Carcassonne, France (9/26, 2002)

Noise- and microwave experiments in moving CD , igner crystals and vortex lattice

Atsutaka MAEDA
Dep. Basic Science, The niv. Tokyo

Outline

1) Dynamic Phase diagram of driven vortices In high-T_c superconductors
2) Comparison between vortices and CD
   - spectrum
   - dynamical coherence volume
3) Collective charge excitation in spin ladder $(Sr,Ca)_{1-x}Cu_{24}O_{41}$: CD or igner crystal?

Collaborators

Dynamic Phase diagram of driven vortices

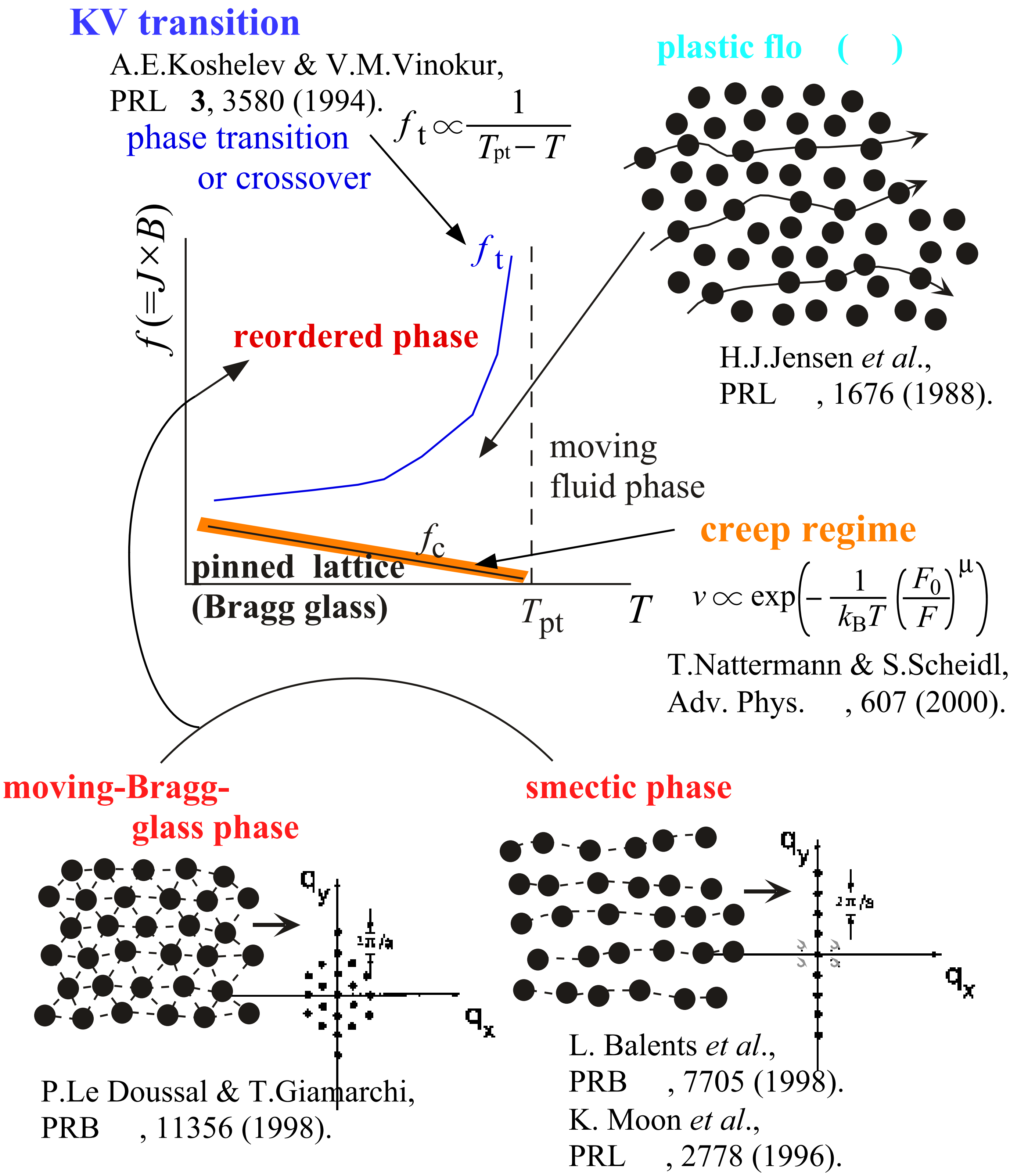
Y. Togawa	Dep. Basic Science, UT (now at Tonomura group)
H. Kitano	Dep. Basic Science, UT
T. Tsuboi	Dep. Basic Science, UT (now at Agilent Technology)
T. Hanaguri	Dep. Adv. Material Res., UT

Experiments in the spin ladder

R. Inoue	Dep. Basic Science, UT
H. Kitano	Dep. Basic Science, UT
N. Motoyama	Dep. Adv. Material Res., UT
K. Kojima	Dep. Adv. Material Res., UT
S. Uchida	Dep. Adv. Material Res., UT

Ne concepts proposed in driven vorte system

- plasticity
- dynamic reordering
- static channels *etc.*

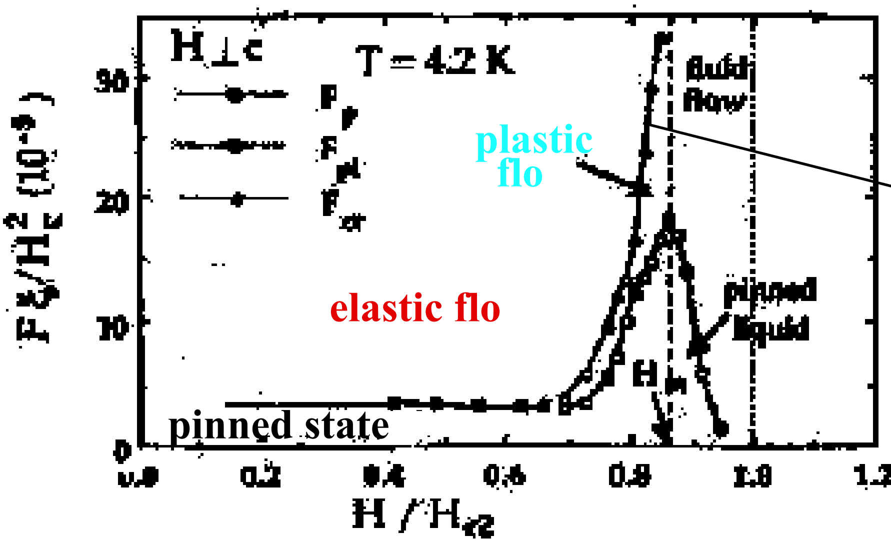


KV transition in NbSe2

dynamic phase diagram of conventional type- S (NbSe$_2$)

S. Bhattacharya *et al.*, PRL , 2617 (1993).

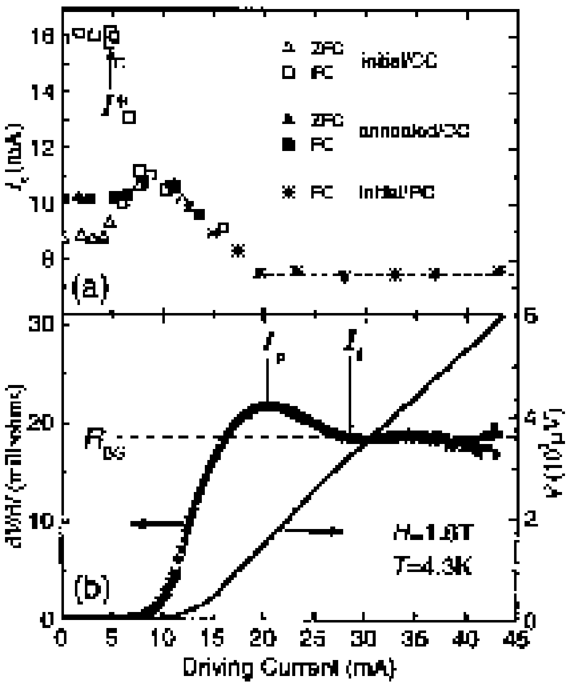
I - *V*, d*V*/d*I*, noise, pulse responce *etc*.

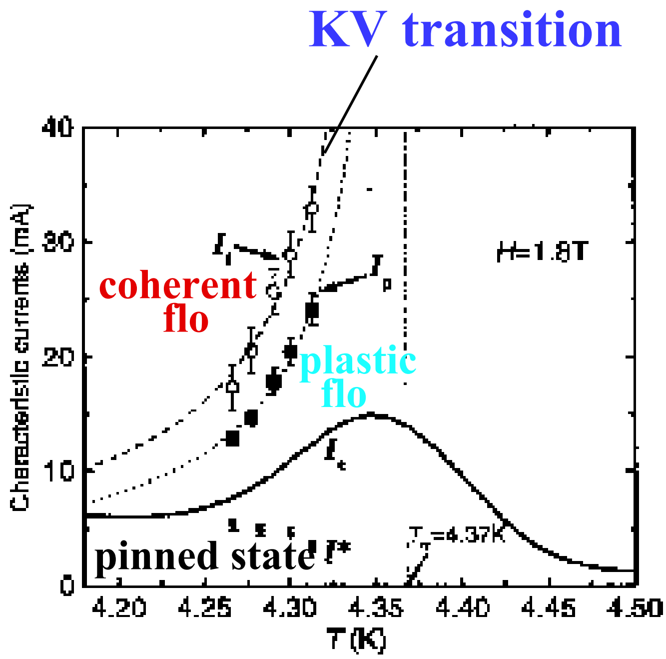


KV transition

$$f_t \propto \frac{1}{T_{pt} - T}$$

Z. Xiao *et al.*, PRL , 3265 (2000).





S (Bi2212 *H* *c*)

plastic flo — local density noise (spatial correlation)
T. Tsuboi *et al.*, PRL , 4550 (1998).
Lorentz microscopy
A. Tonomura *et al.*, Nature **3** , 308(1999).

coherent flo — conduction noise (ashboard noise)
Y. Togawa *et al.*, PRL , 3716 (2000).

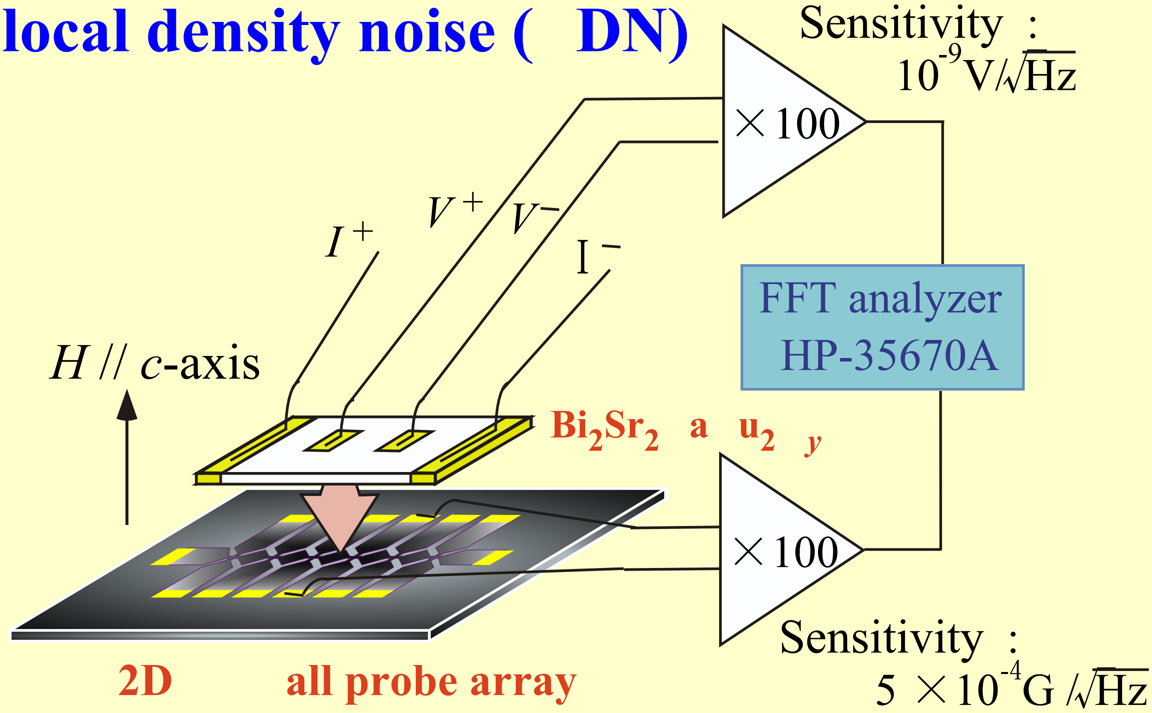
perimental approach

monitoring temporal order of driven vortices

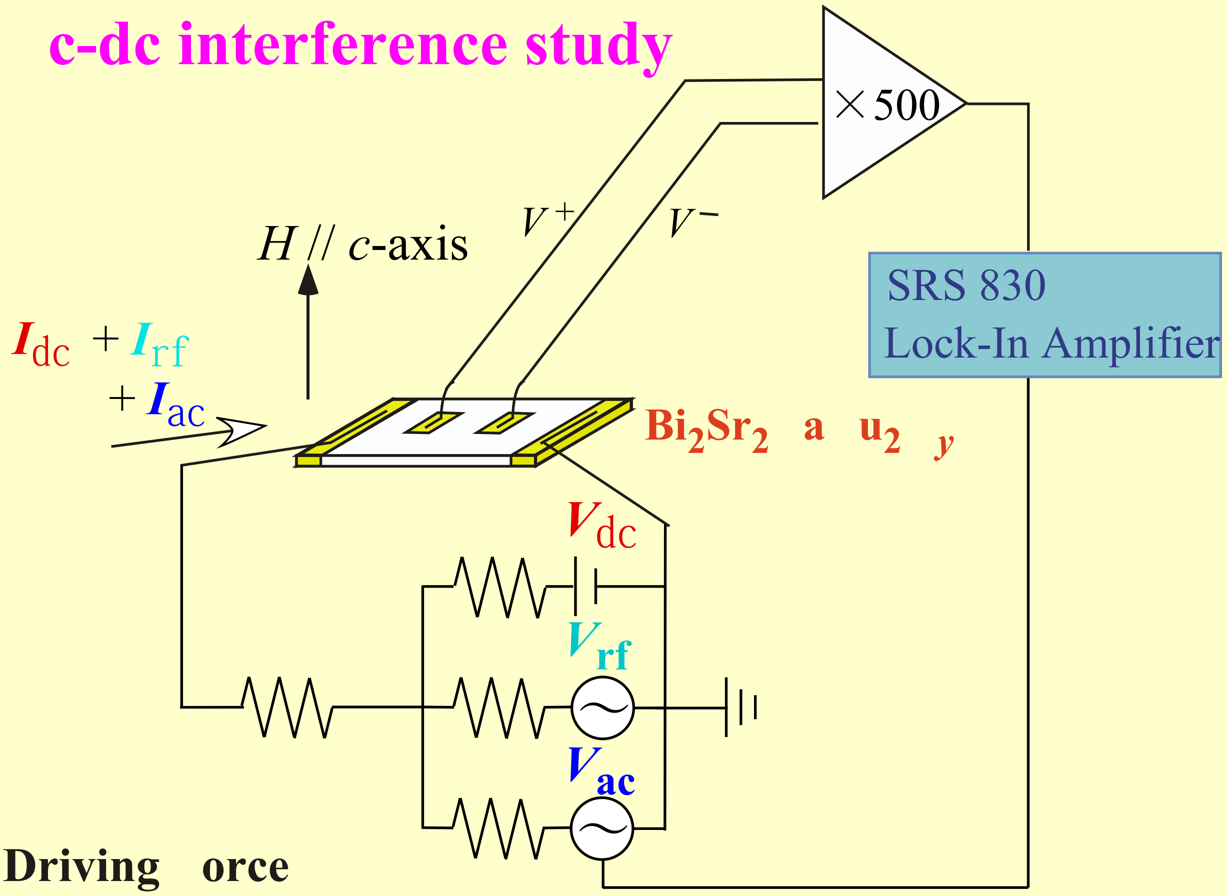
1 Noise measurement

( ) conduction noise (N)

( ) local density noise (DN)



2 c-dc interference study



Driving orce

I_{dc} $I_{rf}\sin(w_{rf}t)$ $I_{ac}\sin(w_{ac}t)$ (I_{dc} I_{rf} I_{ac})

<< Significance of simultaneous noise measurements >>

Local density noise : $\delta \boldsymbol{B} = \phi_0 \, \delta n$

.J.Yeh and Y.H. Kao, PRB **44**, 360(1991).
T.Tsuboi *et al*., PRL **80**, 4550(1998).

[Driven vortex system]

density fluctuations (δn)

&

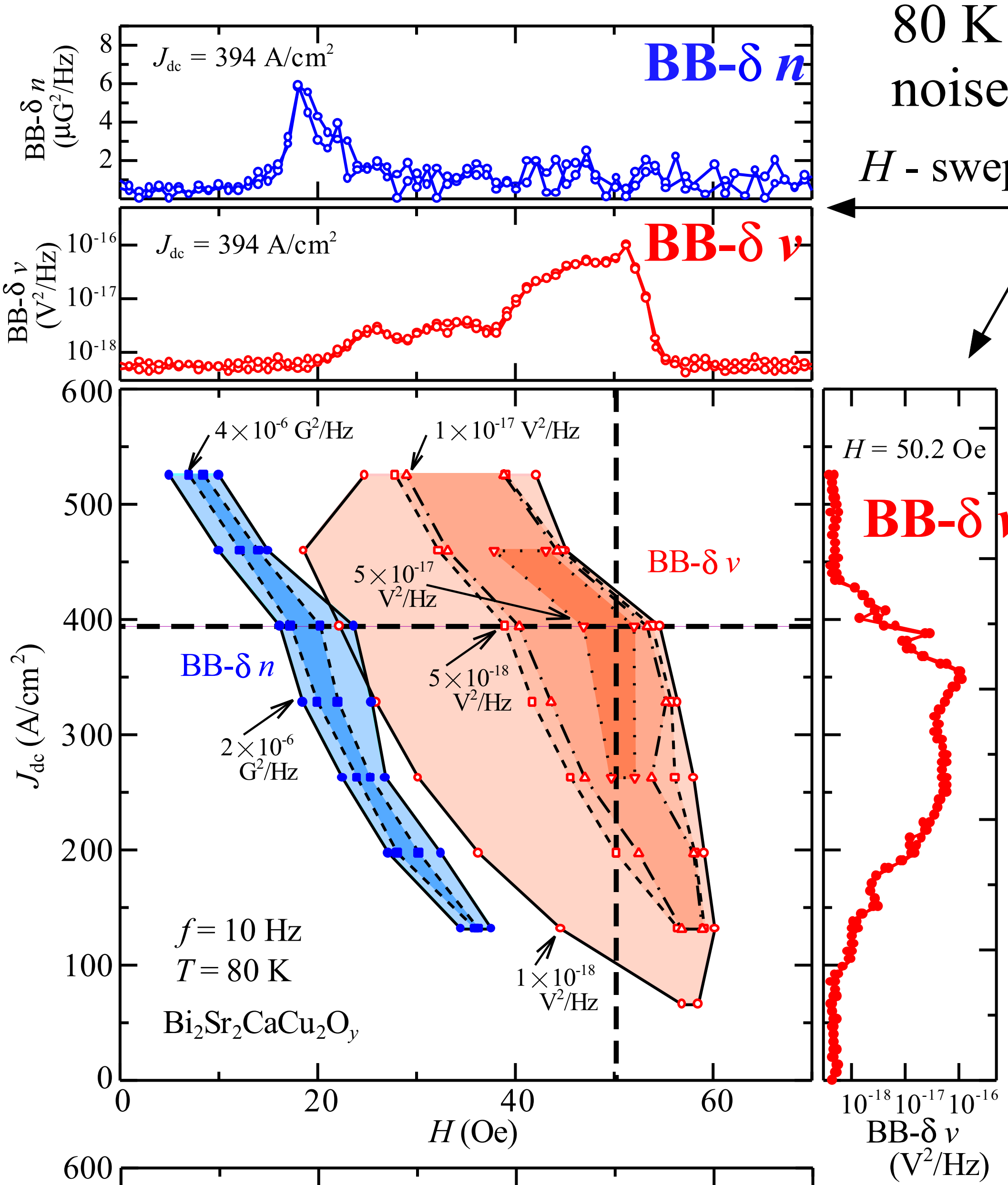
velocity fluctuations (δv)

$$\delta V = \int \delta \boldsymbol{E} \, \mathrm{d}\boldsymbol{l} = \int (\delta \boldsymbol{B} \times \boldsymbol{v} + \boldsymbol{B} \times \delta \boldsymbol{v}) \, \mathrm{d}\boldsymbol{l}$$

Conduction noise :

J.R.Clem, Phys. Rep. **75**, 1(1981).
S.Bhattacharya & M.J.Higgins, PRL **70**, 2617(1993).
A.C.Marley *et al*., PRL **74**, 3029(1995).
G.D Anna *et al*., PRL **75**, 3521(1995).
H.Safar *et al*., PRB **52**, 6211(1995).

80 K
noise contour map



H - swept

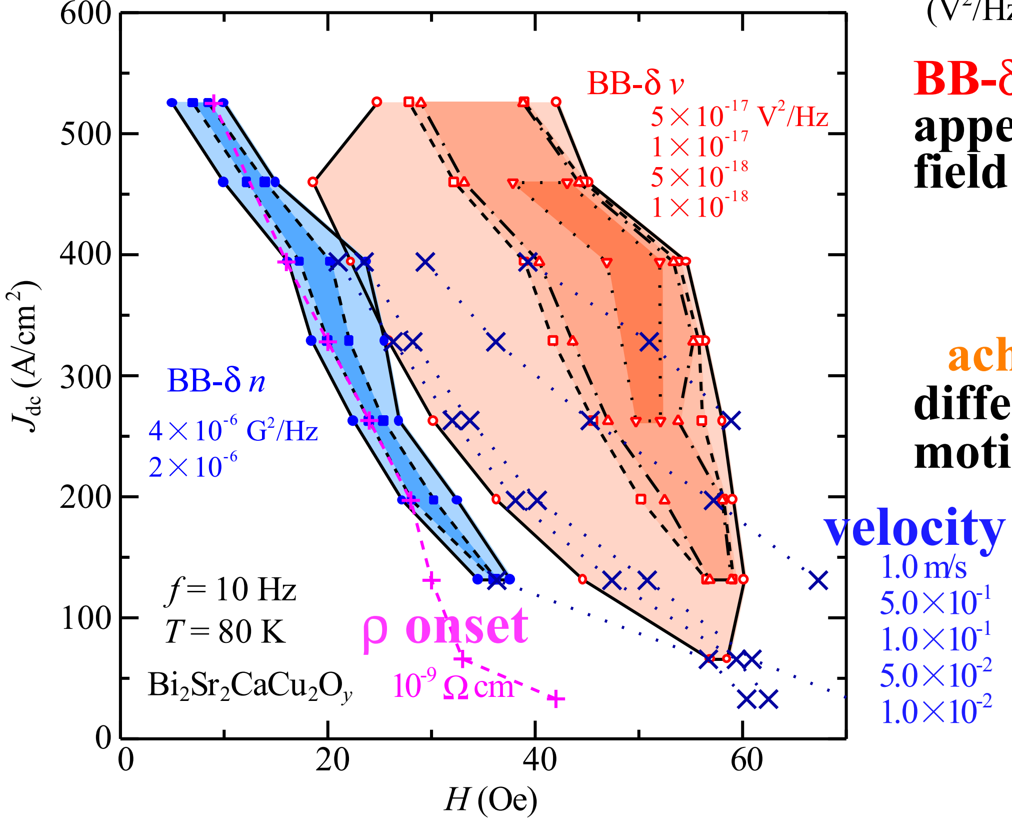
F* = *J* × *B

J - swept

Boundary of noise is independent of ho to s eep in *J*-*H* plane

H_{pt}(0 A/cm^2)
= 60 Oe

Broadband noise appeared in vor-te -solid regime

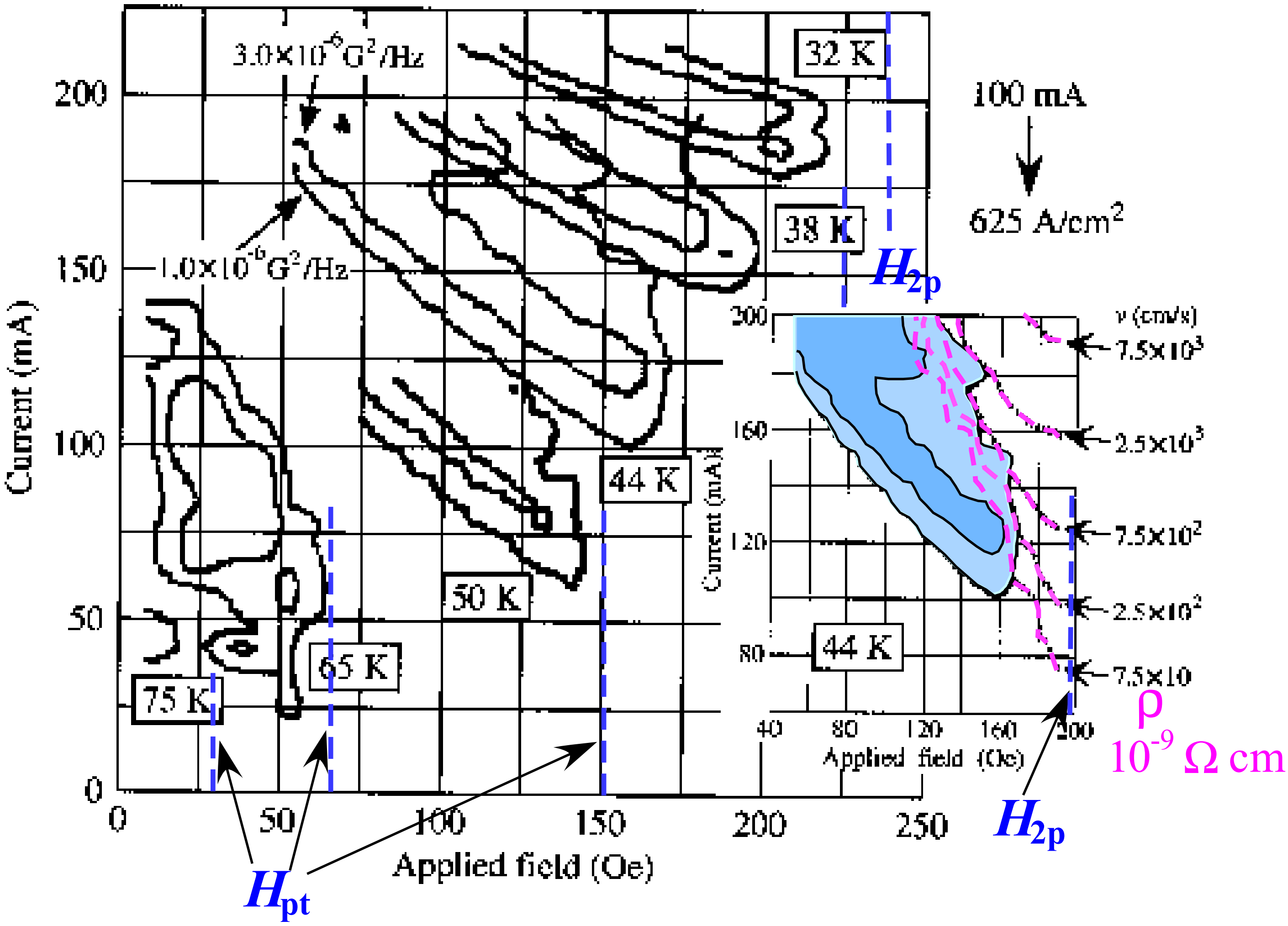


BB-δ *v* and BB-δ *n* appeared in different field region

ach BBN corresponds to different ind of vorte motion

BB-δ*n* noise po er spectral density contour map

T.Tsuboi *et al.*, PRL , 4550 (1998).
A.Maeda *et al.*, PRB , 054506 (2002).



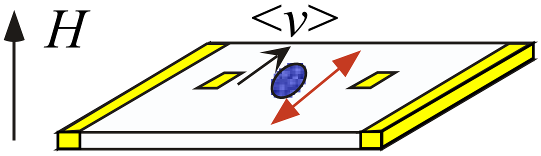
- **BB-δ*n* appeared near resistivity onset**
- **BB-δ*n* appeares even in lo -*T* regime here 2nd pea effect occurs**

BB-δ*n* spatial correlation method

➡ channel-li e plastic flo

c-dc nterference ffect of Vortices

another techni ue to detect developement of temporal order

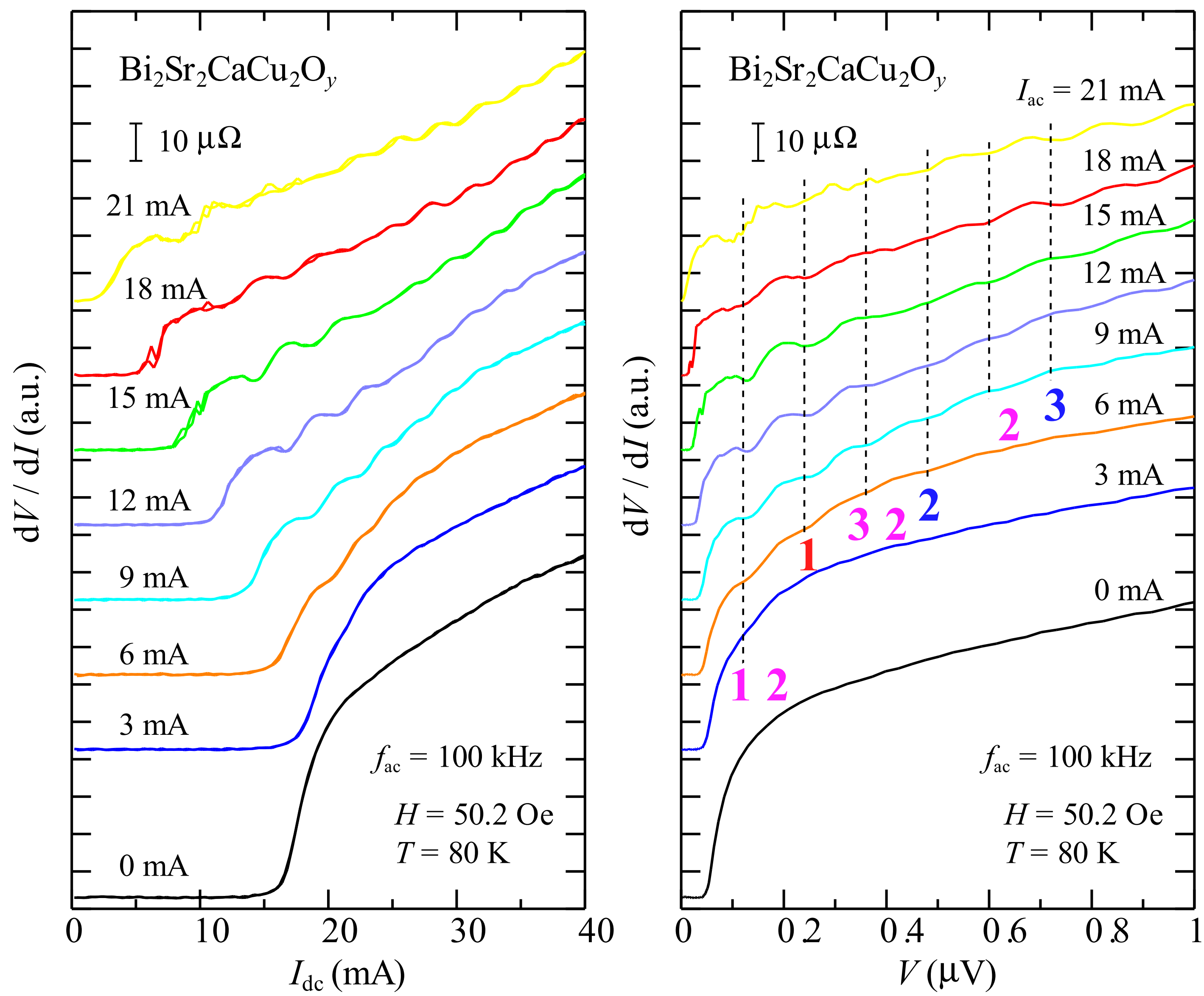


Driving orce

I_{dc} $I_{ac}\sin(w_{ac}\,t)$

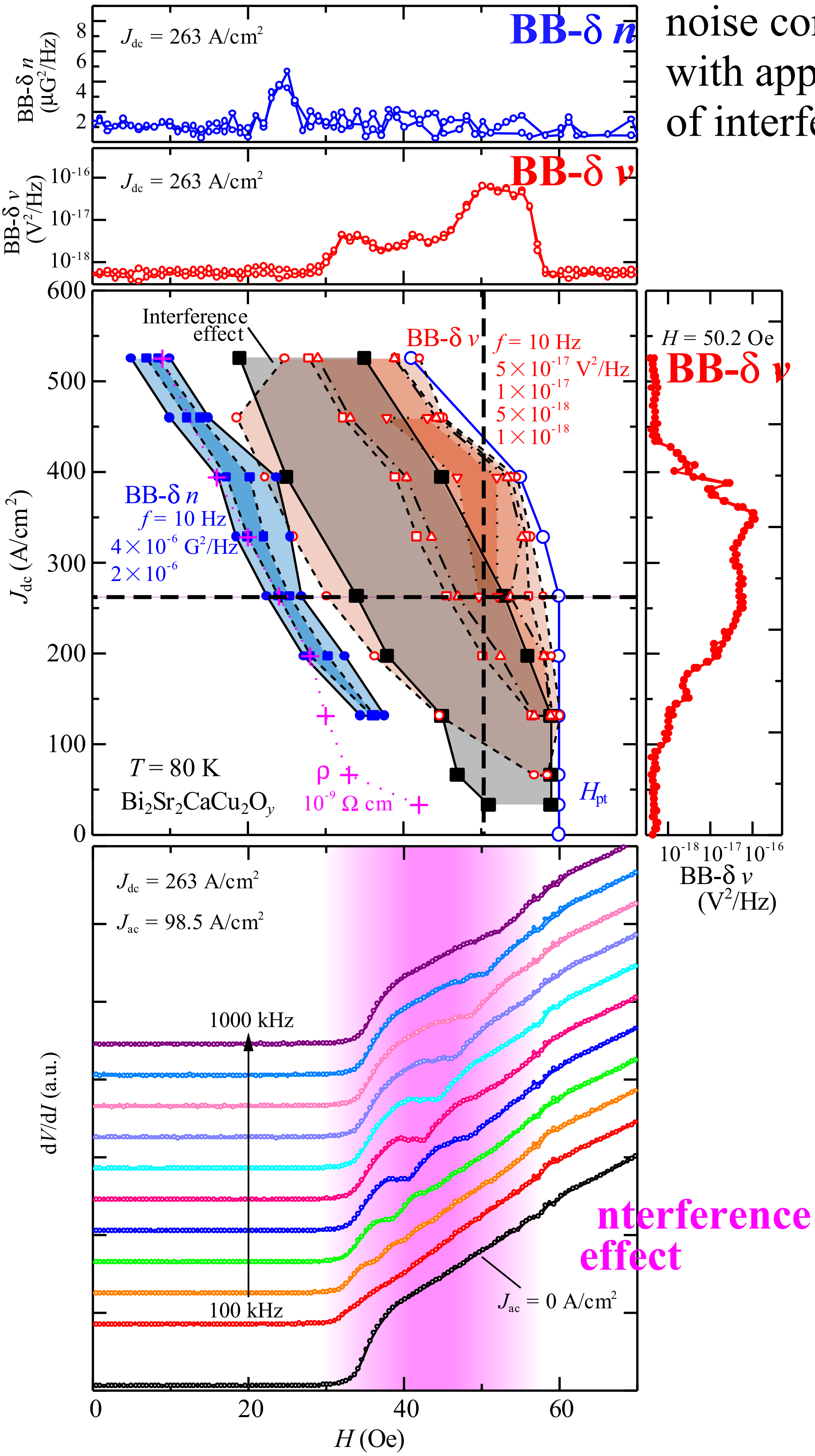
$p\,f_{ac}$ f $\frac{1}{a}\,\frac{\rho\,j}{B}$ $\sqrt{\frac{\sqrt{3}}{2}\,\frac{E}{\sqrt{\phi_0 B}}}$

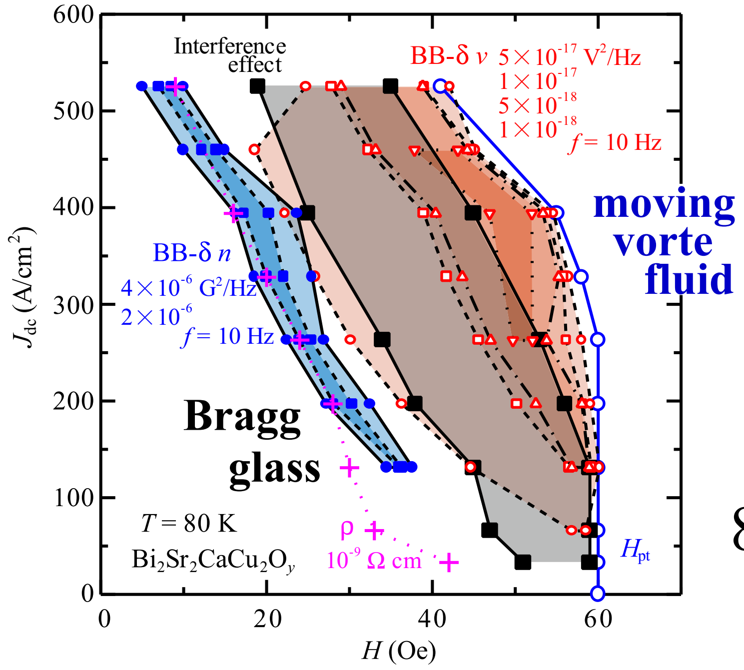
15 mA ～ 100 A/cm^2



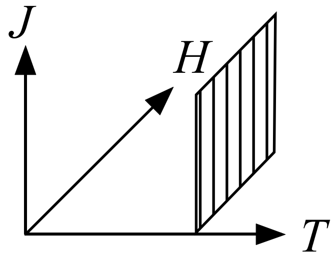
temporal order of driven vortices develops
in a certain field region in vorte -solid regime

80 K
noise contour map
with appearence region
of interference effect

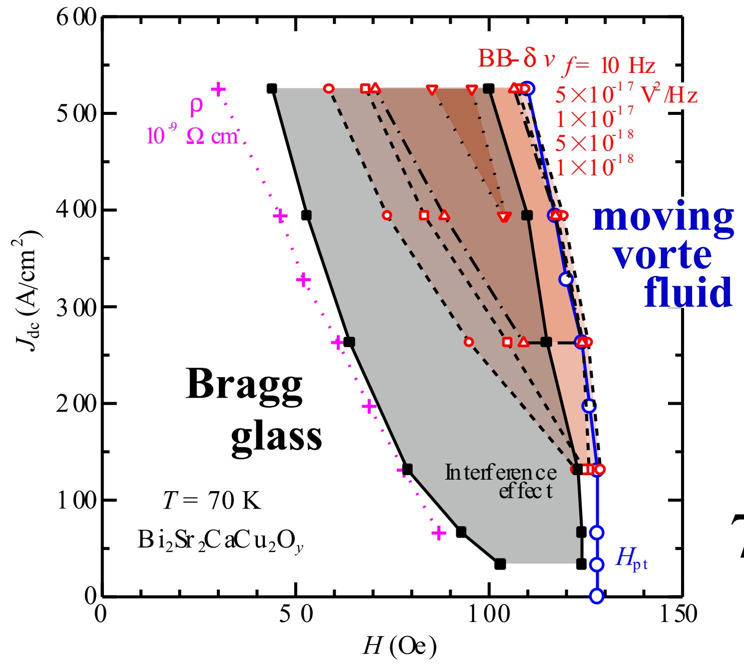




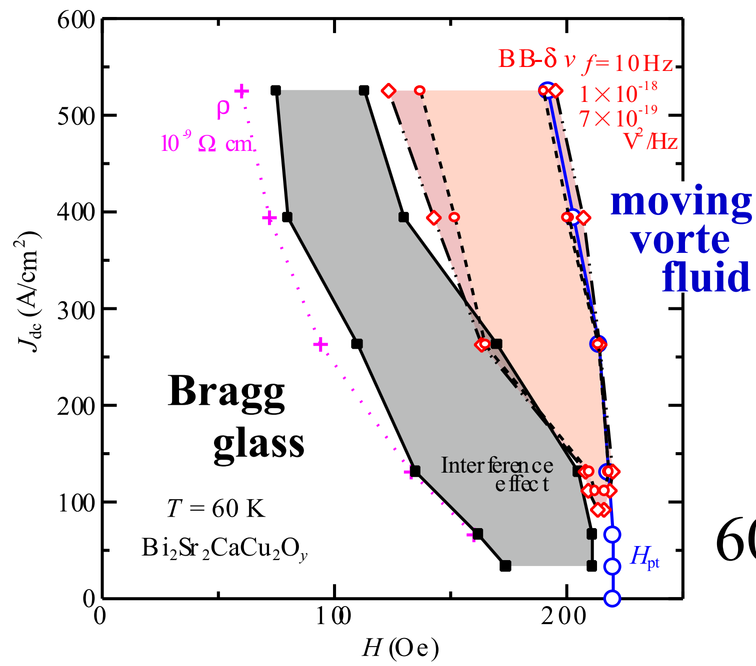
80 K



***J* - *H* plane**
including results of
noise contour
interference effect
resistivity
H_{pt} (vorte -lattice phase transition field)



70 K

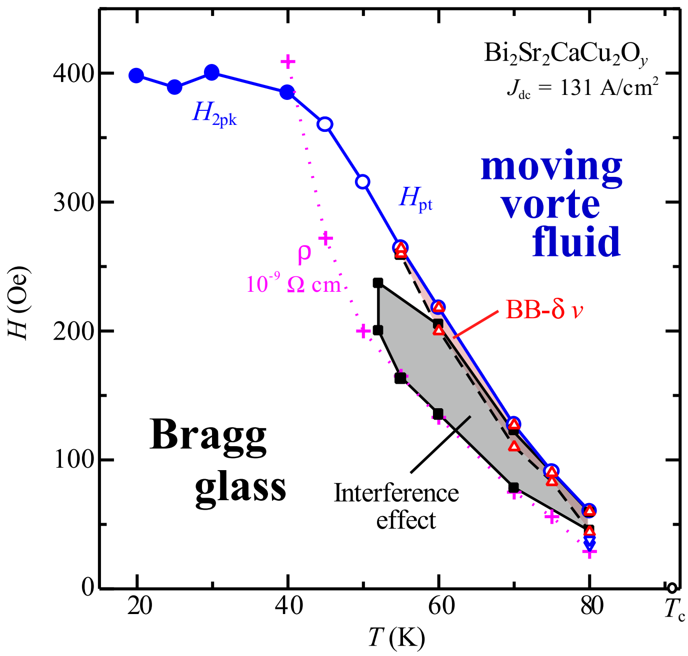


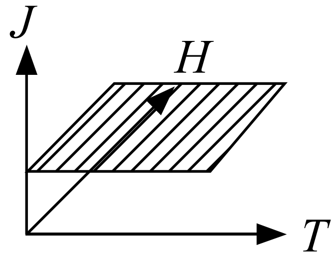
60 K

ith decreasing *T*
BB-δ*v* becomes to appear after disappearance of interference effects

↓

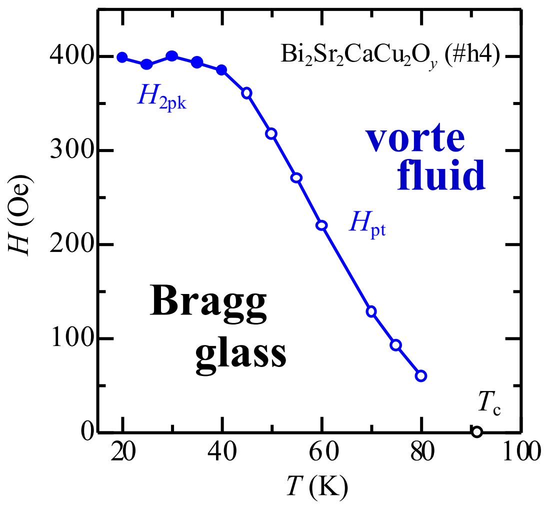
BB-δ*v* seems to appear hen temporal order of coherent flo decreases

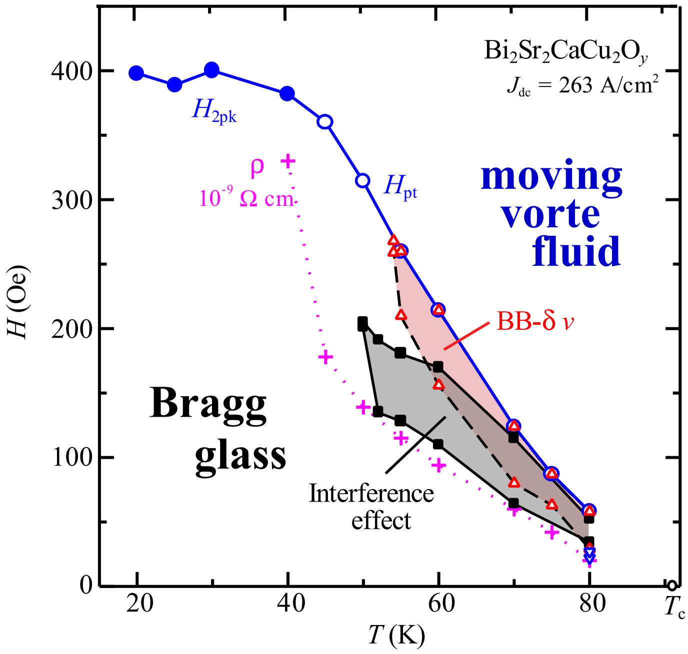




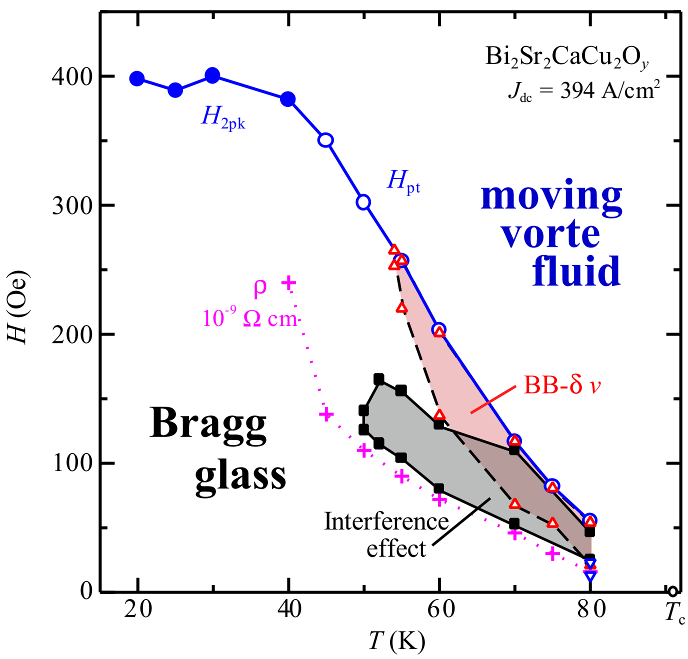
131 A/cm²

static phase diagram

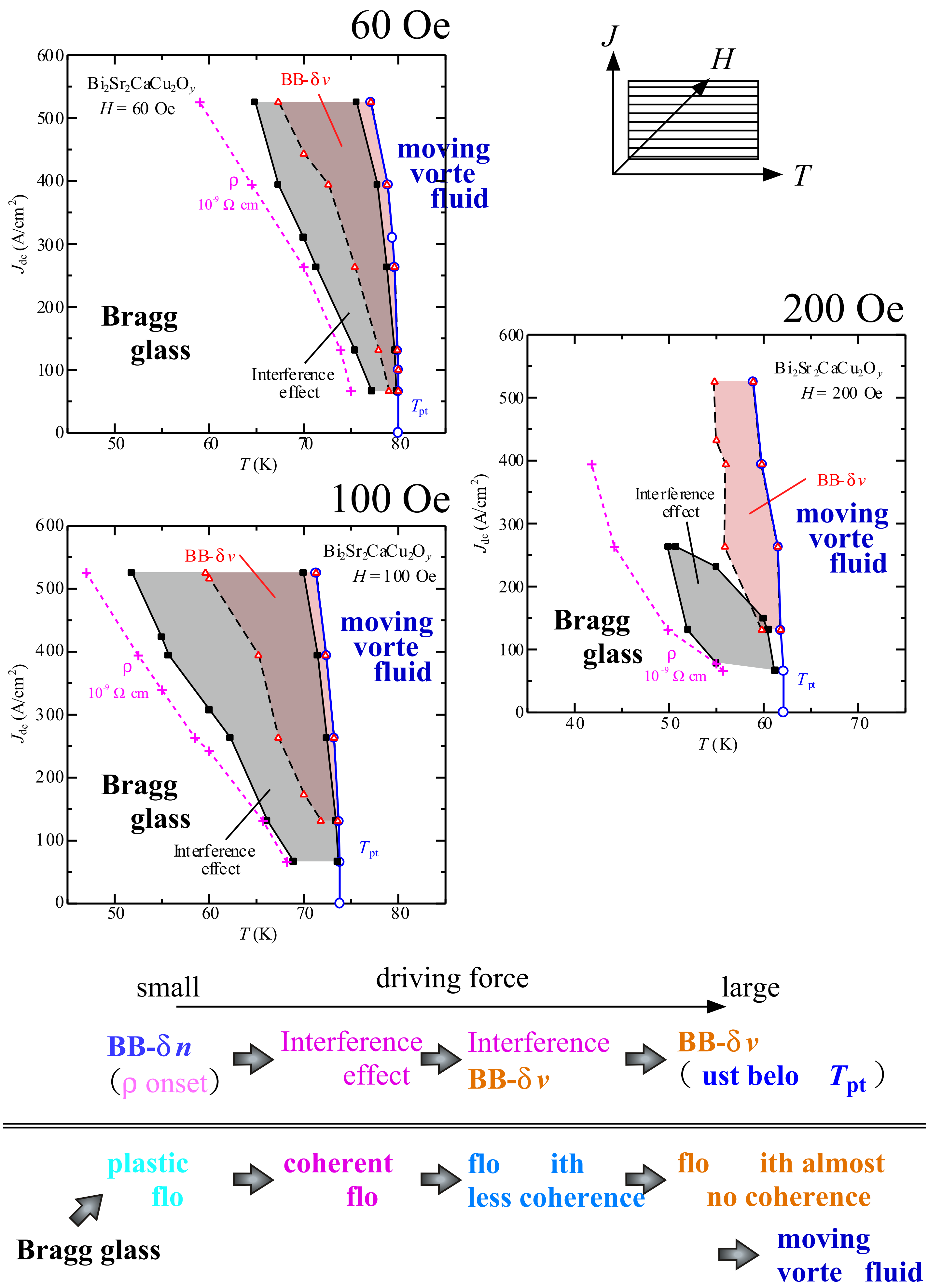




263 A/cm²



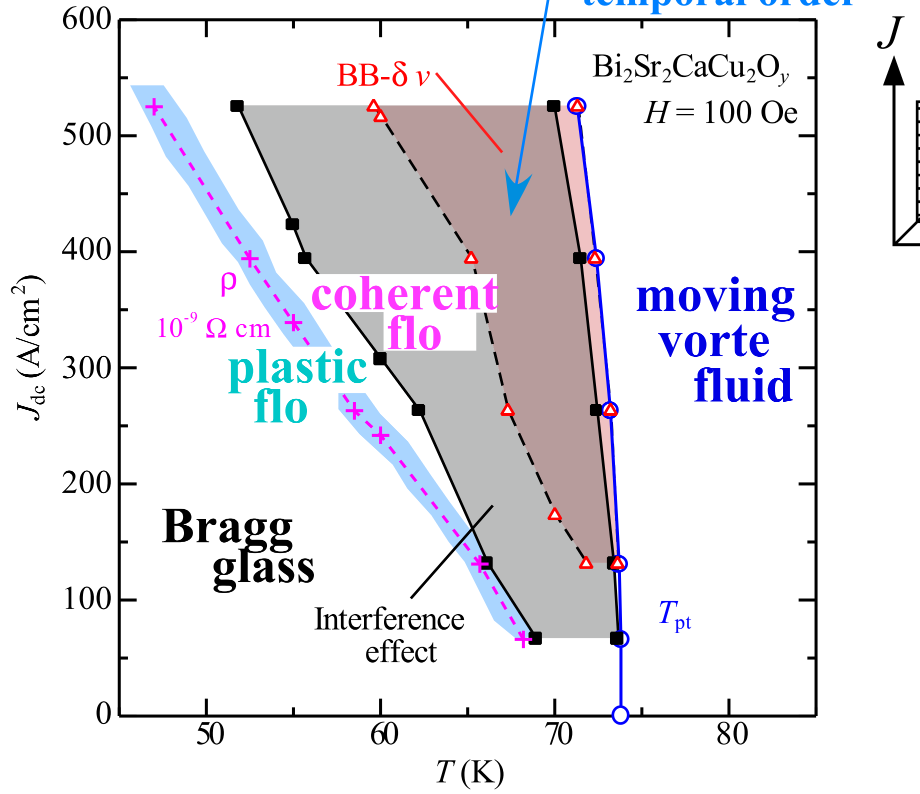
394 A/cm²

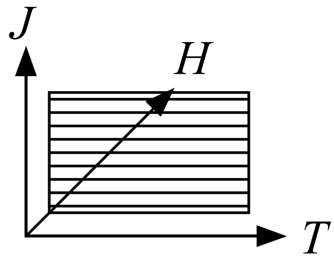


60 Oe
$Bi_2Sr_2CaCu_2O_y$
H = 60 Oe
BB-δv
moving
vorte
fluid
ρ
10^{-9} Ω cm
Bragg
glass
Interference
effect
T_{pt}
J_{dc} (A/cm^2)
T (K)
J
H
T
200 Oe
$Bi_2Sr_2CaCu_2O_y$
H = 200 Oe
Interference
effect
BB-δv
moving
vorte
fluid
Bragg
glass
ρ
10^{-9} Ω cm
T_{pt}
100 Oe
BB-δv
$Bi_2Sr_2CaCu_2O_y$
H = 100 Oe
moving
vorte
fluid
ρ
10^{-9} Ω cm
Bragg
glass
Interference
effect
T_{pt}
small
driving force
large
BB-δn
(ρ onset)
Interference
effect
Interference
BB-δv
BB-δv
(ust belo T_{pt})
plastic
flo
coherent
flo
flo ith
less coherence
flo ith almost
no coherence
Bragg glass
moving
vorte fluid

Dynamic phase diagram of driven vortices

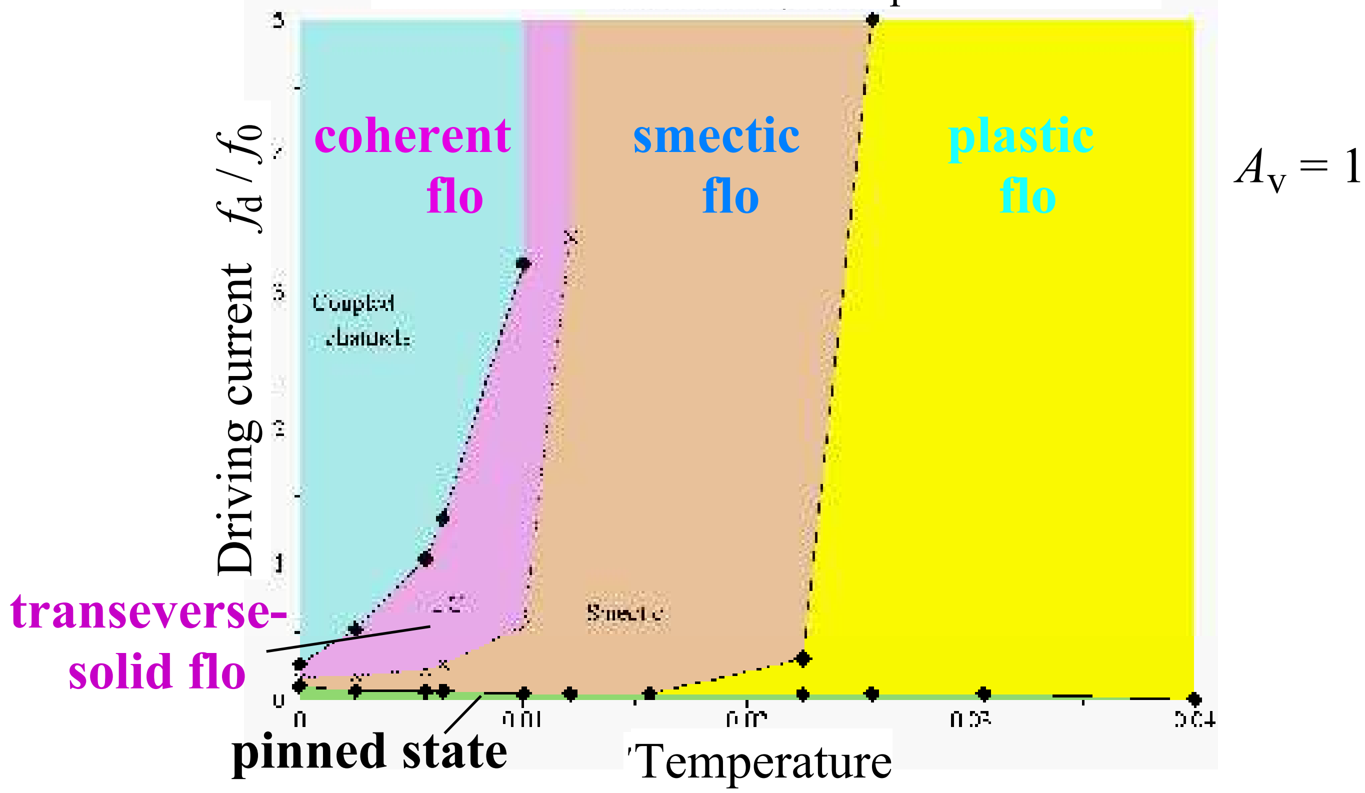
Bi2212





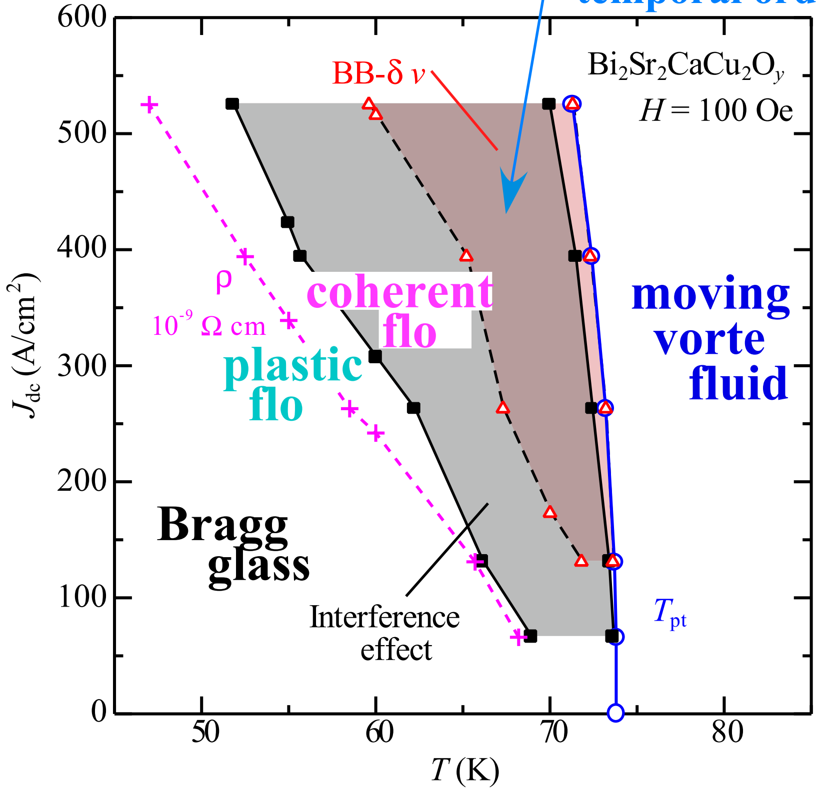
Simulation

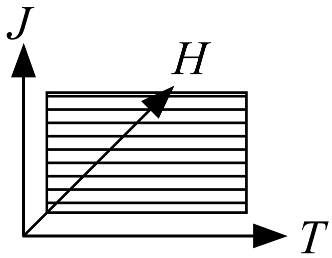
ea pinning C. J. Olson *et al.*, PRL **1**, 3757 (1998).
private communication



Dynamic phase diagram of driven vortices

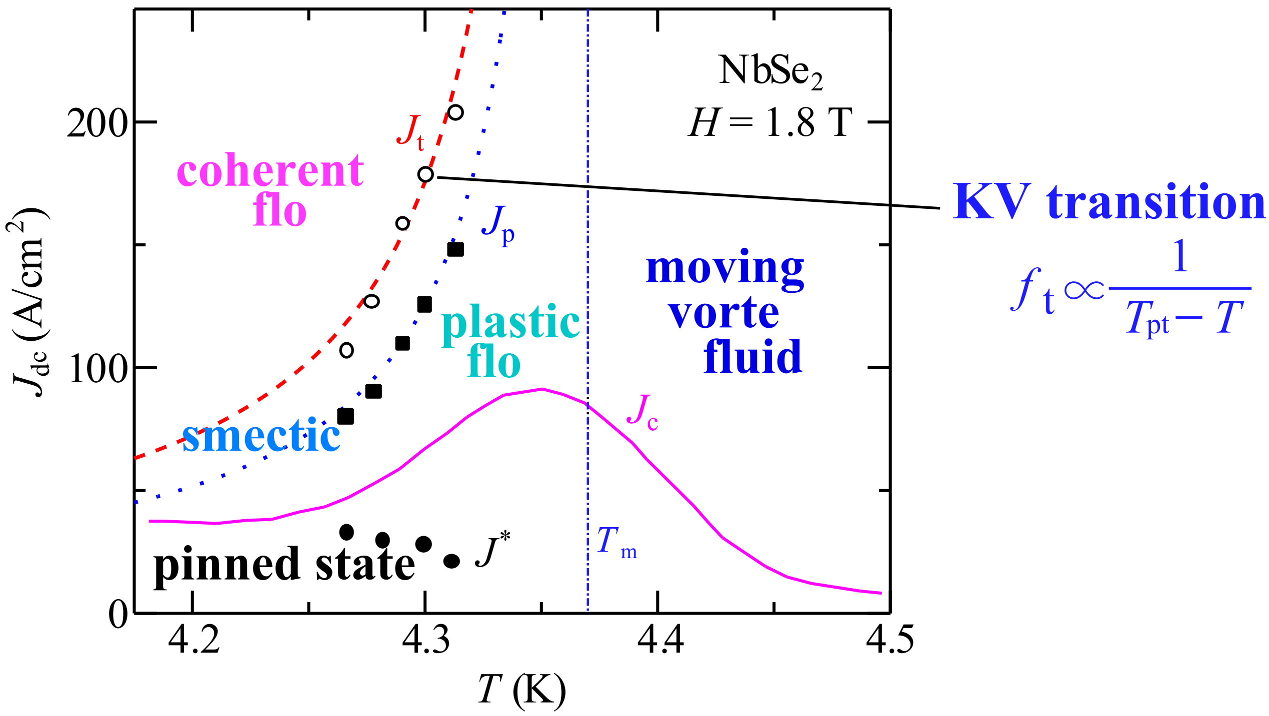
Bi2212





NbSe$_2$

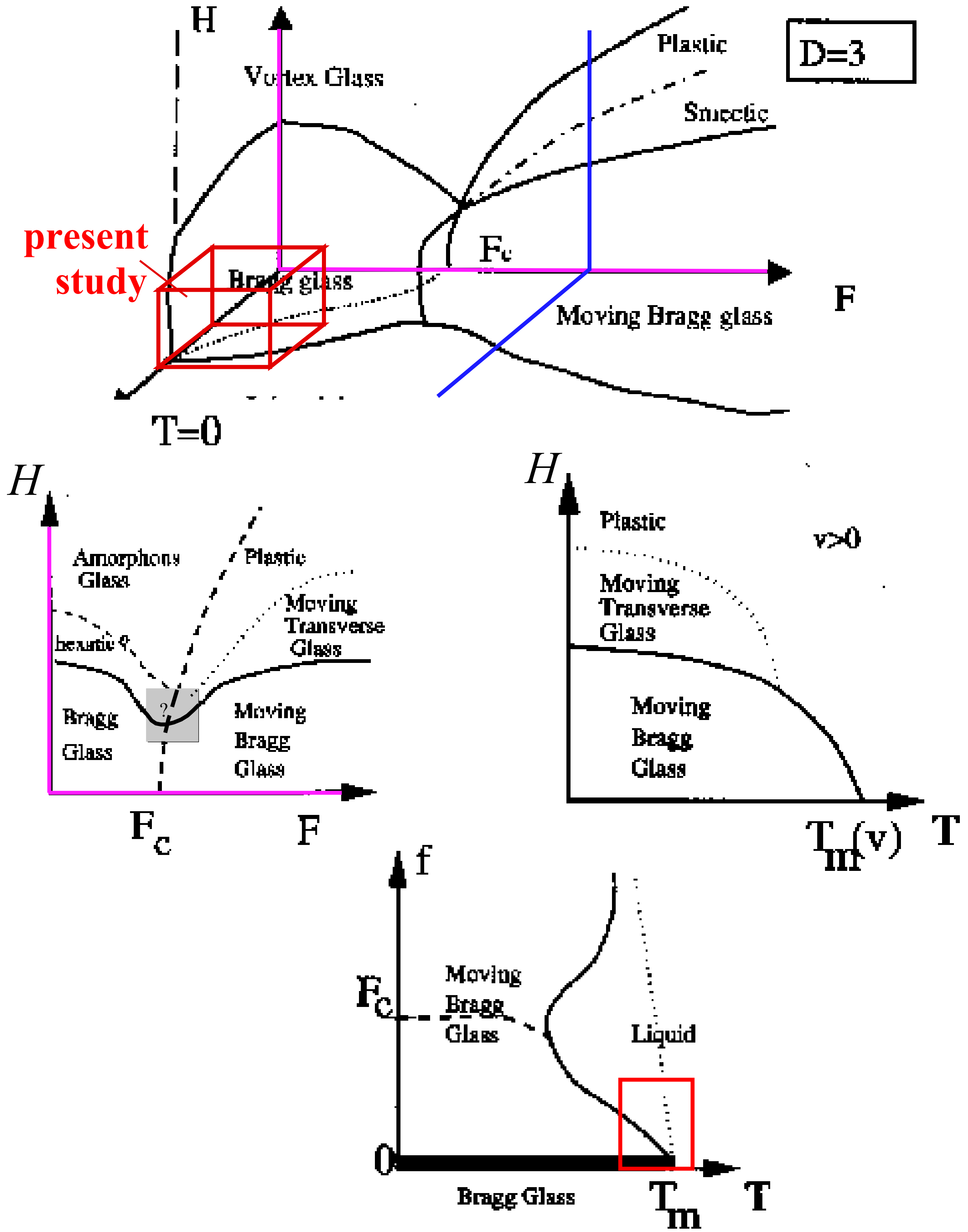
Z. Xiao *et al.*, PRL , 3265 (2000).



hase boundary corresponding to KV transition is not found in the dynamic phase diagram of Bi2212

Dynamic phase diagram of driven vortices

P. Le Doussal & T. Giamarchi, PRB , 11356 (1998).



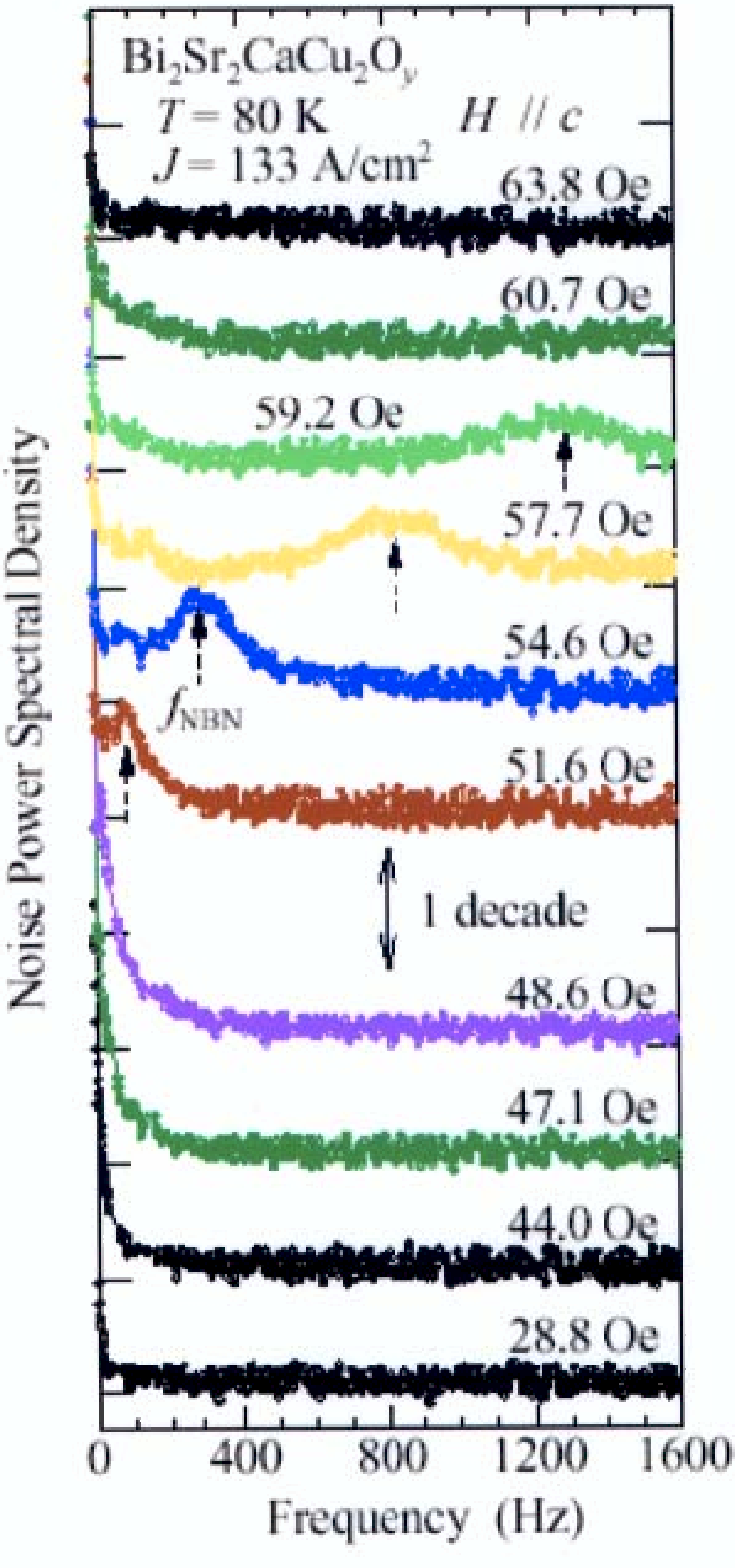
Vortices in SC (2D) vs CD (1D)

Similarity *v* difference

1) Coherent motion (washboard motion) in the so-called creep regime

--elementary process of sliding motion--

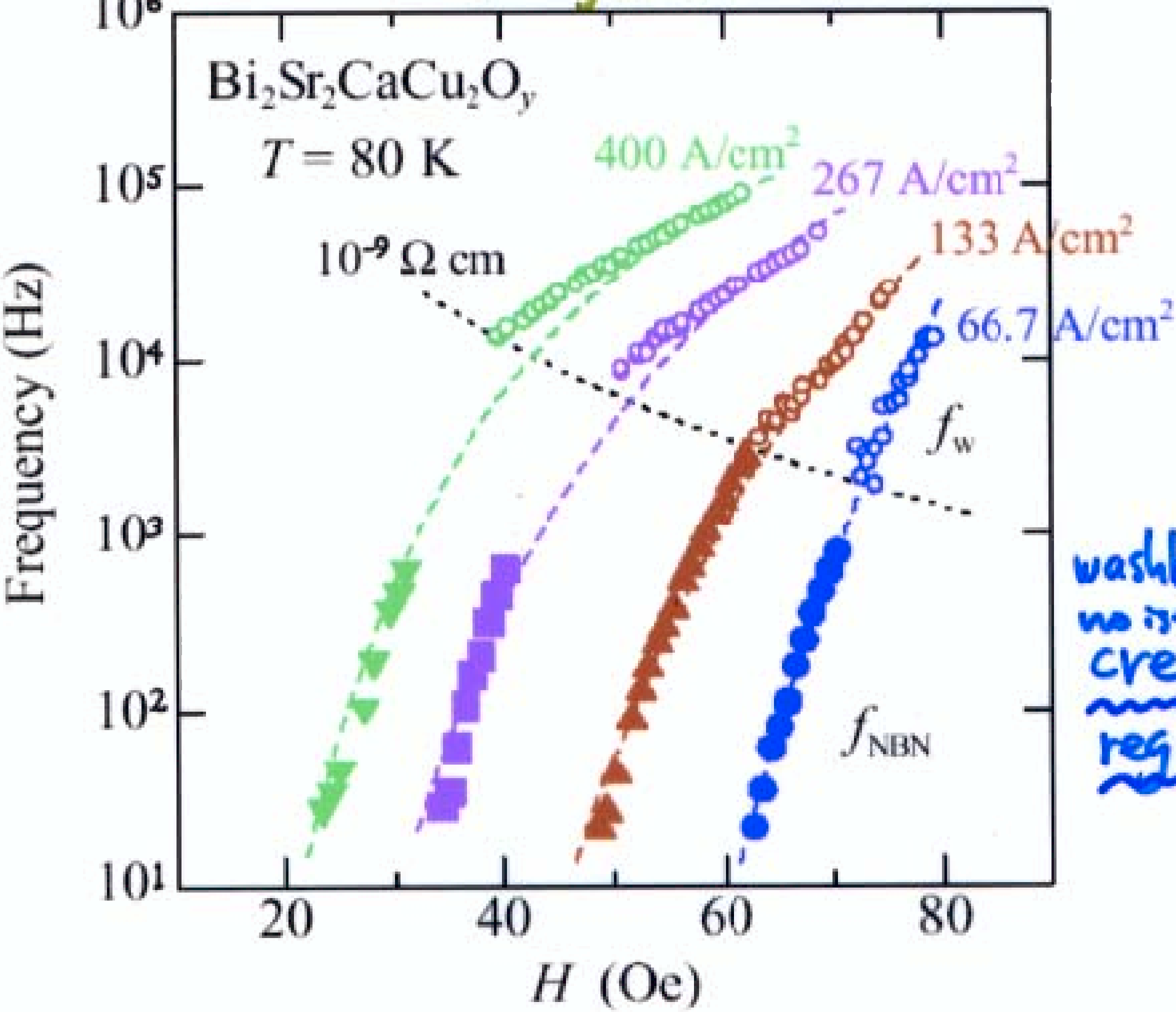
2) Deterioration of coherence with increasing driving force


Bi2Sr2CaCu2Oy
T = 80 K
H // c
J = 133 A/cm2
63.8 Oe
60.7 Oe
59.2 Oe
57.7 Oe
54.6 Oe
fNBN
51.6 Oe
1 decade
48.6 Oe
47.1 Oe
44.0 Oe
28.8 Oe
0
400
800
1200
1600
Frequency (Hz)
Noise Power Spectral Density

f = J × B

85 (2000) 3716.

Y. Togawa et al. PRL



washboard noise in creep region

- evidence of the washboard motion
- "resistivity" measurement below usual sensitivity

$f_{WB} = \langle v \rangle / a$

$f_{WB} = \frac{j}{aB} \rho$

$\therefore f_{WB} \propto \rho$

(empirical)

$\rho \sim \rho_0 \exp\left(-\left(\frac{H_0}{H}\right)^{\alpha}\right)$ $\alpha \simeq 1.0$

((cf) T. Nattermann and S. Scheidl : Adv. Phys. 49 (2000) 607.)

P. 2793

1 dim

Temporally Ordered Collective Creep and Dynamic Transition in the Charge-Density-Wave Conductor $NbSe_3$

S. G. Lemay and R. E. Thorne

Laboratory of Atomic and Solid State Physics, Clark Hall, Cornell University, Ithaca, New York 14853-2501

Y. Li and J. D. Brock

School of Applied & Engineering Physics, Cornell University, Ithaca, New York 14853-2501

(Received 22 December 1998)

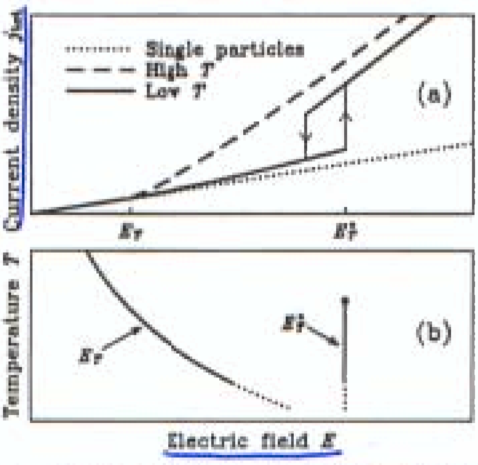


FIG. 1. (a) Form of $j_{tot}(E)$ in the CDW conductor $NbSe_3$. Dotted line: single-particle current density $j_s \propto E$. Dashed line: total current density $j_{tot} = j_s + j_c$ at high temperatures ($T > 2T_P/3$). Solid line: j_{tot} at low T. The difference between the solid or dashed lines and the dotted line gives the CDW current density j_c. (b) Temperature dependence of E_T and E_T^* in $NbSe_3$.

Fig 14

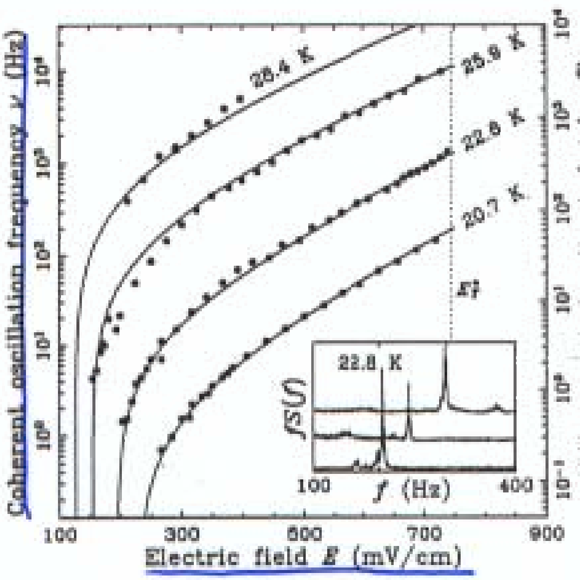


FIG. 2. Coherent oscillation frequency ν and current density j_c versus electric field E. The solid lines are a fit to Eq. (1). The intersection of the lines with the horizontal axis corresponds roughly to the measured E_T at each temperature. The dotted vertical line indicates E_T^*. Inset: Spectral density $S(f)$ at 22.8 K for $E/E_T = 2.63$, 2.77, and 2.88; the curves are offset vertically for clarity.

Fig. 15

$$j_{CDW}(E,T) = \sigma_0 (E - E_T) \exp\left(-\frac{T_0}{T}\right) \exp\left(\alpha \frac{E}{T}\right)$$

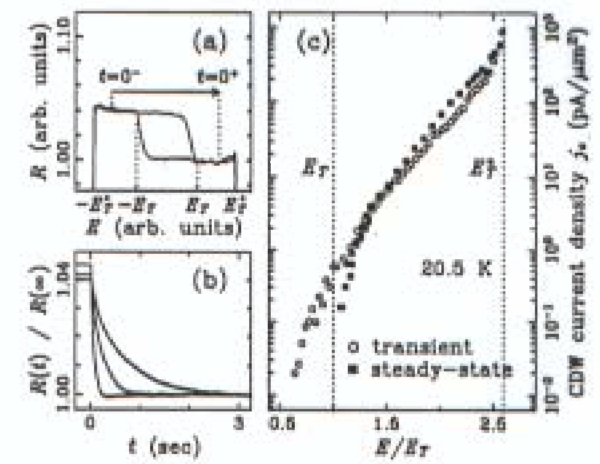


FIG. 3. (a) Single-particle resistance R of a 70 μm segment adjacent to a current contact versus electric field E. (b) $R(t)/R(\infty)$ for the same segment following a reversal of the polarity of E, as indicated by the arrow in (a), for $E/E_T = 1.40$, 1.69, and 1.93. (c) Comparison of j_c calculated from $R(t)$ [12] with j_c obtained from measurements of the coherent oscillation frequency. The current contacts were 630 μm apart, and $E_T(20.5\ K) = 49$ mV/cm.

Fig. 16

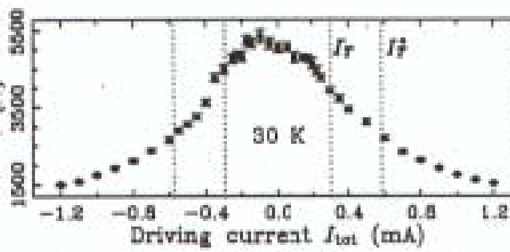
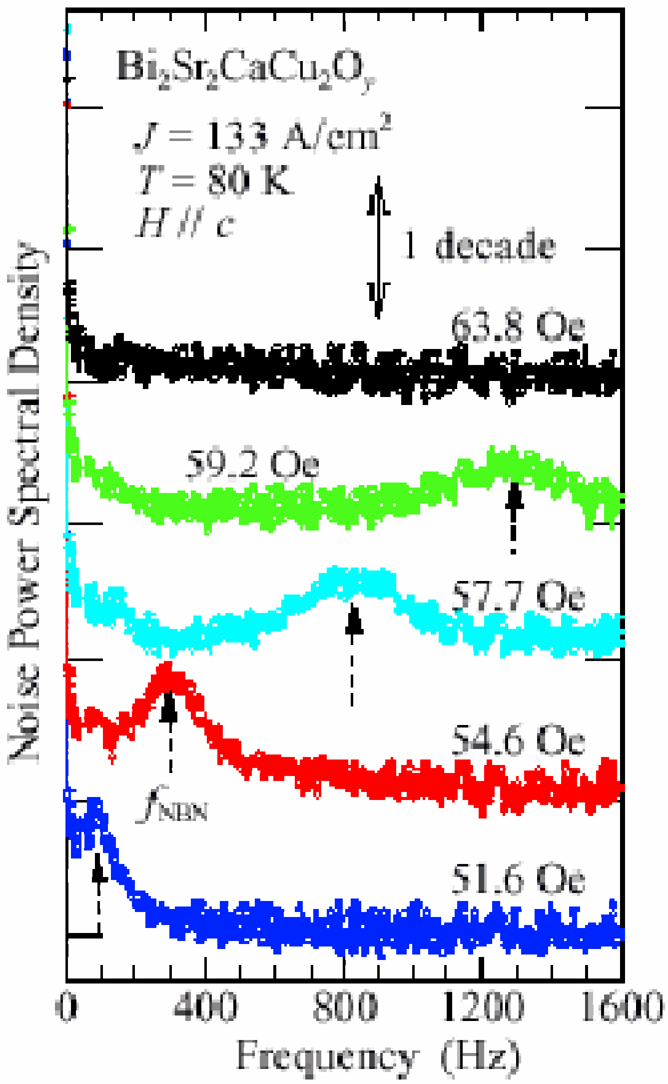


FIG. 4. Inverse CDW peak half-width (corrected for instrumental resolution) in the [1 0 0] direction versus I_{tot}. I_T^* and an upper bound for I_T were determined from measurements of dV/dI_{tot} and of the sharp increase in $1/f$-like noise, respectively.

Fig. 17



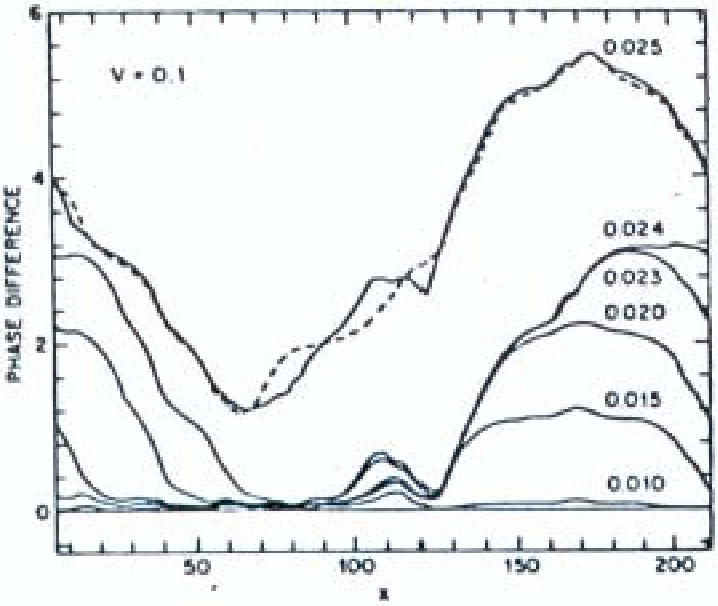
- Rapid shift of NBN to higher frequencies with increasing field

- Broading of NBN

CDW (1D)

P. Littlewood PRB 32 (1986) 6694.

(also Matsukawa - Takayama SSC 53 (1984) 45.)

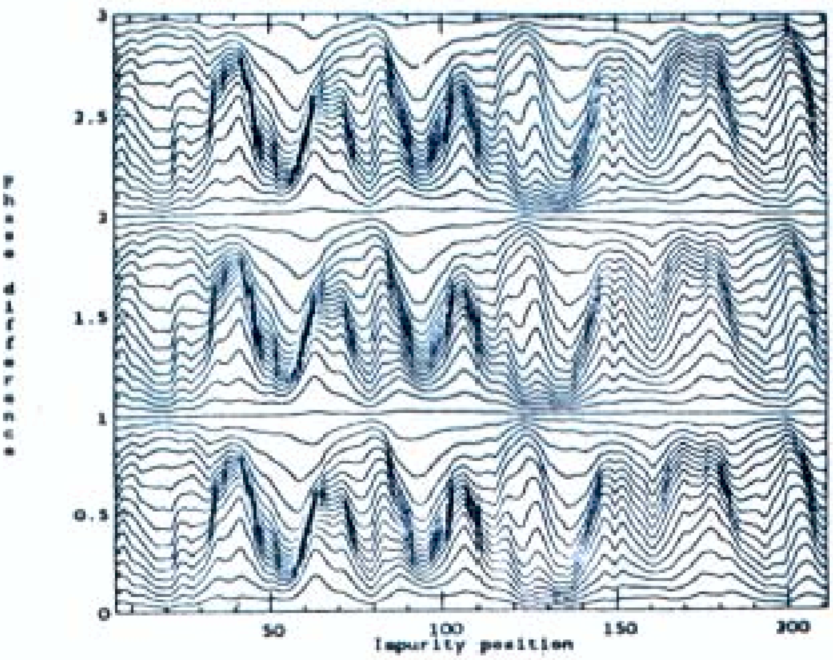


$\rho(x) = \rho_0 + \rho_1 \cos(Qx + \phi)$

$n(x) \propto \frac{\partial \phi}{\partial x}$

$j(x) \propto \frac{\partial \phi}{\partial t}$

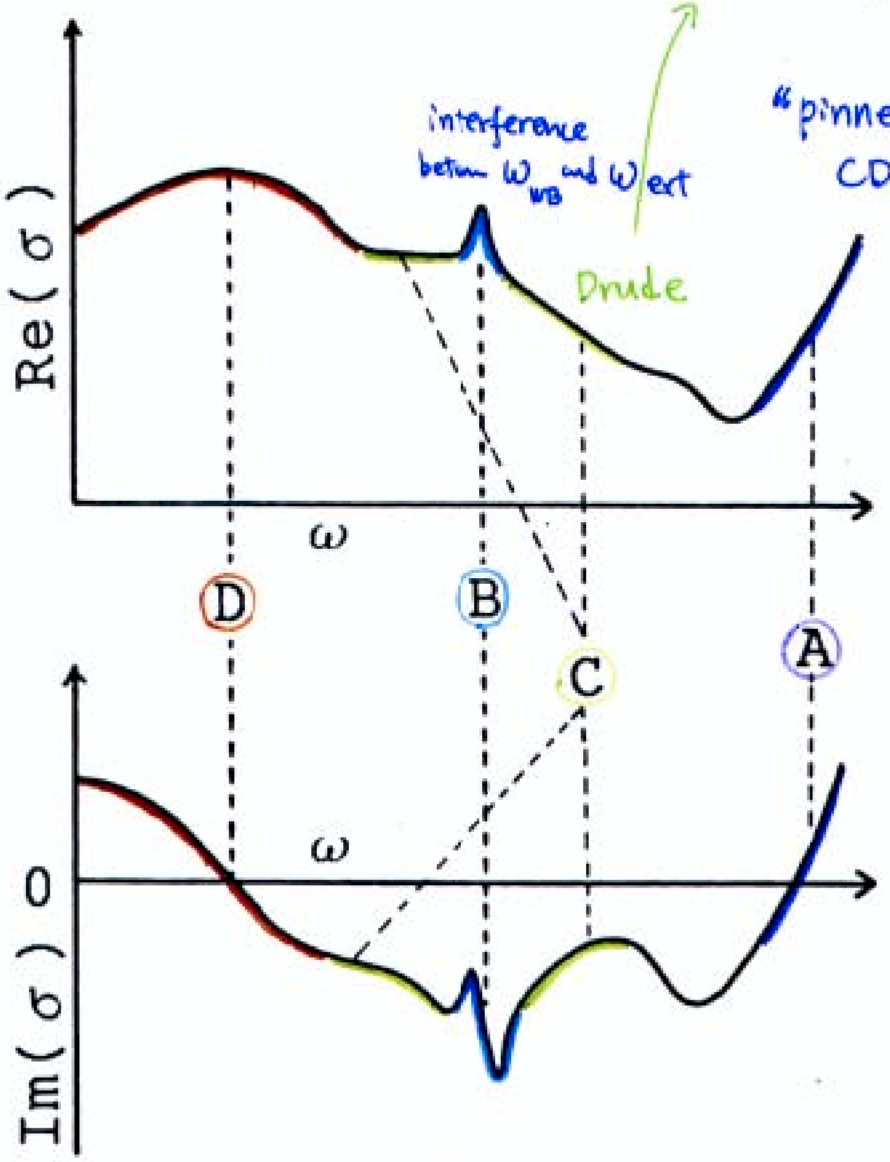
The results of numerical calculations[36] showing the phase of the pinned CDW as a function of a dimension perpendicular to the non-linear current flow for varying electric fields. The top curve is a snapshot of a moving CDW showing the pinned configuration (dashed line) obtained by removing the field.



elementary process
||
kink formation
and
its propagation
during
the short time

The results of numerical calculations[36] showing the phase of the moving CDW as a function of a dimension perpendicular to the non-linear current flow. Each curve is a snapshot of the moving CDW taken at equal time intervals. The temporal periodicity comes from the finite size of the numerical calculation. Note that dc motion of the CDW is accompanied by large fluctuations.

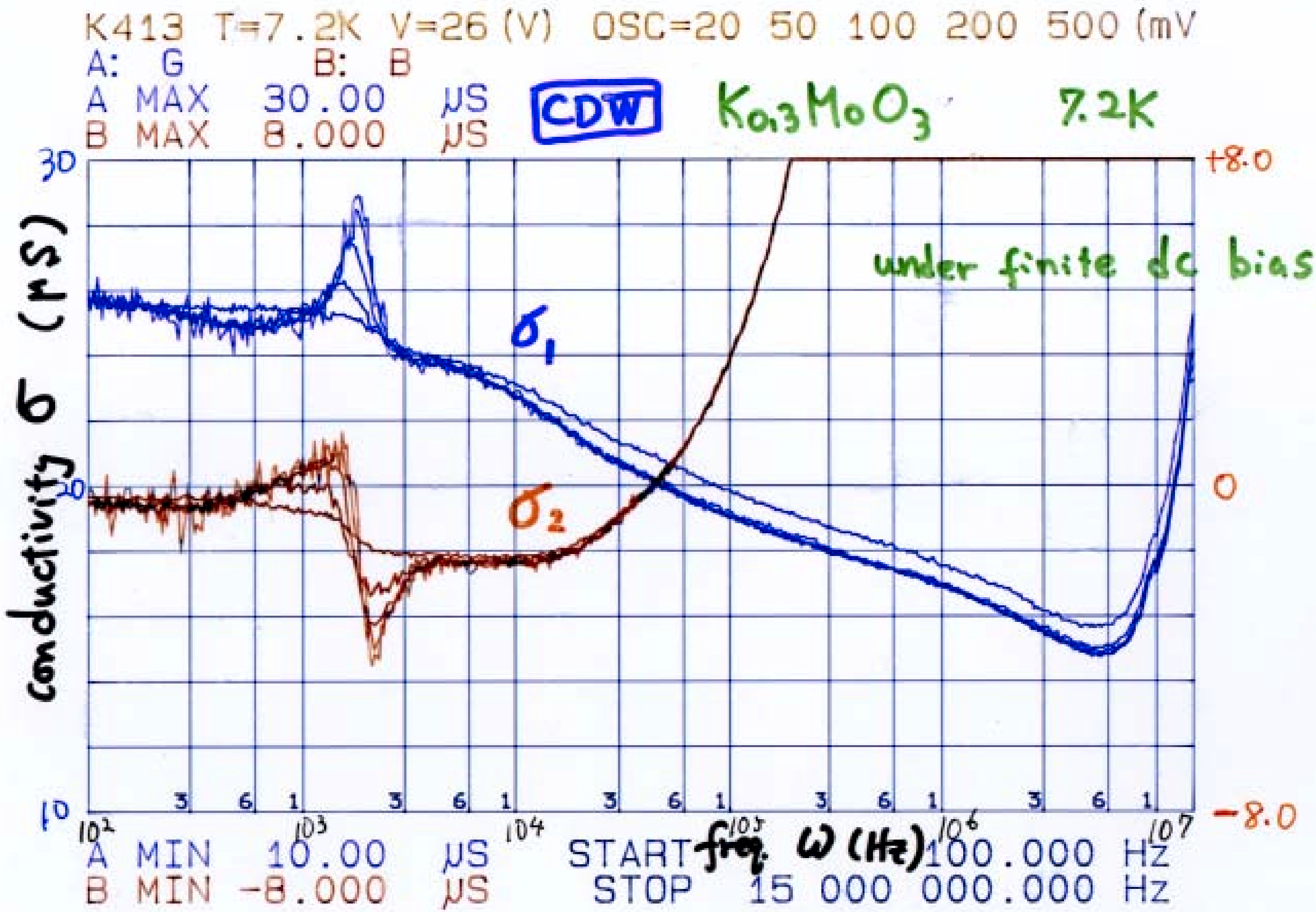
$$\sigma(\omega) = \frac{\sigma_0}{1 + i(\omega/\omega_{WB})}$$



Notomi et al. PRB42 (1990) 3303.

$\omega \ll \omega_{WB}$: freely moving $\approx$ sliding

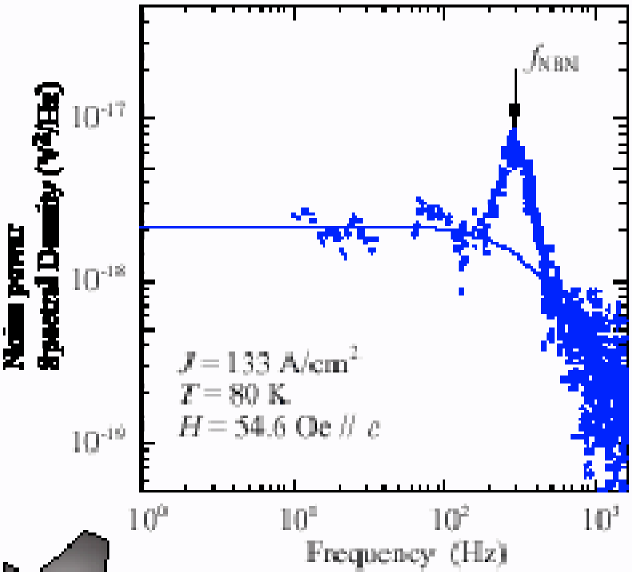
$\omega \gg \omega_{WB}$: "pinned" even for $E_{dc} > E_T$


K413 T=7.2K V=26(V) OSC=20 50 100 200 500 (mV
A: G B: B
A MAX 30.00 μS
B MAX 8.000 μS
CDW
$K_{0.3}MoO_3$
7.2K
under finite dc bias
σ1
σ2
conductivity σ (μS)
freq. ω (Hz)
A MIN 10.00 μS
B MIN -8.000 μS
START 100.000 Hz
STOP 15 000 000.000 Hz

<spectrum analysis>

$P \ll 1$

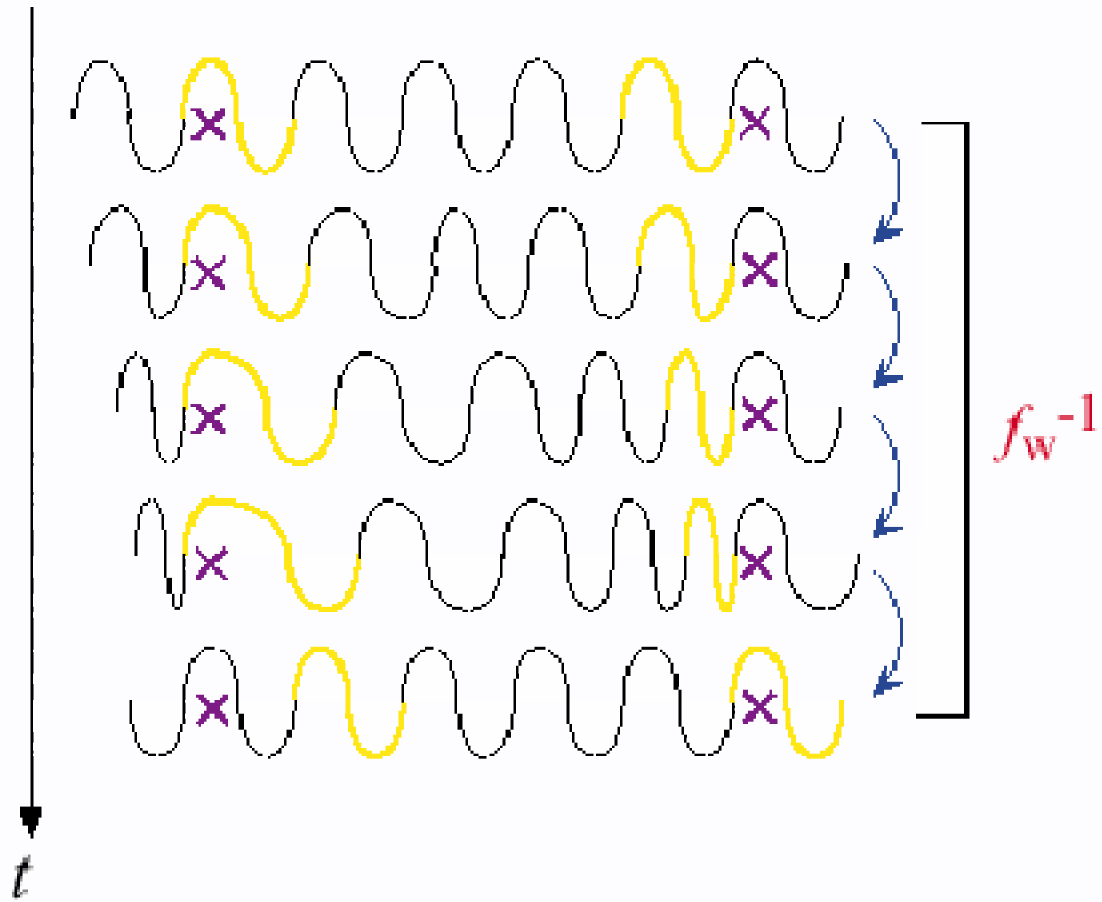
$V_0 \sim V_{ff}$

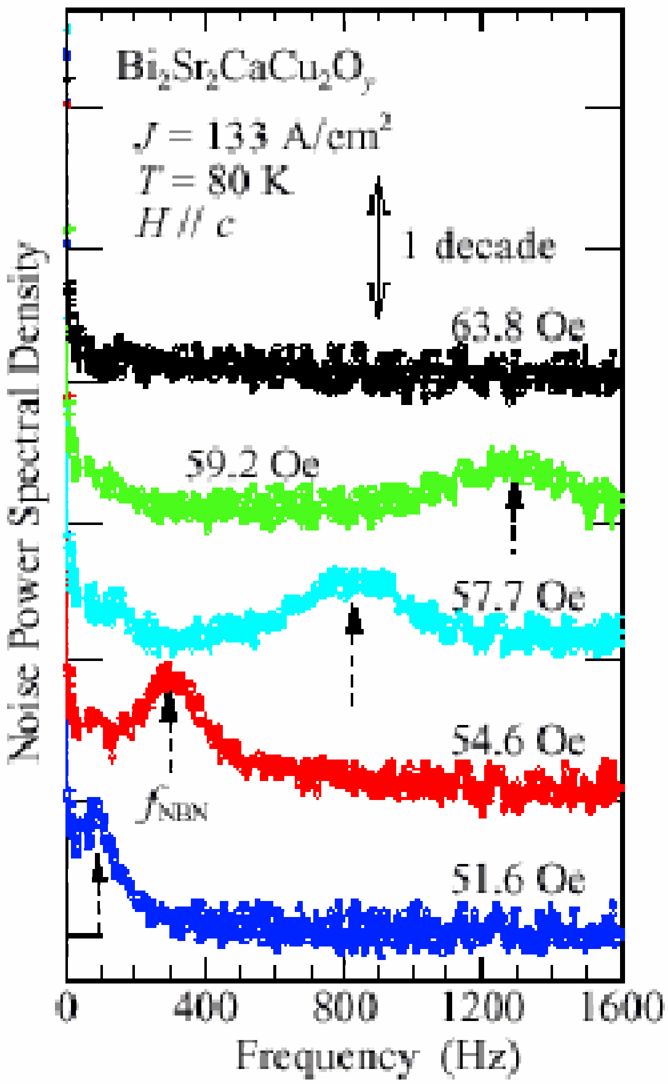


Lorentzian spectrum

Washboard noise

[Vortex Motion]



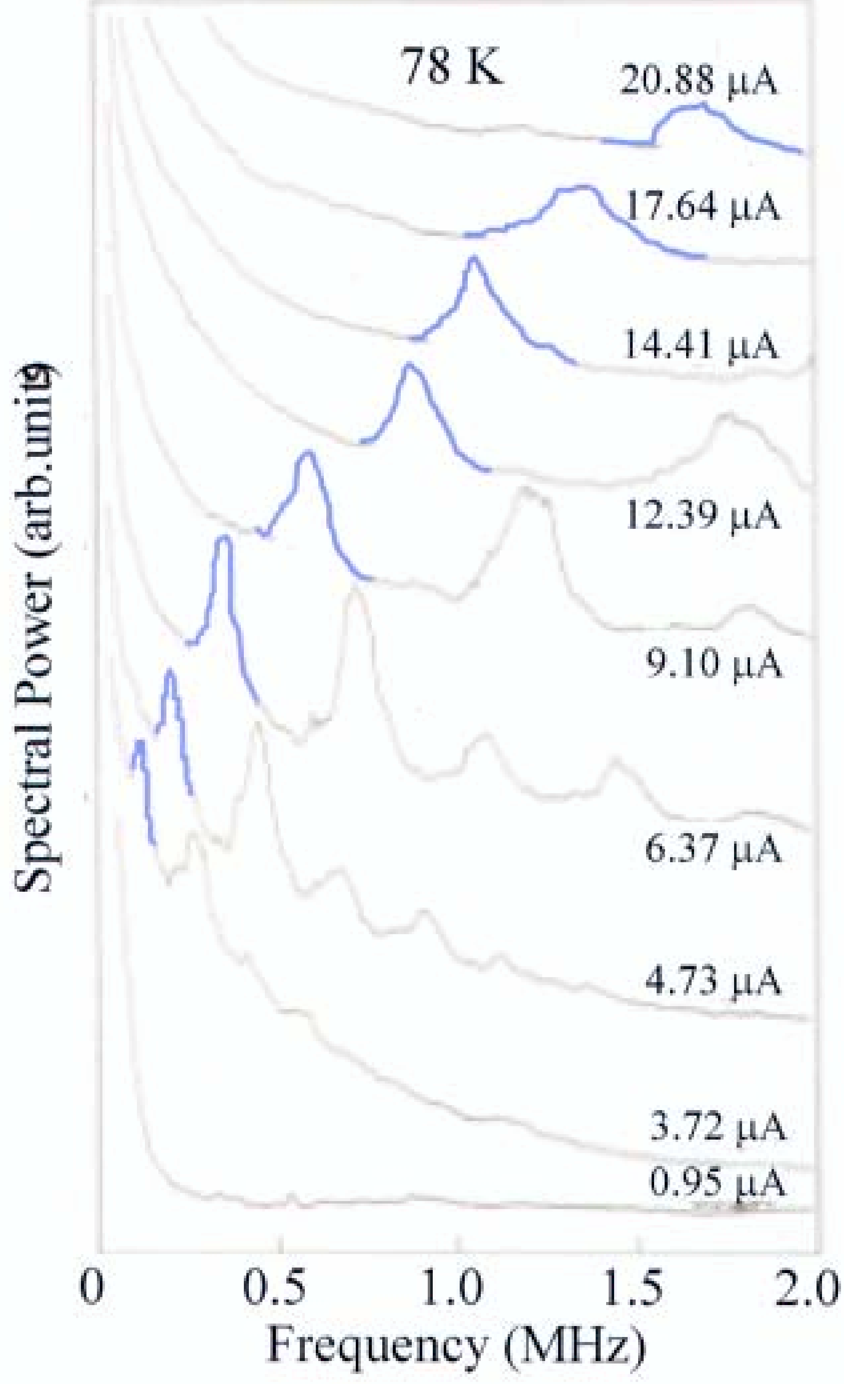


- Rapid shift of NBN to higher frequencies with increasing field

- Broading of NBN

Washboard Modulation in **Charge-Density Wave**

TaS_3 930(monoclinic)



A. Maeda *et al.*,
J. Phys. Soc. Jpn. 54, 1912 (1985).

Deterioration of the coherence of dc driven vortices

Contrary to theoretical predictions

Similar phenomena in a CD system, m-TaS_3

(semiconducting)

(Maeda et al. J. Phys. Soc. Jpn (1985))

Also contrary to

(a) Experiment in another CD system $NbSe_3$

(metallic)

(Thorne et al.)

(b) Numerical simulation for 1dim CD

(Matsukawa et al.)

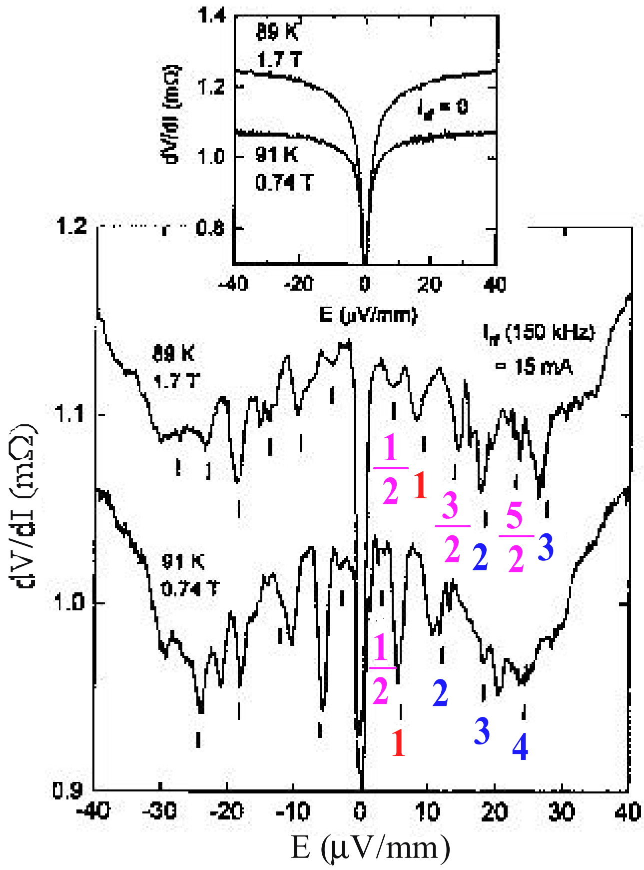
--did not take account of plastic deformation

mportance of plastic deformation

for realistic description of the phenomena

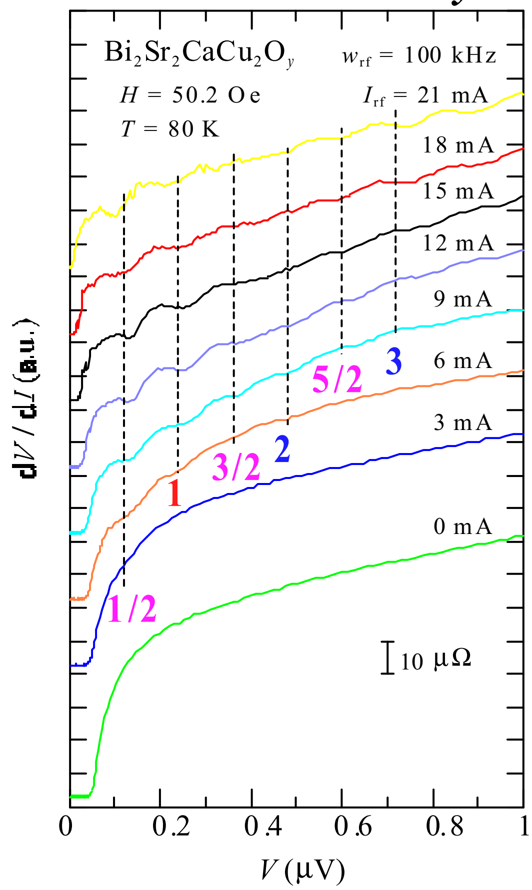
[Driven Vortices] 2D driven sytem

$YBa_2Cu_3O_y$



J.M.Harris *et al*.,PRL **74**, 3684 (1995).

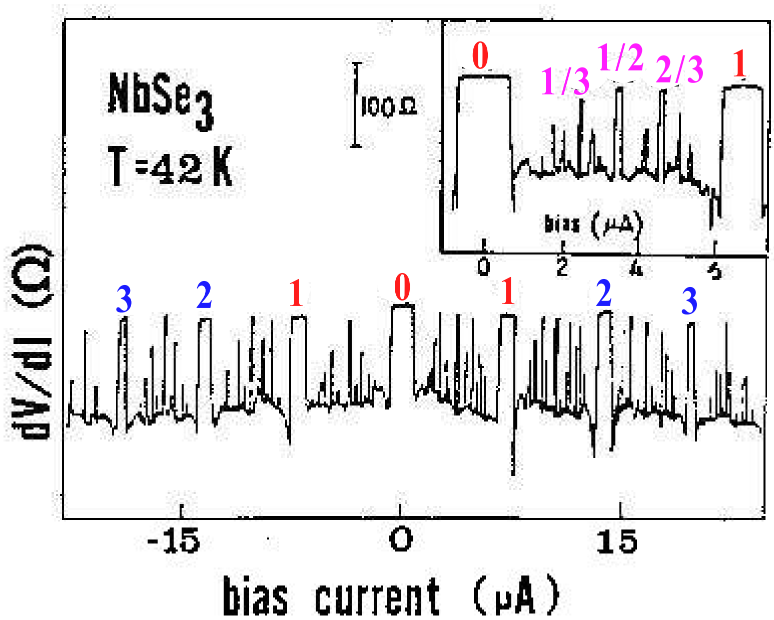
$Bi_2Sr_2CaCu_2O_y$



main peak & harmonics
sub-harmonics (1/2 series)

[Sliding CDW] 1D driven system

$NbSe_3$



main peak & harmonics
(perfect mode-locking)
sub-harmonics
(many series)

R.P.Hall and A.Zettel,PRB **30**, 2279 (1984).

Vortices in SC (2D) vs CD (1D)

Similarity *v* difference

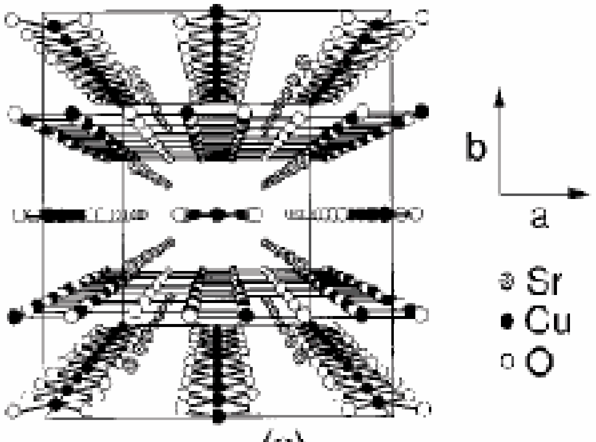
1) Coherent motion (washboard motion)
in the so-called creep regime
common to vortex and CD

--elementary process of sliding motion
stick-slip like motion of phase kinks

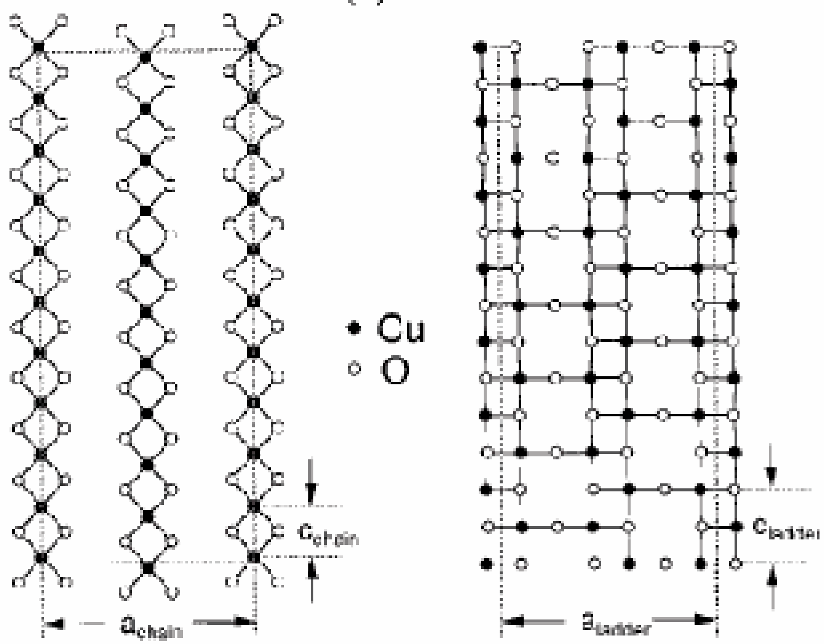
2) Deterioration of coherence
with increasing driving force

Vortices in SC is less coherent than CD
difference in dimensionality?

Spin Ladder $Sr_{14-x}Ca_xCu_{24}O_{41}$



(a)

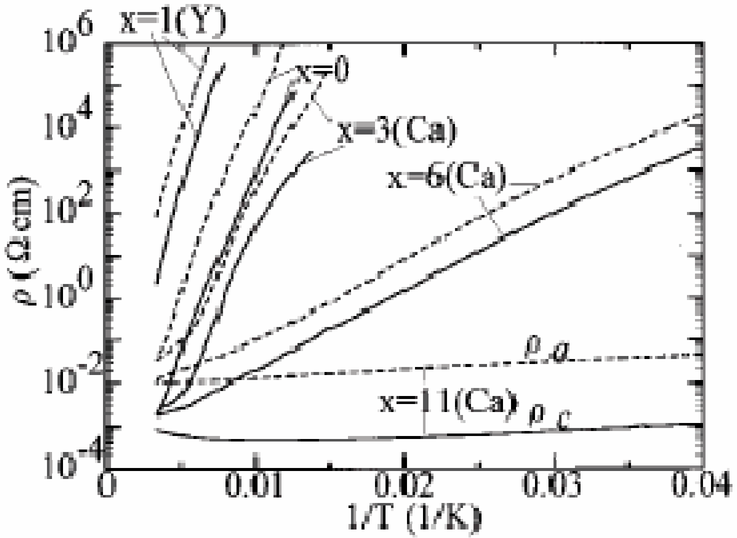


(b) (c)

chains ladders

Carrier doping in spin ladder structure
expect superconductivity
(E. Dagotto and T. M. Rice: PRB45 (1992) 5744)

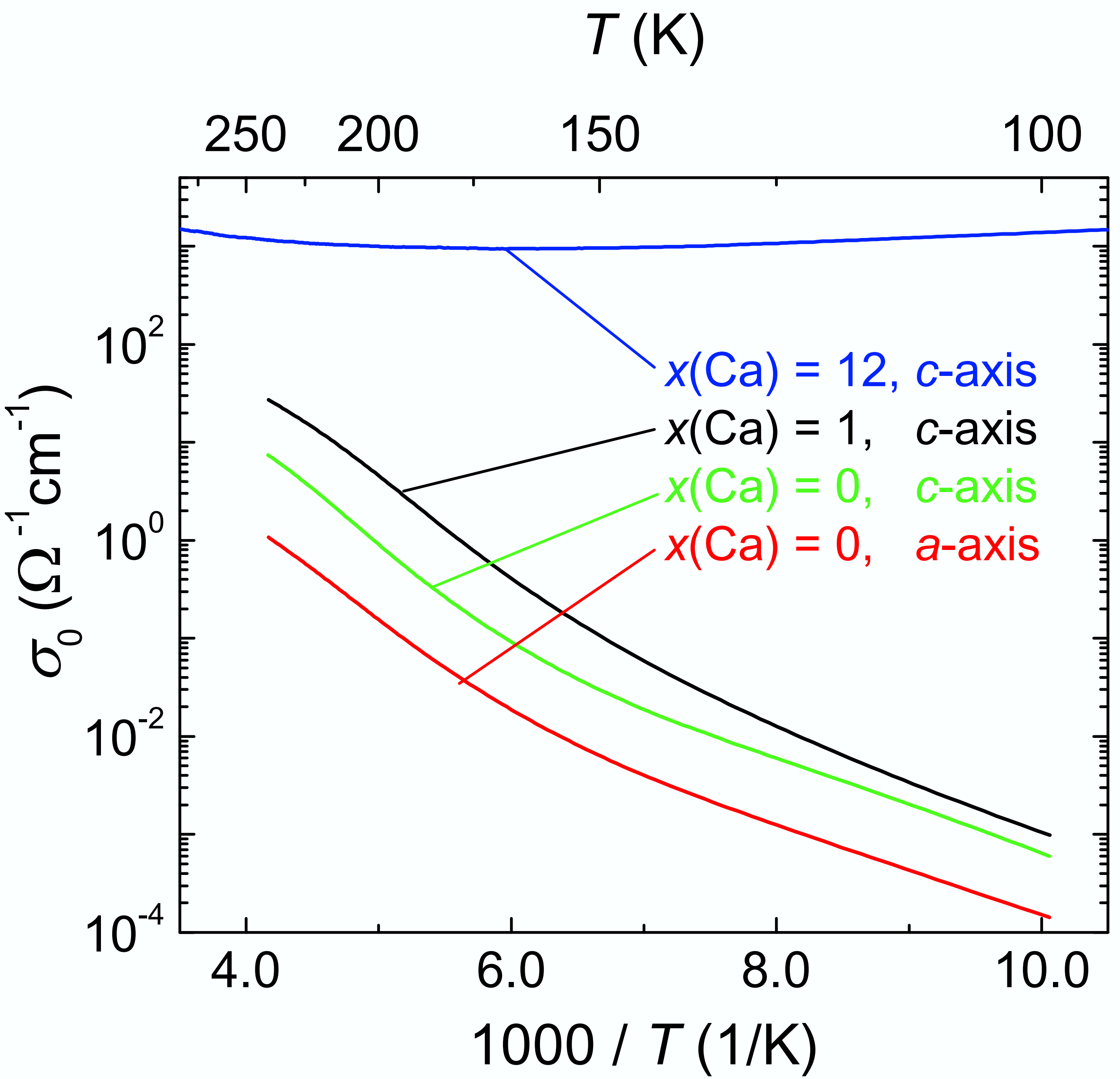
Sr substitution by isovalent Ca
Insulator→metallic
(N. Motoyama *et al.*: PRB 55, R3386 (1997))



superconductivity in heavily doped crystal
(M. Uehara *et al.*: JPSJ 65 (1996) 2764.)

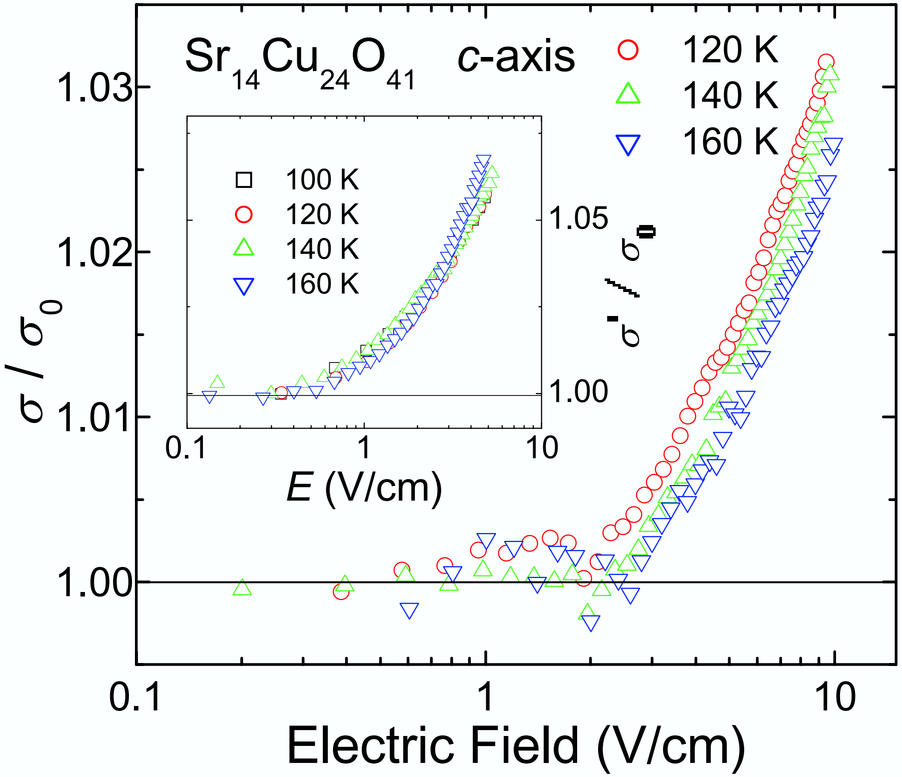
Role Ca : charge transfer from chain to ladder
(T. Osafune *et al.*: PRL **78**, 1980 (1997))

Ohmic conductivity

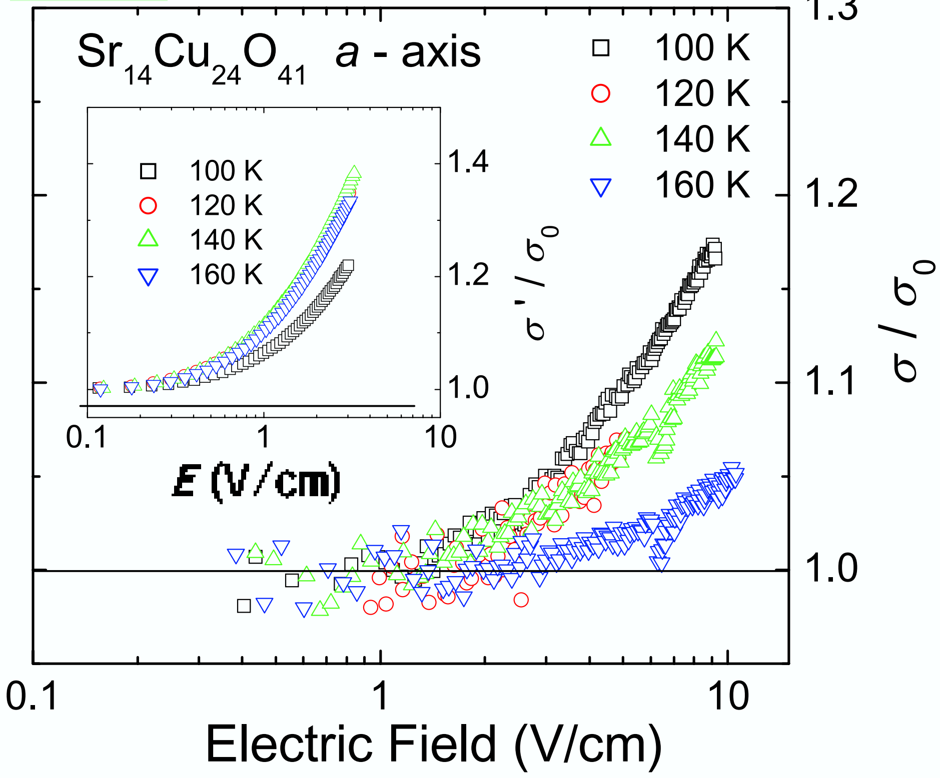


NLC in the ladder- and rung directions of $Sr_{14}Cu_{24}O_{41}$

ladder



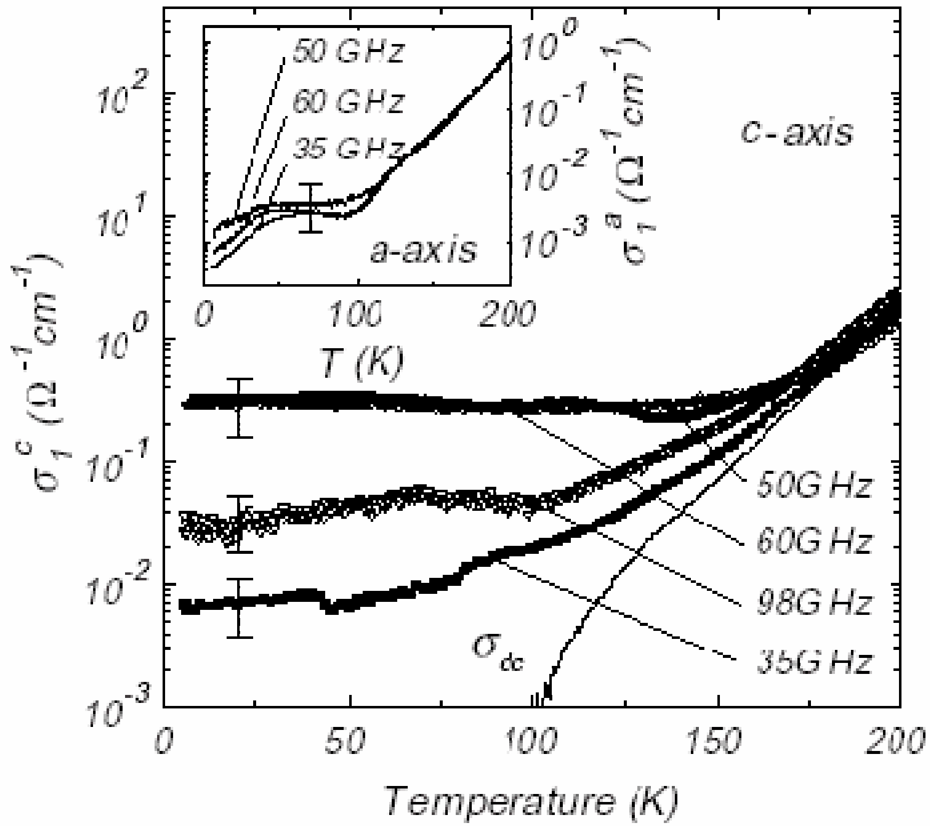
rung



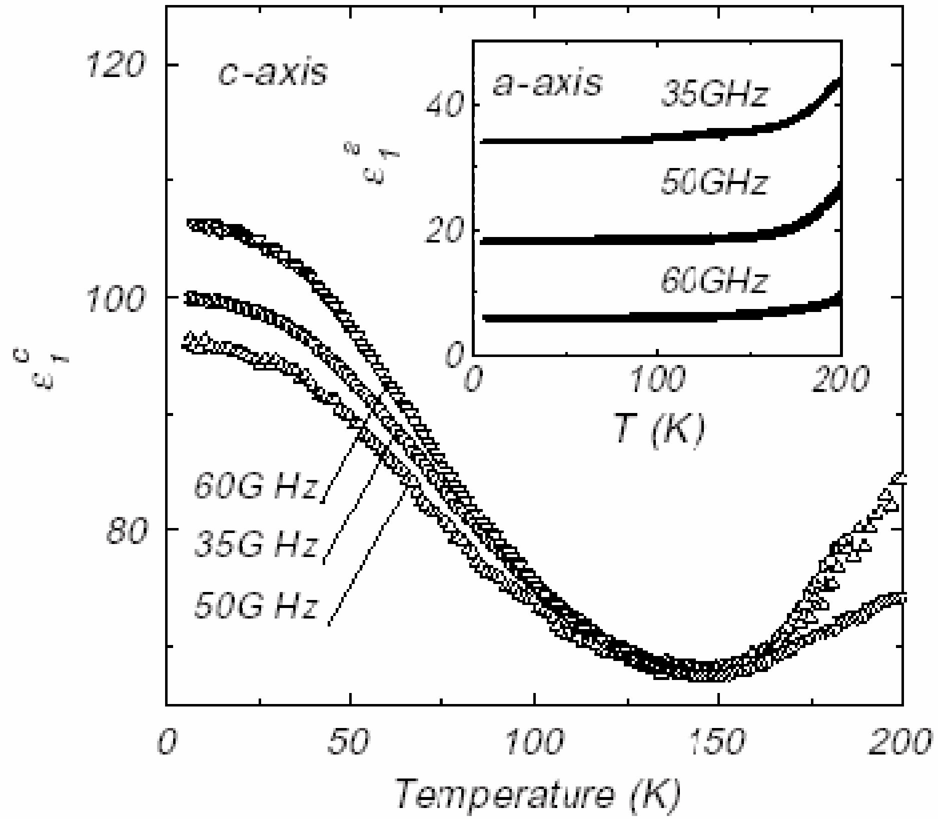
- *Small increase* ($\Delta\sigma \sim$ 3% at 10 V/cm)
- NLC starts between 0.1-2.0 V/cm
- $\sigma(E)/\sigma_0$ was almost *independent of T*

- *Large increase* ($\Delta\sigma \sim$ 20% at 5 V/cm)
- The existence of characteristic field is *less clear*
- $\sigma(E)/\sigma_0$ *strongly depends on T*

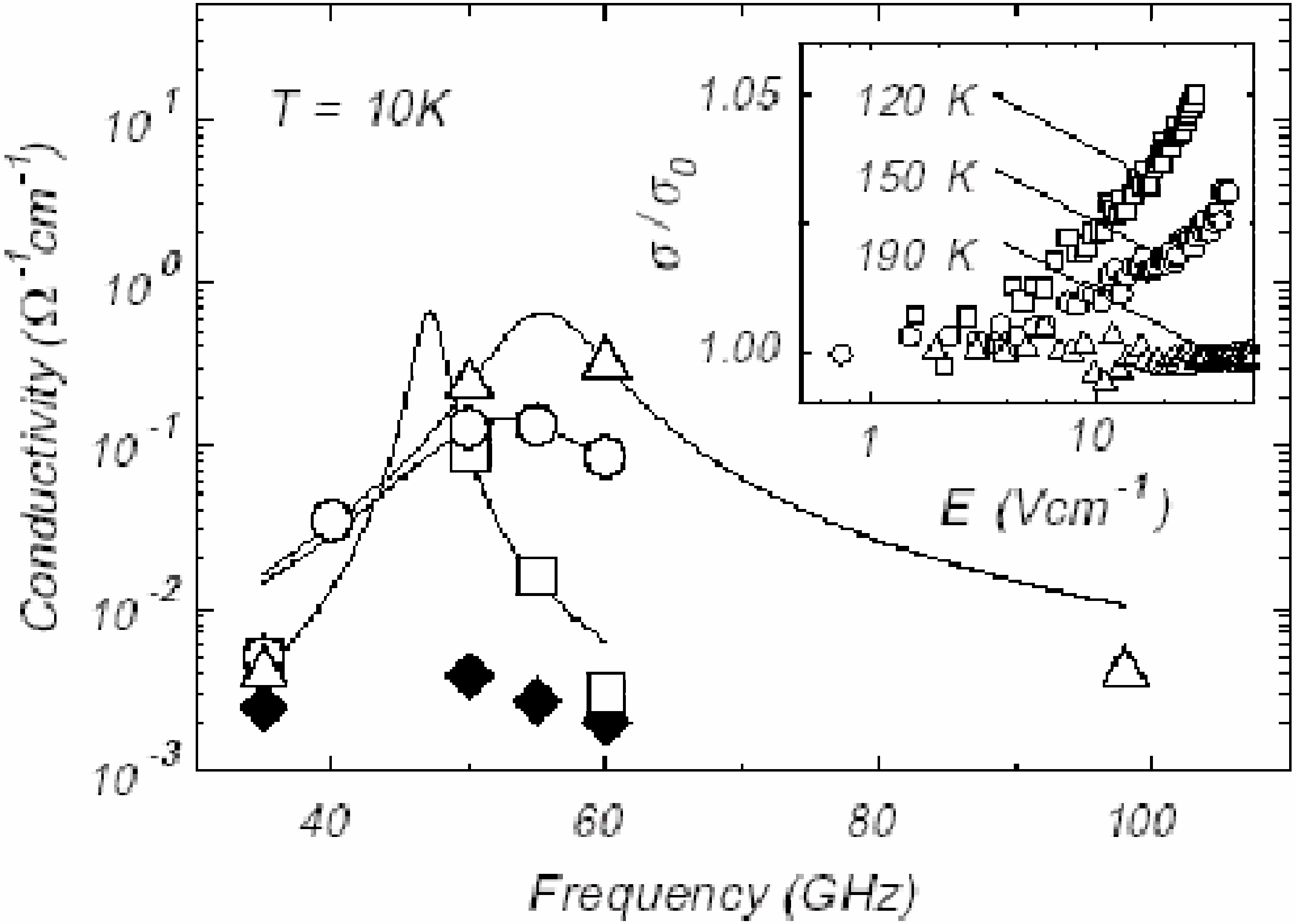
The NLC was quite different between the two directions

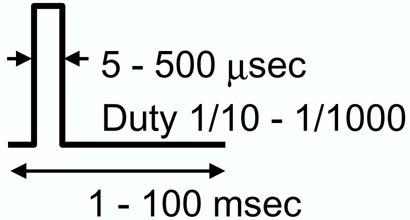


Extra conductivity at microwaves



Large dielectric constants at microwaves





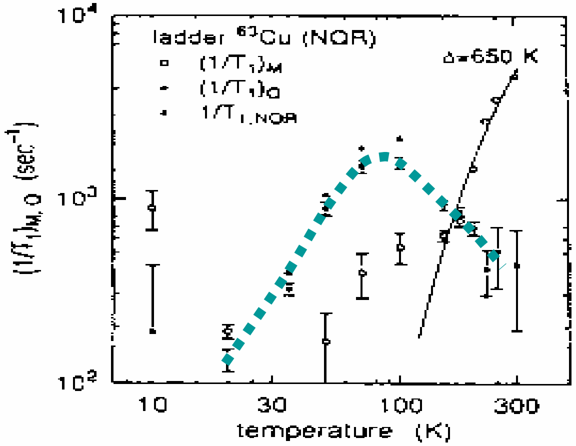
a boxcar averager (SRS-SR250) and
a digital oscilloscope (TDS420A)

Local maximum around at 50 GHz (10 K)   observed up to 150 K

single-particle resonance :**unli ely** $(\omega_0 \ll T)$ **collective**

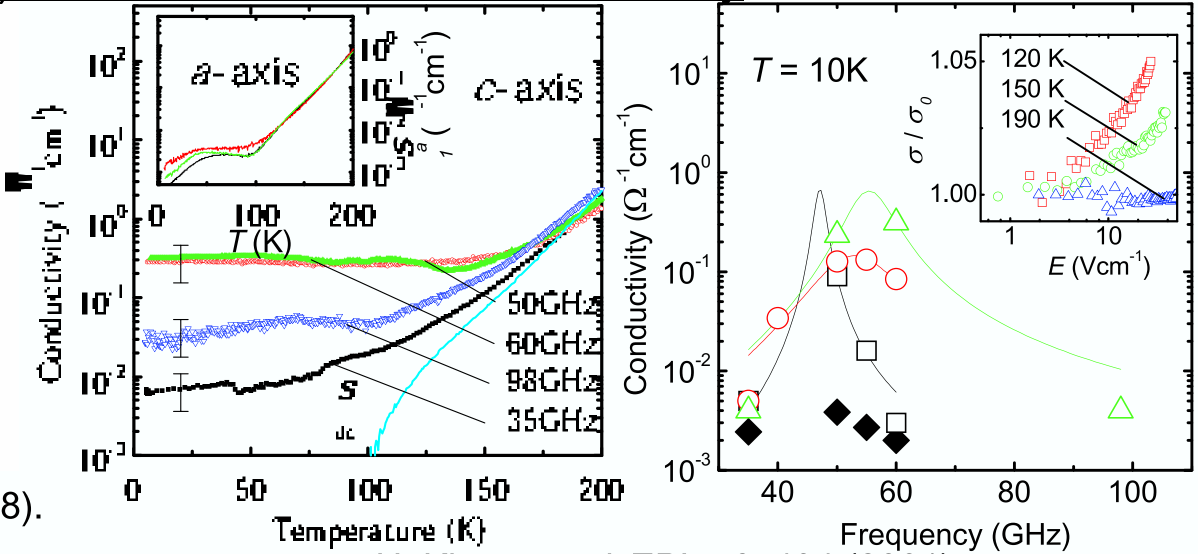
The collective charge excitation in the ladder planes of $Sr_{14}Cu_{24}O_{41}$

(1) NQR



M. Takigawa *et al*. PRB 57, 1124 (1998).

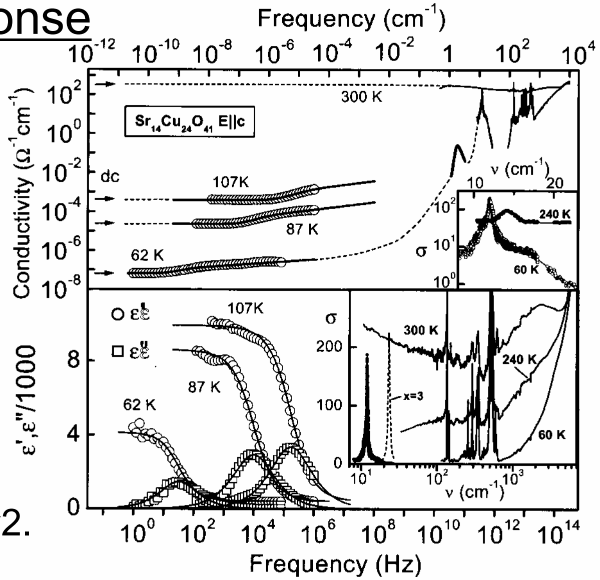
(2) MW and nonlinear dc conductivity



H. Kitano *et al*. EPL 56, 434 (2001).

(3) Optical Response

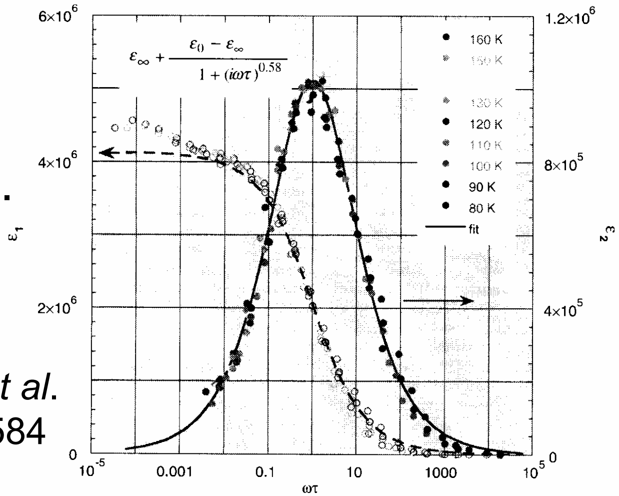
also
nonlinear σ(E)



B. Gorshunov *et al*.
cond-mat/0201413v2.

(4) Low-ω Dielectric Response

also
switching,
Ramman sct.



G. Blumberg *et al*.
Science 297, 584
(2002).

(1) A peak in $\sigma_1(\omega)$ at ω_0

$\omega_0 << T$: collective origin

$_0 \approx 0.1 - 1V / c$

(2) Nonlinear conduction (>E0) $e \; _0 \approx \; ^{*}\omega_0^2 \lambda$ $\omega_0 / 2\pi \approx 50 \; H$

$\lambda \approx \; \_$ $^{*} \approx \; _0$

charge orderded state without lattice distortion

(3) $\sigma(E)$, $\sigma(\omega)$ only in the ladder direction

(4) $\sigma(E)$: characteristic of low doped materials

a collective mode

characteristic of low dimensional correlated systems

$4k_F$-CDW

Wigner crystal

onclusion

( ) perimental determination of dynamic phase diagram of driven vortices in a high-T_c BS by a coupled study of density- and conduction noise and ac-dc interference effect

1) Bragg glass →plastic flo → coherent flo
→less coherent flo → incoherent flo
→moving vorte li uid

2) Different dynamic phase diagram from that of conventional $NbSe_2$

3) Different from e pectation of numerical simulation

) No phase boundary corresponding to the K-V transition

) characteristic decrease of coherent temporal order in the high driving force region

(B) Vortices and D 2D vs 1D

1) dynamical coherence better developed in the D

2) Similar elementary process (similarity in the spetctra)

( ) ollective charge dynamics in the spin ladder

1) Scaling in the nonlinear conduction

2) Very small oscillator strength similar to the SD suggesting moving igner crystal in 1D