COHERENT INTERLAYER AND INTERCHAIN TRANSPORT IN $NbSe_3$ AMD GRAPHITE UNDER HIGH MAGNETIC FIELDS

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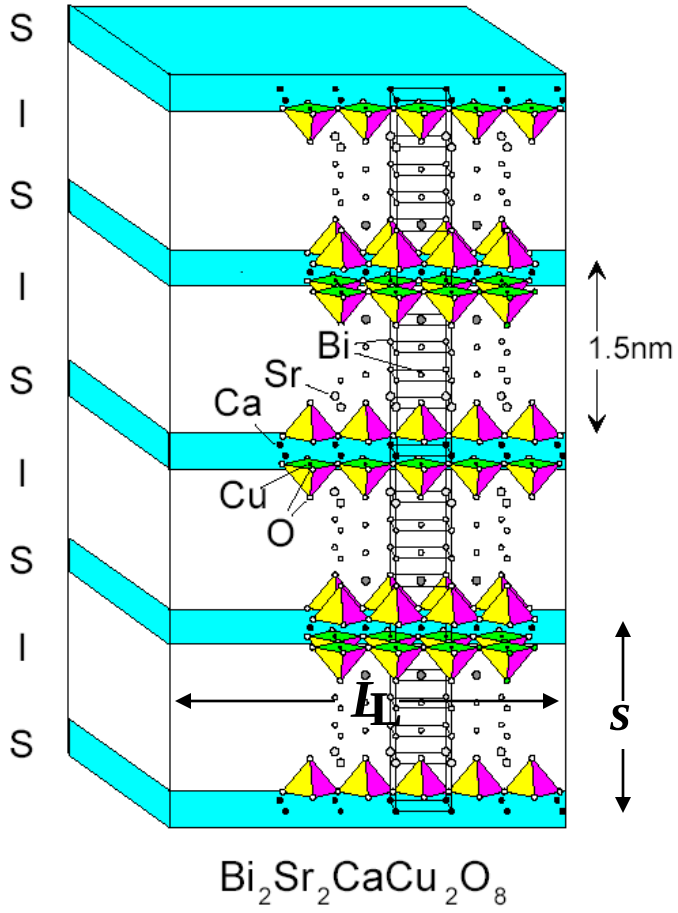
D. Vignolles, W. Escoffier	**LNCMP, Toulouse**

OUTLINE

1. **Introduction to intrinsic Josephson effects in HTS and interlayer tunneling gap spectroscopy.**
2. **CDW gap spectroscopy. Intragap states.**
3. **Field induced CDW state in $NbSe_3$ and graphite.**
4. **Coherent nonlinear transport across the chains in $NbSe_3$ under perpendicular magnetic fields.**
5. **Conclusions.**

1. Introduction to intrinsic Josephson effects in HTS.



IJE - Josephson effects on naturally layered crystalline structure of layered superconductors

Early ideas in 70-s: W.E.Lawrence, S.Doniach 1971

L.N. Bulaevskii 1973

Further development in 90-s, after discovery of HTS

L.Bulaevskii, J.Clem, L.Glazman 1992

stationary IJE for **short stacks $L < 2\lambda_J$,**

$\lambda_J = s\,\lambda_c/\lambda_{ab} \sim 1\mu m$ in Bi-2212

$$I_c(H) = I_{c0}\left|\frac{\sin\left(\frac{\pi sLH}{\Phi_0}\right)}{\frac{\pi sLH}{\Phi_0}}\right| \qquad \Phi_0 = \frac{hc}{2e}$$

DC Intrinsic Josephson effect

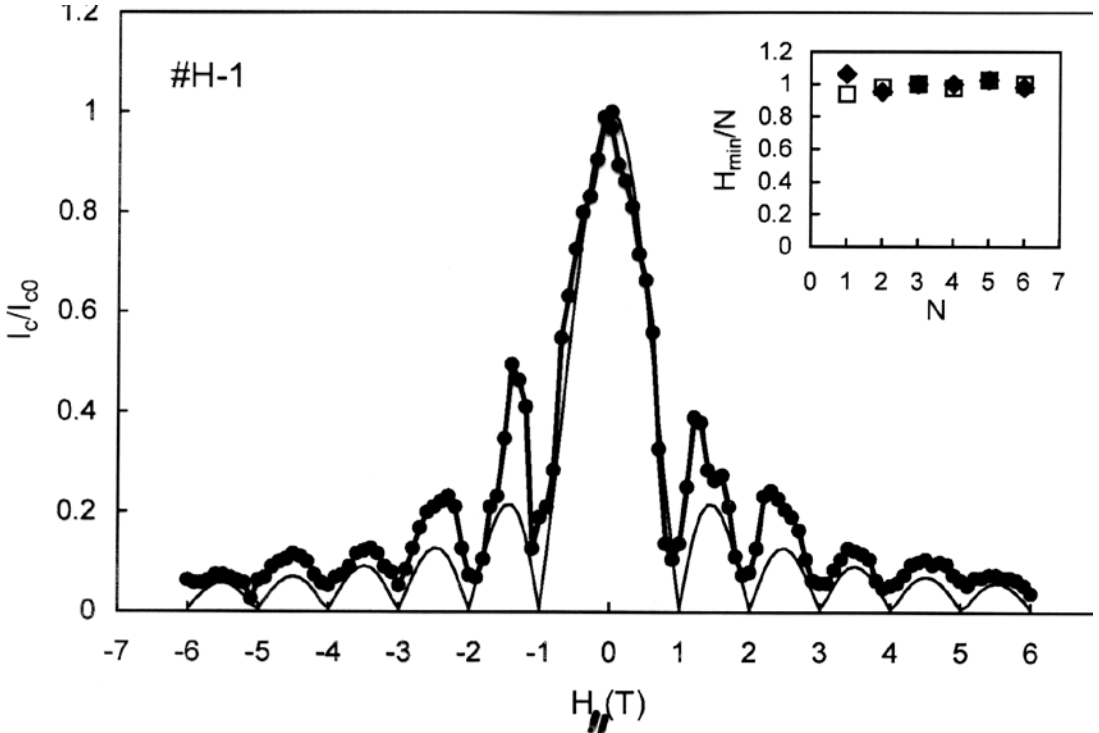
Yu.I.Latyshev, N. Pavlenko, S-J.Kim, T.Yamashita ISS-99, Morioka

Physica C, 2001

$$I_c(H) = I_c(0)\left|\frac{\sin x}{x}\right|$$

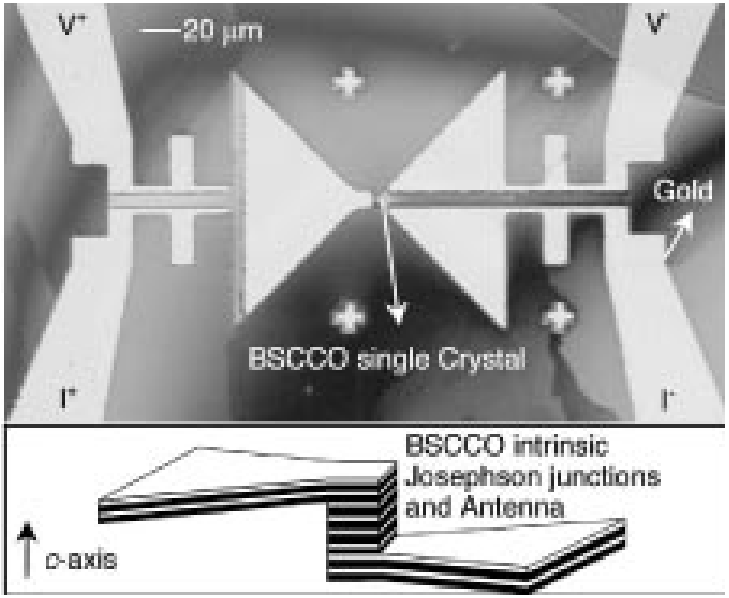
$$x = \frac{\pi s L H}{\Phi_0}$$

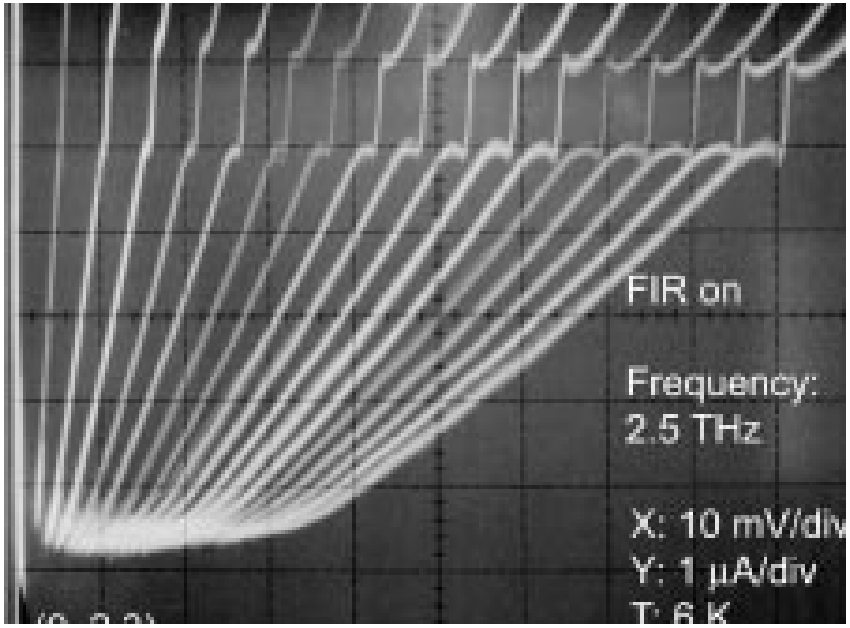
$$\Phi_0 = \frac{hc}{2e}$$



FIB fabricated Bi-2212 mesa, *L*=1.4 μm, *s*=1.5 nm, Δ*H*=1 T

AC Intrinsic Josephson effect

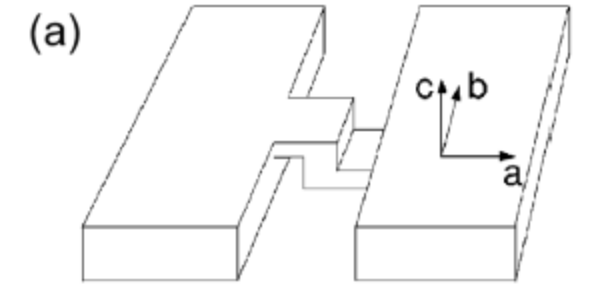


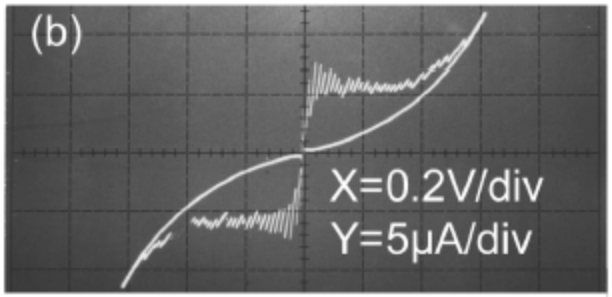


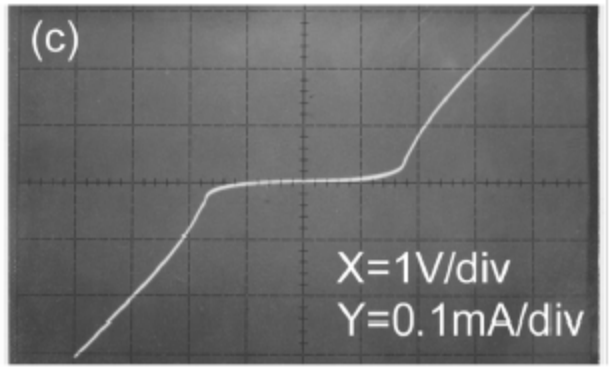
H.B. Wang, T. Yamashita, P.H. Wu, PRL 2001

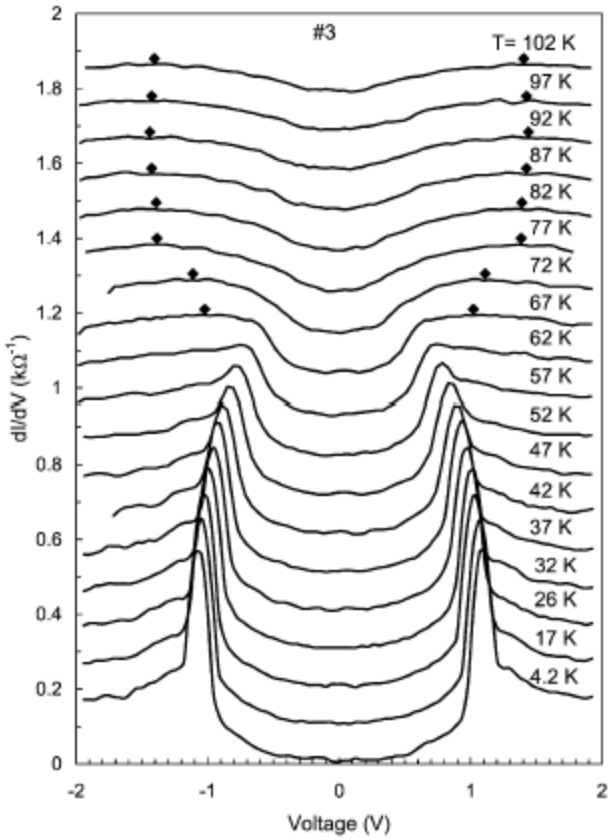
Quasiparticle tunneling

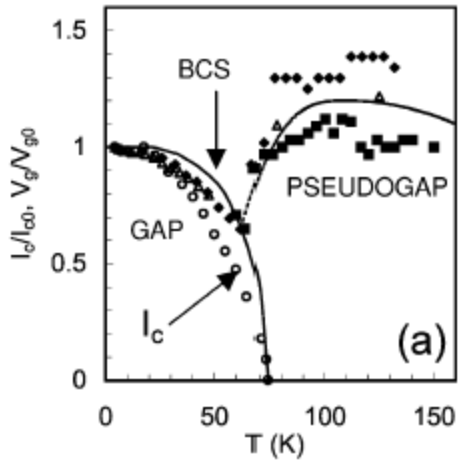
Quasiparticle tunneling over a gap: multibranched IVs, gap/pseudogap spectroscopy









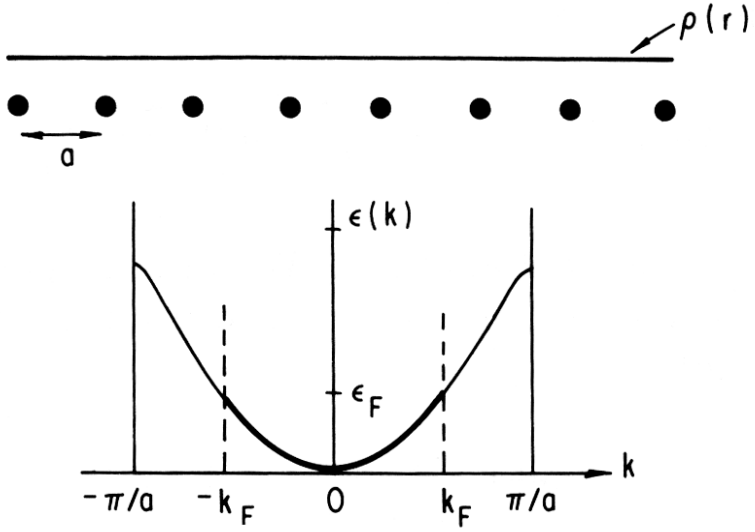


Yu.I. Latyshev et al.ISS Conf. 1999, Physica C, 2001; V.M. Krasnov et al. PRL, 2000, 2001

2. CDW gap spectroscopy. Intragap states.

CDW state

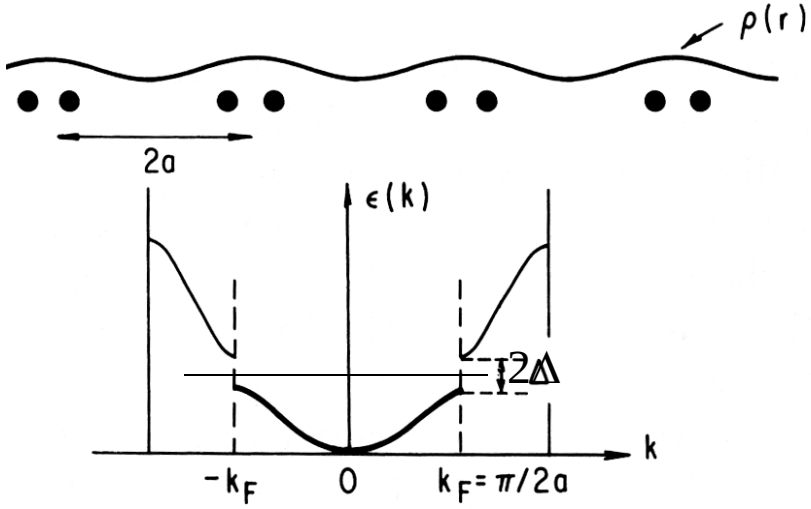
Peierls transition. CDW state.



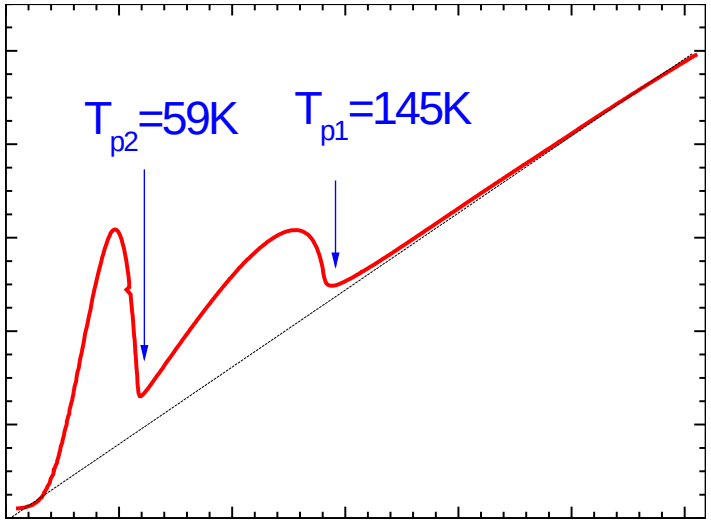
The gap is opened at the Fermi-surface. Condensed electron density is spatially modulated.

The order parameter in the ground state is

$\Delta_0 = A \cos(Qx + \varphi)$ with Q the CDW wave vector $\boldsymbol{Q = 2k_F}$ and φ the arbitrary phase in the ICDW state.

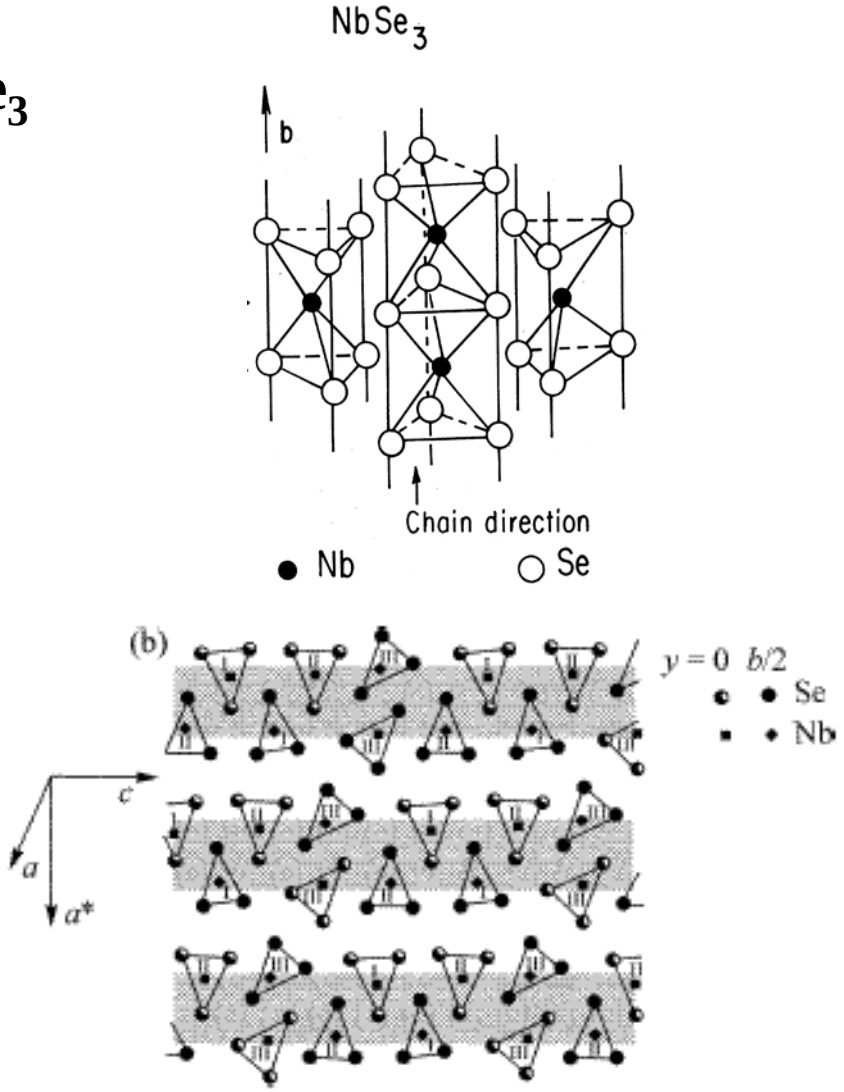


$NbSe_3$



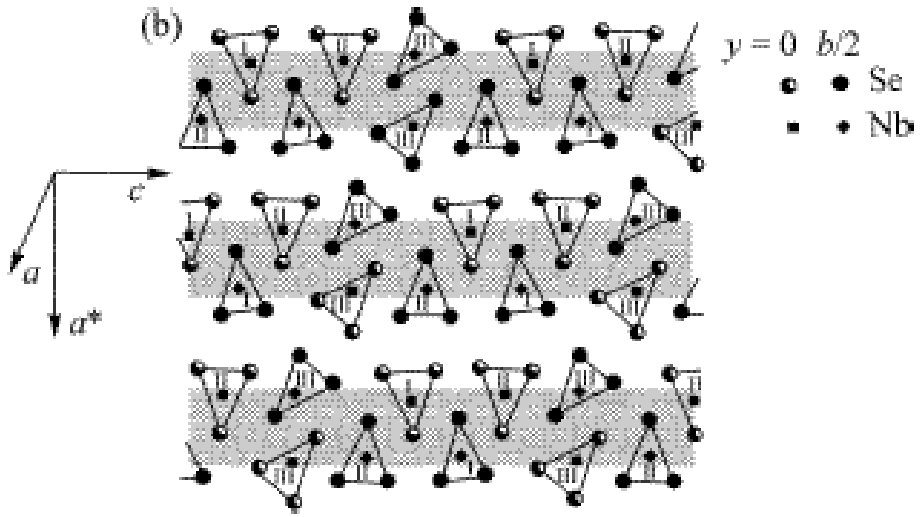
$\sigma_b/\sigma_{a^*}=10^3\text{-}10^4$

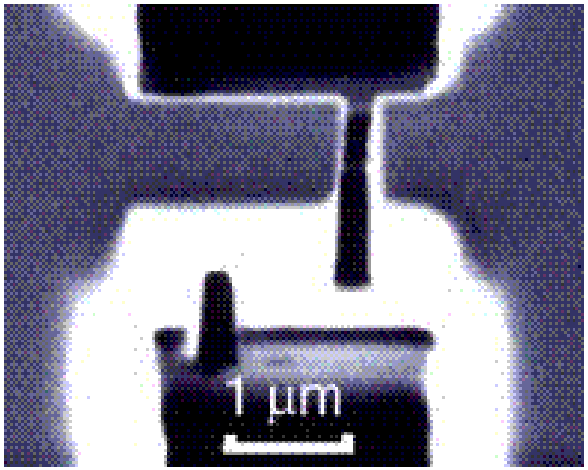
$\sigma_b/\sigma_c=10\text{-}20$



Crystalline structure

CDW interlayer tunneling spectroscopy: $NbSe_3$

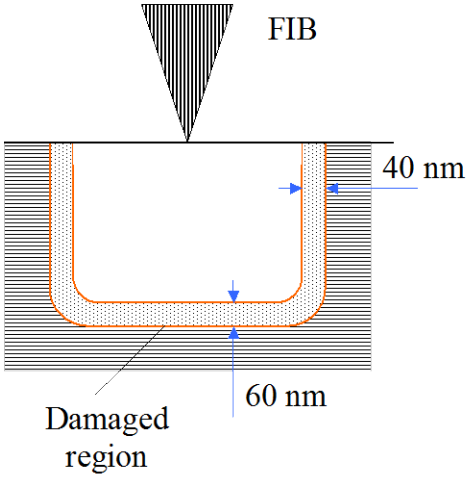




The elementary prisms are assembled in elementary conducting layers with higher density of conducting chains (shaded layers in a figure) separated by a double barrier of insulating prism bases. That results in a very high interlayer conductivity anisotropy $\sigma_{a*}/\sigma_b \sim 10^{-3}$ at low temperatures compared with intralayer anisotropy $\sigma_c/\sigma_b \sim 10^{-1}$.

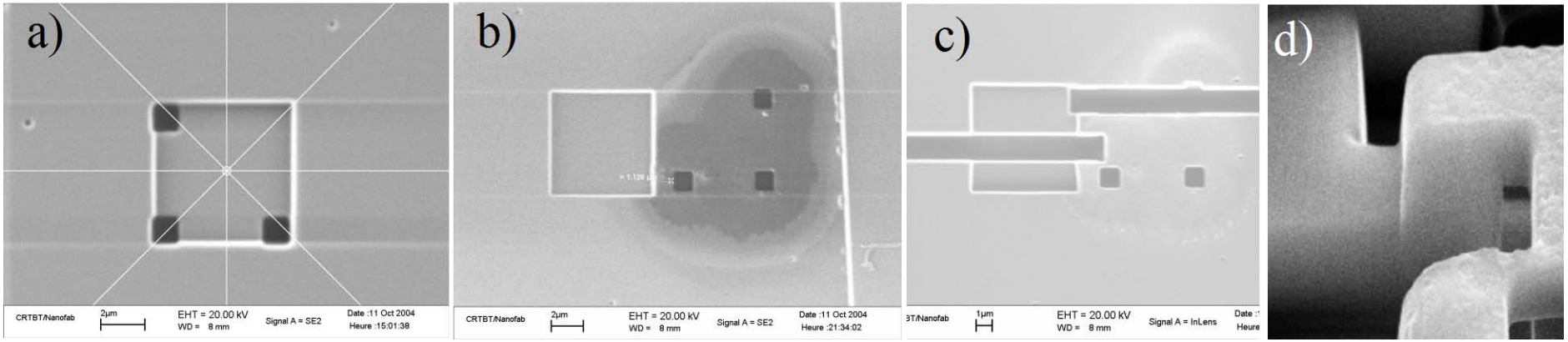
That provides the ground for interlayer tunneling spectroscopy of CDW layered materials.

Mesa fabrication by double sided etching with focused ion beam (FIB)



FIB machine

Seiko Instruments Corp. SMI-3050
Ga+ ions 15-30 kV
Beam current : 0.3 pA – 50 nA
Minimal beam diameter: 4 nm

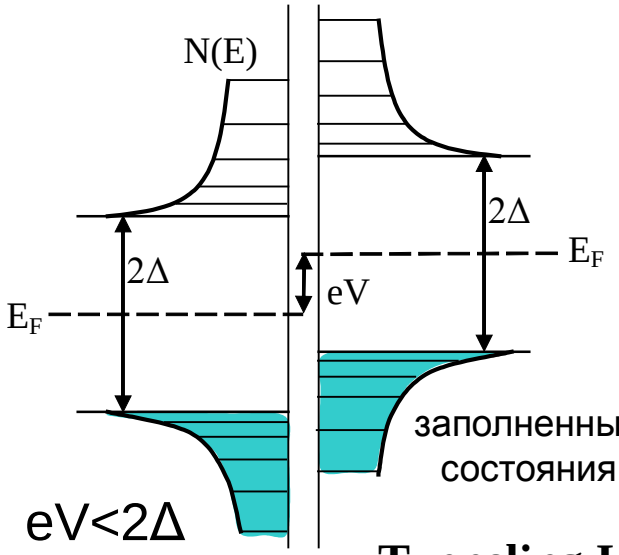


Stages of the double sided FIB processing technique for fabrication of the stacked structure; (d) SEM image of the structure. The structure sizes are 1μ x 1μ x 0.01 - 0.3μ

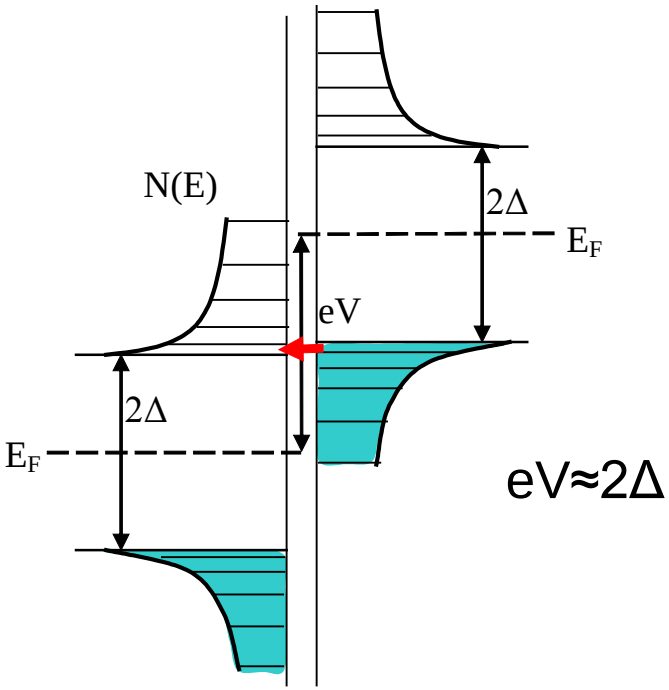
Yu. I. Latyshev et al. Supercond.Sci.Techn. 2007

Determination of the energy gap from tunneling measurements

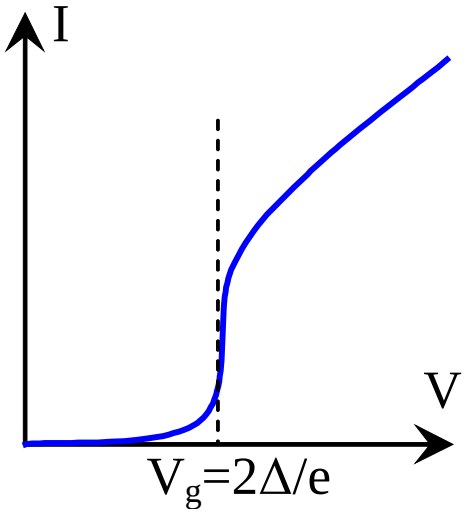
Tunneling juction S-I-S,



Tunneling junction S-I-S at eV ≈ 2Δ

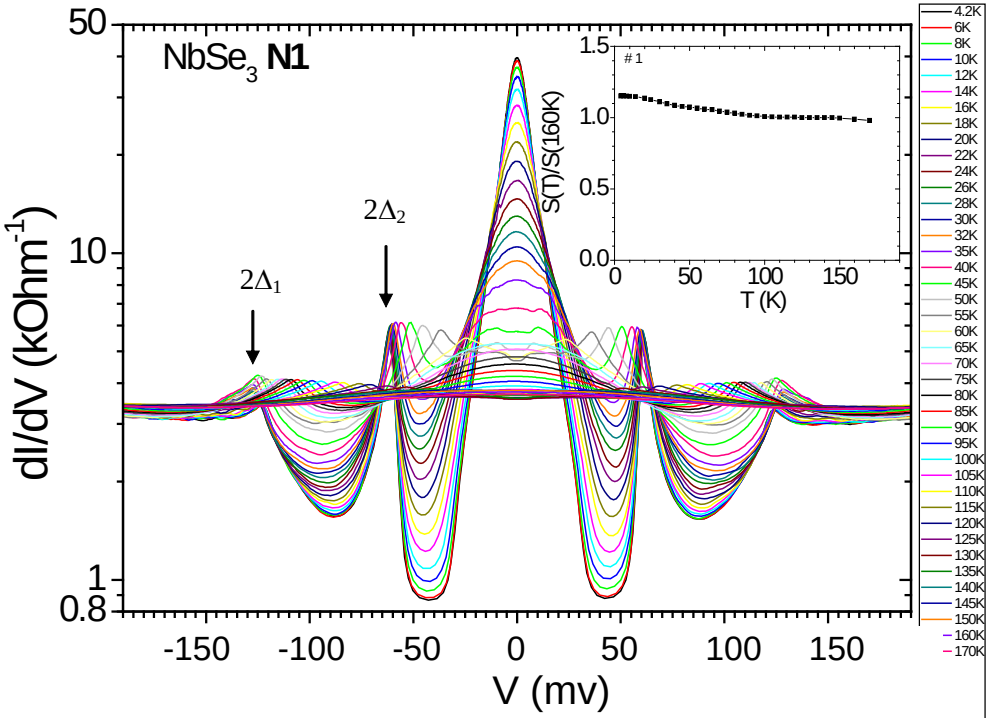


Tunneling I-V characteristic

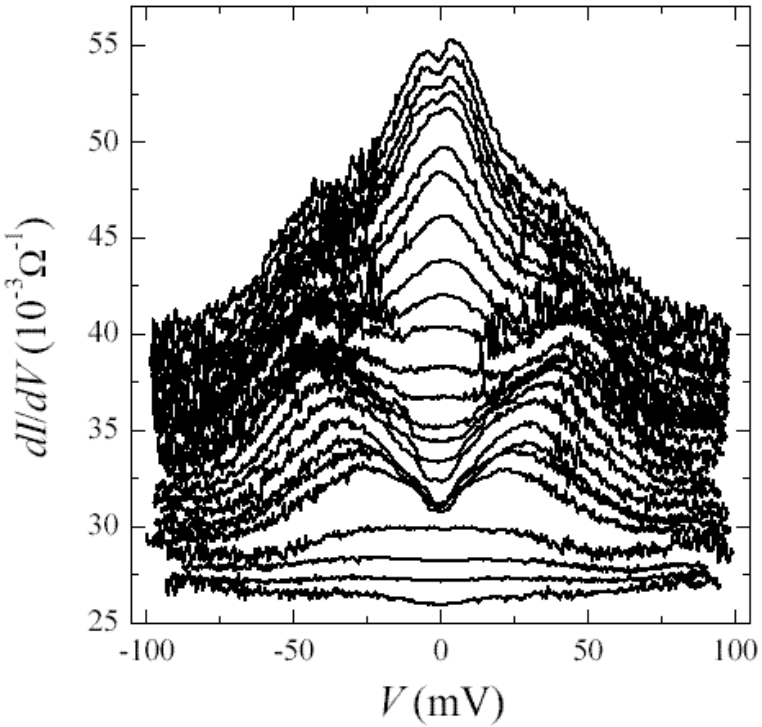


Temperature evolution of the spectra

Point contact spectra $NbSe_3$-$NbSe_3$ along the *a**-axis A.A. Sinchenko et al., 2003

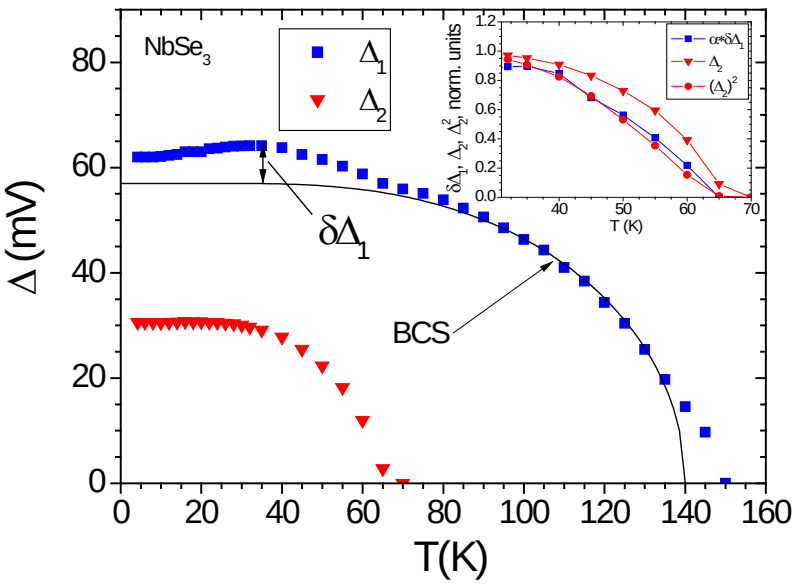


4.2K→ 170K



Stacked junction behaves as a single junction. We consider that as the weakest junction in the stack.

CDW gap spectroscopy in $NbSe_3$



At low temperatures there are two CDWs

$q_1 = (0, 241, 0)$, $q_2 = (0.5, 0.261, 0.5)$ in reciprocal unit length

$2(q_1 + q_2) \approx (1, 1, 1)$

In according to

R. Bruinsma and S.E. Trulinger PRB 1980
this phase coupling should be accompanied by small enhancement of Δ_1 below T_{p2}

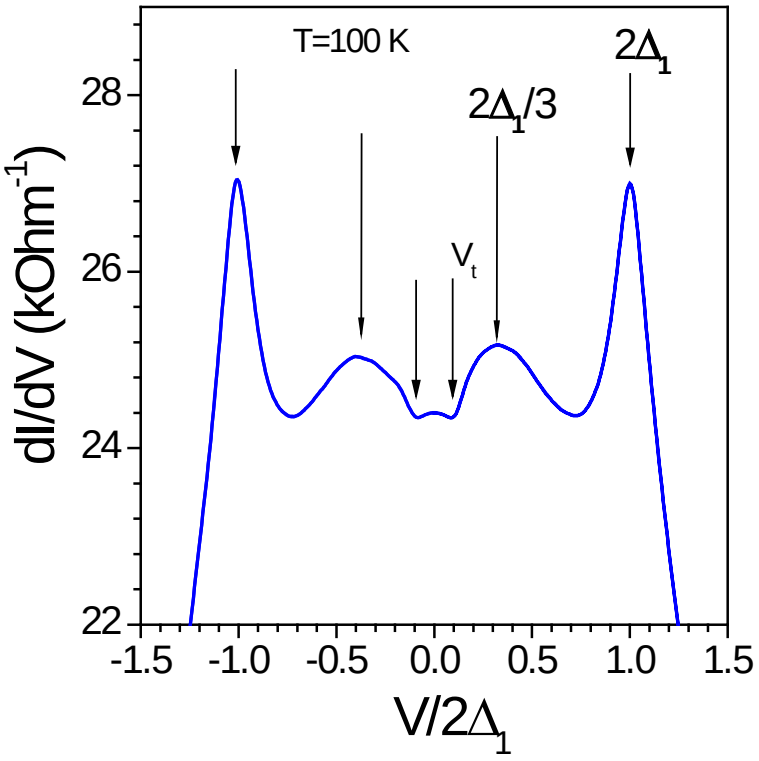
$2\Delta_2 = 60$ mV, $2\Delta_1 = 130$mV

Comparison with other techniques

STM	70	190	Z.Dai et al. PRB 92, D.Roditchev et al.PRB 98
Optics	70		A. Perucci et al. PRB 2004
ARPES	90		J. Schafer et al. PRL 2003
Microcon	60	140	A.A. Sinchenko and P. Monceau PRB 2007

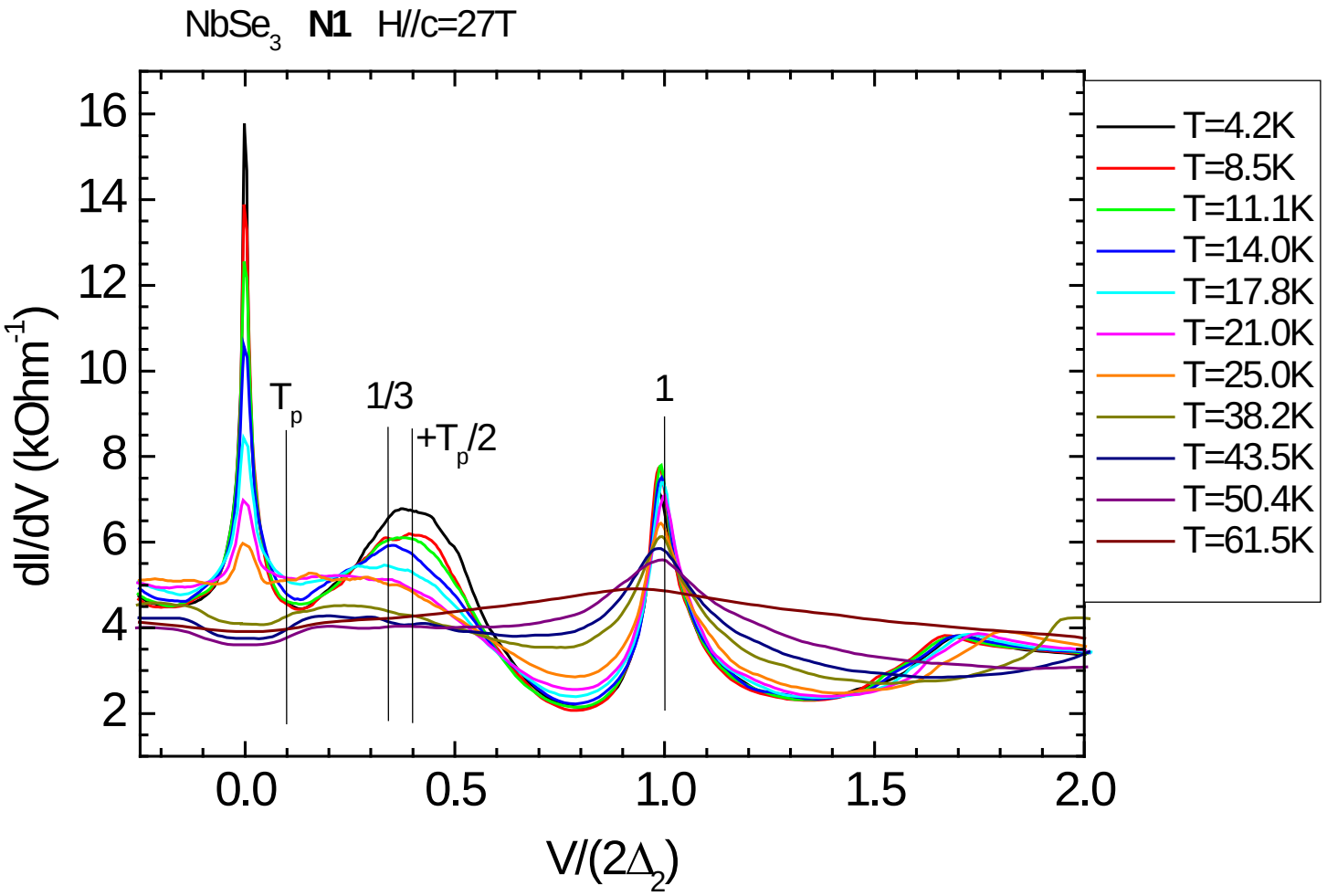
Intragap states: $NbSe_3$

Yu.I. Latyshev, P. Monceau, S. Brazovskii,
A.P. Orlov, Th. Fournier, PRL 2005, 2006



There are two new features inside the CDW gap with characteristic energies $V_s \sim 2\Delta/3$ and $V_t \sim 2\Delta/10$ which has been identified as the amplitude and phase excitations of CDW.

Temperature evolution of the spectra under high field



Intragap peak in strong parallel field was observed in the wide temperature range up to 30 K.

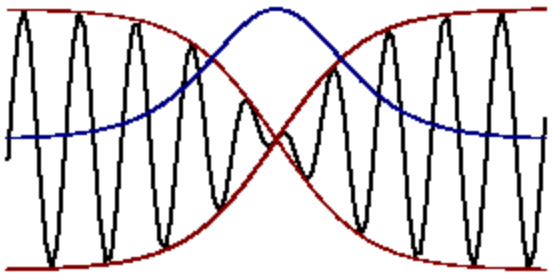
CDW amplitude solitons

(π-solitons)

Amplitude solitons in the incommensurate CDW (ICDW)

The order parameter in the ground state is $\Delta_0 = A \cos(Qx + \varphi)$ with Q the CDW wave vector $Q = 2k_F$ and φ the arbitrary phase in the ICDW state and A=const. That means that ground state is degenerated with respect to $A \leftrightarrow -A$.

That leads to the possibility of configuration with accepting of one electron and formation of new ground state with $A=\tanh(x/\xi_0)$ called amplitude soliton (AS).



AS is a self-localized state with an energy

$E_s = 2\Delta_0/\pi$ S.A. Brazovskii, Sov. Phys.-JETP, 1980

This state is more preferable since its energy is smaller than the lowest energy Δ_0 of the free band electron by $\approx\Delta_0/3$.

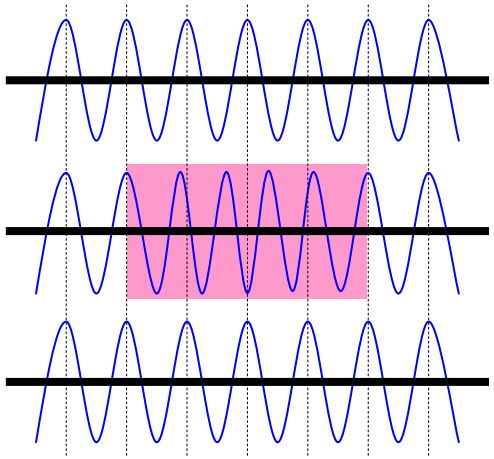
CDW π-soliton is a kind of atomic scale π-junction

The existence of ASs has not been reliably demonstrated yet.

CDW phase solitons

(2π- solitons)

CDW phase solitons



S.A. Brazovskii 80-s,

S. Brazovskii and S.I. Matveenko 2007

CDW excitation when one CDW period is put into or taken out of one chain,

excess phase changes within phase soliton by 2π

local breaking of interchain phase coherency

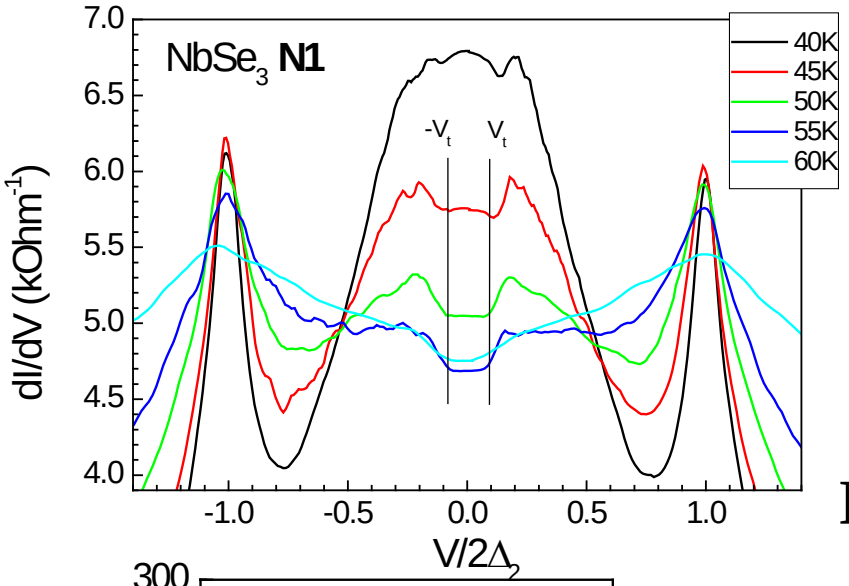
Interchain phase decoupling

Interchain phase decoupling happens with creation of 2π solitons

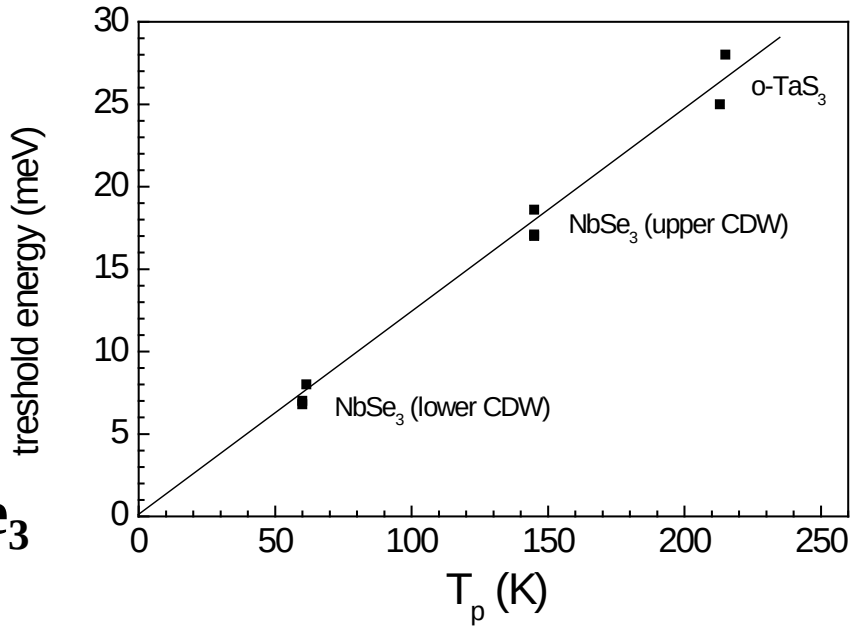
Interplain phase decoupling happens with formation of CDW dislocation lines, or CDW vortices, that **can be induced by electric fields across the layers**

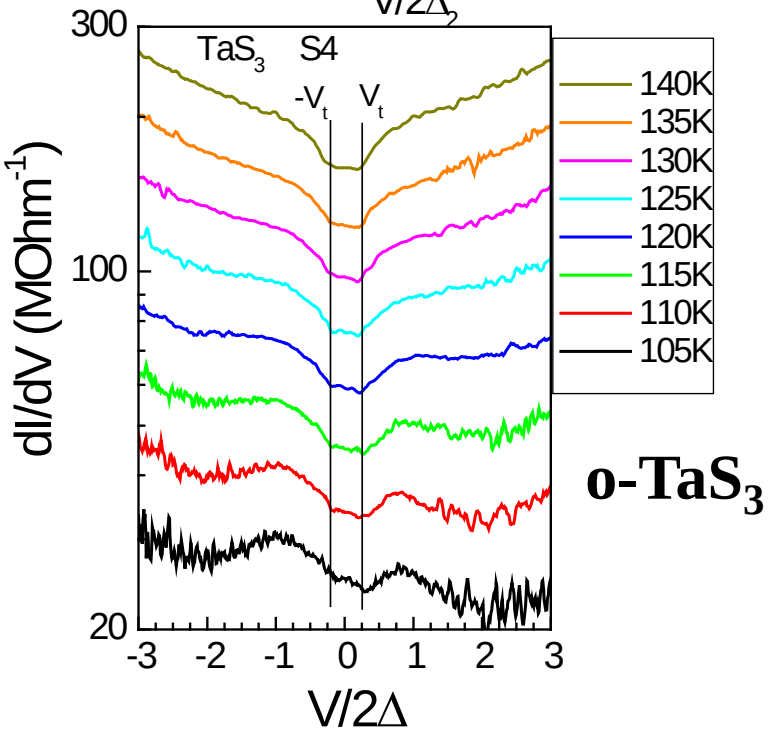
The energy of creation of CDW dislocation line is **~ kTp**

Threshold voltage scaling with Tp



$NbSe_3$





$o\text{-}TaS_3$

Yu.I. Latyshev, P. Monceau, S. Brazovskii, A.P. Orlov, Th. Fournier, PRL 2006

$$eV_{th} \approx 0.2\,\Delta \approx 1.3\,kT_p$$

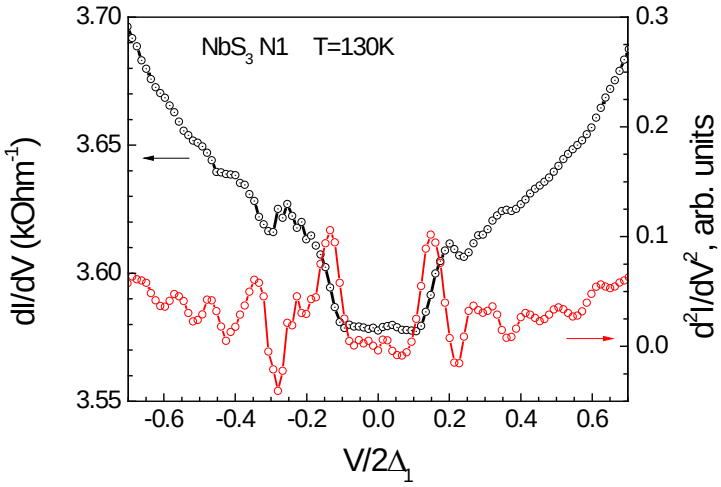
Theory S. Brazovskii, S.I. Matveenko, cond-mat 2007

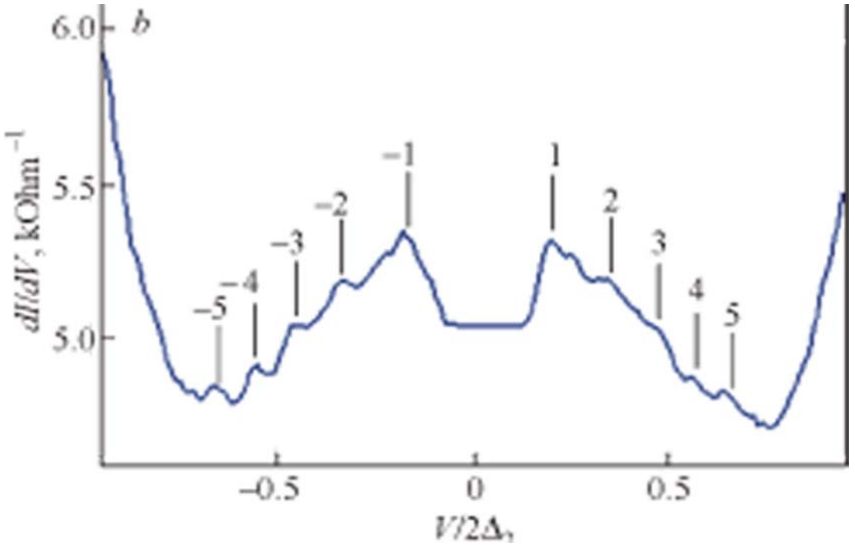
$$E_{ps} \approx kT_p \text{ per chain}$$

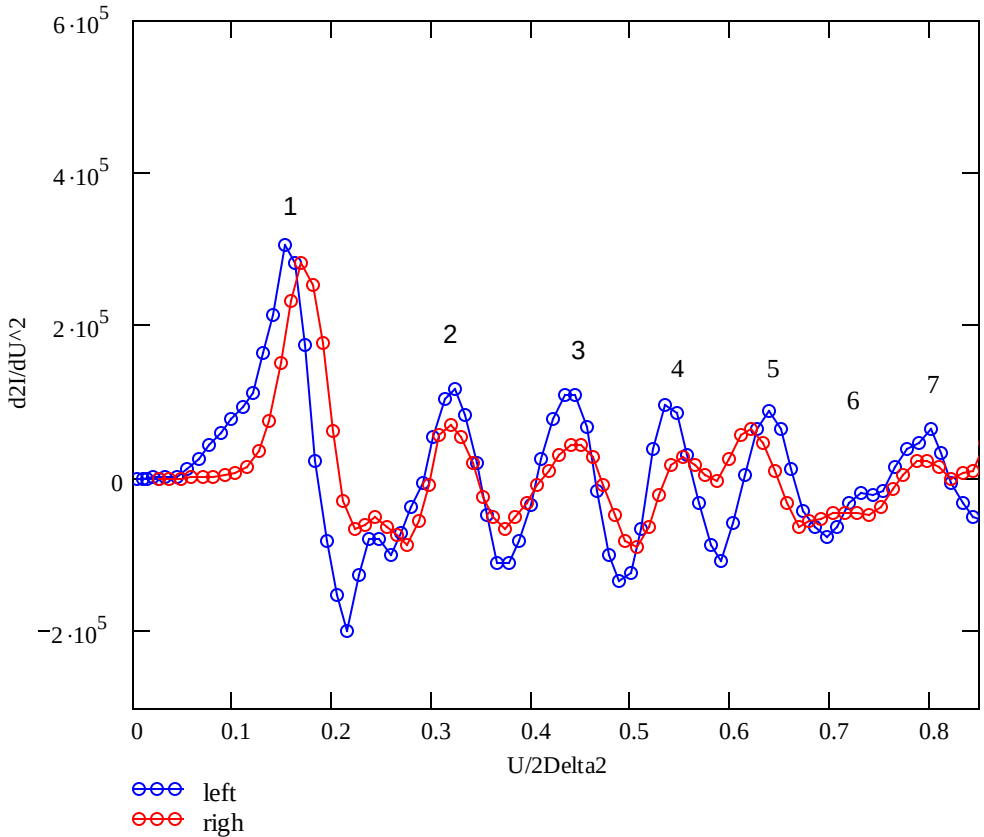
Threshold and staircase structure

CDW 2

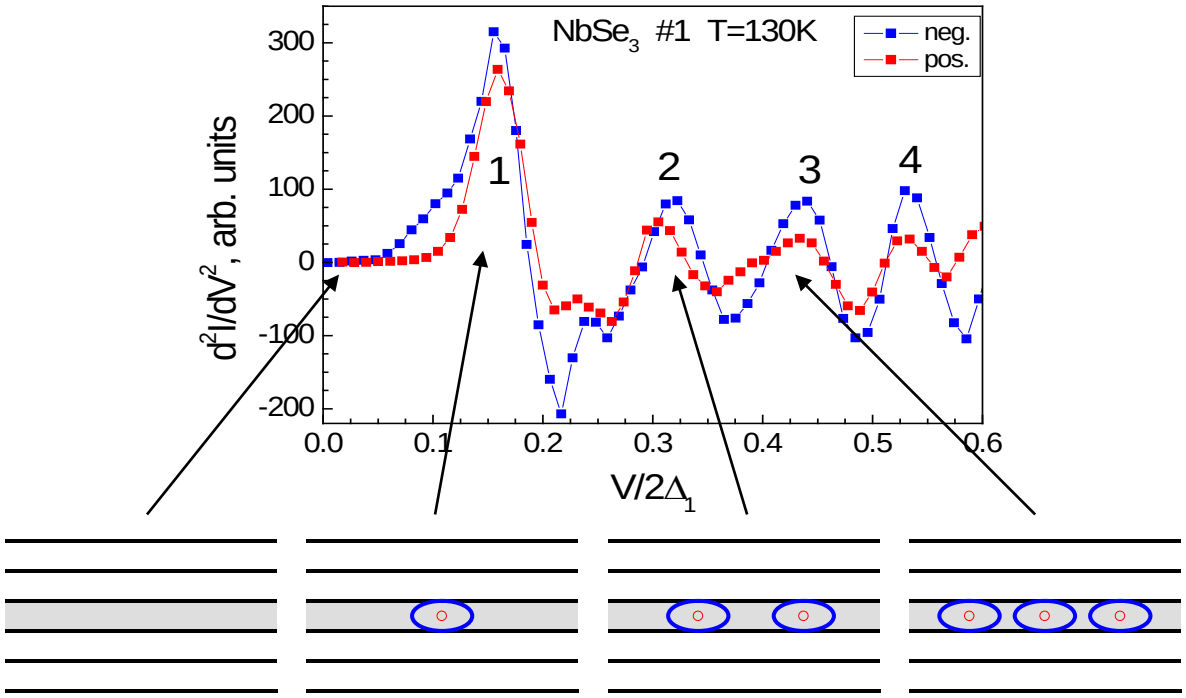
CDW 1







Yu.I. Latyshev, P. Monceau, S.Brazovskii, A.P. Orlov, Th.Fournier, PRL 2006

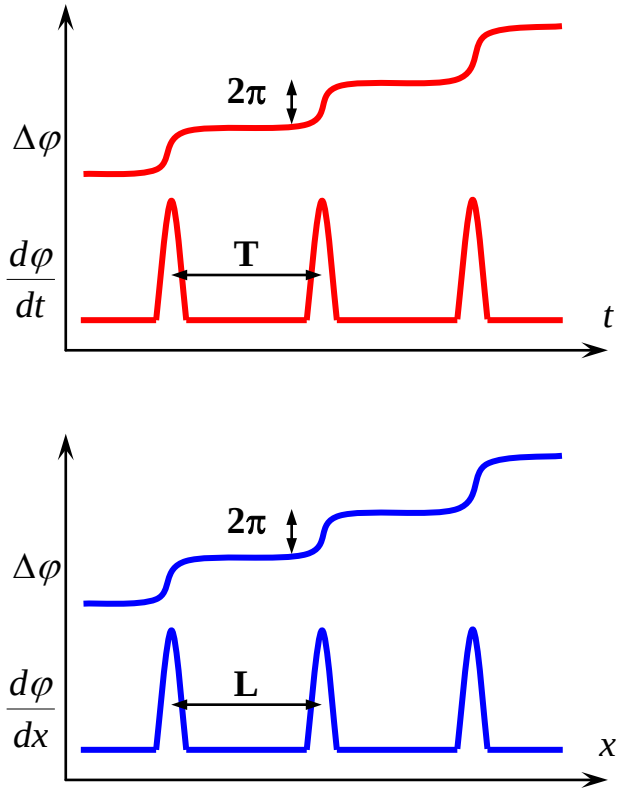


When dislocation cores start to overlap at high voltage bias all the voltage drops on a single elementary junction. That can explain puzzling equivalence of the behaviour of the stacked junction and point contact containing one junction.

Duality of phase topological defects in layered HTS and CDW systems

HTS J-vortex	**CDW 2πsoliton**
flux	Charge
$\Phi_0=hc/2e$	$Q_0=2e$
H // layers	E⊥ layers
H_{c1}	E_t

Analogy of DL array with AC Josephson effect



Josephson junction at $I>I_c$

$2eV = h\, d\varphi/dt$

Phase difference changes in time.
Period of Josephson oscillations is inversely proportional to V

CDW coupled junction at $V>V_t$

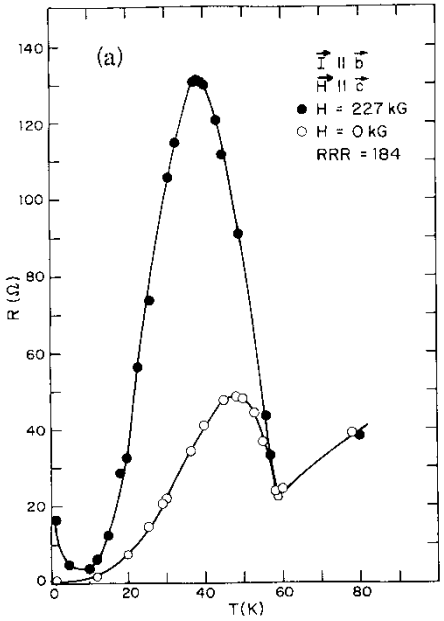
$2eV = h\, v_F\, d\varphi/dx$

Phase difference changes in space.
Period of CDW DL array also is inversely proportional to V

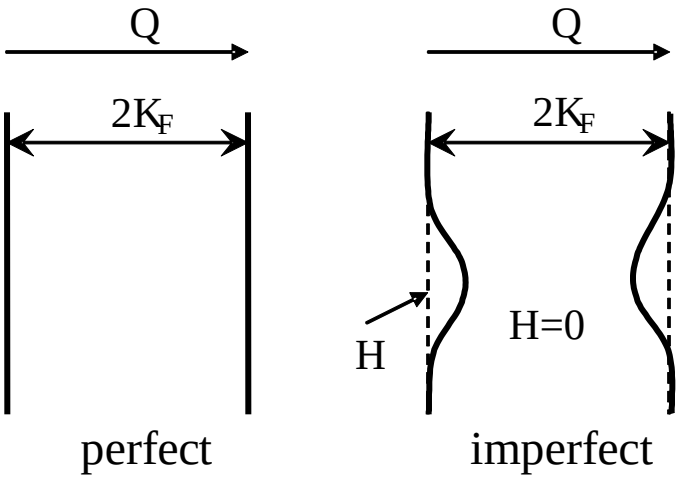
Yu.I. Latyshev, Low. Temp. Phys., 2012

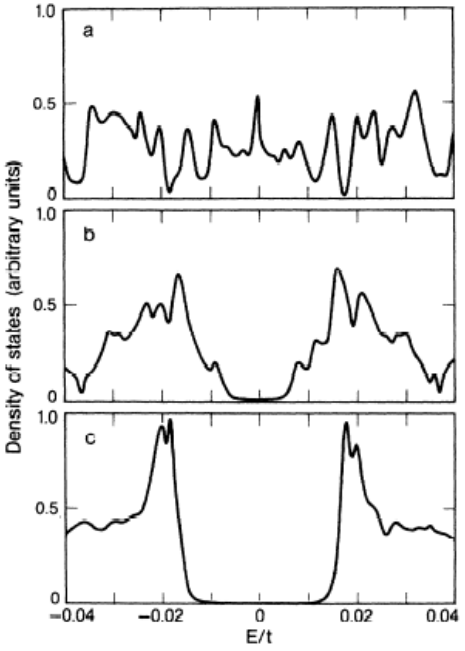
3. Magnetic field induced CDW state in $NbSe_3$ and graphite

Anomalously high magnetoresistance in $NbSe_3$



R.V. Coleman et al. PRL 1985





C.A. Balseiro and L.M. Falikov PR B 1986 magnetic field may increase CDW gap

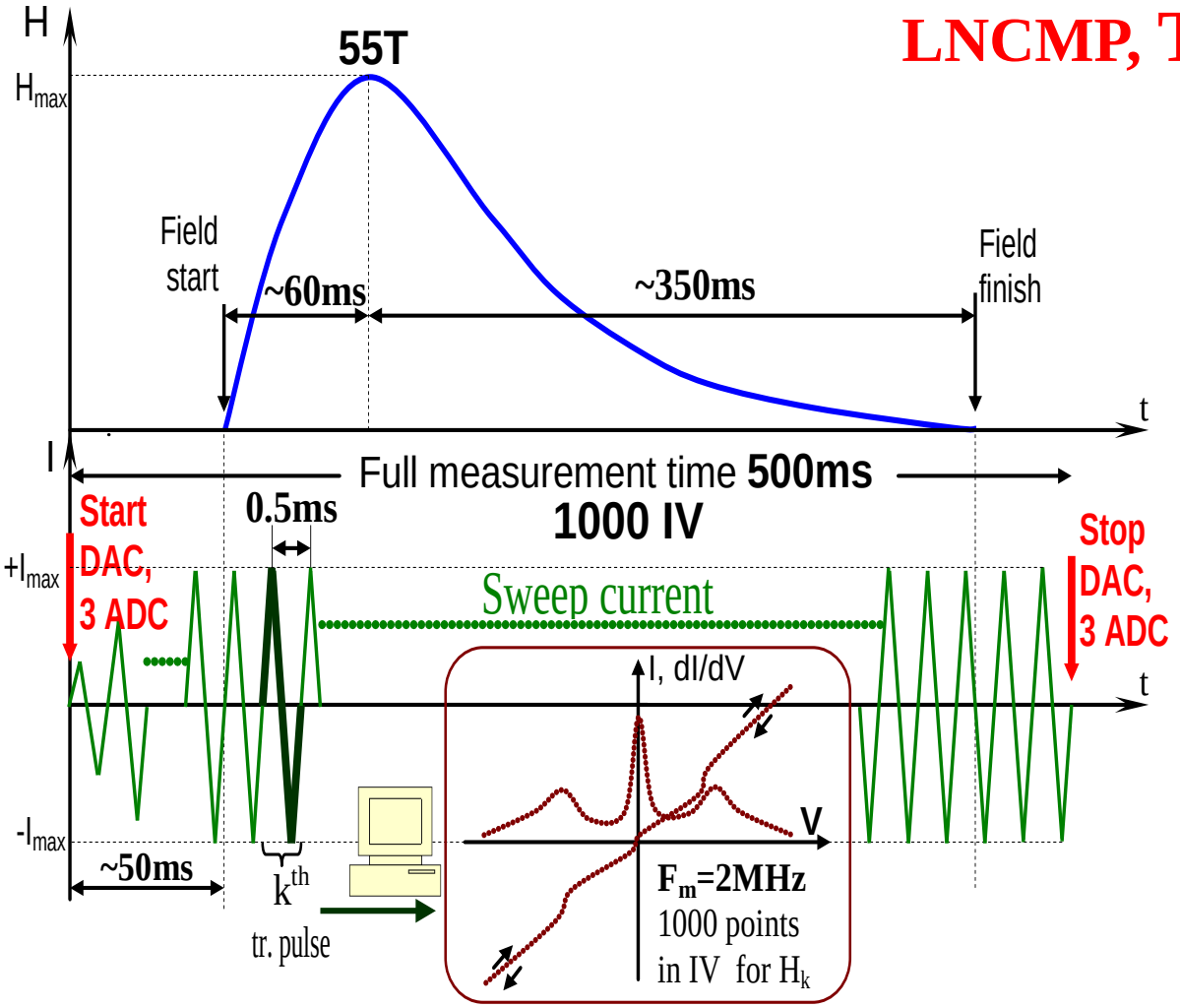
L.P. Gor'kov and A. Lebed, 1984 mechanism is related with improvement of CDW nesting by magnetic field

A. Bjelis, D. Zanchi, G. Montambeaux PR B 1996, cond-mat /1999 also have shown the possibility to increase T_p by magnetic field.

However, until recently there were no tunneling experiments on spectroscopy of CDW gap in high magnetic field and especially in the vicinity of Peierls transition temperature.

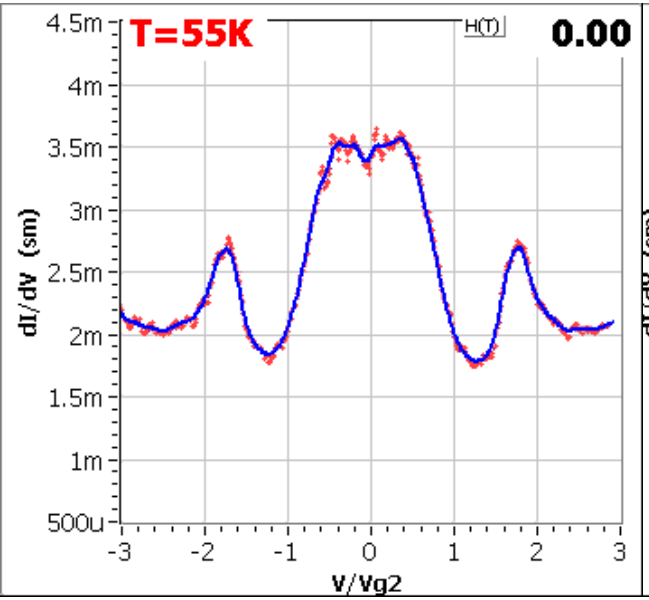
Interlayer tunneling spectra at pulsed magnetic field

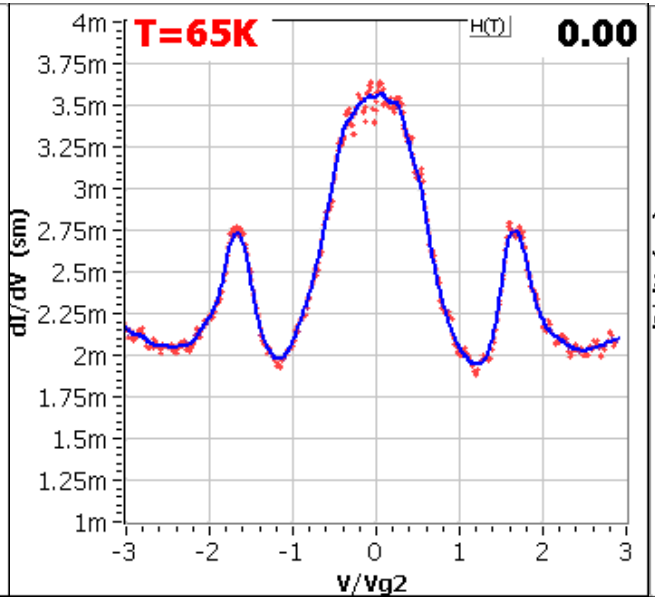
LNCMP, Toulouse

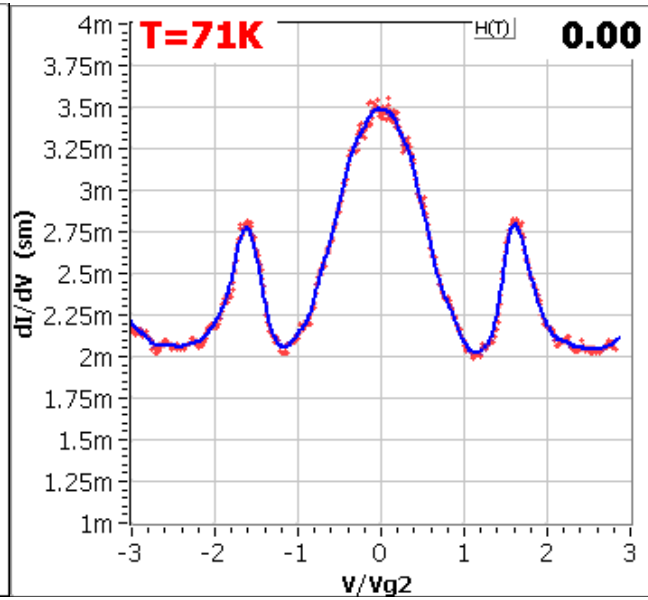


High speed acquisition system

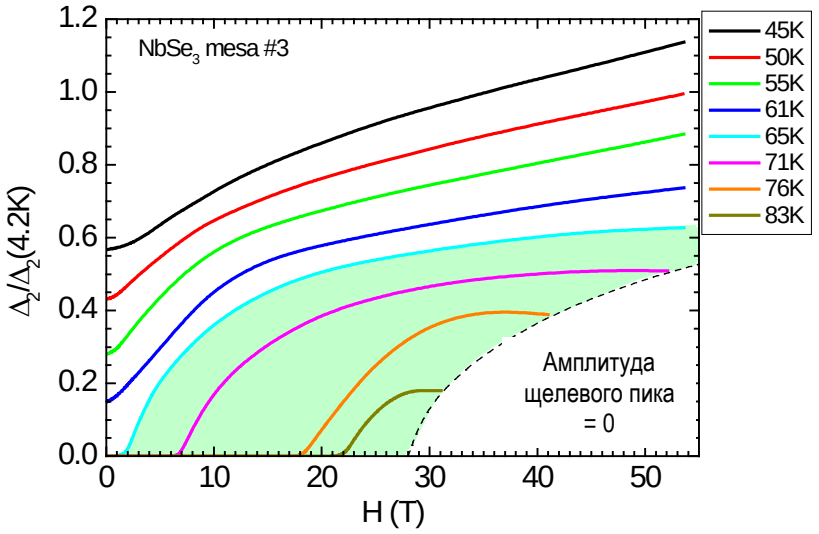
Interlayer tunneling spectra of $NbSe_3$ in high magnetic fields H//a* near Peierls transition temperature T_{p2}.





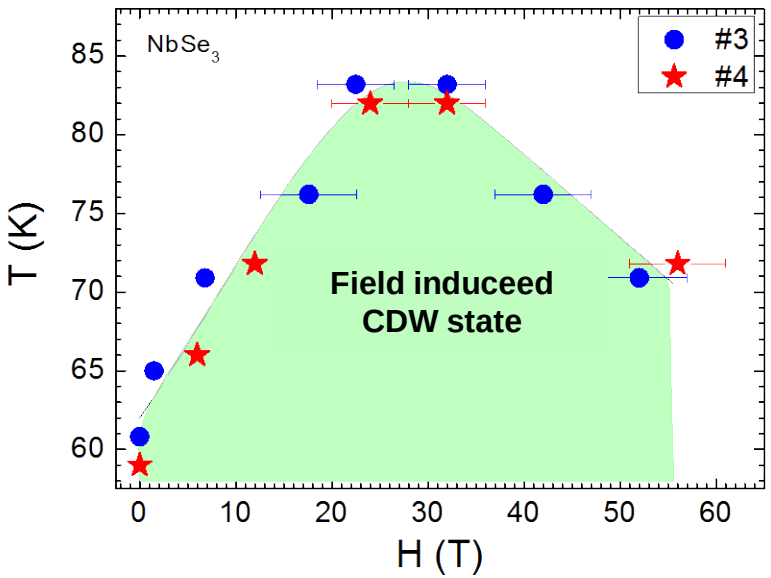


Enhancement and induction of lower CDW gap by magnetic field



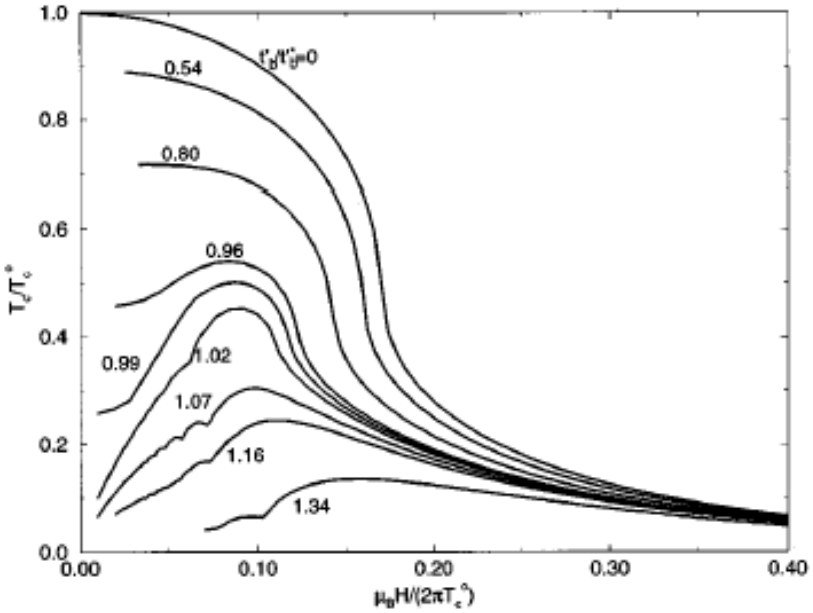
A.P. Orlov, Yu.I. Latyshev, D. Vignolles, P. Monceau, JETP Lett., 87, 502-506, 2008

Phase diagram. Interplay of orbital and Pauli effects.



Non-monotonic behaviour of $T_p(H)$ is defined by interplay between orbital and Pauli effects on CDW pairing. Orbital effect is realized in improving of nesting condition and, thus, in increase of Δ and T_p, while Zeeman shift tends to destroy CDW pairing.

Experimental crossover field corresponds to $H \approx 30T$, $2\mu_B H_0 \approx kT_p$

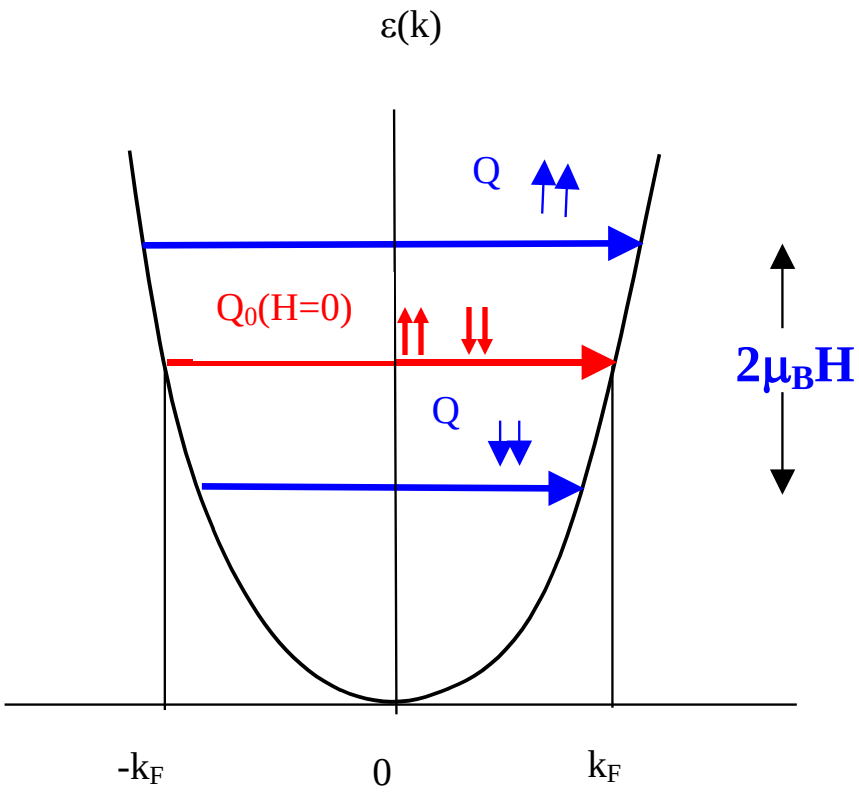


That is consistent with calculatons of Zanchi, Bjelis, Montambeau PRB 1996 for the case of moderate imperfection parameter (valid for $NbSe_3$)

$\mu_B H_0 / (2\pi T_p) \geq 0.1$ or

For T_p = 61 K that corresponds to $H_0 \approx 30T$

Why does eventually T_p drop down with field?



In a zero field the CDW state is degenerated with respect to spin up $\uparrow\uparrow$ and spin down $\downarrow\downarrow$ configurations.

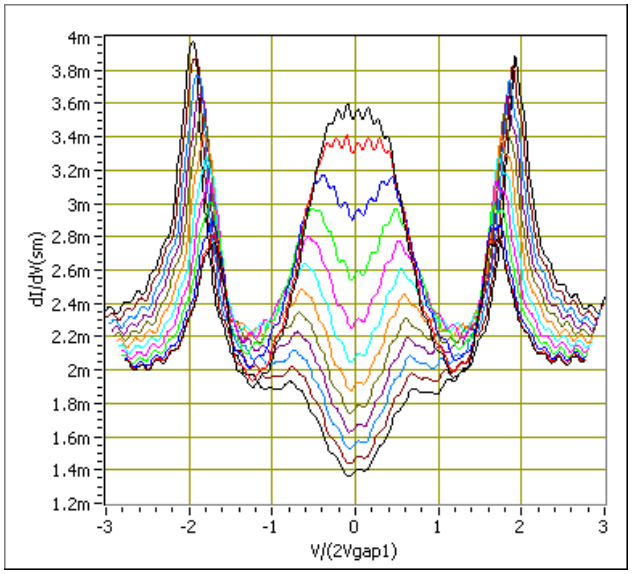
Magnetic field releases degeneration due to Zeeman splitting. As a result $Q_{\uparrow\uparrow}$ CDW vector increases with field while $Q_{\downarrow\downarrow}$ decreases

$$Q_{\uparrow\uparrow} > Q_0 > Q_{\downarrow\downarrow}$$

Therefore a CDW state with a fixed Q_0 tends to be destroyed with field.

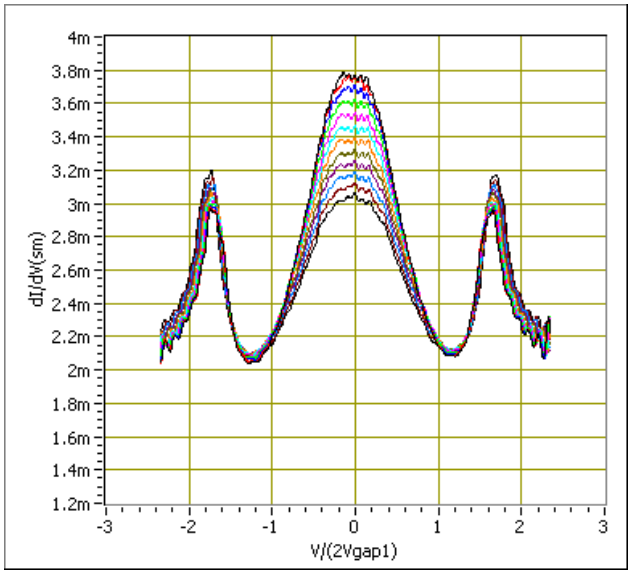
	Super.	**CDW**
charge	**e-e** or **h-h**	**e-h**
momentum	**P=0**	**P= $2p_F$**
spin	$\uparrow\downarrow$	$\uparrow\uparrow$ **or** $\downarrow\downarrow$

T=65K



Influence of field orientation

H⊥ layers



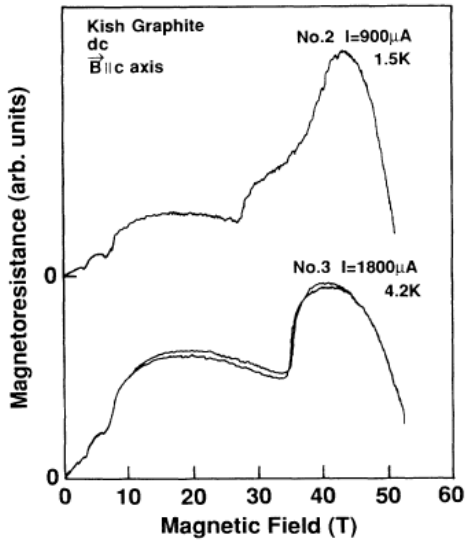
0.00
4.92
9.79
14.73
19.65
24.40
29.31
34.38
39.05
44.00
48.93
53.71

H // layers

No effect at parallel fields

Field induced CDW (?) gap in graphite

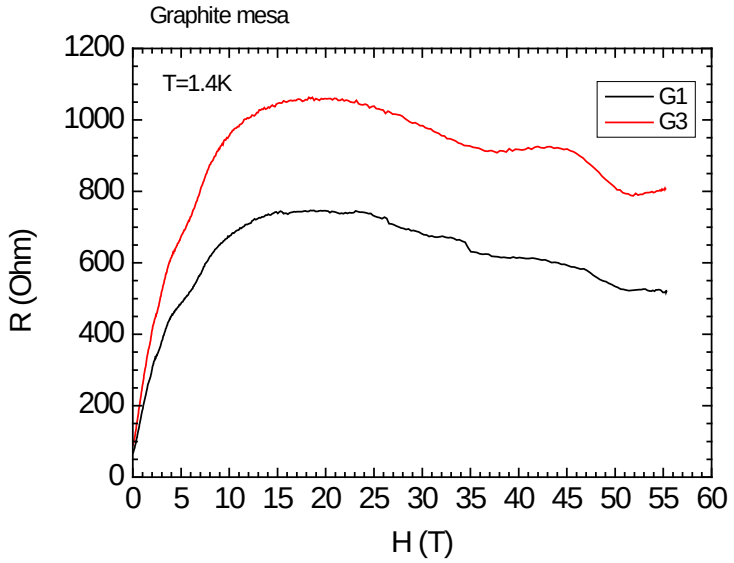
Graphite at strong fields



Observation H. Ochimizu et al., Phys. Rev. B46, 1986 (1992).

Explanation was related with the CDW formation along the field axis
D. Yoshioka and H. Fukuyama, J. Phys. Soc. Jpn. 50, 725 (1981).

We attempted to find CDW gap above 30 T

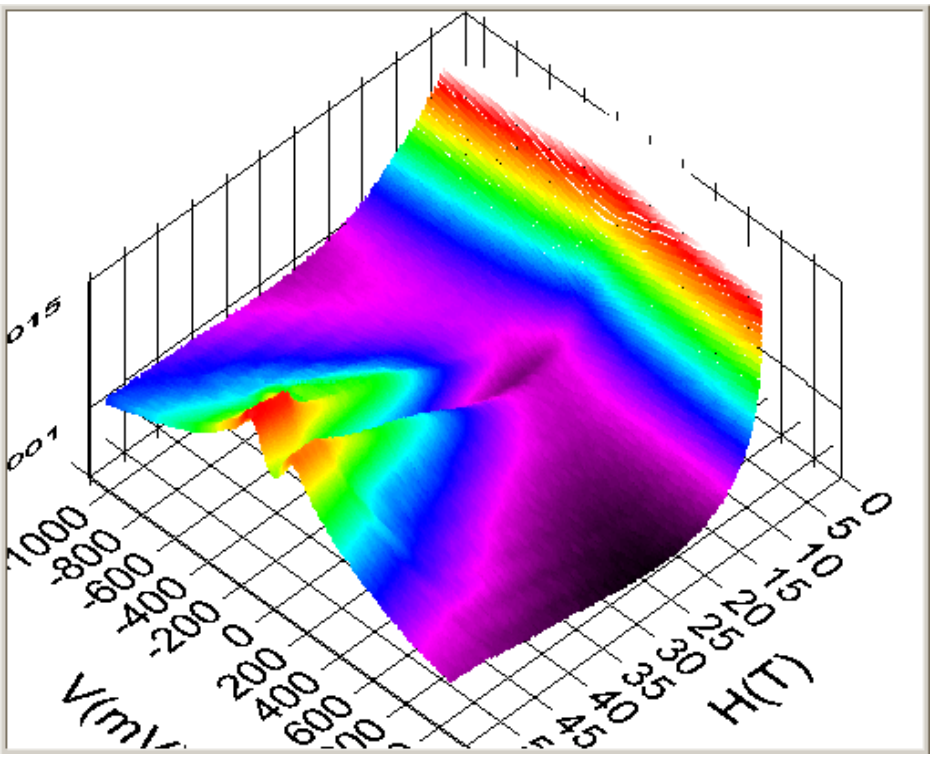


Effect nearly disappeares for 20 graphene layers

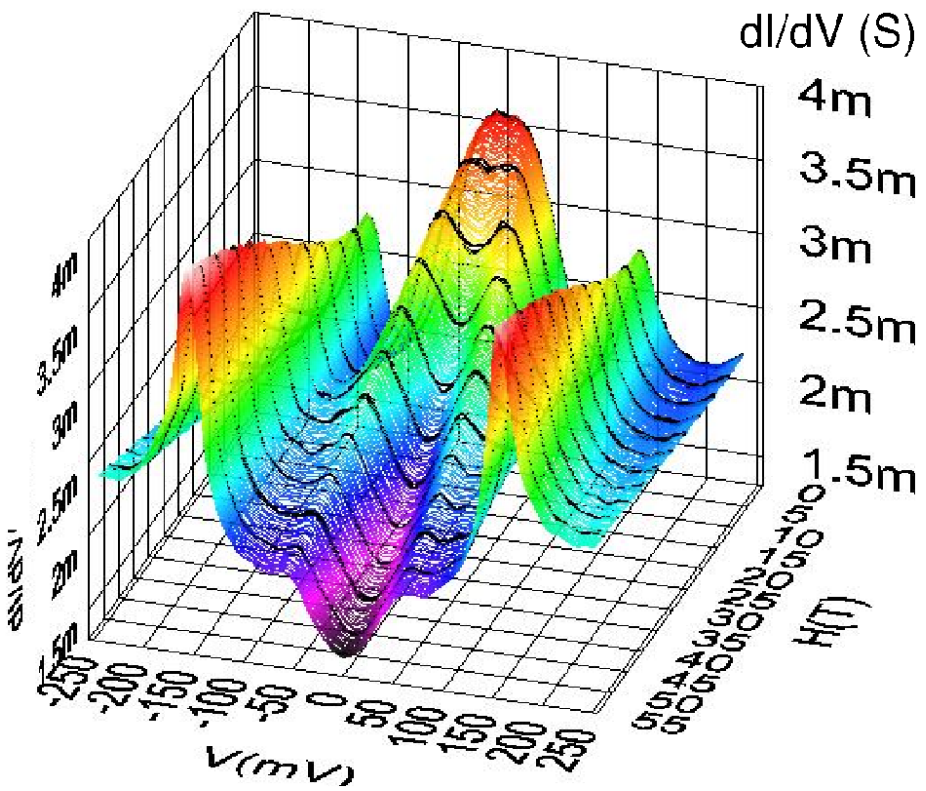
That means that it does not relate with individual graphene layers

Field induced CDW ?

graphite



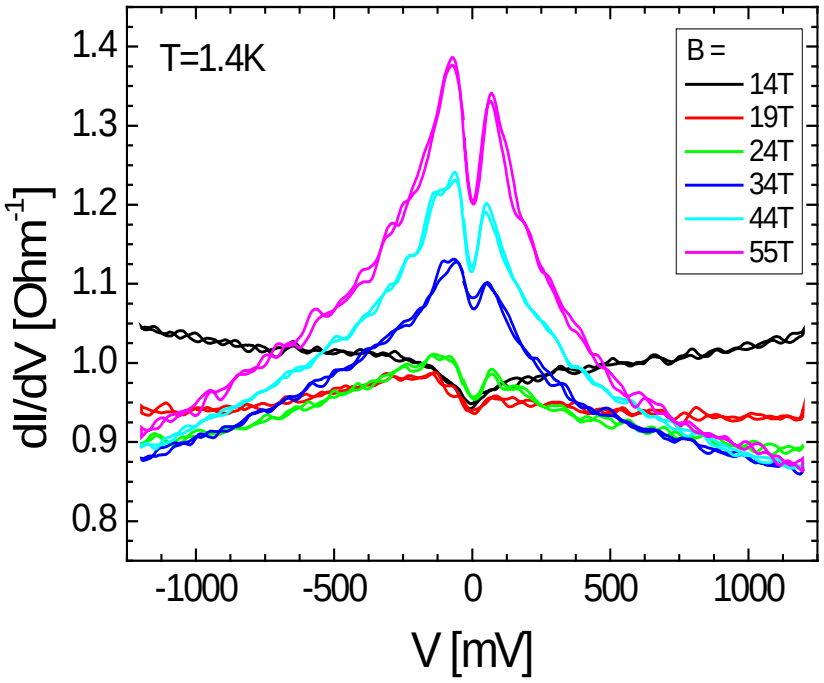
$NbSe_3$



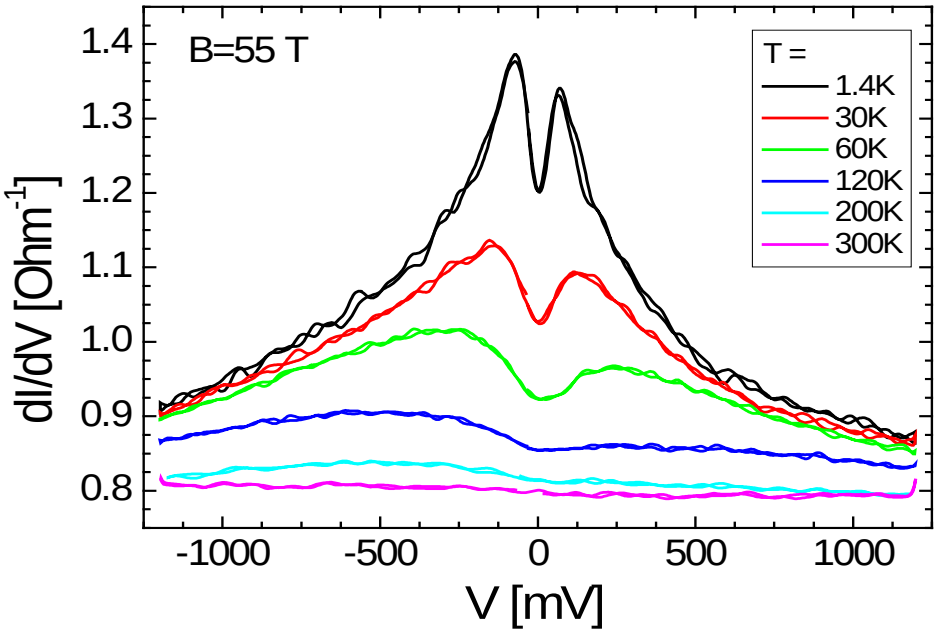
The pictures for both compounds look very similar as well as the values of field induced gap are close 50-70 mV

Field and temperature dependences of the field induced CDW state in graphite

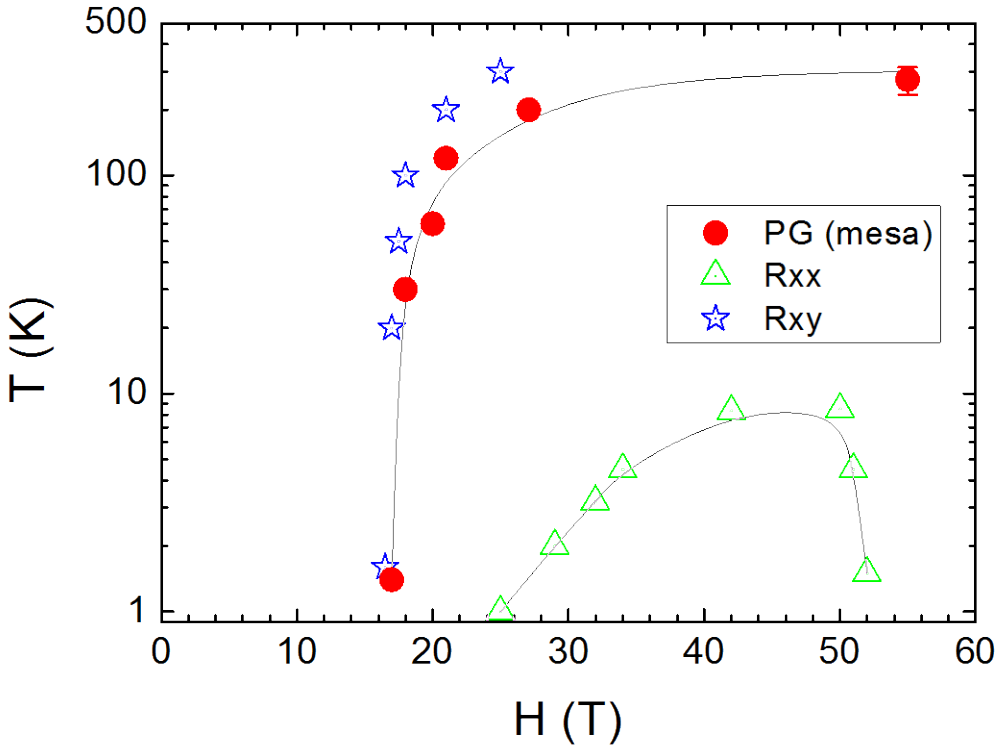
a)



b)



Phase diagram of the field induced CDW state in graphite



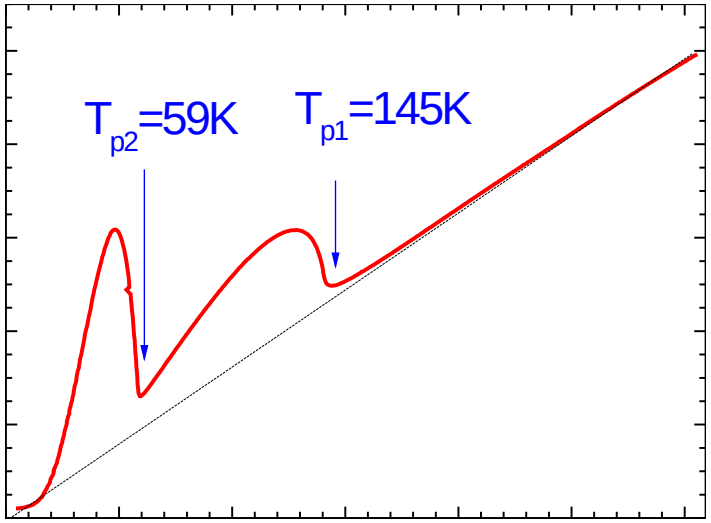
$2\Delta/To$ = 3.1-3.5 close to the BCS value as in field induced CDW state in $NbSe_3$.

The data are consistent with recent Hall effect data in graphite A. Kumar et al., J. Phys.: Condens. Matter 22(2010) 436004.

Yu.I. Latyshev, A.P.Orlov, P, Monceau, D.Vignolles, and W, Escscoffier, Physica B, 2012.

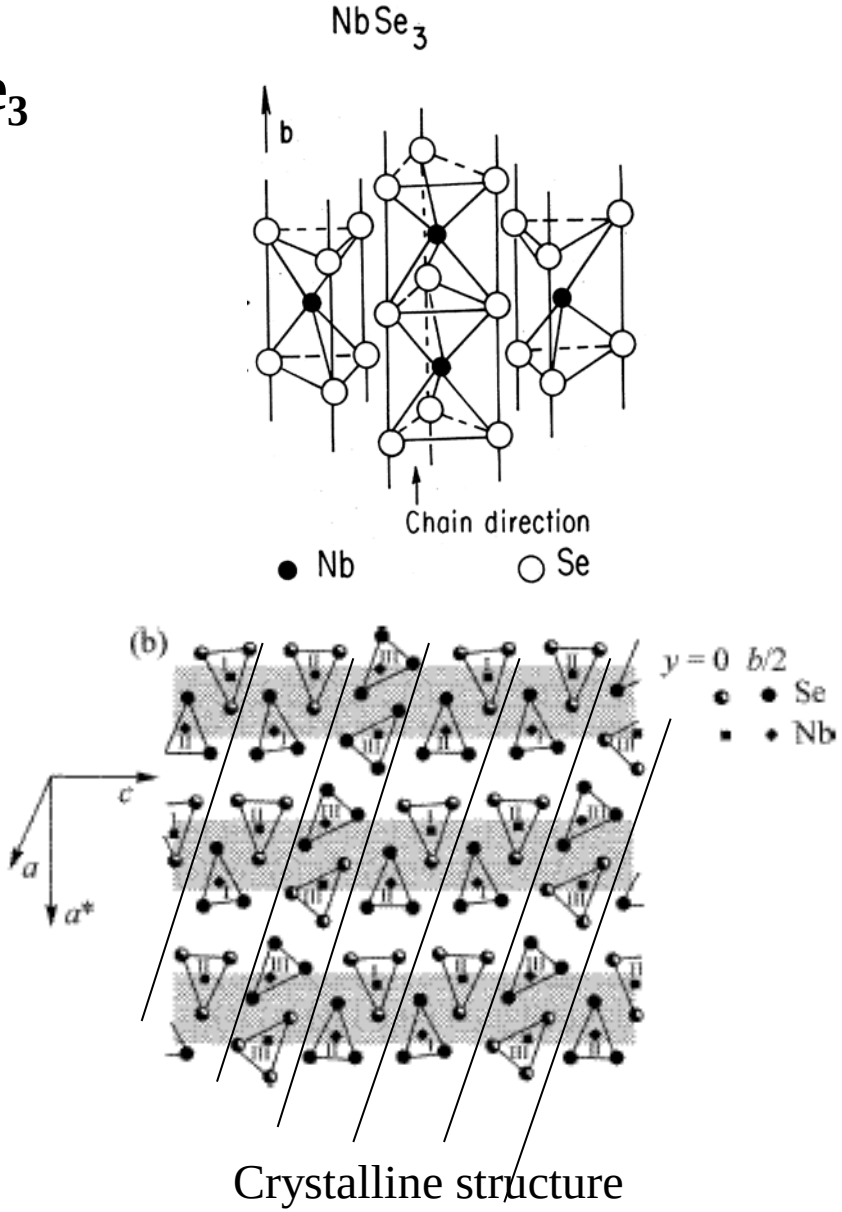
4. Coherent nonlinear transport across the chains in $NbSe_3$ under perpendicular magnetic fields.

$NbSe_3$



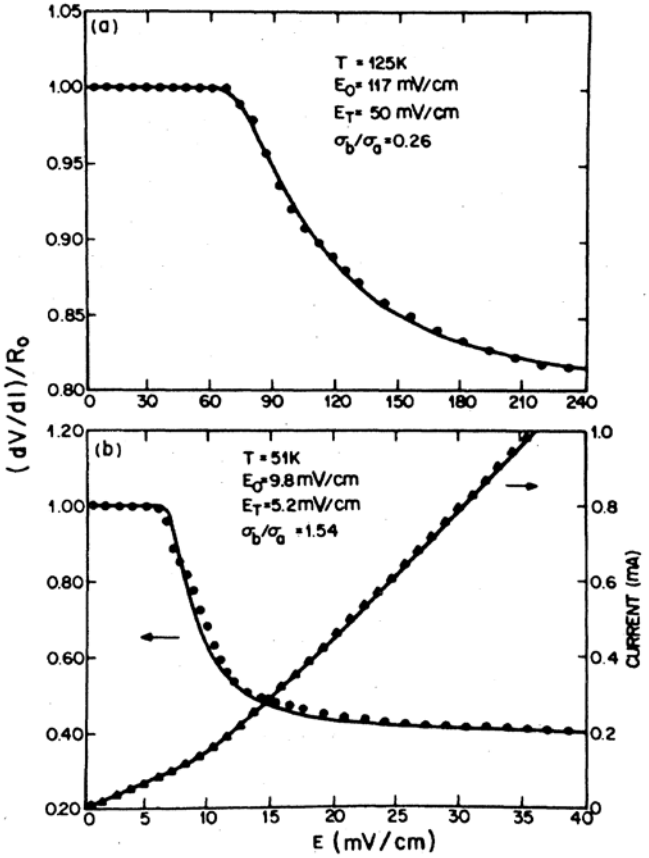
$\sigma_b/\sigma_{a^*}=10^3\text{-}10^4$

$\sigma_b/\sigma_c=10\text{-}20$



Crystalline structure

Sliding CDW along the chains in $NbSe_3$ at high temperatures



CDW depinning above treshold fields.

Sliding CDW contribution to the conductivity

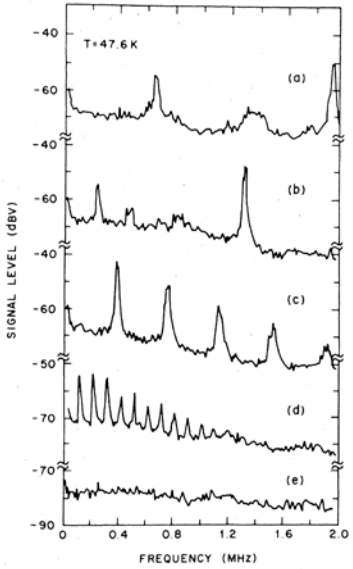
NBN with frequency proportional to CDW current

$\mathbf{J_{CDW} = NeΛf}$ For $NbSe_3$ Λ=4b

Shapiro steps of constant J_{CDW}

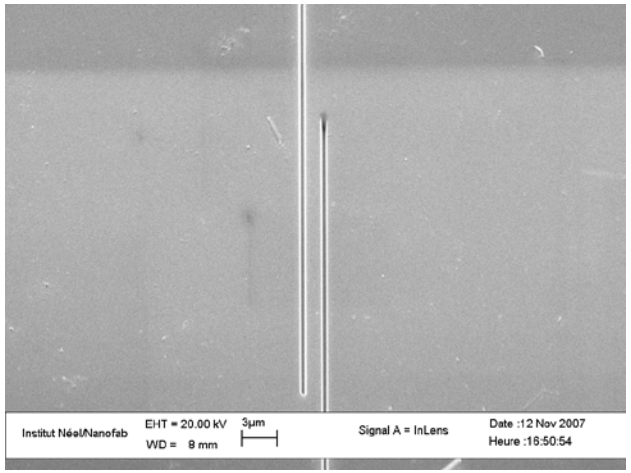
Different from Shapiro steps

in Josephson effect **V= hf/2e**

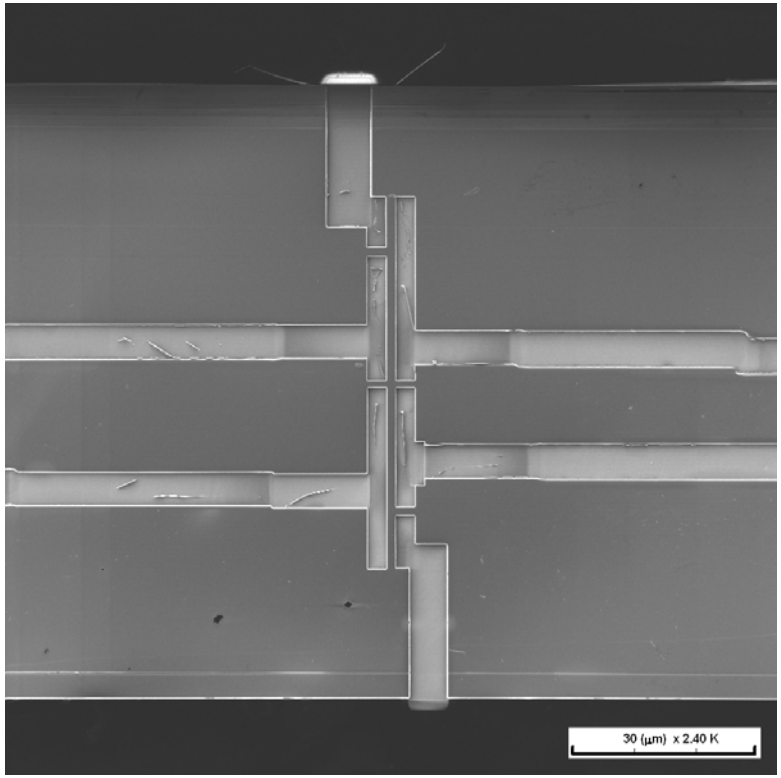


After a revue of G.Gruner Rev. Mod. Phys. 60, 1188 (1988).

Structures



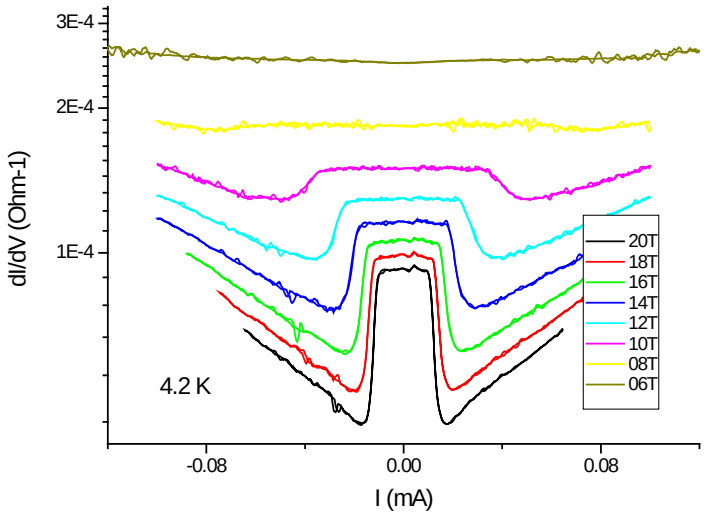
Simple structure

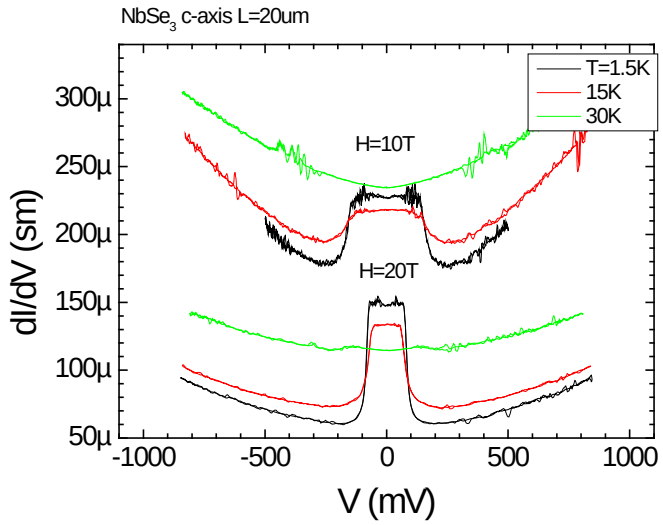


More advanced 6-probes structure with different distances between potential probes and containing the Hall probes.

I //c

Results. Nonlinear transport under magnetic fields



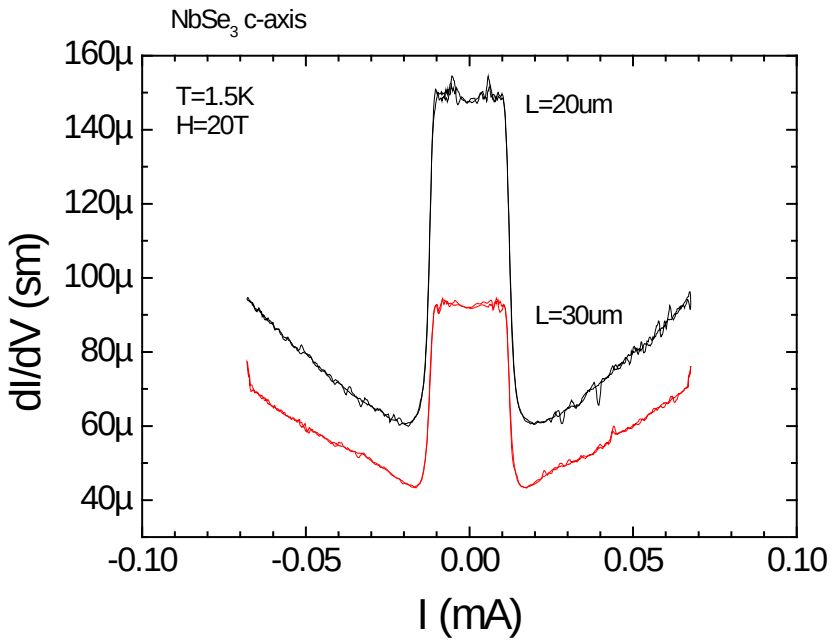


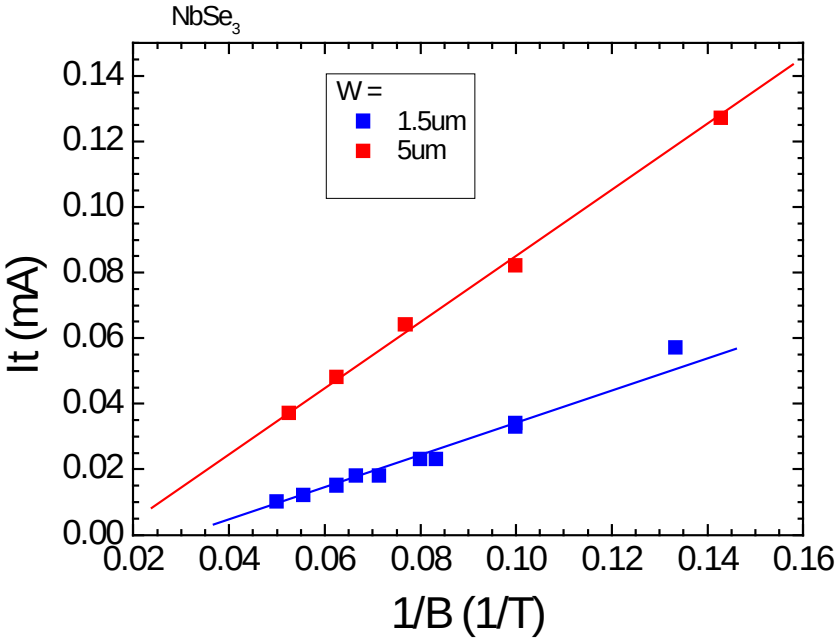
I//c, H//a*

- Threshold type of nonlinearity. Opposite sign to the nonlinearity along the chains: dI/dV drops down above treschold current.

- Nonlinearity appears at low temperatures and at high magnetic fields.

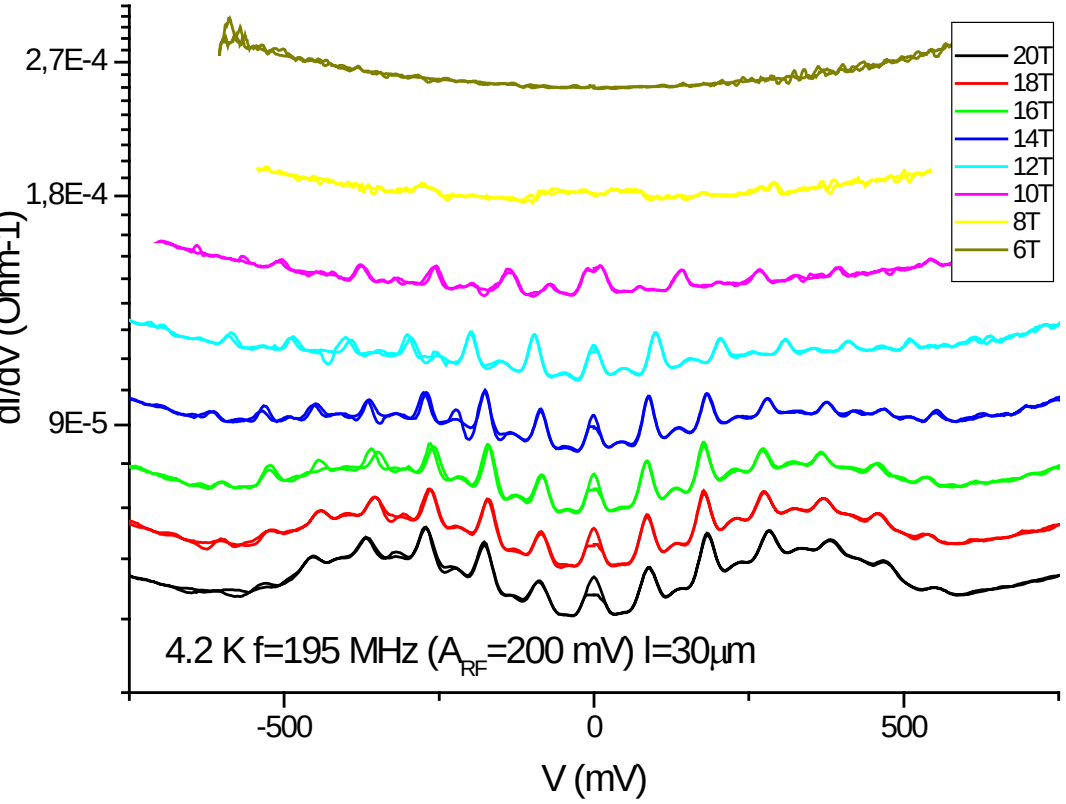
Size and field dependences of threshold current





Threshold current does not depend on the length and is proportional to the width of the sample. Also that is inversely proportional to the value of magnetic field.

Coherent response to the RF-field. Shapiro steps

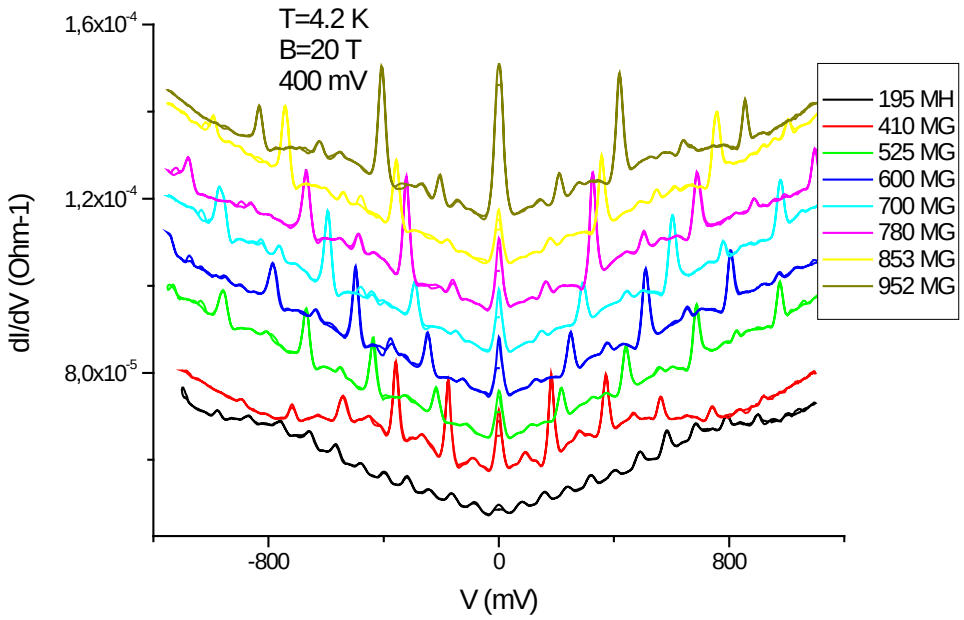


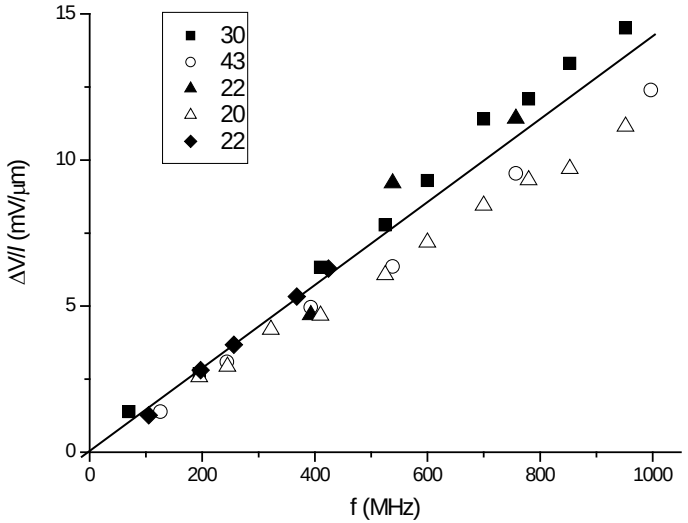
Shapiro steps appear as peaks on dI/dV(V) dependences

They appear at low temperatures and under high magnetic fields, i.e. at the same conditions as a threshold nonlinearity without RF-field..

Peaks position is nearly independent on magnetic field at high fields.

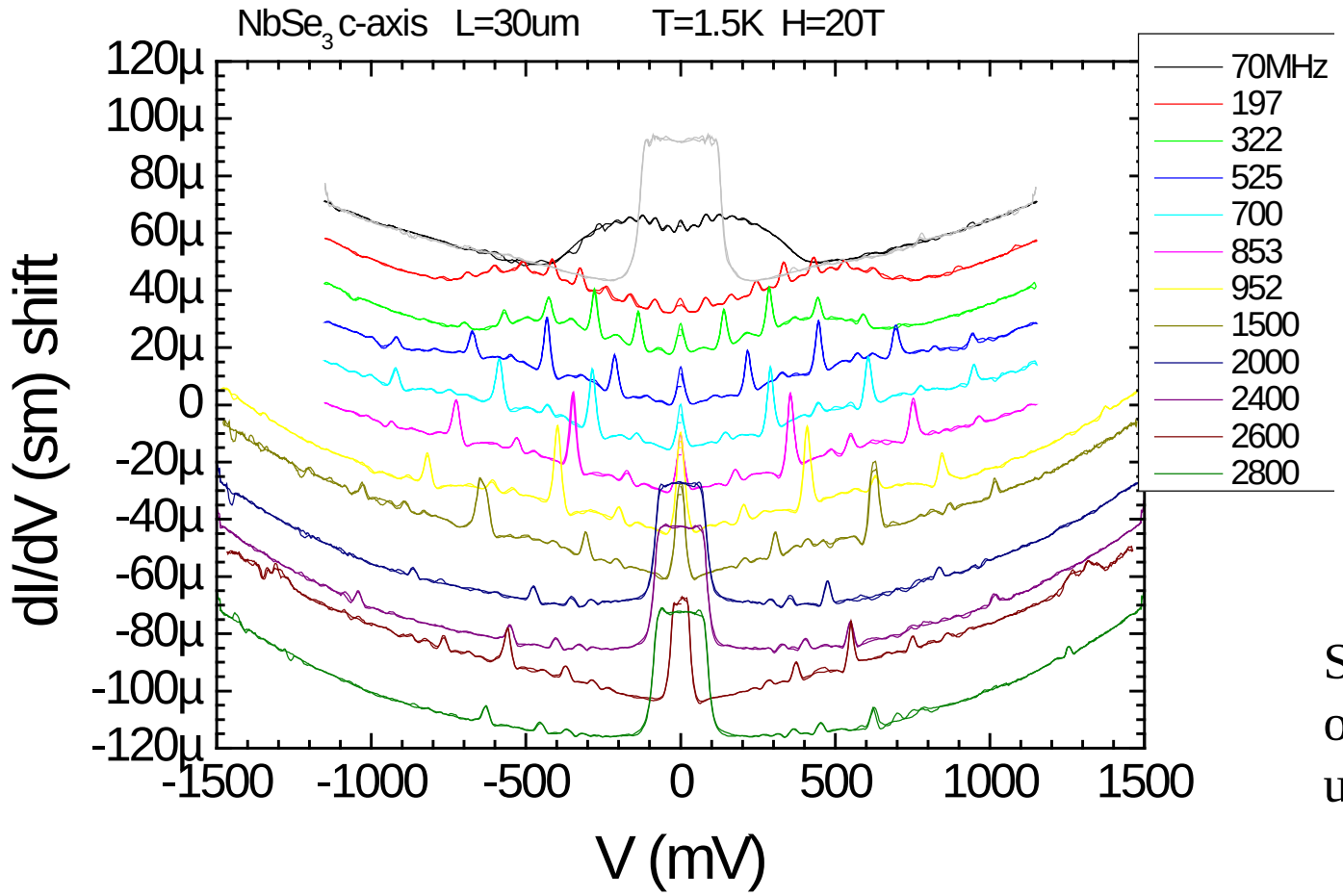
Shapiro steps 2





ΔV is proportional to the frequency and to the sample length.

Shapiro steps 3



Shapiro steps are observable at least up to 3 GHz

Analysis. Critical current

The basic idea is that the threshold is determined by the critical Hall electric field E_{Hc} that induces critical deformation of CDW for the formation of phase dislocation (or excess CDW period) that reduces the number of pocket carriers.

$E_H = V_H / w = R_H I H/dw$

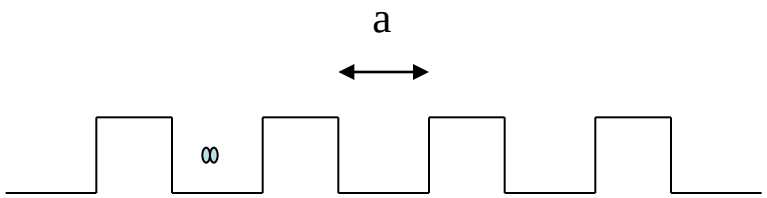
From where

$I_t = E_{Hc} w d / (R_H H)$ $\propto w / H$

as that is observed in the experiment

Experimentally measured value of $E_{Hc} \approx 10$ B/cm $V_t \approx 1$ mV
That is close to the energy of formation of phase slip center Vps in $NbSe_3$

Bloch oscillations



If one consider a charge soliton moving in periodic potential the Bloch equation mimics Josephson relationship **$2eV = \hbar\omega$**

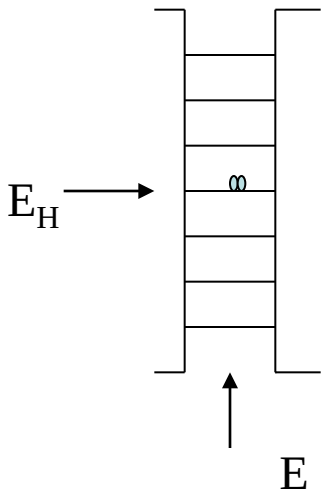
F. Bloch, Z. Phys. **52**, 555 (1928).
In 1928 Bloch demonstrated that electrons in a
periodic lattice potential with period *a* subject to a dc
electric field E_{dc} undergo oscillations with characteristic
frequency

$$\omega_B = \frac{eaE_{dc}}{\hbar}$$

Analysis 2. Shapiro steps.

Mechanism of coherent emission is not clear. One can consider that this is related with motion of CDW dislocations along the bridge.

Estimation of voltage to frequency relation. Experiment gives 12.5 mV/ GHz on 1 micron. 1 micron corresponds to 5 10^3 chains, i.e. for one chain that gives 2.5 μV/GHz. That is close to Josephson relation 2eV/ hf , which produces 2 μV/GHz



Oversimplified model

Phase vortex appear at $E_H > E_{tc} = E_{c1}$ with charge 2e and moves in periodic potential along the channel providing Bloch oscillations with Josephson frequency $f = 2eV_0/h$

SUMMARY

1. **The interlayer tunneling spectroscopy has been developed on a number of layered materials as Bi-2212, $NbSe_3$ and graphite.**

3. **We found intra gap states in$NbSe_3$ associated with excitation of amplitude and phase CDW solitons in $NbSe_3$.**

4. **We found and studied field induced CDW states in $NbSe_3$ and graphite predicted long time ago.**

5. **We found a new threshold type non-linearuty in magnetotransport across the chains in $NbSe_3$, which is accompanied by coherent emission in MHz-GHz frequency range with a frequency proportional to the voltage on the junction as in Josephson relation.**

6. **We proposed qualitative model of both phenomena.**