Superconductivity and Cryogenics for Particle Accelerators

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Outline

- Introduction: thermodynamics and benefit of cooling (10 min)
- Basics of cryogenics (15 min)
- BCS superconductivity (15 min)
- Non-BCS superconductivity (5 min)
- Break (10 min)
- Superconducting magnet (10 min)
- Superconducting RF cavities (20 min)
- Conclusion

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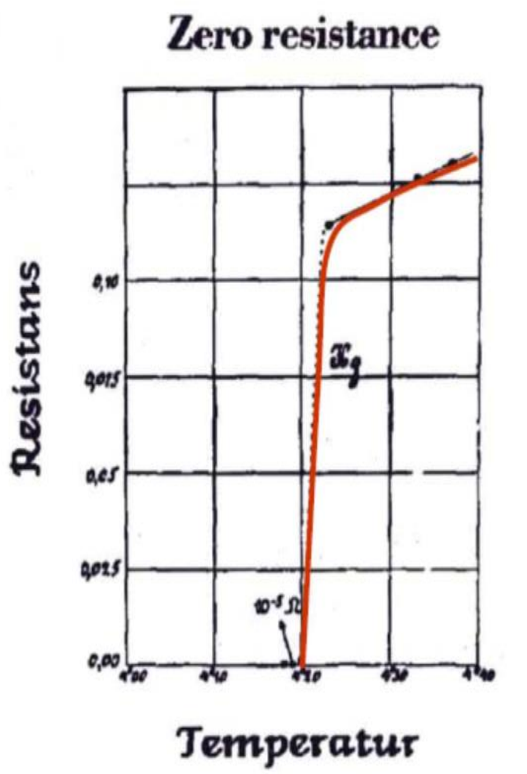
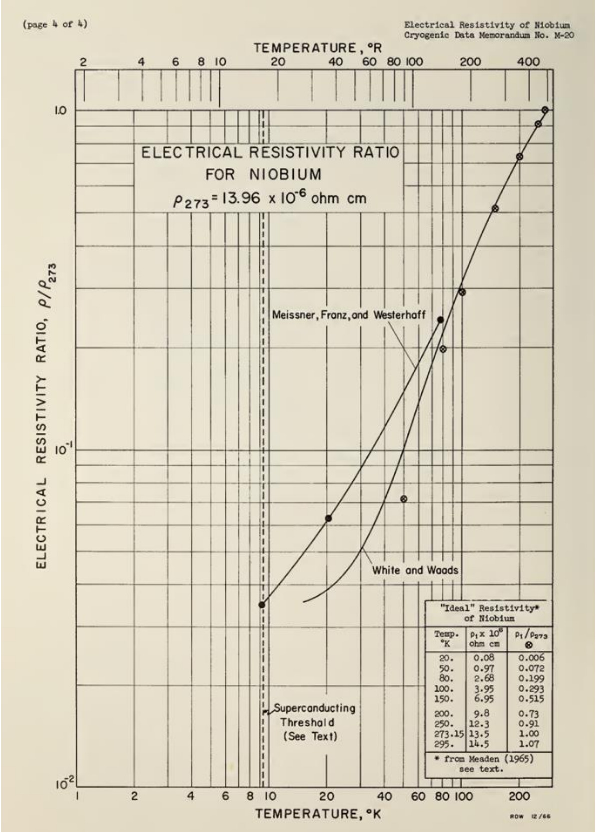
Cooling down to reduce electric loss

Superconducting (Hg)

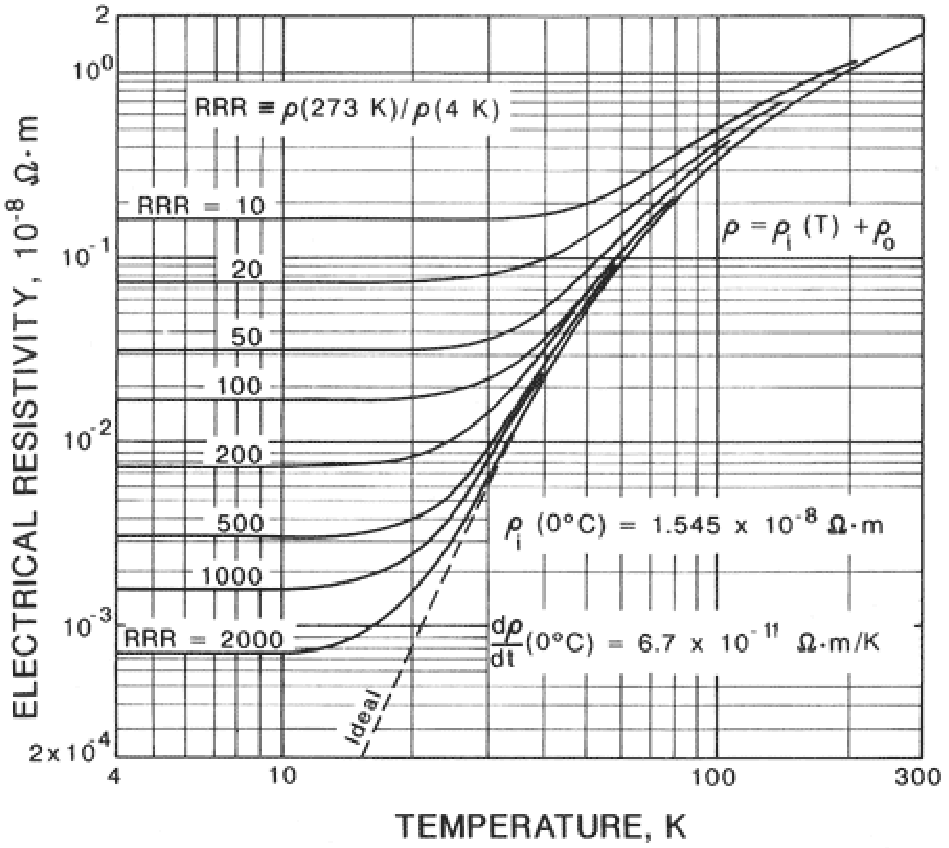


Niobium



https://nvlpubs.nist.gov/nistpubs/Legacy/TN/nbstechnicalnote365.pdf

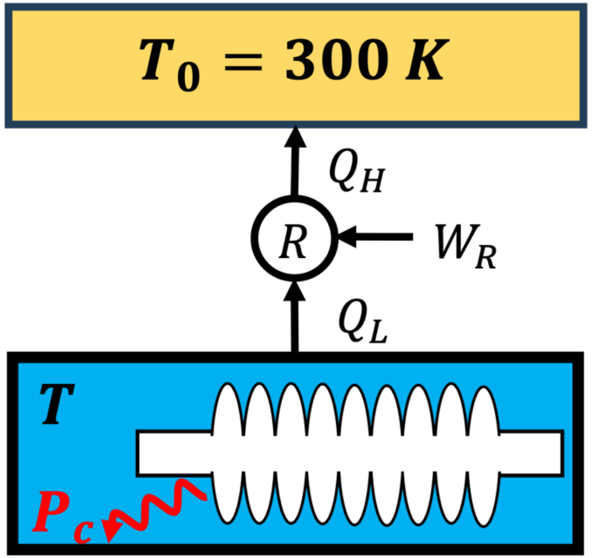
Copper



https://www.copper.org/resources/properties/cryogenic/

Cost of ideal cryogenics

Cooling power 1 W depends on temperature



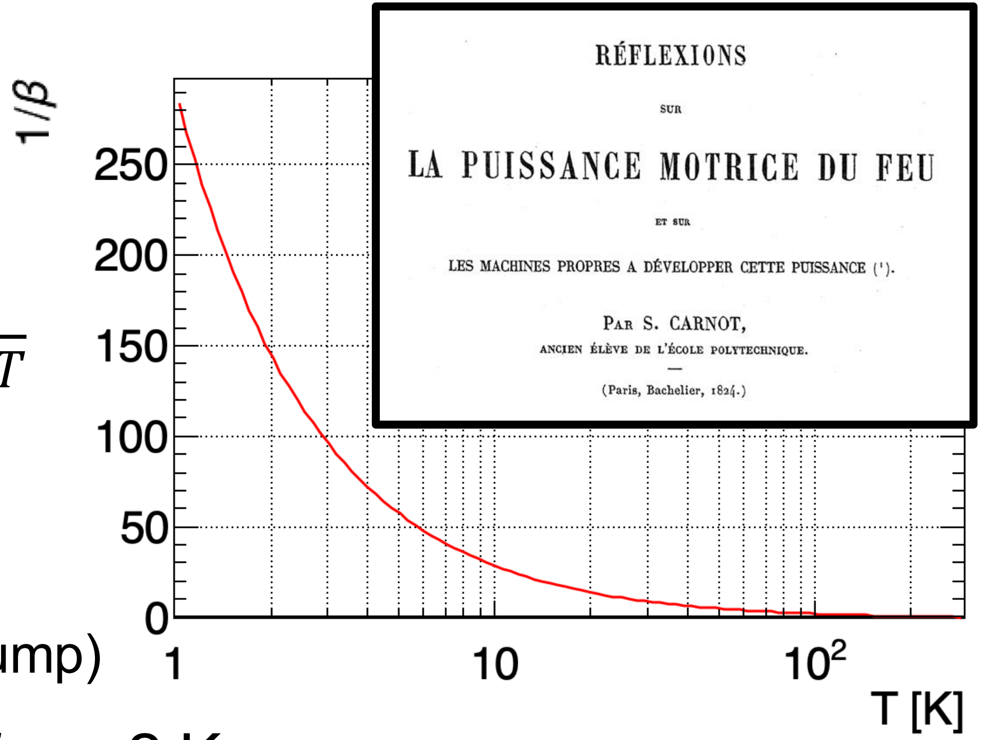
Carnot's theorem

$$\beta = \frac{Q_L}{W_R} = \frac{Q_L}{Q_H - Q_L} = \frac{T}{T_0 - T}$$

Required power

$$P_{cryo} > \frac{P_c}{\beta}$$

(be careful about logical jump)



RÉFLEXIONS

SUR

LA PUISSANCE MOTRICE DU FEU

ET SUR

LES MACHINES PROPRES A DÉVELOPPER CETTE PUISSANCE (¹).

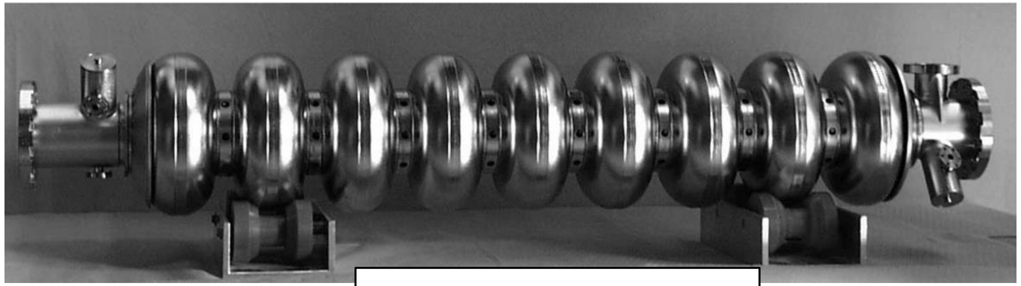
PAR S. CARNOT,

ANCIEN ÉLÈVE DE L'ÉCOLE POLYTECHNIQUE.

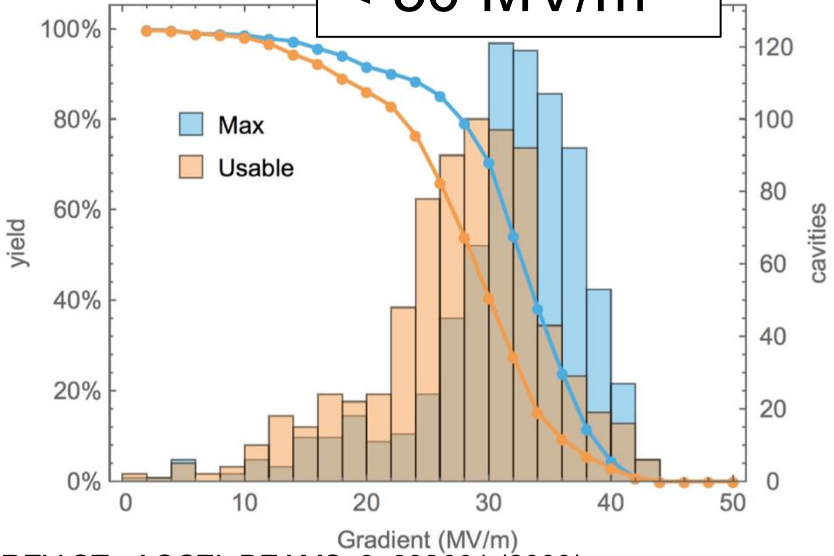
(Paris, Bachelier, 1824.)

- We may need >150 W to evacuate 1 W from 2 K
- Cryogenics is an option if the resistance is improved better than this factor
    - Or some applications (eg superconductors) are not feasible at warm

Superconducting niobium cavities (TESLA)

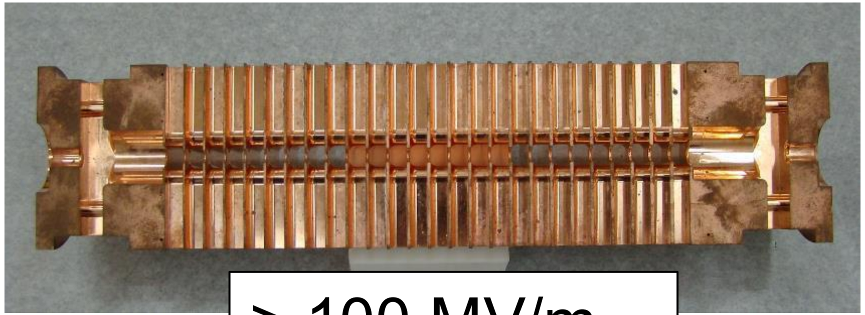


< 50 MV/m



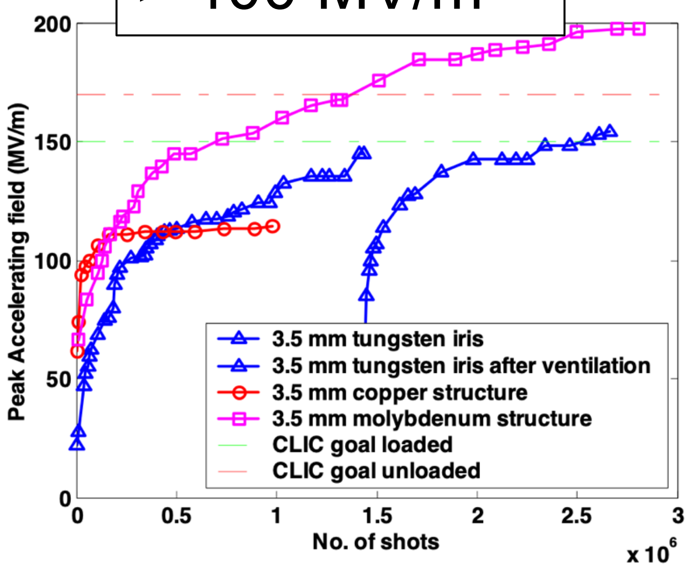
PHY REV ST - ACCEL BEAMS, **3**, 092001 (2000)
PHY REV ACCEL BEAMS 20, 042004 (2017)

Normal conducting copper cavities



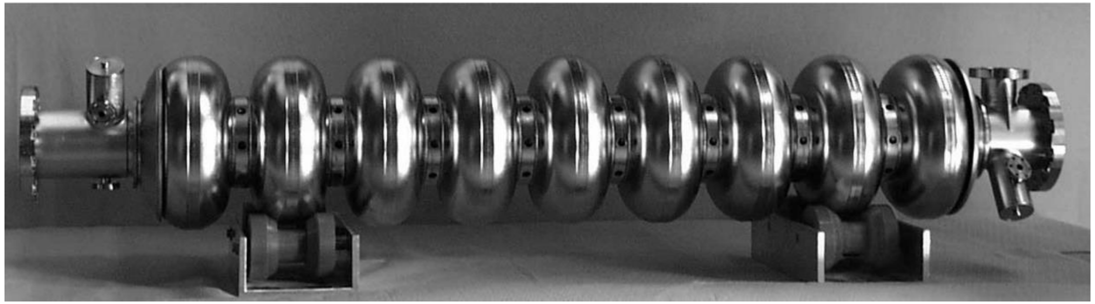
> 100 MV/m

$> \times 2$

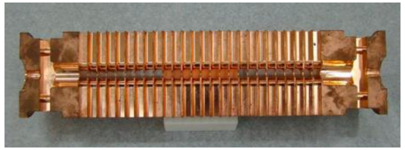


Courtesy: Walter Wuensch

Aperture

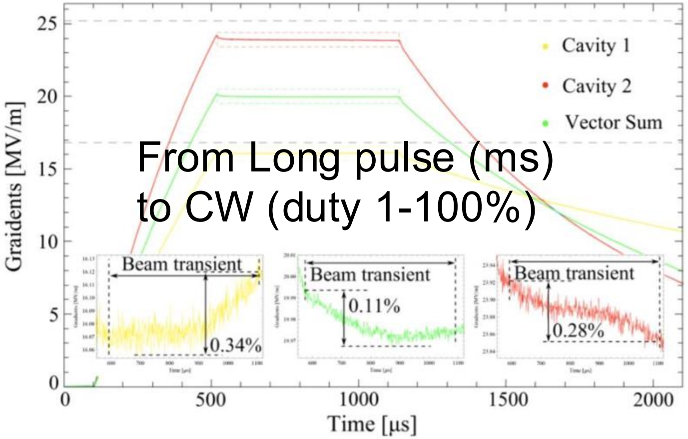


Superconducting cavities have high gradient at low frequency
→ large aperture (ILC: ϕ70 mm)

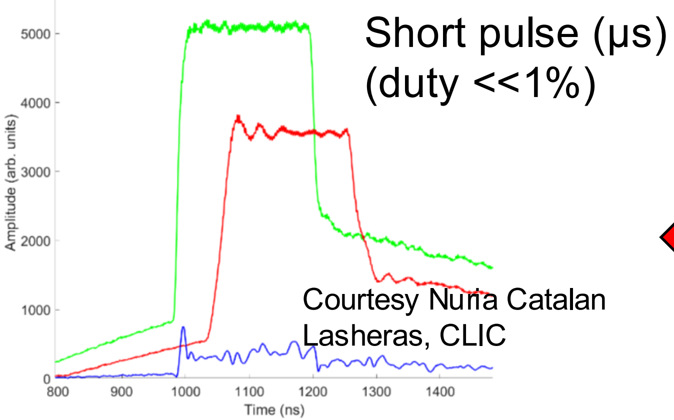


Normal conducting cavities are efficient at high frequency
→ small aperture (CLIC X-band: around ϕ3 mm)

Pulse length and duty cycle

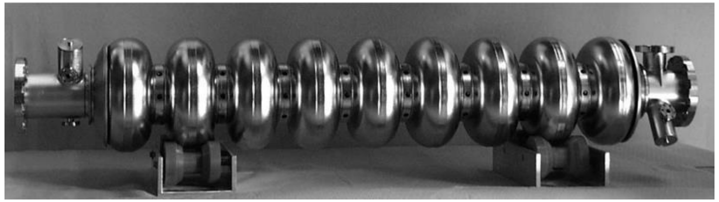


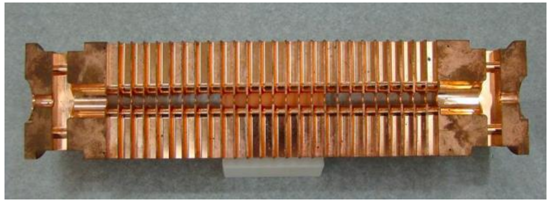
M. Omet
SRF2021
lecture

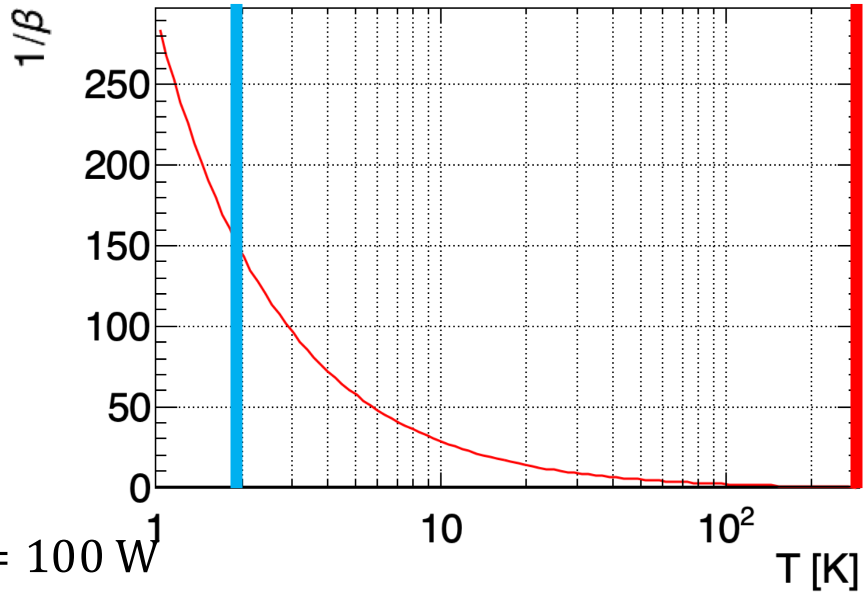


SC cavities' quality factor
$\times 10^{6}$
than copper cavities
→ power dissipation
$\times 10^{-6}$
but in ***cryogenics***!

SC vs NC cavities and cooling







<u>SC cavities</u>

$P_c = 100\ \mathrm{W}$ (CW)
Duty cycle 10^{-2}
$T = 2\ \mathrm{K}$

<u>NC cavities</u>

$P_c = 10\ \mathrm{MW}$ (CW)
Duty cycle 10^{-5}
Water cooling

$P_{NET} \sim 100\ \mathrm{W} \times 1\% \times 150 = 150\ \mathrm{W}$

$P_{NET} \sim 10\ \mathrm{MW} \times 10^{-5} \times 1 = 100\ \mathrm{W}$

- Short pulsed NC cavities and long pulsed SC cavities are similar in power consumption
  - If we need very long pulse or CW beam (LEP, FCCee, LCLSII) → SC cavities
  - If we need very short pulse beam (LCLS) → NC cavities
  - If we need CW but with low energy (may storage rings) → NC cavities
- Linear colliders are on the boarder: both SC (ILC) and NC (CLIC) may be OK

Carnot cycle is unrealistic at all

Thermodynamics does not include characteristic time constant
→ Carnot cycle gives maximum efficiency in quasi-static process ($\Delta t \rightarrow \infty$)
→ Power (work per time) is in trade off with the efficiency

PRL117 190601 (2016)

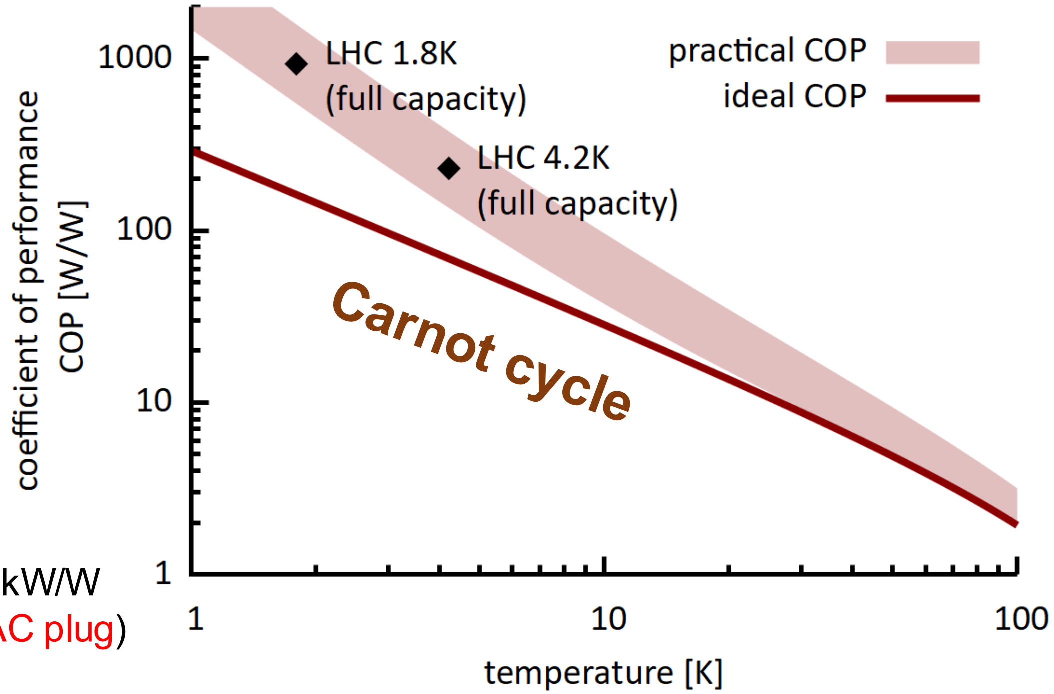
$$P_c \leq \bar{\Theta}\beta_L \eta(\eta_C - \eta)$$

We lose useful power if efficiency η is too good approaching to Carnot η_C

In addition, more practical limitations further degrade the efficiency

→ Around 1 kW is necessary to evacuate 1 W from 2 K

(typically 5 kW/W @ 2 K for AC plug)



→ If the power loss of the device improves by $>10^3$ by cooling, 2 K operation is beneficial

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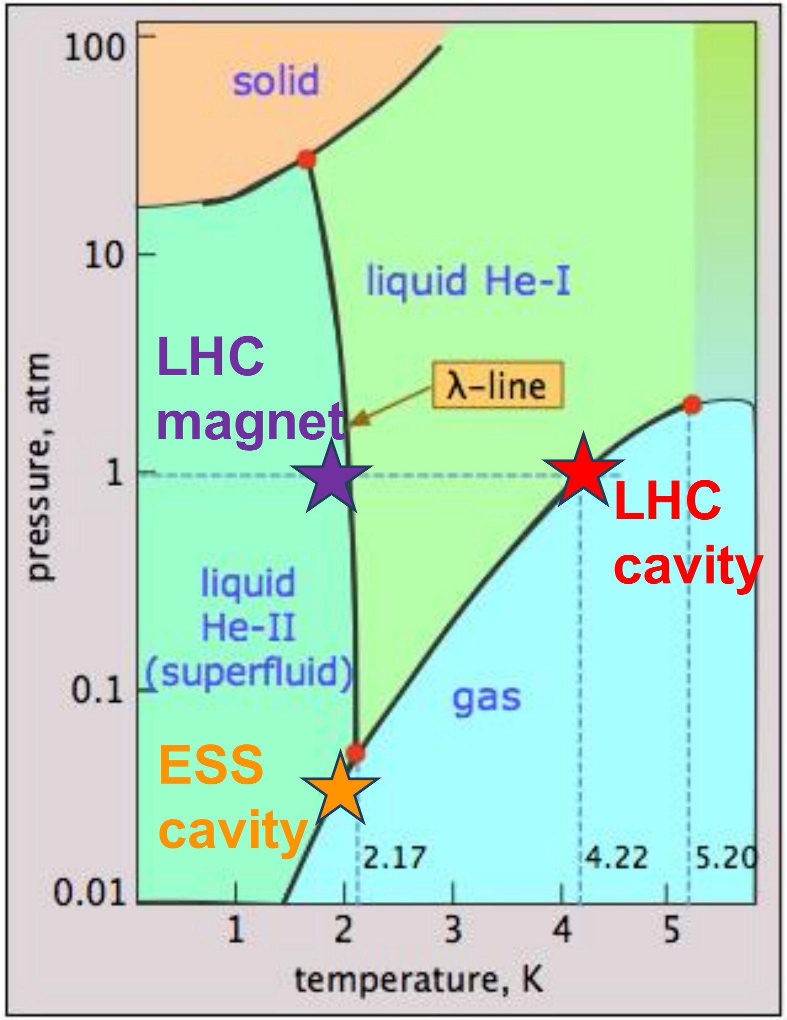
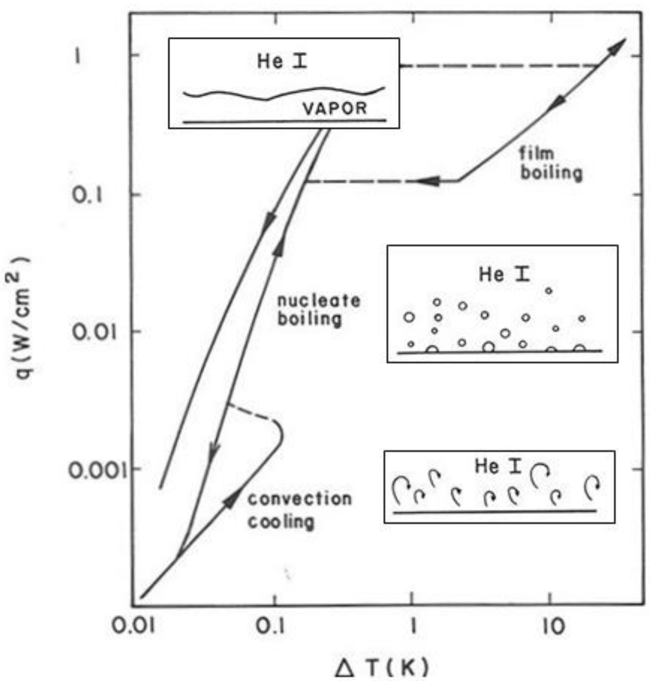
Cavities and magnets are in liquid helium

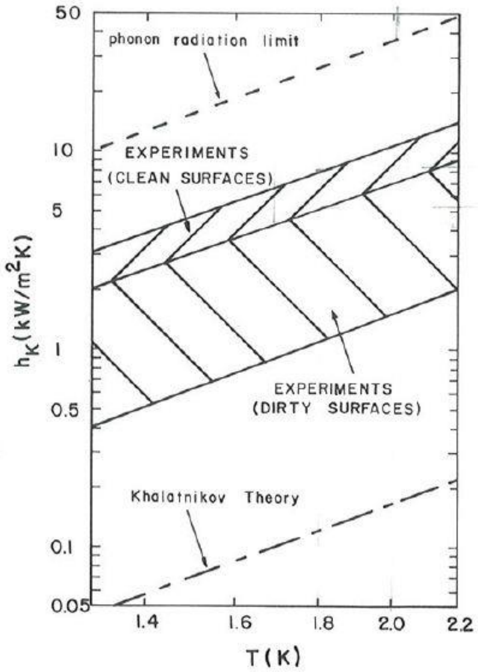


Normal helium (He-I)



~100 W/m²/K

Superfluid helium (He-II)

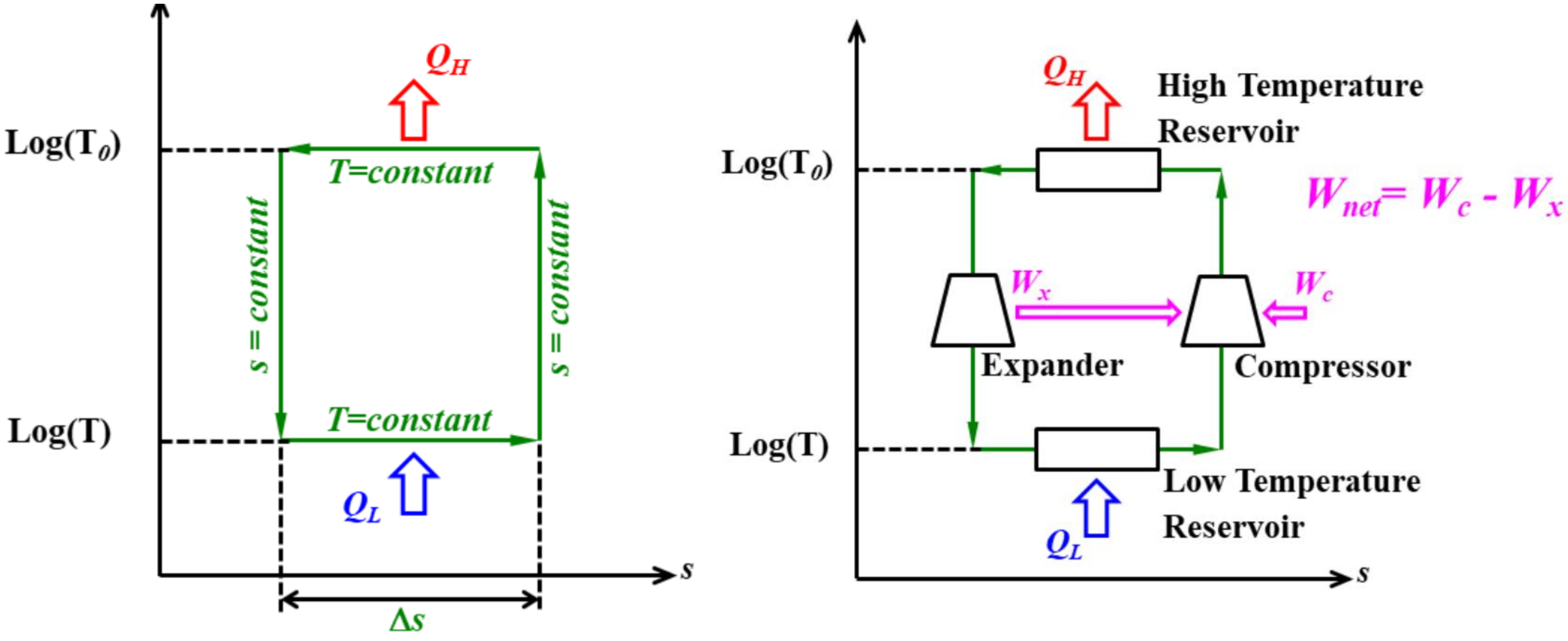


~ 5000 W/m²/K

We need to liquify gas helium!

S. W. Van Sciver, “Helium cryogenics”, Plenum press, 1986

Courtesy: Nusair M. Hasan

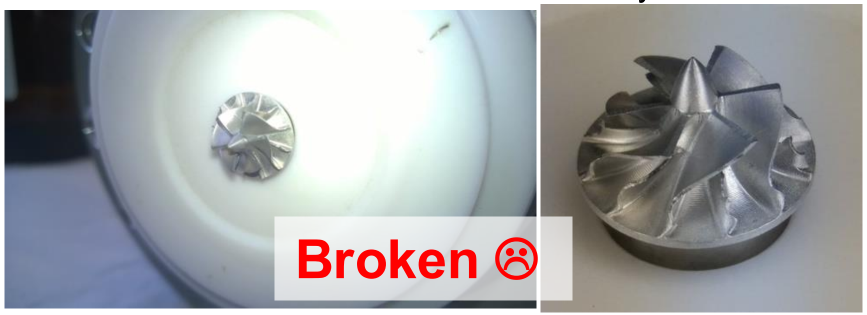


- Combination of adiabatic and isothermal processes
- Expander & compressor are the key components
- A Carnot cycle could theoretically generate LHe but requires unrealistically high pressure

Isentropic expansion and isothermal + isobar compression

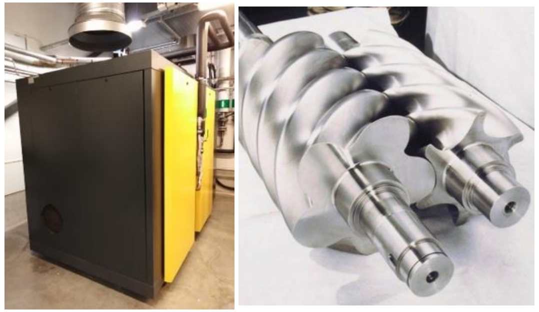
Turboexpander (expansion turbine)

Courtesy: M. Pierens



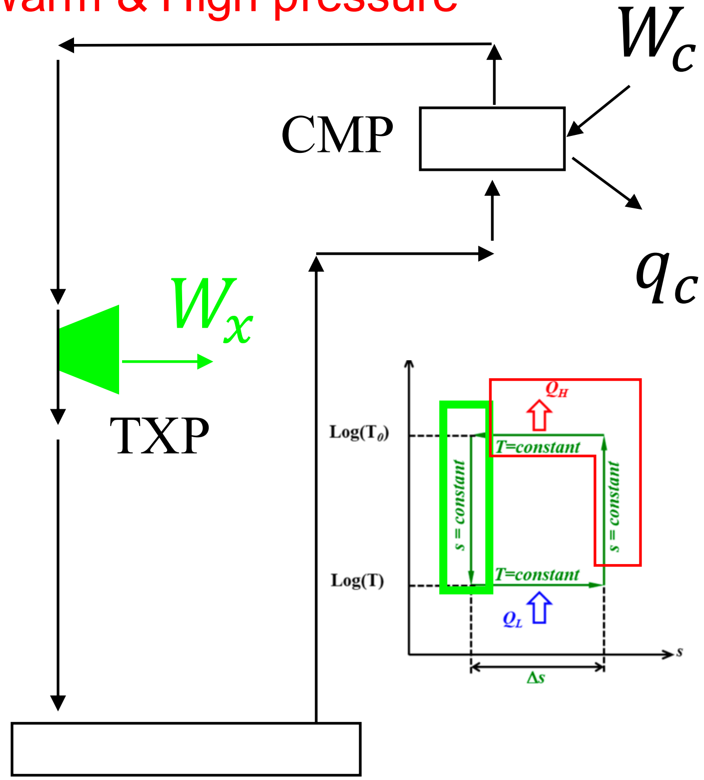
isentropic (=reversible adiabatic) expansion

Compressor



Reversed-modified Joule (Brayton) cycle

Warm & High pressure



Cold & low pressure

Remarks

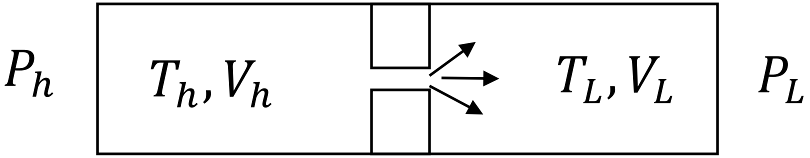
- Isobar process → Joule cycle ≠ Carnot cycle
- Weak points (and expensive!) of a cryogenic facility
  - If your accelerator is down, maybe one of them are out of order
- Not used for liquefaction of helium alone practically
  - Turbine does not like LHe

→ Another process needs to be combined

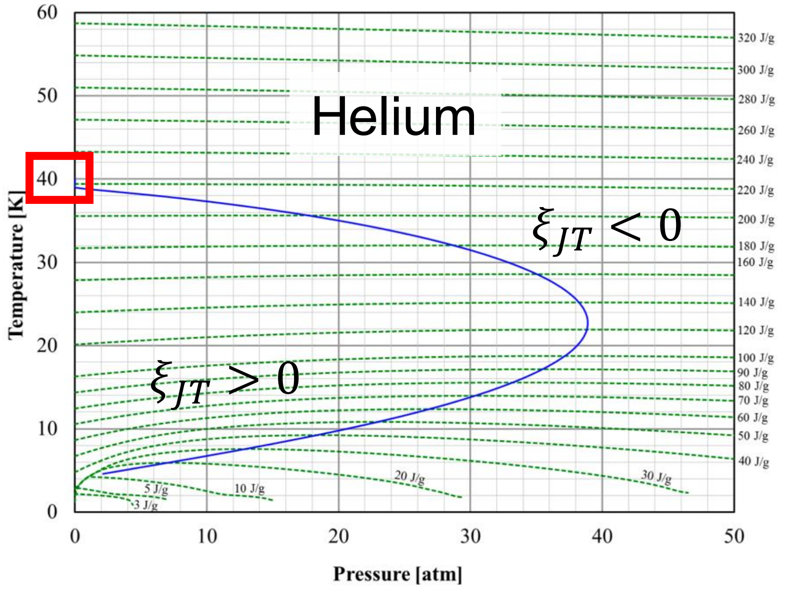
Adiabatic expansion and Joule Thomson effect

Joule-Thomson (JT) process is isenthalpic (irreversible adiabatic)

Adiabatic ≠ isentropy ($ds \geq d'Q/T$)



$$H = U_h + P_h V_h = U_L + P_L V_L$$



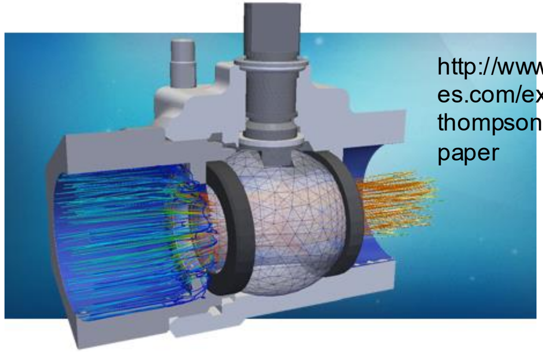
JT coefficient

$$\xi_{JT} = \left(\frac{\partial T}{\partial P}\right)_H$$

$\xi_{JT} < 0$ (→ $T_h < T_L$): heating

$\xi_{JT} > 0$ (→ $T_h > T_L$): cooling

$\xi_{JT} = 0$ at reverse temperature

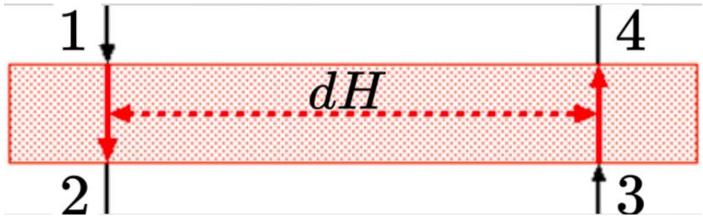


http://www.pretechnologies.com/experience/joule-thompson-cooling-white-paper

He Liquefier is made of i) compressor ii) turbine iii) JT valve

Heat exchanger profits from cold return gas to enhance the liquefaction yield

$$H_4 = H_3 + dH$$

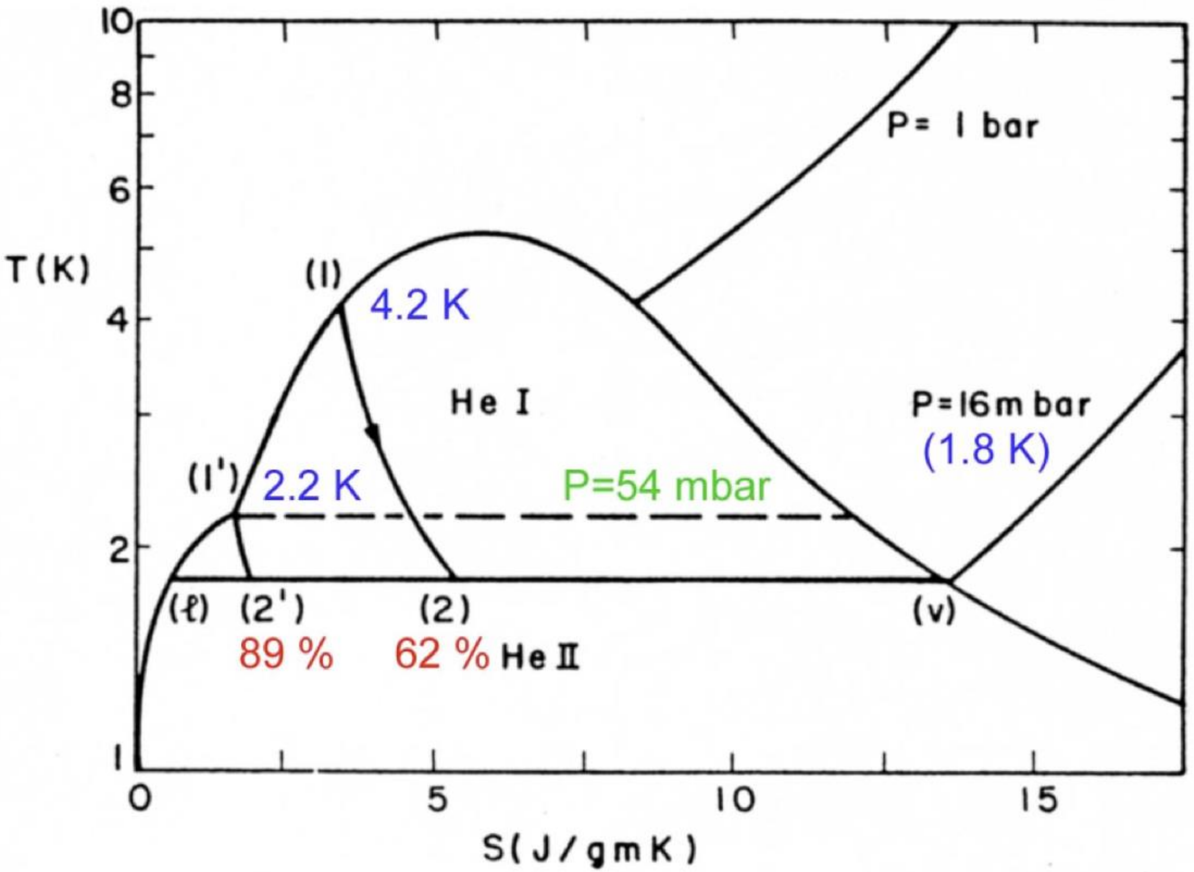


$$H_2 = H_1 - dH$$

If temperature before the JT valves is
- 4.2K → 62%
- 2.2K → 89%

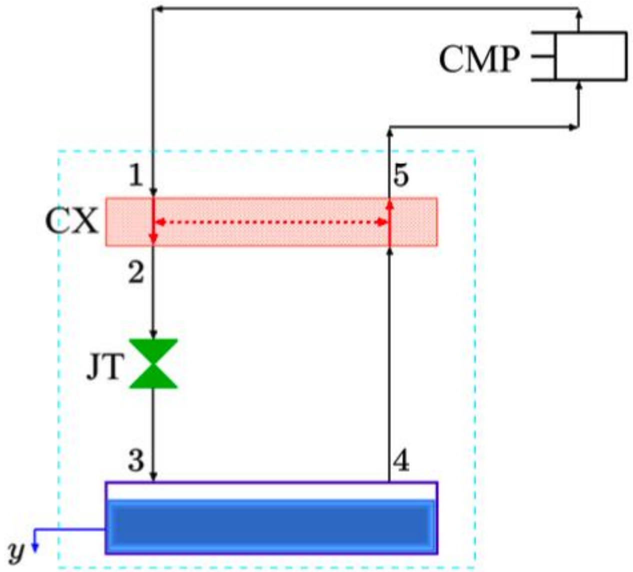
Superfluid is generated by pumping down to 30 mbar

Courtesy: Elias Waagaard

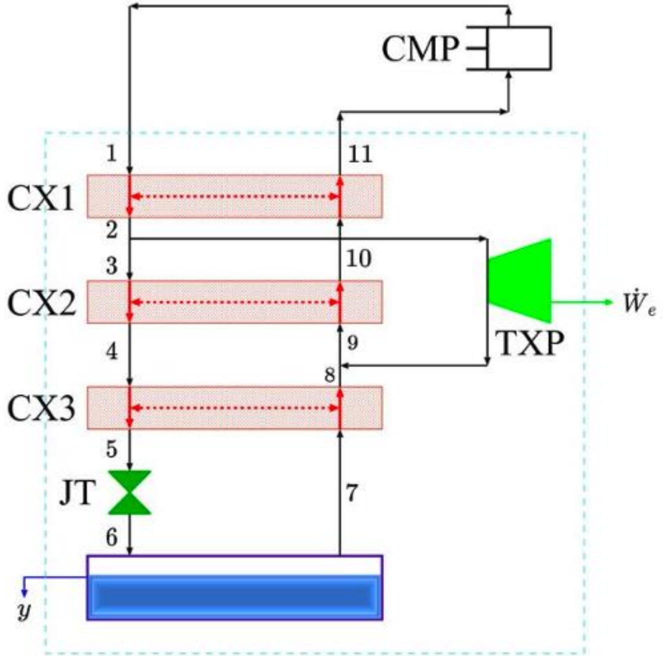


Van Sciver S. W. "Helium Cryogenics", Plenum Press (1986)

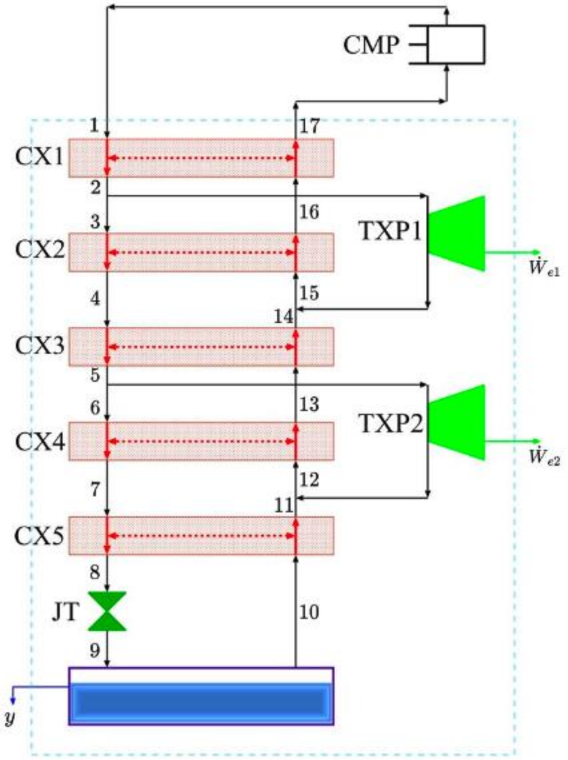
Linde cycle



Claude cycle



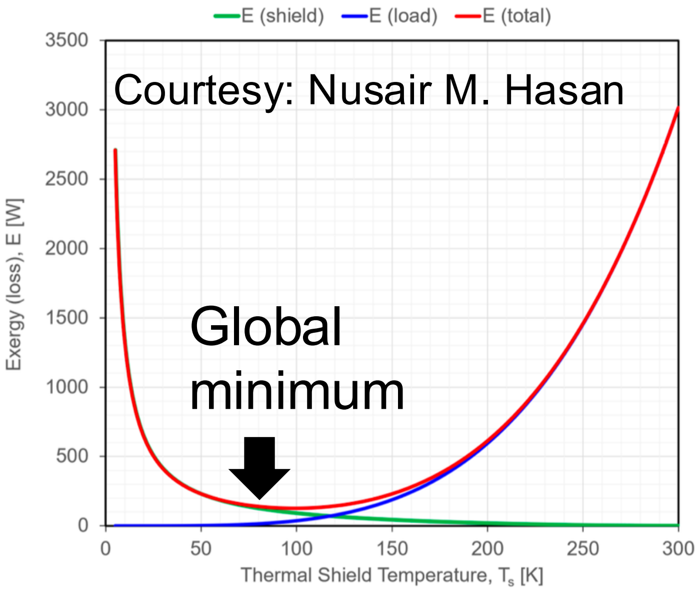
Collins cycle

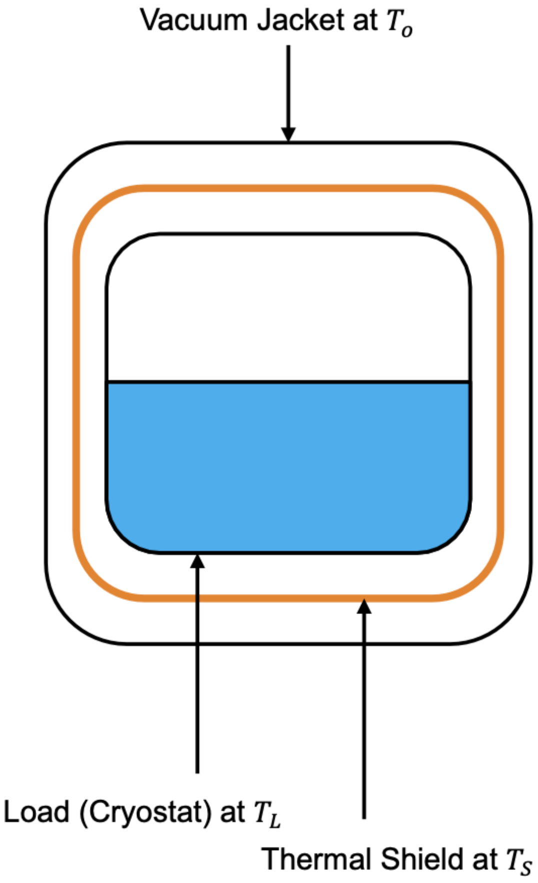


Courtesy: Elias Waagaard

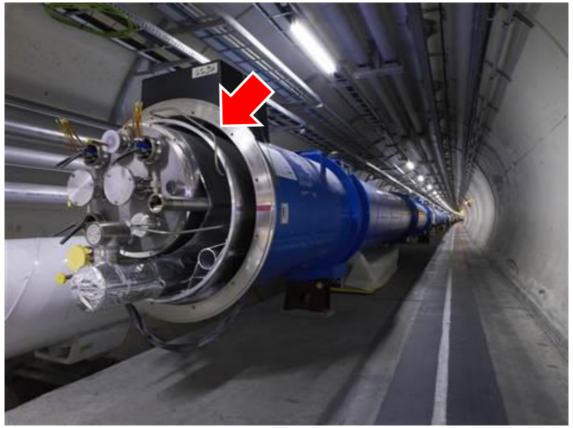
Stephan Boltzmann: $q = \epsilon A \sigma T^4$

- Intersect the thermal radiation by intermediate temperature
- Easier to evacuate heat at higher temperature



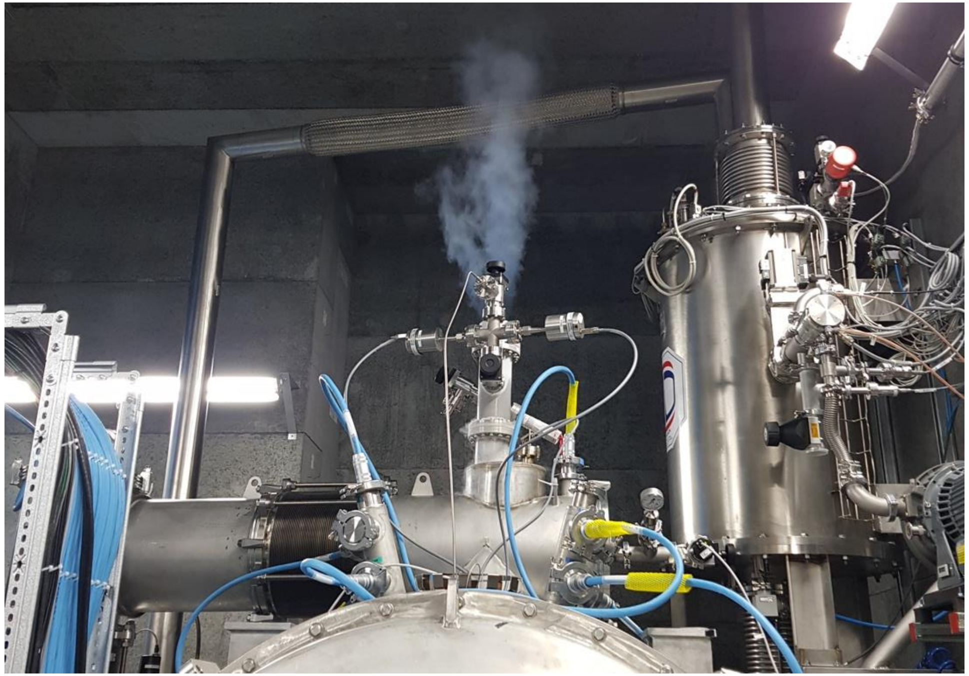


Multilayer Insulation (MLI)



LHC dipole

3 months after I got a staff position



High power RF → SC cavity quenched by multipacting → wrong interlock setup → Overpressure in LHe → Rupture disk burst → no mechanical damage

3 months after I started PhD in particle physics

Courtesy of R. Schmidt, CERN

Defect in soldering joint → resistive (magnet quench itself was NOT the trigger)→ Electrical arc → He goes into isolation vacuum → helium boiled off → mechanical damage

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Ohm’s law

Applied DC electric field *E*

DC Current *J*

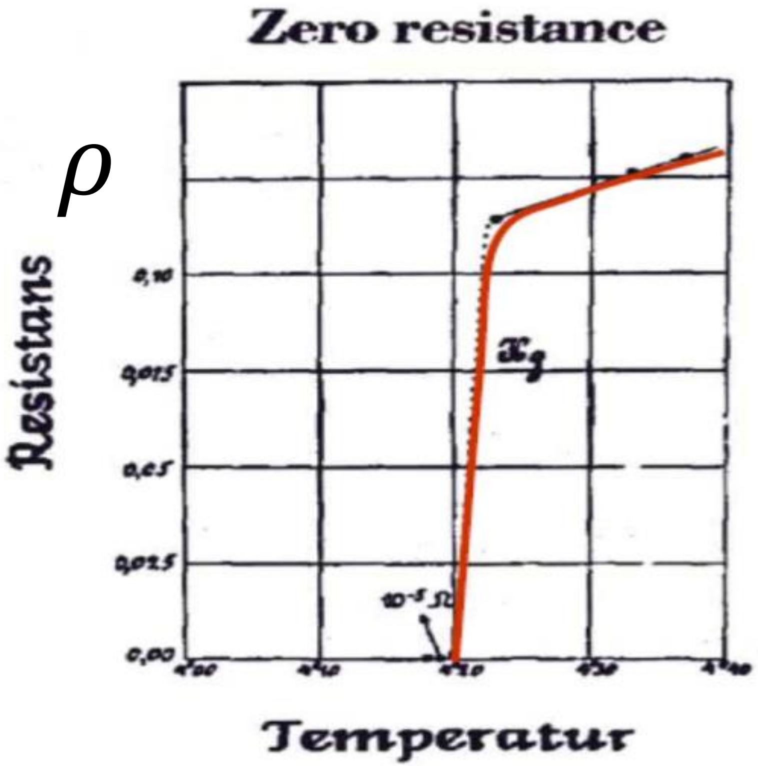
DC resistivity ρ

$$\rho \equiv \frac{E}{J}$$

DC conductivity σ

$$\sigma = \frac{1}{\rho} \equiv \frac{J}{E}$$

Cool down the resistor…



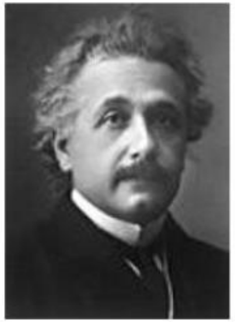
Heike Kamerlingh Onnes

Nobel prize in 1913

$\boldsymbol{\rho = 0}$ below transition temperature T_c

Challengers for microscopic theory of superconductors

J. Schmalian, arxiv:1008.0447



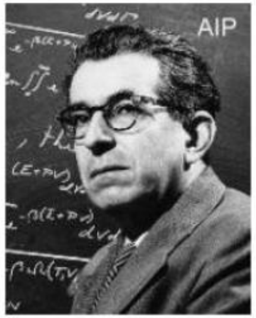
Albert Einstein
(1879-1955)

Niels Bohr
(1885-1962)

Ralph Kronig
(1905-1995)

John Bardeen
(1908-1991)

Werner Heisenberg
(1901-1976)



Fritz London
(1900-1954)

Lev D. Landau
(1908-1968)

Felix Bloch
(1905-1983)

Léon Brillouin
(1889 -1969)

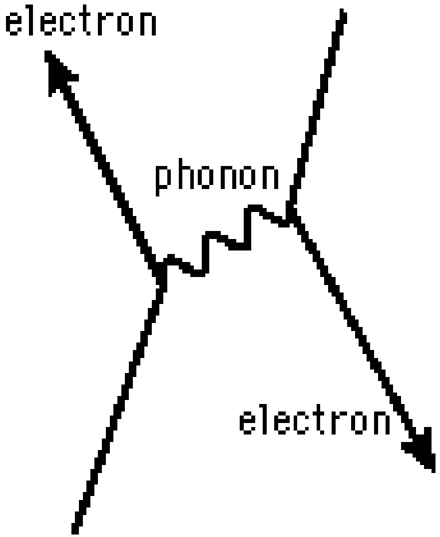
Max Born
(1882-1970)

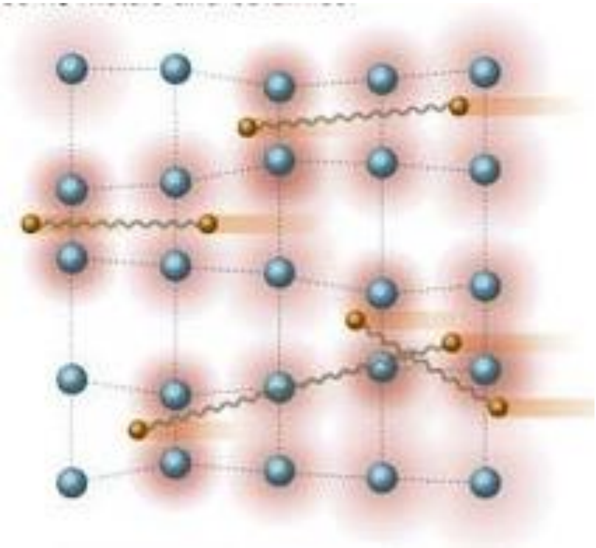
Herbert Fröhlich
(1905-1991)

Richard Feynman
(1918-1988)

A lot of models…all failed ☹
Development of quantum field theory in many body problems was necessary…

Theory of superconductor in equilibrium





John Bardeen

Leon Cooper

John Robert Schrieffer

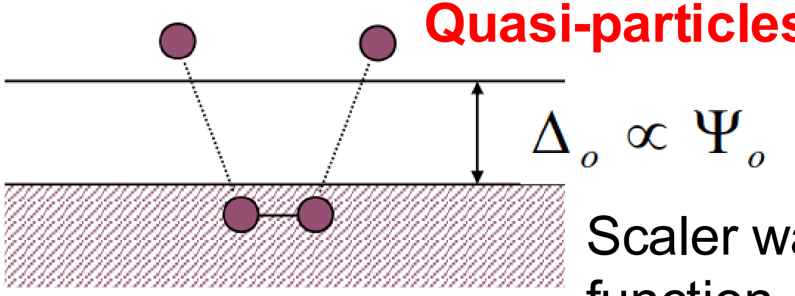
Cooper pair: Composite boson

Two electrons are bounded by something (phonon) → effective Hamiltonian $\mathcal{H}_{BCS}$

Mean field approximation + Variational method (+other approximations…)

$$\mathcal{H}_{BCS}|\Phi_0\rangle = E|\Phi_0\rangle$$

Solution: superconducting gap

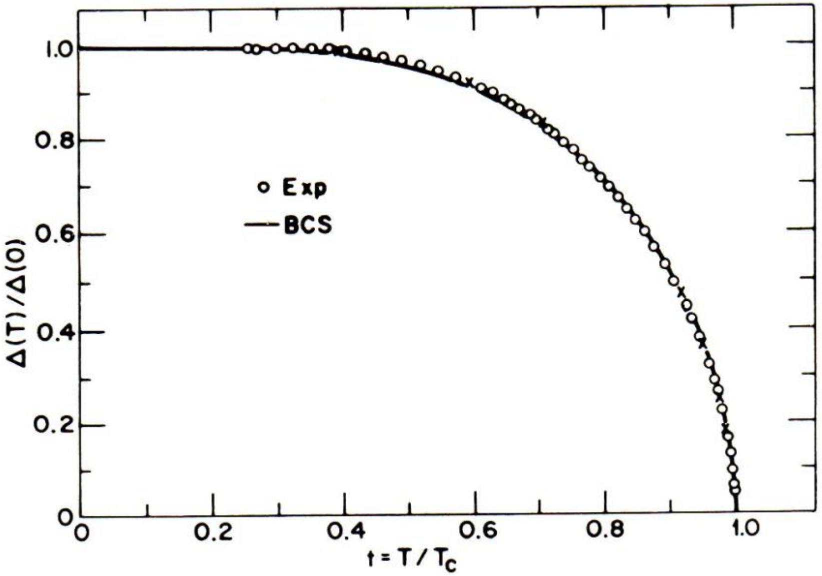


Scaler wave function

- The Cooper pair needs certain amount of energy to be broken
- The cause of Ohmic loss, stochastic scattering of one single electron by phonon or impurity **cannot break the pair**
  →No DC loss

Self-consistent gap equation

$$\Delta = N(E_F)V \int_{\Delta}^{\hbar\omega_D} \frac{\Delta}{\sqrt{\xi^2 + \Delta^2}} \tanh\left(\frac{1}{2}\frac{\sqrt{\xi^2+\Delta^2}}{k_B T}\right) d\xi$$



The Equilibrium state of conventional superconductor was understood !

→ In this lecture, we try to obtain qualitative insight of the phenomenon

Electrons in a perfect metal are free (independent)

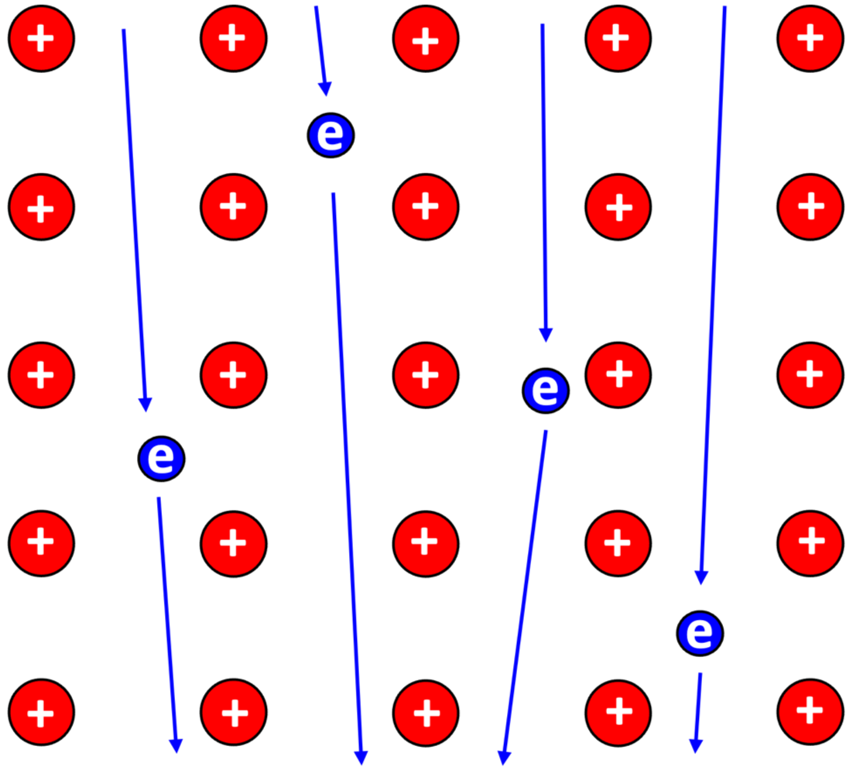
Perfectly periodic potential by ions does ***NOT*** scatter electrons (Bloch's theorem)

These electrons are ***NOT*** our favorite elementary particle of

$$m = 511\,\mathrm{keV}$$

These electrons are ***dressed*** by complicated electromagnetic property of metals to have an effective mass m^* given by a band structure

→ ***Quasi-particles***



In reality, imperfection causes quasi-particle scattering

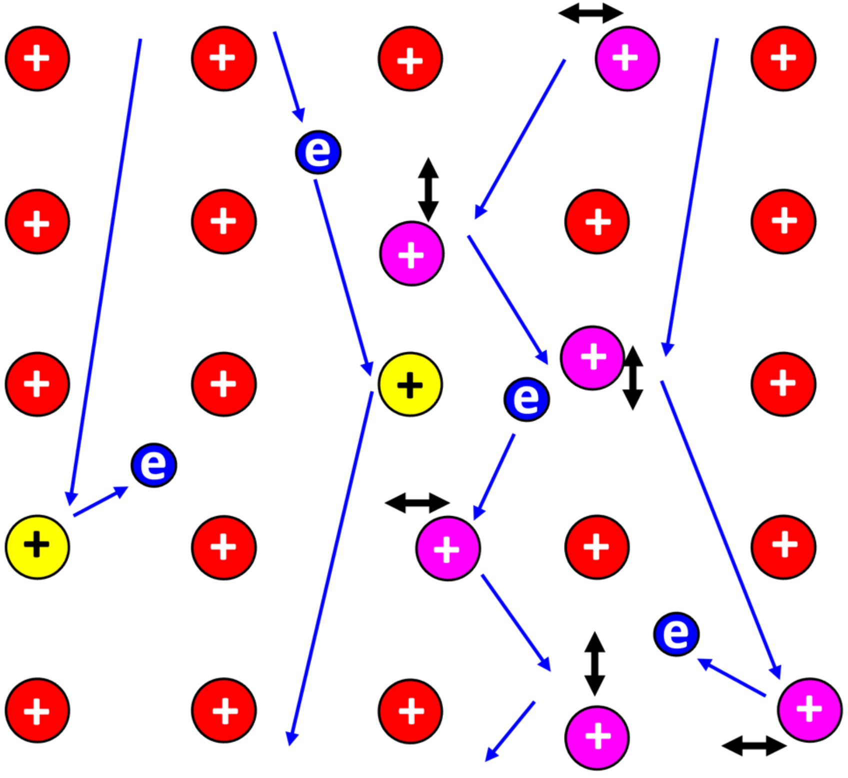
Electrons in a real metals show Ohmic loss

<u>Imperfections causes ***local*** scattering</u>

1. Impurity, defects (scattering time τ_{def})
2. Lattice vibration, phonon (τ_{ph})

Total scattering time

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{def}}} + \frac{1}{\tau_{ph}}$$



<u>Macroscopic phenomenology (Drude model)</u>

An electron accelerated by an electric field

$$m^* \frac{dv}{dt} = -eE$$

is scattered by imperfections per τ, and its velocity relaxes to a mean velocity

$$\langle v \rangle = -\frac{e}{m^*} E\tau$$

Electric current is a collective flow of n electrons

$$j = -en\langle v \rangle = \boxed{\frac{e^2 n\tau}{m^*}} E$$

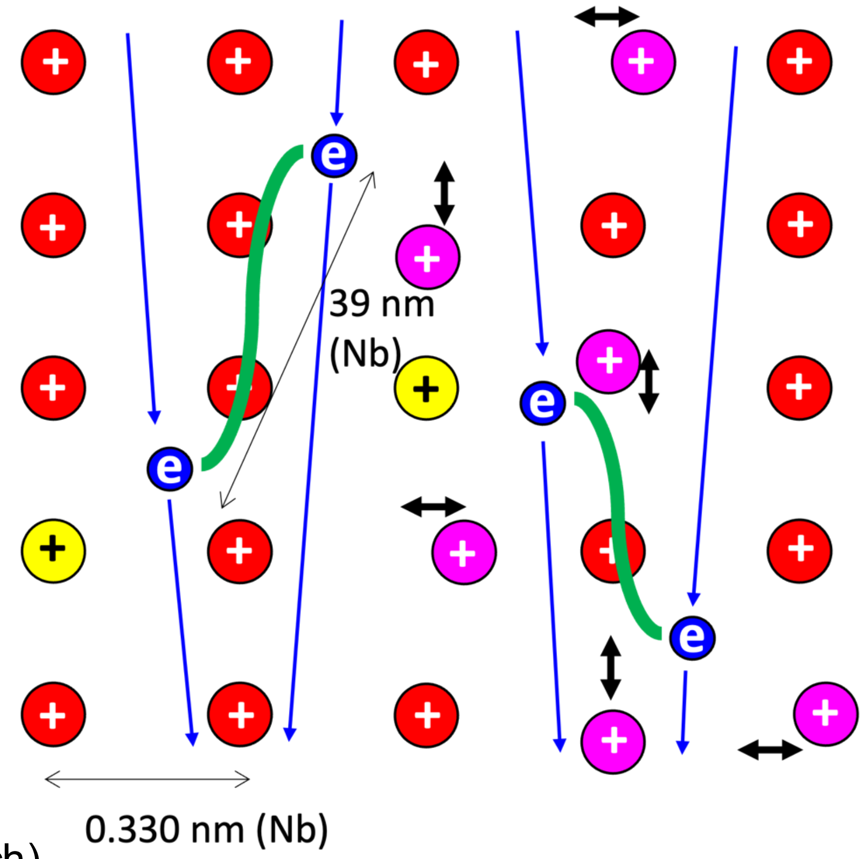
Ohm's law

$$\boldsymbol{j} = \sigma \boldsymbol{E}$$

Electrical conductivity σ

If electrons ***in a distance*** (>39 nm) are bounded, ***local*** (< 0.5 nm) scattering can be avoided

Any small attractive interaction V between electrons can lead to a ***Cooper pair*** coupled with an energy 2Δ, below critical temperature T_c

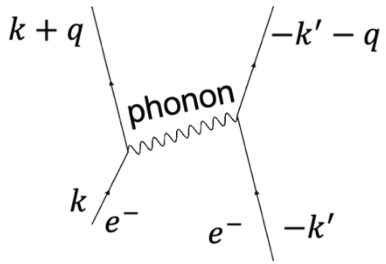


BCS gap equation (1957)

Non-perturbative!

$$\Delta = n(E_F)V \int_{\Delta}^{\hbar\omega_D} \frac{\Delta}{\sqrt{\xi^2+\Delta^2}} \tanh\left(\frac{1}{2}\frac{\sqrt{\xi^2+\Delta^2}}{k_B T}\right) d\xi$$

Classical superconductors' attractive potential is from ***longitudinal mode of lattice vibration***



If energy transfer $|\epsilon_{k+q}-\epsilon_k|$ is smaller than phonon energy the interaction is attractive (Flöhlich)
→ Eliashberg's strong coupling superconductor (1960)

Implication of no scattering?

No scattering

$$m^* \frac{\partial \langle v \rangle}{\partial t} = -eE$$

generates super-current

$$j_s = -en_s \langle v \rangle$$

$$\rightarrow \frac{\partial j_s}{\partial t} - \frac{n_s e^2}{m^*} E = 0$$

Apply $\nabla \times$ from the left

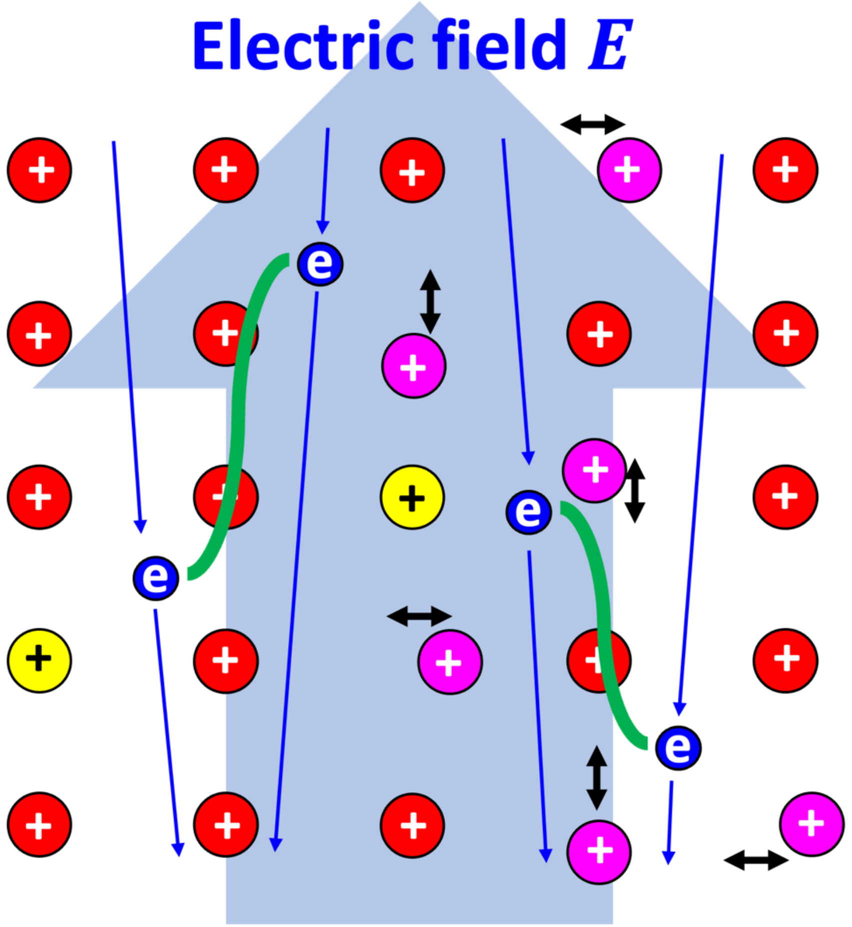
$$\frac{\partial}{\partial t}(\nabla \times j_s) - \frac{n_s e^2}{m^*} \nabla \times E = 0$$

$\sim \nabla \times \boldsymbol{B}/\mu_0$; $\nabla \times E = -\frac{\partial \boldsymbol{B}}{\partial t}$

leads to

$$\frac{\partial}{\partial t}\left[\nabla^2 \boldsymbol{B} - \frac{1}{\lambda_L^2}\boldsymbol{B}\right] = 0$$

$$\lambda_L^2 \equiv \frac{m^*}{n_s e^2 \mu_0}$$

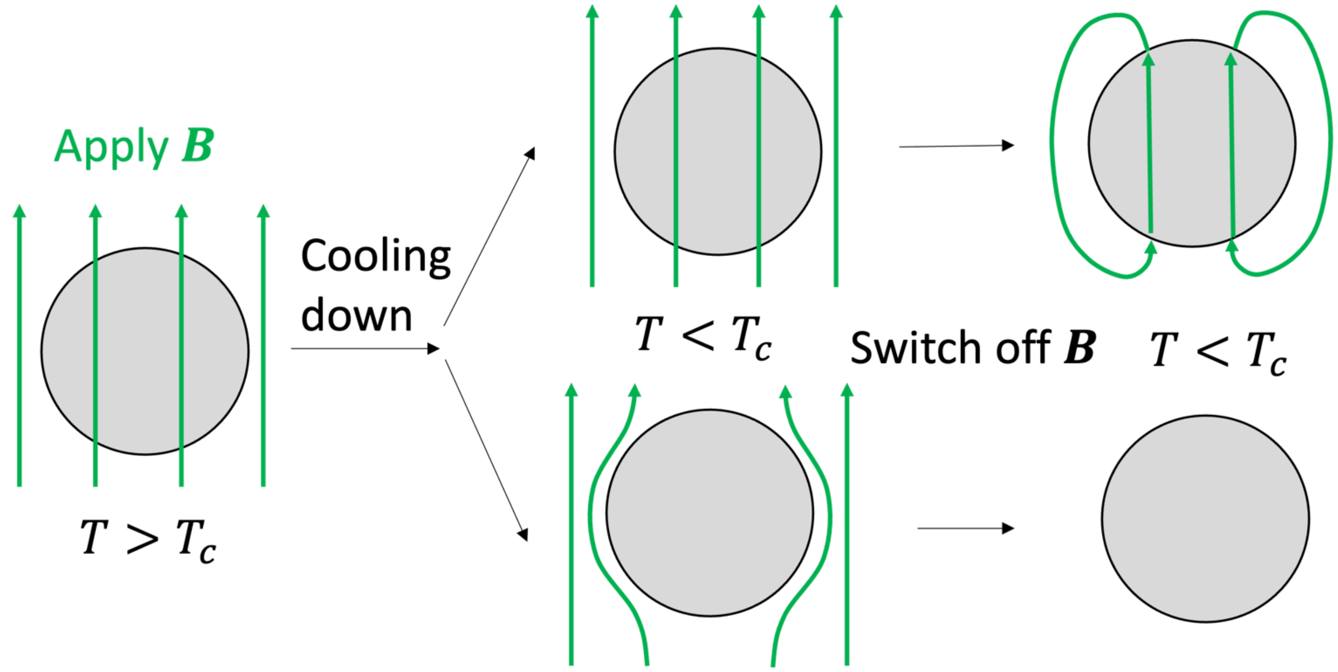


Constant of time

→ Initial condition before phase transition $T > T_c$ must be preserved

Superconductor ≠ Perfect electric conductor

Meissner effect **differentiates them**



Perfect Electric Conductor

$$\nabla^2\left(\frac{\partial \boldsymbol{B}}{\partial t}\right) - \frac{1}{\lambda_L^2}\left(\frac{\partial \boldsymbol{B}}{\partial t}\right) = 0$$

Preserve initial condition!

Superconductor

Zero field!

$$\nabla^2 \boldsymbol{B} - \frac{1}{\lambda_L^2}\boldsymbol{B} = 0$$

London equation

Additional constraint (broken Gauge symmetry)

Superconductivity is a thermodynamical state which expels magnetic fields and cannot be explained by classical electrodynamics → beyond the scope of this lecture ☹

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- Introduction: thermodynamics and benefit of cooling (10 min)
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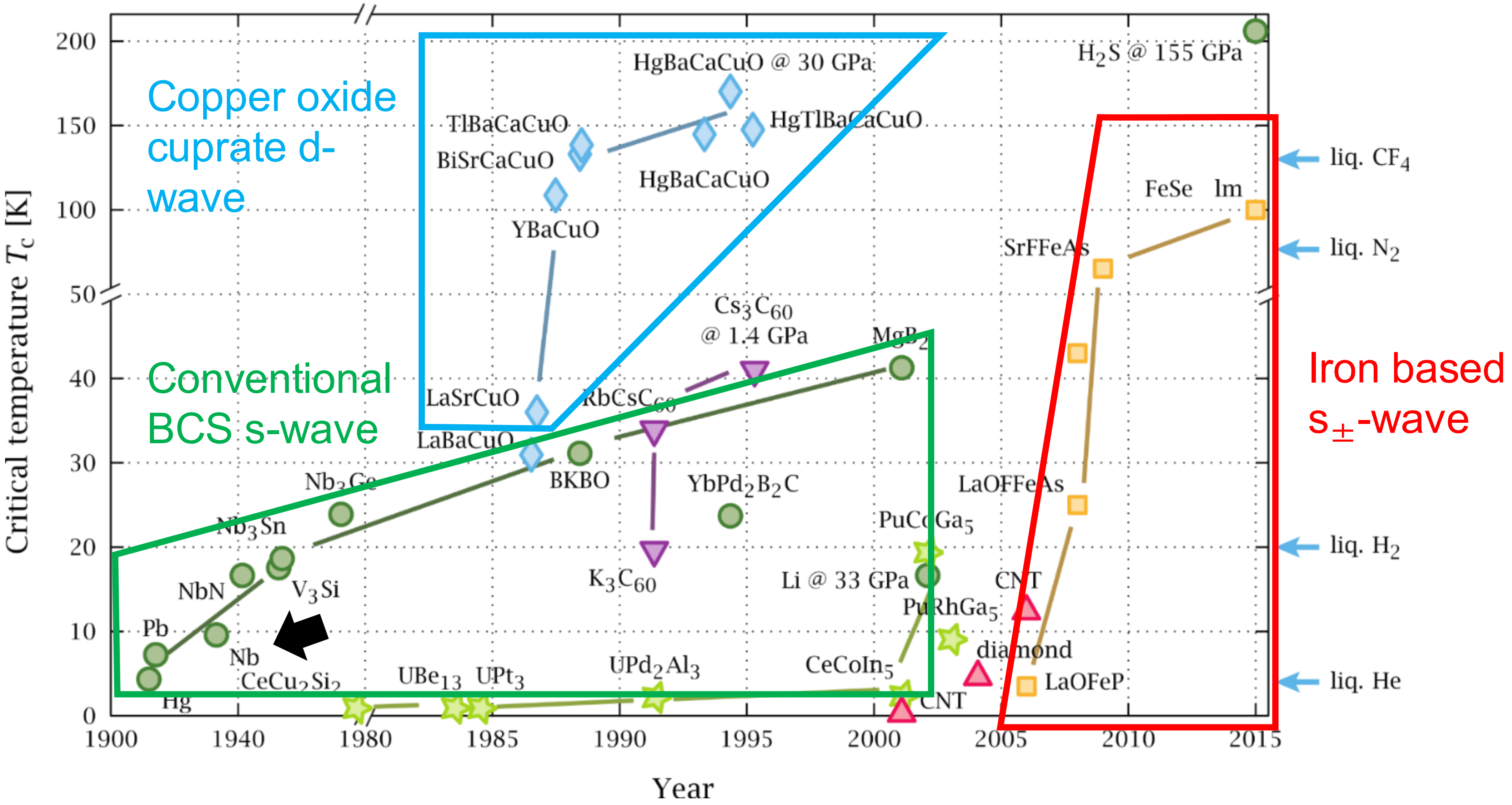
BCS and non BCS superconductors



- BCS superconductors (1911)
  - Example: Hg, Al, Sn, Pb, Nb, NbN, NbTi, Nb_3Sn, …, MgB_2 (?)
  - Phonon mediated Cooper pairs
  - Application: superconducting magnet, cavities, detectors, qubit
- Cooper oxide superconductors (discovered in 1986)
  - Example: YBCO, …
  - Fundamental theory unknown (Coulomb repulsive force generates correlation ?)
  - Application: magnet, current lead, beam screen, dark matter detector, etc
- Iron based superconductors (discovered in 2008)
  - Example: Ba-122, FeSeTe, …
  - Fundamental theory unknown (Spin internation generates correlation ?)
  - Application: magnet, current lead, dark matter detector, cavities (?), etc
- More fancy superconductors…

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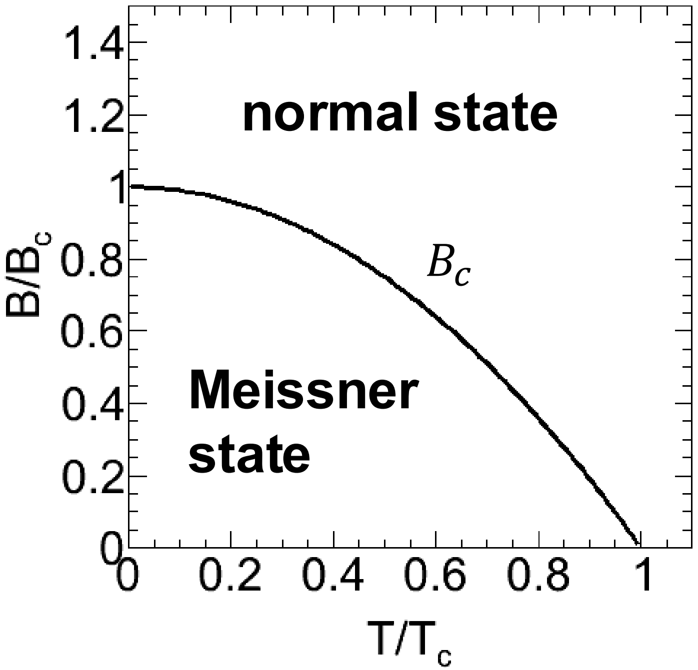
Strong but *static* magnetic field: Type-I vs Type-II

Type-I

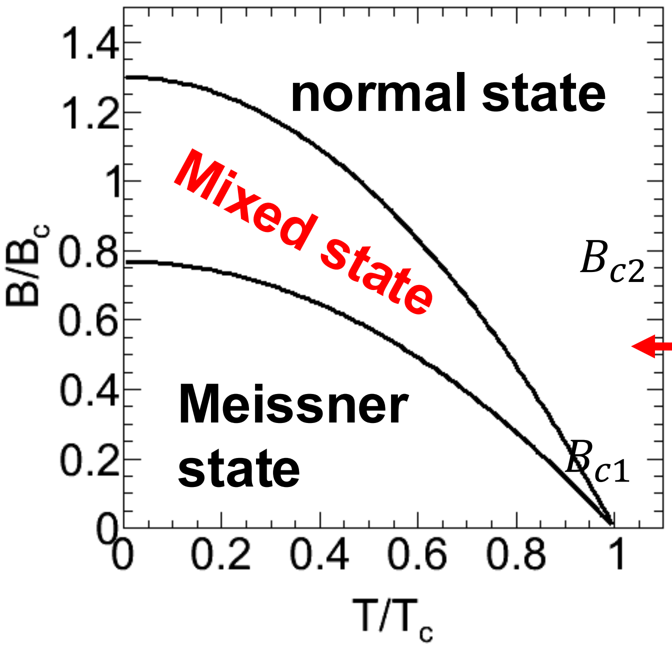
$$\kappa = \frac{\lambda}{\xi} < \frac{1}{\sqrt{2}} = 0.71$$



$$\kappa_{Pb} \sim \frac{28\text{ nm}}{71\text{ nm}} \sim 0.40$$

Type-2

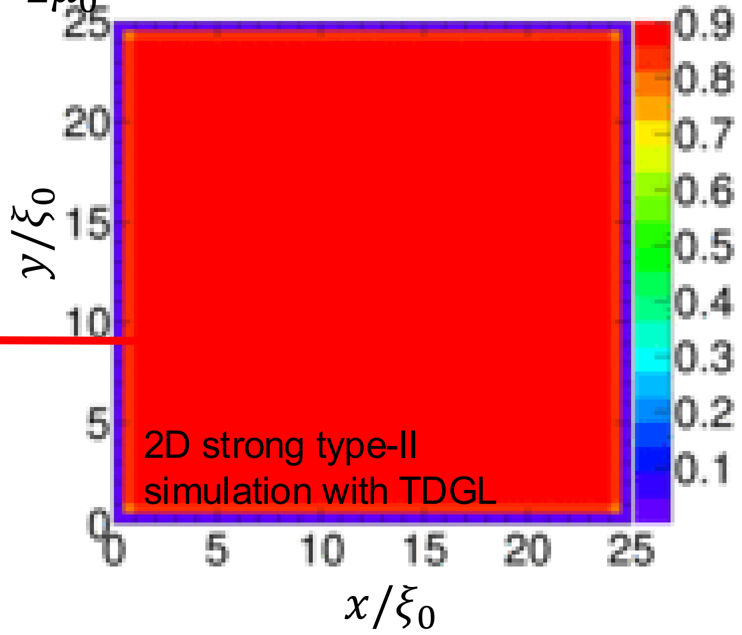
$$\kappa = \frac{\lambda}{\xi} > \frac{1}{\sqrt{2}} = 0.71$$



$$\kappa_{Nb} \sim \frac{36\text{ nm}}{39\text{ nm}} \sim 0.92$$

Stabilized by NC/SC boundary energy

$$\frac{1}{2\mu_0}(\xi_0 B_c^2 - \lambda_L B^2) < 0 \text{ for } B > B_{c1}$$

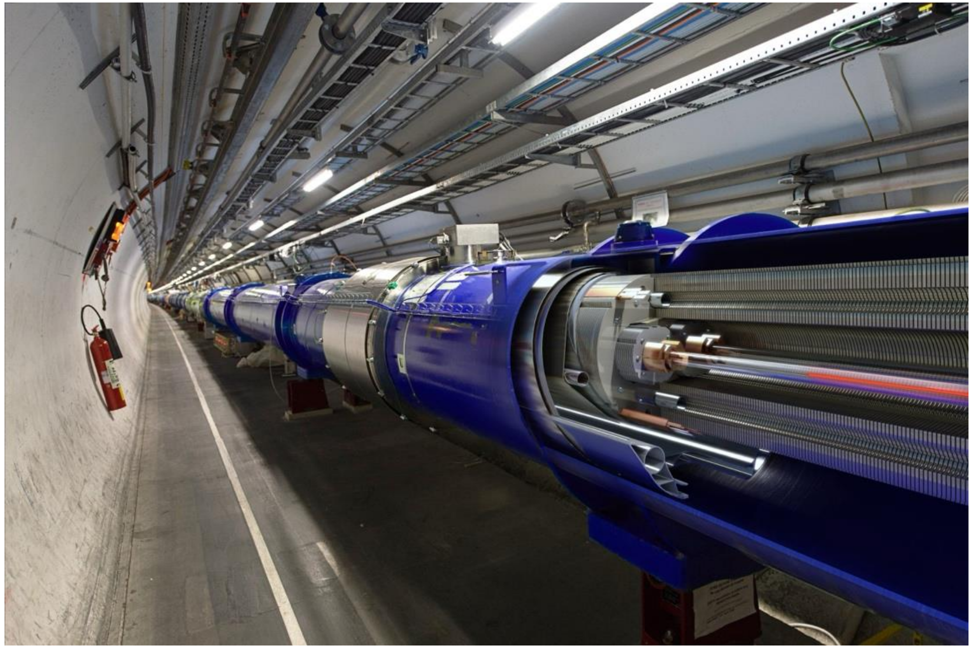


Without pinning centers, type-II ***traps*** magnetic flux if $B > B_{c1}$

Quantized flux $\Phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15}$ Wb

SC magnet and cavities in different states

DC Magnetic fields in magnets to bend the trajectory (Mixed state)



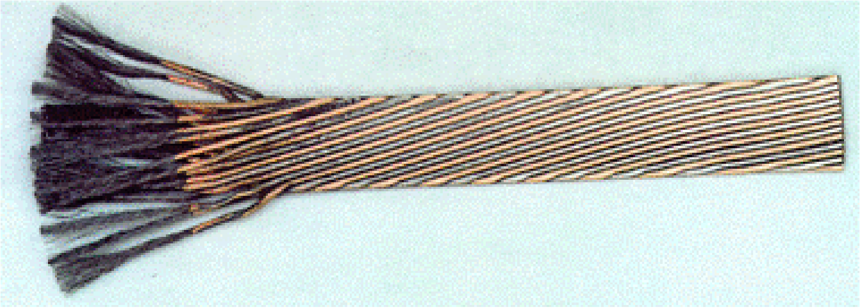
RF Electric fields in cavities to accelerate the beam (Meissner state)

DC vs RF is qualitatively different in superconducting devices

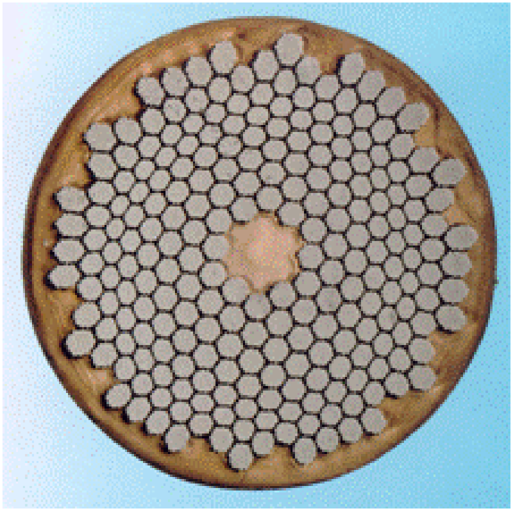
SC magnet cables: made of filaments

<u>Rutherford cable</u>

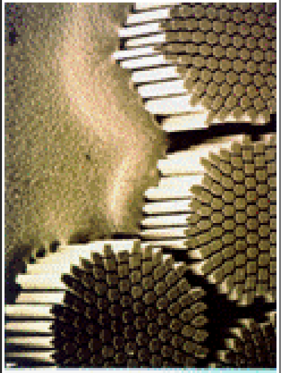
NbTi filaments embedded in copper matrix for heat and current → LHC magnets



Cable



Strand



6 um

Filaments

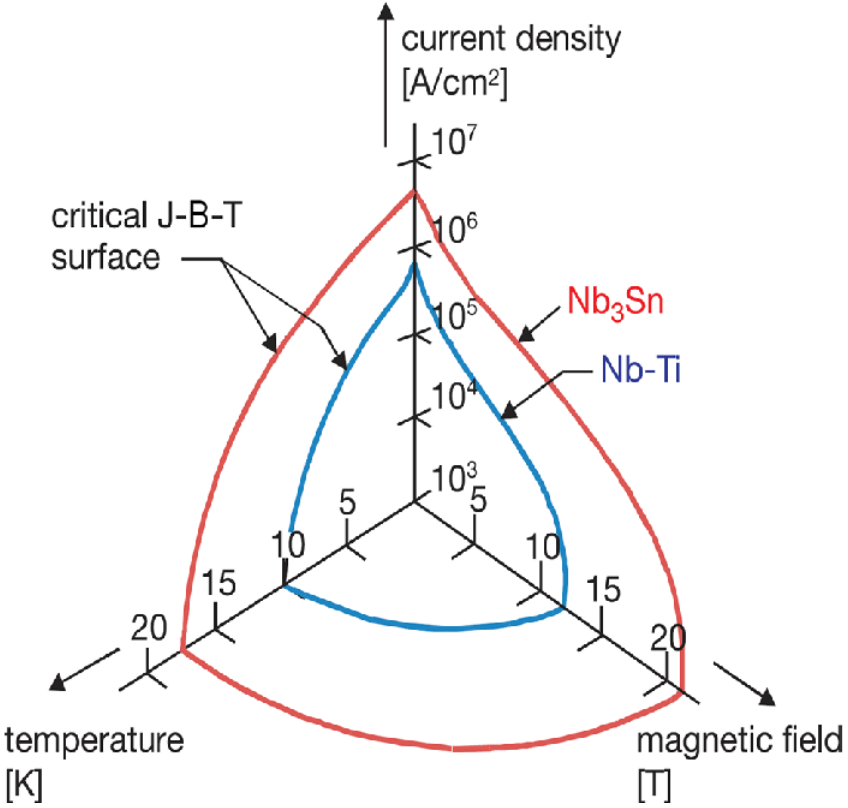
↔ 0.825 mm

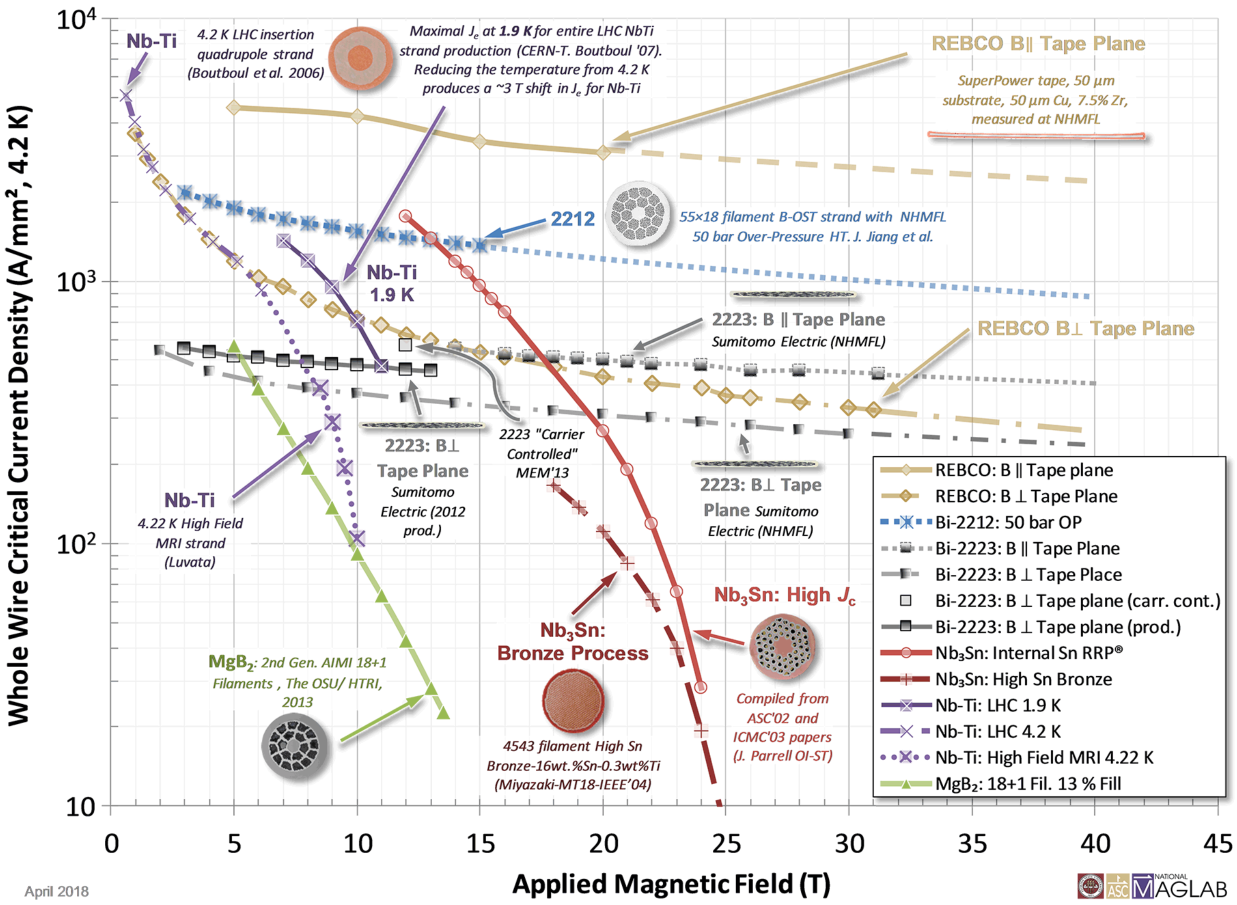
<u>In LHC :</u>
1200 magnets
7600 km of cable
36 strands per cable
6400 filaments per strands

→ Total length of filaments 10 times the distance between earth and sun !!!

The NbTi materials is exposed to 8.3 T >> Hc1 at 1.9 K → Mixed state

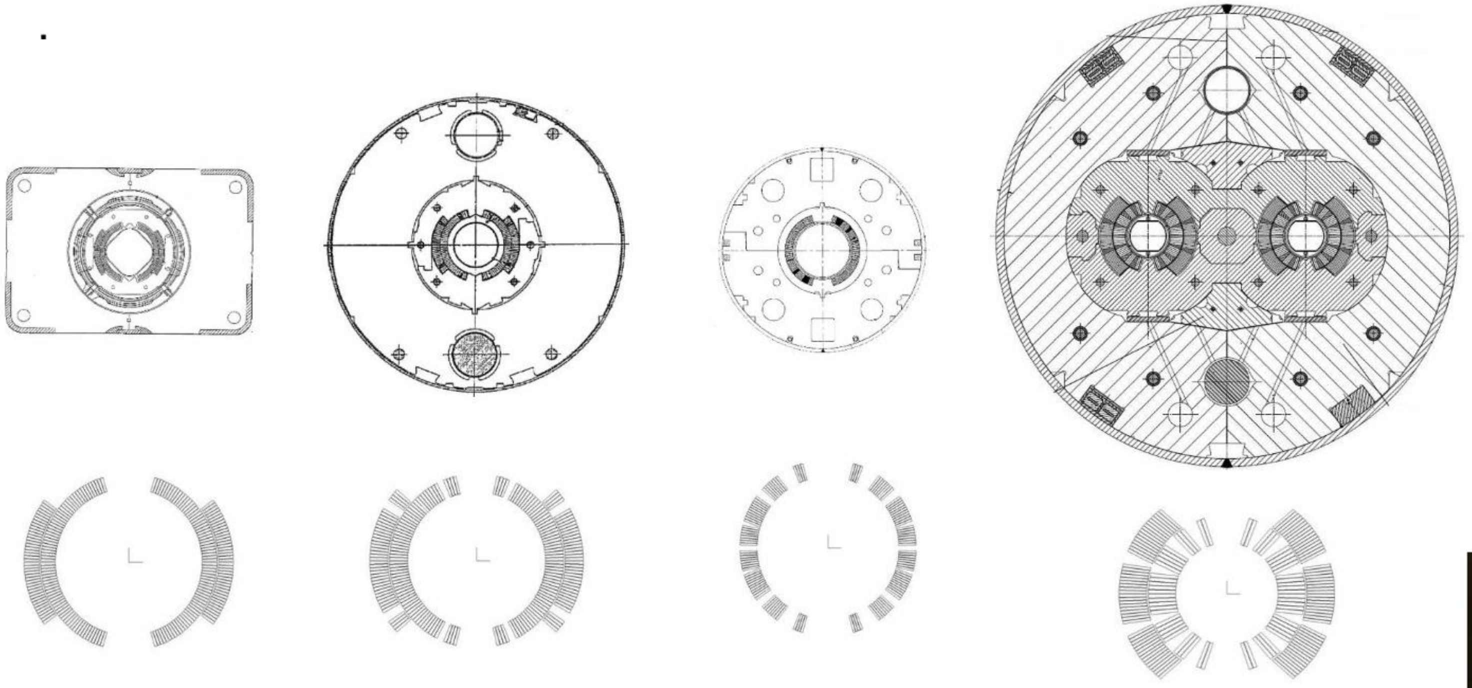
Critical current density





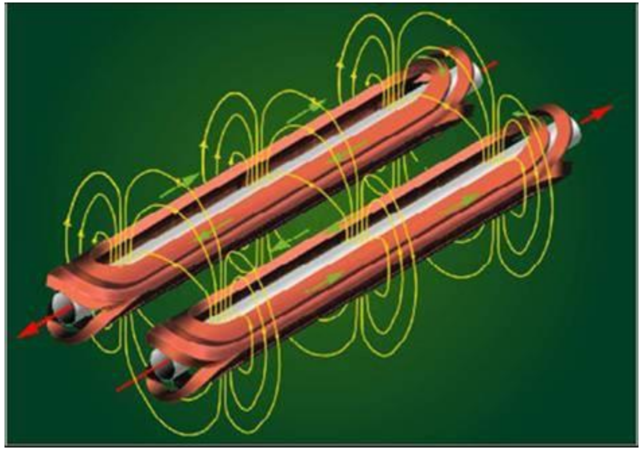
M. E. Ladd et al https://doi.org/10.1007/s10334-023-01085-z

SC dipole: history of NbTi

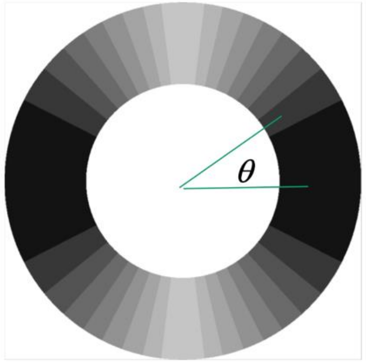


Tevatron	HERA	RHIC	LHC
76 mm bore	75 mm bore	80 mm bore	56 mm bore
B = 4.4 T	B = 5.0 T	B = 3.5 T	B = 8.34 T
T = 4.2 K	T = 4.5 K	T = 4.3-4.6 K	T = 1.9 K
first beam 1983	first beam 1991	first beam 2000	first beam 2008

Courtesy G. d. Rijk and P. Ferracin, CERN

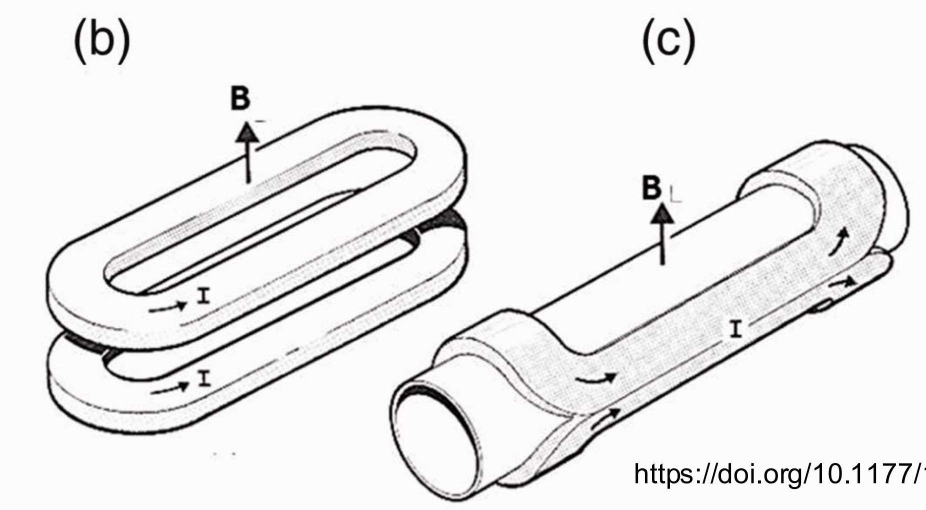


$$J = J_0 \cos\theta$$

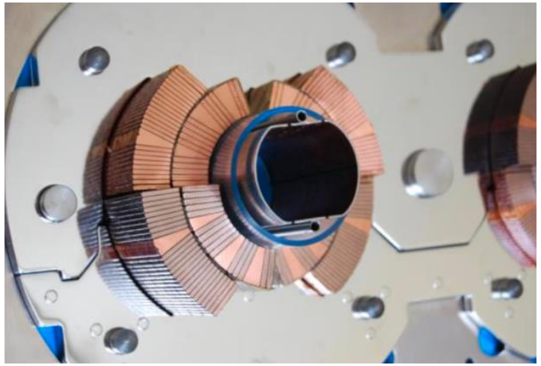


$\cos\theta$ current distribution gives pure dipole field

Baseline: $\cos\theta$ (racetrack or saddle)



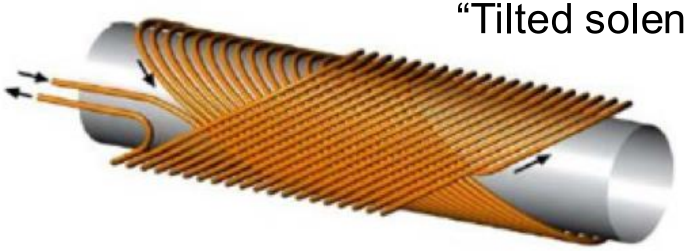
https://doi.org/10.1177/15280837166612



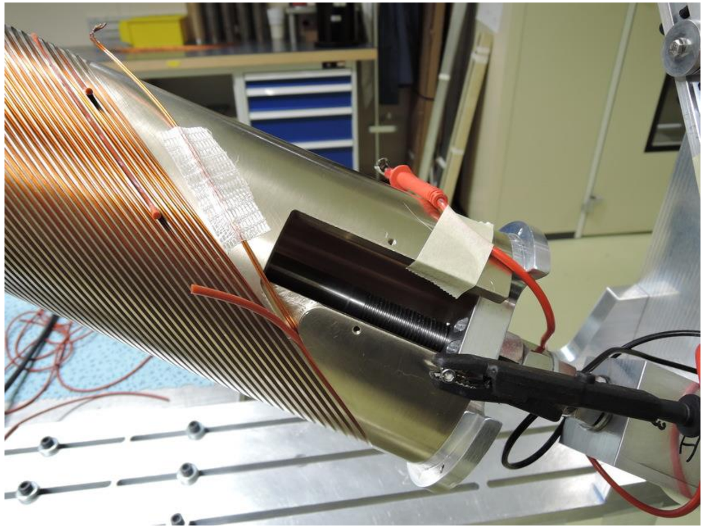
Courtesy G. d. Rij, M. Wilson,

Canted $\cos\theta$ (CCT)

“Tilted solenoid”



Proposed in 1960s realized recently

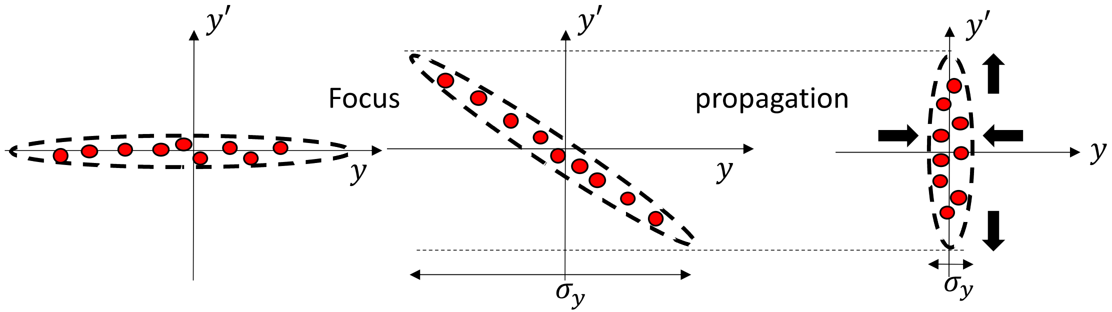


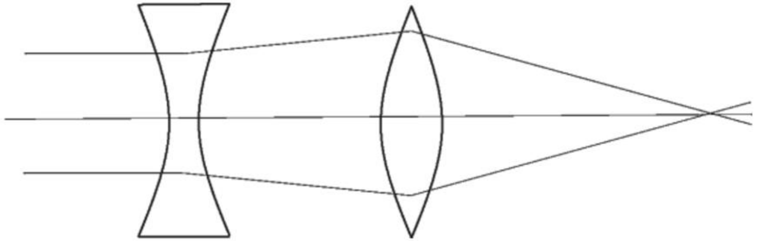
https://home.cern/news/news/engineering/new-life-old-technology-canted-cosine-theta-magnets

Lorentz force is not only for bending trajectory

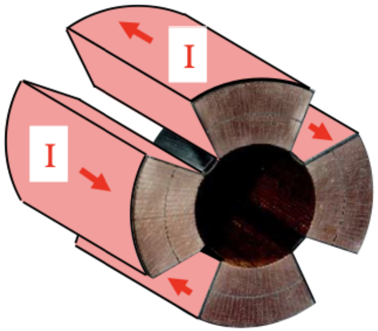
$$\frac{d(mv_\theta)}{dt}.\overrightarrow{u_\theta} - m\frac{v_\theta^2}{\rho}.\overrightarrow{u_r} = eE_\theta.\overrightarrow{u_\theta} + ev_\theta B_z.\overrightarrow{u_r}$$

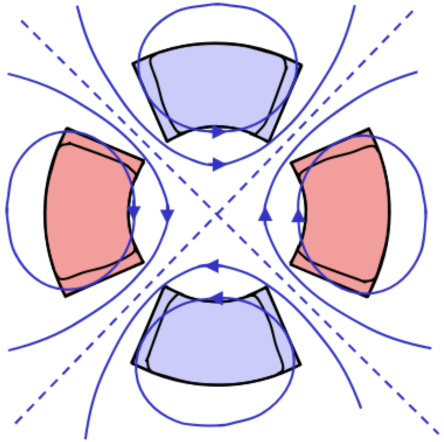
Focusing and defocusing of a group of charged particles (bunch) are crucial for beam transport and luminosity at collision

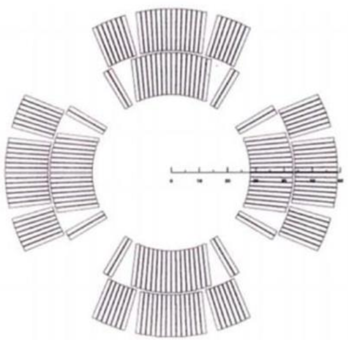




Implemented by quadrupole magnets







Courtesy G. d. Rij

SC vs NC magnets: typical and exception

$$p[\mathrm{GeV}/c] = 0.3 \times \rho[\mathrm{m}] \times B[\mathrm{T}]$$

SC magnet

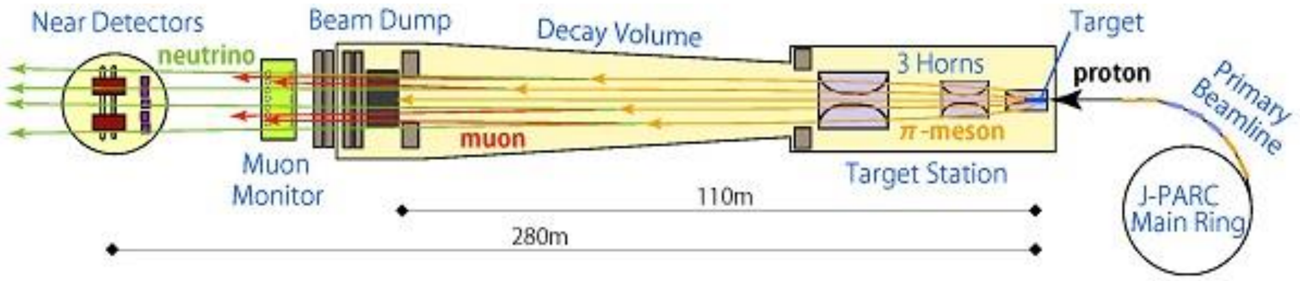
- Strong field (>0.2 T) steady state
- Typically proton circular machine
- Ex) 7 TeV & 8.3 T at LHC

NC magnet

- Weak field (<0.2 T) steady state
- Typically electron circular machine
- Ex) 90 GeV & 0.13 T at LEP

Short pulsed NC magnet

https://j-parc.jp/Neutrino/en/nu-facility.html



- Separate π^+ and π^- for neutrino and anti-neutrino
  - Too high radiation → SC magnet may not survive
  - Coincidence time window with neutrino detector
- Strong field (2 T) for short pulse 5 μs (every 2-3 seconds)

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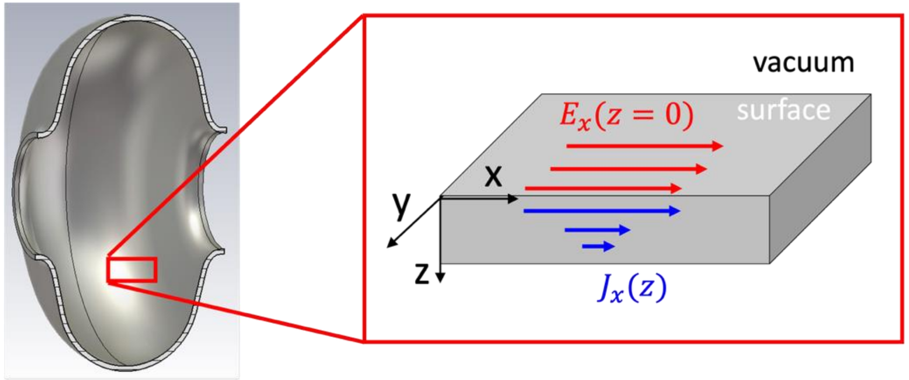
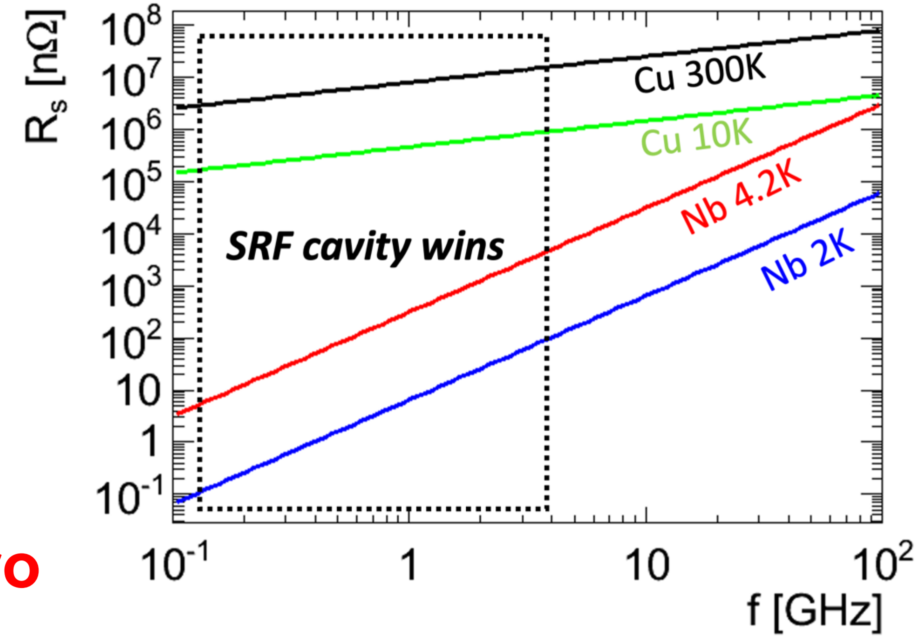


Local surface resistance

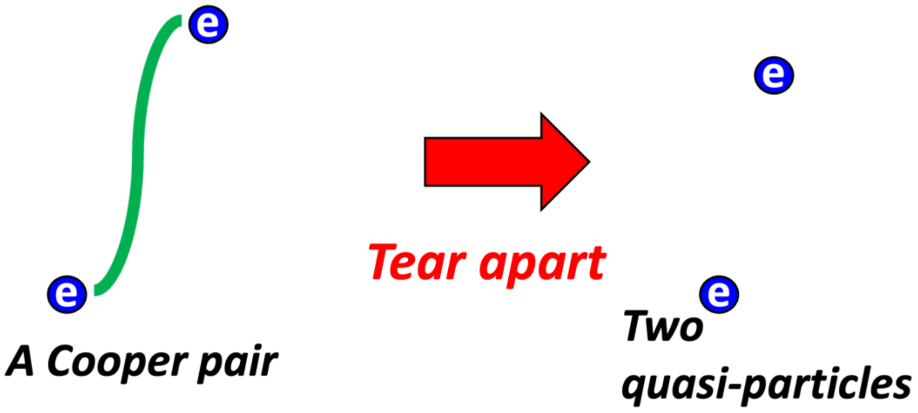
$$R_s \equiv \mathrm{Re}\left(\frac{E_x(z=0)}{\int_0^\infty J_x(z)dz}\right)$$

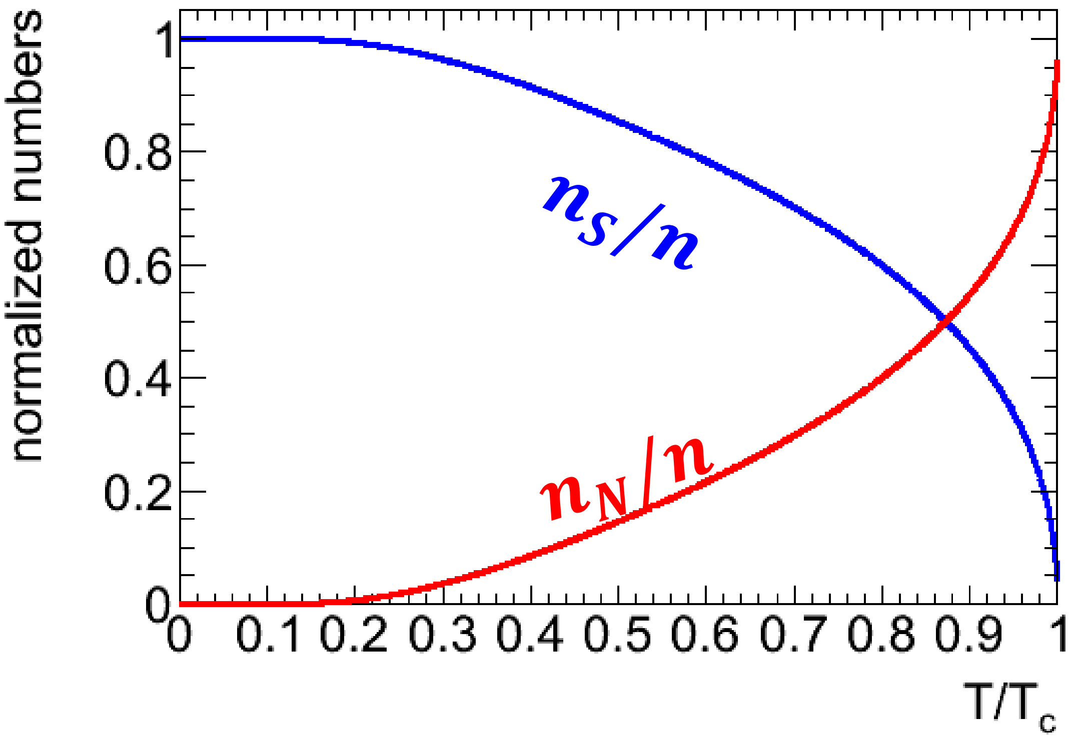
Normal conducting (Cu) $R_s = \sqrt{\frac{\pi f \mu_0}{\sigma}} \propto f^{1/2}$

Super- conducting (Nb) $R_s = \frac{Af^2}{T}\exp\left(-\frac{\Delta}{k_B T}\right) \propto f^2$



Superconducting R_s is small but non zero





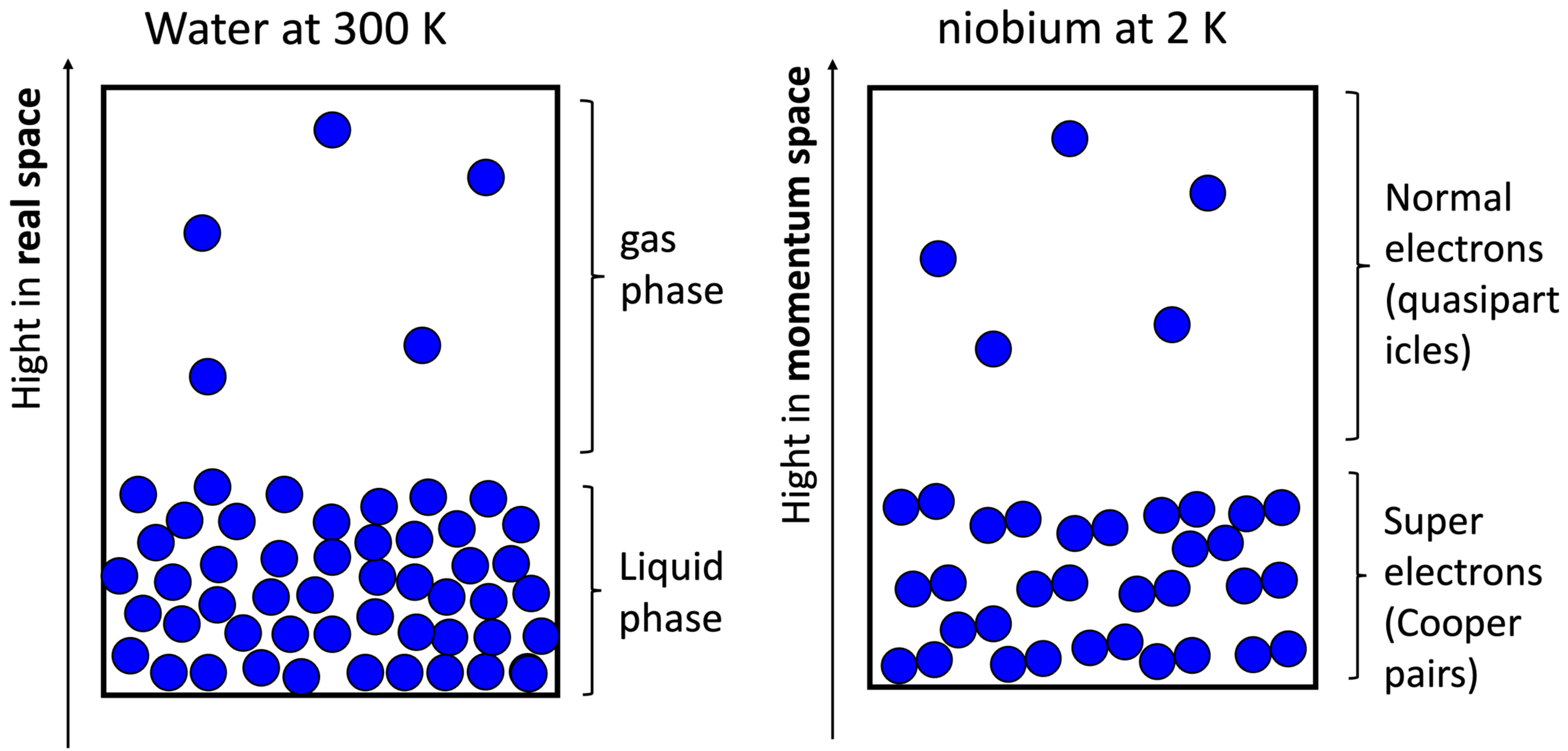
At finite temperature $0 < T < T_c$, these two states are ***in thermal equilibrium***

# of quasiparticles: $n_N \sim \exp\left(-\frac{\Delta}{k_B T}\right)$

# of electrons in Cooper pairs: $n_S \sim n - n_N$

Quasi-particles (~normal conducting electrons) still exist if $T > 0$

Coexistence of Cooper pairs and quasi-particles



Supercurrent

$$\frac{\partial j_s}{\partial t} - \frac{n_S e^2}{m^*} E = 0$$

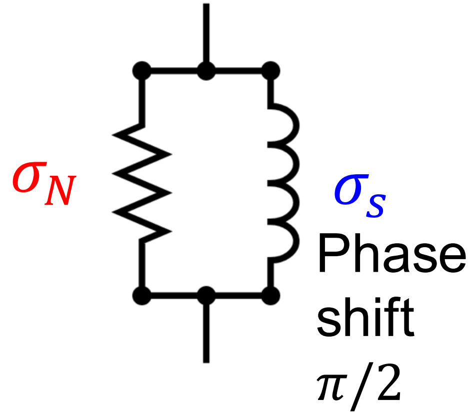
$$j_s = j_0 \exp(i\omega t)$$

$$j_s = -i\frac{n_S e^2}{m^* \omega} E \qquad \frac{n_S e^2}{m^* \omega} \equiv \sigma_s$$

Normal current

Ohm's law →

$$j_N = \frac{n_N e^2 \tau}{m^*} E \qquad \frac{n_N e^2 \tau}{m^*} \equiv \sigma_N$$



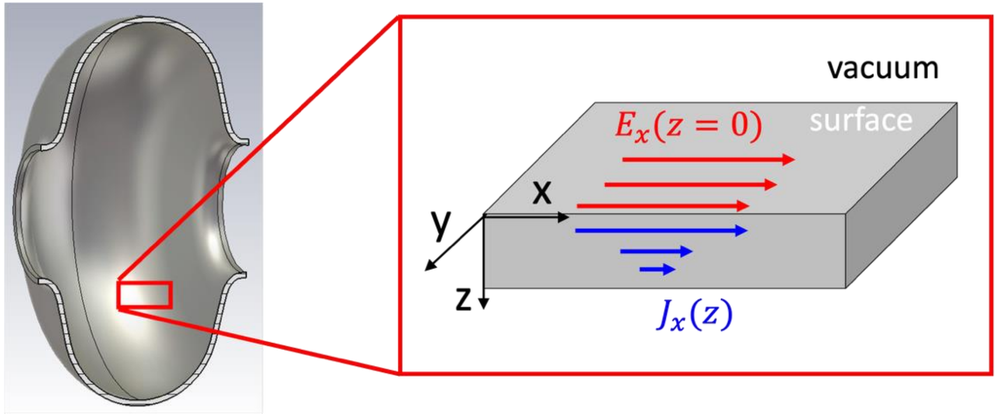
Total current induced by RF

$$j = j_S + j_N \quad \rightarrow \quad j = (\sigma_N - i\sigma_S)E$$

Dissipation by quasi-particles →resistive

Inertia of Cooper pairs → inductive

Surface resistance of superconductor



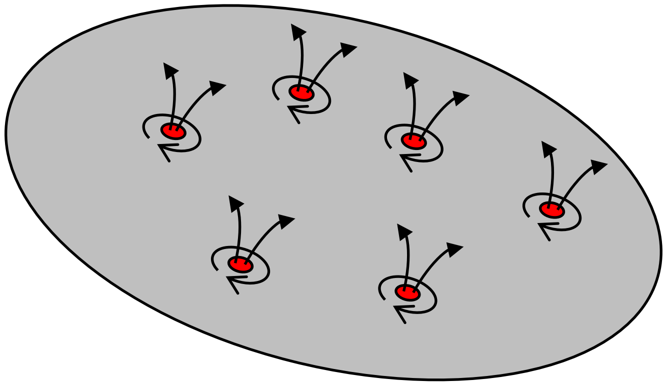
$$\sigma_N = \frac{e^2 n_N \tau}{m^*} \propto n_N \propto \exp\left(-\frac{\Delta}{k_B T}\right)$$

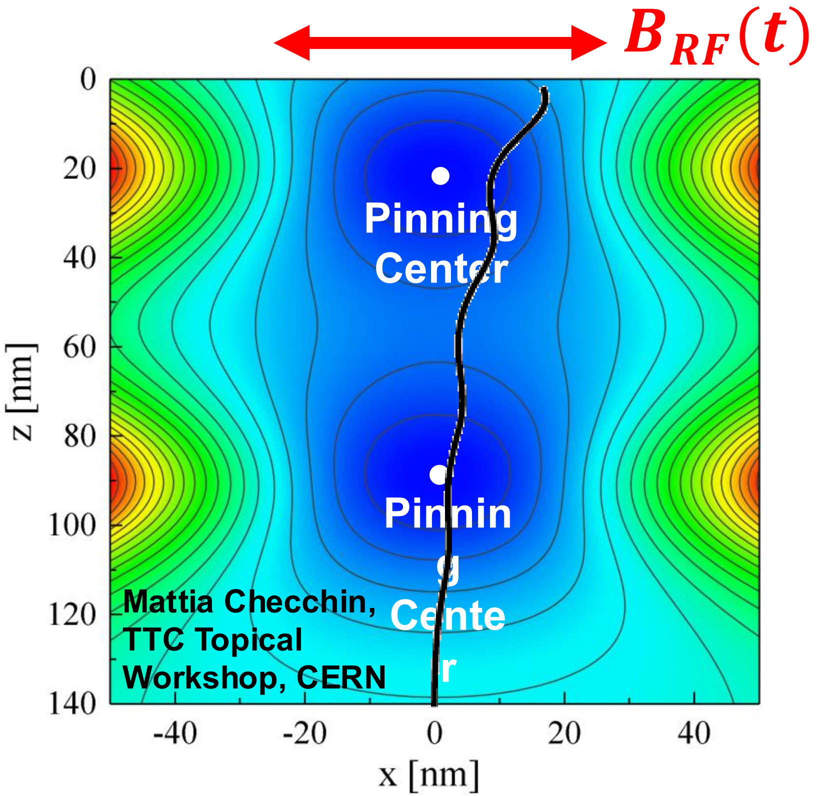
$$\begin{cases} j_x = (\sigma_N - i\sigma_S)E_x \\ E_x(z) = E_0 \exp(-z/\lambda_L) \end{cases} \rightarrow R_s \equiv \mathrm{Re}\left(\frac{E_x(z=0)}{\int_0^\infty J_x(z)dz}\right) \sim \frac{1}{2}\frac{\sigma_N}{\sigma_S}\sqrt{\frac{\omega\mu_0}{\sigma_S}} = \frac{\mu_0^2}{2}\lambda_L^3 \sigma_N \omega^2 > 0$$

Lessons

- One origin of the finite R_s of superconductors is quasi-particles
- Quasi-particles are thermally activated from Cooper pairs at $0 < T < T_c$
- R_s exponentially decreases by lower T because quasi-particles are frozen out
- Higher RF frequency increases $R_s \sim \omega^2$
- Order of magnitude is 10 nΩ

Static trapped magnetic field in SC cavities





Normal conducting area

$$R_{\mathrm{mag}} \sim N \times \pi\xi_0^2 \times R_{\mathrm{n}} \sim \frac{B_{\mathrm{ext}}}{2B_{c2}} R_{\mathrm{n}}$$

Flux number density

Normal conducting

Earth field B_{ext}=50uT
B_{c2}~400 mT (Nb)
R_n~1.3 mΩ at 1.3 GHz (Nb)

$$R_{\mathrm{mag}} \sim 80\mathrm{n}\Omega > R_{BCS}(2K) \sim 10\mathrm{n}\Omega$$

An excellent magnetic shield is mandatory for SC cavities

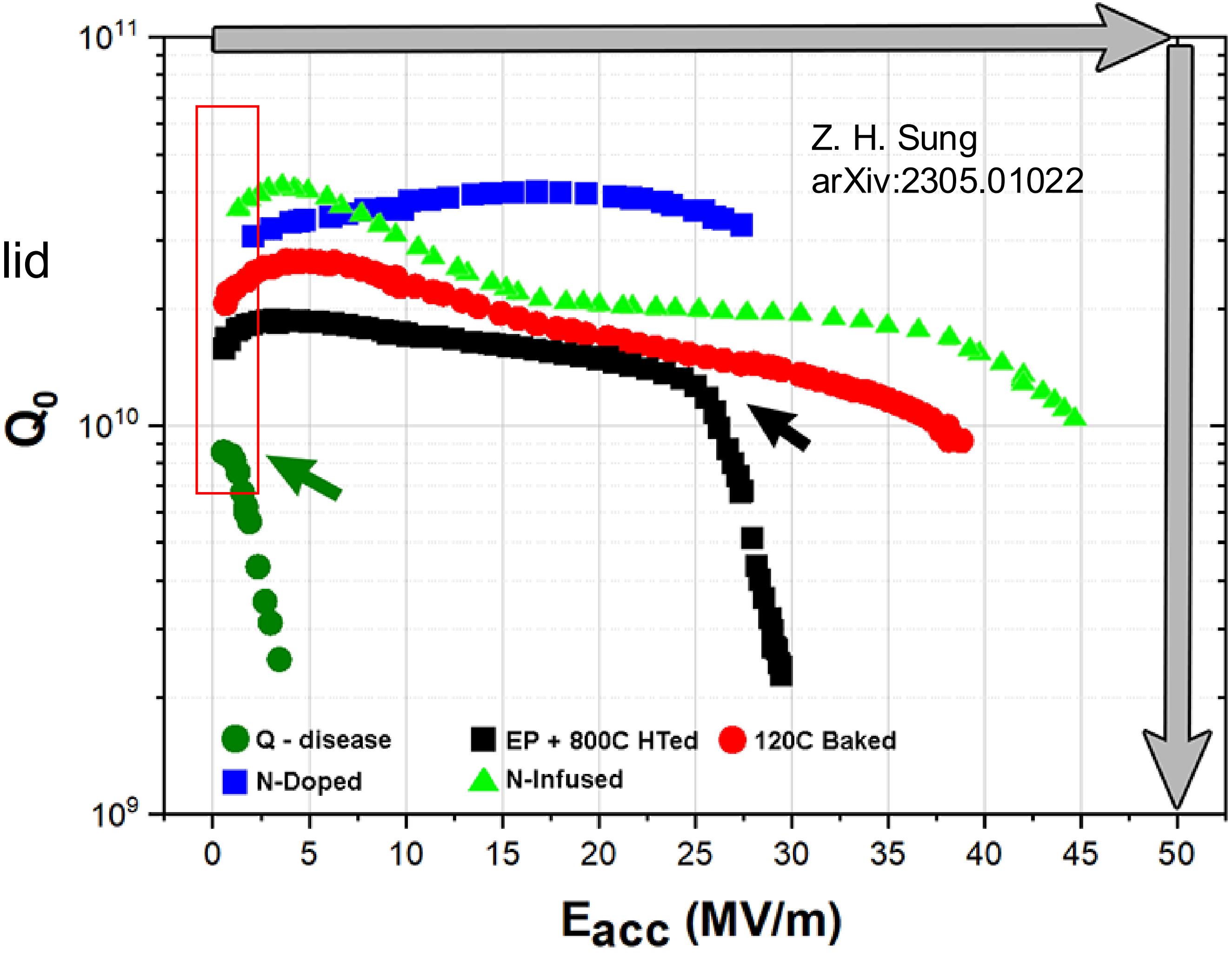
Quality factor vs accelerating gradient

$$Q_0 \equiv \frac{\omega U}{P_c} = \frac{1}{R_s} \boxed{\omega\mu \frac{\int_V H^2 dV}{\int H^2 dS}}$$

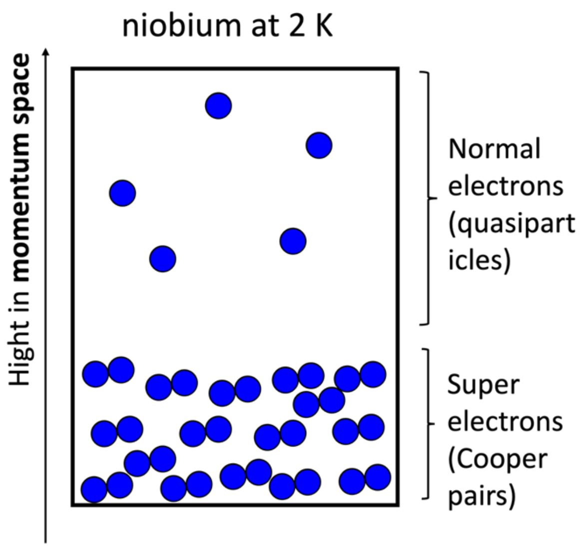
geometrical

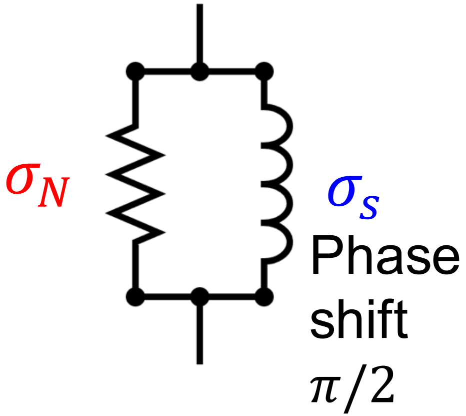
- The established theory in only valid for low external RF field
- The simplest nonequilibrium problem is solved in the linear response theory
- Very tiny difference in surface impacts the results (<10 nΩ physics!)
- We do not have complete theory that explains the nonlinear phenomena in Q vs E

  → Open research field!



- Magnets are operated in strong DC fields
  - The two-fluid circuit is short → no loss
  - Finite loss during ramping up and down the field
  - Magnetic fields are trapped in Mixed state
    - Strong pinning force is manipulated to avoid flux flow (otherwise, loss)
- Cavities are operated in RF fields
  - The phase shift due to Cooper pairs' inertia causes finite loss in quasiparticles
  - Oscillating trapped flux kills the cavity performance
  - Operation in as clean as the Meissner state
    - RF field itself does not penetrate due to superheating effect and surface barrier





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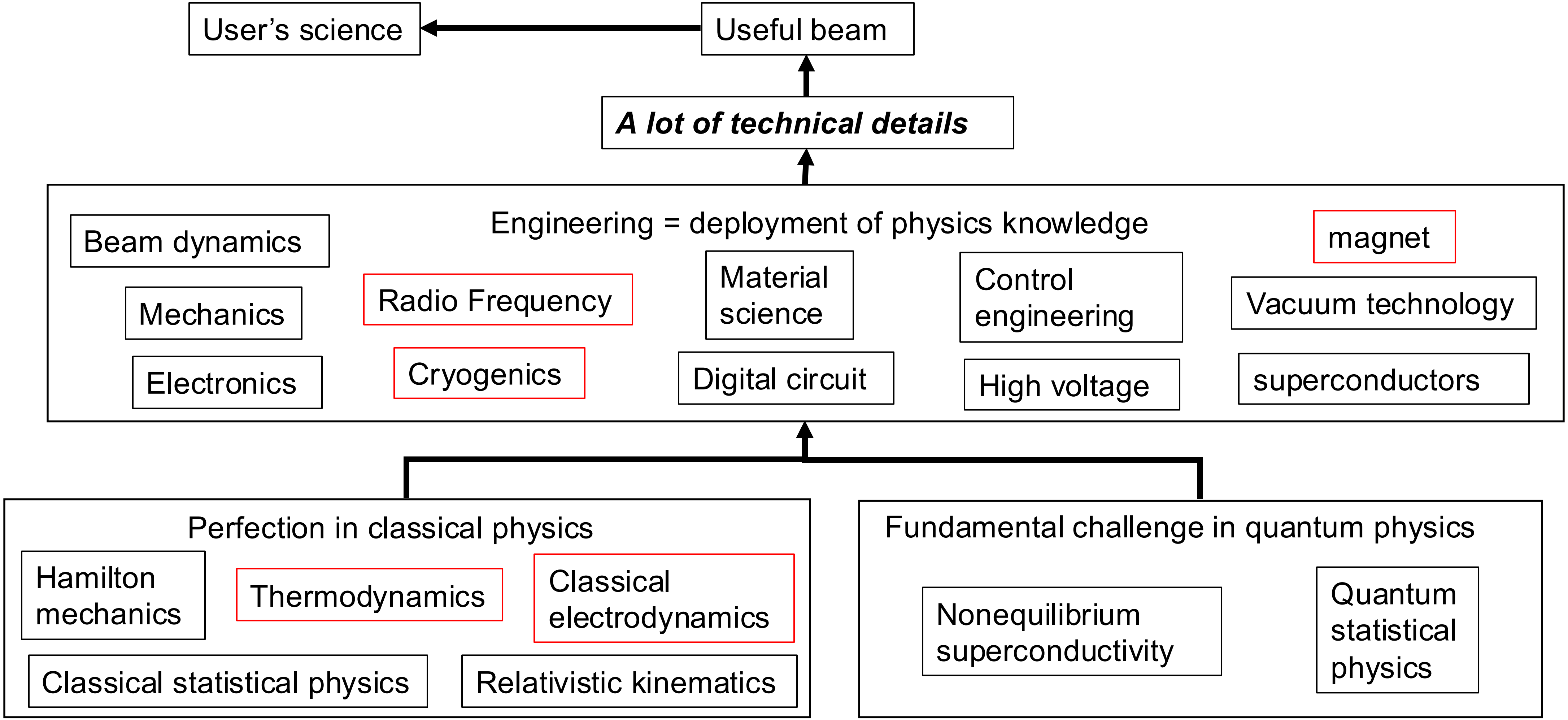
Conclusion: *Superconductivity and Cryogenics for Particle Accelerators*

- Cooling down improves loss but becomes less efficient
  - Superconducting vs normal conducting under the ideal Carnot cycle
  - Carnot cycle is NOT realistic at all: trade off in efficiency and power evacuation
- Superconducting devices are typically operated inside liquid helium
  - Cryogenics is enabled by physics and engineering of thermodynamics
- Superconductivity is macroscopic quantum phenomenon
  - Meissner effect is the most characteristic phenomenon (spontaneously broken Gauge symmetry in the ground stage)
  - Zero DC loss is caused by Cooper pairs
  - Classical electrodynamics can give us some insight with limitation
- Several different superconducting mechanisms are known
  - Only BCS-type SCs are well understood (phonon-mediated correlation) and Copper oxide & iron-based SC are still under devate
- SC magnet are operated in the Mixed state of type-II superconductors
- SC cavities are operated in the Meissner state of type-II superconductors
  - Non-equibrilium phenomenon is the remaining challenge of BCS-type SCs
  - Two-fluid model gives us some insight with limitations

Conclusion: *rich physics in the research field of accelerators*



More about superconducting cavities

Summer Student Lecture Programme 2025

1 Jul 2025, 08:00 → 1 Aug 2025, 13:00 Europe/Zurich

500/1-001 - Main Auditorium (CERN)

Webcast There is a live webcast for this event **Watch**

Monday 21 July

- **09:15** → 10:10 **RF Superconductivity** — 55m
  Speaker: Akira Miyazaki (Université Paris-Saclay (FR))
- **10:25** → 11:20 **Making Predictions at Hadron Colliders** — 55m
  Speaker: Alexander Yohei Huss (CERN)
- **11:35** → 12:30 **Nuclear Physics at CERN** — 55m
  Speaker: Magdalena Kowalska (CERN)

Tuesday 22 July

- **09:15** → 10:10 **Nuclear Physics at CERN** — 55m
  Speaker: Magdalena Kowalska (CERN)
- **10:25** → 11:20 **RF Superconductivity** — 55m
  Speaker: Akira Miyazaki (Université Paris-Saclay (FR))
- **11:35** → 12:30 **Making Predictions at Hadron Colliders** — 55m
  Speaker: Alexander Yohei Huss (CERN)

https://indico.cern.ch/event/1508891/timetable/

More dedicated to students learning particle physics and engineering aspects of particle physics