Classical and High Temperature Superconductors: Practical Applications and Perspectives at CERN

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Transporting Tens of Gigawatts of Green Power to the Market

Brainstorming Workshop

Potsdam 12-13 May 2011

Outline

- Superconductivity for particle accelerators
- Superconductivity at CERN
  - From the start to the LHC era
  - **Nb-Ti**: development toward requirements of applications
  - State-of-the-art Nb-Ti superconductor for the LHC machine
  - **HTS** in the LHC machine
- Superconductivity at CERN for future LHC machine upgrades
  - **Nb-Ti vs Nb_3Sn**
  - **HTS**
- Conclusions

Preamble

CERN exists to provide facilities for **experimental high energy physics**

The use of **Superconductivity** is important in the **quest for higher energy**

- **Spectrometer magnets** provide **magnetic field** to determine the momentum of charged particles. *Higher energies imply larger volumes and higher fields*
- **Accelerator magnets** provide **magnetic field** for bending and focusing particle beams. *Higher energies imply higher fields for a given machine diameter*
- **RF cavities** provide the **electric field** required to accelerate the beams of charged particles. *Higher energies imply greater fields for a given length*

SC magnets and cavities are developed to satisfy these requirements

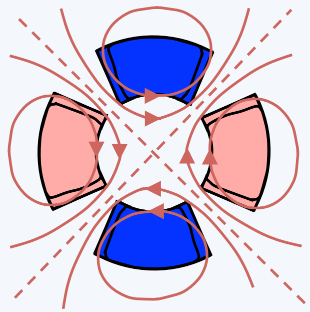
*(With regard to SC magnets, **specific equipment** is required for their powering; efficiency dictates the use of superconductors in **busbars and current leads**)*

Superconductivity and Particle Accelerators

Cryogenics is complicated and expensive,
so what is the interest of superconductivity?

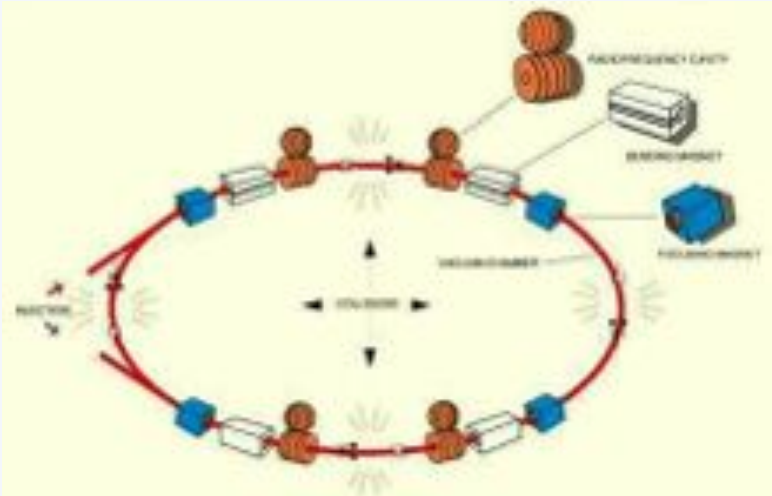
- High current density → **compact windings**
  → ***high magnetic fields and gradients***
- Larger ampere-turns in a small volume→ **no need for iron**
  (but iron is still useful for shielding)
- Reduced power consumption → **lower power bills**
  (when cost of refrigeration power is offset)

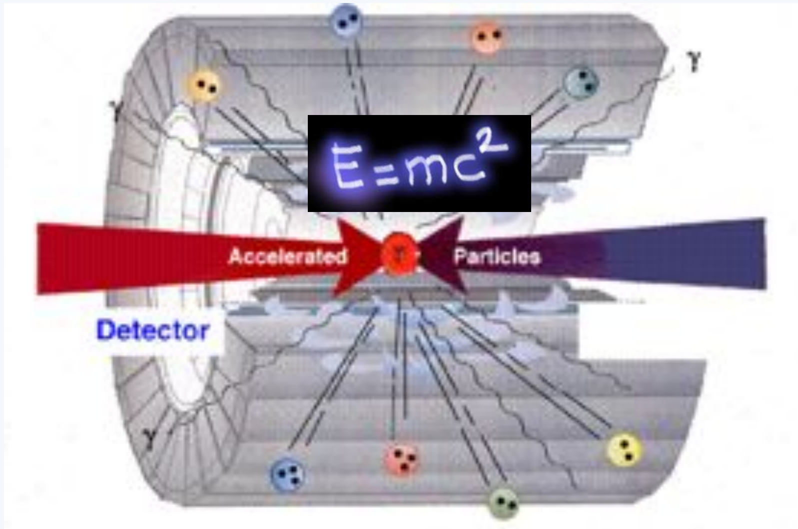
Superconductivity opens up new technical possibilities



- Higher magnetic fields → increased bending power
  → ***greater energy for a given radius***
- Higher electric fields → higher accelerating gradients
  → ***greater increase of energy per unit length***
- Higher quadrupole gradients → more focusing power
  → ***higher luminosity***

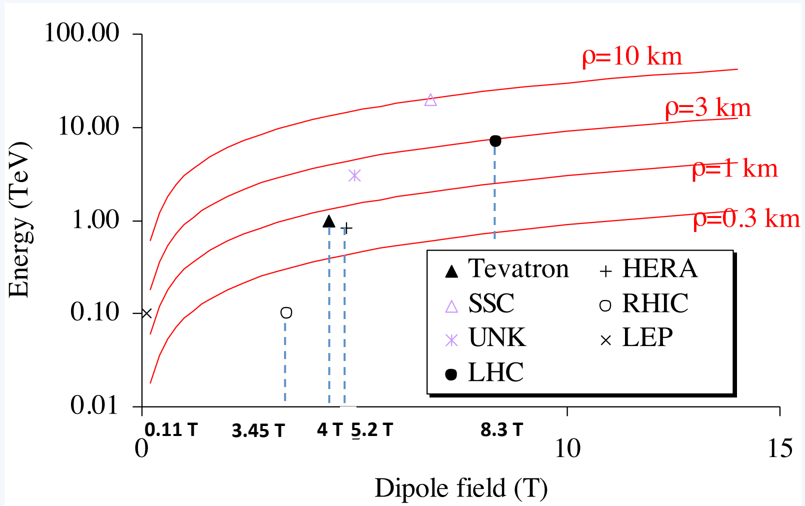
Accelerator Energy and Magnetic Field



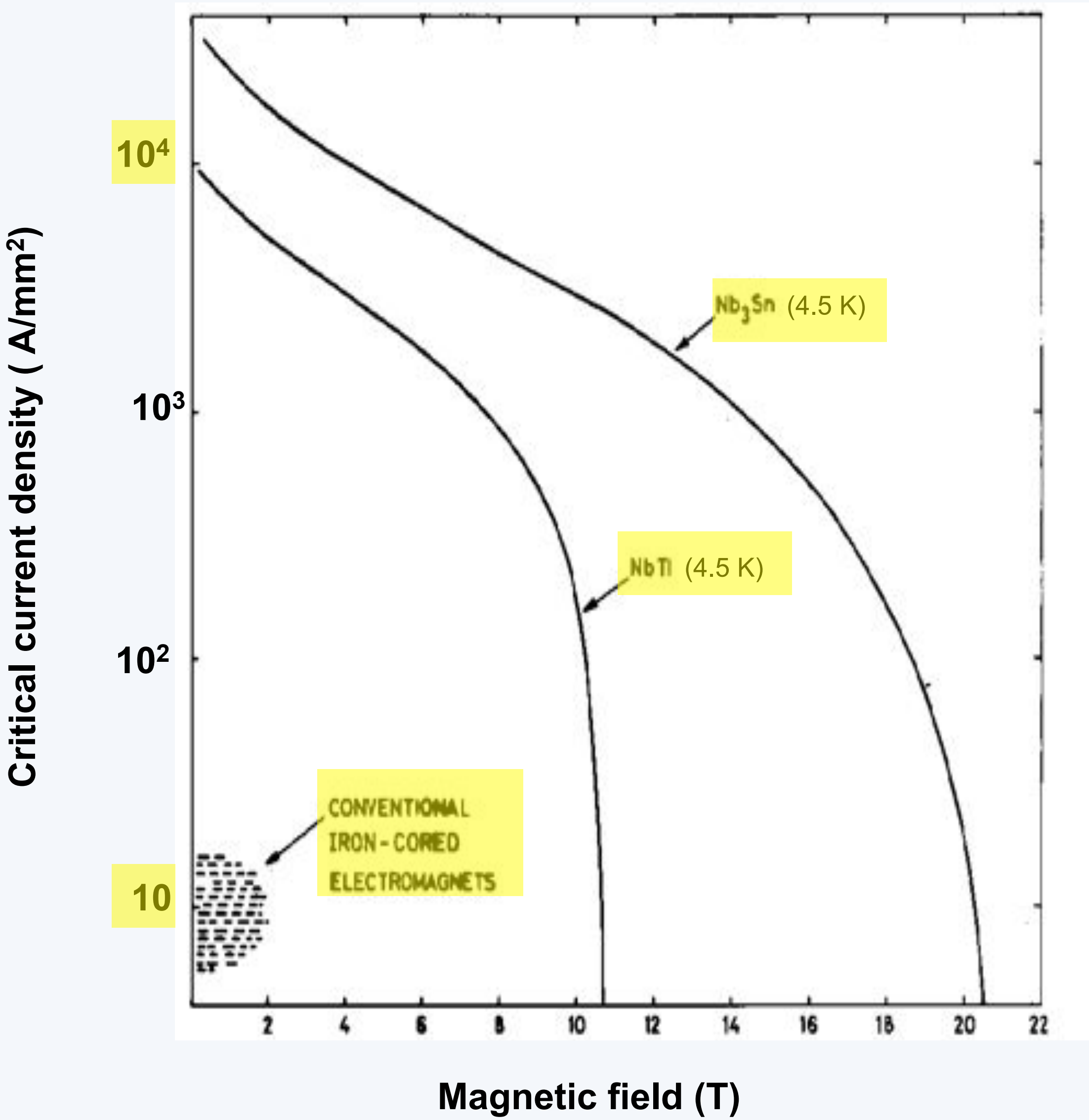


Synchrotron:
E[GeV]=0.29979 B[T] R[m]

High energy → High field magnets



Current Density vs Magnetic Field



Technical Conductors

- Long unit lengths
- Uniform characteristics (I_c,J_c)
- Good mechanical properties – for cabling and for magnet winding
- Stabilizing matrix material
- Flexible design (diameter, filament size and number, RRR…)
- Competitive cost

……….

Nb-Ti for accelerator technology

How did it evolve?

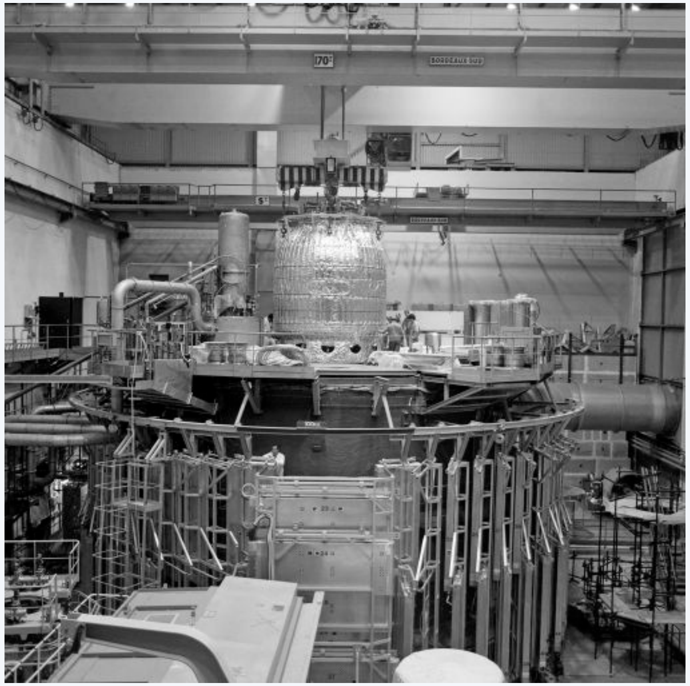
- Early 1960s Experiments with newly discovered type II SC material
- Mid 1960s **Recognition of application for experimental particle physics led to intense activity to understand and develop useful conductors for winding magnet coils**

  → *Importance of filaments, stabilizers, twisting and transposition*

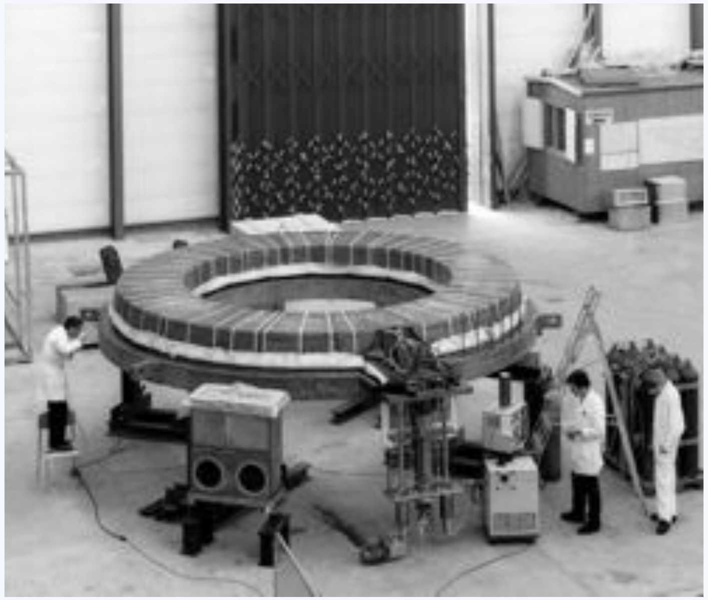
  Defining moment: Brookhaven Summer Study (1968)
- Late 1960s First SC magnets for experiments and beam lines
  Studies for a large SC accelerator → GESSS 1970-74

  Group for European Superconducting Synchrotron Studies

  (IEKP Karlsruhe-D, RHEL Chilton-UK, CEN Saclay-F)
- Early 1970s First SC spectrometer magnets (at CERN **BEBC, Omega**)
- Late 1970s First SC accelerator magnet sub-system (**ISR** low-β insertion at **CERN**)



BEBC magnet: 3.5 T @ 4.5 K, 5700 A
Stored energy: 800 MJ
Φext ~ 6.5 m
Nb-Ti (45 km), J ~10 A/mm^2
Flat composite strip: 61×3 mm^2
200 SC untwisted filaments
3.5 % Nb-Ti in copper matrix
Eddy currents during ramp



Omega magnet: 1.5 T @ 4.5 K, 5000 A
Stored energy: 50 MJ
Φint ~ 3 m
Hollow conductor cooled by forced flow supercritical helium
Nb-Ti (18×18 mm^2), J~14 A/mm^2
Historical milestone in the development of forced flow conductor

ISR (**I**ntersecting **S**torage **R**ing)

Eight **superconducting quadrupoles** for the high-luminosity insertion **installed in 1980** - work on design started in 1973

Gradient : 43 T/m
Inner diam. of coils: 232 mm
Operating current :1600 A @ 5.8 T and 4.5 K
Conductor : rectangular wire
1.8×3.5 mm^2 (± 0.01 mm)
Nb-Ti with copper stabilizer
1250 filaments (50 μm)
Twist pitch: 50 mm

This has been the first **application of superconductivity in a working accelerator**

How did it evolve?

- Mid 1980s Fermilab Tevatron – Ø 2 km – SC magnet system + CDF +D0
- 1980s, 90s **CERN LEP** – Ø 8.5 km – **SC RF system + ALEPH + DELPHI**
- Early 1990s DESY HERA – Ø 2 km – SC magnet system + ZEUS
- Mid 1990s Jlab – CEBAF – SC RF system (+ spectrometers)
- Early 2000s BNL RHIC – Ø 1.2 km – SC magnet system
- Late 2000s **CERN LHC** – Ø 8.5 km – **SC magnet system + ATLAS + CMS**

LEP Low-β Insertions

Quadrupoles for the low-β LEP1 insertions (~1985)
Gradient : 36 T/m
Operating current : 1625 A @ 4 T and 4.5 K
Conductor : rectangular wire, 1.8×3.6 mm^2, 2230 filaments (37 µm)

Quadrupoles for the low-β LEP2 insertions (~1990)
Gradient : 60 T/m
Operating current : 1950 A @ 5.1 T and 4.5 K
Conductor : rectangular wire, 1.5x2.95 mm^2, 2000 filaments (37 µm)

Goal: double luminosity with respect to conventional resistive insertions

(Magnets iron-free and slim to go into the end of the detector magnet)

Conductor Requirements - Wires

What does a conductor for accelerator magnets need to provide?

WIRE

- High and uniform **current density** to produce a large field over a small transverse aperture;
- Small **filaments size** to a) reduce magnetization and assure uniform field - mainly at injection, b) avoid flux jump;
- **Filaments twist** to minimize coupling effects during ramping (eddy currents);
- Appropriate **(Cu/non Cu) ratio** - minimum amount of copper needed for stability and protection, controlled within a strict tolerance (typically 1.5-2 ± 0.05 for accelerator magnets)

Conductor Requirements - Cables

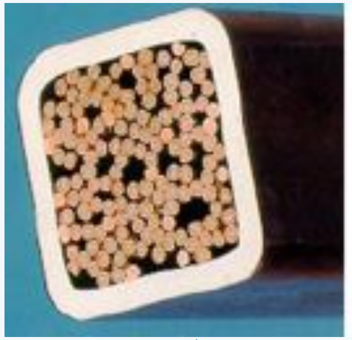
What does a conductor for accelerator magnets need to provide ?

CABLES

- High-current cables (10 - 20 kA range)
- Minimum Jc degradation with respect to virgin strands;
- Uniform current density;
- High filling factor;
- High aspect ratio;
- Precise dimensions;
- Twisted wires to minimize coupling effect during ramping;
- Controlled inter-strand resistance between crossing strands in the cable

Superconducting Cable Types

CIC



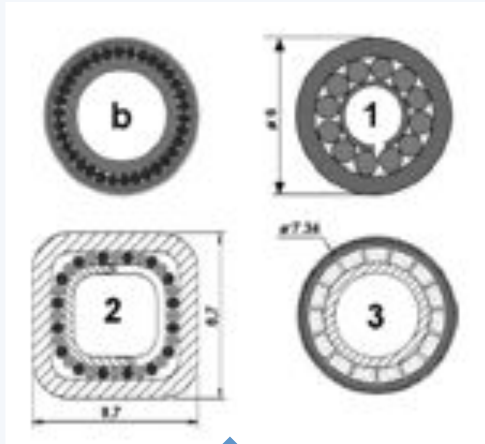
ITER magnets

Rutherford

Accelerator magnets

Tevatron, HERA
RHIC and LHC

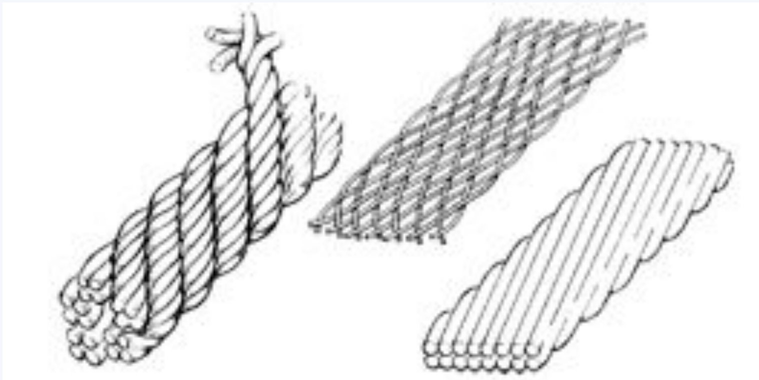
Indirectly cooled



Nuclotron Type (b)
Pulsed SIS 100 magnets

Rutherford

Detector magnets



Rope, Braid and Rutherford cables

Superconductor for the LHC Magnets

- **R&D** Program started in **1988**

- **Contracts** for the LHC cables were signed at the end of **1998** (six firms). Specification aiming at guaranteeing:

  High Technical Requirements;

  Homogeneity of the production;

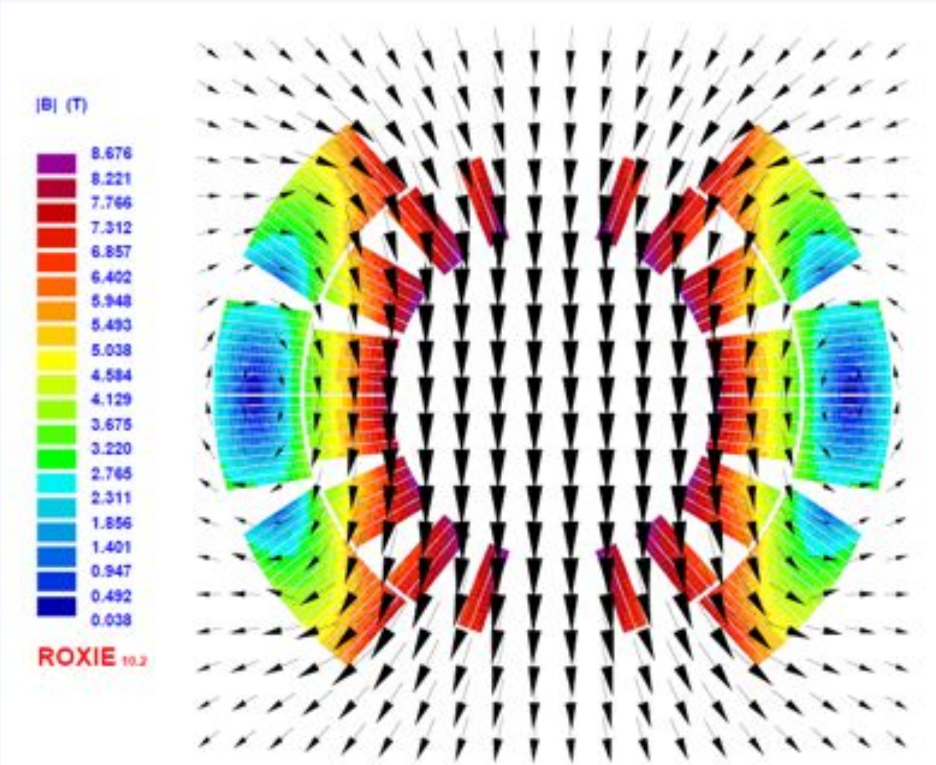
  On-time cable delivery

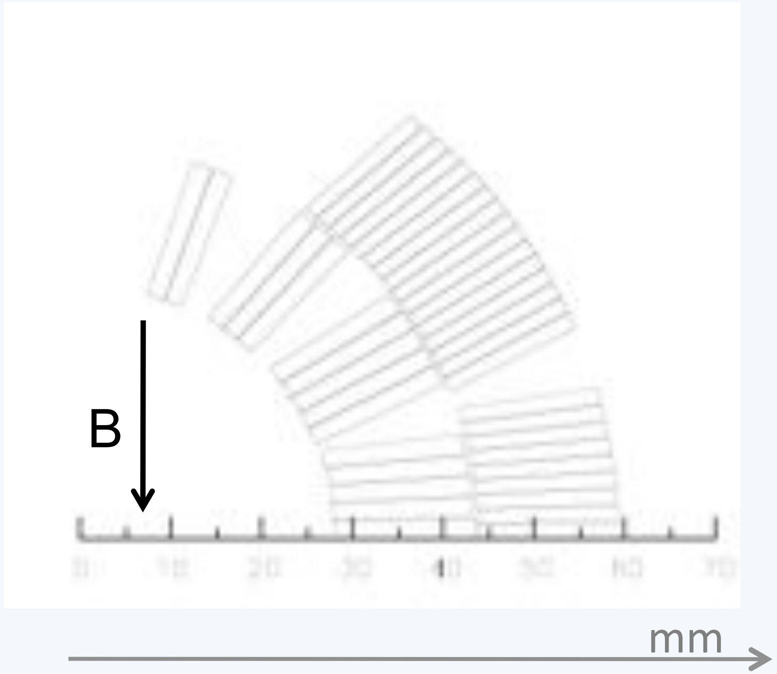
1988 → (10 years) → **1998**

- **Production** of cables –including spare- **ended** in spring **2006**

1998 → (8 years) → **2006**

Superconductor for the LHC Dipole Magnets





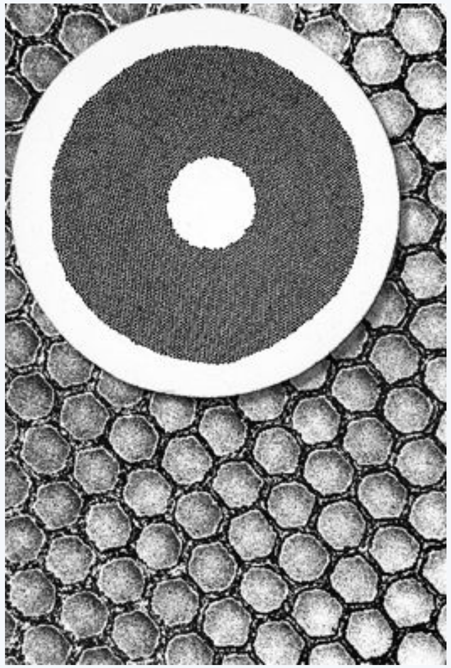
Field Computation for Accelerator magnets
S. Russenschuck

B = 8.3 T
T = 1.9 K

Superconductor for the LHC Magnets

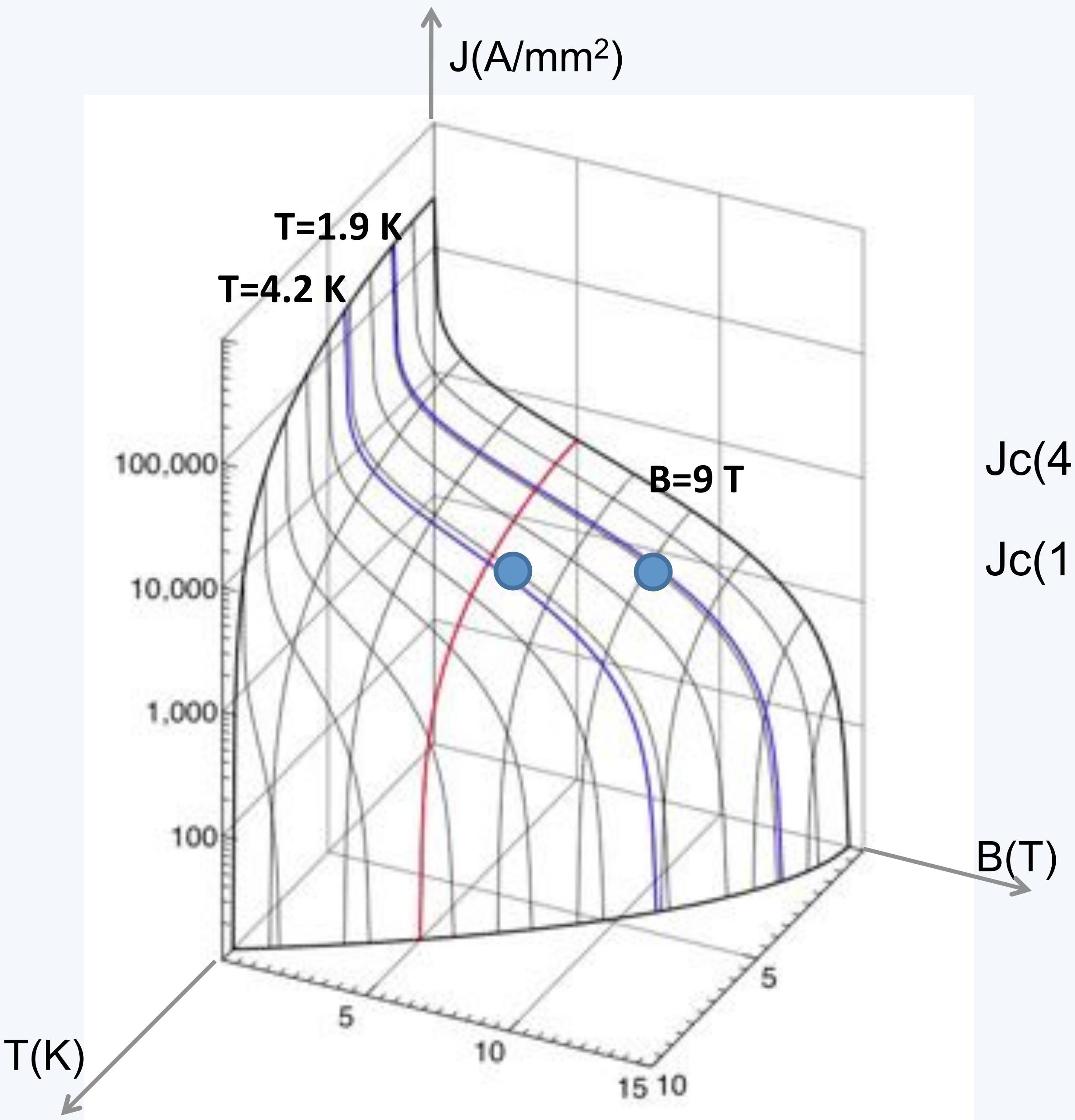
- About **1265 tons** or **7350 km** of superconducting **cables**
- More than **240 000 km** of superconducting **strands**
- About **5300** Nb-Ti/Cu composite billets
- A total of **490 tons** of **Nb-Ti** (47.0±1.0% weight Ti)
- **11900** Unit Lengths of cables

Nb-Ti Billets (Φ = 30 cm)



Strand (Φ = 1 mm)

LHC Strands



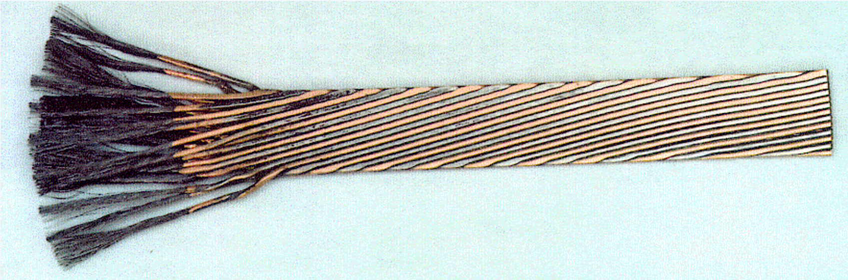
Jc(4.2 K, 6 T)~2300 A/mm^2

Jc(1.9 K, 9 T)~2300 A/mm^2

Strands and Cables for LHC Dipole Magnets

Performance specification

STRAND	Type 01	Type 02
Diameter (mm)	1.065	0.825
Cu/NbTi ratio	1.6-1.7 ± 0.03	1.9-2.0 ± 0.03
Filament diameter (μm)	7	6
Number of filaments	8800	6425
Jc (A/mm^2) @1.9 K	1530 @ 10 T	2100 @ 7 T
μ_0M (mT) @1.9 K, 0.5 T	30 ±4.5	23 ±4.5
CABLE	**Type 01**	**Type 02**
Number of strands	28	36
Width (mm)	15.1	15.1
Mid-thickness (mm)	1.900 ±0.006	1.480 ±0.006
Keystone angle (degrees)	1.25 ±0.05	0.90 ±0.05
Cable Ic (A) @ 1.9 K	13750 @ 10T	12960 @ 7T
Interstrand resistance (μΩ)	10-50	20-80



Cable compaction ~ 91 %

Cabling Machine

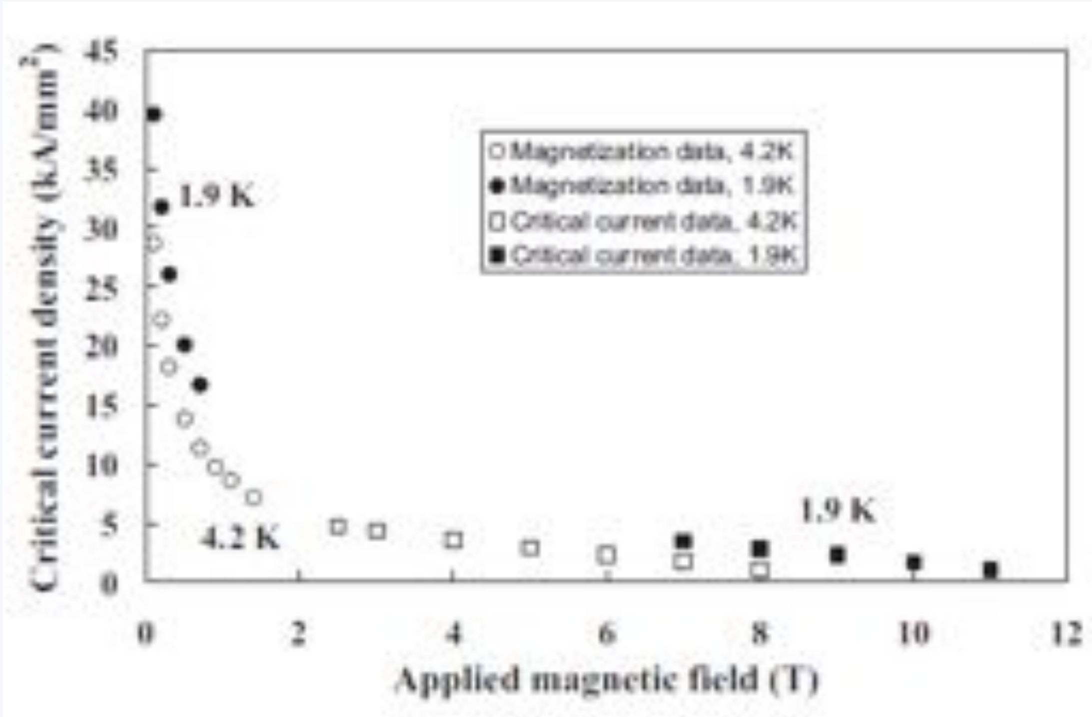
LHC Strands – Measured Current Density

Average strands critical current density (1.9 K)

Supplier	Jc, avg [A/mm²]	σ [A/mm²]
Strand	**01@10T**	
01 B	1708	37
01 E	1684	25
Strand	**02/03@9T**	
02 B	2353	36
02 C	2292	41
02 D	2376	29
02 G	2360	50
02 K	2276	32

1530

2100



Ic01(1.9 K, 10 T) = 513 A
Ic02 (1.9 K, 9 T) = 380 A

About **5500 strands** (Ic virgin and de-cables, RRR, Magnetization) and **2600 cables** (Ic) were measured at cold

LHC Cables – Measured Current Density

Average cables critical current density (4.2 K)

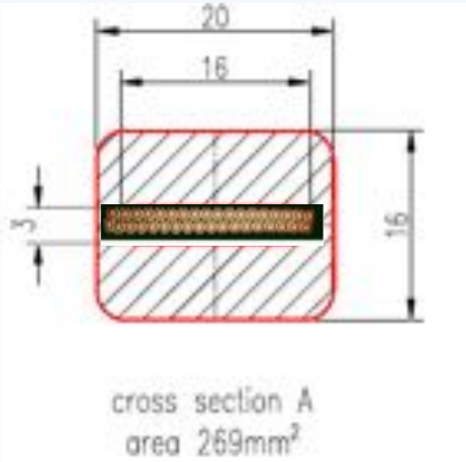
Firm	Average Ic [A]	CV [%]
Cable	**01@ 7 T**	
01B	15258	2.4
01E	15398	1.8
Cable	**02/03 @ 6 T**	
02B5	15146	1.8
02B8	15315	0.9
02C0	14823	1.6
02C9	14958	1.0
02D	14957	1.3
02G	15518	1.6
02K	15113	1.4

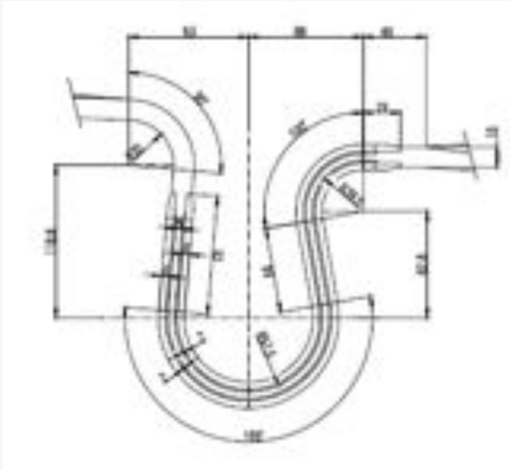
About 8 % higher than specified values

About **2600 cables** (Ic) were measured at cold

Cabling Ic degradation ≤ 3 %

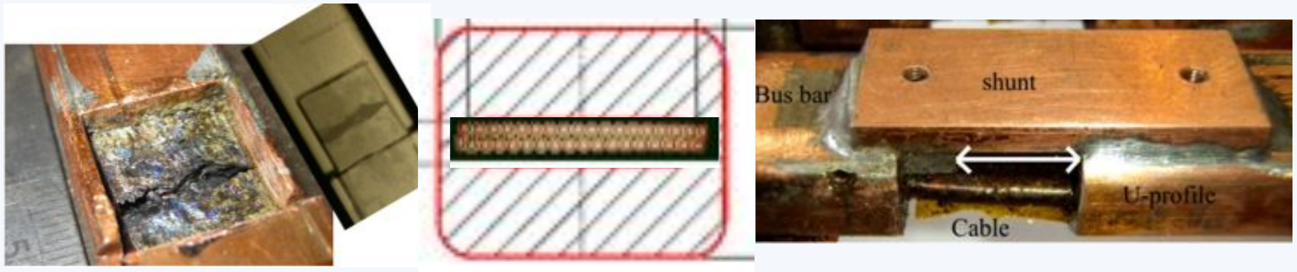
LHC Superconducting Bus-Bar





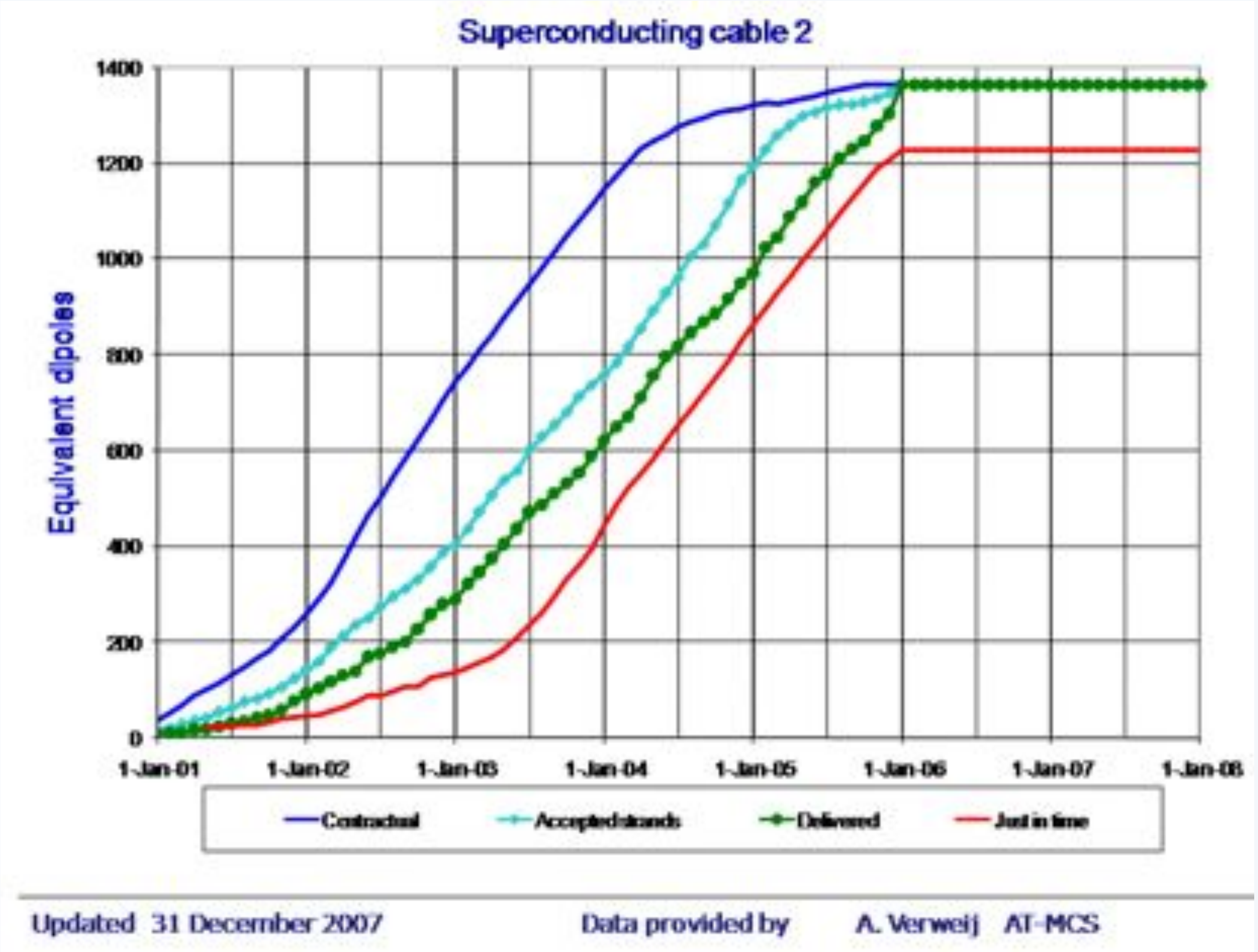
About 174 km of bus-bar produced with cable Type 02

19th September 2008



Defective interconnect burnt in the FReSCa CERN test station (9 kA)

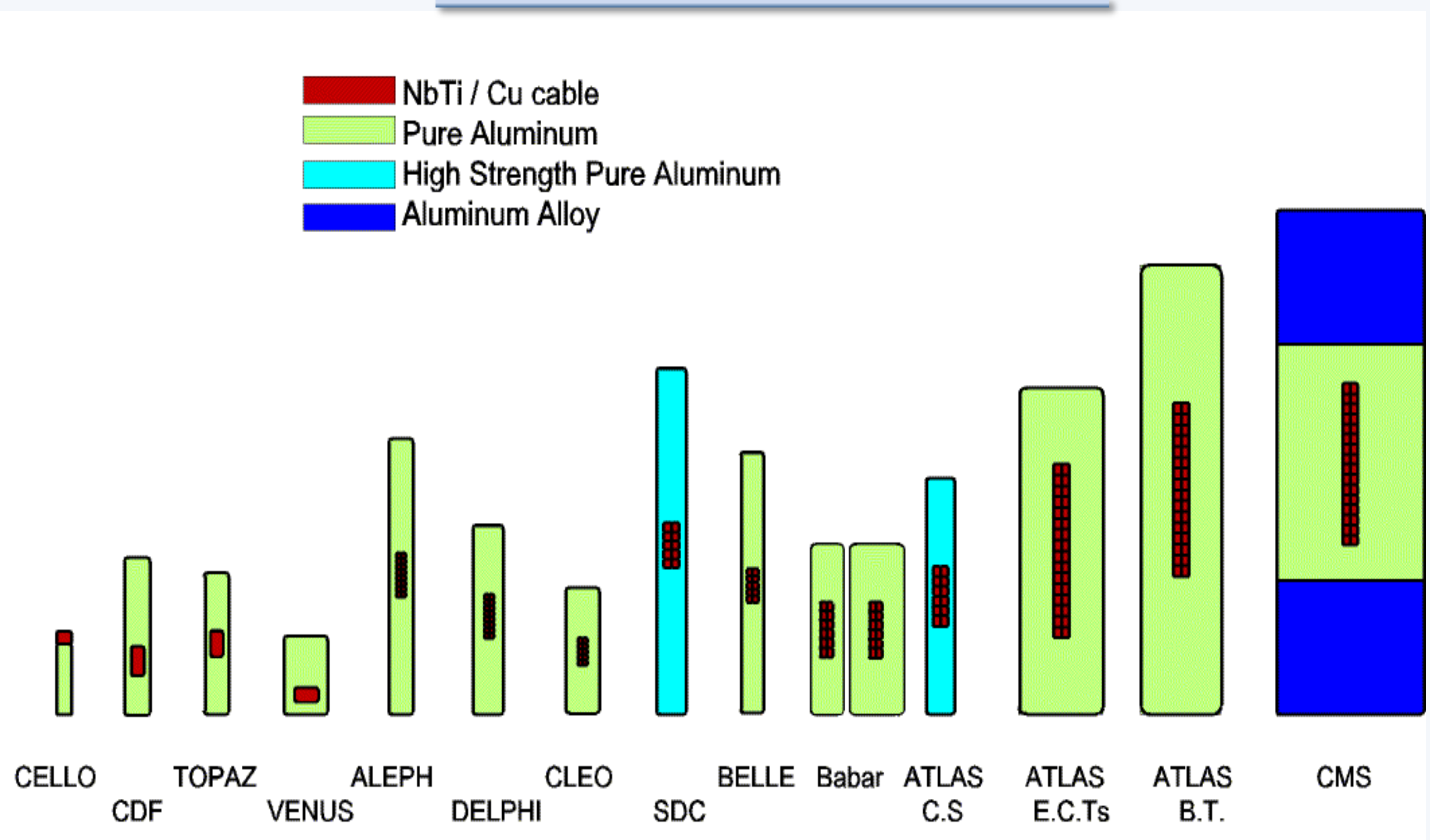
Cable Delivery



Cables for LHC Magnets

Superconducting magnet types	Units #	Coil bore [mm]	Length [m]	Field [T]	Current [A]	Bores #	Cable type	Coil layers
Main dipole	1232	56	15	8.33	11850	2	1, 2	2
Main quadrupole	376	56	3.1	223/m	11870	2	2	2
Matching quad.1	12+38+36	56	2.4/3.4/4.8	200/160/m	5390/4310	2	3	2
Matching quad. 2	24	70	3.4	160/m	3610	2	4, 5	4
Insertion quad. 1	16	70	6.37	215/m	7149	1	6, 7	4
Insertion quad.2	16	70	5.5	215/m	11950	1	8, 9	2
Separation dipole 1	4	80	9.45	3.8	5750	1	10	1
Separation dipole 2	8+4+4	80	9.45	3.8	5750/6050	2	10	1
Various correctors	5800	56	0.15 to 1.2	≤3, ≤110/m	60 - 600	1	wire	multiple

Superconducting Cables for Detector Magnets



Superconductor for the LHC Magnets

- About **1265 tons** or **7350 km** of superconducting **cables**
- More than **240 000 km** of superconducting **strands**
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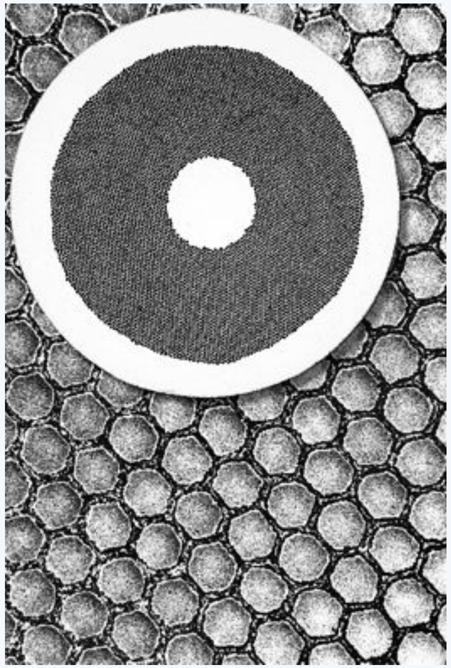
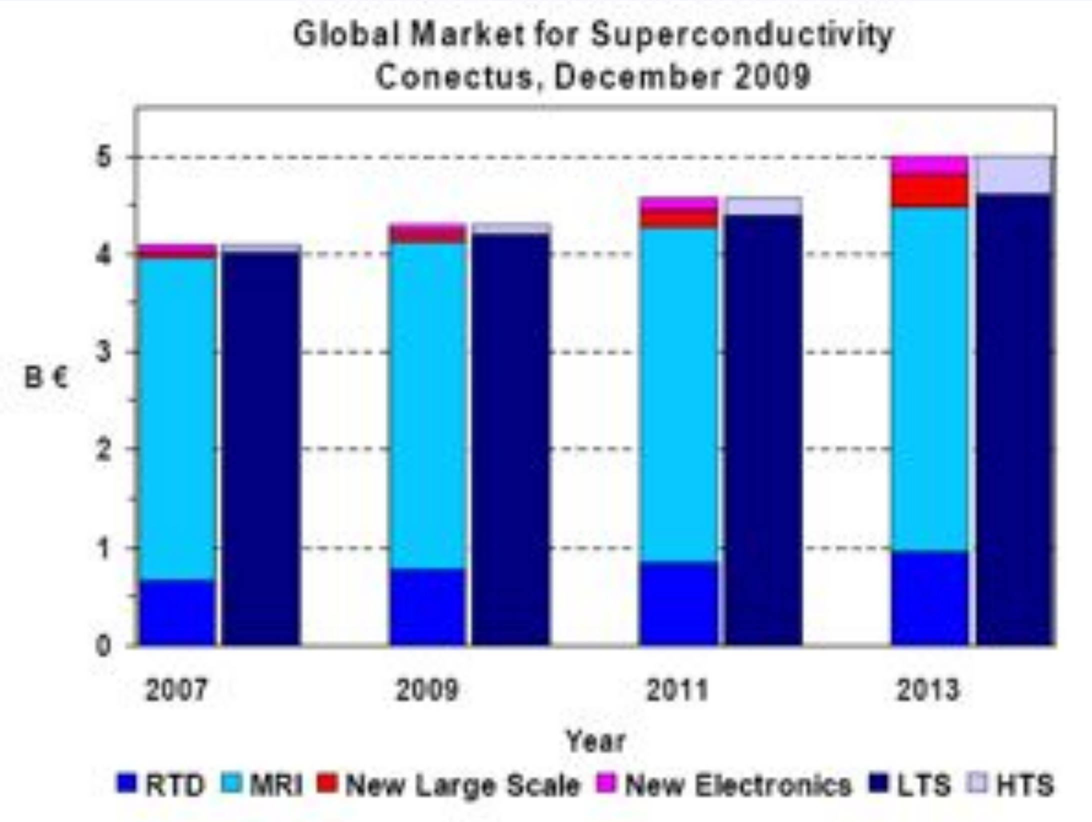
Nb-Ti Billets (Φ = 30 cm)



Strand (Φ = 1 mm)

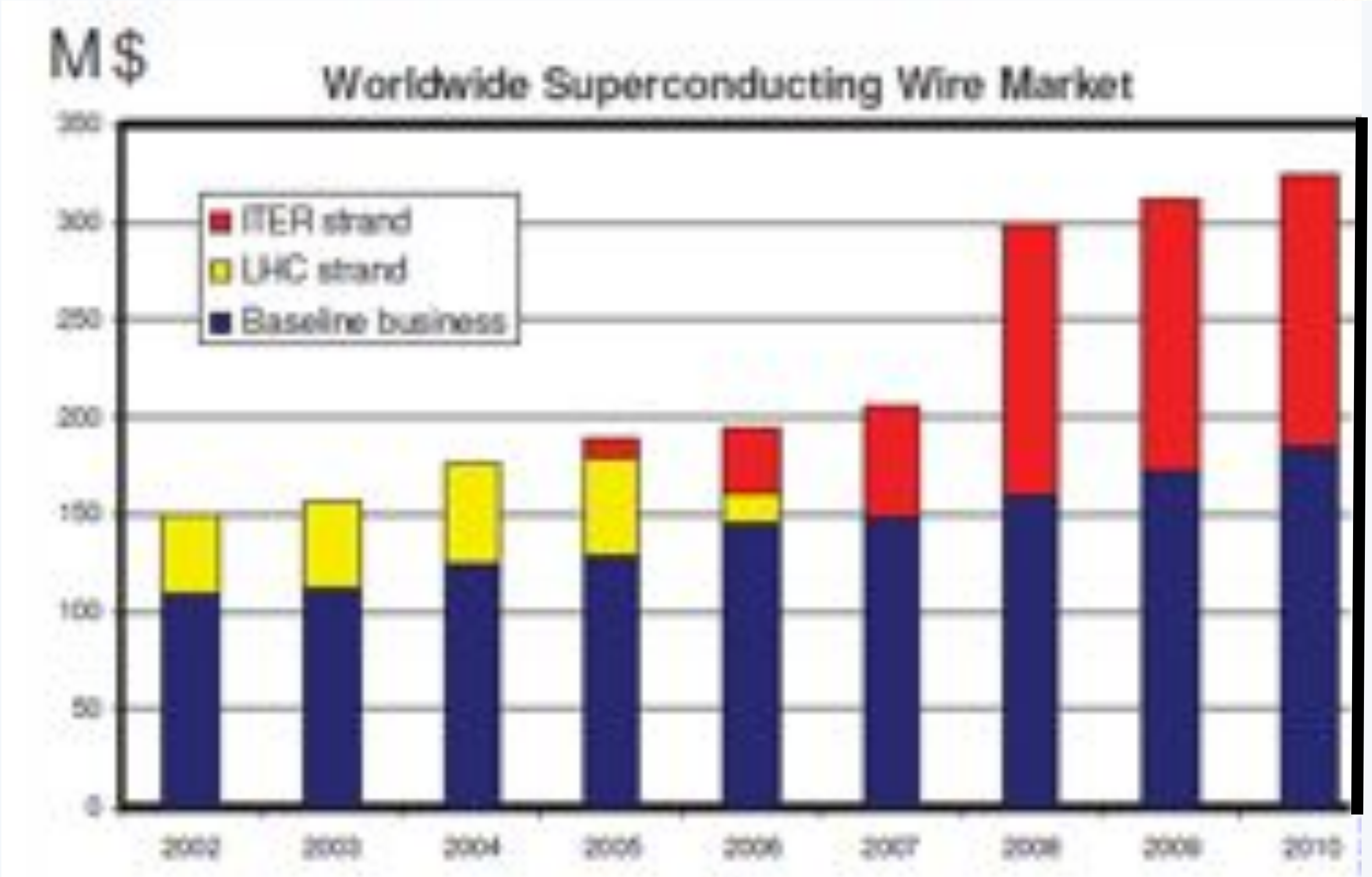
- It is interesting to note that the present commercial superconducting industry for MRI magnets is a **direct spin-off** of the intensive R&D work that was accomplished in the 1960s, on rendering the conductors suitable for winding coils for accelerator magnets

- *In exchange, the accelerator community has benefited from this success via the low price of material due to volume production*
  (more than 50 % of LTS market)



About 25 000 MRI systems with SC solenoids in the world
About 25 km of wire for a 1.5 T magnet, and up to 170 km for a 4 T magnet

Conectus: CONsortium of European Companies (determined) To Use Superconductivity



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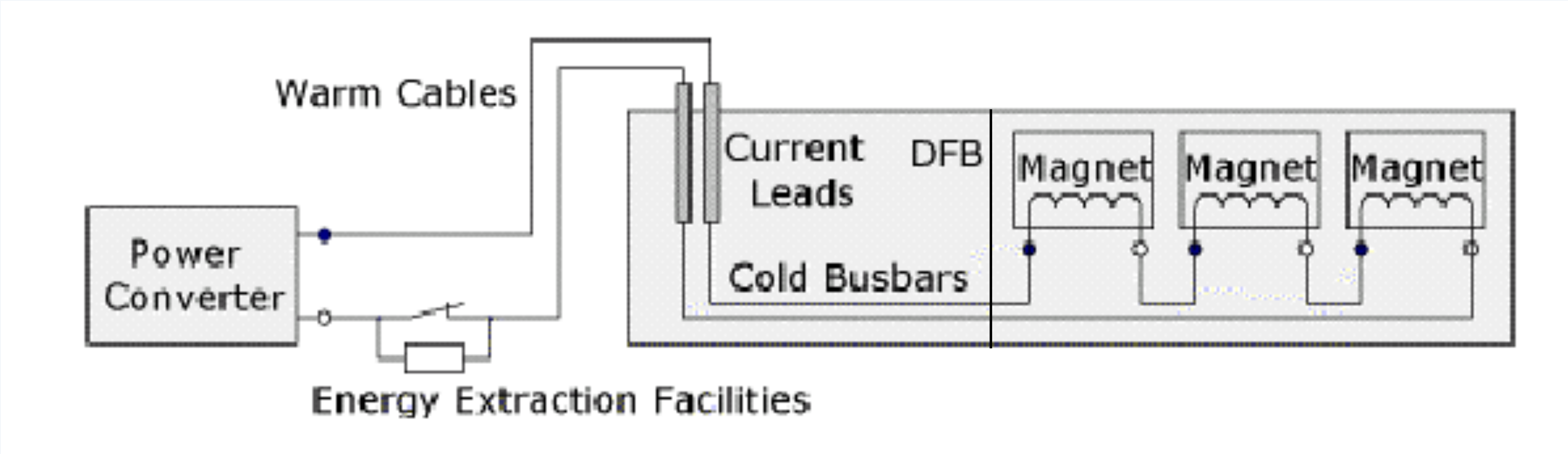
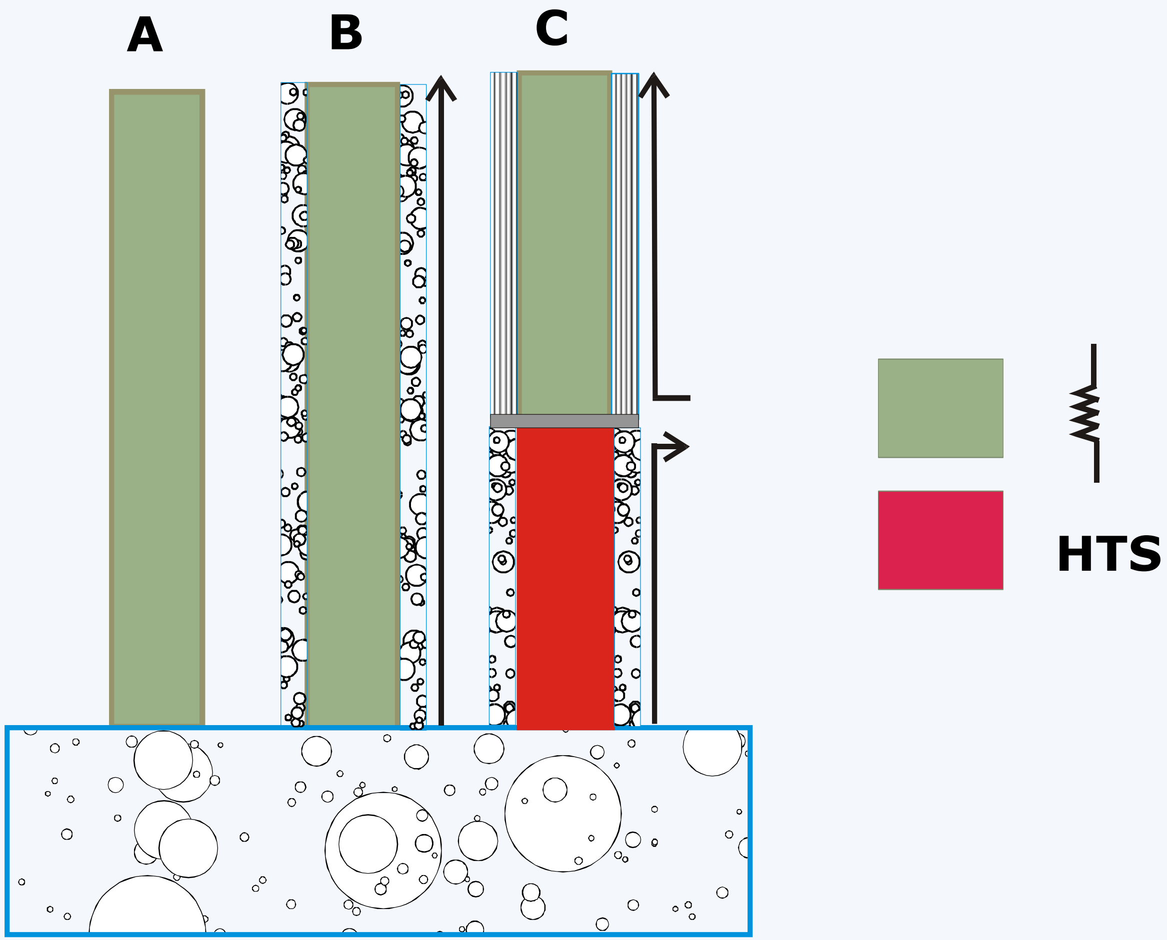
Powering of the LHC Magnets



3300 Current Leads
1800 Electrical Circuits
Itot ~ **3 MA**

Room temperature

LHe temperature

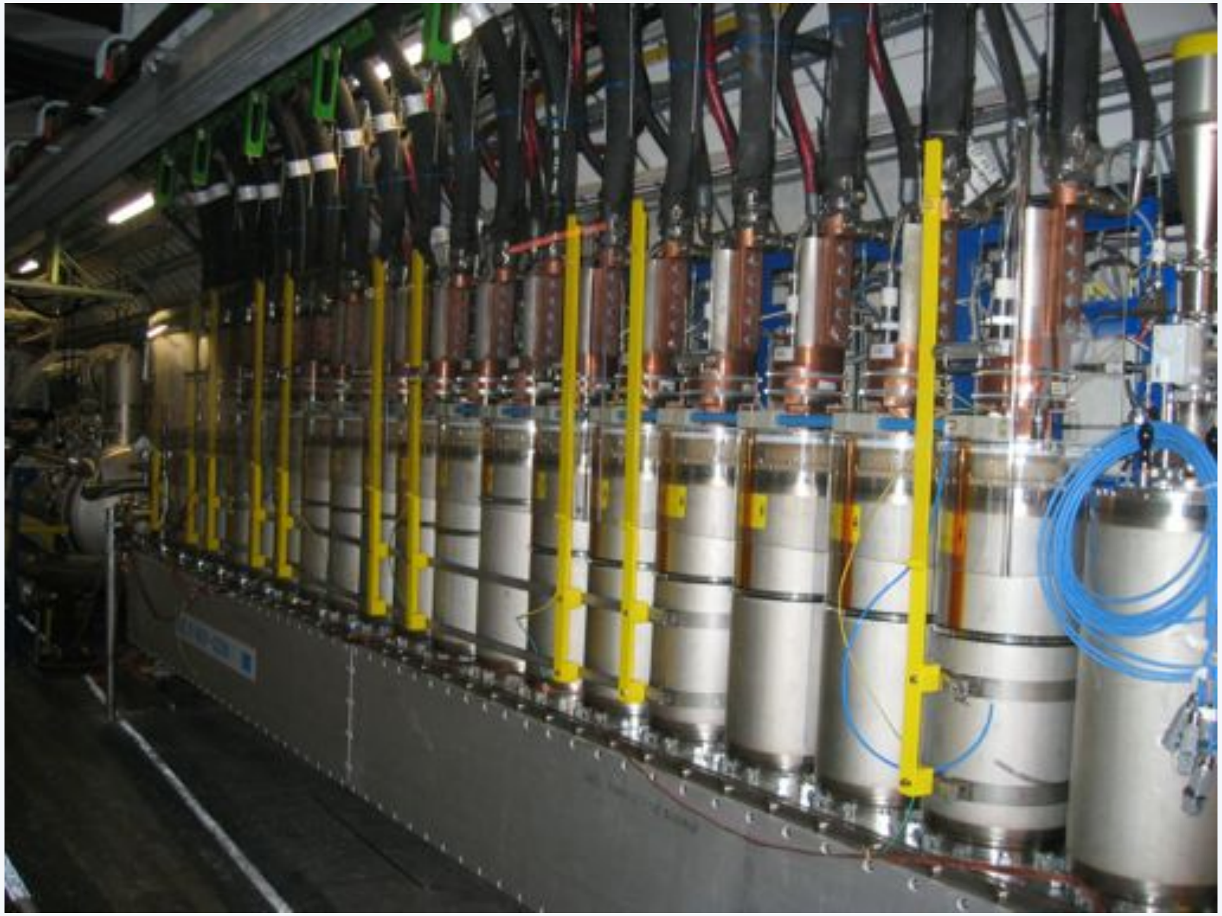


QA = 47 W/kA

QB = 1.04 W/kA

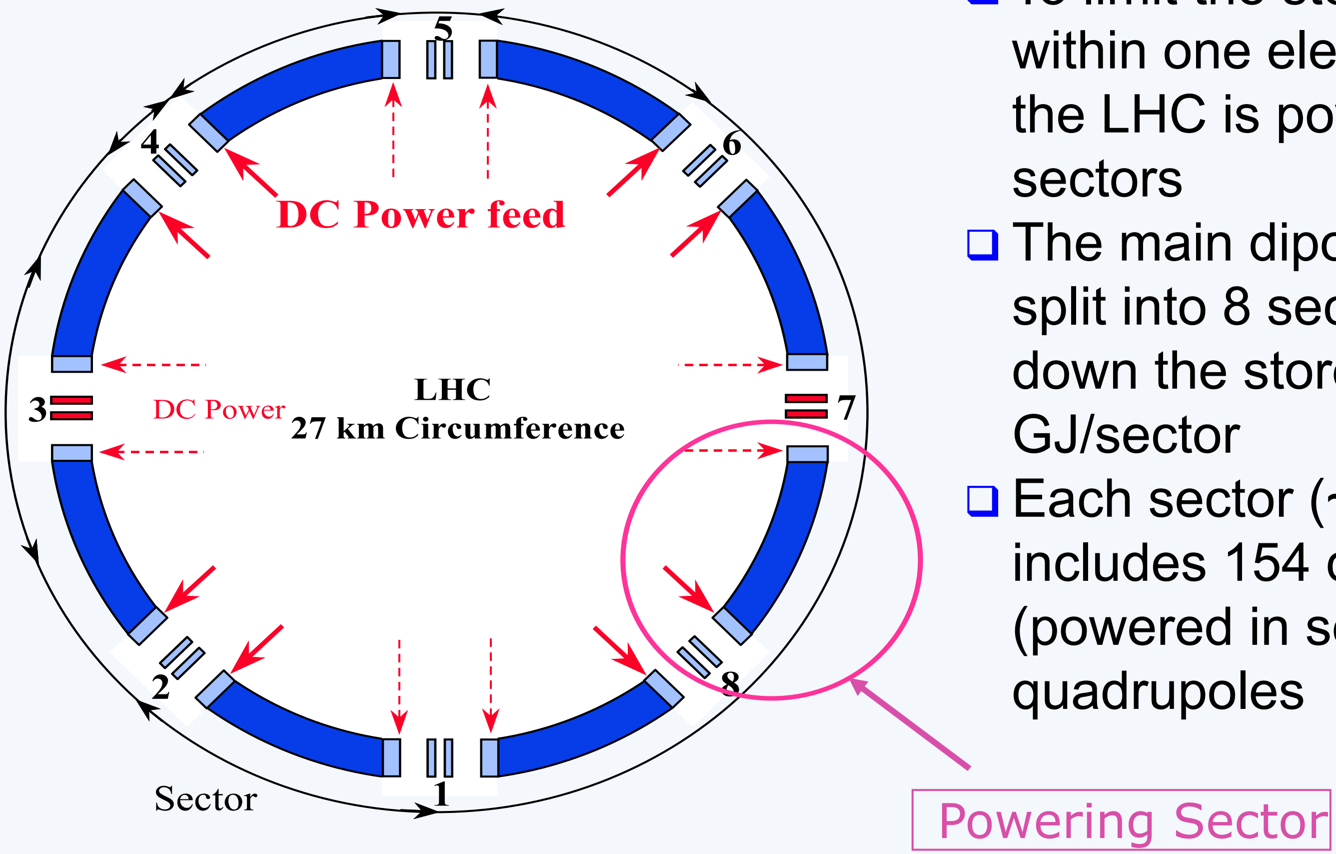
QC ~ 0.1 W/kA

LHC Current Leads



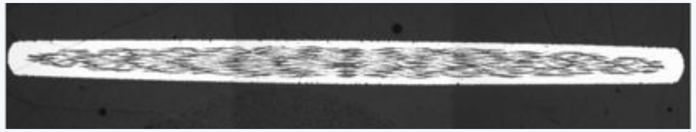
Current in the LHC magnets is transferred via HTS Current Leads

LHC Powering Layout

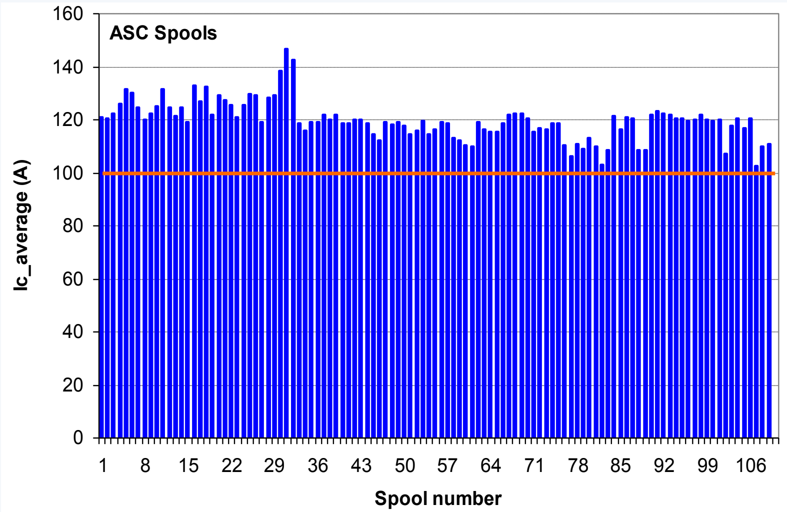


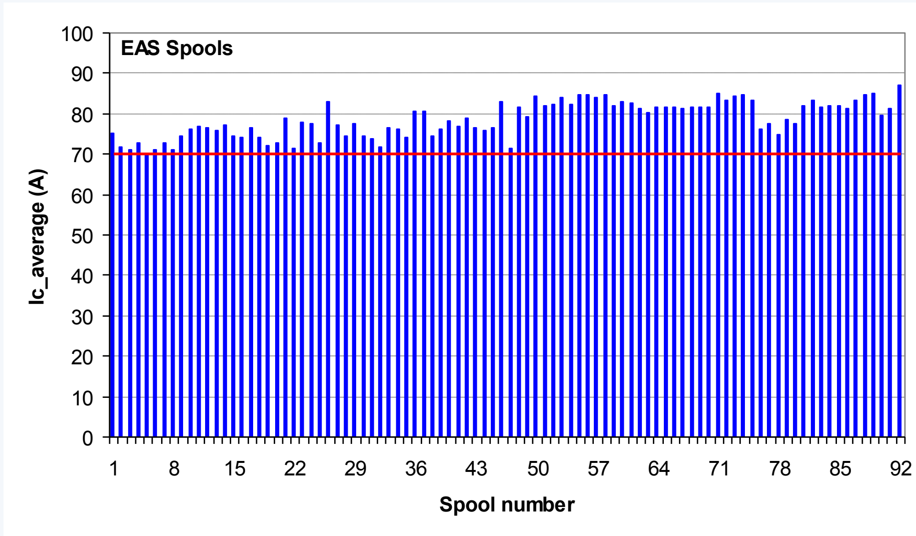
- To limit the stored energy within one electrical circuit, the LHC is powered by sectors
- The main dipole circuits are split into 8 sectors to bring down the stored energy to ~1 GJ/sector
- Each sector (~2.9 km) includes 154 dipole magnets (powered in series) and ~50 quadrupoles

Bi-2223 in the LHC current leads



Bi-2223 tape: **31 km** in total
AgAu5 (wt%)
ULs=100...300 m

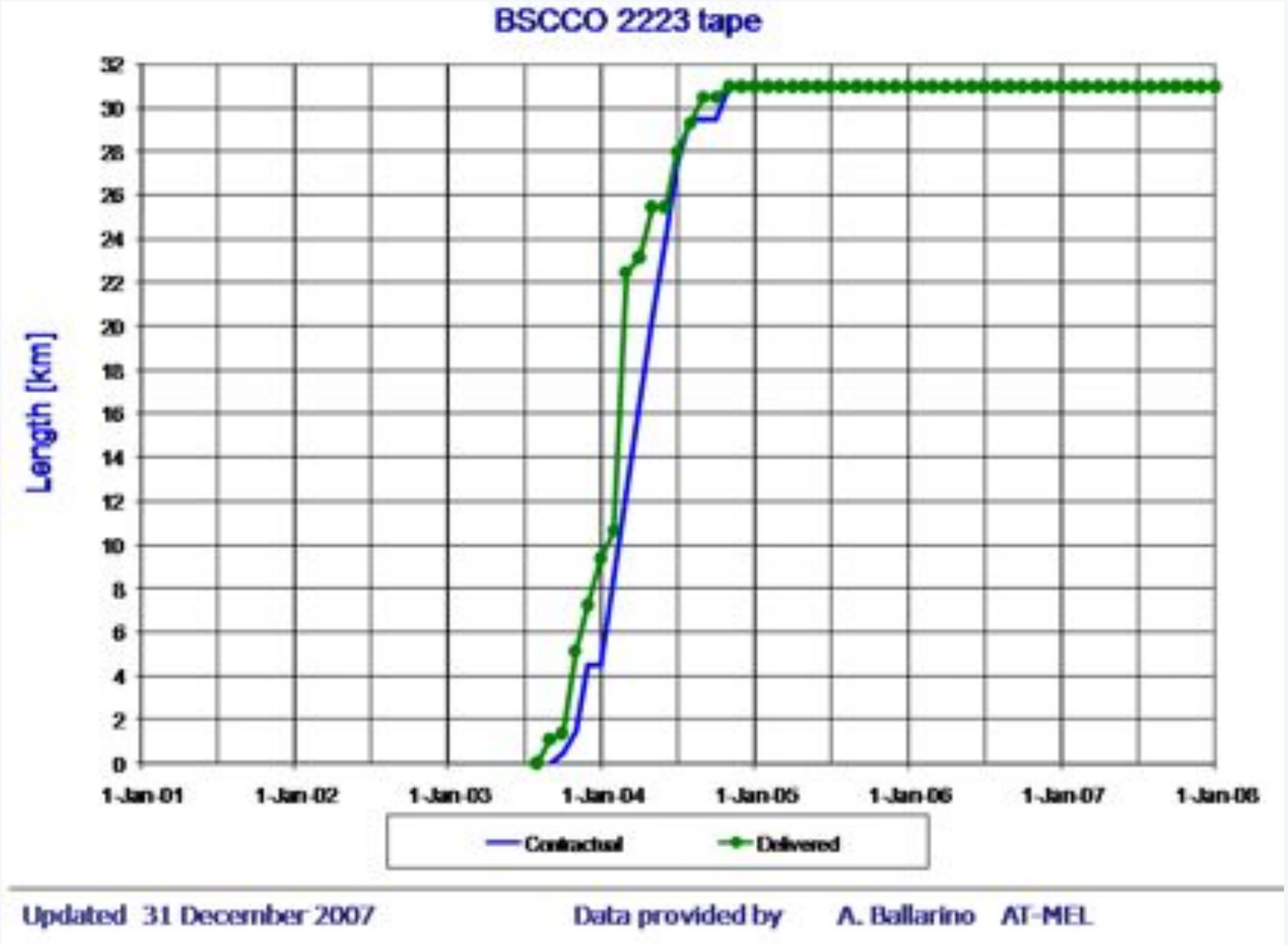




Ic_min (A)	Ic_av (A)	Ic_max (A)	σ (A)
103	120	147	7

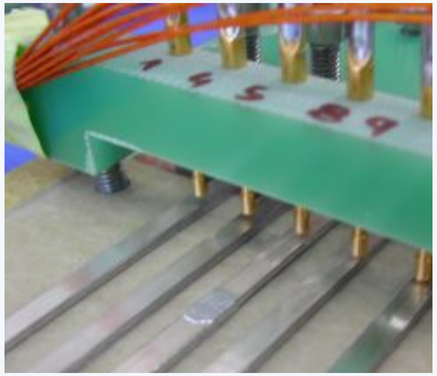
Ic_min (A)	Ic_av (A)	Ic_max (A)	σ (A)
70	79	87	4

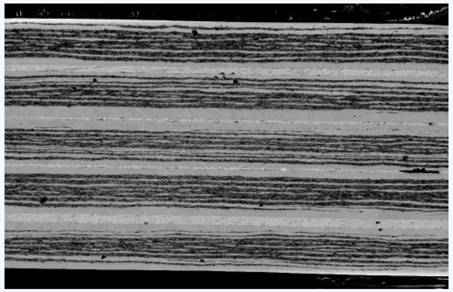
Bi-2223 Tape Delivery

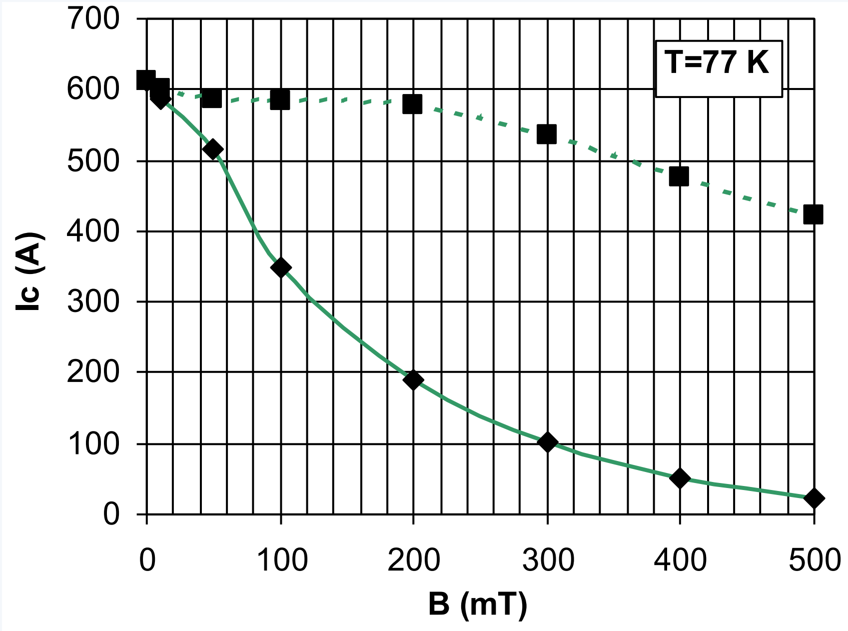


Stacks of Bi-2223 tapes

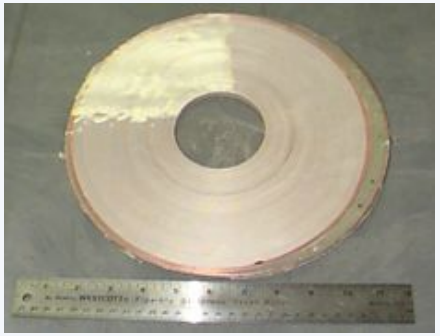
About **10 000** vacuum soldered stacks of tapes

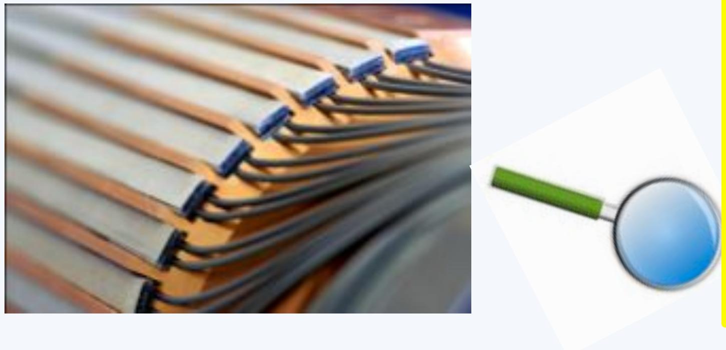


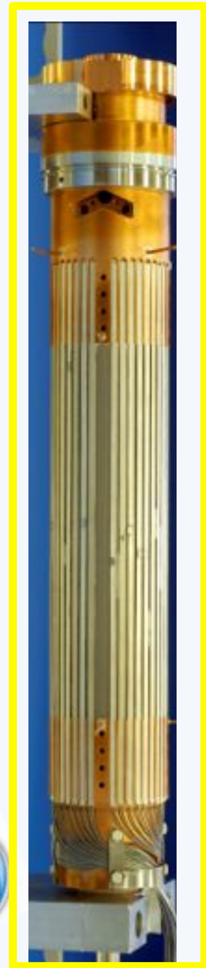


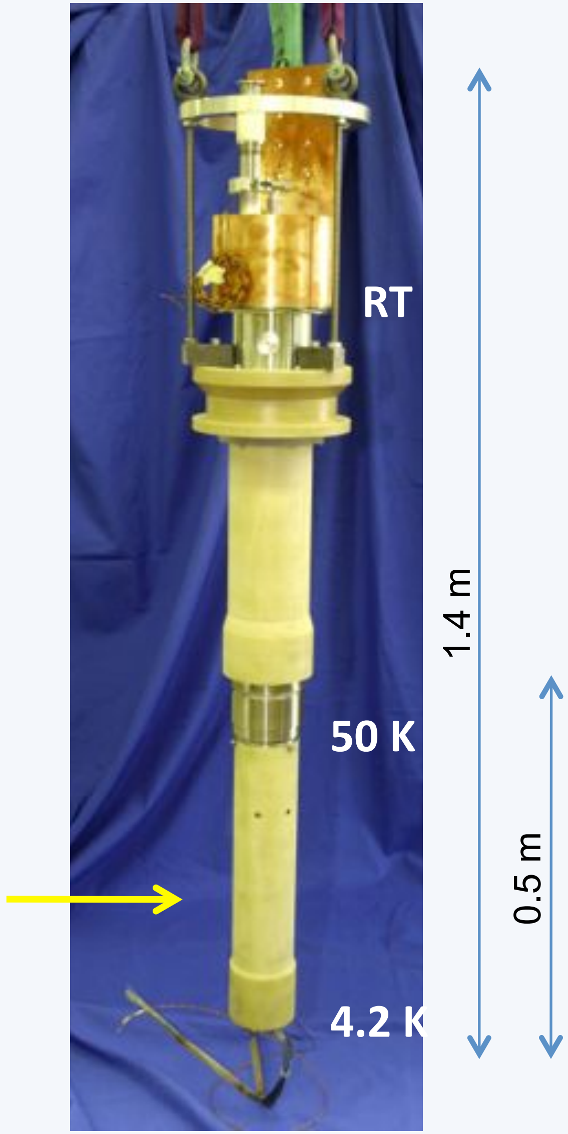


HTS 13000 A Current Lead









LHC HTS Current Leads

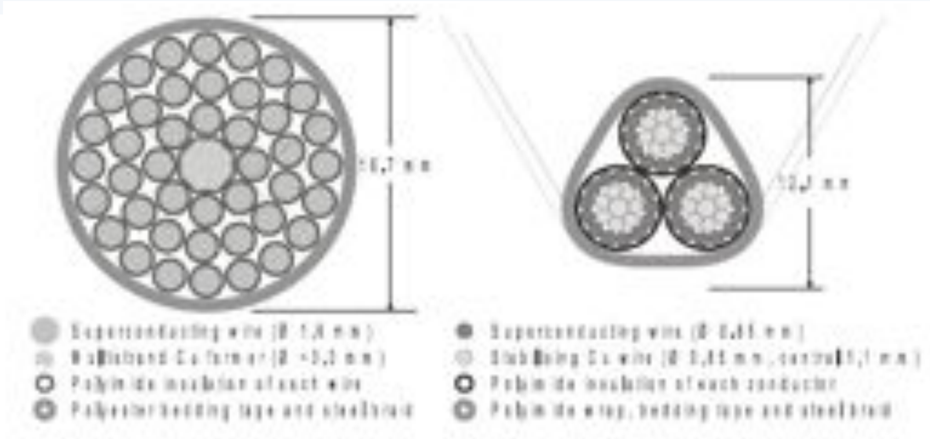
Work on HTS current leads started at CERN in the early 1990s, a few years after the discovery of High Temperature Superconductivity, and intense R&D program has led to their application to the LHC machine

This has been the first large scale commercial application of HTS

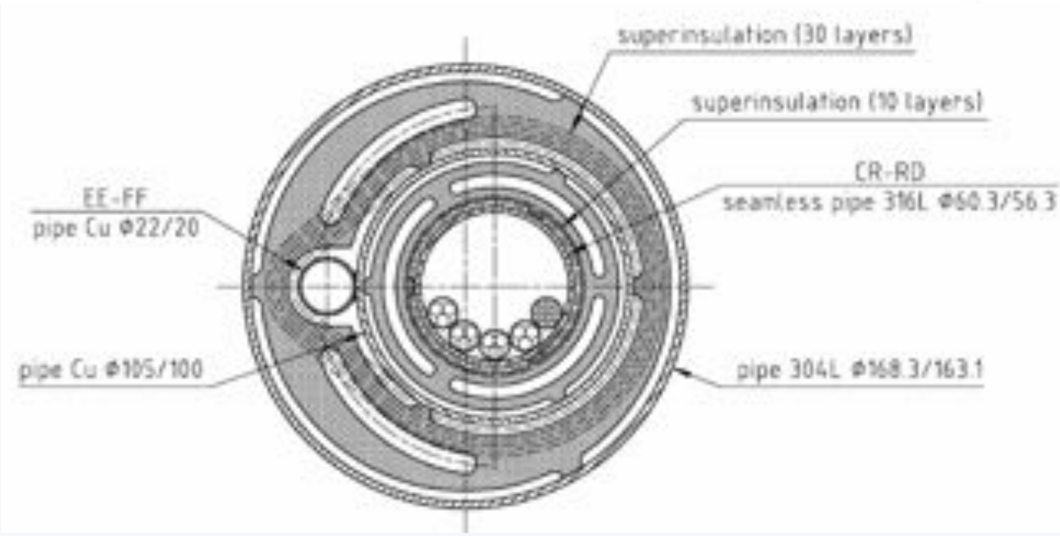
Following this development, the fusion community has also adopted the LHC HTS lead design (ITER, up to 68 kA, W7-X and JT-60)

HTS Current Leads: a successful example of a replacement technology

Existing Superconducting Links at the LHC



Cross sections of the 42 × 600 A cable (left) and the 3 × 6 kA cable (right).



Five superconducting links (P1, P3 and P5)

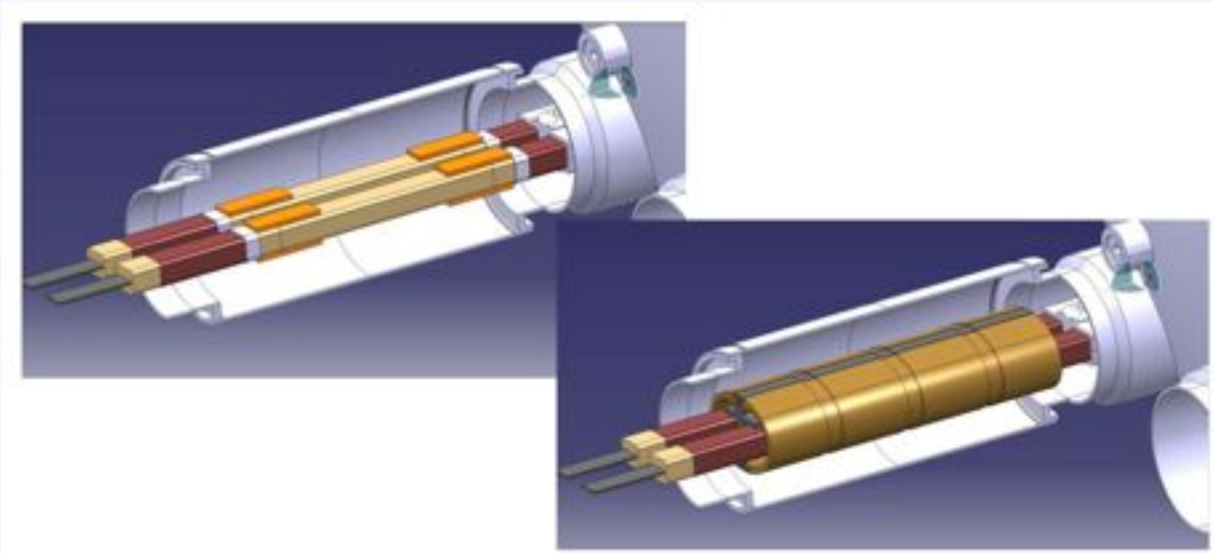
L= 70 m and 500 m

What about the future ?

In two years time:

Consolidation: Interconnections

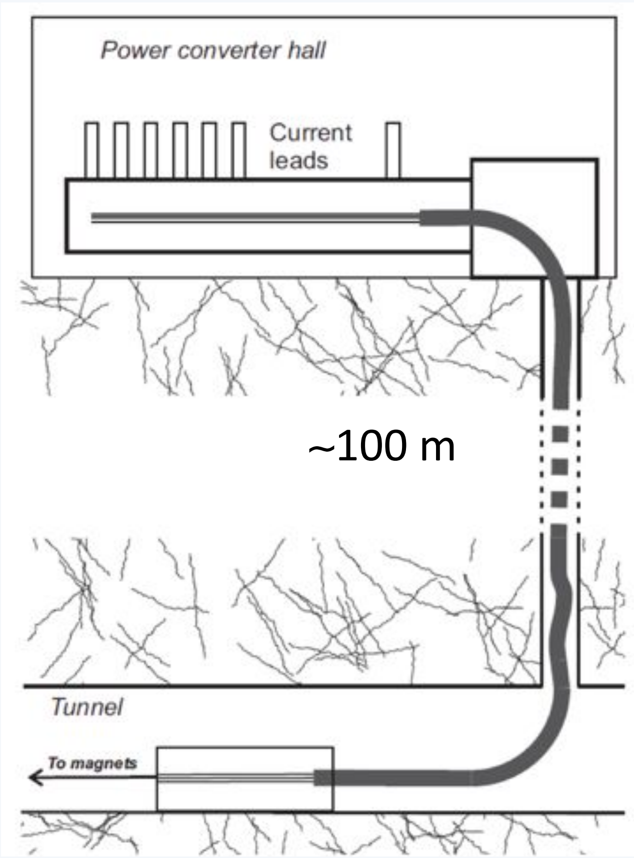
➢ **Splice consolidation** The LHC is limited today to 3.5 TeV to avoid un-protected thermal runaway in defective splices;

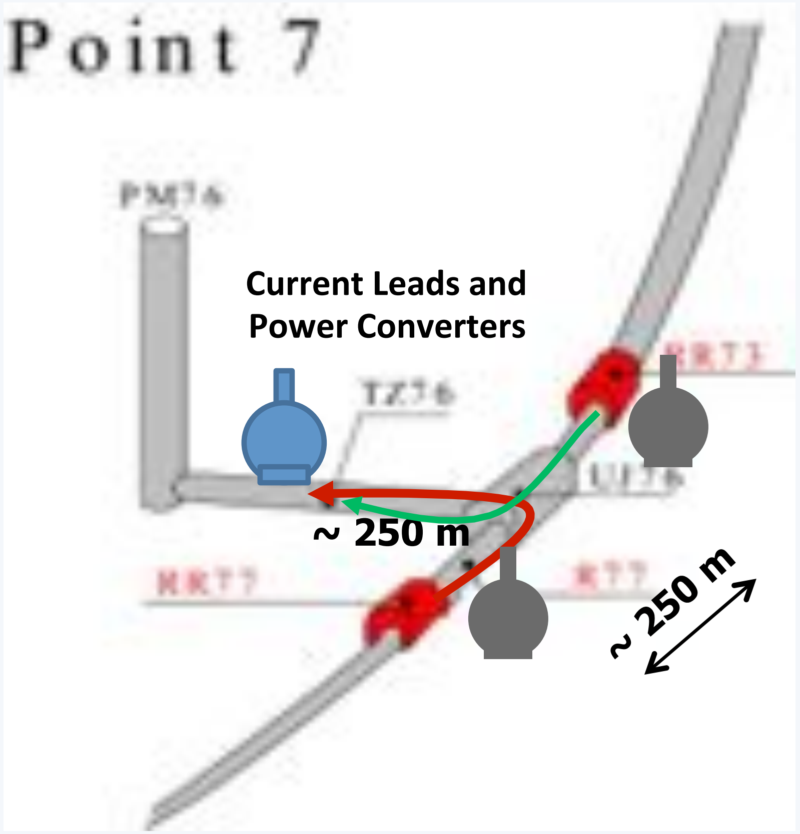


As from now (until 2020) :

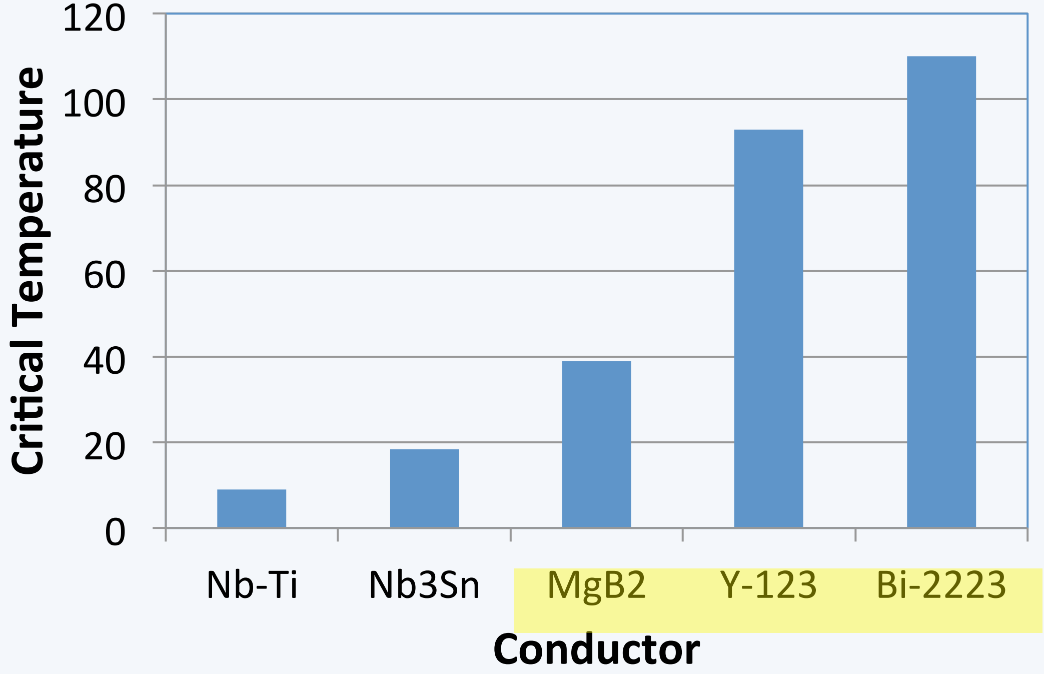
- Development of km long **DC HTS superconducting links**
  Removal of the converters from the cavern

<u>to the **surface** (P1 and P5)</u> or <u>to **remote underground areas** (P7)</u>





Superconductors for Application to LHC Links



Higher Tc → Temperature margin

HTS Superconducting Link

-Transfer of **high currents** (up to about **14 kA**) in superconducting cables

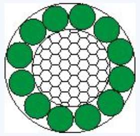
-**Multi-cable system** containing up to about 60 electrically insulated cables transferring in all a maximum current of about **180 kA**;

-**Compact transfer** of about 180 kA over long **horizontal and vertical lengths**. Optimization of differential thermal contractions and of cable supporting structure in particular for the vertical option;

-Optimization of a **new cold powering system** with respect to cryogenic, electrical and mechanical requirements

The project will enable to continue to accumulate expertise with HTS conductors - of interest for future application to magnet technology

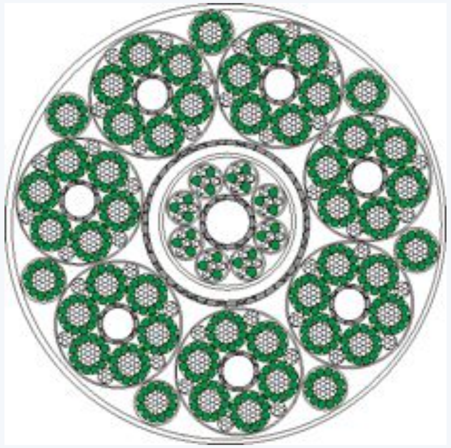
Development of Novel Cable Assemblies



11.8 kA @ 4.2 K

12 wires

Φ = 6 mm

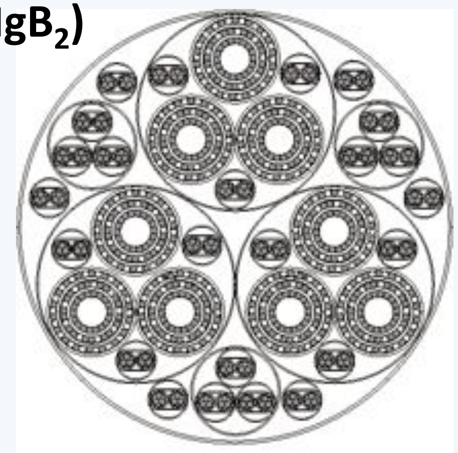


Φ = 62 mm

Itot=100 kA @ 20 K

Cable structure using wires

(MgB_2)



Φ = 75 mm

27 × 6000 A
48 × cables 600 A
Itot = 190 kA

Cable structure using tapes

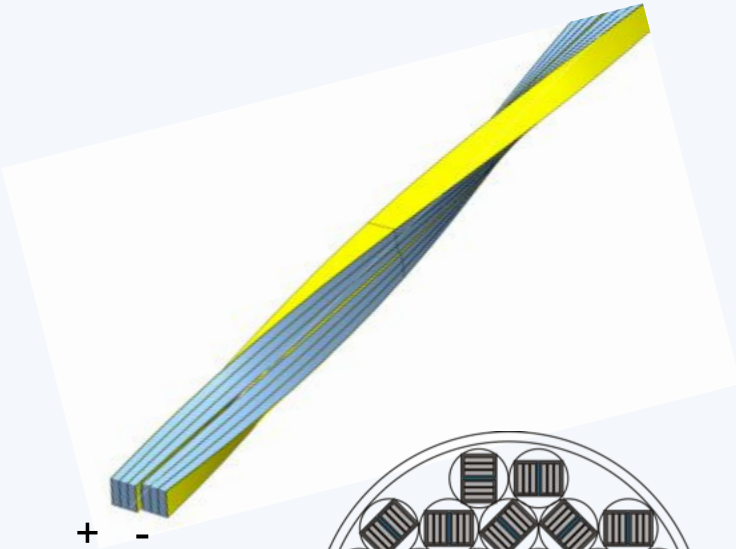
(YBCO or Bi-2223)

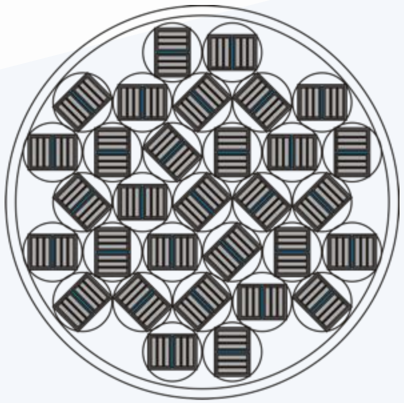
Φ = 70 mm

24 × 6000 A
42 × 600 A
Itot = 169 kA

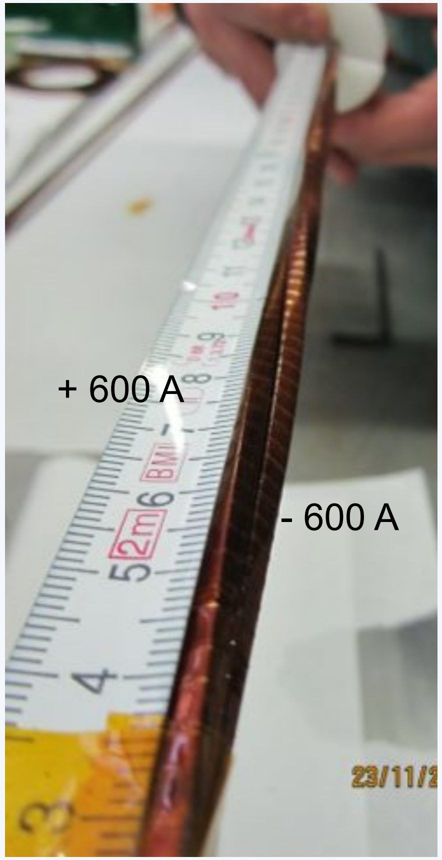
Development of Novel Cable Assemblies

Twisted pair 600 A cable

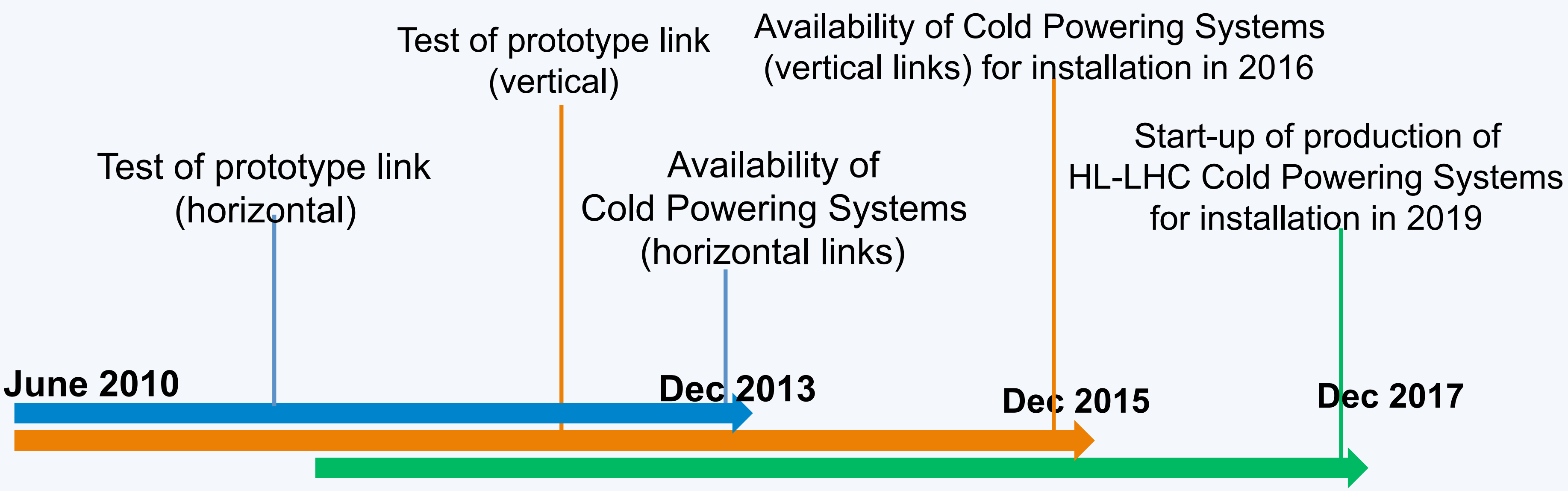




Φ= 27 mm
50 YBCO cables 600 A @ 70 K

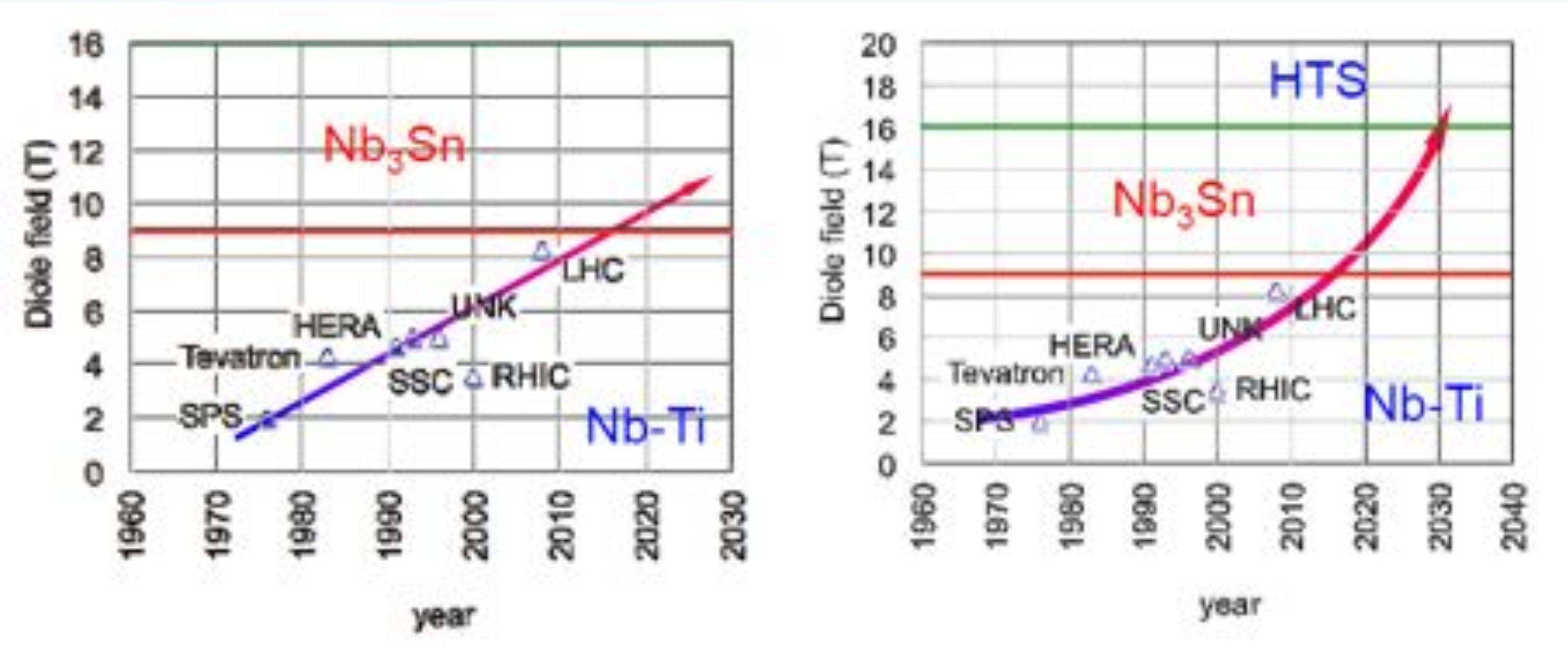


HTS Link Project TimeLine



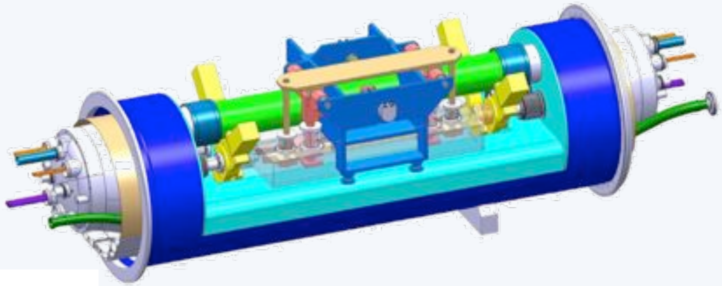
- Horizontal link at P7 (600 A circuits)
- Vertical link at P1 and P5 (7000 A and 600 A circuits)
- Vertical link at P1 and P5 for IR-Upgrade (with 14000 circuits)

Conductor(s) for Future Magnets

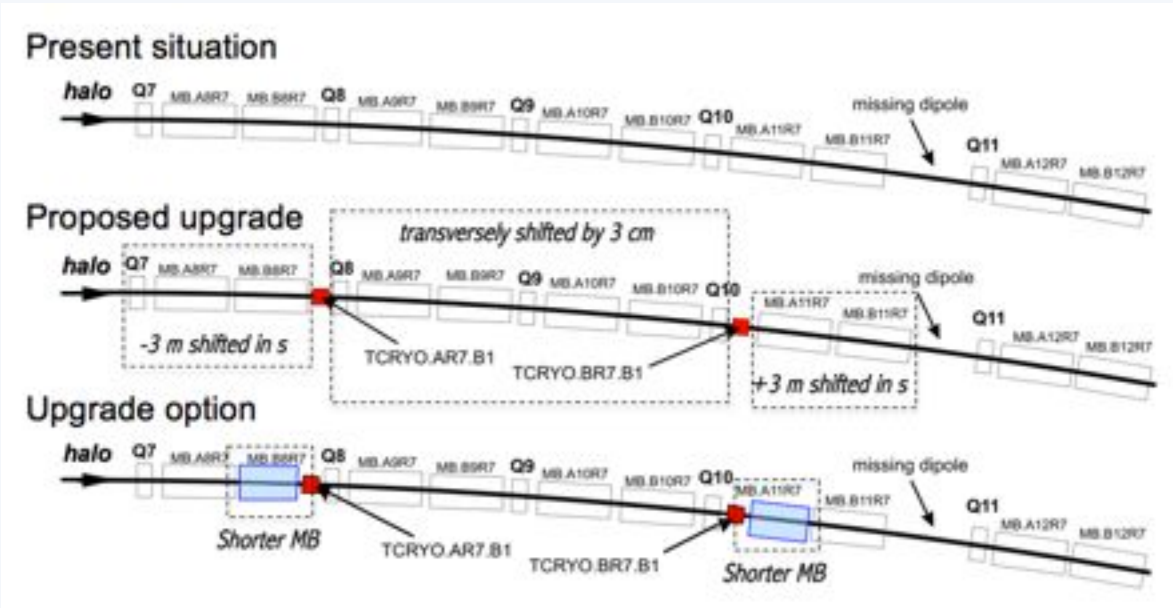


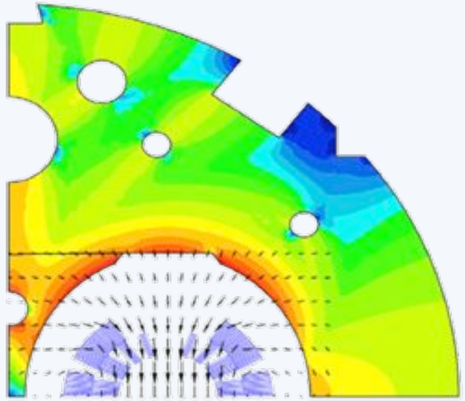
Collimators in the DS Region

Upgrade: Nb_3Sn magnets



Cryo-collimator





Twin aperture dipole

11.7 T, 11 m long

Nb_3Sn Technology

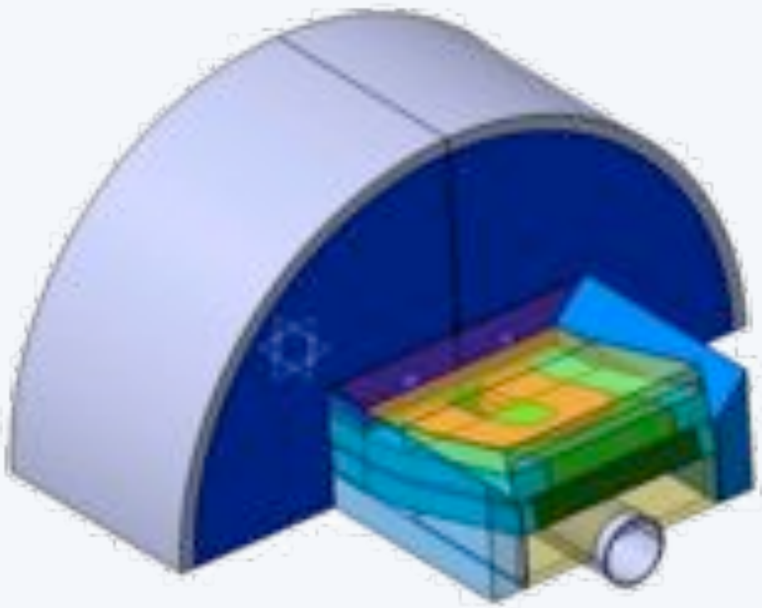
Facility for Cable Tests

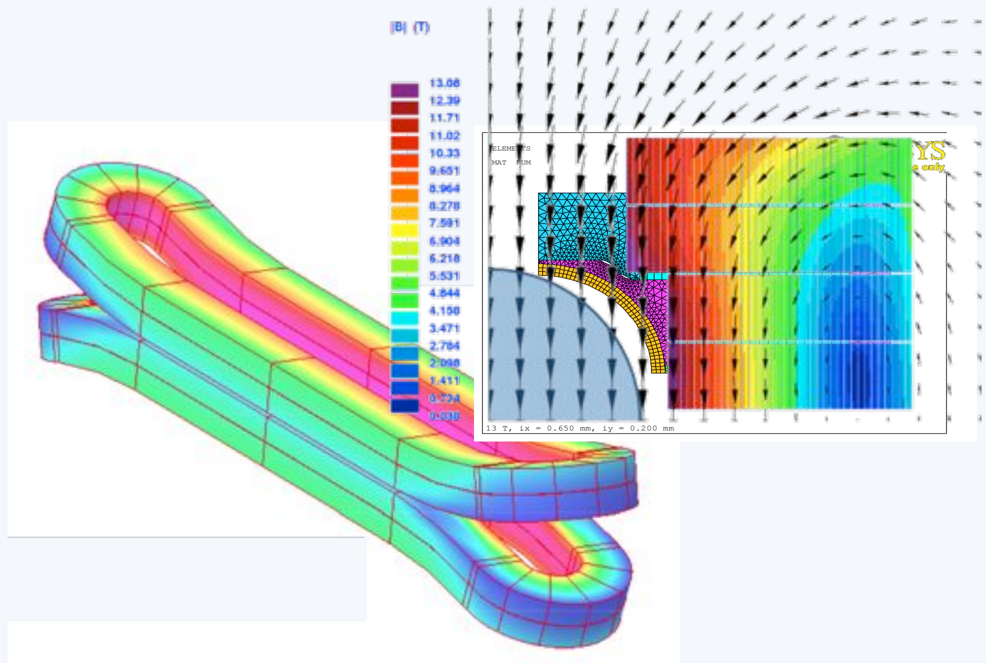
The next three years:

FReSCa-II, 13 T, 100 mm bore test facility for cable tests at 1.9 to 4.3 K

→ Nb_3Sn Technology

B_{nom} = 13 T, B_{SS}=16 T





The magnet will incorporate an HTS YBCO insert (13 T + 6 T)

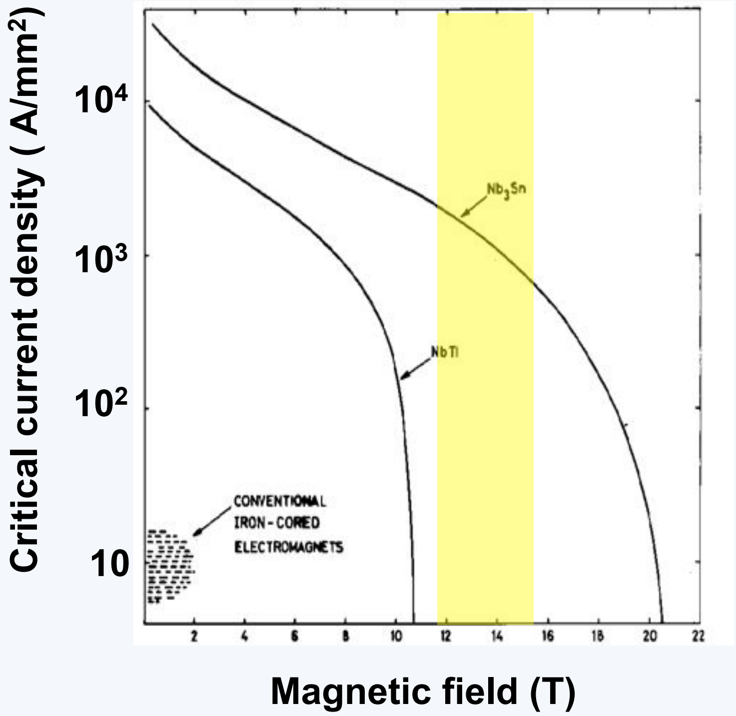
Higher Luminosity

- The main ingredient of the HL-LHC upgrade are IR quadrupoles with G ≈ 170…180 T/m and Φ ≈ 120 mm

- **US-LARP** is engaged in the production of a model by 2013 (4…6 m length) for the decision on the technology to be used (**Nb_3Sn vs. Nb-Ti**)

- The quadrupole magnet production (2 IR's, 4 complete triplets plus spares), shall take place by ≈ 2018

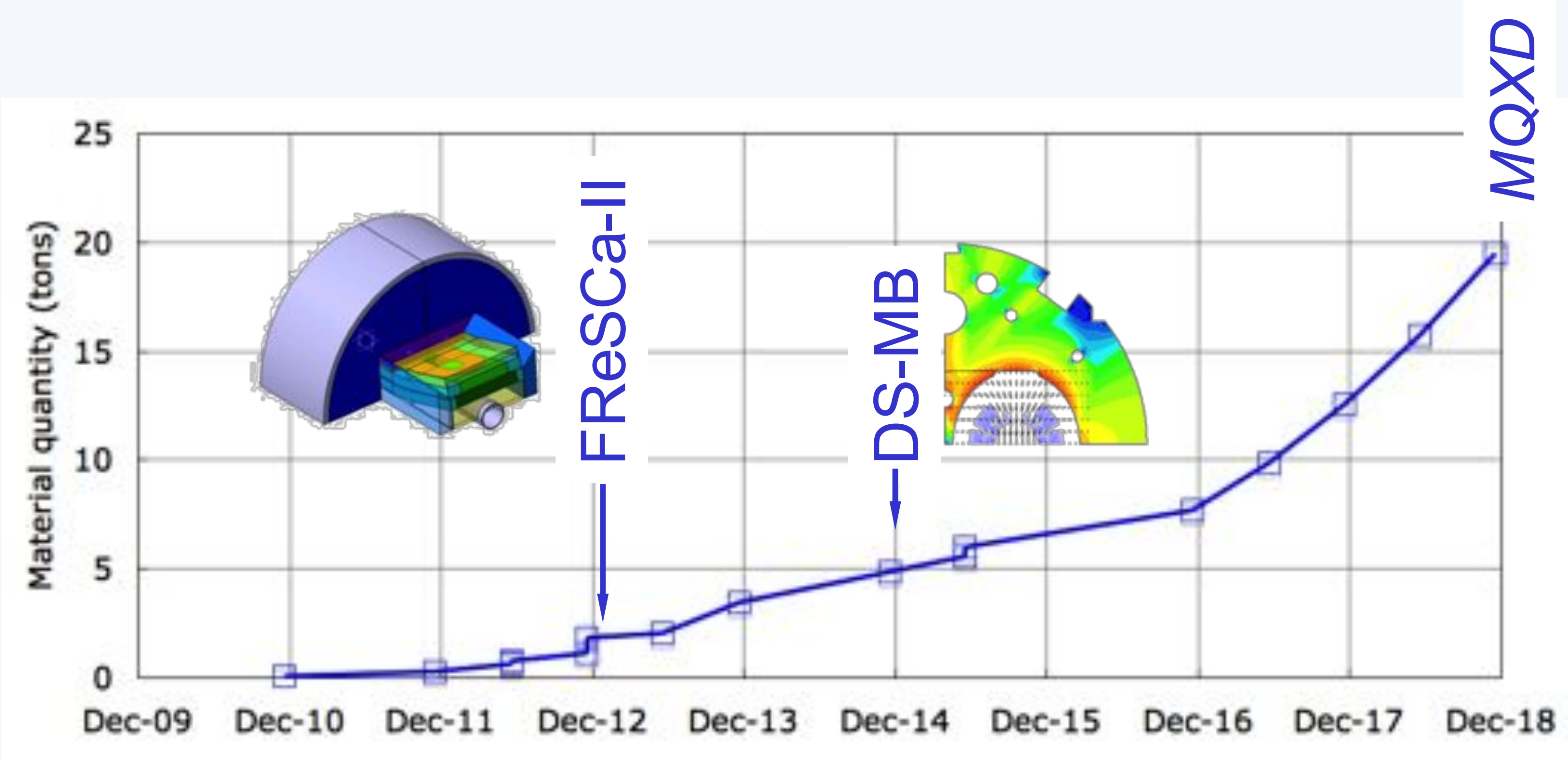
Nb_3Sn



Based on CERN and EuCARD procurements

(4.5 K)		NED	FReSCa-II	DS-MB
Strand diameter	(mm)	1.25	1	0.7
Sub-element diameter	(μm)	50	50	≈ 50
Copper:non-Copper	(-)	1.25	1.25	1.13
J_C(12 T, 4.2 K)	(A/mm²)	3000	2500	**2650**
J_C(15 T, 4.2 K)	(A/mm²)	1500	**1250**	1400
n-index	(-)	30	30	-
RRR	(-)	200	150	60
Piece length	(m)	>300	800	350

Material Needs: LTS



- Approximately 20 tons of *HEP-grade* Nb_3Sn will be needed in the coming 8 years

L. Bottura

Material Needs: HTS

- Conductor needs for R2E and HL-LHC amount to a length in excess of **2000 km of HTS** wire or tape, to be used in cables rated at currents ranging from 600 A to 14000 A

		Φ (mm)	W (mm)	Th (mm)	Tmax (K)	Ic (‡) (A)
(†)MgB_2	**wire**	1.1	-	-	**25**	**≥ 400**
MgB_2	**tape**	-	3.7	0.67	**25**	**≥ 400**
YBCO	**tape**	-	4	0.1	**35**	**≥ 400**
BSCCO 2223	**tape**	-	4	0.2	**35**	**≥ 400**

NOTES:
(†) bending radius $R_B \leq 80$ mm
(‡) at applied field $B \leq 0.5$ T

Conclusions

- Superconductivity has played a major role in the evolution of HE accelerators
- The work-horse conductor has been up to now Nb-Ti. For many applications Nb-Ti remains the conductor of choice
- To go to higher fields, or for specific applications where higher operating temperature is an advantage, A15 type conductor and High Temperature Superconductors are needed. This requirement defines the present and future R&D effort at CERN

Thanks for your attention !

Classical and High Temperature Superconductors:
Practical Applications and Perspectives at CERN

A. Ballarino, CERN

High-energy physics has been a major driving force in the development of applied superconductivity, the two fields becoming an example of unique merging between fundamental physics research and technological development. The continuous quest for higher fields required by high performance magnets for particle accelerators stimulated the development of state-of-the-art conductors suitable for large-scale applications. It is thus that Nb-Ti alloy went through a significant performance improvement and has become a mature industrial conductor, today pushed to its practical limits. The A15 compounds, of which Nb3Sn is the principal example, are presently the conductors of choice for very high field magnets. Due largely to more challenging mechanical characteristics their use to date has been mainly confined to niche applications such as laboratory magnets, but development of conductor suitable for the next generation of accelerator magnets is bearing fruit and the requirements of fusion science is giving impetus to their development on an industrial scale. High-temperature superconductors are more recent innovations for research laboratories. Their unique characteristics have already led to important applications for some auxiliary systems, and thanks to steady progress in performance they may become an attractive alternative to conventional low temperature superconductors for specific types of magnets.

An overview of the application of both low temperature and high temperature superconductors to the CERN Large Hadron Collider is presented, together with perspectives on the future needs of the accelerator.

Dr Amalia Ballarino is a scientist at the European Organization for Nuclear Research (CERN), Geneva, Switzerland. She has been responsible for the development, design and procurement of the several thousand of current leads that today power the superconducting magnets of the Large Hadron Collider (LHC) machine. For the development of the High Temperature Superconducting (HTS) current leads for the LHC, which has been the first large scale commercial application of HTS, she received the award of “Superconductor Industry Person of the Year 2006”. After having participated in the commissioning of the LHC machine, she has been working on the development of a novel HTS bus system which is today of interest for application to the accelerator upgrades. In the framework of this activity she coordinates a European Commission initiative as Task Leader in the Seventh Framework Programme (FP7) Eucard High Field Magnet Work Package (High Tc Link), and more recently she has become Work Package Leader in a FP7 Proposal for a High Luminosity Design Study (Cold Powering System). Dr Ballarino is also a member of the IEC TC-90 committee on standardization in the field of superconductivity.