INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

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SPRING COLLEGE IN CONDENSED MATTER
ON
'PHYSICS OF LOW-DIMENSIONAL SEMICONDUCTOR STRUCTURES'
(23 April - 15 June 1990)

TWO-DIMENSIONAL ELECTRON CRYSTALS- II

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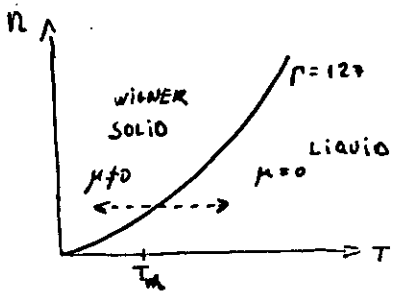
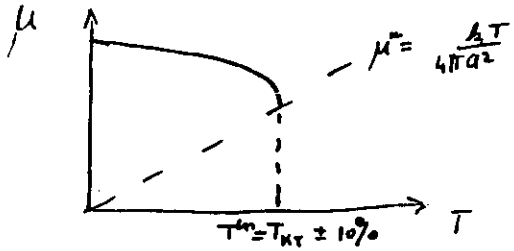
THE NATURE OF THE LIQUID-SOLID TRANSITION IN 2-D - STILL CONTROVERSIAL

THEORIES ON 2-D MELTING

- UNBINDING OF DISLOCATION PAIRS AT $T_{K-T} \Rightarrow$ LOSS OF RIGIDITY $\Rightarrow$ MELTING KOSTERLITZ-THOULESS (72)
  - $T_m = T_{K-T} = \frac{b^2 \mu}{4\pi k_B} \frac{\lambda+\mu}{\lambda+2\mu}$ — b Lattice spacing, μ shear modulus, λ compressibility
  - UNIVERSAL JUMP IN SHEAR MODULUS AT T_{K-T} — HALPERIN-NELSON 78, YOUNG 79
  - TRANSITION IS CONTINUOS
  - TRANSITION PROCEEDS VIA HEXATIC PHASE (NO TRANSLATIONAL ORDER, ALGEBRICALLY DECAYING ORIENTATI ORDER)
- MELTING BY GRAIN BOUNDARY FORMATION (LINE OF DISLOCATION FAVOURED FOR SMALL E_{ME}
  - $T_m^{GB} \lesssim T_{K-T}$ CHUI 82
  - TRANSITION IS FIRST ORDER
- CHARGE DENSITY WAVE MECHANISM RAMAKRISHNAN (83)
  - $T_m^{CDW} \lesssim T_{K-T}$
  - TRANSITION IS FIRST ORDER

EXPERIMENT ON THE MELTING OF THE CLASSICAL CRYSTAL





P.R.L. 53, (1984)

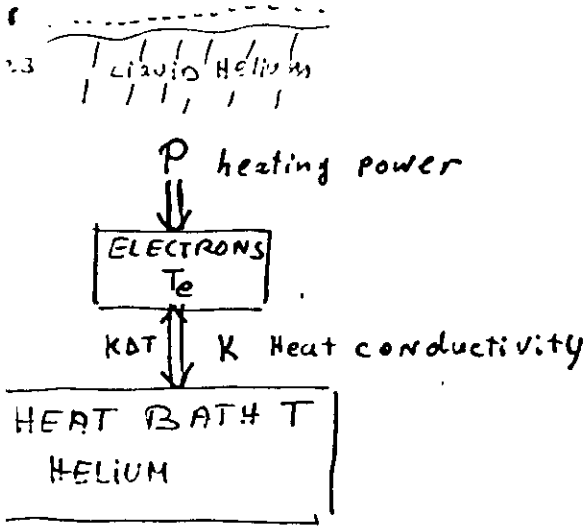
∴ THE MELTING TEMPERATURE IS CONSISTENT WITH A MELTING MECHANISM OF UNBINDING OF PAIRED DISLOCATIONS

- BUT OTHER MELTING MECHANISMS PROPOSED
  - GRAIN BOUNDARY MELTING
  - CHARGE DENSITY WAVE TRANSITION

  $\Rightarrow T^m \leq T_{KT}$

  ALSO CONSISTENT WITH THIS EXPERIMENT
- NEED ANOTHER CRITERION TO DISTINGUISH
  - KT MECHANISM — TRANSITION IS OF CONTINUOUS ORDER — NO DISCONTINUITY IN SPECIFIC HEA
  - OTHER MECHANISMS — FIRST ORDER $\Rightarrow$ SPECIFIC HEAT DISCONTINUITY AT TRANSITION — LATENT HE

OW CAN WE MEASURE SPECIFIC HEAT OF 10^8 ELECTRON
OUPLED TO A BATH OF 10^{23} Helium ATOMS?



NEED TO DECOUPLE ELECTRONS FROM He SUBSTRATE

⇒ $\tau_e \ll \tau_{e\text{-}He}$ - electron-Helium relaxation time

on-thermalization time.

⇒ We can have an electronic temperature

$$T_e \neq T$$

$$\Downarrow$$

$$P = C\frac{dT_e}{dt} + K(T_e - T)$$

$$K = \frac{C}{\tau_{eH}}$$

- HOW CAN WE HEAT ELECTRONS AND NOT SUBSTRATE?

• PUMP ENERGY INTO NORMAL MODE OF ELECTRON SYSTEM WITH R.F. ELECTROMAGNETIC FIELD. THE R.F. POWER DOES NOT COUPLE TO THE HELIUM.

- HOW CAN WE MEASURE T_e?

• MONITOR A TEMPERATURE DEPENDENT PHYSICAL PROPERTY OF THE ELECTRONS

$$\omega_0 \sim \ell^{-\delta^2\langle u^2\rangle} \sim$$

- WHAT IS THE MEASUREMENT TIME SCALE

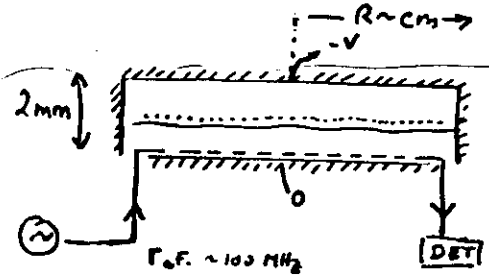
$$\theta \ll \tau_{e\text{-}He}$$

ELECTRON HEATER

RESONANT ABSORPTION IN NORMAL PLASMON MODE OF THE ELECTRON DISC:

$\omega_p(k_{\nu\mu})$

$J'_\nu(k_{\nu\mu}) = 0$

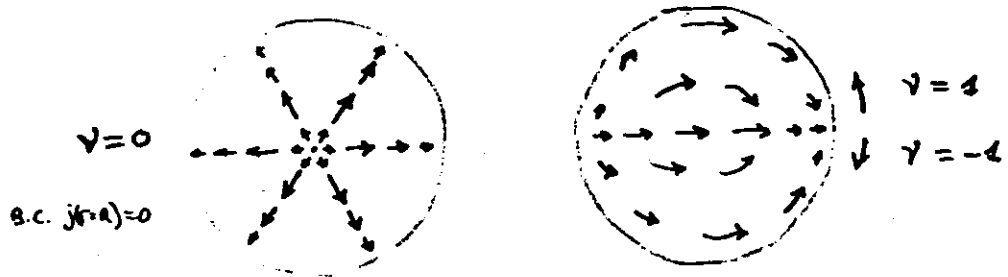


ABSORBED POWER: $P_{abs} = \frac{1}{2} N \frac{(e E_{r.f.})^2}{m_e} \tau$, $\tau = \frac{1}{\pi \Delta\nu} \sim 10^{-8}\,s$

$< 10\,pW$

PLASMON LINEWIDTH

NORMAL MODES OF 2-D ELECTRON DISC OF RADIUS R:



DRUM MODES $\begin{cases} \psi_{\nu\mu} = J_\nu(k_{\nu\mu} r)\cos(\omega t - \nu\theta) & \nu = 0, \pm 1, \pm 2 \\ \omega_{\nu\mu} = c_e k_{\nu\mu} & \text{where } J'_\nu(k_{\nu\mu} R) = 0 \end{cases}$

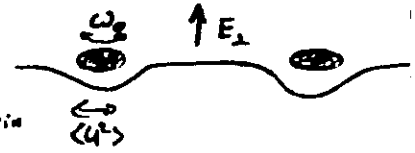
FOR $n = 10^8\ cm^{-2}$, $R = 20\ mm$

FIRST AZIMUTHAL MODE $f = 36\ MHz$

FIRST RADIAL MODE $f = 75\ MHz$

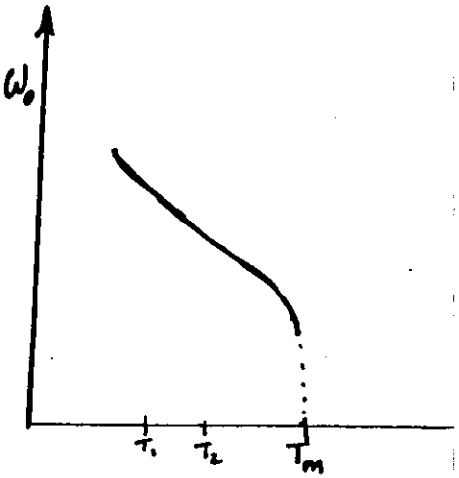
ELECTRON THERMOMETER

IN THE CRYSTALINE PHASE UNDER THE ACTION OF THE PRESSING FIELD $E_\perp$ EACH ELECTRON STAMPS A DIMPLE OF SIZE $\sim \langle u^2 \rangle$ IN WHICH IT VIBRATES AT FREQUENCY ω_0 (Fisher, Halperin PRL)



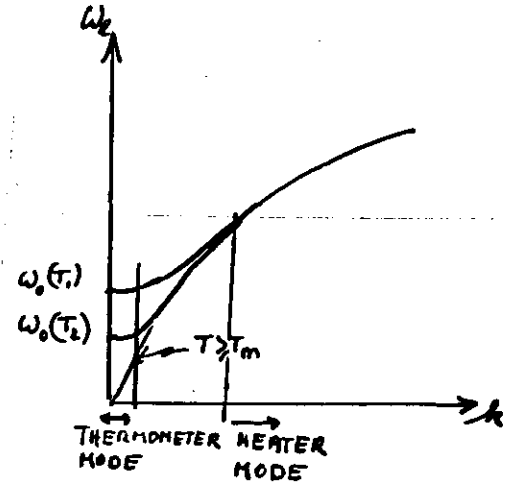
$\omega_0 = e E_\perp \left(\frac{n}{m\alpha}\right)^{1/2} \sum_G e^{-\frac{1}{2}G^2 \langle u^2 \rangle}$

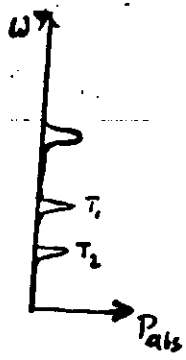
$\langle u^2 \rangle \sim T_e$



LONGITUDINAL MODE DISPERSION:

$\omega_e(k_{\nu\mu}) = \left(\omega_p^2(k_{\nu\mu}) + \omega_0^2(T_e)\right)^{1/2}$





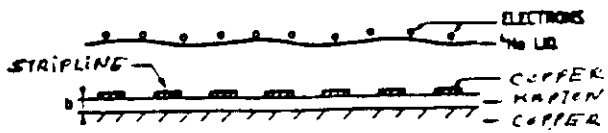
HEATER

THERMOMETER

MEASUREMENT

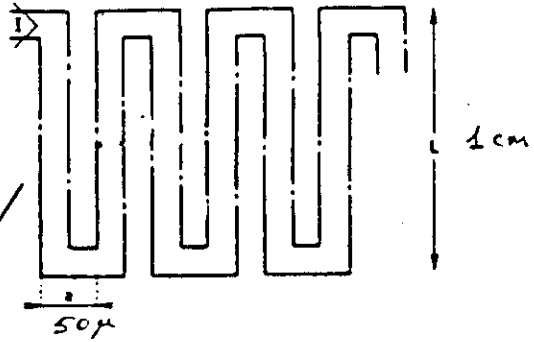
A 50 Ω MEANDER STRIPLINE INDUCES A PLANE WAVE POTENTIAL IN THE ELECTRON PLANE

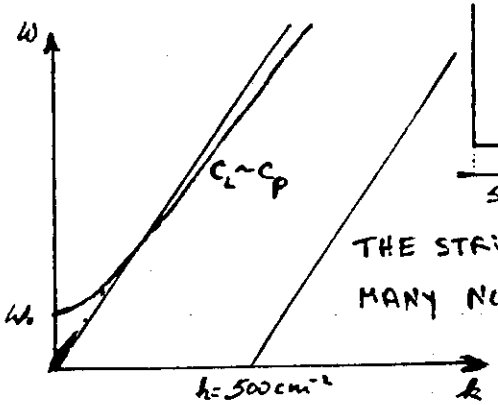
$$\phi_L e^{i(k_L x - \omega t)}$$



range $k_L = \frac{\omega}{c_L}$

$c_L = c\frac{a}{L} = 2\times10^8 \frac{cm}{sec} \simeq c_t$



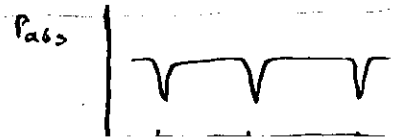


THE STRIPLINE COUPLES TO MANY NORMAL MODES

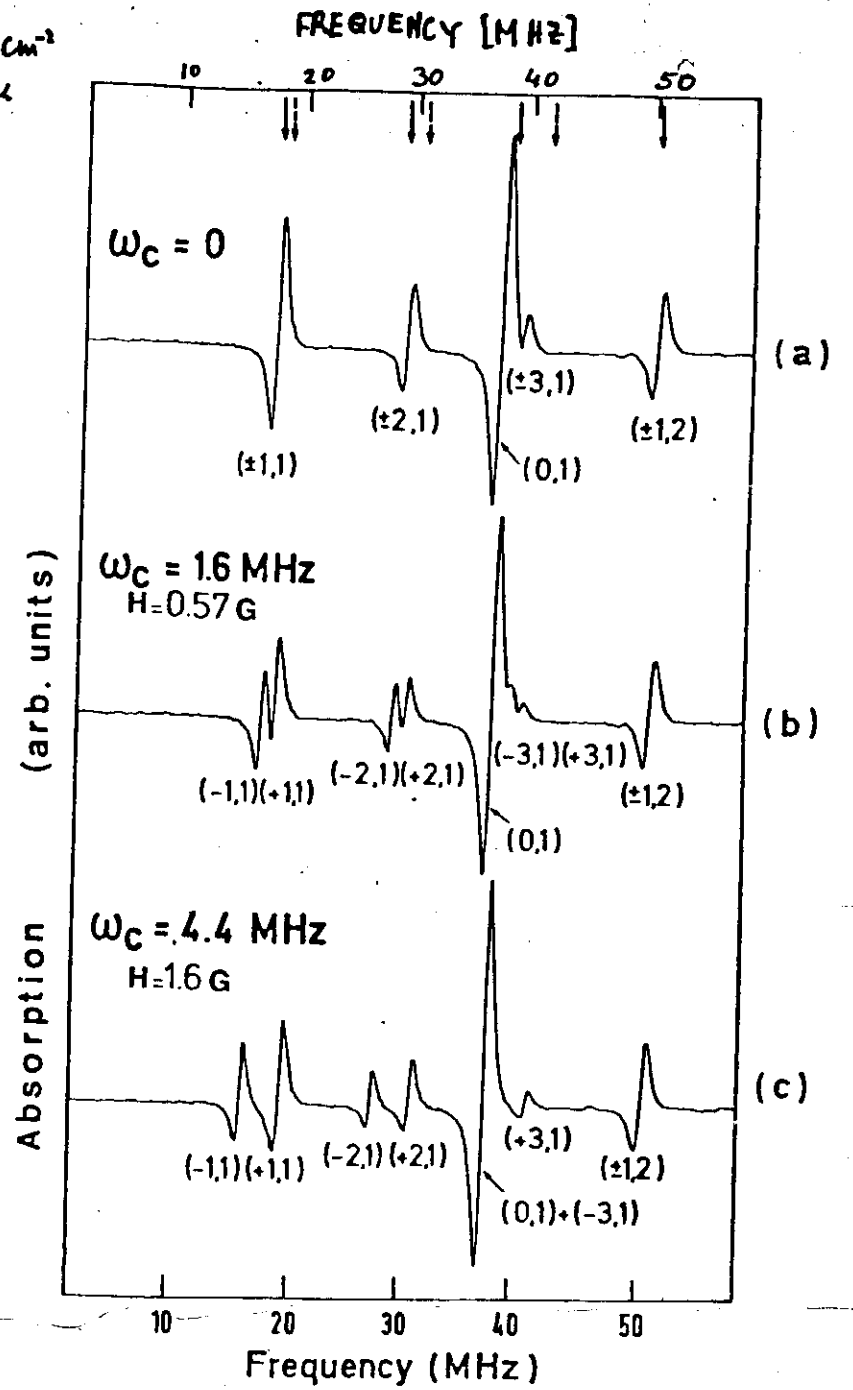
$c_p = c_L$ FOR $n = 0.9\times10^8 cm^{-2}$

WE MEASURE THE POWER ABSORBED BY THE ELECTRONS AS A FUNCTION OF FREQUENCY

$\Rightarrow P_{in}$ —(electrons)— $P_{out} = P_{in}\left(1 - \frac{P_{abs}}{P_{in}}\right)$



$n = 1.7\times10^7 cm^{-2}$
$T = 60 mK$



THERMALIZATION: CAN WE DEFINE $T_e \neq T_{He}$

1. MOMENTUM AND ENERGY RELAXATION MEDIATED BY ELECTRON-RIPPLON SCATTERING

$$H_{int} = \sum_q e E_\perp n_{-q} \xi_q$$

CAPILLARY WAVE (RIPPLON)

$$\Omega_q = \left(\frac{\alpha}{\rho} q^3\right)^{1/2}$$

COLLISION TIME:

$$\tau_c \sim 20\text{-}50 \text{ nsec} \qquad \left(\Delta\nu \sim \frac{1}{2\pi\tau_c} \sim 7\text{-}15 \text{ MHz}\right)$$

τ_c IS THE MOMENTUM RELAXATION TIME.

ELECTRON-RIPPLON COLLISIONS ARE QUASI-ELASTIC. ELECTRONS ARE SCATTERED BY RIPPLONS OF WAVEVECTOR

$$q_T = (2k_B m T)^{1/2}/\hbar$$

WHOSE ENERGY

$$\hbar\Omega_{q_T} \ll k_B T$$

∴ MANY (~1000) COLLISIONS ARE NEEDED TO DISSIPATE THE ELECTRON ENERGY.

$$\therefore \tau_{e\text{-}He} \gg \tau_c \qquad \tau_{e\text{-}He} \sim 300\,\mu\text{sec}$$

CHARACTERISTIC TIME FOR THERMALIZATION WITHIN THE ELECTRON PLANE:

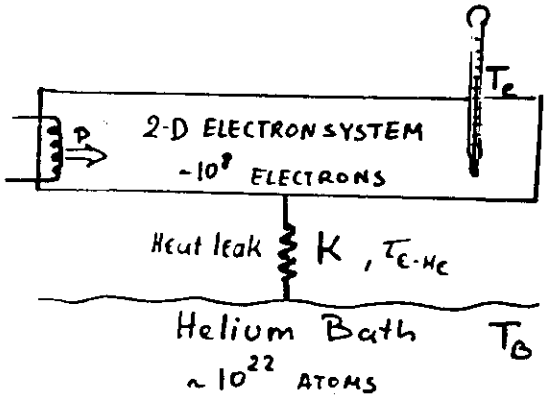
$$\tau_{e\text{-}e} \sim \frac{R}{c_t} \sim 1\,\mu\text{sec}$$

R SIZE OF SYSTEM
c_t transverse sound velocity

$$\therefore \tau_{e\text{-}He} \gg \tau_{e\text{-}e}$$

∴ ON A TIME SCALE $\tau_c \ll t \ll \tau_{e\text{-}He}$ WE CAN DEFINE $T_e \neq T_{He}$.

SPECIFIC HEAT MEASUREMENT

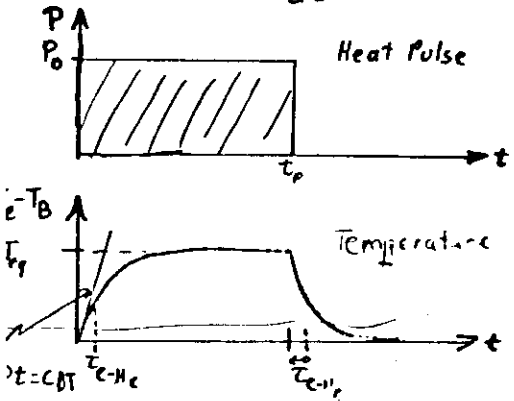


- THERMAL DECOUPLING: $\tau_{e-He} \gg \tau_{e-e}$, $T_e \neq T_B$
- ELECTRON HEATER
- ELECTRON THERMOMETER

θ measurement time
$\tau_{e-He} > \theta > \tau_{e-e}$

PRINCIPLE OF EXPERIMENT

$$P = C\frac{dT_e}{dt} - K(T_e - T_B)$$



$$\Delta T_{eq} = \frac{P_0}{K}$$

$$\tau_{e-He} = \frac{C}{K}$$

$$\boxed{C = \frac{P_0 \tau_{e-He}}{\Delta T_{eq}}}$$

IS SUCH AN EXPERIMENT FEASIBLE ?
- WHAT IS THE SIGNAL TO NOISE RATIO ?

- HOW MUCH POWER DOES IT TAKE TO HEAT $N = 10^8$ electron BY 10 mK ?

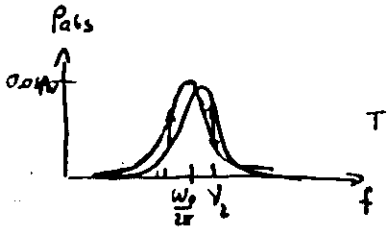
$$P_{abs} \sim NK\Delta T = NC\Delta T/\tau_{eH}$$

($C \sim k_B$; $\tau_{eH} \sim 1000\ \tau_e \simeq 20\mu s$)

$$\therefore \quad P_{abs} \simeq 0.7\ pW$$

- TO PREVENT HEATING THE POWER USED IN MEASURING THE FREQUENCY OF THE THERMOMETER MODE SHOULD BE:

$$P_{abs}^{th} \lesssim 0.01\ pW$$



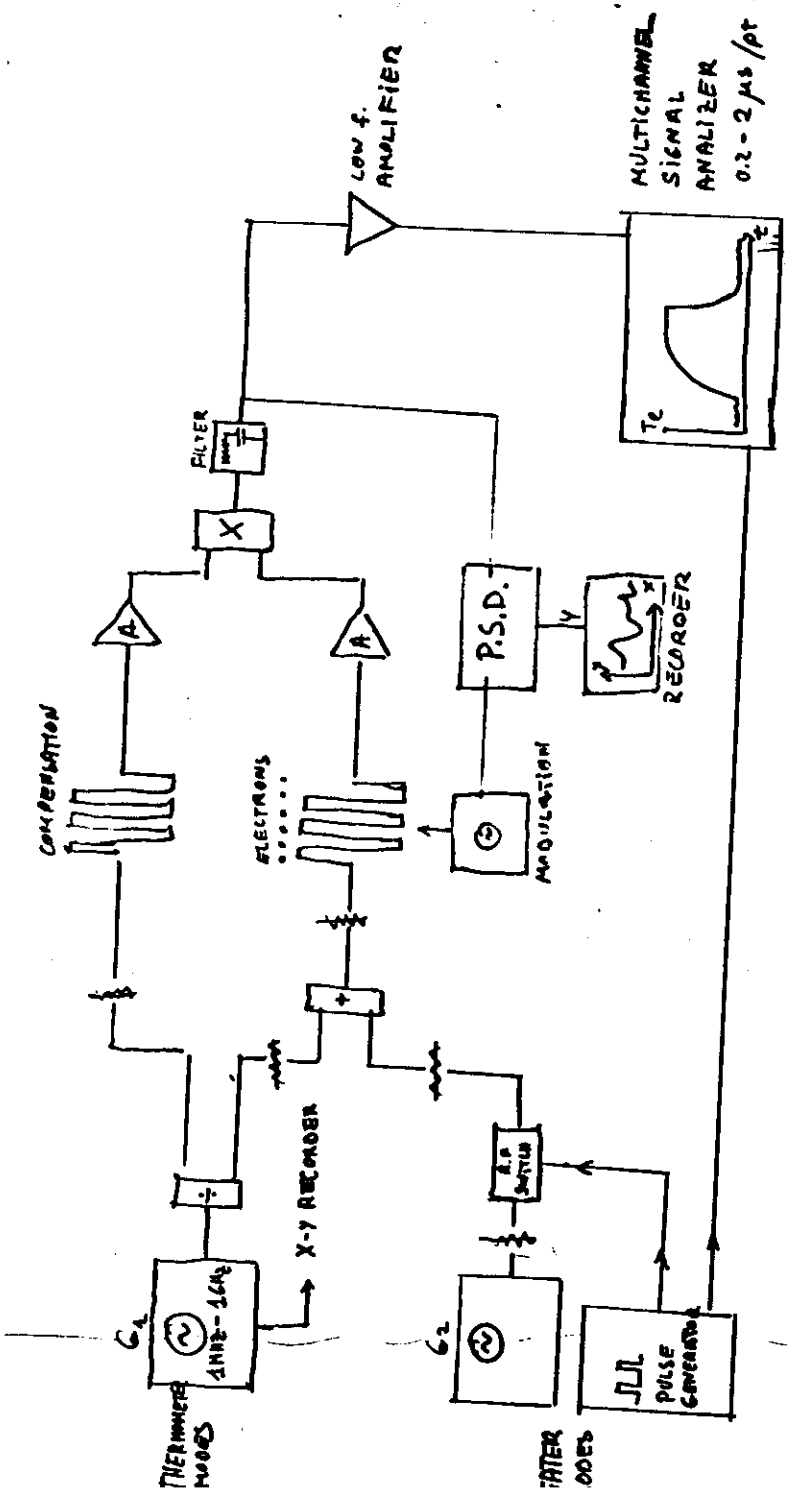
$T = T_0 + 10\,mK$, $\boxed{\Delta P_S \sim 10^{-4}\ pW}$ • signal

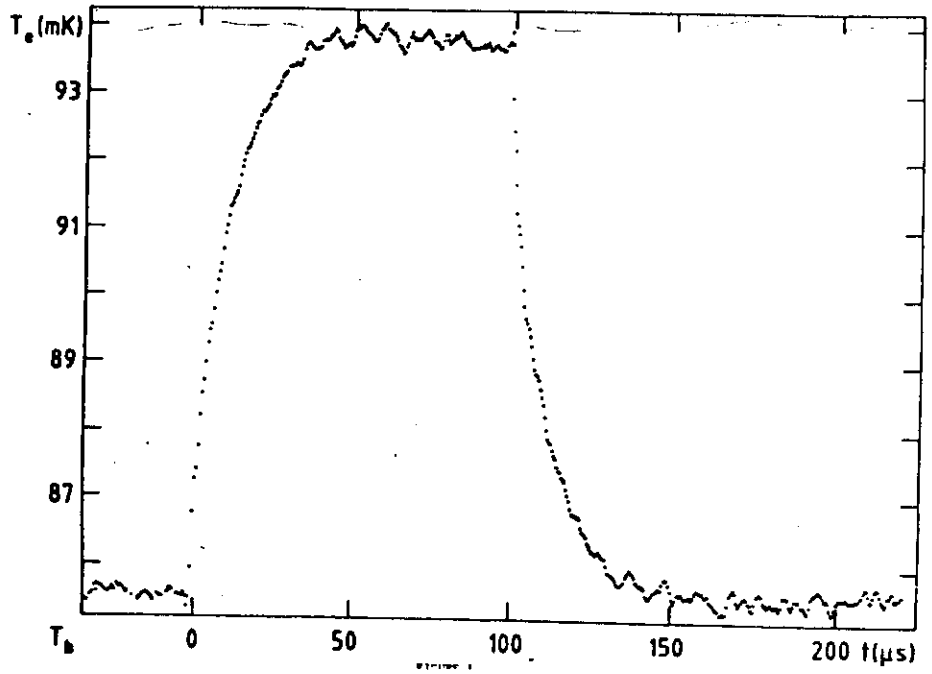
- THE MEASUREMENT NOISE IS GOVERNED BY AMPLIFIERS — NOISE TEMPERATURE OF AMPLIFIERS $\sim T_N \sim 200^\circ K$, B BANDWIDTH OF MEASUREMENT $\Delta f \sim 1MHz$

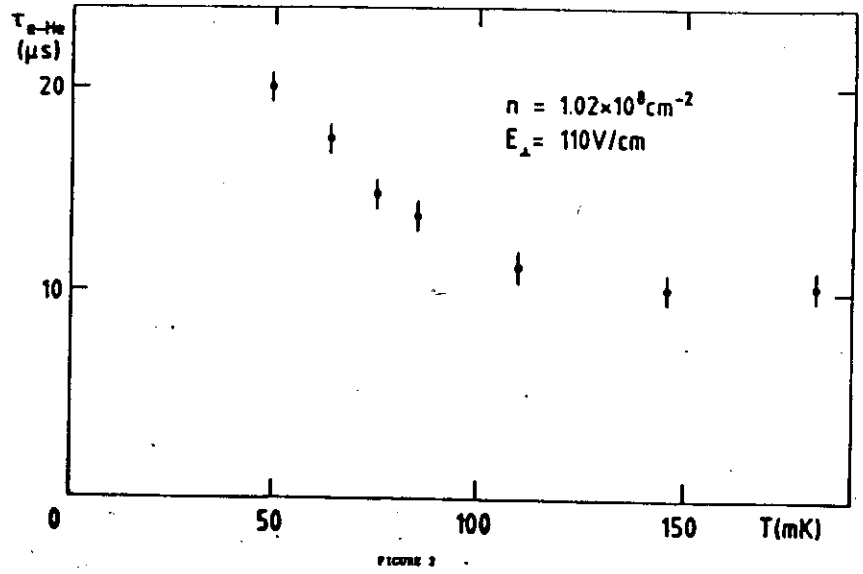
$$\therefore \quad \boxed{P_N = 4k_B T_N \Delta f \sim 1.1 \times 10^{-2}\ pW} = \text{NOISE}$$

$$\therefore \quad S/N \sim \frac{\Delta P_S}{P_N} \simeq 0.09 \Longrightarrow \text{NEED SIGNAL AVERAGING A TIME}$$

$\sqrt{A}\, S/N \sim 50$ AFTER REPEATING THE EXPERIMENT $A = 260\,000$ TIMES


LOW f. AMPLIFIER
MULTICHANNEL SIGNAL ANALIZER
0.2 - 2 μs /pt
FILTER
X
A
A
P.S.D.
Y
RECORDER
COMPENSATION
ELECTRONS
MODULATION
X-Y RECORDER
PULSE GENERATOR

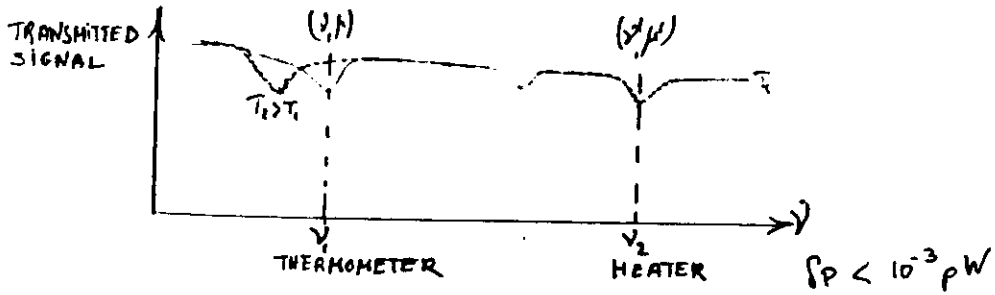

T_e(mK)
93
91
89
87
T_b
0
50
100
150
200 t(μs)

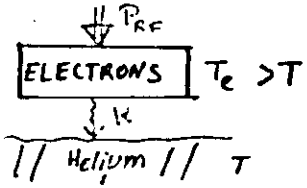

τ_{e-He} (μs)
20
10
0
50
100
150
T(mK)
n = 1.02×10⁸cm⁻²
E⊥ = 110V/cm

EXPERIMENT :

CALIBRATION OF THERMOMETER MODE $\omega_{\mu,\nu}(T)$ BY LETTING THE ELECTRONS REACH THERMAL EQUILIBRIUM WITH HELIUM BATH AT VARIOUS TEMPERATURES

PROCEDURE : PUT KNOWN AMOUNT OF POWER IN HEATER MODE AND MEASURE FREQUENCY DISPLACEMENT OF THERMOMETER MODE



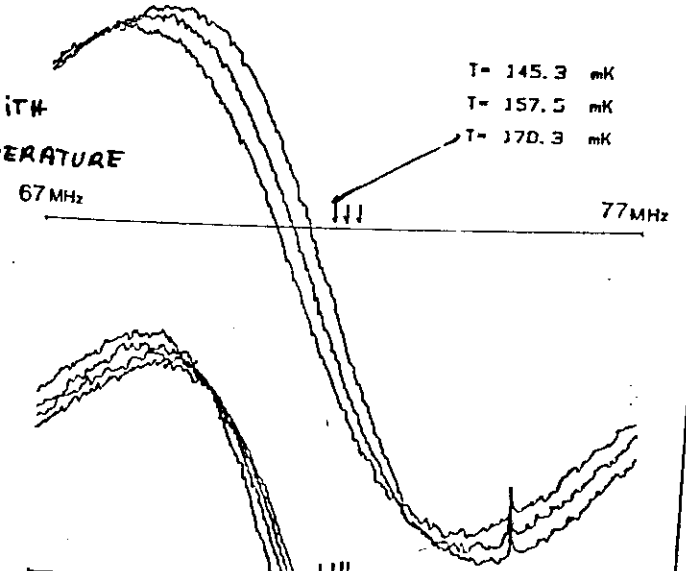


$$C\frac{dT_e}{dt} = -K(T_e - T) + P(t)$$

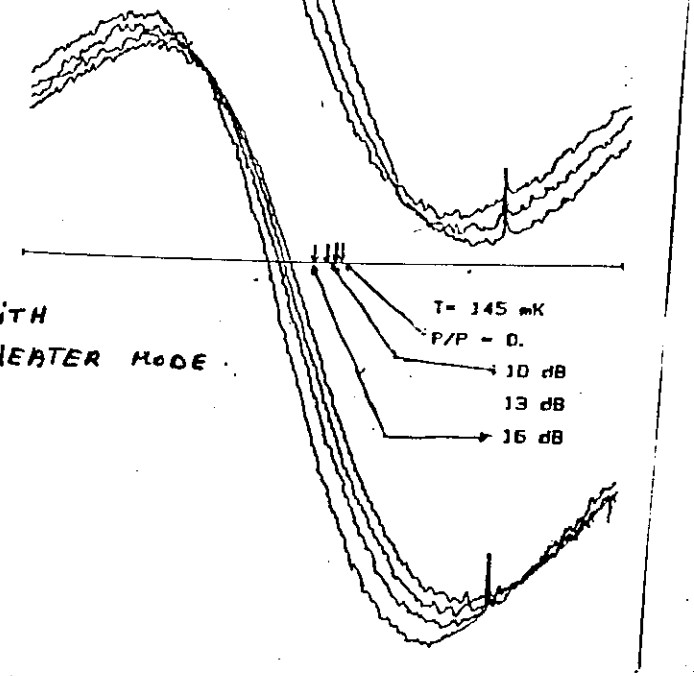
$\Downarrow \frac{dT_e}{dt} = 0$ ΔT_e

CALIBRATION OF ELECTRON THERMOMETER

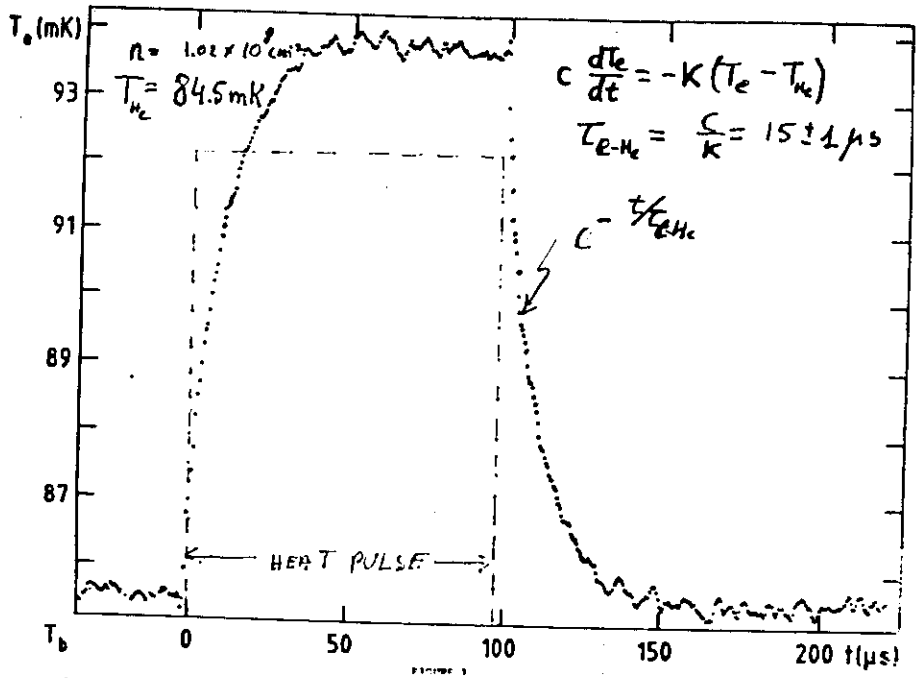
VARIATION OF ω_0 WITH HELIUM BATH TEMPERATURE



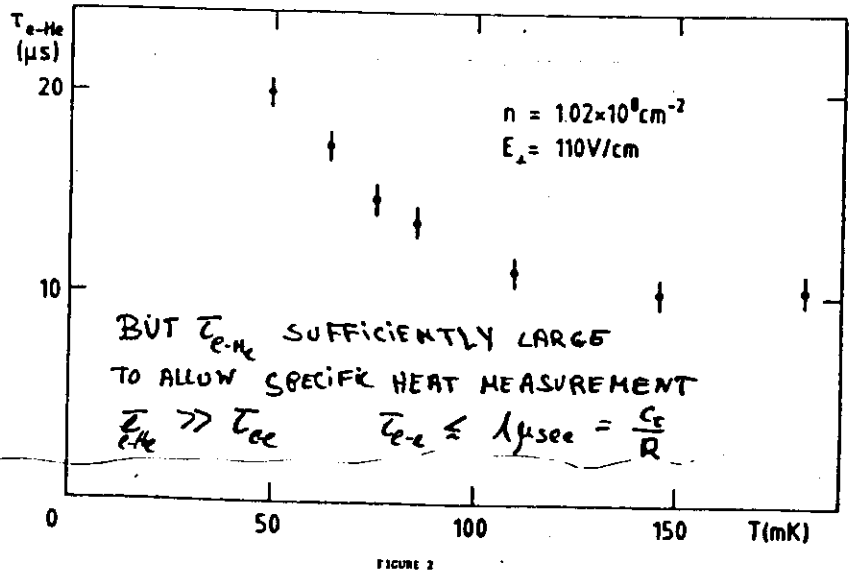
VARIATION OF ω_0 WITH DRIVING POWER IN HEATER MODE.



TIME EVOLUTION OF ELECTRONIC TEMPERATURE DURING AND AFTER A HEAT PULSE



$\tau_{e\text{-}He}$ IS SMALLER THAN PREDICTED BY AN UNCORRELATED ELECTRON MODEL $\sim 300\,\mu sec$

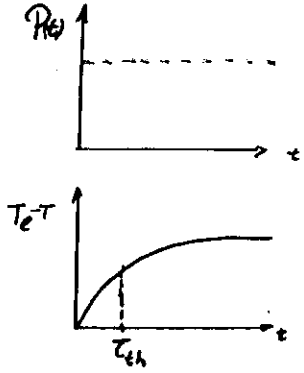


BUT $\tau_{e\text{-}He}$ SUFFICIENTLY LARGE TO ALLOW SPECIFIC HEAT MEASUREMENT

$\tau_{e\text{-}He} \gg \tau_{ee}$ $\quad \tau_{e\text{-}e} \leq 1\,\mu sec = \frac{C_e}{R}$

FIGURE 2

- MEASUREMENT OF THERMAL CONDUCTIVITY $K(T)$ BETWEEN ELECTRONS AND HELIUM BATH.



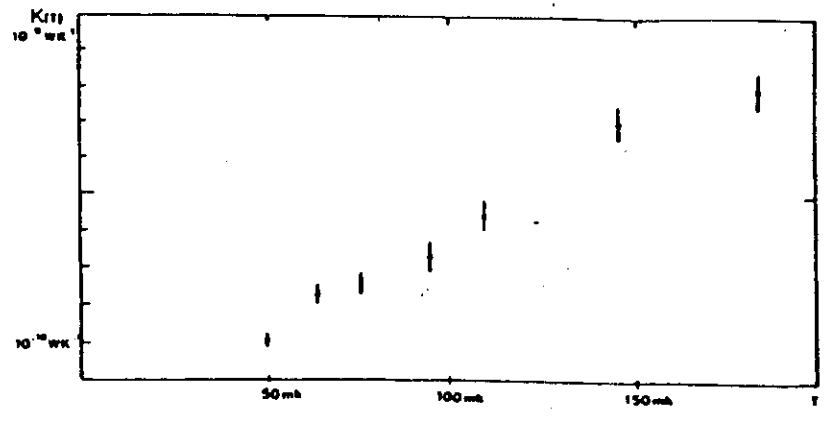
$K = \frac{P}{T_e - T}$

POWER ABSORBED BY EL

$P = Ne^2 |E_{\nu,\mu}|^2 \tau / 2m \leq 0.1$

$E_{\nu,\mu}$ IS CALCULABLE FROM $P_0 < 0.1$nW AND THE GEOMET

$\tau = (\Delta\omega)^{-1} \geq 10^{-8}$ s IS GIVEN B LINEWIDTH $\Delta\omega$.



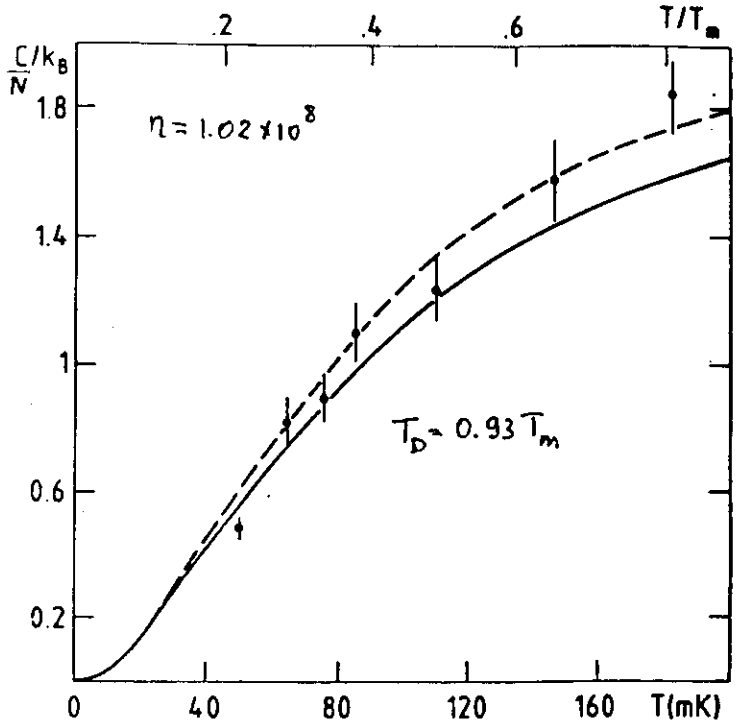
Electron-helium thermal conductance for $n = 1.02 \times 10^8 cm^{-2}$ in the solid phase.

$K(T)$ IS ~100 times larger than predicted from an uncorrelated electron model (Saitoh 82) but has the same qualitative temperature dependence.

∴ correlations play an important role in energy relaxation mechanism (not for momentum relaxation).

THE SPECIFIC HEAT $C = \tau_{e\text{-}He} K$

P.R.L 1987



— CALCULATED PHONON HEAT CAPACITY

$\omega_t^2(k) = \omega_p^2(k) - 5\omega_t^2(k)$

$\omega_t(k) = c_t^0 k$

-- SAME WITH RENORMALIZED TRANSVERSE SOUND VELOCITY

$C_t^2(T) = C_t^2(0)\,(1 - 0.3\,T/T_m)$

- LOW TEMPERATURE LIMIT $C \sim T^2$ NOT ATTAINED
- BECAUSE OF LOW T_D $C \approx 2k_B$ THE CLASSICAL LIMIT

DEFECT CONTRIBUTION NOT DISCERNIBLE AT $T < 0.8\,T_m$
CONSISTENT WITH THEORETICAL ESTIMATE $0.1\,k_B$ (Fisher Halperin 79)
$C_D \sim (E_\perp)^2$

EFFECT OF ELECTRON-HELIUM COUPLING ON SPECIFIC HEAT
FOR $n = 0.8 \times 10^8\ cm^{-2}$ $T = 98\ mK$

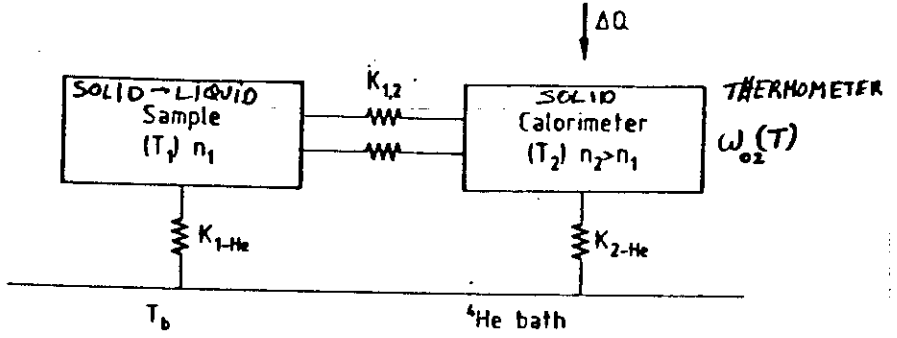
$E_\perp$	$K(T)$	$\Delta\nu$	$\tau_{e\text{-}He}$	C
58 V/cm	2.27×10^{-10} W/K	5.5 MHz	16 μsec	1.0 k_B
93 V/cm	2.97×10^{-10} W/K	8.7 MHz	15 μsec	1.1 k_B

C IS INDEPENT OF COUPLING TO H_e $(E_\perp \to 2 \cdot E_\perp)$

LATENT HEAT MEASUREMENT

THE THERMOMETER MODE ω_0 VANISHES AT T_m

WE USE TWO COUPLED ELECTRON CRYSTALS OF DIFFERENT DENSITIES TO MEASURE THE LATENT HEAT



WE HEAT THE CALORIMETER AND MEASURE ITS TEMPERATURE T_2 WITH $\omega_{02}(T)$

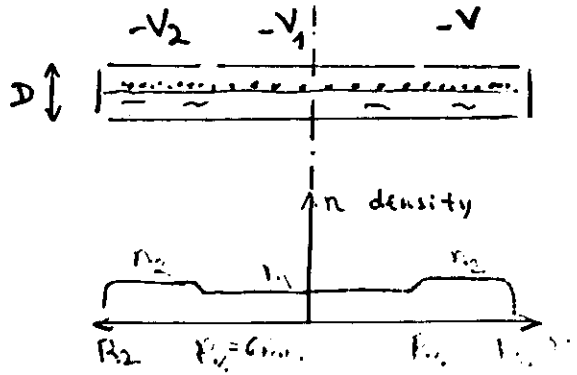
IF THE THERMAL COUPLING IS GOOD: $K_{12} \gg K_{1,2} K_{2\text{-}He} \longrightarrow T_1 = T_2 = T_c$

$\Rightarrow$ TOTAL SPECIFIC HEAT $\boxed{C = C_1 + C_2}$

DECREASE

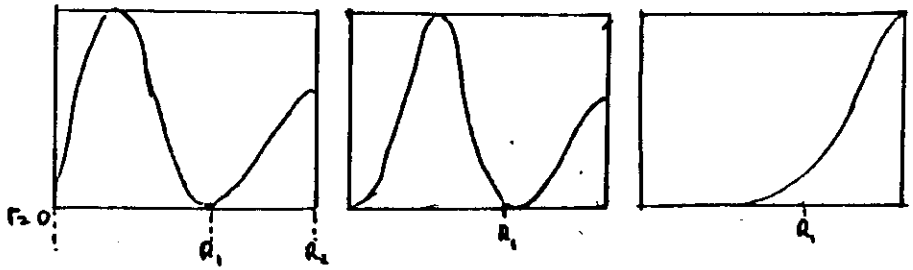
REALIZATION OF THE 2 DENSITY SYSTEM

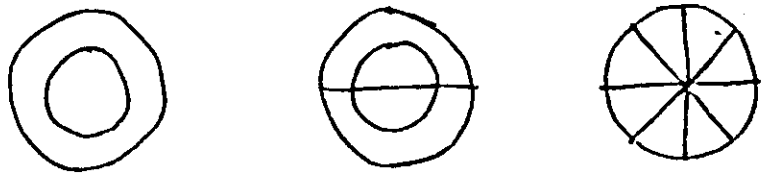
$$\frac{e}{\epsilon}(n_2 - n_1) = (V_1 - V_2)\frac{2}{D}$$



THE NORMAL MODES SPAN ONE OR BOTH DENSITY REGIONS

AMPLITUDE OF NORMAL MODES





0,1 RADIAL

1,2

4,1 AZIMUTHAL

THE AZIMUTHAL MODES ARE LOCALIZED ON THE ANULAR REGION 2 AND CAN BE USED AS HEATER & THERMOMETER

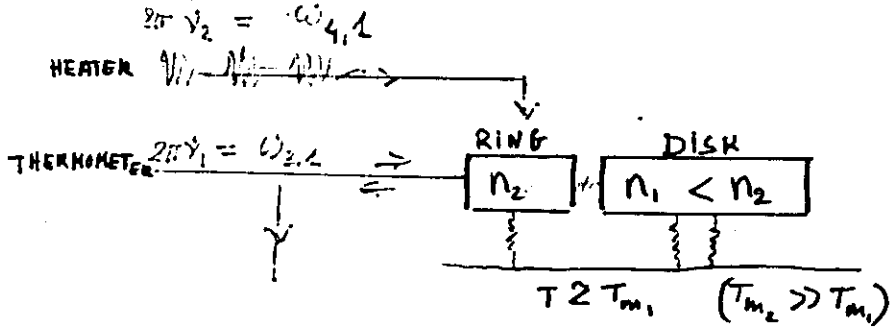
AT LOW TEMPERATURES (1 & 2 SOLID) THE MODE FREQUENCIES:

$$\omega_{\nu,\mu} = \left(\langle\omega_0^2\rangle_{\nu,\mu} + \omega_p^2(k_{\nu,\mu})\right)^{1/2}$$

WHERE $\langle\omega_0^2\rangle_{\nu,\mu} = \alpha_{\nu,\mu}\,\omega_{c_2}^2(T_1) + \beta_{\nu,\mu}\,\omega_{c_2}^2(T_1)$

α, β RELATIVE WEIGHT OF MODE AMPLITUDE IN THE TWO REGIONS. $\Rightarrow$ T_1 AND T_2 CAN BE MEASUR. THERMAL COUPLING CAN BE VERIFIED.

EXPERIMENT



THE MODES USED (4,1), (3,1) EXTEND ONLY OVER THE Ai $\Rightarrow$ THERMOMETER ONLY MEASURES T_2

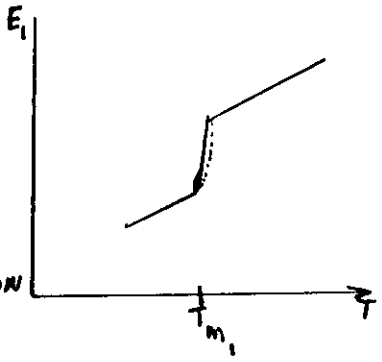
- THERMAL EQUILIBRIUM $T_1 \overset{?}{=} T_2 = T_e$ WAS VERIFIED BY MEASURING $\omega_{1,2}$ which is SENSITIVE TO BOTH T_1 AND T_2 $\Rightarrow$ $\frac{(T_1 - T_2)}{T_2} < 10\%$ CLOSE TO THE TRANSITION

- By HEATING TO $T > T_{m_1}$ ω_{0_1} DISAPPEARED AT

E SEARCH FOR LATENT HEAT AT MELTING

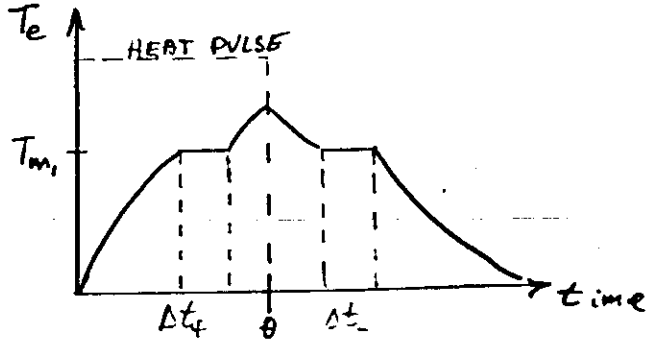
IF THE TRANSITION is OF FIRST ORDER

$$L_1 = \Delta S_1 T_{m_1}$$



IE LATENT HEAT SHOULD APPEAR A PLATEAU IN THE TIME EVOLUTION THE ELECTRONIC TEMPERATURE OCCURING AT $T_e = T_{M_1}$

IRING THE HEATING PULSE AND E SUBSEQUENT RELAXATION :

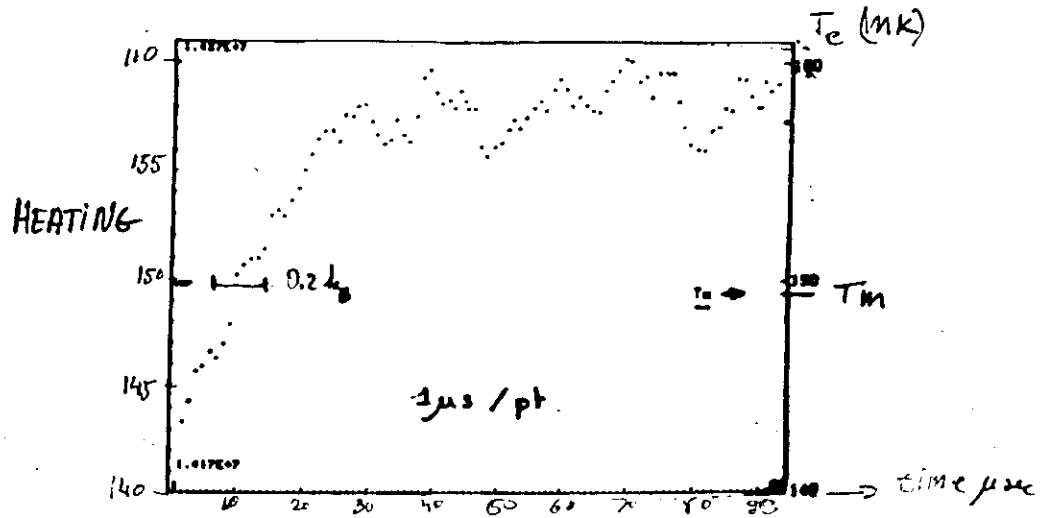


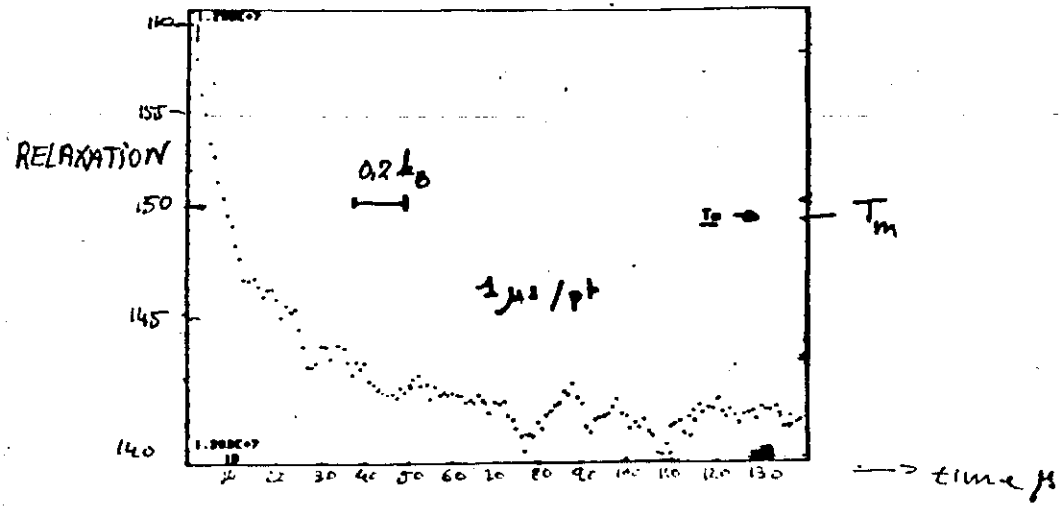
$$\Delta t_+ = L_1 / [P - K_{e\text{-}He}(T_{m_1} - T_{He})]$$

$$\Delta t_- = L_1 / K_{e\text{-}He}(T_{m_1} - T_{He})$$

TIME EVOLUTION OF ELECTRONIC TEMPERATURE AS SYSTEM ℓ IS HEATED THROUGH T_{M_1} BY A 100 μsec PULSE

$T_{He} = 135.5$ mK , HEATER MODE (4,1) , THERMOMETER MODE (3,1)





- NO DISCONTINUITY AT MELTING ⇒ K.T.
- TO WITHIN OUR EXPERIMENTAL UNCERTAINTY OF $\Delta C < 0.2\,b$

- LATENT HEAT MEASUREMENT ⟹ TRANSITION IS CONTINUOUS

$$\Delta S < 0.2\, k_B$$

- NUMERICAL SIMULATIONS ⇒ TRANSITION IS FIRST ORDER

Morf 82	$\Delta S \sim 0.3 k_B$
Kalia, Vashishta	$\Delta S \sim 0.3 k_B$
de Leeuw	

- OUR MEASUREMENT TIMES ARE 1000 – 10000 TIMES LONGER
  WE HAVE 10^5 MORE PARTICLES.

CONCLUSIONS

1. WE HAVE MEASURED THE SPECIFIC HEAT OF A 2-D ELECTRON CRYSTAL (10^8 ELECTRONS) FOR $0.2 T_m < T < 0.8 T_m$

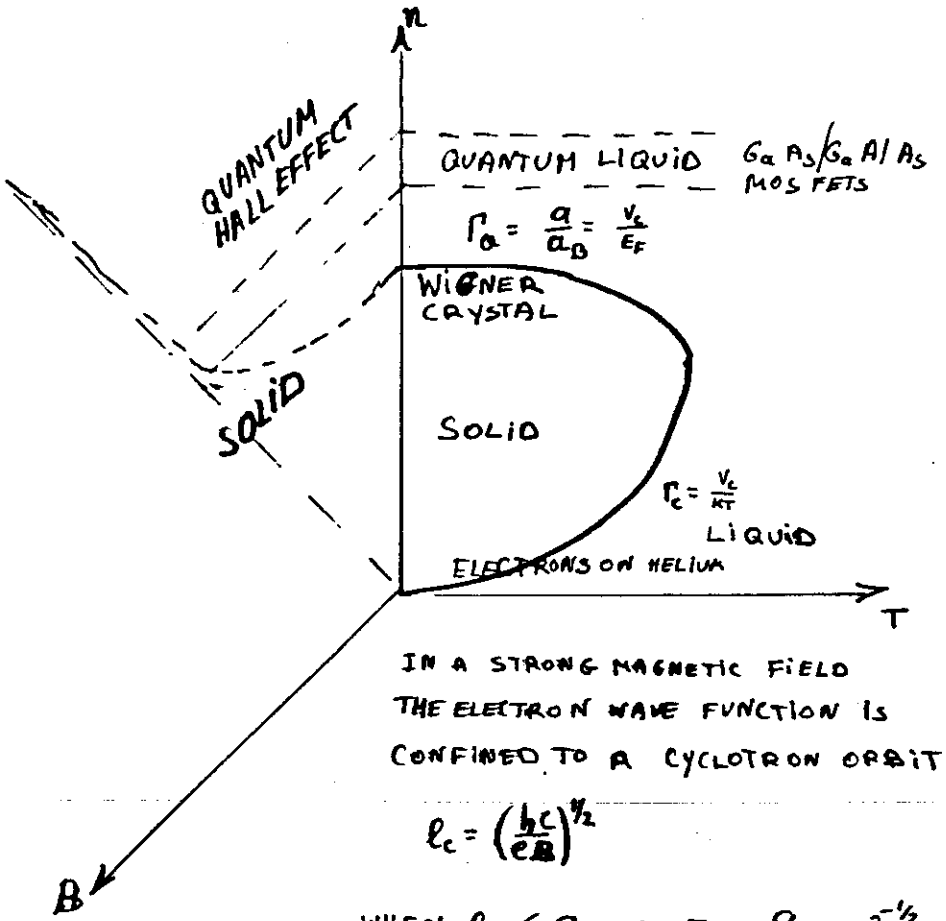
   THE MEASURED SPECIFC HEAT AGREES WELL WITH A PHONON MODEL.

2. WE FOUND NO LATENT HEAT AT MELTING
   - IN ACCORD WITH THE K-TH-N-H-Y PREDICTION OF A CONTINUOUS TRANSITION
   - ALSO IN ACCORD WITH OUR MEASUREMENTS ON THE SHEAR MODULUS

∴ THE TRANSITION IS MEDIATED BY UNBINDING OF DISLOCATION PAIRS.

- WHAT NEXT?
  - HEXATIC PHASE
  - $\mu^m(\omega)$

MAGNETICALLY INDUCED WIGNER CRYSTAL



IN A STRONG MAGNETIC FIELD THE ELECTRON WAVE FUNCTION IS CONFINED TO A CYCLOTRON ORBIT

$$\ell_c = \left(\frac{\hbar c}{eB}\right)^{1/2}$$

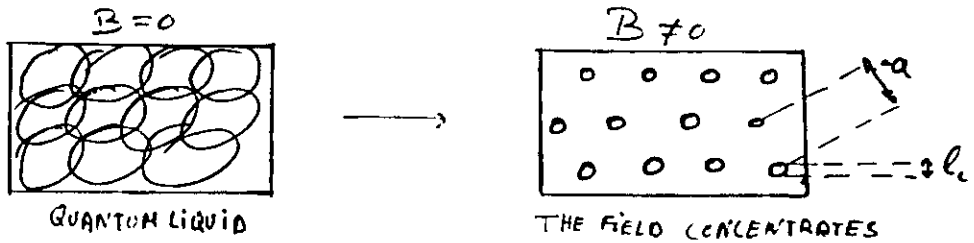
WHEN $\ell_c < a_B \Rightarrow \Gamma_a = \frac{a}{\ell_c} = \nu^{-1/2}$

$\therefore$

IN MAGNETIC FIELD THE TRANSITION OCCURS AT HIGHER DENSITIES

$$n_c = \left(\Gamma_{ac}^{n}\, \ell_c\right)^{-2} > \left(\Gamma_{ac}^{n}\, a_B\right)^{-2}$$

MAGNETICALLY INDUCED WIGNER SOLID



QUANTUM LIQUID
electronic wavefunction
Delocalized

THE FIELD CONCENTRATES e.w.f.
Within a CYCLOTRON ORBIT

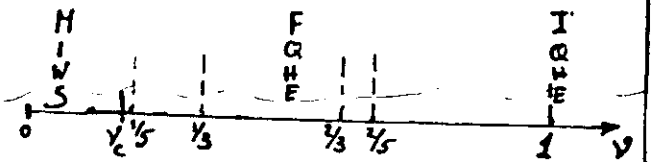
cyclotron radius: $\ell_c = \left(\frac{\phi_0}{2\pi}\frac{1}{B}\right)^{1/2}$, $\phi_0 = \frac{hc}{e}$ fundamental flux unit

filling factor: $\nu = \frac{n\phi_0}{B} = 2\left(\frac{\ell_c}{a}\right)^2$

AT HIGH FIELDS $\ell_c \ll a$ overlap is reduced

AT T=0 FOR $\boxed{\nu \leq \nu_c}$ COULOMB CORRELATIONS ORDER ELECTRONS

(Levesque, Weiss, MacDonald 84) $0.11 \leq \nu_c^{exp} \leq .25$ (MAKI, ZOTOS 83)



2-DIMENSIONAL ELECTRON GAS IN A $GaAs/GaAlAs$ heterojun

$T=0$. NO IMPURITIES & NO HIGH LANDAU LEVEL MIXING

$\Rightarrow E_G \propto \frac{e^2}{\epsilon a} g(\nu)$ ground state energies

THERMODINAMICS DETERMINED BY ν ONLY.

$T \neq 0 \qquad F = \frac{e^2}{\epsilon a} f(\nu, t)$ where $t = \frac{T}{T_{cm}}$.

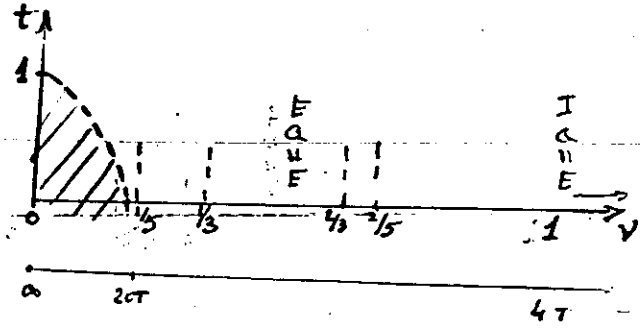
$T_{cm} = \frac{e^2}{k_B \epsilon a} = \left(\frac{n}{10^{11}}\right)^{1/2} \cdot 575\ m^\circ K$

T $\nu=0$, $\ell_c=0$ → CLASSICAL ELECTRON CRYSTAL; STABLE FOR $T \leq T_{cm}$

UNIVERSAL PHASE DIAGRAM

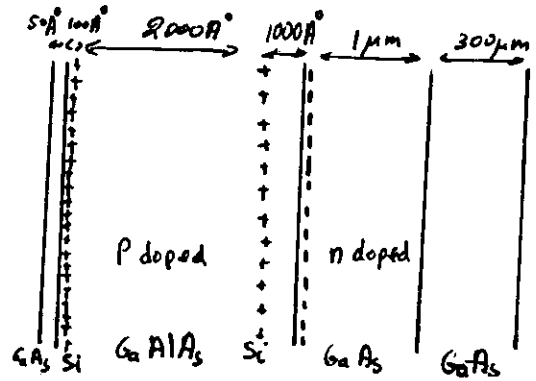
UNITS: $t=\frac{T}{T_m}$, ν

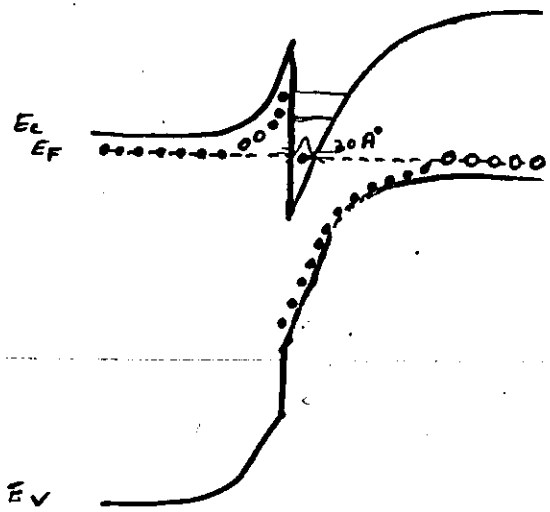
$\Gamma_L \ll 33$



AN EXTERNAL POTENTIAL (RANDOM POTENTIAL DUE TO IMPURITIES) DESTROYS THE SCALING WITH ν, t

IF THE OBSERVED PHENOMENA DO SCALE WITH (ν, t)
⇒ THE UNDERLYING PHYSICS IS STILL DETERMINED BY COULOMB INTERACTION & LANDAU DEGENERACY.





$\epsilon = 13$

$E_B \sim 500K$

$n \geq 3 \times 10^{11} cm^{-2}$

$\mu \leq 10^7 cm^2/Vs$

$\ell_{mfp} \leq 2\mu m$

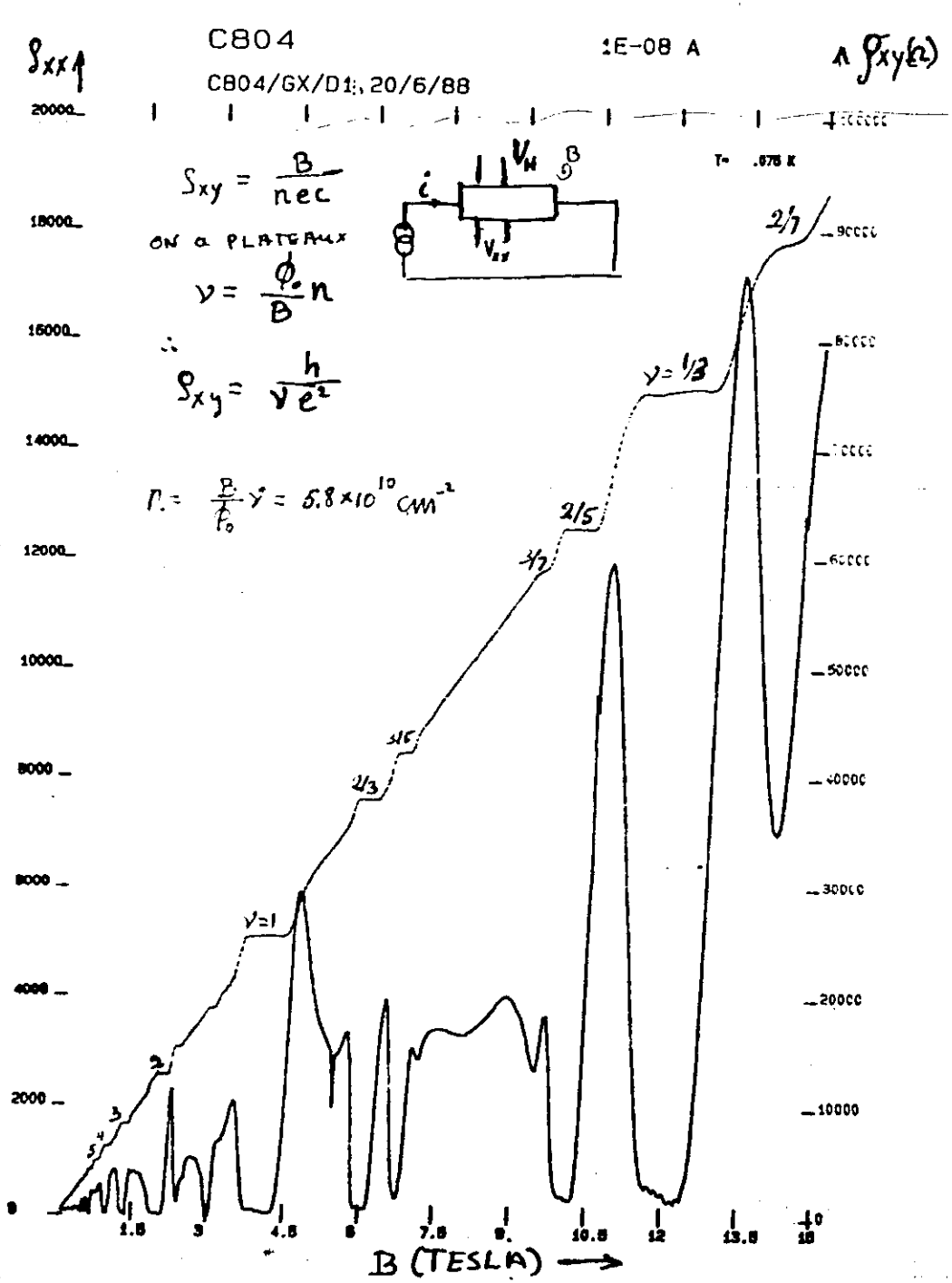
$\tau_{sc} \leq 20 nsec$

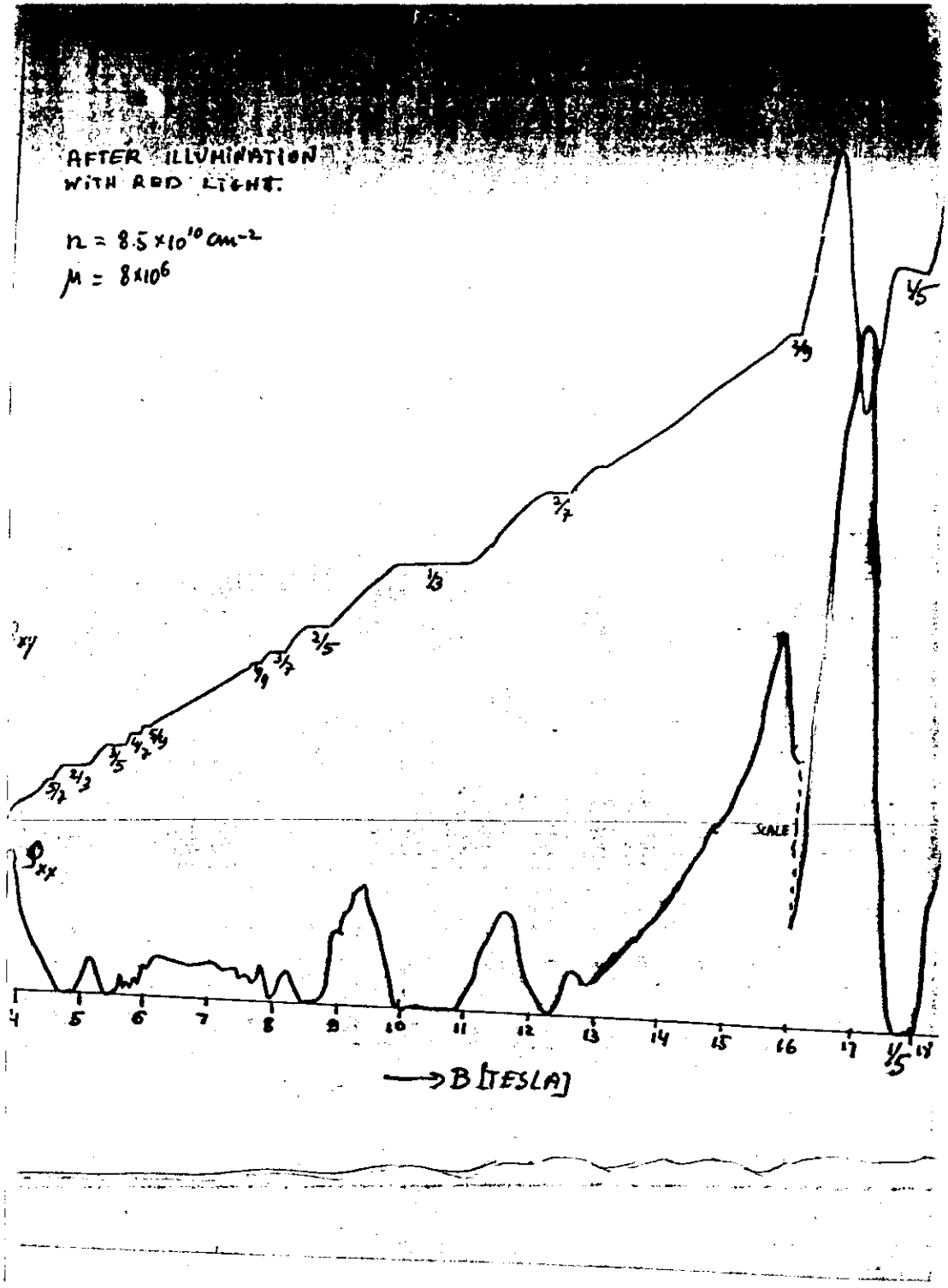
$m^* = 0.07\ m_e$

$n_W = 10^9 cm^{-2}$

SOURCES OF DISORDER:

1. Si DONORS → INCREASE SPACER DISTANCE 1000 – 3000 Å
2. RESIDUAL ACCEPTOR IMPURITIES → SUPERLATTICE TRAP IN GaAs BUFFER REGION
3. ALLOYING → INTRODUCE A FEW MONOLAYERS OF $AlAs$ AT THE INTERACE


C804
1E-08 A
C804/GX/D1:, 20/6/88
ρ_{xx}
ρ_{xy} (Ω)
T= .078 K
$S_{xy} = \frac{B}{nec}$
ON a PLATEAUX
$\nu = \frac{\phi_0}{B} n$
$\therefore \rho_{xy} = \frac{h}{\nu e^2}$
$n = \frac{B}{\phi_0} \nu = 5.8 \times 10^{10}\ cm^{-2}$
V_H
V_{xx}
B
i
ν=1
2/3
3/5
2/5
3/7
ν=1/3
2/7
B (TESLA) →


AFTER ILLUMINATION
WITH RED LIGHT.
$n = 8.5 \times 10^{10}\ cm^{-2}$
$\mu = 8 \times 10^6$
ρ_{xy}
ρ_{xx}
SCALE
1/3
3/7
3/5
2/3
1/5
→ B [TESLA]

HOW IS THE SOLID DIFFERENT FROM THE LIQUID ?

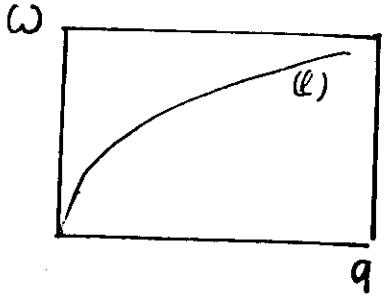
MACROSCOPIC DISTINGUISHING PROPERTY:

RESPONSE TO SHEAR STRESS μ (SHEAR MODU

LIQUID

$\mu = 0 \Rightarrow$ VISCOUS RESPONSE

DAMPED RESPONSE AROUND $\omega = 0$

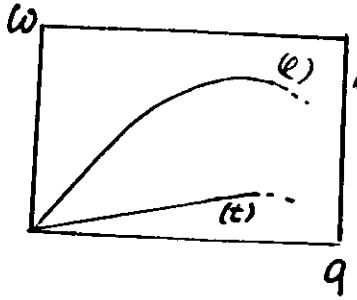


$B = 0$

SOLID

$\mu \neq 0 \Rightarrow$ ELASTIC RESPONSE

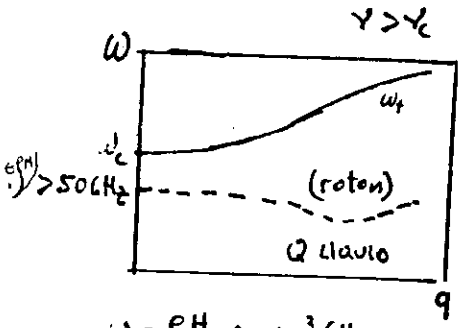
FINITE FREQUENCY TRANSVERSE PHONO



$\omega_c = \left(\frac{ne^2}{m^* c}\, q\right)^{1/2}$

$\omega_t = \left(\frac{\mu}{nm^*}\right)^{1/2} q = c_t q$

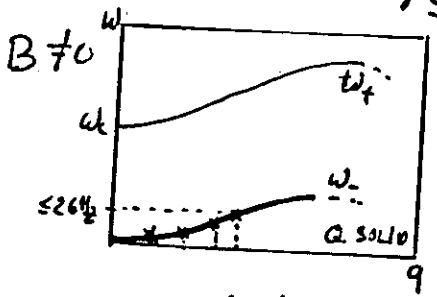
Laughlin Liquid



$\omega_c = \frac{eH}{m^* c} \simeq 10^3\ GHz$

GAP

MiWS



$\omega_t = \left(\omega_c^2 + \omega_c^2\right)^{1/2}$

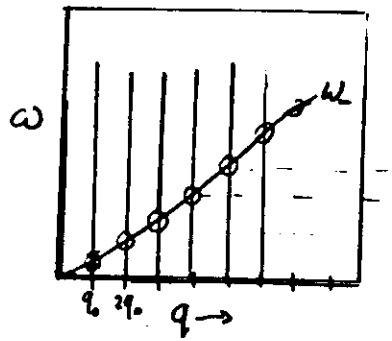
$\omega_- = \frac{\omega_t \omega_c}{\omega_c} \sim \mu^{1/2} q^{3/2}$

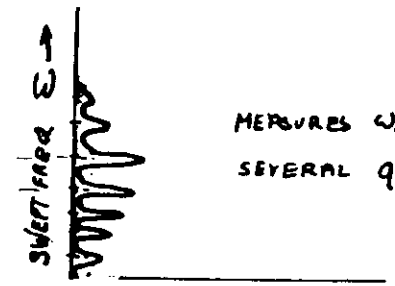
GAPLESS FINITE FREQUENCY BRANC

EXPERIMENT : DESIGNED FOR POSITIVE IDENTIFICATION OF MiWS BY DETECTING MAGNETO-TRANSVERSE MODE ω_- LOCK FOR RESONANT ABSORPTION OF R.F. POWER

PRINCIPLE OF EXPERIMENT

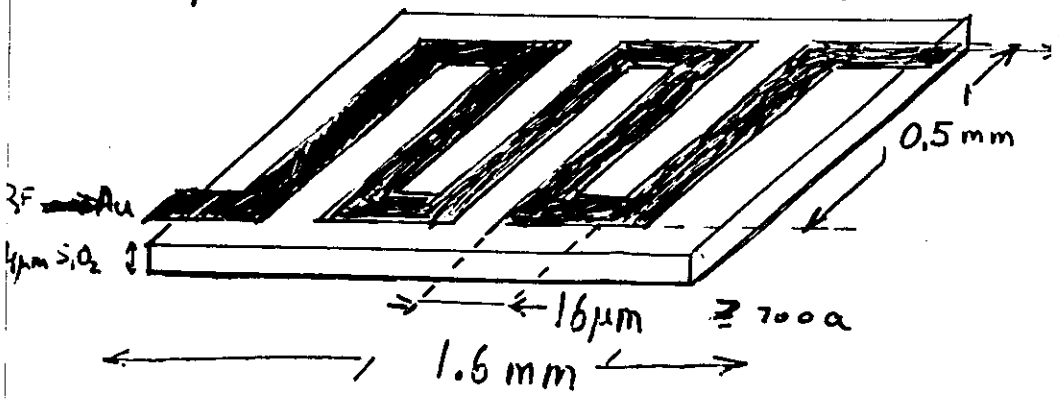
- MEASURE $\omega_-(q)$ at SEVERAL q
- COUPLE ELECTRONS TO MEASURING SYSTEM WITH COMB-LIKE DISPERSION RELATION OF SPATIAL HARMONIC





meander strip line:

$\vec{E} = \sum_p E_p \exp(ipq_0 x)\, e^{i\omega t}\, e^{-pq_0 z}$

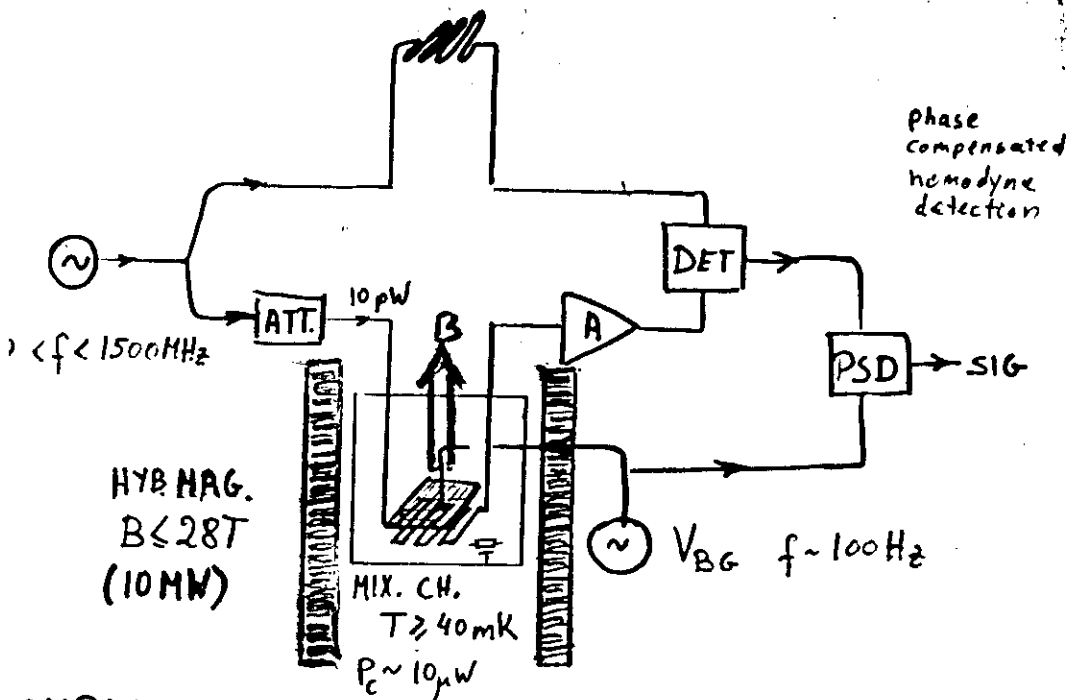


$q_0 = 2\pi/16\mu m \sim 4000\ cm^{-1}$

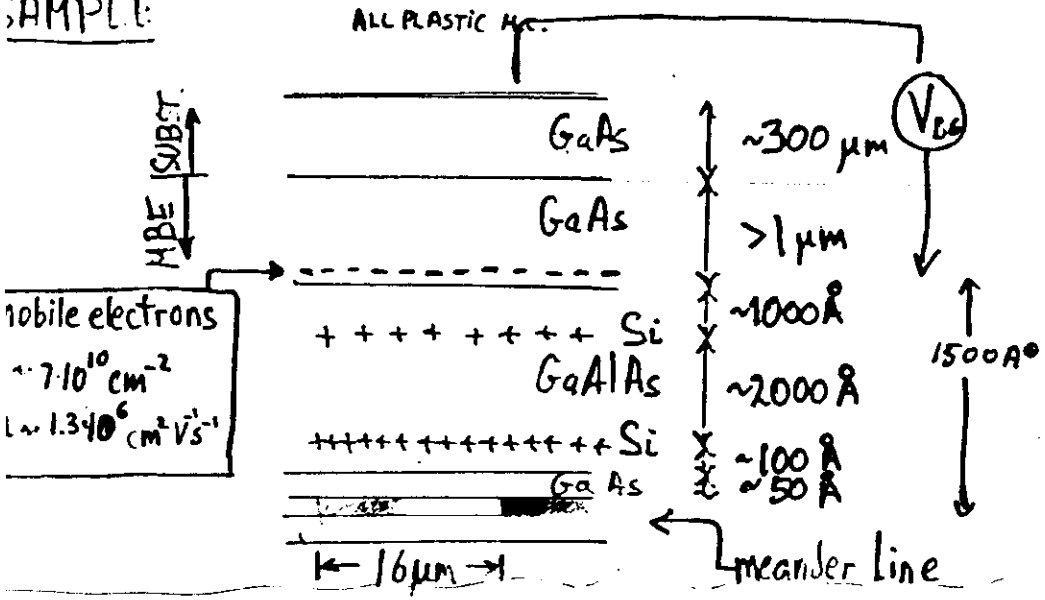
$Z_c \sim 50\Omega$

$E_p \sim e^{-pq_0 z}$ - ELECTRON NEED TO BE WITHIN

'PERIMENT



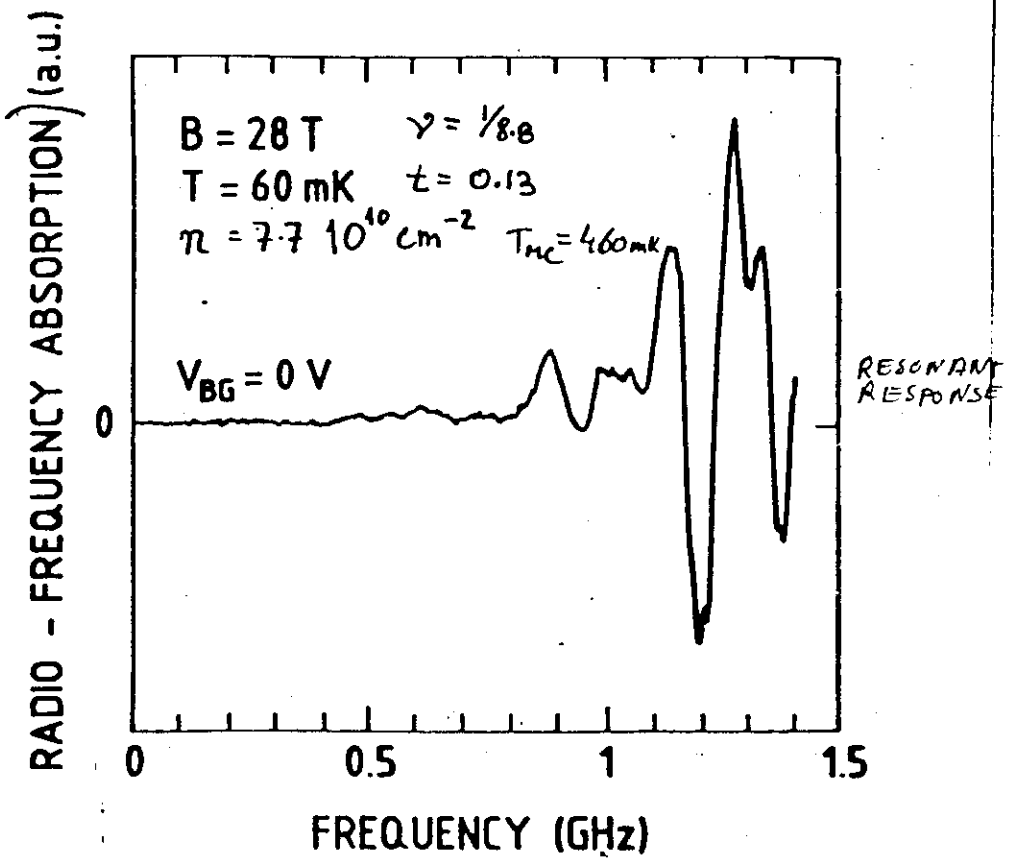
SAMPLE

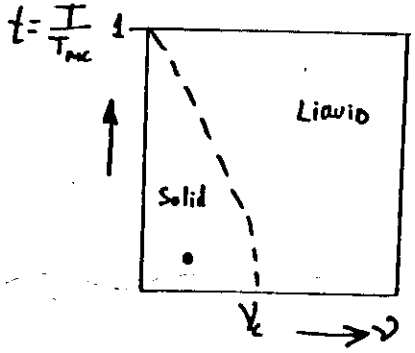


TRANSPORT MEASUREMENT (SIMULTANEOUS)

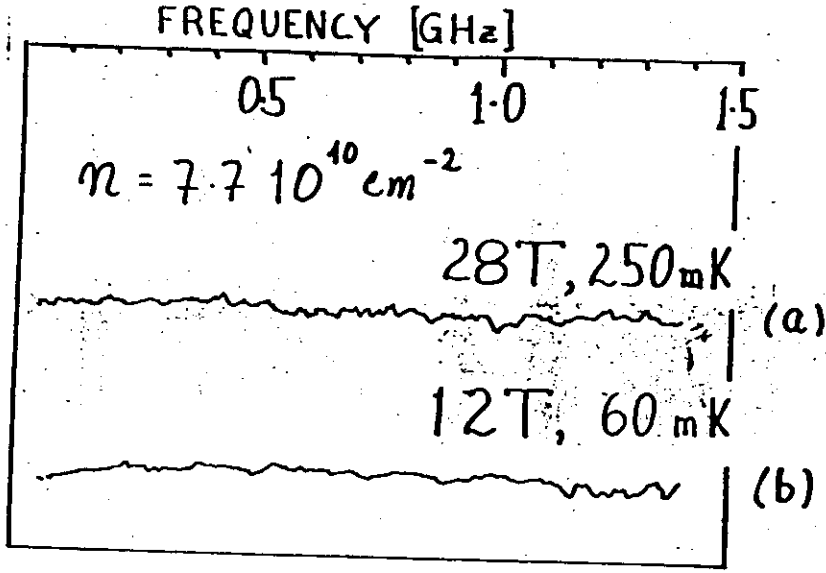
- LOW FREQUENCY (S_{R_H}) guarded measurement
- LOW CURRENT ~ 100 pA/cm
- UP TO 20 MΩ □^-1

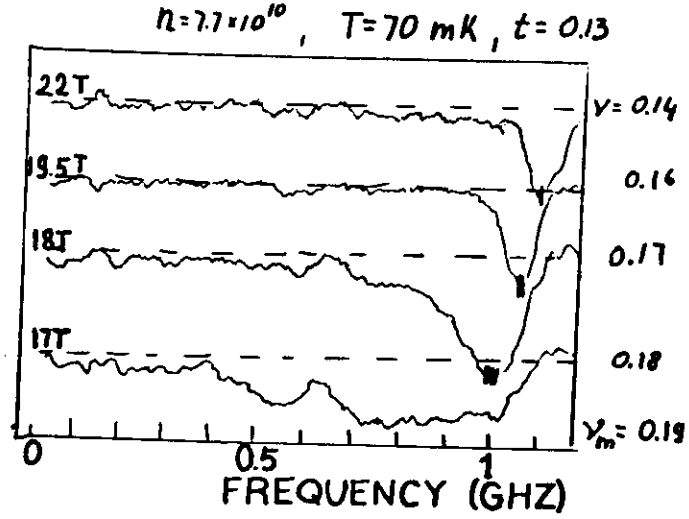
ELECTRON SIGNAL IN THE EXPECTED SOLID PHASE (VERY LOW t and ν)





How does the MIWS signature disappear near melting?

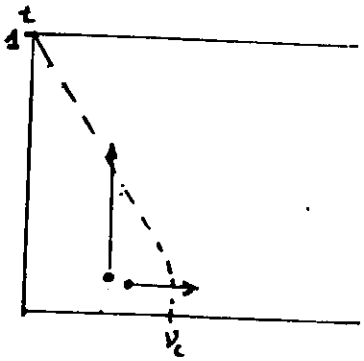




$\omega_- \propto \mu^{1/2}_{(t,\nu)} \xrightarrow[\nu \to \nu_m]{} c$

+ Line broadens

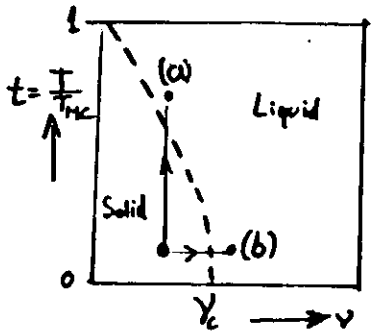
∴ μ Softens near



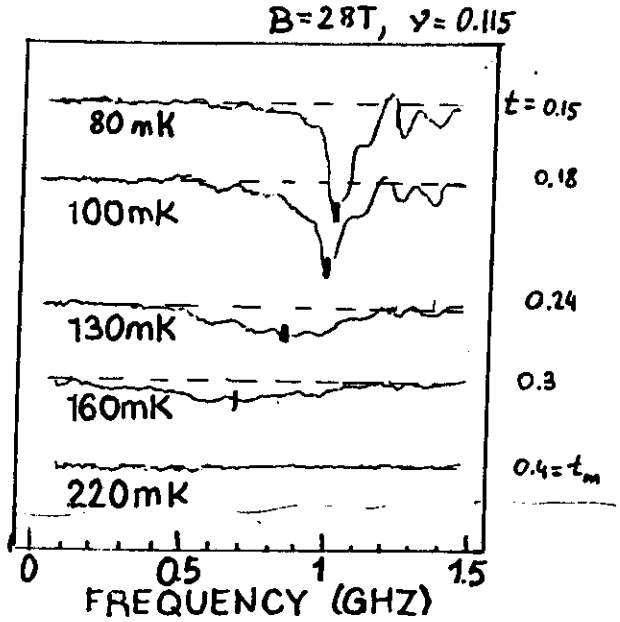
$\omega_- \propto \mu^{1/2}_{(t,\nu)} \xrightarrow[t \to t_m]{} 0$

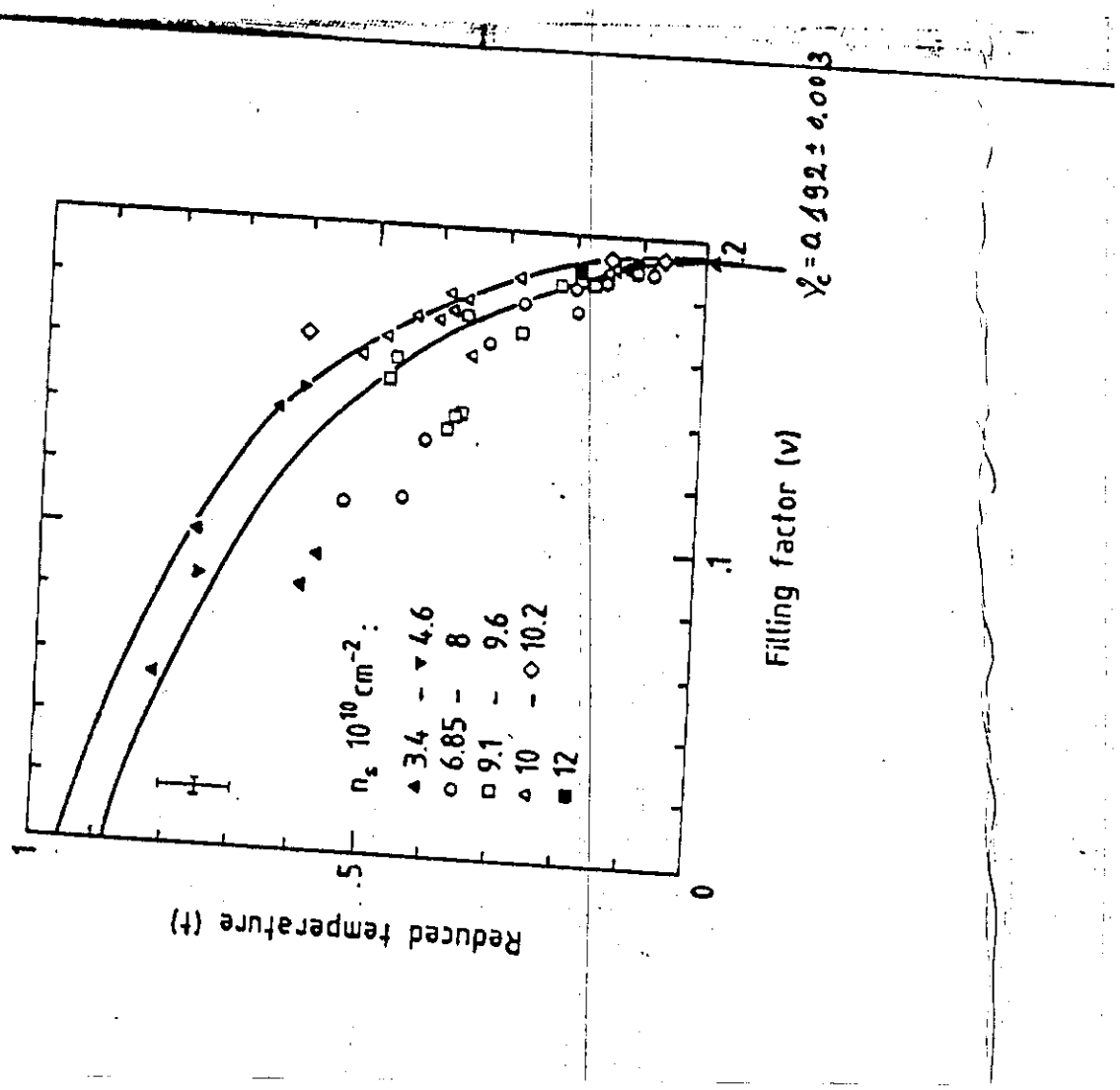
+ Line broadens

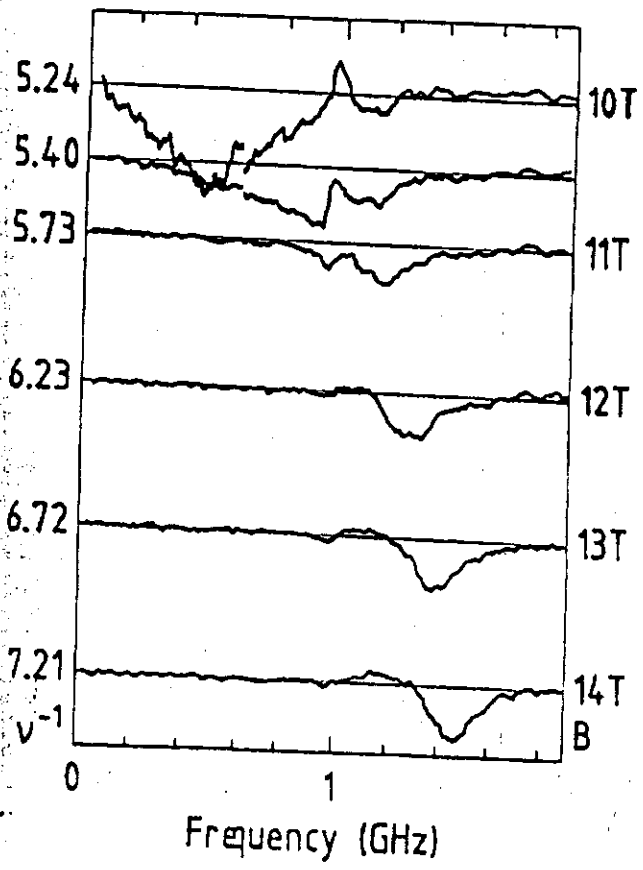
μ Softens near

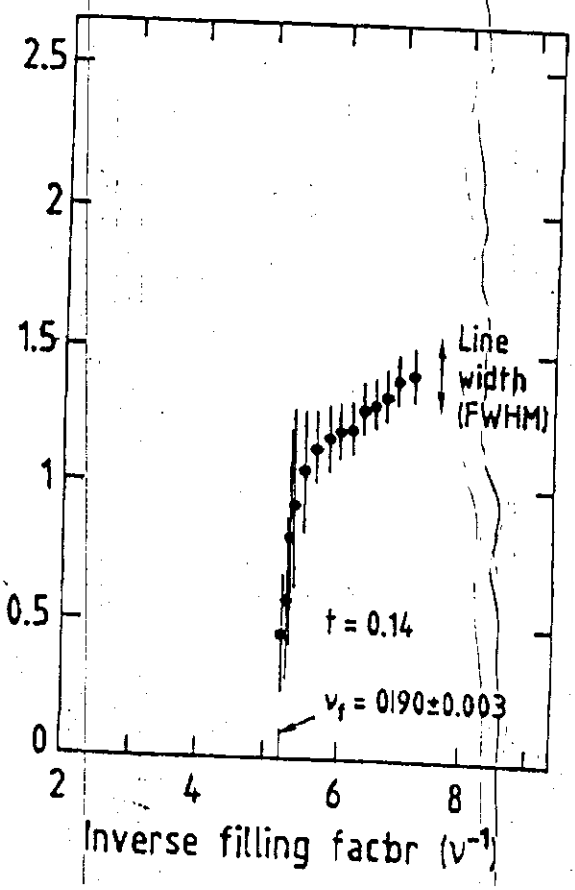


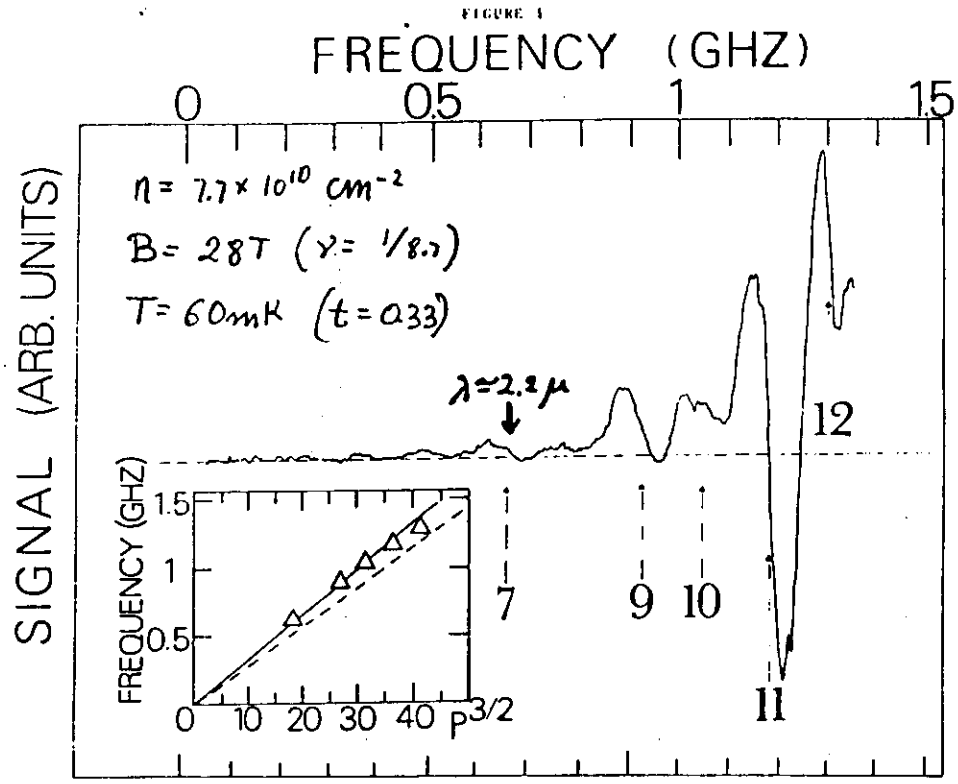
NO ELECTRON SIGNAL IN THE LIQUID PHASE.
(Large t, ν)

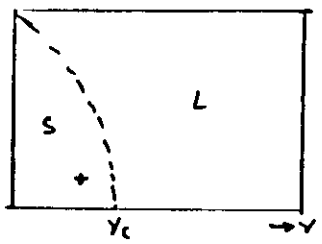



$\gamma_c = 0.192 \pm 0.003$
Filling factor (ν)
Reduced temperature (t)
n_s 10^{10}cm^{-2}:
3.4 - 4.6
6.85 - 8
9.1 - 9.6
10 - 10.2
12
0
.1
.2
.5
1


5.24
5.40
5.73
6.23
6.72
7.21
10T
11T
12T
13T
14T
ν^{-1}
B
0
1
Frequency (GHz)


Line width (FWHM)
t = 0.14
ν_f = 0190±0.003
0
0.5
1
1.5
2
2.5
2
4
6
8
Inverse filling factor (ν^{-1})





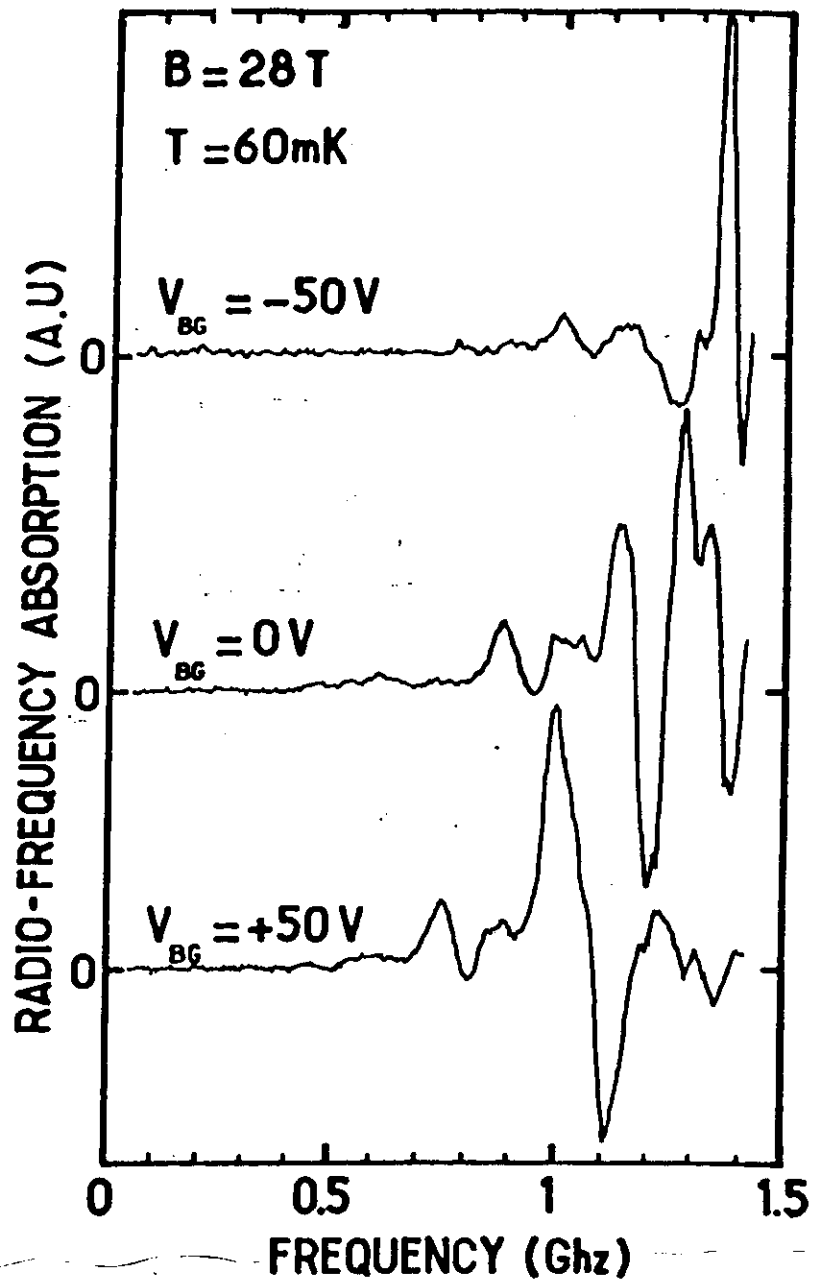
$\omega_- = \frac{\omega_t \omega_c}{\omega_c} \sim \mu^{1/2} q^{3/2}$

$q = p q_0$

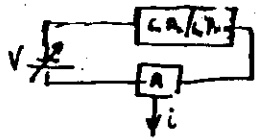
$p = 1, 2, 3 \ldots \quad q_0 = \frac{2\pi}{16\mu} = 3926\,cm^{-1}$

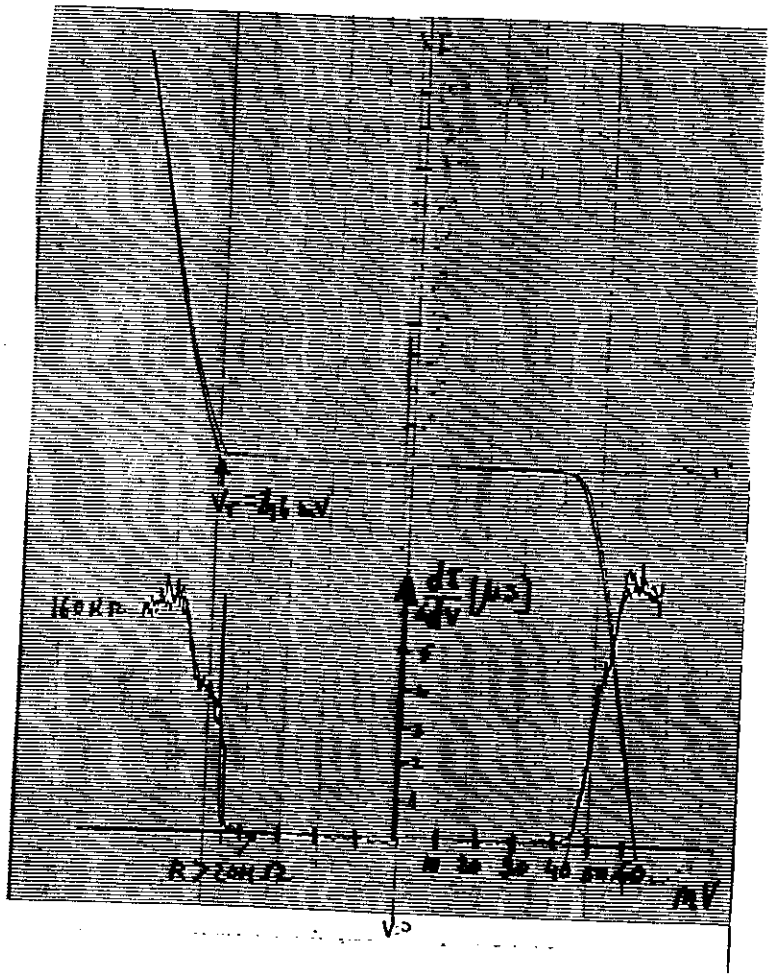
Fit Experimental points to $\omega_- = Const\, p^{3/2}$

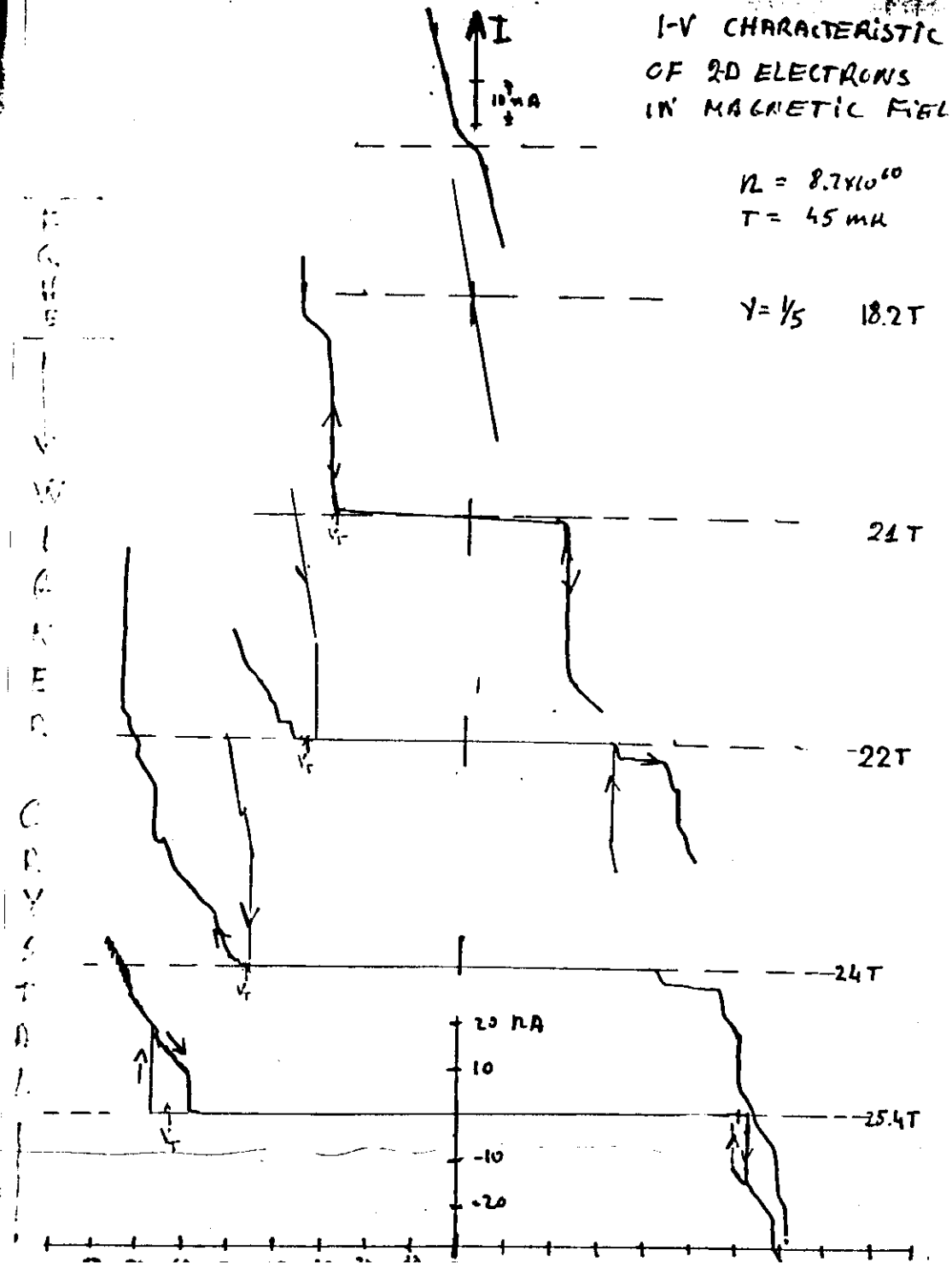
Const. is 10% OFF FROM CALCULATED VALUE IN THE HIGH FIELD LOW T LIMIT.

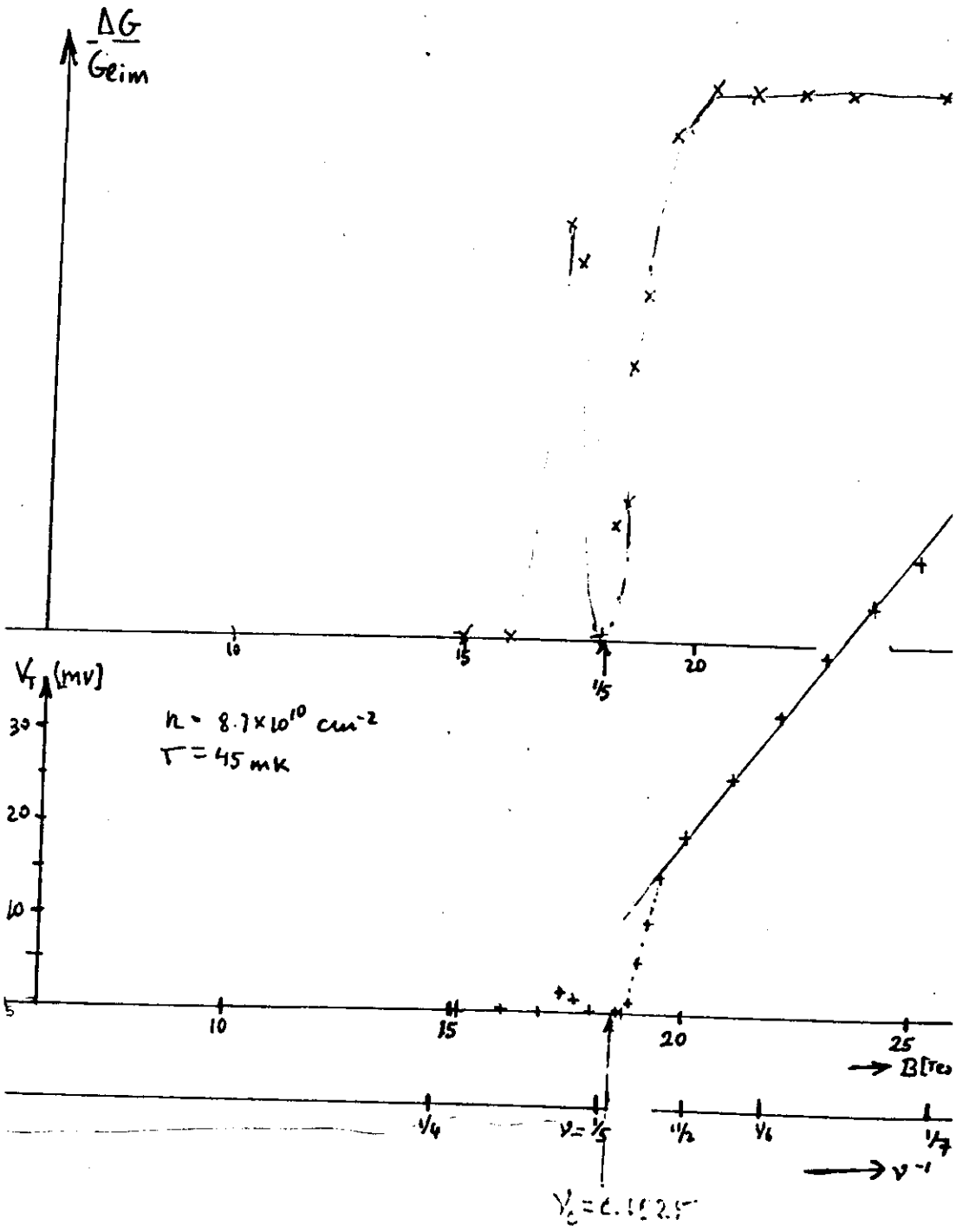


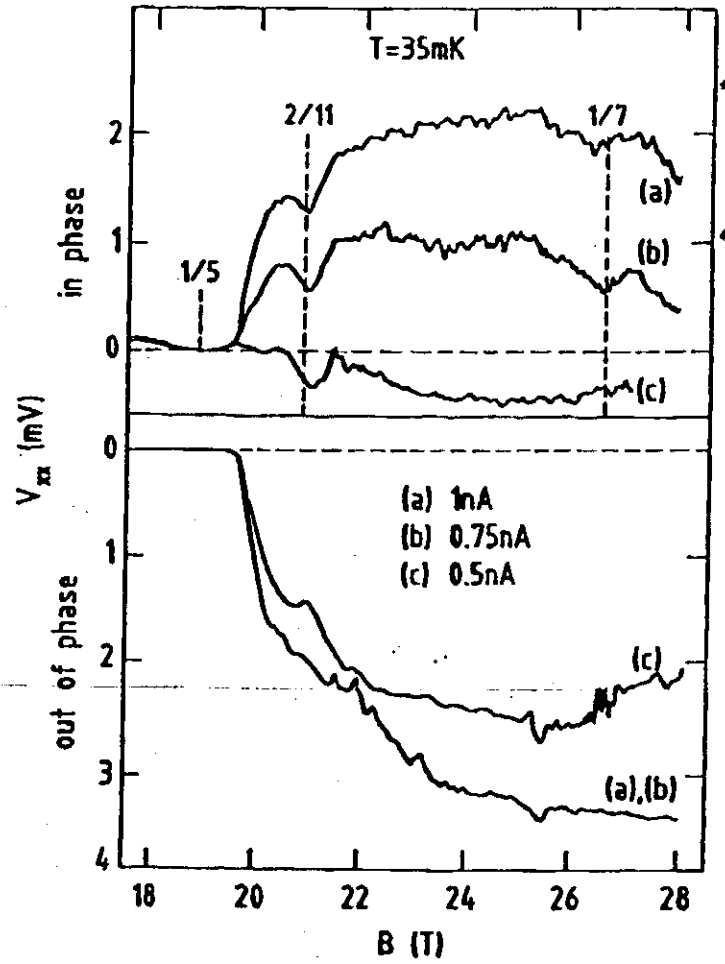
DOES THE WIGNER CRYSTAL CONDUCT CURRENT?





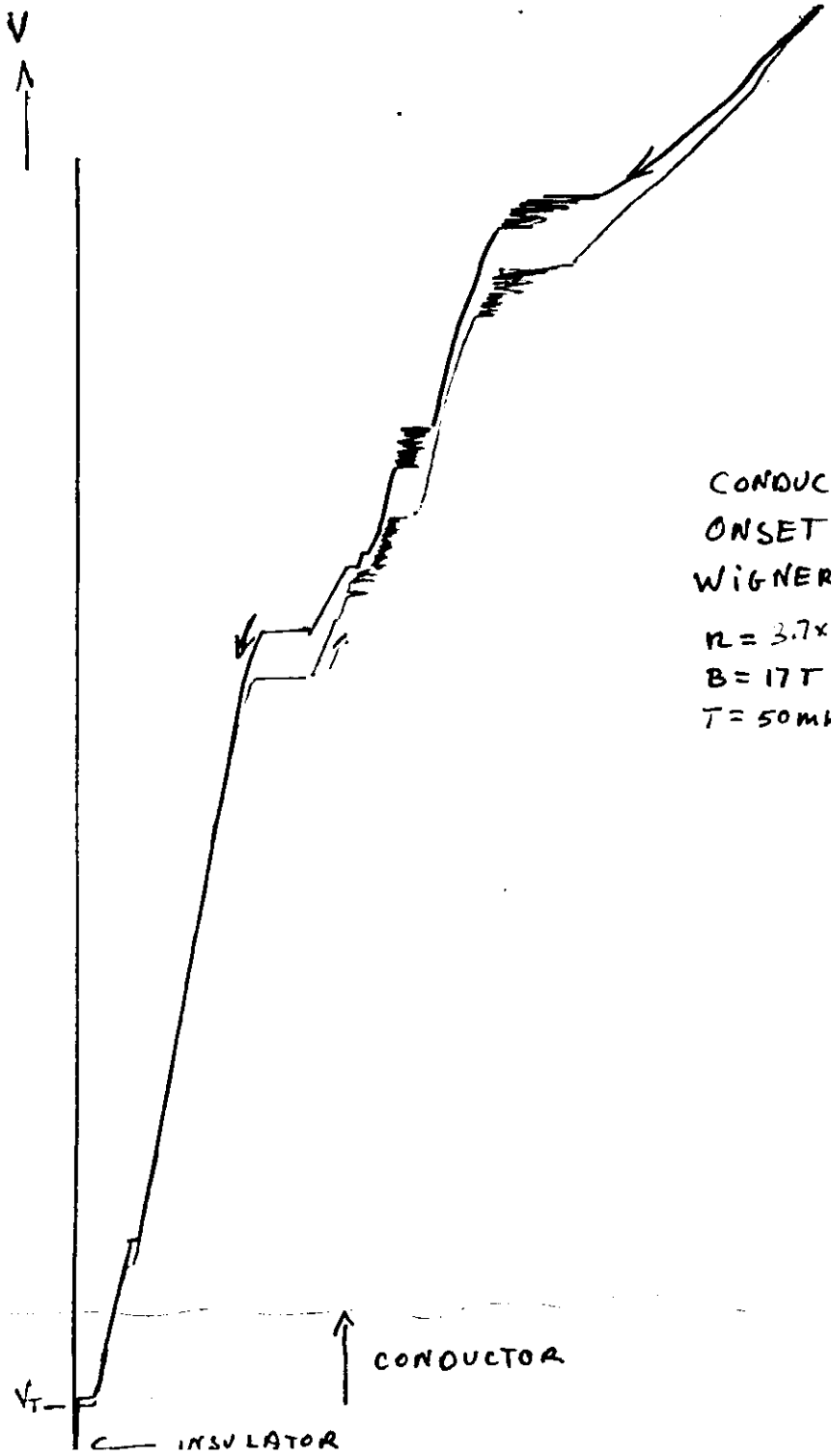






* FEATURE DISAPPEARS FOR T > 100 mK
* NO ANOMALY IN THERMAL BEHAVIOR

$$\delta\theta = \frac{V_T}{i C_s} \frac{2\pi}{T}$$



CONDUCTIVITY ONSET IN WIGNER CRYSTAL

$n = 3.7 \times 10^{11}\ cm^{-2}$

$B = 17\ T$

$T = 50\ mK$

- THE THRESHOLD FIELD BEHAVIOUR IS CHARACTERISTIC OF A DEPINNING FIELD FOR A CHARGE DENSITY WAVE, AS EXPECTED FOR A MIWS OF FINITE DOMAIN SIZE PINNED BY A RANDOM FIELD

- $E_T = \frac{V_T}{L} \sim 30\ mV/cm$ for the lowest T.

- IN THE WEAK PINNING MODEL THE PINNING FREQUENCY

E_T $\qquad \omega_{Pin}^2 = \frac{\pi e E_T}{m a} \Rightarrow f_p \sim 7\ GHz$

AND THE DOMAIN SIZE

$$L_D \sim 5\mu.$$

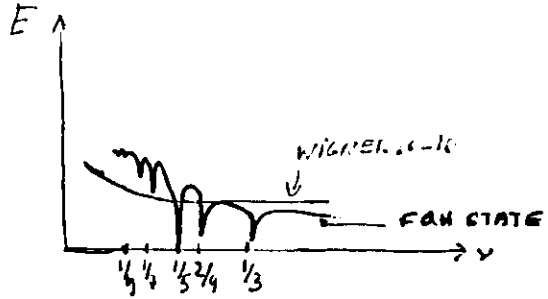
- $$\omega_- = \frac{(\omega_{Pin}^2 + \omega_c^2)^{1/2}(\omega_{Pin}^2 + \omega_p^2)^{1/2}}{\omega_c}$$

at 25 Tesla, $h = 10 L_D$ $\Rightarrow$ $\omega_c = 25\ GHz$, $\omega_p = 400\ GHz$, $\omega_c = 100006Hz$ $\Big\}$ $\gg \omega_{Pin}$

The pinning does not modify our spectrum in a qualitative way.

WHAT HAPPENS TO THE FQHE?

- THE FQHE STATE IS THE GROUND STATE FOR $\nu = 1/r$, $\nu > 2/3$
- $1/5 < \nu < 2/3$ REENTRANT SOLID PHASE
- $\nu \leq 0.192$ WIGNER SOLID



SPECULATIVE
- ENERGY DEPENDENCE ON FILLING FACTOR

- WHAT ABOUT OTHER FRACTIONS?

$T > T_M^L$ · 1/7 – GOLDMAN et al. P.R.L. 61, (911) 881
· 2/11 – WILLETT et al.

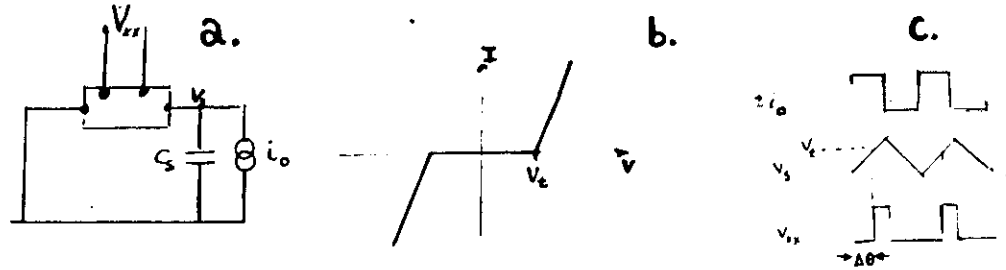
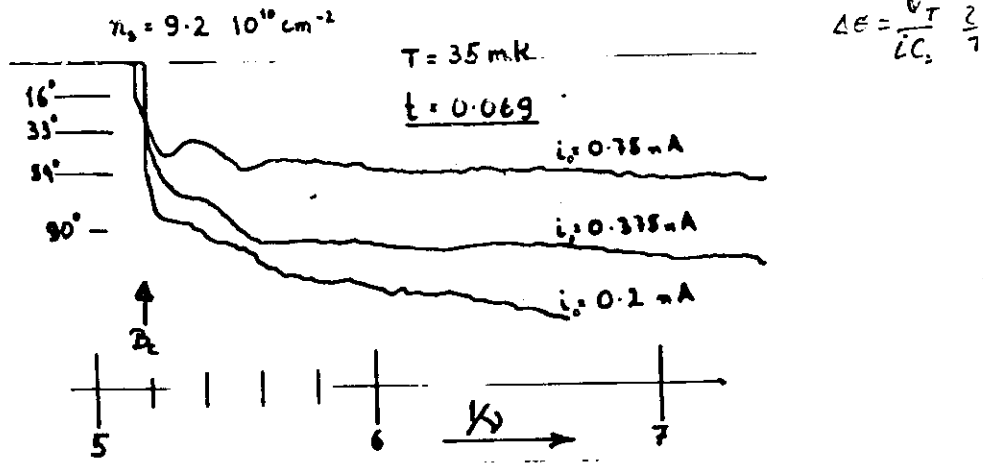


Figure 1. a. Schematic of measurement setup. b. nonlinear impedance of a pinned Wigner solid. C. waveforms of voltage across shunt capacitance and sample with impedance portrayed in b in response to a square wave applied current.



$\Delta\theta = \frac{V_T}{iC_s}\frac{2}{7}$

Figure 2. Field dependence of phase lag of longitudinal voltage V_{xx} with respect to current source for three different source current amplitudes.

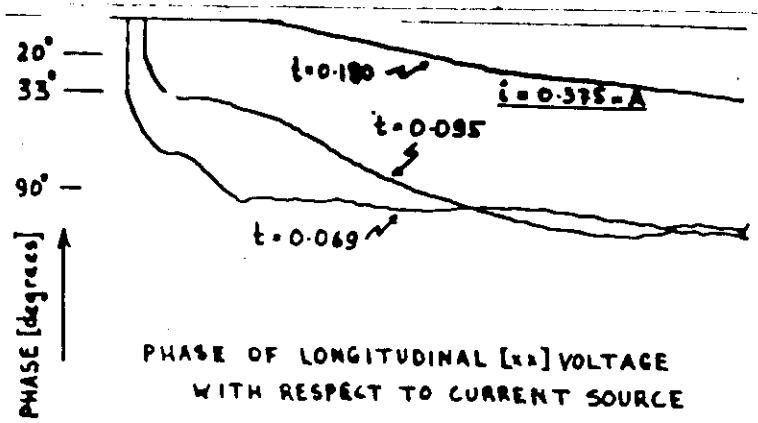


Figure 3. Field dependence of phase lag $\Delta\Theta$ for three different temperatures. $t = T/T_{MC}$ is the reduced temperature.

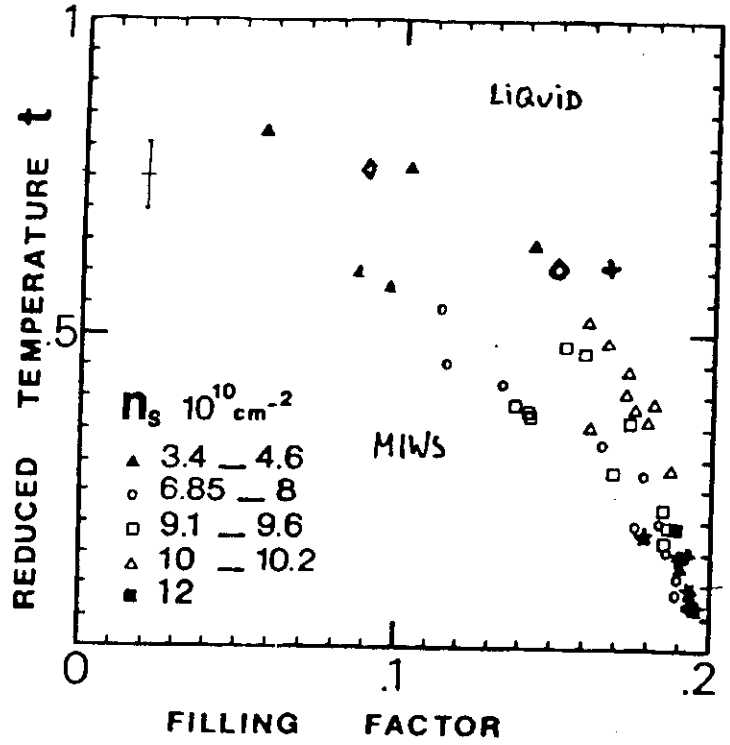


Figure 4. Phase diagram of MIWs melting as obtained from r.f. measurements. ★ are the points obtained from phase lag discontinuity measurements.

SUMMARY

OUR EXPERIMENTAL RESULTS SUGGEST: THE LIQUID SOLID TRANSITION OF THE 2DES

IN THE CLASSICAL REGIME IS MEDIATED BY UNBINDING OF PAIRED DISLOCATIONS K.T. N.H.Y.

- $T_M = T_{KT}$
- NO LATENT HEAT AT MELTING

IN THE QUANTUM REGIME THE MAGNETICALLY INDUCED WIGNER SOLID OCCURS FOR

- $\nu \leq 0.192$
- THE WIGNER CRYSTAL BEHAVES LIKE A PINNED CHARGE DENSITY WAVE. THE PINNING THRESHOLD APPEARS ABRUPTLY AT THE LIQUID-SOLID TRANSITION, AND SIMULTANEOUSLY WITH THE ONSET OF ELASTIC RESPONSE TO SHEAR