



神奇的超導體

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Superconductivity

CREATING THE FUTURE

TODAY



The 200 Horsepower Motor

uses high temperature superconducting rotor coils. The high temperature superconducting motors are much smaller, lighter and more efficient when compared to a conventional motor. Utilities and industry will be able to lower



大綱

- 什麼是超導體？
- 超導體的神奇特性。
- 超導體的應用。
- 超導體的展望。

感謝成功大學材料科學及工程學系陳引幹教授提供資料

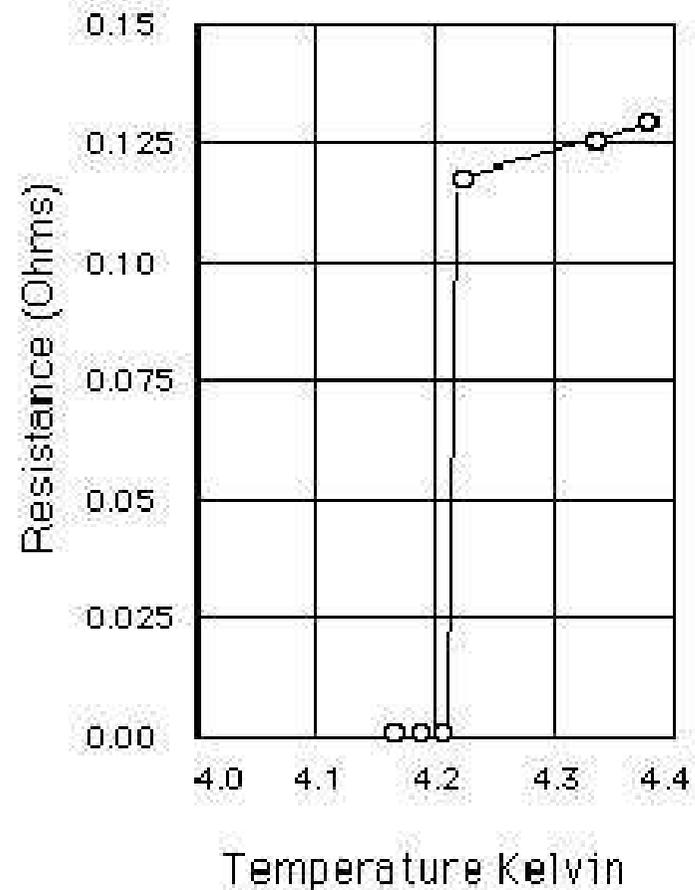


什麼是超導體? — 電阻消失

Superconductivity was first discovered in 1911 by the Dutch physicist, **Heike Kammerlingh Onnes**.

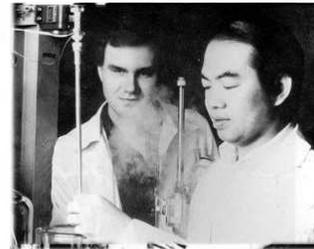
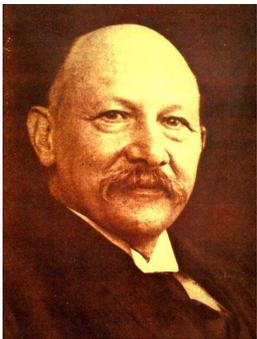
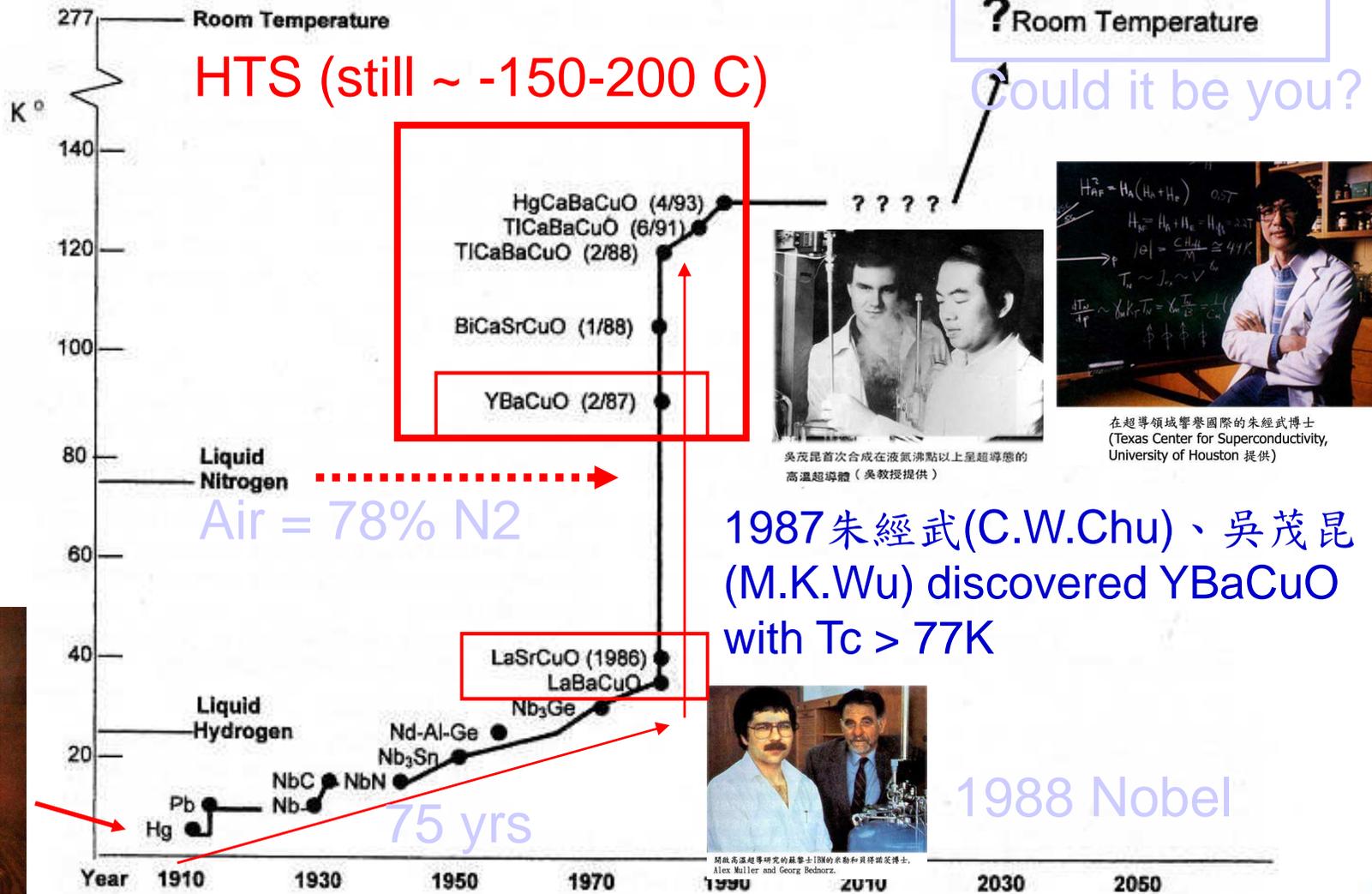


Temperature dependence of resistance of mercury.

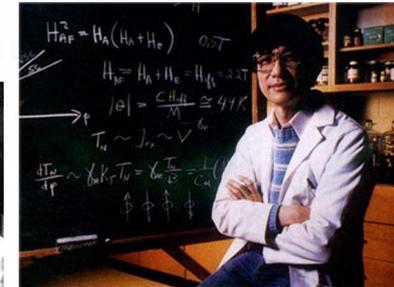


Discovery of High Temperature Superconductors

超導材料發現的歷史



吳茂昆首次合成在液氮沸點以上呈超導態的高溫超導體 (吳教授提供)



在超導領域響譽國際的朱經武博士 (Texas Center for Superconductivity, University of Houston 提供)



開啟高溫超導研究的蘇聯士1團的索爾和貝得諾茨博士, Alex Müller and Georg Bednorz.

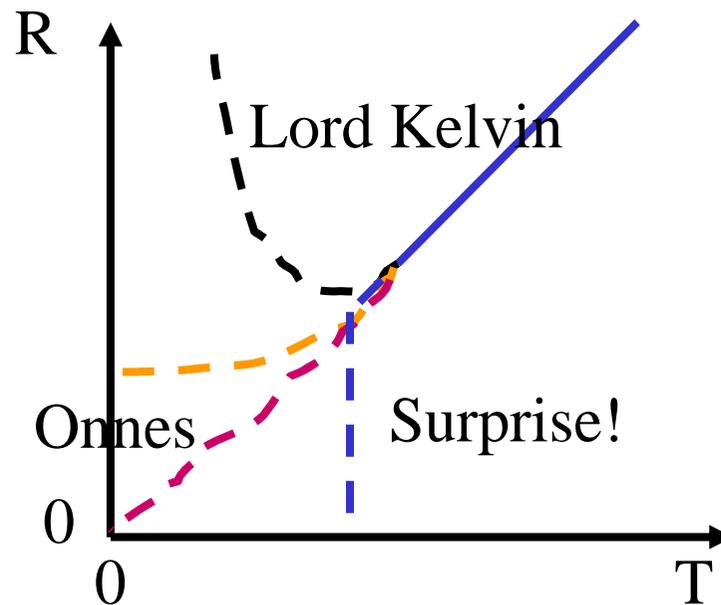


超導體的神奇特性

(1) 電阻消失

為何電阻消失如此令人驚訝?

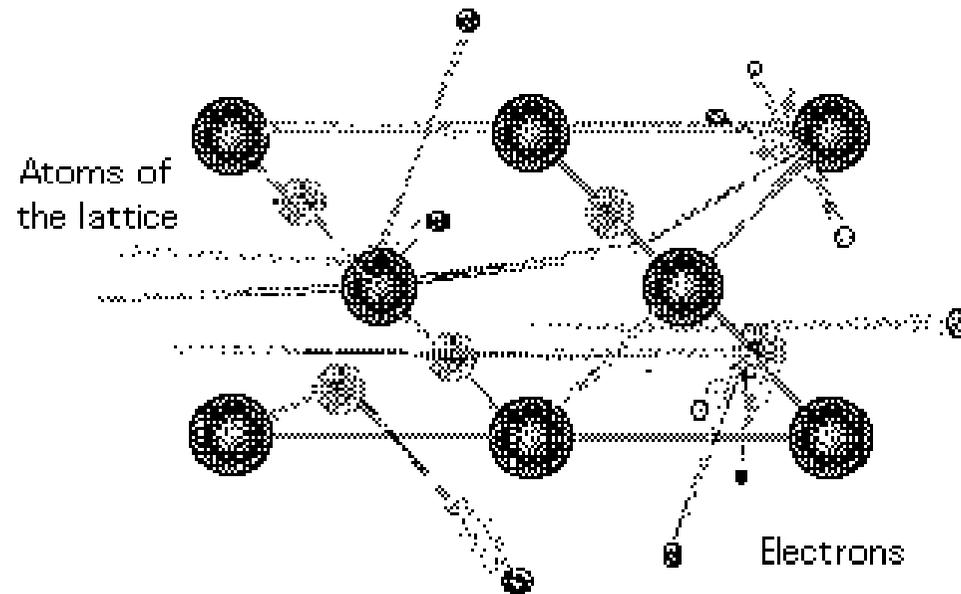
According to Onnes, "Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive state".



為何正常態導體有電阻？

電阻不會完全消失

Normal State

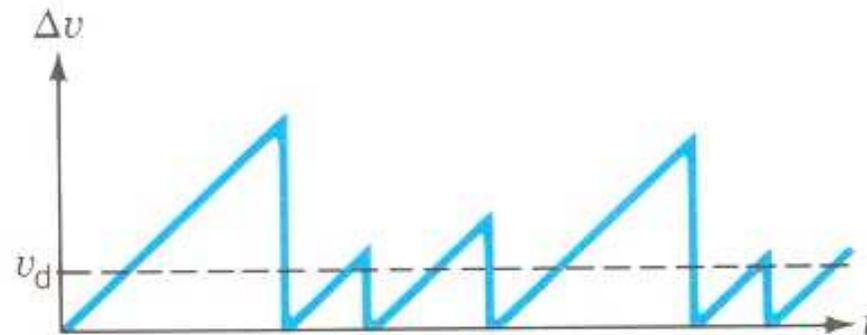


Drude Model

$$\frac{d\vec{v}_i}{dt} = \frac{q\vec{E}}{m} \quad \vec{v}_i - \vec{v}_{i0} = \frac{q\vec{E}}{m} \Delta t \quad \langle \vec{v}_i - \vec{v}_{i0} \rangle = \langle \vec{v}_i \rangle - \langle \vec{v}_{i0} \rangle = \frac{q\vec{E}}{m} \langle \Delta t \rangle$$

$$\vec{v}_d = \langle \vec{v}_i \rangle \quad \langle \vec{v}_{i0} \rangle = 0 \quad \tau = \langle \Delta t \rangle \quad v_d = \frac{qE}{m} \tau = \frac{q\tau}{m} E = \mu E$$

$$v_d = \frac{J}{nq} \quad E = \frac{m}{nq^2\tau} J \quad \rho = \frac{m}{nq^2\tau} \quad \sigma = \frac{nq^2\tau}{m}$$



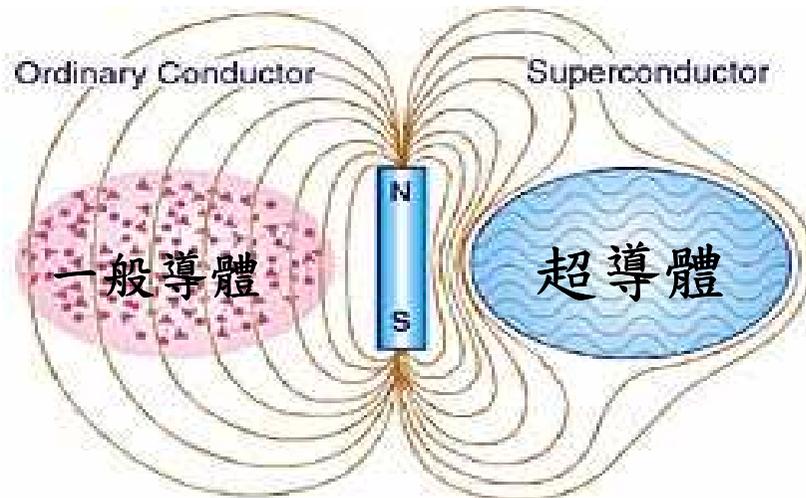
The change in speed Δv acquired by an electron between collisions fluctuates in time. The change, averaged over all electrons, is called the drift speed v_d .



超導體的神奇特性

(2) 完全反磁效應

超導體的內部磁通量為零，磁力線無法進入超導體，這個性質又稱為「**麥士那效應 (Meissner effect)**」。這種現象產生的過程是：當超導體放入磁場中時，超導體和一般導體一樣會產生感應電流，而超導體的電阻為零，因此只要磁場存在，電流就能一直流動，此電流即為「屏蔽電流」。屏蔽電流在超導體周圍產生與外部磁場方向相反的磁場，因而阻擋外部磁場進入(如圖所示)。



Eddy Current Demonstration

牛頓雜誌 56期 1988年 1月號



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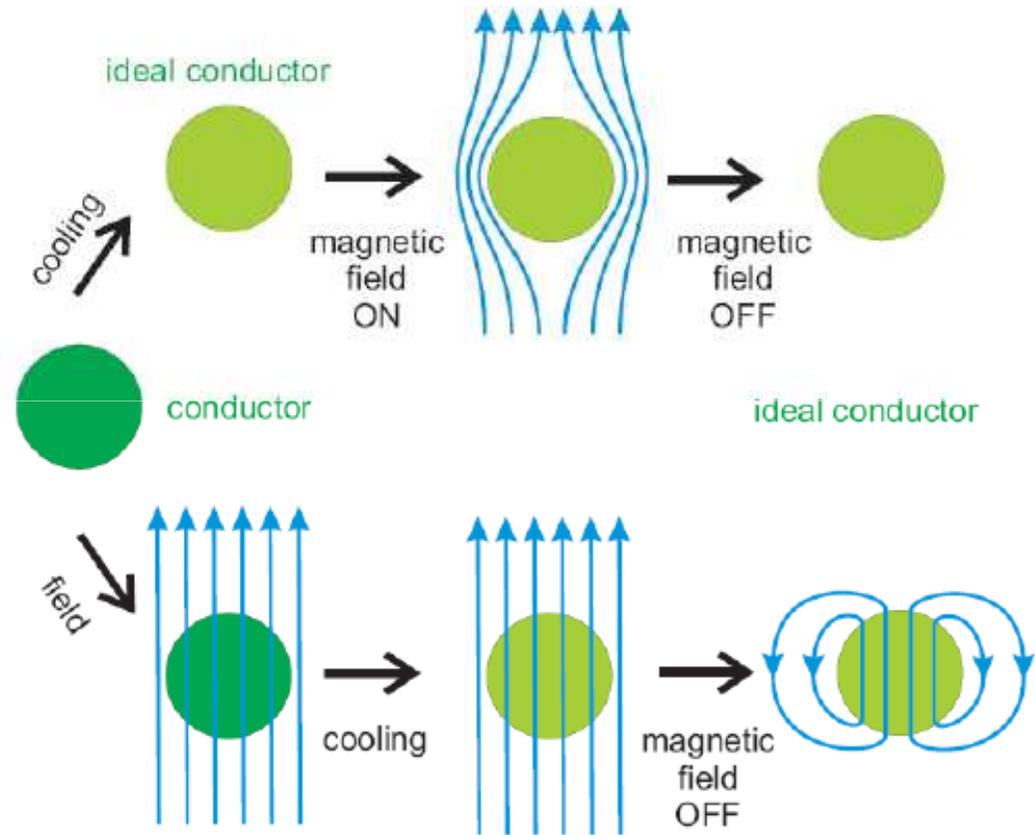
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超導體只是電阻為零的完美導體?

an ideal conductor

Magnetic field induces a screening current (Lentz' rule) which generates an opposite magnetic field inside the sample



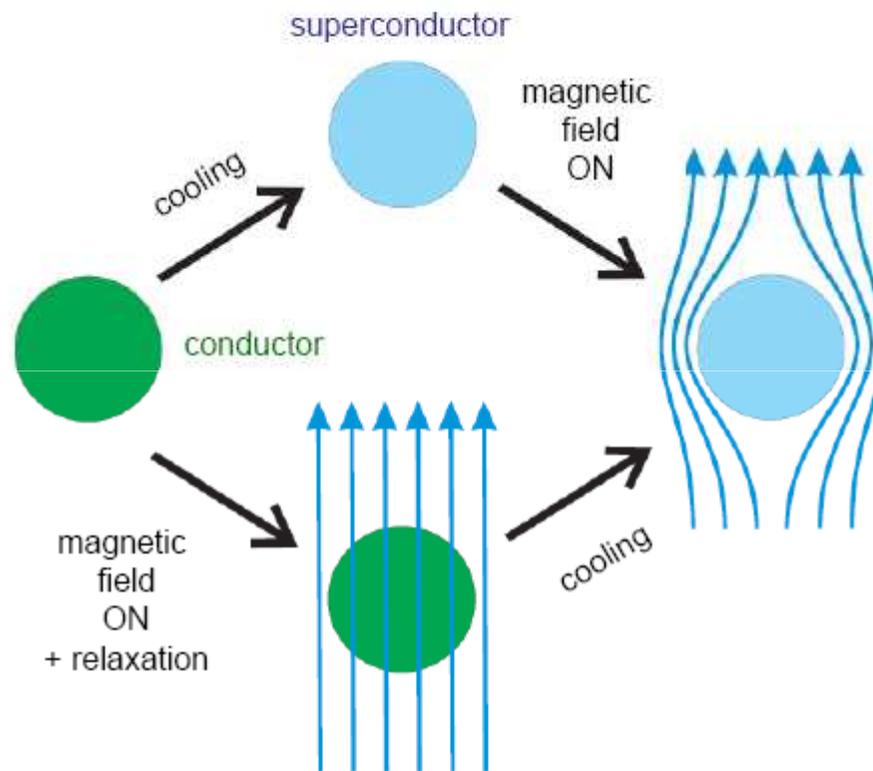
An ideal conductor in magnetic field



超導體不是電阻為零的完美導體！

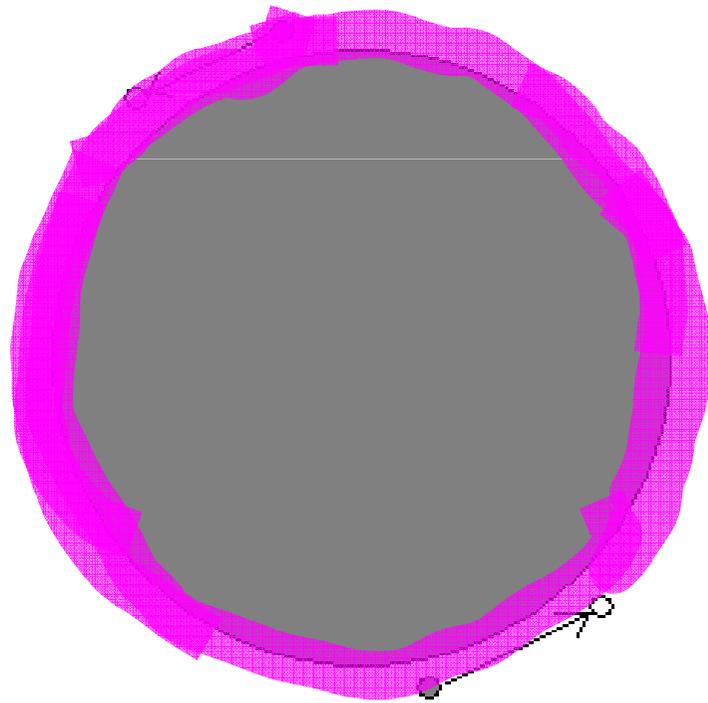
Meissner effect:

Superconductor always expels the magnetic flux



電子集結成對

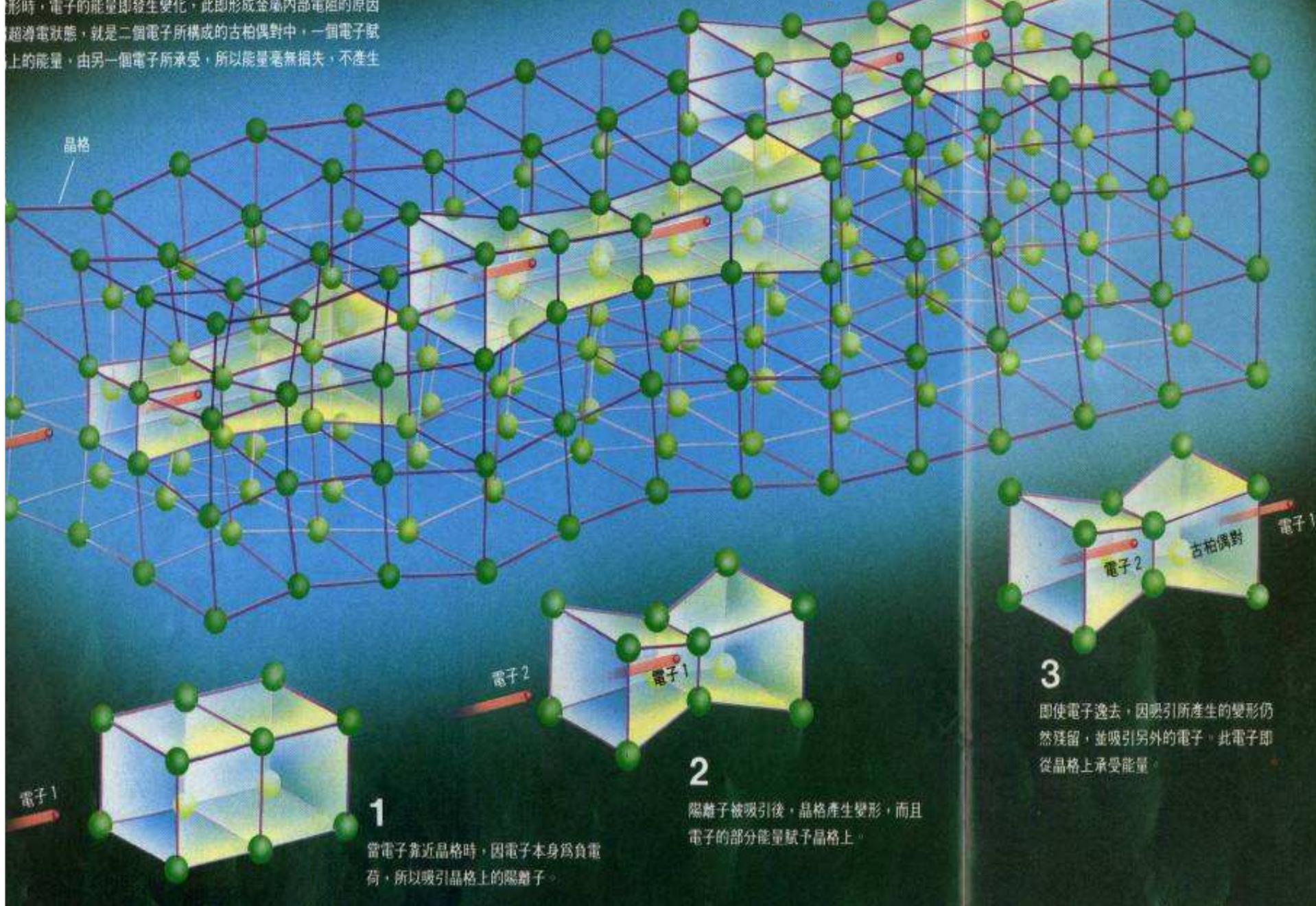
古柏(Leon N. Cooper)探討電子在導體中的運動，發現若導體中的電子有微弱的吸引力，就會集結成對。後來也因此被命名為「古柏對」。



電性質與電子的古柏偶對

電子雲中，呈陽離子狀態的金屬原子係成晶格狀排列。當晶格形時，電子的能量即發生變化，此即形成金屬內部電阻的原因。超導電狀態，就是二個電子所構成的古柏偶對中，一個電子賦上的能量，由另一個電子所承受，所以能量毫無損失，不產生

電子之間吸引力的來源



巨觀的量子態

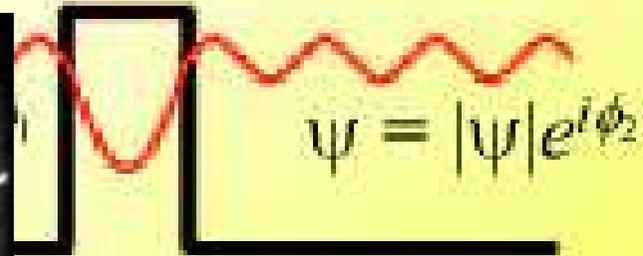
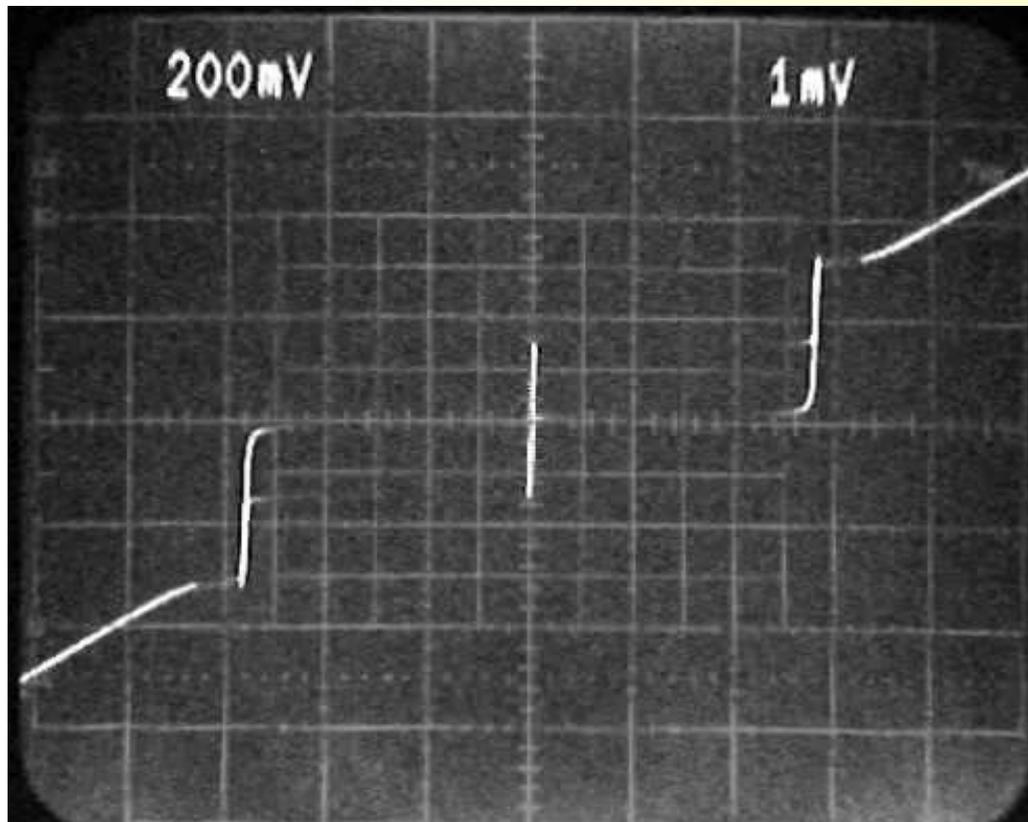
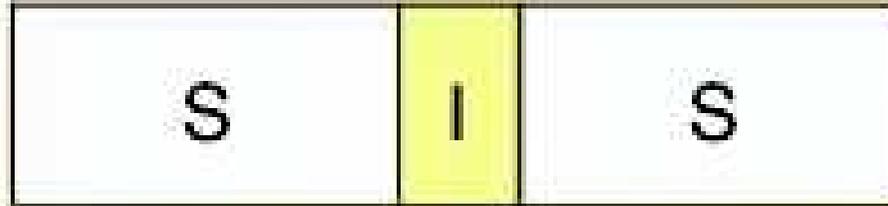
1957年，J. Bardeen, L. N. Cooper及R. J. Schrieffer提出解釋超導現象的微觀理論(BCS理論)：發現古柏對會集結成一個**巨觀的量子態**。即所有的古柏對都可用一個波函數來描述。

$$|G\rangle = \prod_{k'} (u_{k'} + v_{k'} C_{k'\uparrow}^+ C_{-k'\downarrow}^+) |0\rangle$$



約瑟芬結

Josephson junctions



$$\sin \phi, \phi = \phi_1 - \phi_2$$

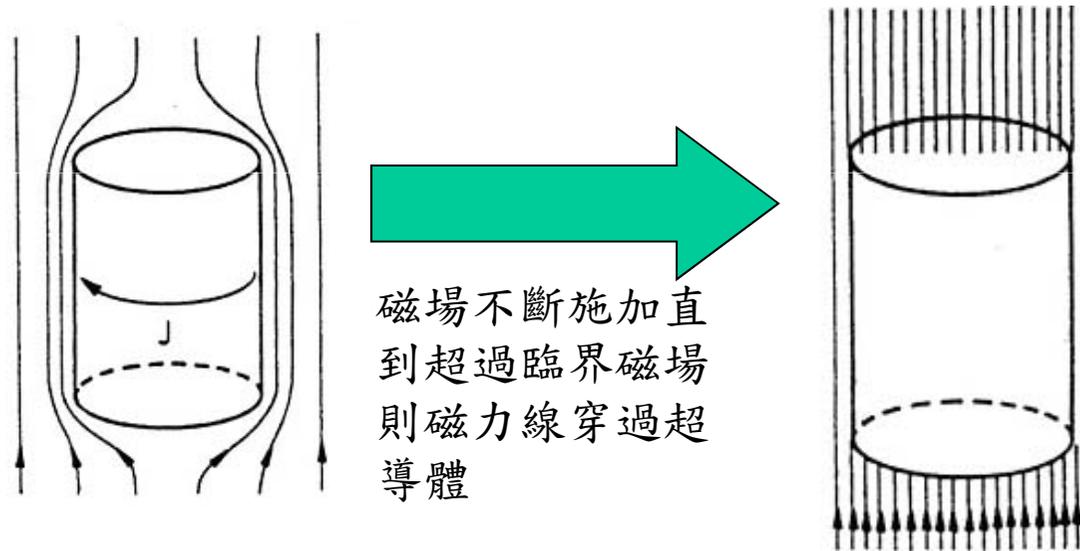
$$\frac{-2eV}{\hbar}$$



超導體的分類

第一類超導體(Type I)

外加磁場一旦超過超導臨界磁場值，超導狀態便消失，讓所有外加磁場穿過。



Ref: 國立成功大學材料工程學系

陳引幹教授 高溫超導材料與其磁浮上之應用

<http://psroc.phys.ntu.edu.tw/bimonth/v27/609.doc>



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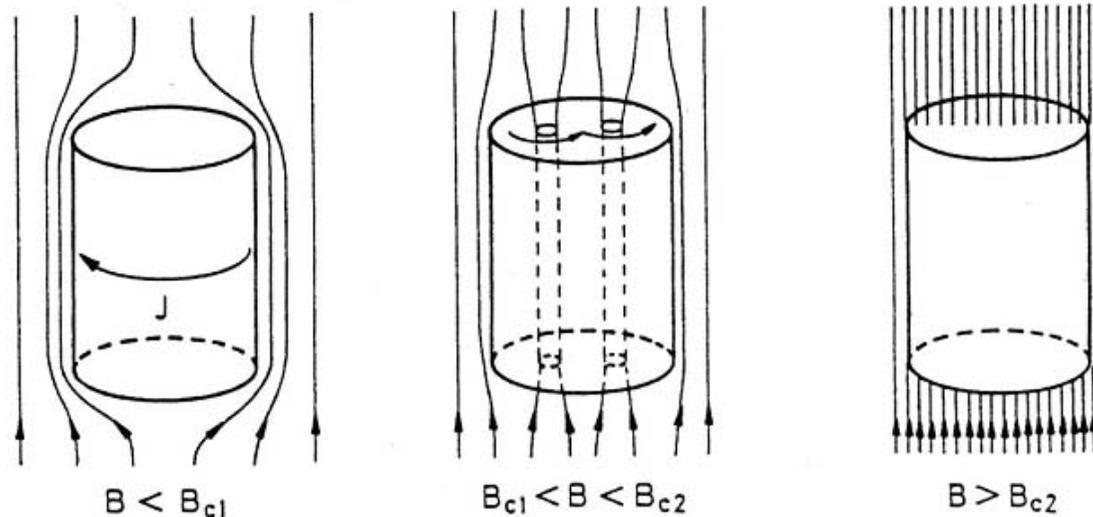
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超導體的分類

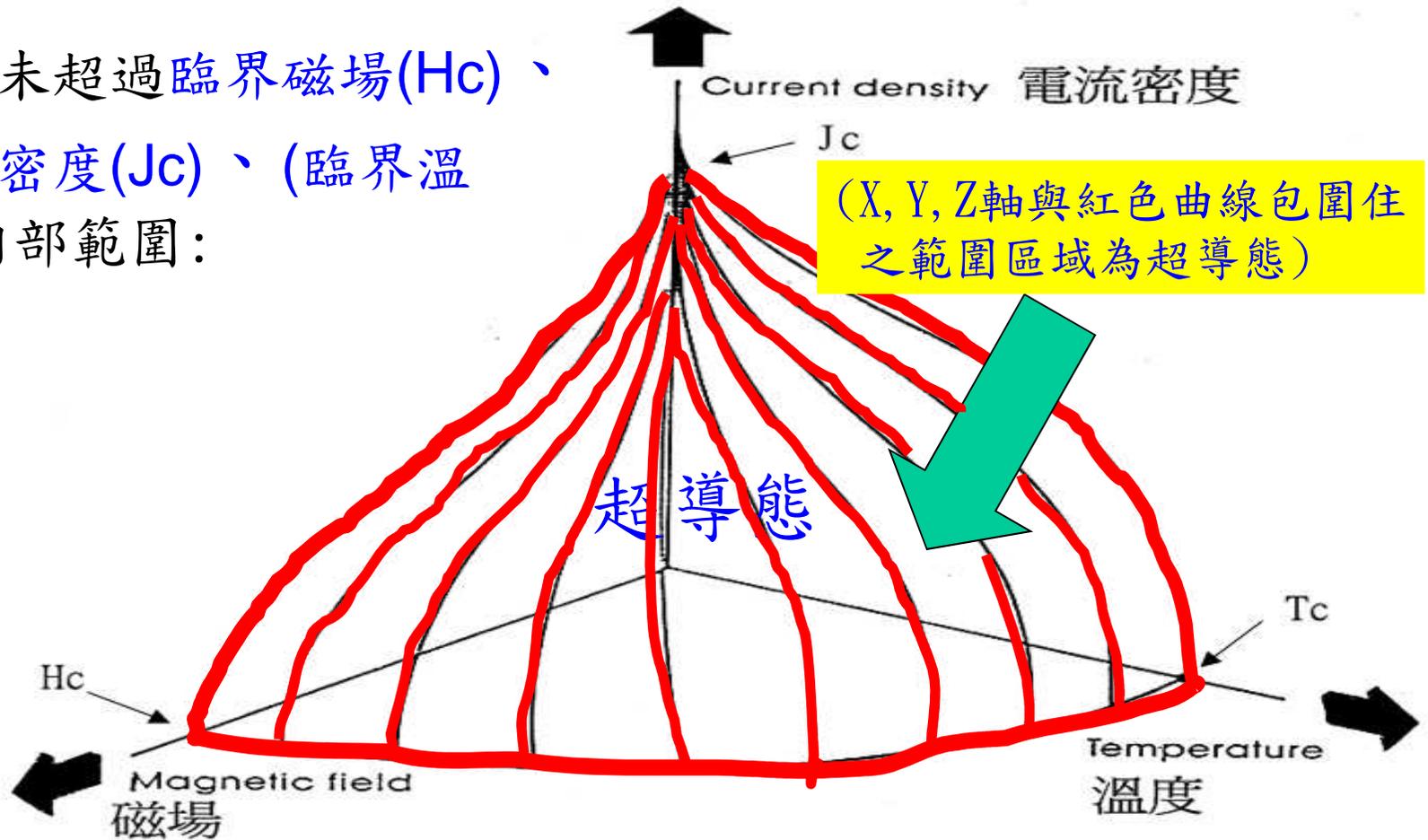
第二類超導體(Type II)

有兩個臨界磁場值($B_{C1} < B_{C2}$)，當外加磁場超過較低的一(B_{C1})，內部則有少數的地方不具超導特質，使磁力線可以穿過。一直到外加磁場超過另一上限值(B_{C2})，超導態才消失，讓所有外加磁場穿過。



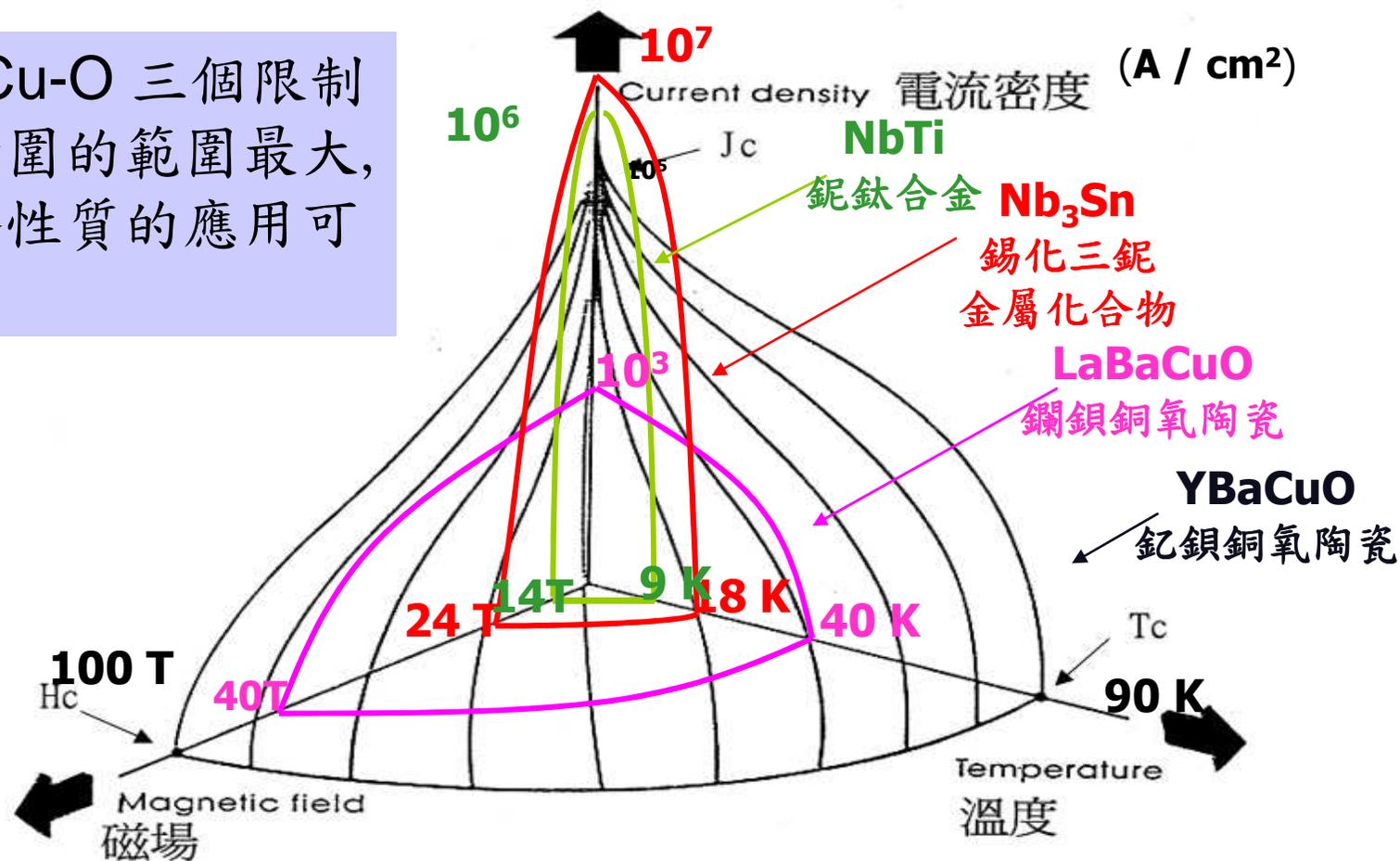
超導體發生超導態的條件

超導態乃未超過臨界磁場(H_c)、
臨界電流密度(J_c)、(臨界溫度 T_c)之內部範圍：



不同種類超導體之三限制因素範圍示意圖

Y-Ba-Cu-O 三個限制因素所圍的範圍最大，即超導性質的應用可較廣。



超導體的應用

- **Power transmission** 電力傳輸。
- **Magnetic Levitation (Maglev)** 磁浮列車。
- **Motor /Generator** 超導馬達/發電機。
- **Nuclear Magnetic Resonance (NMR)/
Magnetic Resonant Imaging (MRI)** 超導線圈。
- **SQUIDs** 超導量子干涉儀



超導線材



含2,120根，微米左右直徑的鈮-鈦合金纖維，
以銅為基體的複合超導線材截 (美國Supercon提供)

NbTi 低溫超導線材



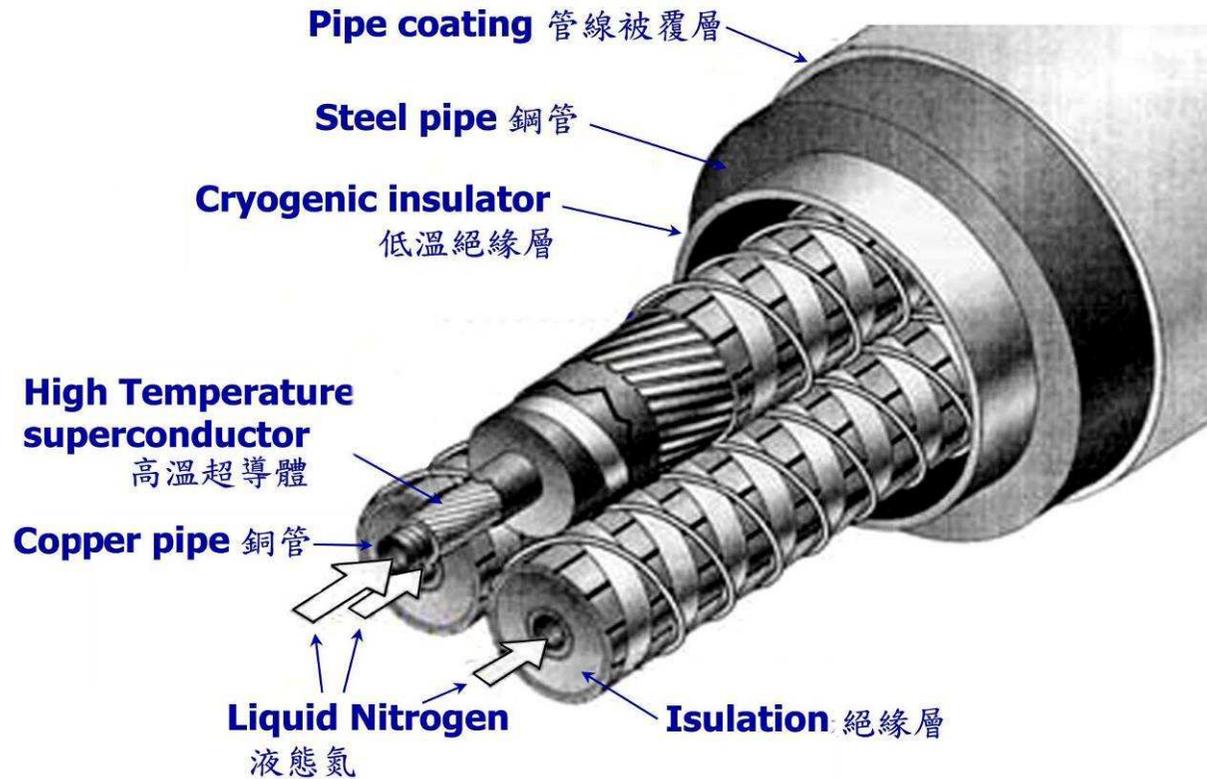
鈹系粉末在銀套管中經滾壓製成的高溫超導帶材

Bi系 高溫超導線材

超導線材相較於一般線材的不同在於沒有能量的消耗，因為超導的零電阻特性，電子在晶格中運動並不會與晶格碰撞產生熱能，也就不會有能量損耗的問題出現！！



高溫超導傳輸電纜的設計



由於低溫的需求，超導線材必須有平行的液氮管道保持冷卻，液氮在定點的區間內循環，難免的，氣化的部分需要再進行液化，這些困難都可以解決，但經濟效應大為減低！

美國 Underground System, Inc.



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超導電纜的測試



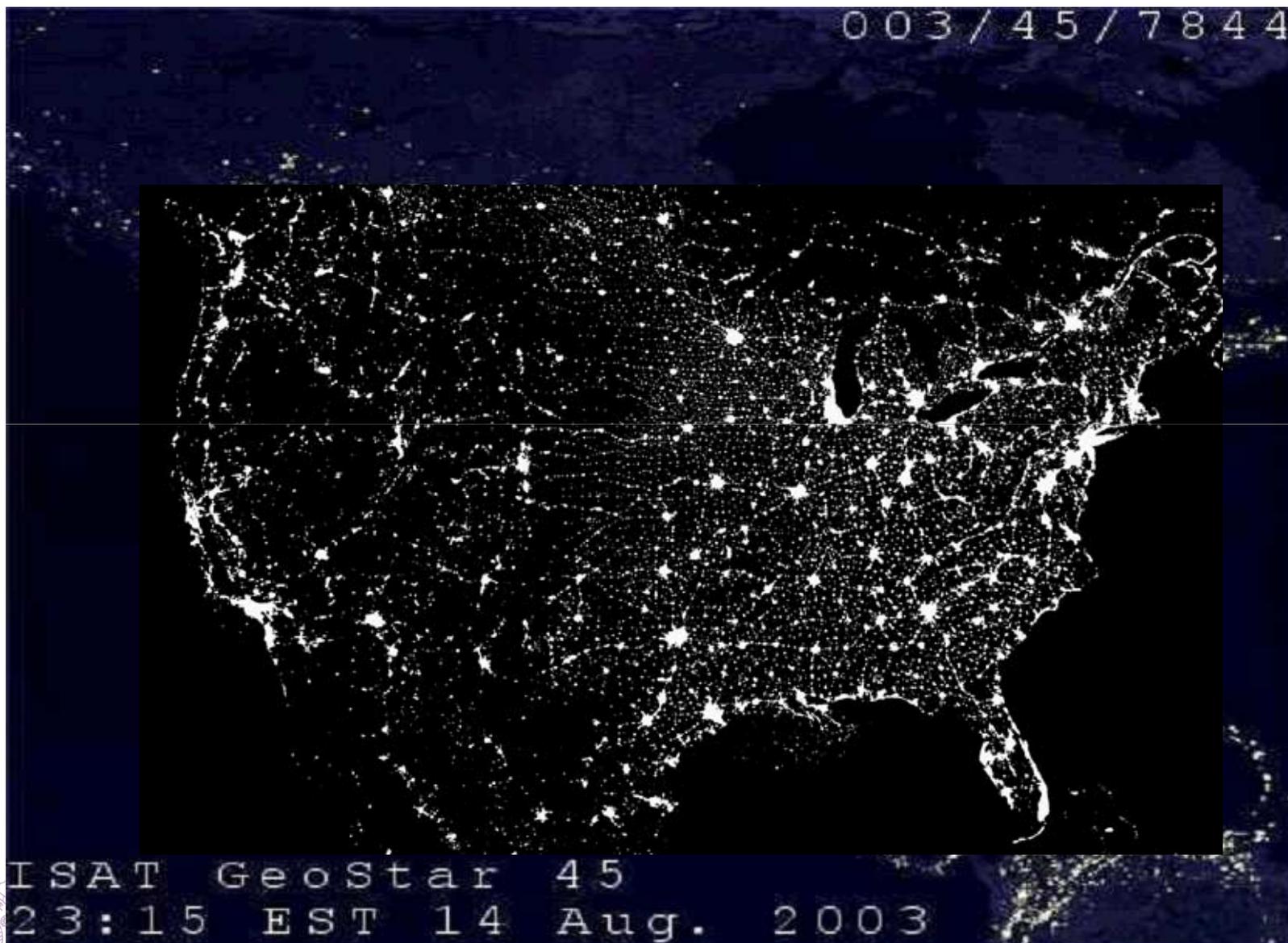
實驗室中兩組超導電纜測試管道（英國 Brookhaven National Laboratory 提供）

十萬伏的高壓電必須高架或是深埋地底，並以介電材料覆蓋，減少對環境安全的負面效應。超導輸電線可用大電流、低電壓，沒有這方面的顧慮而且節省能源，有利於環保

參考: 何建民 低溫、超導、磁浮，台灣書店印行 p.70 1996



2003年美國東北部大規模的停電(Black out)



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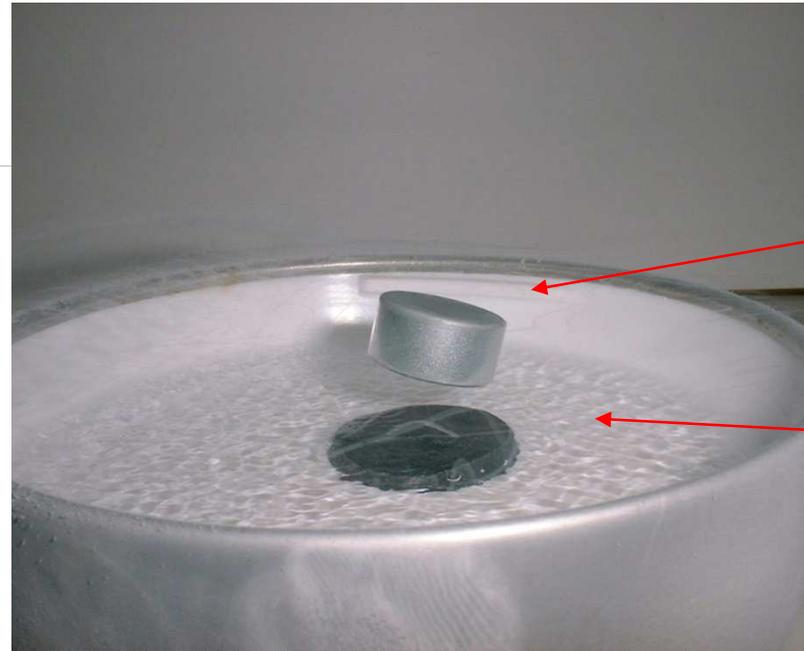


Levitation experiments

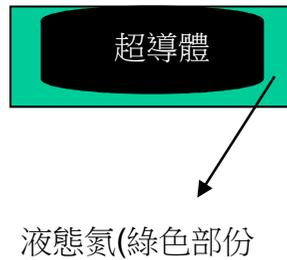
超導磁浮創意競賽 <http://www.hitcworld.org/>



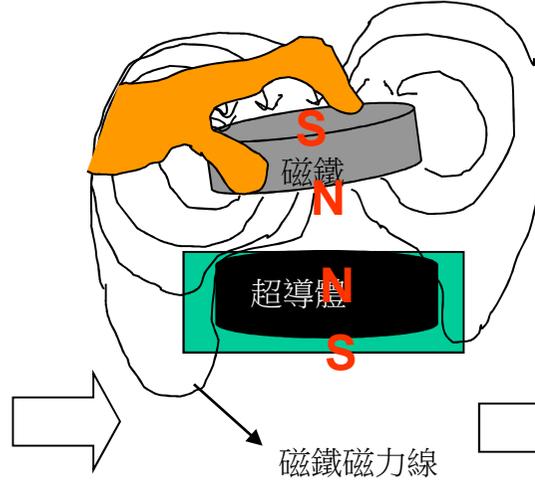
Meissner-Ochenfeld effect
plus flux trapping



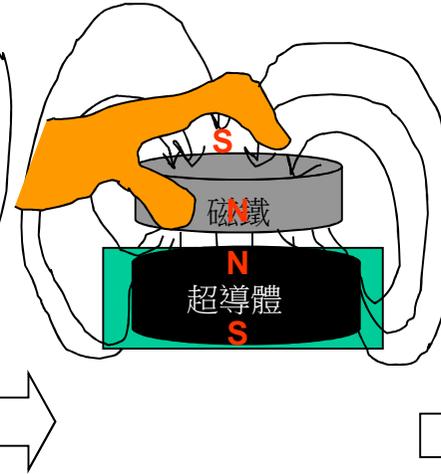
先利用液態氦將超導體冷卻至超導臨界溫度以下



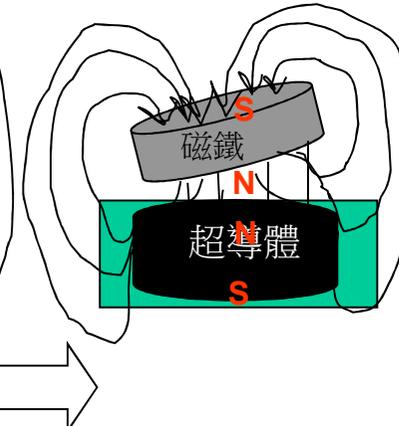
將磁鐵靠近超導體時，會感受到反磁作用力且磁束無法穿過超導體



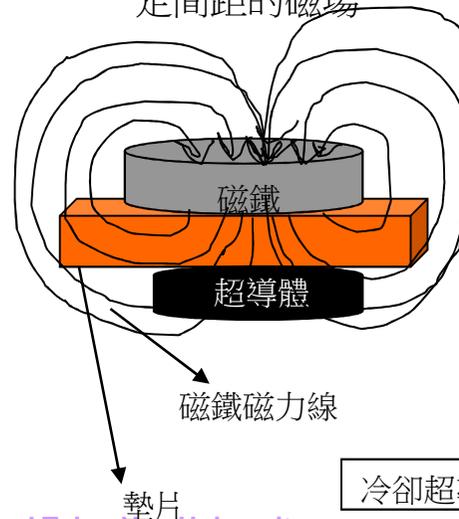
迫使磁鐵靠近超導體使磁束貫穿超導體



手放開後，最後磁浮情況通常會傾斜



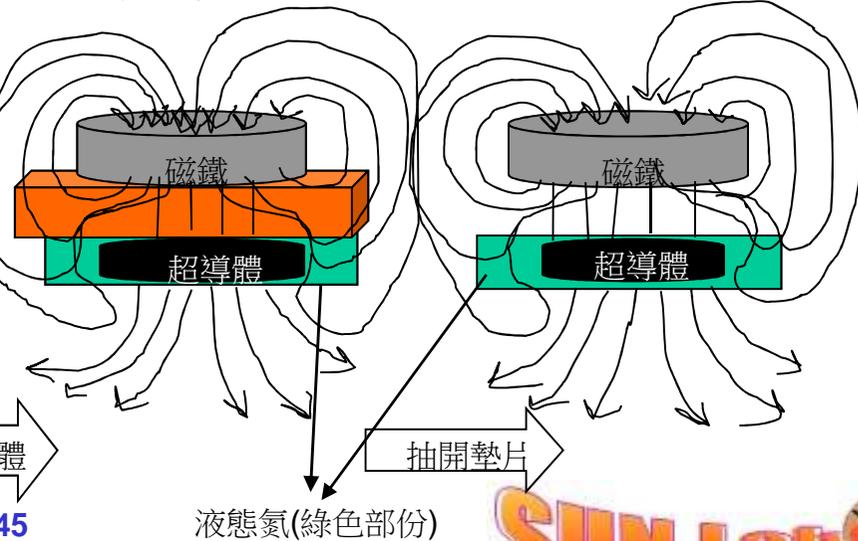
給超導體一固定間距的磁場



利用液態氦冷卻超導體



磁浮體相當穩定不傾斜

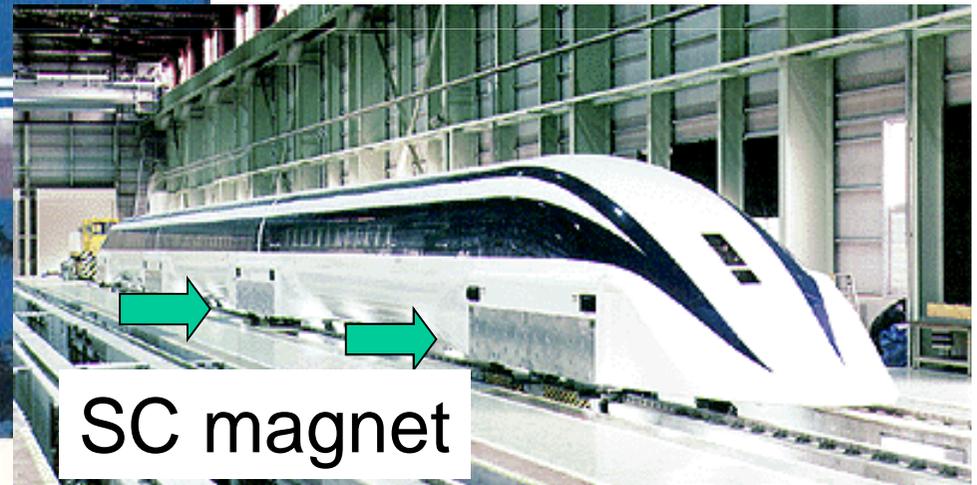


超導磁浮列車

日本Yamanachi (山梨線) 磁浮列車



- 磁浮列車的優點：
- (1) 省能源
 - (2) 低噪音
 - (3) 高速：(550 km/hr)
真空中(1600 km/hr)



(財)鐵道綜合技術研究所
Railway Technical Research Institute

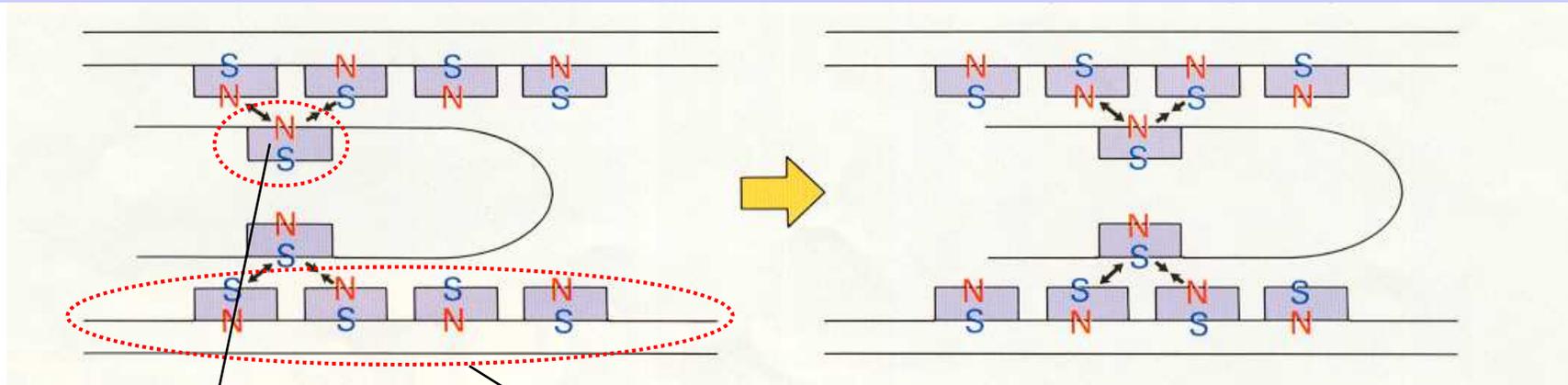


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日本Yamanachi(山梨線)超導磁浮列車-推進原理

被安裝在軌道兩旁牆上的推進線圈是由變電所所提供之三相交變電流，產生變換的磁場，使得軌道兩旁之推進線圈的電流一正一反不斷地流動，車上裝設之超導磁鐵(低溫超導線圈)便會受到推進線圈產生的變換磁場有著連續的吸引力與推進力，速度的調整，則由可將電流做正反轉的周波數來決定，周波數的轉換，又由地上發電廠的周波數裝置來操作。



超導磁鐵

軌道兩旁牆上的推進線圈



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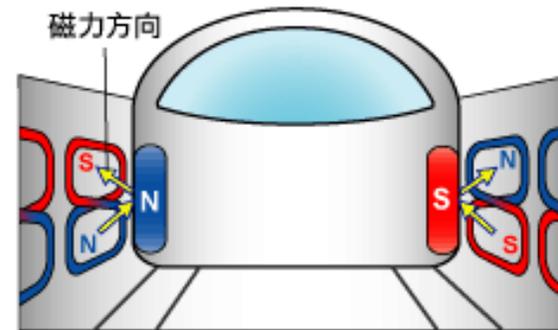
車體懸浮原理

磁氣浮上の原理

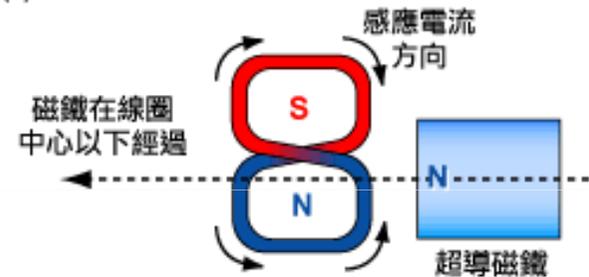
安裝在軌道旁之8字形線圈，當裝有超導磁鐵的車身以低於8字形線圈軸心位置快速通過時，8字形線圈會因感應出電流而成為一電磁鐵，此結果使得超導磁鐵會有一推力及拉力使之向上，所以車身便可磁浮起。

軌道之側向力：

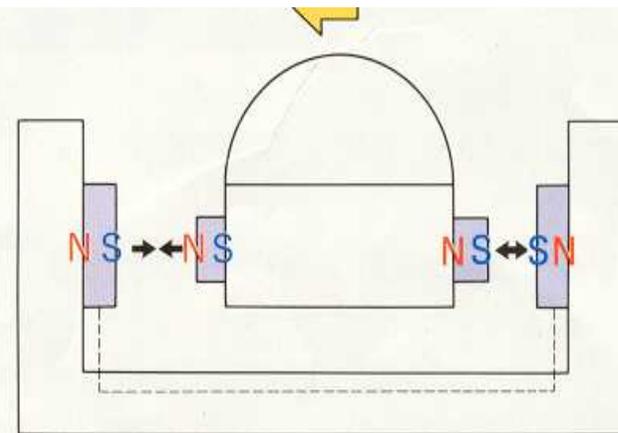
軌道上的磁浮線圈面對面的連結而形成迴路，當正在跑的磁浮車(也就是超導磁鐵)產生側向移動時，迴路會感應出電流，使得對於較靠近軌道的超導磁鐵產生推力，反之較遠離軌道的超導磁鐵則產生吸引力，如此便能使磁浮車車身安全的位在軌道中心的位置。



(a)



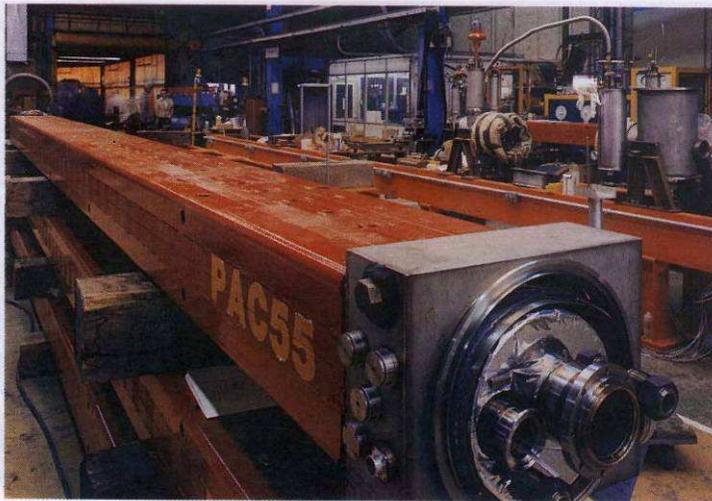
(b)



超導磁鐵在高能物理的應用



(a) 在Tevatron中正常導體磁體下方加裝了一組超導體磁體

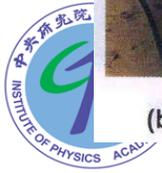


(b) Tevatron中有一千個以上這種的超導磁體

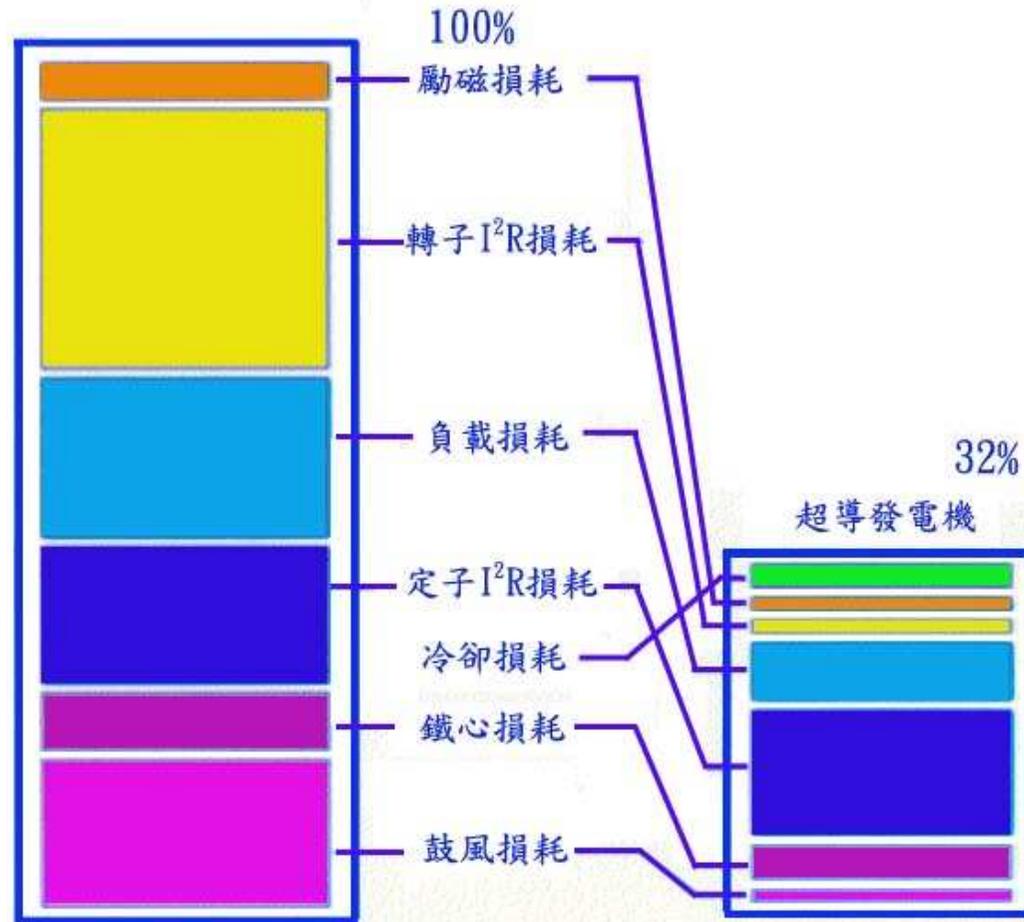


(c) Tevatron中液氮系統可以每小時生產4,600公升，維持超導磁體操作（美國Fermilab Visual Media Services提供）

<http://www.fnal.gov>



傳統發電機和超導發電機的損耗比較



傳統發電機和超導發電機損耗比較
(低壓 1200MVA)



銱-鈦超導轉子使僅有一米長、一米直徑的發電機可以達到兩萬瓩(20 Megawatt)的功率(美國General Electric製作, 圖片由U.S. Air Force Wright Laboratory提供)

- Advantage of SC Generator
- Higher Efficiency
 - Lower weight and volume



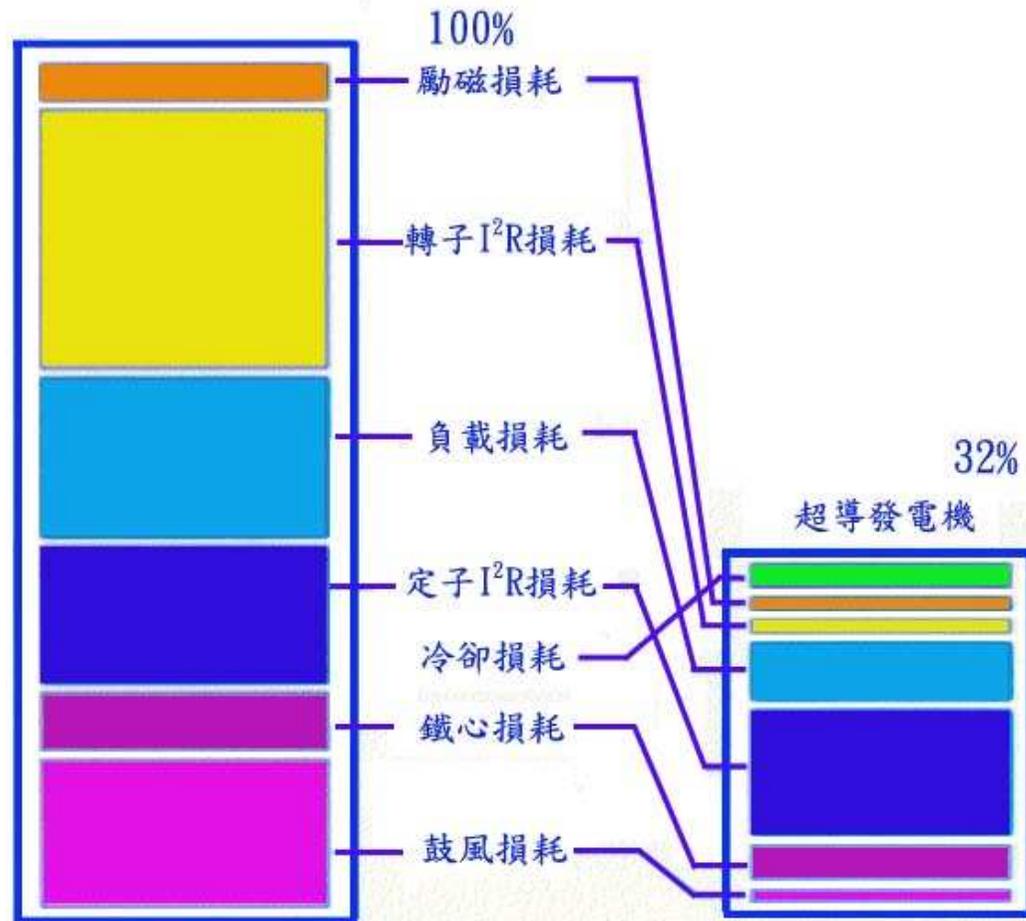
磁浮軸承與飛輪儲能



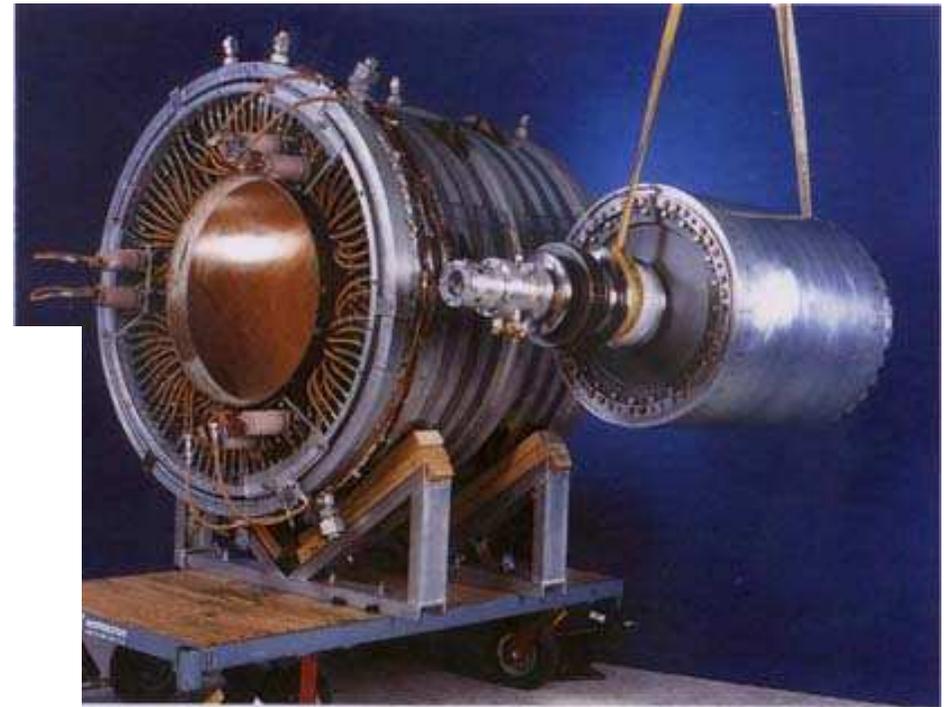
將超導體置入架上之容器中並倒入液態氮使之產生超導態，強磁鐵和單晶粒Y - Ba - Cu - O超導塊材之間利用場冷過程可使磁鐵磁旋浮起並保持固定的距離，以及無接觸、無磨擦的磁懸浮特性。因此地球儀可以完全無接觸地懸掛在空氣中，並可以接近無磨擦、無接觸在空中旋轉(僅有與空氣之摩擦力)。



傳統發電機和超導發電機的損耗比較



傳統發電機和超導發電機損耗比較
(低壓 1200MVA)



一釦超導轉子使僅有一米長、一米直徑的發電機可以達到
百萬瓦(20 Megawatt)的功率(美國General Electric製作,
影片由U.S. Air Force Wright Laboratory提供)

超導故障限流器



超導故障限流器 (SFCL) 是利用超導體的超導/正常態轉變特性，快速而有效地限制電力系統故障短路電流的一種電力設備。SFCL的工作原理是短路電流超過超導體的臨界電流，引起超導體失超，超導體從超導態轉變為正常態，限流器呈現很大阻抗，短路電流得以限制。SFCL具有如下的優點：

1. 增大電力系統的安全性和可靠性；
2. 提高電力質量；
3. 與現有的電力系統保護設施相容；
4. 減少電力系統線路中的斷路器和熔斷器的使用，延緩電力設備的更新以降低成本；
5. 提高系統的運行容量。

專家們預言，就超導技術在電力系統中的應用而言，最先得到實際應用的將可能是超導限流器。

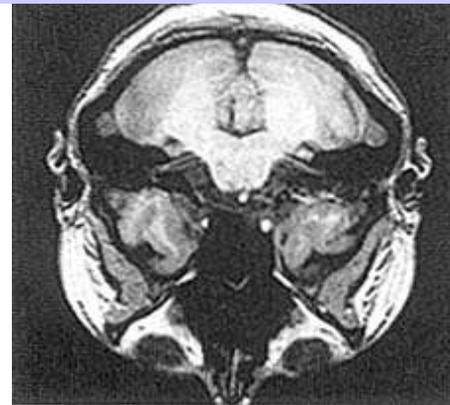


超導磁鐵在醫療上的應用-MRI



INTERMAGNETICS' MRI MAGNETS ARE USED
IN ALL MODELS OF PHILIPS MEDICAL SYSTEMS'
NT SERIES MRI SCANNERS.

所謂核磁共振，是具有核磁矩的物質在一定的恆定磁場和交變磁場同時作用下，會對變化的電磁場產生強烈的共振吸收現象。利用高溫超導體製程的線圈可以通過極大的電流而產生極強的磁場，可以比一般磁鐵高兩個數量級，檢測的靈敏度取決於所加磁場的大小，磁場越大，氫的共振訊號越強得到的圖越清晰，從而提高早期診斷可能性。



美國General Electric Medical System提供



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MRI



INTERMAGNETICS' MRI MAGNETS ARE USED
IN ALL MODELS OF PHILIPS MEDICAL SYSTEMS'
NT SERIES MRI SCANNERS.



A large SC magnet inside

美國General Electric Medical System提供



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MRI

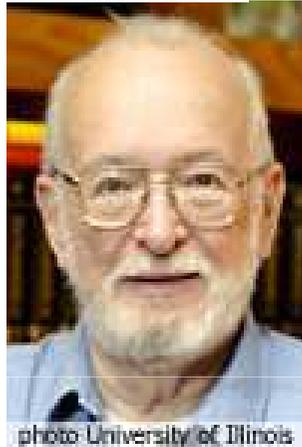
醫學獎



**Peter
Mansfield**

England,

U. of
Nortinheim



**Paul C.
Lauterbur**

USA

U. of Illinois-
Urbana-
Champaign



See details in Brain

奇異公司網站

<http://www.gemed.com.tw/machines>



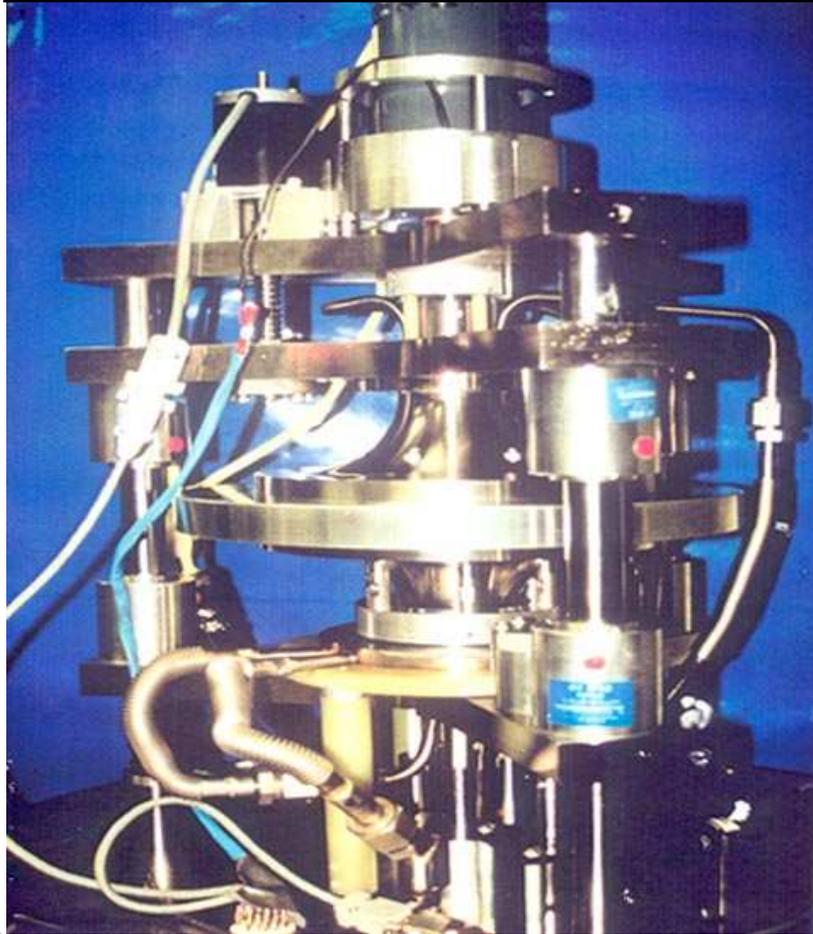
2003 Nobel Medical price

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超導磁性儲能

TcSUH Flywheel (朱唯幹教授)
德州超導中心製作的飛輪儲能



1. 可長期無損耗地儲存能量，其轉換效率可達95%。
2. 可通過採用電力電子器件的變流器實現與電網的連接，回應速度快（毫秒級）。
3. 由於其儲能量與功率調製系統的容量可獨立地在大範圍內選取，可建成所需的大功率和大能量系統。
4. 除了真空和製冷系統外沒有轉動部分，使用壽命長。
5. 在建造時不受地點限制，維護簡單、污染小目前美國、日本、德國等一些發達國家在超導儲能裝置方面的研究上投入了大量的人力和物力，並且有許多在建的超導儲能裝置。

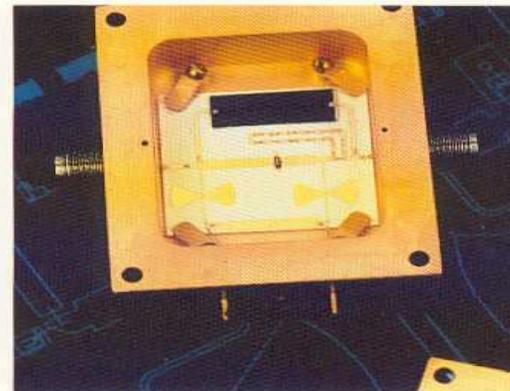


高溫超導濾波器

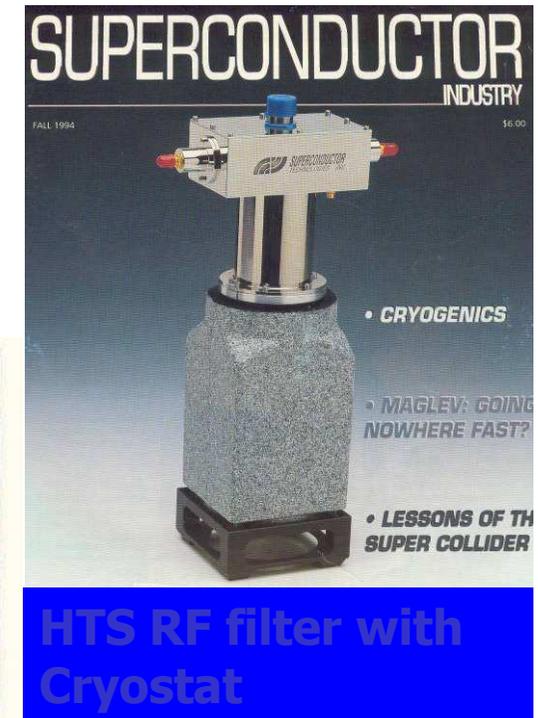
超導體在超導態下電阻為零，意味著超導體的熱噪音十分小，利用超導體做成的濾波器，自然可以將前級放大器中的熱噪音消除，又不引入新的熱噪音，提高了訊噪比

優點：

- ◆ 增加基地台的覆蓋範圍
(Cellular phone base stations coverage)
- ◆ 減少基地台數量 (more channels)
- ◆ 增進通話品質
- ◆ 增長手機使用時間
- ◆ 減少不必要的電磁輻射

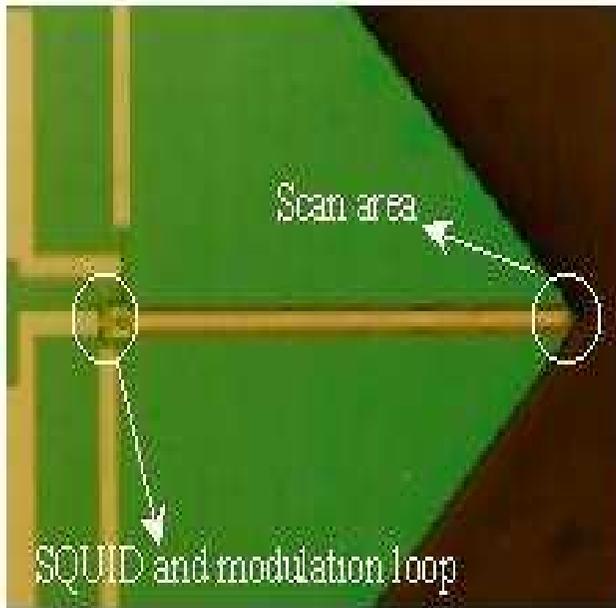


4. This stabilized local oscillator integrates semiconductor and superconductor technologies.

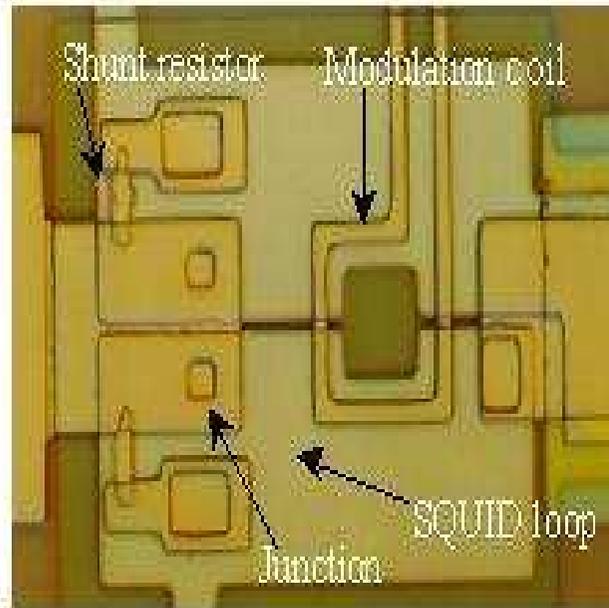


SQUID

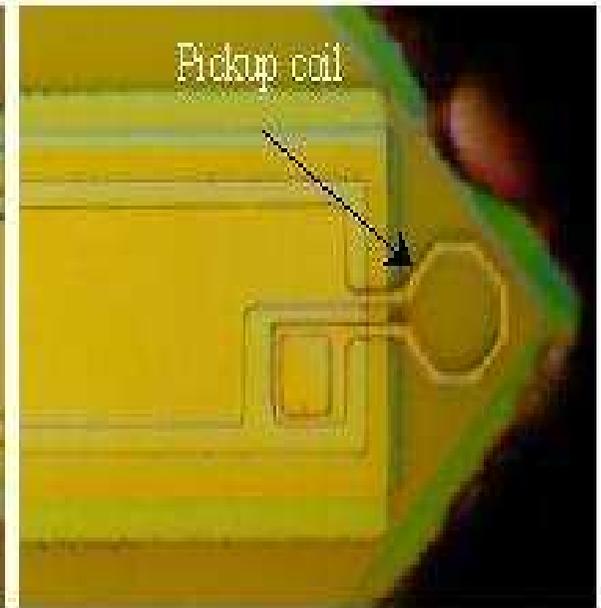
a. Scanning SQUID chip



b. SQUID and modulation area

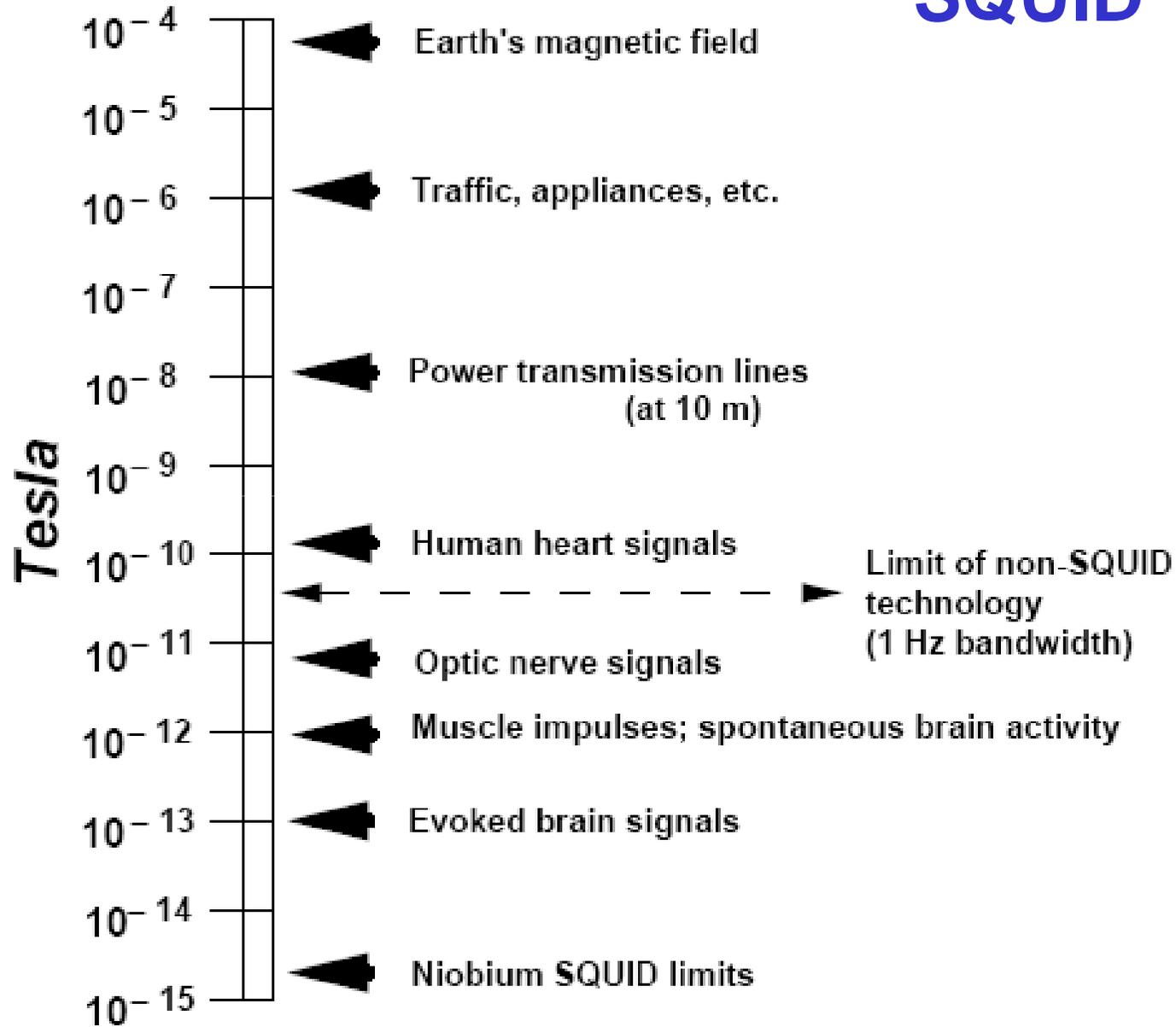


c. Scan area

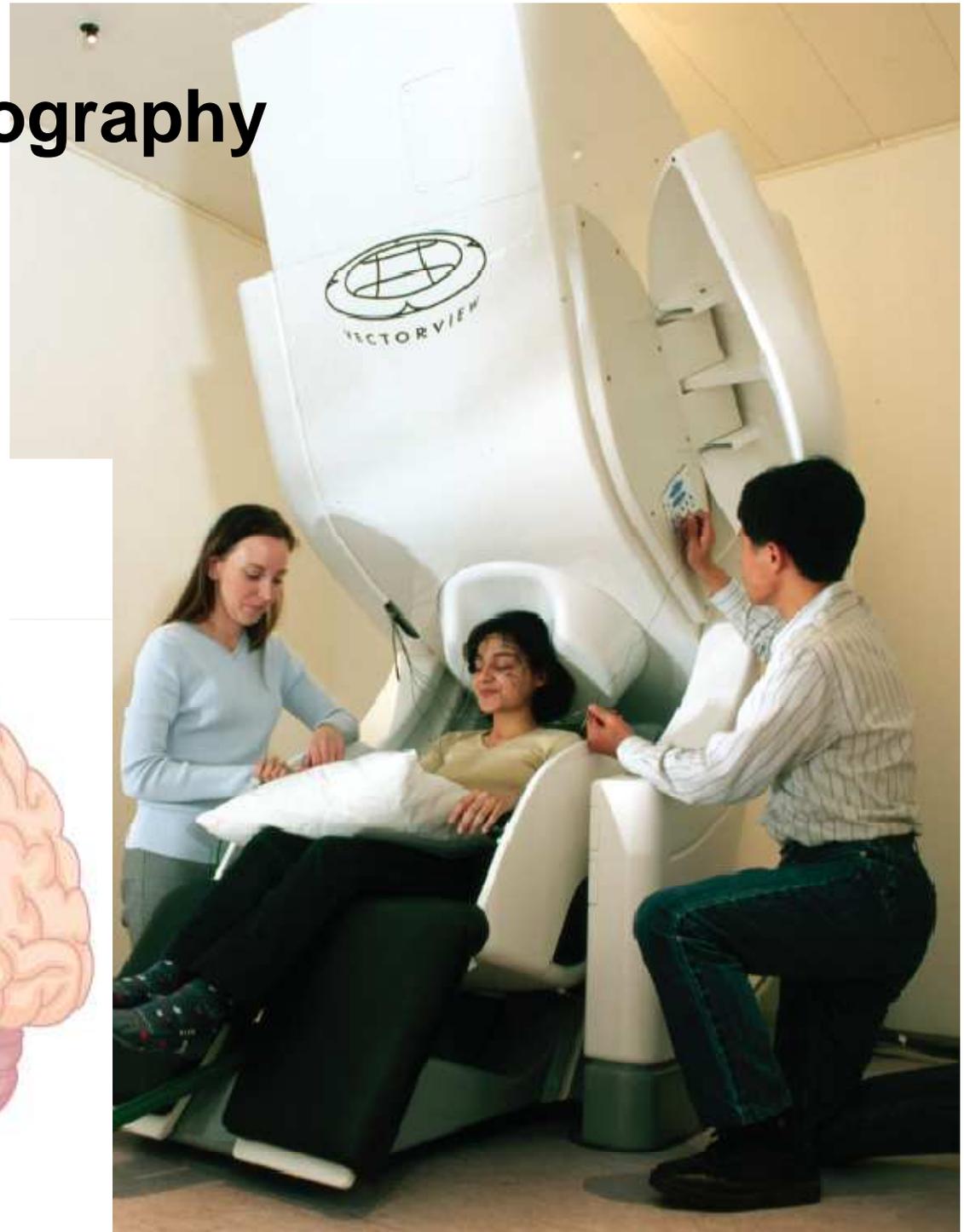
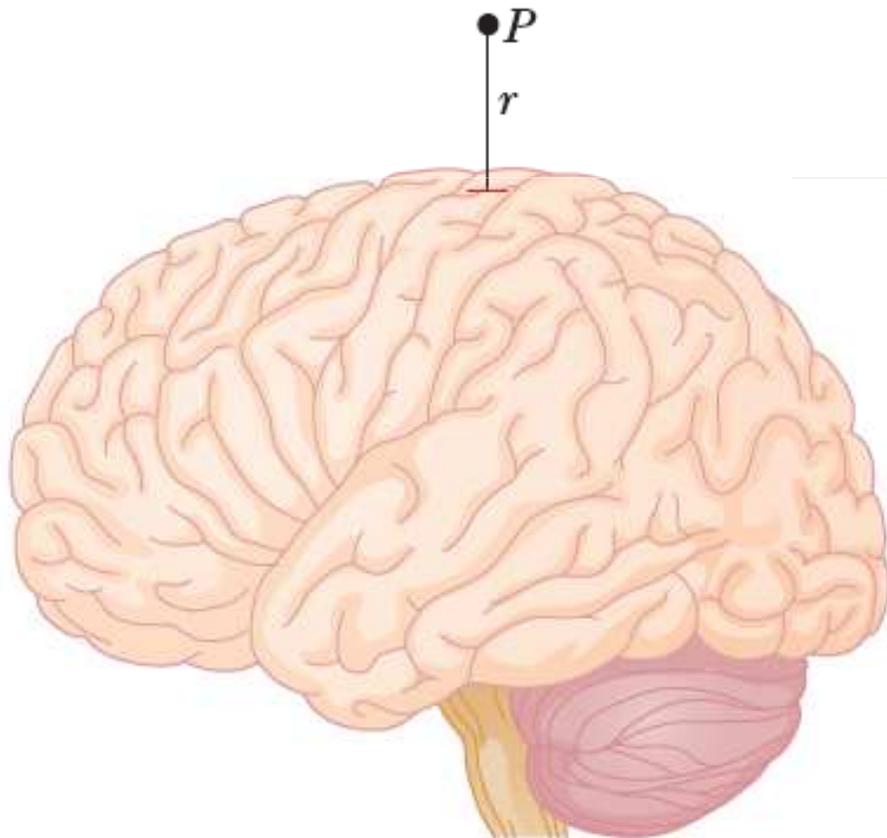


Magnetic Signal Levels

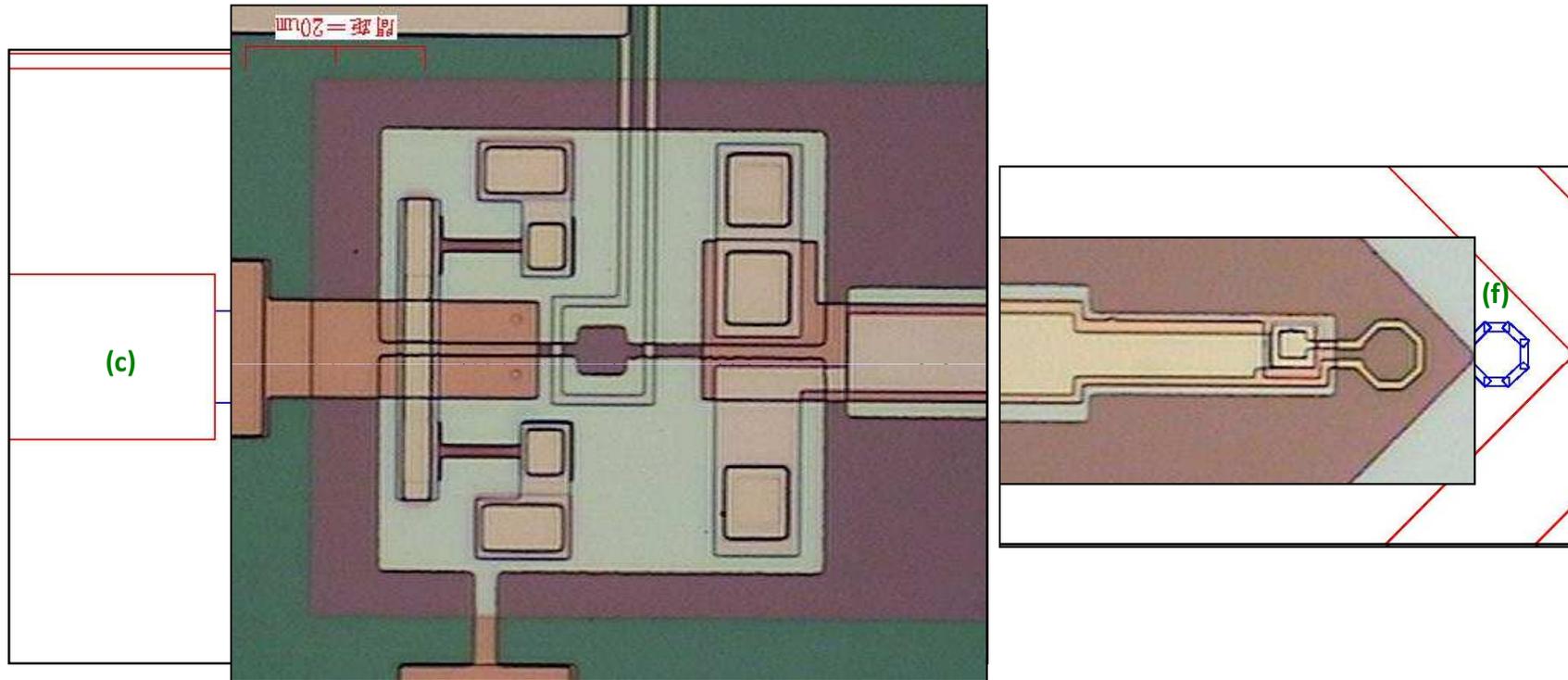
SQUID 的應用



Magnetoencephalography (MEG)



Design for Low T_c dc SQUID



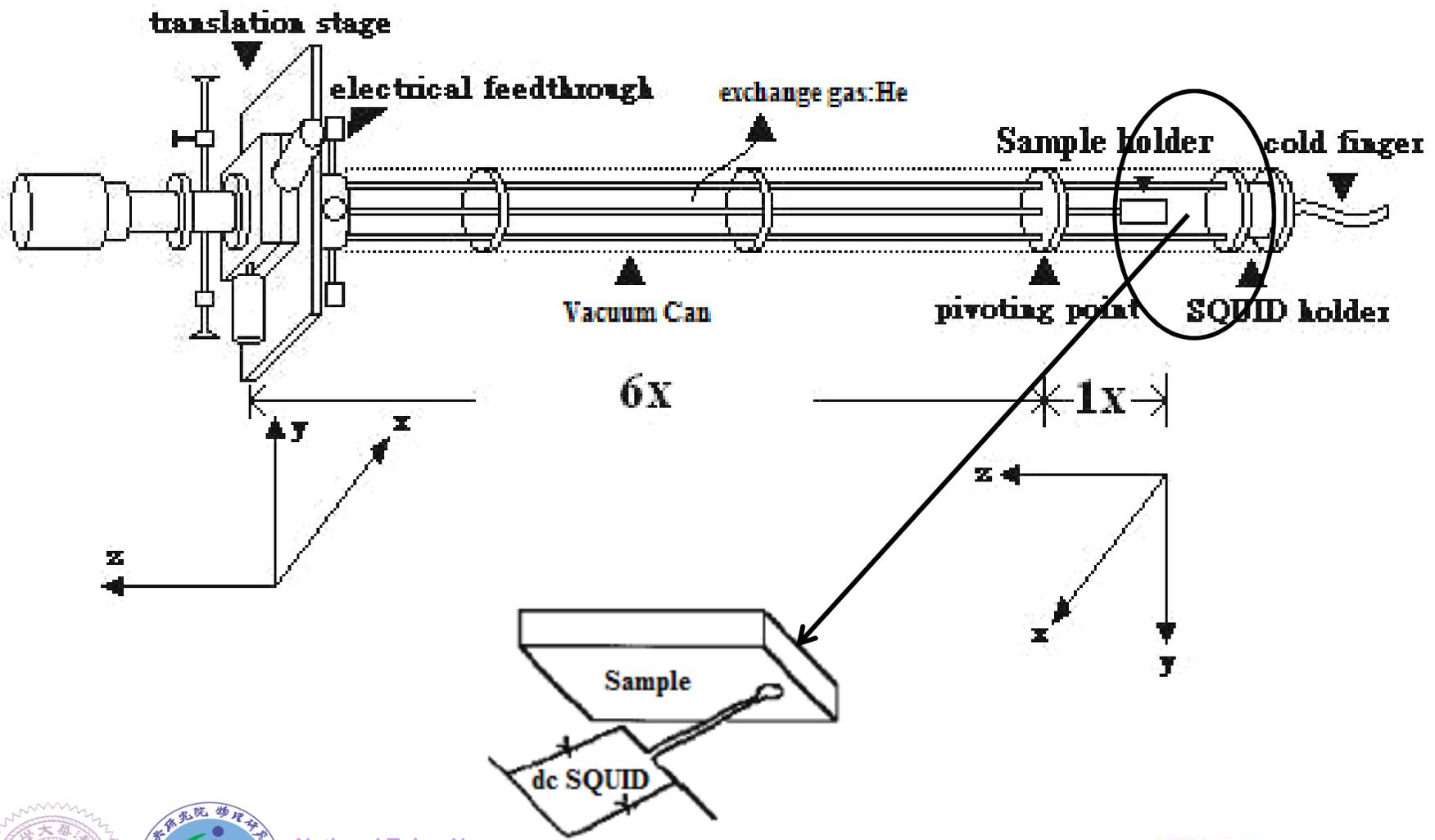
(a) SQUID loop (b) Stripline (c) &(d) Bias current and voltage signal leads (e) Josephson Junction (f) Pick-up coil (g) Shunted resistor (h) Contact hole (i) Modulation coil



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Specification of SSM system

1. Operating temperature: 4.2K
2. SQUID modulation frequency: 100kHz
3. Corresponding transfer function: $1.6\text{V}/\Phi_0$
4. Flux noise: $2 \times 10^{-5} \Phi_0 \text{Hz}^{-1/2}$
5. Residual field reduction: Low temperature mu-metal for reduction
6. External field: Solenoid coil ~ 3 Gauss maximum
7. Spatial resolution: ~10 μm
8. Scanning range: ~1mm x 1mm
9. Motion control: 50N loading maximum, 0.1 μm increment minimum
10. Data acquisition: NI A/D converter ~ 333 kS/s, 16-Bit, 2.5 μV sensitivity

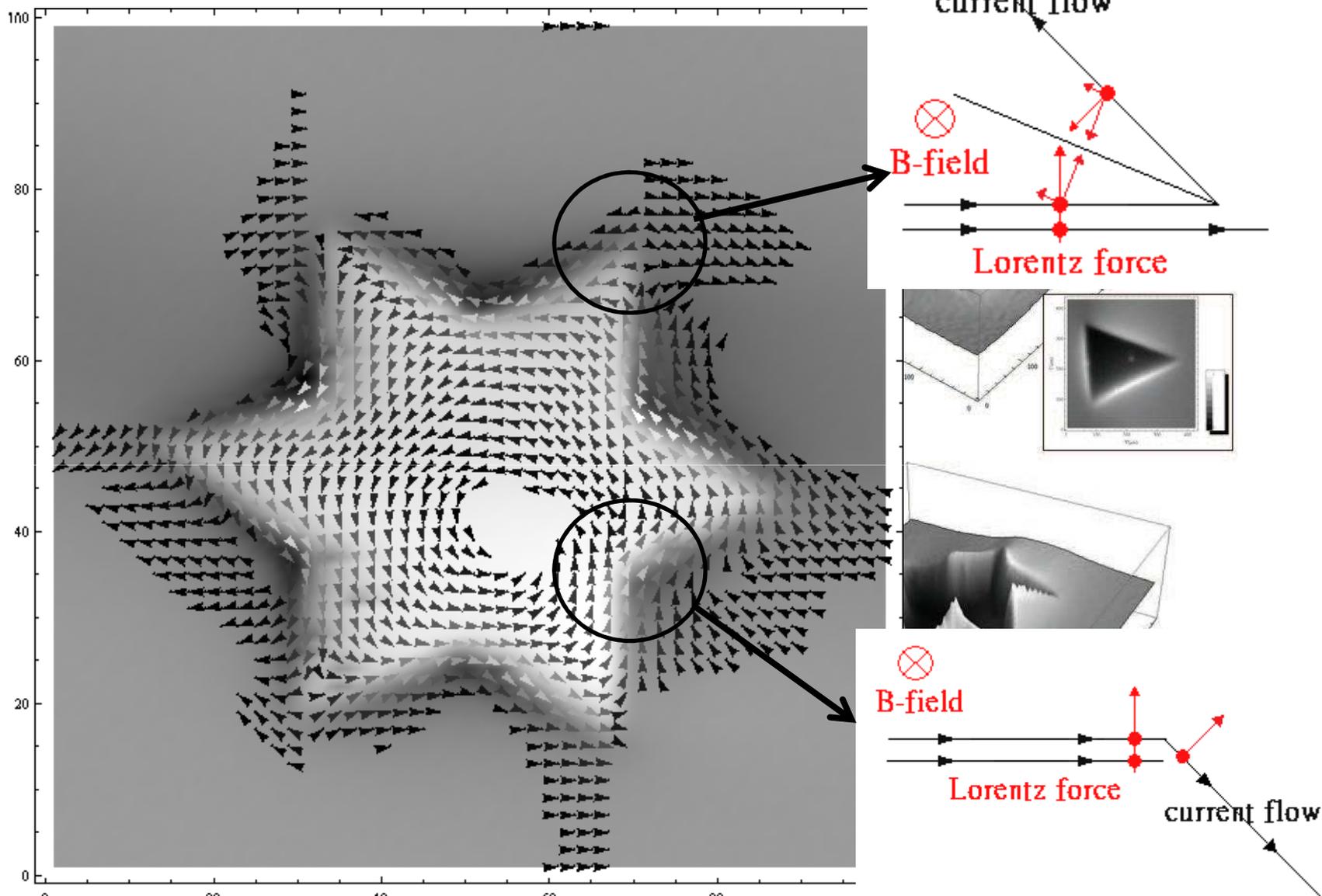


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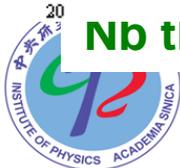
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Shielding current distribution



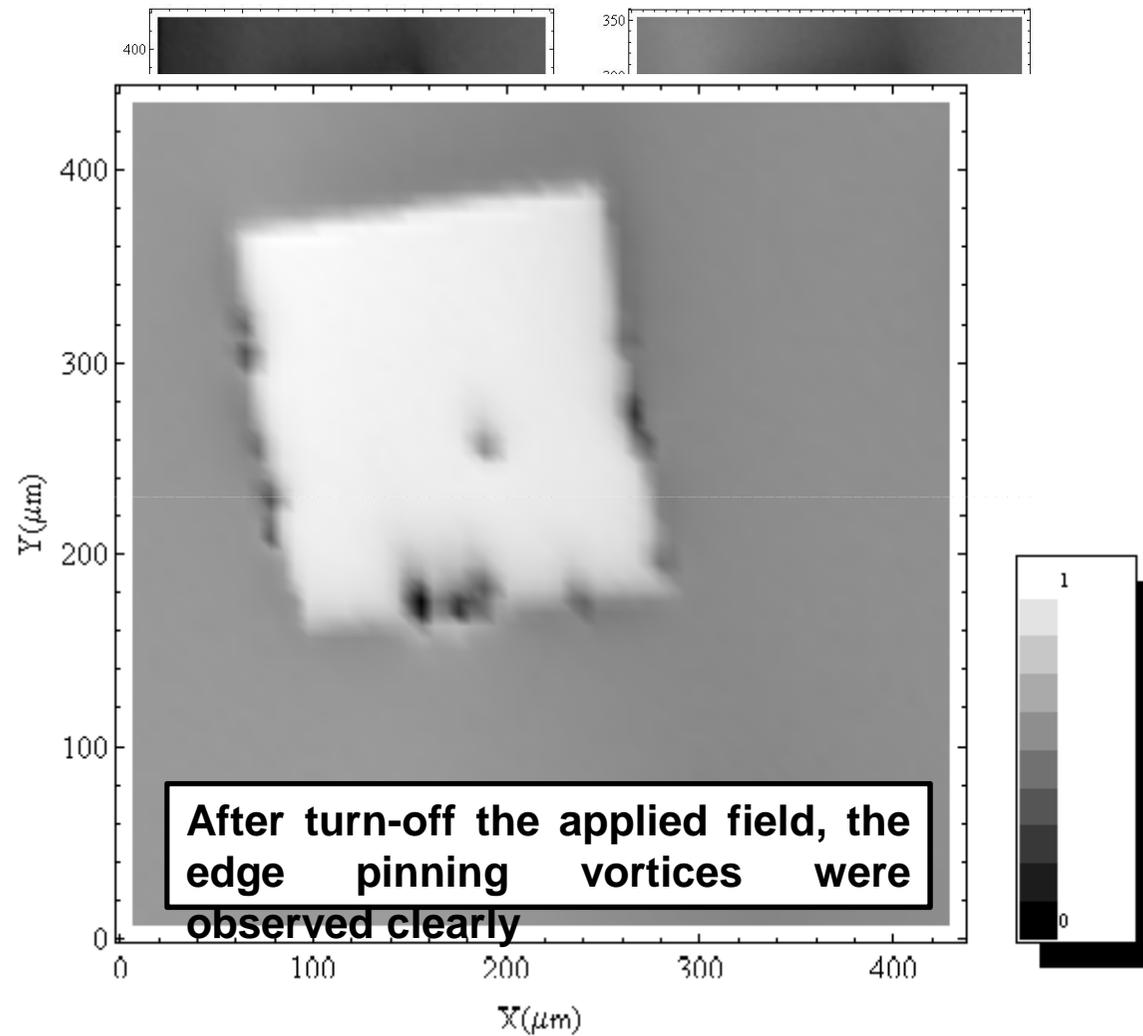
Nb thin film (2000A) within the ambient field below 100mG.



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Edge pinning observation



2K

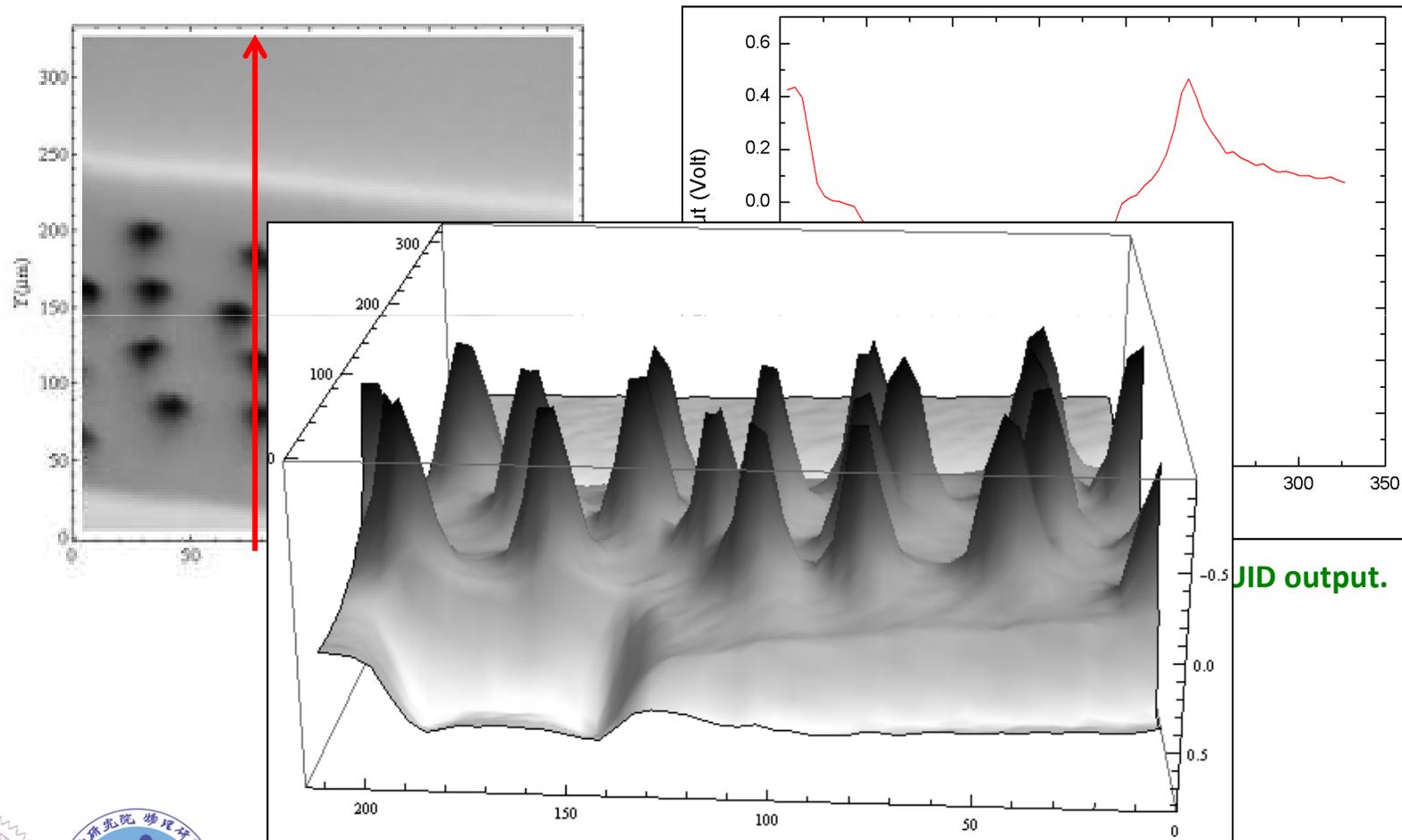
(b)

applied 100mG ambient field (c) applied 200mG ambient field (d)
applied 300mG ambient field



Pinning force estimate

Nb meander line with 200 μm width, 2000 \AA thickness and field cooled at 30mG ambient field.



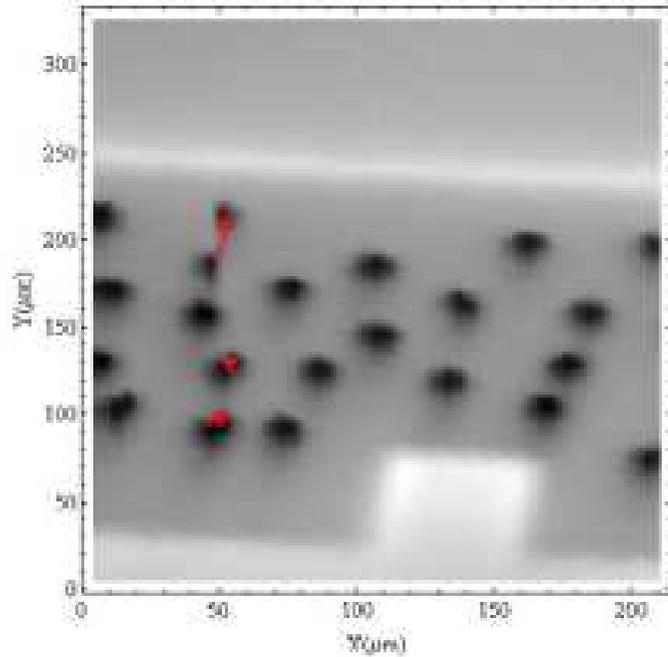
JID output.



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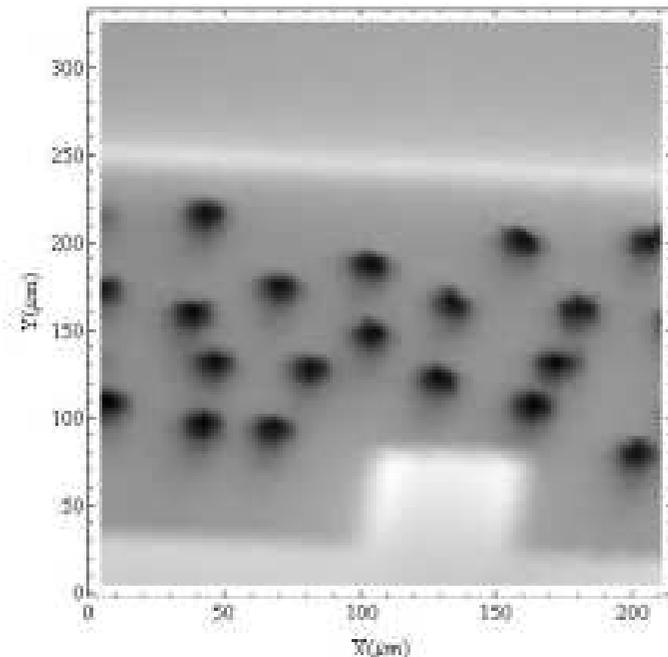
By apply pulse current with duration time: 5 sec and change the amplitude from 10mA to 150mA

The pinning force per unit length can be estimated by:

$$f = J_c \times \Phi_0,$$

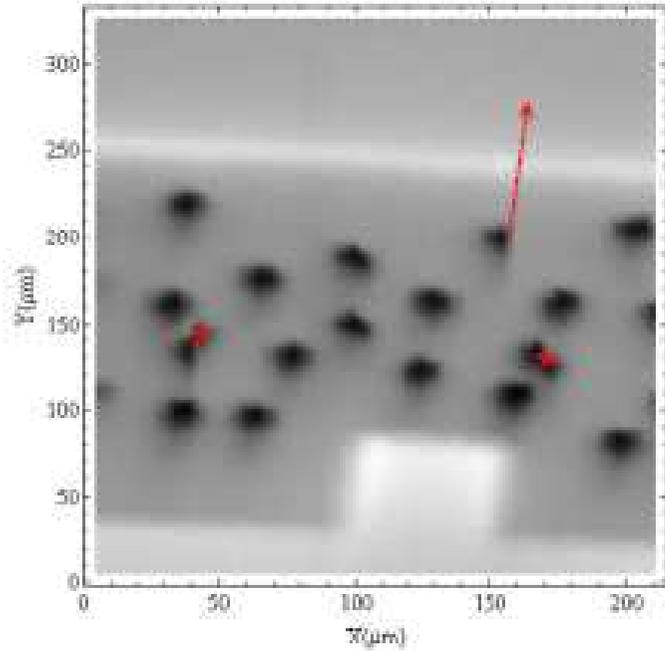
where $J_c = I/A$ is the current density in these meander line

10mA pulse current apply (pinning force per unit length for 3 pinning-sites were below 500 nN/m)

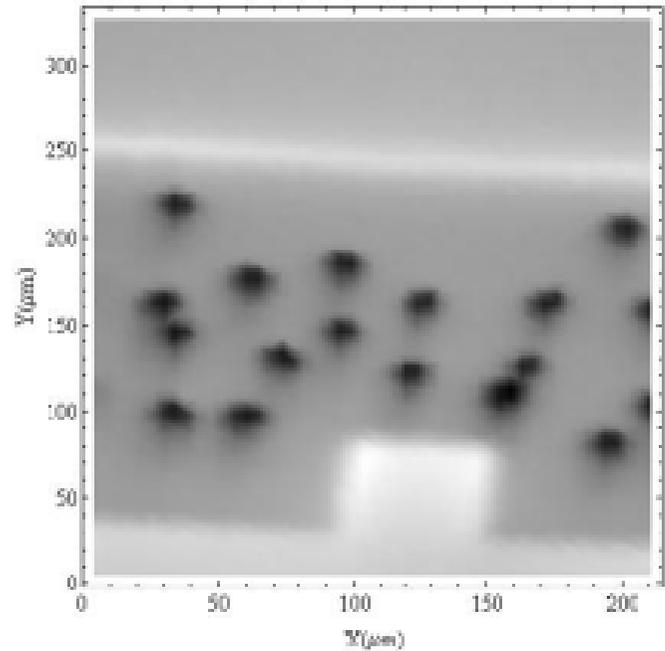


50mA pulse current apply (pinning force per unit length for these pinning-sites were large than about 2.5 μN/m)

ersity



100mA pulse current apply (pinning force per unit length for 3 pinning-sites were below $5 \mu\text{N/m}$)

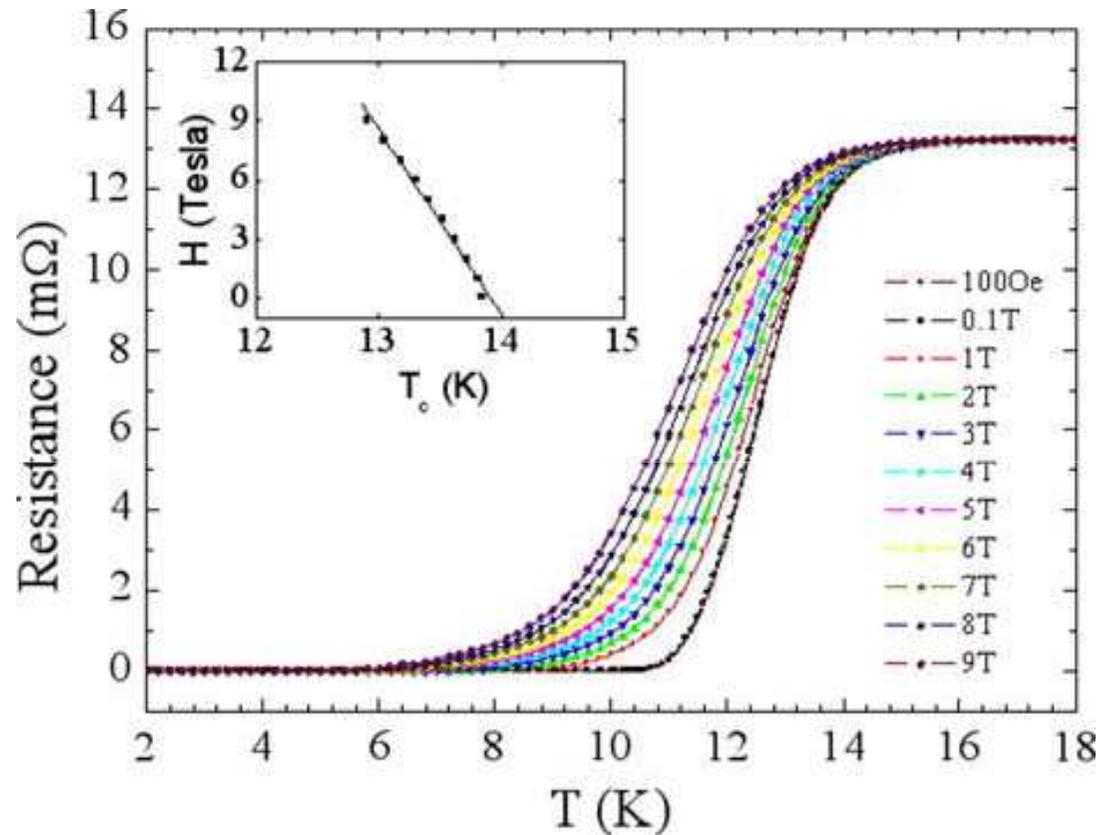


150mA pulse current apply (pinning force per unit length for these pinning-sites were large than $7.5 \mu\text{N/m}$)

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a



Study on $FeSe_xTe_{1-x}$ thin film by SSM



Resistive transition in various magnetic fields of $Fe(Se_{0.5}Te_{0.5})$. The inset shows onset T_c vs. applied field. The estimated upper critical field $H_{c2}(0)$ is 72.5 T

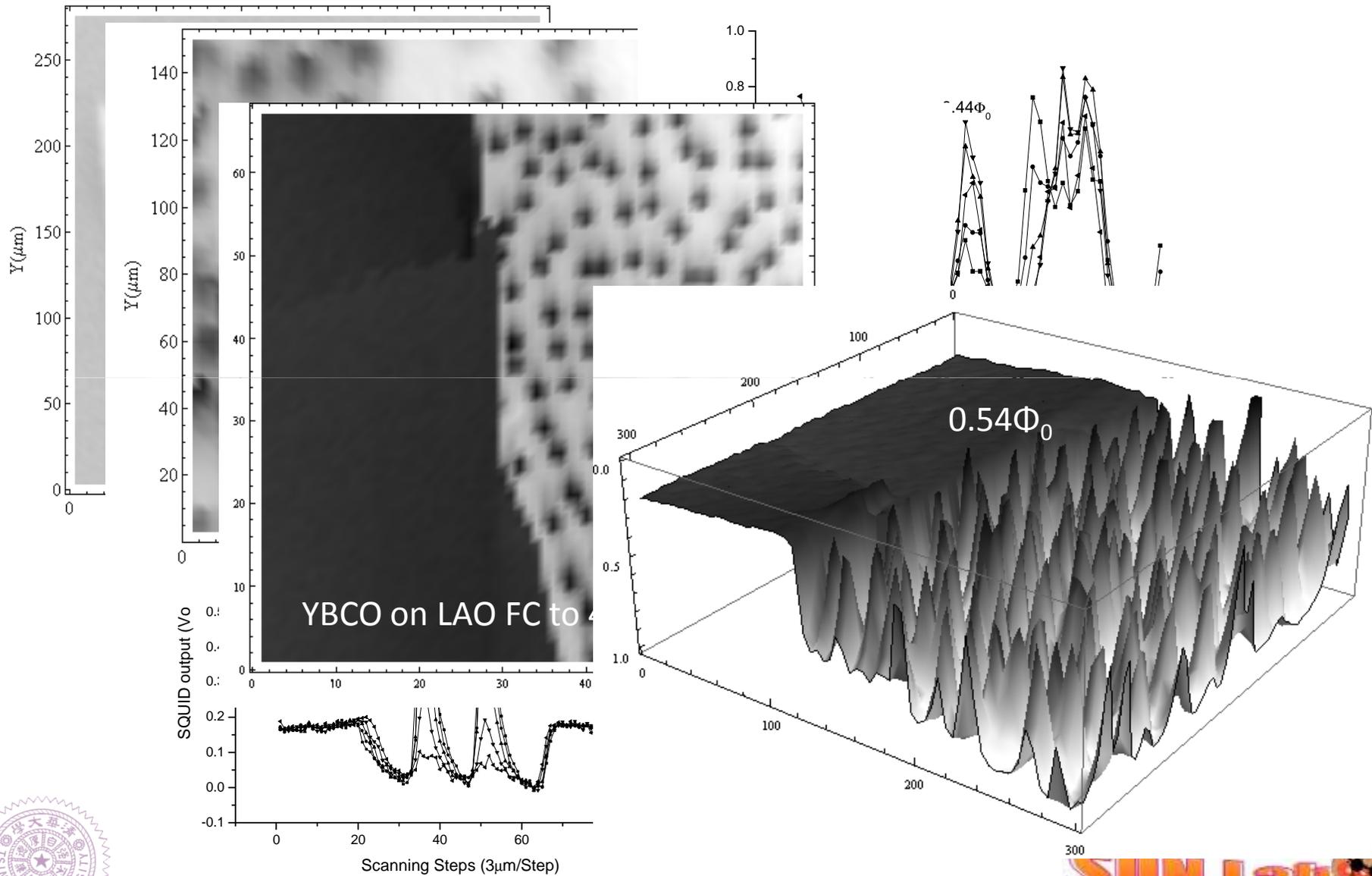


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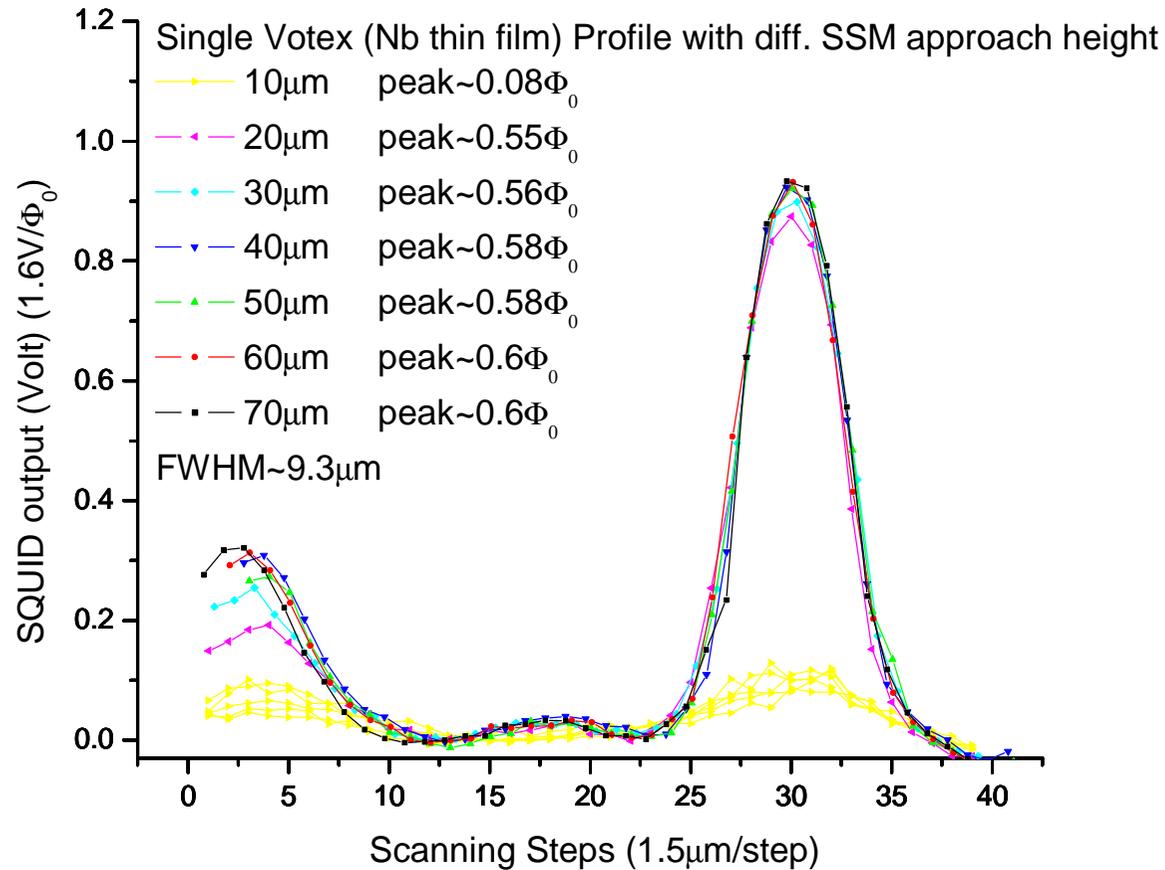
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Vortices at Nb, NbSe₂, YBCO



Single vortex in Nb thin film with different approach heights



Single-vortex sensing by a loop

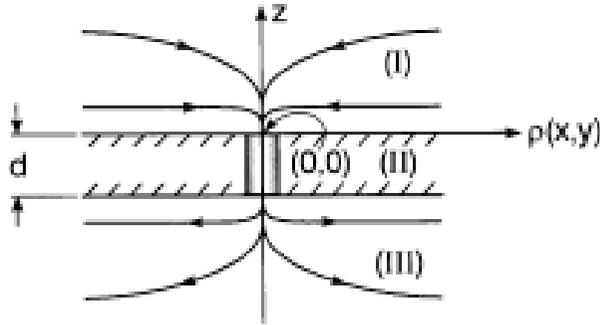


Fig. 1. Schematic depiction of a superconductor film in the presence of a single vortex of chirality $\varphi = -1$. Shown are the chosen cylindrical coordinate system, the domains (I), (II) and (III), the thickness d , the induction $h(\vec{r})$ field-lines flow and the thin cylindrical shaft around the core-line at $\{x, y, z\} = \{0, 0, -d \leq z \leq 0\}$.

$$h_z^{(I)}(q) = \varphi \frac{\Phi_0 \beta^2}{2\pi} \times \frac{q \tan(D[q]d/2)}{D[q](q + D[q] \tanh(D[q]d/2))}$$

Where φ is the chirality of a single vortex, $\beta = 1/\lambda$, and $D[q] = (q^2 + \beta^2)^{1/2}$

$$h_z^{(I)}(\rho, z) = \int_0^\infty dq J_0(q\rho) e^{-qz} h_z^{(I)}(q)$$

Where $J_0(z)$ is the regular Bessel function of order 0, and $h_z^{(I)}$ is the weighting factor.

By substituting the weighting factor

D. Agassi, J.R. Cullen. Physica C 334(2000)274–282



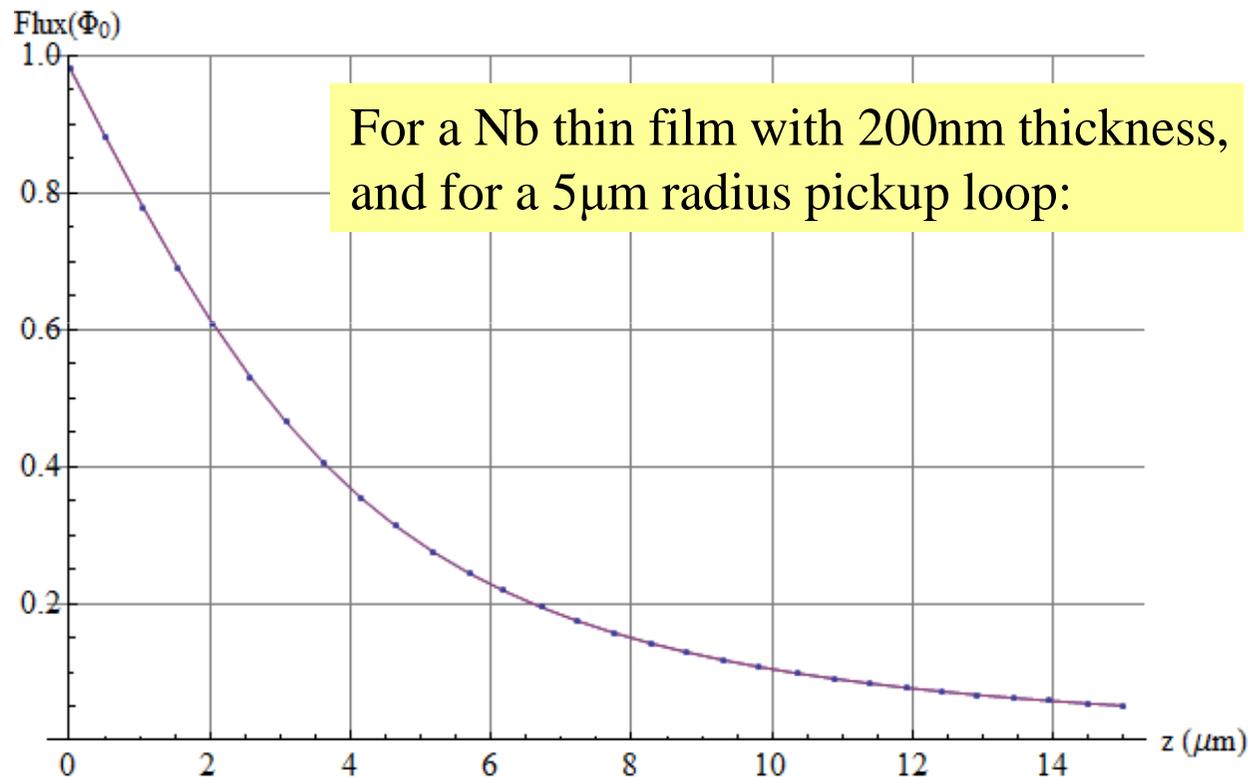
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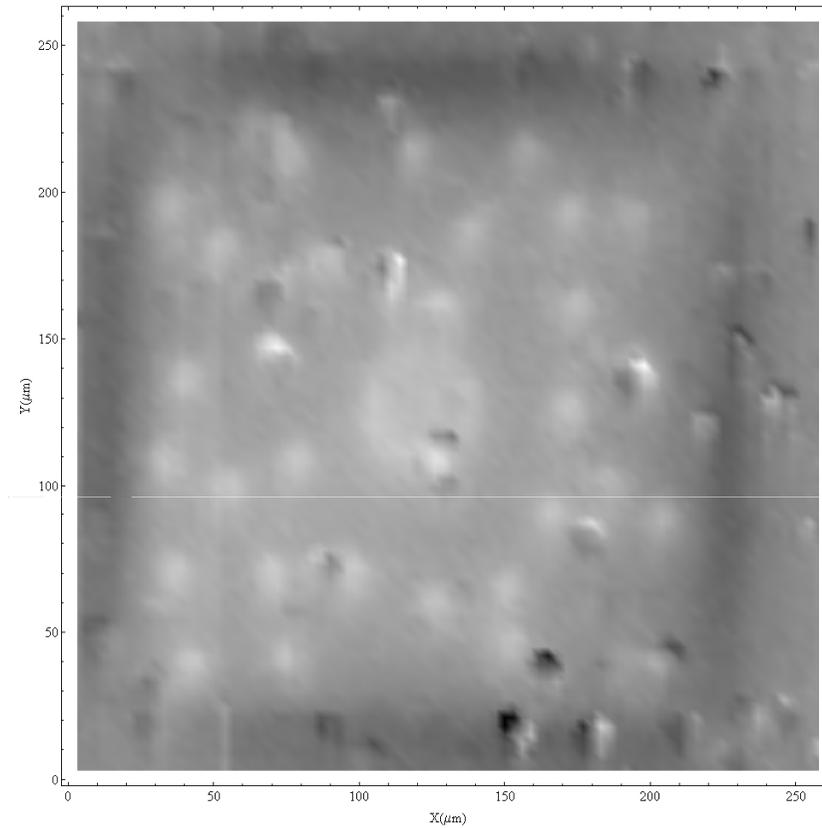
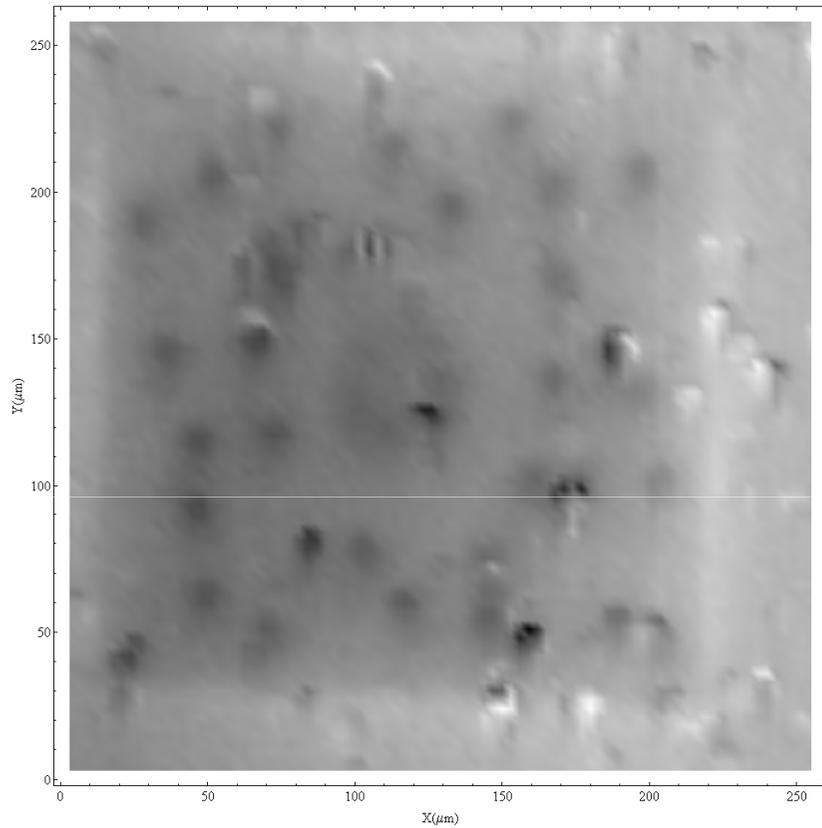
Single-vortex sensing by a loop

Calculated flux when the pickup coil is directly above the vortex core, assuming that the pickup coil radius is a :

$$\Phi[z] = \int \vec{B} \cdot d\vec{a} = \int_0^{2\pi} \int_0^a h_z^I[\rho, z] \rho d\rho d\phi$$



Study on $\text{FeSe}_{0.3}\text{Te}_{0.7}$ thin film



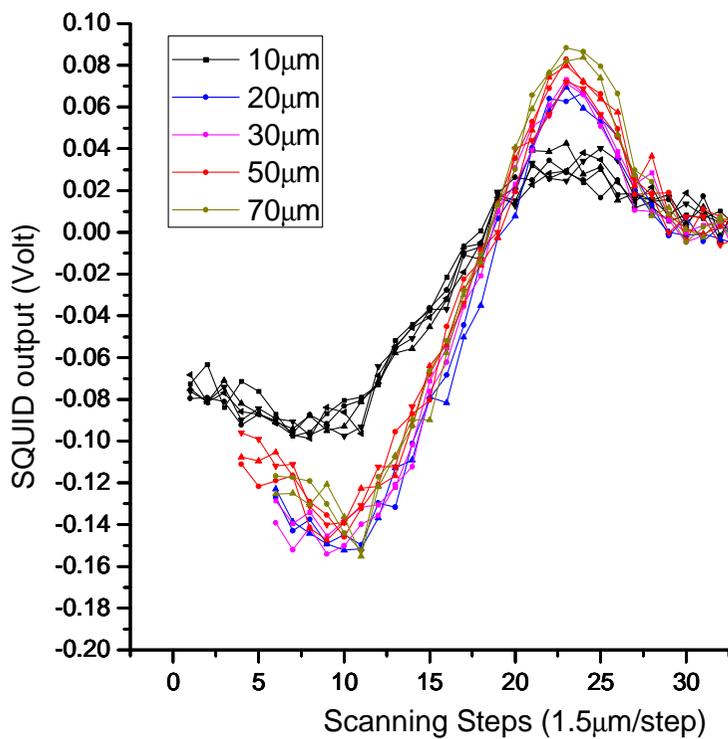
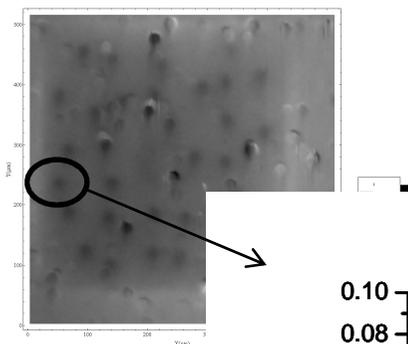
FC at $\pm 10\text{mG}$



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Single Vortex in FeSe_{0.3}Te_{0.7}



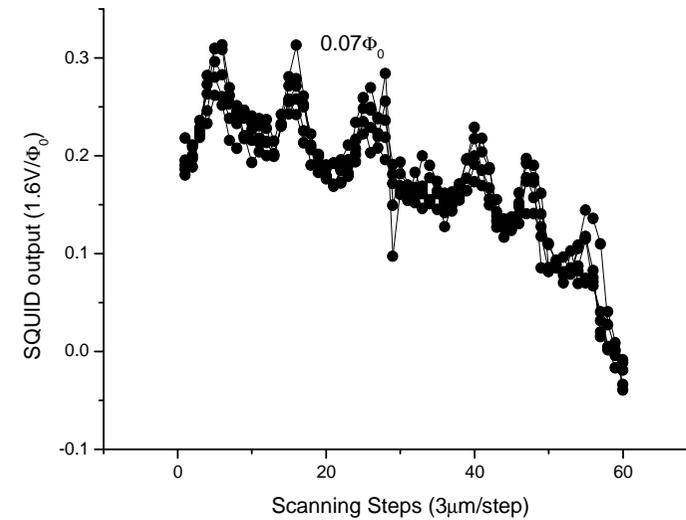
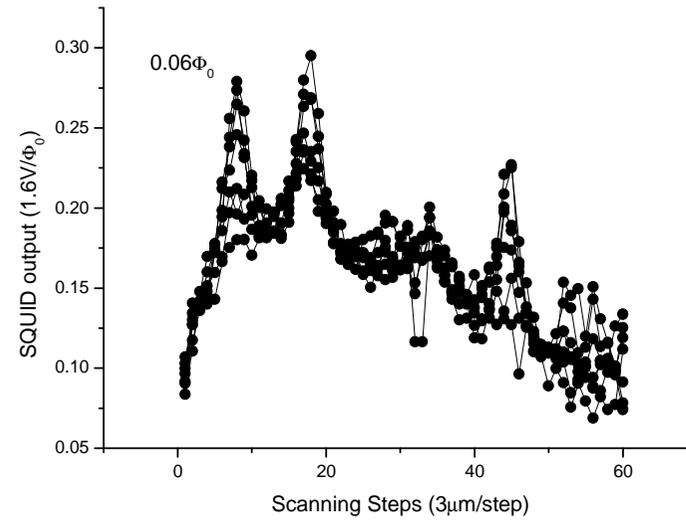
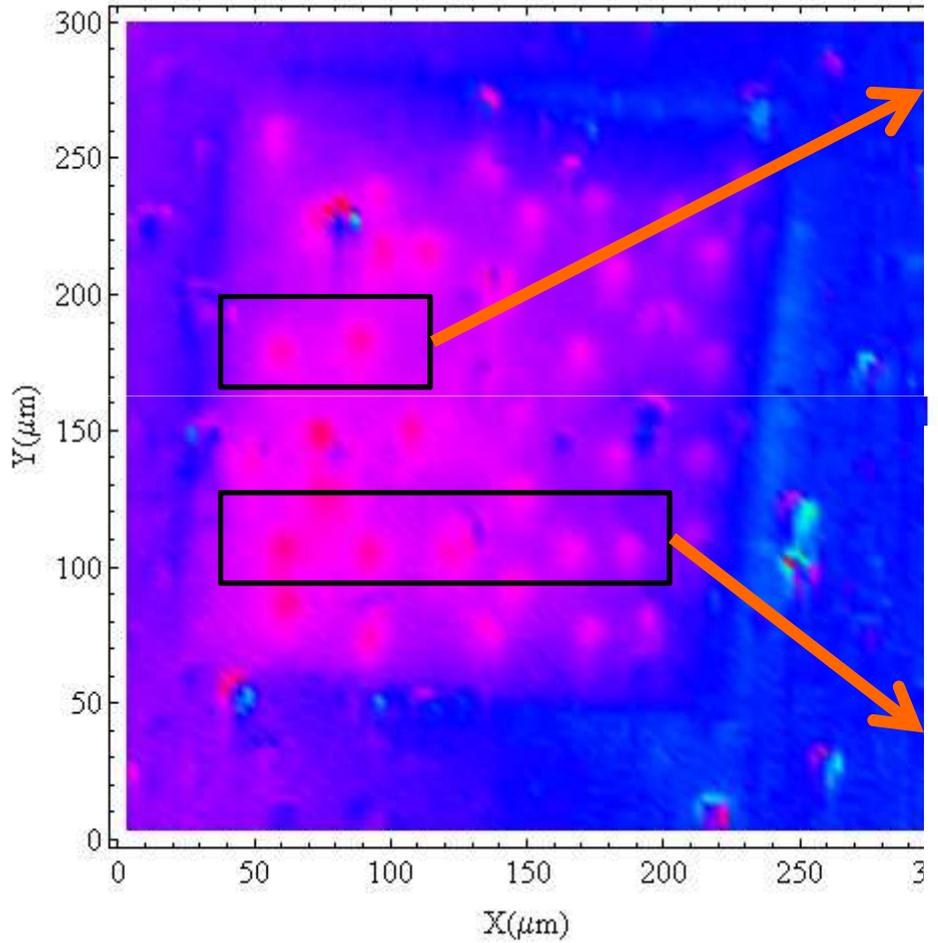
Approach length	Observed Φ_0	FWHM
10 μm	0.026 Φ_0	10.76 μm
20 μm	0.055 Φ_0	9.87 μm
30 μm	0.054 Φ_0	9.83 μm
50 μm	0.055 Φ_0	9.83 μm
70 μm	0.066 Φ_0	10.2 μm



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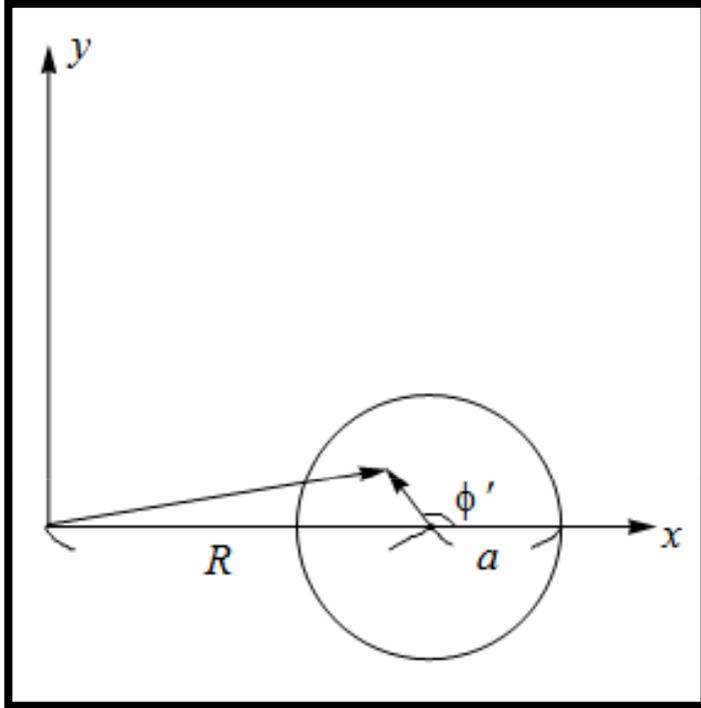
Vortices in $\text{FeSe}_{0.3}\text{Te}_{0.7}$



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Simulation a Real Flux Scanning



$$x = R + \rho' \cos[\phi']$$

$$y = \rho' \sin[\phi']$$

$$\rho = \sqrt{x^2 + y^2} = \sqrt{R^2 + \rho'^2 + 2R\rho' \cos[\phi']}$$

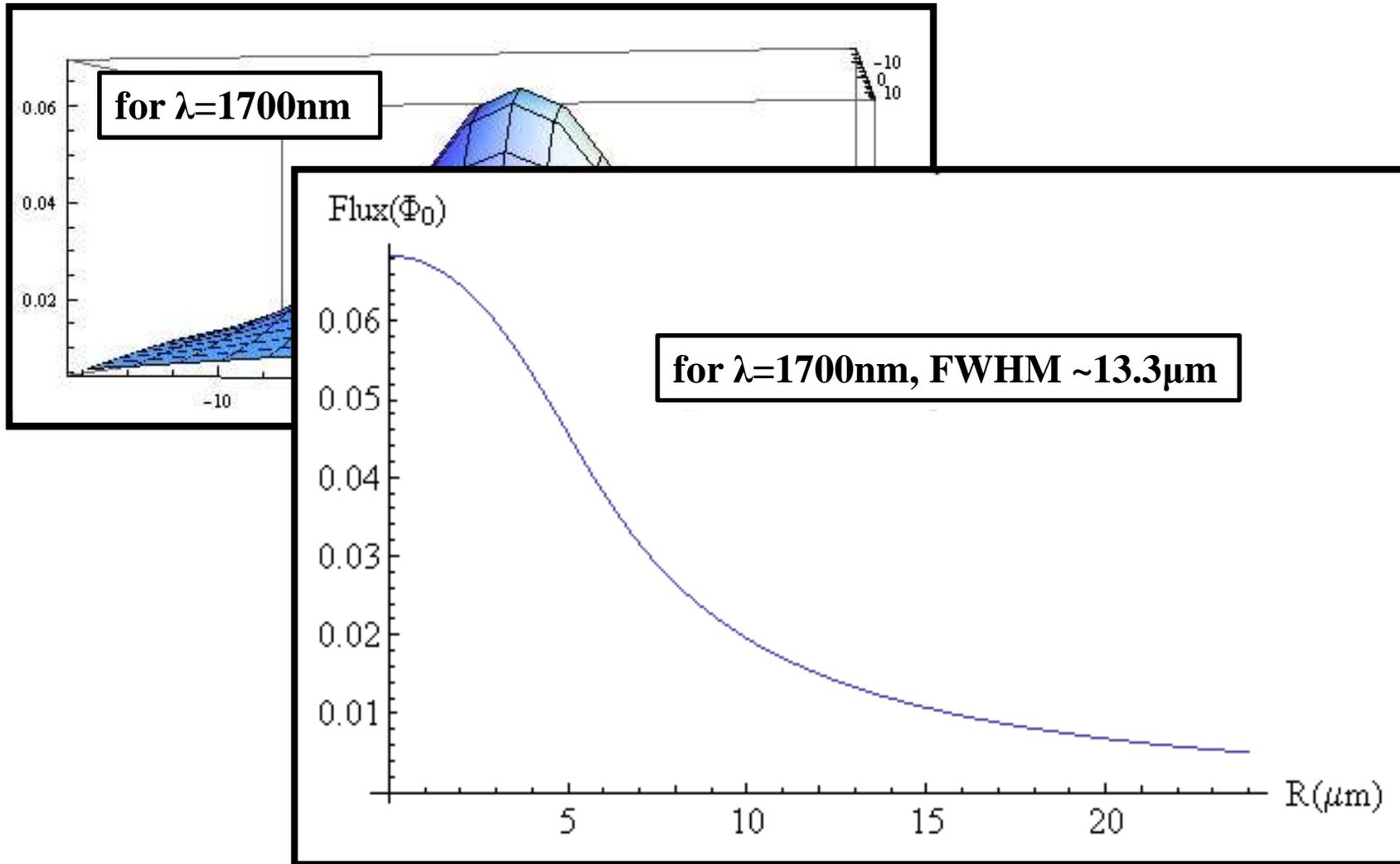
$$\Phi = \int_0^a \int_0^{2\pi} h_z^I[\rho] \rho' d\rho' d\phi'$$



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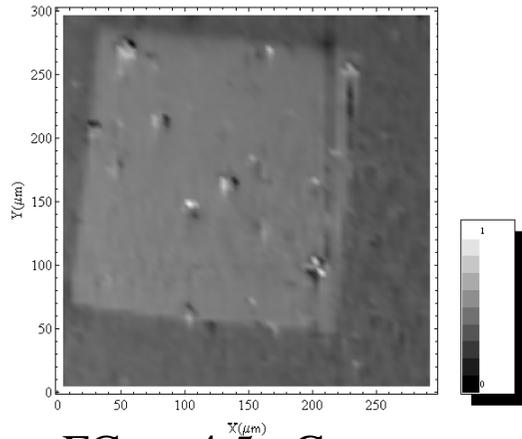




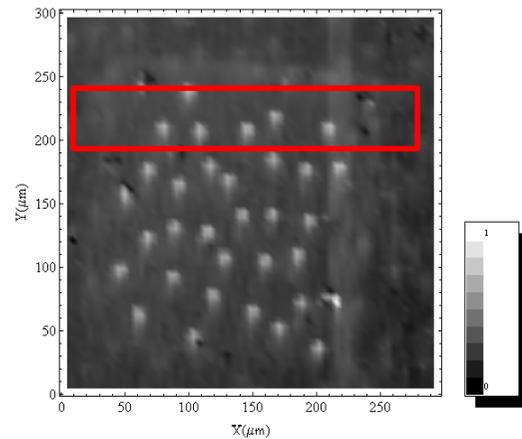
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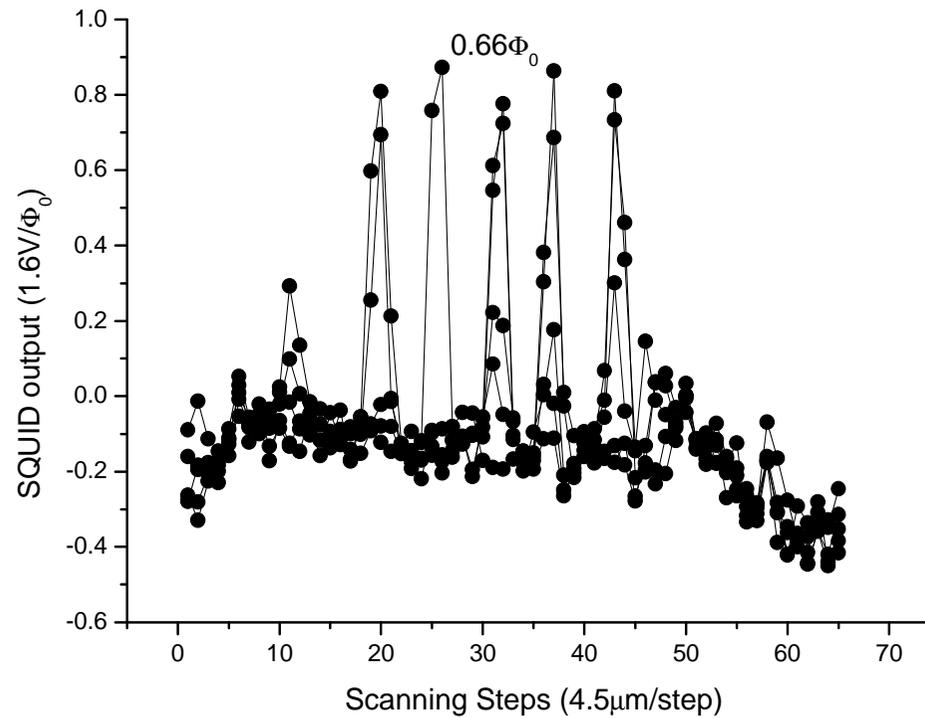
Deposited Nb square (300x300 μm^2) on $\text{FeSe}_{0.3}\text{Te}_{0.7}/\text{STO}$



FC at -4.5mG



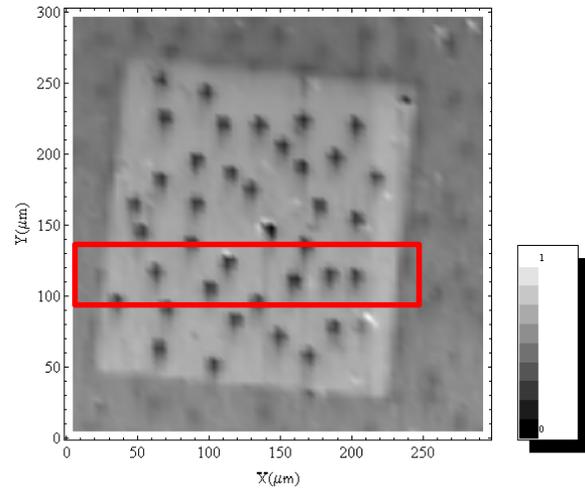
FC at 10mG



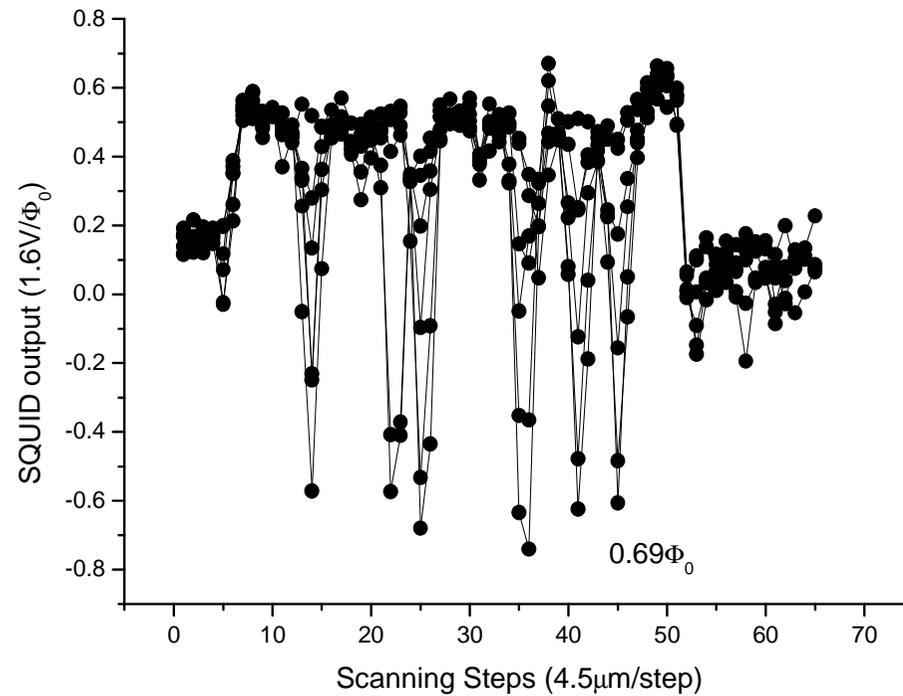
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Deposited Nb square (300x300 μm^2) on $\text{FeSe}_{0.3}\text{Te}_{0.7}/\text{STO}$

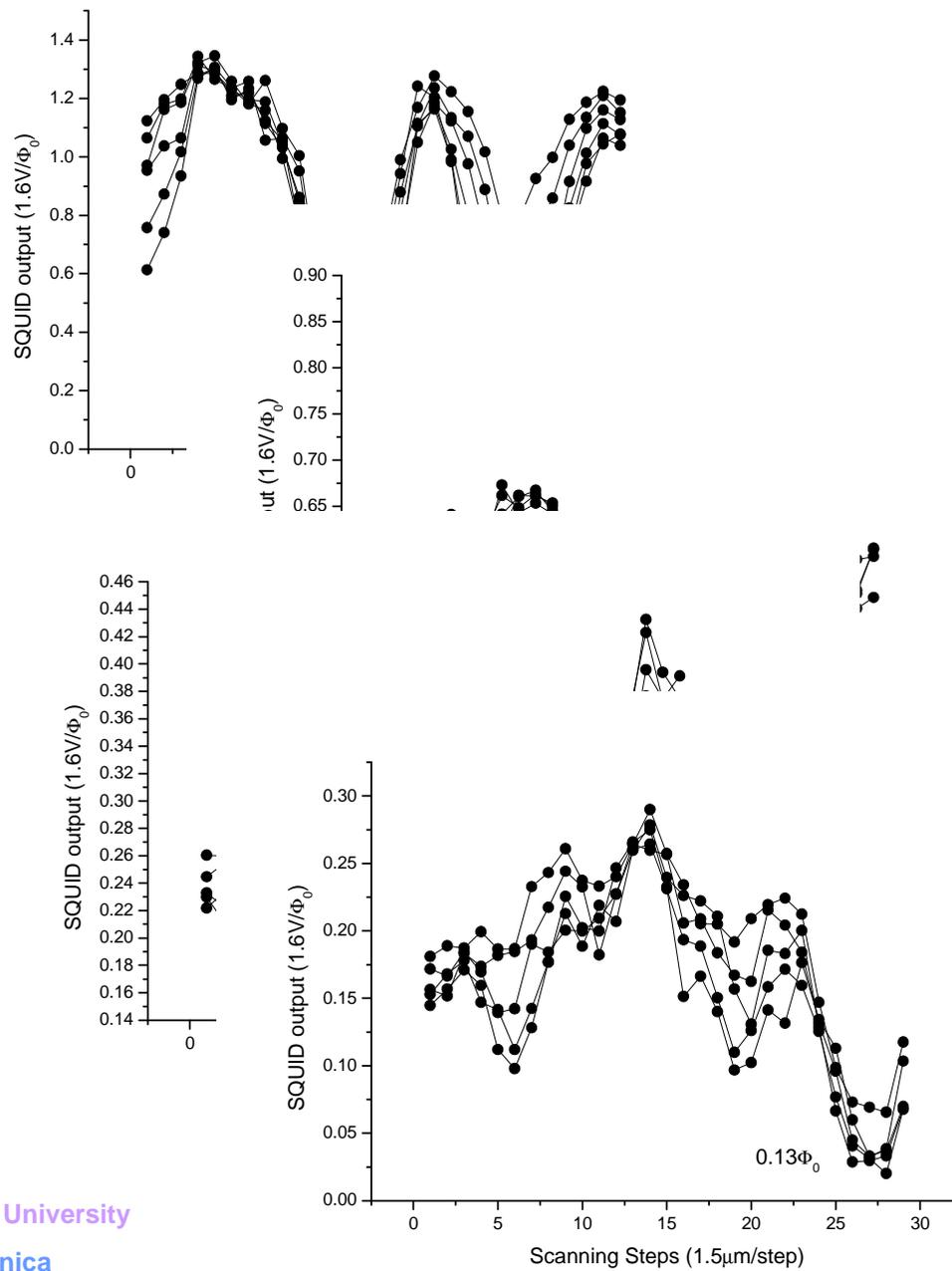
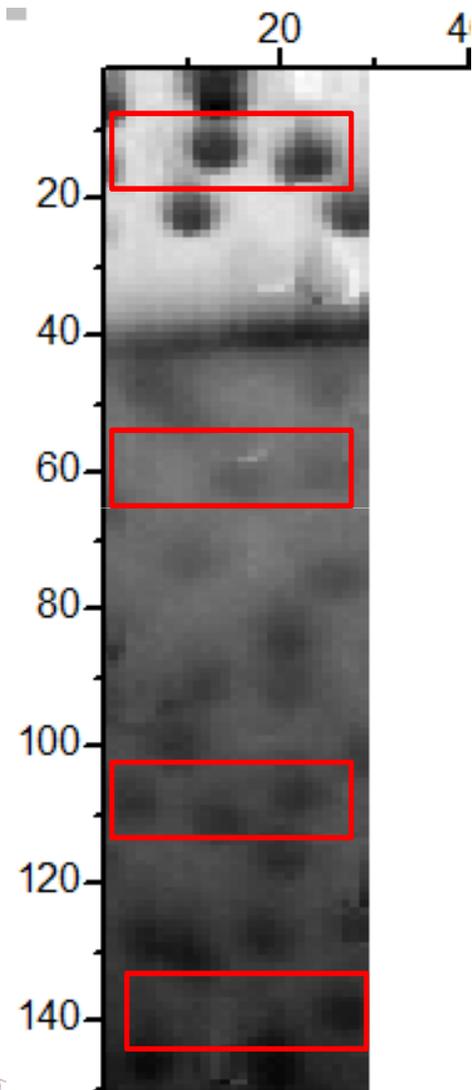


FC at -10mG



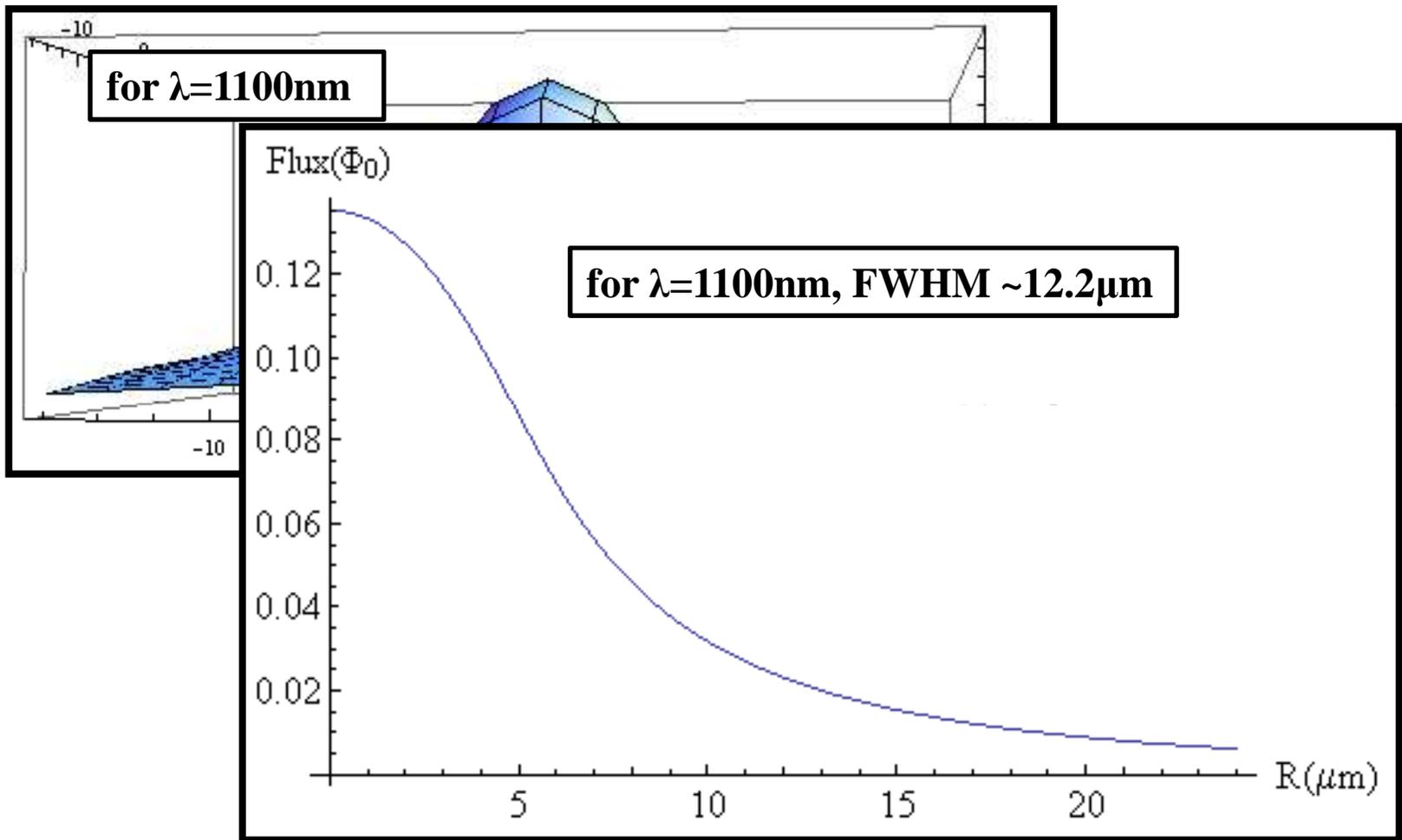
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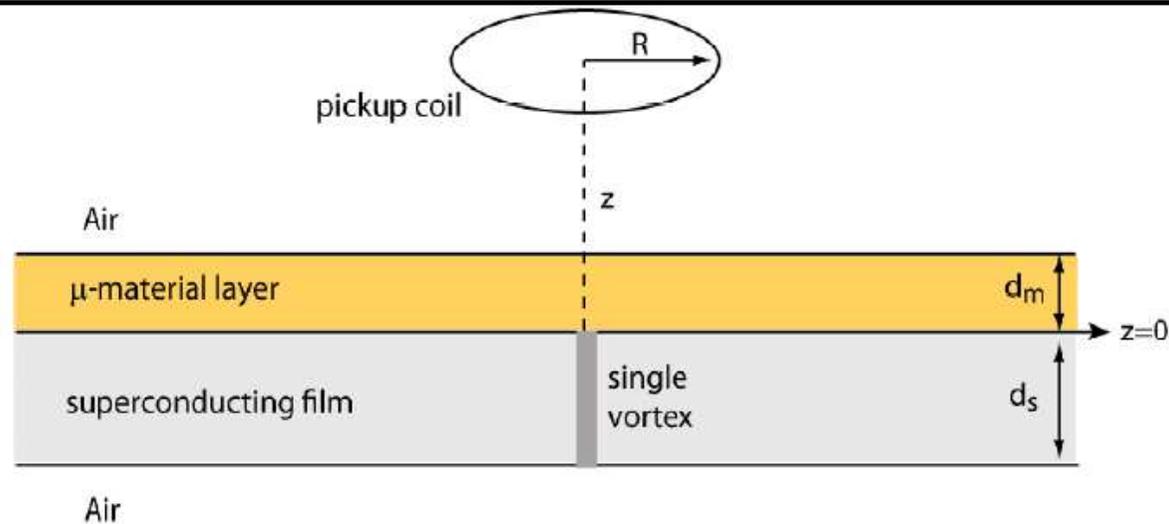




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Simulation results of sensing single vortex trapping in a high-permeability and superconductor bi-layer



The magnetic flux measured by pickup coil is

$$\frac{\Phi}{\Phi_0} = \frac{R}{\lambda^2} \int_0^\infty \frac{a(k)}{k} J_1[k R] e^{-k z} dk$$

where $a(k)$ is

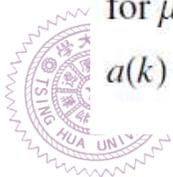
$$a(k) = \frac{(e^{dm k} k \mu (k (-1 + \text{Cosh}[ds \mathcal{D}] + \mathcal{D} \text{Sinh}[ds \mathcal{D}]))}{(\mathcal{D} (k \mathcal{D} \text{Cosh}[ds \mathcal{D}] (2 \mu \text{Cosh}[dm k] + (1 + \mu^2) \text{Sinh}[dm k]) + ((k^2 + \mathcal{D}^2) \mu \text{Cosh}[dm k] + (k^2 + \mathcal{D}^2 \mu^2) \text{Sinh}[dm k]) \text{Sinh}[ds \mathcal{D}]))}$$

$$\mathcal{D} \equiv \sqrt{k^2 + 1/\lambda^2}$$

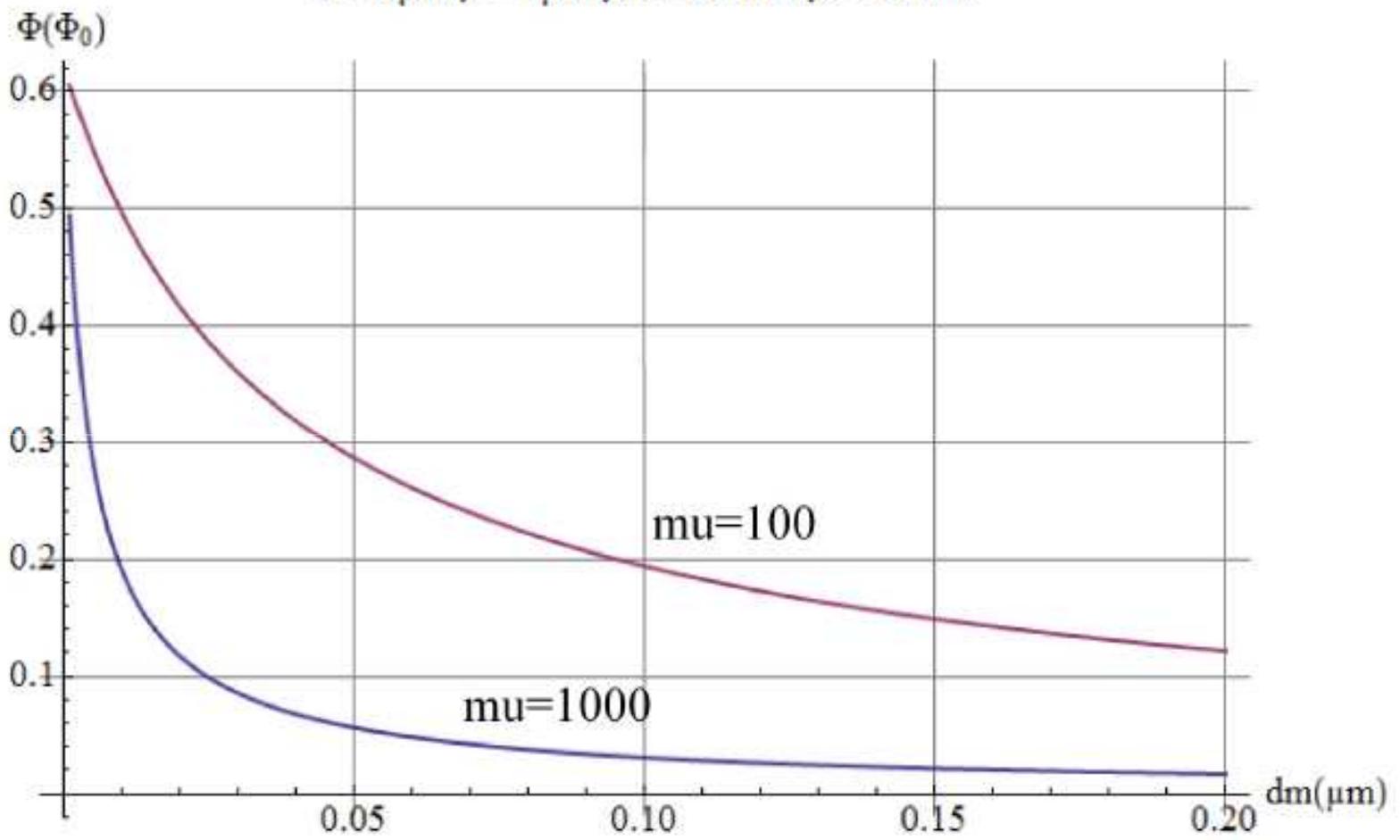
for $\mu = 1$ (no magnetic layer)

$$a(k) \rightarrow \frac{k}{\mathcal{D}^2 + k \mathcal{D} \text{Coth}\left[\frac{ds \mathcal{D}}{2}\right]}$$

which has been solved in *Physica C* 334, 274 (2000)



$R=5\mu\text{m}, z=2\mu\text{m}, ds=150\text{nm}, \lambda=50\text{nm}$



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結語與展望

Physics Today (January 2008, page 30):

Issues and Events

Next-generation high- T_c superconducting wires debut in the power grid

Electric power companies are demonstrating the capacity of new flexible wire to deliver more current in less space and to limit power surges.

超導的應用還在起步階段。
新的超導體還在不斷地被發現。
超導體的研究工作令人興奮而且大有可為。





Thank you for your attention



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