ICMAB EXCELENCIA SEVERO OCHOA
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

SEPTEMBER 17-20, 2018
SALA D'ACTES CARLES MIRAVITLLES
ICMAB-CSIC, Bellaterra, Spain

MATENER2018
SEVERO OCHOA SUMMER SCHOOL
ON MATERIALS FOR ENERGY

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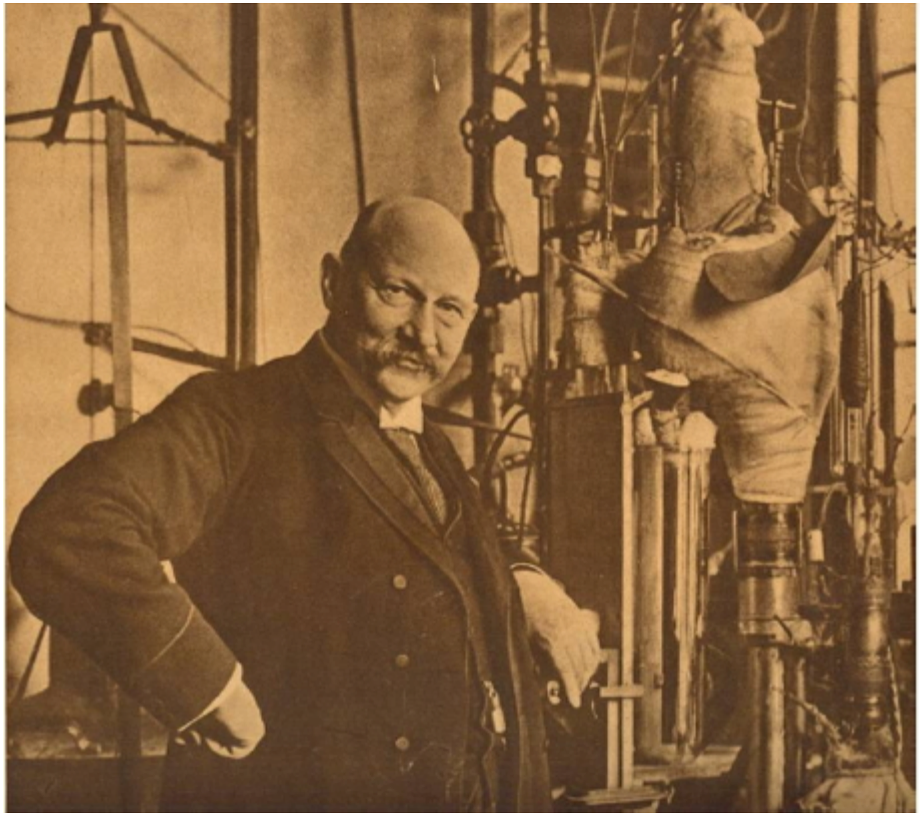
Superconductivity II
Large Scale Applied Superconductivity

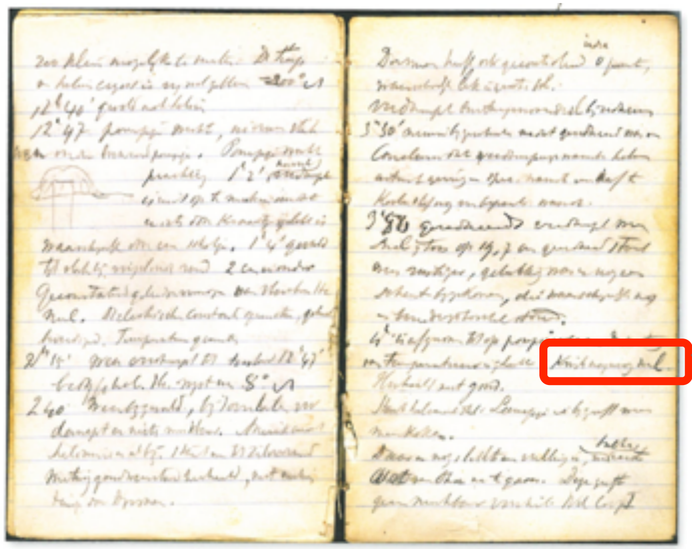
Pascal Tixador

Grenoble-INP, Université de Grenoble Alpes, CNRS
G2ELab, Institut Néel

UNIVERSITÉ Grenoble Alpes · Grenoble INP · CNRS · NÉEL institut · G2E Lab Grenoble Génie Electrique Grenoble Electrical Engineering

100 years ago: Avril, 8, 1911





“Mercury nearly zero”

Objectives and outline

The main purpose is to provide informations about applied superconductivity from phenomena to applications through materials.

- Introduction
- Historical references
- Superconductivity for large scale applications
- Superconducting material (REBCO tapes)
- Superconducting applications
- Fault Current Limiter (FCL)

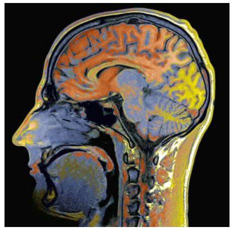
Introduction

Superconductivity: industrial activity

Niche market but industrial market

- About 5 185 MEuros (worldwide market in 2012)
- **Medical imaging** (2500 MRI per year, 30 000 in service)
  - Non invasive extremely useful tool
  - ***"MRI*** (Magnetic Resonance Imaging) has transformed super-conductivity from scientific laboratory to everyday use; ***Superconductivity*** made MRI a commercial reality" M. Parizh (Phillips).
- **RMN high resolution Spectrometer RMN**
  - Indispensable and outstanding analysis tool
- Thermonuclear Fusion (ITER)
  - Solar energy for tomorrow energy
- High energy physics
  - Origins of universe (LHC)

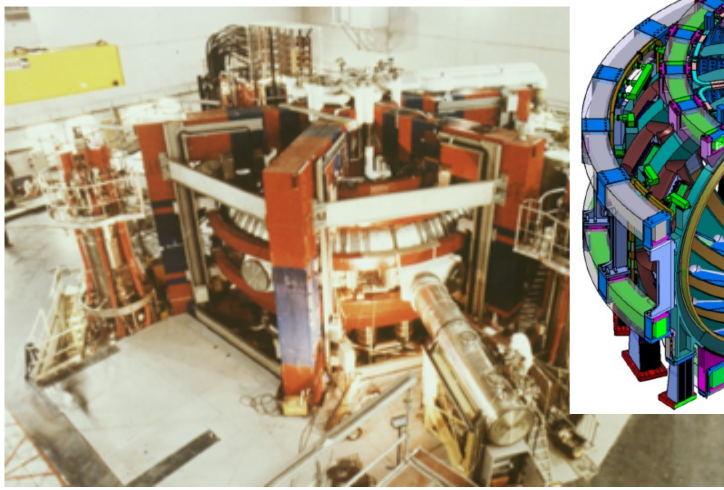
Main superconducting applications

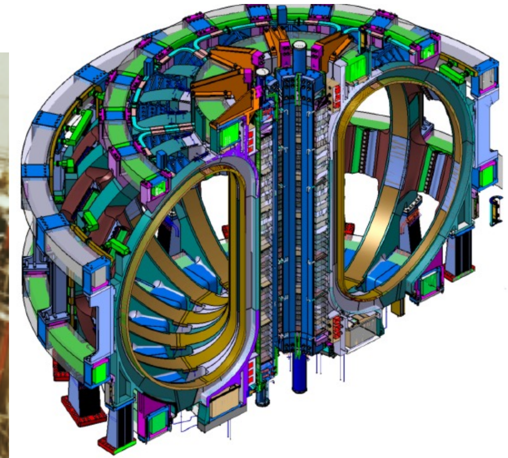


40 000
in service

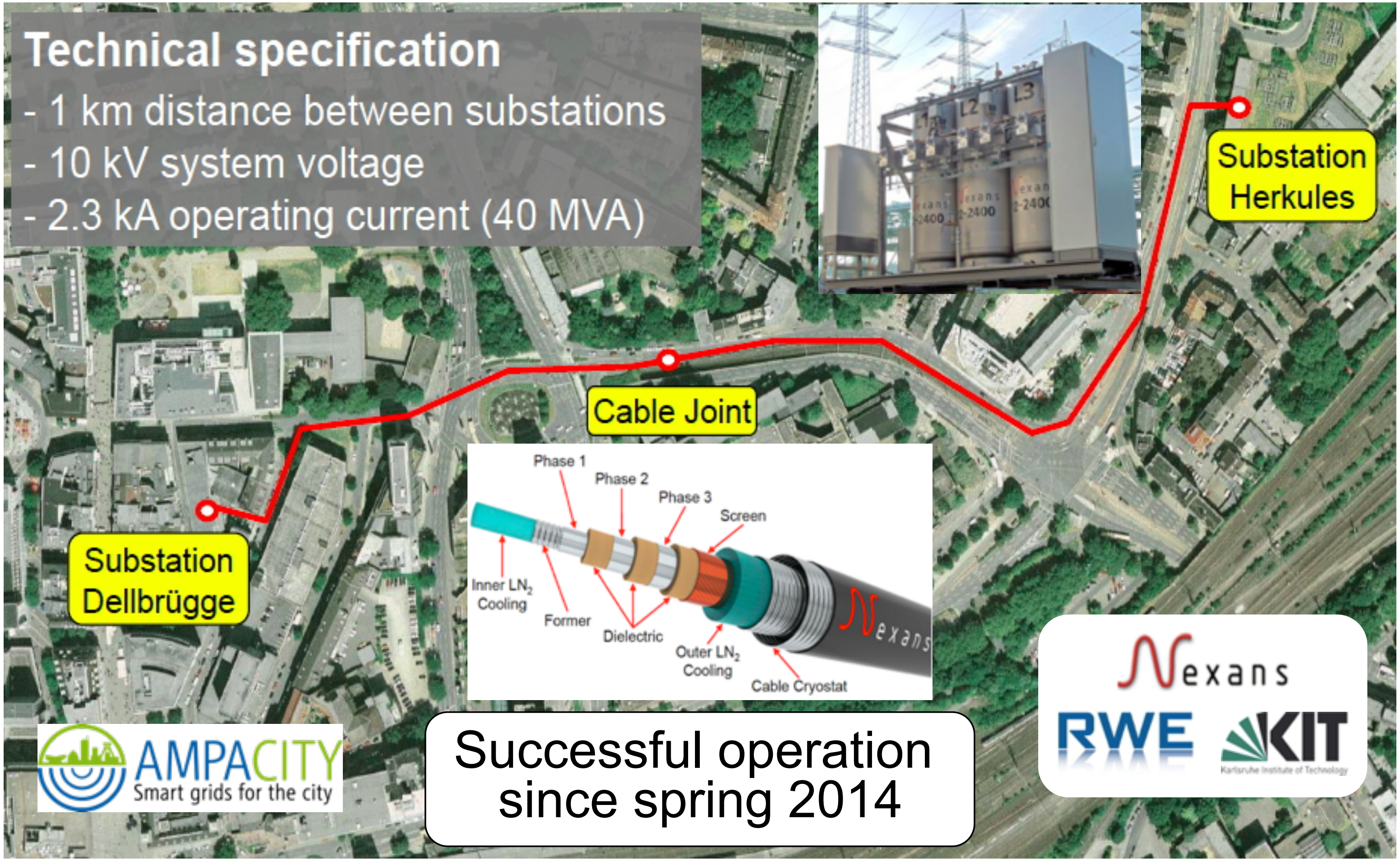
27 km
(100 km)

40 MW
(900 MW)





Cable + FCL project: AMPACITY

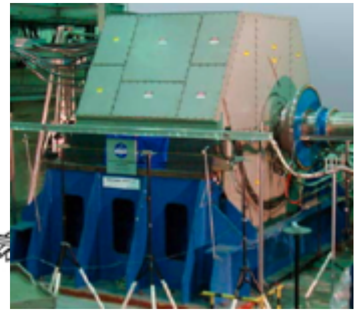


Courtesy M. Stemmle

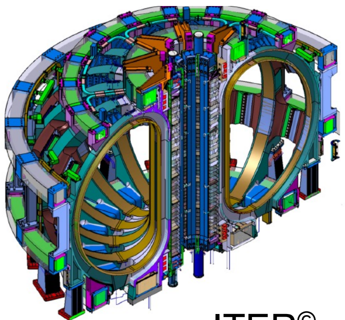
« Superconducting » world

Siemens©

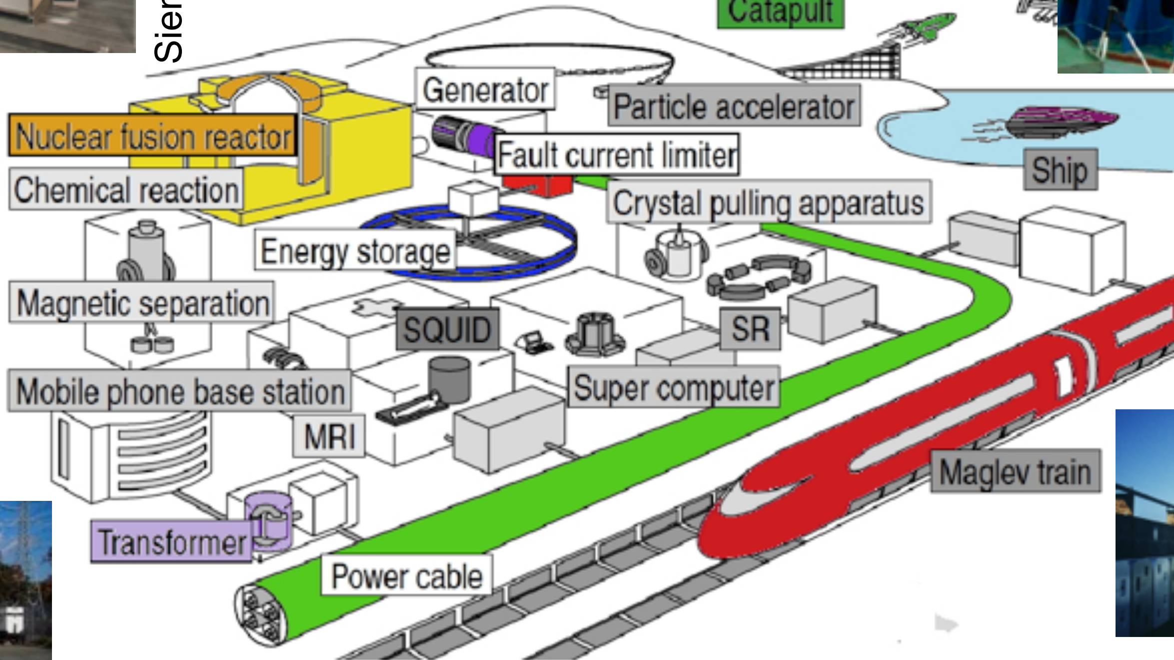
NEXANS©



AMSC©



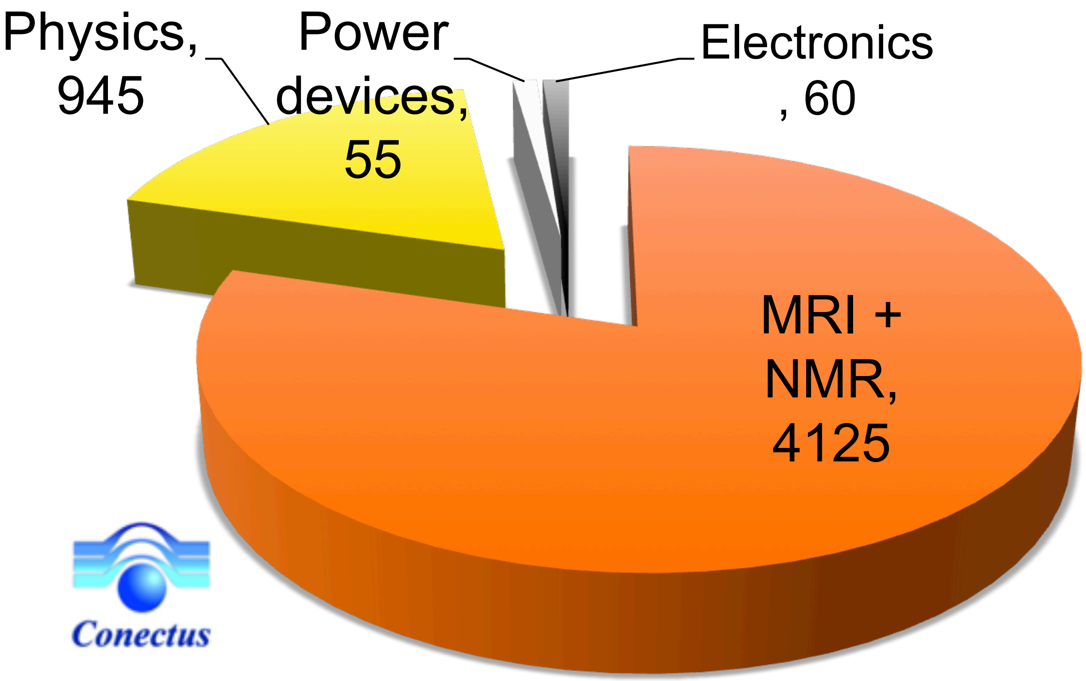
ITER©

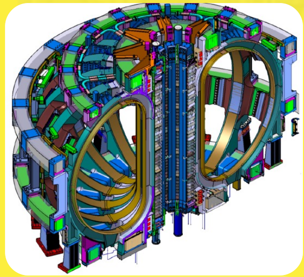


SEI technical review

NEXANS©

Superconductivity market (2011)



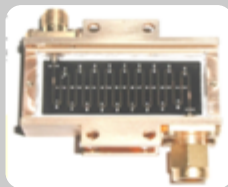


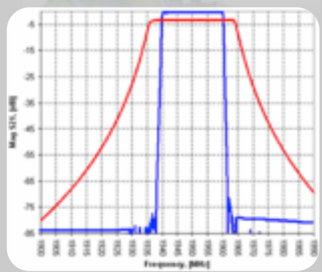
Total : 5080 MEuros (2011)

LTS market: 5050 M€

HTS market: 30 M€

HTS





Some companies

Big companies

- Siemens
- Oxford Instruments Superconductivity
- GE
- Philips
- NEXANS
- SuperPower Furikawa
- …

SME and start ups

- THEVA
- Oxolutia
- …

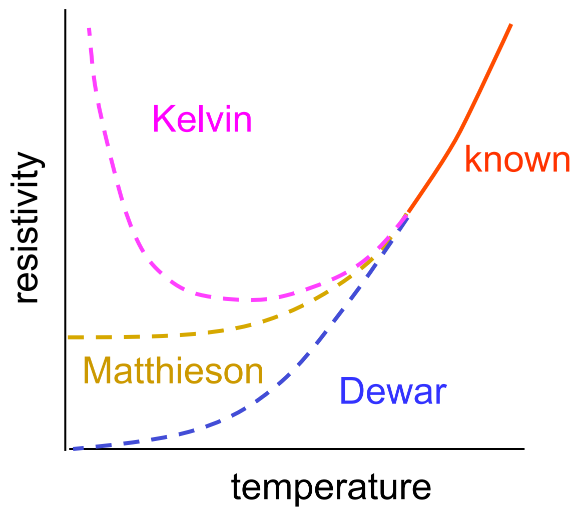
Some historical references

Beginning of the story

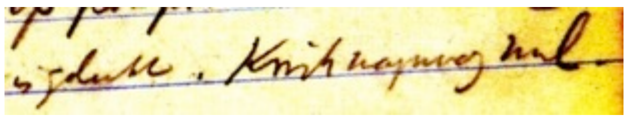
Once in Leiden …

Superconductivity discovery

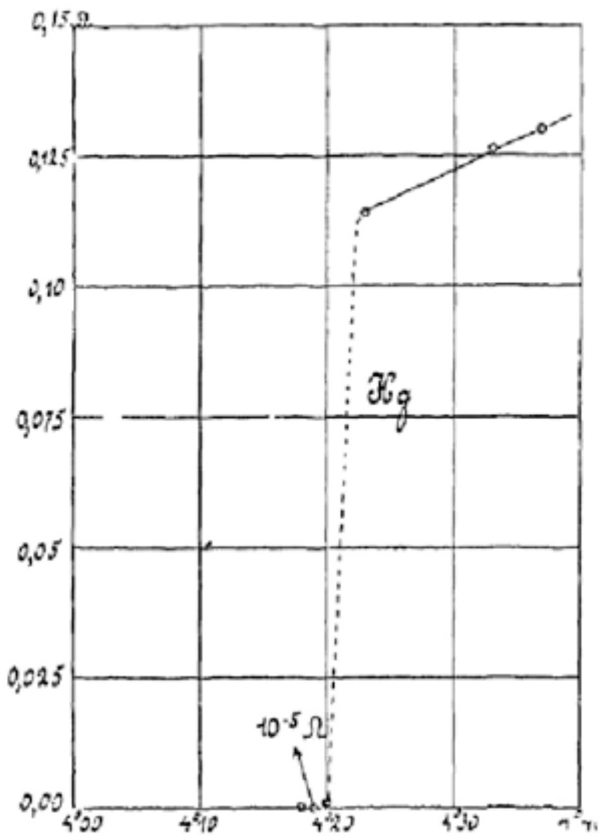
- Metal resistivity studies

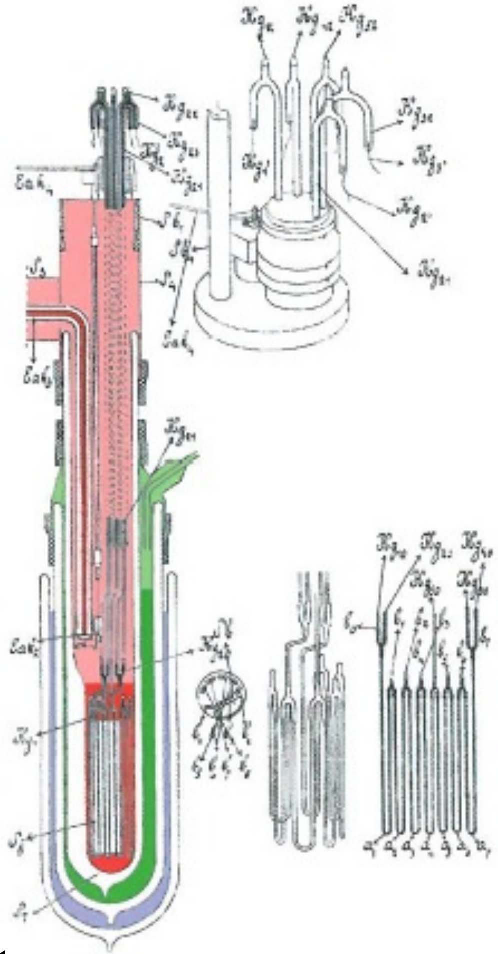


April 8, 1911



Heike Kammerlingh Onnes
Notebook #56



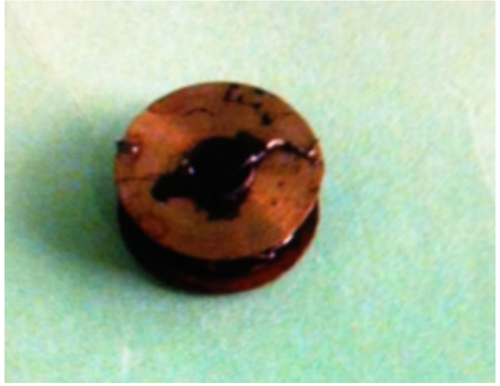


October 26, 1911 **G. Holst**

Big hopes

H. K. O. visionary immediatly saw one SC application: magnets.
Generation of large magnetic flux densities with little power
=> Project 10 T magnet in 1913.

Lead (Pb) magnet (1913)
9968 magnet



Tin (Sn) magnet (1913)
9969 magnet

Low magnetic field destroy superconductivity
⇒ Have to wait type II superconductors (end of 50')
(discovered in Soviet Union earlier - Shubnikov /Abrikosov)

Introduction - History

- 1908 : Helium liquefaction
- 1911 : superconductivity discovery
- 1933 : Meissner effect
- 1957 : microscopic theory BCS
- 1958 : type II superconductors (NbSn, NbZr)

- 1960 : High current densities under fields for NbSn
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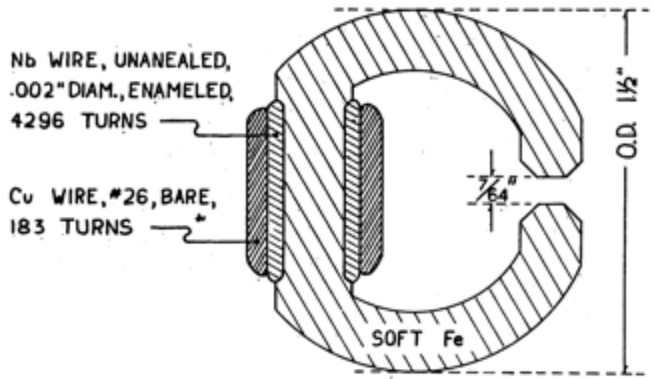
First SC (NbZr) magnet

Oxford Instrument
Sir Martin Wood
March 1962.



G. Yntema, 1954

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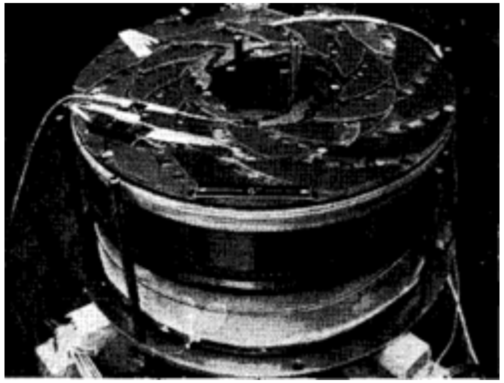
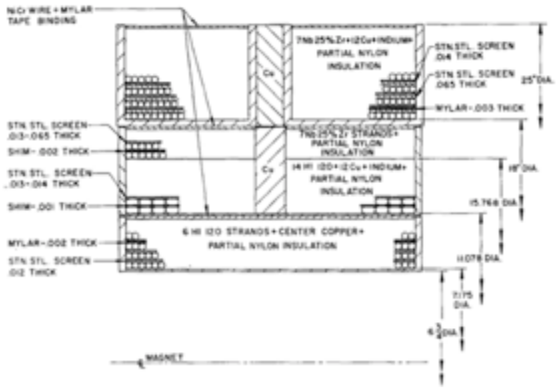
SC and high energy physics





Superconductivity and Accelerators: the Good Companions

Martin N. Wilson
Oxford Instruments, Tubney Woods, Abingdon, OX13 5QX, UK.

Roy Aleksan, ASC 2012

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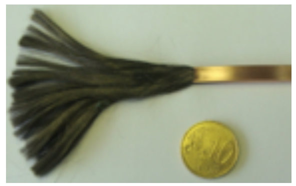
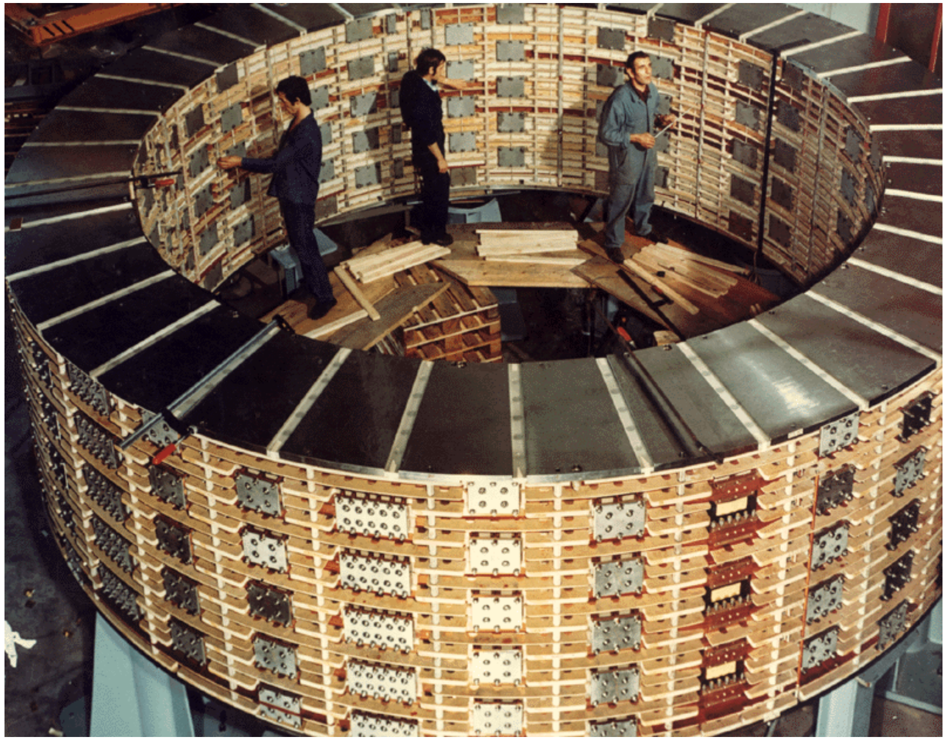
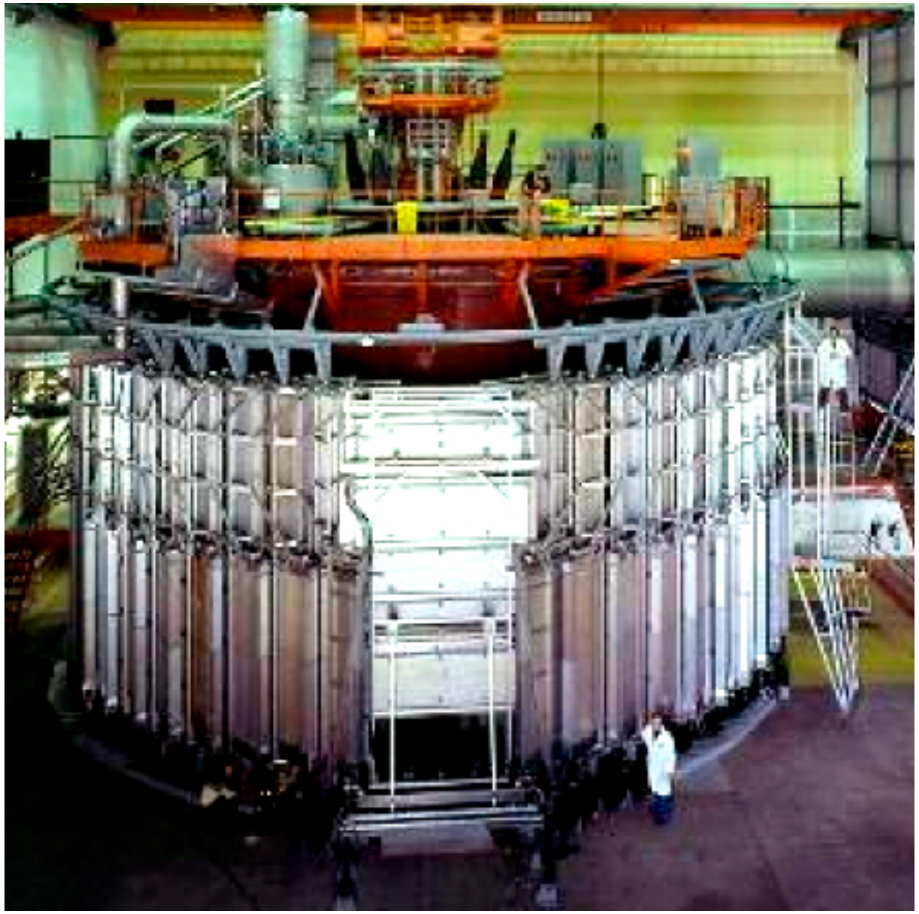
- 1968 : multifilamentary composite (Rutheford Lab.)
- 1974 : CERN bubble chamber (830 MJ)



CERN bubble chamber (BEBC)

$\varnothing_{int}$ = 3.7 m
B_o = 3.5 T
W_{mag} = 800 MJ





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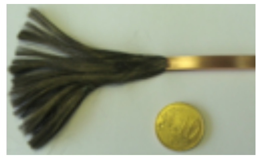

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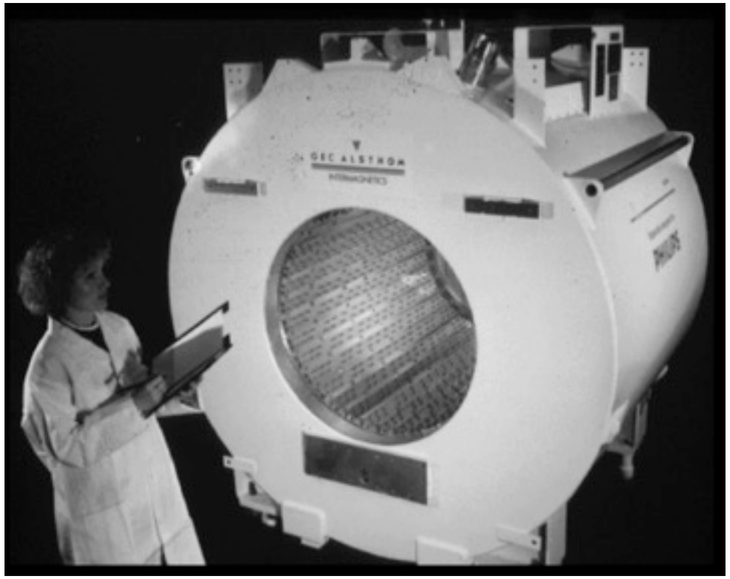
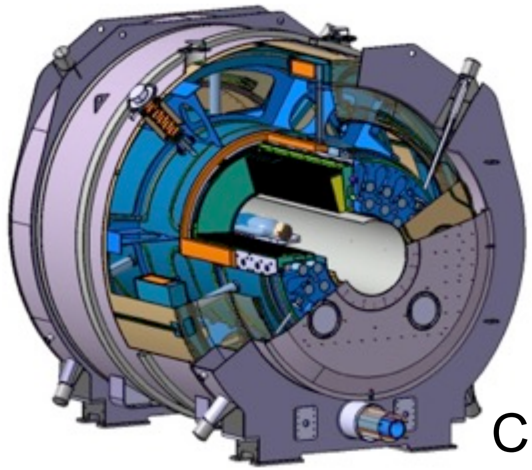
- 1982 : first MRI images (first commercial SC application)

SC magnets and imaging system





CEA

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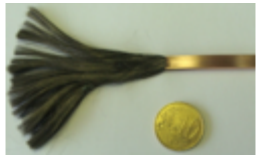
- 1987 : “high Tc” discovery

High T_c discovery

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

Condensed Matter
Zeitschrift für Physik B
© Springer-Verlag 1986

1986

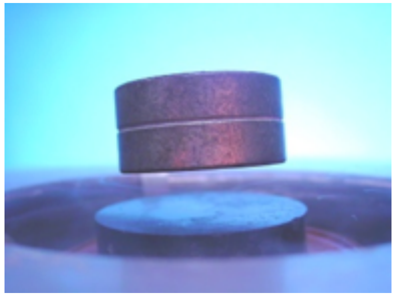
Possible High T_c Superconductivity in the Ba–La–Cu–O System

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

Received April 17, 1986

Metallic, oxygen-deficient compounds in the I
tion $Ba_xLa_{5-x}Cu_5O_{5(3-y)}$ have been prepar
$x=1$ and 0.75, $y>0$, annealed below 900 °C
phases, one of them a perovskite-like mixed
the samples show a linear decrease in resis
increase, interpreted as a beginning of local
to three orders of magnitude occurs, reminisc
tivity. The highest onset temperature is ob
reduced by high current densities. Thus, it re
bute possibly also from 2D superconductin
of one of the phases present.

1987



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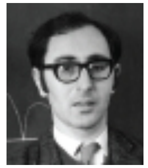

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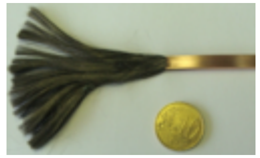

- 1968 : multifilamentary composite (Rutheford Lab.)
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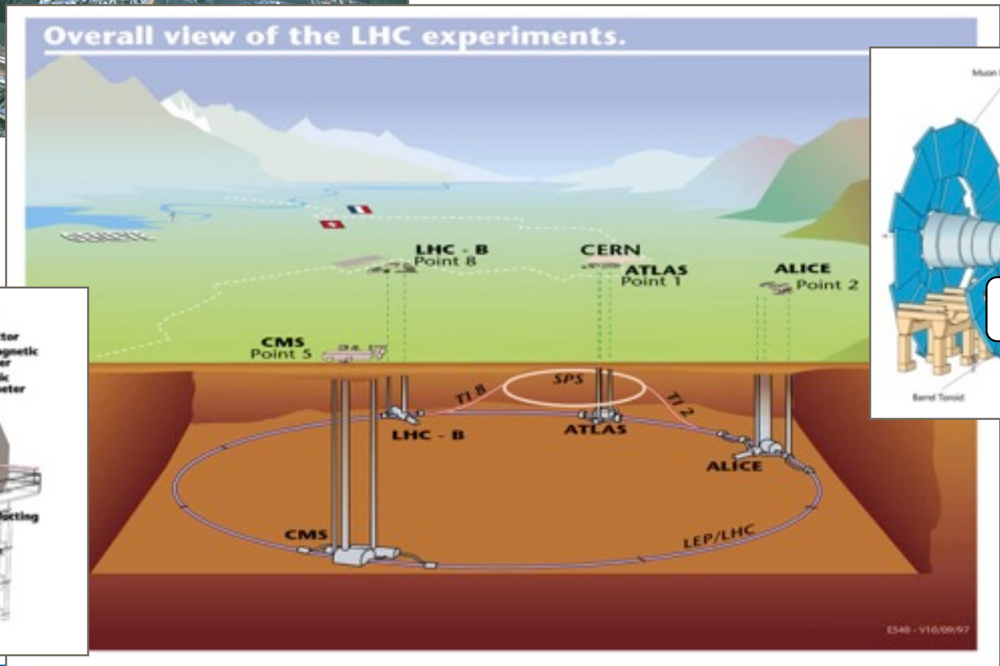
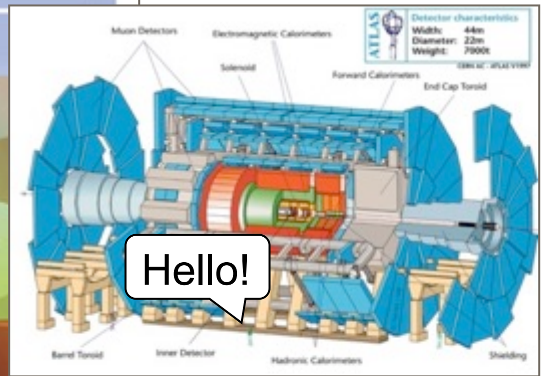
- 1987 : “high Tc” discovery
- 2007 : starting of the biggest SC system: LHC

LHC: bigest SC system

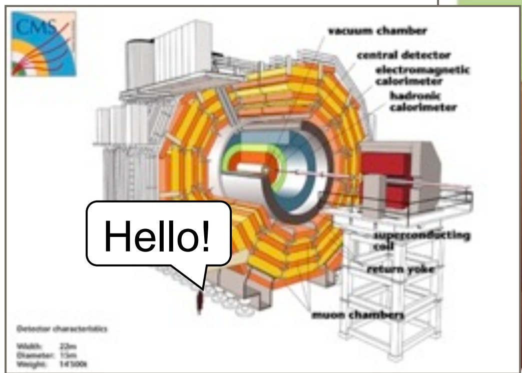
1232 dipoles
392 main quadrupoles
+ experiences (ATLAS, CMS…)



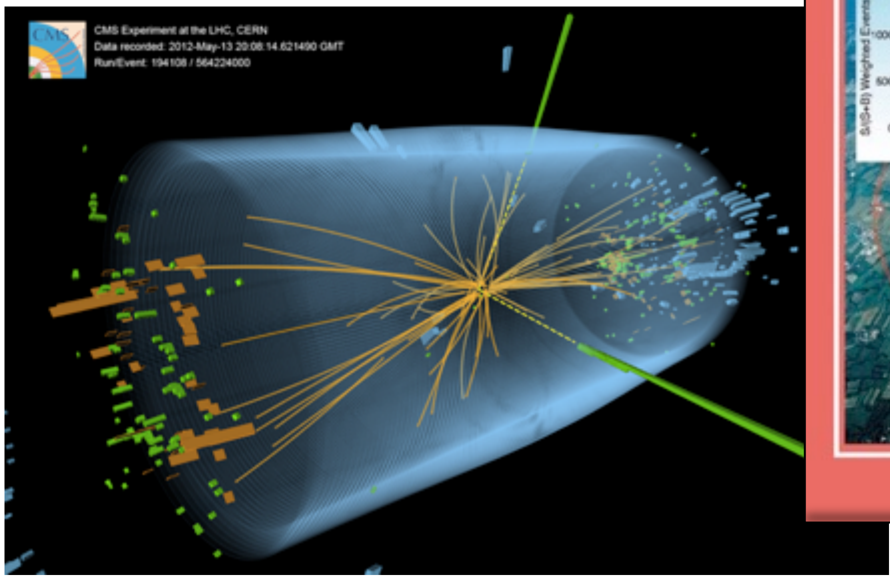
ATLAS

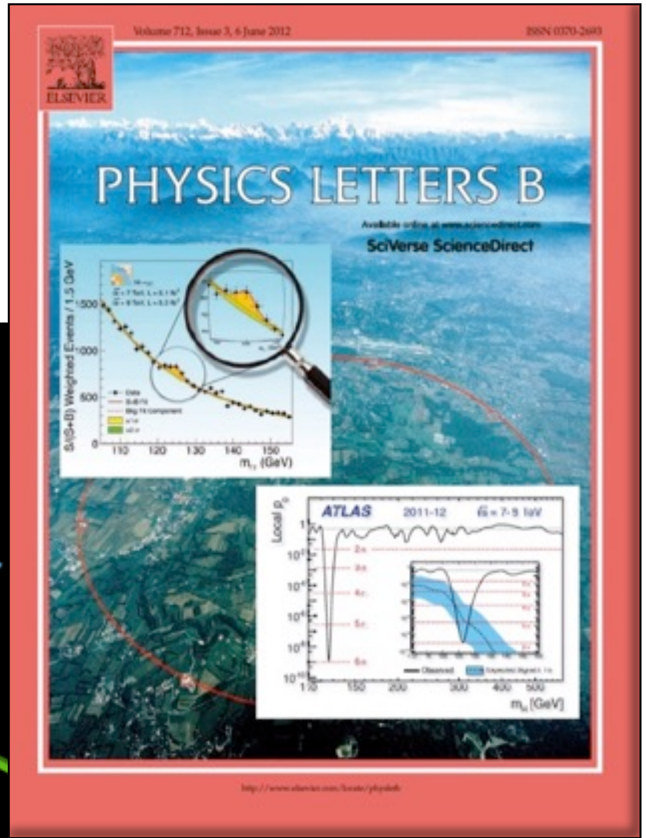


CMS



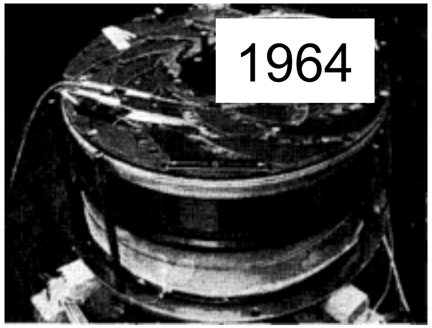
July 4, 2012: day H at CERN





Summary: applied superconductivity

End of 50': high J_c under field
Applied SC is born



Argonne magnet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of one of the phases present.

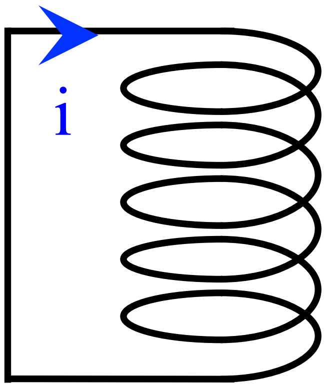
1987

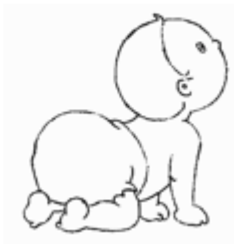
Superconductivity for large scale applications

Superconductor

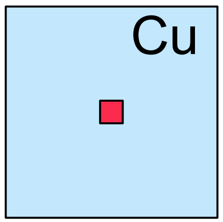
Superconductor:
perfect conductor, but not ideal!

$P_{DC} = 0$





100.00 A

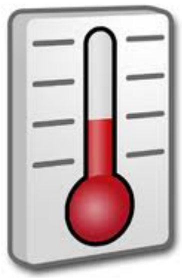


SC
Hundred
A/mm^2

90.00 A
99.93 A

$T < T_c$

$\Rightarrow$ Cryogenic

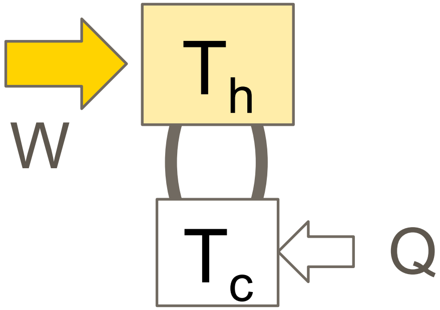


- Cost
- ***Psychological Fear***

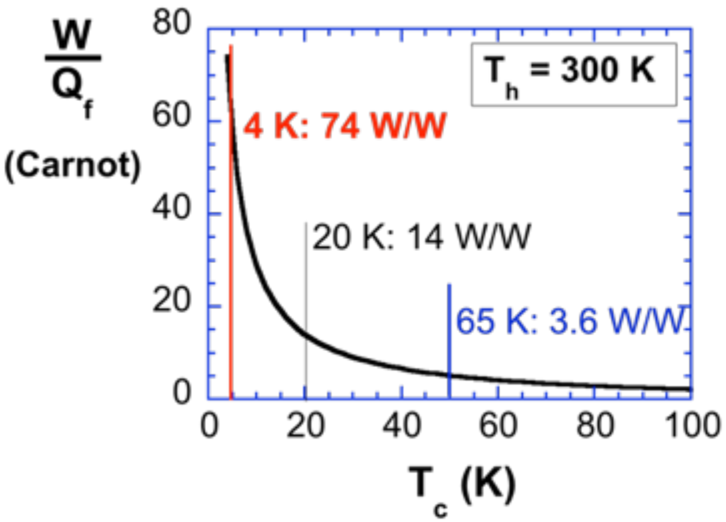
$+ H < H^* \; \& \; J < J_c$

+ Superconductor cost

Cost of energy removal at low temperatures

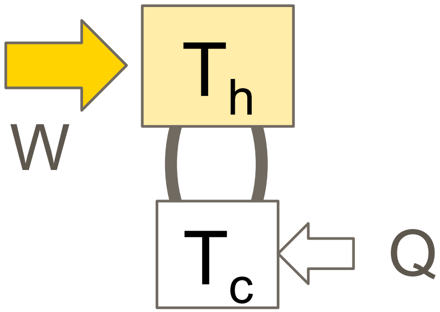


$$\frac{W_{min}}{Q} = \frac{T_h - T_c}{T_c} \; \frac{1}{\eta_{ref}}$$



- 1 liter He (LTS) ≈ 5 €
- 1 liter N_2 (HTS) ≈ 0.08 €

Cost of energy removal at low temperatures



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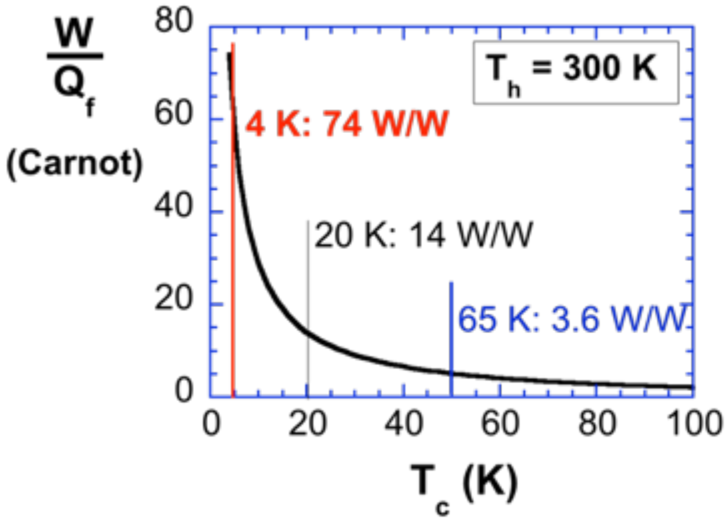
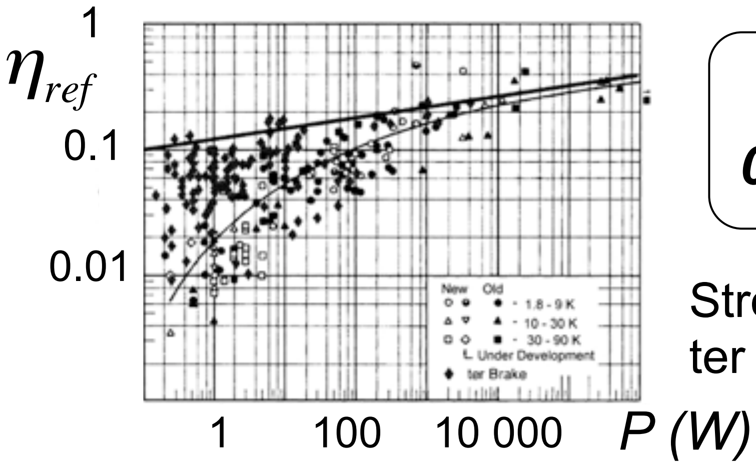




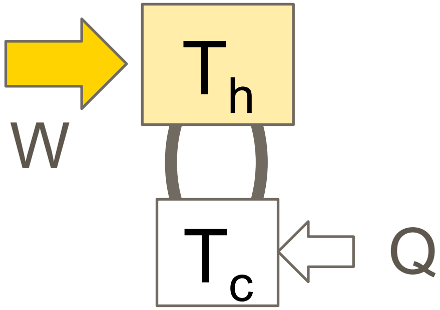
η_{ref}

0.1 – 0.3

Strobridge
ter Brake

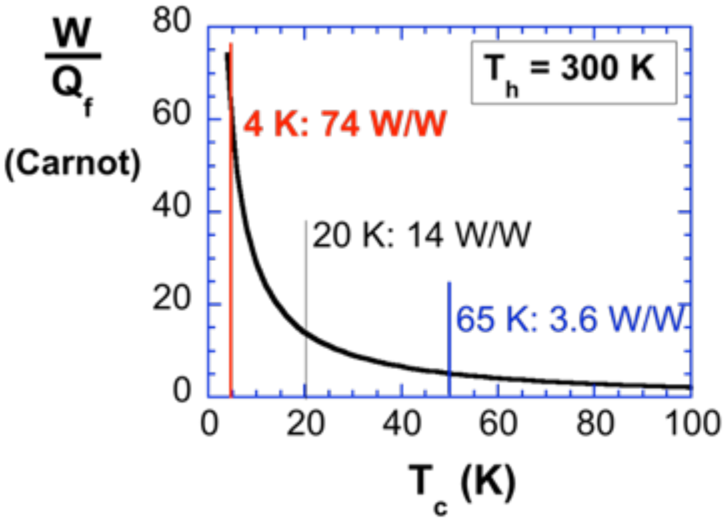
- 1 liter He (LTS) ≈ 5 €
- 1 liter N_2 (HTS) ≈ 0.08 €

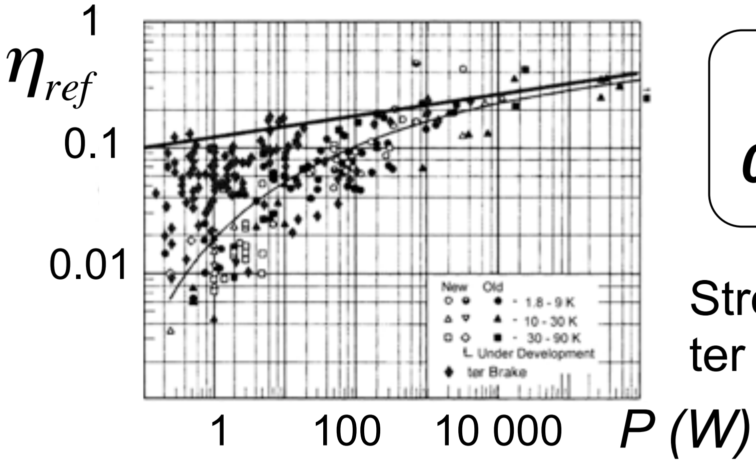
Cost of energy removal at low temperatures



$$\frac{W_{\min}}{Q} = \frac{T_h - T_c}{T_c} \frac{1}{\eta_{ref}}$$

=> Strong interest to operate at "high" temp.





η_{ref}

0.1 – 0.3

Strobridge
ter Brake

- 1 liter He (LTS) ≈ 5 €
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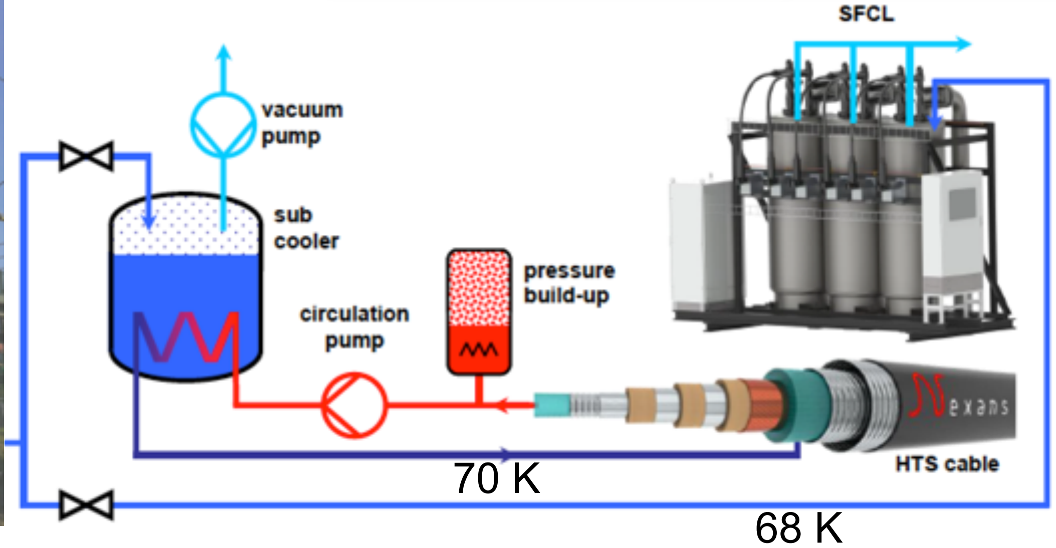
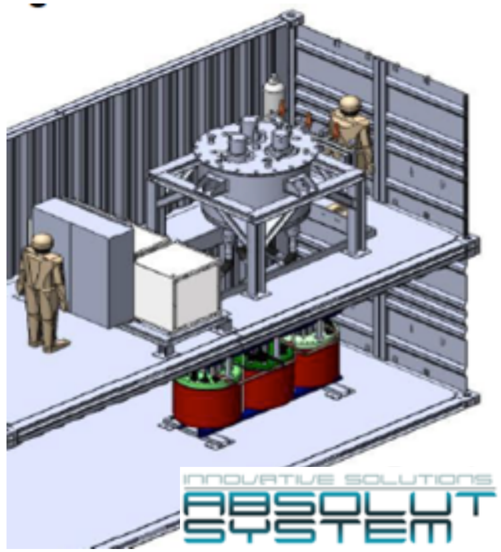
Liquid N_2: environ^t friendly cooling fluid & electrical insulation

Two main cooling solutions

Comonly used in industry

LN2 production overstep 60 000 tons/day for some large plants





Liquid N_2: environ^t friendly cooling fluid & good electrical insulater

AC losses

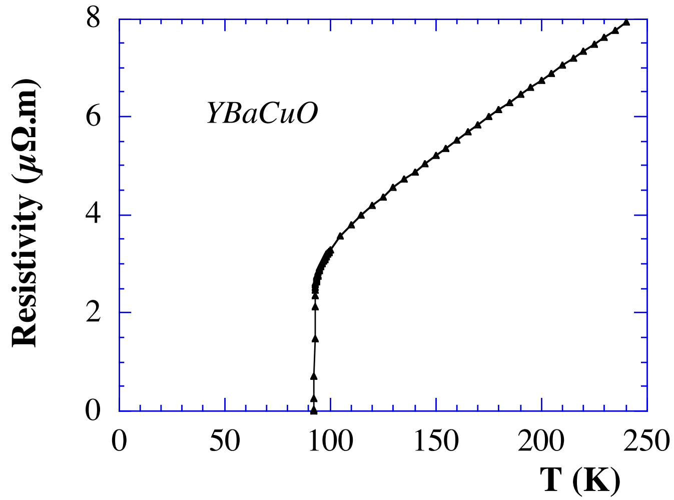
$P_{DC} = 0$ But $P_{AC} \neq 0$

Faraday law: $\overrightarrow{curl}\,\vec{E} = -\dfrac{\partial \vec{B}}{\partial t}$ $\qquad \vec{E} + \vec{J} : losses\left(\delta P = \vec{E}\,\vec{J}\left[W/m^3\right]\right)$

AC losses may be reduced by a suitable structure but not suppressed.

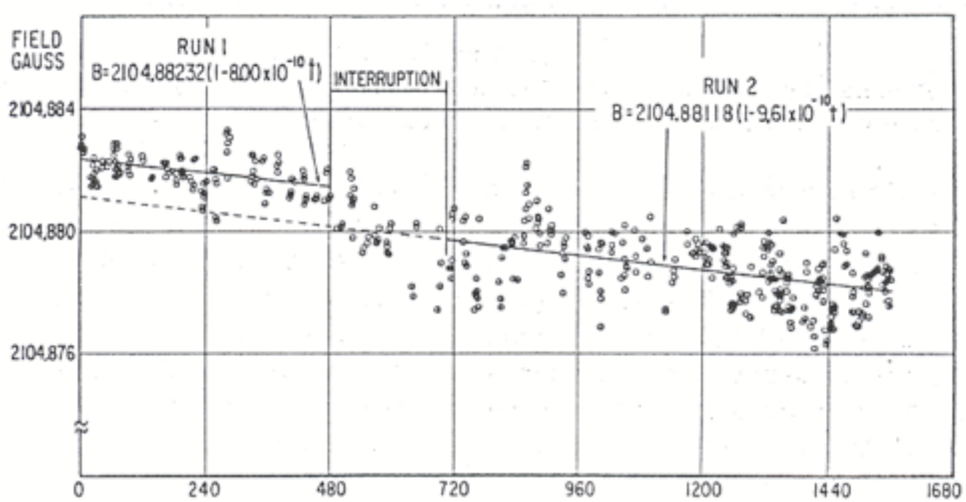
=> Interest more in DC than AC

Perfect conductivity $P_{DC} = 0$

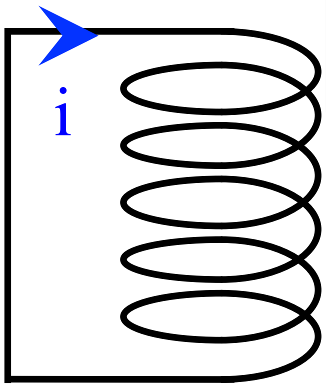


Field decrease measurement => τ

Mills & Files experiment (1962)



(hours)



100.00 A

90.00 A
99.93 A

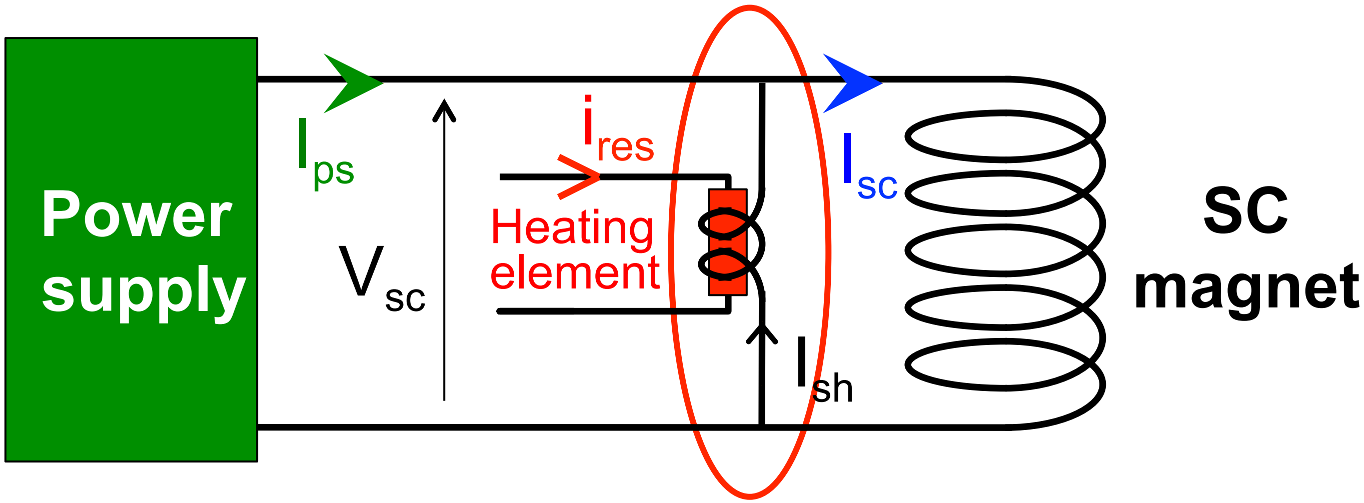
Experimental time constants:

Test 1 : τ = 144 000 years

=> $\rho < 10^{-25}\ \Omega m$

Persistent mode

How to induce a current in a SC coil?



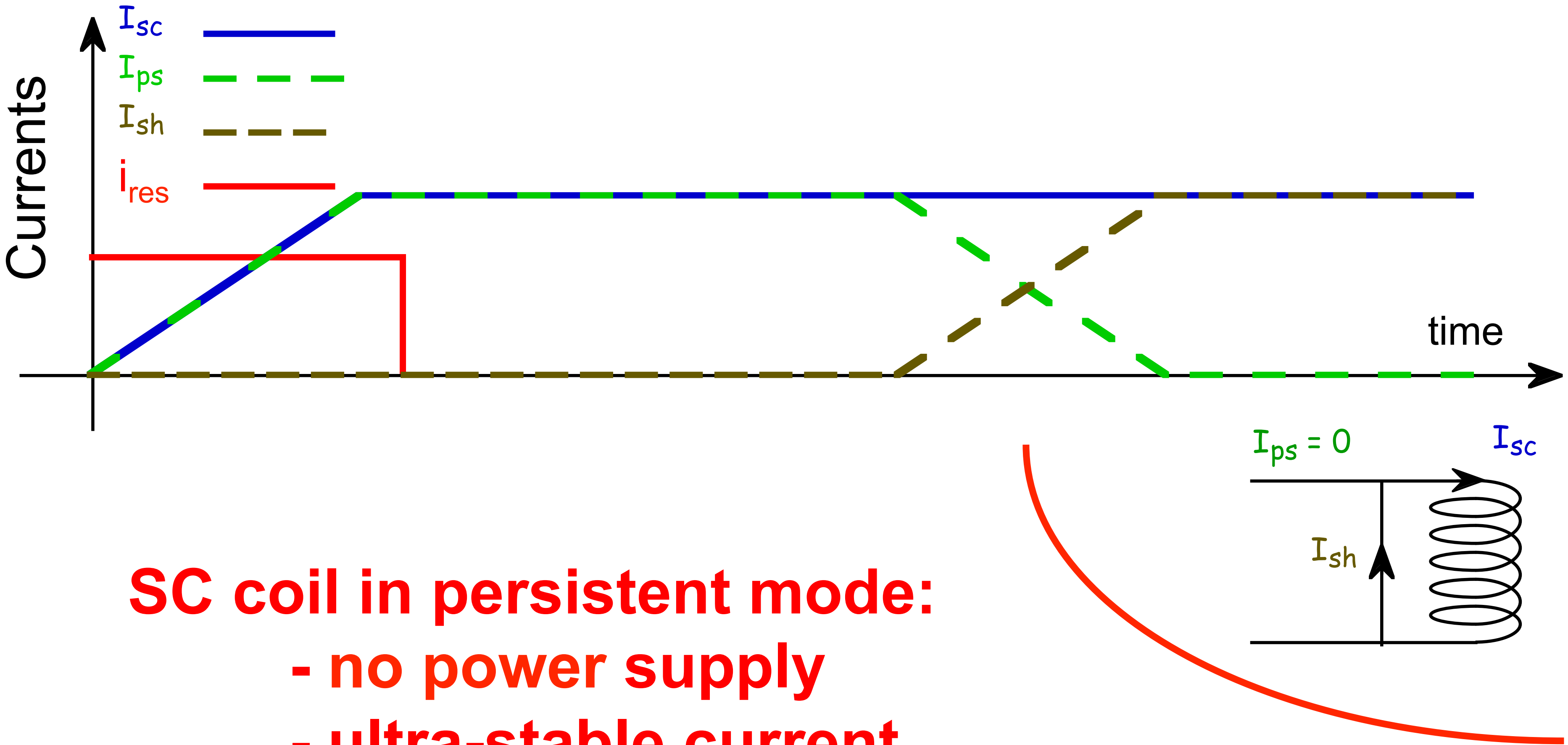
SC shunt with thermal control

- heating: normal state, high resistance

- no heating: SC state

(SC shunt with field control as well)

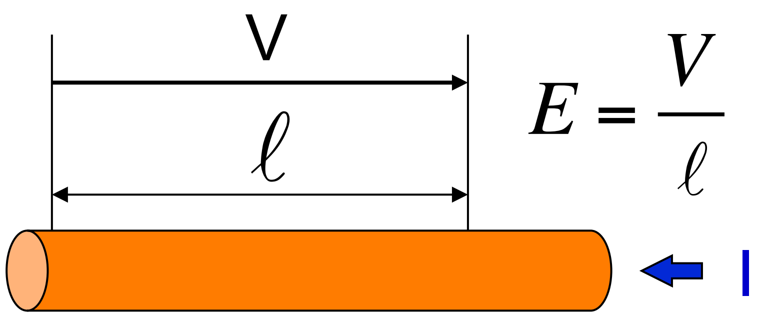
Current supply: end of cycle



SC coil in persistent mode:
- no power supply
- ultra-stable current

Perfect conductivity

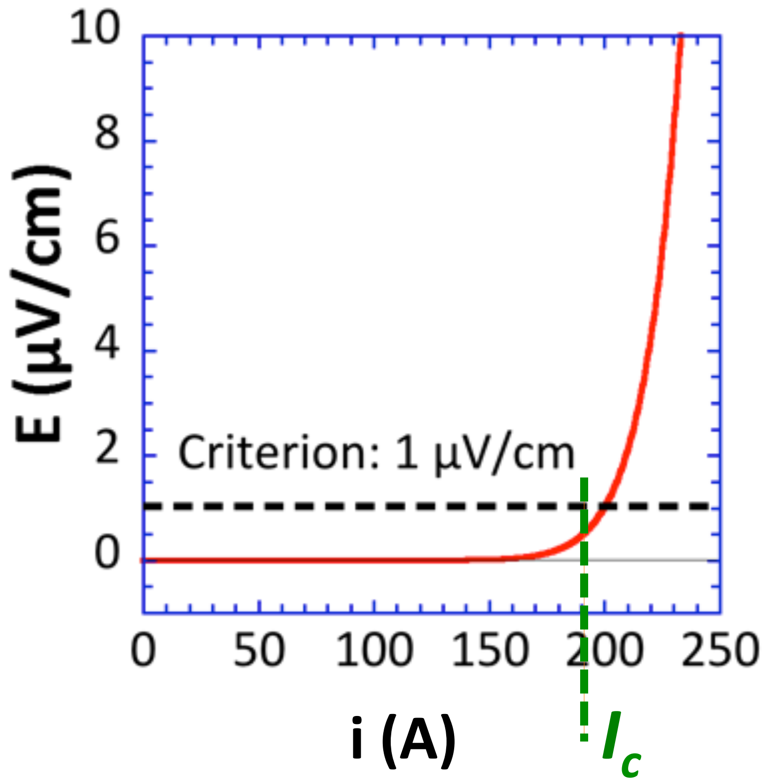
ρ = 0 => I/J infinite?



$$E = \frac{V}{\ell}$$

V: voltage (V)

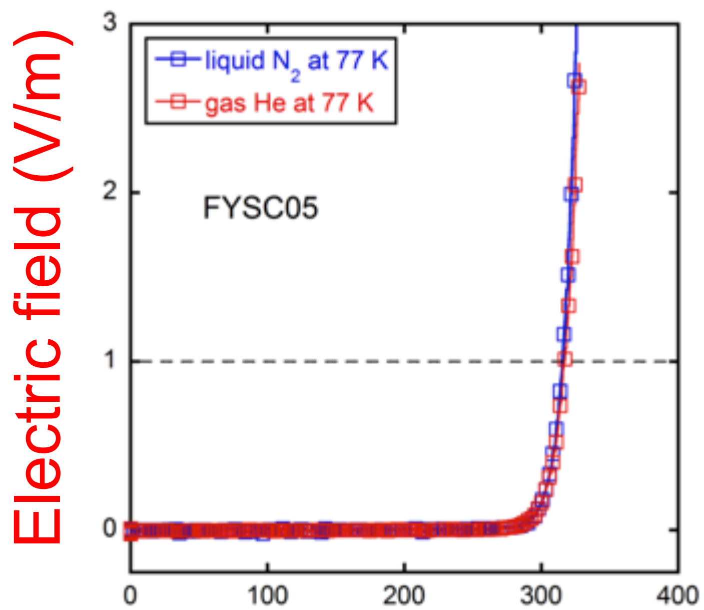
E: electric field (V/m) (µV/cm)



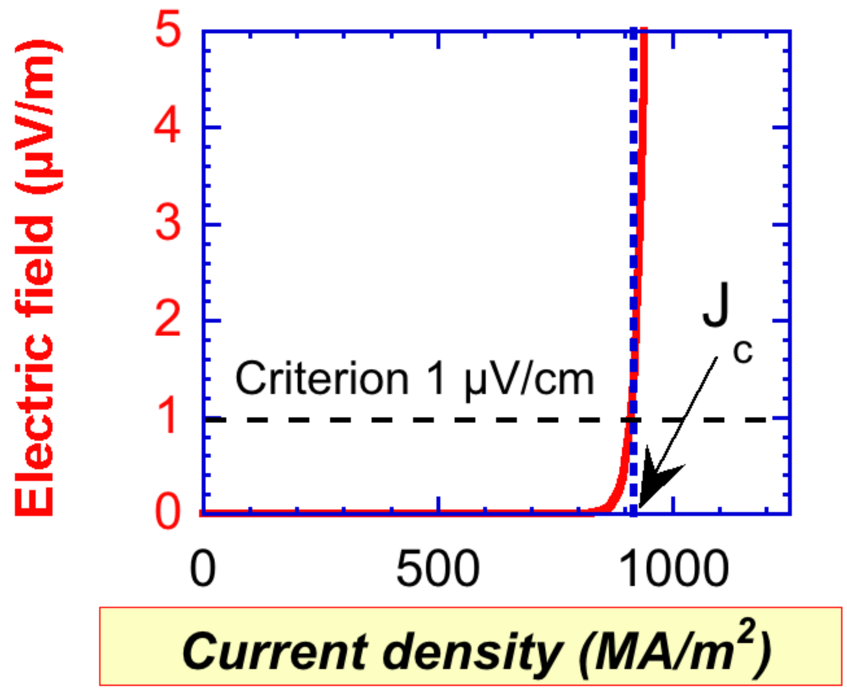
Criterion to define I_c
E = 100 µV/m (1 µV/cm)
International standart

E-J Characteristics

Experimental E(I) curve

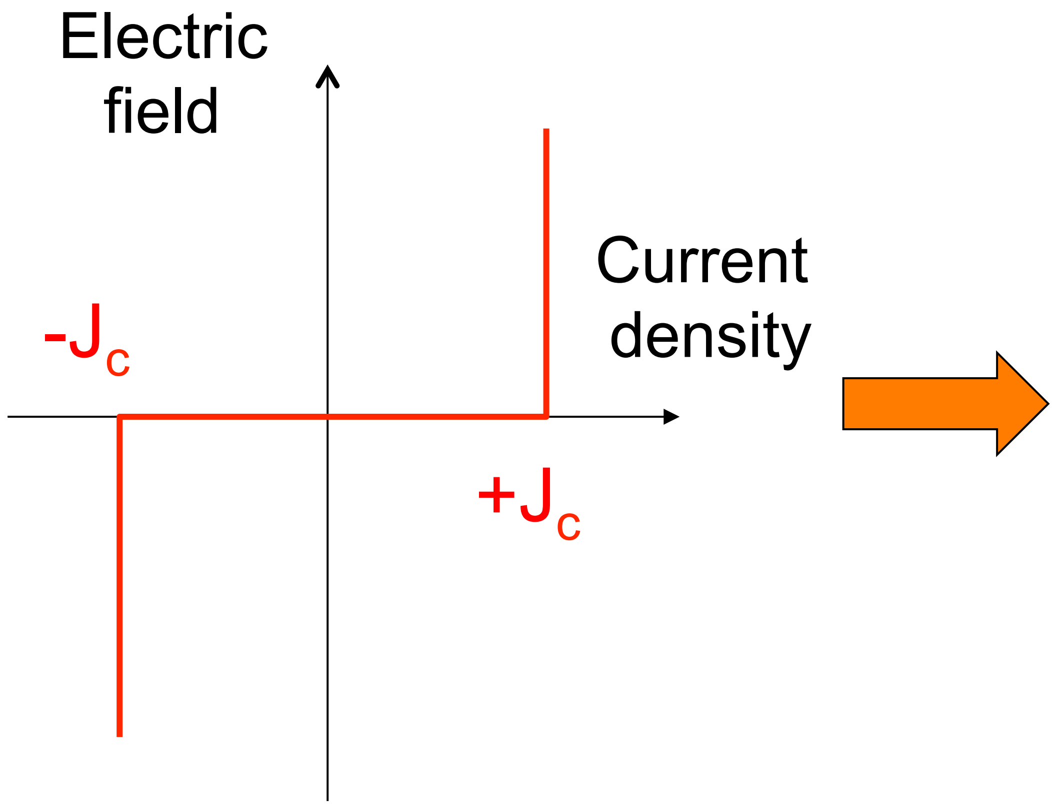


MODEL



- Relation valid for local current density
- Infinite stiffness

E-J – Critical State Model



Local current density

ONLY 3 values

- 0
- $+ J_c$
- $- J_c$

Critical state model (CSM)

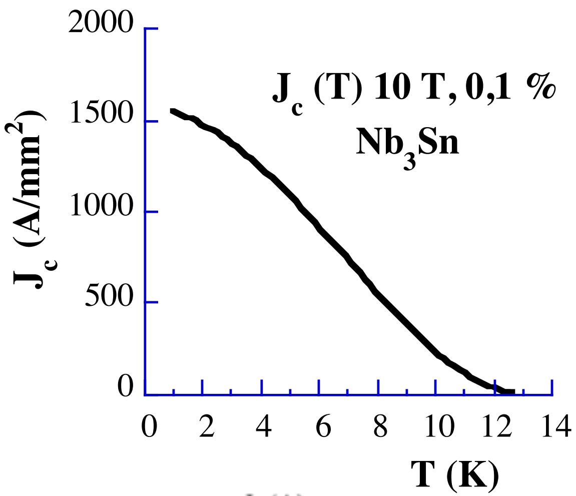
Critical State Model – Bean model

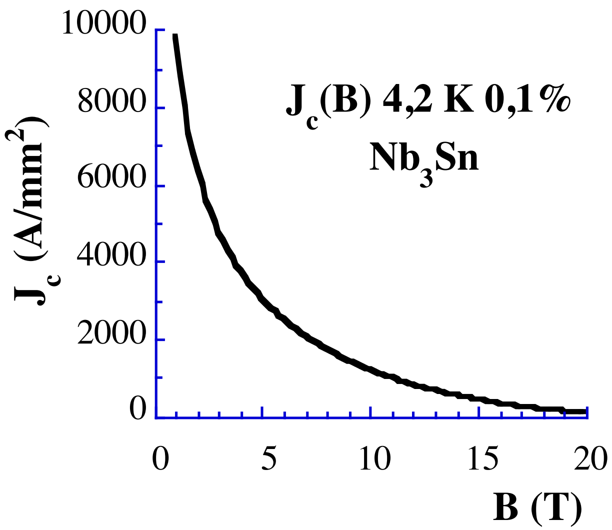
Bean model:
Critical state model
+
J_c constant (not function of B)

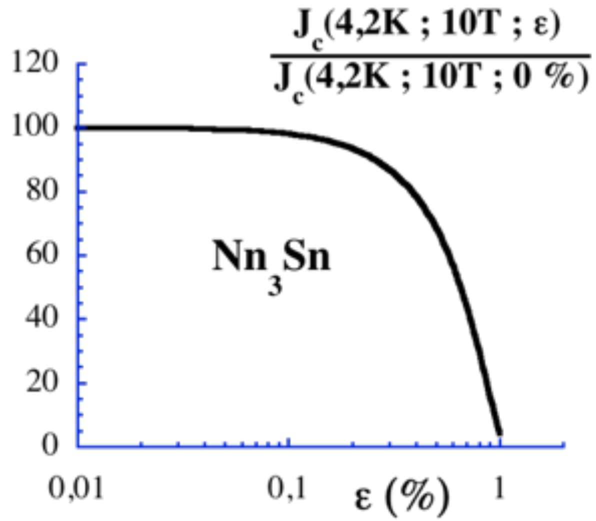
Bean Model very used
Especially for analytical expressions

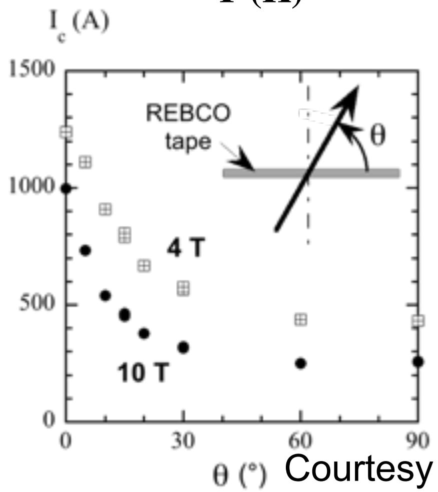
Critical current density J_c

$$J_c = J_c\,(T, B, (\theta), (\varepsilon))$$

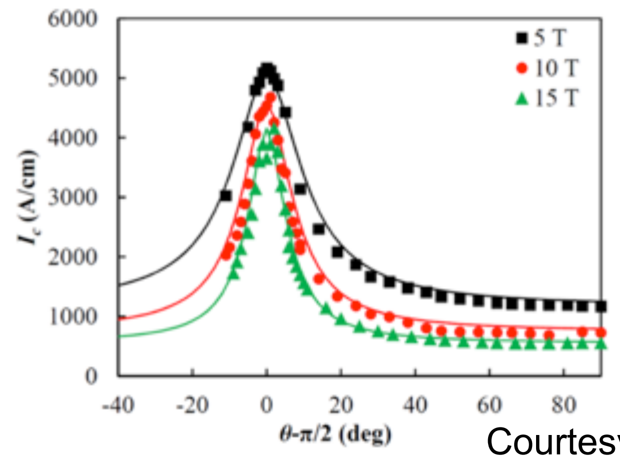








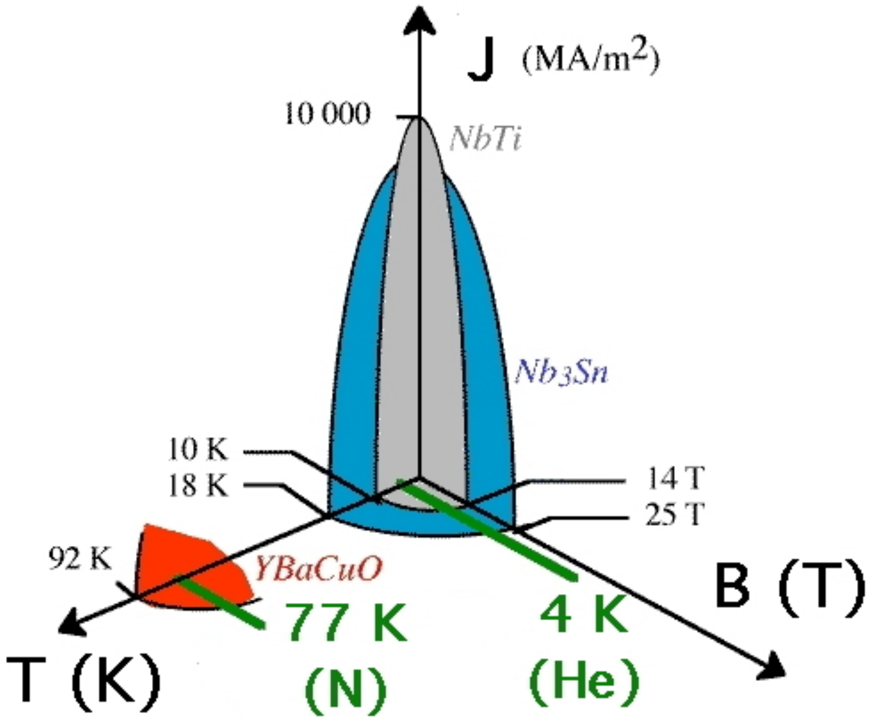
Courtesy T. Benkel

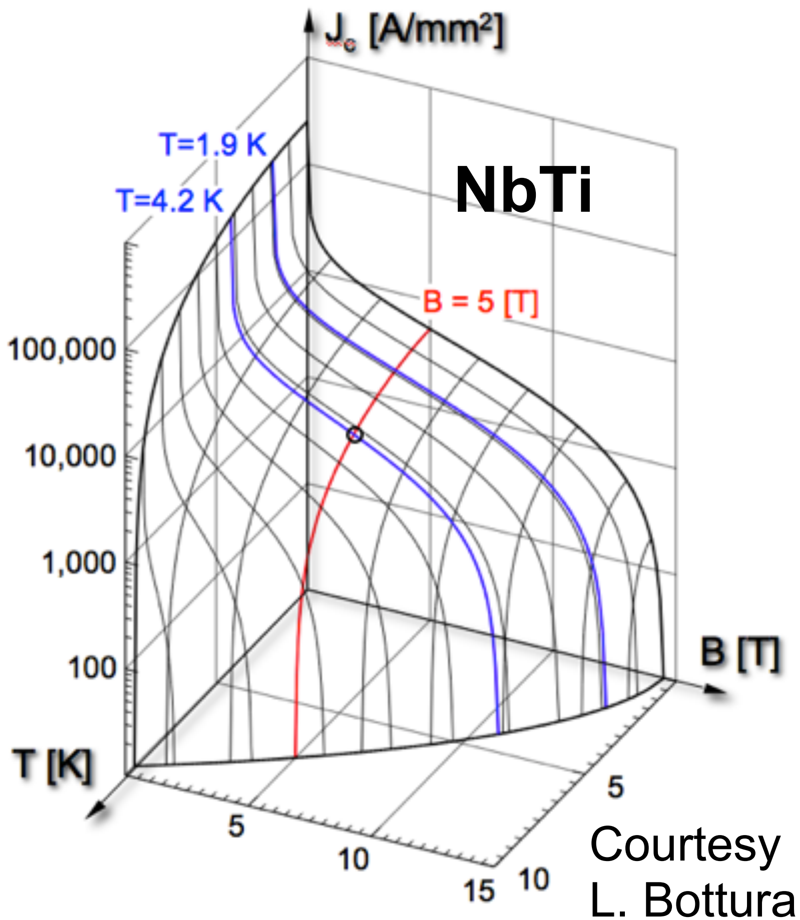


Courtesy J. Fleiter

Critical surface

- Three main dependent limits (T_c, B_c, J_c): critical surface





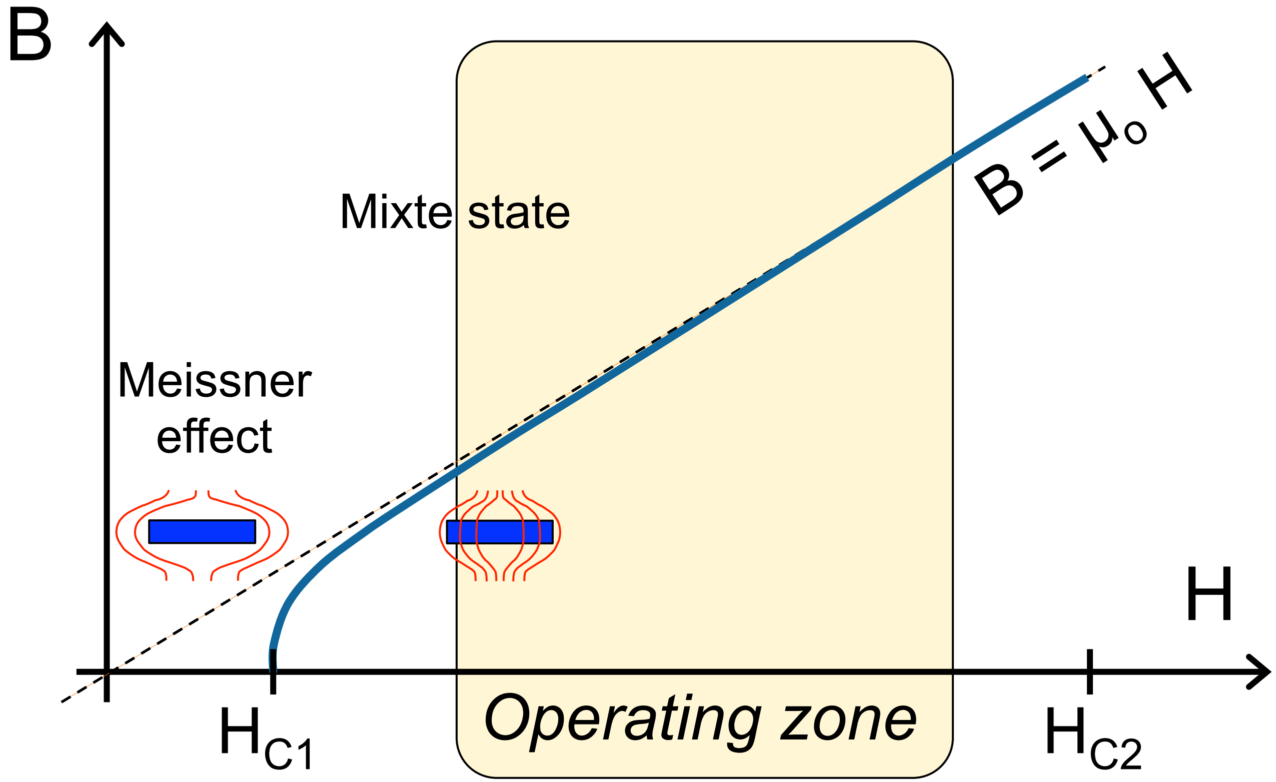
Courtesy L. Bottura

- T_c & H_c: intrinsic
- J_c: elaboration (pinning)

B-H characteristic

B = 0 in a superconductor (Meissner effect)

Forget the Meissner effect for large scale applications!



$$B \approx \mu_o H$$

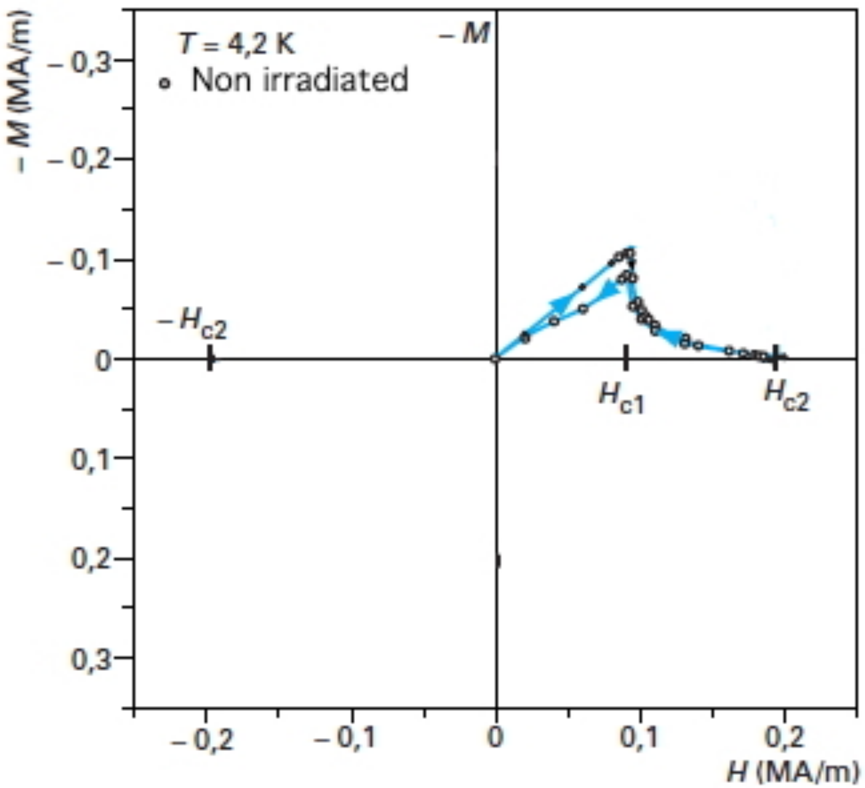
$\mu_o H_{C1}$ (0 K)

NbTi: 10 mT
Nb_3Sn: 17 mT
YBCO: ≤ 70 mT

Not to scale!

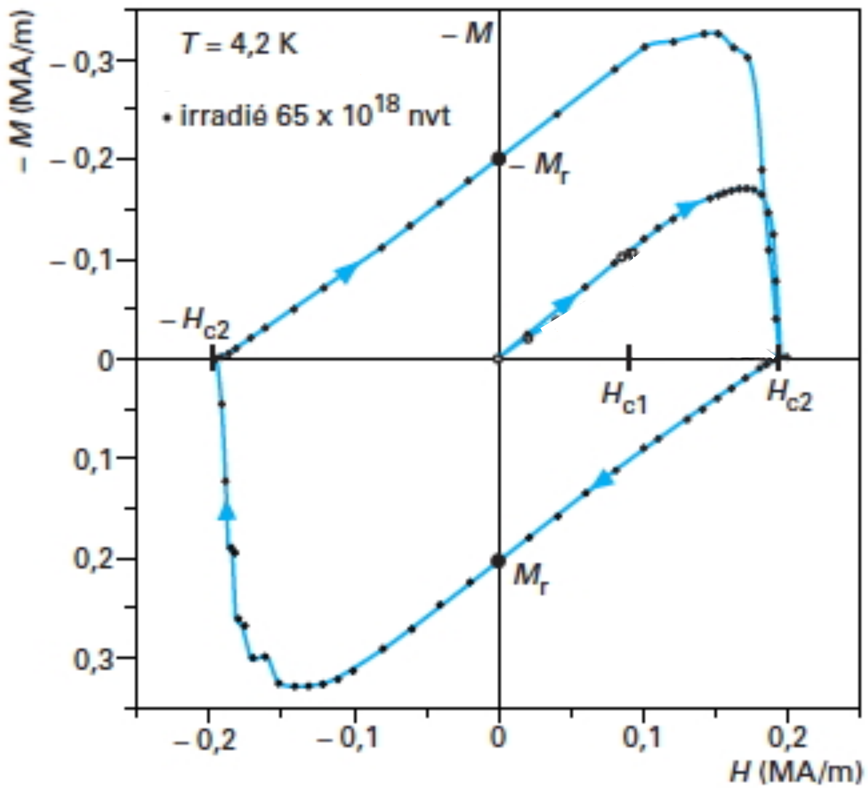
B-H characteristic (M-H)

$$B = \mu_o (H + M) \quad \Rightarrow \quad -M = H - \frac{B}{\mu_o}$$



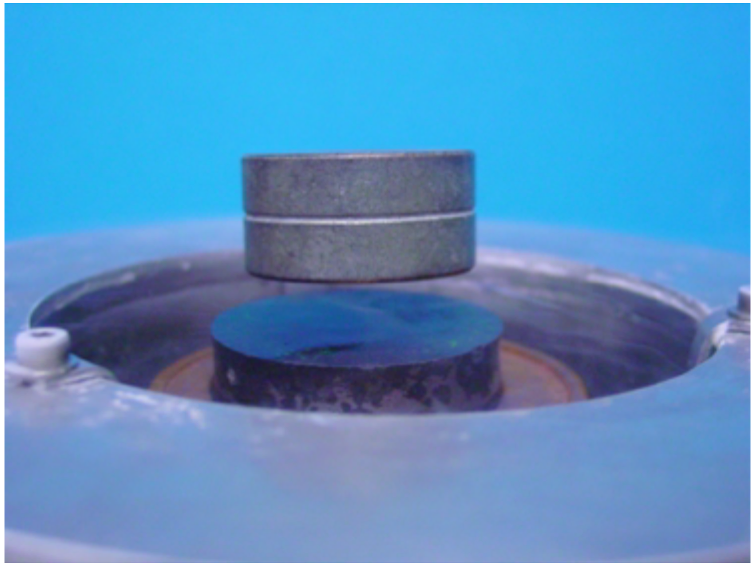
Non irradiated Nb sample

From Sekula and Kernohan

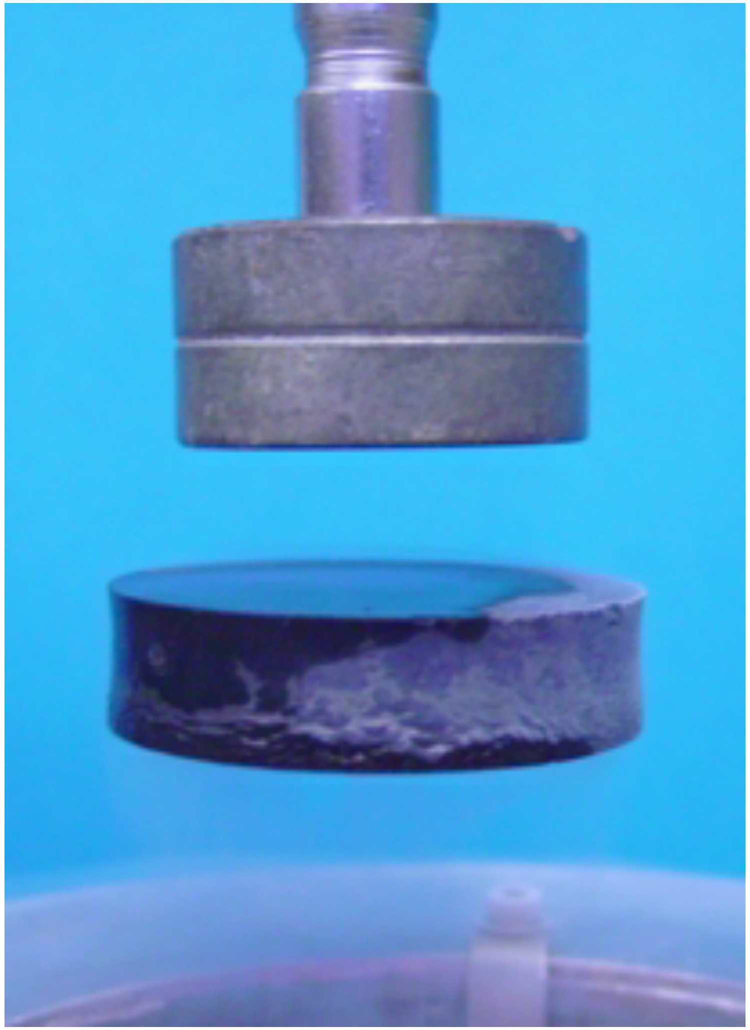


Irradiated Nb sample

Levitation experiment



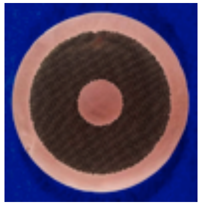
Based on induced current
(Lenz law)
and absence of damping



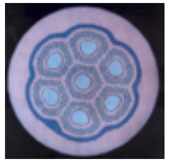
Superconducting wires

Low T_c

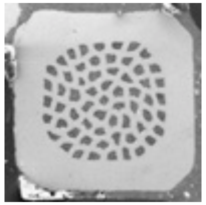
- NbTi (3000 t/y) – *9.5 K*



- Nb_3Sn (25 t/y ~~ITER~~) – *18 K*

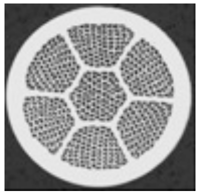


- MgB_2 – *39 K*

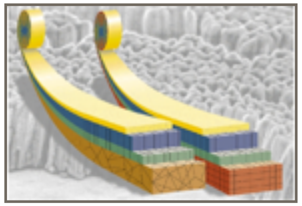


High T_c

- BiSrCaCuO (1G)
  85 – 110 K



- ReBaCuO (2G) – *90 K*



Thin tape

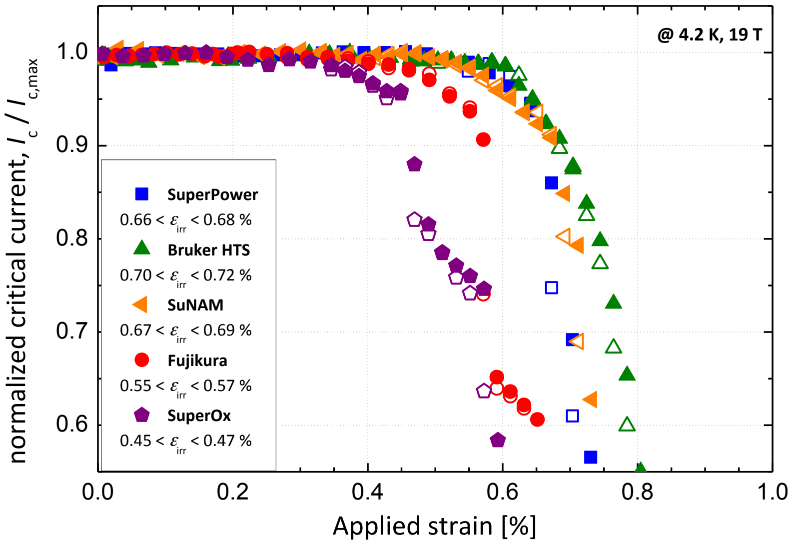
Mechanics: must be stress tolerant!

Fundamental for LTS magnet

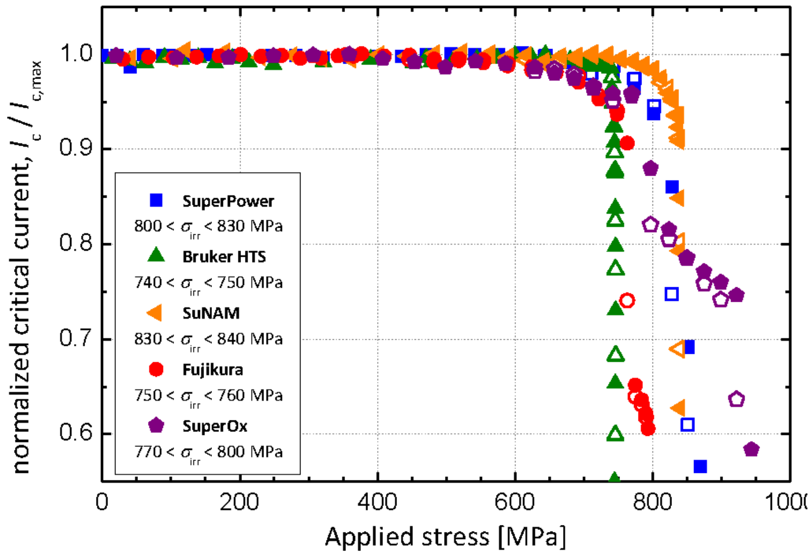
- Ultra sensitive to mechanical perturbations

High mechanical performances often required

- Magnets: high J and B => high Lorentz force (JB)
- Solenoid: σ = J B R (independant turns)



I_c vs. axial stress



Summary

- Superconductivity market exists
  - 5 185 Meuros in 2012
  - Dominated (> 60 %) by MRI and NMR
  - Fully still dominated by LTS (> 90 %), NbTi
- Persistent mode for SC magnet
  - Resistive (inductive) shunt to inject current
  - Very stable current and no power supply

Outline

- Introduction
- Historical references
- Superconductivity for large scale applications
- Superconducting material (REBCO tapes)
- Superconducting applications
- Fault Current Limiter (FCL)

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Superconductivity II
Superconducting Materials - ReBCO tapes

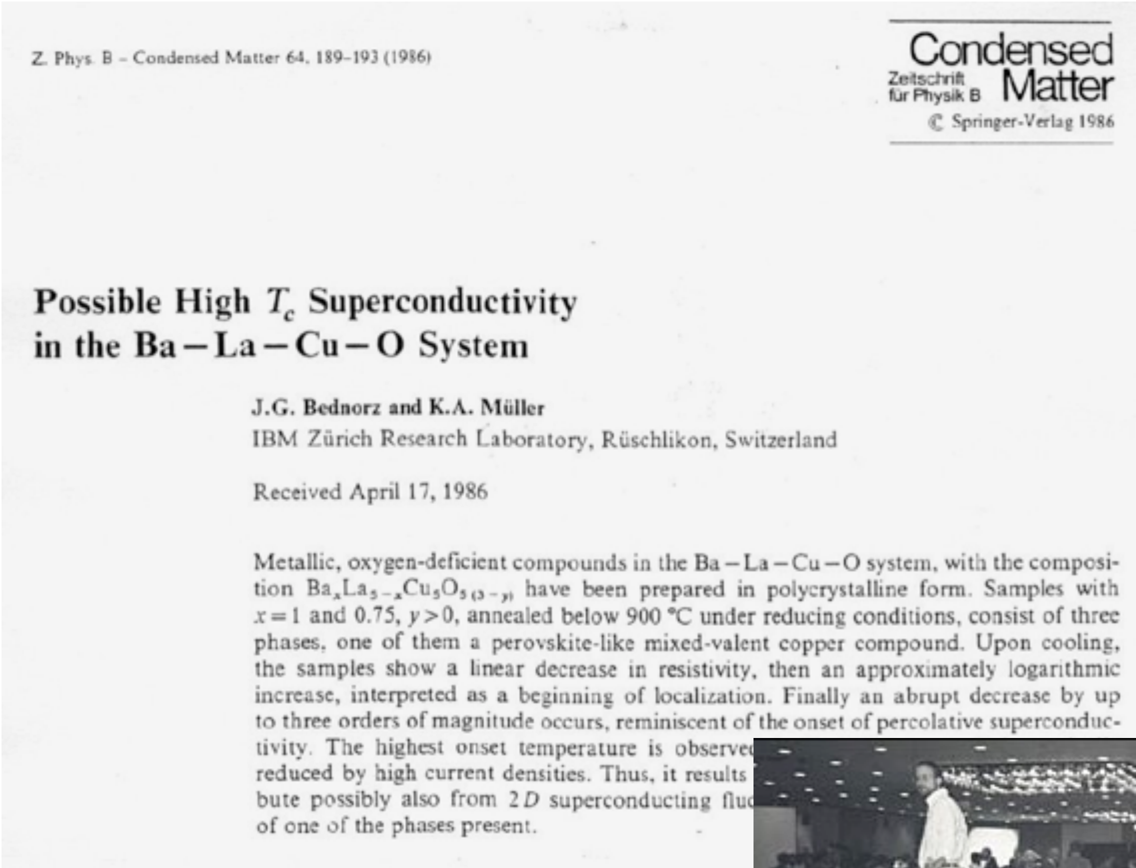
Pascal Tixador
Grenoble-INP, Université de Grenoble Alpes, CNRS
G2ELab, Institut Néel

UNIVERSITÉ Grenoble Alpes · Grenoble INP · CNRS · NÉEL institut · G2E Lab

Summary LTS

- LTS by far the most used SC
  - 5050 M€ / 30 M€ for HTS (SC devices 2011)
- Two main LTS materials: NbTi & Nb_3Sn
- NbTi is by far the most used SC
  - 3000 tons/year
  - Easy to use and handle
  - Limited in field: 9 T (4 K) & 12 T (1.8 K)
- Nb_3Sn complex to handle (brittle, reaction)
  - B < 23.5 T (1.8 K)

HTS breakthrough



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

Condensed Matter
Zeitschrift für Physik B

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
reduced by high current densities. Thus, it results
bute possibly also from 2D superconducting fluc
of one of the phases present.

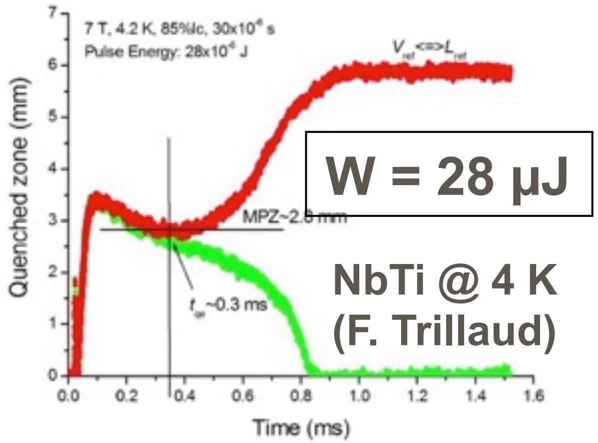
YBaCuO
January 1987

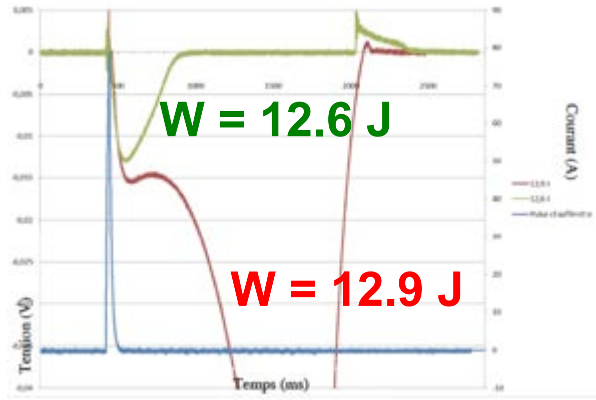
Woodstock of
Physics 1987

HTS interest

Stability

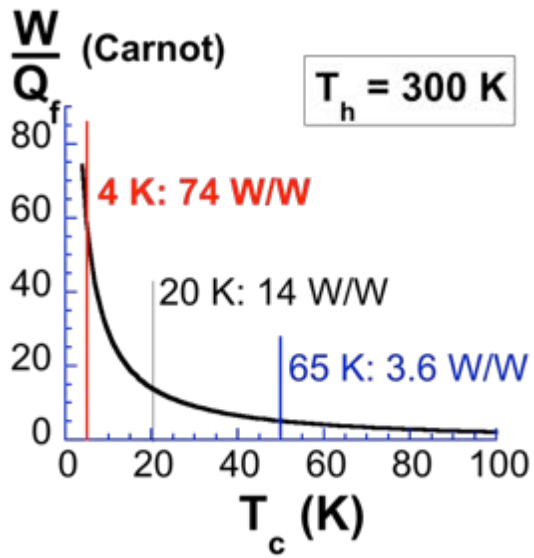
(behaviour against perturbations)





REBCO @ 4 K (B. Vincent)

Cryogenics

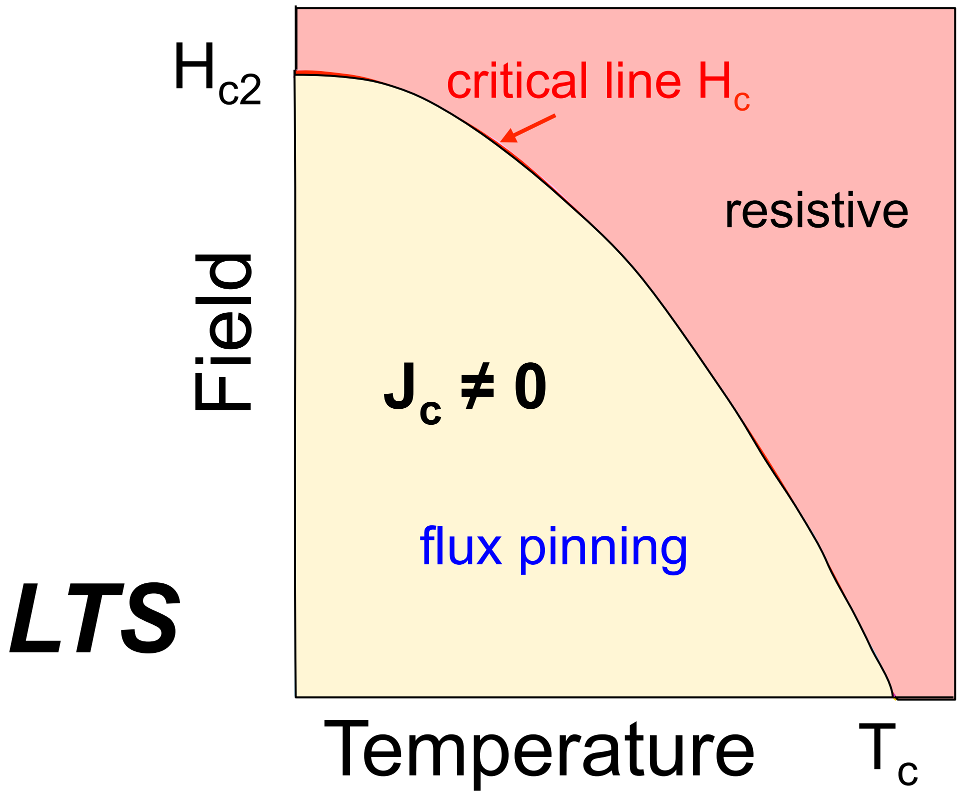


- 1 liter He: 5 €
- 1 liter N_2: < 0.1 €

Liquid N_2: industrial fluid

HTS specificities

Phase diagram of a superconductor - LTS

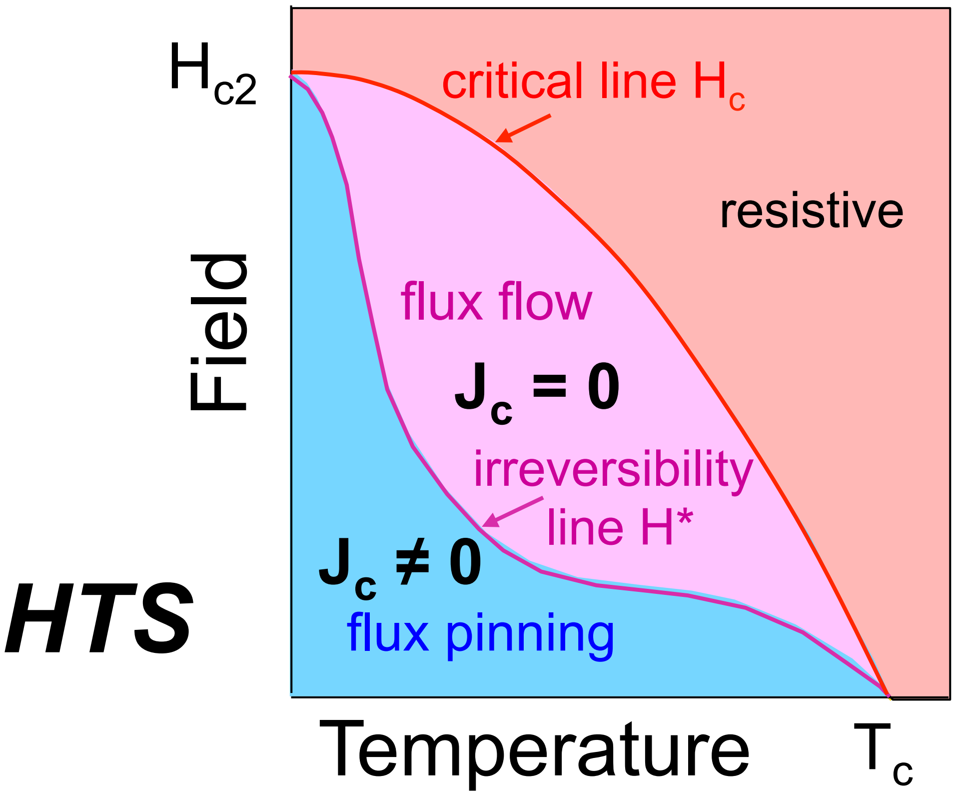


One single line

- Critical line $H_c(T)$
  - Relevant: $J_c = 0$

HTS specificities

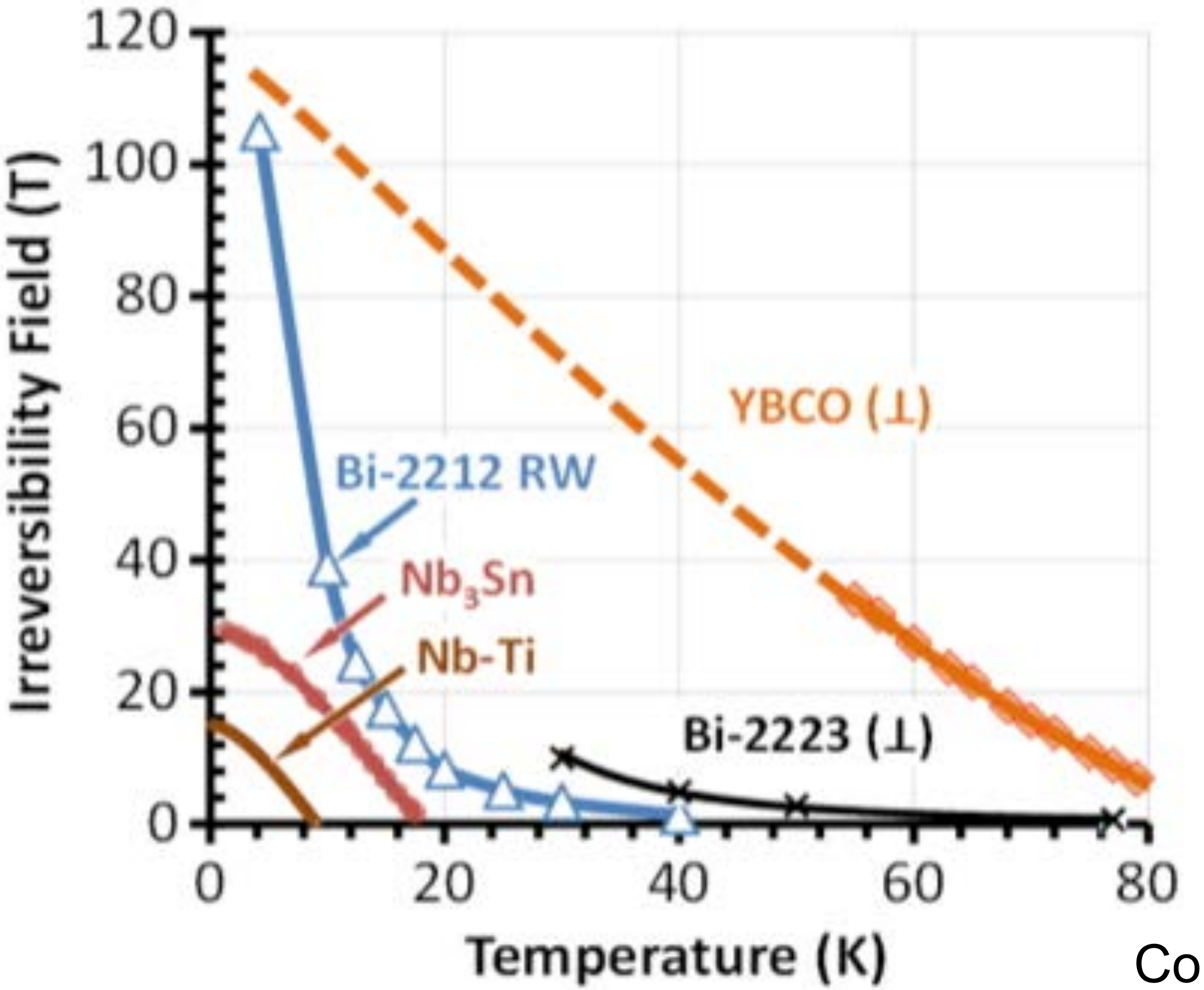
Phase diagram of a superconductor - HTS



Two lines

- Critical line $H_c(T)$
  - Not relevant: $J_c = 0$
- Irreversibility line $H^*(T)$
  - Relevant: $J_c \neq 0$

Irreversibility lines

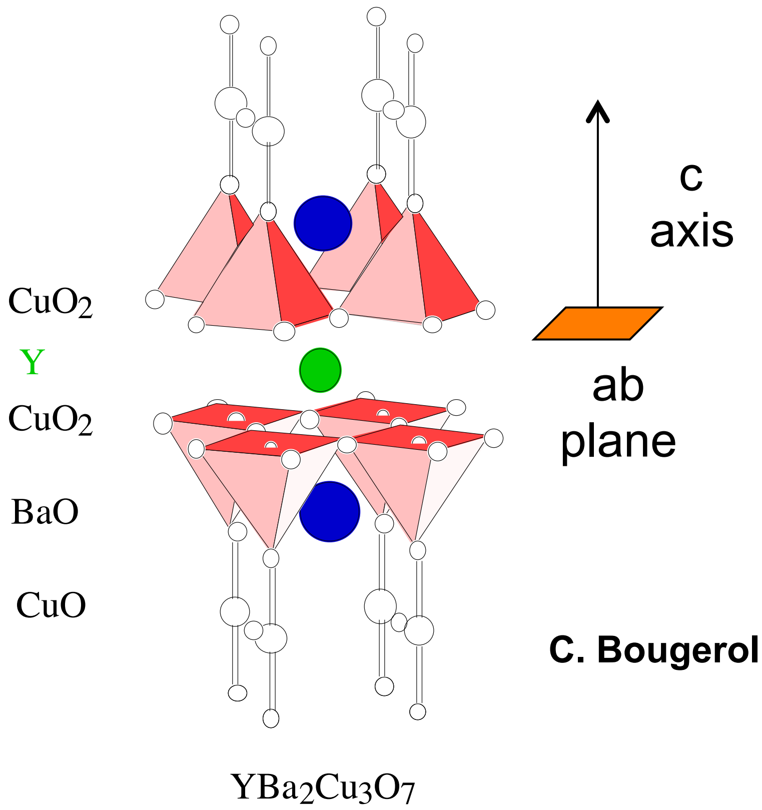


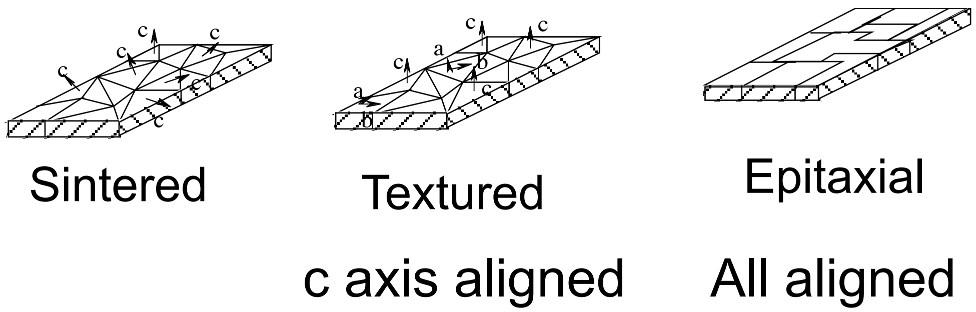
Strong interest for YBaCuO

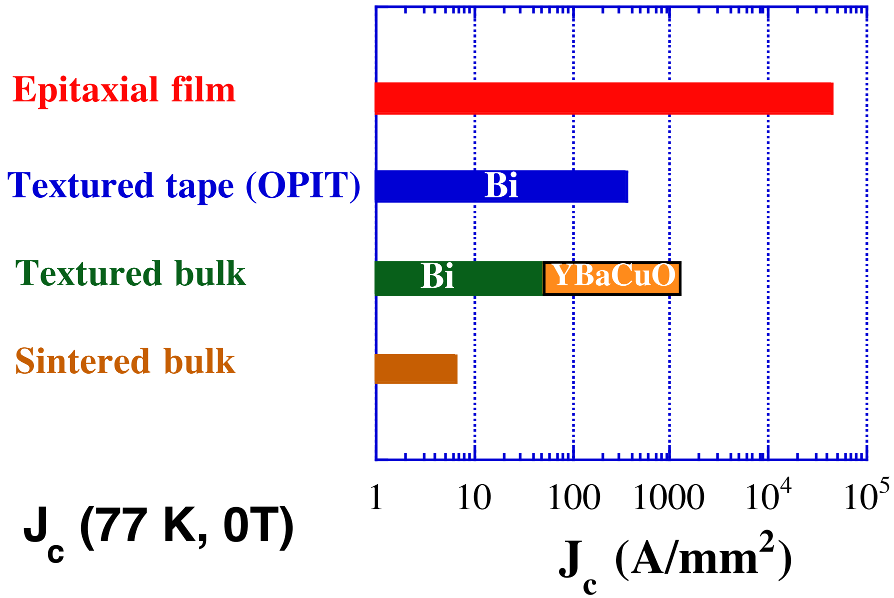
Courtesy D. Larbalestier

HTS specificities

High anisotropy



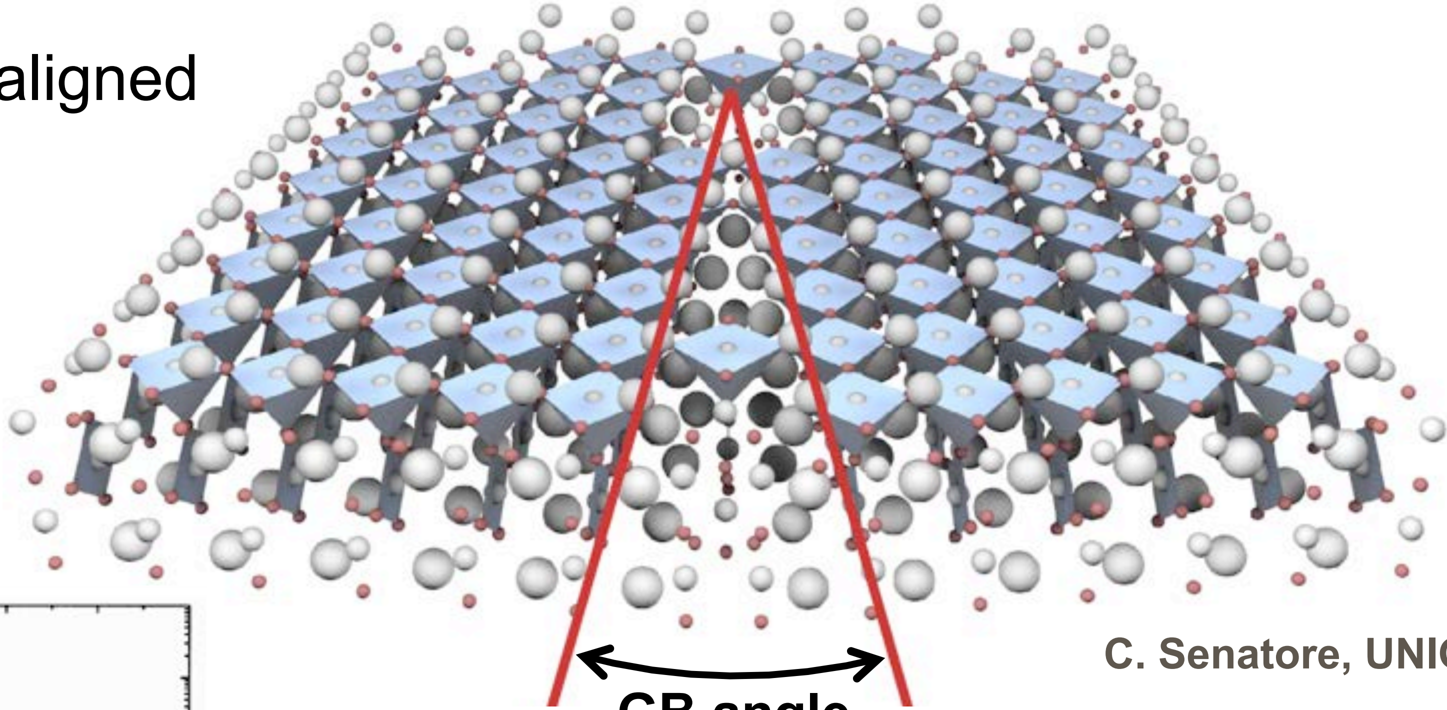




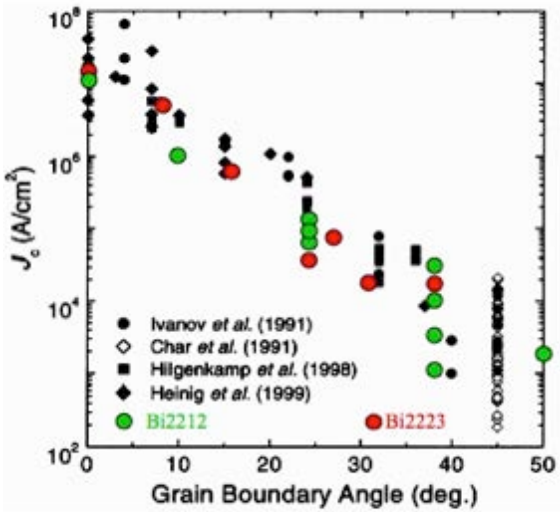
- Ceramic brittle materials
- Very sensitive to defects (ξ)

HTS specificities

ab planes aligned



C. Senatore, UNIGE



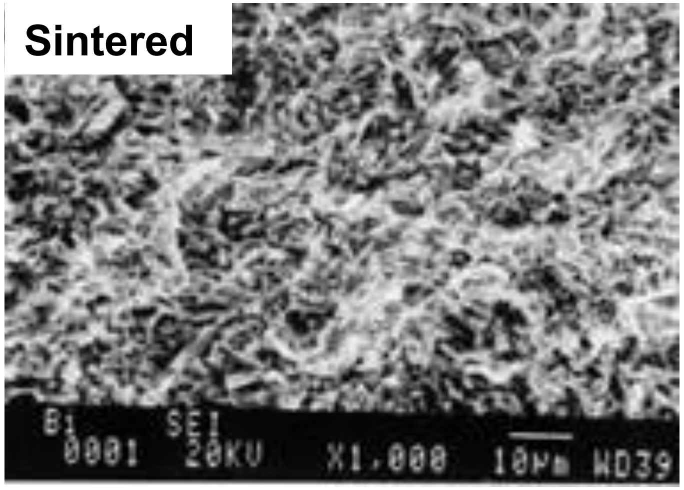
ab planes alignement not sufficient!

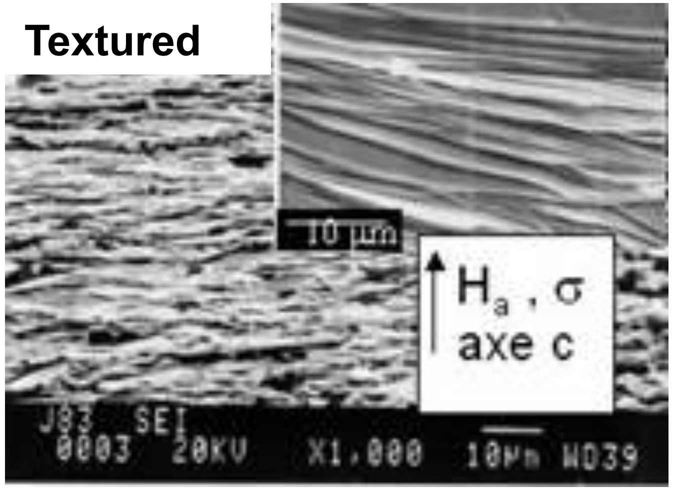
Deviations higher than 6 degrees already reduce J_c significantly

Challenge: make a „crystal“ on km lengths!

Texturation

- Mechanical texturation (drawing): 1G BSCCO





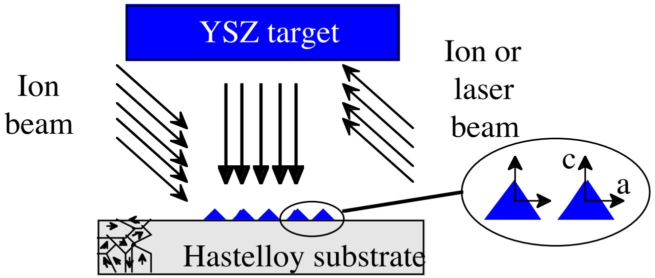
- Texturation by epitaxial deposition: 2G YBCO
  - Requires to deposit on a textured support

Coated conductors

Coated conductors - two main techniques

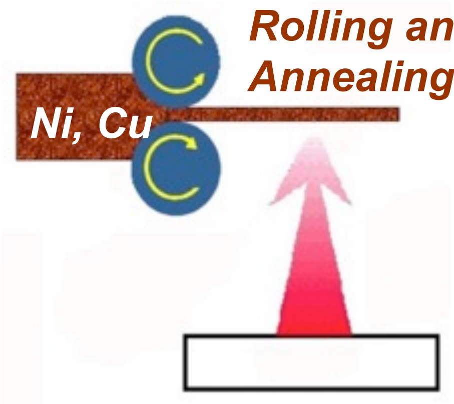
Basis: deposition on a textured support
Textured layer on a substrate or textured substrate

Ion Beam Assisted Deposition (IBAD)



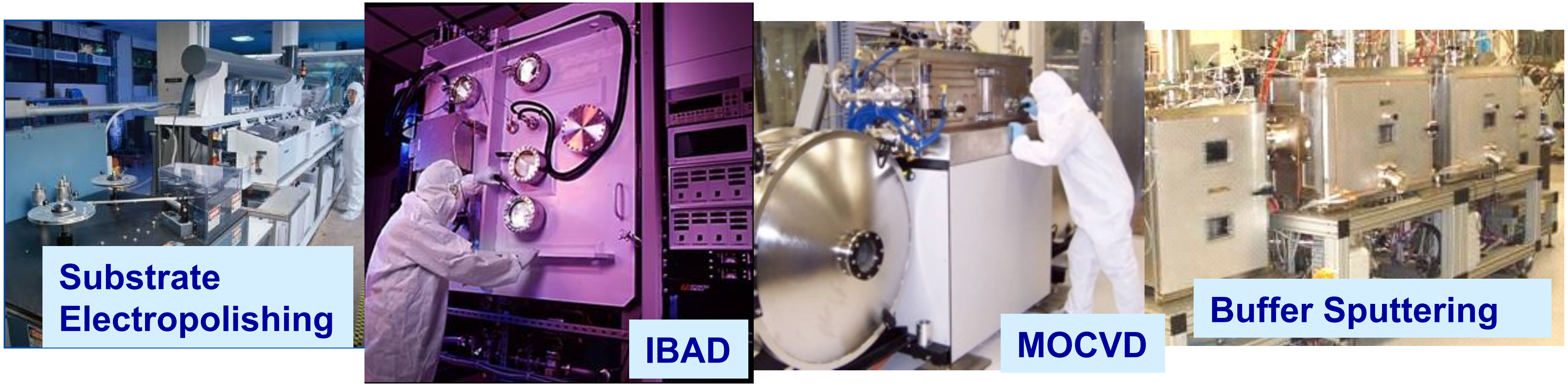
Textured buffer layer

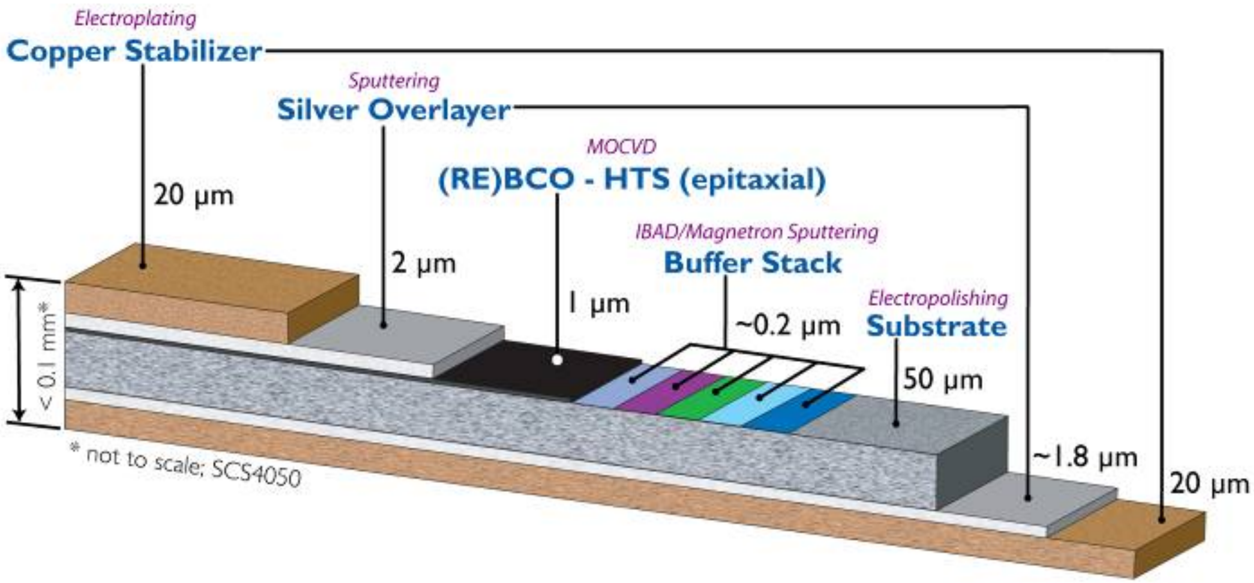
Rolling Assisted Biaxially Textured Substrates (RABiTS)



Textured substrate

Coated conductors – IBAD process





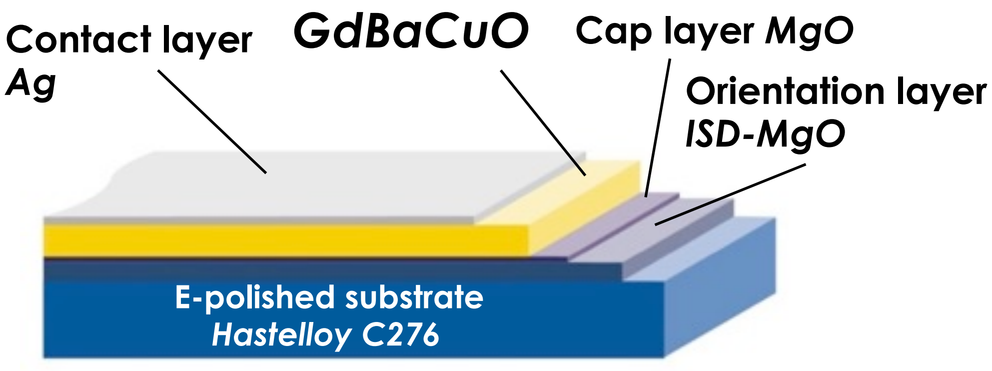
Deposition methods

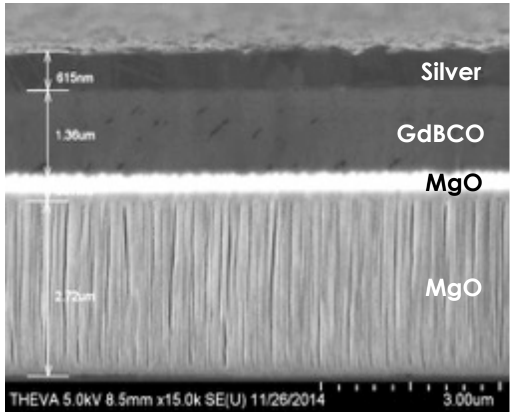
- Physical
- Chemical

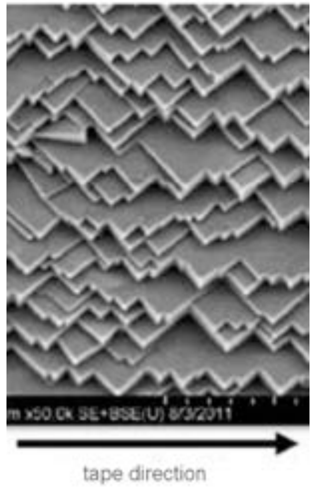
SuperPower Inc.
A Furukawa Company

Coated conductors

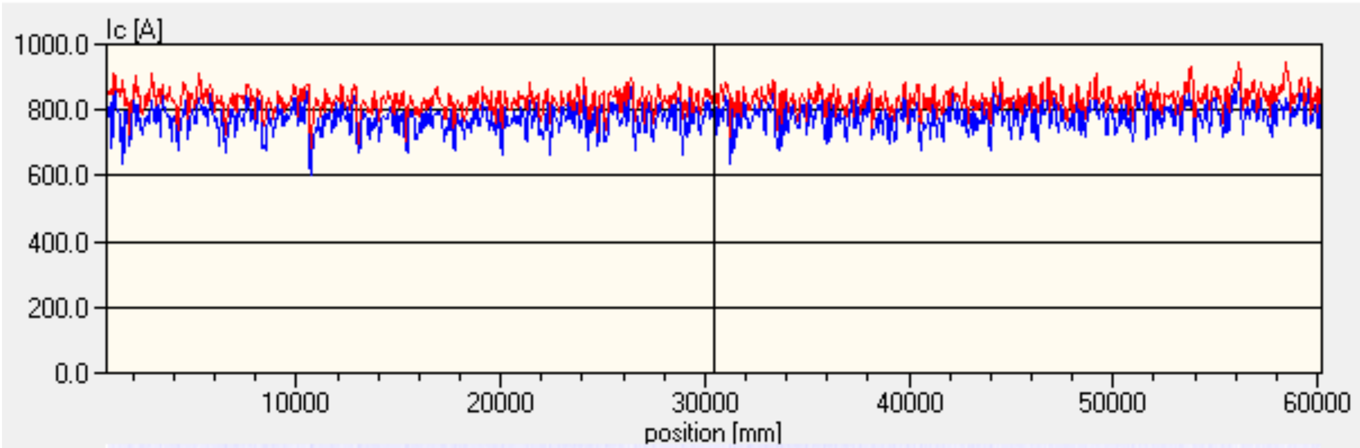
THEVA



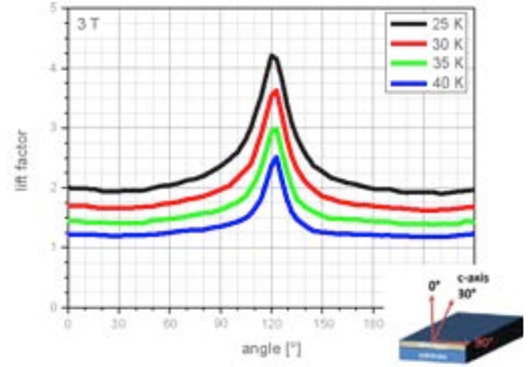




MgO surface



I_c ≈ 700 A/cm-w (77 K, sf)



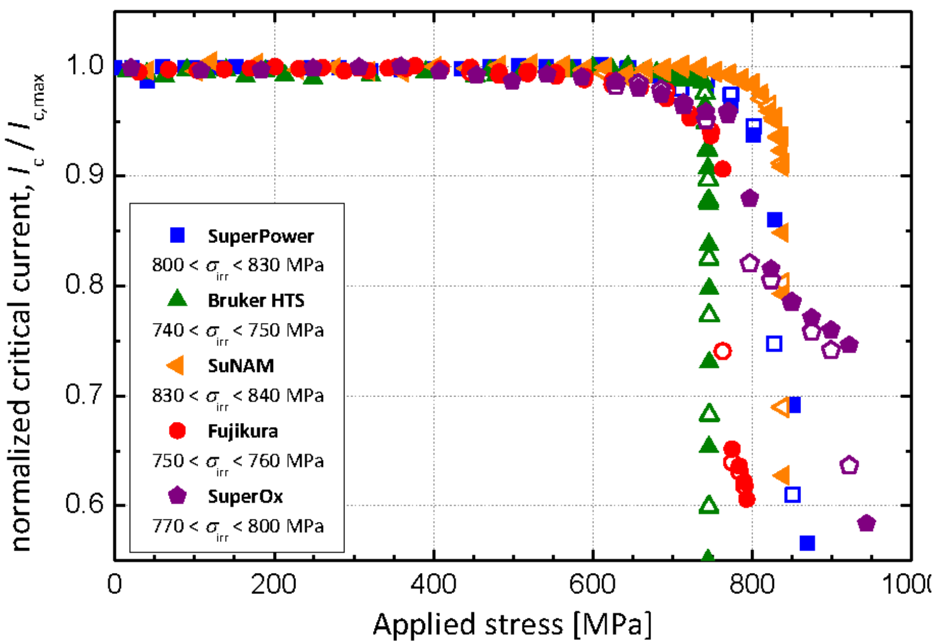
Inclined Substrate Deposition (ISD) process

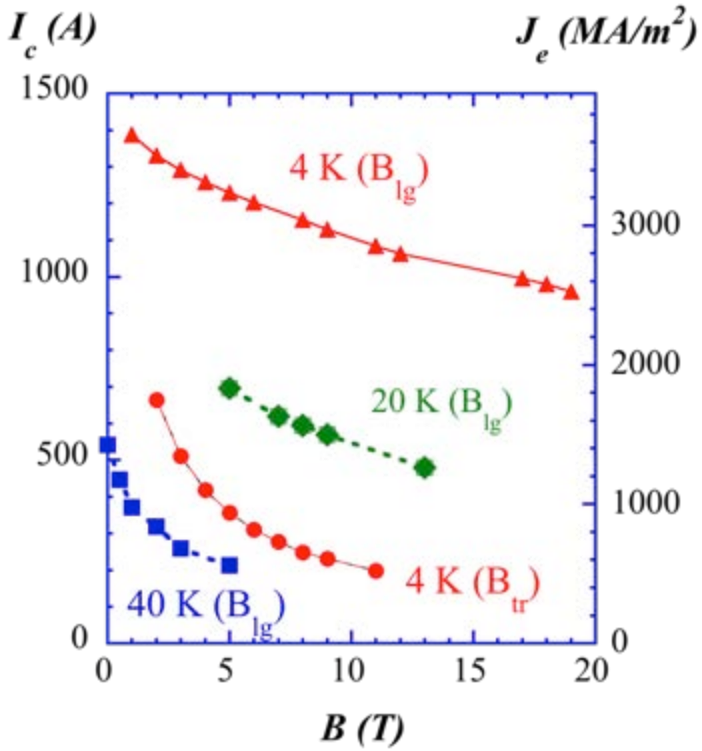
Université Grenoble Alpes

Coated conductors

Typical critical characteristics

I_c vs. axial stress





Performances fit main applications
Really technical superconducting conductor

HTS materials summary

Cost, cost and cost!

- PIT: niche applications, a few manufacturers
- MgB_2: niche applications (pending CC?)
- CC: large hopes, a lot of manufacturers

A lot of room for improvements

HTS applications

- First application: HTS current leads
- Second application: FCL, HTS high field insert

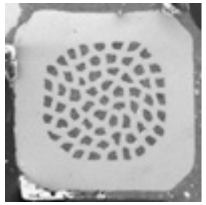
Superconducting materials

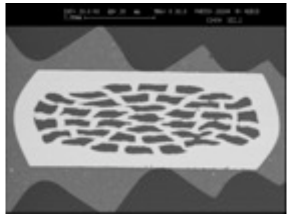
Low T_c

- **NbTi (3000 t/an)**

- **Nb_3Sn (15 t/an)**

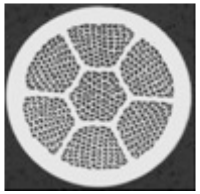
- **MgB_2**

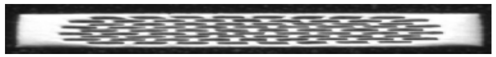




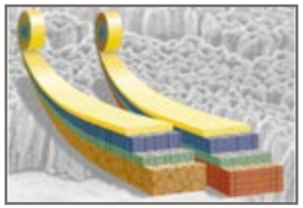
High T_c

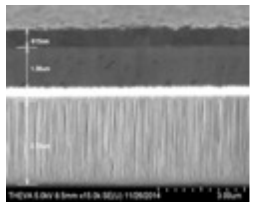
- **BiSrCaCuO (1G)**





- **YBaCuO (2G)**



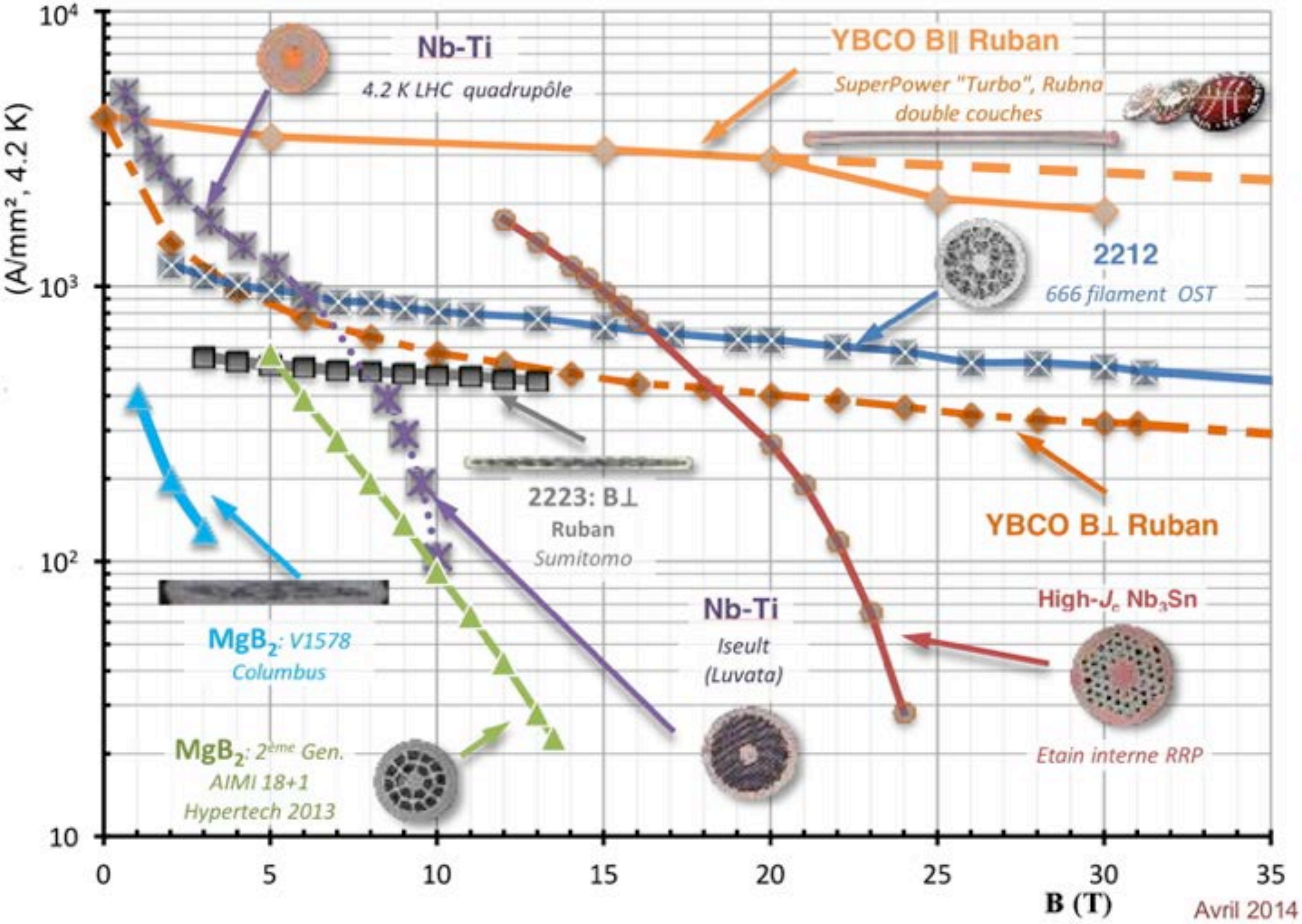


Superconducting materials

Material	State	Length	Cost*	Applications
NbTi	Mature	/	Low (1) (< Cu)	< 9 T (4 K) < 12 T (1,8 K)
Nb_3Sn	Still progresses	/	5 - 10	> 12 T
MgB_2	R & D Margins	km	5 – 10	< 3 T @ 20 K
BSCCO (1G)	R & **D** Progress	km	50 – 100 (Ag)	(inserts)
YBCO (2G)	**R & D** Cost	Hundred m	100 – 250 (process)	Inserts

*** : €/kA/m (77 K, 0 T, HTS), (4 K, B_o, LTS)**

Superconducting materials



Summary HTS – Take home message

- HTS devices still very small market (30 M$ / 5050 M$)
- HTS: 2 wire generations
  - 1G: BSCCO tape and round wire (niche market)
  - 2G: YBCO coated conductor (great hopes)
- 1G: niche market due to high intrinsic cost (Ag)
- 2G: low material cost, high process cost
  - High performances (J_{ce}, mechanics)
  - Anisotropy, delamination, cable
- MgB_2: low cost, competition to LTS for medium fields at about 20 K, DC applications, advances underway

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Superconductivity II
Superconducting Application Introduction

Pascal Tixador

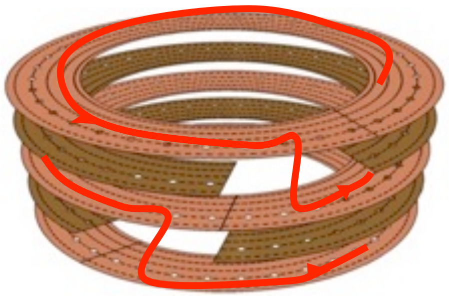
Grenoble-INP, Université de Grenoble Alpes, CNRS
G2ELab, Institut Néel

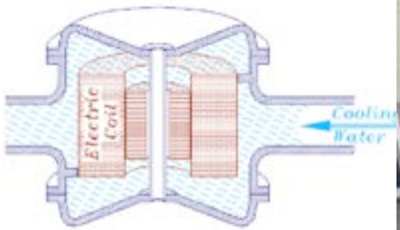
Superconductor interests

- High current densities under magnetic fields
  - Volume reduction
- No loss in DC environment
  - Energy savings
  - Possible energy storage
  - Magnetic bearings
- SC to dissipative state transition
  - Fault current limitation

Comparison for a magnet

	Bitter	Supercon.	Ratio
Magnetic flux density (T)	10	11	1.1
Core (mm)	500	500	1
Supply (kW)	14 000	5	2 800
Cooling (kW)	200 (pumps)	100 (liquefier)	2





Losses in SC (under critical surf.)

Function of the electromagnetic environment

- Time constant electromagnetic environment
  - No or very low losses
- Time variable electromagnetic environment
  - Losses: AC losses

$$\overrightarrow{curl}\,\vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \vec{E} + \vec{J} : losses\,(\delta P = E\,J)$$

=> Interest more in DC than AC

Superconductor uses

Applications with large stored magnetic energy

$$W_{mag} = \frac{1}{2} \iiint_{Espace} B \cdot H \; dxdydz = \frac{1}{2\,\mu_o} \iiint_{Espace} B^2 \; dxdydz$$

- Applications difficult without superconductors
- New types of applications
- Improvment of conventional applications

Applications difficult without SC

Superconductivity inescapable

Devices difficult to design without superconductivity

- High magnetic flux densities
- Large magnetized volumes

MRI	RMN Spectrometer	Magnets	High energy physics	Thermonuclear fusion

Philips©

30 000

Bruker©

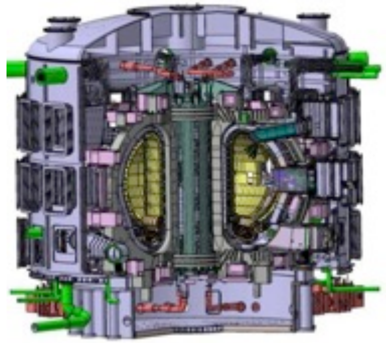
78 %

CNRS©

Cern©

27 km (100)

40 MW (900)

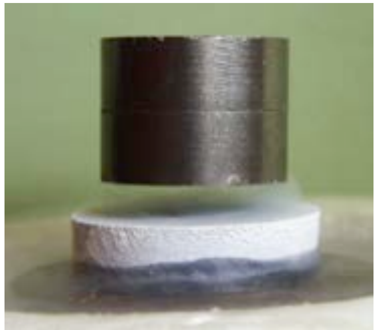


ITER©

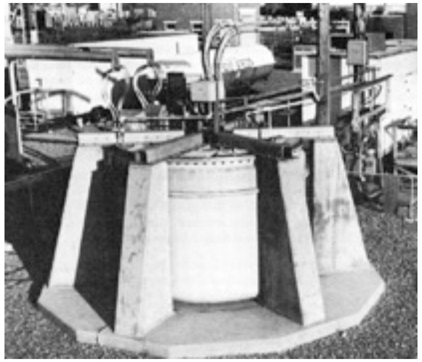
20 %

New types of applications

New functions Innovative devices Properties inherent to superconductors ▪ quench from SC to normal state ▪ No DC losses		
Magnetic bearings	**Fault Current Limiter (FCL)**	**SMES (magnetic storage)**



NEXANS©



IEEE©

Improved devices

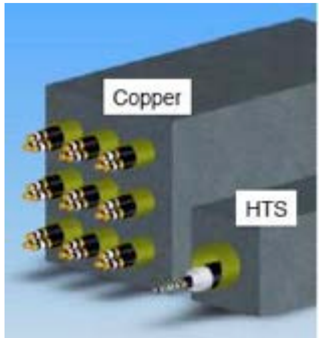
Improvement of resistive devices

- Enhanced compactness & efficiency, weigth reduction
  - no DC loss

+

Possibility to integrate innovative fonctions (limitation)

Electrical rotating machine	Cables	Transformers

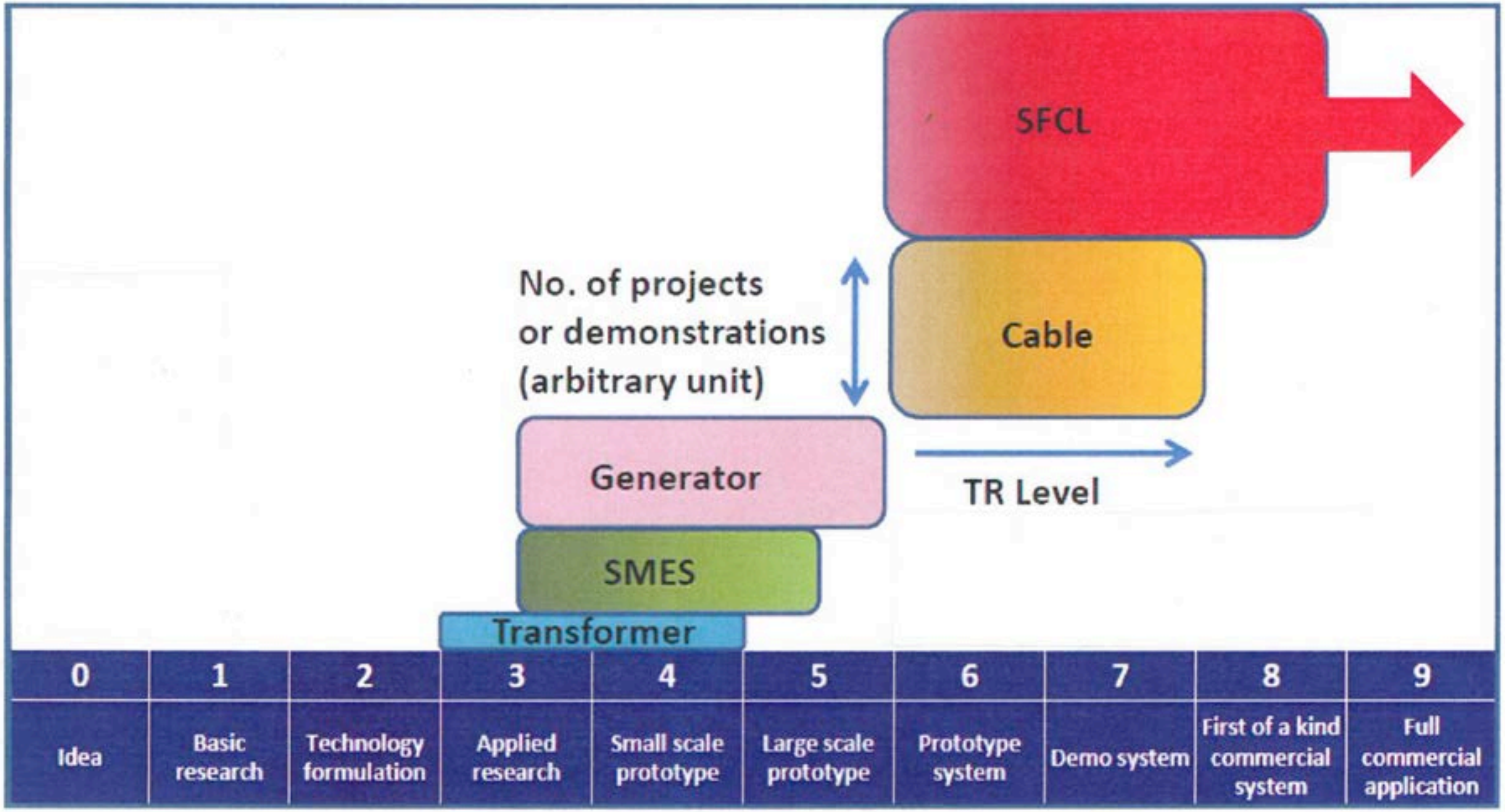


Siemens©

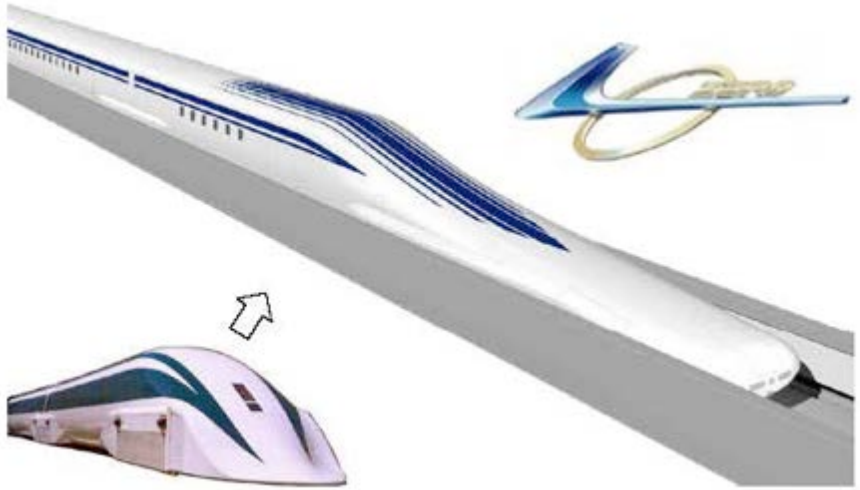
Supercond. and large scale applications

- Higher power Quality and security
  - FCL, Low impedance cable, high short-circuit power, high meshing
- Higher power density
  - Transfo. & machine (30 / 50 %), cable (> 50 %)
- Enhanced efficiencies
  - Transfo. (50 % (> 80 % mobile)), machines (30/50 %) magnets (> 90 %)

SC power application - Summary



Maglev



505 km/h

Project approved by Japan:

- Tokyo-Nagoya 2027 – 286 km – 40 min (5.5 trillion yen)
- Tokyo-Osaka 2045 – 438 km – 67 min (9 trillion yen total 65 b€)

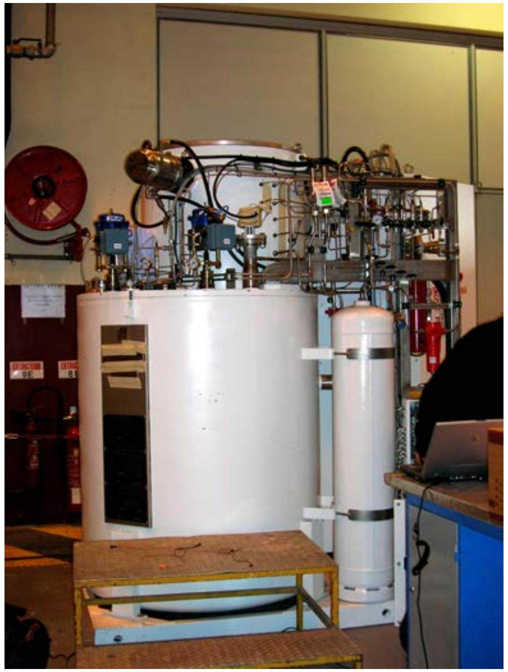
Tests (Yamanashi test line - 42.8 km): > 10^6 km

Superconducting power devices

- Only very few industrial devices
  - NbTi magnets for magnetic separation
  - A very few FCL
  - Many very successful experiments
- Three main reasons
  - Resistive systems in general high performances
  - Cryogenic cost and **fear**
  - SC device: revolution, not simple evolution

Superconducting power devices economically possible only with HTS at moderate cost

Do not forget



250 W @ 20 K

AIR LIQUIDE
TECHNIQUES AVANCEES

250g – 0.2 W @ 77 K

200 kV bushing

Fields perfectly mastered

if correctly designed!

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Superconducting Fault Current Limiter (FCL)

Pascal Tixador

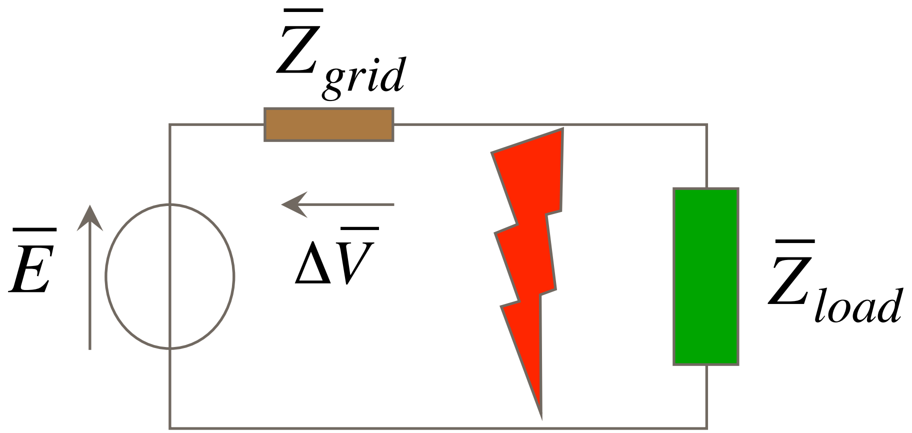
Grenoble-INP, Université de Grenoble Alpes, CNRS

G2ELab, Institut Néel

UNIVERSITÉ Grenoble Alpes · Grenoble INP · cnrs · NÉEL institut · G2E Lab Grenoble Génie Electrique Grenoble Electrical Engineering

Fault Current Limiter (FCL) - Need

Ultra simple representation of a grid:



Grid design: compromise

- Power quality low Z_{grid}
  - ✓ ΔV
  - ✓ Perturbation

Fault current E/Z_{grid}

- ✓ Device over-design
- ✓ Breaker cutting capacity

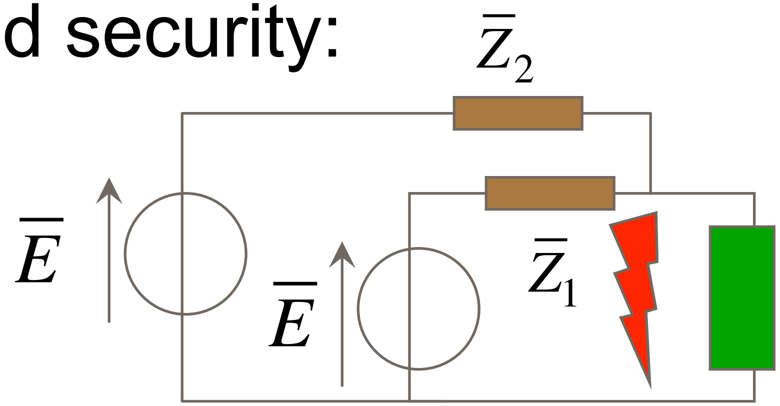
Need for a fault current limiter

Electric grids:

- extremely important in our countries
- critical infrastructures

Security and power quality: two main demands today

Improved security:



Effective but if fault:

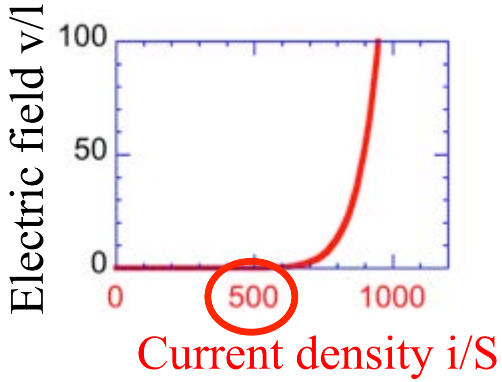
$I_{cc} = I_{cc1} + I_{cc2}$

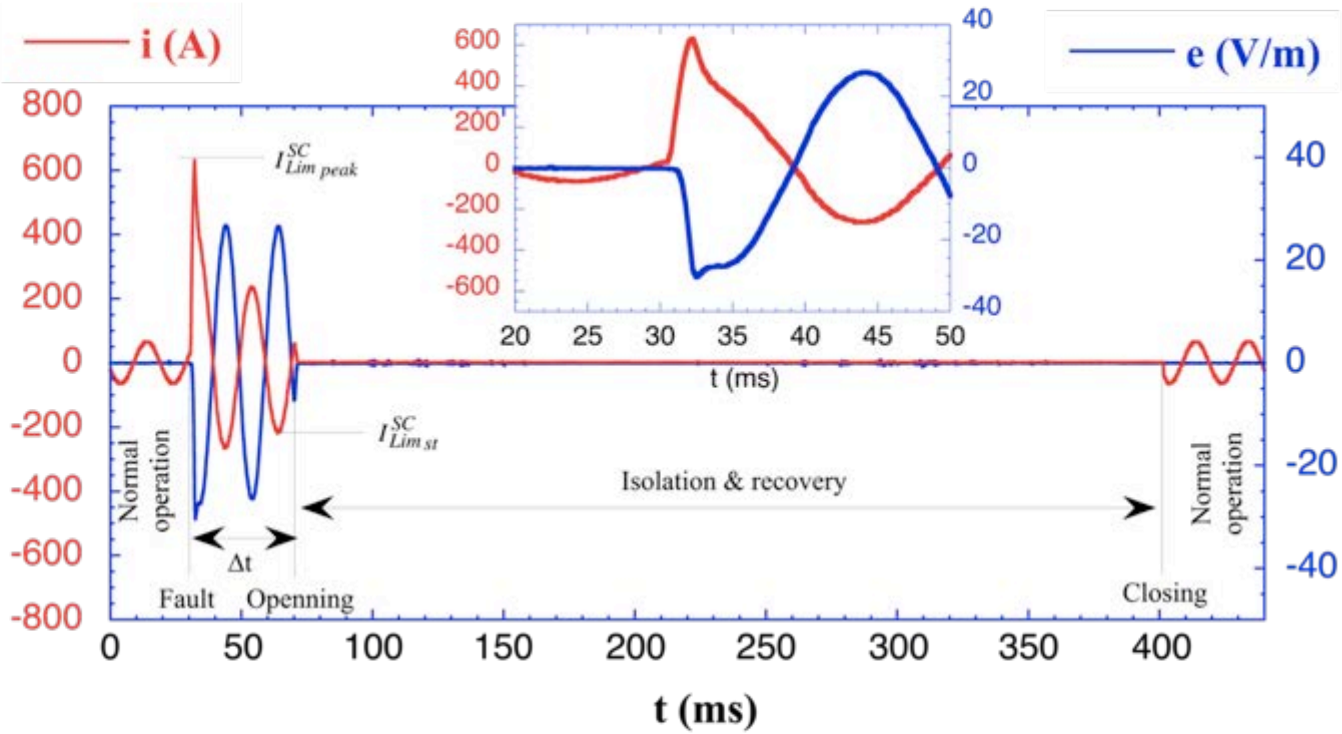
FCL required

No today satisfying FCL

Superconductivity brings attractive response

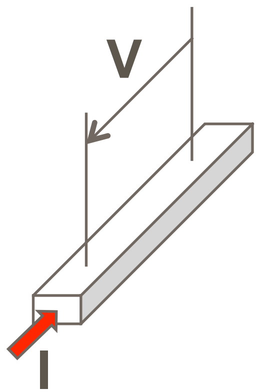
SC FCL

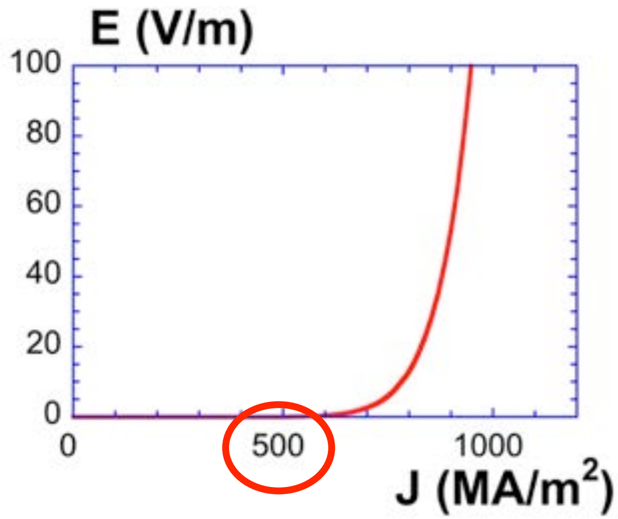


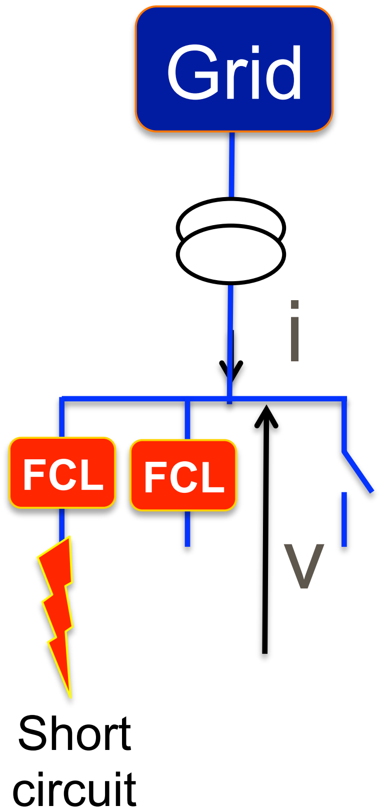


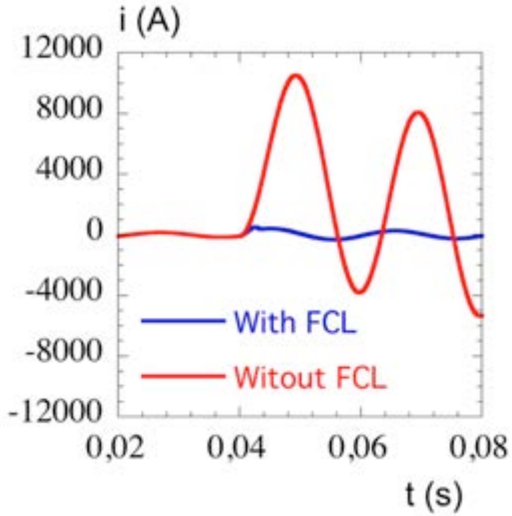
FCL makes possible a low grid (zero!) impedance BUT a low fault current. Graal for grid designers!

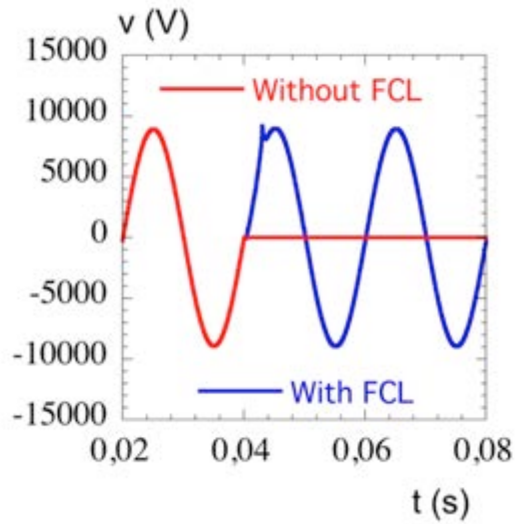
Fault Current Limiter - FCL











SFCL
- Nearly invisible in NO
- Self triggering
- Fail safe
- Automatic recovery

Uses
- Current limitation
- Fault « isolation »

FCL – State of the art

Italy 9 kV / 0.2 kA

Germany 12 kV / 0.8 kA

Korea 23 kV / 0.63 kA

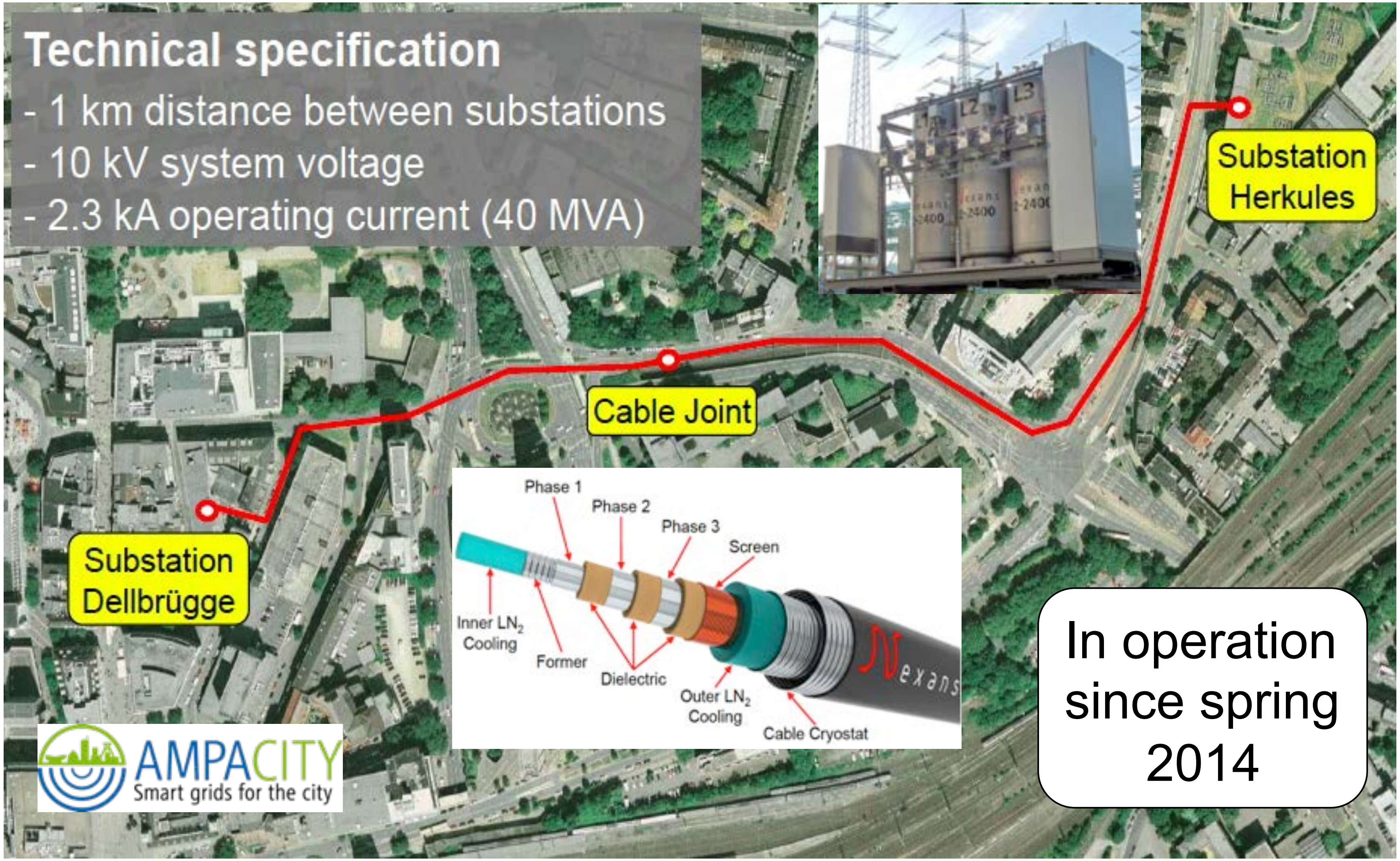
China 220 kV / 0.8 kA

APPLIED MATERIALS®

USA (Santa Clara) 15 kV / 1 kA

Many successful experiences. Some test experiences

AMPACITY project: cable + FCL



Courtesy M. Stemmle

FCL from SIEMENS in Augsburg

„ASSiST“ – SFCL for public 10 kV grid of Stadtwerke Augsburg, Bavaria, Germany

swa Netze SIEMENS

SFCL based Solution (SFCL+switchgear+control+DAQ) successfully installed and inaugurated in 03/2016.

gefördert von
Bayerisches Staatsministerium für
Wirtschaft und Medien, Energie und Technologie

Details

- Collaboration of Siemens EM, CT & Stadtwerke Augsburg
- Integration of MTU's extended testing facility of combined heat and power unit requires reduction of short-circuit current
- Combination of superconducting 15 MVA SFCL with ultrafast breaker and parallel series reactor
- Closed cooling system (cold heads included) – no blow-off during limitation
- Reduction of losses compared to conventional solution
- Increased system stability, no voltage drop
- Large area breaker up-grade dispensable
- Timeline:
  - Apr. 15, 2014: project start
  - Mar. 15, 2016: official inauguration
  - till Jan. 15, 2017: data acquisition & monitoring (to Siemens Erlangen)
  - Continued operation planned after project end

Testing at CT, Erlangen

Installation area

Installed vessels

Inauguration ceremony

Courtesy Tabea Arndt - Siemens

FCL: market starts! Birmingham (UK)

Commercial SCFCL in Western Power Distribution (UK)

Bus tie coupling

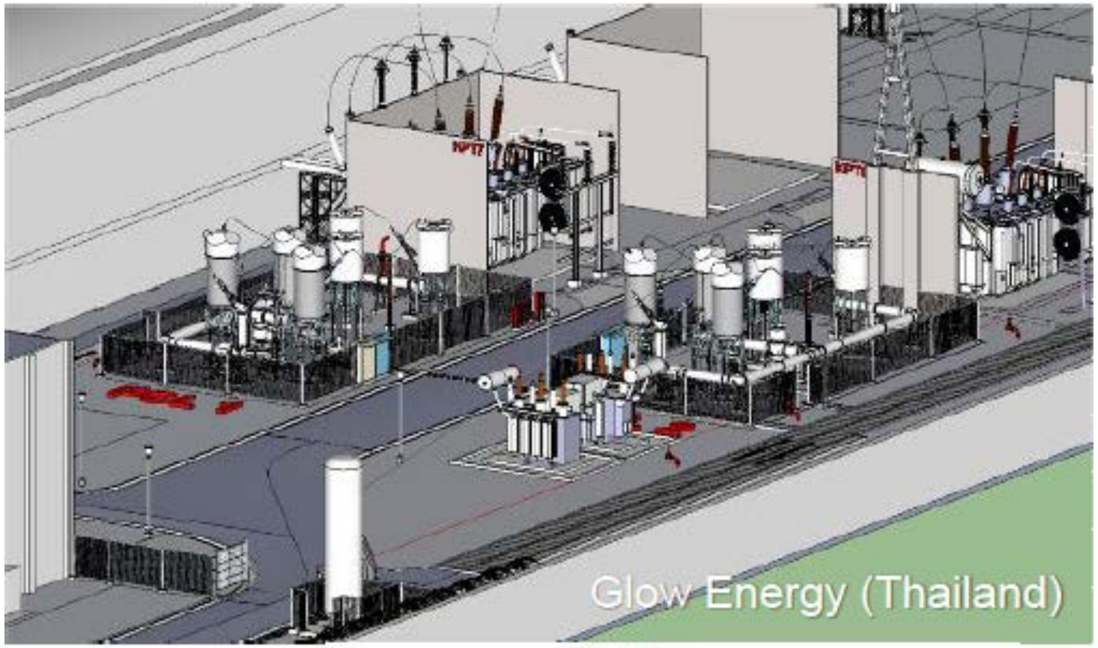
Location	Chester	Bournville
U_a	12 kV	12 kV
I_a	1.6 kA	1.05 kA
I_{pros}	20 kA peak	22 kA peak
I_{lim}	9.9 kA peak	7.7 kA peak
Δt	100 ms	100 ms
Recovery	30 s	30 s
Location	Outdoor	Indoor
Cooling power (RT)	18-50 kW	18-30 kW

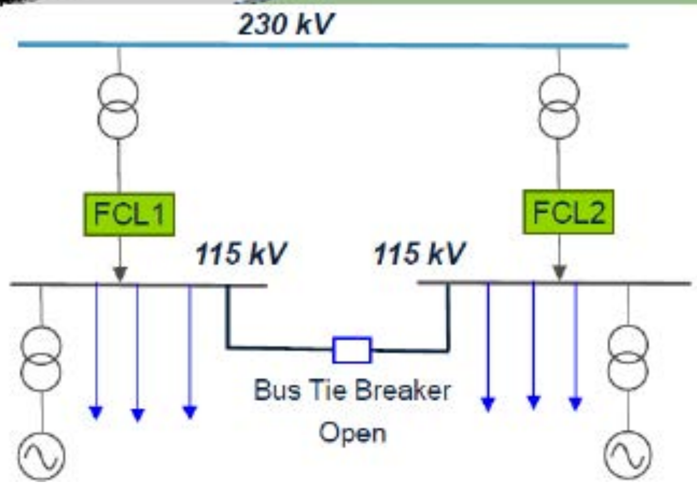
SCFCL put in operation late 2015

WESTERN POWER DISTRIBUTION

SCFCL 12 kV / 1.6 kA Starting end 2015

FCL: market starts! Rayong (Thailand)





Voltage	115 kV
Rated current	550 A
Iprospective	5 kA
Ilim	2.5 kA
Shunt (react)	15 Ω
BIL	550 kV
AC withstand	230 kV

SCFCL- Conclusions

- SCFCL: an innovative device for a real demand (better grids)
  - High short-circuit power but low fault currents (Graal!)
- First commercial SCFCLs in MV (Birmingham) and HV (Thailand)
- SCFCLs already out of the laboratory development phase
- Now midway between the pilot projects & industrial deployment
- Many people still think SFCL remains a laboratory device
  - Communication about field test experiences
- Grid designers should know that they have a new device
- Have to suppress the psychological fear against cryogenics
- Field tests on long periods to remove last utility's fears
- A lot of space for improvements
- Conductor cost should no more be an issue
- Cryogenic could be critical for cost

Conclusion, take home message

- LTS market: mature niche market still growing
  - MRI, NMR (physics)
  - 4 K cryogenics remains an economical hurdle
- HTS market emerges
  - Cryogenics no more an economical hurdle
  - Conductor remains today an economical hurdle
  - Lot of advances in YBCO, many actors
  - Superconductivity: enabling technology
    - SC FCL, VLI cable, rot. mach. for wind farm, planes…
  - HTS market takes off with a few FCL orders
  - Fears (cryogenics) should be overcome
    - Field tests on long periods to remove last utility's fears
  - Communications
    - SC FCL exist: a new device for grids

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Gràcies!