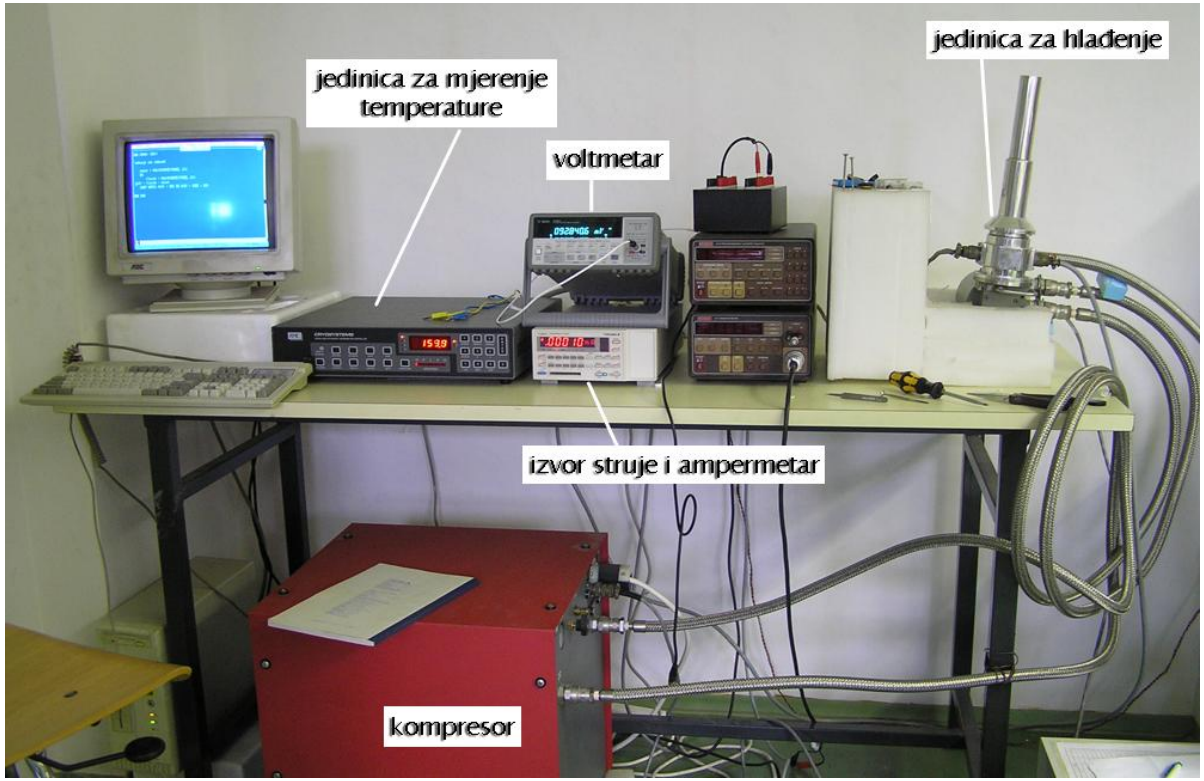
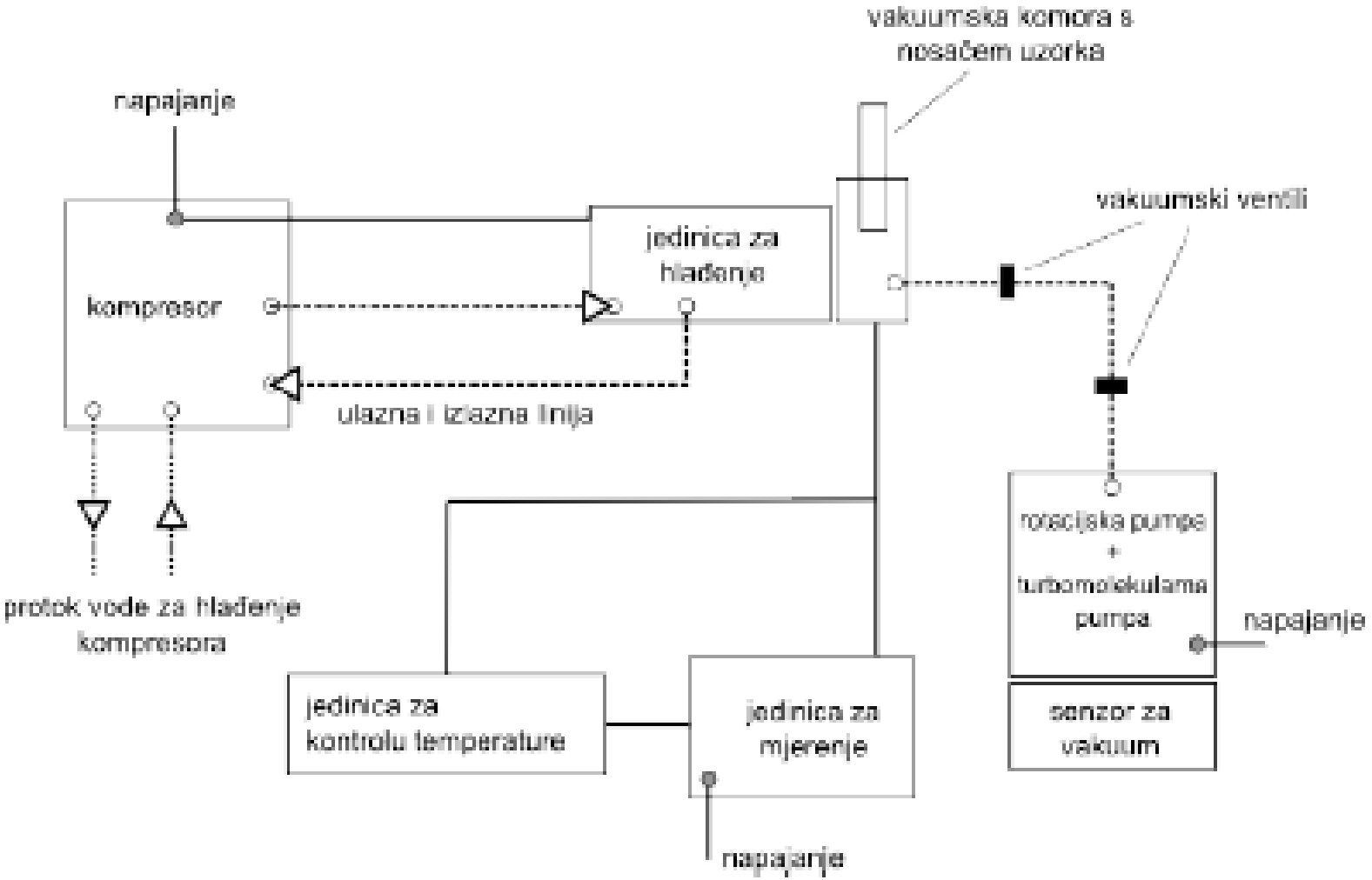
Postav za mjerenje otpornosti

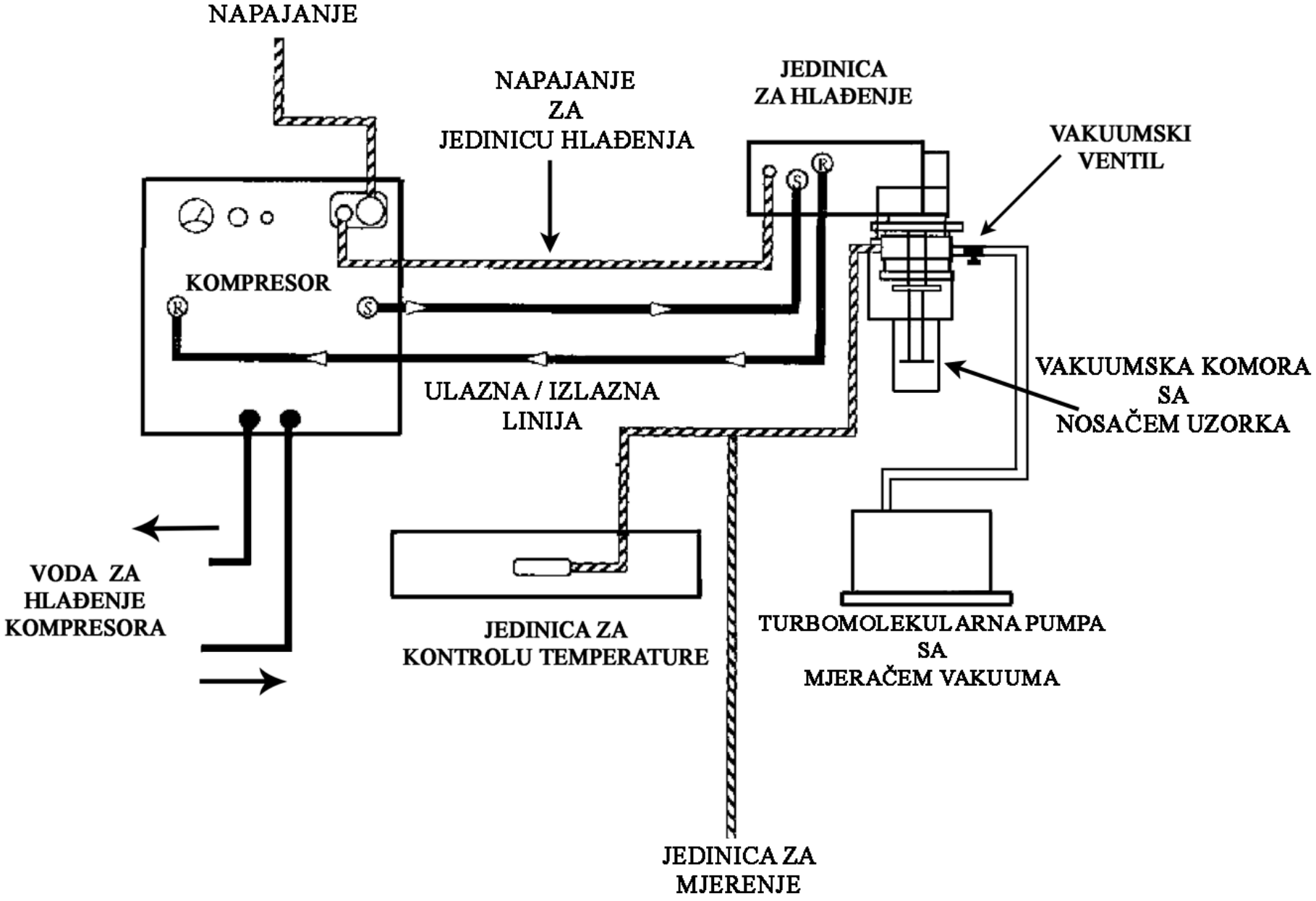


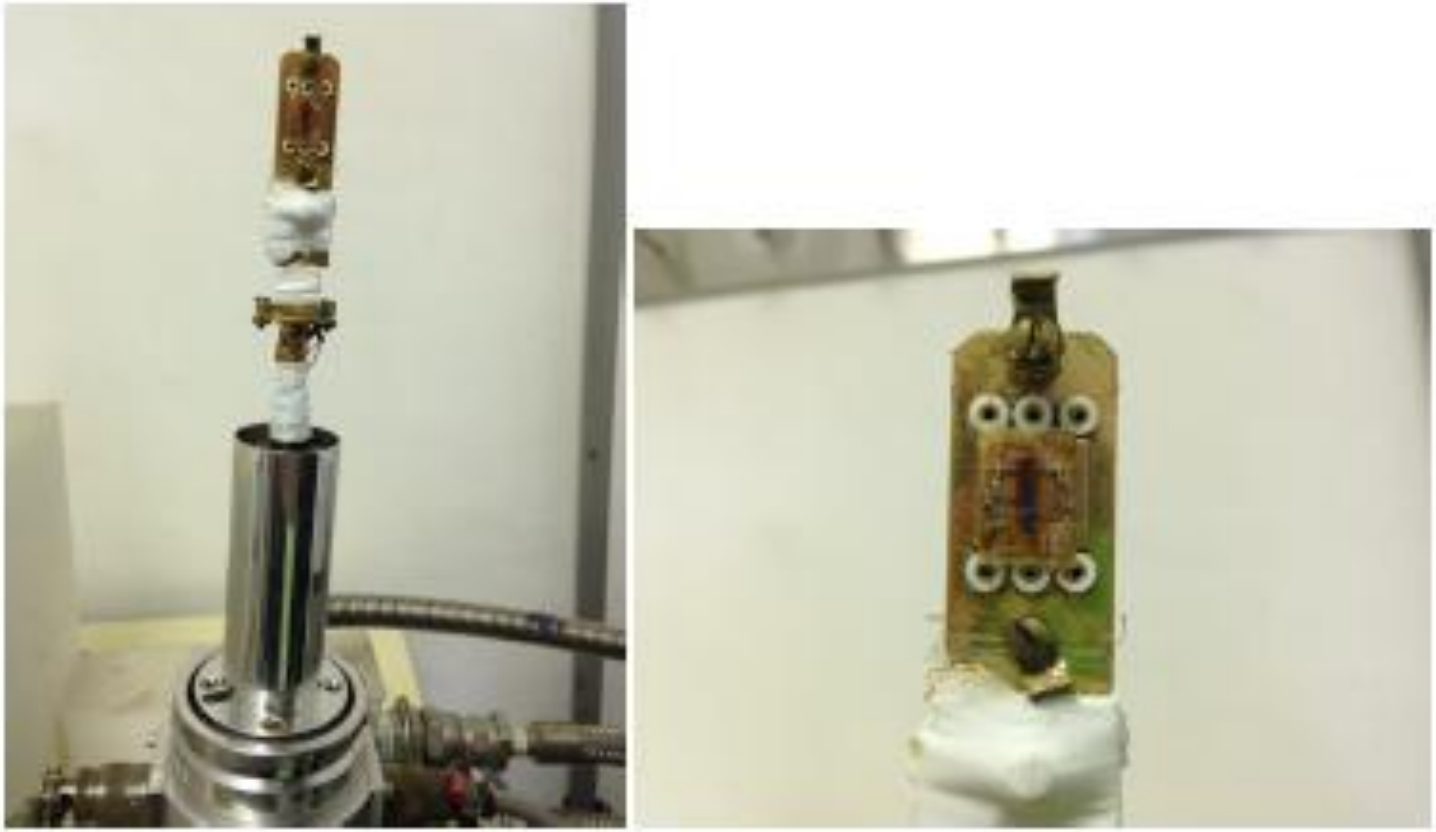
- Mjerenje istosmjernom strujom, metodom četiri kontakta, u području 10-290 K
- Za hlađenje je korišten hladnjak sa zatvorenim ciklusom (CCR)
- Procesom upravlja prilagođeni računalni program
- Turbomolekularna pumpa održava vakuum (10^-6 Pa)
- Silazno i uzlazno temperaturno ovisno mjerenje napona



Slika 4.15: Shema mjernog postava.

Cijeli postav može se podjeliti na sustav za hlađenje i sustav za mjerenje.


NAPAJANJE
NAPAJANJE ZA JEDINICU HLAĐENJA
JEDINICA ZA HLAĐENJE
VAKUUMSKI VENTIL
KOMPRESOR
R
S
R
S
ULAZNA / IZLAZNA LINIJA
VAKUUMSKA KOMORA SA NOSAČEM UZORKA
VODA ZA HLAĐENJE KOMPRESORA
JEDINICA ZA KONTROLU TEMPERATURE
TURBOMOLEKULARNA PUMPA SA MJERAČEM VAKUUMA
JEDINICA ZA MJERENJE



Slika 4.14: Otvorena komora s uzorkom na stalku.

Postavljanje kontakata na uzorak

Na uzorak je potrebno postaviti četiri kontakta (dva naponska i dva strujna). Uzorci su izrezani iz trake metalnog stakla dobivene "melt spinning" metodom

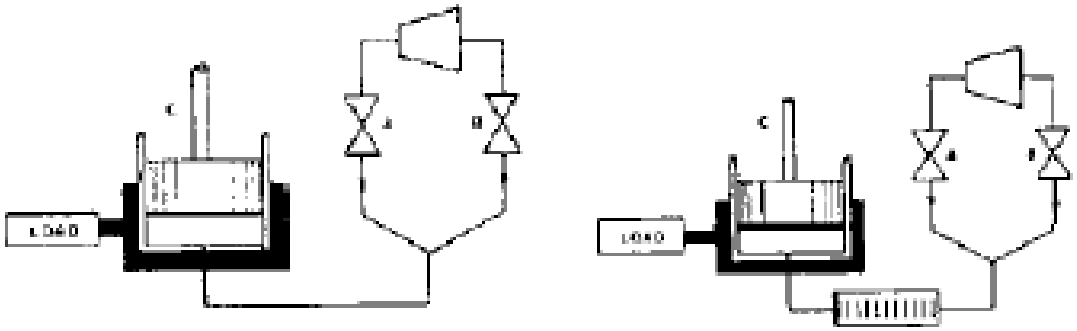
Dugi su oko $5mm$, široki $1.5mm$ i debeli $0.03mm$, slika (4.14). Kontakti se rade tako da se tanka bakrena žica kontaktno vari na uzorak. Kontaktno varenje radi se s uređajem prikazanim na slici (4.13). U uređaju se nabija kapacitor. Pincetom koja ima bakrene krajeve, koji su spojeni u krug s kapacitorom, pritisne se bakrena žičica na uzorak i zatim se kapacitor, preko sklopke, isprazni i žičica se zavari za uzorak.

Slika 4.13: Aparat za varenje.

Sustav hlađenja čine helijev hladnjak (CHR), koji se sastoji od kompresora i rashladne jedinice te sustava za postizanje vakuuma, kojeg čine rotacijska i turbomolekularna vakuumska pumpa i senozr za vakuum.

Helijev hladnjak radi na istom principu kao i obični hladnjak samo što umjesto freona, kao rashladnog plina, koristi helij. Radna temperatura helijevog hladnjaka je, za razliku od običnog, na destak K. Kompresor se podmazuje uljem i hladi vodom tijekom rada. Rashladna jedinica se sastoji od cilindra i klipa te dva ventila i radi na manjim brzinama nego kompresor. Kompresor i rashladna jedinica su odvojeni ($\sim 2m$).

Tok helija u hladnjaku je ciklički, a shema rada prikazana je na slici (4.16).

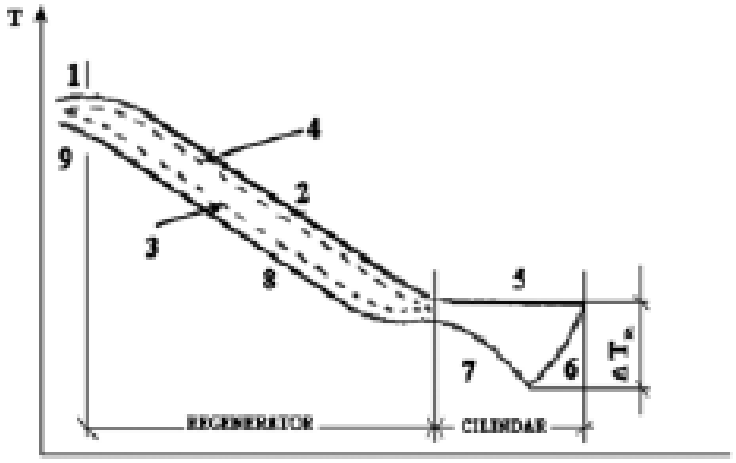


(a) (b)

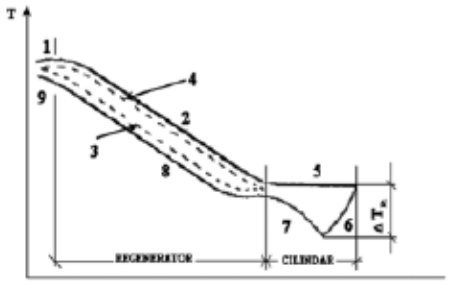
Slika 4.16: Shema rada helijevog hladnjaka. a) bez regeneratora, b) s regeneratorom.

Izvor komprimiranog plina povezan je s cilindrom C preko ulaznog ventila A.

B je izlazni ventil koji propušta plin niskog tlaka natrag u kompresor. U početku ciklusa klip je na dnu cilindra, ventil A se otvara i cilindar se uz podizanje klipa puni komprimiranim plinom. B ventil je zatvoren. Zatim se A ventil zatvara, a B ventil otvara i komprimirani plin ekspandira pri čemu se hladi. Plin u cilindru je sada hladniji od komore koja se hladi i ona predaje toplinu plinu preko zidova cilindra. Klip se zatim spušta i ispumpava preostali plin koji odlazi kroz otvoreni B ventil. Međutim, opisani ciklus neće postići željeno hlađenje. Potrebno je ulazni plin ohladiti izlaznim plinom prije nego on uđe u cilindar. To se postiže regeneratorom koji izvlači toplinu iz ulaznog plina, sprema je, i zatim predaju izlaznom plinu. Regenerator je napravljen od materijala velike efektivne površine, velikog toplinskog kapaciteta i male toplinske vodljivosti. Toplinski profil ciklusa s regeneratorom je na slici (4.17).



Slika 4.17: Temperaturni profil ciklusa s regeneratorom.



Slika 4.17: Temperaturni profil ciklusa s regeneratorom.

Koraci u ciklusu su sljedeći:

a) Klip je na dnu cilindra. Komprimirani plin, sobne temperature, ulazi u kroz ventil A (1).

b) Klip se podiže, a plin prolazi kroz regenerator koji apsorbira toplinu iz plina pri čemu se zagrijava (3-4). Plin se hladi (2).

c) Ohlađeni plin pod tlakom puni cilindar. Temperatura plina je sada praktički jednaka temperaturi komore koja se hladi (5).

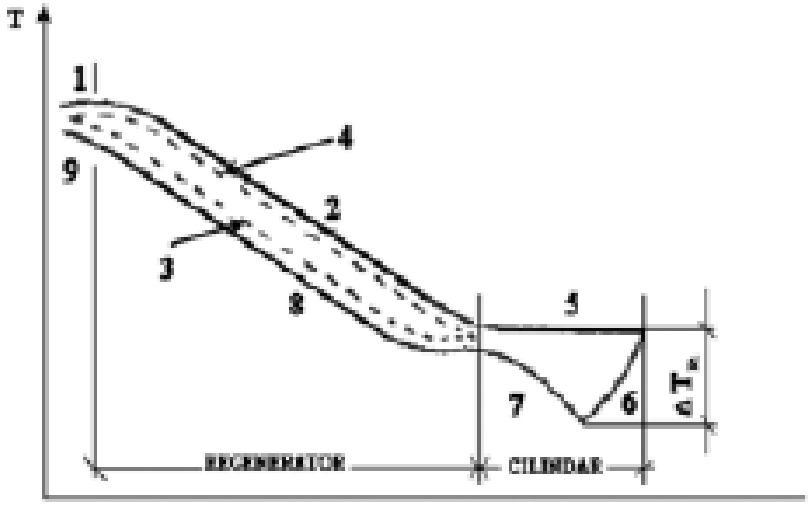
d) Zatvara se ulazni ventil A, a otvara se izlazni B. Plin ekspandira i dodatno se ohladi za temperaturu ΔT (6).

e) Toplina iz komore prolazi preko zidova cilindra na plin i zagrijava ga na temperaturu blisku onoj na kojoj je bio kada je ušao u cilindar (7).

f) Prilikom ekspanzije dio plina prolazi kroz regenerator i zagrijava se (8) tako što preuzima toplinu od regeneratora koji se pritom hladi (4-3).

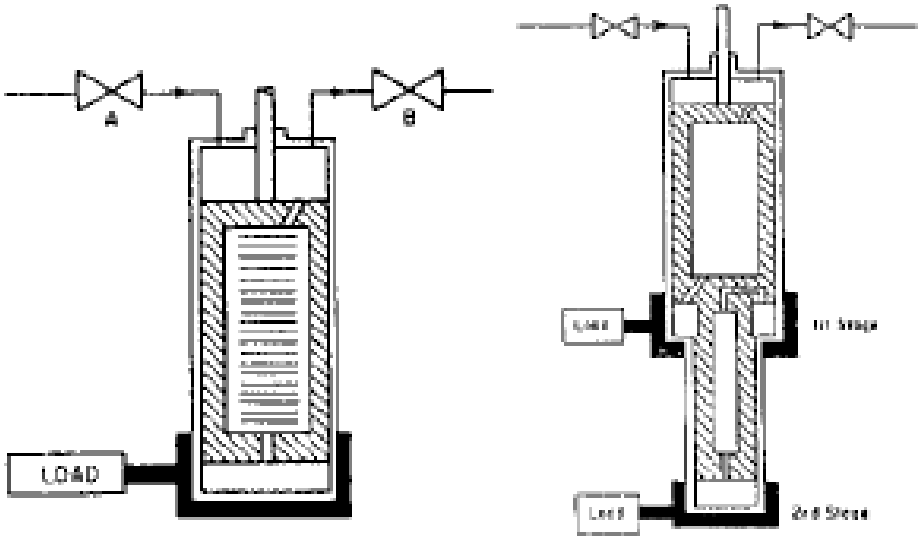
g) Klip se spušta i istiskuje ostatak hladnog plina kroz regenerator. Zbog efikasnosti regeneratora koja je manja od 100% uvijek postoji razlika u temperaturi regeneratora i plina pa je izlazni plin, u bilo kojoj točki dijagrama, uvijek malo hladniji nego ulazni plin.

h) Plin pod niskim tlakom i približno na sobnoj temperaturi napušta jedinicu za hlađenje kroz ventil B (9). Plin odlazi u kompresor gdje se tlači i pri tome održava na sobnoj temperaturi, a zatim ulazi u novi ciklus.



Slika 4.17: Temperaturni profil ciklusa s regeneratorom.

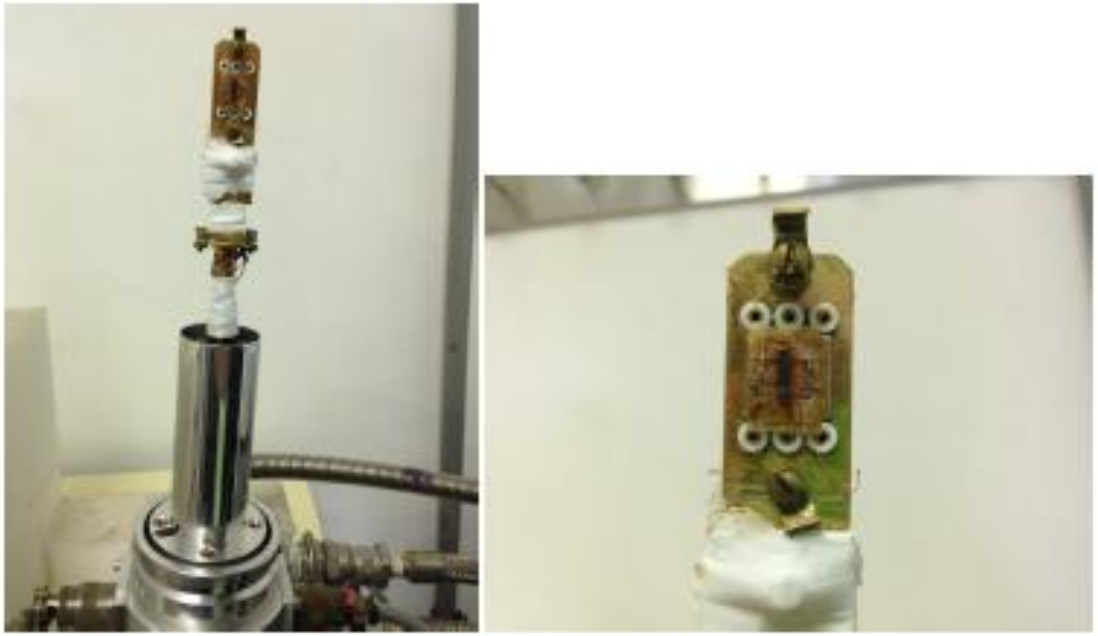
U praksi se regenrator nalazi unutar samog klipa. Cilindar je zatvoren s obje strane, a plin prolazi kroz klip u kojem je regenerator, slika (4.18). Na taj način pojednostavljuje se izvedba rashladne jedinice jer, u ovom slučaju, se tlakovi s dvije strane cilindra brzo izjednače i nije potrebno korištenje visokotlačnih brtvi i sile na klip su puno manje. Sustav s jednim regeneratorom može hladiti na temperature u rasponu od $30 - 80K$. Dodavanjem drugog (nekad i trećeg) regeneratora postižu se temperature ispod $10K$. U sustavu s dva regeneratora postoje tri prostora unutar cilindra u kojima se plin može nalaziti. Između gornjeg i srednjeg dešava se prvi stupanj hlađenja, a između srednjeg i donjeg drugi stupanj hlađenja, slika (4.18b).



(a) (b)

Slika 4.18: Klip s regeneratorom u cilindru. a) jedan regenerator, b) dva regeneratora.

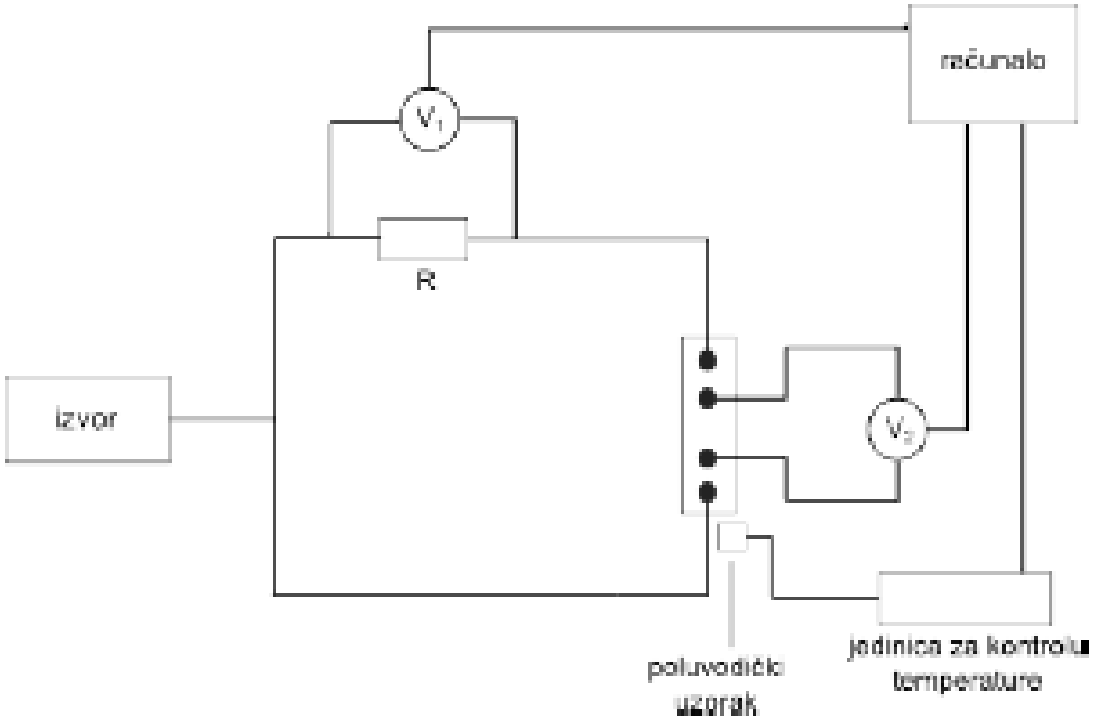
Stalak s uzorkom se nalazi u komori koja se hladi. Čitavo vrijeme u komori se održava visoki vakuum ($< 10^{-8} mbar$). Vakuumom se postiže bolja termalna izolacija, ali se i sprječava utjecaj kondenzata na mjerenje otpora. Prilikom hlađenja, ukoliko u komori ima vodene pare ili dušika, oni će se kondenzirati na uzorku što će utjecati na mjerenje. Vakuum se postiže rotacijskom i turbomolekularnom pumpom. Najprije s radom kreće rotacijska pa se na tlaku od oko $10^{-8} mbar$ pali i turbomolekularna pumpa. Stanje vakuuma prati se senzorom za vakuum.



Slika 4.14: Otvorena komora s uzorkom na stalku.

Sustav za mjerenje sastoji se od mjerne jedinice i jedinice za kontrolu temperature. Mjernu jedinicu čine izvor (*Yokagava*), dva voltmetra (*Agilent 34401A*), otpornik i računalo. Jedinica za kontrolu temperature (*LakeShore*) mjeri temperaturu uzorka.

Shema sustava za mjerenje je na slici (4.19).



Slika 4.19: Shema postava za mjerenje otpora.

Gornja shema prikazuje DC metodu mjerenja. Na nekoliko uzoraka napravljena je i AC metoda. Kod AC metode korišteno je lock-in pojačalo koje je istovremeno služilo i kao izvor. Općenito AC mjerenje pokazivat će manje šuma. Naime, kod DC mjerenja, ukoliko se koriste manje struje (prevelika struja može zagrijati uzorak), mogu se pojaviti određeni kapacitivni doprinosi zbog nehomogene raspodjele struje između kontakata. Kod AC metode takvi doprinosi biti će eliminirani jer lock-in pojačalo može odvojiti samo signal koji je u fazi s referntnim signalom, a taj predstavlja samo Ohmski doprinos otporu koji želimo mjeriti. AC metodom se izbjegava i šum koji dolazi od toga što se, kod DC mjerenja, temperatura između $+I$ i $-I$ može razlikovati. Pokazalo se, ipak, da DC metoda sa strujom od $5mA$ (što i dalje nije prevelika struja) daje gotovo iste rezultate kao i AC metoda za manje struje.
Jedinica za kontrolu temperature ima poluvodički uzorak koji se nalazi u komori u blizini mjerenog uzorka i neovisno o izvoru mjeri mu otpor metodom četiri kontakta. Jedinica za kontrolu temperature pokazuje temperaturu dobivenu iz poznate temperaturne ovisnosti otpora poluvodiča.

Table C-1. Comparison of Liquid Helium and Liquid Nitrogen

PROPERTY	LIQUID HELIUM	LIQUID NITROGEN
Boiling Point @1 atm, in K	4.2	77
Thermal Conductivity (Gas), w/cm–K	0.083	0.013
Latent Heat of Vaporization, Btu/liter	2.4	152
Liquid Density, pounds/liter	0.275	0.78

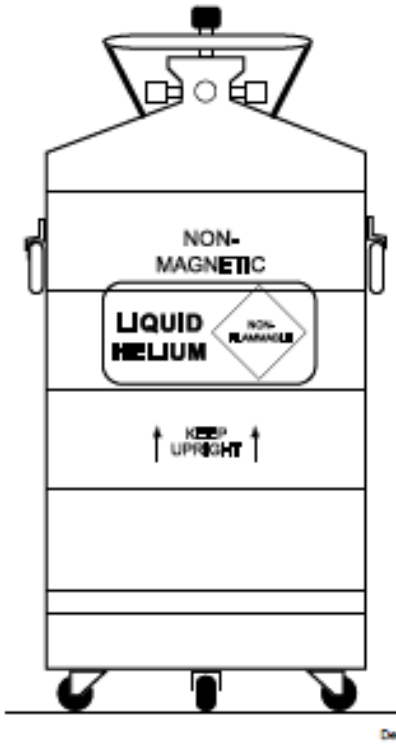


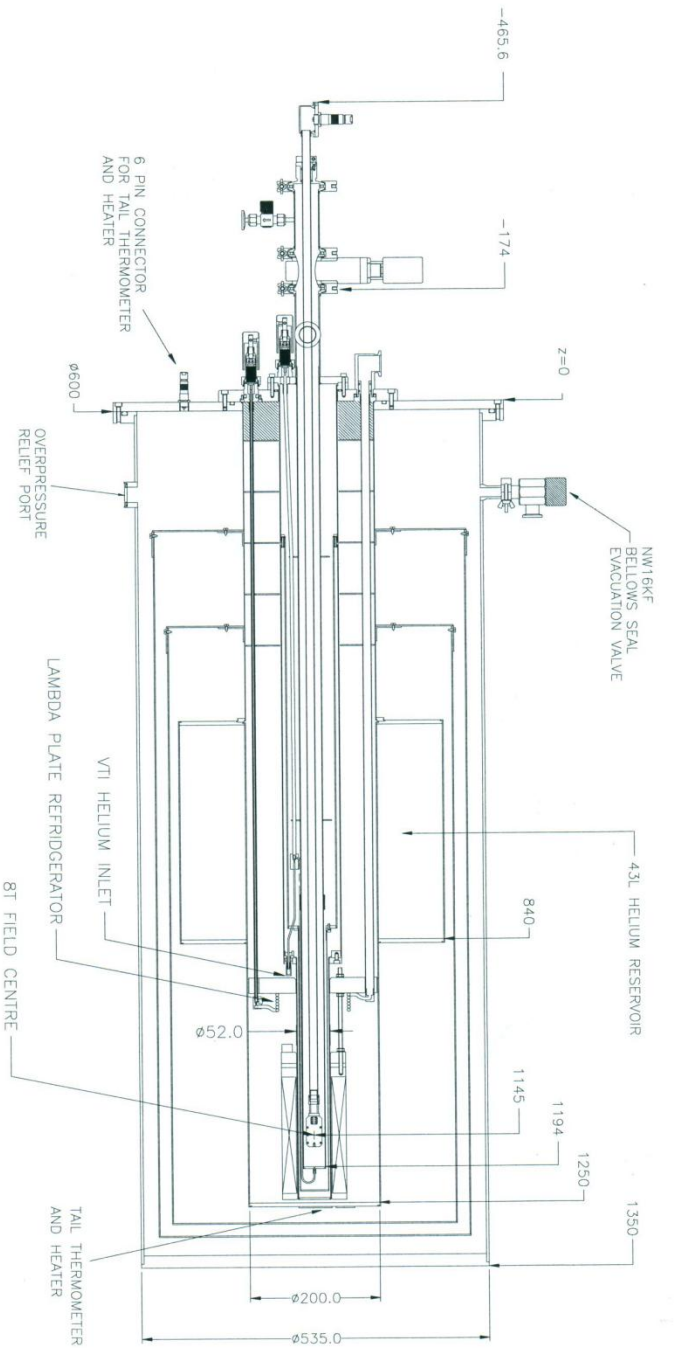
Figure C-1. Typical Cryogenic Storage Dewar

Table B-2. Recommended SI Values for Physical Constants

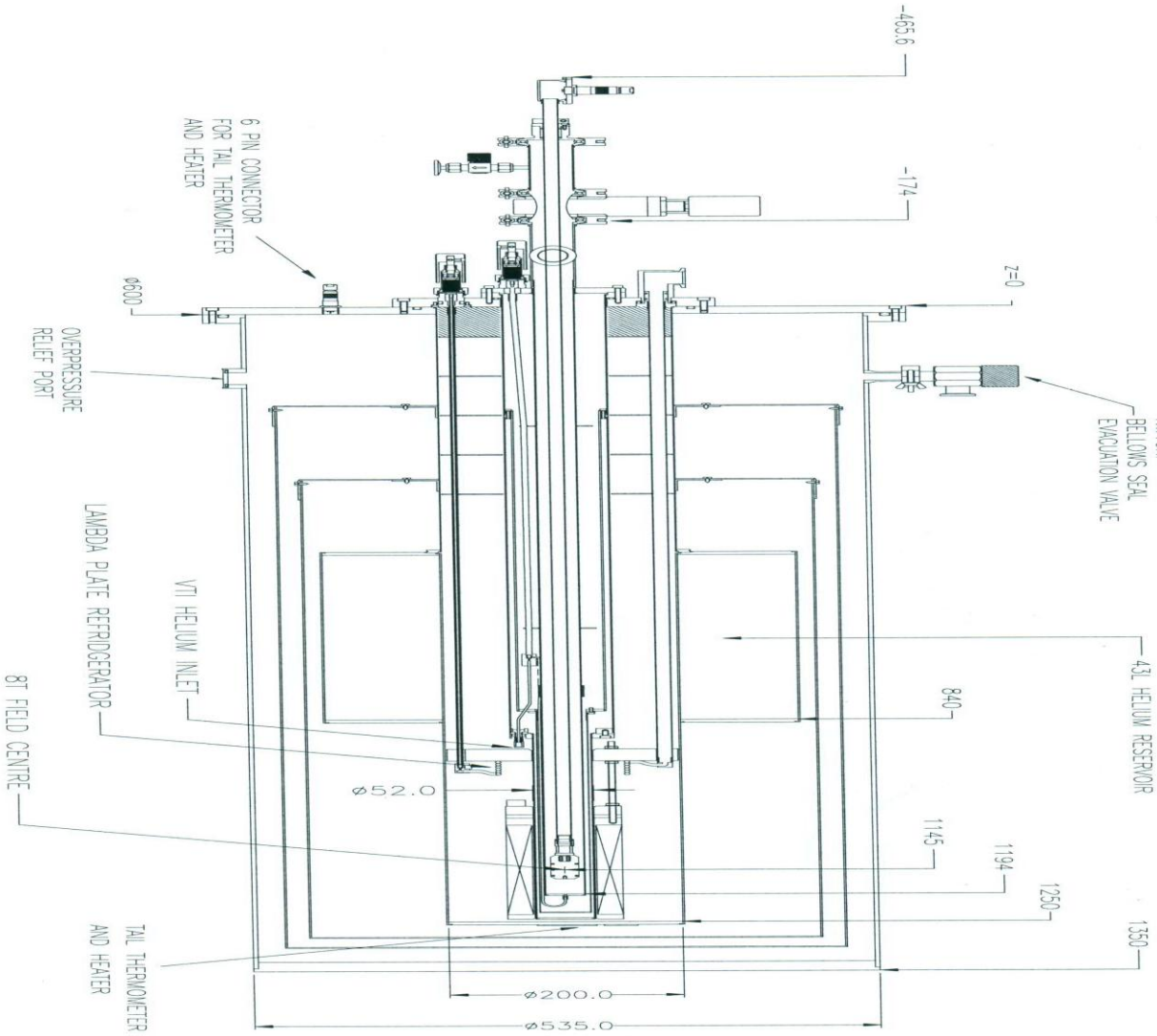
Quantity	Symbol	Value (SI units)
Permeability of Vacuum	μ_0	$4\pi \times 10^{-7}$ H m^{-1}
Speed of Light in Vacuum	c	2.9979×10^{8} m s^{-1}
Permitivity of Vacuum	$\varepsilon_0 = (\mu_0 c^2)^{-1}$	8.8542×10^{-12} F m^{-1}
Fine Structure Constant, μ0ce2/2h	α α^{-1}	0.0073 137.0360
Elementary Charge	e	1.6022×10^{-19} C
Plank's Constant	h $h = h/2\pi$	6.6262×10^{-34} J Hz^{-1} 1.0546×10^{-34} J s
Avogadro's Constant	N_A	6.0220×10^{23} mol^{-1}
Atomic Mass Unit	$1\ u = 10^{-3}$ kg mol$^{-1}/N_A$	1.6605×10^{-27} kg
Electron Rest Mass	m_e	0.9109×10^{-30} kg 5.4858×10^{-4} u
Proton Rest Mass	m_p	1.6726×10^{-27} kg 1.0073 u
Neutron Rest Mass	m_n	1.6749×10^{-27} kg 1.0087 u
Magnetic Flux Quantum	$\phi = h/2e$ h/e	2.0679×10^{-15} Wb 4.1357×10^{-15} J Hz^{-1} C^{-1}
Josephson Frequency-Voltage Ratio	2e/h	483.5939 THz V^{-1}
Quantum of Circulation	$h/2m_e$ h/m_e	3.6369×10^{-4} J Hz^{-1} kg^{-1} 7.2739×10^{-4} J Hz^{-1} C^{-1}
Rydberg Constant	R_∞	1.0974×10^{7} m^{-1}
Proton Moment in Nuclear Magnetons	μ_P/μ_N	2.7928
Bohr Magneton	$\mu_B = eh/2m_e$	9.2741×10^{-24} J T^{-1}
Proton Gyromagnetic Ratio	γ_P	2.6752×10^{8} s^{-1} T^{-1}
Diamagnetic Shielding Factor, Spherical H_2O Sample	$1 + \sigma(H_2O)$	1.0000
Molar Mass Constant	R	8.3144 J mol^{-1} K^{-1}
Molar Volume, Ideal Gas ($T_0 = 273.15$K, $p_0 = 1$ atm)	$V_m = RT_0/p_0$	0,0224 m^3 mol^{-1}
Boltzman Constant	$k = R/N_A$	1.3807×10^{-23} J K^{-1}
Stefan-Boltzman Constant	$\sigma = (\pi^2/60)\ k^4/h^3\ c^2$	5.6703×10^{-8} W m^{-2} K^{-4}
First Radiation Constant	$c_1 = 2\pi hc^2$	3.7418×10^{-16} W m^{-2}
Second Radiation Constant	$c_2 = hc/k$	0.0144 mK
Gravitation Constant	G	6.6720×10^{-11} N m^2 kg^{-2}

He kriostat

Kriostat


-465.6
-174
z=0
6 PIN CONNECTOR FOR TAIL THERMOMETER AND HEATER
ø600
OVERPRESSURE RELIEF PORT
NW16KF BELLOWS SEAL EVACUATION VALVE
43L HELIUM RESERVOIR
840
VTI HELIUM INLET
LAMBDA PLATE REFRIDGERATOR
8T FIELD CENTRE
ø52.0
1145
1194
1250
1350
TAIL THERMOMETER AND HEATER
ø200.0
ø535.0

Kriostat


-465.6
-174
z=0
6 PIN CONNECTOR FOR TAIL THERMOMETER AND HEATER
Ø600
OVERPRESSURE RELIEF PORT
NW16KF BELLOWS SEAL EVACUATION VALVE
LAMBDA PLATE REFRIDGERATOR
VTI HELIUM INLET
8T FIELD CENTRE
43L HELIUM RESERVOIR
840
1145
1194
1250
1350
Ø52.0
TAIL THERMOMETER AND HEATER
Ø200.0
Ø535.0

Temperaturna kontrola

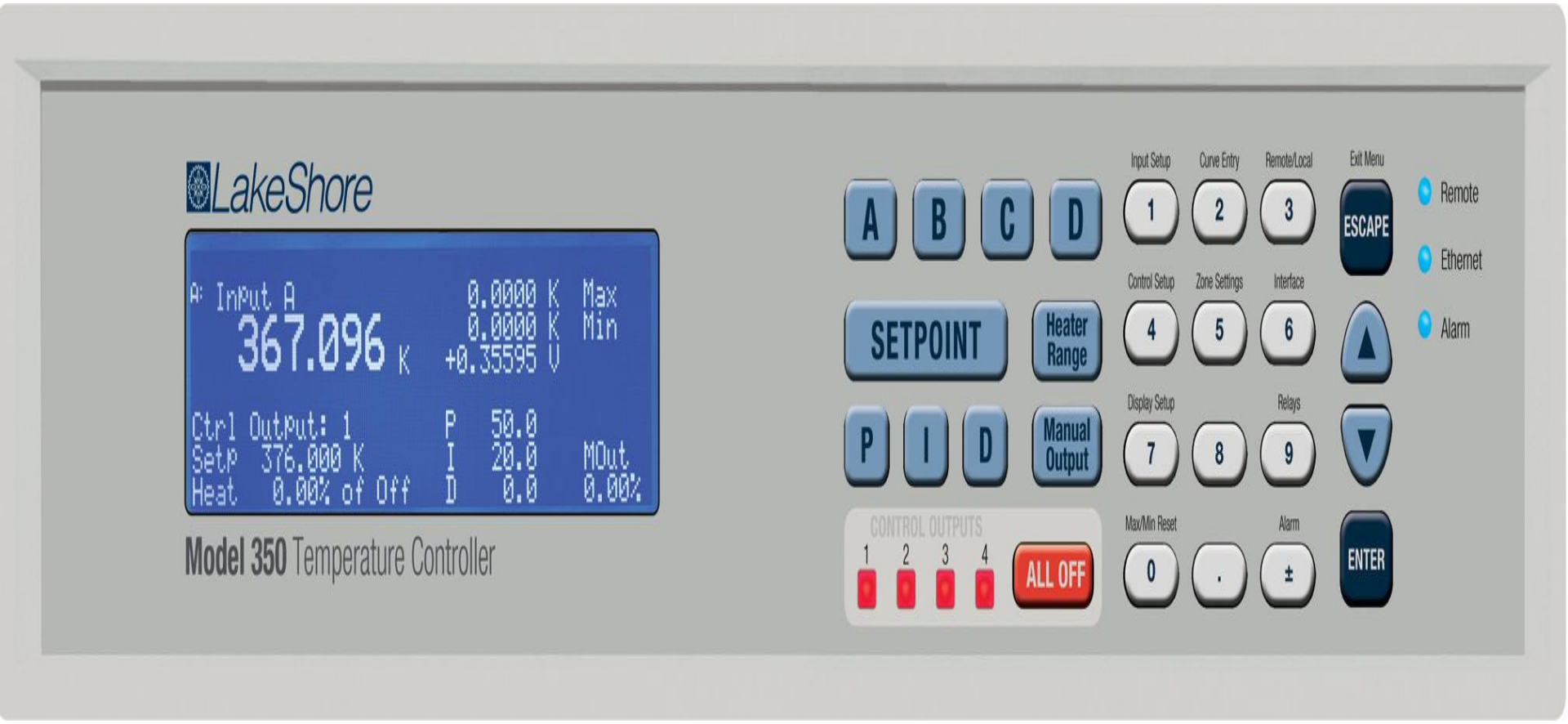


FIGURE 1-2 Displays showing four loop mode, input display mode and custom display mode

FIGURE 3-1 **Model 350 rear panel**

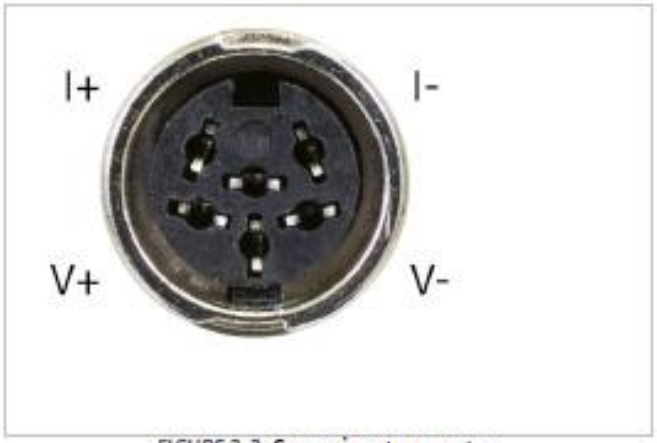


FIGURE 3-3 **Sensor input connector**

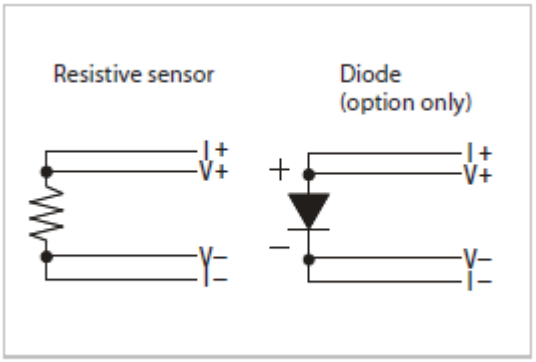


FIGURE 3-4 **4-lead measurement**

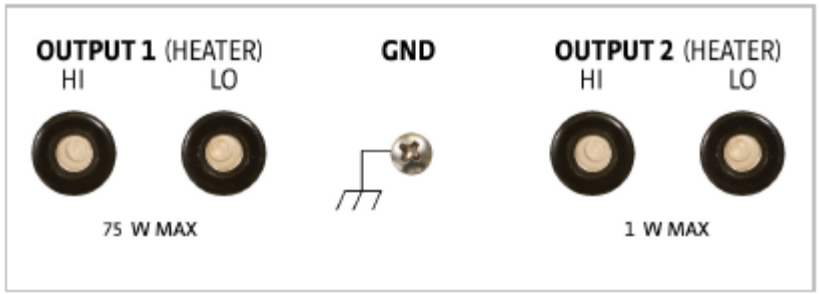


FIGURE 3-9 **Rear panel showing heater output connectors**

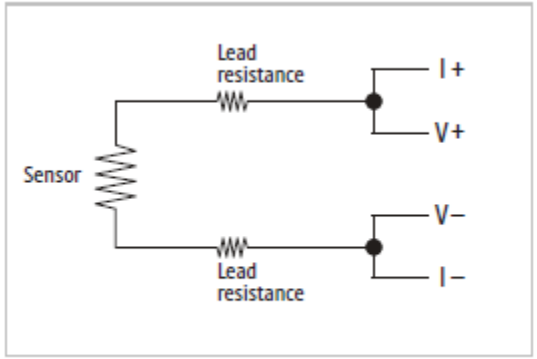


FIGURE 3-5 **2-lead sensor measurement**

		Model	Useful range	Magnetic field use
Negative Temperature Coefficient RTDs	Cernox™	CX-1010	0.1 K to 325 K[1]	T > 2 K & B ≤ 19 T
	Cernox™	CX-1030-HT	0.3 K to 420 K[1]	T > 2 K & B ≤ 19 T
	Cernox™	CX-1050-HT	1.4 K to 420 K[1]	T > 2 K & B ≤ 19 T
	Cernox™	CX-1070-HT	4 K to 420 K[1]	T > 2 K & B ≤ 19 T
	Cernox™	CX-1080-HT	20 K to 420 K[1]	T > 2 K & B ≤ 19 T
	Germanium	GR-300-AA	0.35 K to 100 K	Not recommended
	Germanium	GR-1400-AA	1.8 K to 100 K	Not recommended
	Rox™	RX-102B	0.1 K to 40 K	T > 2 K & B ≤ 10 T
	Rox™	RX-103	1.4 K to 40 K	T > 2 K & B ≤ 10 T
	Rox™	RX-202	0.5 K to 40 K	T > 2 K & B ≤ 10 T
Positive Temperature Coefficient RTDs	100 Ω platinum	PT-102/3	14 K to 873 K	T > 40 K & B ≤ 2.5 T
	100 Ω platinum	PT-111	14 K to 673 K	T > 40 K & B ≤ 2.5 T
	Rhodium-iron	RF-800-4	1.4 K to 500 K	T > 77 K & B ≤ 8 T
Diodes (3062)	Silicon Diode	DT-670-SD	1.4 K to 500 K	T ≥ 60 K & B ≤ 3 T
	Silicon Diode	DT-670E-BR	30 K to 500 K	T ≥ 60 K & B ≤ 3 T
	Silicon Diode	DT-414	1.4 K to 375 K	T ≥ 60 K & B ≤ 3 T
	Silicon Diode	DT-421	1.4 K to 325 K	T ≥ 60 K & B ≤ 3 T
	Silicon Diode	DT-470-SD	1.4 K to 500 K	T ≥ 60 K & B ≤ 3 T
	Silicon Diode	DT-471-SD	10 K to 500 K	T ≥ 60 K & B ≤ 3 T
	GaAlAs Diode	TG-120-P	1.4 K to 325 K	T > 4.2 K & B ≤ 5 T
	GaAlAs Diode	TG-120-PL	1.4 K to 325 K	T > 4.2 K & B ≤ 5 T
	GaAlAs Diode	TG-120-SD	1.4 K to 500 K	T > 4.2 K & B ≤ 5 T
Capacitance (3061)		CS-501	1.4 K to 290 K	T > 4.2 K & B ≤ 18.7 T
Thermocouples (3060)	Type K	9006-006	3.2 K to 1505 K	Not recommended
	Type E	9006-004	3.2 K to 934 K	Not recommended
	Chromel-AuFe 0.07%	9006-002	1.2 K to 610 K	Not recommended

[1] *Non-HT version maximum temperature: 325 K*

TABLE 1-1 ***Sensor temperature range (sensors sold separately)***

	Example Lake Shore Sensor	Temperature (K)	Nominal Resistance/ Voltage	Typical Sensor Sensitivity[2]	Measurement Resolution: Temperature Equivalents	Electronic Accuracy: Temperature Equivalents	Temperature Accuracy Including Electronic Accuracy, CalCurve™ and Calibrated Sensor	Electronic Control Stability[3]: Temperature Equivalents
Cernox™ (1 mV)	CX-1010-SD with 0.1L calibration	0.1 0.3 0.5 4.2 300	21389 Ω 2322.4 Ω 1248.2 Ω 277.32 Ω 30.392 Ω	-558110 Ω/K -10785 Ω/K -2665.2 Ω/K -32.209 Ω/K -0.0654 Ω/K	5.4 µK 28 µK 113 µK 931 µK 153 mK	±69 µK ±272 µK ±938 µK ±6.5 mK ±1.7 K	±4.1 mK ±4.3 mK ±4.9 mK ±11 mK ±1.8 K	±10.8 µK ±55.6 µK ±225 µK ±190 µK ±306 mK
Cernox™ (10 mV)	CX-1050-SD-HT[4] with 1.4M calibration	1.4 4.2 77 420	26566 Ω 3507.2 Ω 205.67 Ω 45.03Ω	-48449 Ω/K -1120.8 Ω/K -2.4116 Ω/K -0.0829 Ω/K	6.2 µK 89 µK 1.2 mK 12 mK	±261 µK ±2.1 mK ±38 mK ±338 mK	±4.3 mK ±6.1 mK ±50 mK ±412 mK	±12.4 µK ±178 µK ±2.5 mK ±24.1 mK
Germanium (1 mV)	GR-50-AA with 0.05A calibration	0.1 0.3 0.5 1.4 4.2	2317 Ω 164 Ω 73.8 Ω 24.7 Ω 13.7 Ω	-71858 Ω/K -964 Ω/K -202.9 Ω/K -13.15 Ω/K -1.036 Ω/K	4.2 µK 31.1 µK 49.3 µK 228 µK 2.9 mK	±21 µK ±130 µK ±244 µK ±1.2 mK ±11 mK	±4.0 mK ±4.1 mK ±4.2 mK ±5.2 mK ±15 mK	±8.3 µK ±62.2 µK ±98.6 µK ±456 µK ±5.8 mK
Germanium (10 mV)	GR-300-AA with 0.3D calibration	0.3 1.4 4.2 100	35180 Ω 448.6 Ω 94.46 Ω 2.72 Ω	-512200 Ω/K -581.3 Ω/K -26.56 Ω/K -0.024 Ω/K	2 µK 17 µK 38 µK 4.2 mK	±47 µK ±481 µK ±1.8 mK ±151 mK	±4.0 mK ±4.5 mK ±5.8 mK ±171 mK	±3.9 µK ±34.4 µK ±75.3 µK ±8.3 mK
Germanium (10 mV)	GR-1400-AA with 1.4D calibration	1.4 4.2 77 100	35890 Ω 1689 Ω 3.55 Ω 2.8 Ω	-94790 Ω/K -861.9 Ω/K -0.05 Ω/K -0.021 Ω/K	11µK 35 µK 2 mK 4.8 mK	±257 µK ±900 µK ±83 mK ±175 mK	4.3 mK 4.9 mK 94 mK 195 mK	±21.1 µK ±69.6 µK ±4 mK ±9.5 mK
Rox™ (1 mV)	RX-102B-CB with 0.02C calibration	0.1 0.5 1.4 4.2 40	3549 Ω 2188 Ω 1779 Ω 1546 Ω 1199 Ω	-12578 Ω/K -1056 Ω/K -198 Ω/K -40.0 Ω/K -3.41 Ω/K	79.5 µK 284 µK 1.5 mK 7.5 mK 88 mK	±908 µK ±2.7 mK ±13.7 mK ±65.4 mK ±727 mK	4.9 mK 6.7 mK 18 mK 69 mK 803 mK	±159 µK ±568 µK ±3.0 mK ±15.0 mK ±176 mK
Platinum RTD 500 Ω Full Scale	PT-103 with 14J calibration	30 77 300 500	3.66 Ω 20.38 Ω 110.35 Ω 185.668 Ω	0.191 Ω/K 0.423 Ω/K 0.387 Ω/K 0.378 Ω/K	0.5 mK 0.7 mK 7.8 mK 7.9 mK	±22 mK ±34 mK ±140 mK ±223 mK	±31 mK ±44 mK ±164 mK ±274 mK	±1.0 mK ±1.4 mK ±15.5 mK ±15.9 mK
Silicon Diode	DT-670-CO-13 with 1.4H calibration	1.4 77 300 500	1.664 V 1.028 V 0.5596 V 0.0907 V	-12.49 mV/K -1.73 mV/K -2.3 mV/K -2.12 mV/K	0.8 mK 5.8 mK 4.3 mK 4.7 mK	±13 mK ±76 mK ±47 mK ±40 mK	±20 mK ±113 mK ±82 mK ±94 mK	±1.6 mK ±11.6 mK ±8.7mK ±9.4 mK
Silicon Diode	DT-470-SD-13 with 1.4H calibration	1.4 77 300 475	1.6981 V 1.0203 V 0.5189 V 0.0906 V	-13.1 mV/K -1.92 mV/K -2.4 mV/K -2.22 mV/K	0.8 mK 5.2 mK 4.2 mK 4.5 mK	±13 mK ±68 mK ±44 mK ±38 mK	±20 mK ±105 mK ±79 mK ±87 mK	±1.5 mK ±10.4 mK ±8.3 mK ±9.0 mK
GaAlAs Diode	TG-120-SD with 1.4H calibration	1.4 77 300 475	5.3909 V 1.4222 V 0.8978 V 0.3778 V	-97.5 mV/K -1.24 mV/K -2.85 mV/K -3.15 mV/K	0.21 mK 16 mK 7 mK 6.3 mK	±6 mK ±179 mK ±60 mK ±37 mK	±13 mK ±216 mK ±95mK ±86 mK	±410 µK ±32.3 mK ±14.0 mK ±12.7 mK
Capacitance	CS-501	4.2 77 200	6.0 nF 9.1 nF 19.2 nF	27 pF/K 52 pF/K 174 pF/K	74 mK 39 mK 12 mK	NA	Calibration not available from Lake Shore	±14.8 mK ±7.7 mK ±23 mK
Thermocouple	Type K	75 300 600 1500	-5862.9 µV 1075.3 µV 13325 µV 49813 µV	15.6 µV/K 40.6 µV/K 41.7 µV/K 36.1 µV/K	26 mK 9.9 mK 9.6 mK 11 mK	±252 mK[5] ±38 mK[5] ±184 mK[5] ±718 mK[5]	Calibration not available from Lake Shore	±51.3 mK ±19.7 mK ±19.2 mK ±22.2 mK

[2] Typical sensor sensitivities were taken from representative calibrations for the sensor listed
[3] Control stability of the electronics only, in an ideal thermal system
[4] Non-HT version maximum temperature: 325 K
[5] Accuracy specification does not include errors from room temperature compensation

TABLE 1-2 ***Typical sensor performance***

Sensor type	Temperature	Resistance typical, R_s (Ω)	Sensitivity typical[1] (Ω/K)[1]	Thermal resistance typical, R_t (Ω)[2]	Excitation current (1 mV setting)	Typical self-heating ΔT_{SH} (mK)[3]	Measurement resolution (Ω)[4]	Instrument noise (μK)[5]	Instrument accuracy (gain & offset)[6]	Instrument accuracy (mK)[6]	Sensor uncertainty (mK)[7]	Total uncertainty = self-heating ± (instrument + sensor) (mK)[8]
RX-102B	100 mK	3,546	–12,578	6×10^7	10 nA	+0.02	10	800	±100 Ω (0.1%rng) ±0.04%rdg	±8.1	±4	+0.0 ±12.1
					30 nA	+0.2	3	240	±30 Ω (0.1%rng) ±0.04%rdg	±2.5		+0.2 ± 6.5
					100 nA	+2.1	1	80	±10 Ω (0.1%rng) ±0.04%rdg	±0.9		+2.1 ± 4.9
GR-50	100 mK	2,317	–71,858	6×10^7	10 nA	+0.0	10	140	±100 Ω (0.1%rng) ±0.04%rdg	±1.4	±4	+0.0 ± 5.4
					30 nA	+0.1	3	42	±30 Ω(0.1%rng) ±0.04%rdg	±0.4		+0.1 ± 4.4
					100 nA	+1.4	1	14	±10 Ω (0.1%rng) ±0.04%rdg	±0.2		+1.4 ± 4.2
					300 nA	+12.5	0.3	4	±2 Ω (0.07%rng) ±0.04%rdg	±0.0		+12.5 ± 4
CX-1010	100 mK	21,389	–558,110	2×10^9	10 nA	+4.3	10	18	±100 Ω (0.1%rng) ±0.04%rdg	±0.2	±4	+4.3 ± 4.2
					30 nA	+38.5	3	6	±30 Ω(0.1%rng) ±0.04%rdg	±0.1		+38.5 ± 4.1

1. Temperature Control Catalog, Appendix G: Sensor Temperature Response Data Tables
2. Temperature Control Catalog, Appendix E: Temperature Measurement System
*3. $T_{SH} = I^2 R_e R_t$, Typical Self-Heating Error = Excitation Current2 * Sensor Resistance * Thermal Resistance*
4. Temperature Equivalent Noise = Instrument Measurement Resolution ÷ Sensitivity
5. TABLE 1-3: Input Specifications
6. Temperature Equivalent Instrument Accuracy = (Instrument Gain Accuracy + Instrument Offset Accuracy) ÷ Sensitivity
7. Temperature Control Catalog, Appendix D: Sensor Calibration Accuracies
8. Total Uncertainty = Instrument Accuracy + Sensor Uncertainty + Self-Heating Error

TABLE 2-1 Ultra-low temperature considerations

PID Control

For closed-loop operation, the Model 350 temperature controller uses an algorithm called PID control. The control equation for the PID algorithm has three variable terms: proportional (P), integral (I), and derivative (D). See FIGURE 2-4. Changing these variables for best control of a system is called tuning. The PID equation in the Model 350 is:

$$\text{Heater Output} = P\left[e + I\int(e)\,dt + D\,\frac{de}{dt}\right]$$

where the error (e) is defined as: e = Setpoint – Feedback Reading.

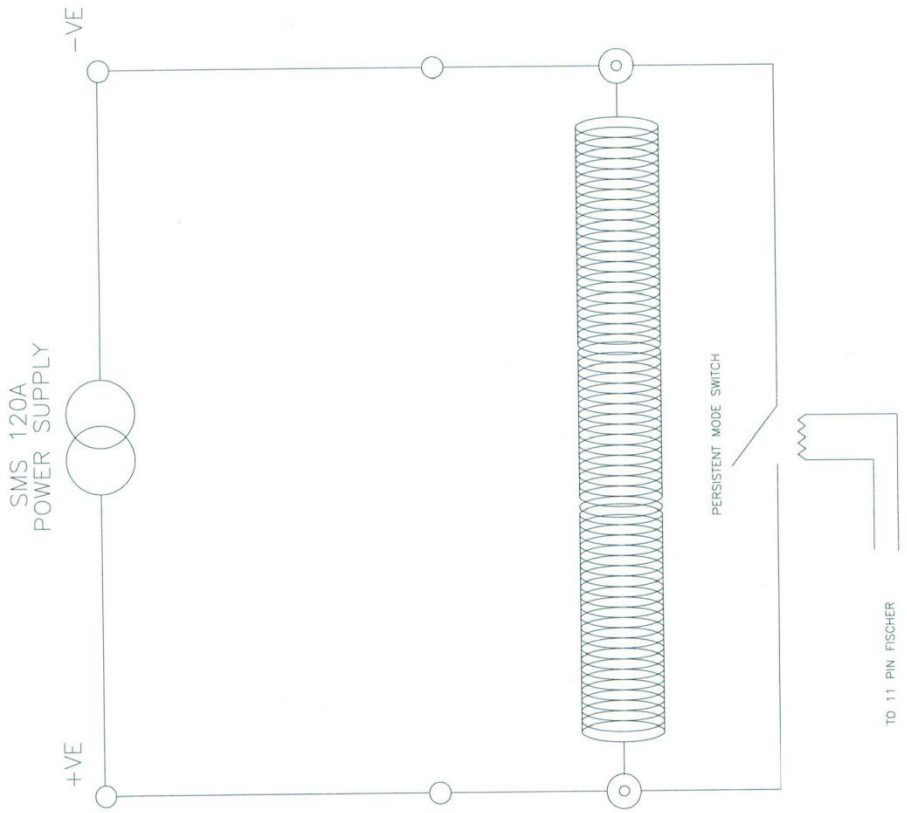
In the control loop, the integral term, also called reset, looks at error over time to build the integral contribution to the output:

$$\text{Output (I)} = PI\int(e)dt$$

The derivative term, also called rate, acts on the change in error with time to make its contribution to the output:

$$\text{Output (D)} = PD\frac{de}{dt}$$

Supravodljivi magnet



Model 625

Superconducting
Magnet Power Supply

- True 4-quadrant (bipolar) 60 A, 5 V output
- 0.1 mA output setting resolution
- Linear regulation minimizes noise and ripple to 0.006% of maximum current into a 1 mΩ load.
- 1.0 mA stability per hour
- Two units can be connected in parallel for ±120 A operation

Figure 1-1. Model 625 Front Panel

1.2 SPECIFICATIONS

Output

Type:	Bipolar, Four Quadrant, DC Current Source
Current Generation:	Linear regulation with digital setting and analog control
Current Range:	±60 A
Compliance Voltage:	±5 V maximum (nominal, both source and sink)
Maximum Power:	300 W
Load Reactance:	0 H to 100 H
Current Ripple (Max):	4 mA RMS at 60 A, (0.007%) into 1 mΩ load (significantly reduced into a reactive load or at lower current)
Current Ripple Frequency:	Dominated by line frequency and its harmonics
Temperature Coefficient:	±15 ppm of full scale/°C
Line Regulation:	15 ppm/6% line change
Source Impedance:	25 Ω
Stability (1 h):	1 mA/h (after warm-up)
Stability (24 h):	10 mA/24 h (typical, dominated by temperature coefficient and line regulation)
Isolation:	Output optically isolated from chassis to prevent ground loops
Parallel Operation:	2 units can be paralleled for ±120 A, ±5 V operation
Protection:	Quench, Line Loss, Low Line Voltage, High Line Voltage, Output Over Voltage, Output Over Current, Over Temperature, Remote Inhibit (on critical error conditions, magnet discharges at 1 V nominal)

Persistent Switch Heater Output (PSHO)

Current Range:	10 mA to 125 mA
Compliance Voltage (minimum):	12 V or 21 V selectable
Heater Resistance (minimum):	10 Ω
Setting Resolution:	1 mA
Accuracy:	±1 mA
Operation:	On/Off with lockout delay of 5 s to 100 s
Protection:	Open or shorted heater detection, error message if off and on output currents differ
Connector:	BNC

Interface

IEEE-488.2 Interface	
Features:	SH1,AH1,T5,L4,SR1,RL1,PP0,DC1,DT1,C0,E1
Reading Rate:	To 10 readings/s
Software Support:	National Instruments LabVIEW driver (consult Lake Shore for availability)
Serial Interface	
Electrical Format:	RS-232C
Baud Rates:	9600, 19200, 38400, 57600
Reading Rate:	To 10 readings/s
Connector:	9-pin D-sub
Output Current Monitor	
Sensitivity:	60 A = 6 V
Accuracy:	±1% of full scale
Noise:	1 mV
Source Impedance:	20 Ω
Connector:	Shared 15-pin D-sub

Figure 2-1. Typical Superconducting Magnet

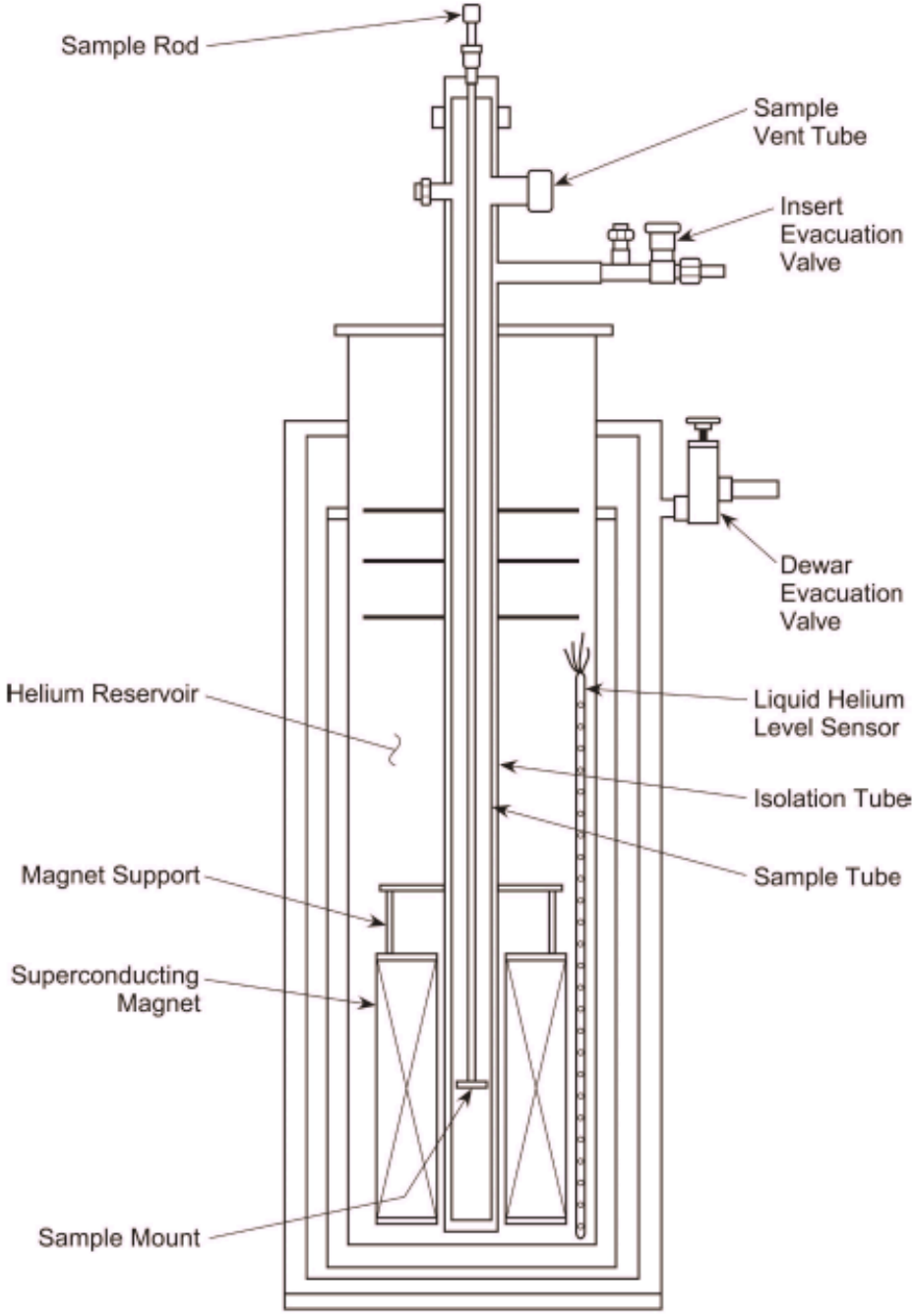


Figure 2-2. Cutaway of a Typical Helium Dewar, Magnet, and Insert

Figure 3-1. Model 625 Rear Panel

Digital_IO.bmp

Pin	Name	Pin	Name
1	Fault Out Common	14	Fault Out
2	NC	15	NC
3	Remote Inhibit Common	16	Remote Inhibit
4	NC	17	NC
5	Trigger Out Common (not used)	18	Trigger Out (not used)
6	NC	19	NC
7	Trigger In Common	20	Trigger In
8	NC	21	NC
9	NC	22	NC
10	NC	23	NC
11	NC	24	NC
12	NC	25	NC
13	NC		

Figure 3-4. Model 625 Digital Input/Output Connector

Heater Output.bmp

Figure 3-6. Persistent Switch Heater Output Connector

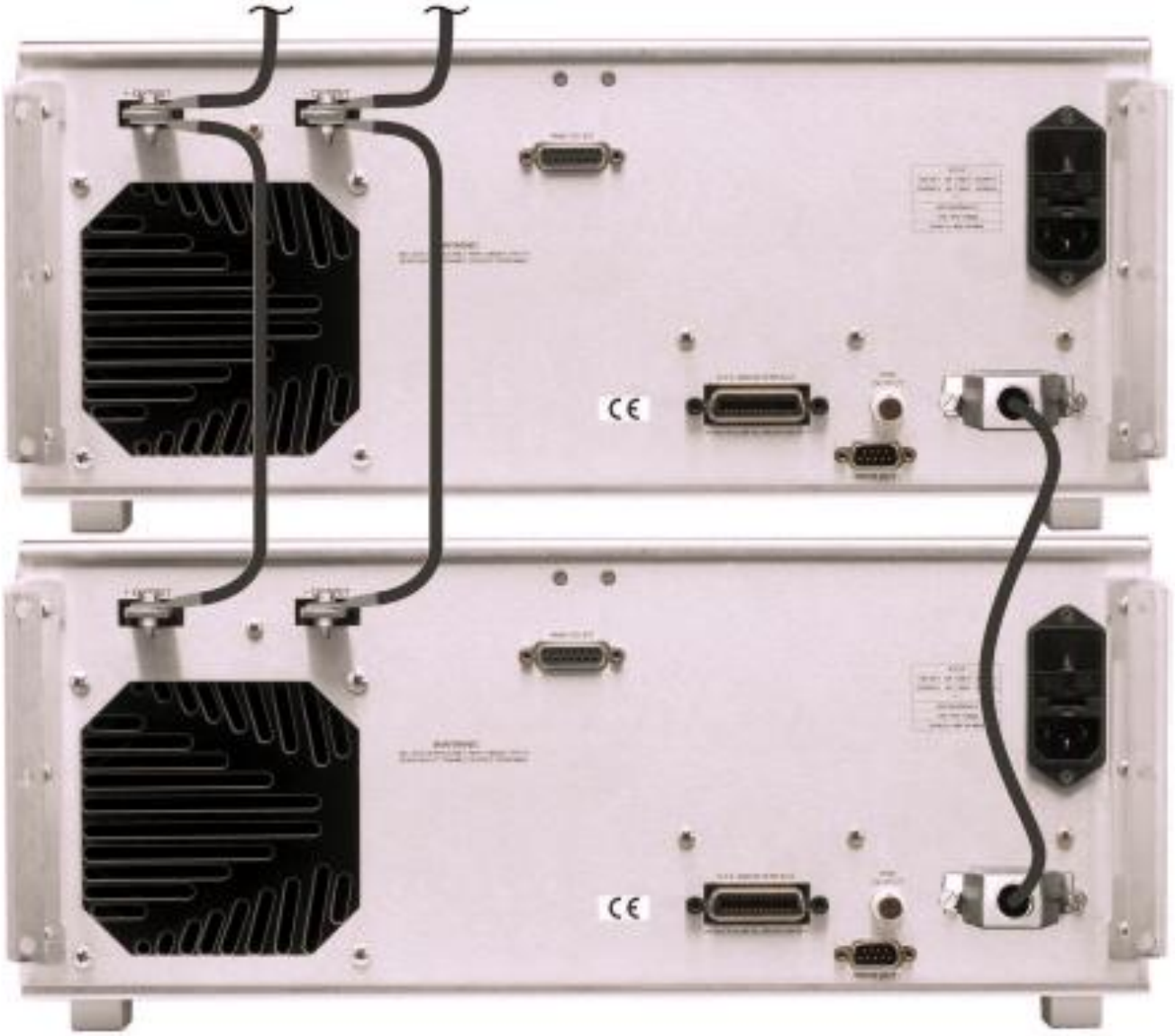


Figure 3-7. Connecting Two Power Supplies in Parallel

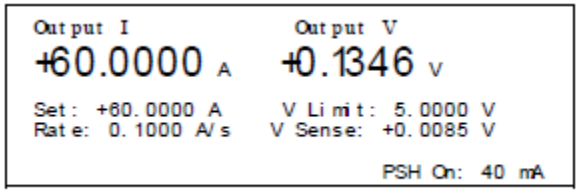


Figure 4-1. Model 625 Output Current Display

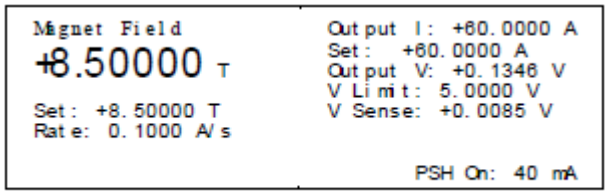
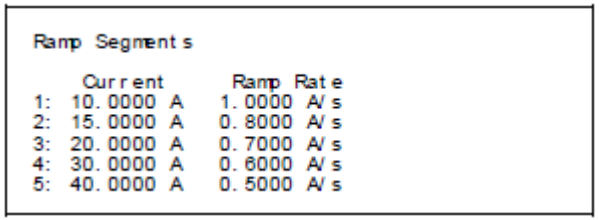
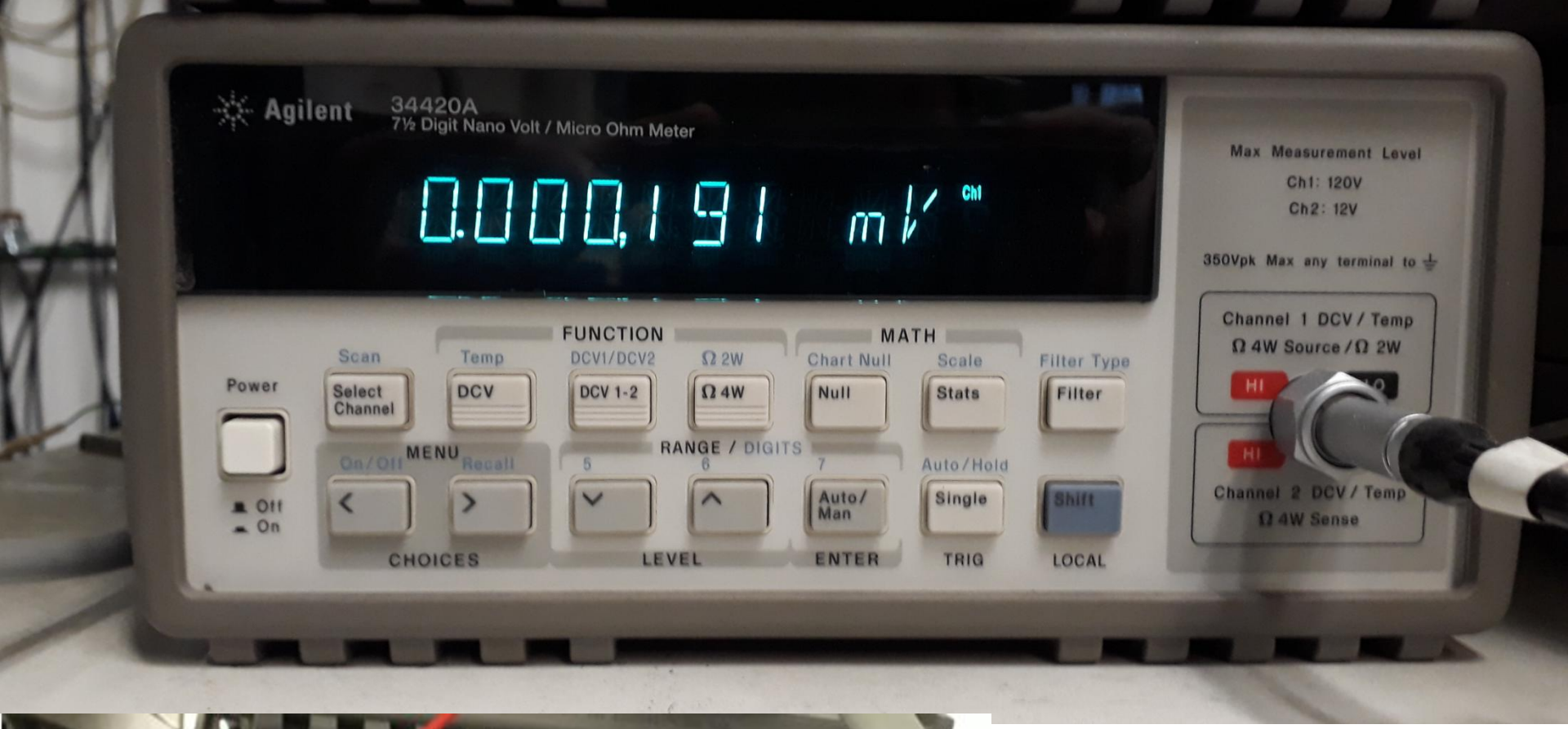


Figure 4-2. Model 625 Magnet Field Display



Strujni izvori


WARNING
GP-IB(IEEE488)
CAL SOURCE
EXT TRIG & OUTPUT
MODEL 765111
NO. 27D217244 B
YOKOGAWA
48-63Hz 30VA MAX
TERM
HI
LO
SEN
OUT
G
230VAC
200VAC
GPIB
EXT TRIG & OUTPUT
230VAC



Nanovoltmetar

Model 5210

Dual Phase Lock-in Amplifier

SIGNAL RECOVERY Model 5210

- Frequency range: 0.5 Hz to 120 kHz
- Voltage sensitivity: 100 nV to 3 V full-scale
- Current input mode sensitivities: 10 fA to 300 nA full-scale
  10 fA to 3 μA full-scale

- Line frequency rejection filter
- Dual phase demodulator with X-Y and R-θ outputs
- Fundamental (sine wave) or square-wave response modes
- Very low phase noise of < 0.005° rms.
- 3½-digit output readings
- Oscillator with variable amplitude and frequency
- Output time constants from 1 ms to 3 ks with 6 or 12 dB/octave roll-off
- Four external auxiliary ADC inputs
- One external DAC output
- Full range of auto-modes
- Standard GPIB (IEEE-488) and RS232 interfaces
- Two liquid crystal displays (LCD) and an analog panel meter for control and display of instrument outputs

Model 5210

Dual Phase Lock-in Amplifier

Model 5210

Dual Phase Lock-in Amplifier


DAC AUX OUT
TTL REF IN
ADC AUX INPUTS
CH 1
CH 2
CH 3
CH 4
TTL REF OUT
ADC EXT TRIG IN
X PID MONITOR
WARNING
CAUTION
MODIFICATION INSTALLED
RS232
GPIB
EG&G PARC
MODEL
SERIAL
K-0604309
HEATER FUSE
HEATER OUTPUT
HI
LO
IEEE-488 INTERFACE
DIGITAL I/O
RELAYS
ANALOG OUT 1
ANALOG OUT 2
INPUT A
INPUT B

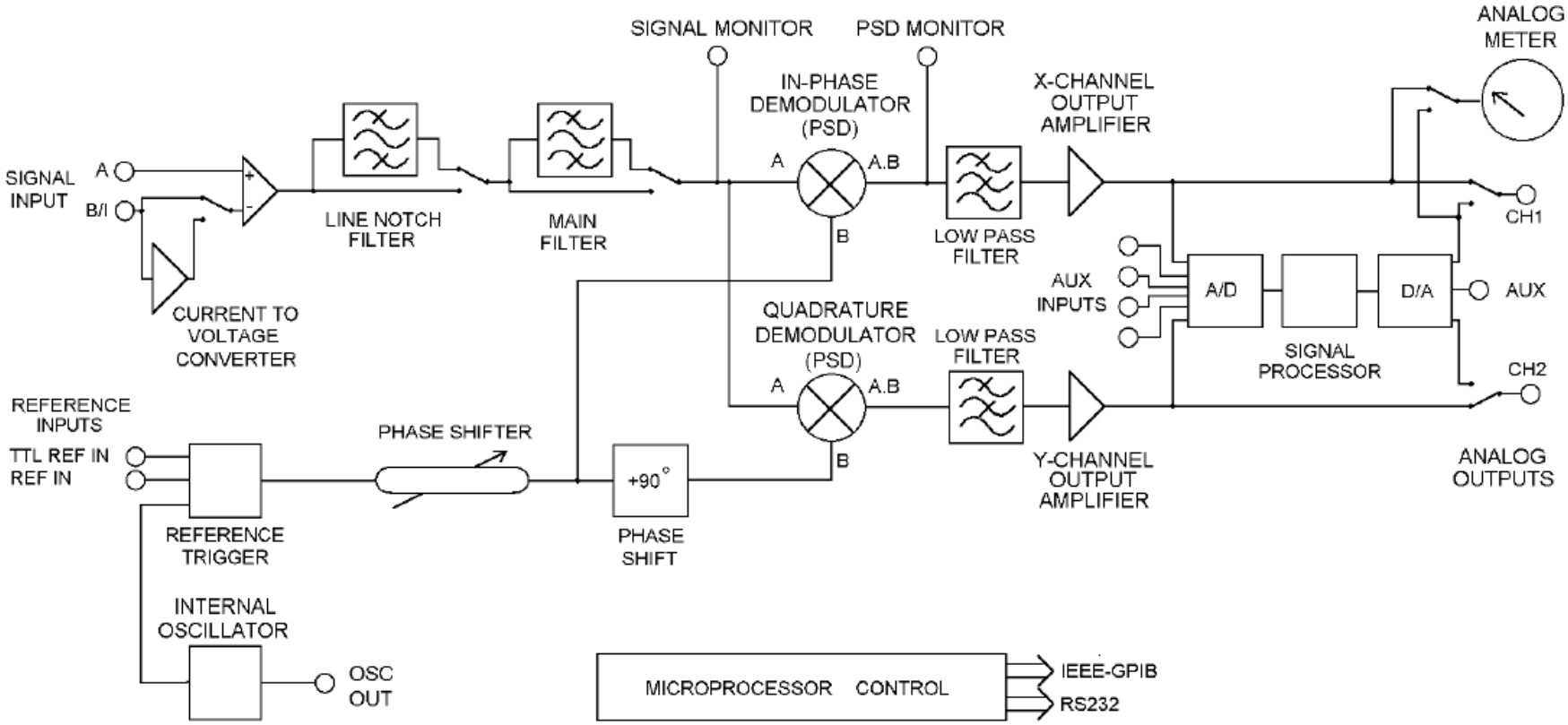


Figure 3-1, Model 5210 - BLOCK DIAGRAM

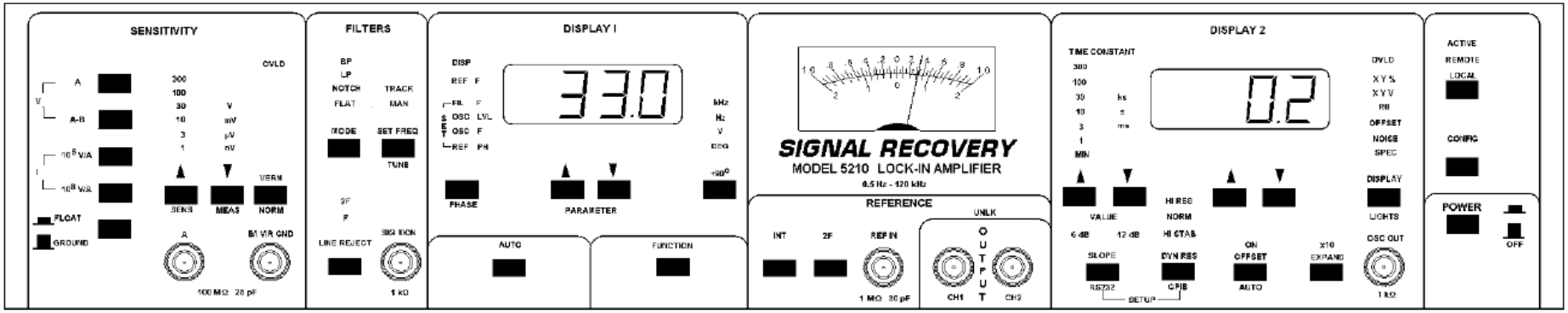
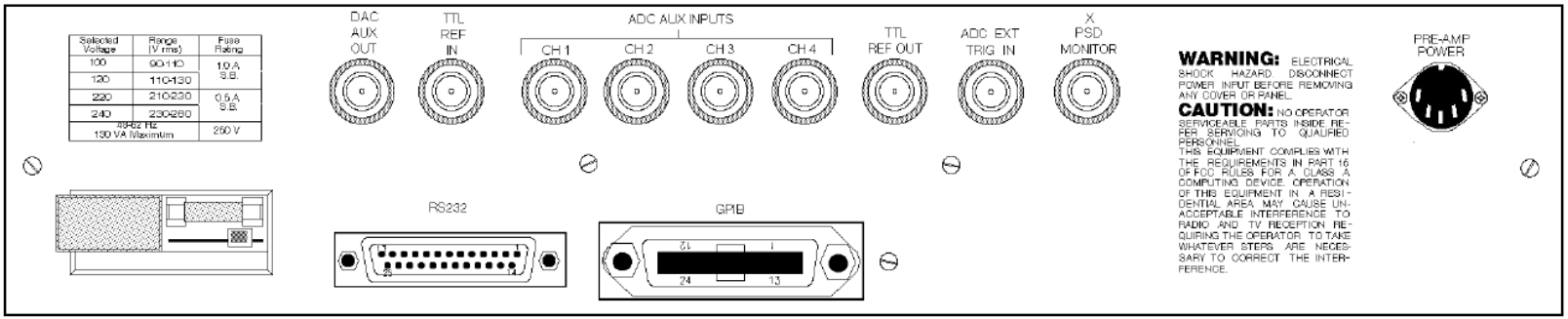


Figure 4-1, Model 5210 Front Panel Layout



Selected Voltage	Range (V rms)	Fuse Rating
100	90-110	1.0 A S.B.
120	110-130	
220	210-230	0.5 A S.B.
240	230-260	
48-62 Hz 130 VA Maximum		250 V

Figure 4-2, Model 5210 Rear Panel Layout

Full-scale Sensitivity
3 V
1 V
300 mV
100 mV
30 mV
10 mV
3 mV
1 mV
300 µV
100 µV
30 µV
10 µV
3 µV
1 µV
300 nV
100 nV

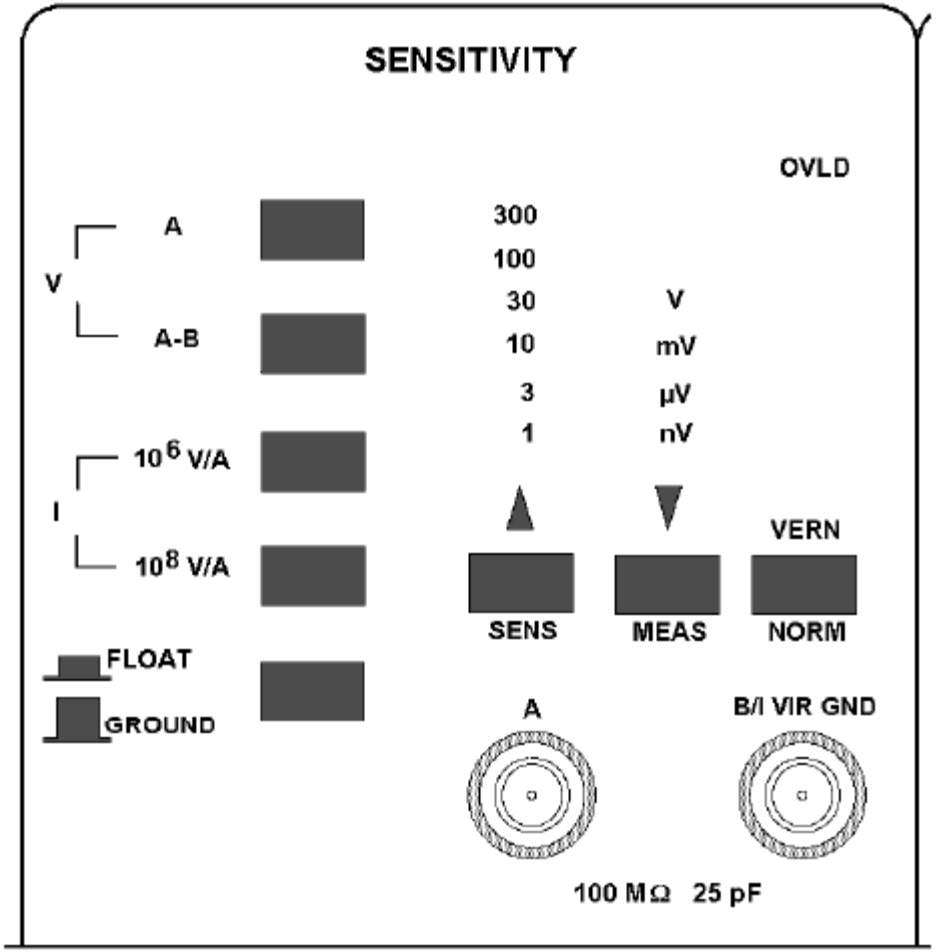


Figure 5-1, SENSITIVITY Group

Auto-Measure

The secondary function of the **SENSITIVITY** ▼ key is to initiate an auto-measure operation. Pressing the red **AUTO** key and then the **SENSITIVITY** ▼ key will start this function, which consists of the following steps:

1) The red **AUTO** indicator lights.

2) The signal channel filter is set to the bandpass mode.

3) The signal channel filter frequency is tuned to the reference frequency by means of an auto-tune operation.

4) An auto-sensitivity operation is performed.

5) An auto-phase operation is performed.

6) The **AUTO** indicator extinguishes.

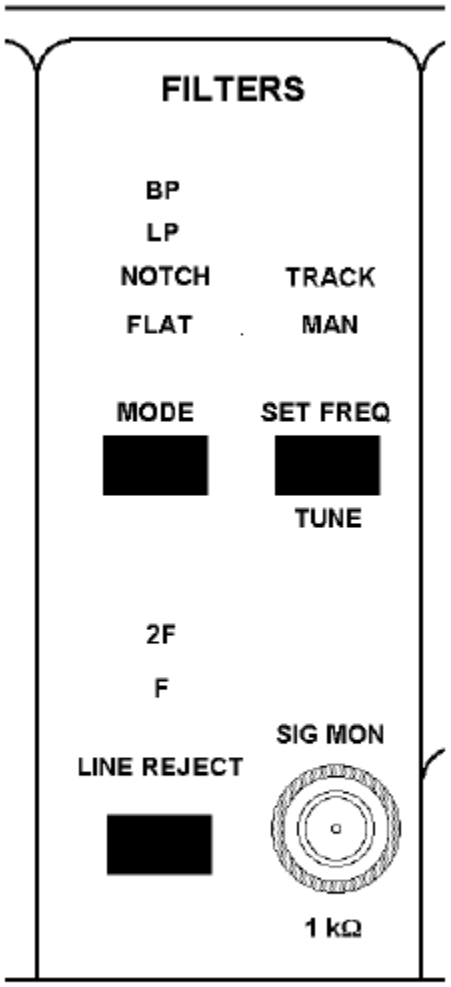


Figure 5-2, FILTERS Group

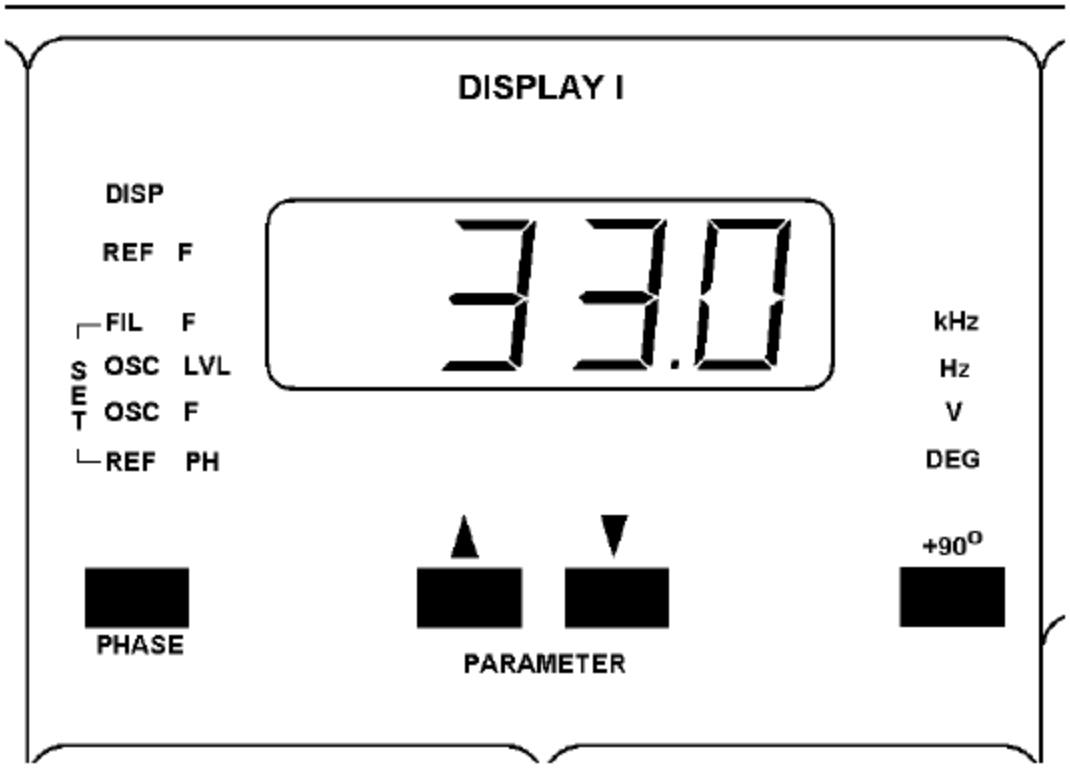


Figure 5-3, DISPLAY 1 Group

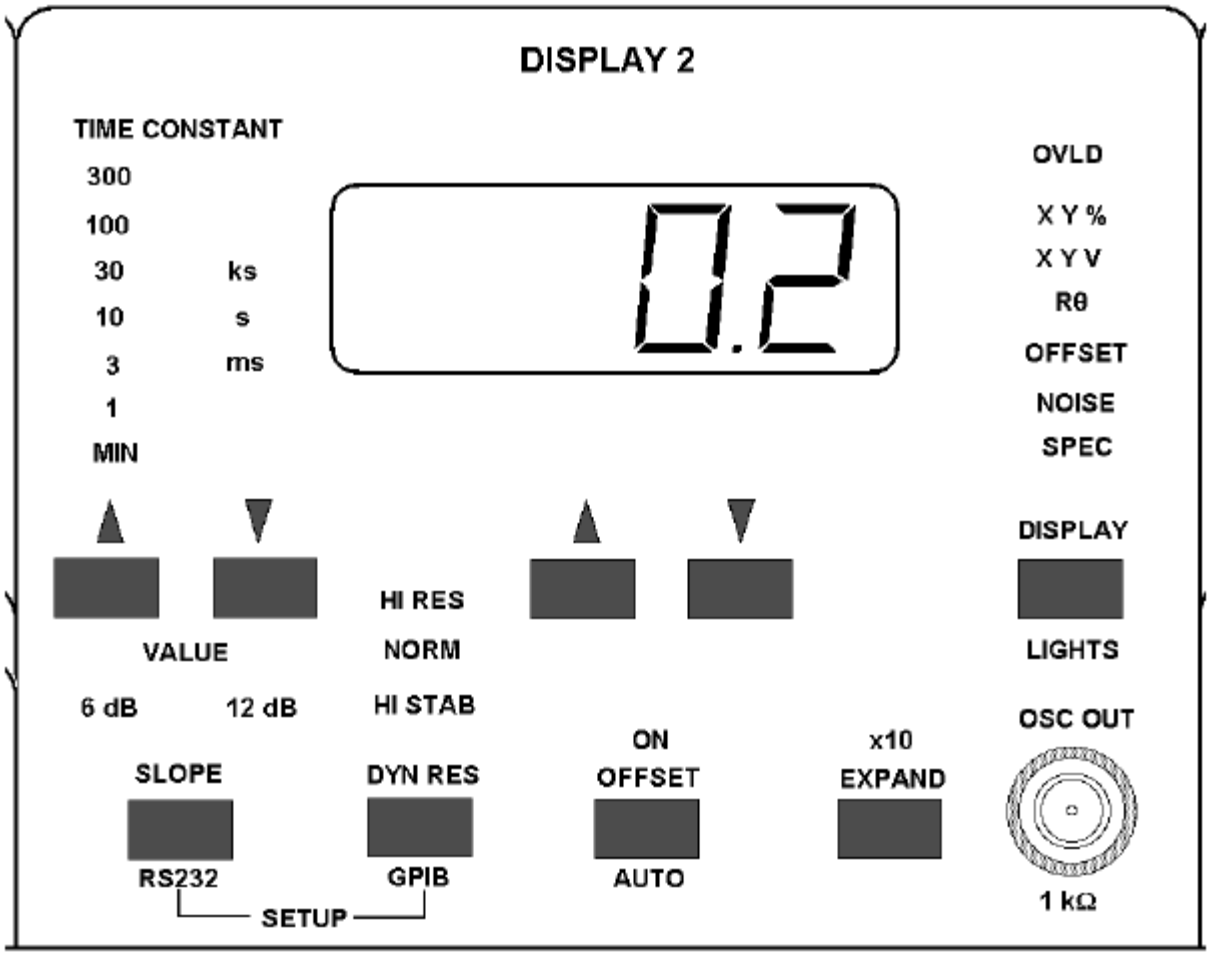


Figure 5-9, DISPLAY 2 Group

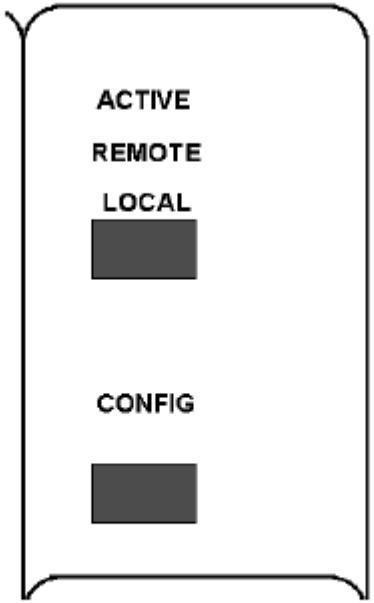


Figure 5-10, Interface Group

Table C-1. Comparison of Liquid Helium and Liquid Nitrogen

PROPERTY	LIQUID HELIUM	LIQUID NITROGEN
Boiling Point @1 atm, in K	4.2	77
Thermal Conductivity (Gas), w/cm–K	0.083	0.013
Latent Heat of Vaporization, Btu/liter	2.4	152
Liquid Density, pounds/liter	0.275	0.78

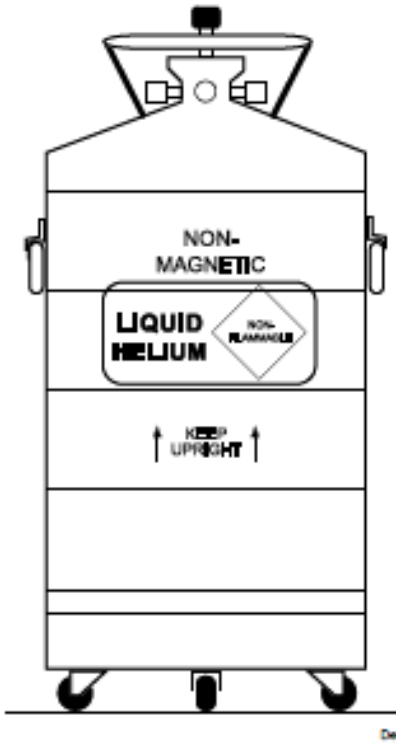


Figure C-1. Typical Cryogenic Storage Dewar

Table B-2. Recommended SI Values for Physical Constants

Quantity	Symbol	Value (SI units)
Permeability of Vacuum	μ_0	$4\pi \times 10^{-7}$ H m^{-1}
Speed of Light in Vacuum	c	2.9979×10^{8} m s^{-1}
Permitivity of Vacuum	$\varepsilon_0 = (\mu_0 c^2)^{-1}$	8.8542×10^{-12} F m^{-1}
Fine Structure Constant, μ0ce2/2h	α α^{-1}	0.0073 137.0360
Elementary Charge	e	1.6022×10^{-19} C
Plank's Constant	h $h = h/2\pi$	6.6262×10^{-34} J Hz^{-1} 1.0546×10^{-34} J s
Avogadro's Constant	N_A	6.0220×10^{23} mol^{-1}
Atomic Mass Unit	$1\ u = 10^{-3}$ kg mol$^{-1}/N_A$	1.6605×10^{-27} kg
Electron Rest Mass	m_e	0.9109×10^{-30} kg 5.4858×10^{-4} u
Proton Rest Mass	m_p	1.6726×10^{-27} kg 1.0073 u
Neutron Rest Mass	m_n	1.6749×10^{-27} kg 1.0087 u
Magnetic Flux Quantum	$\phi = h/2e$ h/e	2.0679×10^{-15} Wb 4.1357×10^{-15} J Hz^{-1} C^{-1}
Josephson Frequency-Voltage Ratio	2e/h	483.5939 THz V^{-1}
Quantum of Circulation	$h/2m_e$ h/m_e	3.6369×10^{-4} J Hz^{-1} kg^{-1} 7.2739×10^{-4} J Hz^{-1} C^{-1}
Rydberg Constant	R_∞	1.0974×10^{7} m^{-1}
Proton Moment in Nuclear Magnetons	μ_P/μ_N	2.7928
Bohr Magneton	$\mu_B = eh/2m_e$	9.2741×10^{-24} J T^{-1}
Proton Gyromagnetic Ratio	γ_P	2.6752×10^{8} s^{-1} T^{-1}
Diamagnetic Shielding Factor, Spherical H_2O Sample	$1 + \sigma(H_2O)$	1.0000
Molar Mass Constant	R	8.3144 J mol^{-1} K^{-1}
Molar Volume, Ideal Gas ($T_0 = 273.15$K, $p_0 = 1$ atm)	$V_m = RT_0/p_0$	0,0224 m^3 mol^{-1}
Boltzman Constant	$k = R/N_A$	1.3807×10^{-23} J K^{-1}
Stefan-Boltzman Constant	$\sigma = (\pi^2/60)\ k^4/h^3\ c^2$	5.6703×10^{-8} W m^{-2} K^{-4}
First Radiation Constant	$c_1 = 2\pi hc^2$	3.7418×10^{-16} W m^{-2}
Second Radiation Constant	$c_2 = hc/k$	0.0144 mK
Gravitation Constant	G	6.6720×10^{-11} N m^2 kg^{-2}

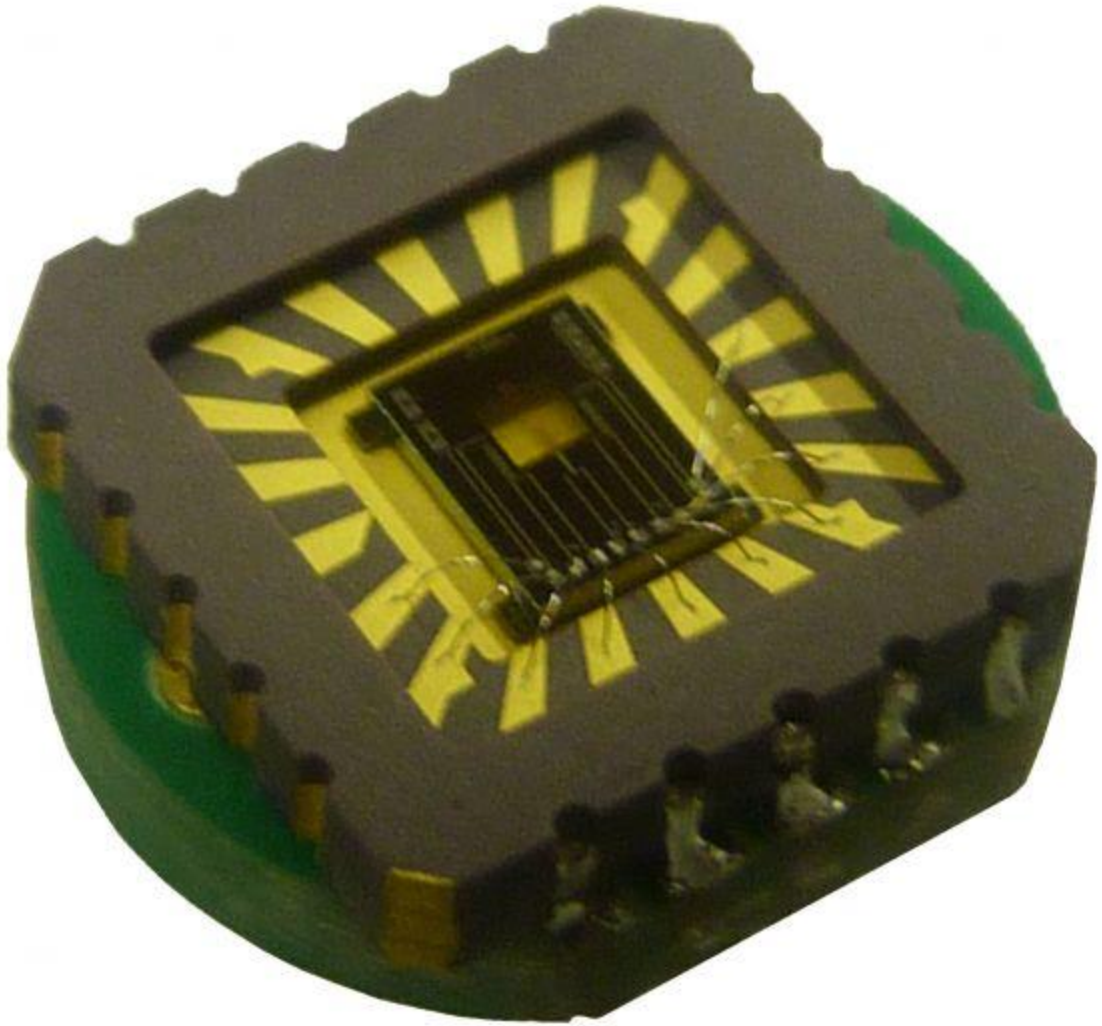
Nosač uzoraka

Nosač uzoraka za mjerenje anizotropnih svojstava uzorka

Nosač uzoraka za mjerenje anizotropnih svojstava uzorka

Nosač uzoraka za mjerenje toplinske vodljivosti

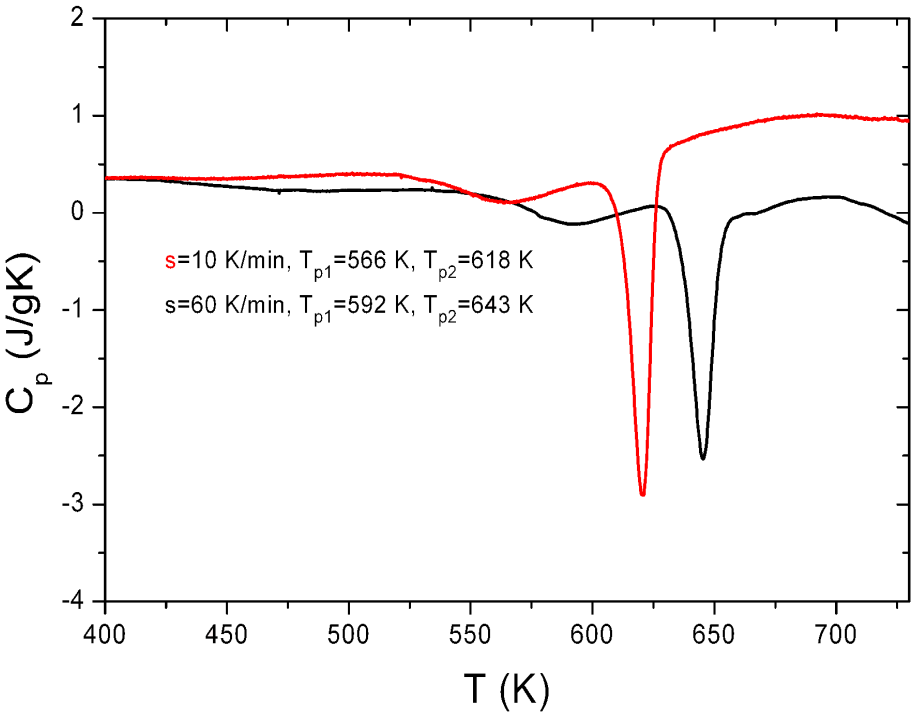
Nosač uzoraka za mjerenje toplinskog kapaciteta



Rezultati
DSC i x-ray mjerenja

- $Zr_{80}Ni_{20}$ uzorci su grijani brzinom 10 ili 60 K/min
- Javlja se oštar egzoterm iznad 600 K, na većoj temperaturi za uzorak grijan većom brzinom
- Blaži egzoterm uočljiv je na nižoj temperaturi, posljedica izlučivanja ω-Zr faze
- Prema Kissingerovom modelu temperature ta dva egzoterma povezane su relacijom:

$$s = AT_{p1,p2}^2 \exp\left[-\frac{E_{ai}}{k_B T_{p1,p2}}\right]$$



Toplinski tok c_p uzoraka $Zr_{80}Ni_{20}$ metalnog stakla pri aniliranju

- **Aktivacijske energije uzoraka su:**

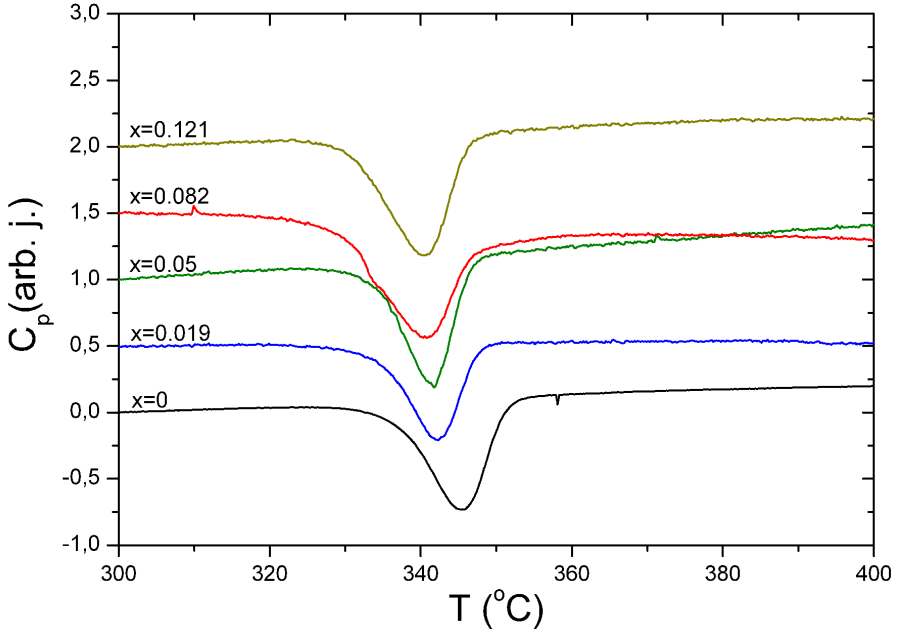
  E_{a1}=(2.0 ± 0.1) eV **E_{a2}=(2.4 ± 0.1) eV**

- **Za određivanje energija se koriste rezultati više brzina grijanja**

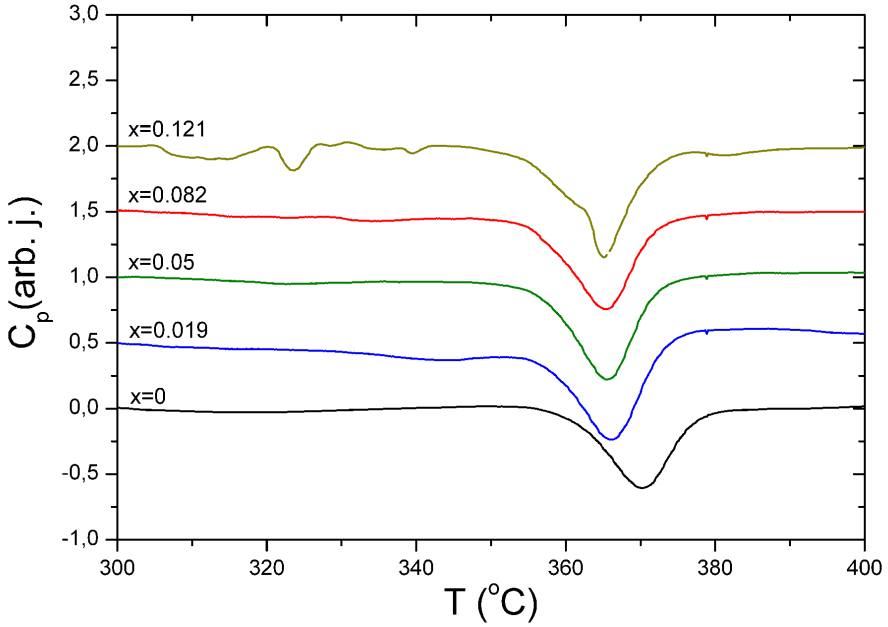
Utjecaj vodika na stabilnost:

10 K/min

- Povećanje koncentracije vodika smanjuje temperaturu egzoterma
- Ovisnost je jača za manju koncentraciju vodika (x_H)
- Slična ovisnost kod grijanja brzinom 10 K/min i 60 K/min
- Uvođenjem vodika ekspandira amorfna struktura, povećava se difuzivnost pa se atomi lakše pomiču prema stabilnijim konfiguracijama
- Time se smanjuje E_a i T_p
- Viša temperatura egzoterma za veću brzinu grijanja
- Proces je aniliranja se pokazao kao ireverzibilan



60 K/min



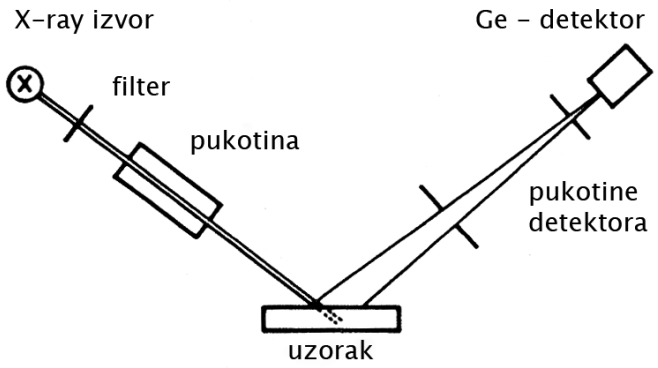
X-ray rezultati

- Braggov zakon daje ovisnost položaja maksimuma o udaljenosti između centara raspršenja

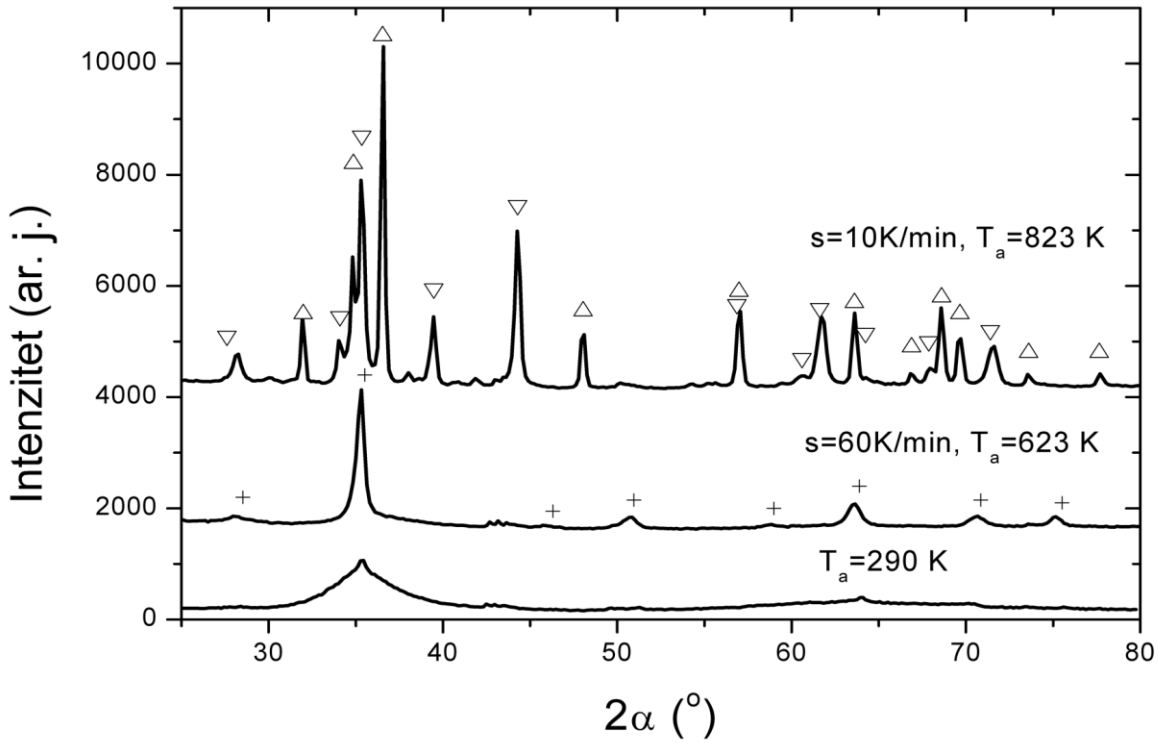
$$2d\sin(\theta) = n\lambda$$

- Korištenjem širine maksimuma na polovici širine $\Delta\beta$, položaja maksimuma α i valne duljine λ, pomoću Scherrerove formule računa se veličina kristala

$$D = 0.9\lambda/(\Delta\beta\cos\alpha)$$



- Amorfni uzorak daje širok maksimum, ne javljaju se maksimumi kristalnih struktura
- Uzorak grijan brzinom 60 K/min do 623 K sadrži vrhove koji su prilagođeni ω-Zr rešetci koja koegzistira s amorfnom matricom
- Uzorak grijan brzinom 10 K/min do 823 K pokazuje prisustvo kristala Zr_2Ni i α-Zr, došlo je do drugog stupnja kristalizacije

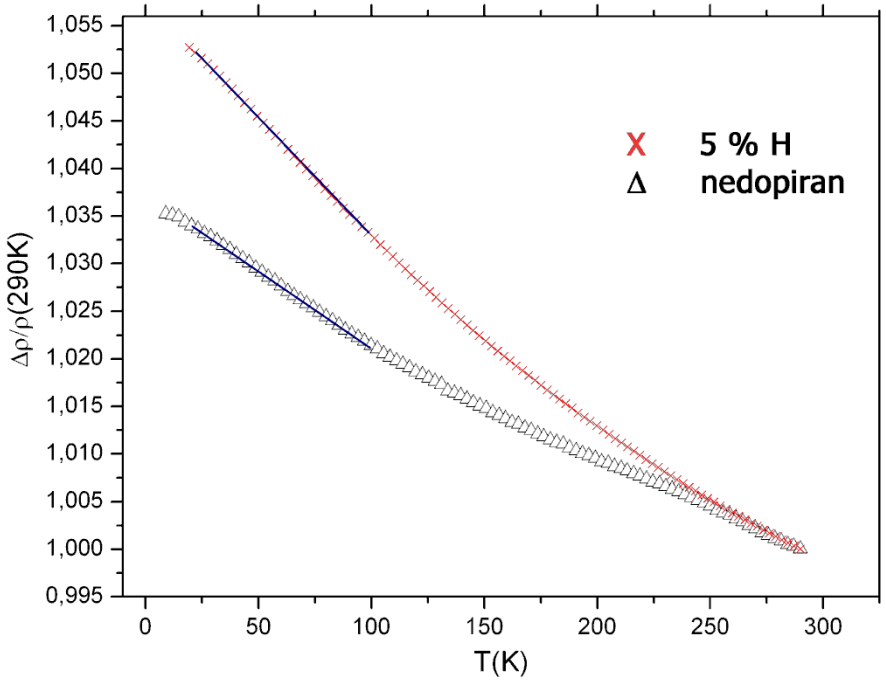


- Staklasti uzorak:
  2α=35.9
  Δβ=3.7
  D=2.3 nm

- S=60 K/min
  2α=35.9
  Δβ=3.7
  D=2.3nm
  ω-Zr (P6/mmm)

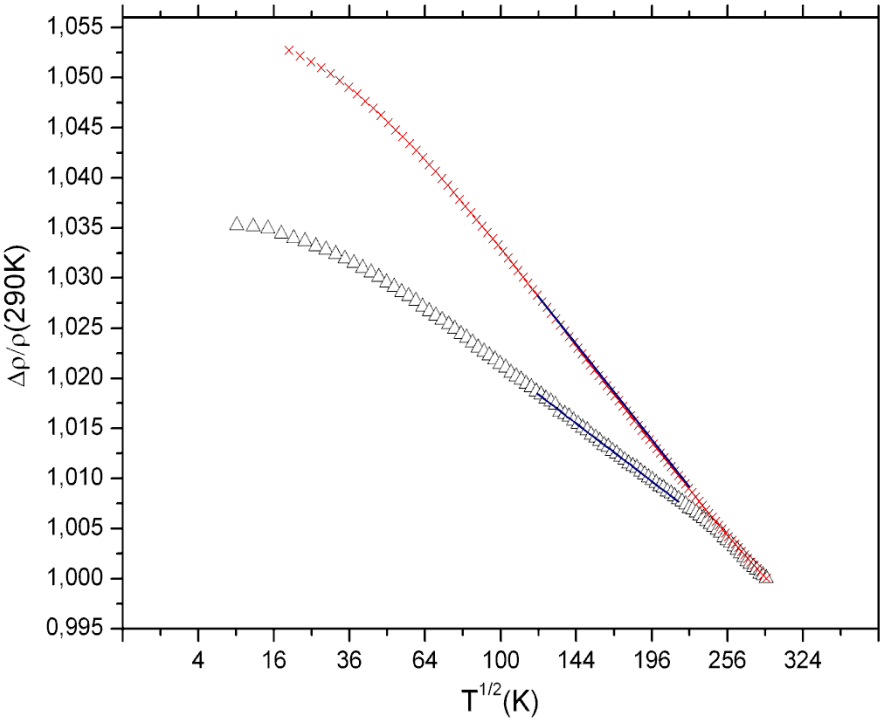
- S=10 K/min :
  $2\alpha_1$=35.35 $\Delta\beta_1$=0.4
  D_1=20.9 nm
  Zr_2Ni (I4/mcm)
  $2\alpha_2$=36.43 $\Delta\beta_2$=0.35
  D_2=23.9 nm
  α-Zr (P6_3/mmc)

Otpornost staklastih uzoraka



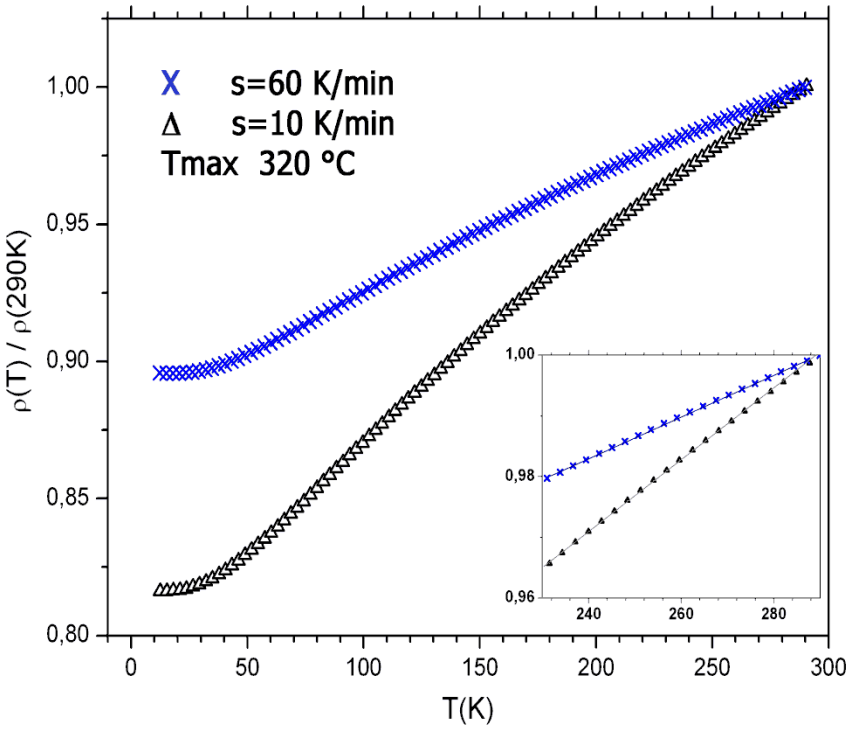
- Dominantan je doprinos slabe lokalizacije, negativan TCR
- Slabo vidljiva saturacija oko 10 K
- Dopirani uzorak (5% H) ima veću apsolutnu vrijednost TCR-a – manja stabilnost uzorka

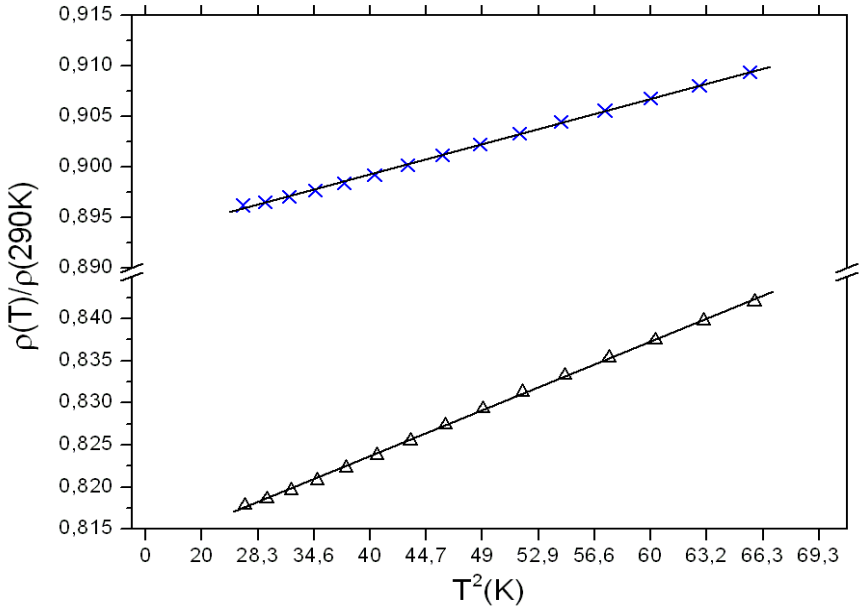
- **Ovisnost $\rho \sim T$ području 25-100 K**
- **$\tau_i \propto T^{-p}$ =2**
- **Na T > 100 K ovisnost $\rho \sim T^{1/2}$ p=1**



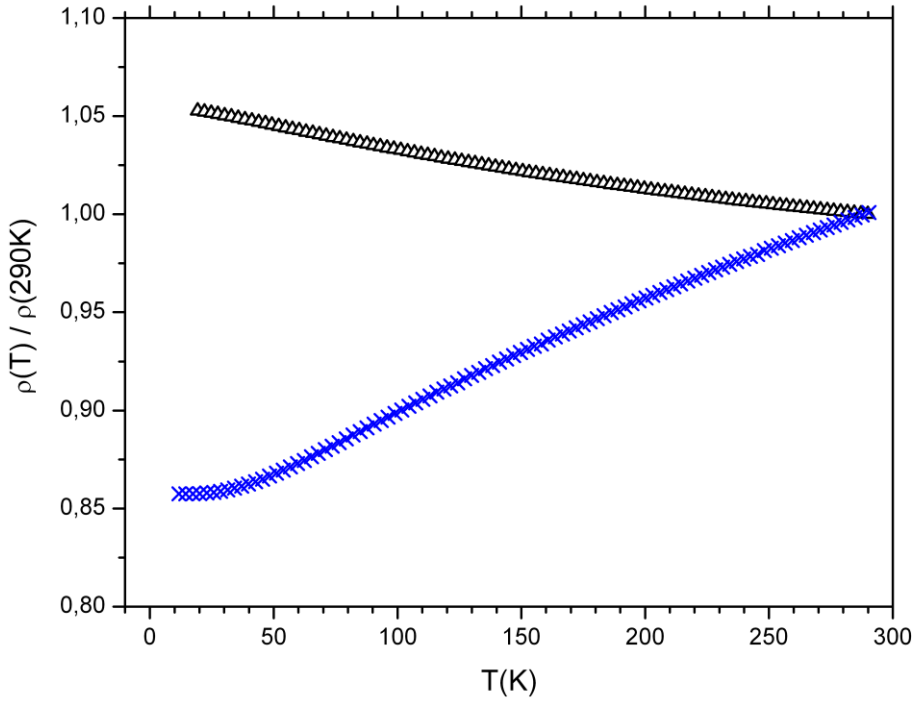
Otpornost aniliranih uzoraka

- Anilirani uzorci $Zr_{80}Ni_{20}$ imaju pozitivan TCR
- Uzorak grijan manjom brzinom ima veći TCR, oba su grijana do ispod drugog egzoterma (do 320°C)
- Debyeva temperatura Θ_D za ove uzorke je blizu T=200 K
- Linearna ovisnost za $T>\Theta_D$, iznad 200 K





- Ovisnost $\rho \sim T^2$ niskim temperaturama ($T<\Theta_D$)
- U skladu sa Ziman-Faberovom teorijom (Nagelov model) gdje je predviđena takva ovisnost



- Usporedba relativne otpornosti staklastog i aniliranog uzorka (dopiranih vodikom, x= 0.05)
- Staklasti uzorak:
  $\rho(290K)=(170 \pm 10)\ \mu\Omega cm$
- Anilirani uzorak (s=10 K/min):
  $\rho(290K)=(100 \pm 10)\ \mu\Omega cm$

- **Ponašanje je u skladu s Mooijevom korelacijom koja predviđa negativan TCR za otpornosti veće od 150 μΩcm i pozitivan TCR za manje vrijednosti**
- **Poslijedica kristalizacije – smanjenje otpornosti i promjena predznaka TCR-a**

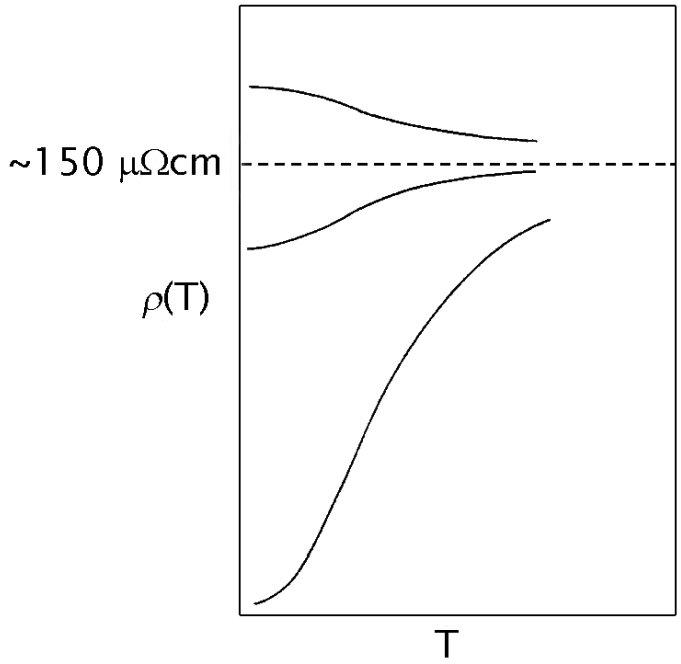
Mooijeva korelacija

- **Slijedi iz eksperimentalnih opažanja vodljivosti metalnih stakala**

1. Otpornost stakala ρ>100 $\mu\Omega$cm je neosjetljiva na detalje elektronske strukture i atomskog rasporeda

2. Negativan temperaturni koeficijent otpornosti (TCR) stakala otpornosti ρ>150 $\mu\Omega$cm

3. Saturacija otpornosti pri ρ=150-200 $\mu\Omega$cm na visokim temperaturama



- **Takvo ponašanje je posljedica približavanja srednjeg slobodnog puta međuatomskim razmacima**

Ziman-Faberova teorija

- Temelji se na Drudeovom modelu
- Primjenjiva na stakla niske otpornosti i kristalinične metale
- Elektroni su opisani ravnim valovima, vektora $\vec{k}$, srednji slobodni put je veći od međuatomskih udaljenosti
- Vrijeme relaksacije – recipročno vjerojatnosti prijelaza

$$\frac{1}{\tau} = \int (1 - \cos\theta)\, W(\theta)\, d\Omega$$

- Strukturni faktor

$$S(\vec{q}) = \frac{1}{N}\langle |\sum_i e^{i\vec{q}\vec{R}_i}|^2 \rangle$$

$$\vec{R}_i = \vec{l}_i + \vec{u}_i$$

- Kvadrat matričnog je

$$|\langle \vec{k}|V|\vec{k}'\rangle|^2 = \frac{1}{N}|v(\vec{q})|^2 S(\vec{q})$$

- Otpornost

$$\rho = \frac{12\pi V_0}{e^2\hbar\nu_F^2}\int_0^1 S(\vec{q})|\nu(\vec{q})|^2 \left(\frac{q}{2k_F}\right)^3 d\left(\frac{q}{2k_F}\right)$$

- Ziman i Fal vode parcijalne strukturne faktore i koncentracije komponenti

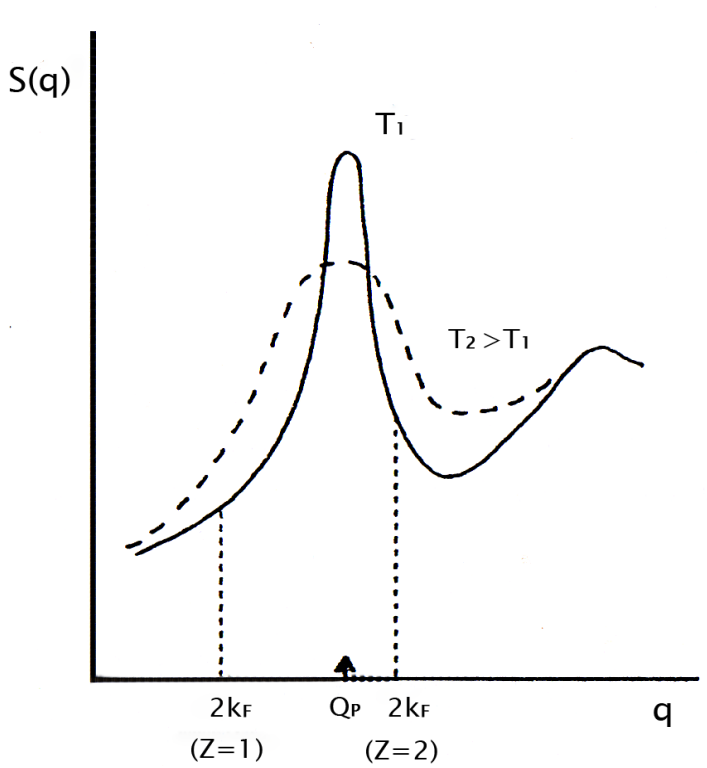
- Za oblik strukturnog faktora bitan je položaj fermijevog valnog vektora tekućih metala ili stakala, $2k_F$

$$k_F = \left(\frac{3\pi^2 Z}{V_0}\right)^{\frac{1}{3}}$$

- Za prikladan opis stakala uvodi se rezonantno raspršenje vodljivih elektrona na 3d-vrpci

  v(q) -> *t* (k,k')

- Cote i Meisel uvode strukturni faktor otpornosti, a Nagel koristi oblik



Strukturni faktor tekućih metala i metalnih stakala

$$S^p(q) \simeq 1 + [S_{T=0}(q) - 1]\, e^{-2[W(T)-W(0)]}$$

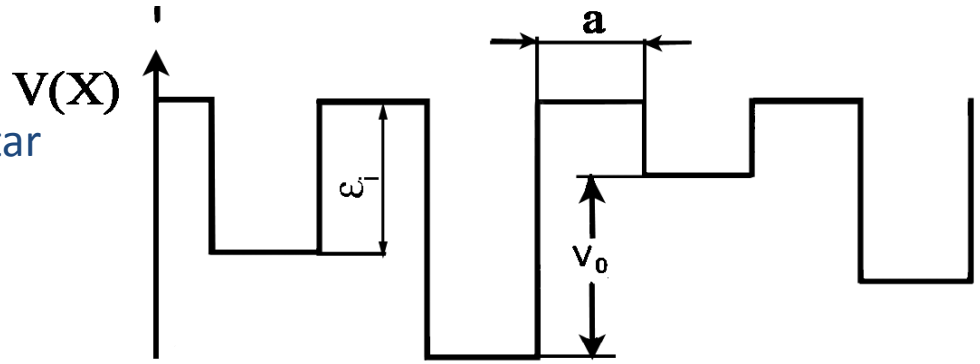
$$W(T) \simeq W(0)\left[1 + \tfrac{2}{3}\pi^2\left(\tfrac{T}{\Theta_D}\right)^2\right], \qquad T \ll \Theta_D \qquad \rho \sim T^2$$

$$\simeq W(0)\left[1 + \tfrac{2}{3}\pi^2\left(\tfrac{T}{\Theta_D}\right)\right], \qquad T \gg \Theta_D \qquad \rho \sim T$$

Kvantni doprinosi

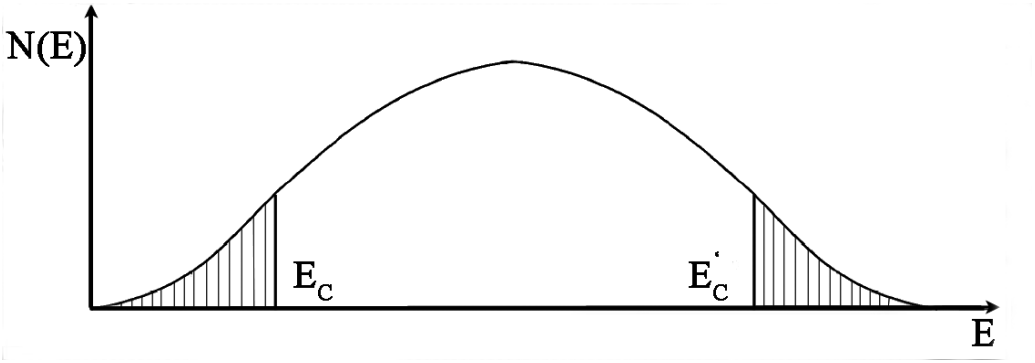
- **Andersonov model lokalizacije** – temeljen na nasumičnosti potencijala amorfne tvari

  • Mjera nereda je interval W unutar kojeg su raspoređene energije ε_i



- **Hamiltonijan sustava** $$H = \sum_i \epsilon_i |i\rangle\langle i| + \sum_{i,j\neq 0} I(j)|i\rangle\langle i+j|$$

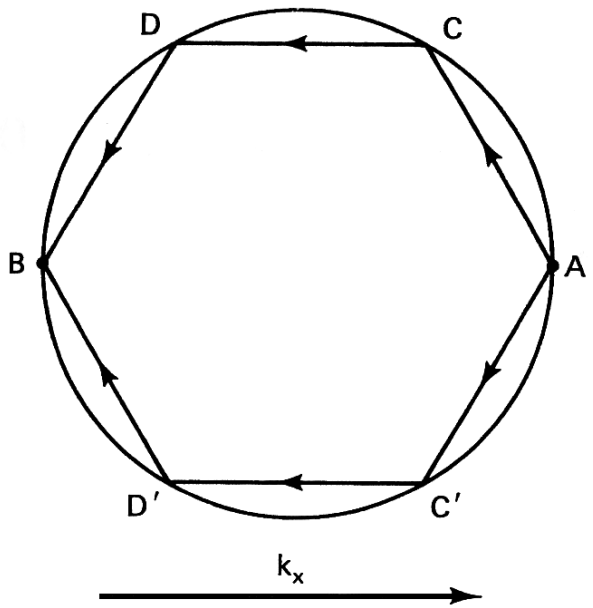
- **Pojava lokalizacije Blochovih stanja i povećanja otpornosti**



Gustoća stanja

- **Slaba lokalizacija** – posljedica interferencije raspršenih parcijalnih valnih funkcija
- Amplituda raspršenog elektrona je dvostruko veća nego u klasičnom slučaju $|C + C'|^2 = |C|^2 + |C'|^2 + |CC'^* + C^*C'| = 4|C|^2$

- **Koherenciju narušava neelastično raspršenje (τ_i), stoga je ona moguća za $\tau<t\_i$**
- **Temperaturna ovisnost** $\tau_i \propto T^{-p}$ **$2<p<4$ za $T<\Theta_D$**



- **Doprinos spin-orbit interakcije: τ_{SO}**

- **Vodljivost:**

$$\sigma_{WL}(T) = \frac{e^2}{2\pi\hbar}\left[3\left(\frac{1}{D\tau_{SO}} + \frac{1}{4D\tau_i}\right)^{1/2} - \left(\frac{1}{4D\tau_i}\right)^{1/2}\right]$$

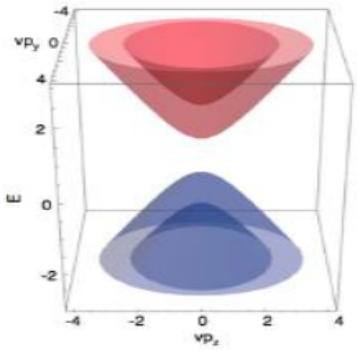
- **Elektron-elektron interakcija – doprinosi na niskim temperaturama, blizu T_c, doprinos u Cooperovom i difuznom kanalu**

Model električne vodljivosti u polianilinu

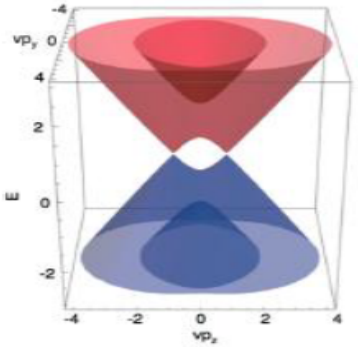
- Dopirani polianilin posjeduje veliki stupanje strukturalnog nereda, stanja na Fermijevoj energiji su likalizirana
- Vodljivost je jedino moguća fononski potpomognutim preskocima između lokaliziranih stanja
- Vodljivost je opisana Mott-ovim modelom vođenja mehanizmom preskoka varijabilnog dosega (VRH)
- Preskoci su varijabilnog dosega jer vjerojatnost preskoka ovisi o dva parametra: - udaljenost između lokaliziranih stanja
  - razlici energija između lokaliziranih stanja

Topološki polumetali

Topološki polumetali ⟶ valentna i vodljiva vrpca dodiruju se u diskretnim točkama ili linijama u 3D. Oko mjesta dodira disperzija je linearna.



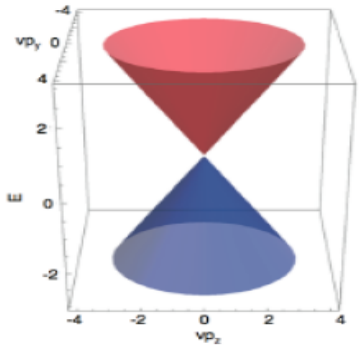
Poluvodič (maseni Dirac)



Weylov polumetal

- Par dvostruko degeneriranih točaka suprotnih kiralnosti.

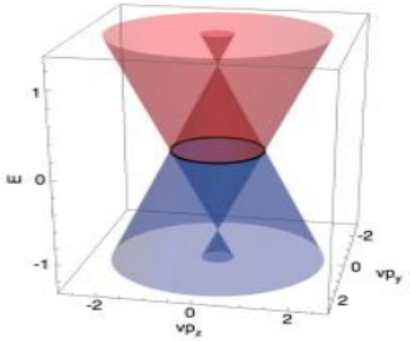
$$H = \pm \hbar v_F \vec{k} \cdot \vec{\sigma}$$



Diracov polumetal

- Četverostruko degenerirana točka (× 2).
- Dvije Weylove točke na istom $\vec{k}$.

$$H = \hbar v_F \begin{pmatrix} \vec{\sigma} \cdot \vec{k} & 0 \\ 0 & -\vec{\sigma} \cdot \vec{k} \end{pmatrix}$$

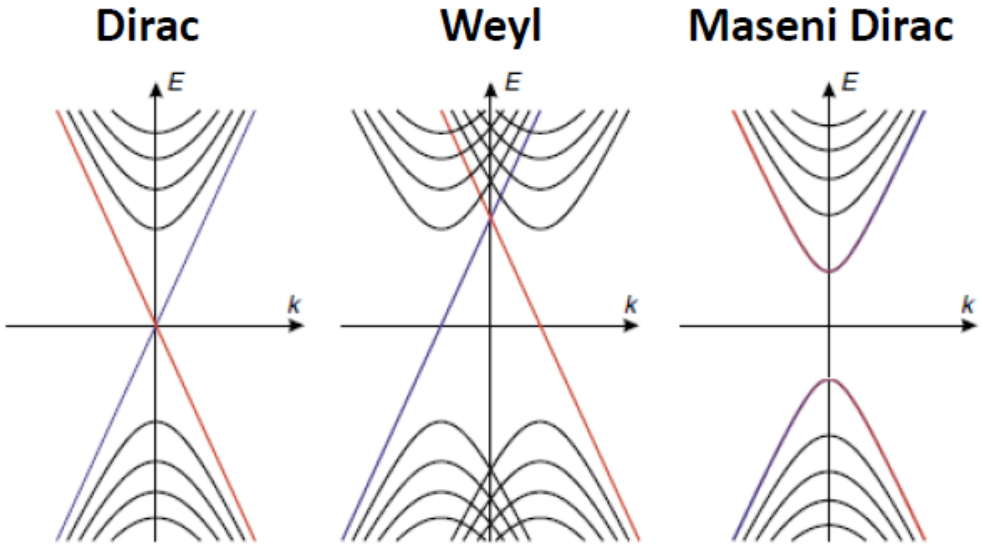


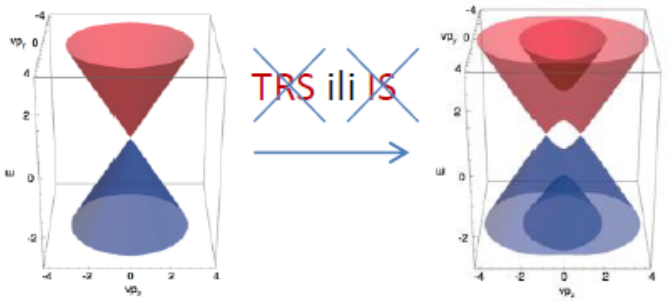
Linijski Diracov polumetal

- Vrpce se dodiruju duž linija.

E_F na, ili što bliže točkama dodira ⟶ Weylovi/Diracovi fermioni

Diracov polumetal u magnetskom polju





$\vec{B}$ slama simetriju na vremensku inverziju i, ovisno o smjeru, simetriju koja čuva Diracovu točku.

Landauovi nivoi:

$$\varepsilon_{n,k} = \begin{cases} \frac{\hbar e B}{m}(n+\gamma) + \frac{\hbar^2 {k_z}^2}{2m} & \text{Trivial } (\gamma = \frac{1}{2}) \\ \hbar v_F \sqrt{2B(n+\gamma) + {k_z}^2} & \text{Weyl } (\gamma = 0) \\ \hbar v_F \sqrt{2B(n+\gamma+C^2 sin^2\theta) + {k_z}^2} & \text{Dirac } (\gamma = 0) \end{cases}$$

θ je kut između $\vec{B}$ i osi simetrije koja čuva Diracove točke

Diracov polumetal u magnetskom polju

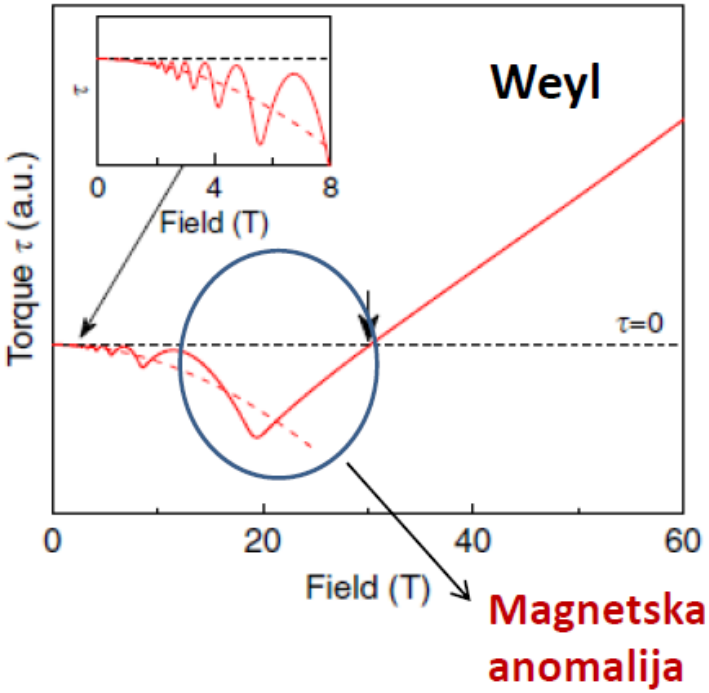
Landauovi nivoi

$$\varepsilon_{n,k} = \begin{cases} \frac{\hbar eB}{m}(n+\gamma) + \frac{\hbar^2 {k_z}^2}{2m} & \text{Trivial } (\gamma = \frac{1}{2}) \\ \hbar v_F \sqrt{2B(n+\gamma) + {k_z}^2} & \text{Weyl } (\gamma = 0) \\ \hbar v_F \sqrt{2B(n+\gamma+C^2 sin^2\theta) + {k_z}^2} & \text{Dirac } (\gamma = 0) \end{cases}$$

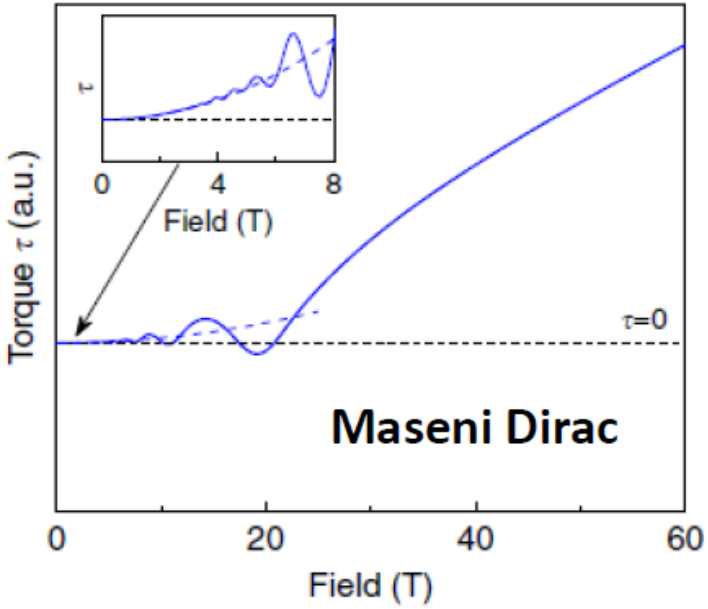
Magnetizacija u kvantnom limitu ($n = 0$)

$$M_{n=0} = -\frac{\partial \varepsilon_{0,k}}{\partial B}$$

$$\vec{\tau} = \vec{M} \times \vec{B}$$



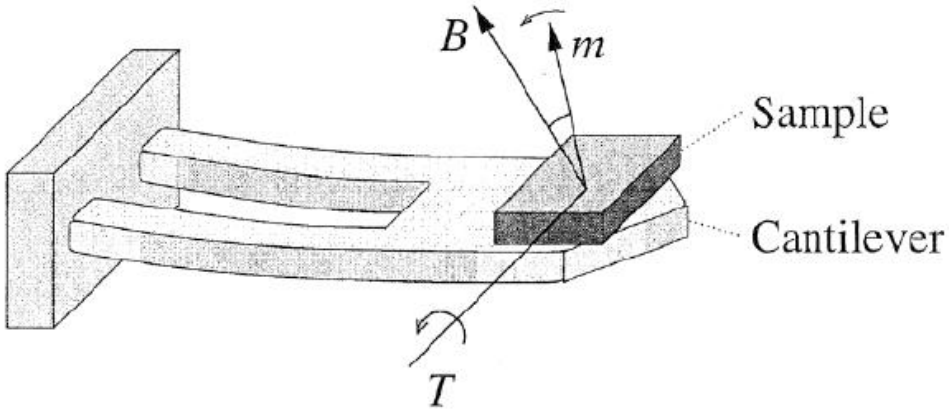
Simulirani $\vec{\tau}$ za Weylov i maseni Diracov polumetal u kvantnom limitu.



Preuzeto iz Moll, P. J. *et al* (2016). *Nature Communications*.

Mjerenje magnetskog momenta sile

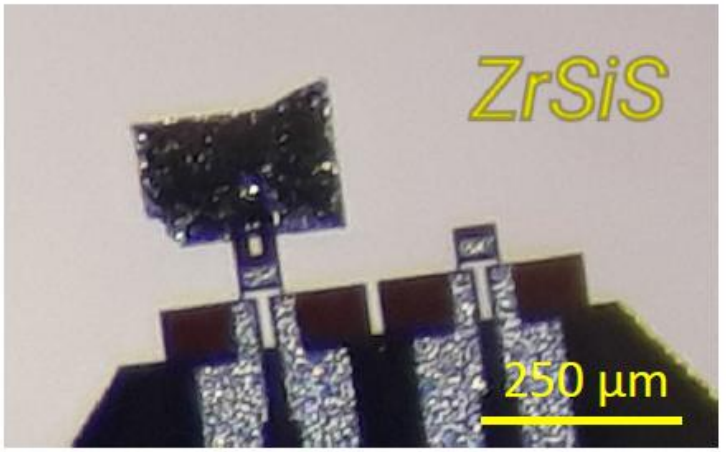
Metoda piezopoluge

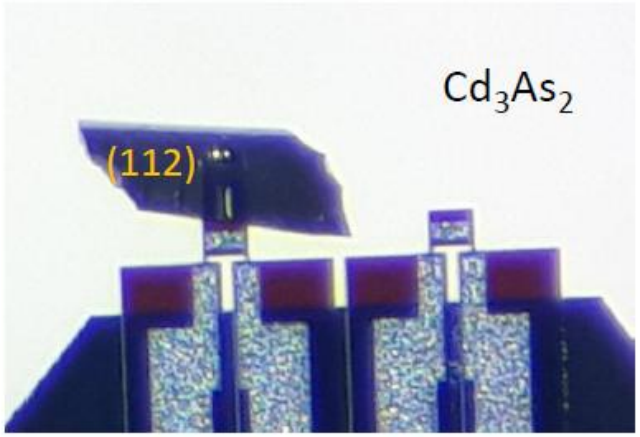


Mjeri se otpor piezootpornog senzora na polugi.

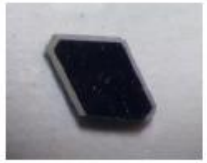
Magnetski anizotropan uzorak.

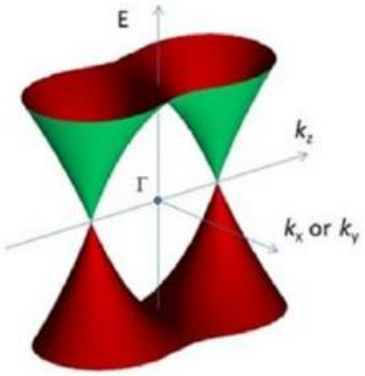
$$\vec{\tau} = \vec{M} \times \vec{B} \propto B^2$$





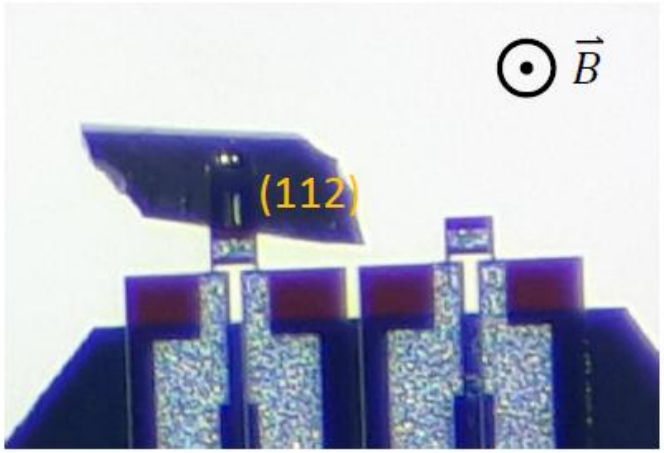
Cd_3As_2

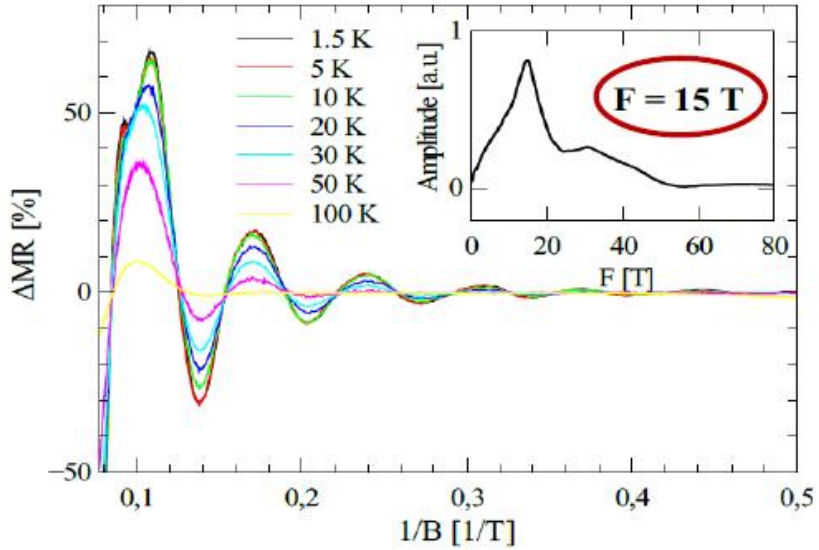




Cd_3As_2

- Diracov polumetal.
- Par Diracovih točaka na osi rotacijske simetrije.



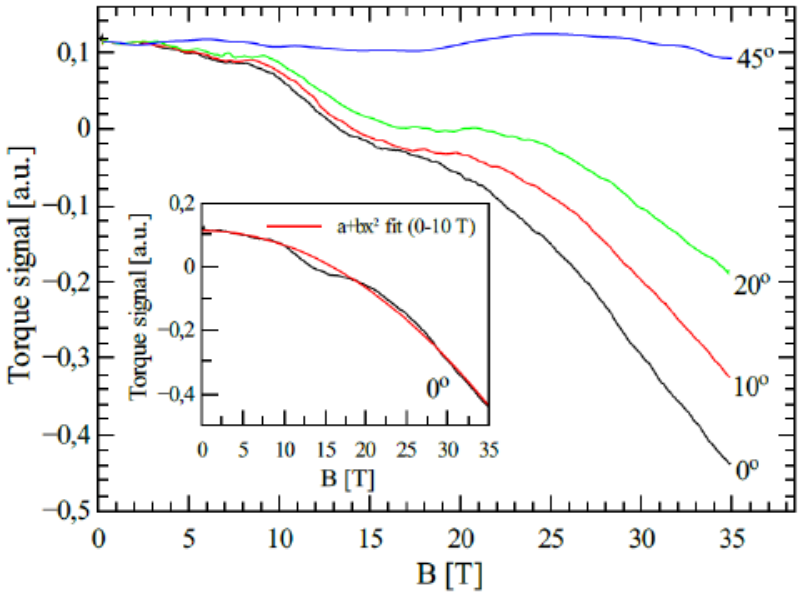


Kvantne oscilacije u magnetootporu Cd_3As_2.

$\vec{\tau}$ je mjeren na 2 K u poljima do 35 T za različite kutove θ između polja i normale na (112) ravninu.

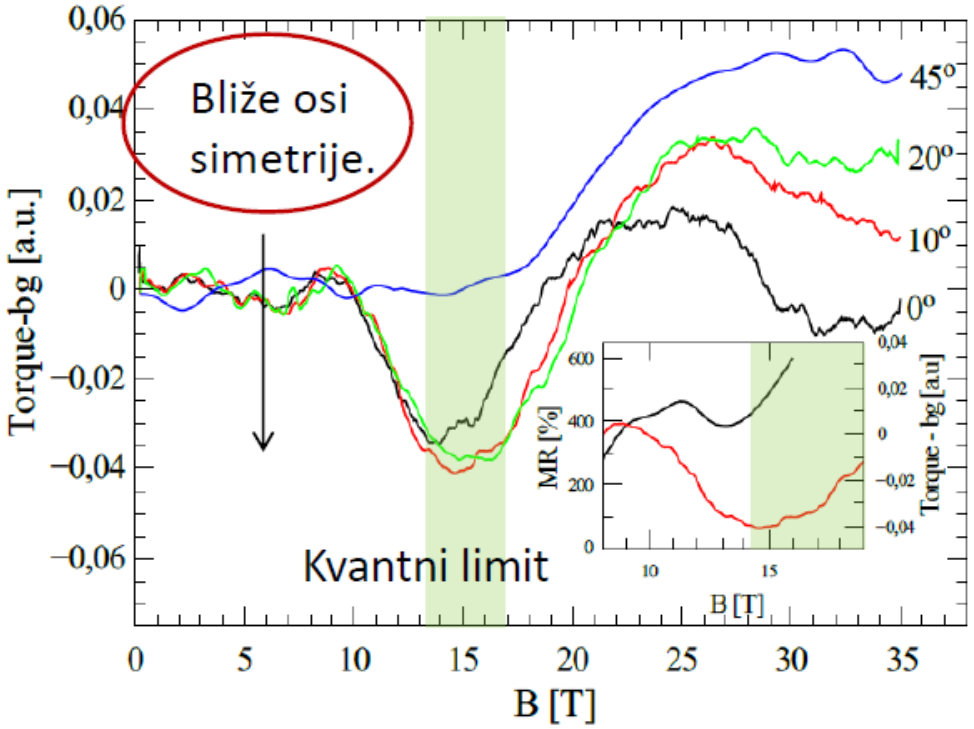
Cd_3As_2

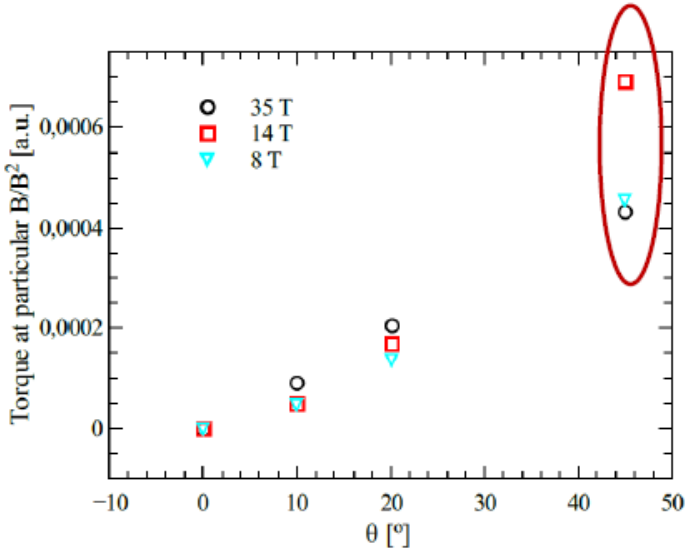
Sirovo mjerenje τ s B^2 ovisnošću.



Vidljiva je kutno ovisna magnetska anomalija oko kvantnog limita.

τ -B^2 pozadina.

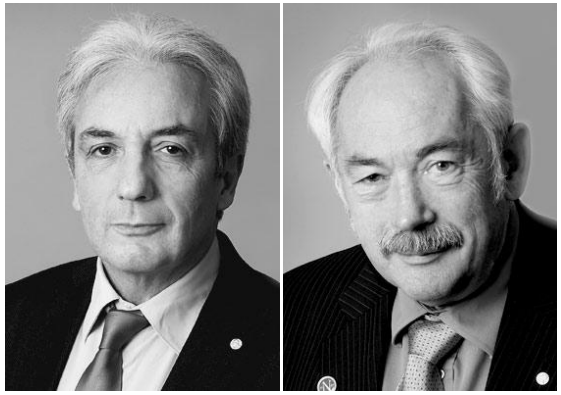


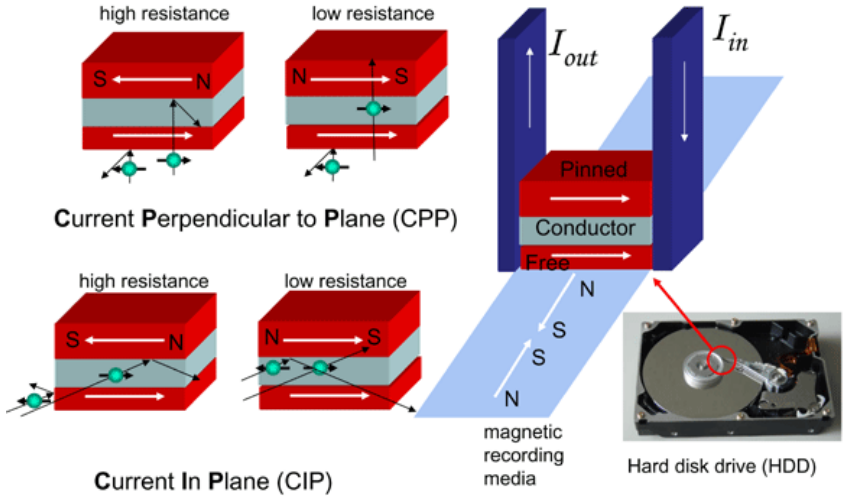


τ na tri vrijednosti polja skaliran s B^2.

Primjer znanstvenog otkrića

- The Nobel Prize in Physics 2007 was awarded jointly to **Albert Fert** and **Peter Grünberg** "for the discovery of **Giant** Giant Magnetoresistance (GMR)"





Gigantski magnetootpor

- Članak iz 1988.g. : M. N. Baibich, J. M. Broto, **A. Fert**, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazelas, **Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices**, Phys. Rev. Lett. **61**, 2472 (1988)
- ideja iz 1970. g. – korištenje spinski polariziranih struja
- koncept ostvaren tek 1988. g. razvojem tehnologije (MBE) – tanki slojevi magnetskih i

Giant Magnetoresistance of (001) Fe/(001) Cr Magnetic Superlattices

M. N. Baibich,[a] J. M. Broto, A. Fert, F. Nguyen Van Dau, and F. Petroff
Laboratoire de Physique des Solides, Université Paris-Sud, F-91405 Orsay, France

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(Received 24 August 1988)

We have studied the magnetoresistance of (001)Fe/(001)Cr superlattices prepared by molecular-beam epitaxy. A huge magnetoresistance is found in superlattices with thin Cr layers: For example, with $t_{Cr}=9$ Å, at $T=4.2$ K, the resistivity is lowered by almost a factor of 2 in a magnetic field of 2 T. We ascribe this giant magnetoresistance to spin-dependent transmission of the conduction electrons between Fe layers through Cr layers.

PACS numbers: 75.50.Rr, 72.15.Gd, 75.70.Cn

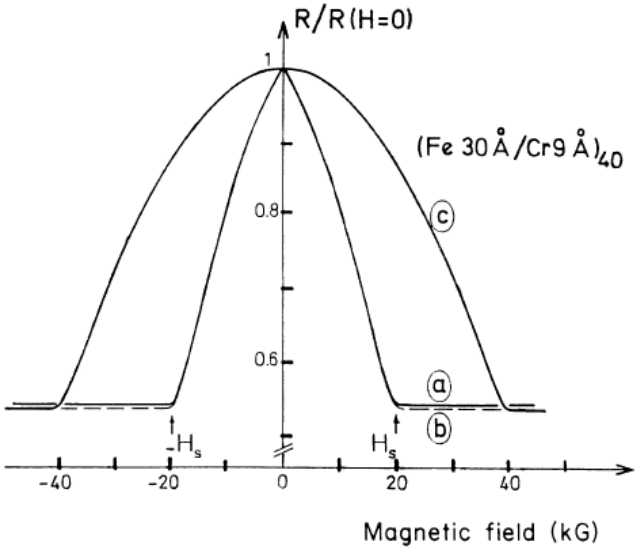
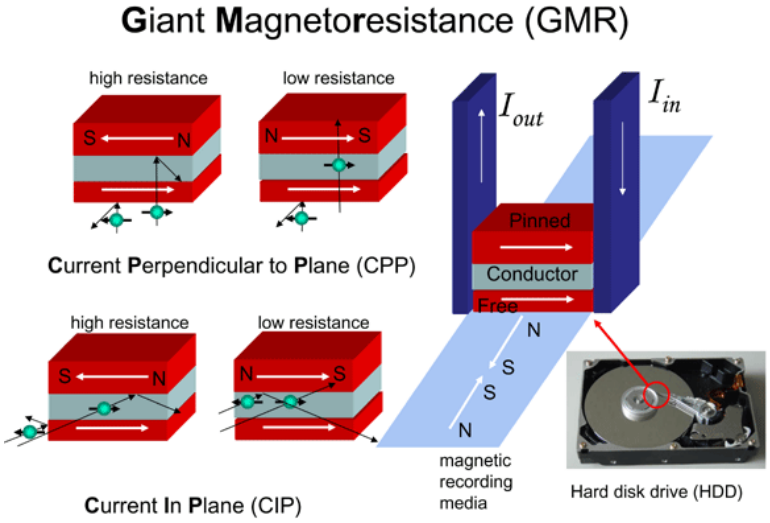
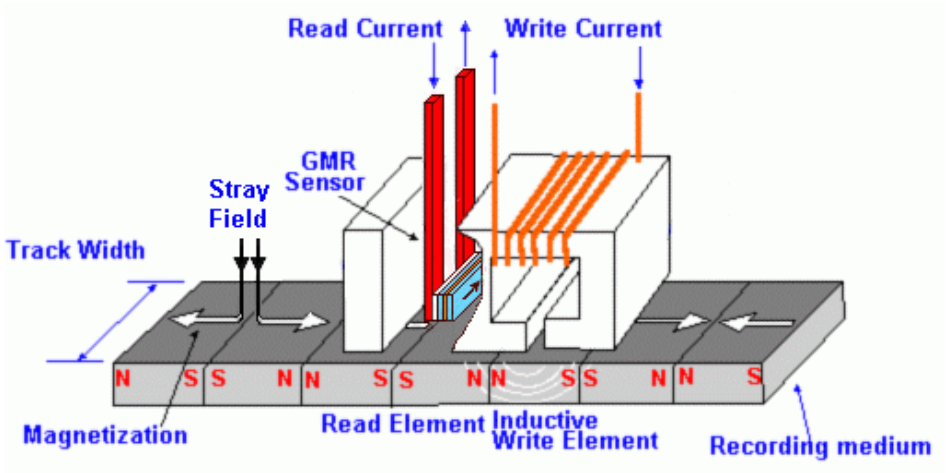


FIG. 2. Magnetoresistance of a [(Fe 30 Å)/(Cr 9 Å)]$_{40}$ superlattice of 4.2 K. The current is along [110] and the field is in the layer plane along the current direction (curve *a*), in the layer plane perpendicular to the current (curve *b*), or perpendicular to the layer plane (curve *c*). The resistivity at zero field is 54 $\mu\Omega$ cm. There is a small difference between the curves in increasing and decreasing field (hysteresis) that we have not represented in the figure. The superlattice is covered by a 100-Å Ag protection layer. This means that the magnetoresistance of the superlattice alone should be slightly higher.

Gigantski magnetootpor

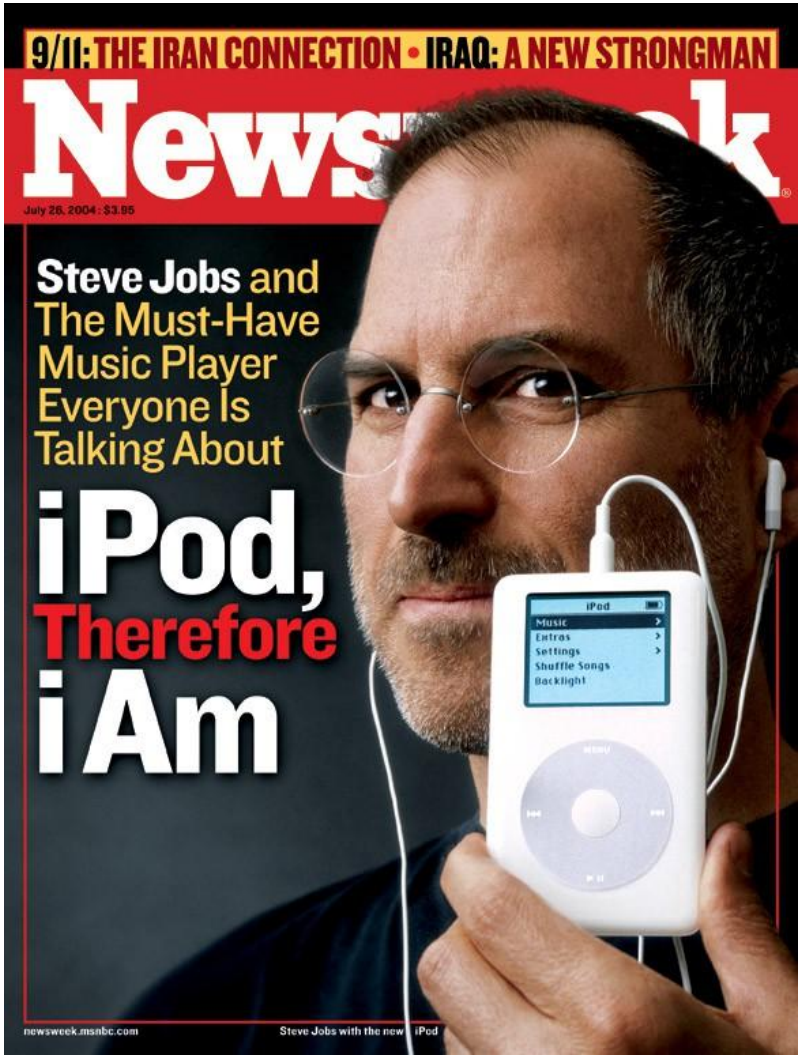
- rođena je **spintronika**
- omogućen razvoj sve manjih tvrdih diskova



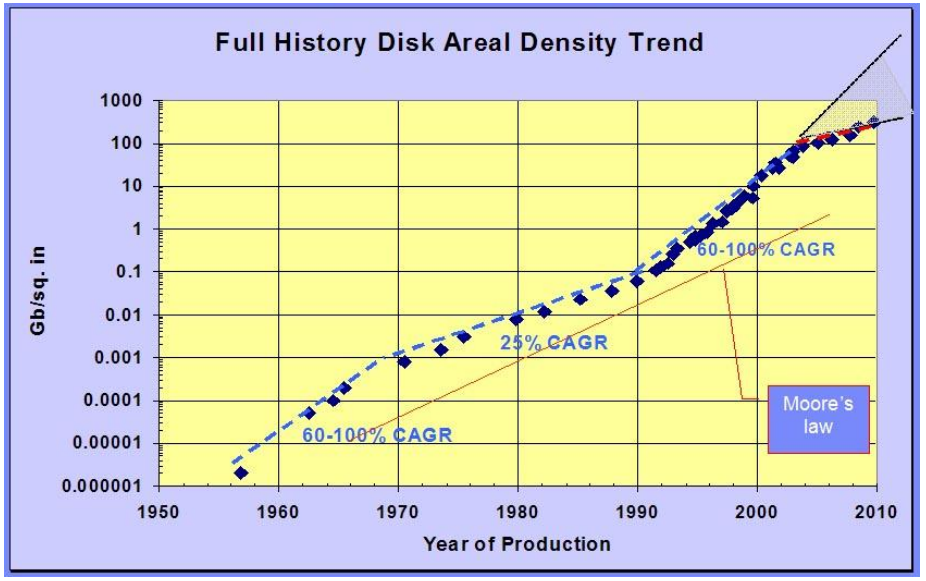


- usavršavanje preuzela **industrija**
- Nobelova nagrada: *the greatest benefit on*

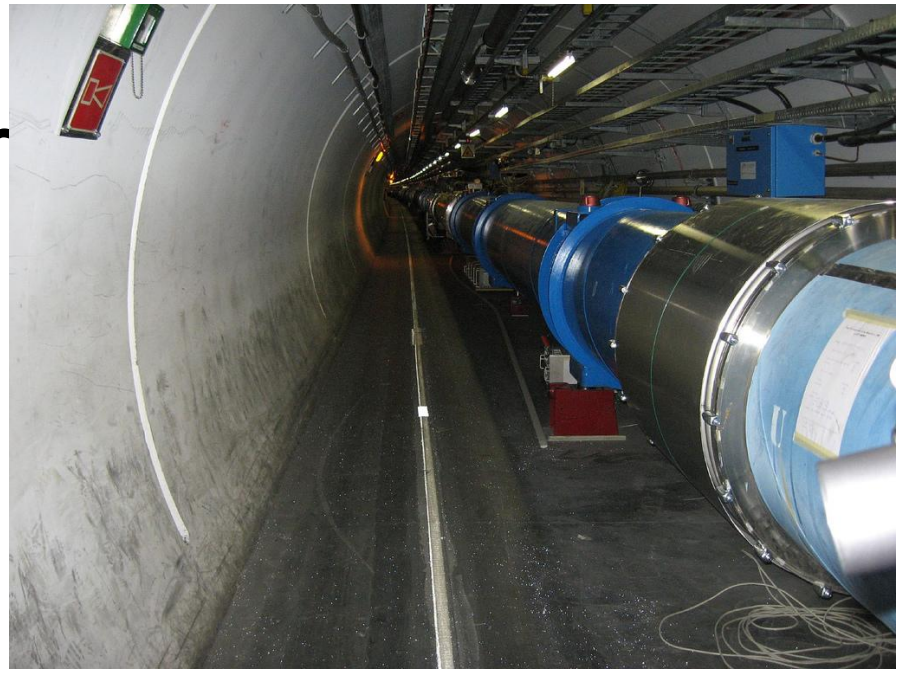
Gigantski magnetootpor



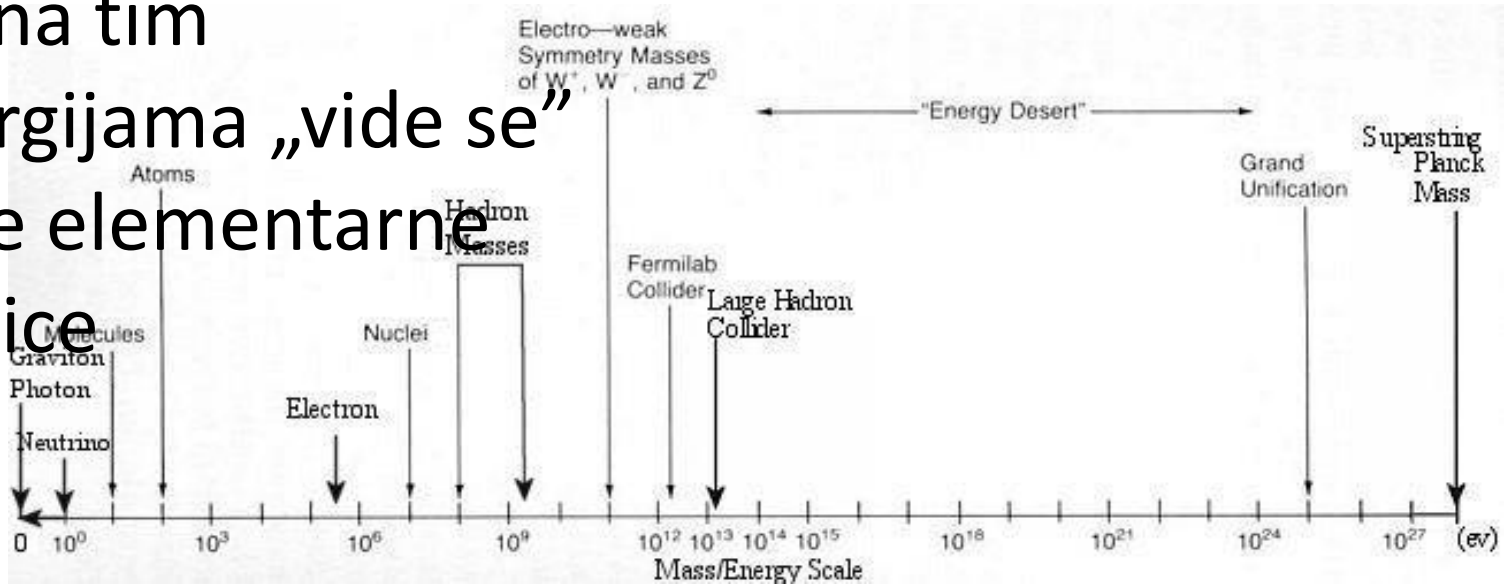
The small white player has a 1,000 song capacity thanks to its 5GB hard drive



Primjer



- ubrzavanje čestica (protona) do 6.5 TeV (13 TeV kombinirano)
- tek na tim energijama „vide se” neke elementarne čestice



Važnost eksperimentalne fizike za šire društvo

- J. Liebing (~1850. g.): …Stoga, što znamo prirodi, ovisi o onome što možemo učiniti, a to ovisi o uređajima kojima raspolažemo, materijalima kojima raspolažemo za gradnju uređaja i vještini kojom koristimo te uređaje.”
- napredna tehnologija – proizvodnja u „laboratorijskim” uvjetima: fizika, kemija, biologija
- zasnovana na znanstvenim otkrićima i koristi uređaje razvijene za eksperimentalnu fiziku

Primjer: proizvodnja procesora