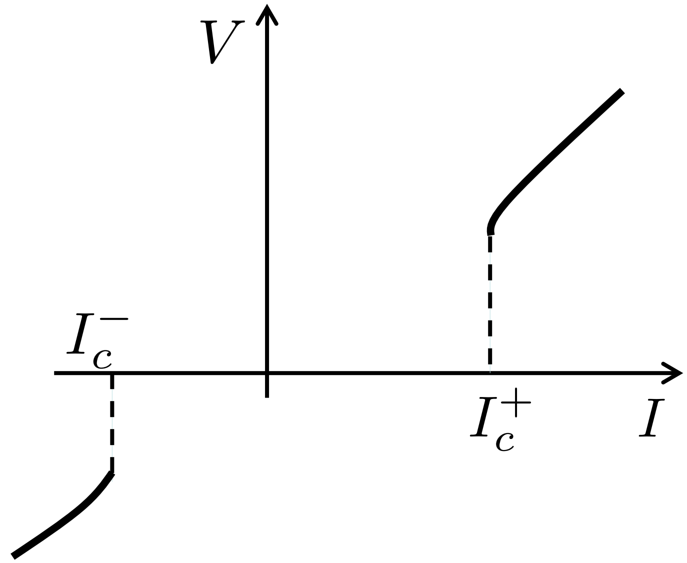
Usual diode



Superconducting diode



Supercurrent

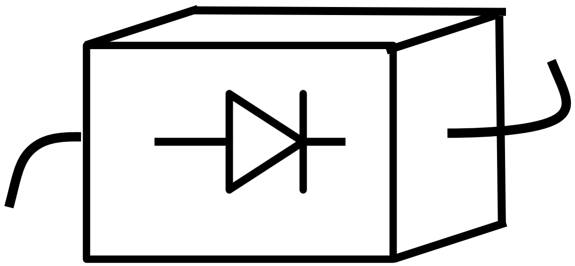


$t \to -t$ means $I \to -I$

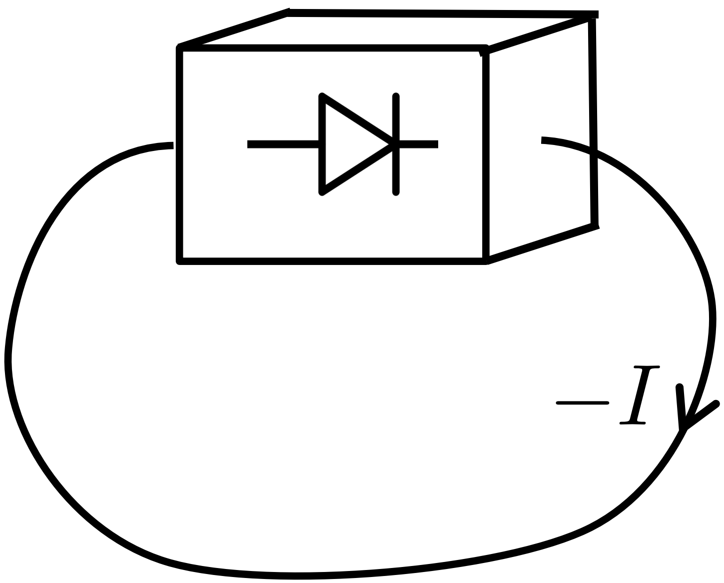
$$I_c^+ = I_c^-$$

Time reversal symmetry

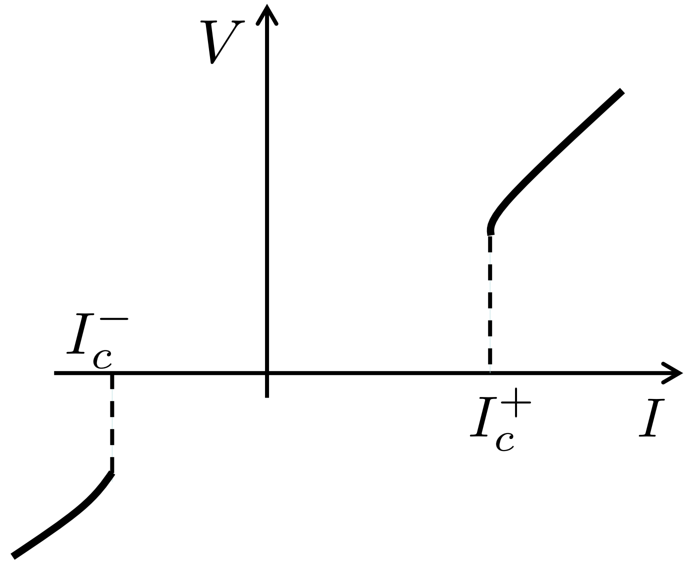
Usual diode



Superconducting diode



Supercurrent



$t \to -t$ means $I \to -I$

One needs to break time reversal symmetry!

$$I_c^+ \neq I_c^-$$

Time reversal symmetry

$$I_c^+(H) = -I_c^-(-H)$$

Diode effect if $$I_c(H) \neq I_c(-H)$$

Time reversal symmetry

$$I_c^+(H) = -I_c^-(-H)$$

Diode effect if $$I_c(H) \neq I_c(-H)$$

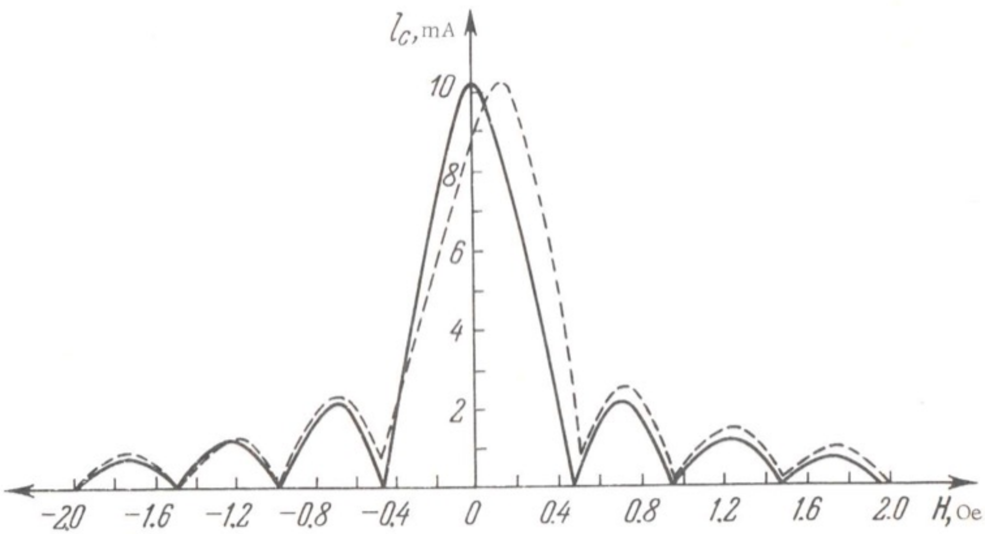


FIGURE 45. Theoretical and experimental dependence of the critical current on the magnetic field for $L \approx 2\lambda_J$.

Kulik & Yanson book

Time reversal symmetry

$$I_c^+(H) = -I_c^-(-H)$$

Diode effect if $$I_c(H) \neq I_c(-H)$$

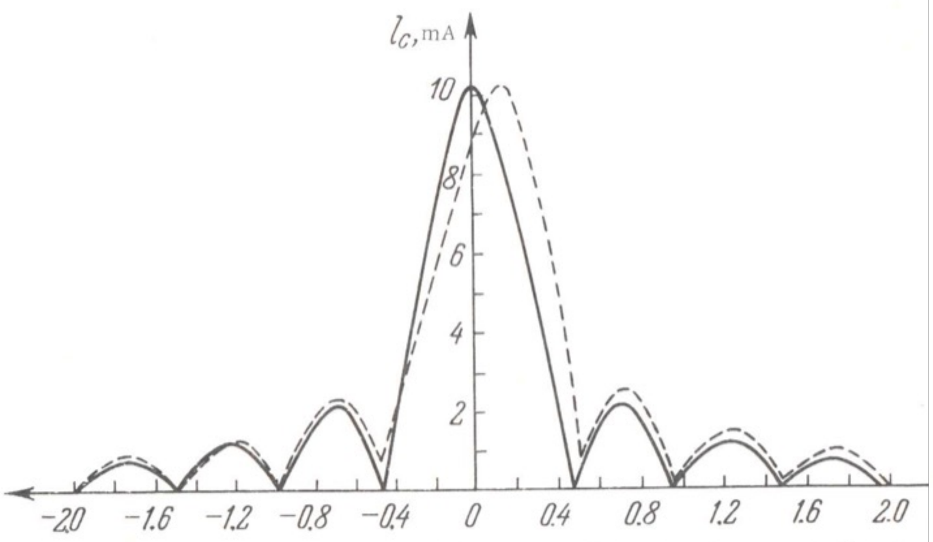


FIGURE 45. Theoretical and experimental dependence of the critical current on the magn
field for $L \approx 2\lambda_J$.

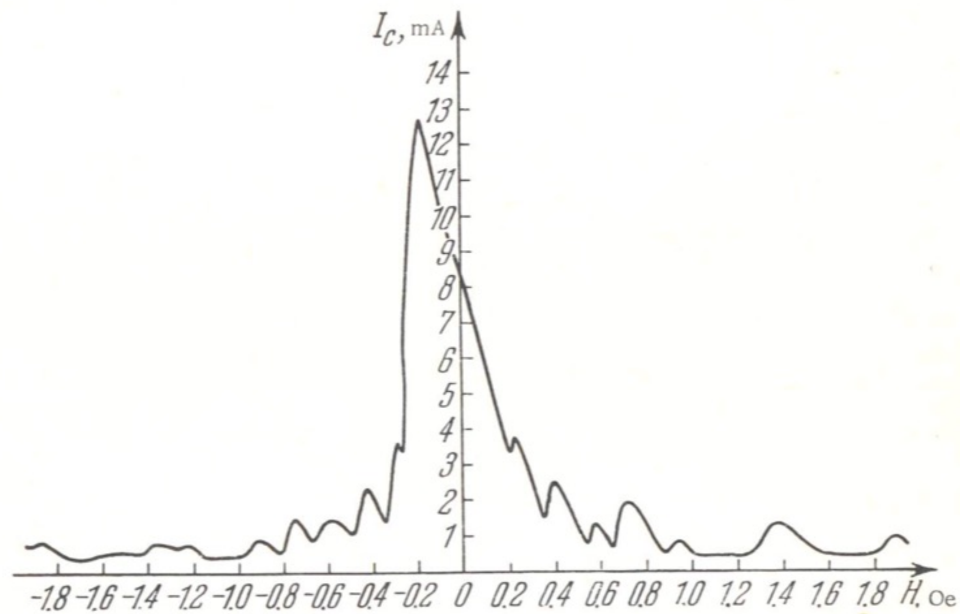


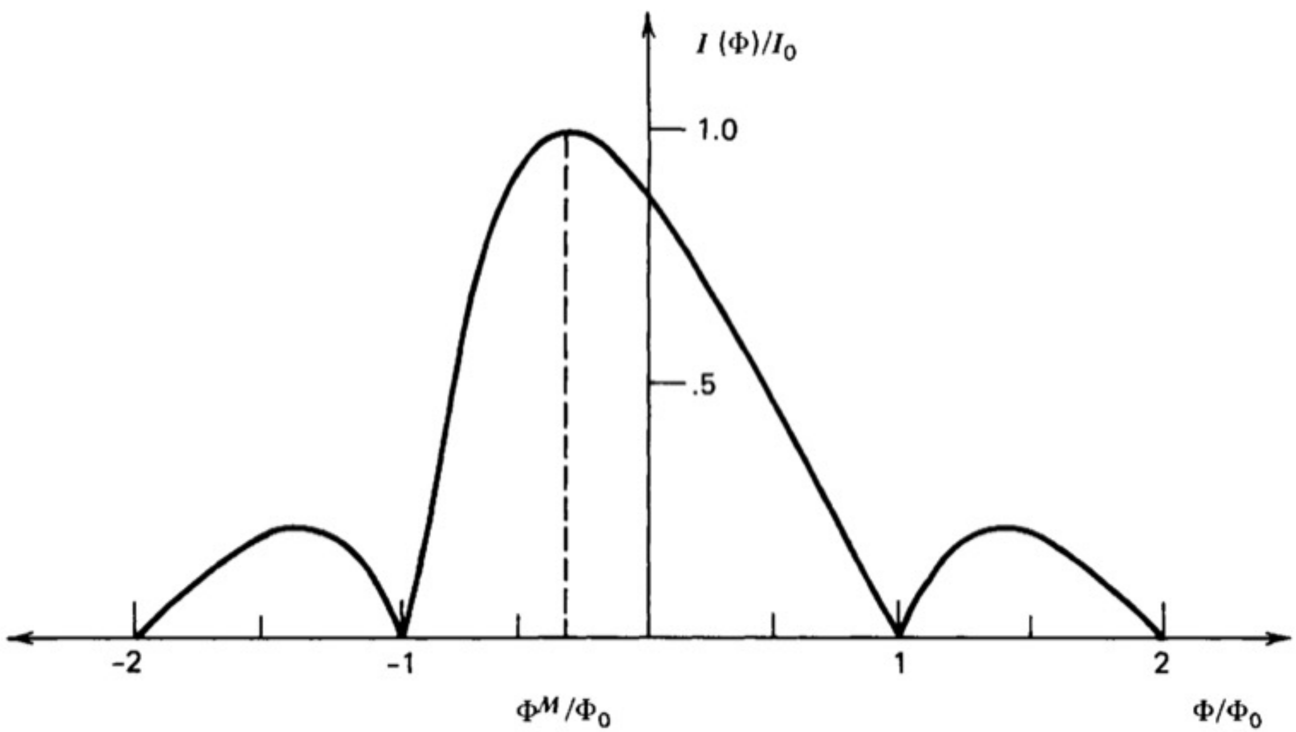
FIGURE 47. Experimental dependence of the critical current on the magnetic field for the junction with $L \approx 5\lambda_J$.

Kulik & Yanson book

Time reversal symmetry

$$I_c^+(H) = -I_c^-(-H)$$

Diode effect if $$I_c(H) \neq I_c(-H)$$



Barone & Paterno book

A Superconducting Reversible Rectifier That Controls the Motion of Magnetic Flux Quanta

J. E. VILLEGAS, SERGEY SAVEL'EV, FRANCO NORI, E. M. GONZALEZ, J. V. ANGUITA, R. GARCÍA, AND J. L. VICENT

Authors Info & Affiliations

SCIENCE. 14 Nov 2003

Guidance of vortices and the vortex ratchet effect in high-T_c superconducting thin films obtained by arrangement of antidots

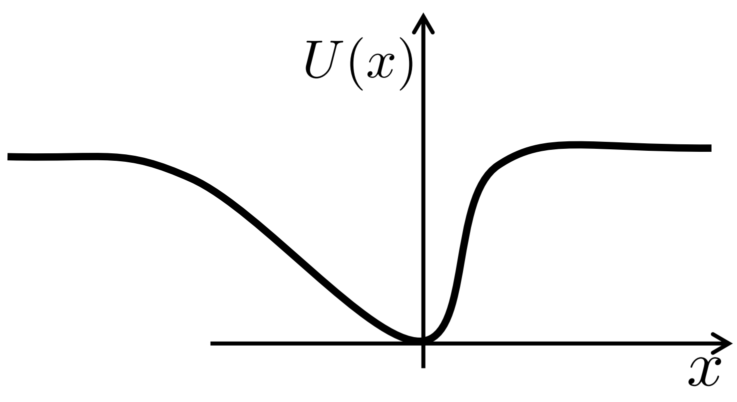
R. Wördenweber, P. Dymashevski, and V. R. Misko

Phys. Rev. B **69**, 184504 – Published 20 May 2004

Controlled multiple reversals of a ratchet effect

•Clécio C. de Souza Silva, Joris Van de Vondel, Mathieu Morelle & Victor V. Moshchalkov

Nature **volume 440**, pages651–654 (2006)



Atomically thin superconductors

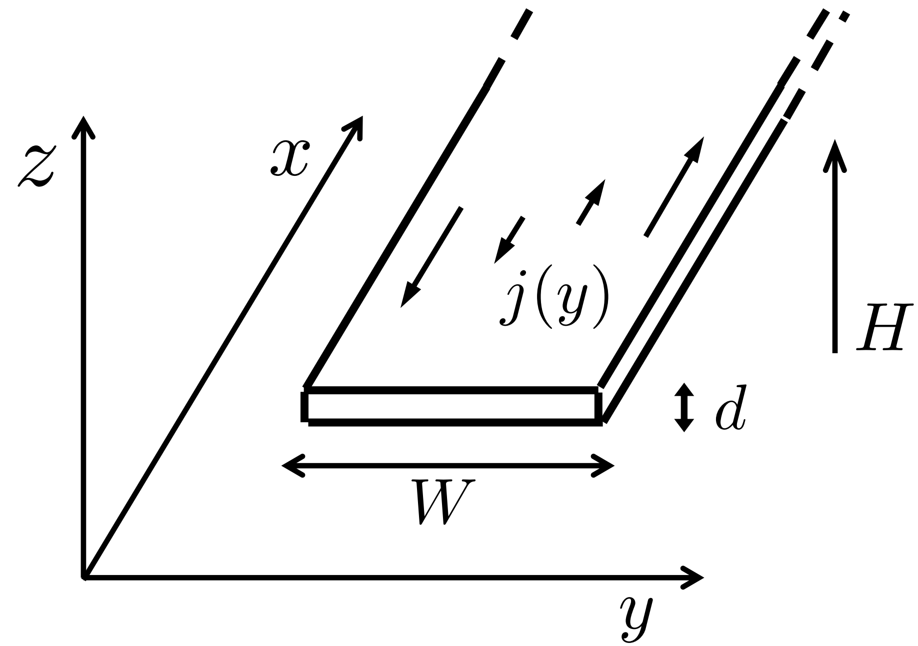
$$\lambda_\perp = \lambda^2/d \sim 20 - 50\mu m > W \sim 10\mu m$$

For $\lambda_\perp \gg W$

Magnetic field is not screened

Currents flow everywhere

$$j = -\rho_s A = \rho_s H y$$



Critical current is dominated by the Bean – Livingston surface barrier

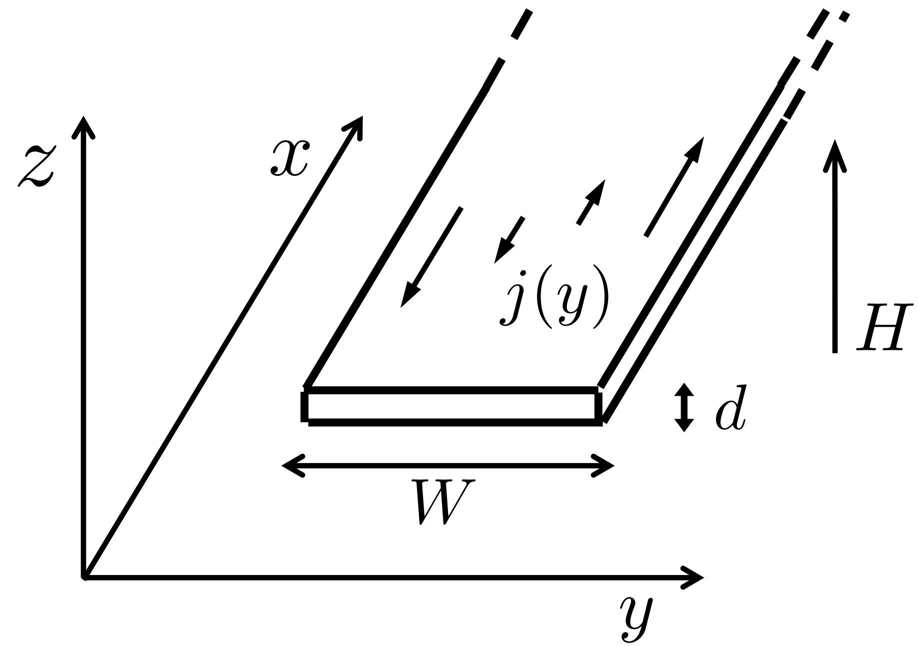
“Surface” current $j \sim j_0$ flows everywhere inside the sample

V. V. Shmidt (1970), G. M. Maksimova (1998)

Atomically thin superconductors

London equation for $i(y) = j(y)d$

$$i(y) = -\frac{cd}{4\pi\lambda^2}\left[A - \frac{\Phi_0}{2\pi}\nabla\theta\right]$$



Taking curl

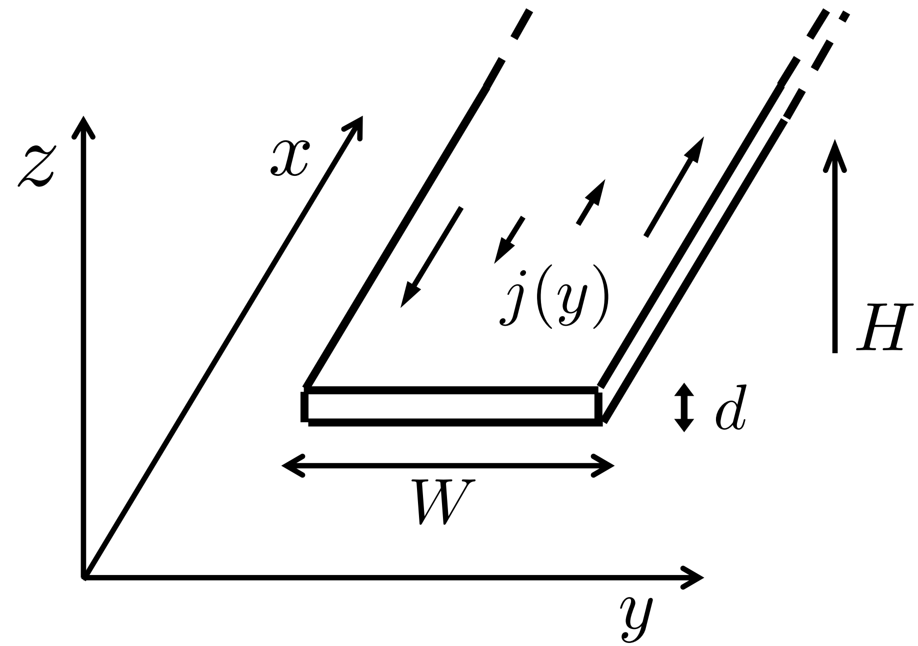
$$\frac{d\,i}{d\,y} = \frac{cd}{4\pi\lambda^2}\left[H - \frac{2}{c}\int_{-W/2}^{W/2}\frac{i(y')dy'}{y'-y} - n(y)\Phi_0\right]$$

A. I. Larkin & Yu. N. Ovchinnikov (1971)

Atomically thin superconductors

London equation for $i(y) = j(y)d$

$$i(y) = -\frac{cd}{4\pi\lambda^2}\left[A - \frac{\Phi_0}{2\pi}\nabla\theta\right]$$



Taking curl

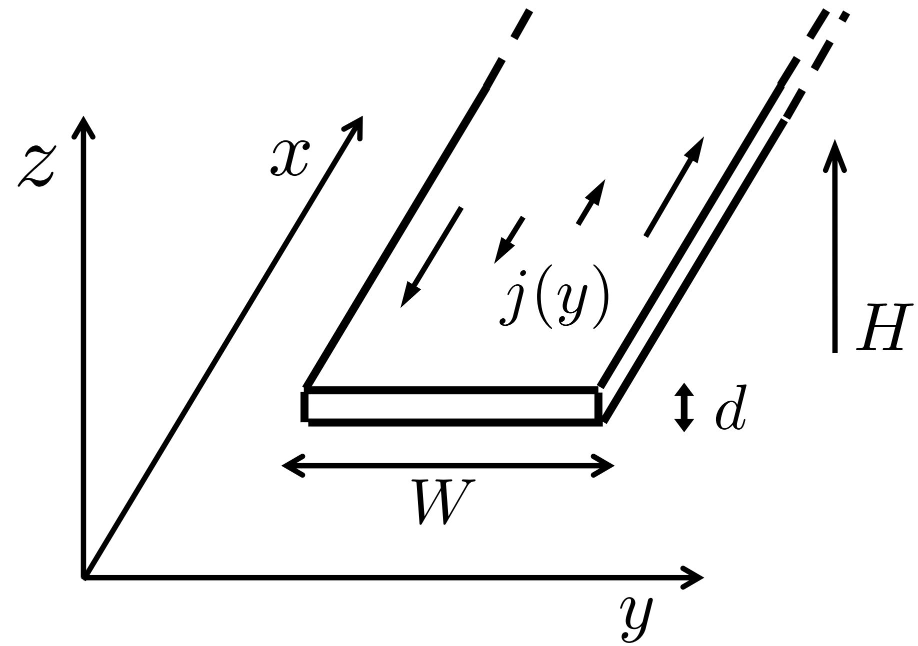
$$\frac{d\,i}{d\,y} = \frac{cd}{4\pi\lambda^2}\left[H - \frac{2}{c}\int_{-W/2}^{W/2}\frac{i(y')dy'}{y'-y} - n(y)\Phi_0\right]$$

The self field from current scales as Wd/λ^2 and can be neglected

Atomically thin superconductors

London equation for $i(y) = j(y)d$

$$i(y) = -\frac{cd}{4\pi\lambda^2}\left[A - \frac{\Phi_0}{2\pi}\nabla\theta\right]$$



Taking curl

$$\frac{d\,i}{d\,y} = \frac{cd}{4\pi\lambda^2}\left[H - n(y)\Phi_0\right]$$

In the narrow film limit where $Wd/\lambda^2 \ll 1$

Current distribution: Meissner phase

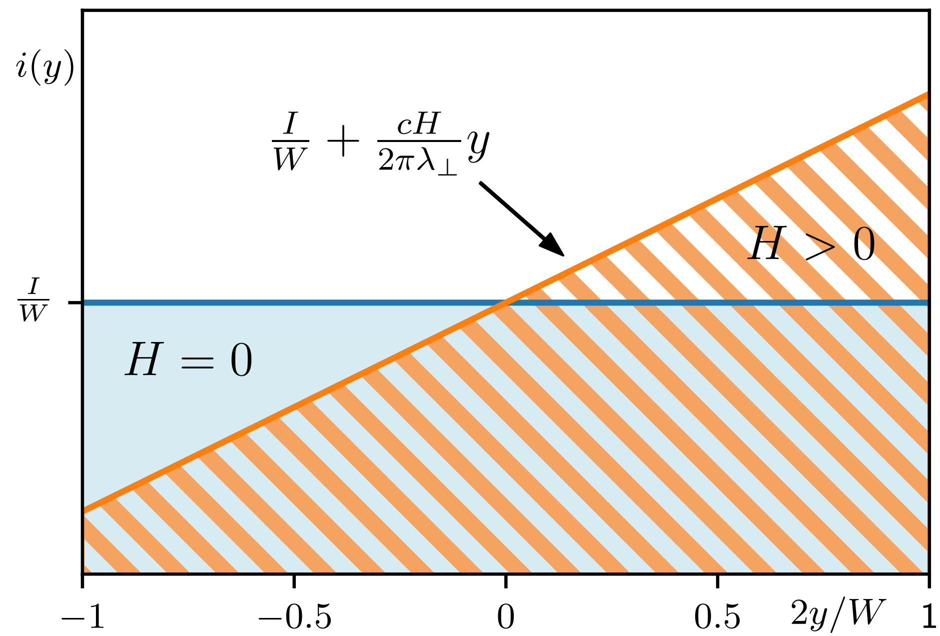
$$\frac{d\,i}{d\,y} = \frac{cd}{4\pi\lambda^2}\left[H - n(y)\Phi_0\right]$$

In absense of vortices $n(y) = 0$

$$i(y) = \frac{I}{W} + \frac{cd\,H}{4\pi\lambda^2}y$$

When $I = 0$, vortices enter the sample at the **penetration field**

$$H_s \equiv \frac{2\Phi_0}{3\sqrt{3}\pi\xi W} \sim \frac{\lambda}{W}H_c$$



Critical current: Meissner phase

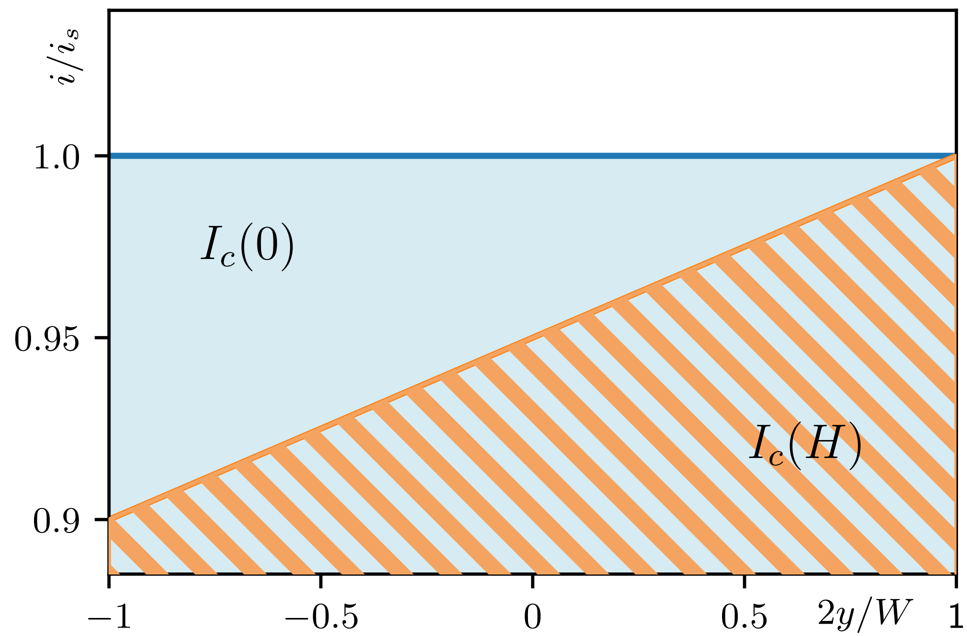
The condition for criticality is

$$\frac{I_c(H)}{W} + \frac{cd\,H}{4\pi\lambda^2}\frac{W}{2} = i_s \simeq i_0$$

giving

$$I_c(H) = \frac{cd}{8\pi}\frac{W^2}{\lambda^2}(H_s - |H|)$$

in the Meissner phase



The Meissner currents $j \propto H$ add to the transport current leading to the peculiar linear dependence on the magnetic field

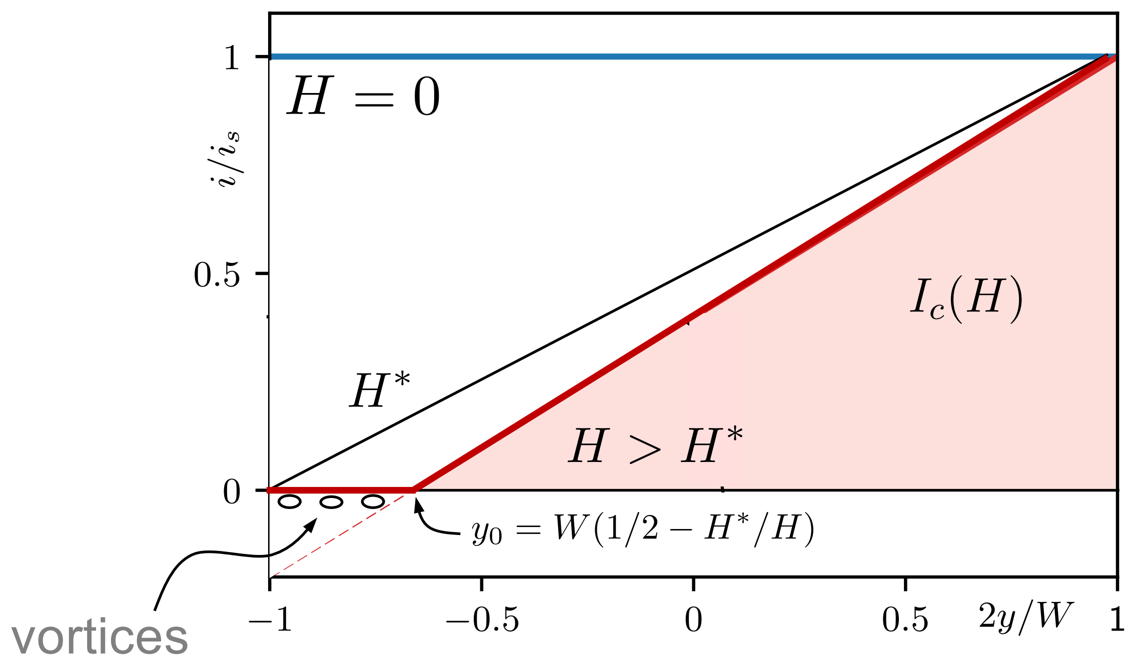
Critical current: mixed state

$$\frac{d\,i}{d\,y} = \frac{cd}{4\pi\lambda^2}\left[H - n(y)\Phi_0\right]$$

For fields larger than

$$H^* = H_s/2$$

the film enters the mixed state



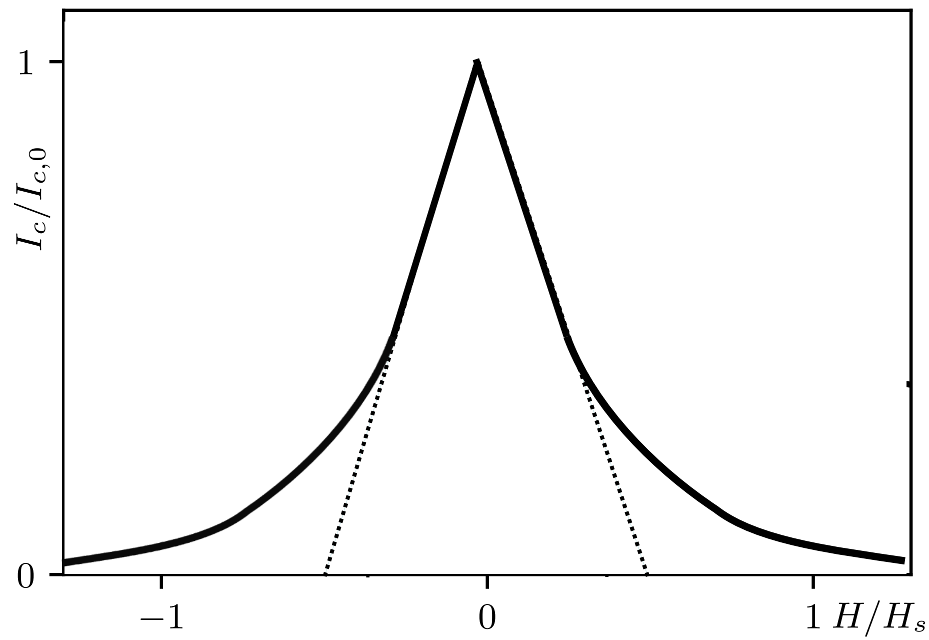
Critical current: field-dependence

In the Meissner state

$$I_c(H) = \frac{cd}{8\pi}\frac{W^2}{\lambda^2}(H_s - |H|)$$

In the mixed state

$$I_c(H) = \frac{cd}{32\pi}\frac{W^2}{\lambda^2}\frac{H_s^2}{H}$$



This triangular shape of $I_c(H)$ is the smoking gun of the surface barrier

PHYSICAL REVIEW B, VOLUME 64, 014503

Influence of edge barriers on vortex dynamics in thin weak-pinning superconducting strips

B. L. T. Plourde* and D. J. Van Harlingen
Department of Physics, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, Illinois 61801

D. Yu. Vodolazov
Department of Physics, Nizhny Novgorod University, Gagarin Avenue 23, 603600, Nizhny Novgorod, Russia

R. Besseling, M. B. S. Hesselberth, and P. H. Kes
Kamerlingh Onnes Laboratorium, Leiden University, P. O. Box 9504, 2300 RA Leiden, The Netherlands

(Received 17 November 2000; published 5 June 2001)

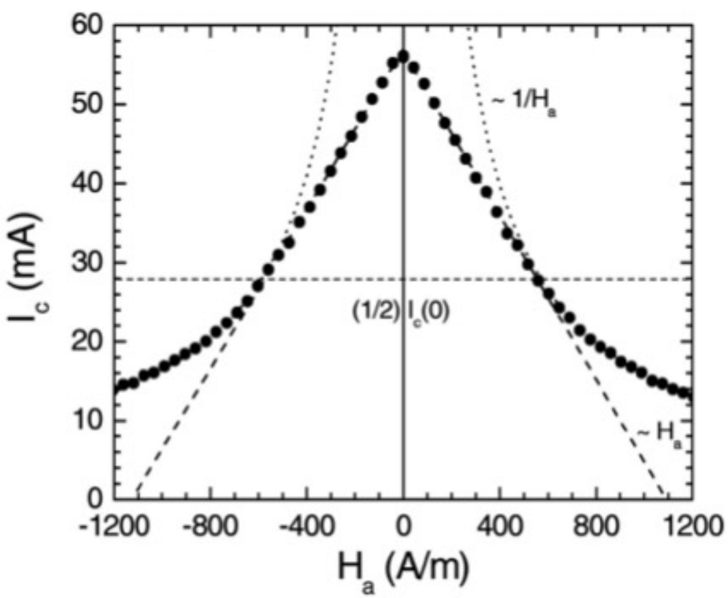


FIG. 1. I_c vs H_a for a 25 μm wide, 200 nm thick *a*-MoGe strip. Linear fits at low field have slopes of -51.9 μm ($H_a>0$) and 50.6 μm ($H_a<0$). Curved lines are fits to a_1/H_a, with a_1 equal to $15.9 A^2/m$ ($H_a>0$) and $-16.4 A^2/m$ ($H_a<0$).

PHYSICAL REVIEW B, VOLUME 64, 014503

Influence of edge barriers on vortex dynamics in thin weak-pinning superconducting strips

B. L. T. Plourde* and D. J. Van Harlingen
Department of Physics, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, Illinois 61801

D. Yu. Vodolazov
Department of Physics, Nizhny Novgorod University, Gagarin Avenue 23, 603600, Nizhny Novgorod, Russia

R. Besseling, M. B. S. Hesselberth, and P. H. Kes
Kamerlingh Onnes Laboratorium, Leiden University, P. O. Box 9504, 2300 RA Leiden, The Netherlands
(Received 17 November 2000; published 5 June 2001)

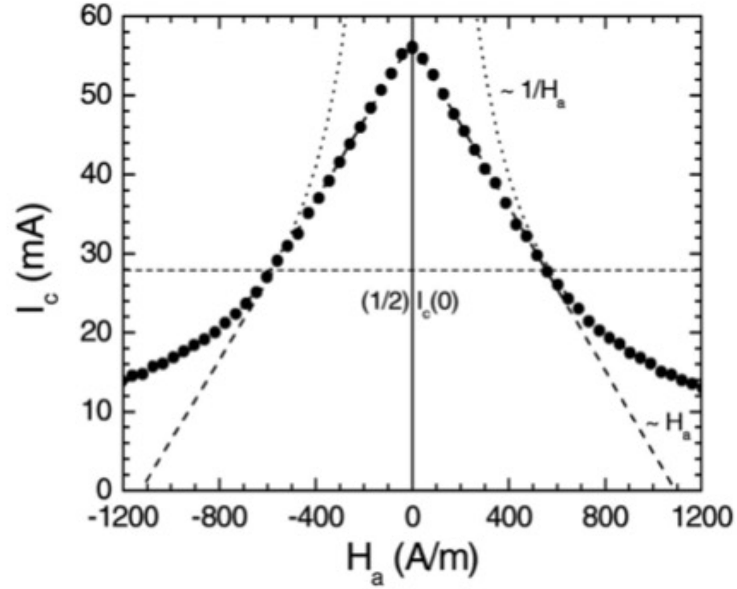
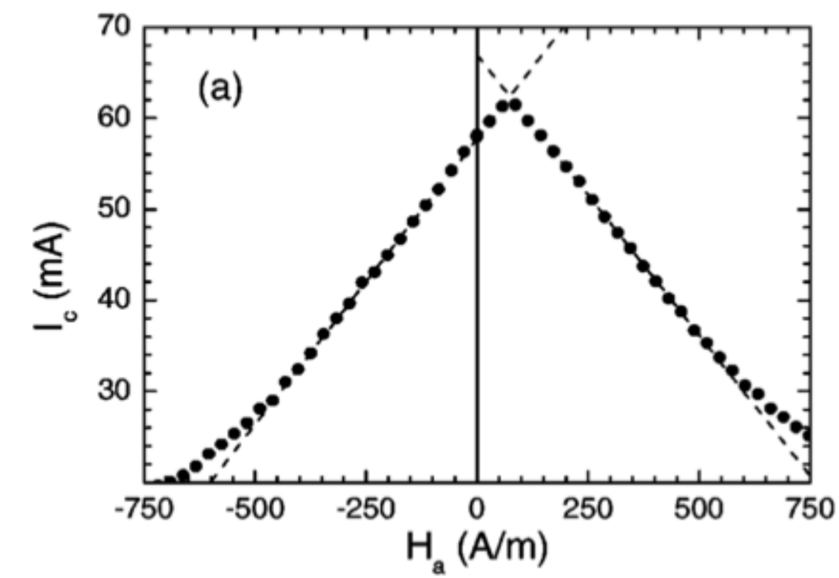


FIG. 1. I_c vs H_a for a 25 μm wide, 200 nm thick *a*-MoGe strip. Linear fits at low field have slopes of -51.9 μm ($H_a>0$) and 50.6 μm ($H_a<0$). Curved lines are fits to a_1/H_a, with a_1 equal to $15.9A^2/m$ ($H_a>0$) and $-16.4A^2/m$ ($H_a<0$).



SC diode?

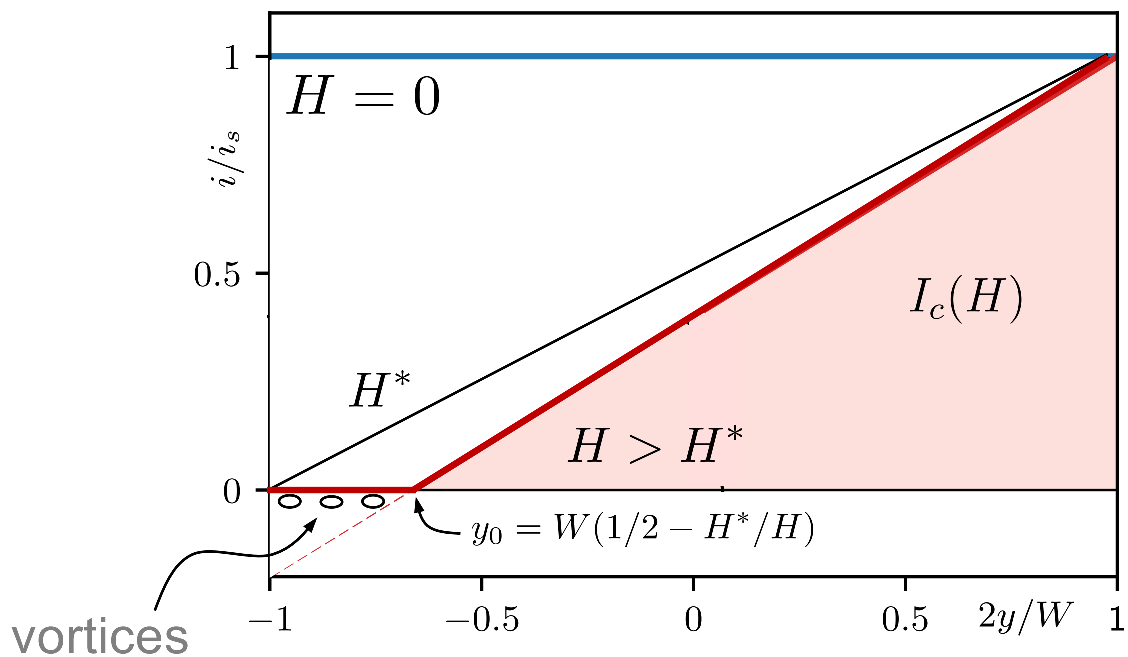
Critical current: mixed state, no pinning

$$\frac{d\,i}{d\,y} = \frac{cd}{4\pi\lambda^2}\left[H - n(y)\Phi_0\right]$$

For fields larger than

$$H^* = H_s/2$$

the film enters the mixed state



Critical current: mixed state with pinning

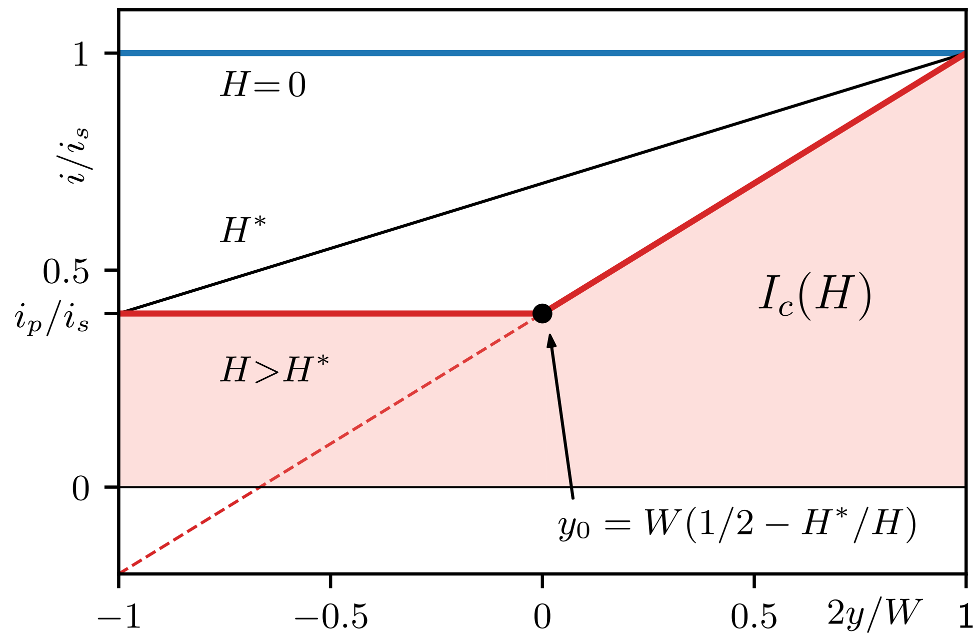
$$\frac{d\,i}{d\,y} = \frac{cd}{4\pi\lambda^2}\left[H - n(y)\Phi_0\right]$$

For fields larger than

$$H^* = (H_s - H_p)/2$$

the film enters the mixed state

$$H_p = \frac{8\pi}{cd}\frac{\lambda^2}{W} i_p$$



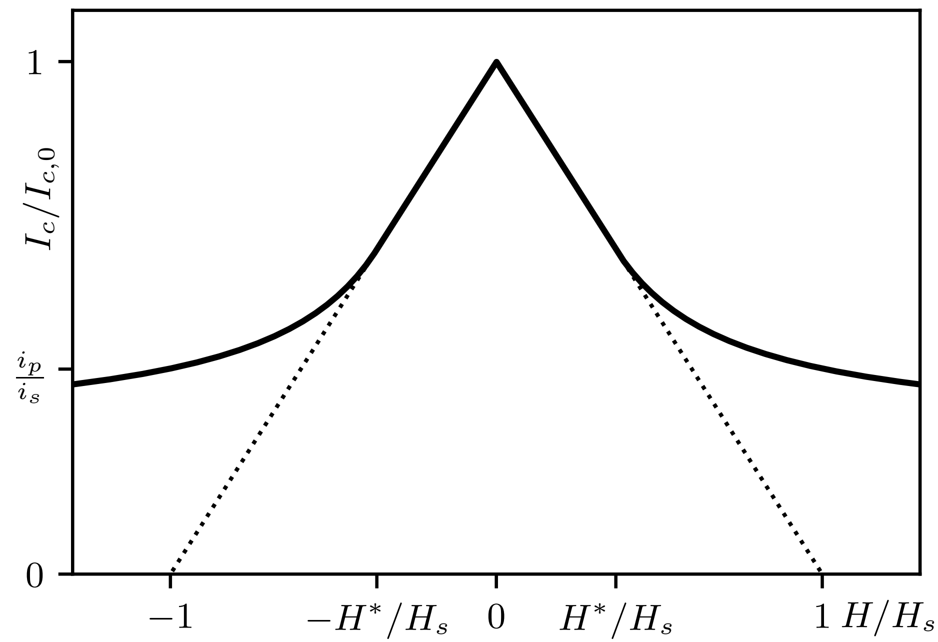
Critical current: field-dependence

In the Meissner state

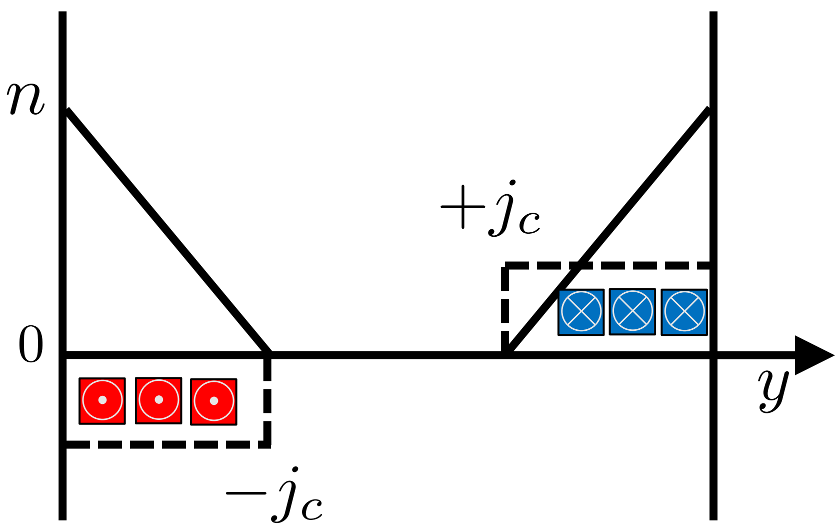
$$I_c(H) = \frac{cd}{8\pi}\frac{W^2}{\lambda^2}(H_s - |H|)$$

In the mixed state

$$I_c(H) = \frac{cd}{8\pi}\frac{W^2}{\lambda^2}\left[H_p + \frac{(H^*)^2}{H}\right]$$



Bulk versus surface

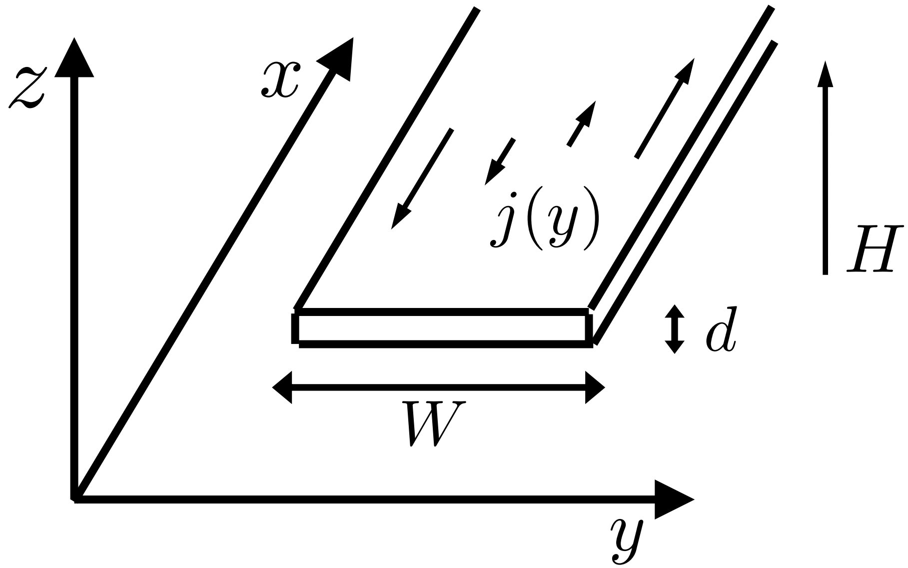


Bean state:

Field profile is **linear,** vanishes in bulk

$$\nabla \times \mathbf{B} \propto \begin{cases} j = \pm j_c & \text{at the edges} \\ j = 0 & \text{in the bulk} \end{cases}$$

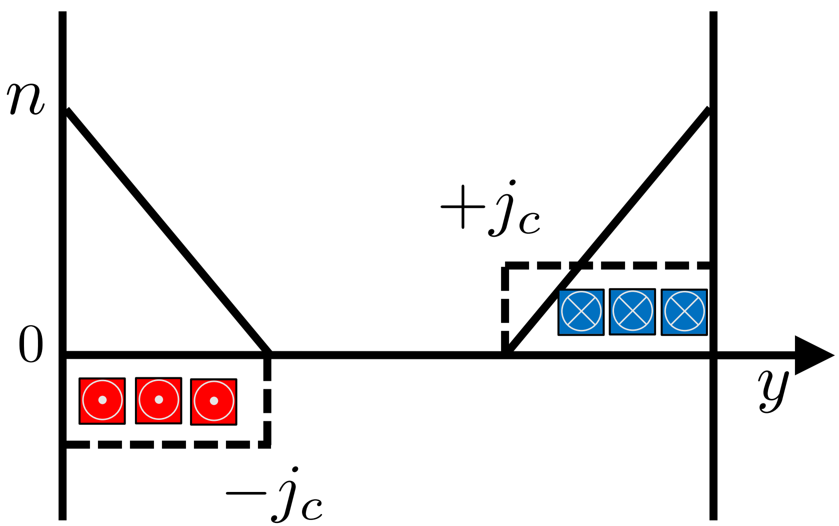
Bulk versus surface



Thin film:

Magnetic field is **not screened**

Current profile is **linear** $j \propto Hy$

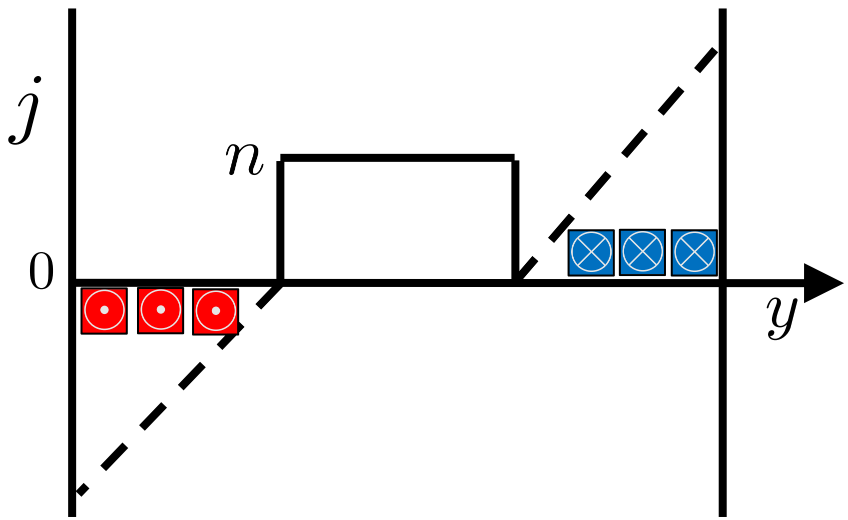


Bean state:

Field profile is **linear,** vanishes in bulk

$$\nabla \times \mathbf{B} \propto \begin{cases} j = \pm j_c & \text{at the edges} \\ j = 0 & \text{in the bulk} \end{cases}$$

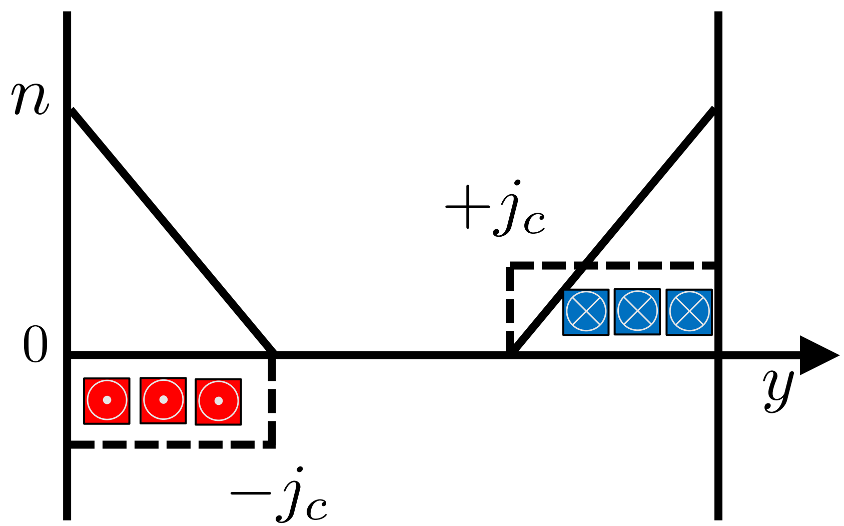
Bulk versus surface



Thin film:

Magnetic field is **not screened**

Current profile is **linear** $j \propto Hy$



Bean state:

Field profile is **linear,** vanishes in bulk

$$\nabla \times \mathbf{B} \propto \begin{cases} j = \pm j_c & \text{at the edges} \\ j = 0 & \text{in the bulk} \end{cases}$$

Asymmetric films: surface barriers

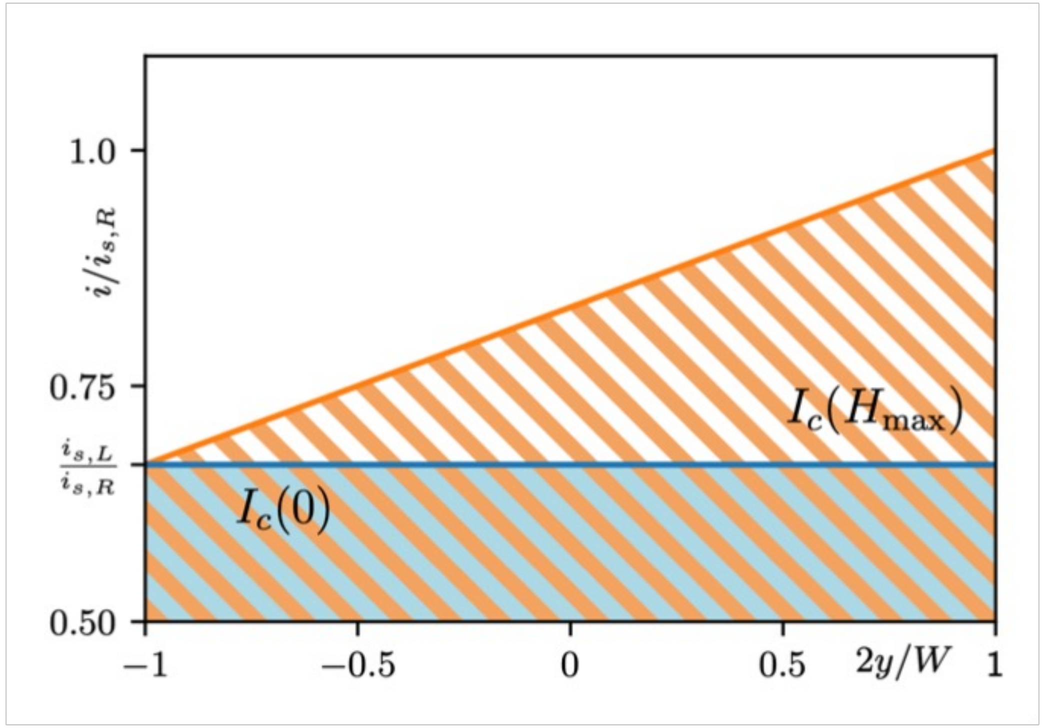
In samples with asymmetric edges, the left and right surface barriers are different.

The critical current peak shifts to a finite field $H_{\rm max}$

$$H_{\rm max} = \frac{4\pi}{cd}\frac{\lambda^2}{W}(i_{s,R} - i_{s,L})$$

and

$$I_c(0) = I_c(H_{\rm max}) - \frac{cd}{8\pi}\frac{W^2}{\lambda^2}H_{\rm max}$$



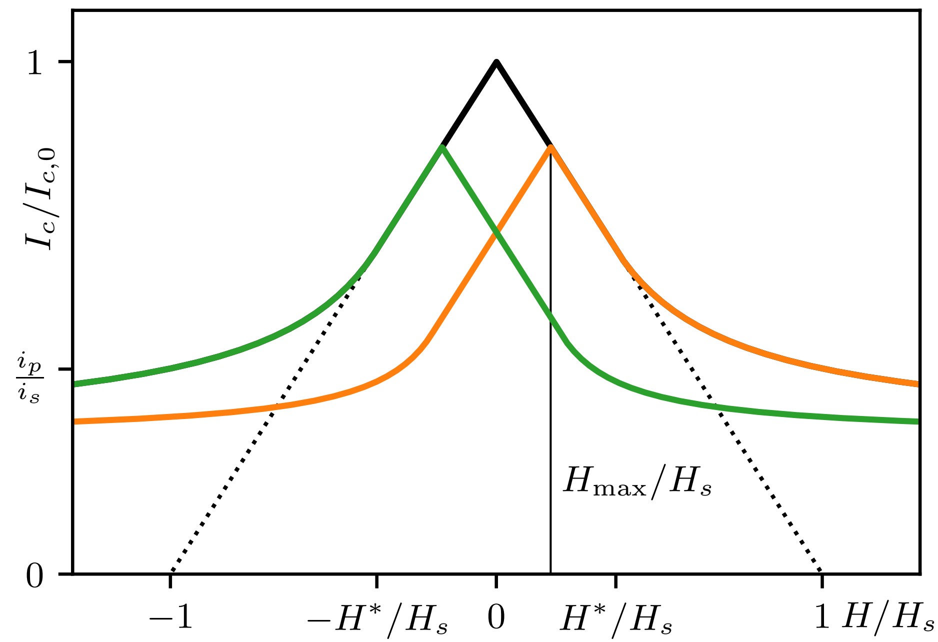
Asymmetric films: critical current

Positive and negative
critical currents are different

$$I_c^+(H) = -I_c^-(-H)$$

but

$$I_c(H) \neq I_c(-H)$$



B. T. Plourde, et al., PRB **64** (2001)
D. Y. Vodolazov, F. M. Peeters, PRB **72** (2005)

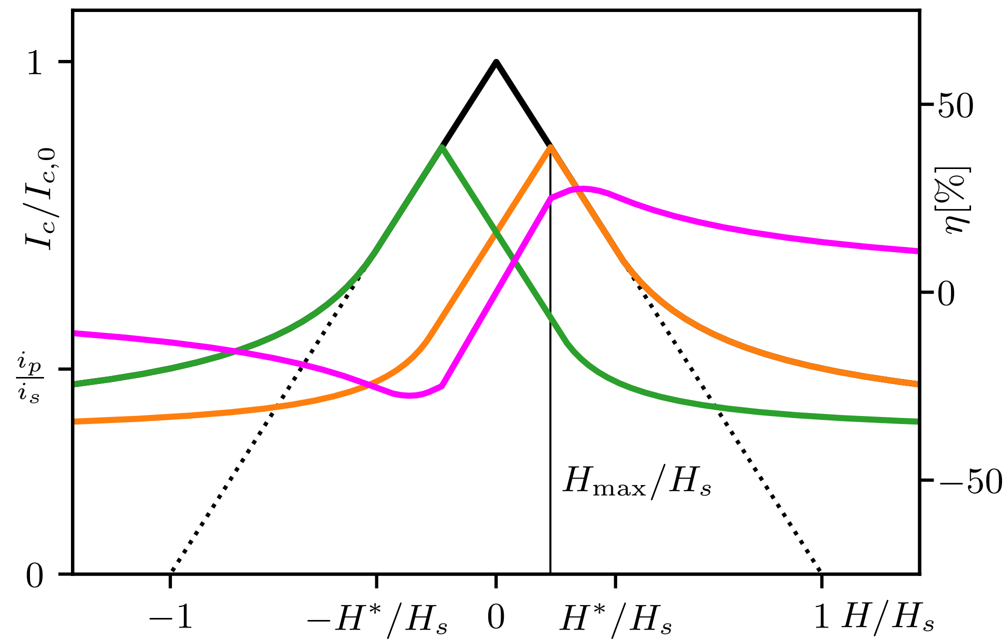
Asymmetric films: critical current

Positive and negative
critical currents are different

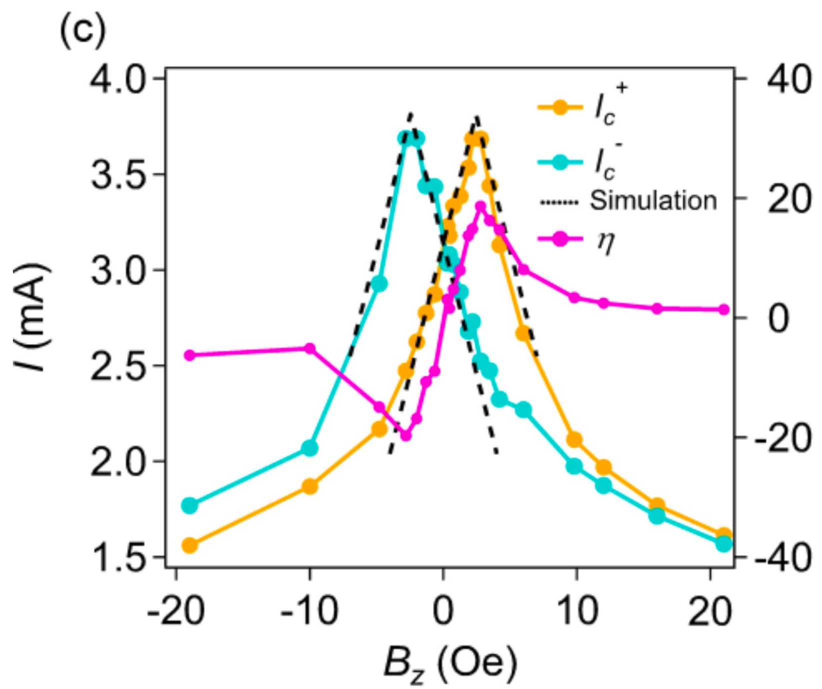
$$I_c^+(H) = -I_c^-(-H)$$

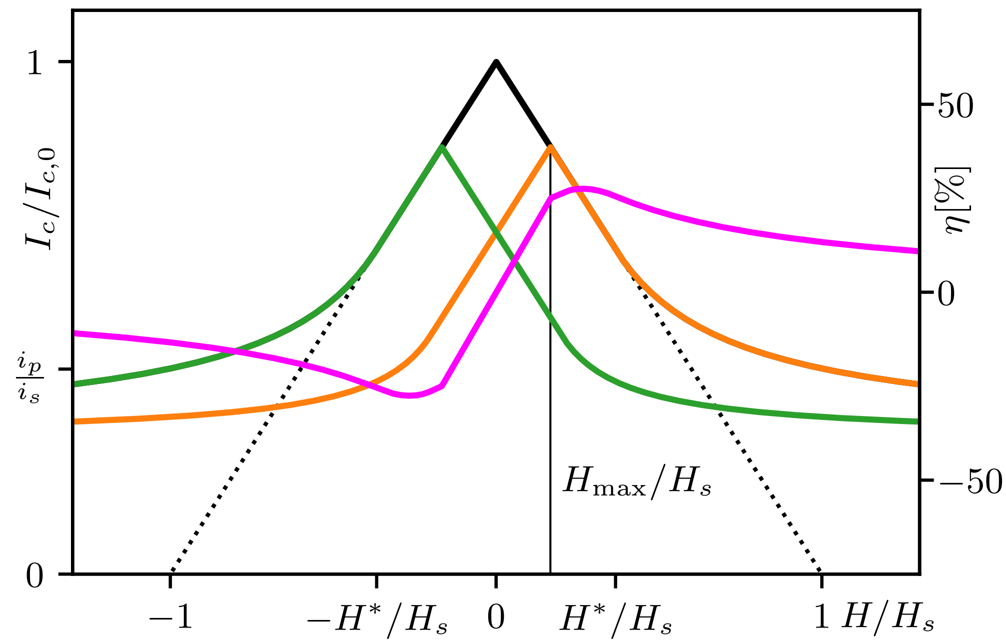
Nonreciprocal transport gives rise to
SC diode effect with efficiency

$$\eta(H) = \frac{I_c^+(H) - I_c^-(H)}{I_c^+(H) + |I_c^-(H)|}$$



Asymmetric films: critical current





Y. Hou, et t al. , arXiv:2205.09276v5

Critical state

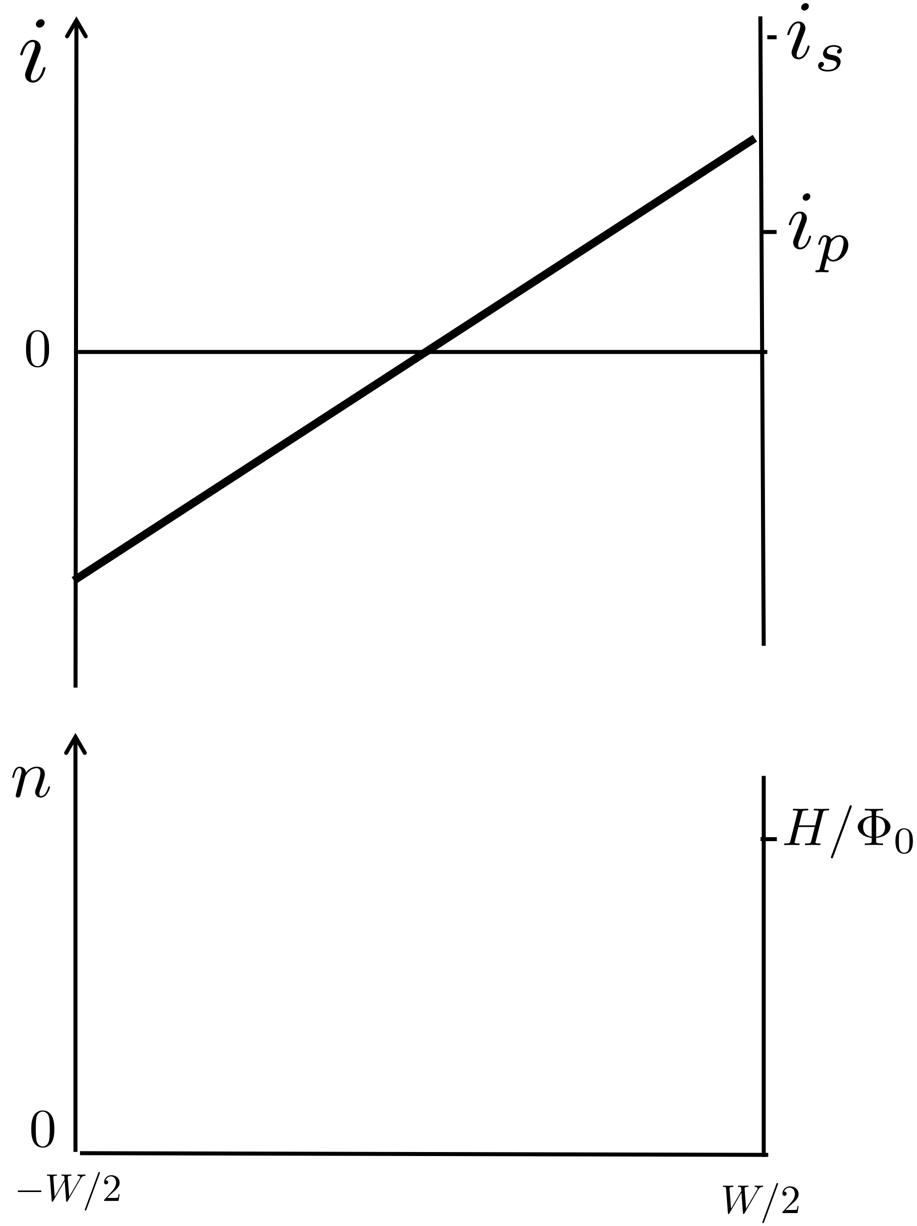
Critical state

Meissner state

In the vortex free region

$$i(y) = \frac{cd\,H}{4\pi\lambda^2} y$$

No vortices



Critical state

$$\mathbf{M} = \frac{1}{2c}\int \mathbf{r}\times\mathbf{j}\,dV$$

For a stripe

$$m = \frac{1}{c}\int dy\, i(y) y$$

In the Meissner state, $|H| < H_s$

$$m = -\frac{dH}{4\pi\lambda^2}\frac{W^3}{24} = -\frac{H}{4\pi}\frac{W^2}{24}\frac{W}{\lambda_\perp}$$

Due to demagnetizing effects it is only by a factor $\sim W/\lambda_\perp$ smaller than the magnetization of a cylinder with diameter W.

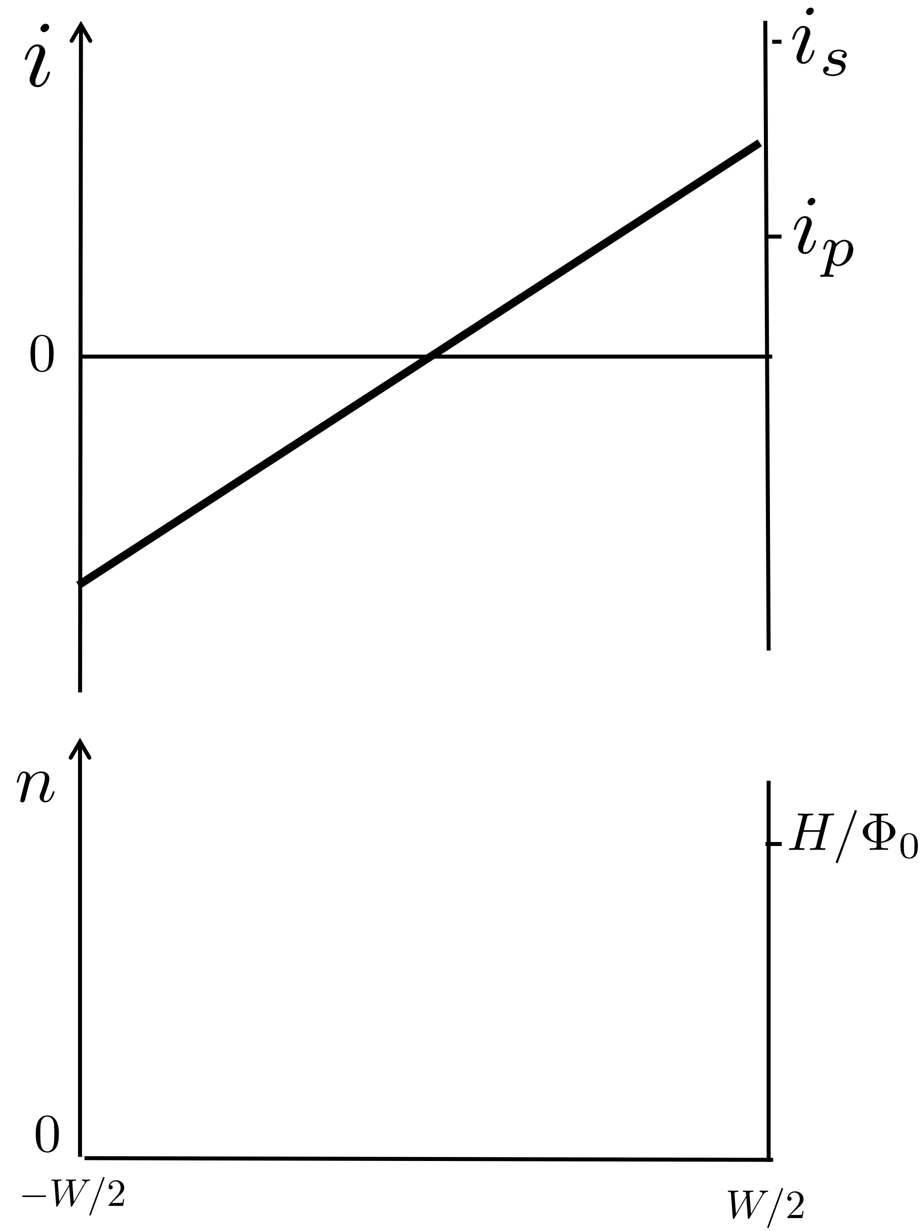
Critical state

Meissner state

In the vortex free region

$$i(y) = \frac{cd\,H}{4\pi\lambda^2}y$$

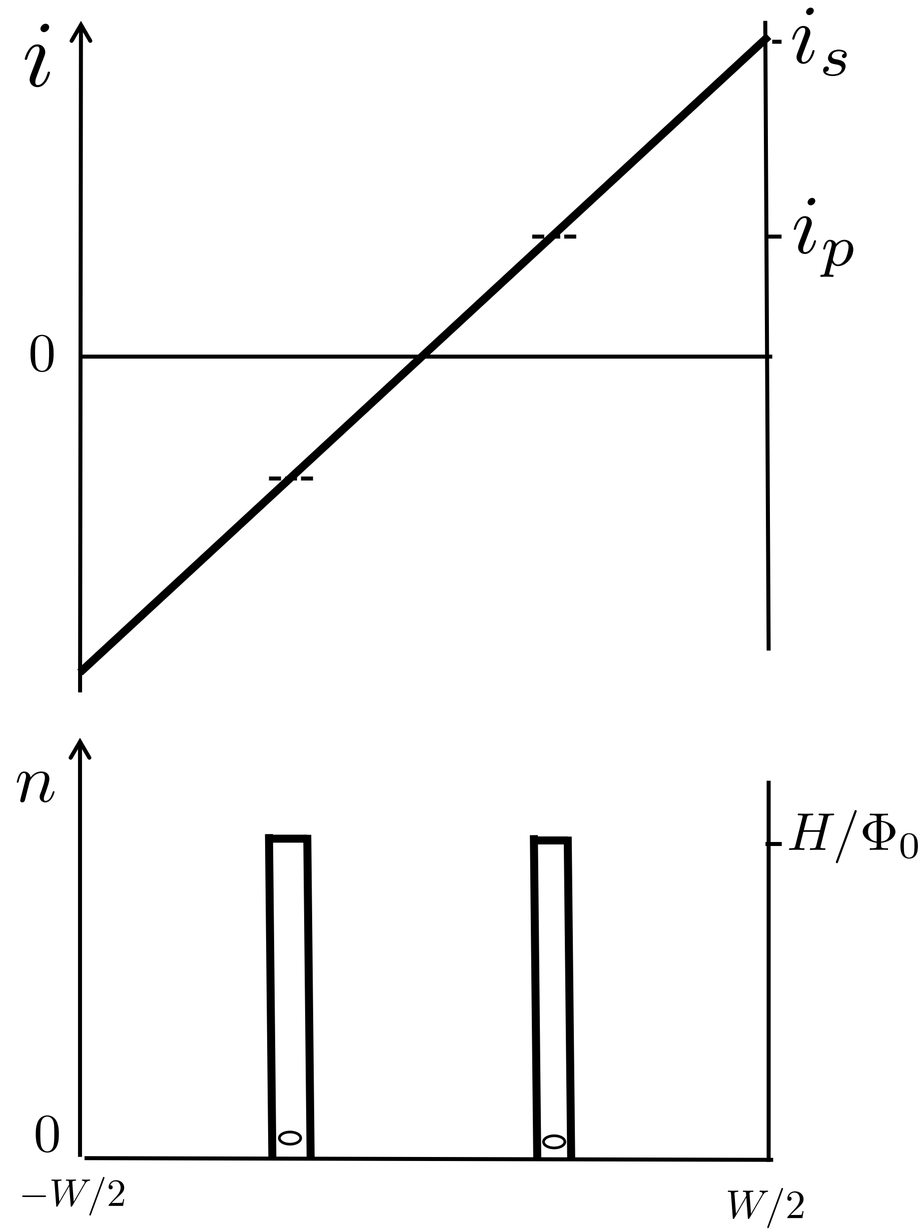
No vortices



Critical state

Just above the penetration field

Vortices start to penetrate, but are trapped in a region where the Meissner current reaches depinning current i_p



Critical state

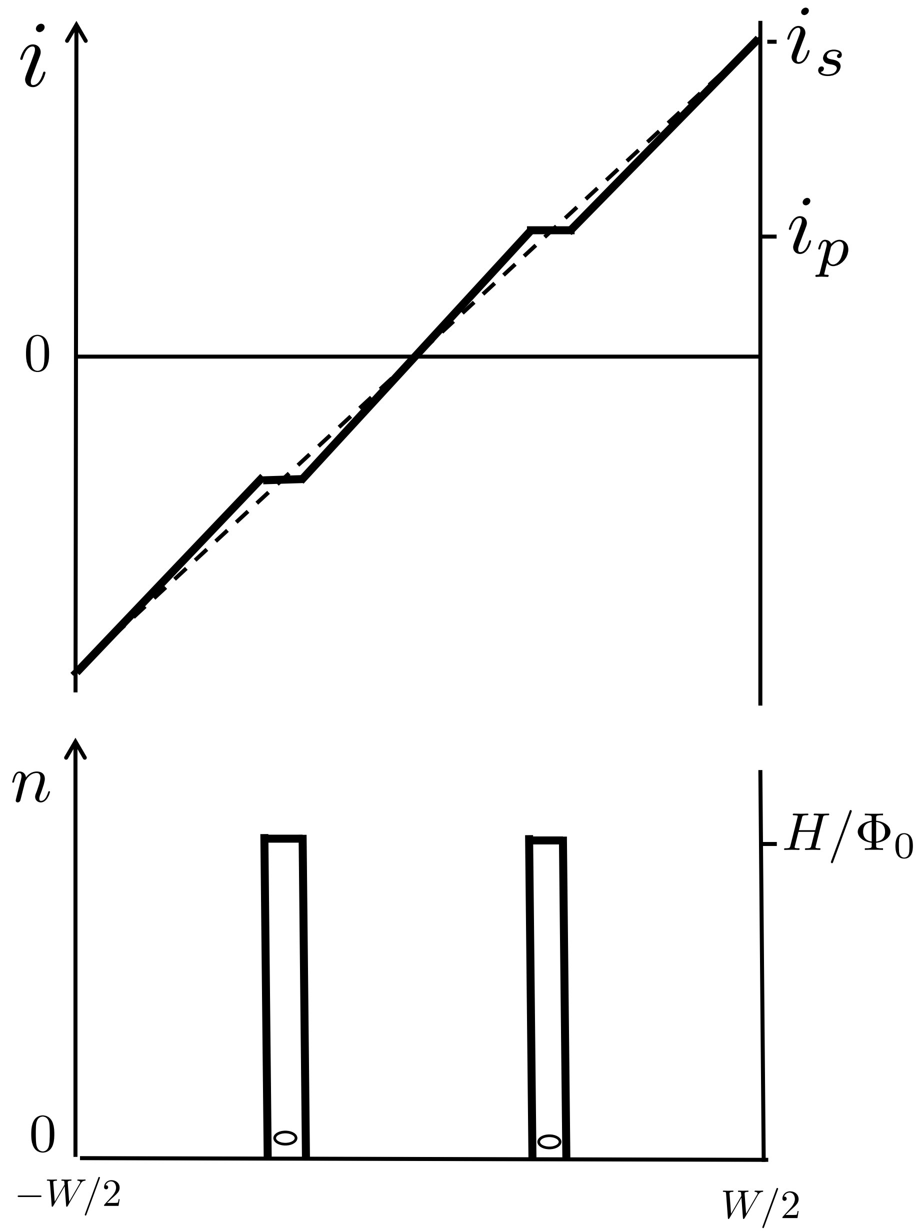
Above the penetration field

In the vortex free region

$$i(y) = \frac{cd\,H}{4\pi\lambda^2} y$$

In the vortex filled region

$$i = i_p \qquad\qquad n = H/\Phi_0$$



Critical state

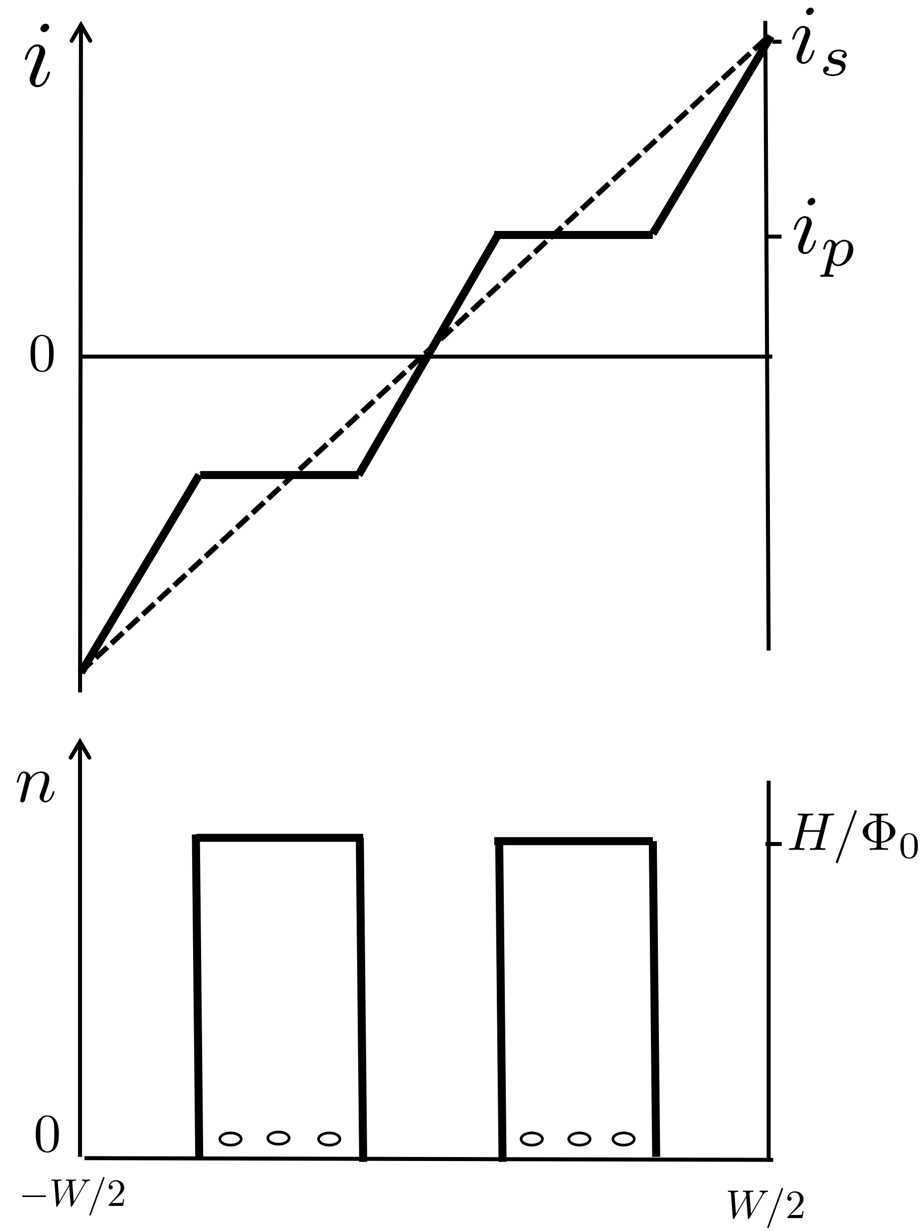
Above the penetration field

In the vortex free region

$$i(y) = \frac{cd\,H}{4\pi\lambda^2} y$$

In the vortex filled region

$$i = i_p \qquad\qquad n = H/\Phi_0$$



Critical state

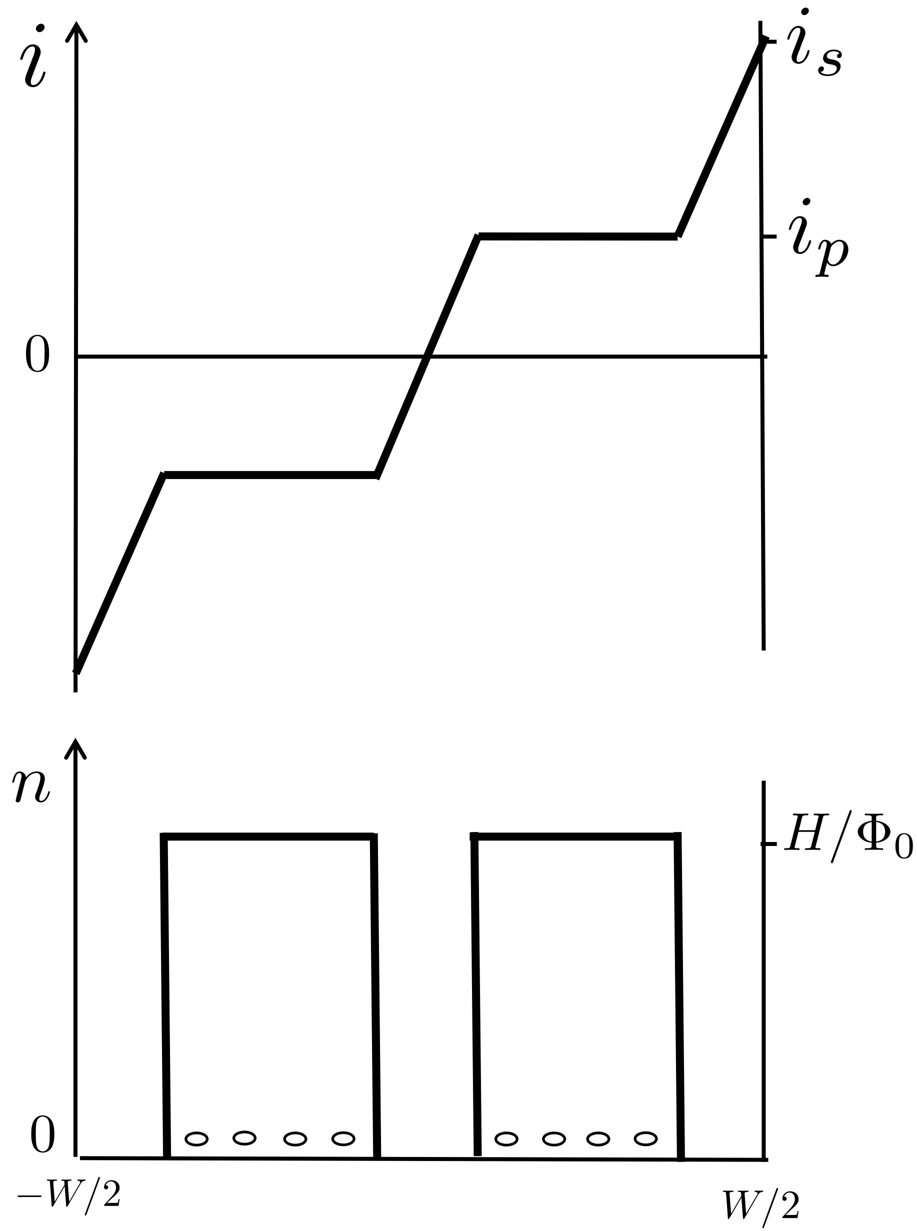
Increasing external field

In the vortex free region

$$i(y) = \frac{cd\,H}{4\pi\lambda^2} y$$

In the vortex filled region

$$i = i_p \qquad\qquad n = H/\Phi_0$$

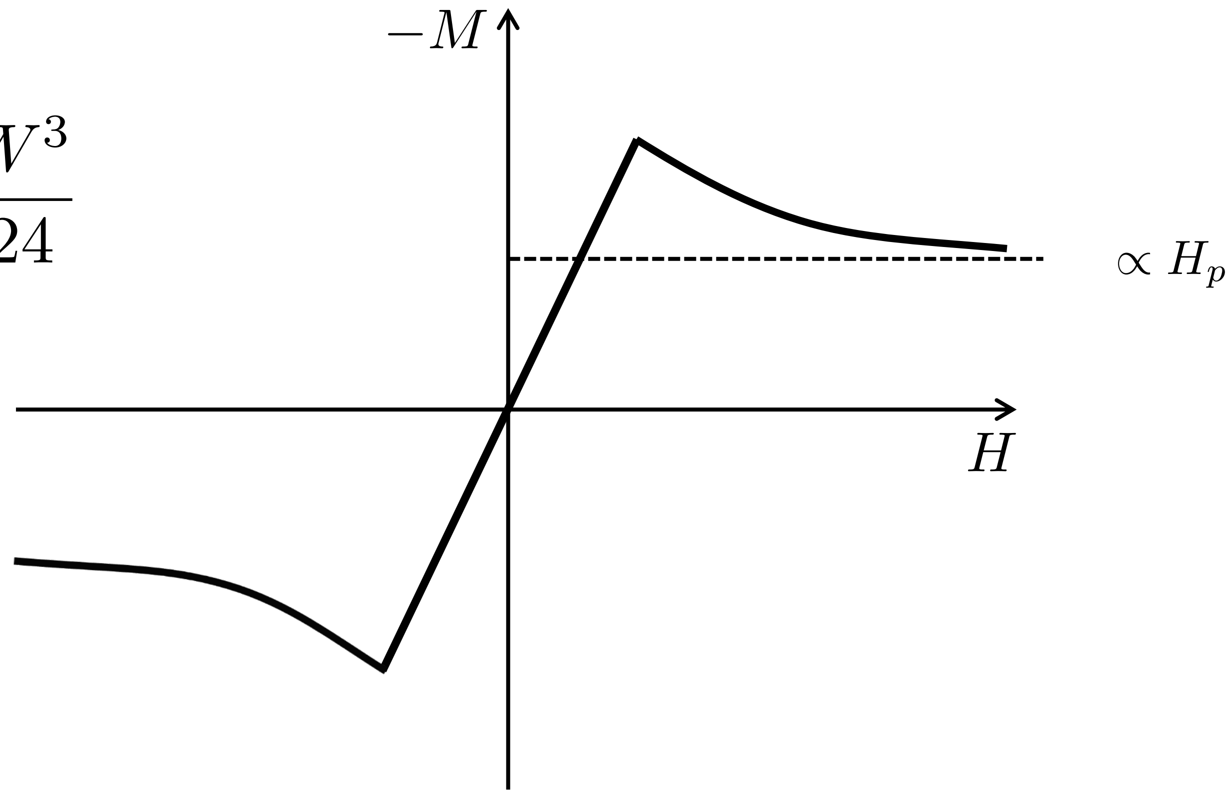


Critical state

Magnetization, $H > H_s$

$$m(H) = \frac{dH}{4\pi\lambda^2}\frac{W^3}{24}\left[1 + \frac{1}{2}\left(1 - \frac{2H^*}{H}\right)^3 - \frac{1}{2}\left(\frac{H_p}{H}\right)^3 - \frac{3}{2}\left(1 - \frac{H_s}{H}\right)\right]$$

$$m(H \to \infty) = \frac{3}{2}\frac{dH_p}{4\pi\lambda^2}\frac{W^3}{24}$$



Critical state

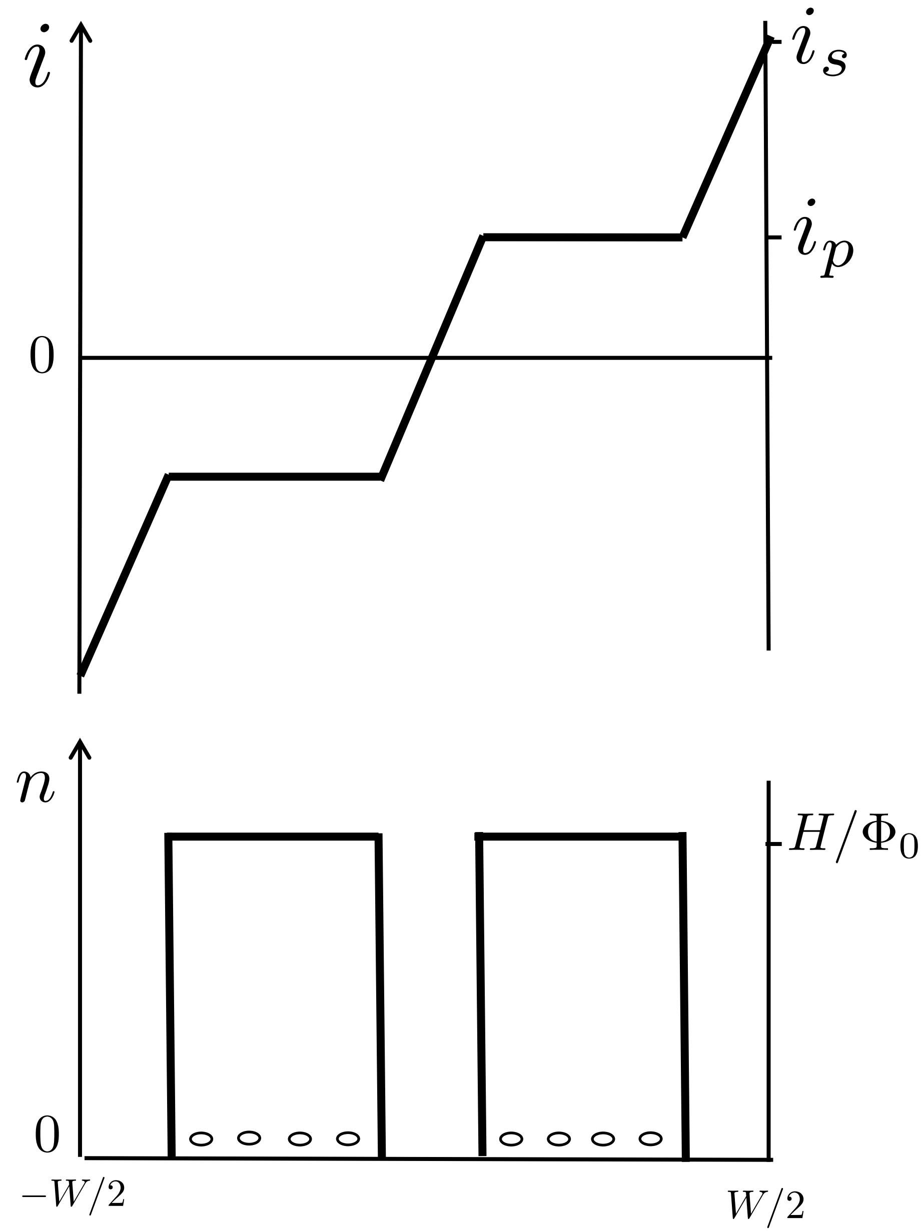
Decreasing external field

In the vortex free region

$$i(y) = \frac{cd\,H}{4\pi\lambda^2}y$$

In the vortex filled region

$$i = i_p \qquad\qquad n = H/\Phi_0$$



Critical state

Decreasing magnetic field from H_0

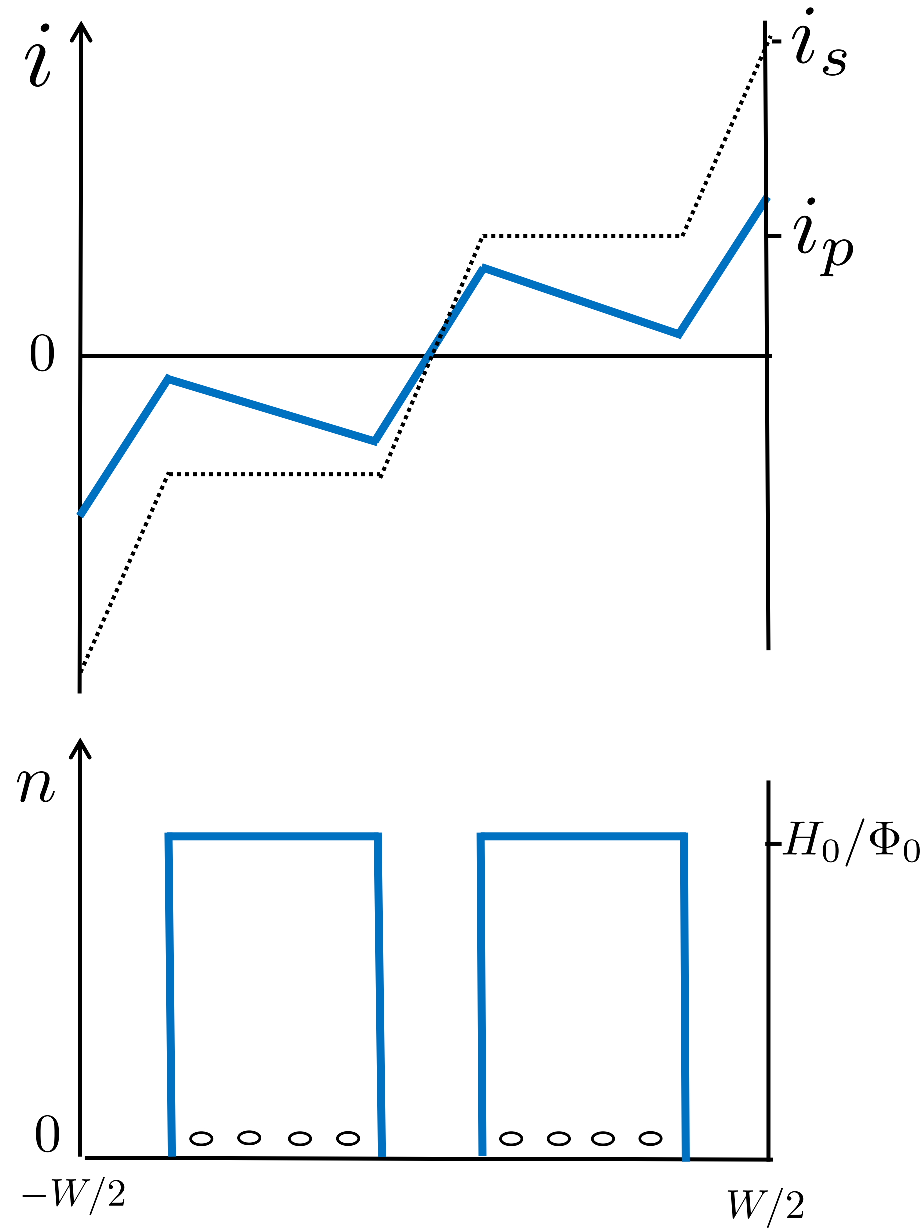
$$\frac{d\,i}{d\,y} = \frac{cd}{4\pi\lambda^2}\left[H - n(y)\Phi_0\right]$$

In the vortex free region

$$i(y) = \frac{cd\,H}{4\pi\lambda^2}y$$

In the vortex filled region $n = H_0/\Phi_0$

$$i(y) = \frac{cd\,(H - H_0)}{4\pi\lambda^2}y + i_p$$

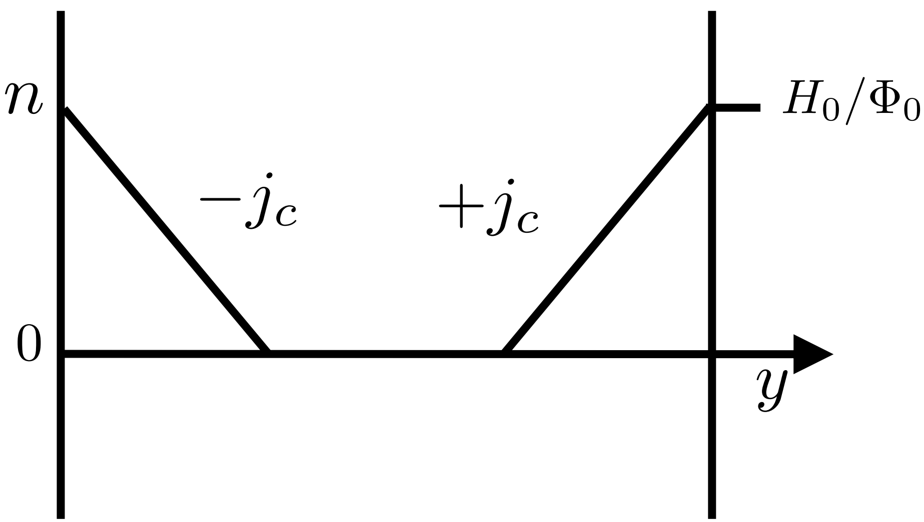


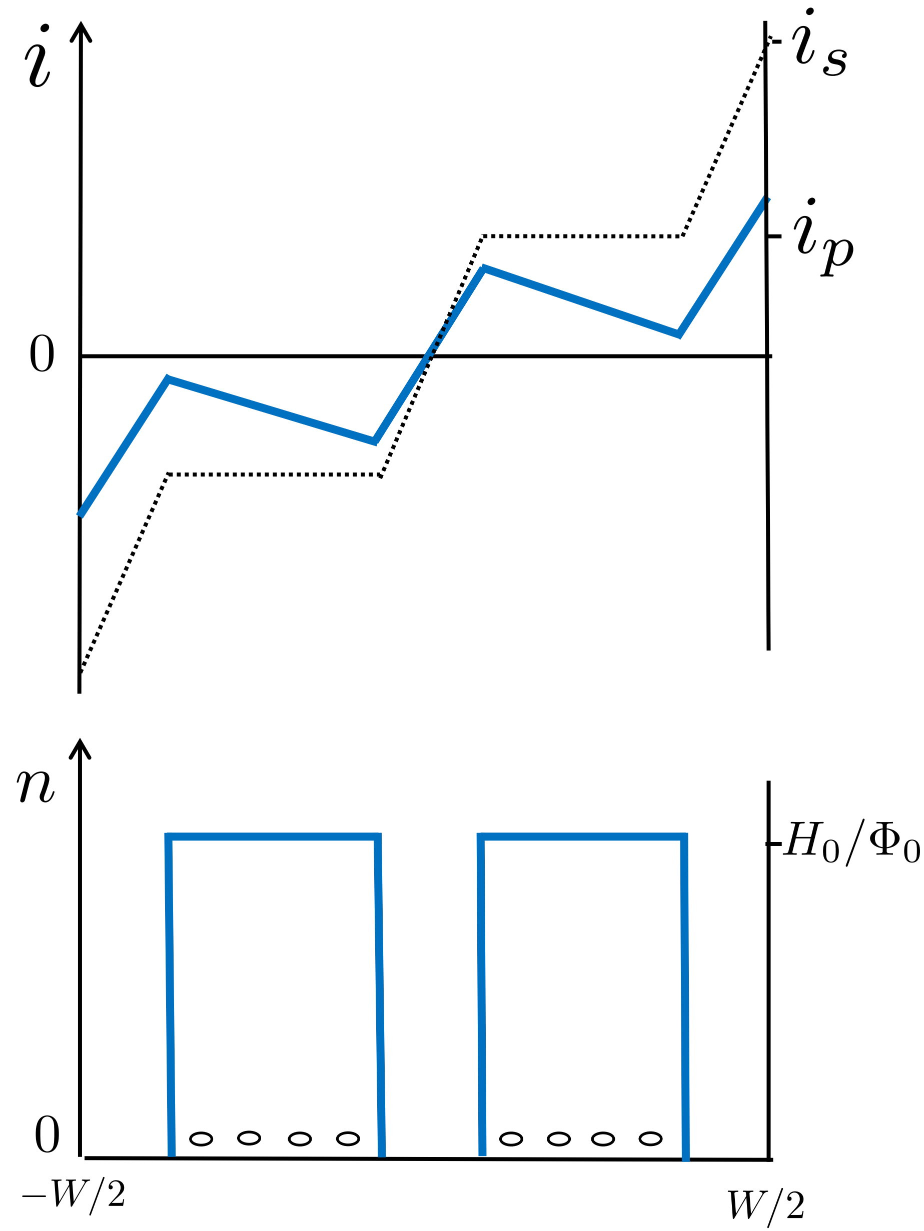
Critical state

Decreasing magnetic field from H_0

In the vortex filled region current can be less than critical current.

Different from the usual sand pile Bean model.



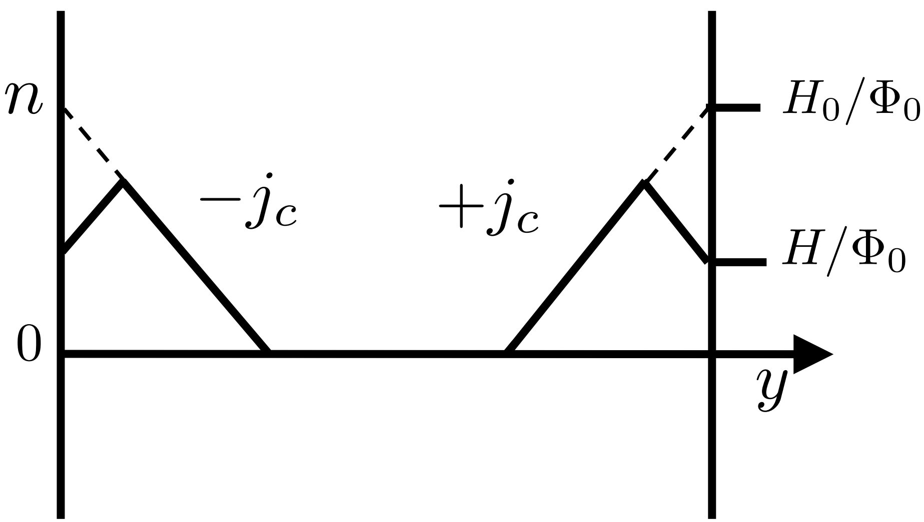


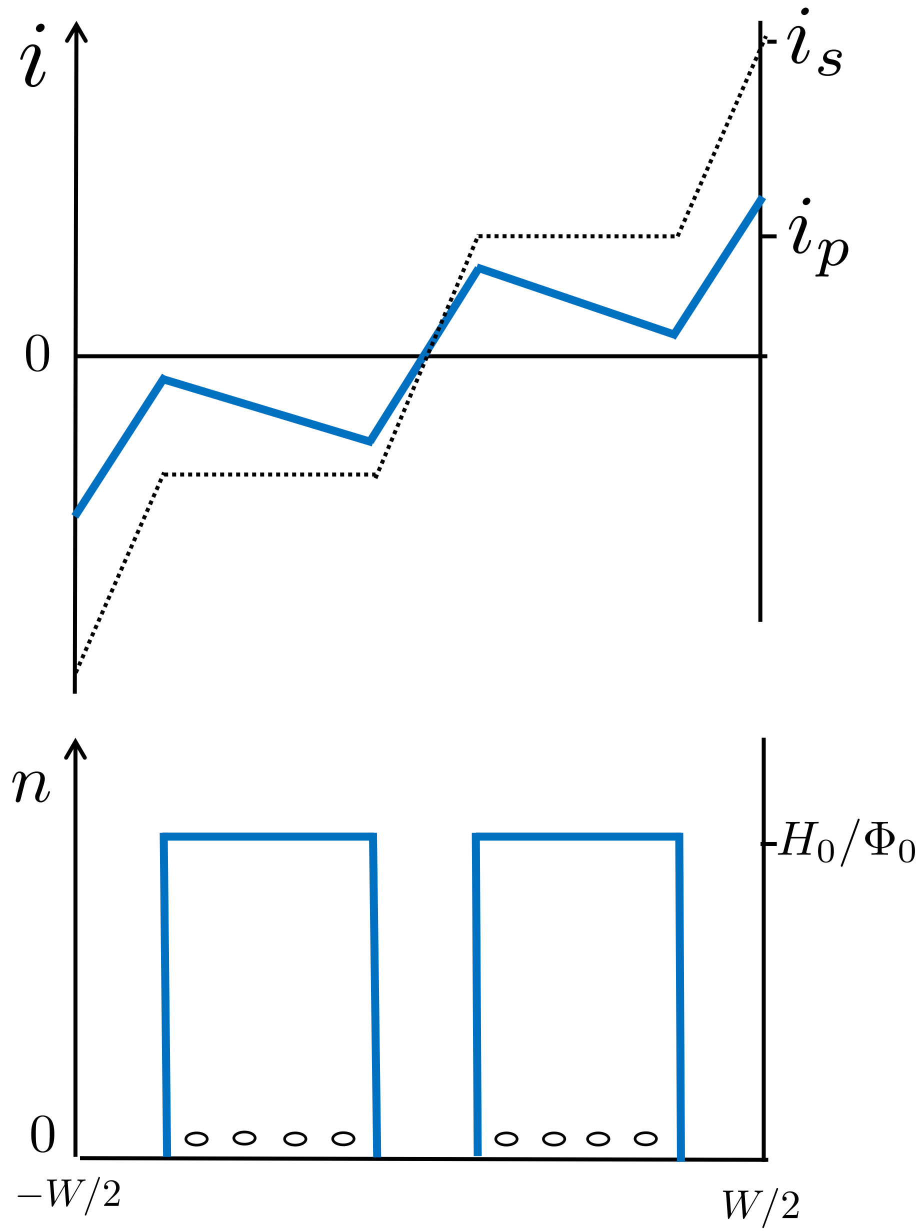
Critical state

Decreasing magnetic field from H_0

In the vortex filled region current can be less than critical current.

Different from the usual sand pile Bean model.





Critical state

Decreasing magnetic field from H_0

$$\frac{d\,i}{d\,y} = \frac{cd}{4\pi\lambda^2}\left[H - n(y)\Phi_0\right]$$

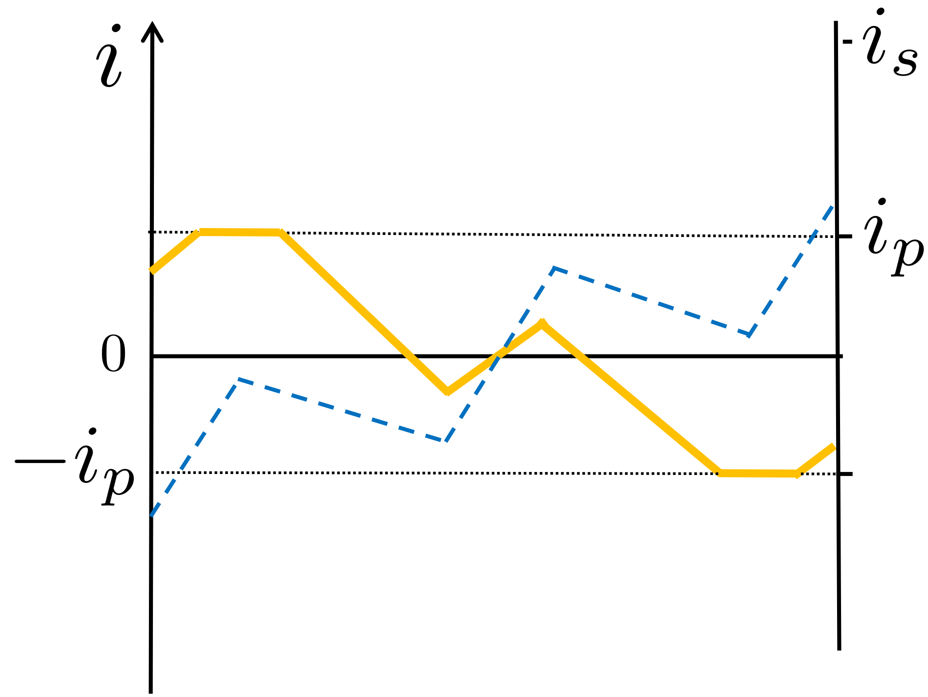
In the vortex free region

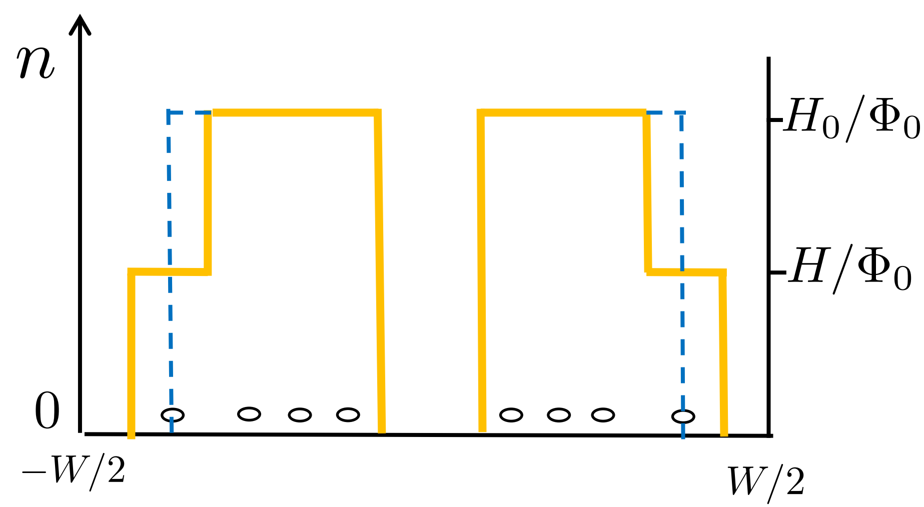
$$i(y) = \frac{cd\,H}{4\pi\lambda^2}y$$

In the vortex filled region $n = H_0/\Phi_0$

$$i(y) = \frac{cd\,(H - H_0)}{4\pi\lambda^2}y + i_p$$

When current in the vortex plateau drops below $-i_p$ vortices move out





Critical state

Decreasing magnetic field from H_0

$$\frac{d\,i}{d\,y} = \frac{cd}{4\pi\lambda^2}\left[H - n(y)\Phi_0\right]$$

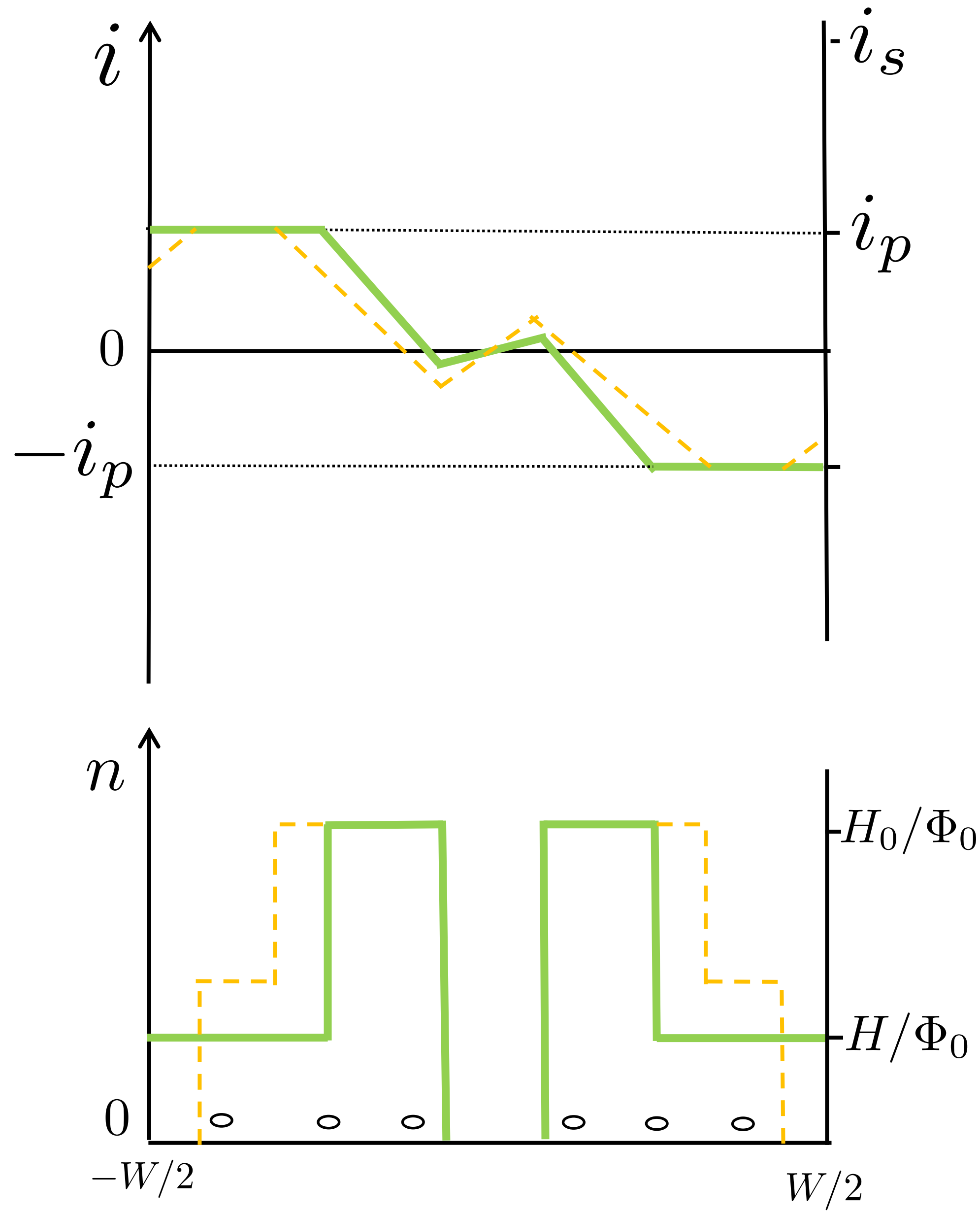
In the vortex free region

$$i(y) = \frac{cd\,H}{4\pi\lambda^2}y$$

In the vortex filled region $n = H_0/\Phi_0$

$$i(y) = \frac{cd\,(H - H_0)}{4\pi\lambda^2}y + i_p$$

At lower fields vortices start to leave the sample



Critical state

Decreasing magnetic field from H_0

$$\frac{d\,i}{d\,y} = \frac{cd}{4\pi\lambda^2}\left[H - n(y)\Phi_0\right]$$

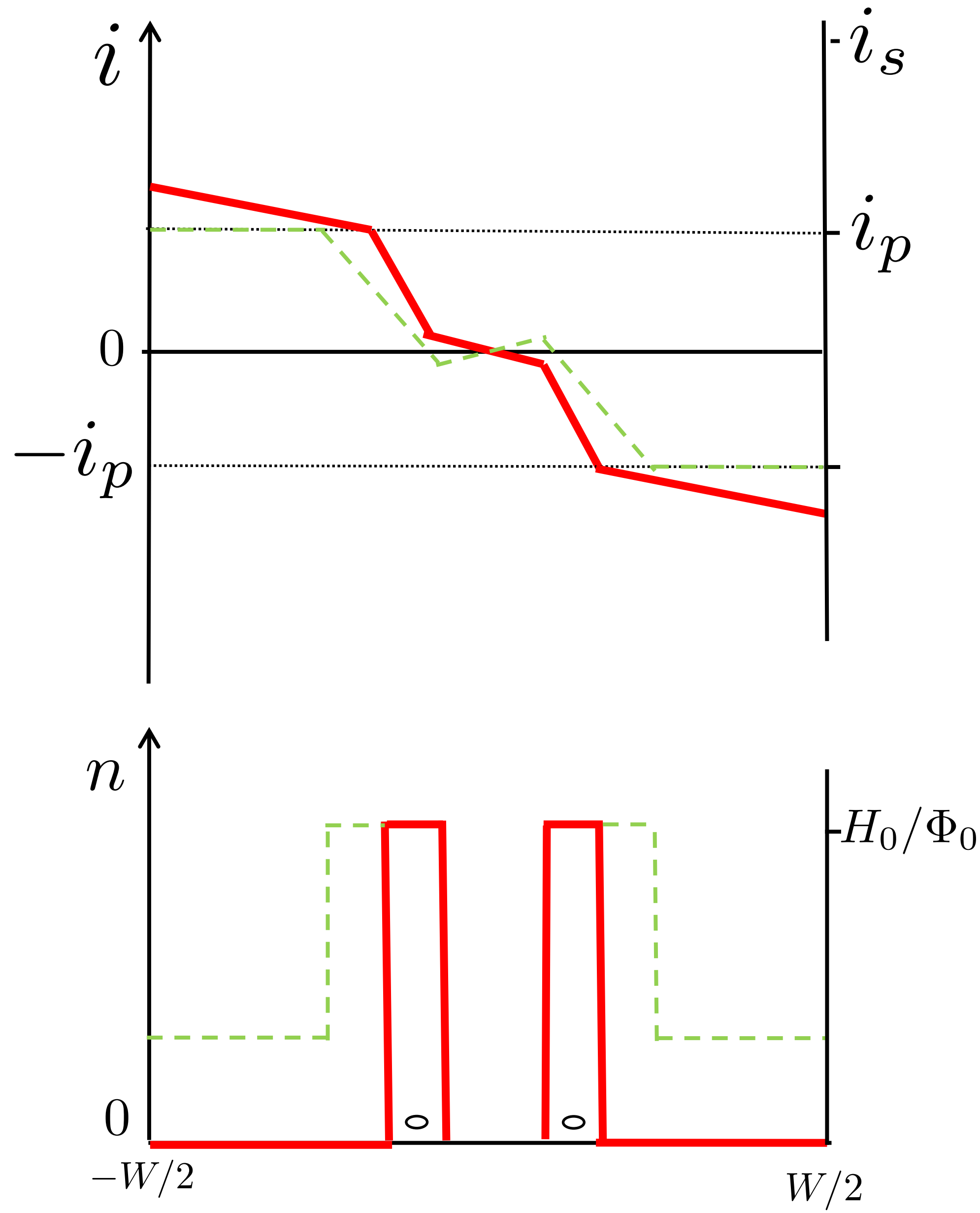
In the vortex free region

$$i(y) = \frac{cd\,H}{4\pi\lambda^2}y$$

In the vortex filled region $n = H_0/\Phi_0$

$$i(y) = \frac{cd\,(H - H_0)}{4\pi\lambda^2}y + i_p$$

Later outer plateau disappears and we have the Meissner state there



Critical state

Decreasing magnetic field from H_0

$$\frac{d\,i}{d\,y} = \frac{cd}{4\pi\lambda^2}\left[H - n(y)\Phi_0\right]$$

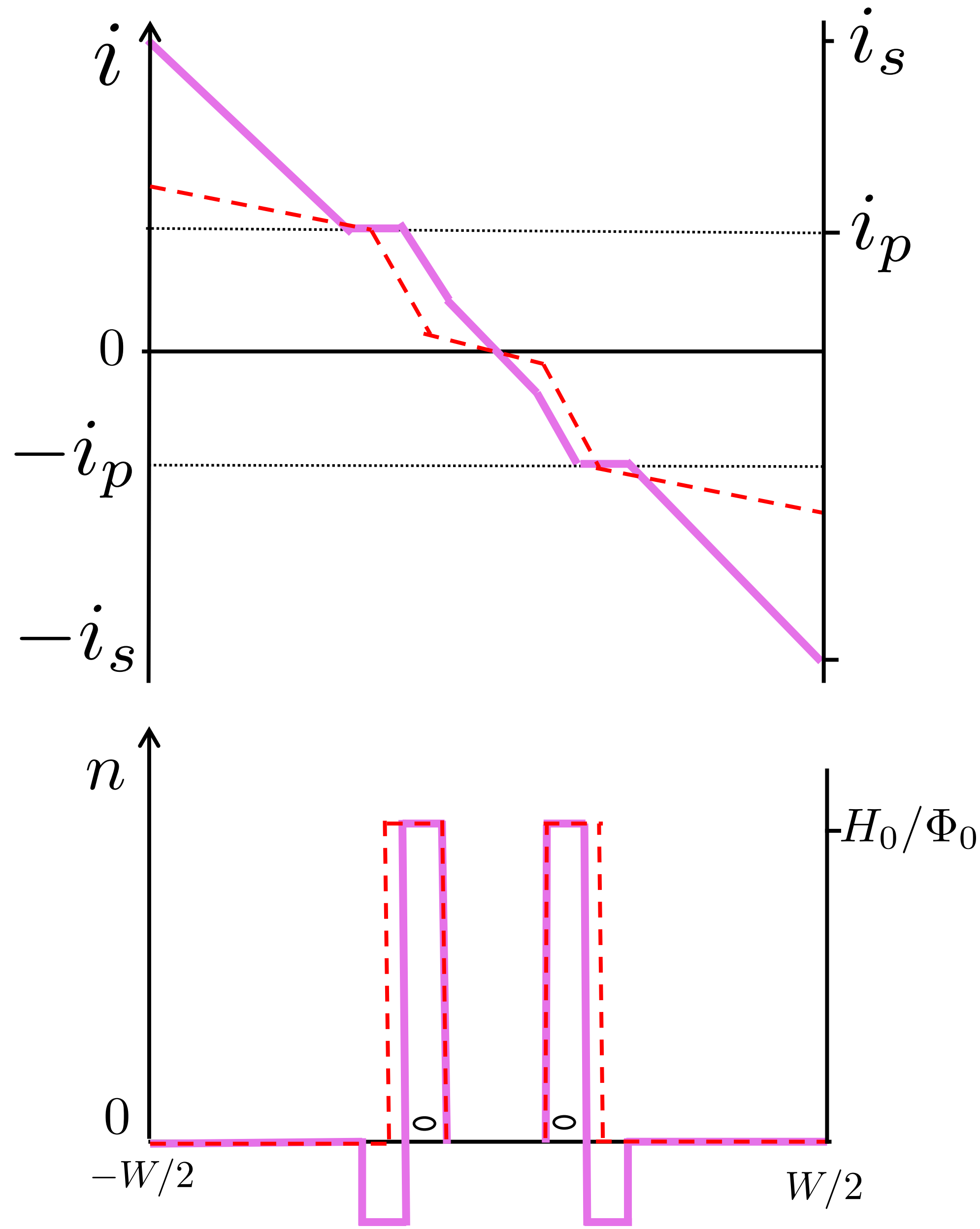
In the vortex free region

$$i(y) = \frac{cd\,H}{4\pi\lambda^2}y$$

In the vortex filled region $n = H_0/\Phi_0$

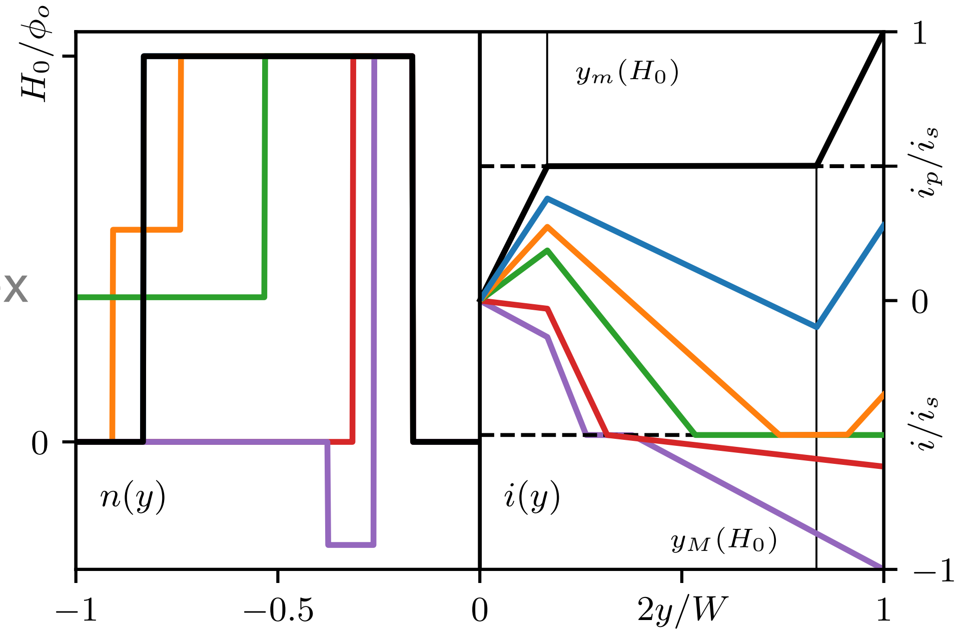
$$i(y) = \frac{cd\,(H - H_0)}{4\pi\lambda^2}y + i_p$$

Eventually antivortices appear from the edges

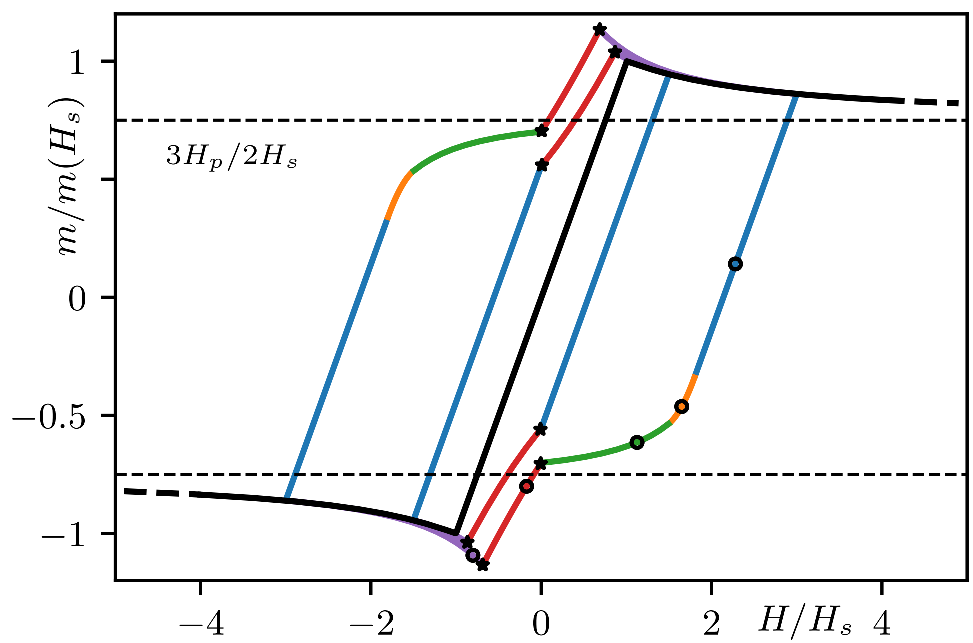


- **Summary of different regimes**

- **Imaging:** vortices coexist next to antivortex inside thin film



- **Magnetic moment**



Conclusions

- For atomically thin superconducting films the penetration length $\lambda_\perp = \lambda^2/d$ can easily exceed the sample width, allowing magnetic field to fully penetrate inside the system.
- Domination of surface barrier.
- Asymmetric edges lead to nonsymmetric $I_c(H)$ and to superconducting diode effect.
- The critical state of such superconductors looks very different from the usual Bean state in bulk materials.

Thank you for you attention.