Grenoble

Néel institut

Grenoble

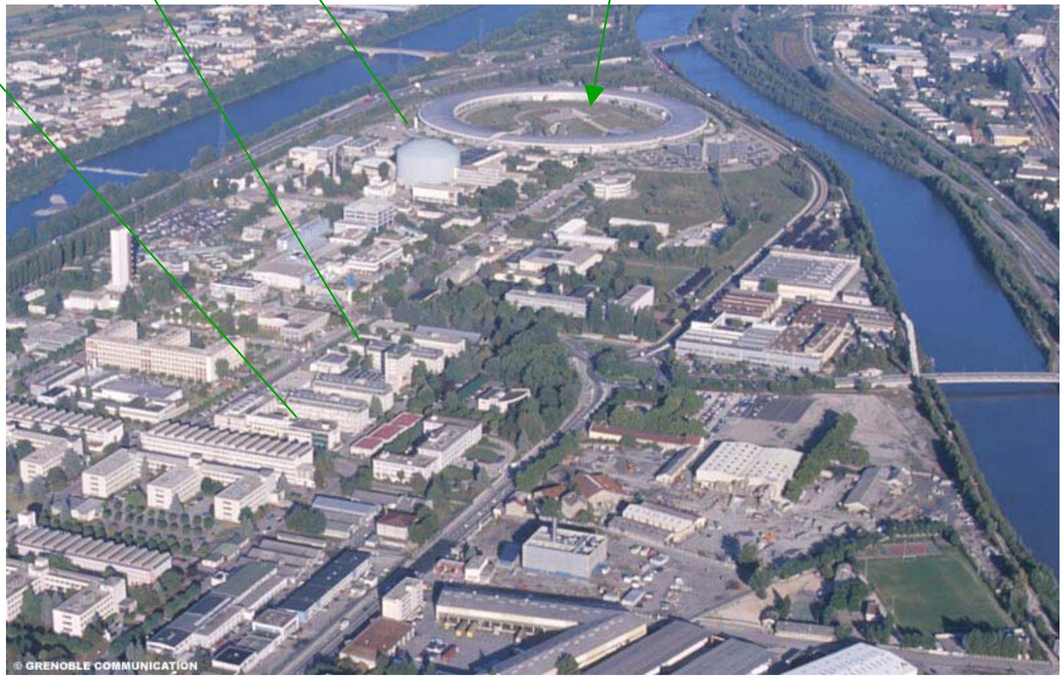
I Néel

Ghmfl (35T)

ILL

ESRF

CEA



University Joseph Fourier

Penetration depth

P. Rodière

H-$NbSe_2$

Superconducting at T_c=7K.

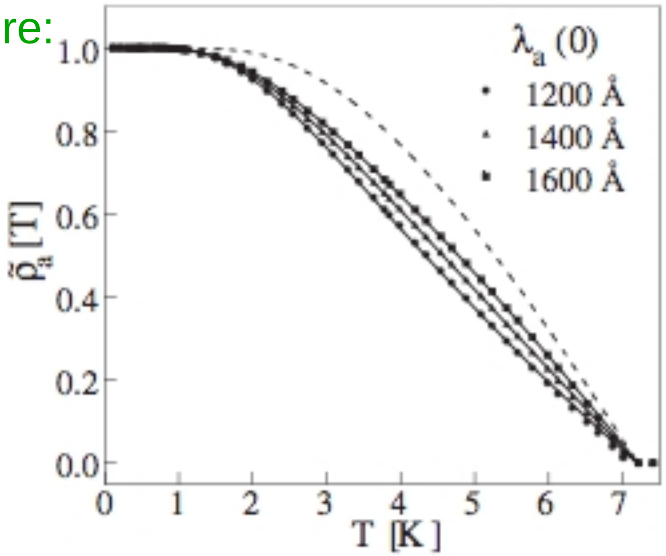
↕

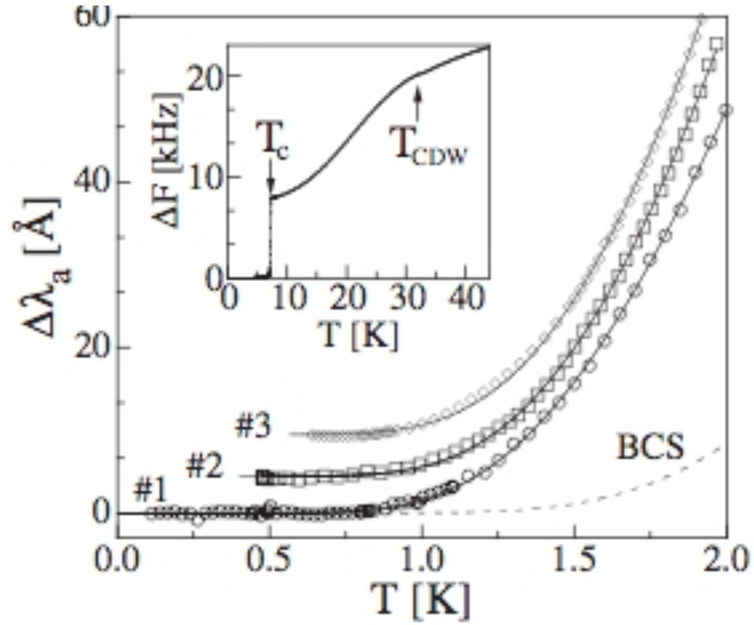
Charge density wave ordering at T=33K

One gap of two Nb sheets is reduced by CDW

High temperature: two gaps

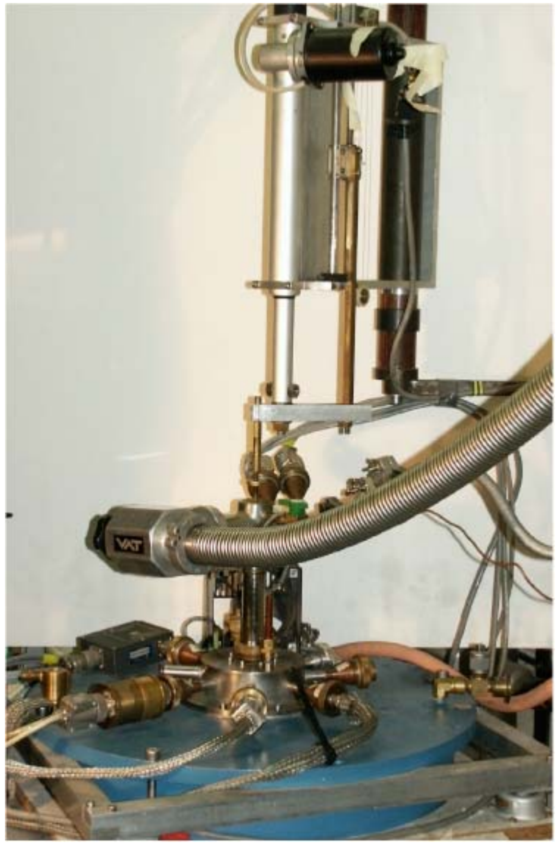
Superfluid density





PRL 98, 057003 (2007)

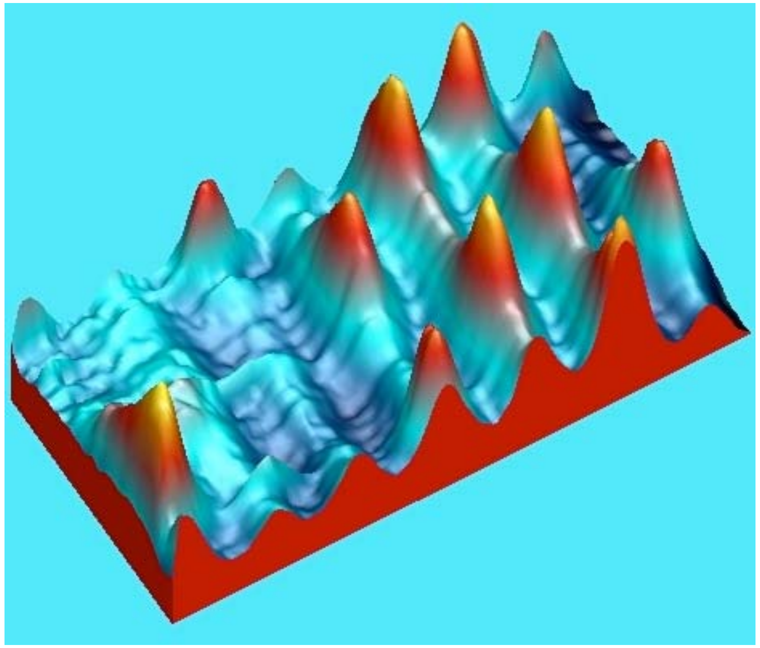
Magnetometry at 100mK C. Paulsen



developed by C. Paulsen

- absolute Values of M and χ
- high sensitivity: (10^{-7} à 10^{-9} emu)
- TBT (T_{min} = 75 mK), champ fort (≤ 8 T)
- frequency range (1mHz à 15kHz)
- high stability

Vortex coalescence, vortex chains and crossing vortices in the anisotropic spin-triplet superconductor Sr_2RuO_4



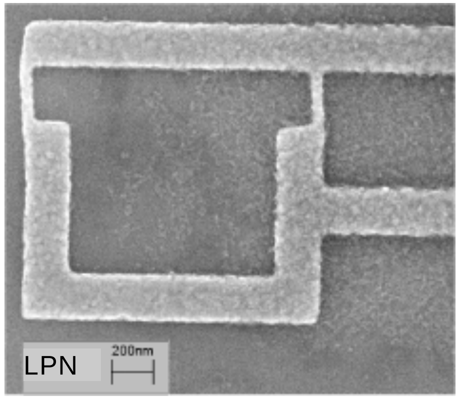
Klaus Hasselbach

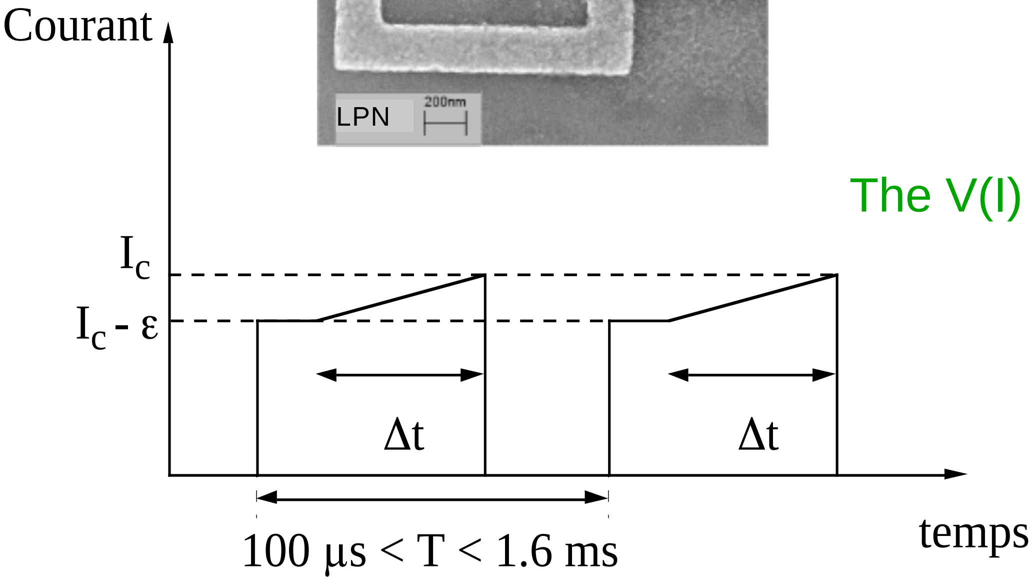
Voicu O. Dolocan

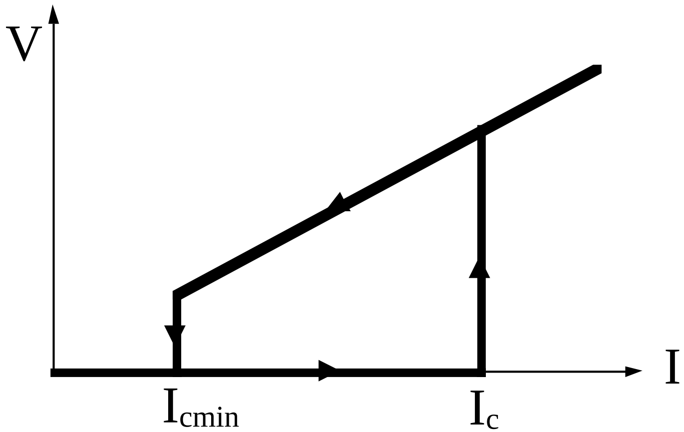
outline

- Grenoble scanning µSQUID microscopy
- Sr_2RuO_4 overview
- Sr_2RuO_4 Vortex state
- Quantitative SµSM G2

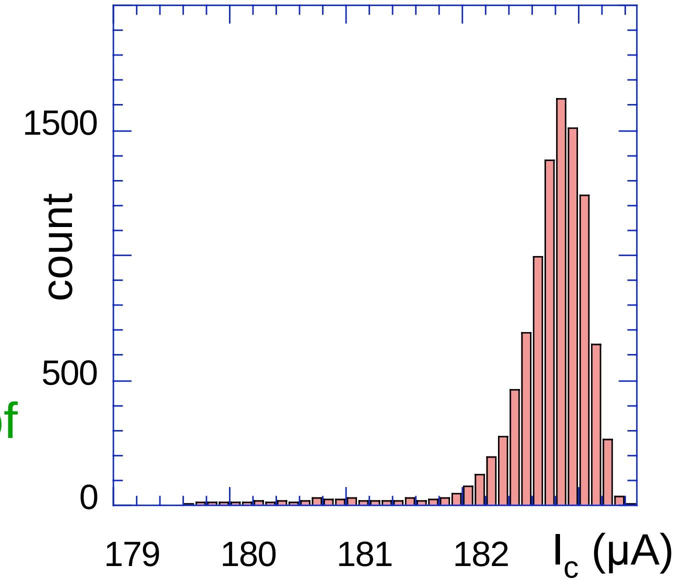
Principle of the µSQUID measurement







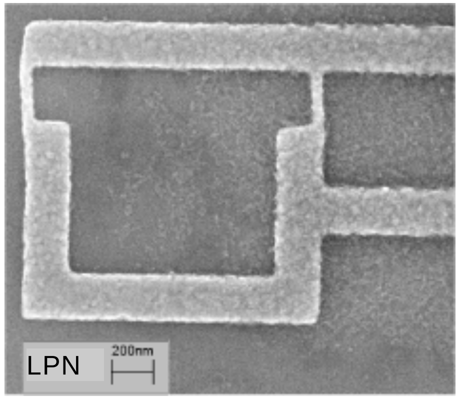
The V(I) characteristic of a µSQUID is hysteretic.

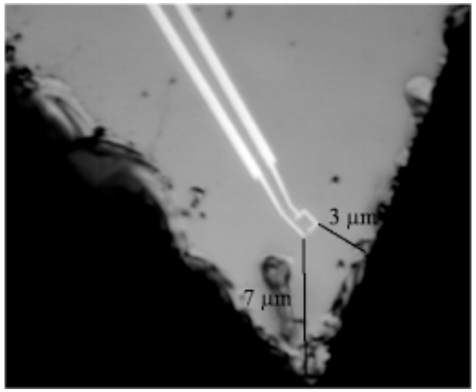


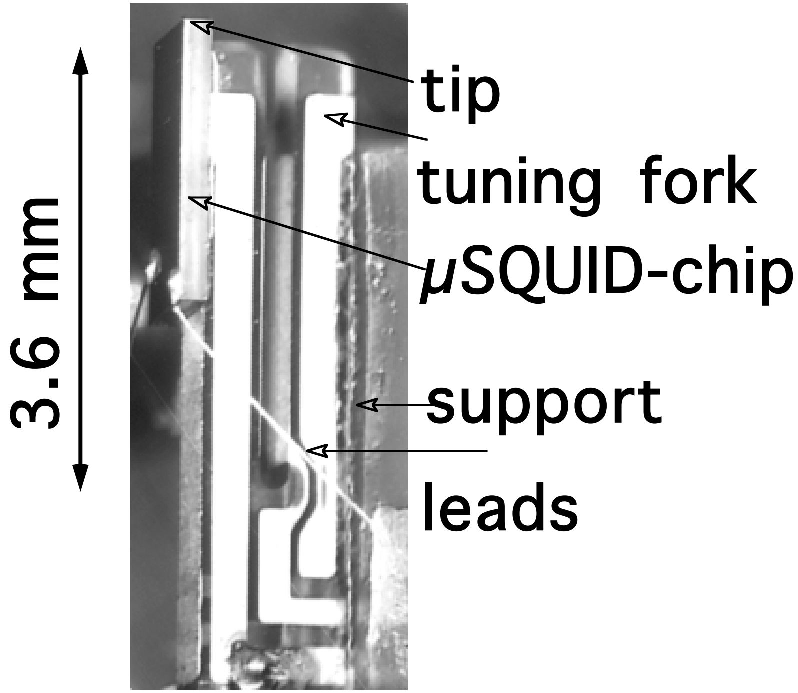
sampling frequency of 10 kHz, flux sensitivity of the µSQUID is: $10^{-5}\ \Phi_0 / \sqrt{\text{Hz}}$

µSQUID Scanning Force Microscope

- Vortex imaging: penetration depth sets lower limit to spatial resolution
- Al SQUID loop of 1.2µm diameter





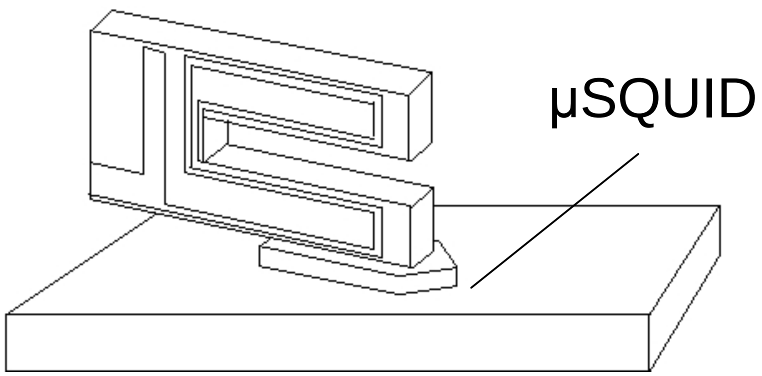


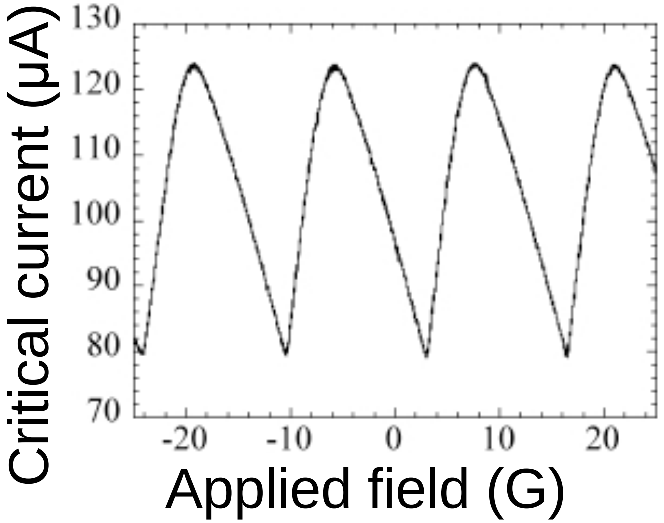
- High magnetic field sensitivity

- The tuning fork is used for distance control between the SQUID and the sample

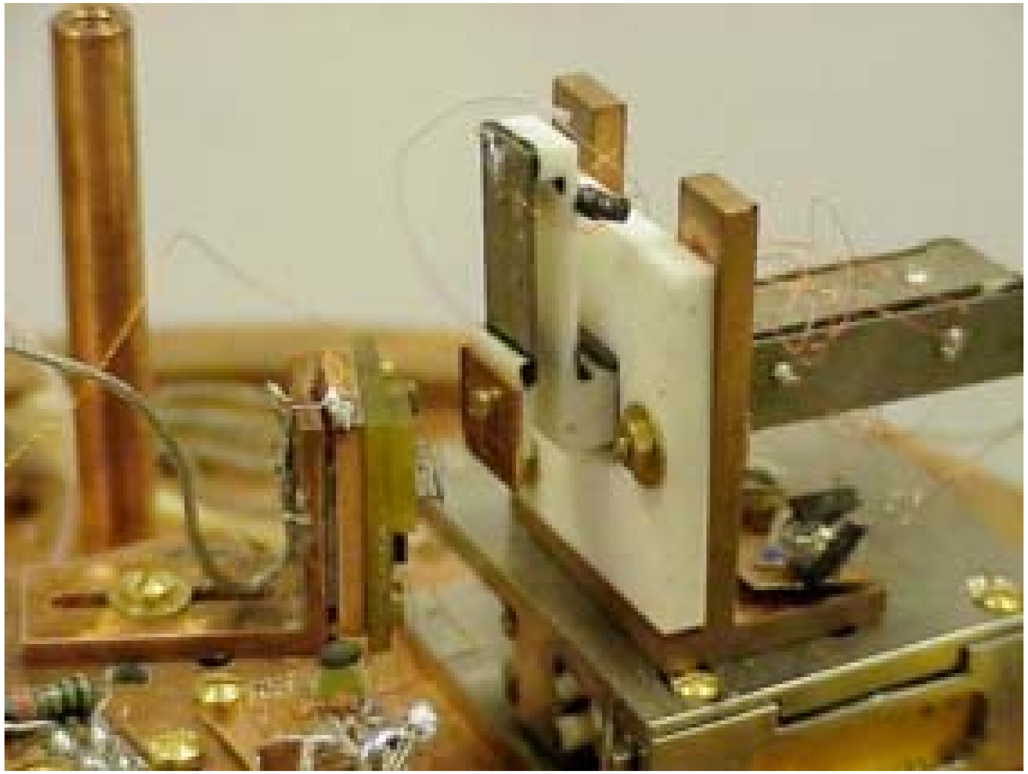
C. Veauvy et al., RSI 73, 3825(2002)

µSQUID Scanning Force Microscope



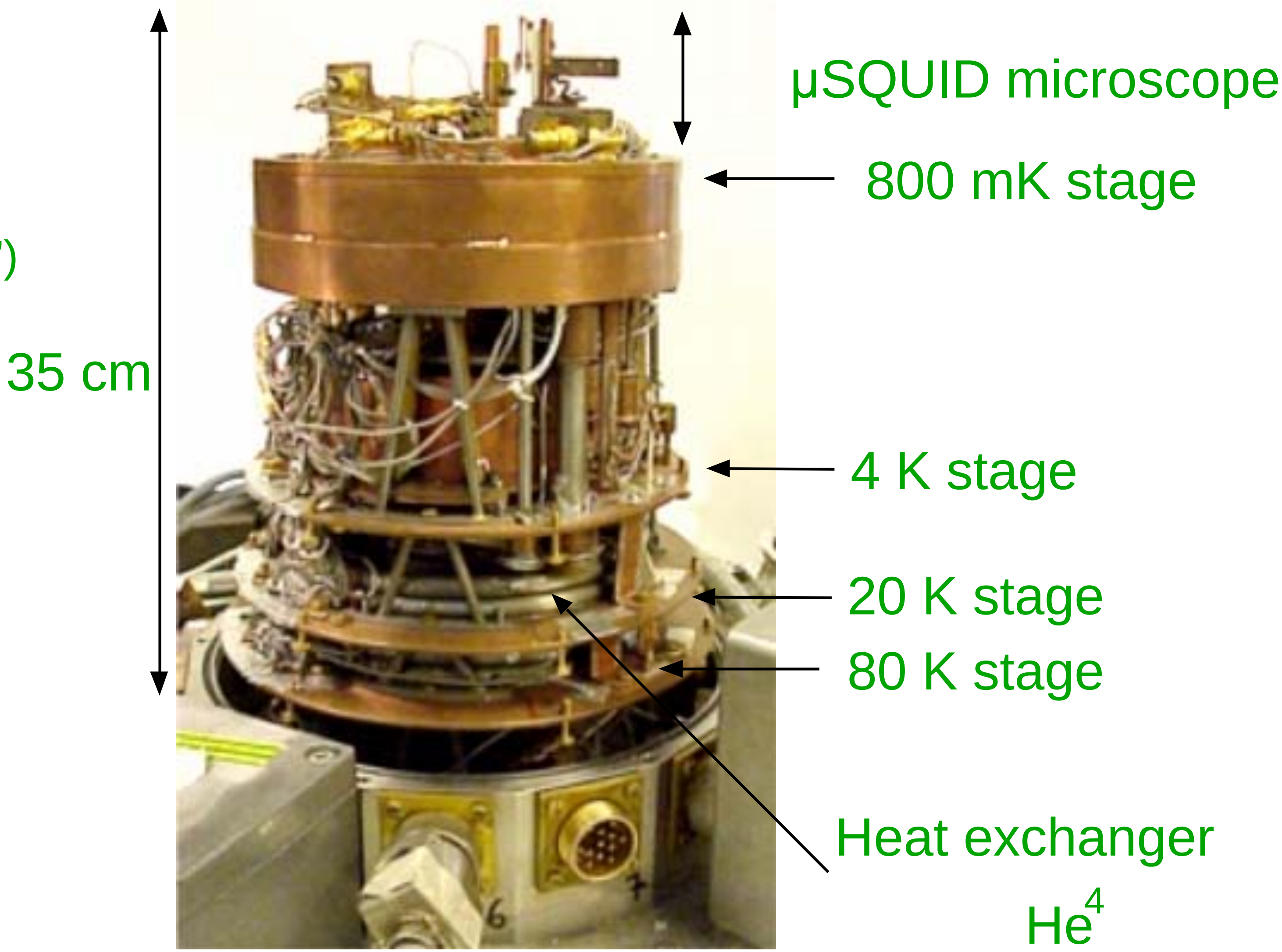


µSQUID Scanning Force Microscope



Dilution refrigerator

inverted dilution refrigerator (“Sionludi”)
T_{min} = 0.025 K
(A. Benoit
and M. Caussignac
I. Néel-CNRS
Commercialized

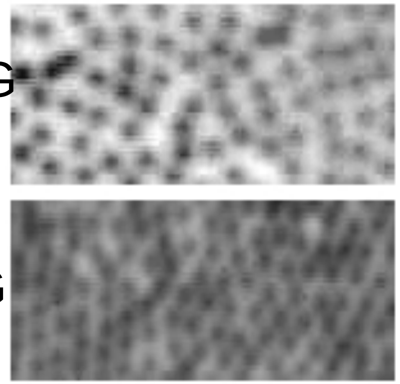


$NbSe_2$ Formation of vortex lattice

H ∥ c, FC

Low fields (< 4 Gauss) no correlation between vortices

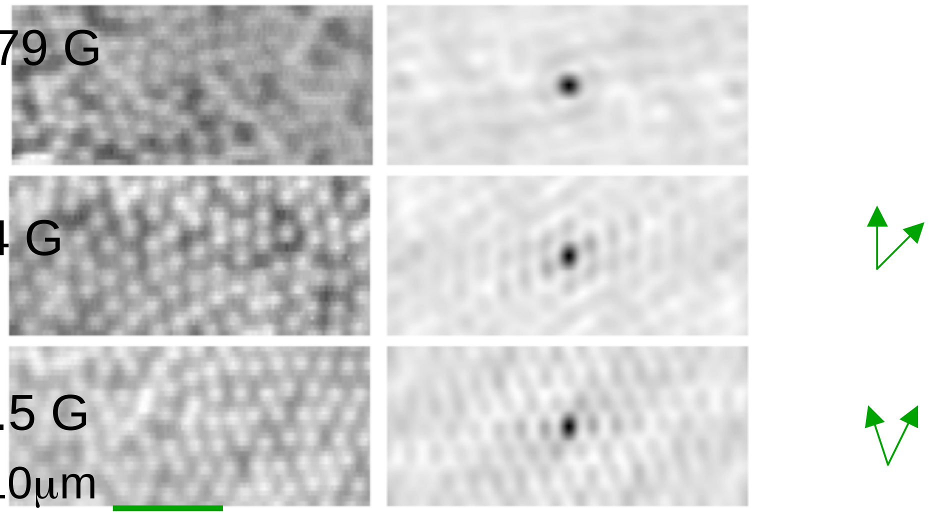
Higher field (5 Gauss) vortices close together
➡ regular lattice appear



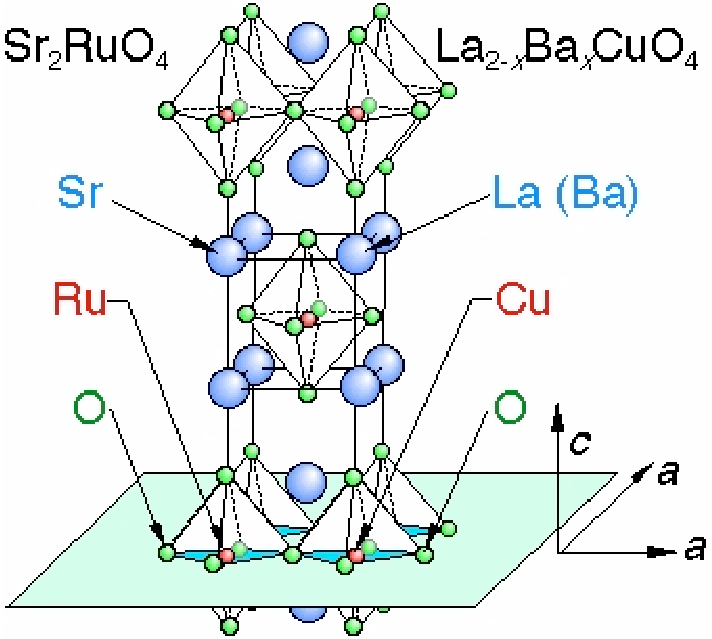
Intermediate region (3.8-5 Gauss)

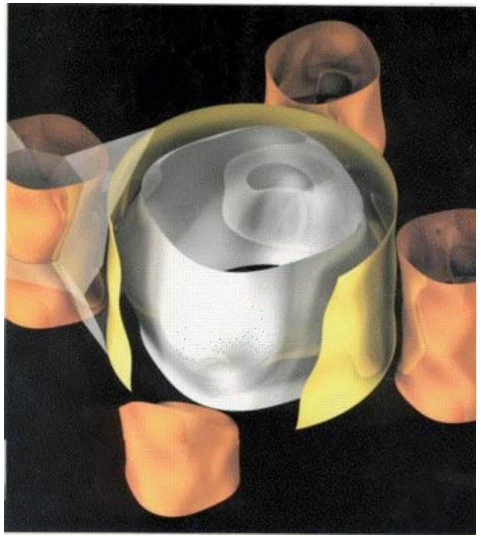
Increasing the field the vortex lattice changes orientation

The lattice is not fixed by the crystallographic axes



Sr_2RuO_4 Structure and Properties





2D Fermi cylindrical surface

Perovskite structure with distance between ab planes c=12.5Å

	ab	c
ξ (0) (Å)	660	33
λ (Å)	1500	30000
$H_{c1}(0)$ (G)	10	50

Maeno, Sigrist, Rice Physics Today 54, 42, (2001)

Spontaneous magnetization in zero field

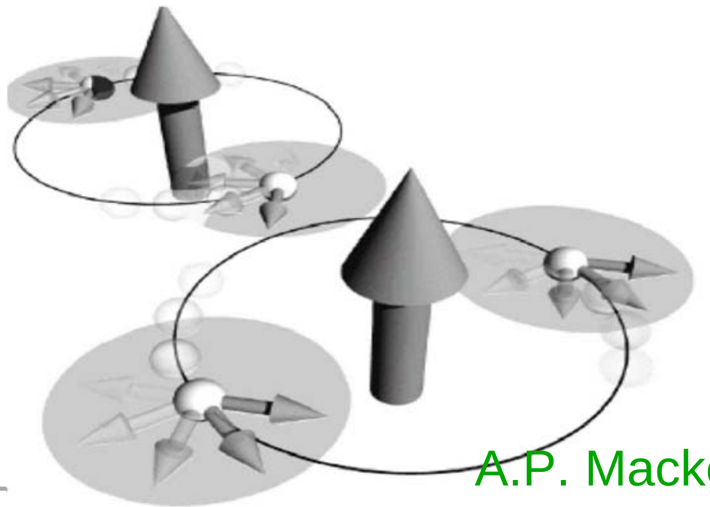
- μSR technique Luke Nature
- magneto optical Kerr effect Kapitulnik PRL 2007

time-reversal symmetry is broken at T_c

⇓

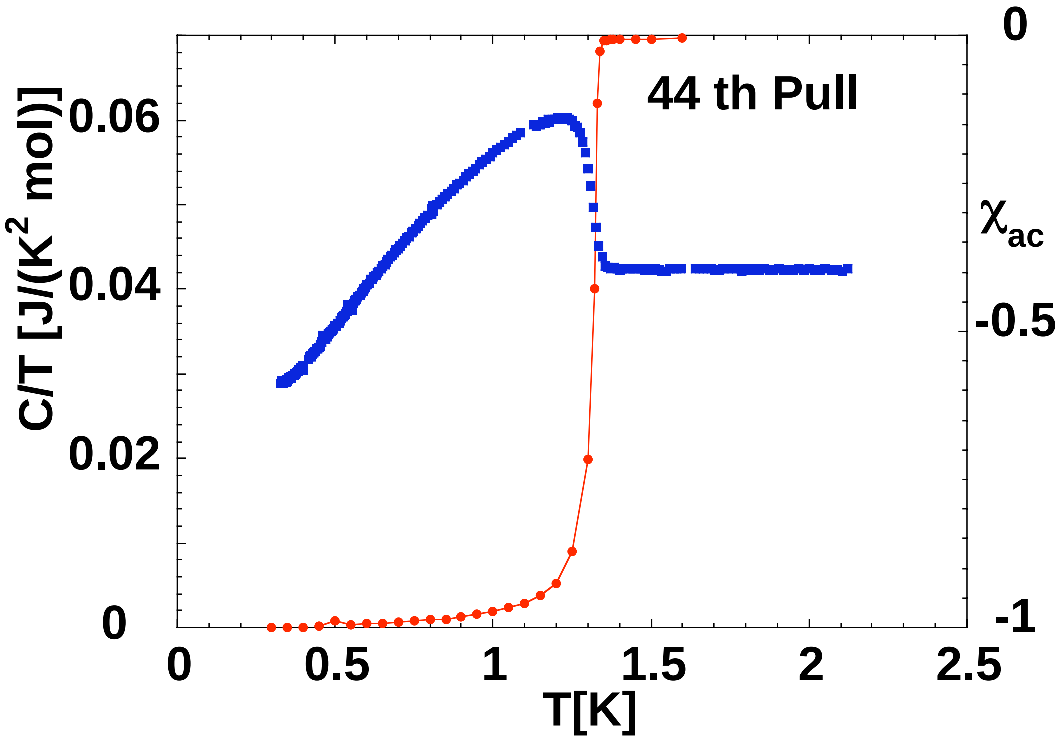
multidimensional order parameter

Detection of domain walls in sc state (Moler and Kirtley)



A.P. Mackenzie and Y. Maeno, Rev.Mod.Phys. 75, 657(2003)

Crystal Growth of Sr_2RuO_4



floating zone Image furnace

Institut Néel, Cybernetix,France

$Sr_3Ru_20_7$

$SrRu0_3$ ferromagnetic T_c 150 K (perovscite)

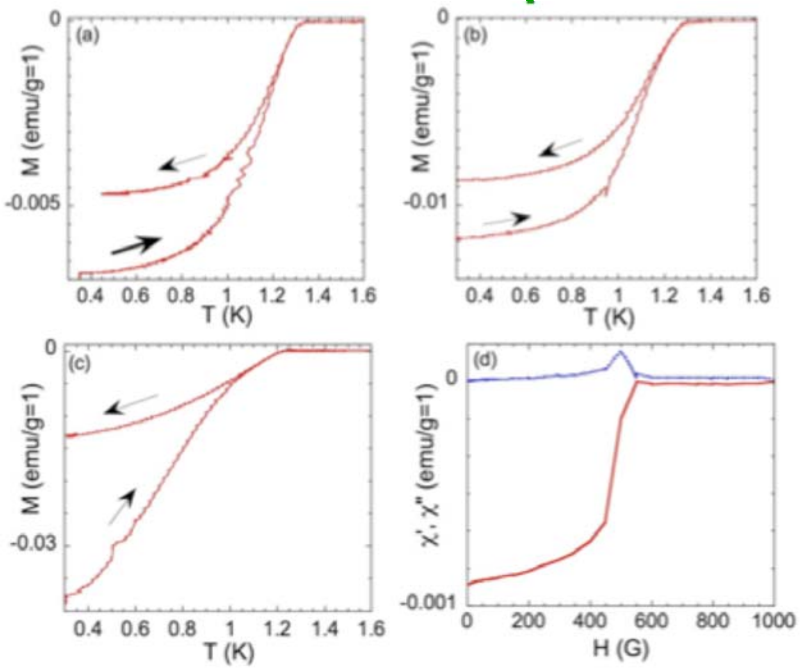
Soussine, Flouquet, Servant, Lejay

Magnetic Properties: preliminary

ZFC 5G

ZFC 10G

H//c



ZFC 50G

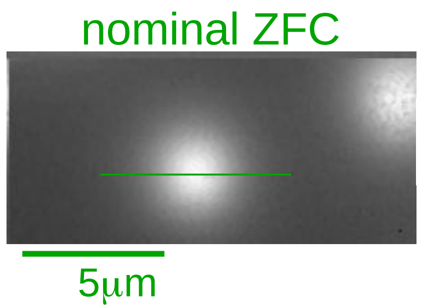
T=0.28K

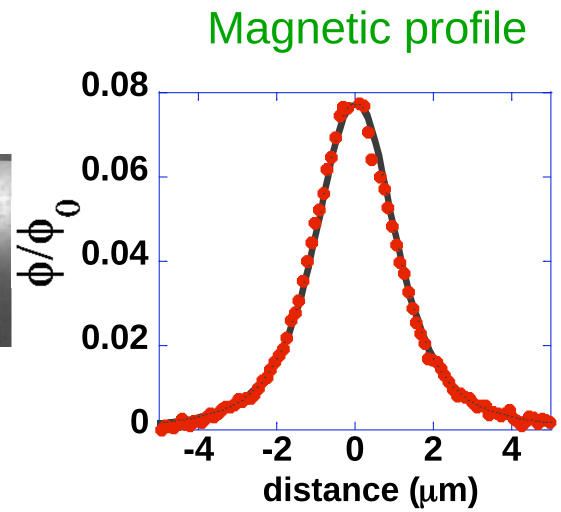
Carley Paulsen et al. Strong Flux expulsion->Weak pinning

Unusual Magnetic Response in Superconducting Mixed State of Sr_2RuO_4
Kenichi TENYA, Shingo YASUDA, Makoto YOKOYAMA1 , Hiroshi AMITSUKA, Kazuhiko DEGUCHI2 and Yoshiteru MAENO3;4
LETTERS Journal of the Physical Society of Japan Vol. 75, No. 2, February, 2006, 023702 2006 The Physical Society of Japan

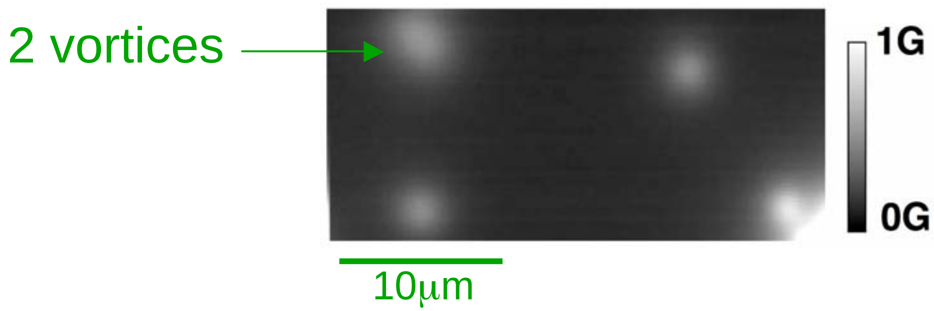
Sr_2RuO_4 Vortex structure

Observation of
individual vortices for magnetic
field applied along the c-axis





λ=0.175±0.05μm at 0.4 K considering
a SQUID height of 1.15 μm

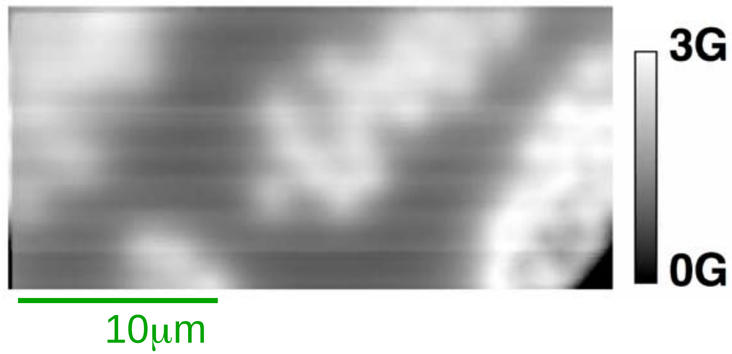


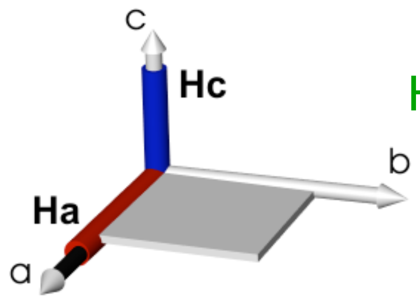
Even at low fields (0.1G FC) the
vortices are close together

But no vortex lattice is observed increasing the magnetic field

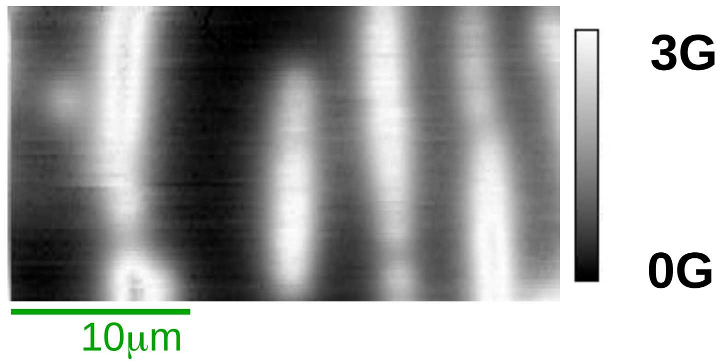
Sr_2RuO_4 Coalescence of vortices

At **2G FC** (∥c) all the magnetic field is condensed in domains of flux





Hc=2G FC + Ha=10G FC



Applying an in-plane field the domains are easily stretch in the field direction

⇩

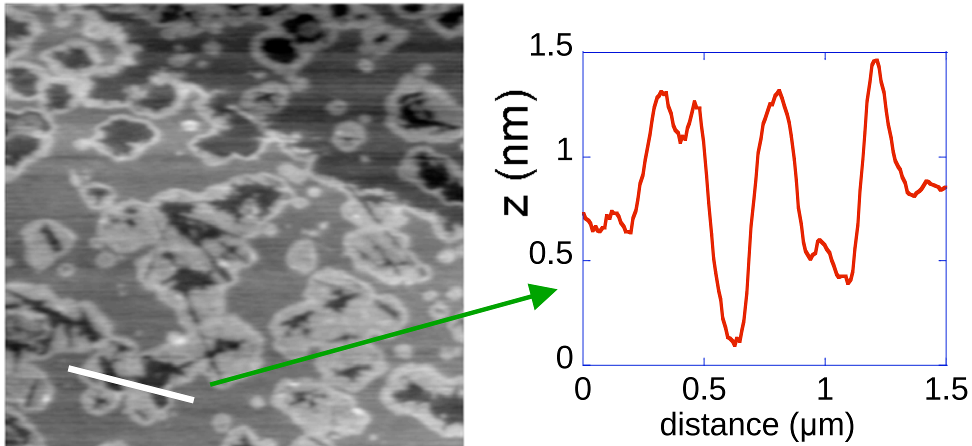
The domains are only weakly pinned by some barriers in the material

V. O. Dolocan et al., PRL 95, 097004(2005)

Sr_2RuO_4 Domains <-> surface

The surface corrugation is only 13 Å in Sr_2RuO_4 (c)

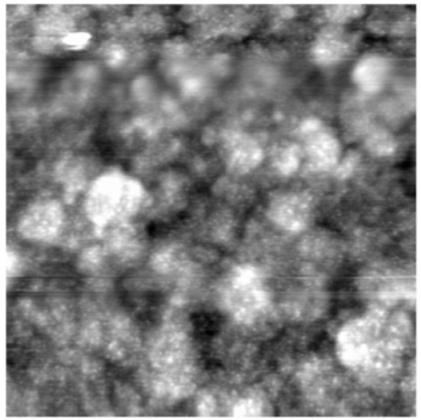
Lateral corrugation is 1 μm



Sr_2RuO_4

AFM image 4μmx4μm

The surface corrugation in $NbSe_2$ is 30 Å and a hexagonal vortex lattice is observed



O.Fruchart (IN) $NbSe_2$

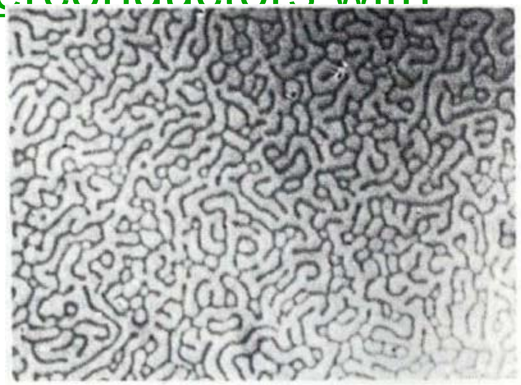
The whole ensemble of experiments suggests that the weak pinning in Sr_2RuO_4 is intrinsic

Sr_2RuO_4 Flux domains

Scenario

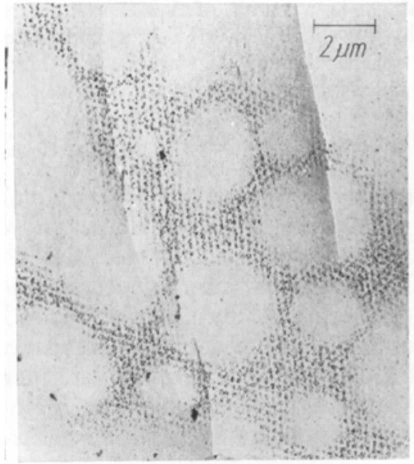
2.Vortex-Vortex attraction is predicted for superconductors with k close to 1/√ 2. (1970-1980)

Type I superconductors form regions with lamellar flux structures and superconducting domains.



100μm

Nb is known to present a vortex lattice formed in bundles or stripes separated by flux free domains. « intermediate, mixed state »

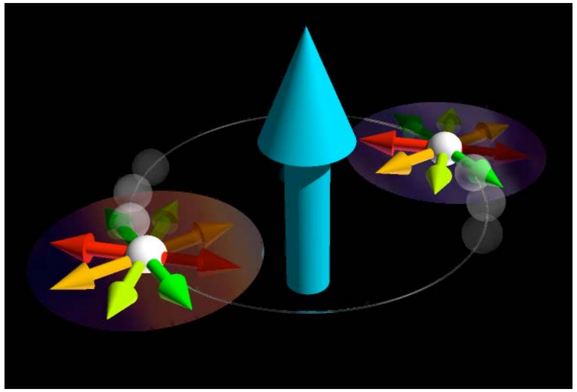


κ~2,

Individual vortices are observed in conventional superconductors (Essmann).

- Sr_2RuO_4 is a type II superconductor
- We observe vortex cluster

Sr_2RuO_4 Domain theory



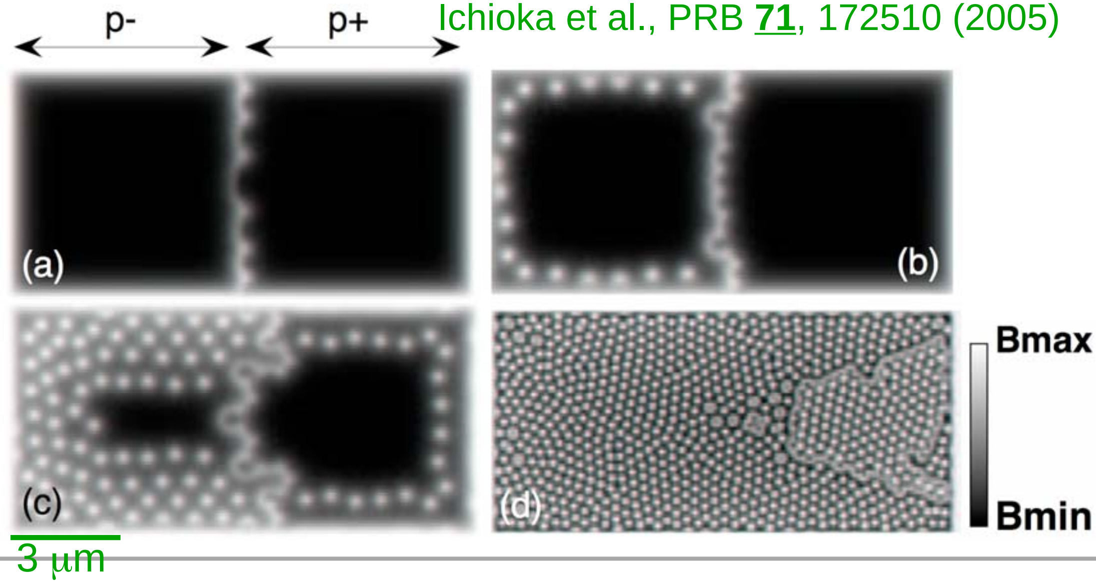
The multi-dimensional order parameter **d**(**k**)=**z**($k_x \pm ik_y$) is compatible with most experiments

Domain walls between domains with a different order parameter $k_x \pm ik_y$ (p±) pin weakly the magnetic flux (M. Sigrist)

Ichioka et al., PRB **71**, 172510 (2005)

Numerical simulations that show the field penetration in the p+ and p- domains

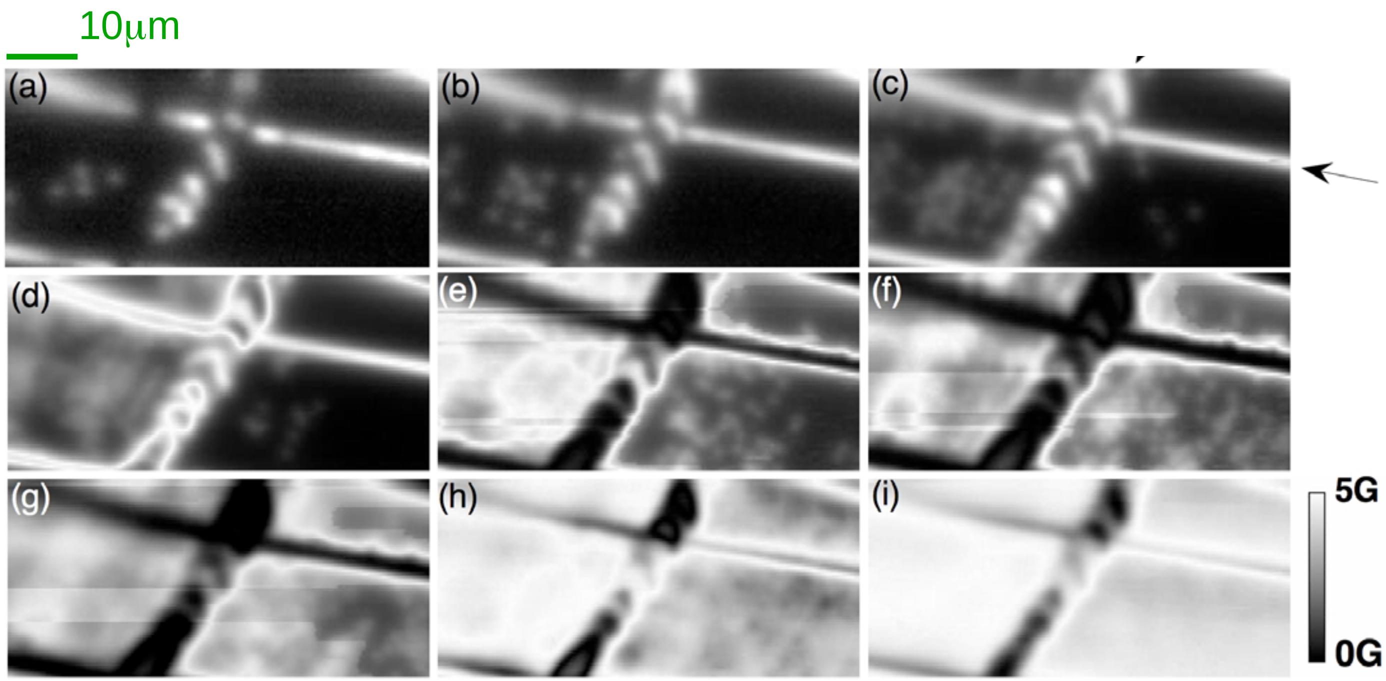
$T=0.5T_c$



Domains in Sr_2RuO_4

FC images

H||c T=0.4K



(a)2G, (b)3G, (c)4G, (d)8G, (e)9G, (f)10G, (g)11G, (h)20G, (i)50G

Imaging above a zone with surface defects

V.O. Dolocan

Physica C 460 (2007) 277-280

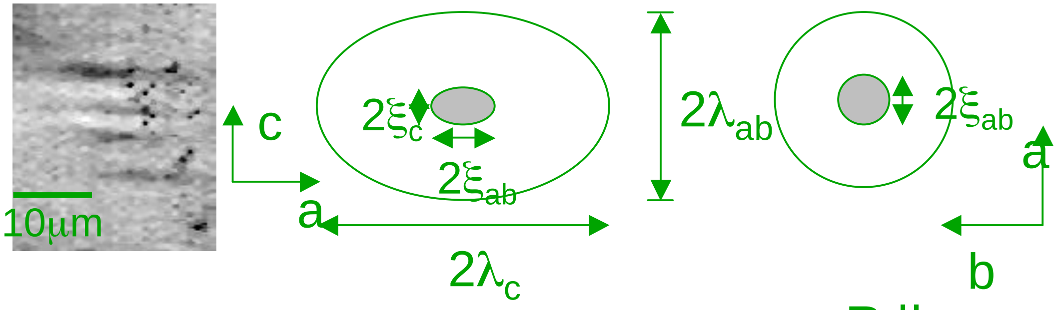
One region is favored by the direction of applied field

Would line defects pin the domain walls?

The observed domain formation due to the apparition of domain of different chirality?

Anisotropic Superconducting Materials

GL theory
Effective electron mass
anisotropy

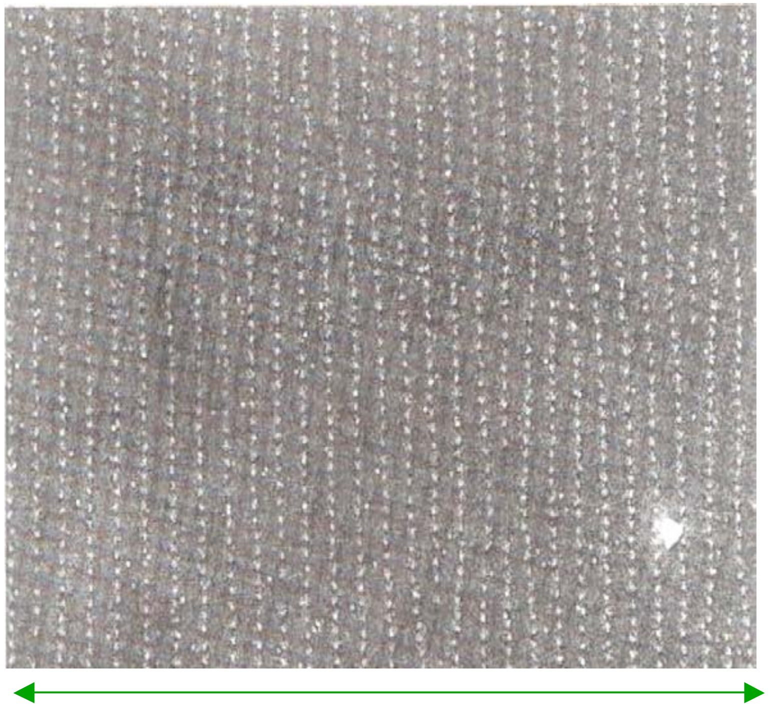


B || b **B || c**

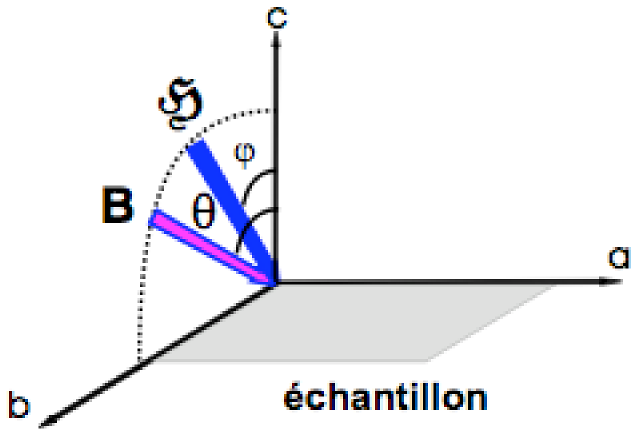
$$\gamma = \lambda_c/\lambda_{ab} = \xi_{ab}/\xi_c = (m_c/m_{ab})^{1/2}$$

Anisotropy γ	3.3	5-8	20	>55
	$NbSe_2$ 3D	YBCO 3D	Sr_2RuO_4 3D-2D?	BSCCO 2D
	c=12.5Å ξ_c=25Å	c=12Å ξ_c=5Å	c=12.5Å ξ_c=33Å	c=30.9Å ξ_c=4Å

Vortex chains Experiments



Bitter decoration and SEM micrograph
of the vortex chains in YBaCuO
23.3 G //ab 8.5 G ⊥ ab
ab face is observed
Gammel et al, Phys. Rev. Lett. 68, 3343, (92)



$$\tan\theta = \gamma^2 \tan\phi$$

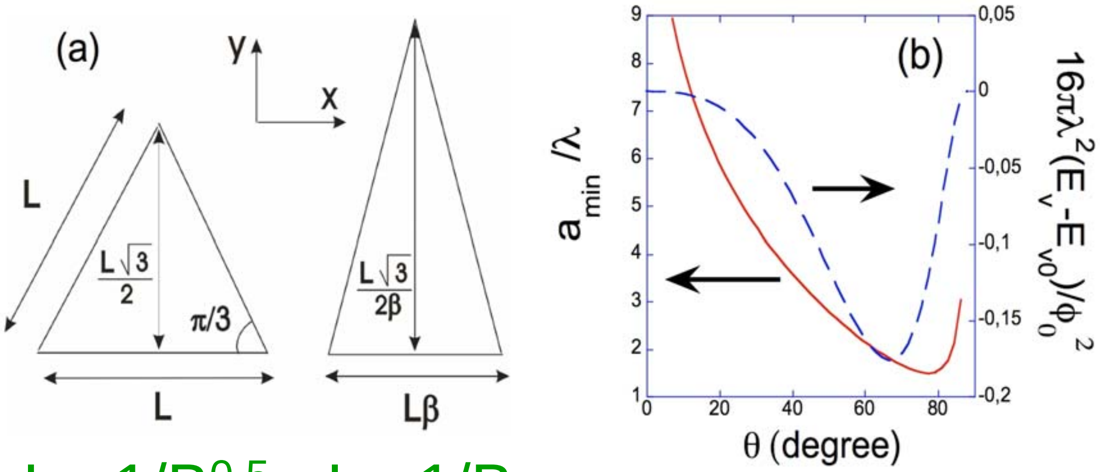
$$\gamma^2 = 400 \text{ for } Sr_2RuO_4$$

A. V. Balatskii, L. I. Burlachkov, and L. P. Gorkov, Magnetic properties of anisotropic type II superconductors, Sov. Phys. JETP 63 (1985), 866-871.

Sr_2RuO_4 Formation of vortex chains

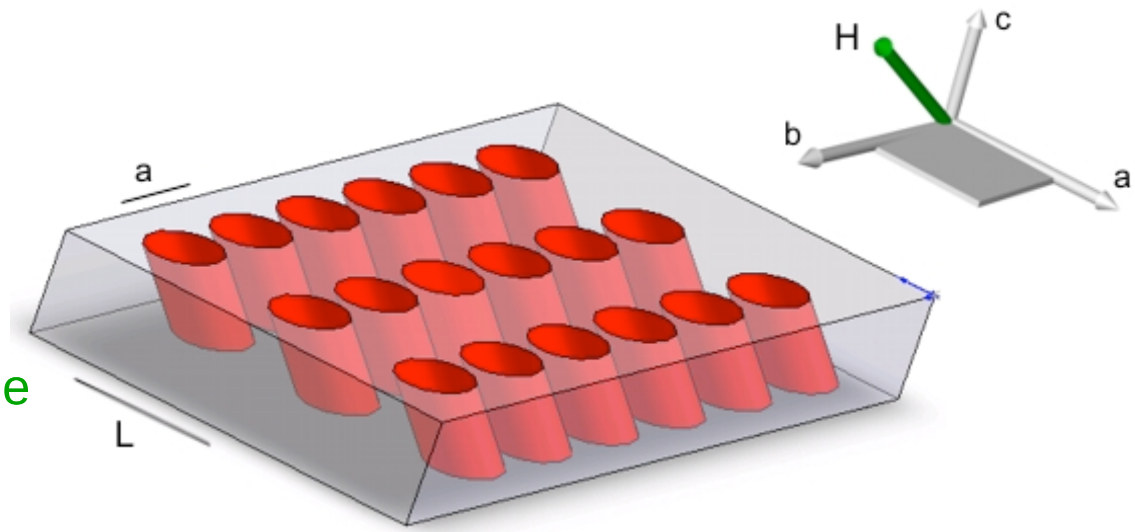
VV inter

When the magnetic field is tilted from c-axis the regular triangular lattice distorts



$L= 1/B^{0.5}$ $L= 1/B$

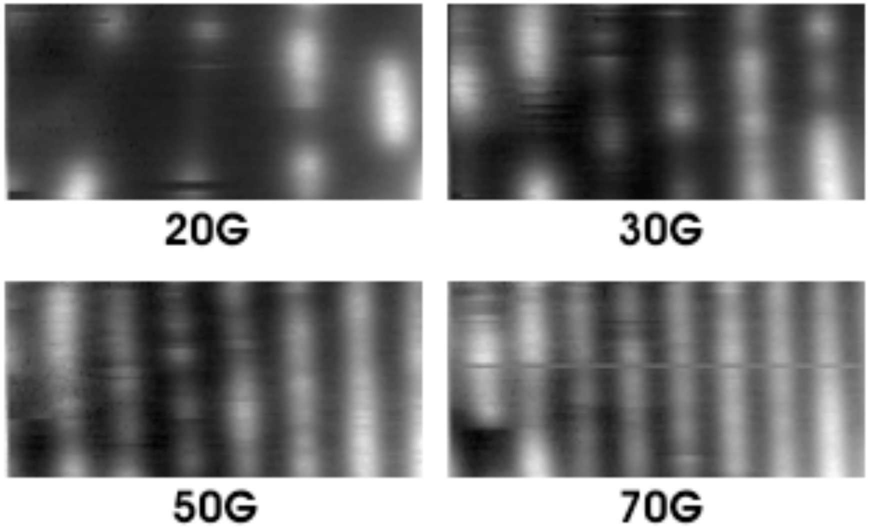
The vortex chains form due to a dipolar-like attraction between tilted vortices, in the (H,c-axis) plane



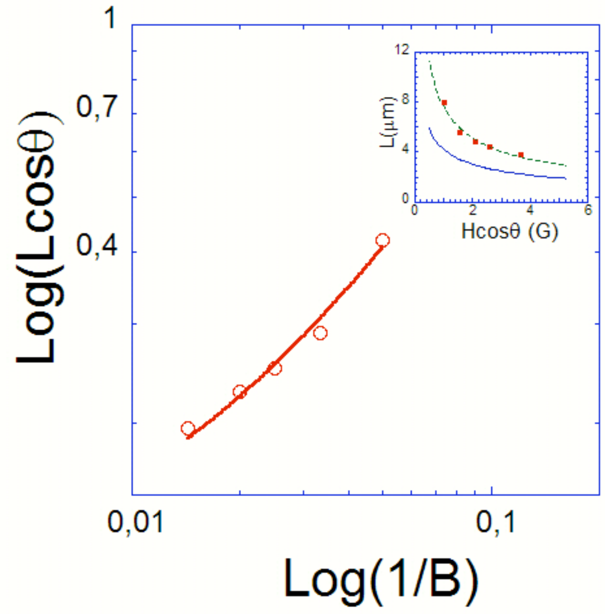
NÉEL institut

Sr_2RuO_4
Field dependence of vortex chains

In plane magnetic field increases field cooling



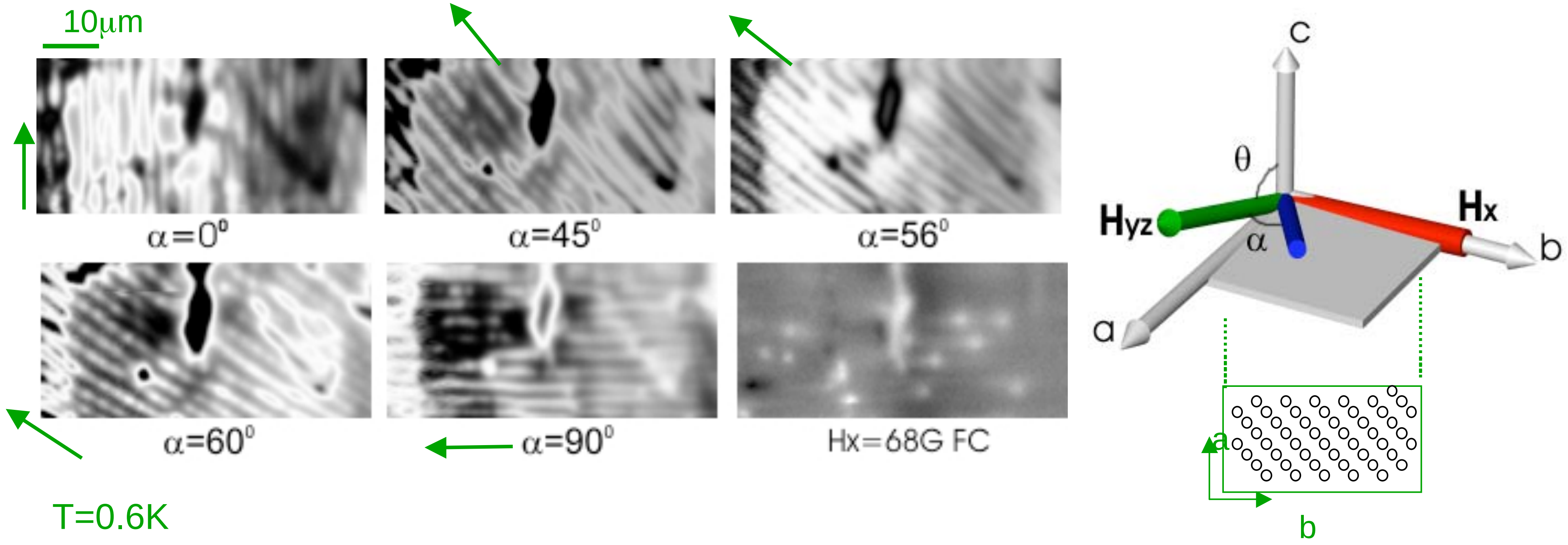
31µm x 15 µm   T=0.35K θ=87°



At low fields anisotropic London theory -> Normal distance between chains varies as B^{-1}

The interchain distance tends to the isotropic limit with increasing perpendicular field

Sr_2RuO_4 Chain rotation in ab plane



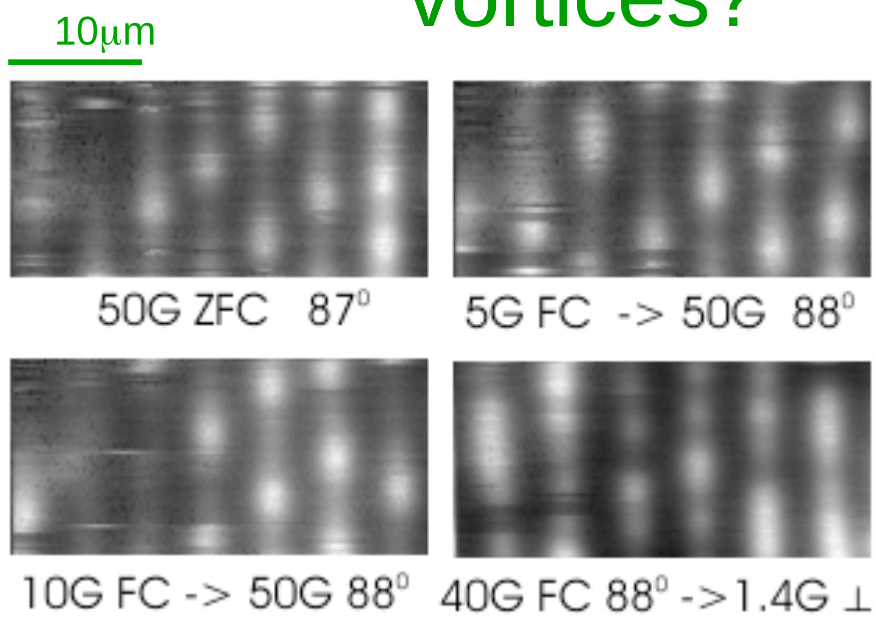
The chains change easily their direction, which is fixed by the H_{rez} and the anisotropy axis

When only a field on the ab plane is applied a tail is present on individual vortices

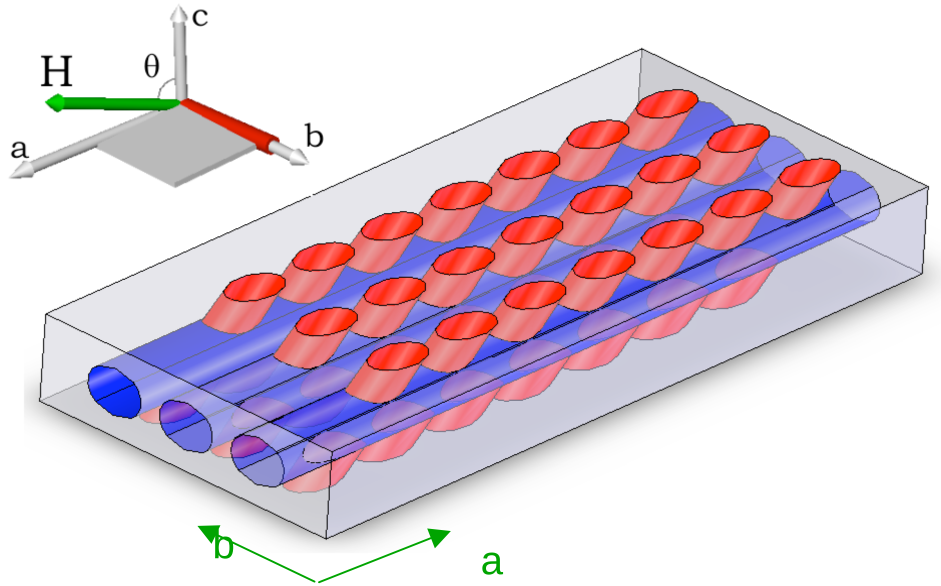
⇩

Pinning on flux channels

Sr_2RuO_4 Two types of in plane vortices?



Possibility:



T=0.35K

Dolocan, V.O. et al.

Phys. Rev. B **74,** 144505, 2006

- Flux channels preferentially into ab plane
- Vortices nucleate on flux channels
- Tendency of anticorrelation between vortices in adjacent chains

Distorted hexagonal lattice on the flux channels?

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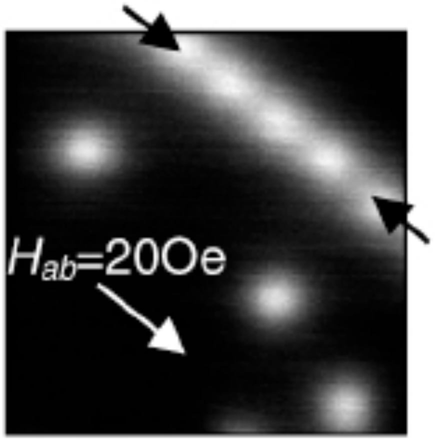
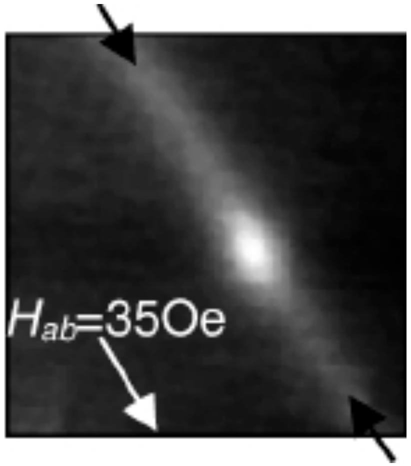
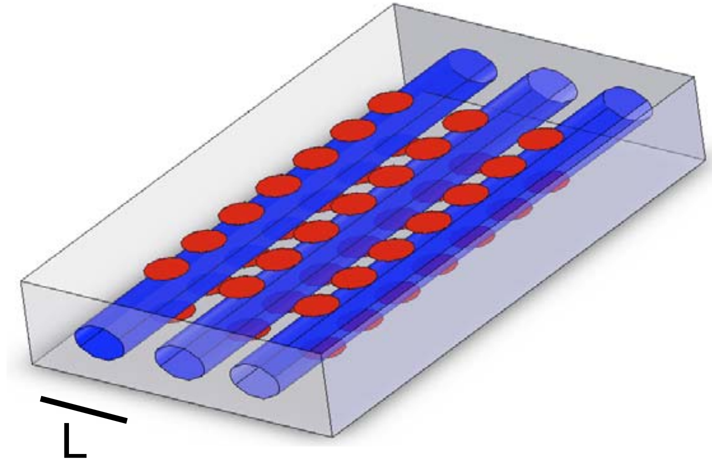
Sr_2RuO_4 <-> BISCCO

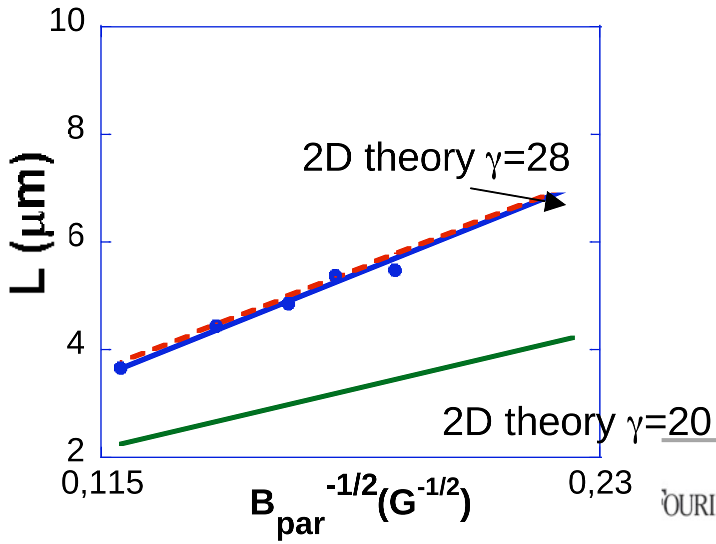




2D limit:



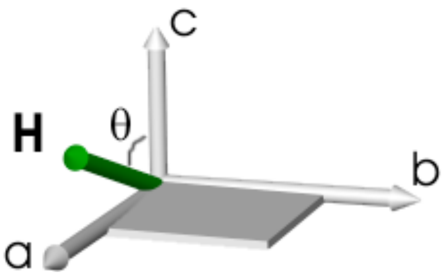
$$L = \sqrt{\frac{\sqrt{3}\gamma\Phi_0}{2B_{inplane}}}$$

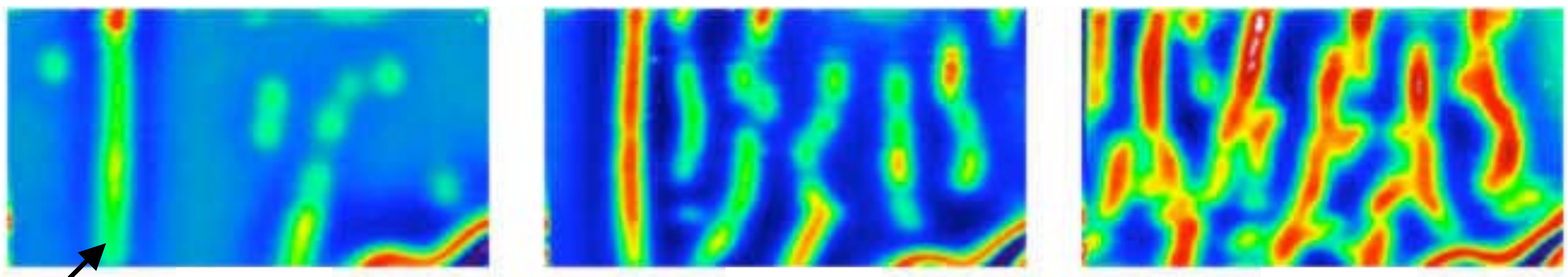


Biscco SHPM Bending PRL 94 67001

Sr_2RuO_4 Anisotropy and domains

H=10G FC T=0.3K

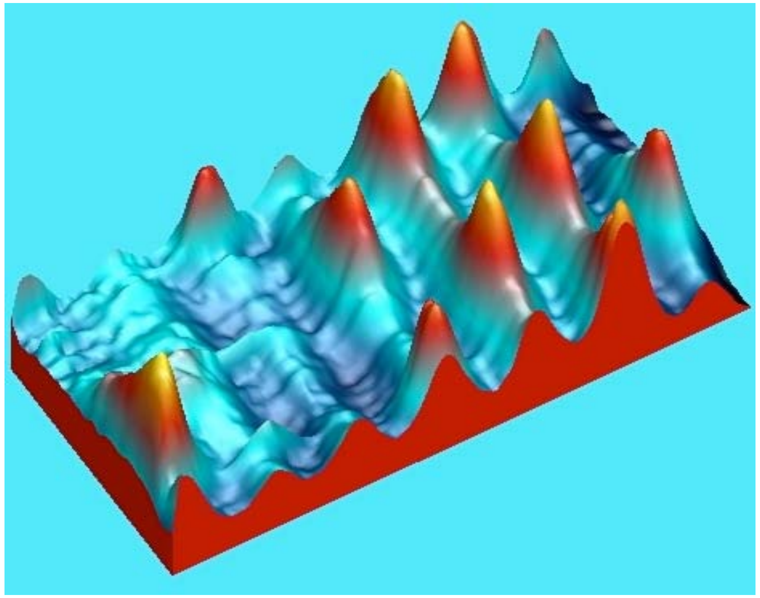




When the direction of magnetic field is approaching the c-axis more field is penetrating the sample ⟹ the chains bend

Competition between
the anisotropy -> the vortex chain structure
and coalescence -> domains

Sr_2RuO_4



- Vortex coalescence-domains

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- Vortex chains are present at low fields

- Vortex channels are decorated by Abrikosov vortices

⟹ Sr_2RuO_4 opens also a new field in vortex physics

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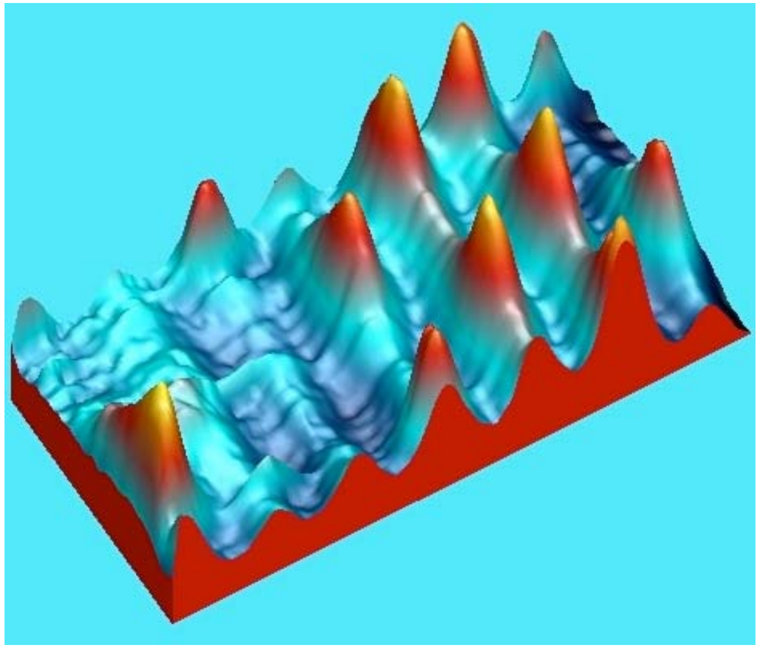

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