Superconductivity for particle accelerators

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CERN, Geneva (Switzerland)

CAS Course on Advanced Accelerator Physics
Warsaw, 27 September-9 October 2015

Contents

- Superconductivity in a nutshell
- Superconductivity and accelerators
- Superconducting magnets for accelerators
- Superconducting RF cavities for accelerators
- Superconducting current leads and powering links
- Some ongoing and future projects
- Selected bibliography

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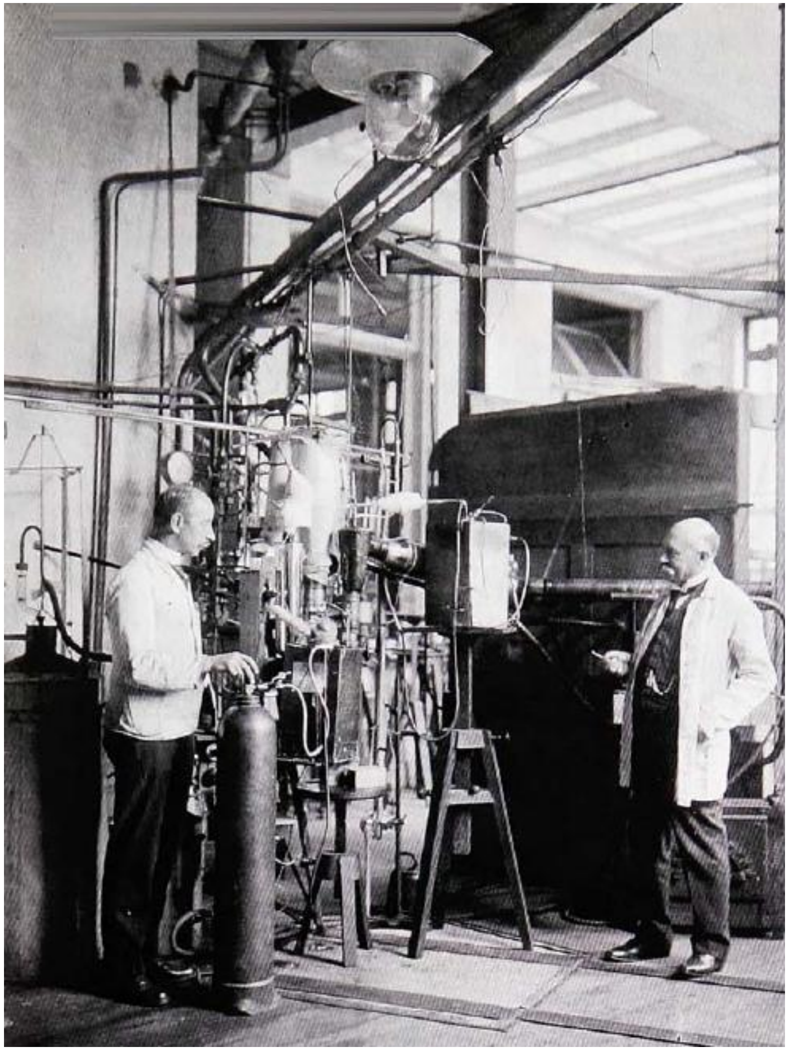
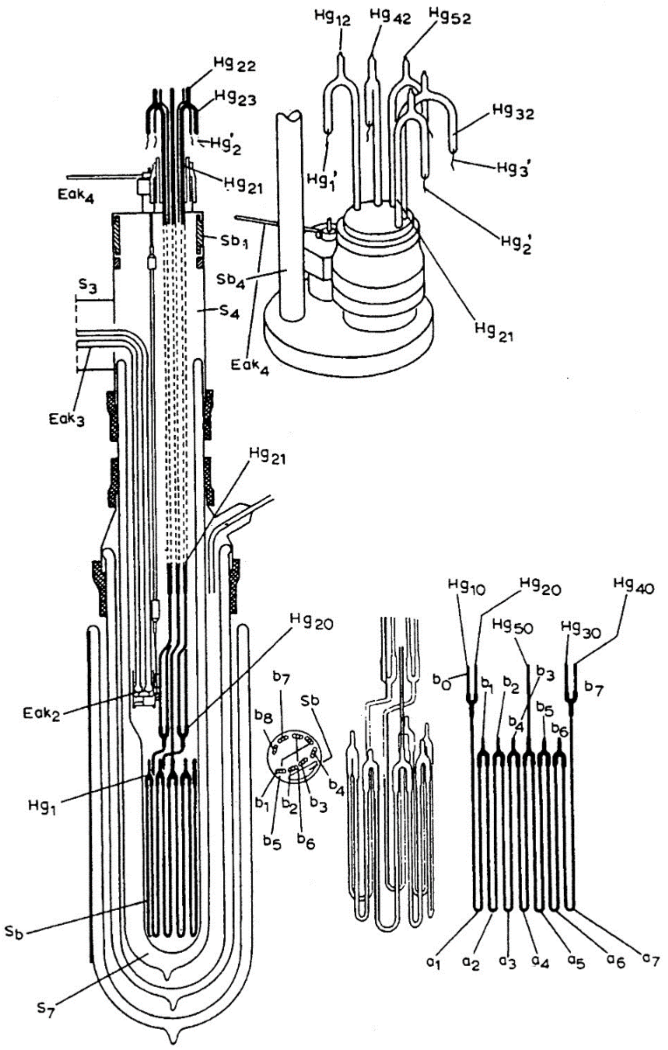
First liquefaction of helium at Leyden laboratory (1908) allows to study matter close to absolute zero

Heike Kamerlingh Onnes

"Door meten tot weten"
Knowledge by measurement



Onnes' measurement of electrical resistivity of mercury at low temperature



At a time when the atomic theory was not established, measuring electrical resistivity vs temperature was a way to explore the scattering of charge carriers and thus the structure of metals

To study properly the effect of temperature, the sample must be free from impurities

Mercury, a metal in the liquid state at room temperature, could be easily purified by distillation (it boils at 357 ºC)

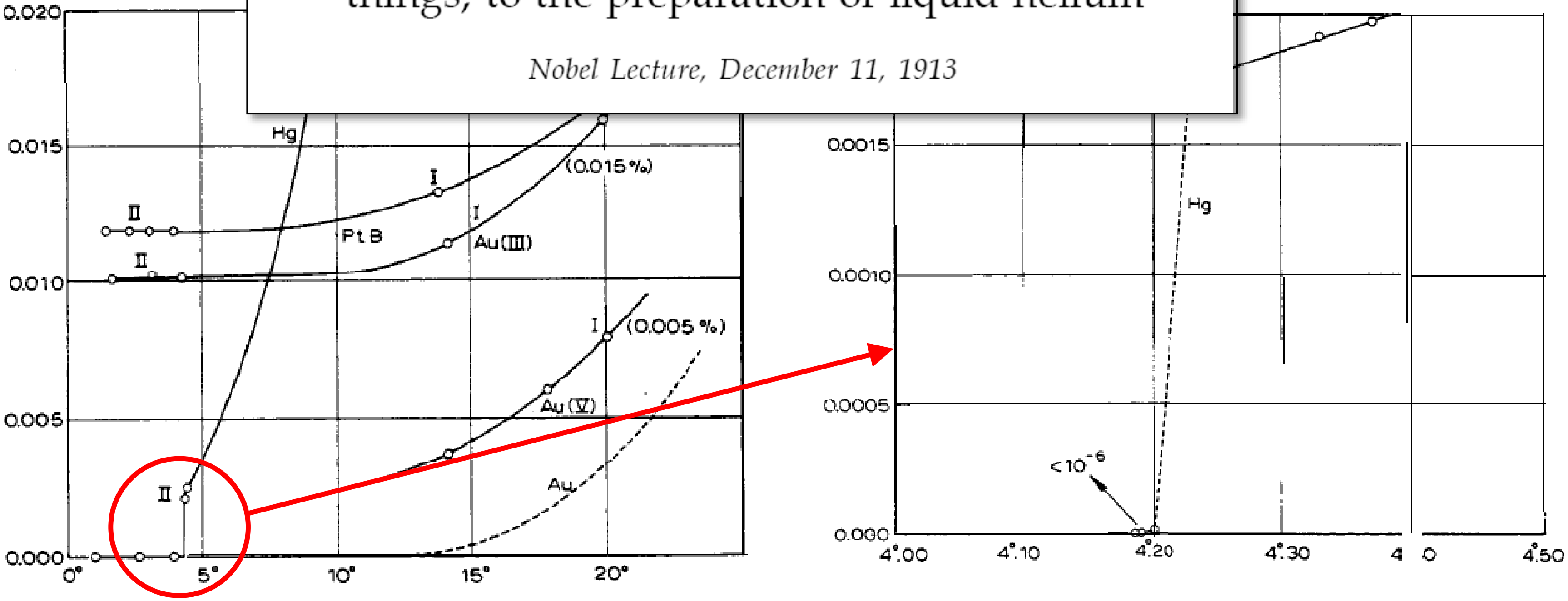
H.K. Onnes produced « wires » of mercury by filling glass tubes with connection electrodes: the « wires » get solid upon cooling at -39 ºC

Discovery of superconductivity (1911)

HEIKE KAMERLINGH ONNES

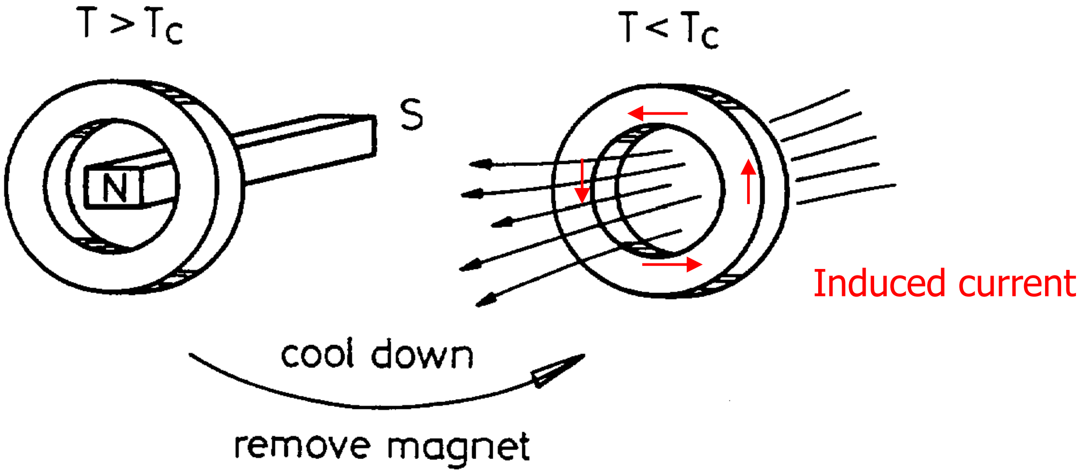
Investigations into the properties of substances at low temperatures, which have led, amongst other things, to the preparation of liquid helium

Nobel Lecture, December 11, 1913



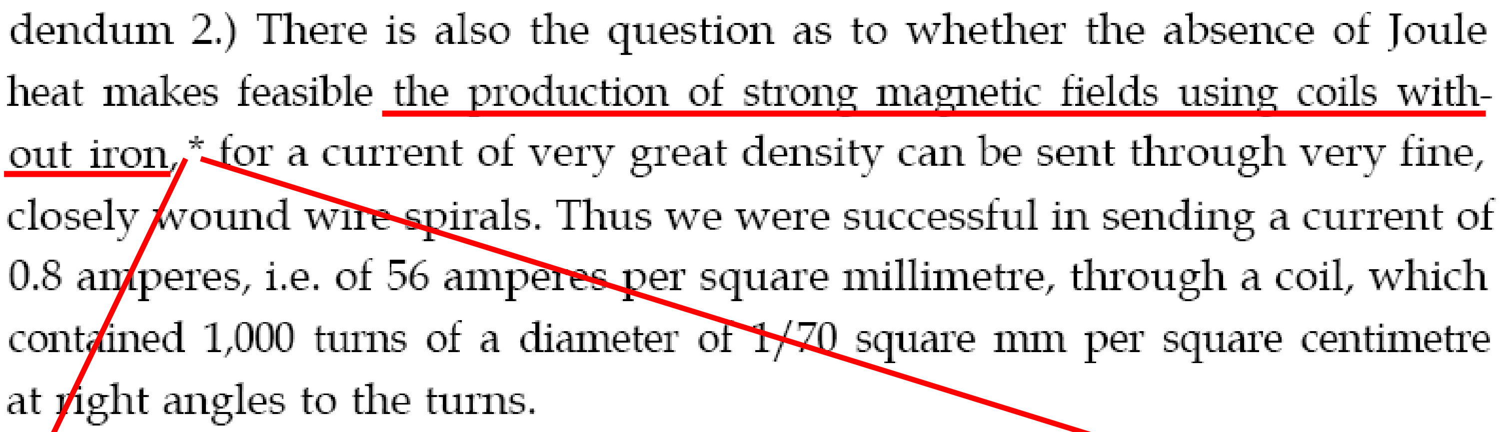
Thus the mercury at 4.2°K has entered a new state, which, owing to its particular electrical properties, can be called the state of superconductivity.

A superconductor shows zero resistance to d.c.



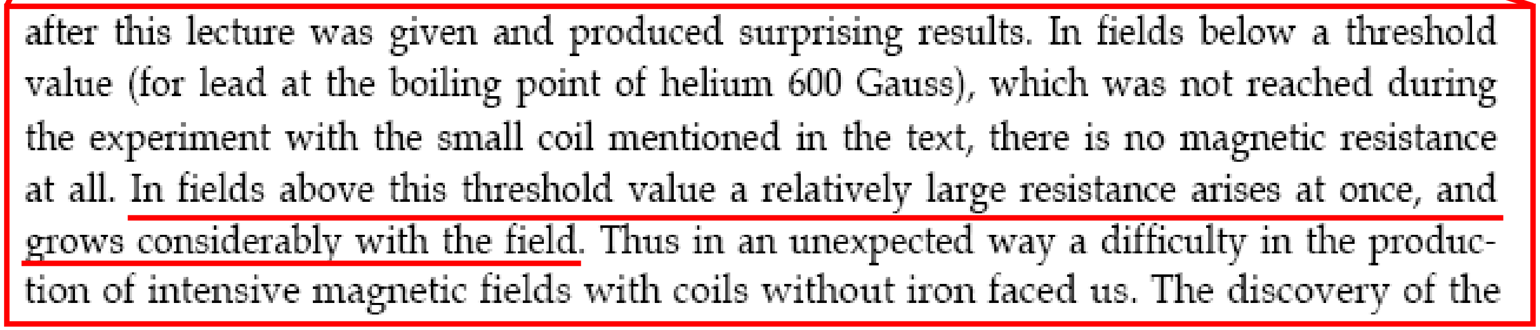
The current induced in a ring of superconducting material flows without losses almost indefinitely. Measurements showed a typical time constant for current decay of 100’000 years, i.e. a few billionths per hour!

Onnes immediately tries to use superconductivity for building high-field magnets…



dendum 2.) There is also the question as to whether the absence of Joule heat makes feasible the production of strong magnetic fields using coils without iron,* for a current of very great density can be sent through very fine, closely wound wire spirals. Thus we were successful in sending a current of 0.8 amperes, i.e. of 56 amperes per square millimetre, through a coil, which contained 1,000 turns of a diameter of 1/70 square mm per square centimetre at right angles to the turns.

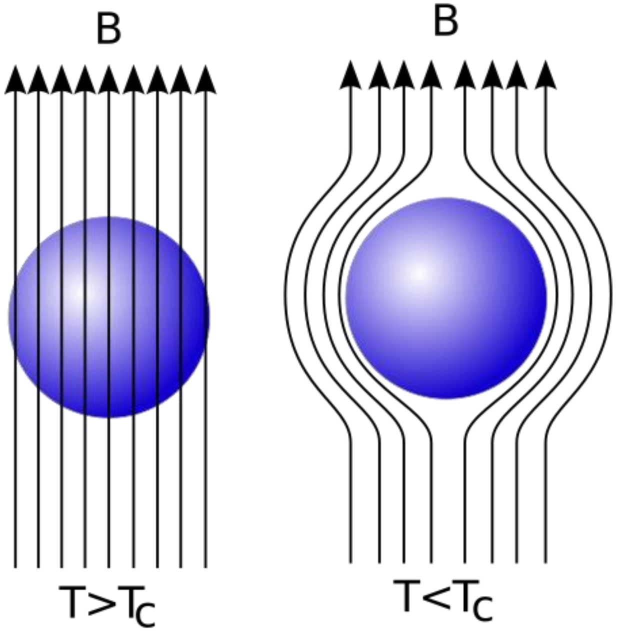
…but stumbles upon their « critical field »!



after this lecture was given and produced surprising results. In fields below a threshold value (for lead at the boiling point of helium 600 Gauss), which was not reached during the experiment with the small coil mentioned in the text, there is no magnetic resistance at all. In fields above this threshold value a relatively large resistance arises at once, and grows considerably with the field. Thus in an unexpected way a difficulty in the production of intensive magnetic fields with coils without iron faced us. The discovery of the

Discovery of the Meissner effect (1933)

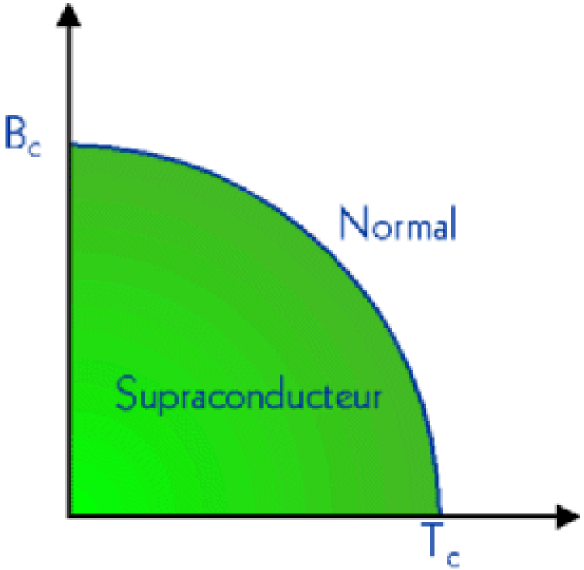
Walther Meissner



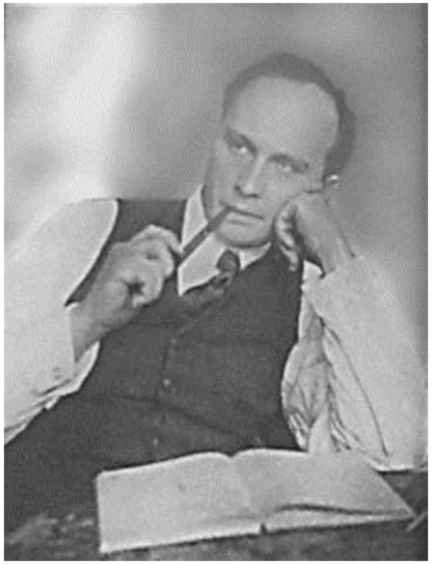
A superconductor excludes magnetic field from its interior (perfect diamagnet)

Application of a magnetic field above a limit value B_c destroys superconductivity

The superconducting state only exists in a limited domain of temperature and magnetic field

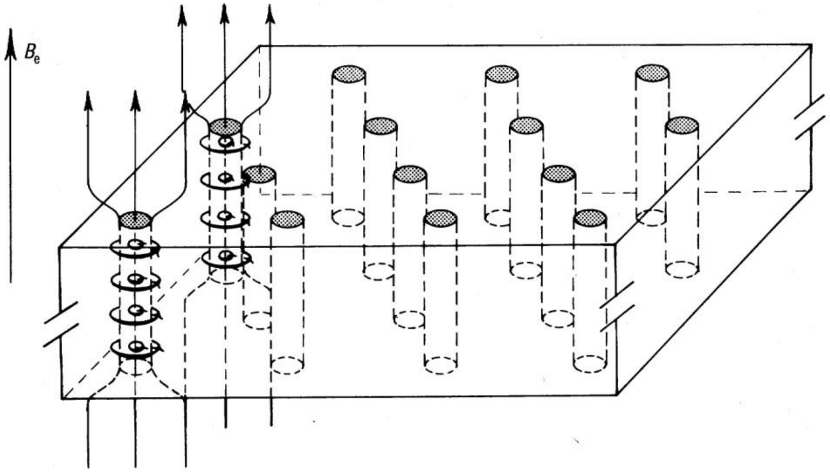


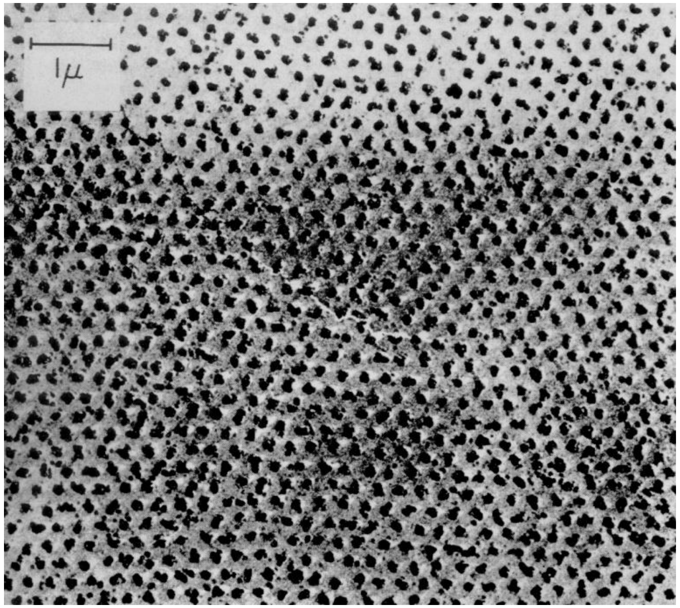
Vortex lattice of type-II superconductors (1954)
Field penetrates locally without destroying superconductivity

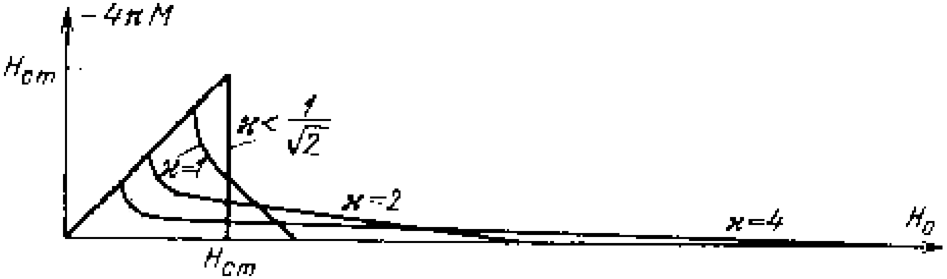


Lev Shubnikov

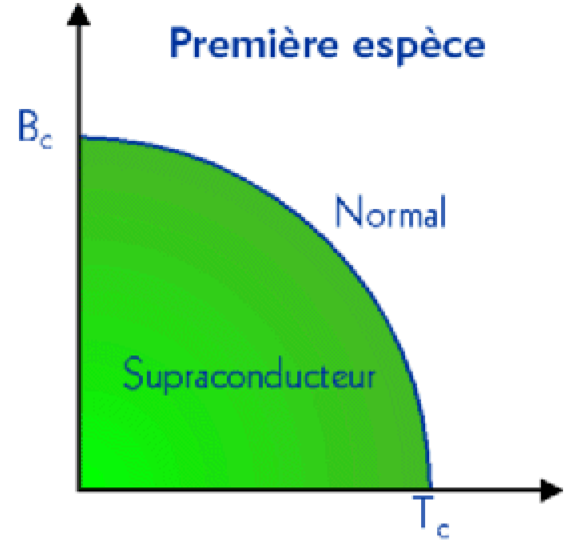
Alexei Abrikosov

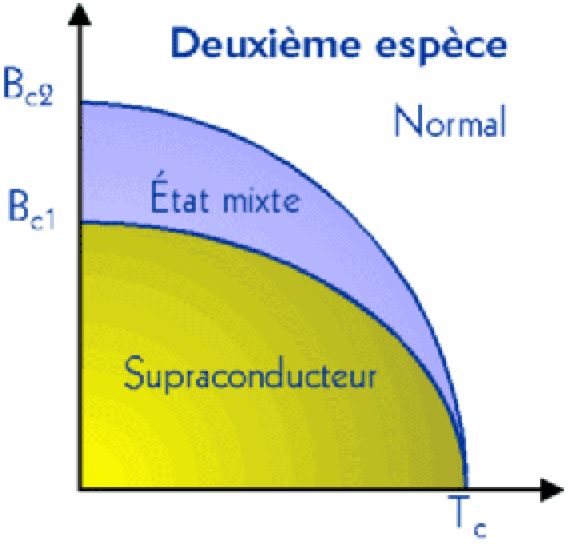


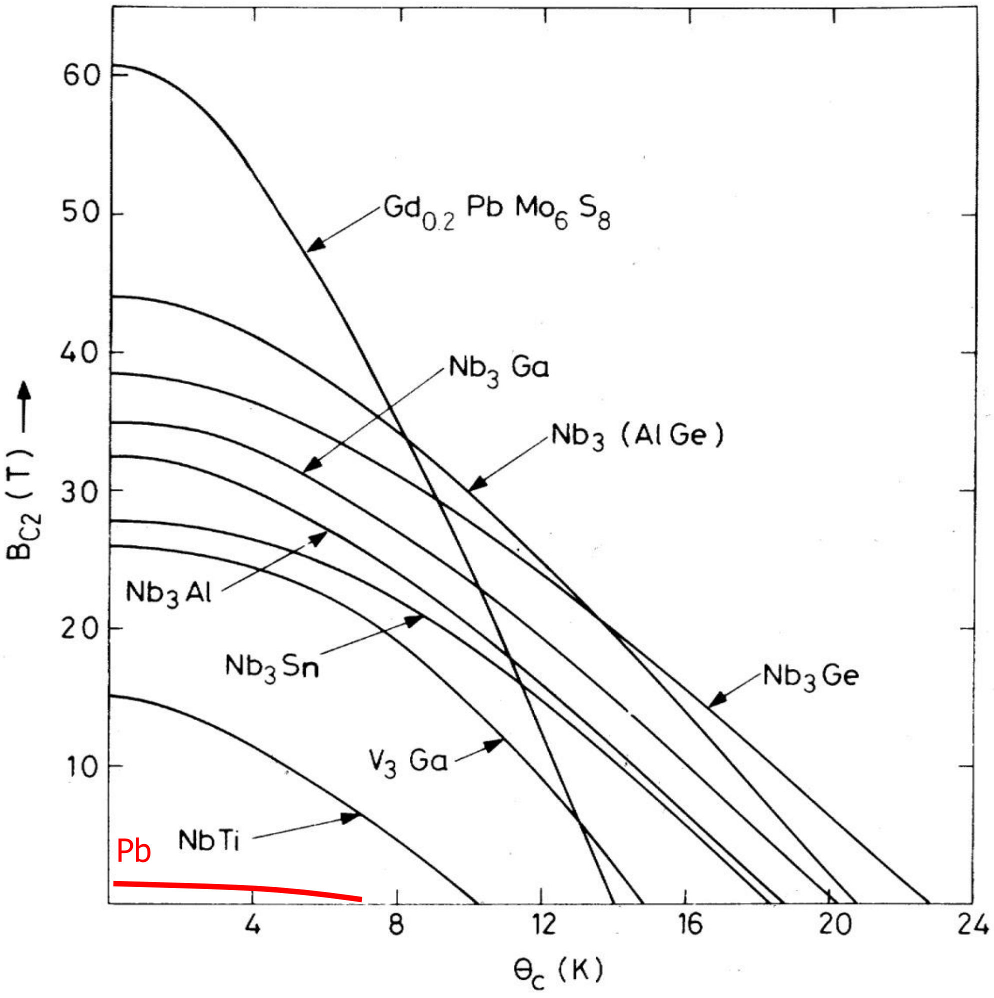




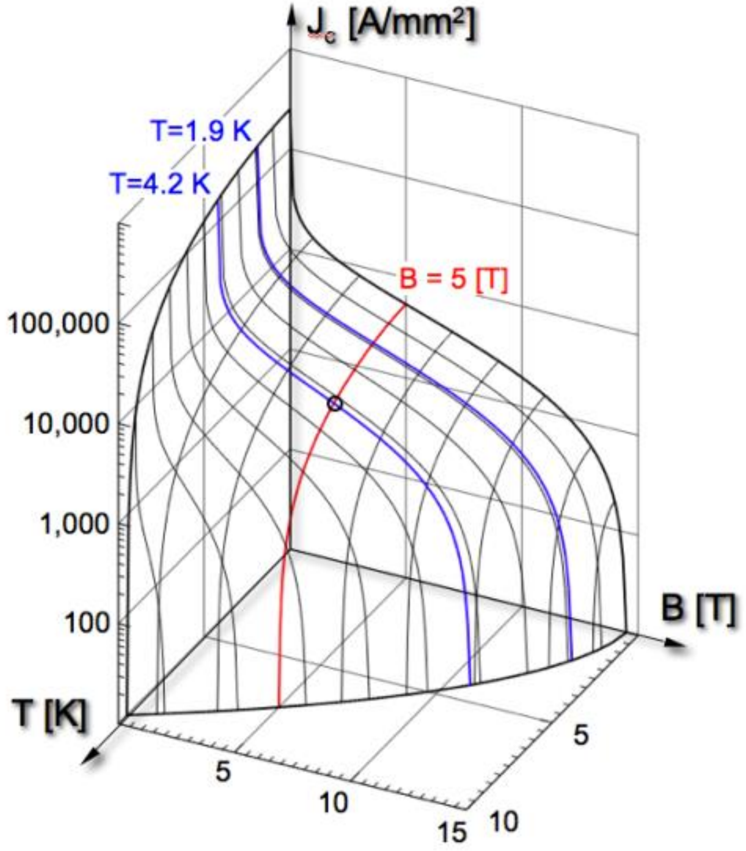
Type II superconductors are practical materials







Using superconductivity



Critical surface of Nb-Ti

- The superconducting state only occurs in a limited domain of (low) temperature, magnetic field and current density, limited by the «critical surface» of the material

- The working point must remain below the «critical surface» of the superconductor

- Operating at lower temperature increases the working range in the magnet design plane (J_c,B)

- In practice, operate at temperature well below T_c

Microscopic theory of superconductivity (1957)

PHYSICAL REVIEW VOLUME 108, NUMBER 5 DECEMBER 1, 1957

Theory of Superconductivity*

J. Bardeen, L. N. Cooper,† and J. R. Schrieffer‡
Department of Physics, University of Illinois, Urbana, Illinois

(Received July 8, 1957)

A theory of superconductivity is presented, based on the fact
that the interaction between electrons resulting from virtual
exchange of the energ
between the less than
energy, $\hbar\omega$. I conducting
this attracti he repulsi
Coulomb inte described
individual-pa te of a sup
formed from nal state c
in which elec pairs of
and moment the norn
amount prop $)^2$, consiste
isotope effec et of excit

one-to-one correspondence with those of the normal phase is
obtained by specifying occupation of certain Bloch states and by
t to form a al pair con-
he theory y nsition and
fect in the Calculated
ific heats a eir temper-
n are in go nt. There is
for indivi h decreases
$.5kT_c$ at T s of matrix
single-parti xcited-state
ing wave f tion expan-
ulations of given.

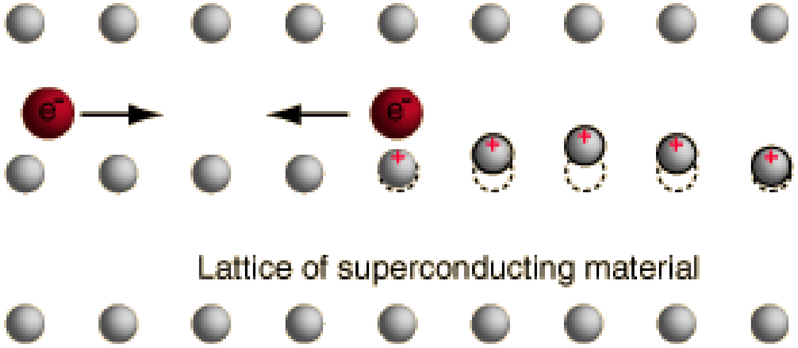
John Bardeen

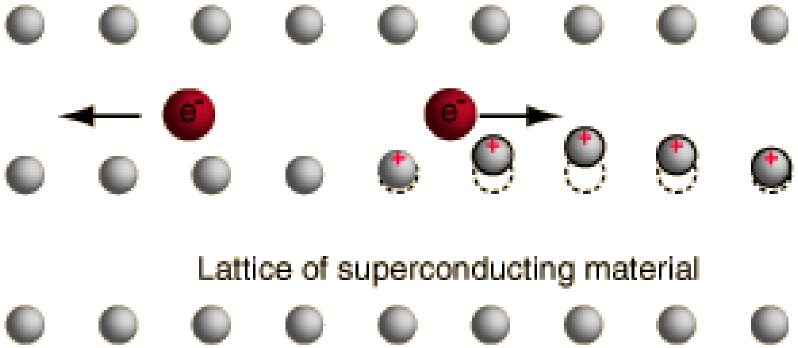
Leon Neil Cooper

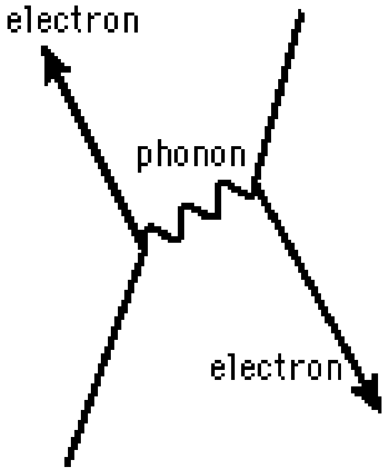
John Robert Schrieffer

BCS theory of superconductivity

- Three major insights:
  - Effective forces between conduction electrons can sometimes become attractive in a solid rather than repulsive, due to electron-phonon coupling

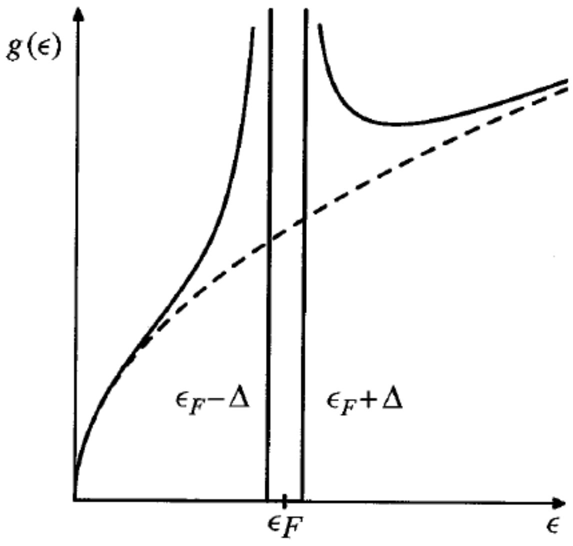




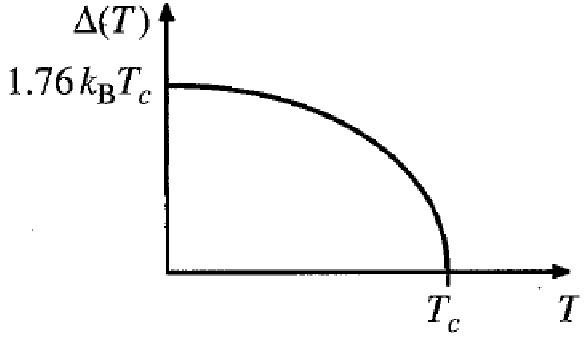


BCS theory of superconductivity

- Three major insights:
  - Effective forces between conduction electrons can sometimes become attractive in a solid rather than repulsive, due to electron-phonon coupling
  - This attractive interaction between two electrons outside an occupied Fermi surface can form a stable bound state («Cooper pair»), however weak the attractive force
  - The many-particle wave function describing the pairing of all electrons near the Fermi surface has the form of a coherent state. The density of states shows an energy gap 2Δ at the Fermi level, corresponding to the binding energy of a pair



The width of the gap depends on temperature; its value at zero temperature is proportional to the critical temperature



BCS theory of superconductivity

- The BCS theory predicts the critical temperature from properties of the solid

Electron density of states at Fermi level

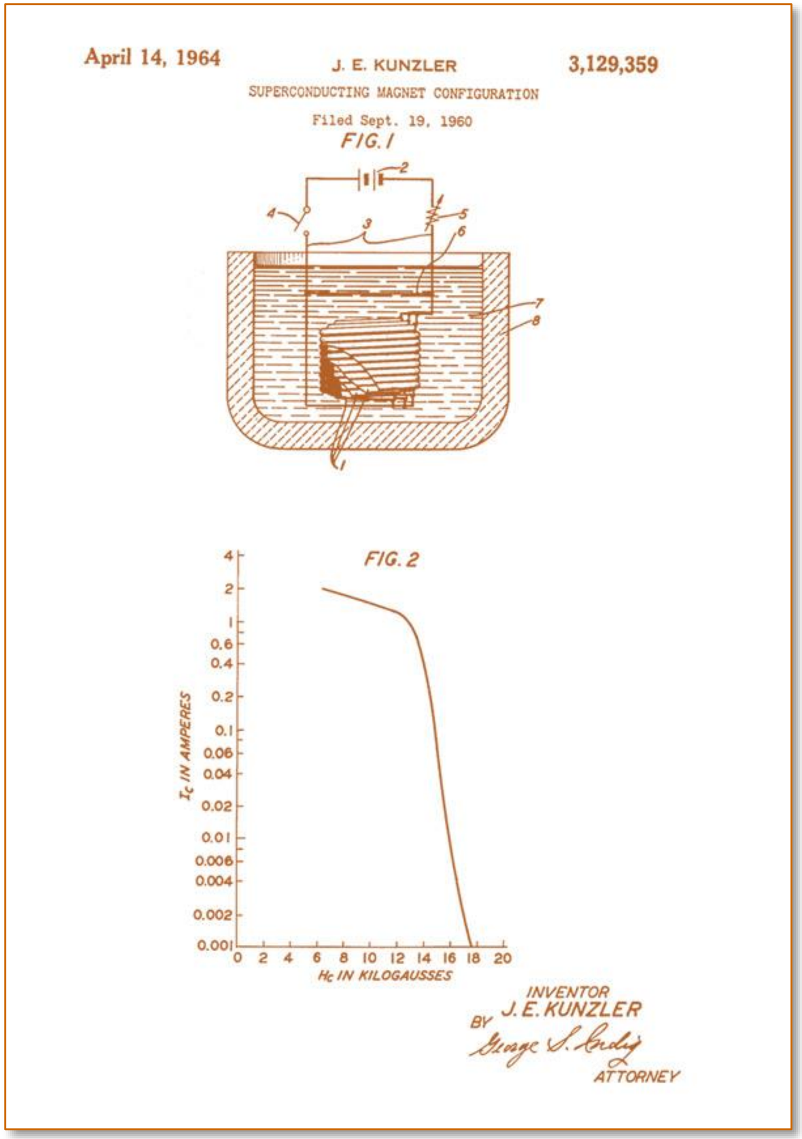
$$k_B T_c = 1.13\,\hbar\omega_D \exp\left(-{}^{1}/_{U\mathcal{D}(\mathcal{E}_F)}\right)$$

Debye energy

Electron-lattice interaction

- Hence, critical temperature of BCS superconductor increases with
  - Energetic phonons (Debye energy)
  - Strong electron-lattice interaction (bad normal conductors)
  - High electron density of states at Fermi level

First « high-field » superconducting magnet (1960)



April 14, 1964

J. E. KUNZLER

3,129,359

SUPERCONDUCTING MAGNET CONFIGURATION

Filed Sept. 19, 1960

FIG. 1

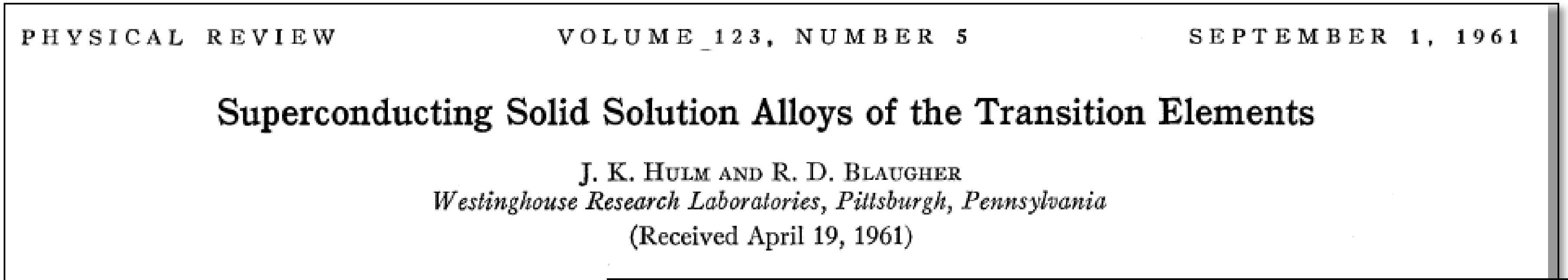
FIG. 2

INVENTOR
J. E. KUNZLER
BY George S. Indig
ATTORNEY

Patent filed in 1960 by J. Kunzler, of Bell Laboratories (registered in 1964)

1.5 T reached with magnet wound from molybdenium-rhenium alloy wire

Discovery of Nb-Ti alloys (1961)



PHYSICAL REVIEW VOLUME 123, NUMBER 5 SEPTEMBER 1, 1961

Superconducting Solid Solution Alloys of the Transition Elements

J. K. Hulm and R. D. Blaugher
Westinghouse Research Laboratories, Pittsburgh, Pennsylvania

(Received April 19, 1961)

The solid solution alloys formed by
tested for superconductivity down to
row of the periodic table, two transit
proximately equal to 4.7 and 6.4, respe
upper maximum is absent. Similar ma
rows of the periodic table, thus confir
normal density-of-states function, N(0
these peaks lying at about the same com
ent work. The relationship of T_c to N(
data are also presented for alloys comp
In this case, the form of the relationsh

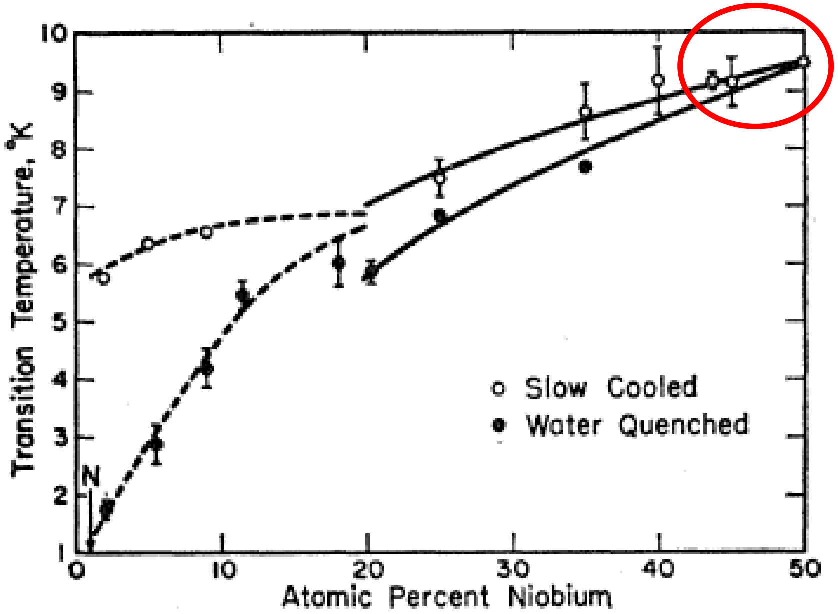
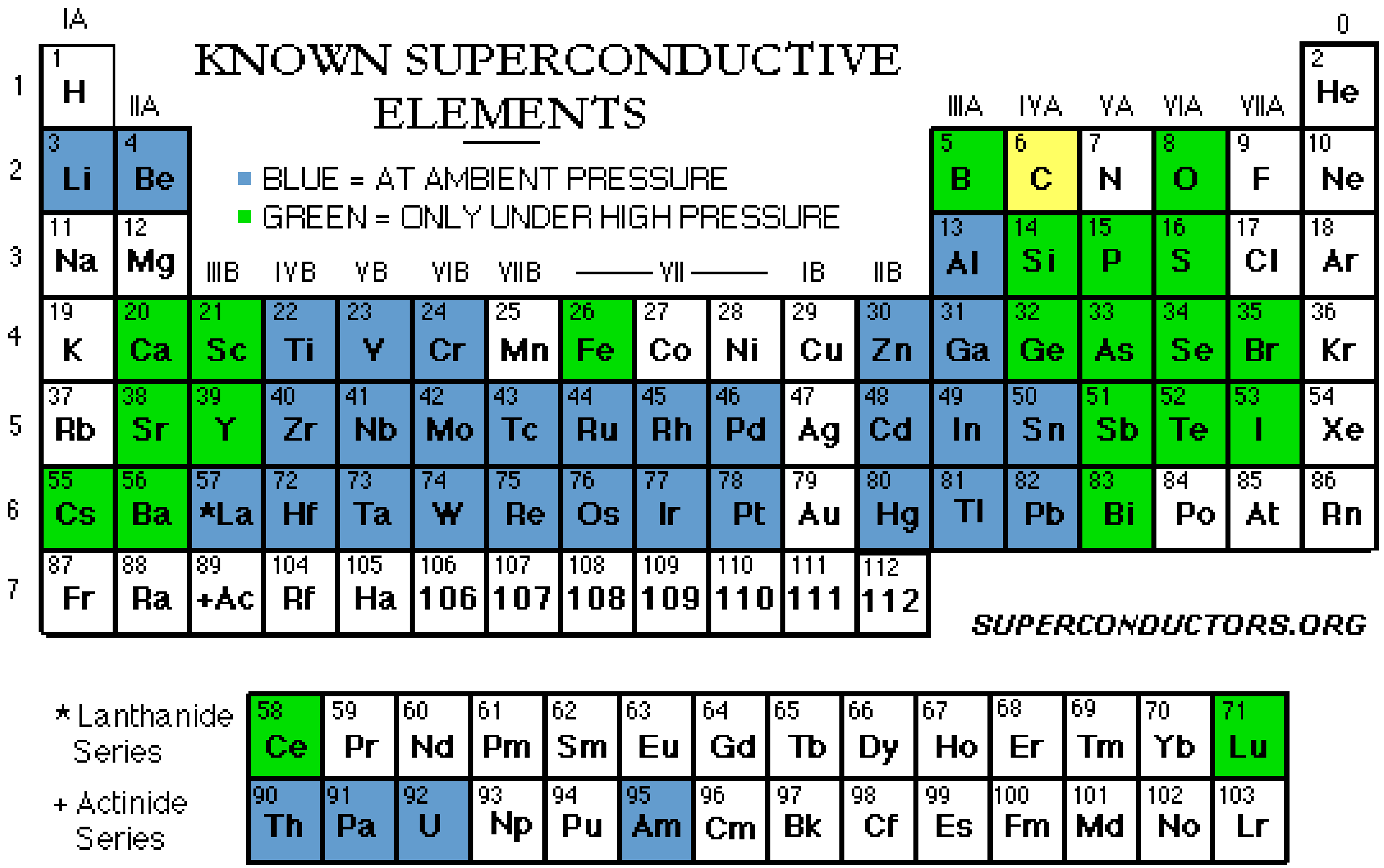


Fig. 6. Transition temperature versus composition for titanium-niobium alloys prepared by different types of heat treatment.

A very frequent phenomenon…
at low enough temperature



KNOWN SUPERCONDUCTIVE ELEMENTS

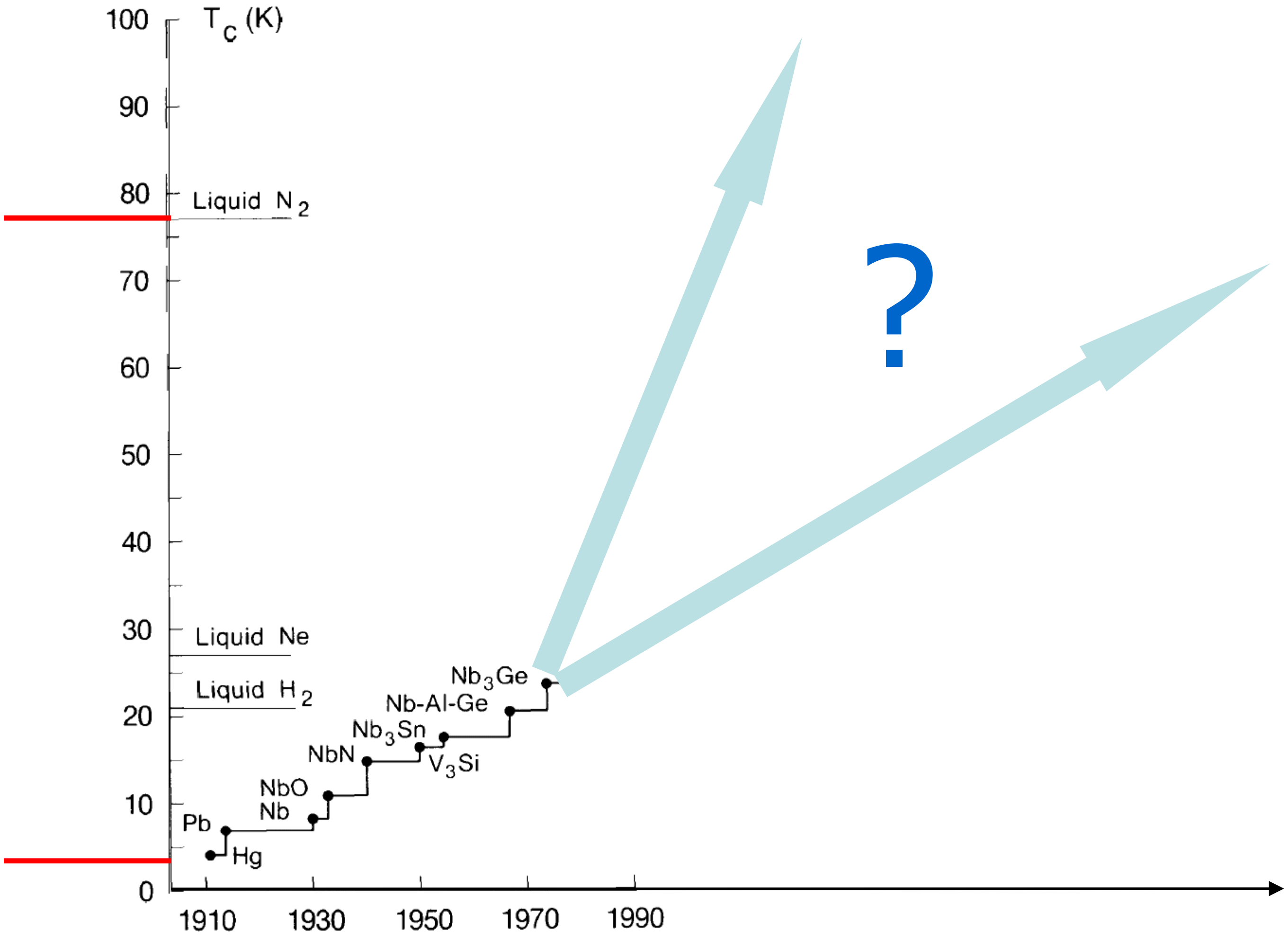
🟦 BLUE = AT AMBIENT PRESSURE
🟩 GREEN = ONLY UNDER HIGH PRESSURE

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII	VII	VII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

SUPERCONDUCTORS.ORG

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Towards higher temperatures?



Discovery of « high » temperature superconductors (1986)

Z. Phys. B – Condensed Matter 64, 189–193 (1986)

Possible High T_c Superconductivity in the Ba – La – Cu – O System

J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

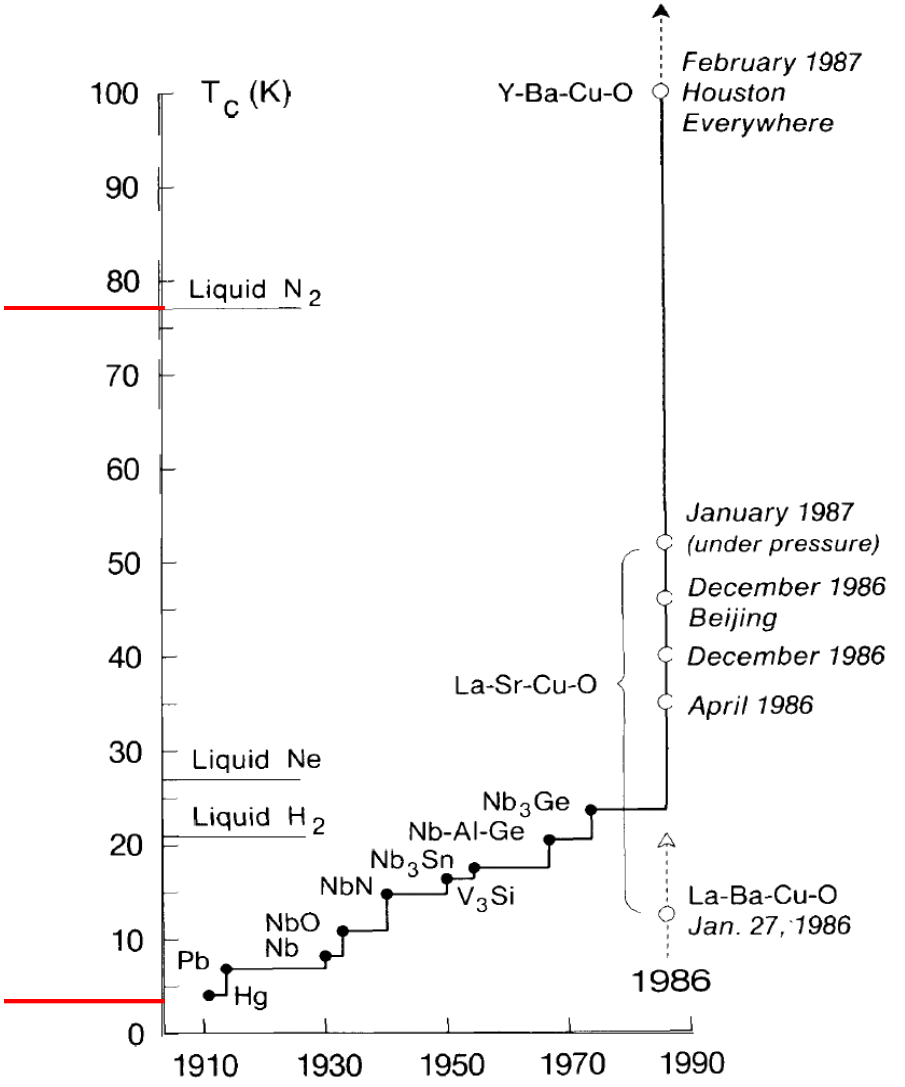
Received April 17, 1986

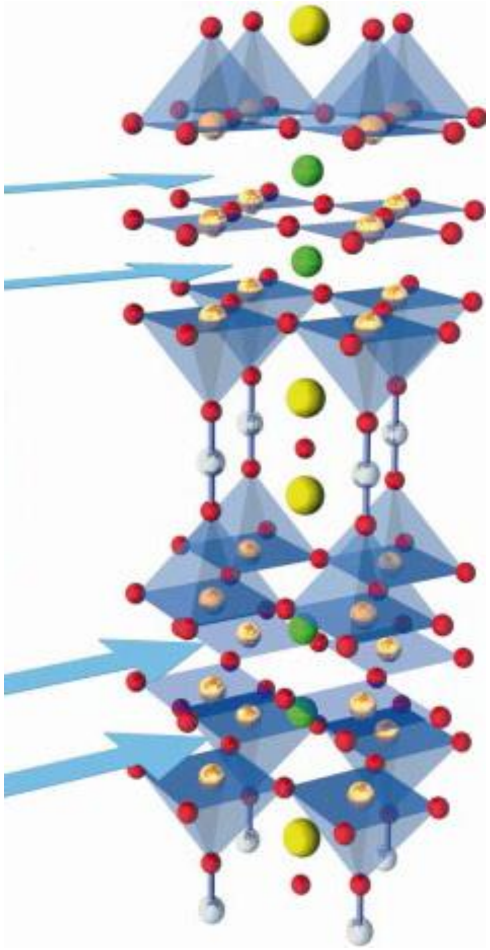
Metallic, oxygen-deficient compounds in the Ba – La – Cu – O system, with the composition $Ba_xLa_{5-x}Cu_5O_{5(3-y)}$ have been prepared in polycrystalline form. Samples with $x=1$ and 0.75, $y>0$, annealed below 900 °C under reducing conditions, consist of three phases, one of them a perovskite-like mixed-valent copper compound. Upon cooling, the samples show a linear decrease in resistivity, then an approximately logarithmic increase, interpreted as a beginning of localization. Finally an abrupt decrease by up to three orders of magnitude occurs, reminiscent of the onset of percolative superconductivity. The highest onset temperature is observed in the 30 K range. It is markedly reduced by high current densities. Thus, it results partially from the percolative nature, bute possibly also from 2*D* superconducting fluctuations of double perovskite layers of one of the phases present.


J. Georg Bednorz


K. Alexander Müller

« High » temperature superconductors





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Compactness through higher fields

- <u>Circular Accelerators</u>

$$p \simeq 0.3 \quad B \quad r$$

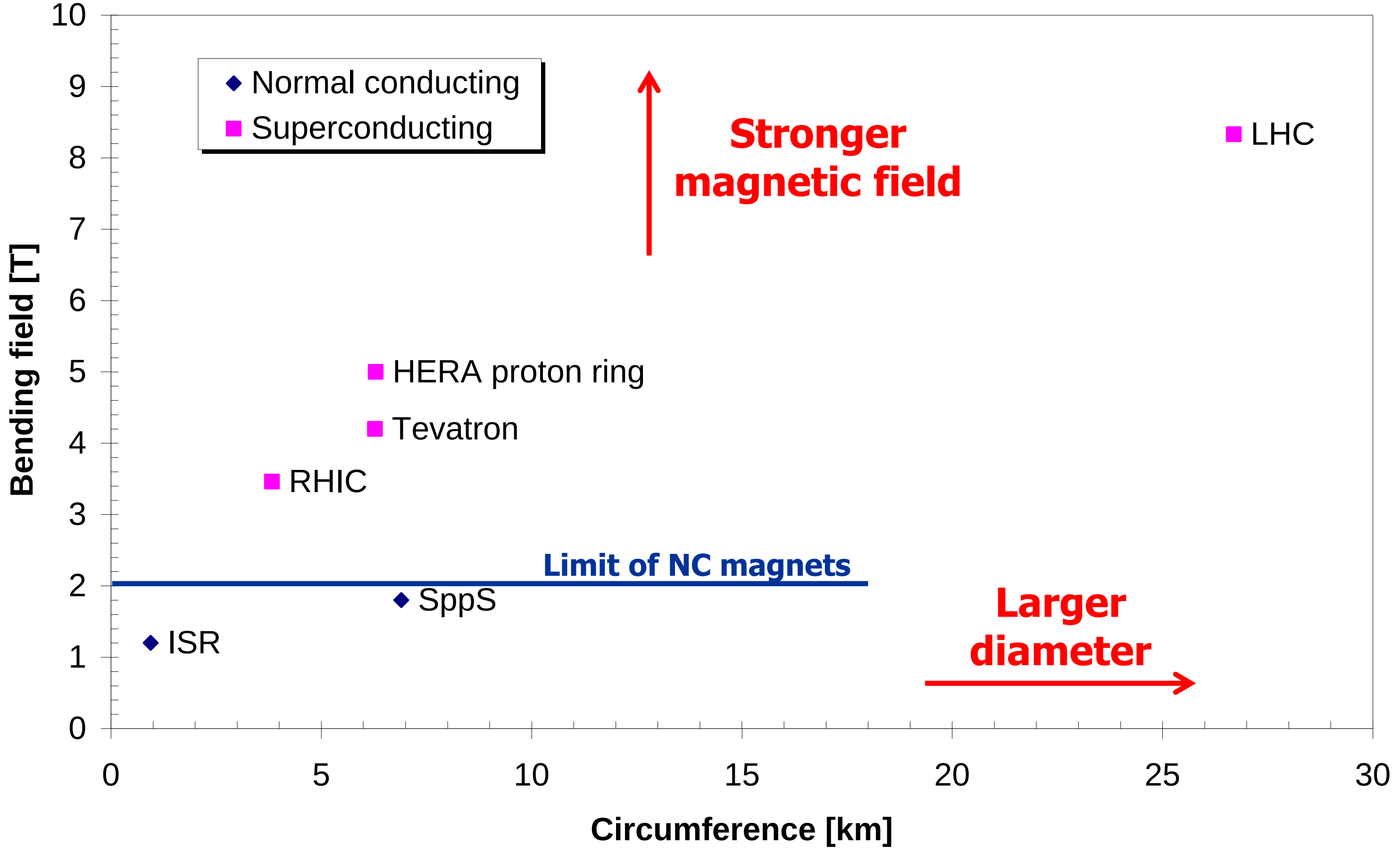
[GeV/c] [T] [m]

-> superconducting bending and focussing magnets

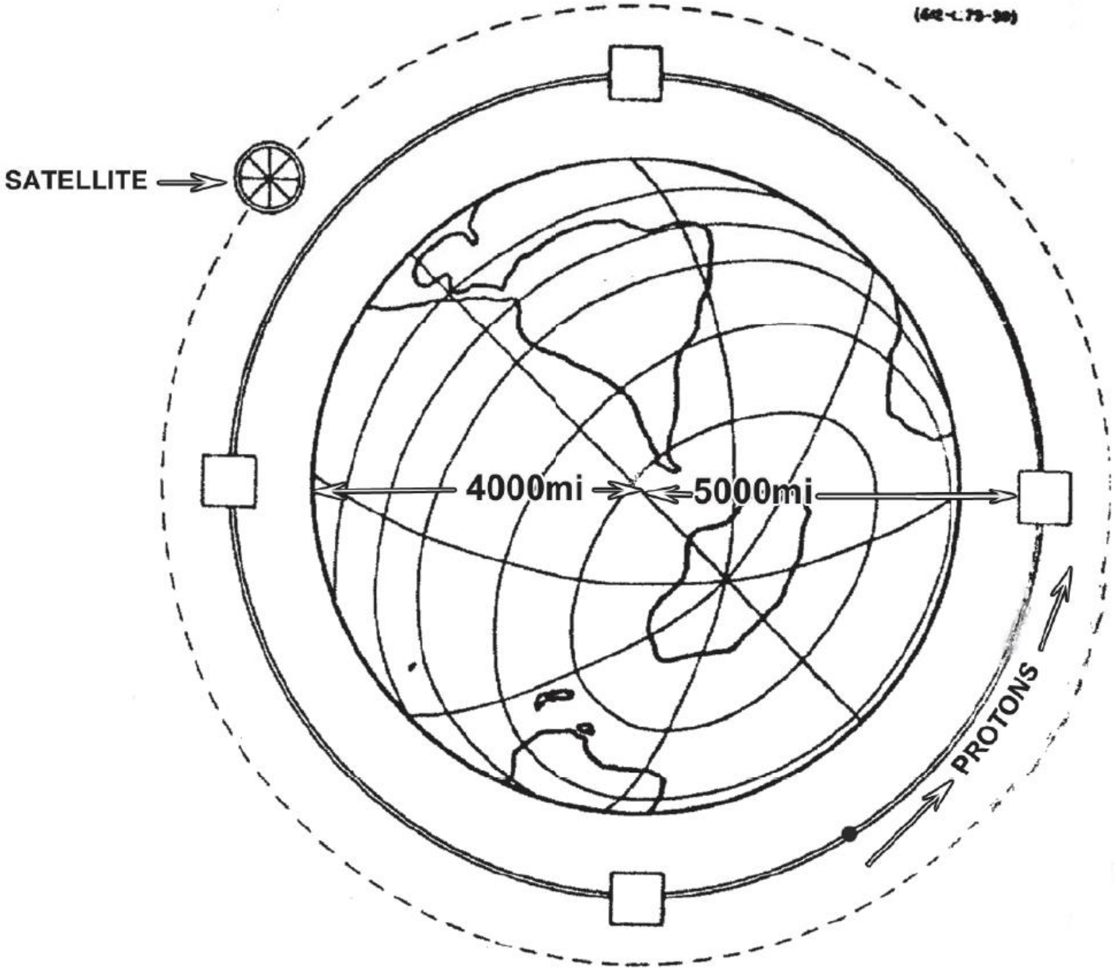
  - high-energy hadron synchrotrons
  - compact electron synchrotrons

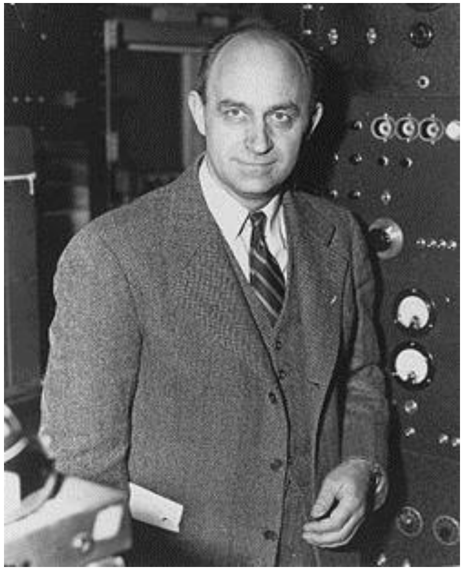
– LHC (r = 2.8 km), B = 8.33 T for p = 7 TeV/c

Evolution of hadron colliders



Fermi's 1954 concept for the « Ultimate Accelerator » was not superconducting!

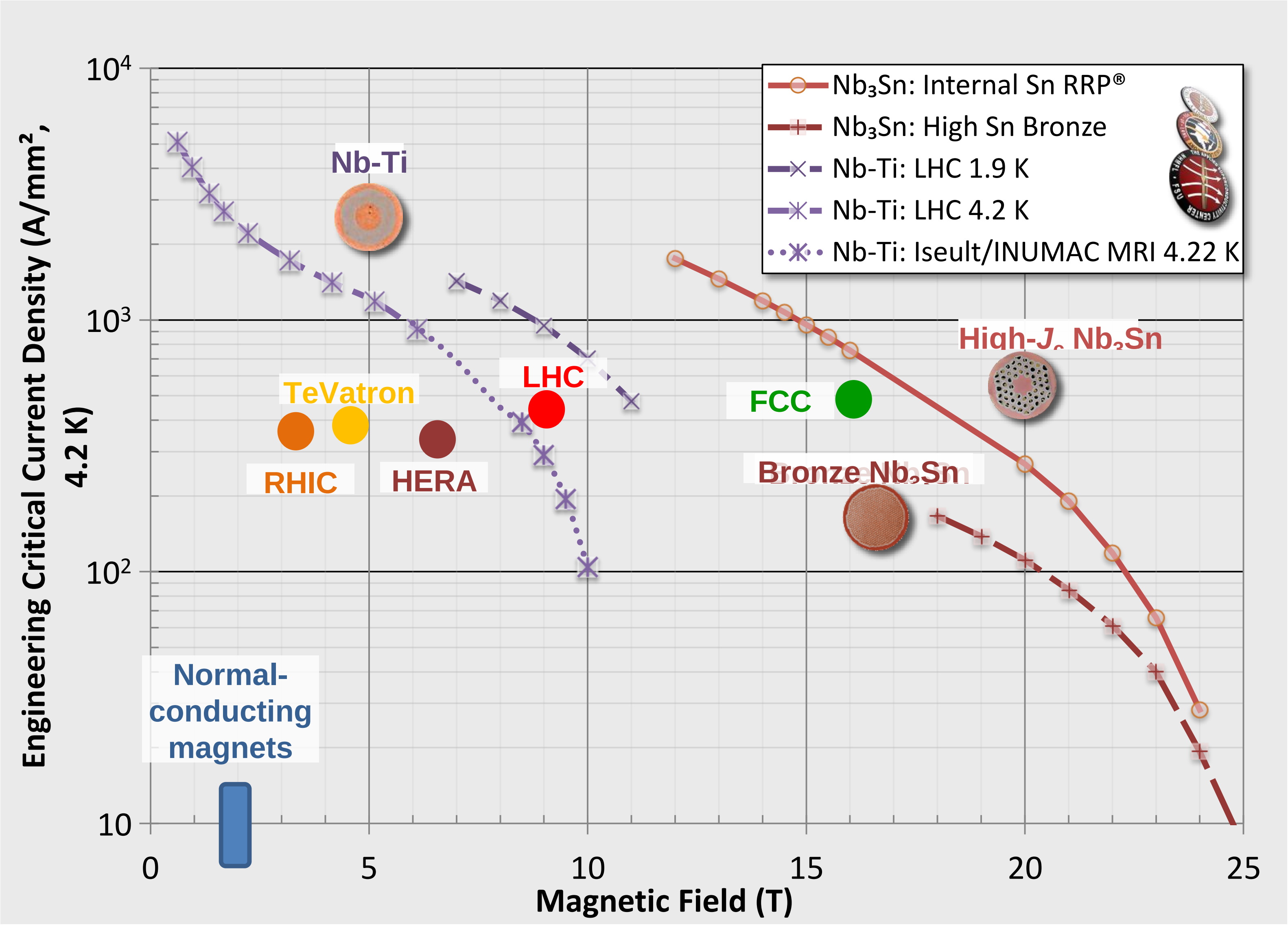




E_{beam} = 5000 TeV
B = 2 T
R = 8000 km ~ 5000 miles

E. Fermi, APS Lecture, Columbia University, 29 January 1954

Superconductivity in accelerators for higher magnetic fields



Compactness through higher fields

- Circular Accelerators

$$p \simeq 0.3 \quad B \quad r$$

[GeV/c] [T] [m]

-> superconducting bending and focussing magnets

  - high-energy hadron synchrotrons
  - compact electron synchrotrons

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- Linear Accelerators

$$p = f \quad E \quad L$$

[MeV/c] [MV/m] [m]

-> superconducting acceleration cavities

  - high-energy linacs

– E-XFEL (L = 1.6 km), E = 23.5 MV/m for p = 17.5 GeV/c

Such accelerating gradients are within reach of normal-conducting RF

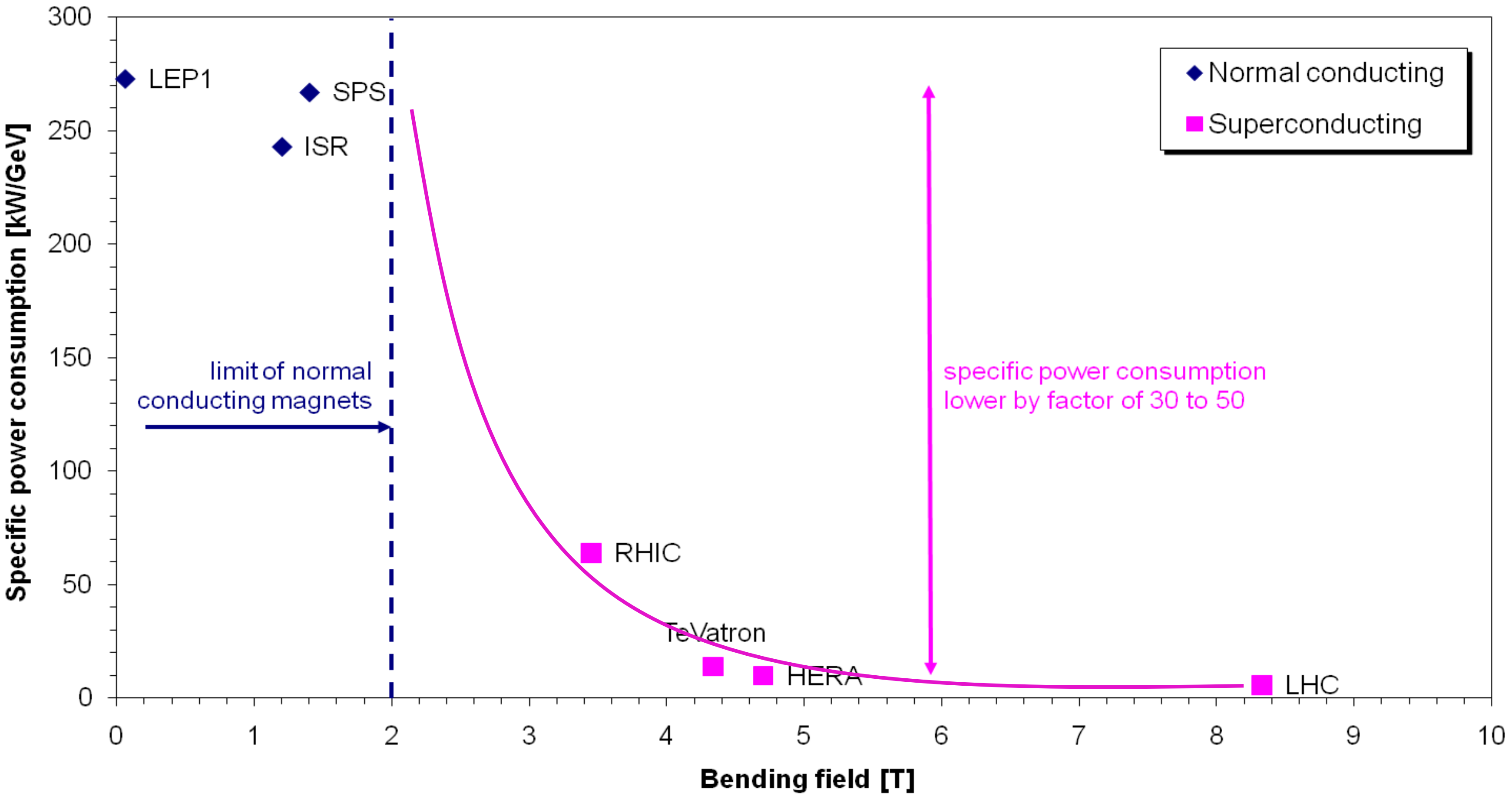
Magnet power consumption

- Normal conducting (copper)
  - Power dissipation per unit length $P/L \sim \rho_{Cu}\, jB$
  - Total power dissipation $P \sim \rho_{Cu}\, jBr \sim \rho_{Cu}\, jp$
- Superconducting
  - Total power (refrigeration) $P \sim C \sim r$

-> independent of magnetic field

	Normal conducting	**Superconducting (LHC)**
Magnetic field	1.8 T (limited by iron saturation)	8.3 T (limited by critical surface of Nb-Ti)
Field geometry	Defined by pole pieces	Defined by windings
Current density in windings	10 A/mm^2	400 A/mm^2
Electromagnetic forcess	20 kN/m	3400 kN/m
Electrical power from grid	10 kW/m	2 kW/m

Superconductivity in circular accelerators for lower power consumption



RF cavity power consumption

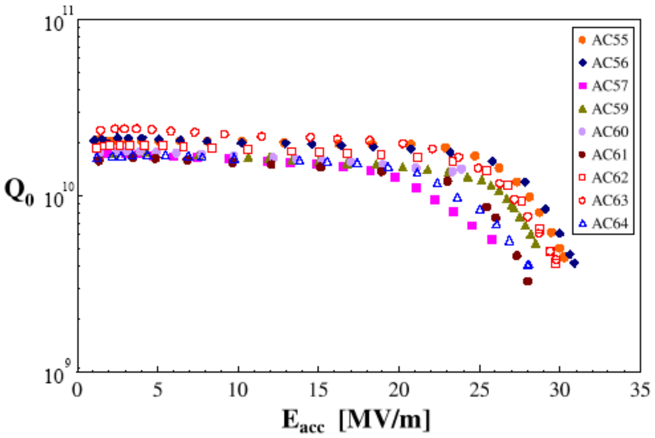
- Power dissipation in RF cavity
  - Power per unit length $P/L \sim R_s\, E^2/\omega$
  - *Q* factor of resonator $Q \sim 1/R_s$

-> to reduce power dissipation, need high Q at high field

-> superconductivity allows very high Q values

-> the power is however dissipated at low temperature: the electrical consumption must take into account the efficiency of cryogenic refrigeration

SC cavities Nb at 1.5 GHz



Example of Q values for cavities at 500 MHz

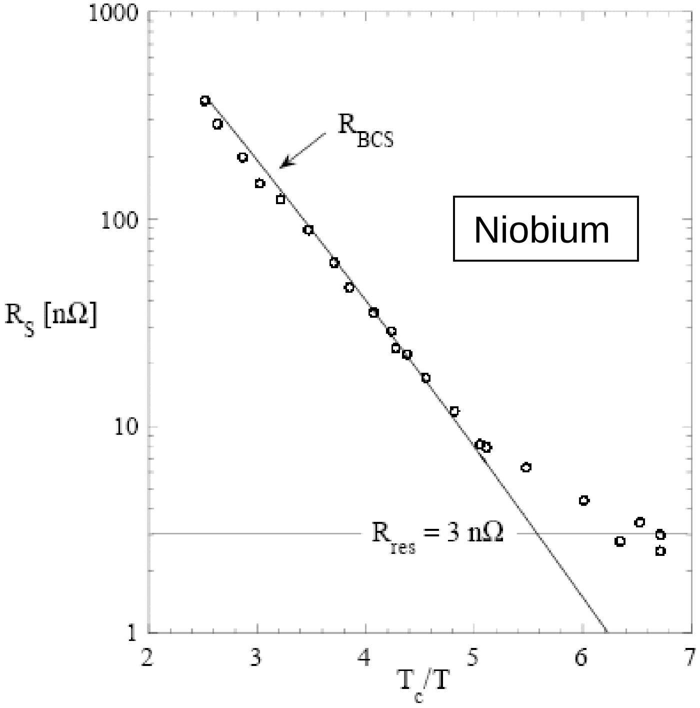
Cavity	**Normal conducting (Copper)**	**Superconducting**
Q	$4.\ 10^4$	$4.\ 10^9$
P at 4.2 K [W/m]	-	0.7
P at 290 K [W/m]	35’000	350

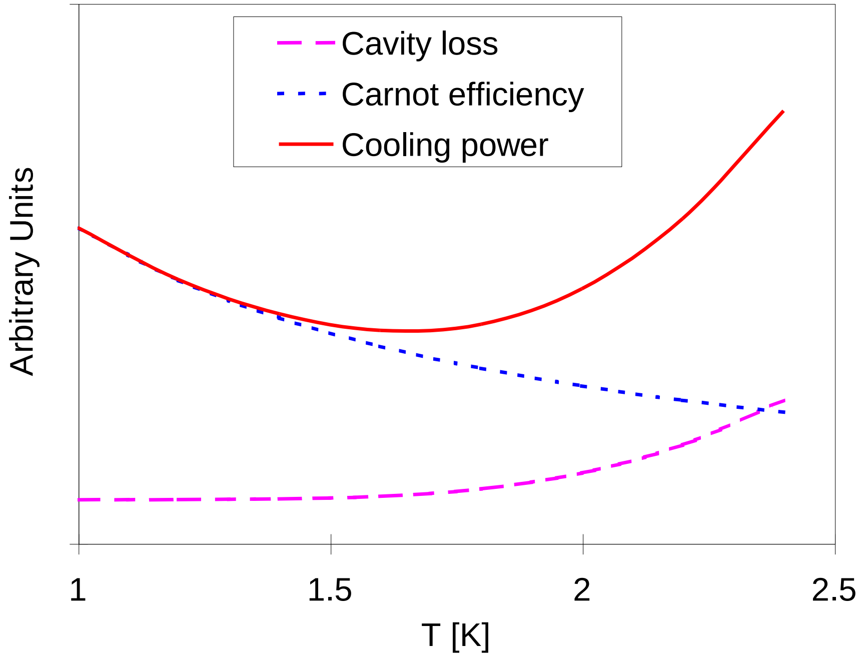
SC RF limits power dissipation in high-gradient, high duty factor (and c.w.) accelerators

Optimum operation temperature

- Surface resistance of superconductor
  - BCS theory $R_{BCS} = (A\omega^2/T)\exp(-BT_c/T)$
  - For practical materials $R_S = R_{BCS} + R_0$
  - Refrigeration (Carnot) $P_a = P(T_a/T - 1)$

-> optimum operating temperature, depending upon ω and R_0





Limiting energy stored in beam

- Energy W stored in beam of circular accelerator of circumference C

$$W \approx 3.34 \ p \ \ I_{beam} \ \ C$$

[kJ] [GeV/c] [A] [km]

⇒ *For a given beam intensity, beam stored energy is lower for a smaller machine*

Example: LHC

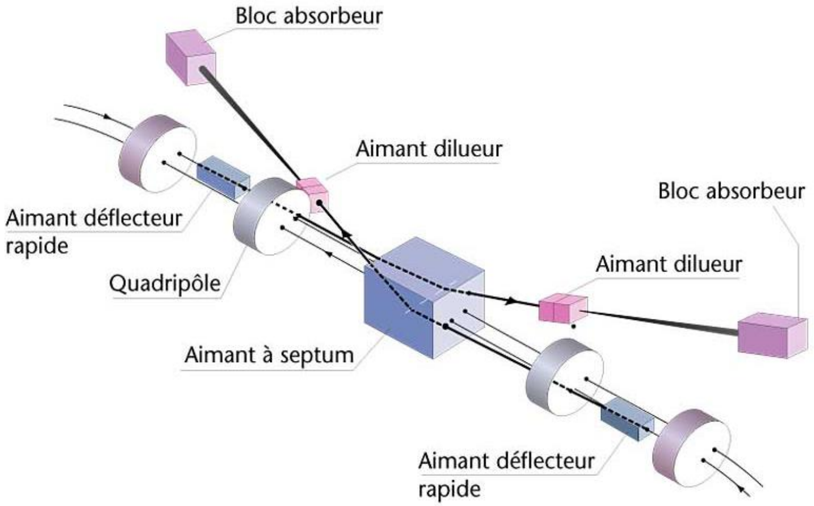
$p = 7000 \, \mathrm{GeV/c}$

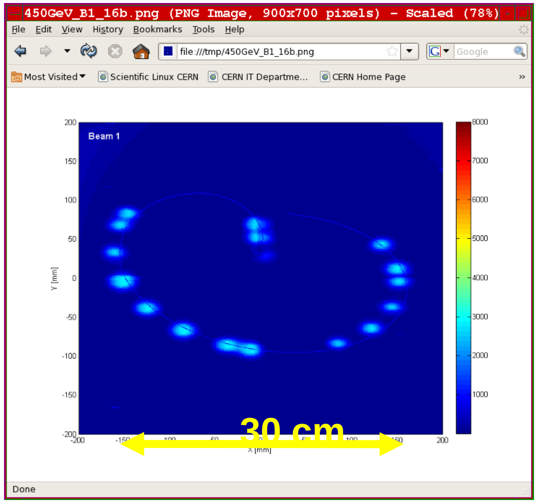
$I_{beam} = 0.56 \, \mathrm{A}$

$C = 26.7 \, \mathrm{km}$

$W \approx 350 \, \mathrm{MJ}$

⇒ *Enough to heat and melt ~500 kg of copper*





Low wall impedance for beam stability

- Interaction between the beam and the wall of the beam pipe can be characterized by a transverse impedance

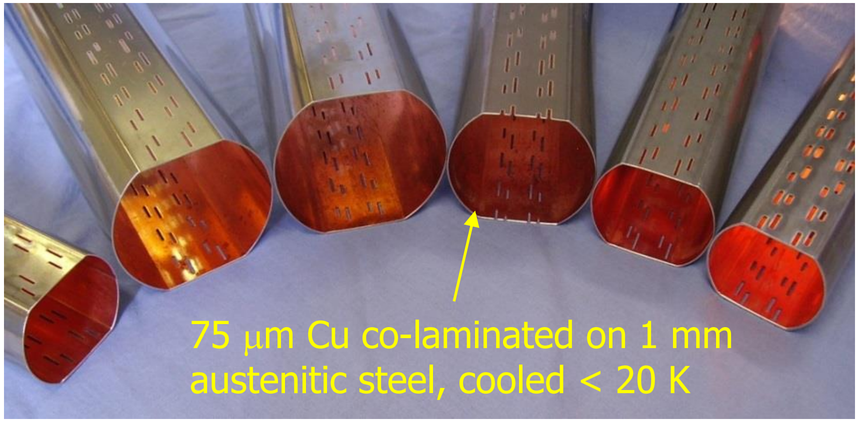
$$Z_T(\omega) \sim \rho\, C/\omega\, b^3$$

ρ electrical resistivity of wall

b half-aperture of beam pipe

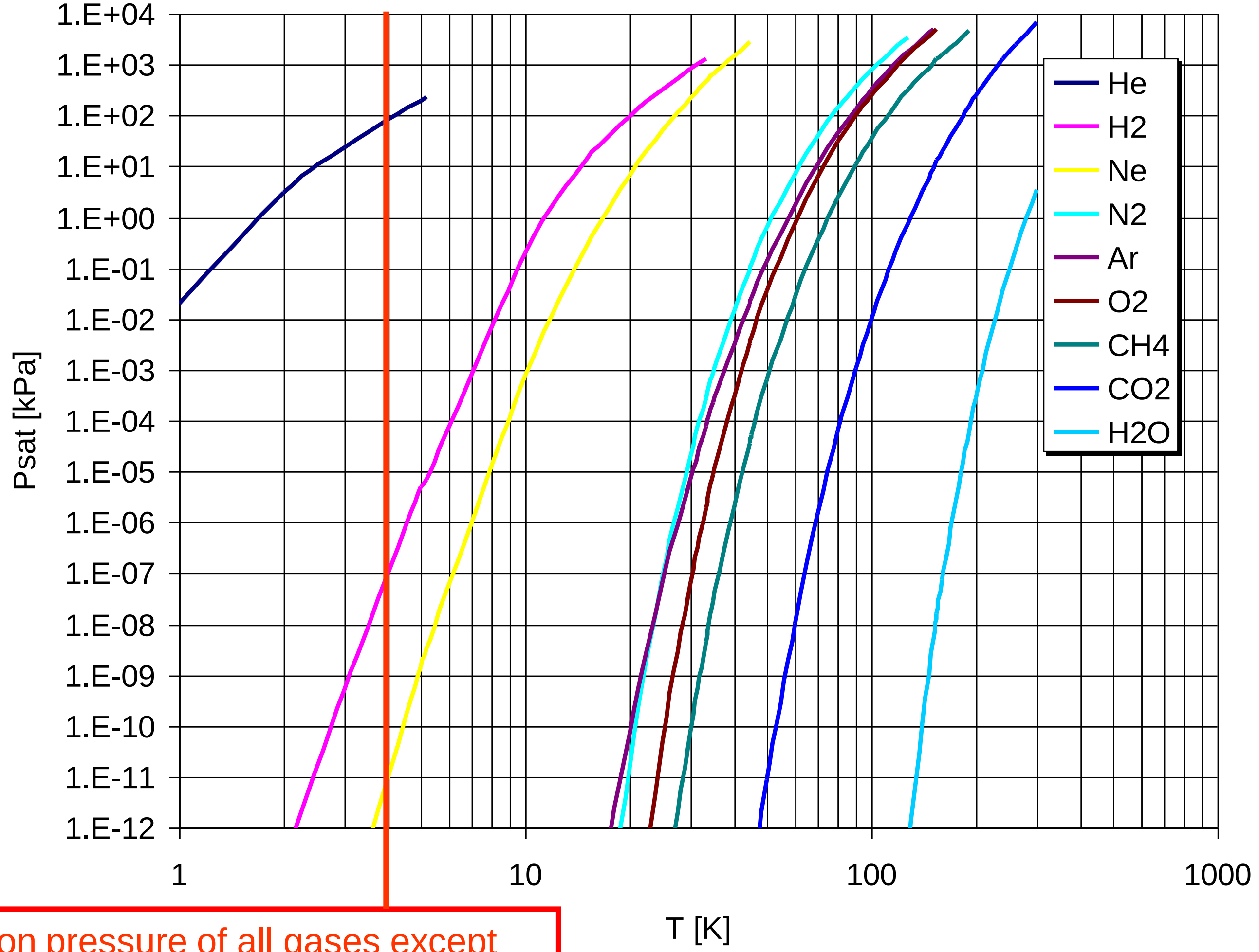
- This interaction leads to power dissipation and to beam instabilities
  - Important in large accelerators
  - Must be compensated by feedback provided that characteristic time for development of the instability be long enough $\tau \sim 1/Z_T$
  - ⇒ In a large accelerator with small aperture, low transverse impedance is achieved by reducing ρ i.e. with a good electrical conductor (copper) at low temperature

LHC beam screens



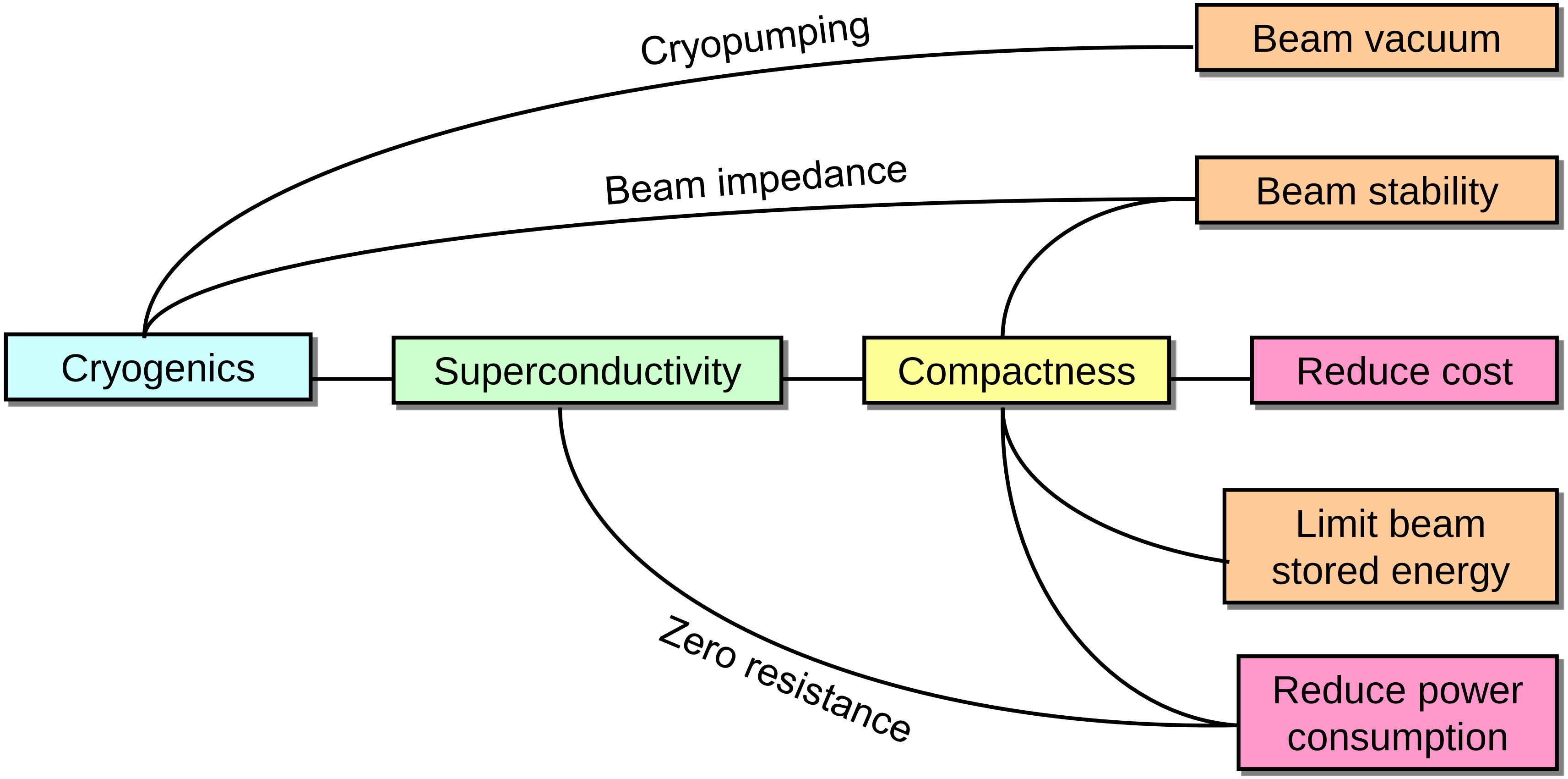
75 μm Cu co-laminated on 1 mm austenitic steel, cooled < 20 K

Cryopumping of beam vacuum



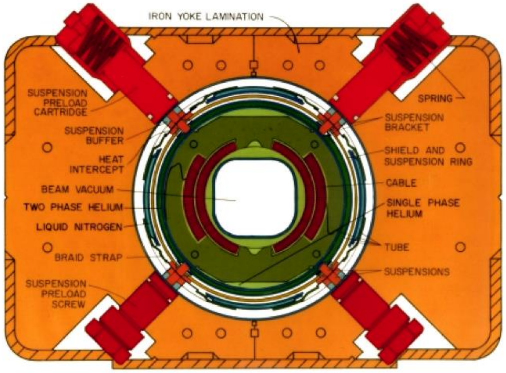
Saturation pressure of all gases except helium vanish at cryogenic temperature

Rationale for superconductivity & cryogenics in particle accelerators



How ? ← → **Why ?**

The Tevatron at Fermilab (Batavia, USA)
The first superconducting particle accelerator



Started operation in 1983 as synchrotron, upgraded as collider (1.8 TeV c.m.)

Circumference 6.3 km

Magnetic field 4.4 T

990 main superconducting magnets, cooled at 4.4 K by supercritical helium

The LHC at CERN
The largest scientific instrument in the world

Started operation 2008

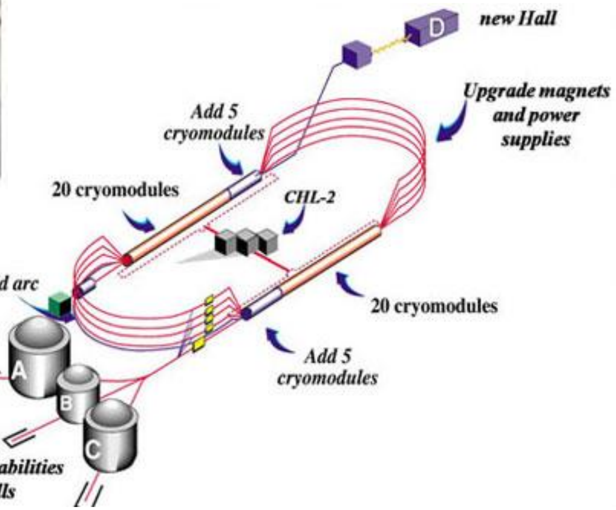
Circumference 26.7 km

Magnetic field 8.3 T

1706 main superconducting magnets, cooled at 1.9 K by superfluid helium

CEBAF at the Jefferson Lab (Newport News, USA)

The first large-scale superconducting RF accelerator



Started operation 1995, upgraded 2014

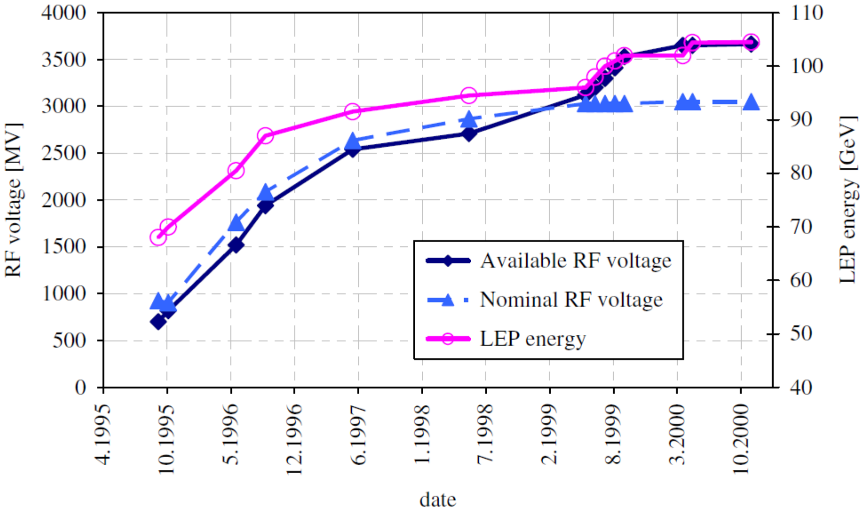
Two recirculating c.w. linacs producing 12 GeV electron beams

1.5 GHz Nb cavities

50 cryomodules cooled at 2 K in superfluid helium

LEP2 at CERN
288 Nb-on-Cu SC cavities at 352 MHz

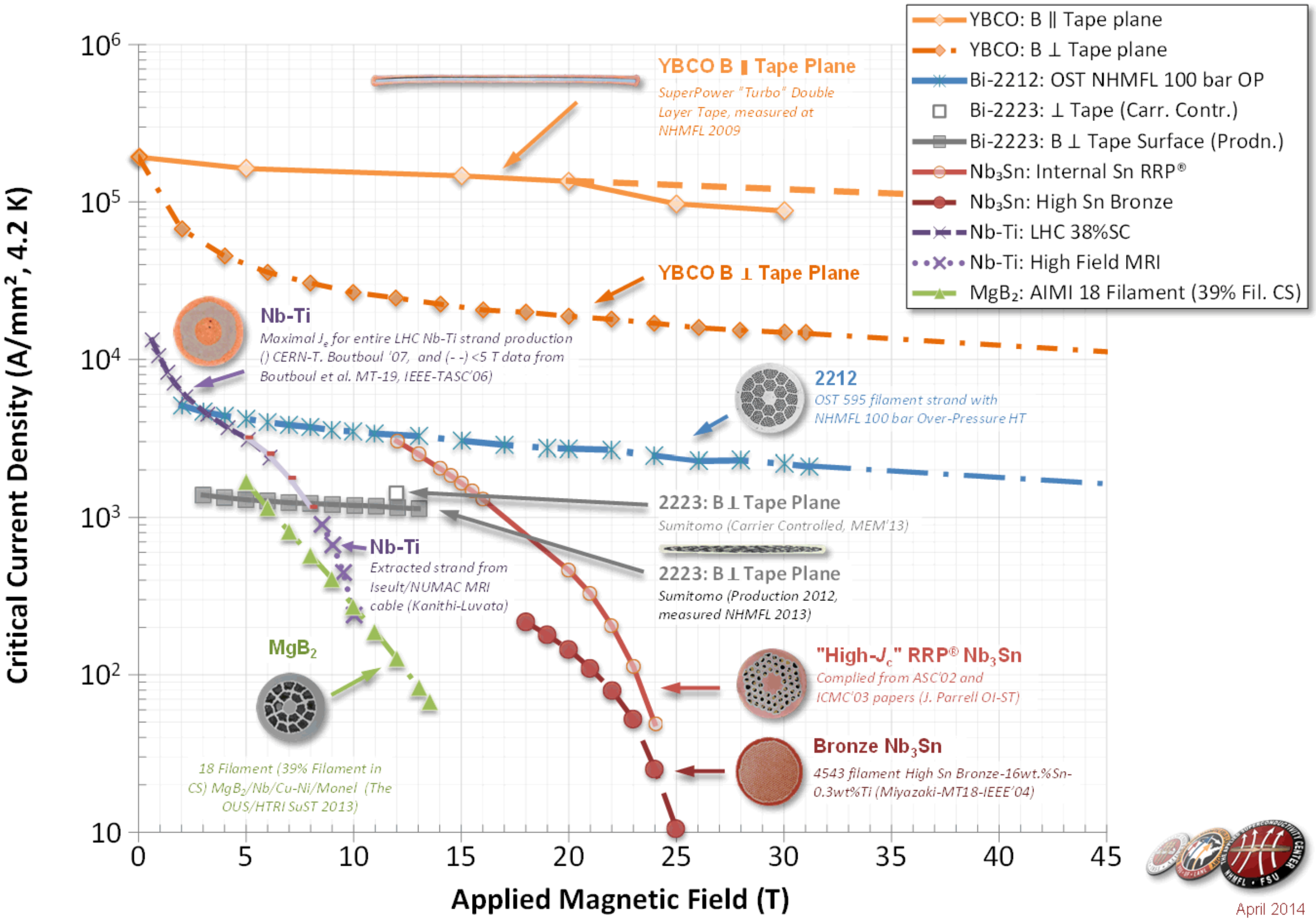
RF frequency	352.209 MHz
No. of cells/cavity	4
No. of cavities/module	4
No. of modules installed	72
Module length	11.28 m
Liquid helium/module	800 l
R/Q (circuit Ohm)	232 Ω
Active length (four cells)	1.70 m
Nominal gradient	6 MV/m
Q_o at 6 MV/m (4.5 K)	3.2×10^9
Q_{ext} Main coupler (nominal)	2.2×10^6
Dynamic cryogenic losses at 6 MV/m per cavity	<70 W
Static cryogenic losses per complete module	<90 W



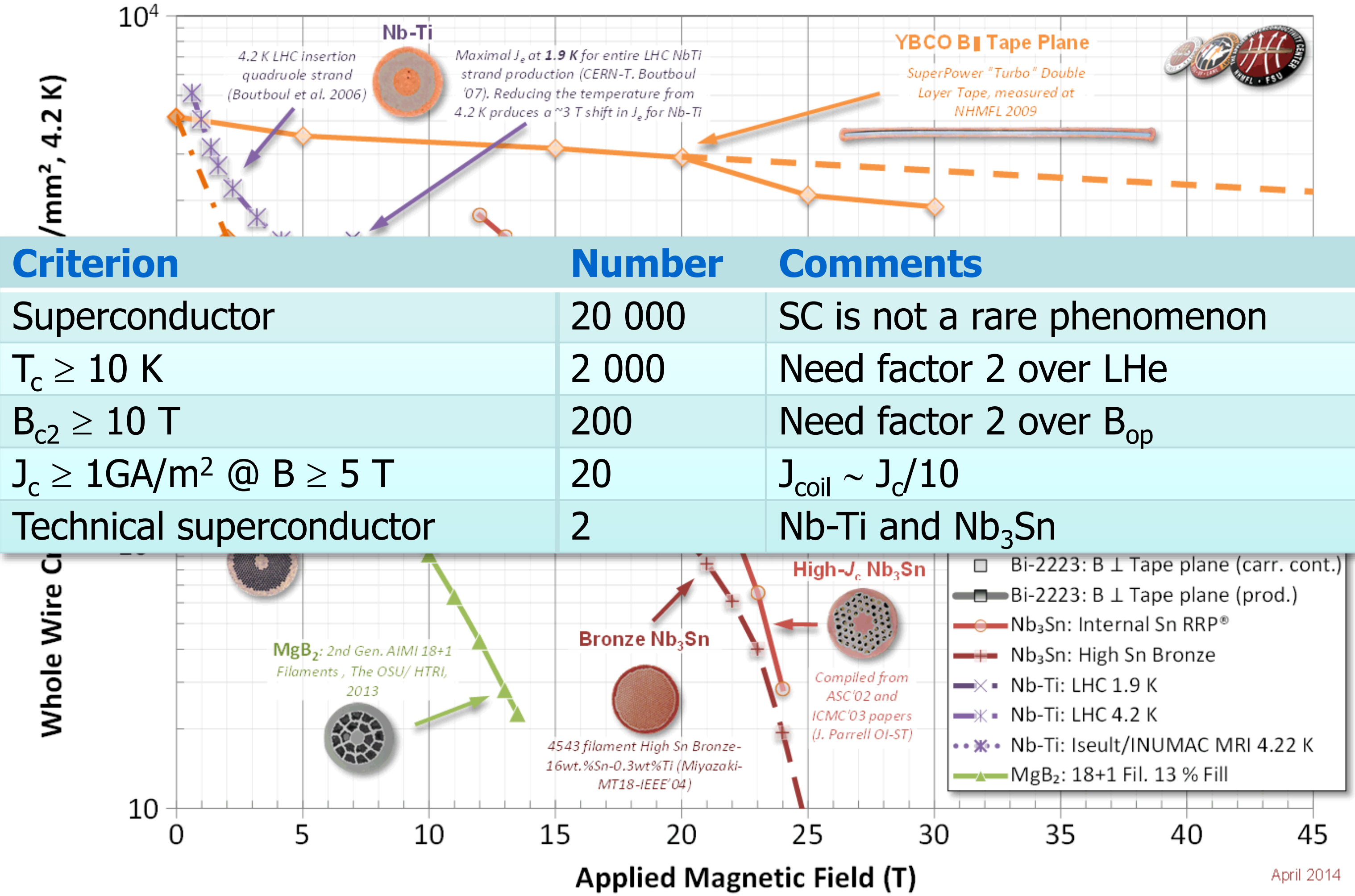
Contents

- Superconductivity in a nutshell
- Superconductivity and accelerators
- **Superconducting magnets for accelerators**
- Superconducting RF cavities for accelerators
- Superconducting current leads and powering links
- Some ongoing and future projects
- Selected bibliography

Critical current density vs applied field of technical superconductors



Engineering current density vs applied field of technical superconductors



Criterion	**Number**	**Comments**
Superconductor	20 000	SC is not a rare phenomenon
$T_c \geq 10$ K	2 000	Need factor 2 over LHe
$B_{c2} \geq 10$ T	200	Need factor 2 over B_{op}
$J_c \geq 1 GA/m^2$ @ $B \geq 5$ T	20	$J_{coil} \sim J_c/10$
Technical superconductor	2	Nb-Ti and Nb_3Sn

Practical superconductors

Type	Status	Comments
Nb-Zr	Dismissed	First SC magnet
Nb-Hf	Dismissed	Used in Homer (KIT)
V_3Ga	Dismissed	Small coil test
Nb-Ti	Mature	> 2000 tonnes/year
Nb_3Sn	Industry development	100 tonnes/year (50% ITER) Margin of improvement
Bi-2223	Industry R&D	500 kg/y? (1-2 manufacturers)
Bi-2212	Industry and Lab R&D	100 kg/y? (only one manufacturer)
YBCO /REBCO	Industry and Lab R&D	1 tonne/y? (> 5 manufacturers)
MgB2	Industry and Lab R&D	> 1 tonne/y (4-5 manufacturers)

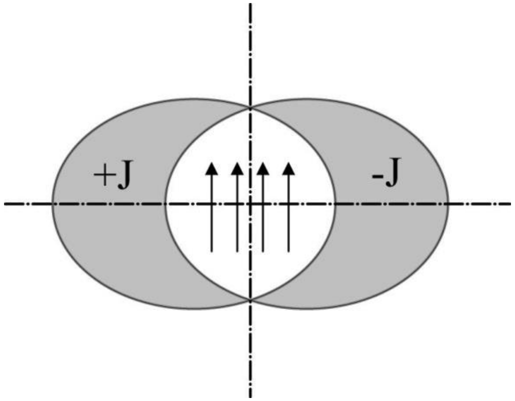
L. Rossi

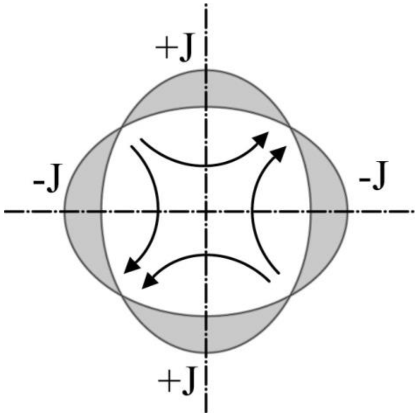
Producing the field: current distributions

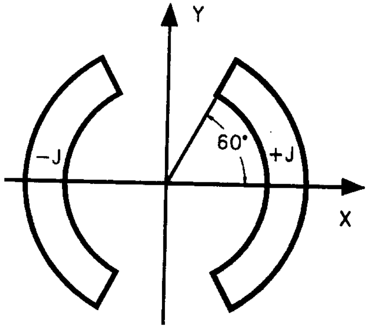
In a superconducting magnet, the field level and geometry is basically given by the current distribution in the coils

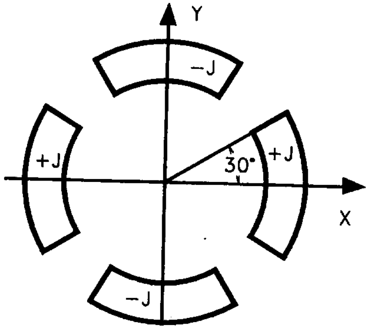
Two intersecting ellipses with uniform current density generate uniform dipole and quadrupole fields ⇒ "**cos θ**" geometry

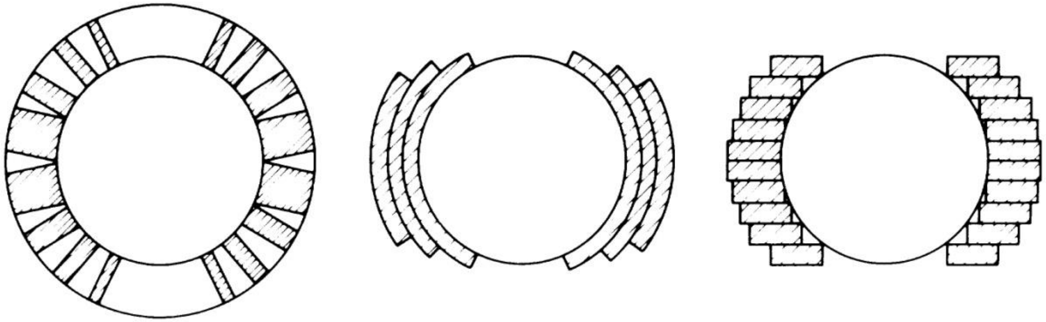
In practice, this can be approximated by current sheets, leading to "**block**" or "**layer**" coil designs





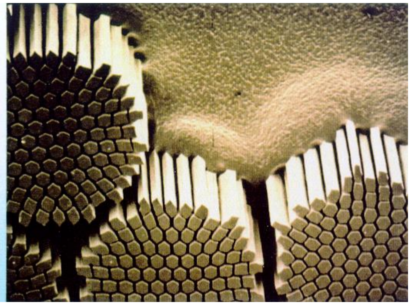






“Rutherford” superconducting cable

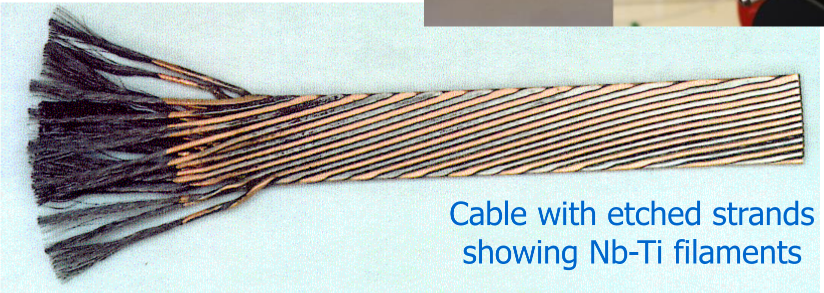
- Invented at the Rutherford Laboratory (UK) in the 1970s
- Challenge: produce a high-current (>kA) conductor for superconducting magnets
- Constraints
  - Small-diameter filaments for thermal stability and low remanent magnetization
  - Transposed wires for electromagnetic decoupling and low AC losses
  - Flat, keystoned, high-precision geometry for winding cos θ coils
  - Dielectrically rigid, mechanically resistant insulation with helium porosity



7 μm Nb-Ti filaments in Cu matrix

Cable insulation by double polyimide wrap

Keystoned cable made of ~1mm strands



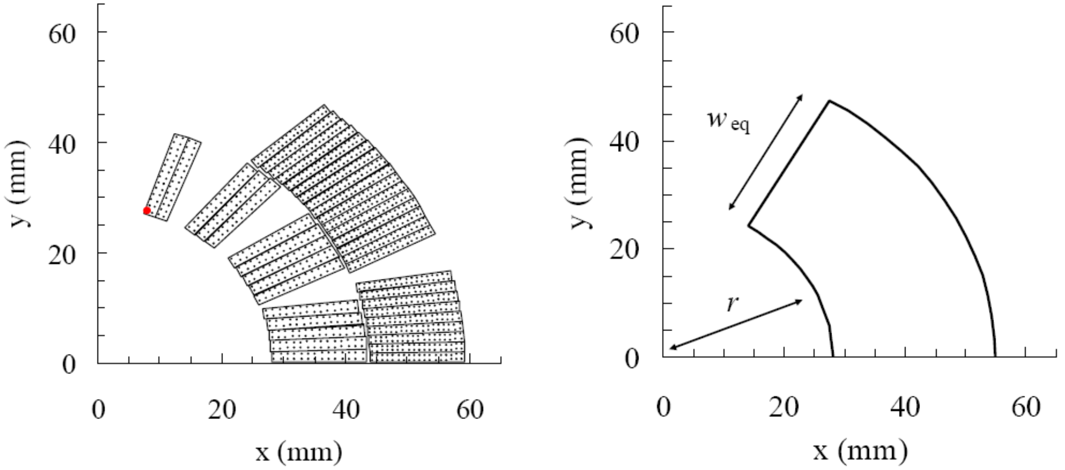
Cable with etched strands showing Nb-Ti filaments

Field of single-layer dipole coil

Average current density in coil

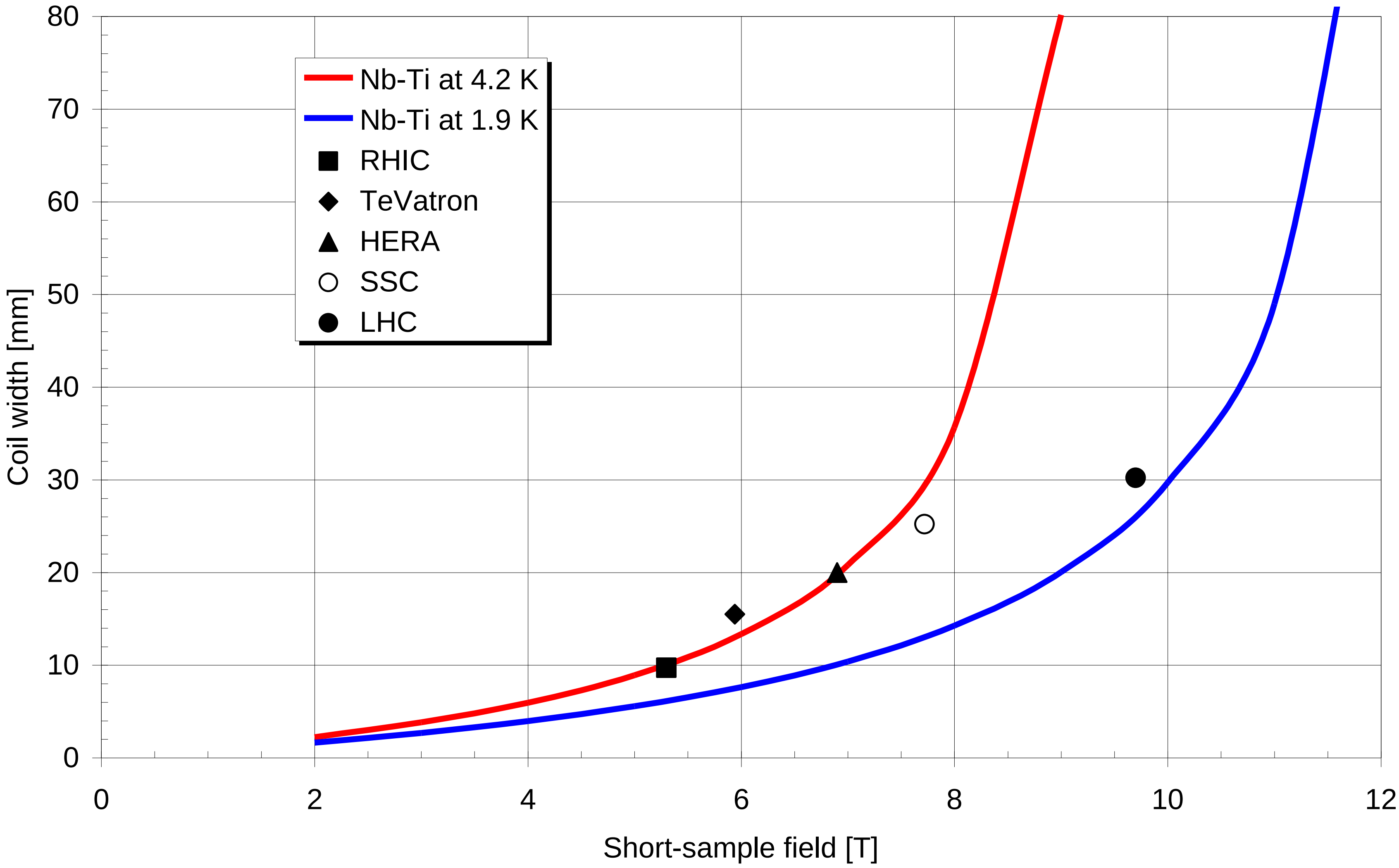
$$B = \frac{\mu_0 \sqrt{3}}{\pi} \; j_{tech} \; w$$

Coil width

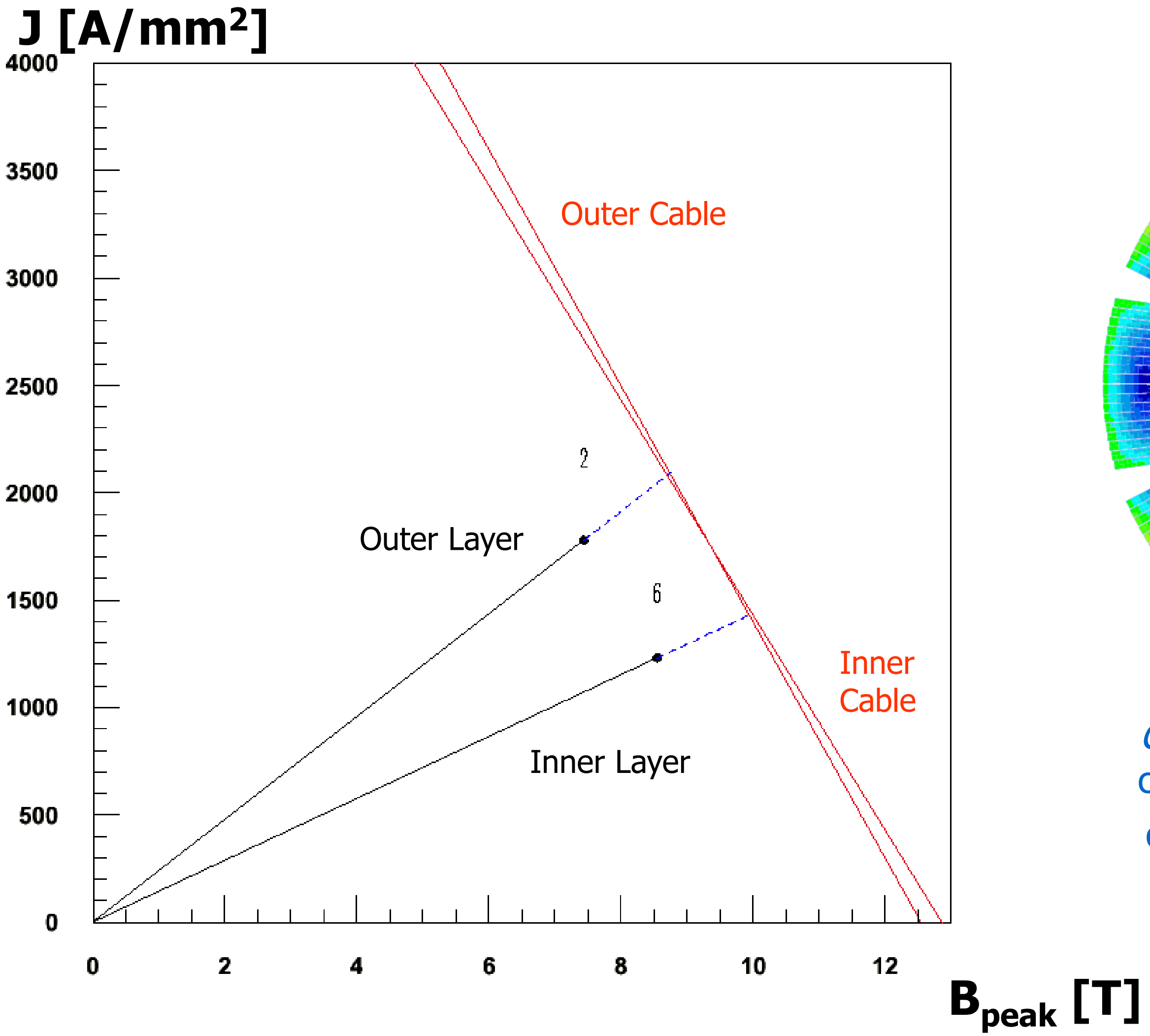


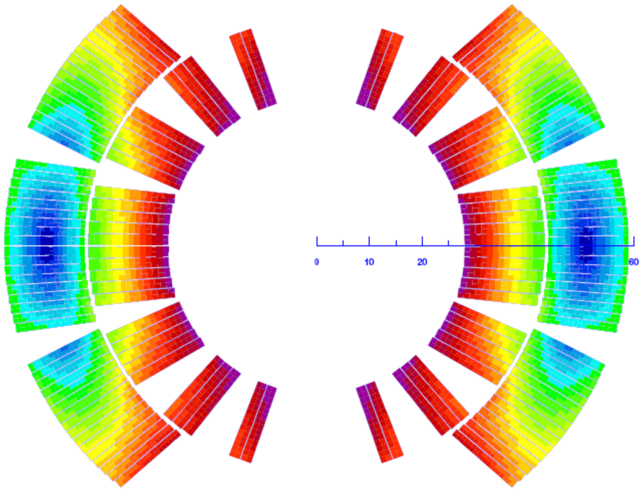
Superconducting cos θ dipoles in Nb-Ti

Coil width vs field



Load lines of LHC main dipole

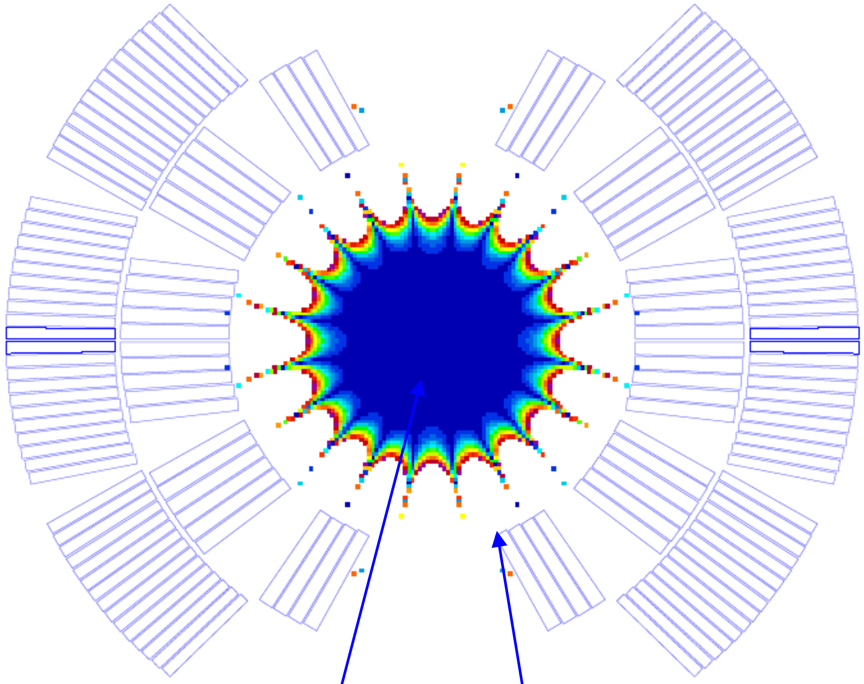




Current grading permits the outer cable, which sees a lower field, to operate at higher current density

Inter-layer splice in graded coil

Field quality in superconducting magnets
Conductor placement



« Good field » region
$\Delta B/B < 10^{-4}$

Magnet
« aperture »

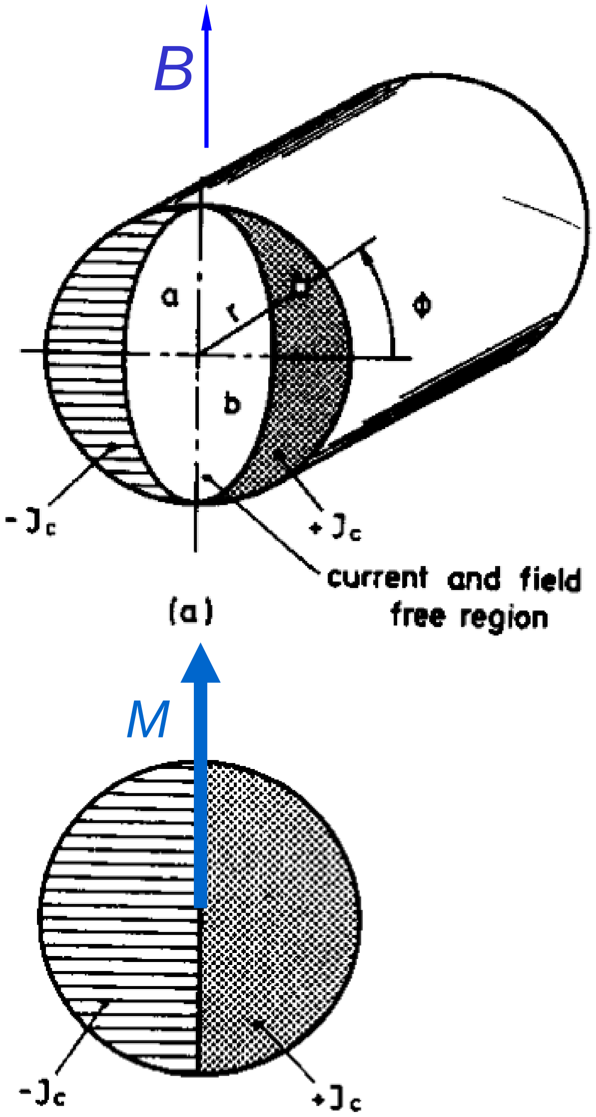
- In superconducting magnets, the field quality is determined by the positioning precision of a finite number of conductors and not by the geometry of the iron yoke, so it can never be as good as in conventional "iron-dominated" magnets
- As a consequence, the « good field » region is substantially smaller than the magnet aperture
- Dynamic aperture = aperture inside which particle orbits are stable
- Dynamic aperture is estimated by computer « tracking » of particle orbits around virtual machines with distributed random and systematic imperfections
- Tracking results are used to define maximum systematic and random deviations of each field multipole

$$B_y + iB_x = B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{r_{ref}} \right)^{n-1}$$

- The field is periodical over a rotation of 2π: it can therefore be represented as a Fourier series, with the field errors as higher harmonics ("multipoles")

Field quality in superconducting magnets

Persistent currents



- Eddy currents flow in part of the superconductor filaments to shield the inside from outer field variations
- Quasi-infinite time constant ⇒ «persistent» currents
- Produce remanent magnetization in superconductor filament

- In case of full penetration in round filament, remanent magnetization is

$$M = \pm \frac{2}{3\pi} \mu_0 \, J_c \, D \, \lambda$$

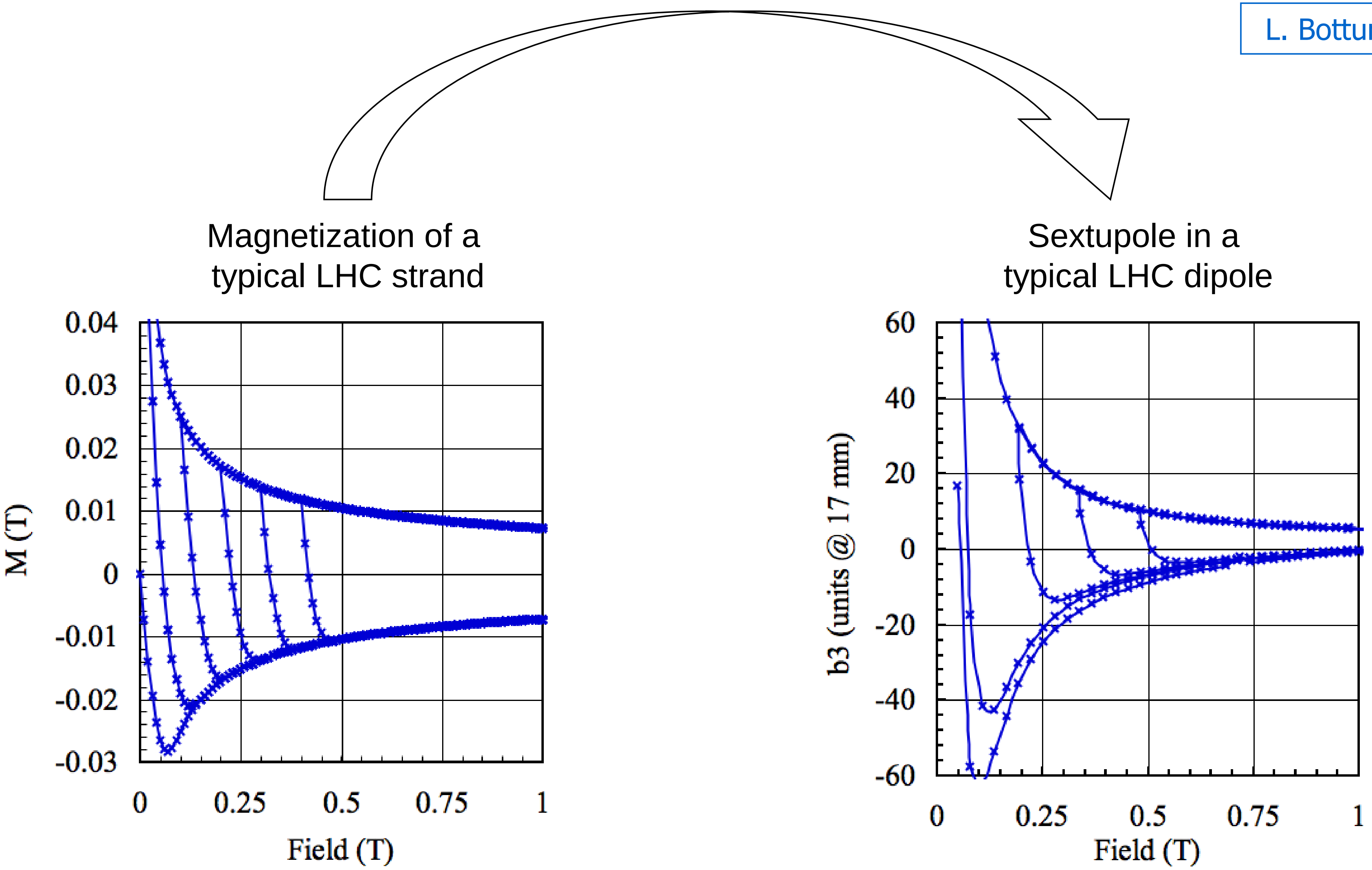
Ratio of SC to total cross-section

Filament diameter

Field quality in superconducting magnets

Persistent currents

L. Bottura

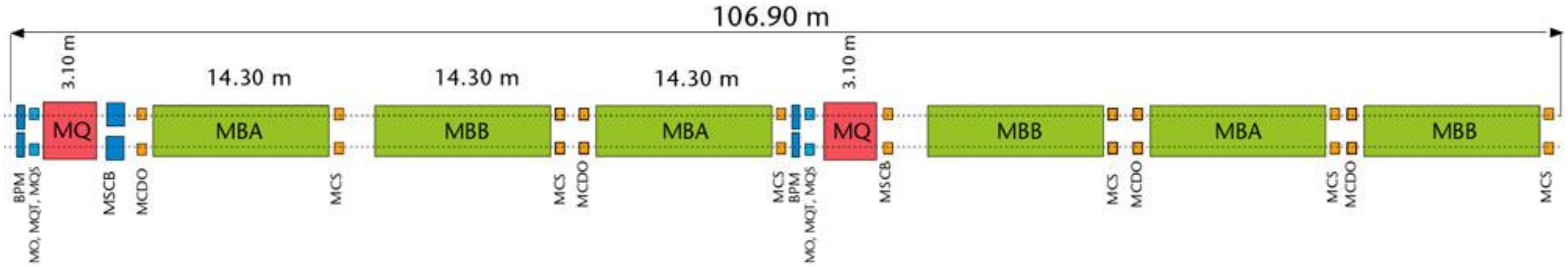


Magnetization of a typical LHC strand

Sextupole in a typical LHC dipole

Obtaining the field quality: corrector magnets

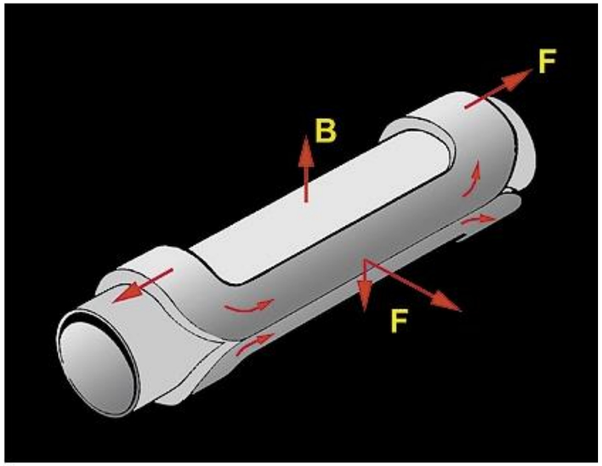
Schematic layout of one LHC cell (23 periods per arc)

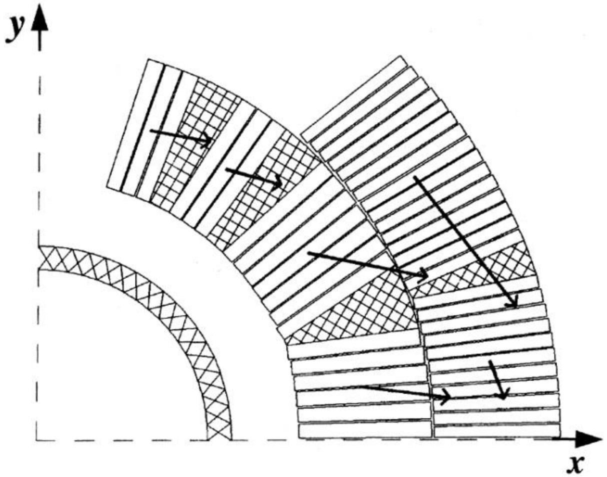


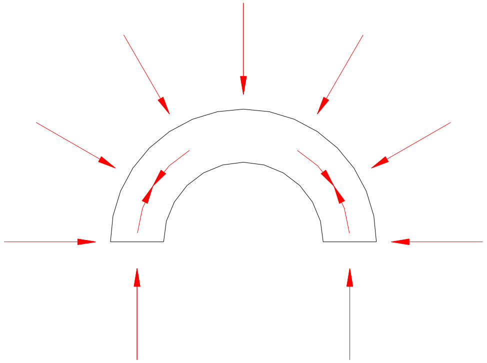
MQ: Lattice Quadrupole
MO: Landau Octupole
MQT: Tuning Quadrupole
MQS: Skew Quadrupole
MSCB: Combined Lattice Sextupole (MS) or skew sextupole (MSS) and Orbit Corrector (MCB)
BPM: Beam position monitor
MBA: Dipole magnet Type A
MBB: Dipole magnet Type B
MCS: Local Sextupole corrector
MCDO: Local combined decapole and octupole corrector

HF226 - v10/99

Containing the electromagnetic forces







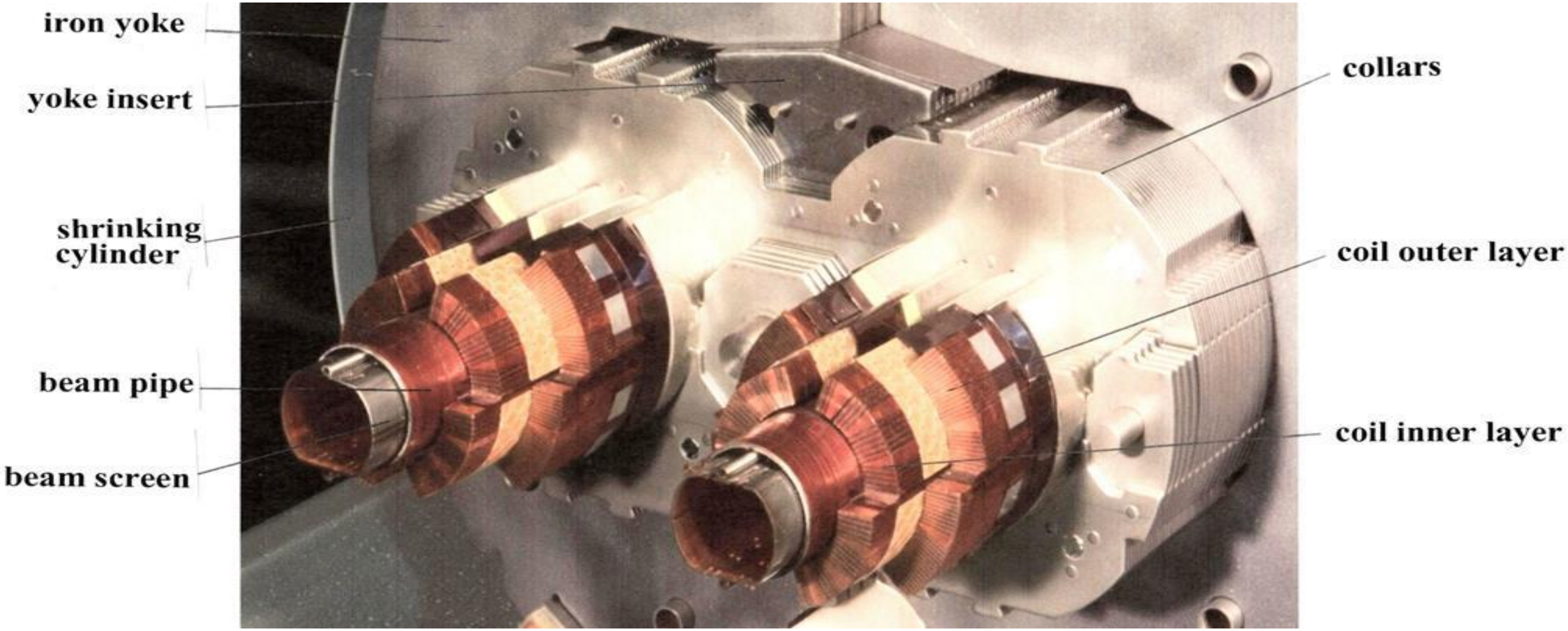
High magnetic field acting on high current generates large **electromagnetic forces** at right angle, which cannot be resisted by the mechanical strength of the conductor: saddle-shaped coils of accelerator magnets are not self-supporting

B = 10 T, I = 10 kA ⇒ 10^5 N/m per turn !

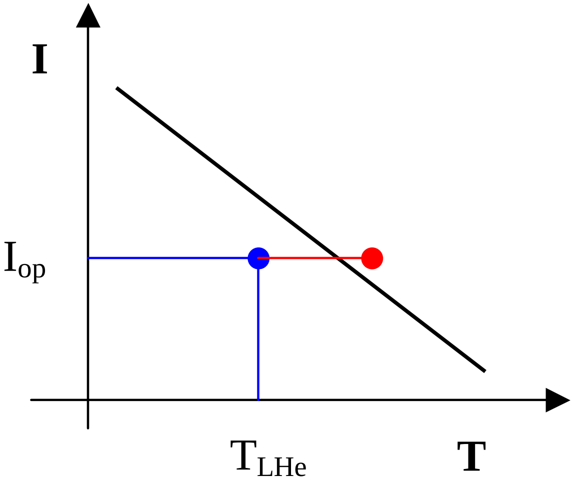
⇒ "**roman arch**" coil geometry to contain the azimuthal component

⇒ external **support structure** against the radial component

Mechanical structure of LHC dipole



Superconductors are basically unstable!



Heat capacity of materials drops at low temperatures

$\Delta T = \Delta E/\gamma C$

ΔE of few μJ on a superconducting strand in the cable generates ΔT pushing the operating point beyond the critical surface $\Rightarrow$ *resistive transition ("quench")*

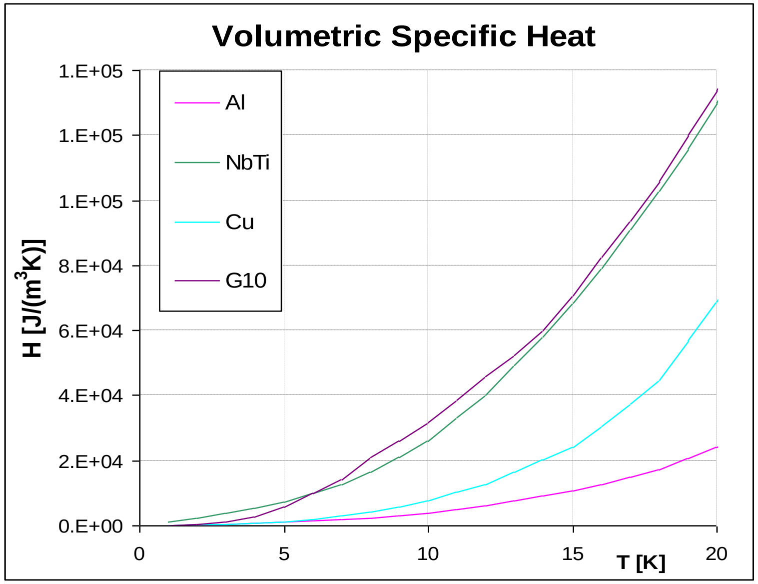
In the LHC main dipoles

Temperature margin of superconductor ~ 1.5 K

Specific quench energy ~ 10 mJ/cm^3

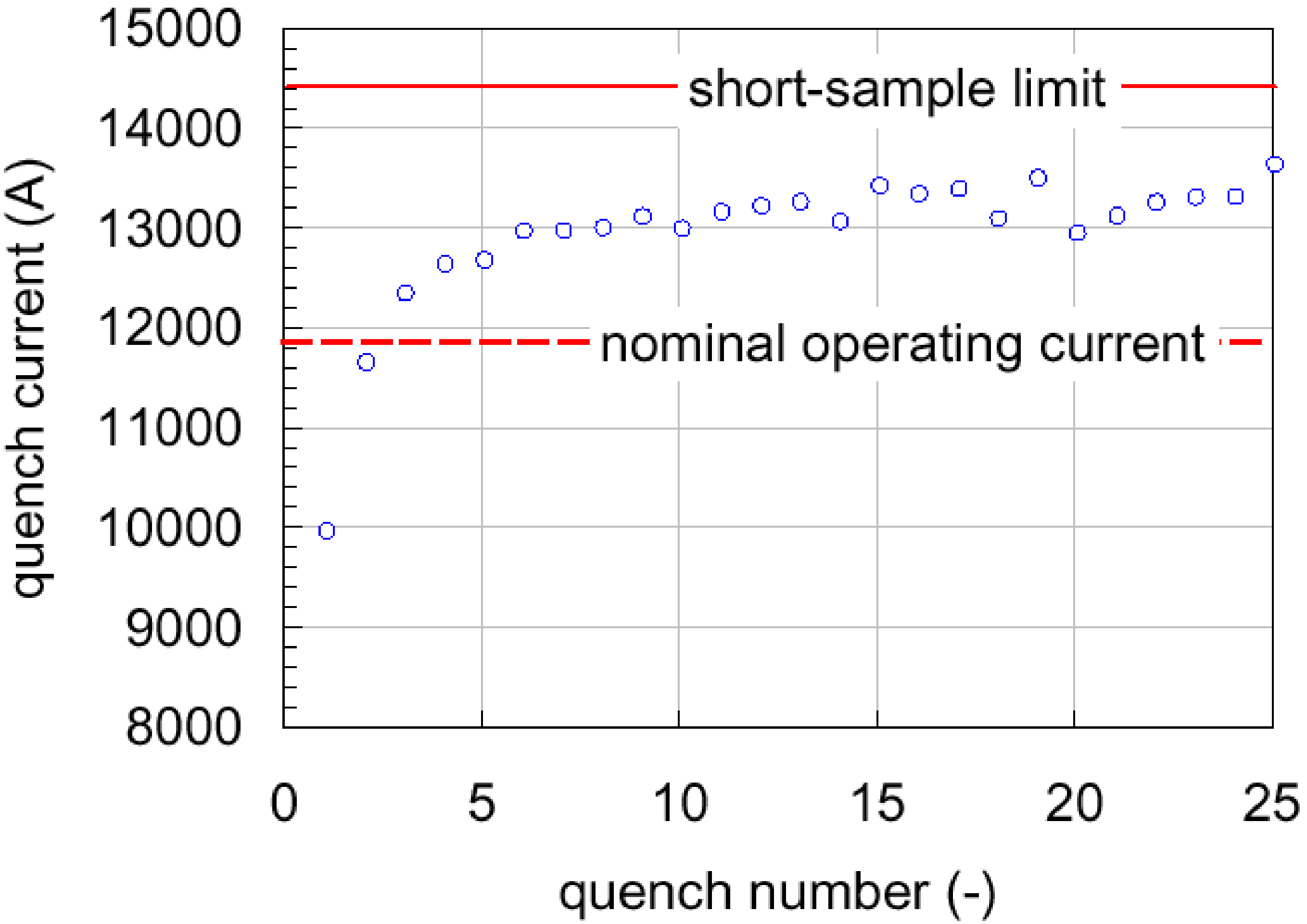
Energy stored inductively in magnet 6.9 MJ

Energy stored in beam 360 MJ



Training of superconducting magnets

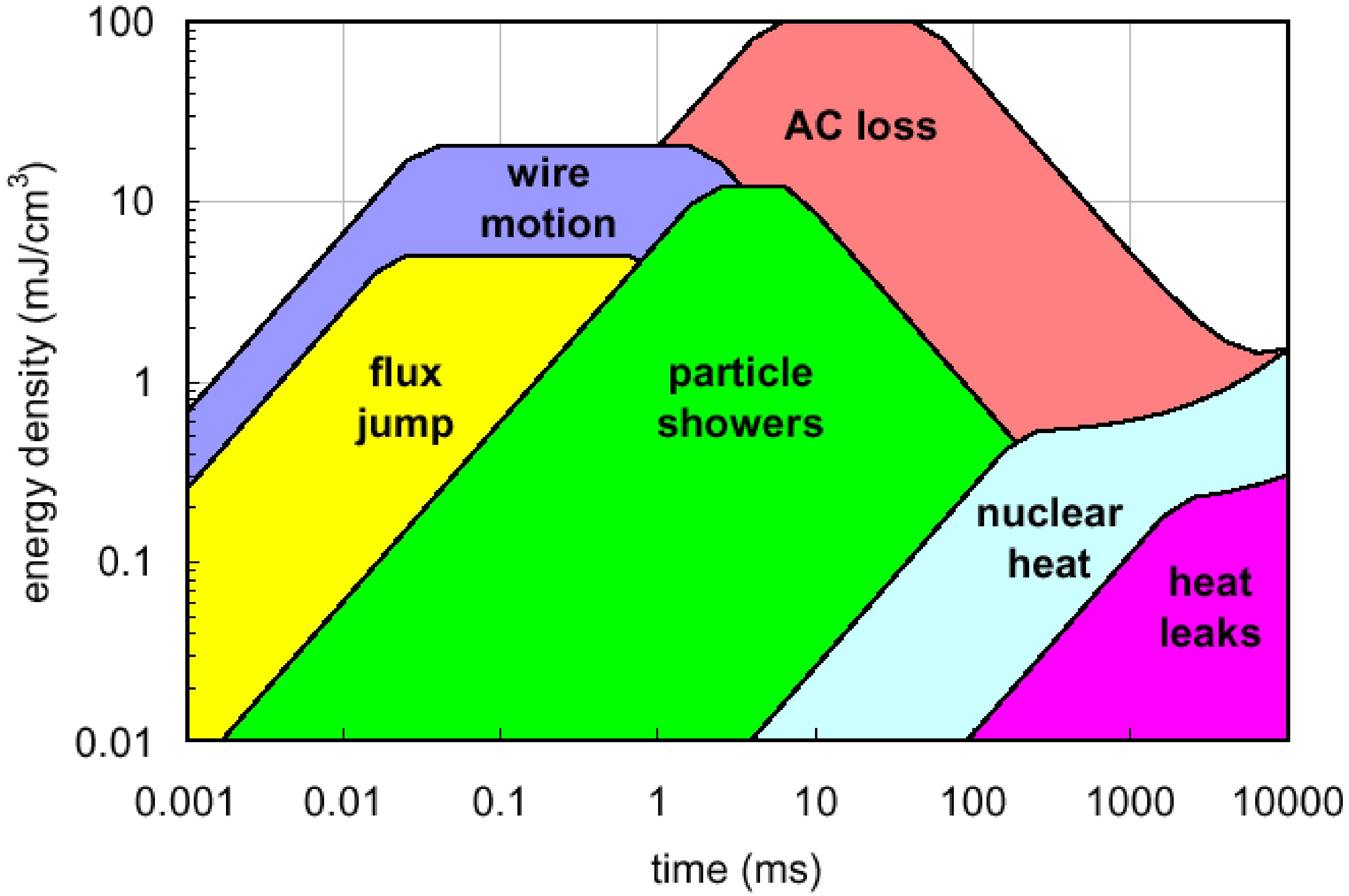
LHC dipole



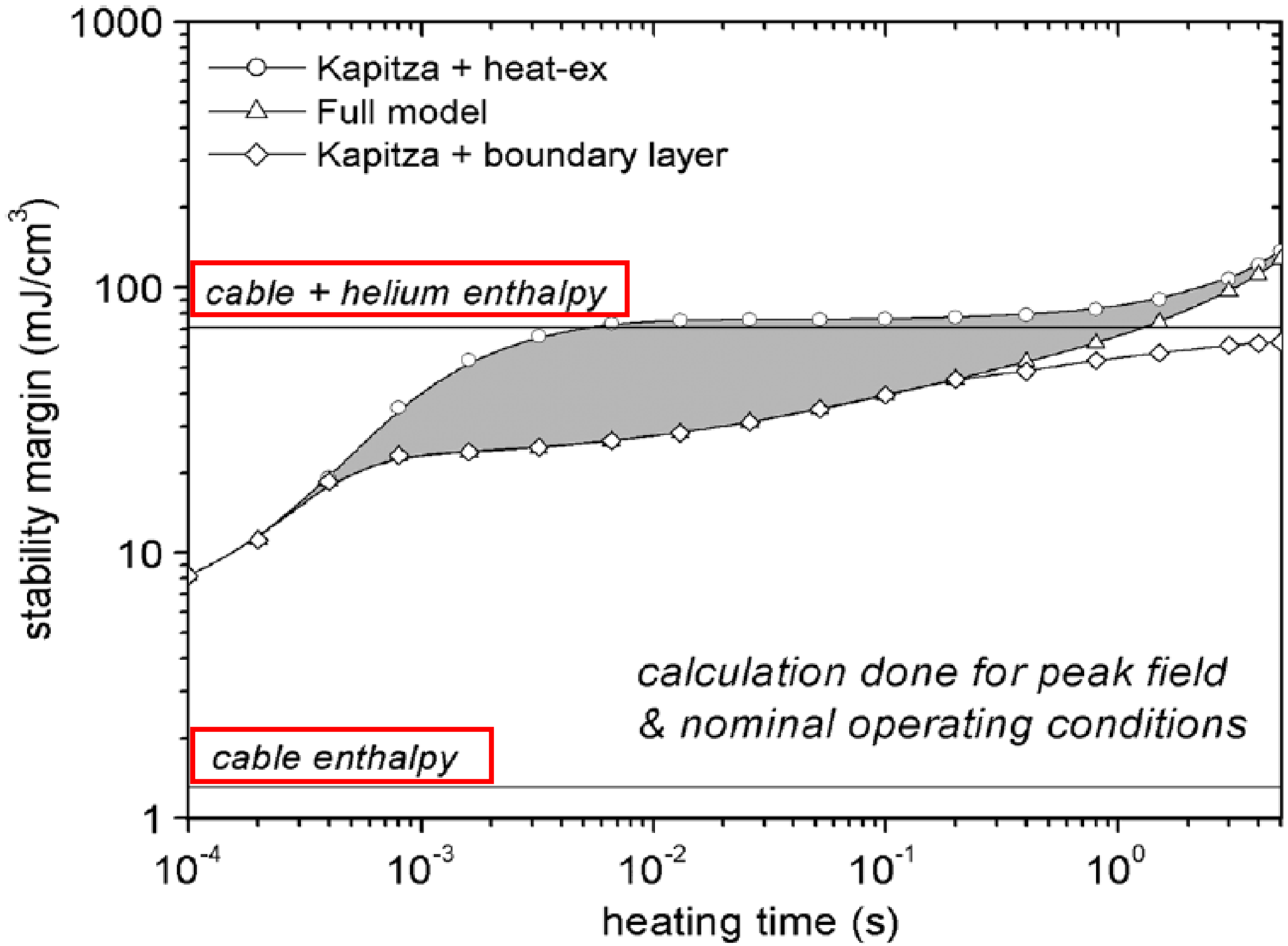
10 T in magnet bore

8.3 T in magnet bore

Typical thermal perturbation spectrum of superconductor in a particle accelerator



Transient stability of superconducting cable
Helium is an essential element of cable stability



SC magnets must resist quench
Hot spot temperature after a quench

Assume that quenched section is heated only by Joule effect and adiabatic (no conduction)

$$J^2(t)\rho(T)dt = \gamma C(T)dT \qquad \int_0^\infty J^2(t)dt = \int_{T_{op}}^{T_m} \frac{\gamma C(T)}{\rho(T)}dT \qquad J_0^2 T_d = U(T_m)$$

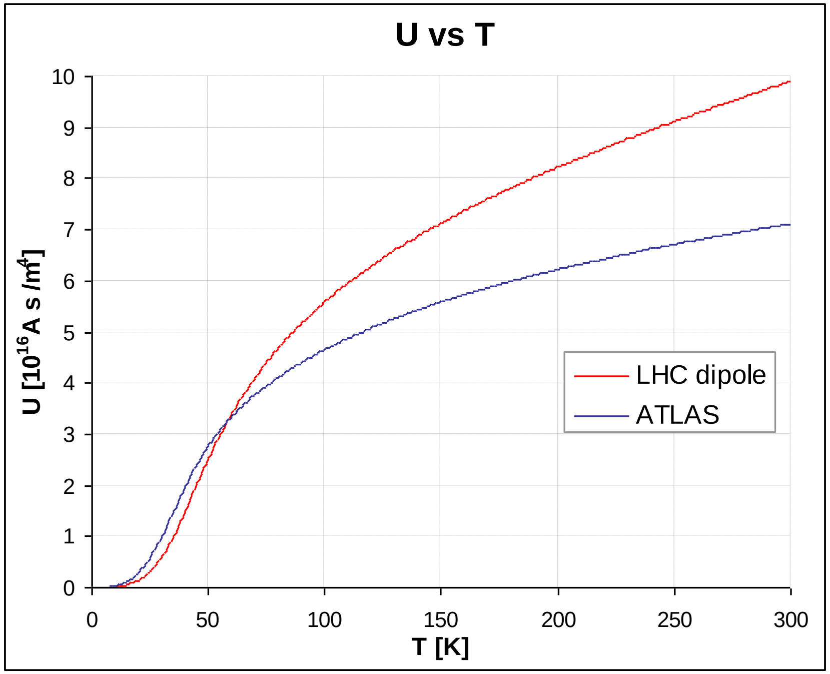
MIITs

To avoid too high hot spot temperature, speed up the quench propagation by any means

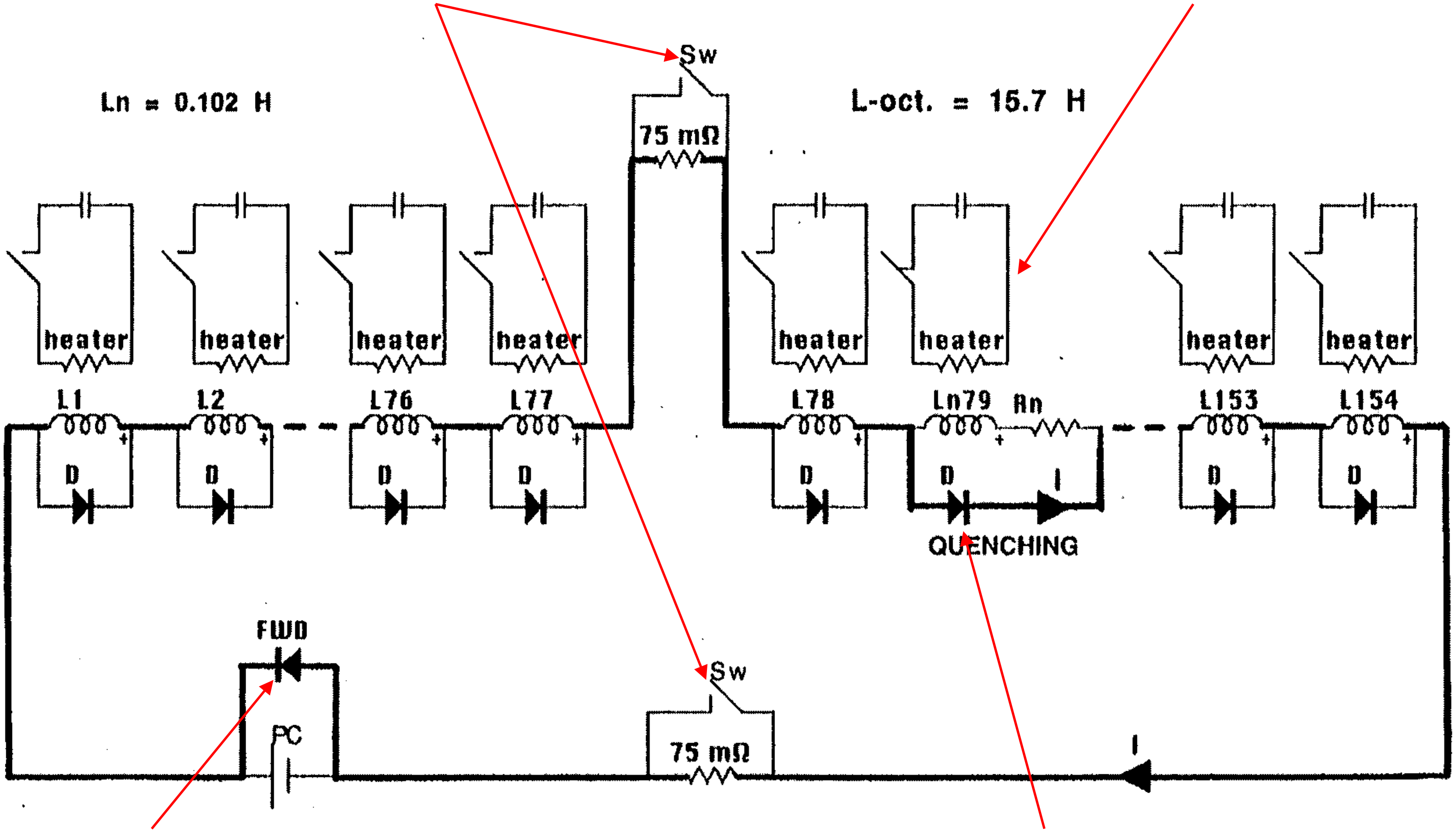
1) **Heater**: must be activated fast and reliably (20 ms)

2) "**Quench-back**" inductively propagated

This goes against having LHe in good contact with the conductor (i.e. against stability)!



LHC magnet circuit protection scheme



Dissipate energy of magnet string by inserting discharge resistor in circuit

Fire heater to spread the quench over maximum coil volume and limit temperature

Free-wheeling diode across power converter

Diode bypasses quenched magnet during current discharge in string

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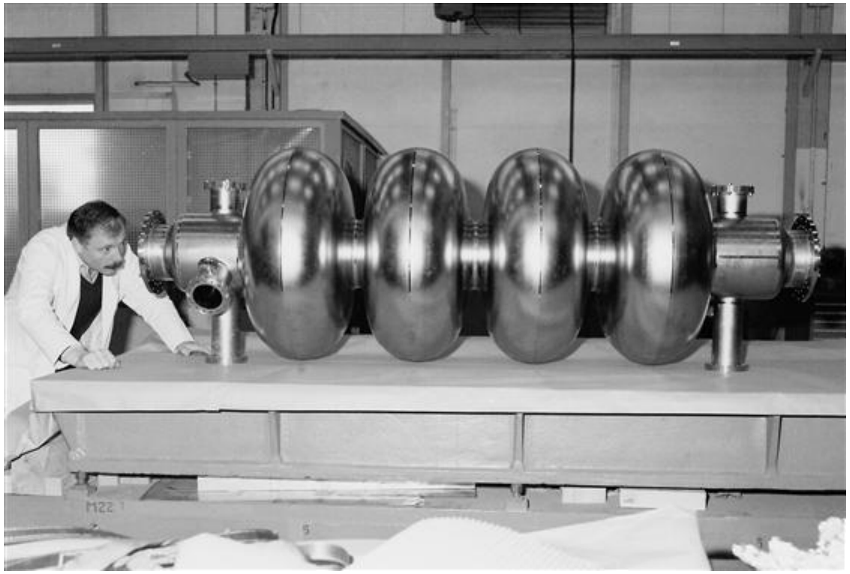
Superconducting RF cavities (elliptical)



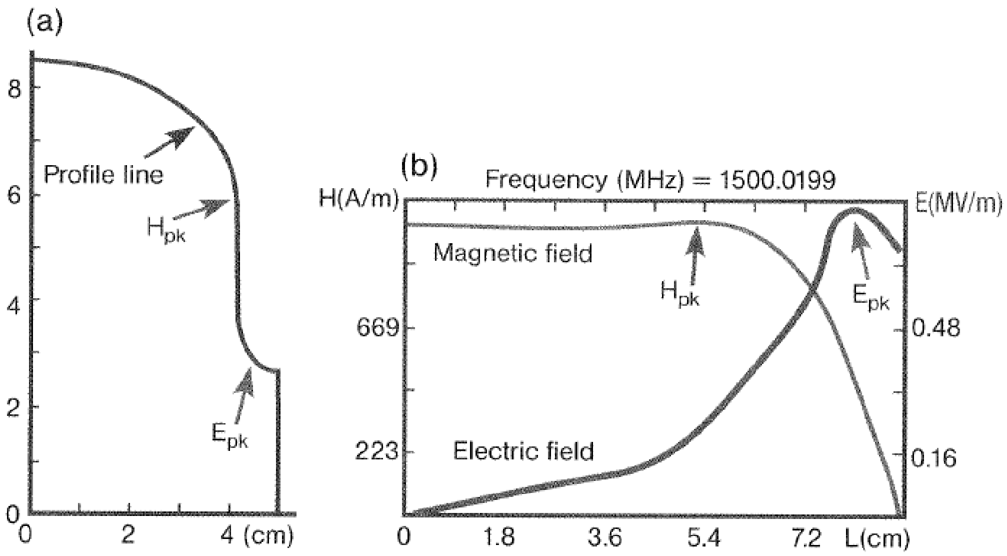
4-cell, 352 MHz Nb on Cu cavity for LEP2

400 MHz Nb on Cu cavities in LHC tunnel

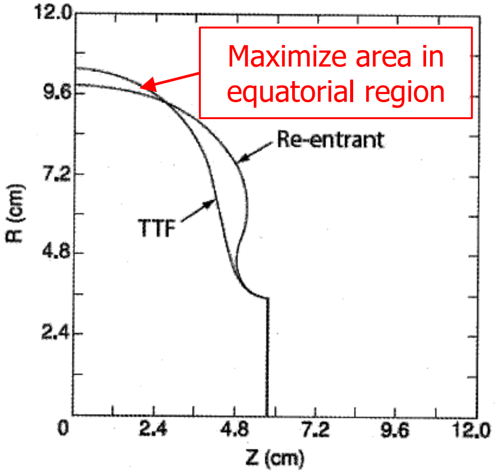
9-cell, 1.3 GHz Nb prototype cavity for the ILC

Optimizing geometry of elliptical SC cavity

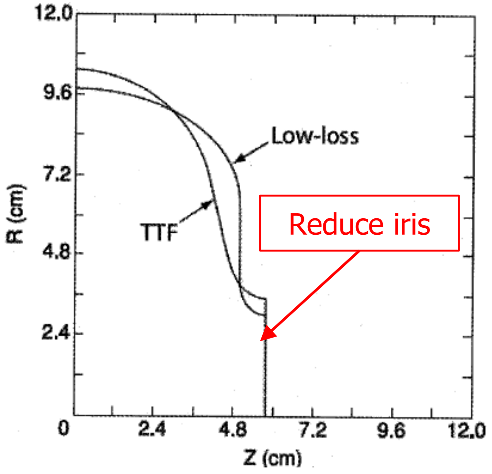
- Optimization strategies
  - Minimize E_{peak}/E_{acc} to limit field emission
  - Minimize H_{peak}/E_{acc} to stay away from critical magnetic field and reduce risk of quench
  - Increase shunt impedance R/Q to reduce power dissipation



- Variant cavity shapes
  - «Re-entrant»
  - «Low-loss»

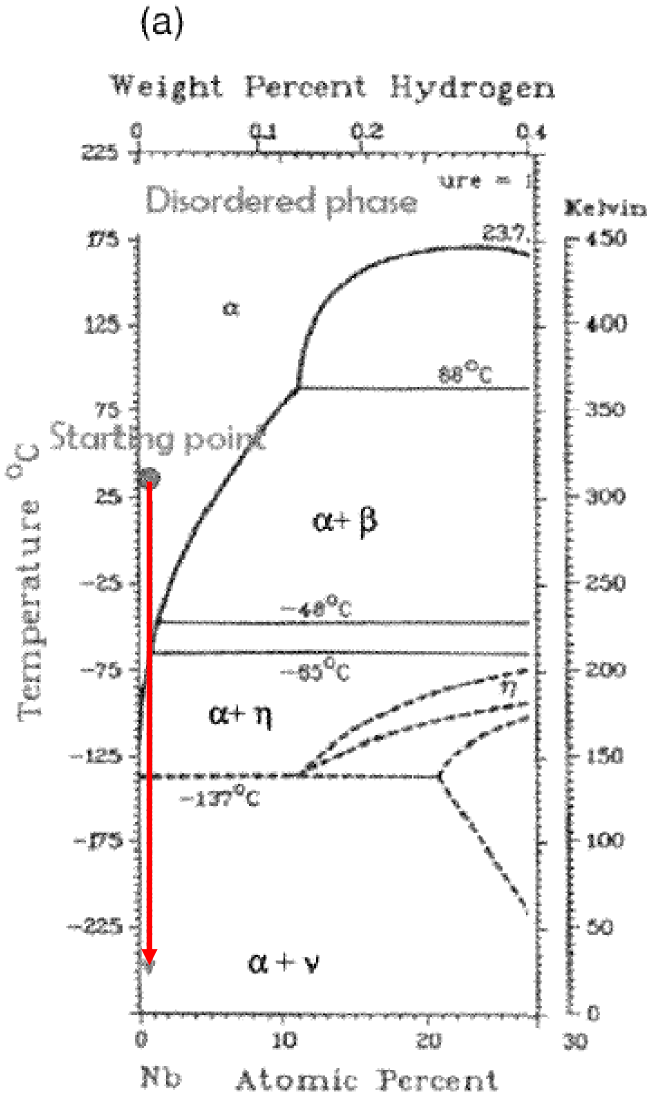


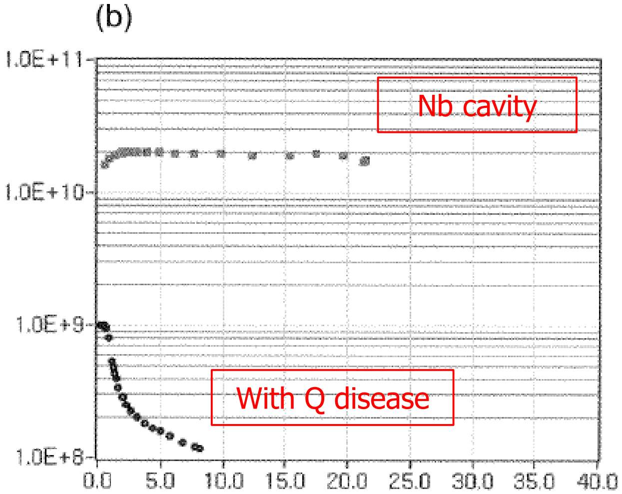
Maximize area in equatorial region



Reduce iris

Performance limitations of SC cavities
Degradation of surface resistance by H-related Q disease

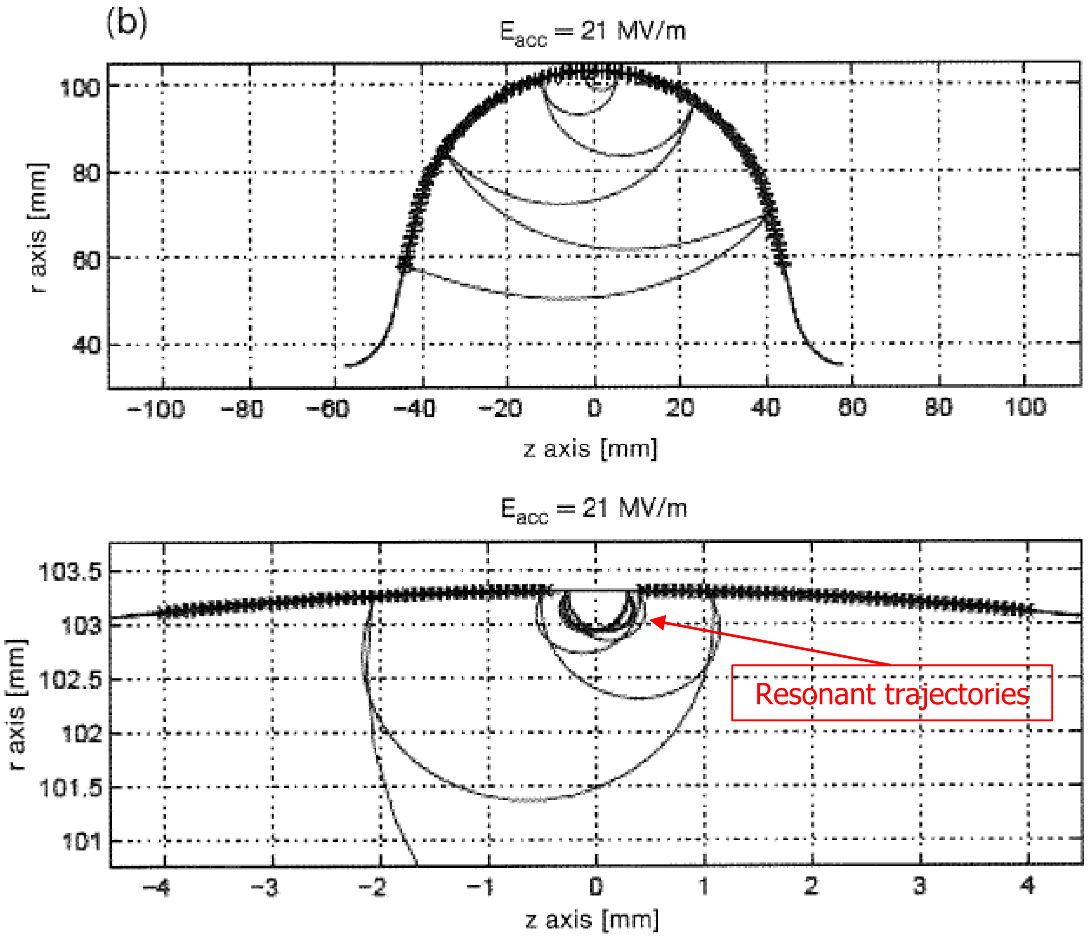




- Mechanism
  - Hydrogen dissolved in Nb precipitates as hydrides at cavity surface
  - Depends on quantity of dissolved H, other impurities, cooldown rate
- Cures
  - H degassing in vacuum at high temperature
  - Fast cooldown

Performance limitations of SC cavities
Multipacting

- Mechanism
  - Multiple-impact resonant electron amplification
  - Leads to local heat deposition, Q decrease and X-ray emission
  - Controlled by SEY from surface
- Diagnostics
  - Heat maps
  - X-ray maps
- Cures
  - Numerical simulation codes to optimize cavity shape
  - Conditioning to reduce SEY

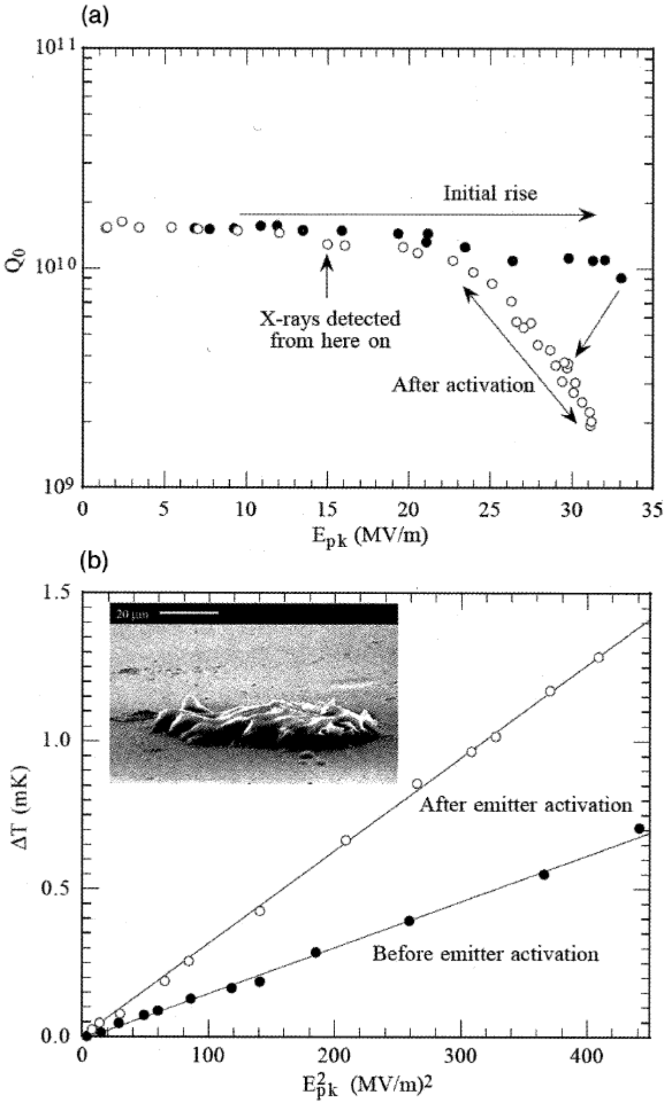


Two-point multipacting in a single-cell 1.3 GHz Nb cavity

Performance limitations of SC cavities
Field emission

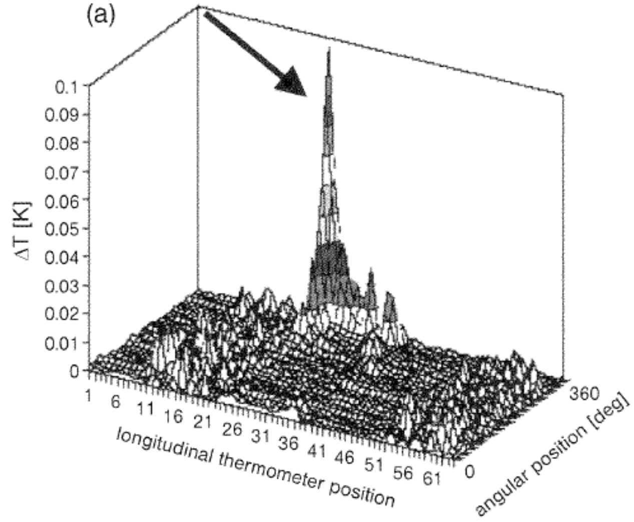
- Mechanism
  - Electron current from high-field emitters on cavity surface, e.g. microparticle contaminants, dust,…
  - Produces Q drop at high field

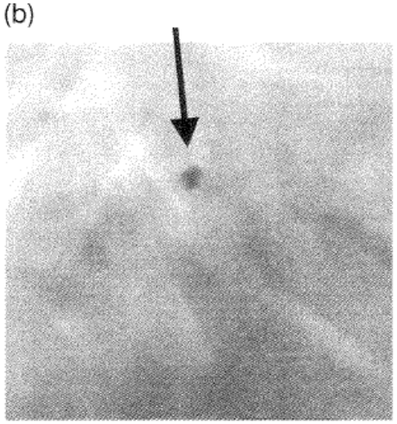
- Cures
  - Surface cleanliness
    - Assembly in class <100 cleanroom
    - High-pressure rinsing
  - *In-situ* elimination of emitters
    - RF processing
    - High pulse-power processing
    - Helium processing



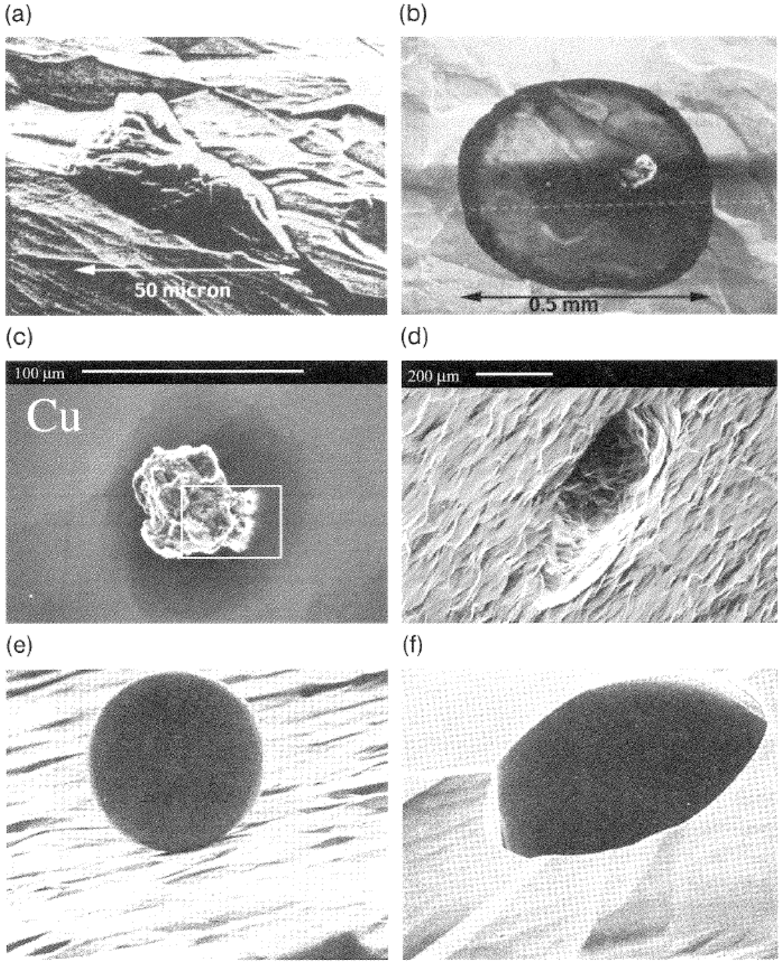
Performance limitations of SC cavities
Surface defects and quench

Ta defect on Nb located by thermometry and confirmed by radiography





(a) crystal inclusion; (b) drying stain; (c) copper particle; (d) sharp-edged pit; (e) Nb ball; (f) weld hole



Cure: smoothness

- Chemical polishing
- Electropolishing
- Single/large grain sheet

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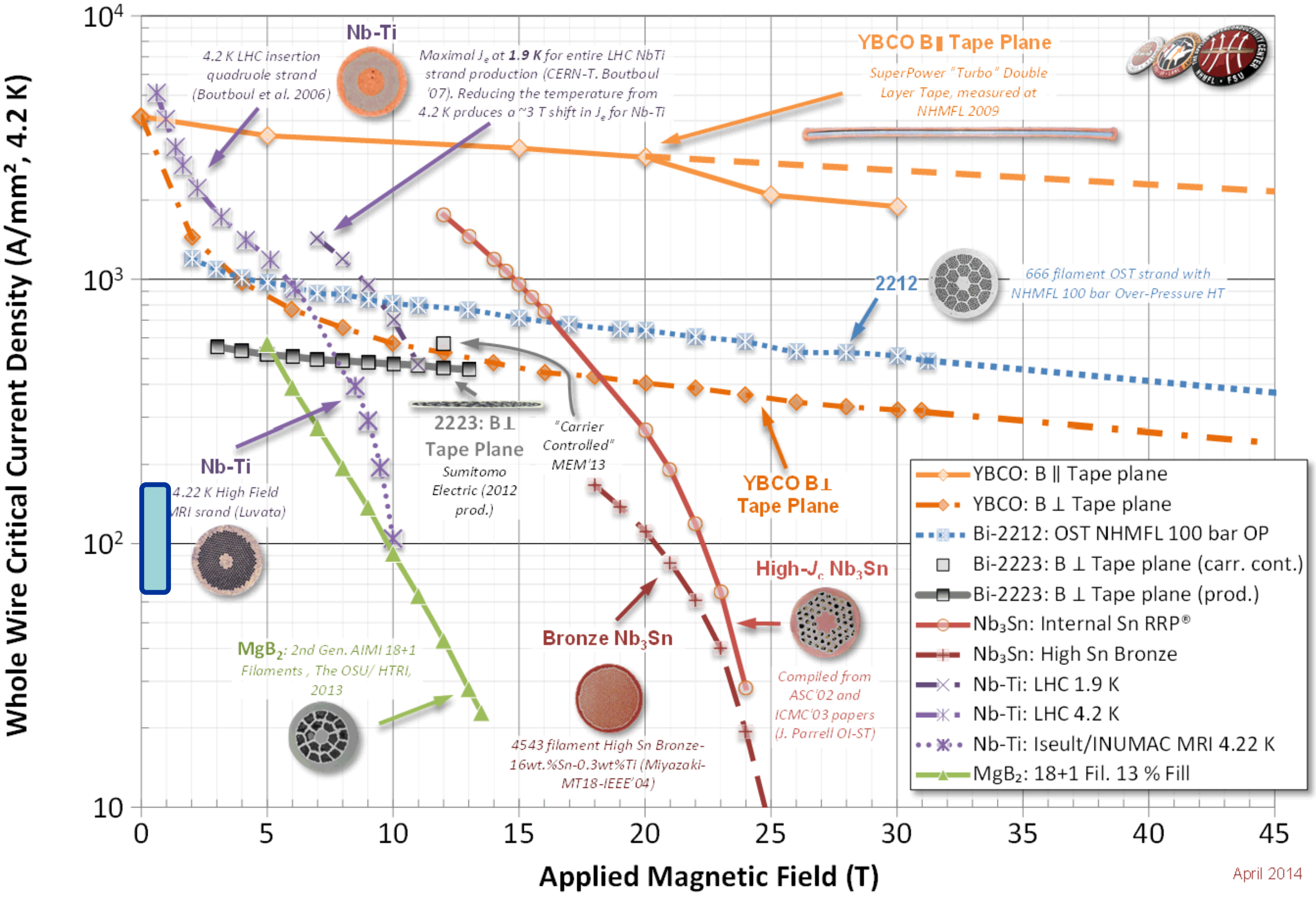
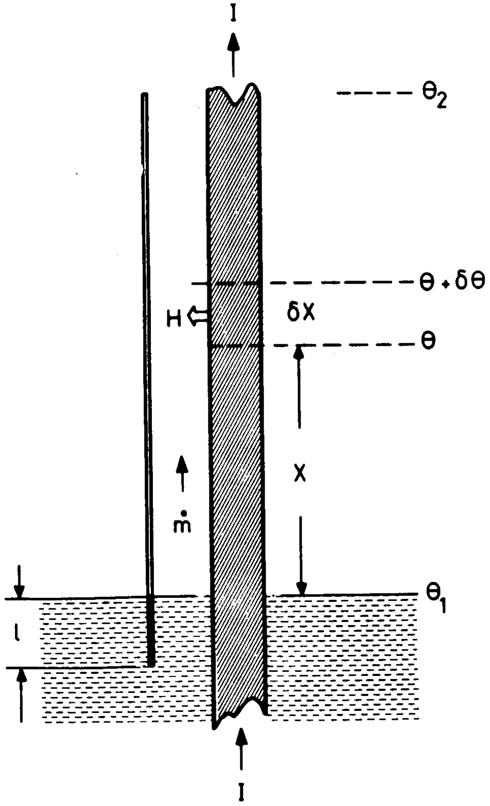
Current leads and cables operate in self-field



Bringing the current into the cryogenic environment: cryogenic current leads



Heat transfer processes at work
- Solid conduction
- Joule heating
- Convective cooling by He vapor

Metals are good electrical AND thermal conductors (Wiedemann-Franz-Lorentz law)

Optimal sizing of current lead results from compromise between heat conduction and Joule heating

Superconductors do not follow WFL law

They are perfect electrical conductors with low thermal conductivity

They can make excellent current leads… up to their transition temperature!

⇒ niche application for "high-temperature" superconductors

Current leads using HTS superconductor
The LHC case

	Resistive (WFL)	HTS (4 to 50 K) Resistive (> 50 K)
Heat inleak to liquid helium	1.1 W/kA	0.1 W/kA
Exergy loss	430 W/kA	150 W/kA
Electrical power of refrigerator	1430 W/kA	500 W/kA

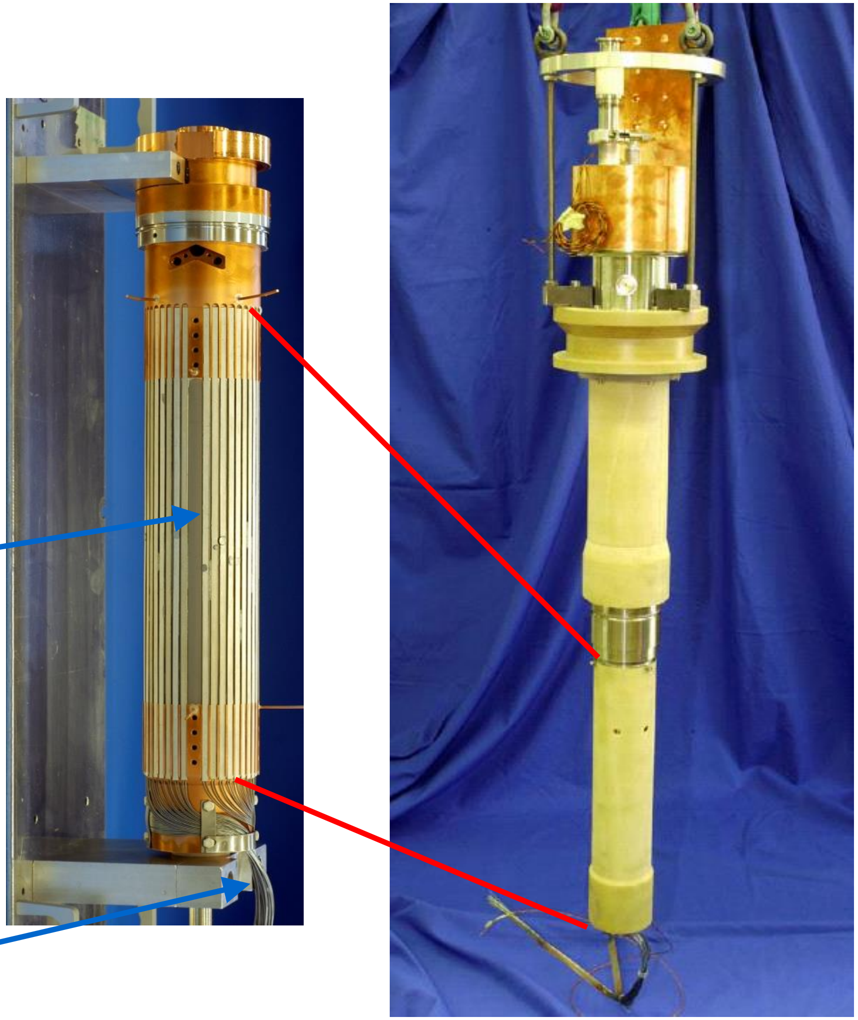
Sum of currents into LHC ~ 1.7 MA, i.e. need current leads for 3.4 MA total rating (in and out)

Economy ~ 3400 W in liquid helium ~ 5000 l/h liquid helium

⇒ capital: save extra cryoplant

⇒ operation: save ~ 3.2 MW

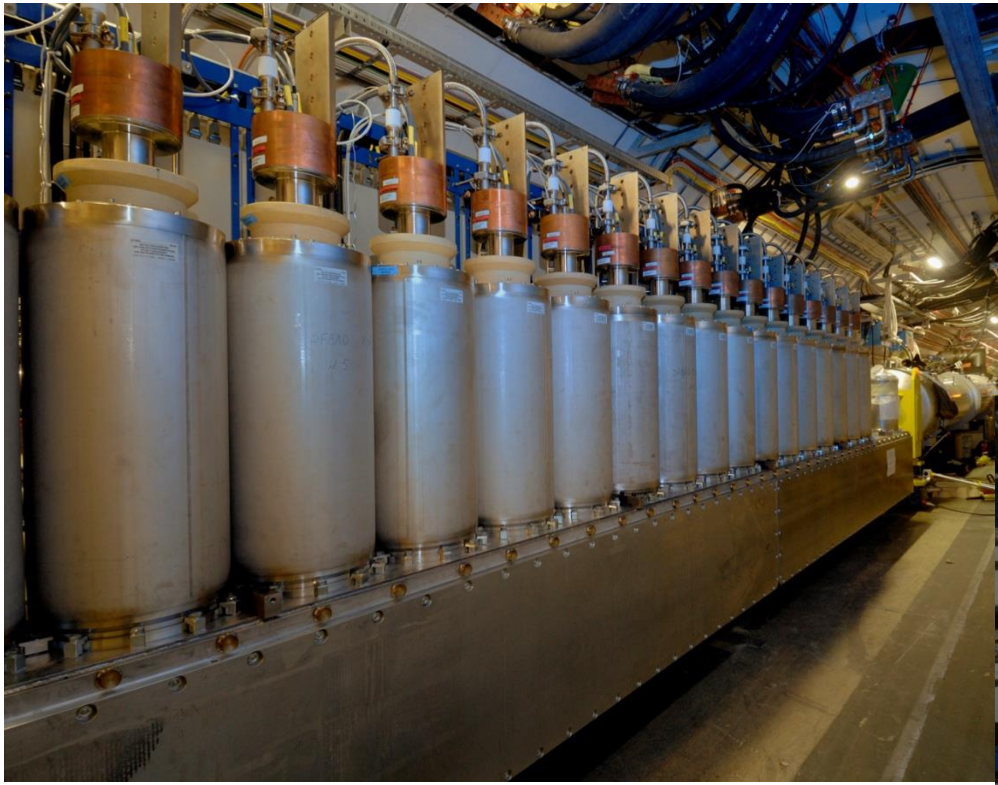
13 kA HTS current lead for LHC



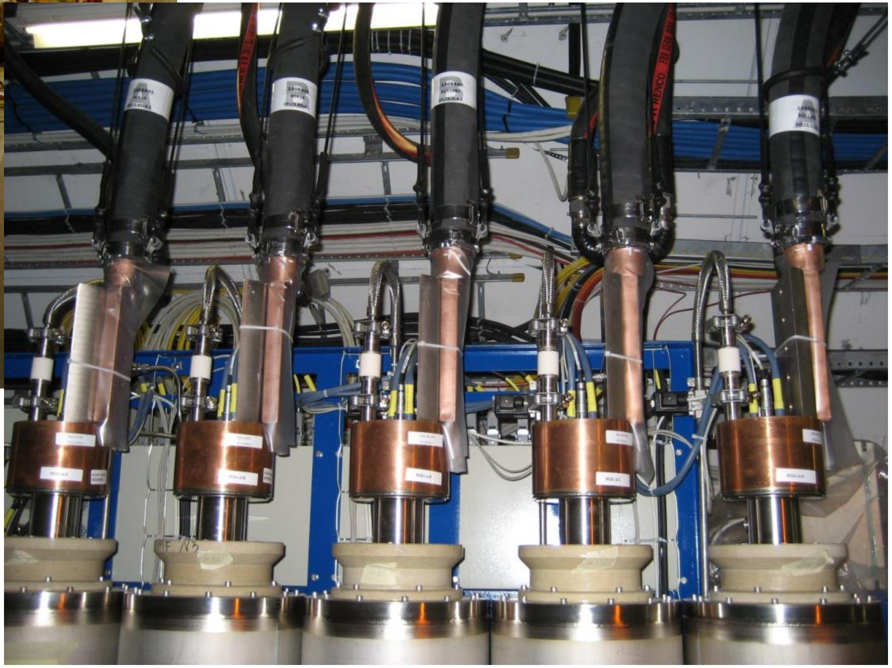
BSCCO
2223 tapes

Nb-Ti
wires

HTS current leads in the LHC tunnel

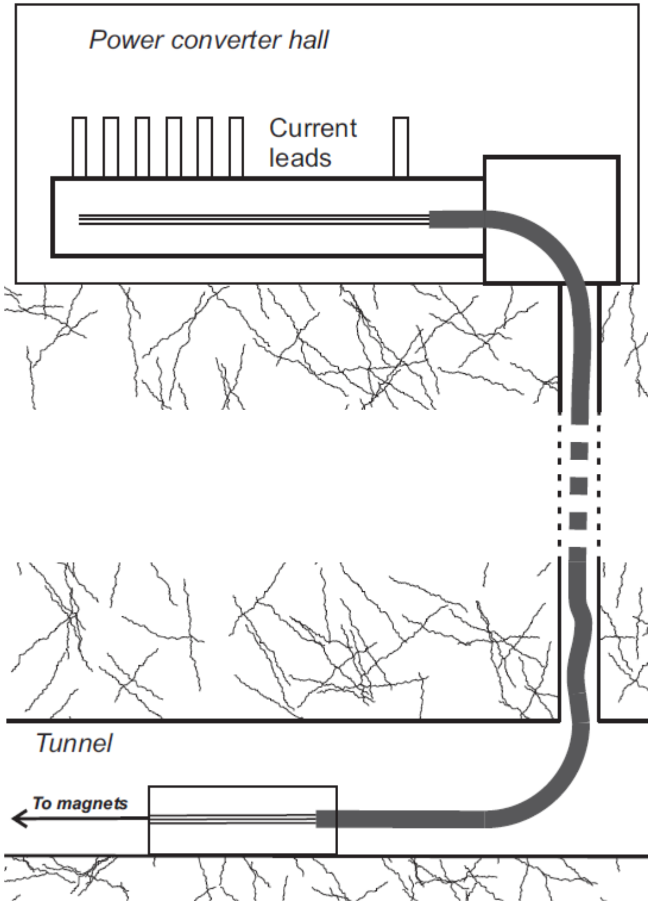


6 & 13 kA leads on electrical feed-box

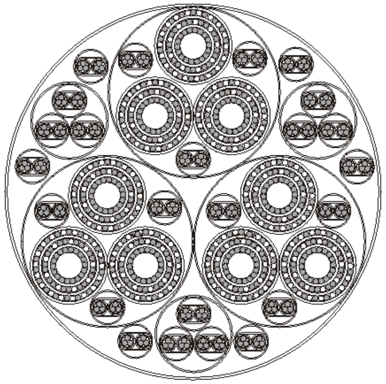


Water-cooled cables on current lead lugs

SC links using MgB_2 wires for HL-LHC



Record current of 20 kA transported at 24 K in MgB_2 cable



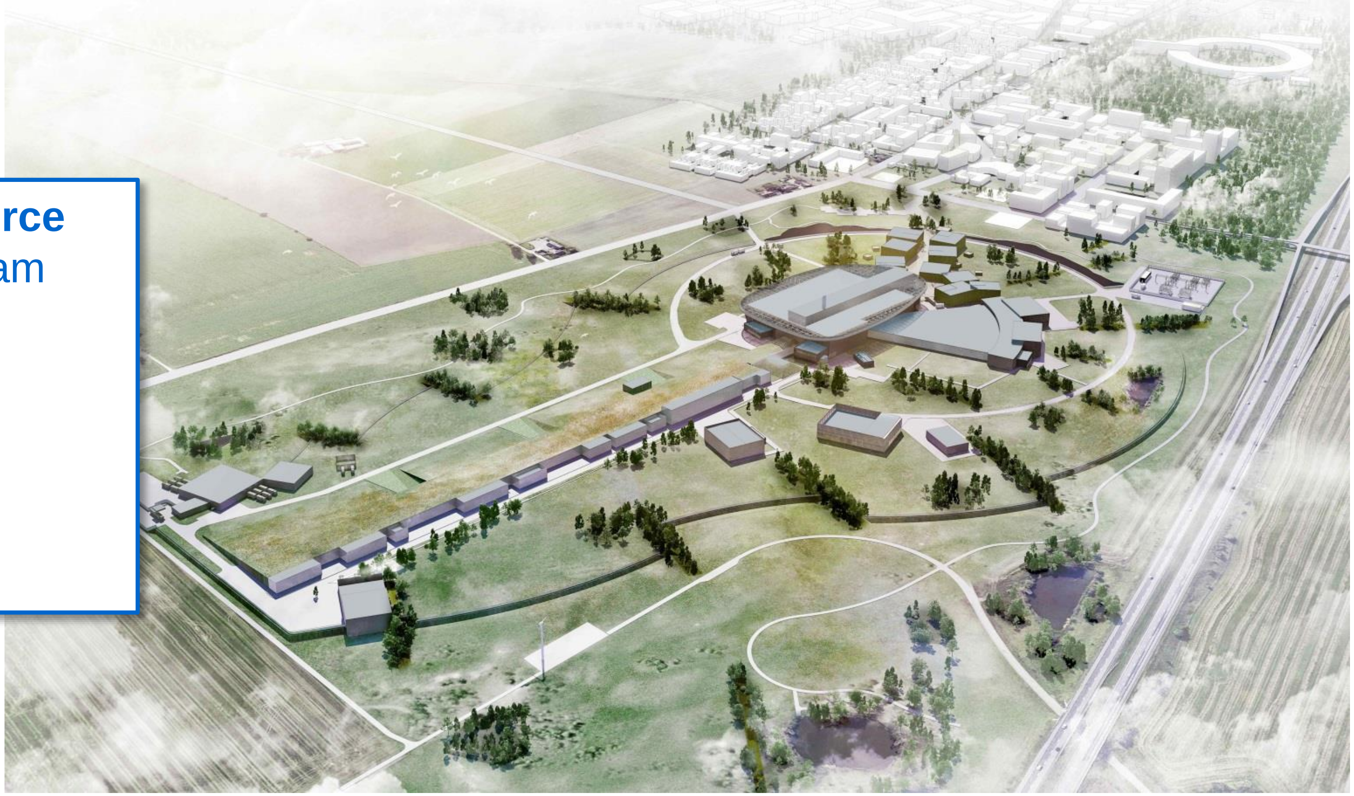
A. Ballarino

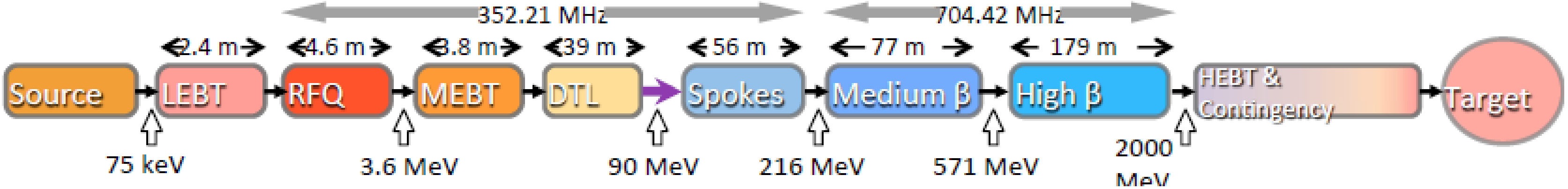
Contents

- Superconductivity in a nutshell
- Superconductivity and accelerators
- Superconducting magnets for accelerators
- Superconducting RF cavities for accelerators
- Superconducting current leads and powering links
- Some ongoing and future projects
- Selected bibliography

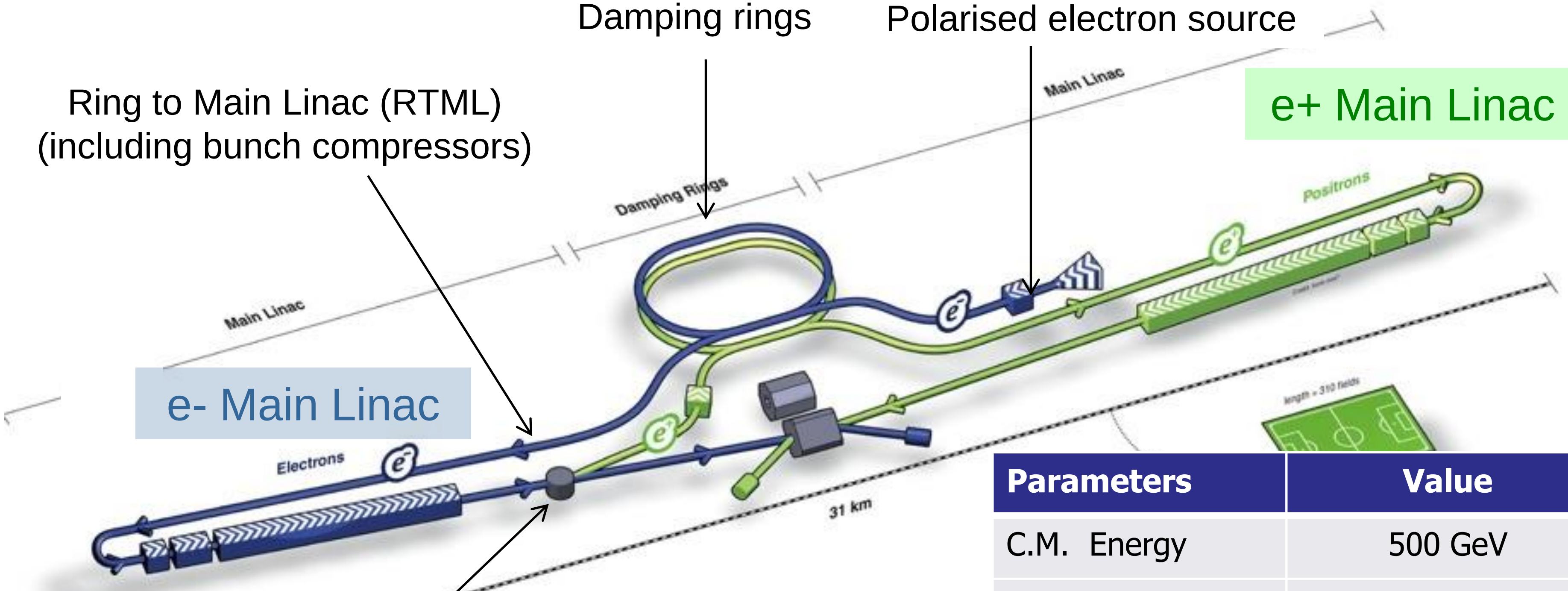
European Spallation Source at Lund, Sweden

Long-pulse neutron source
- 5 MW, 2 GeV proton beam
- 62.5 mA
- 2.86 ms pulse length
- 14 Hz
- Low losses
- High availability > 95 %
- High efficiency





The International Linear Collider (ILC) project



Damping rings

Polarised electron source

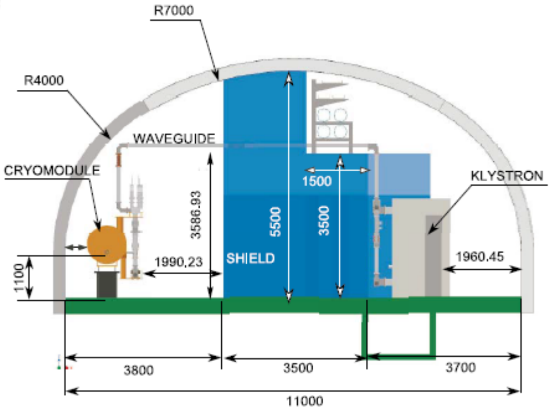
Ring to Main Linac (RTML)
(including bunch compressors)

e+ Main Linac

e- Main Linac

e+ source

ILC Scheme | © www.form-one.de



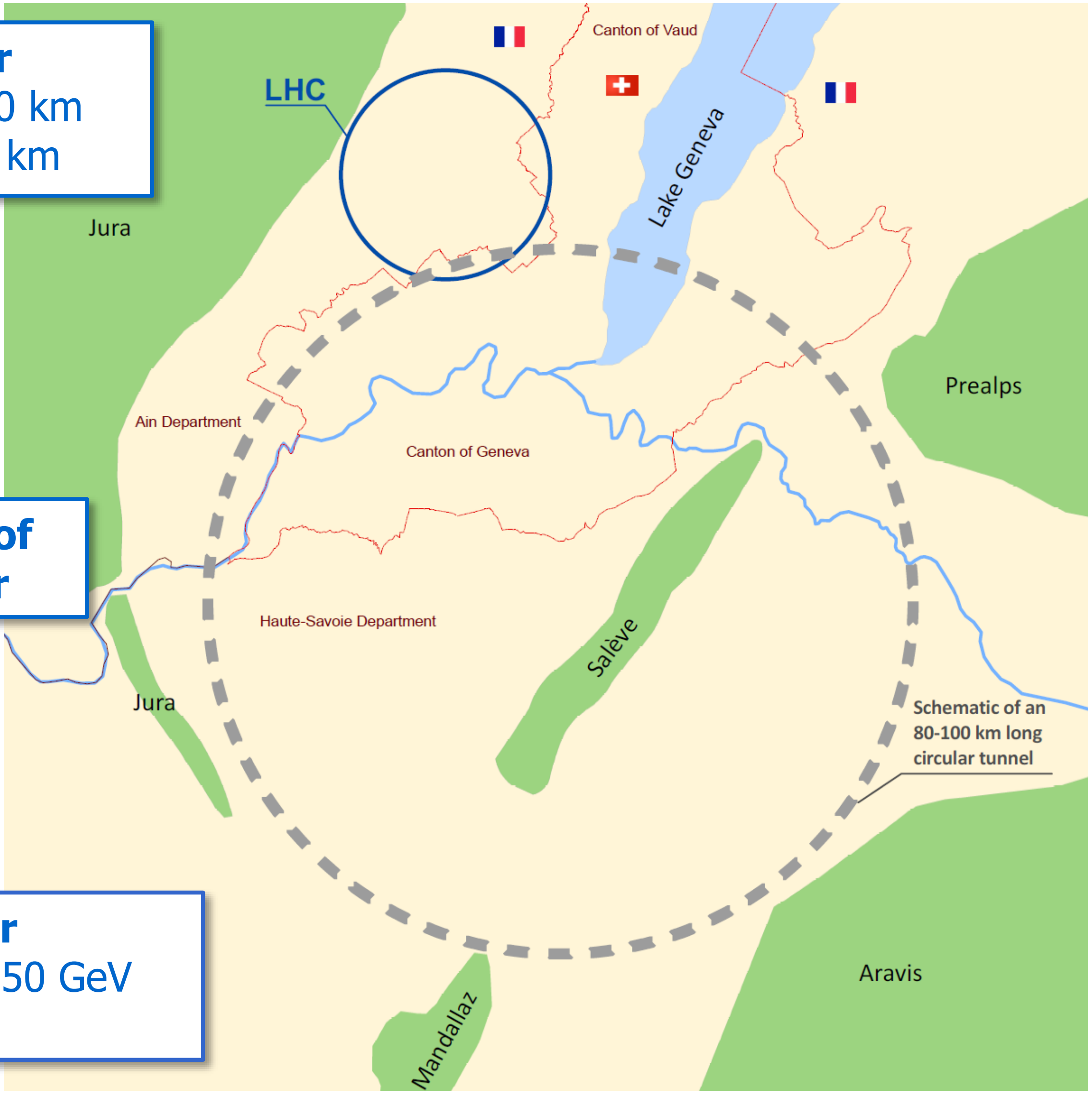
Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} cm^{-2}s^{-1}
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
Gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

Future Circular Colliders (FCC) study at CERN

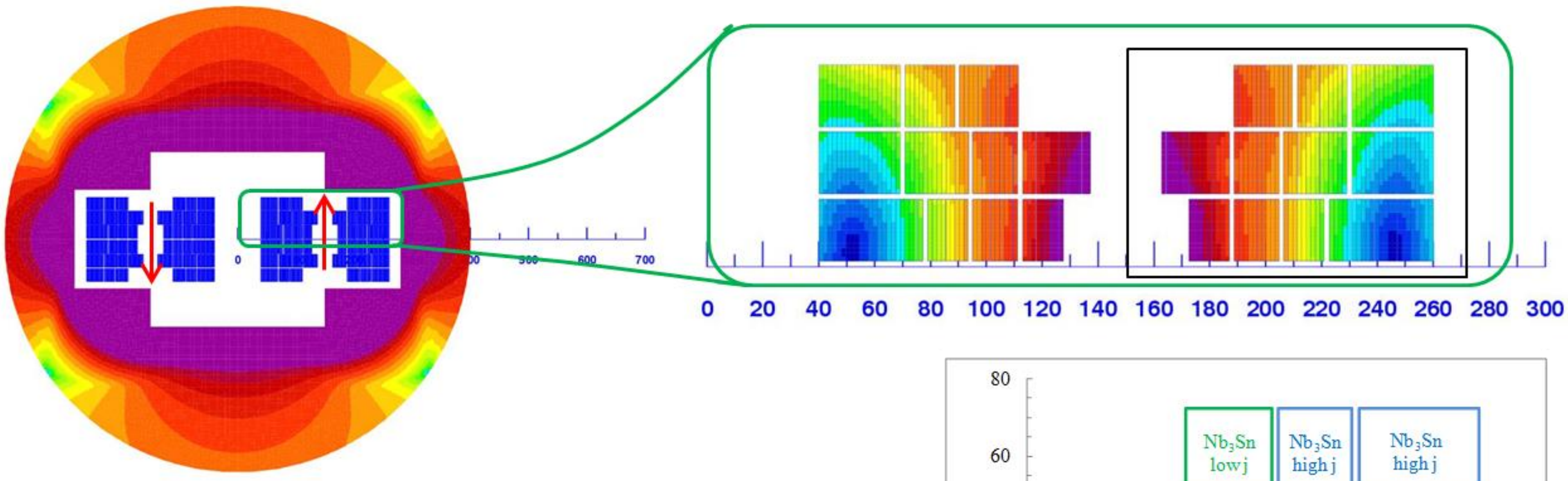
Hadron collider
16 T ⇒ 100 TeV for 100 km
20 T ⇒ 100 TeV for 80 km

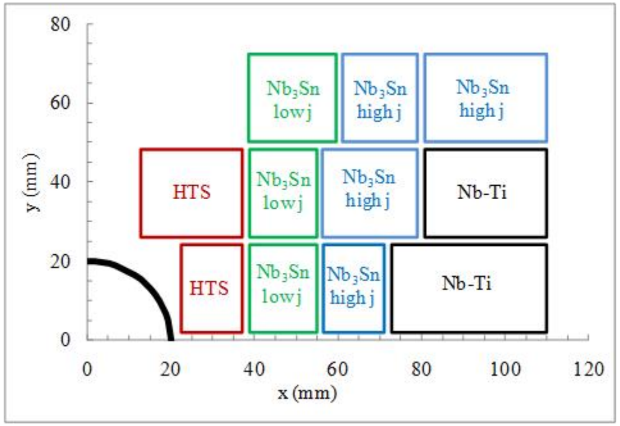
Quasi-circular tunnel of 80-100 km perimeter

e+ e- collider
Collision energy 90 to 350 GeV
Very high luminosity



Conceptual design for a 20 T twin dipole
Nested coils using multiple superconductors





Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380
Nb3Sn (high Jc)	55	37%	13	380
Nb3Sn (Low Jc)	30	20%	15	190
HTS	24	16%	20.5	380

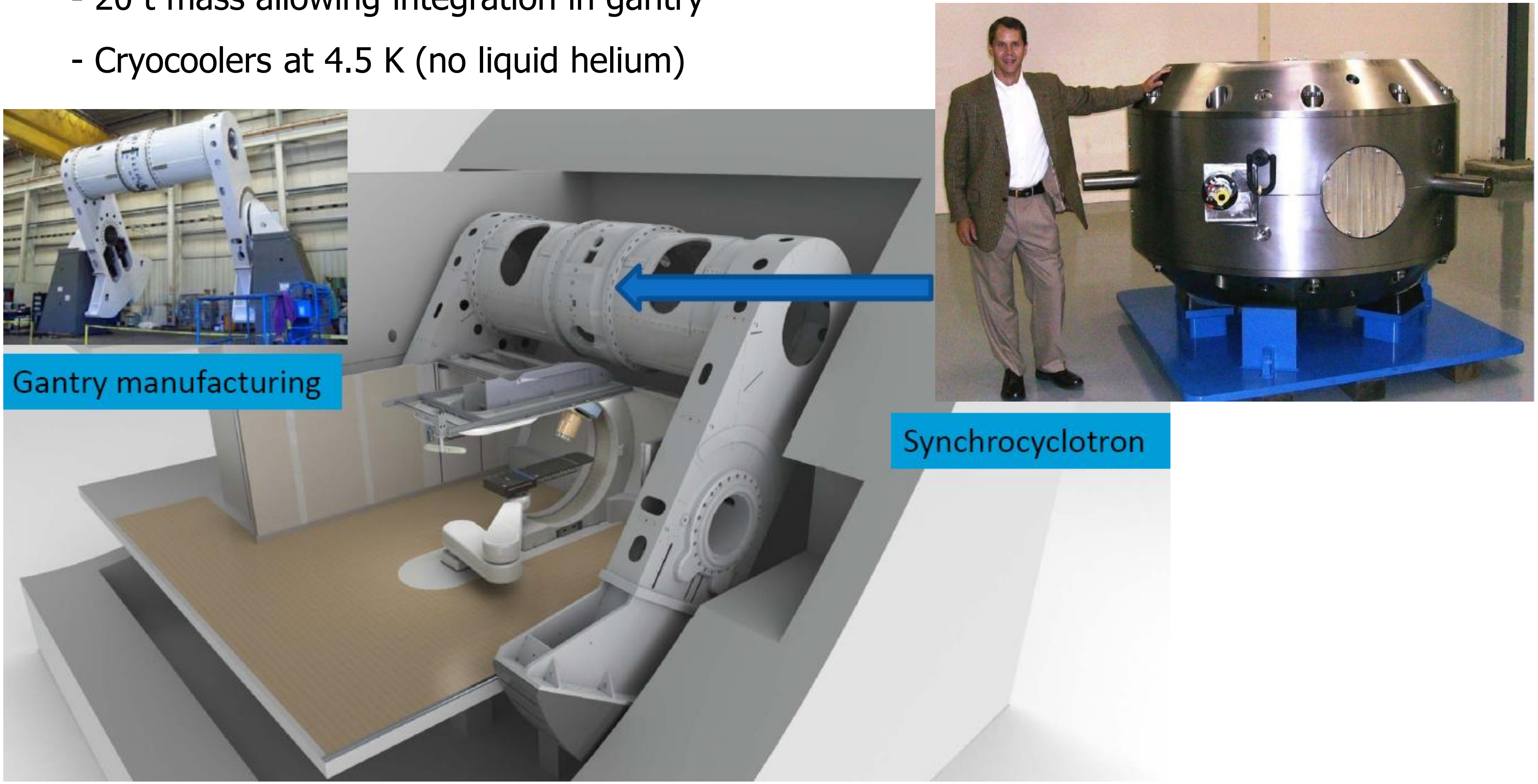
Would yield 33 TeV collision energy in LHC tunnel, 100 TeV in new 80 km tunnel

Magnet design very challenging: 300 mm inter-beam; anticoils to reduce stray flux; multiple powering in the same magnet for field quality

L. Rossi & E. Todesco

Compact SC synchrocyclotron for hadrontherapy
(*Still River Systems*)

- Provides 250 MeV protons
- 20 t mass allowing integration in gantry
- Cryocoolers at 4.5 K (no liquid helium)



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