Classical and High Temperature Superconductors Applications for the LHC and for the LHC Upgrades

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Academia-Industry Matching Event
Fostering Collaborations in Superconductivity
CIEMAT, Madrid
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Outline

- Superconductivity at CERN
- Superconductors for LHC magnets
  - Nb-Ti strands and cables for LHC
  - Nb_3Sn and HTS for LHC upgrades
  - High Temperature Superconductors for LHC
- HTS Current Leads for the LHC machine
- HTS Superconducting Links for LHC upgrades
- 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

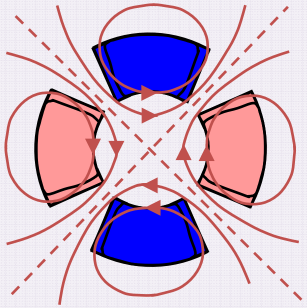
*(With regard to SC magnets, **specific equipment** is required for their powering; efficiency implies the use of superconductors in **busbars** and **current leads**)*

Superconductivity and Particle Accelerators

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

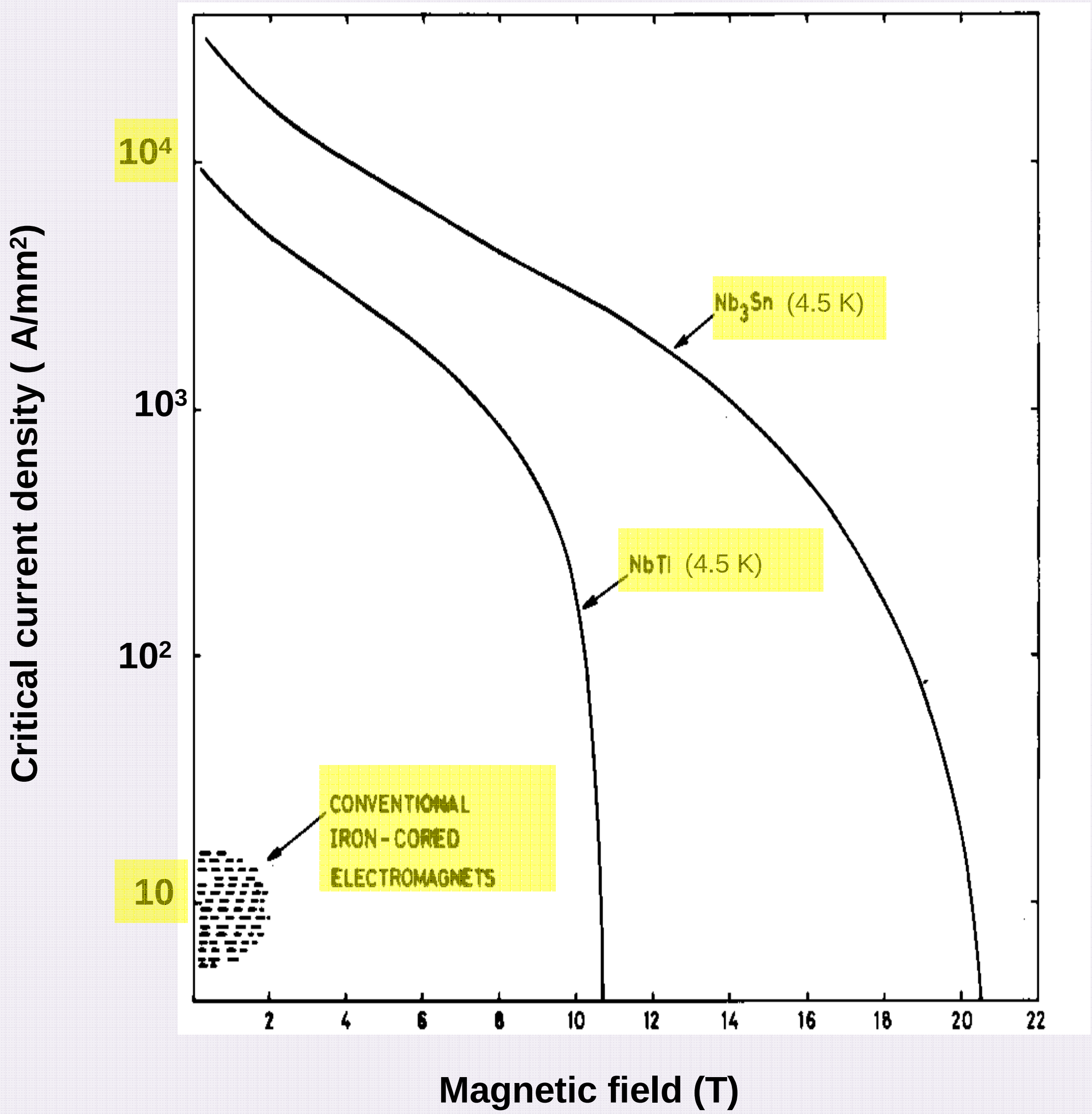
- High current density → **compact windings**
  high magnetic fields and gradients
- Larger ampere-turns in a small volume→ **no need for iron**
  (but iron is still useful for shielding)
- Reduced power consumption → **lower power bills**
  (when cost of refrigeration power is offset)

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***

Current Density vs Magnetic Field



Superconductivity at CERN

- 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)
- **Early 1970s** First SC spectrometer magnets (at **CERN BEBC, Omega**)
- **Late 1970s** First SC accelerator magnet sub-system (**ISR** low-β insertion at **CERN**)
- **1980s, 90s CERN LEP** – Ø 8.5 km – **SC RF system + ALEPH + DELPHI Low-beta Insertions**
- **Late 2000s CERN LHC** – Ø 8.5 km – **SC magnet system + ATLAS + CMS**

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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

10 years

1988 → **1998**

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

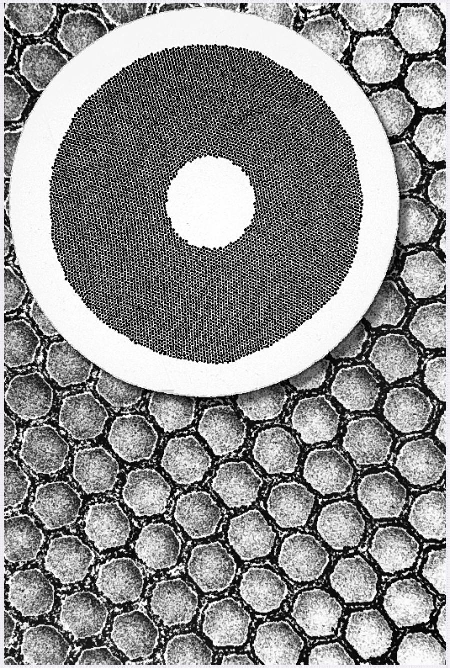
8 years

1998 → **2006**

Superconductor for the LHC Magnets

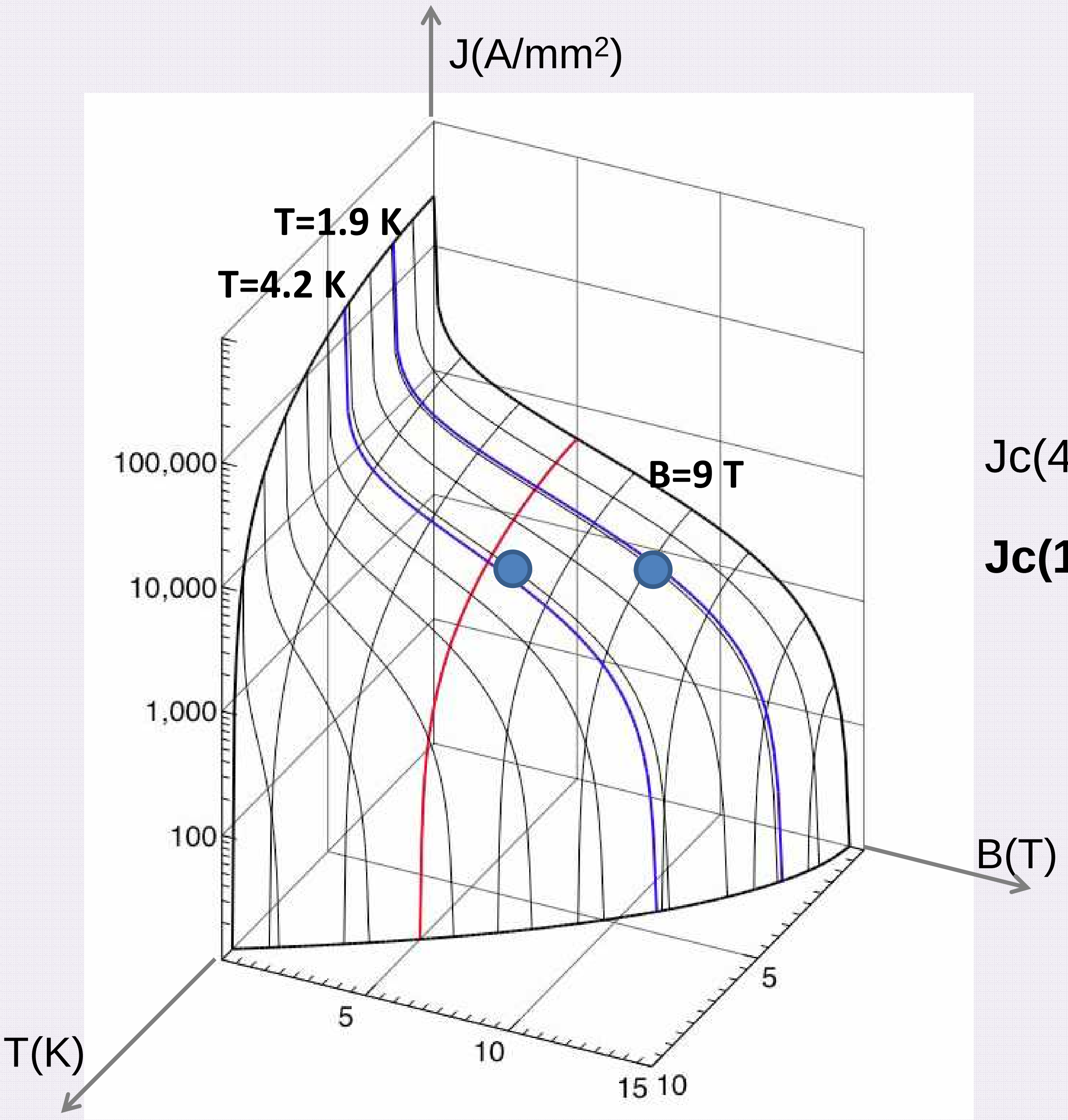
- About **1265 tons** or **7350 km** of superconducting **cables**
- More than **240 000 km** of superconducting **strands**
- About **5300** Nb-Ti/Cu composite billets
- A total of **490 tons** of **Nb-Ti** (47.0±1.0% weight Ti)
- **11900** Unit Lengths of cables

Nb-Ti Billets ($\Phi = 30$ cm)



Strand ($\Phi = 1$ mm)

LHC Strands



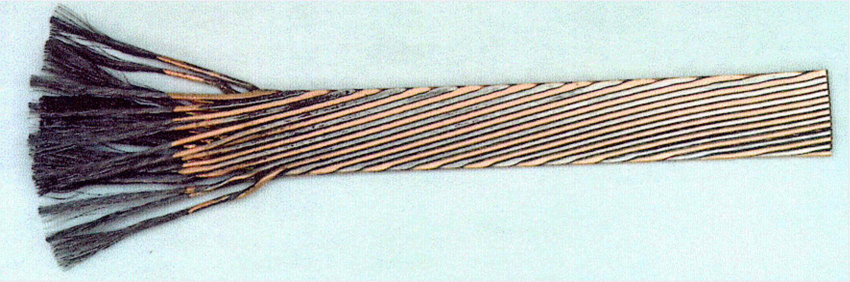
Jc(4.2 K, 6 T)~2300 A/mm^2

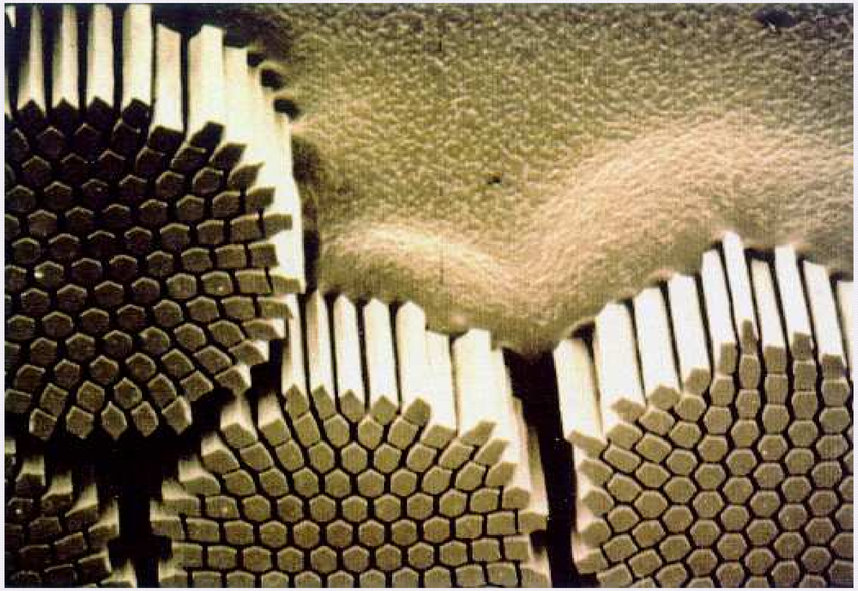
Jc(1.9 K, 9 T)~2300 A/mm^2

Strands and Cables for LHC Dipole Magnets

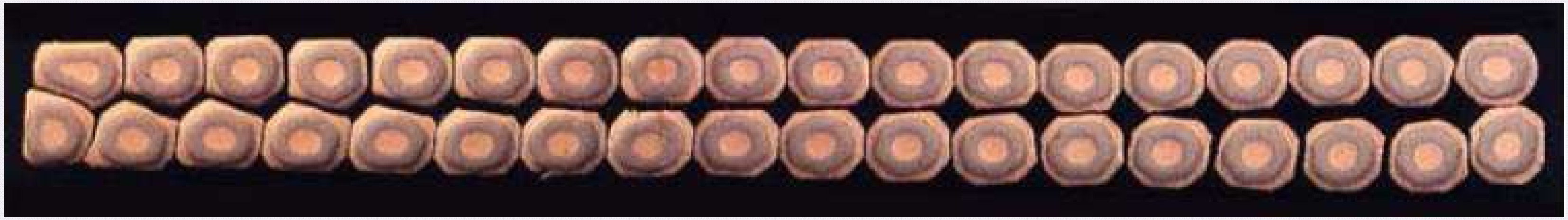
Performance specification

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



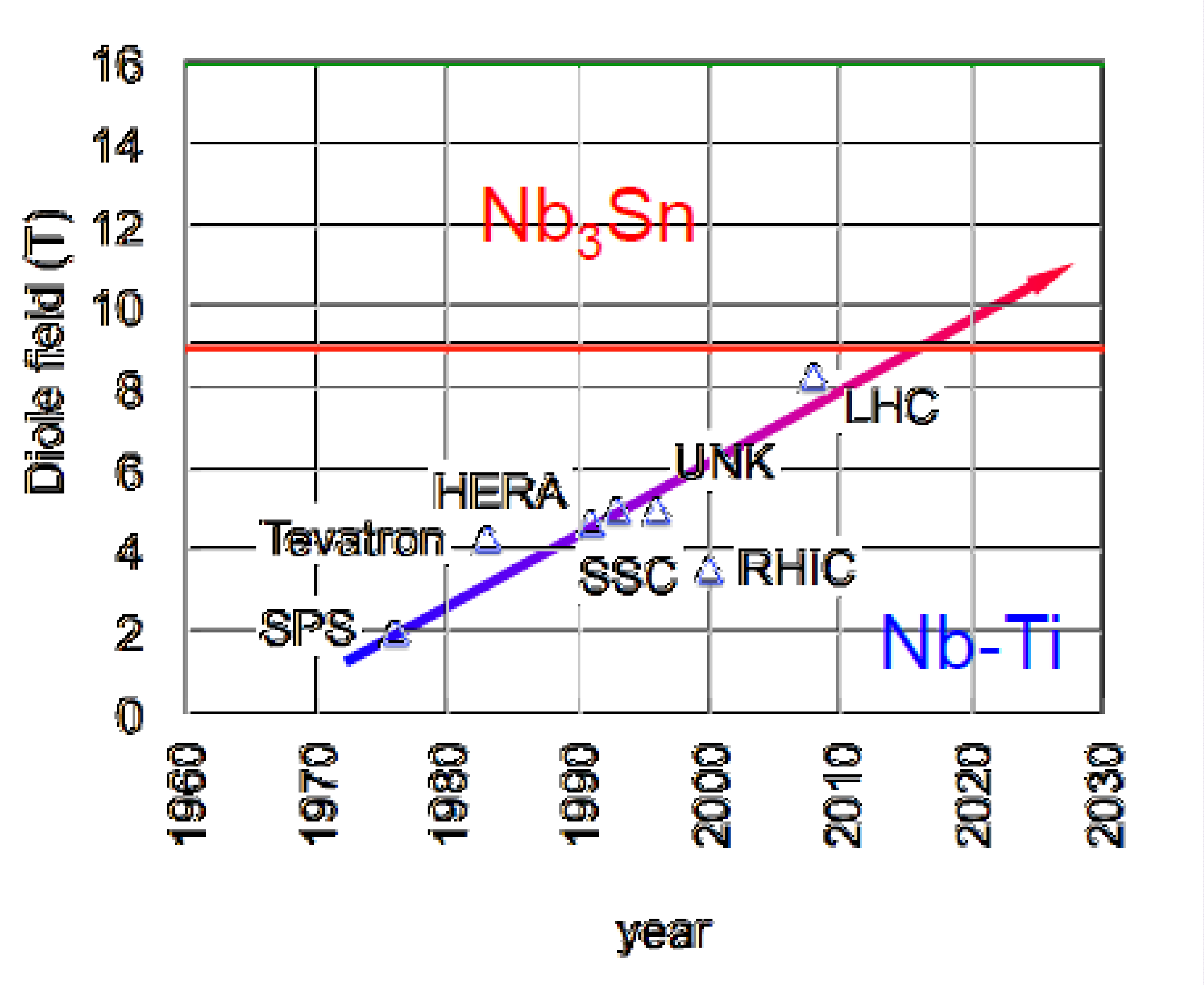


Cable compaction ~ 91 %



Field in Magnets for Accelerators

From Nb-Ti to Nb_3Sn



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Conductor Specification

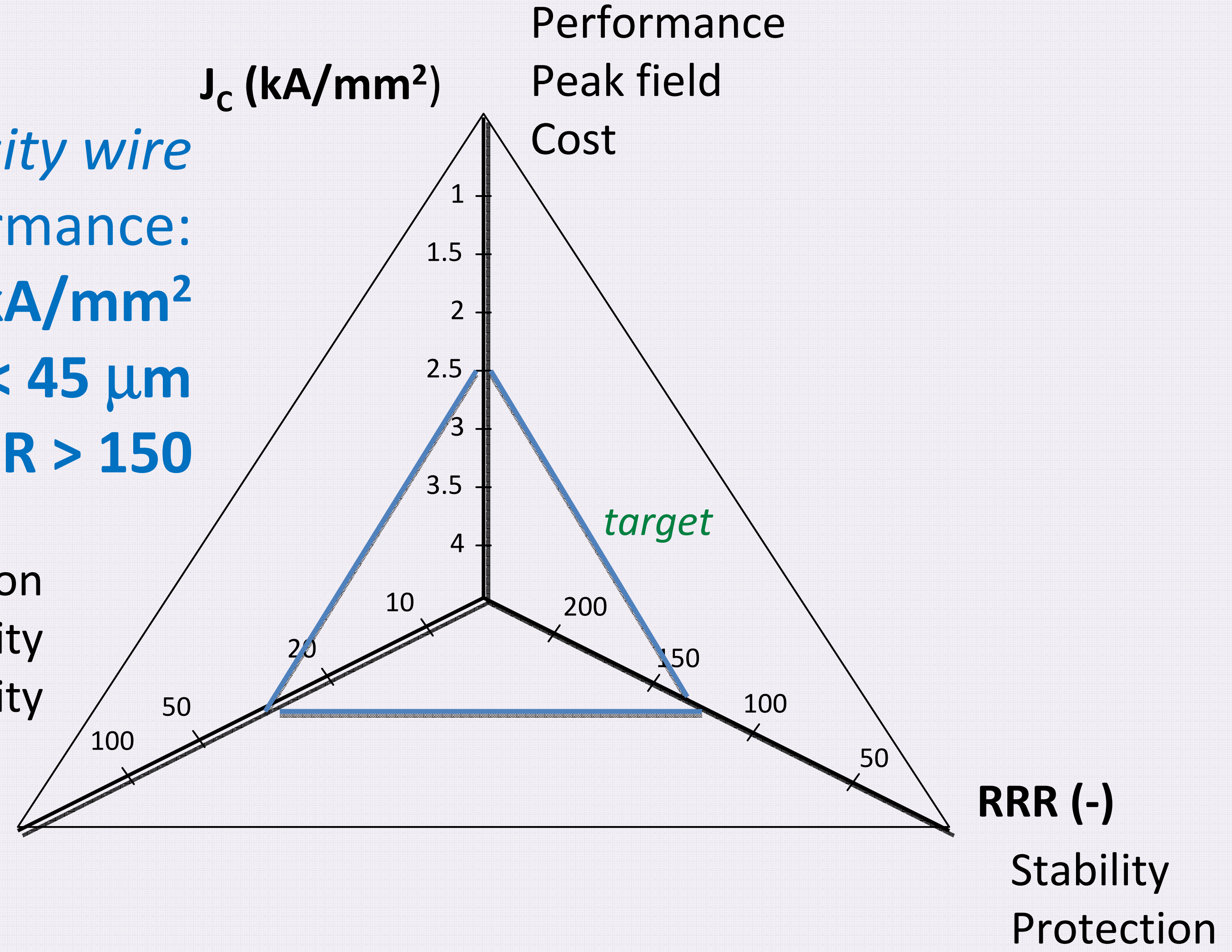
Hi-Luminosity wire

Today performance:

Jc > 2.45 kA/mm^2

D_{fil} < 45 μm

RRR > 150



High-Luminosity LHC

Nb_3Sn for LHC

Jc(1.9 K, 9 T) Nb-Ti LHC wires ~ 2300 A/mm^2

		FRESCA II	11 T DIPOLE	Hi-Lumi QUADRUPOLE
Strand diameter	mm	1	0.7	0.85
Sub-element diameter	mm	< 50 μm	< 45 μm	< 45 μm
Cu to non-copper ratio		1.25	1.15	1.25
Strand twist pitch	mm	24	17	19
Ic(4.2 K, 12 T)	A	> 873	> 439	> 618
Jc(4.2 K, 12 T)	A/mm^2	> 2500	> 2450	> 2450
RRR (after HT)		> 150	> 150	> 150
n-value (4.2 K, 15 T)		> 30	> 30	> 30

RRP

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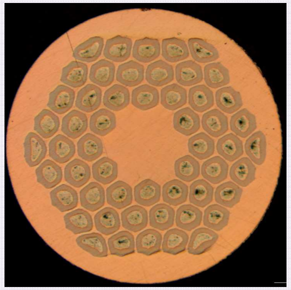

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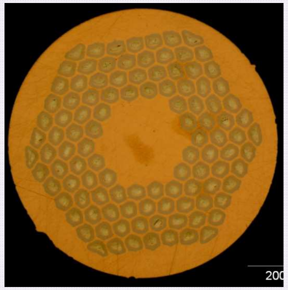

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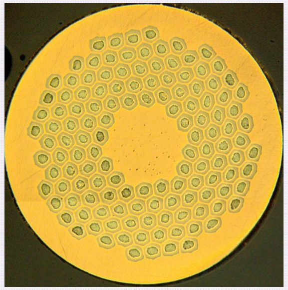

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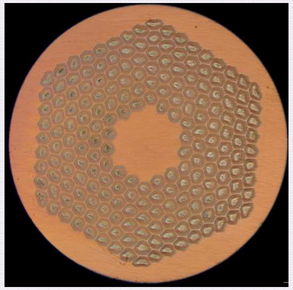

PIT

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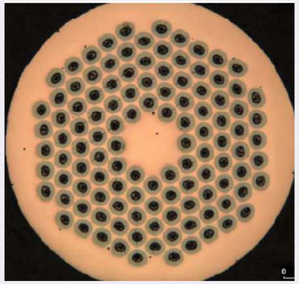

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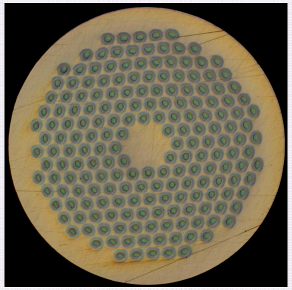
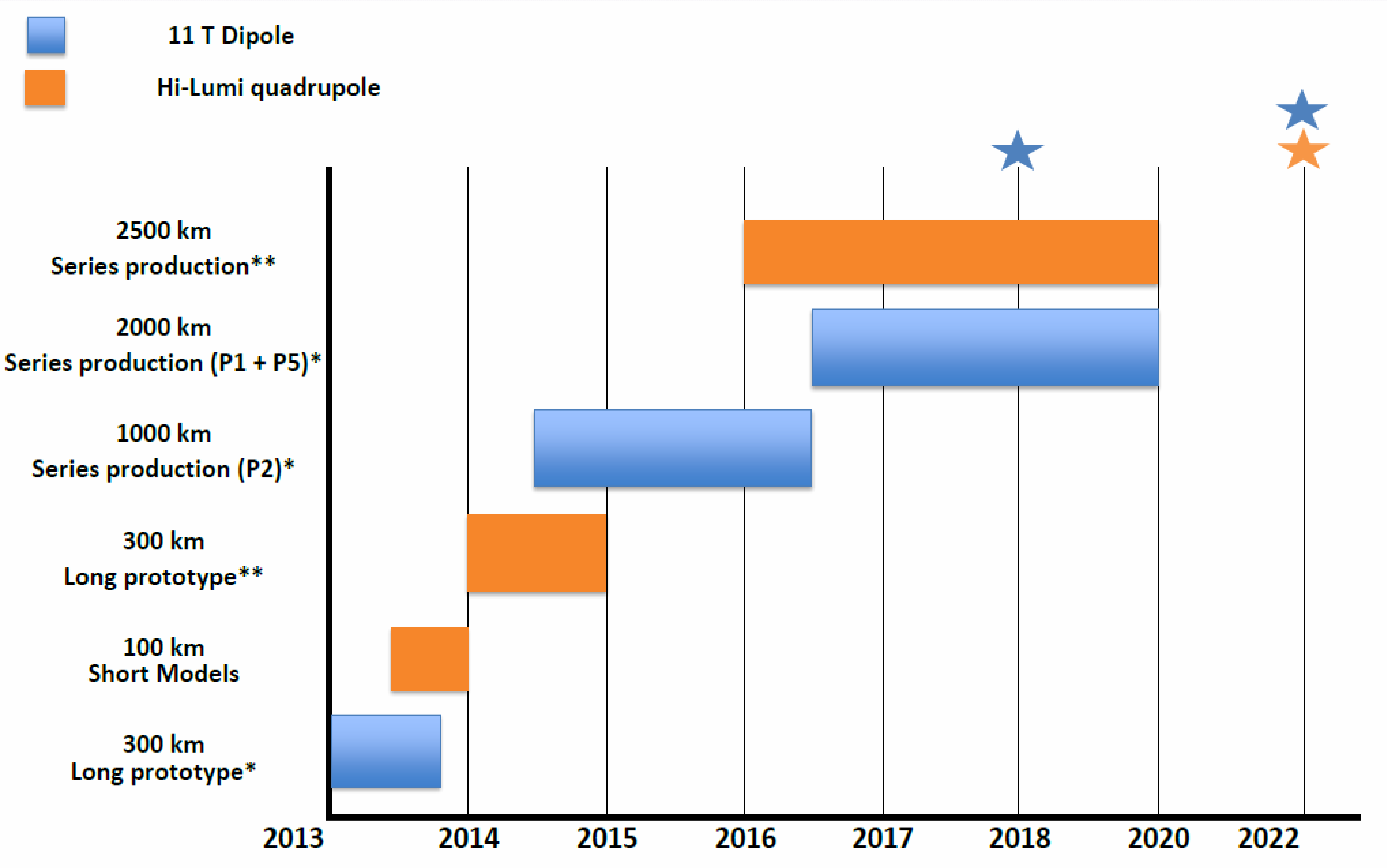


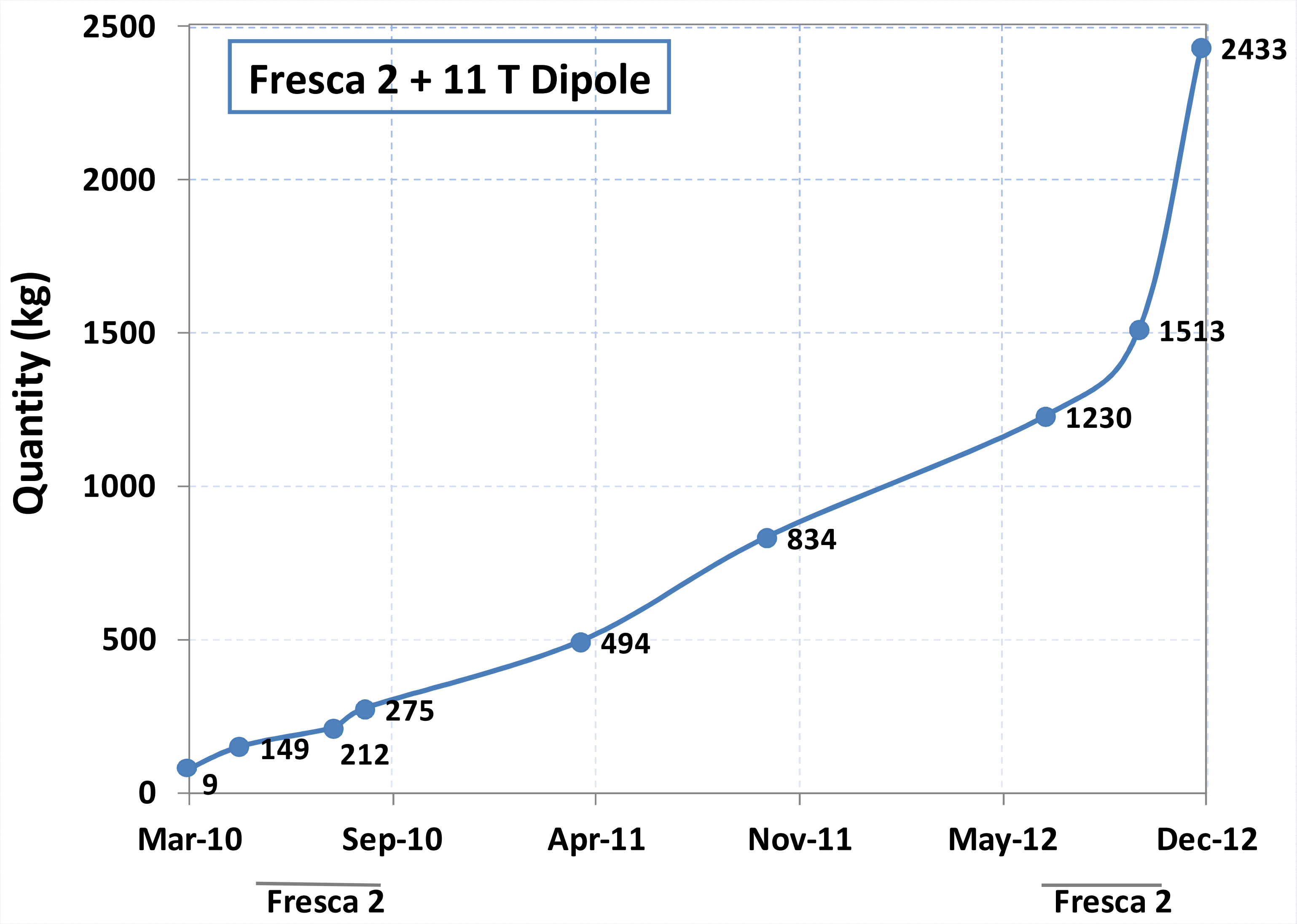
Nb_3Sn for LHC Hi-Luminosity upgrade



*UL ≥ 700 m
**UL ≥ 1000 m

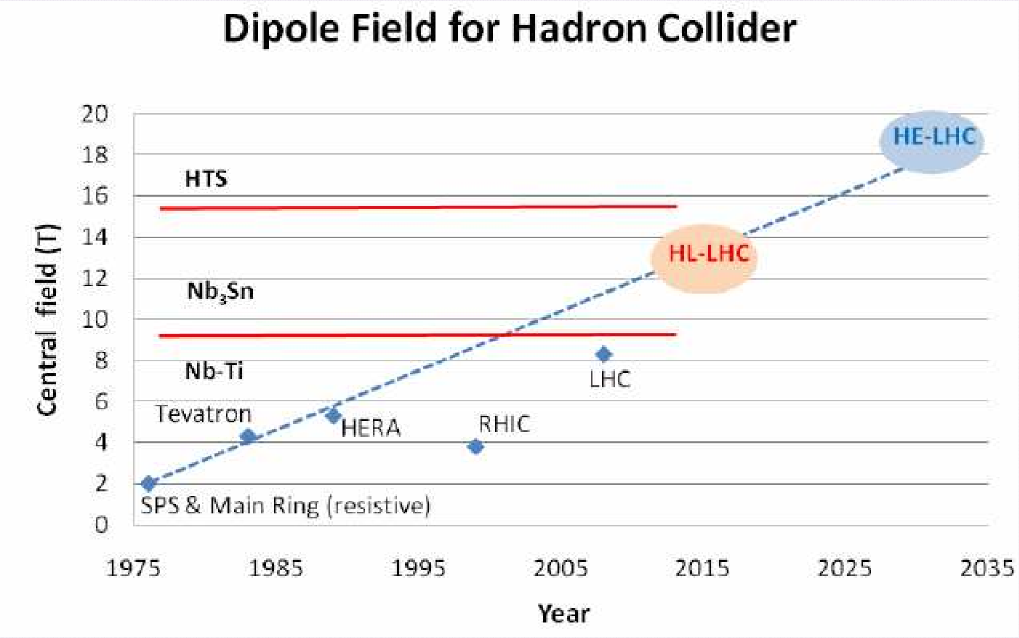
~ 26 tons of HEP-grade of Nb_3Sn conductor

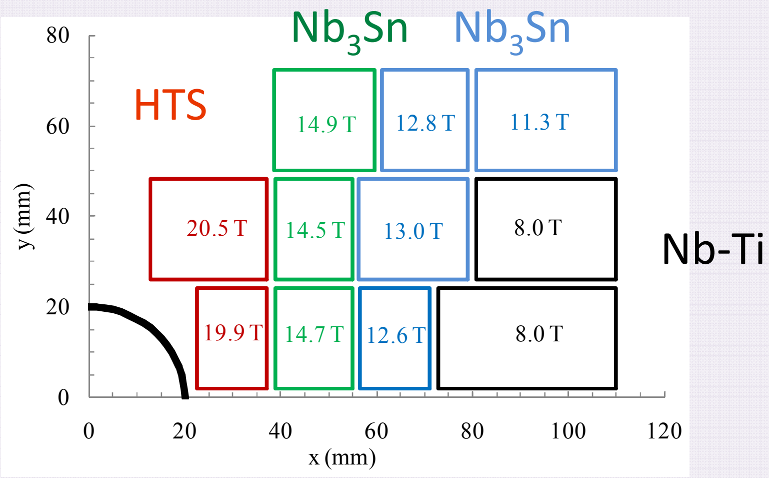
Nb_3Sn conductor procured (2010-2012)



HFM Program – High Energy LHC

Eucard 2 (Lucio Rossi, CERN Edms No. 1152224)

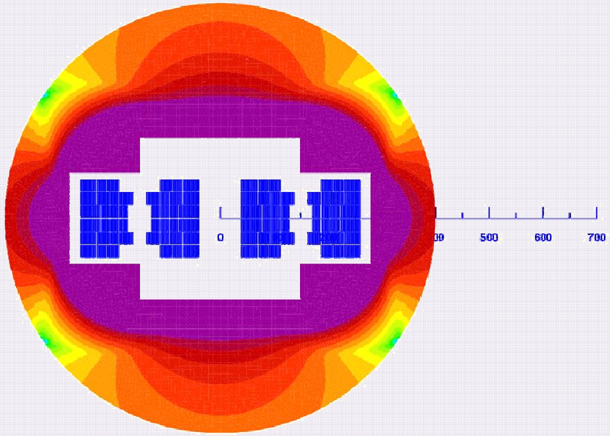




$J_{overall\_HTS}$ **= 400 A/mm^2 @ 20 T**

High Energy: 2×16.5 TeV beams

3000 ft^{-1} in 10-12 years



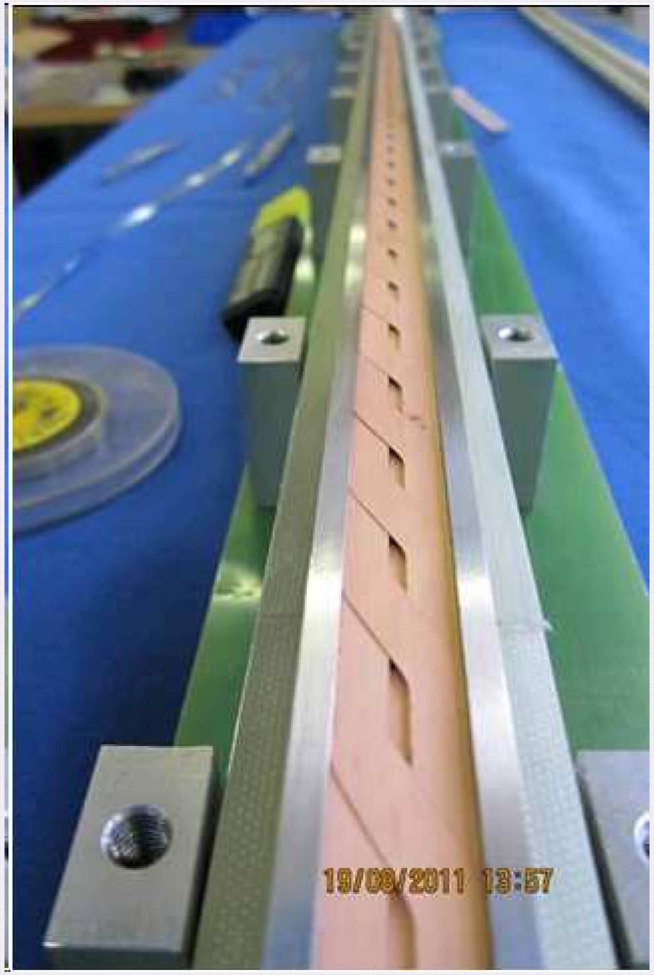
Twin aperture dipole, 20 T, 15 m long, bore spacing 300 mm, iron diameter 800 mm

High Energy LHC

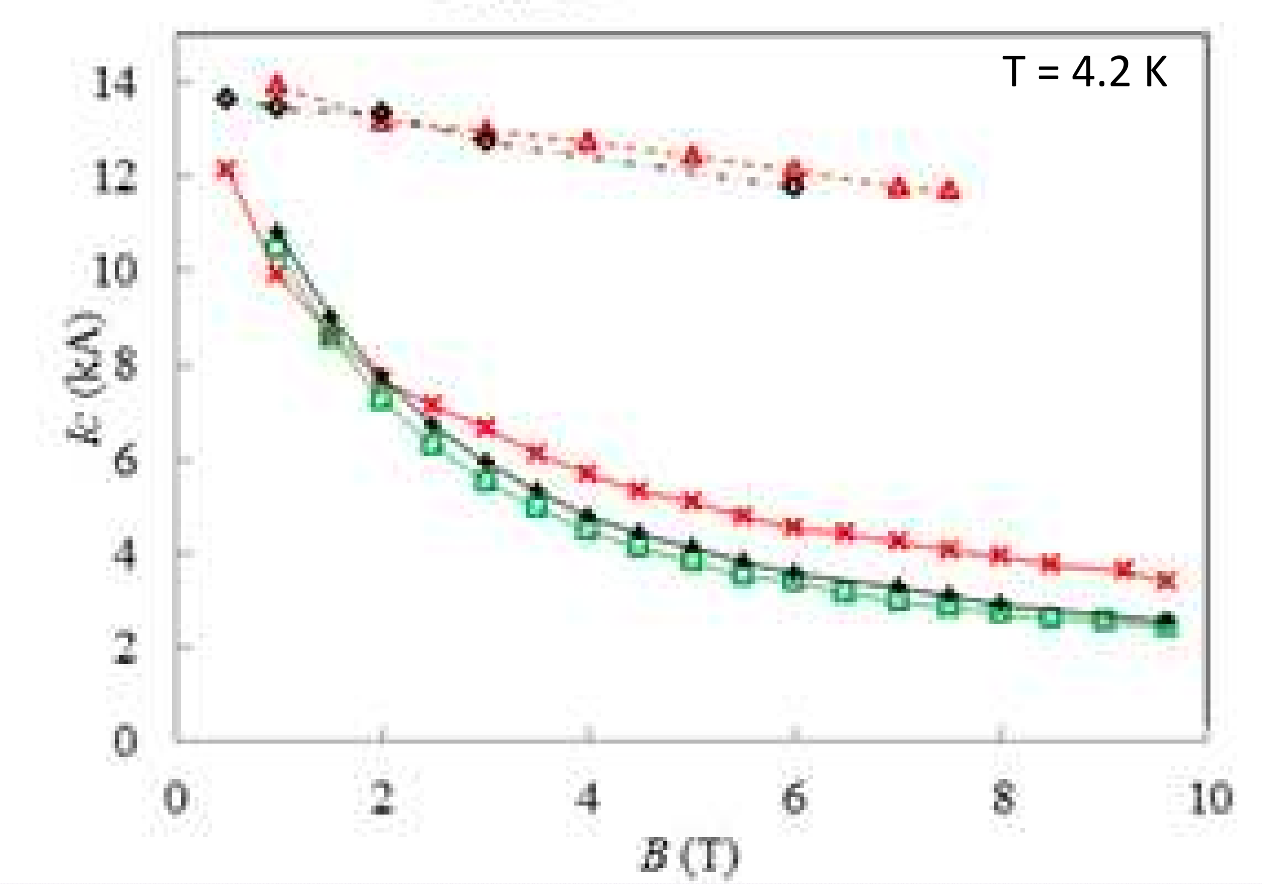
Bi-2212 and YBCO

HTS

Conductor Wires/Tapes		YBCO Bi-2212
J_E(20 T, 4.2K)	(A/mm^2)	≥ **750**
J_E(12 T, 4.2K)	(A/mm^2)	≥ 1000$^{(++)}$
σ(Ic)	(%)	10 %
M(1.5 T, 10 mT/s)	(mT)	100
$\sigma_{\text{tranverse}}$	(MPa)	≥ 150
$\varepsilon_{\text{longitudinal}}$	(%)	≥ ± 0.5
Unit length	(m)	≥ 500



Roebel cables – YBCO Conductor



Measurements @ CERN
Fresca test station

J. Fleiter et al.

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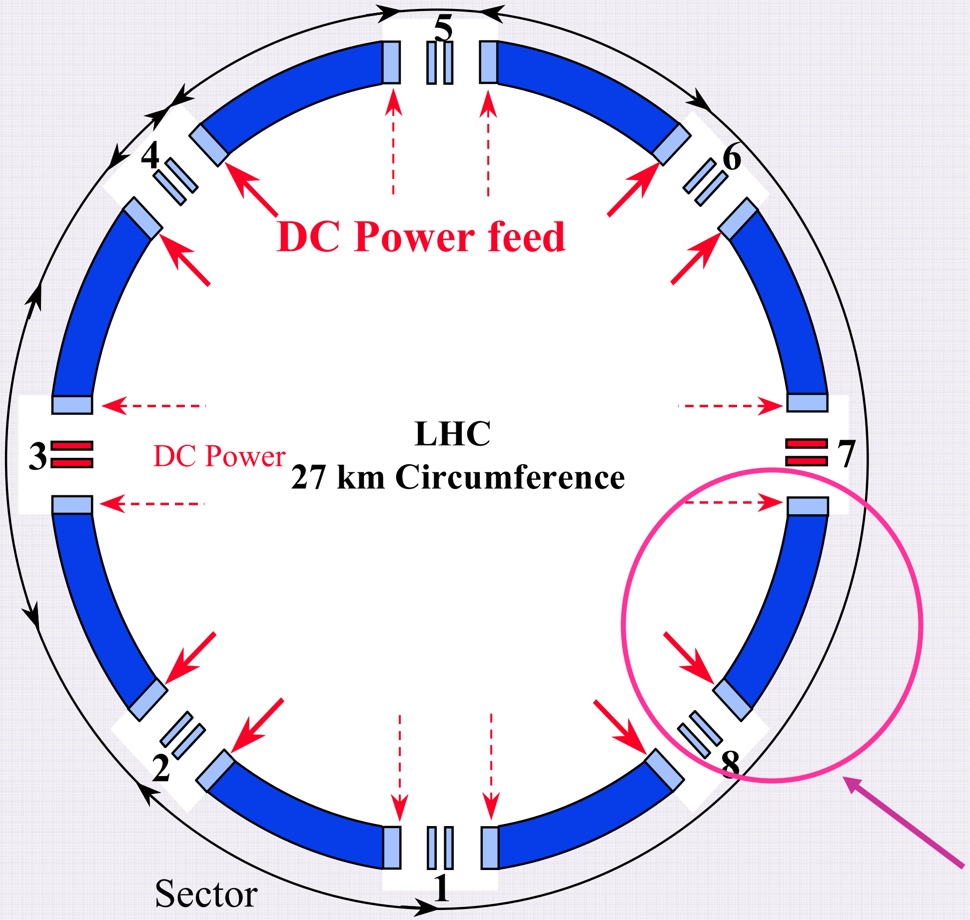
Powering of LHC Machine

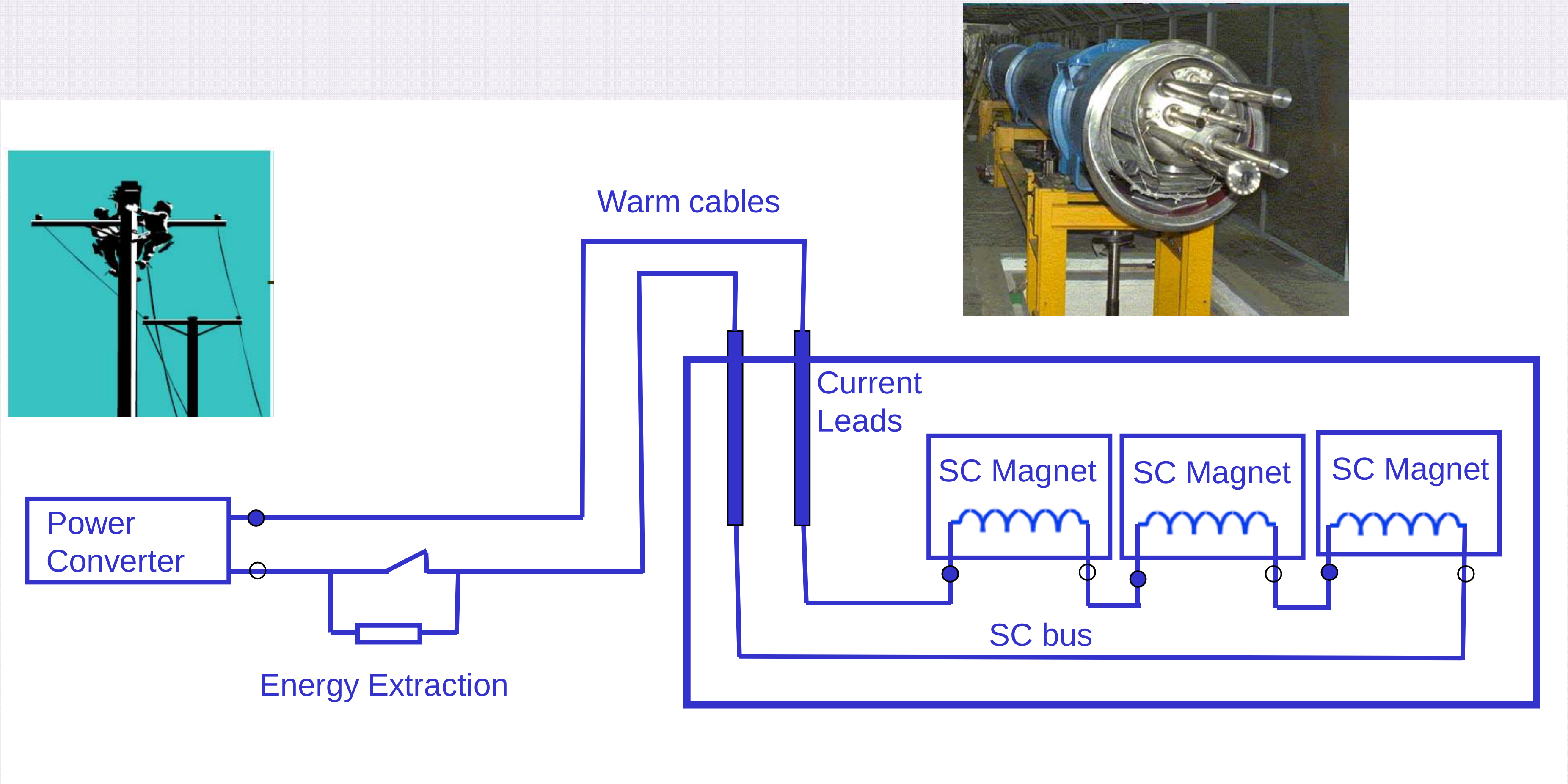


- ❑ To limit the stored energy within one electrical circuit, the **LHC is powered by sectors**
- ❑ The main dipole circuits are split into **8 sectors** to bring down the stored energy to ~1 GJ/sector
- ❑ Each sector (**~2.9 km**) includes 154 dipole magnets (powered in series) and ~50 quadrupoles

Powering Sector

~ 3.4 MA, > 3000 Current Leads, ~ 1500 Electrical Circuits

Powering Superconducting Systems



Warm cables

Current Leads

SC Magnet

SC Magnet

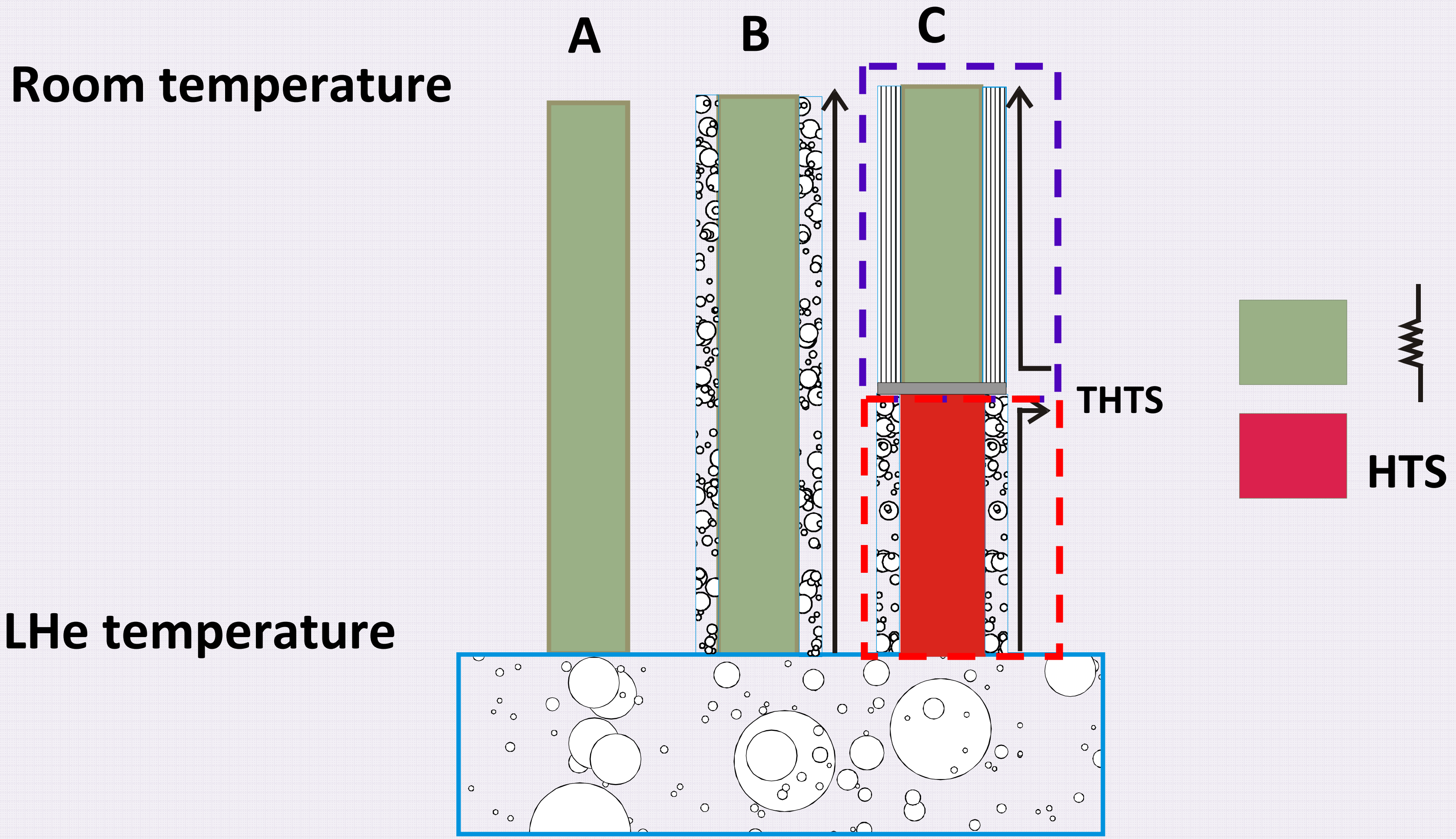
SC Magnet

Power Converter

SC bus

Energy Extraction

Conventional vs HTS leads

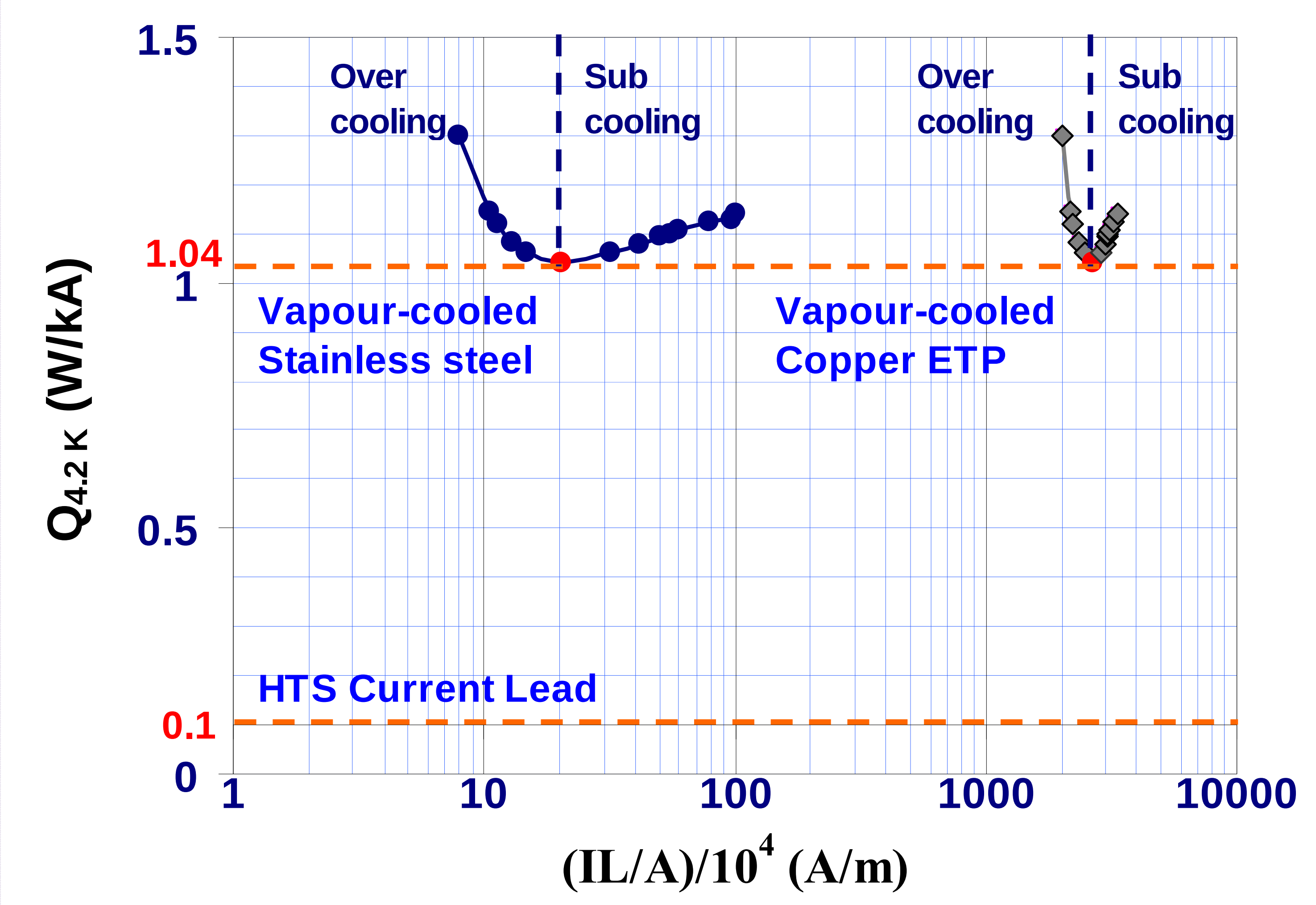


QA = 47 W/kA

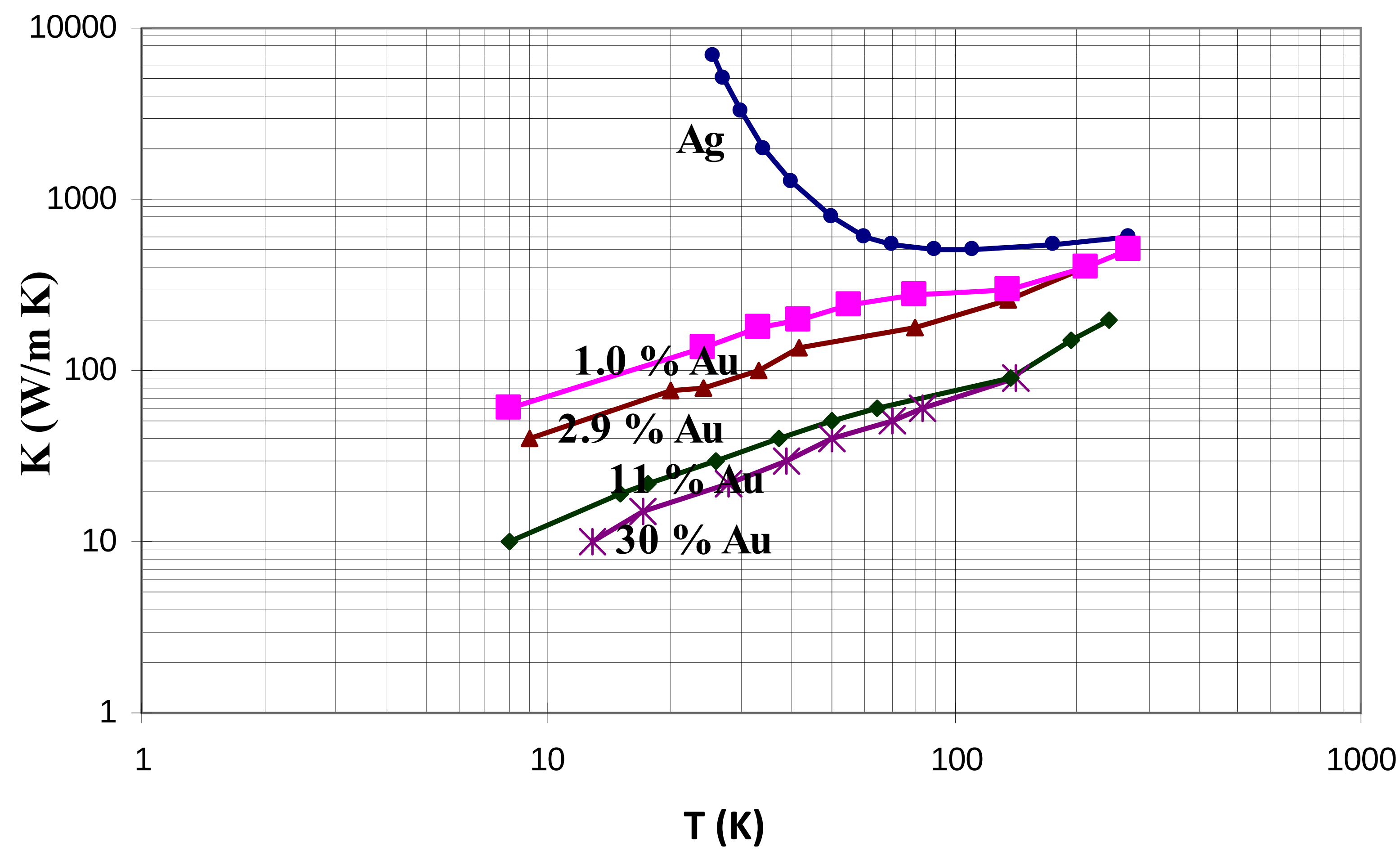
QB = 1.04 W/kA

QC = ?

Conventional vs HTS Leads

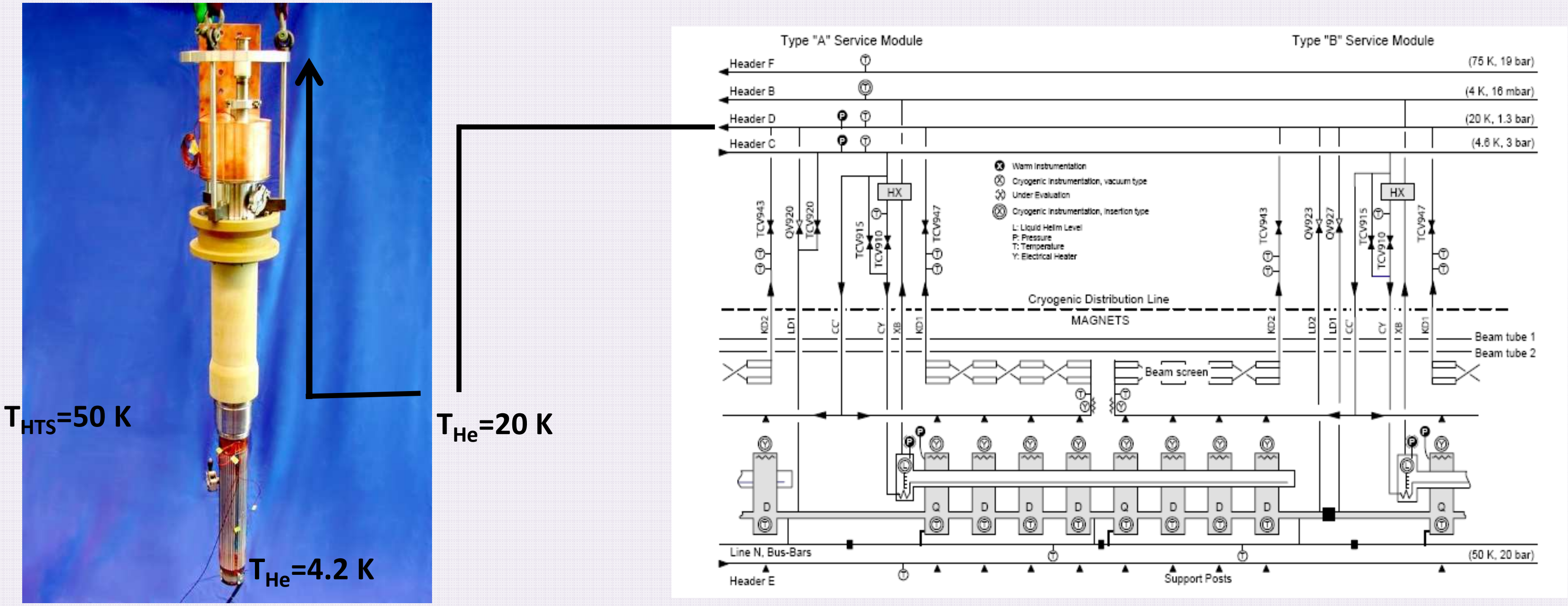


Thermal Conductivity Ag-Au Alloy



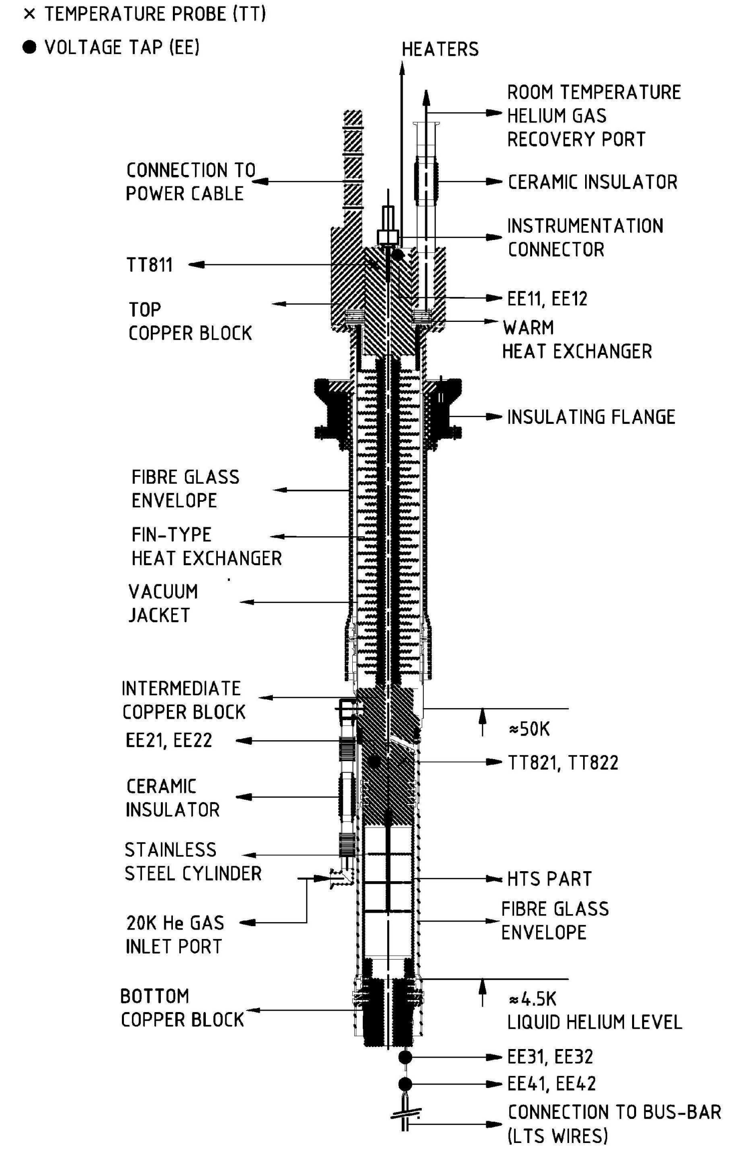
Bi-2223 multi-filamentary tape, Ag-Au matrix

LHC HTS Current Leads

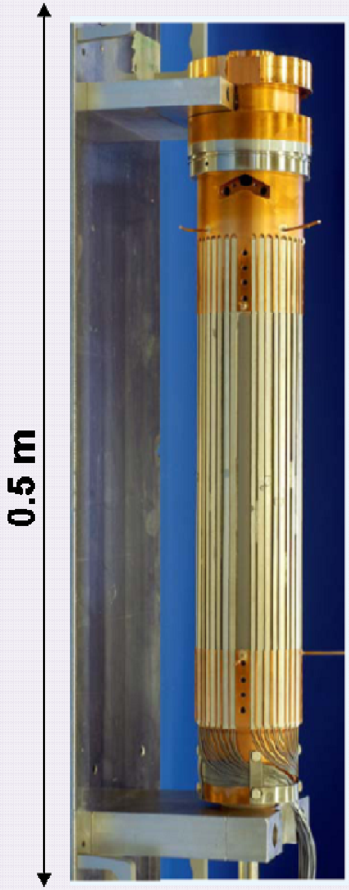


LHC HTS Current Leads

13000 A LHC Lead



HTS Part

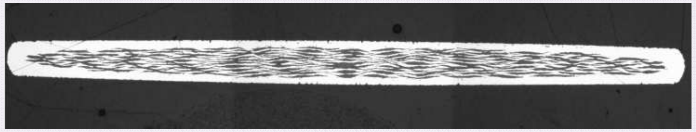


LHC Current Leads: Saving

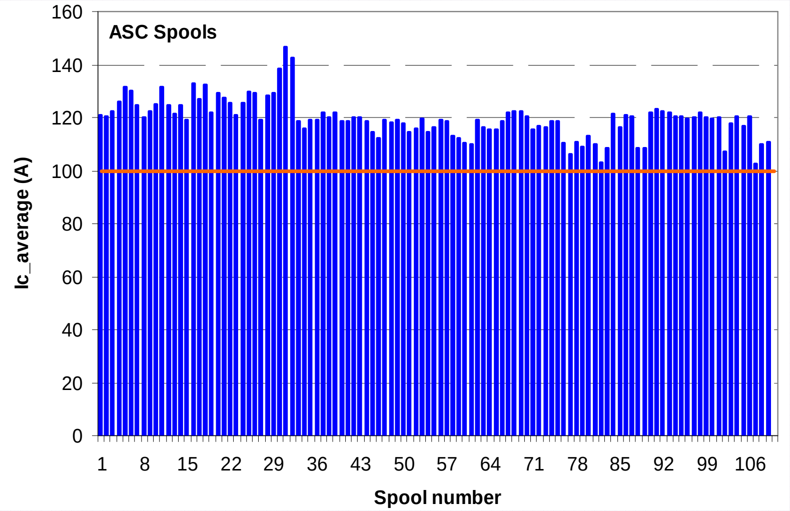
LHC Current = 3 MA

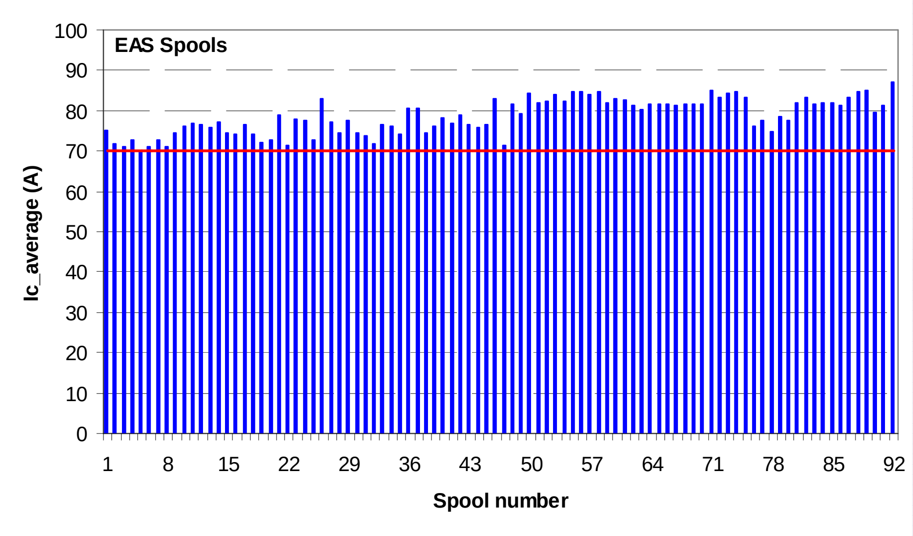
	Conventional leads	**HTS leads**
Heat load into LHe	1.1 W/kA	0.1 W/kA
Exergy consumption	430 W/kA	150 W/kA
Exergy consumption (% conv. lead)	100	35
Total exergetic power	1290 kW	450 kW

Bi-2223 in the LHC current leads



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





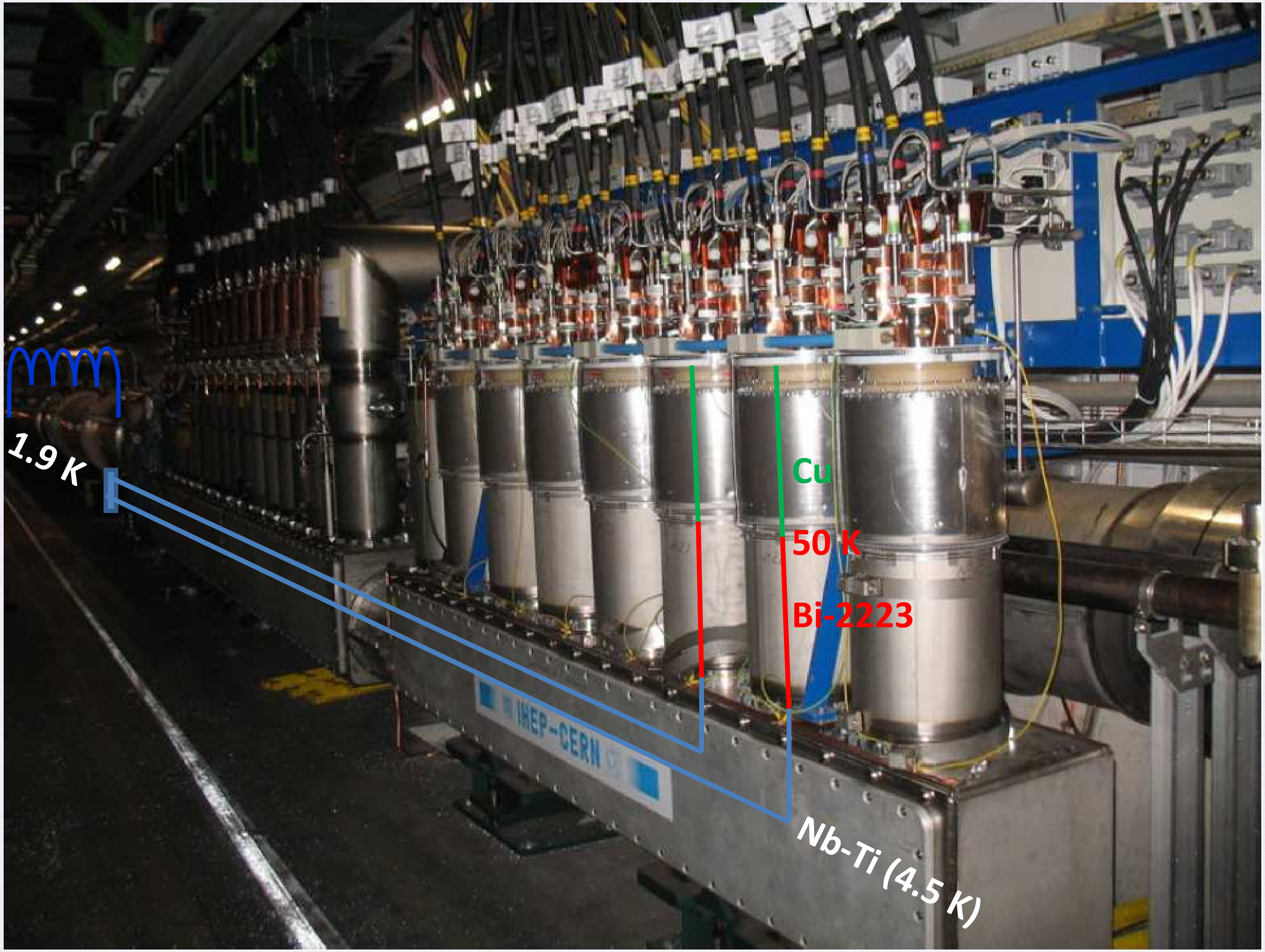
Ic_min (A)	Ic_av (A)	Ic_max (A)	σ (A)
103	120	147	7

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

Contribution from industry and external laboratories

- The development and detailed design of the LHC leads was made at **CERN**, were prototype components were assembled and tested in nominal operating conditions
- The HTS conductor was procured from **Bruker EAS** and **American Superconductors** - USA. The HTS stacks were made at **CERN** and characterized at **CESI** (today **RSE**)
- The series production was made in **CECOM-Rome** (13000 A) and in **BINP-Novosibirsk** (6000 A and 600 A) on the basis of build-to-print specification
- All HTS leads were tested in nominal cryogenic conditions at **ENEA- Rome** (13000 A and 6000 A) and at the **University of Southampton** (600 A) prior to installation at CERN in the LHC cryostats
- The leads were installed in the cryostats at CERN on the surface. The cryostats with the leads were lowered into the LHC tunnel according to LHC installation planning


PR 1&2 - 30 T
CMU 15 000 daN
FARGAMEL
EA-01-1840
TRANSPORT



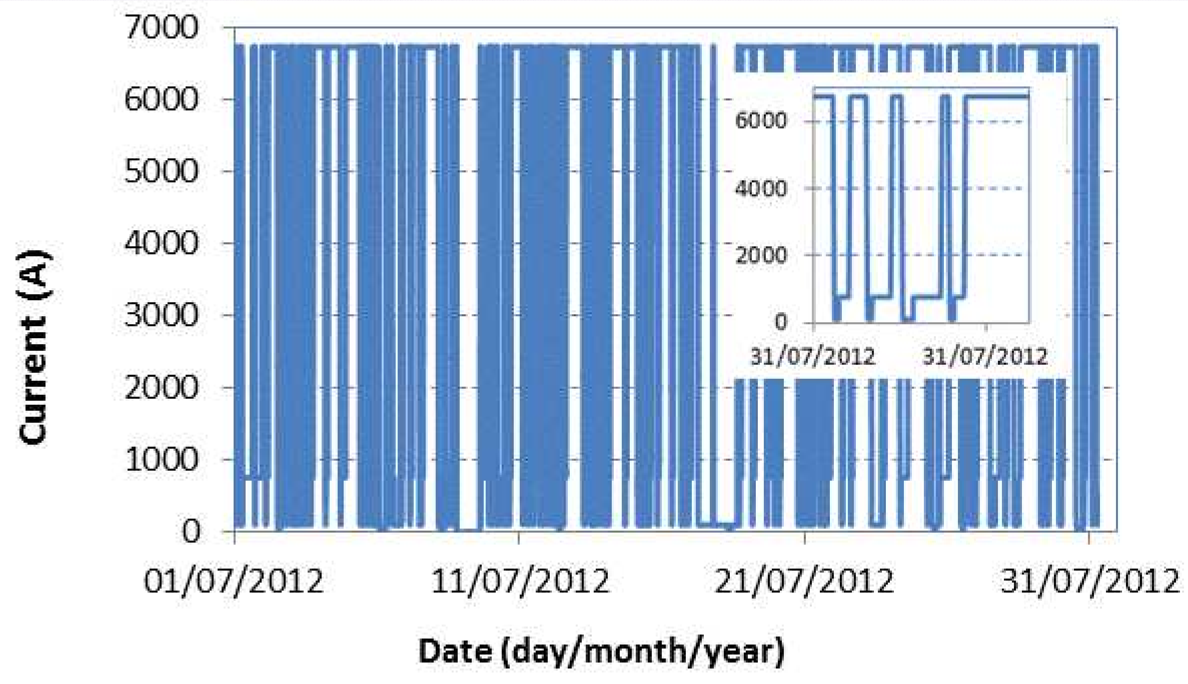
Distribution Feed Box in LHC tunnel at P1 L

Operation in the LHC machine

- ➢**Three years** of operation in the LHC since the hardware commissioning

- ➢**Thousands of electrical cycles** (> 2000) and **two complete thermal cycles** in the accelerator environment. Two resistive transitions induced in two HTS element because of operational issues were followed by the expected response of the QPS system and of the device.

- ➢No failures detected up to know.



Main dipole circuits

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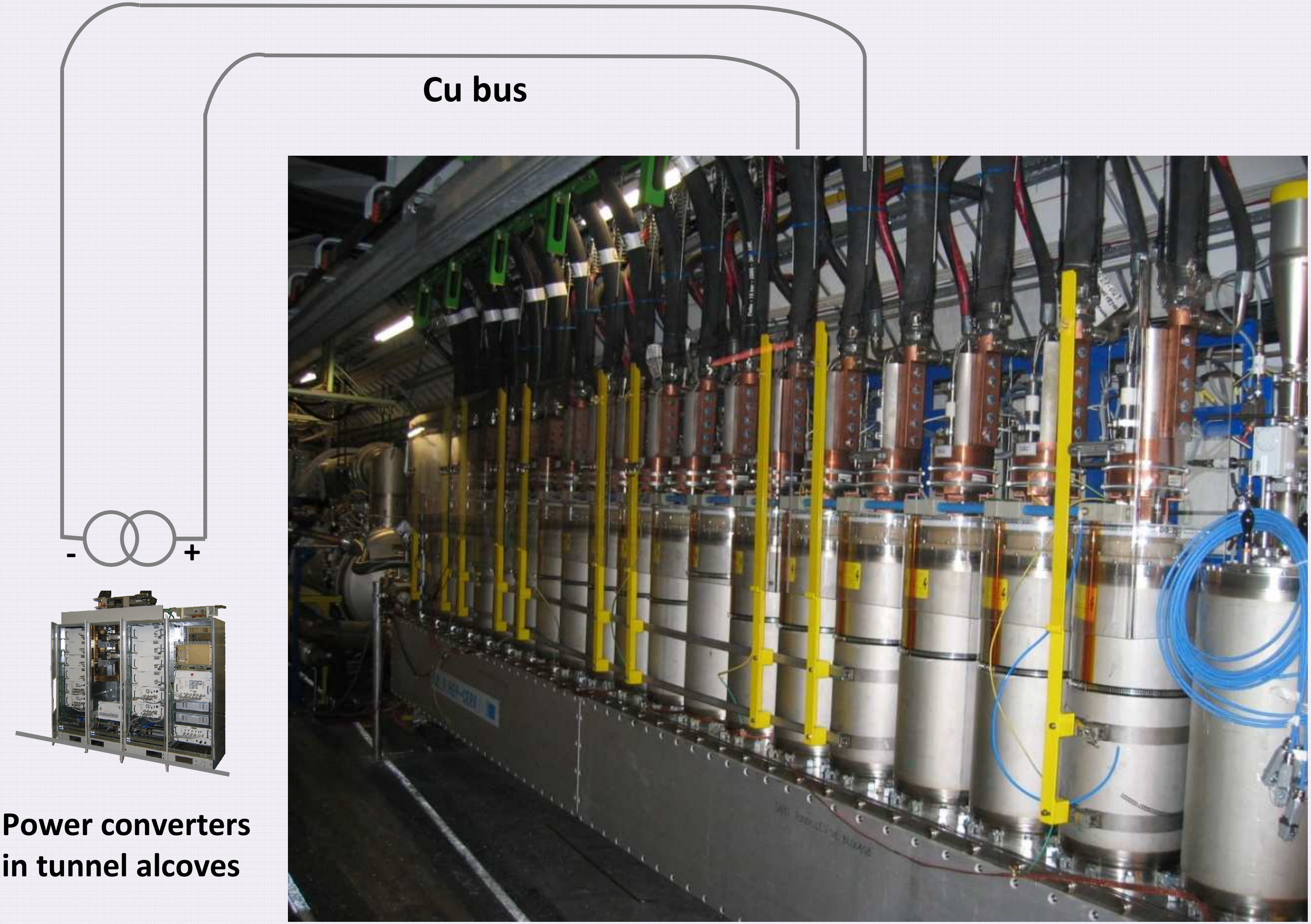


Cu bus

-

+

Power converters in tunnel alcoves

Currents for LHC magnets

Total DC current transferred from a Distribution Feed Box

DFBAP, P1L

Number of leads	Rating (A)
2	13000
12	7000
28	600

DFBLA, P1L

Number of leads	Rating (A)
11	7000
12	120

42 Current Leads
|Itot| = 126800 A

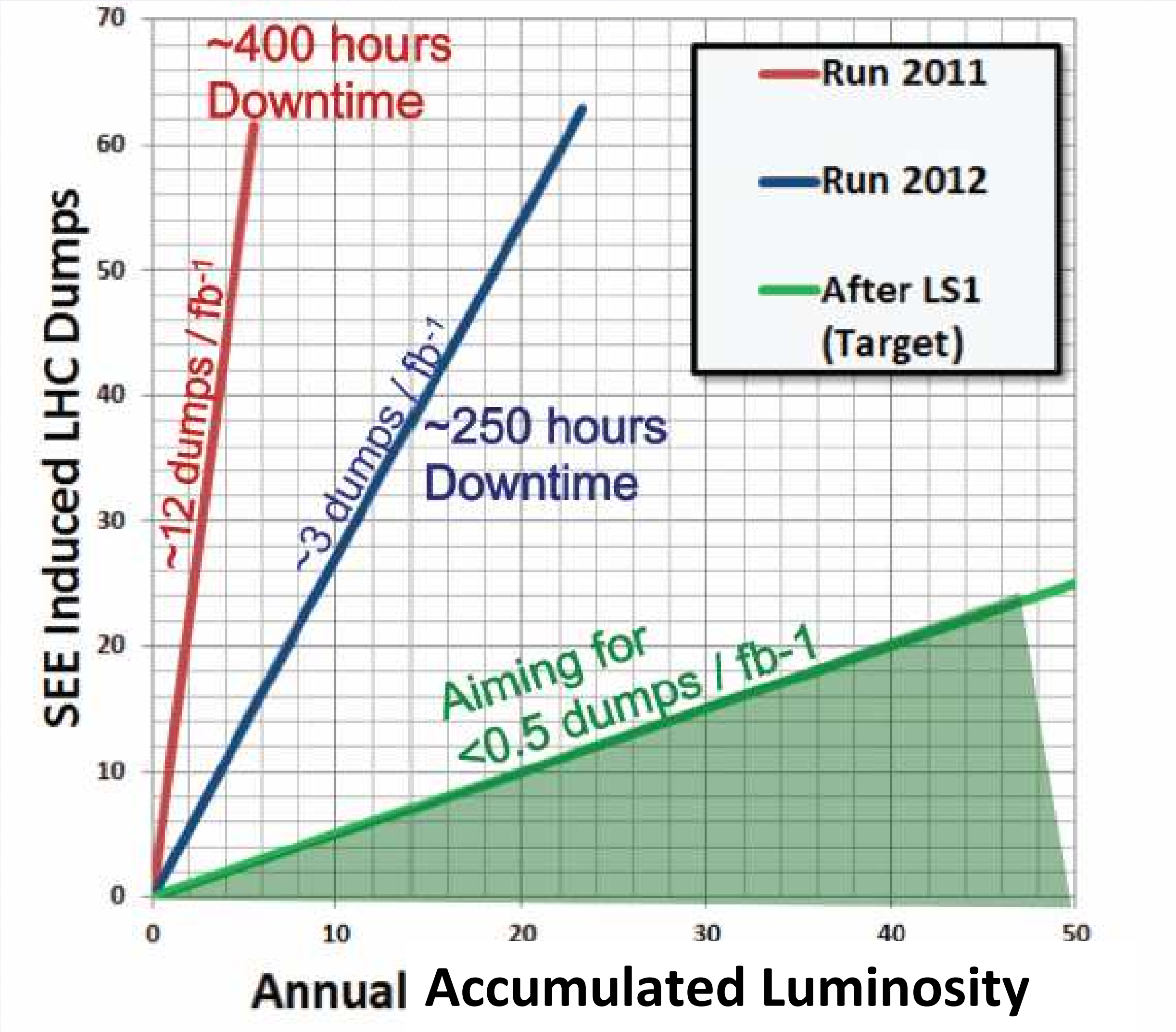
23 Current Leads
|Itot| = 78440 A

- The LHC power converters in the tunnel are operated in a radiation environment and are exposed to high energy particles that can induce single event effects. For this reason, they are considered to be a risk for the reliable running of the machine in particular at high luminosities

- Development of new radiation tolerant converters or their relocation in areas without radiation are being considered –and mitigation actions are, where possible, already taking place

- Civil engineering for the construction of new caverns in the tunnel would be very expensive

Rate of LHC beam dumps due to SEE against luminosity



CERN Bulletin
May 2012

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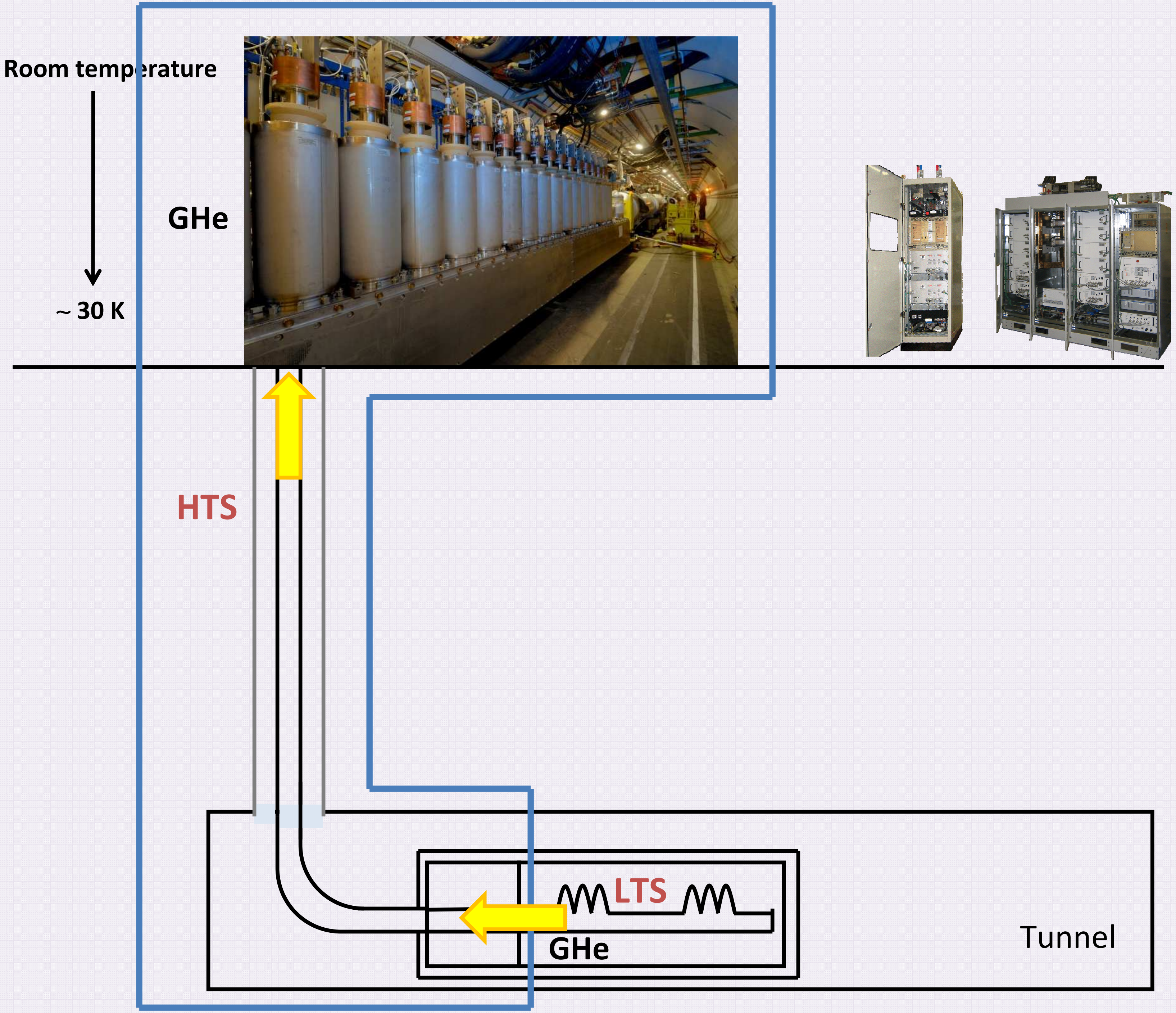


Room temperature

~ 30 K

GHe

HTS

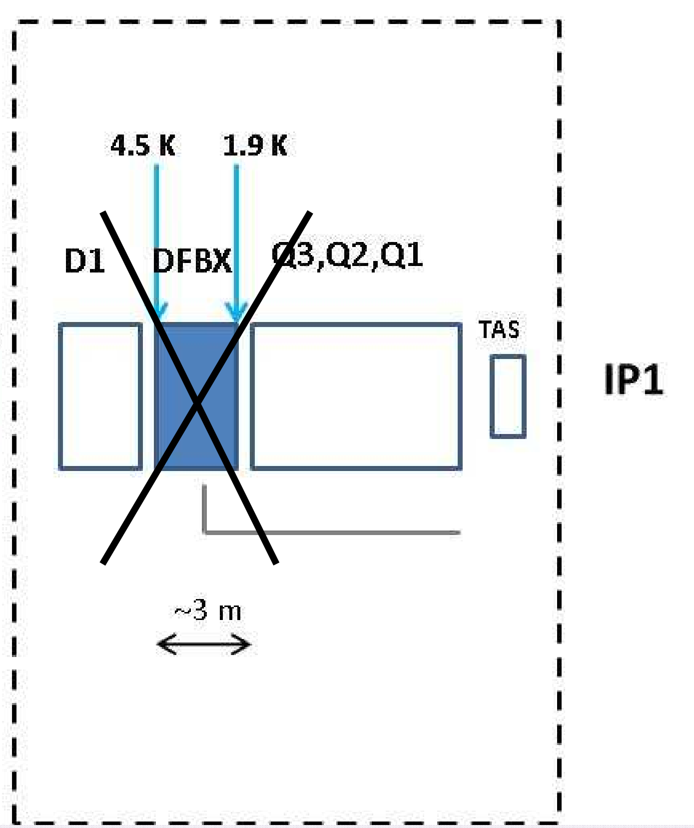
LTS

GHe

Tunnel

Hi-Luminosity Upgrade of the LHC

LHC Triplets



Hi-Luminosity LHC Triplets

Number of leads	Rating (A)	
18	120	Correctors
12	3000	Correctors
2	2400	Corrector
2	400	Corrector
2	13000	Dipole
4	20000	Quadrupoles

40 Current Leads
|Itot |~ 150 kA

Removal of DFB from the tunnel to the surface

Rationale

Powering via superconducting links and remote power converters →

➢ **Free space** in the ring;

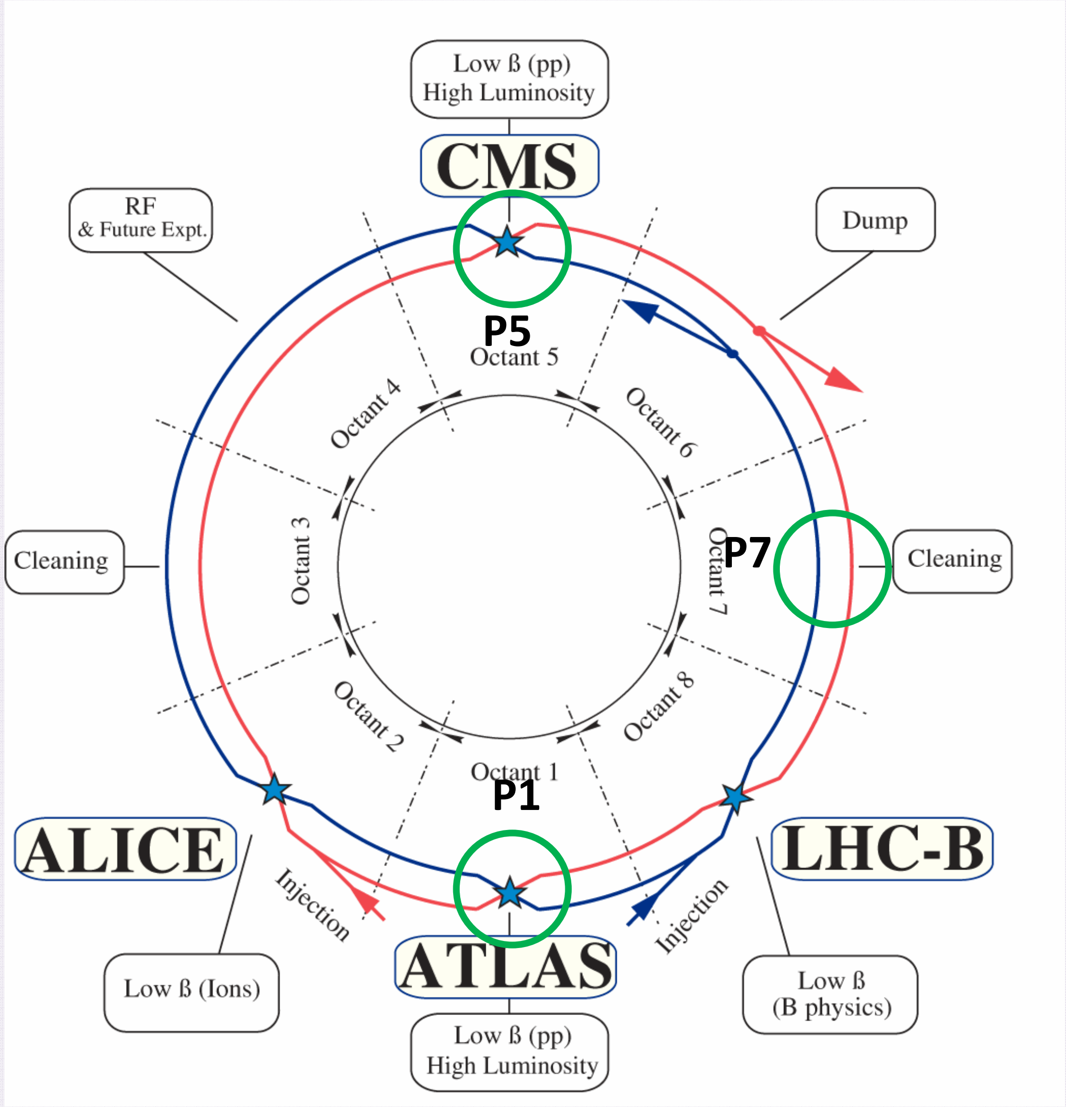
➢ **Safer and easier access of personnel** to power converters, leads and control equipment;

➢ **Reduced time of interventions** (maintenance, repair, diagnostic and routine tests) →

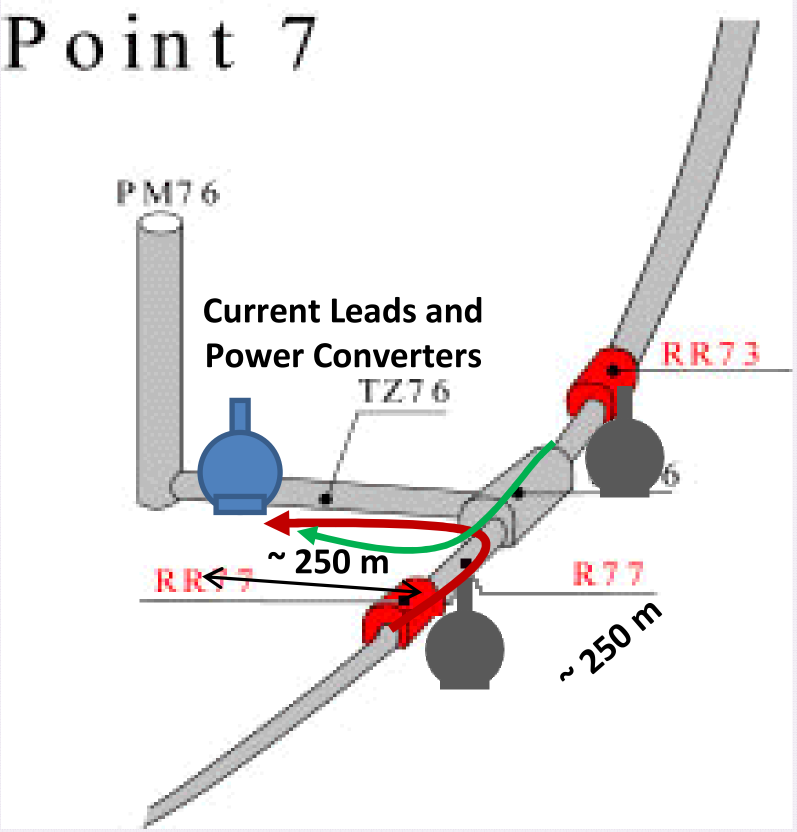
➢ Gain in machine availability;

➢Safer long-term operation of **powering equipment** located in **radiation-free** environment.

Where in the LHC ?



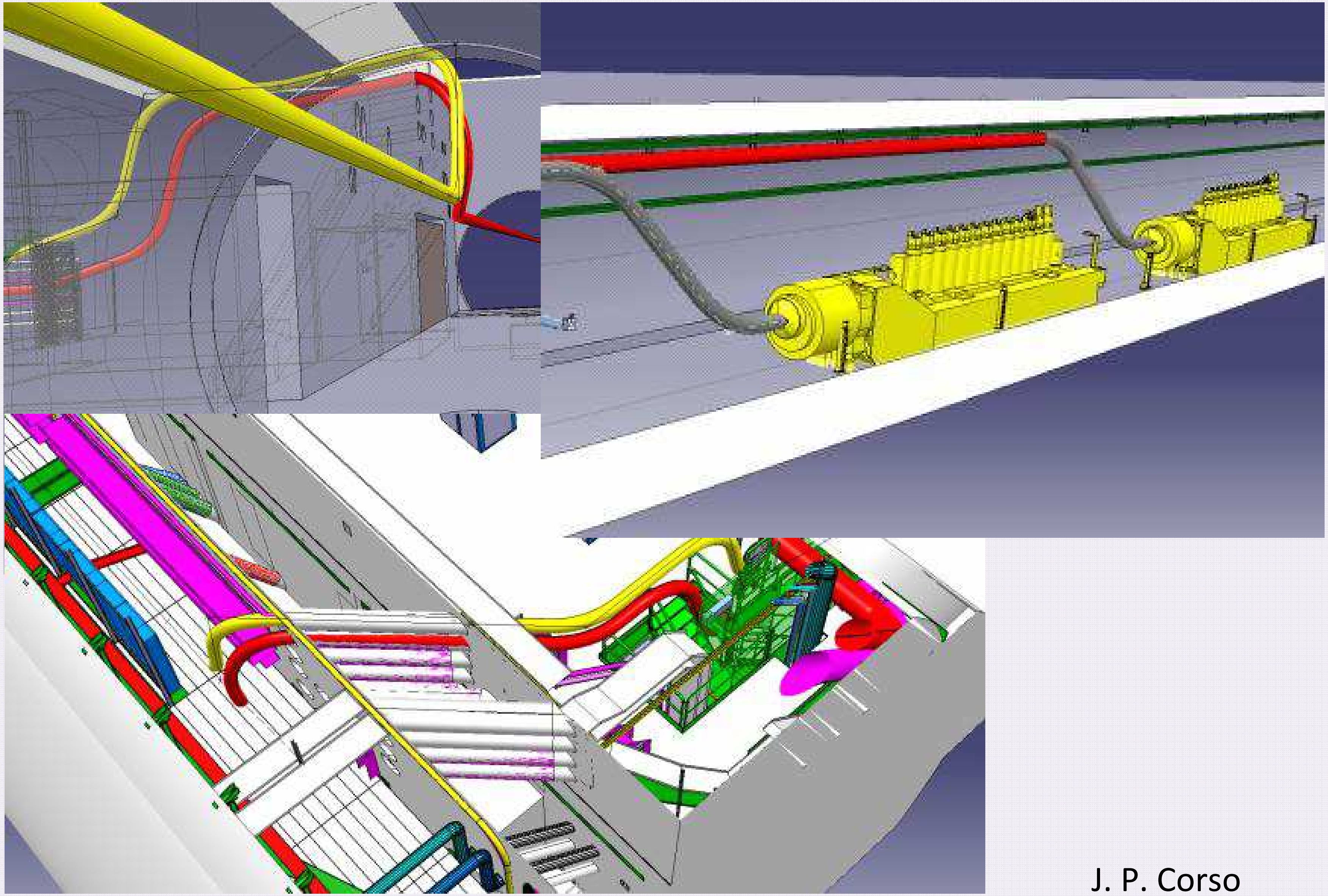
P7: Underground Installation



Two links each about 500 m long

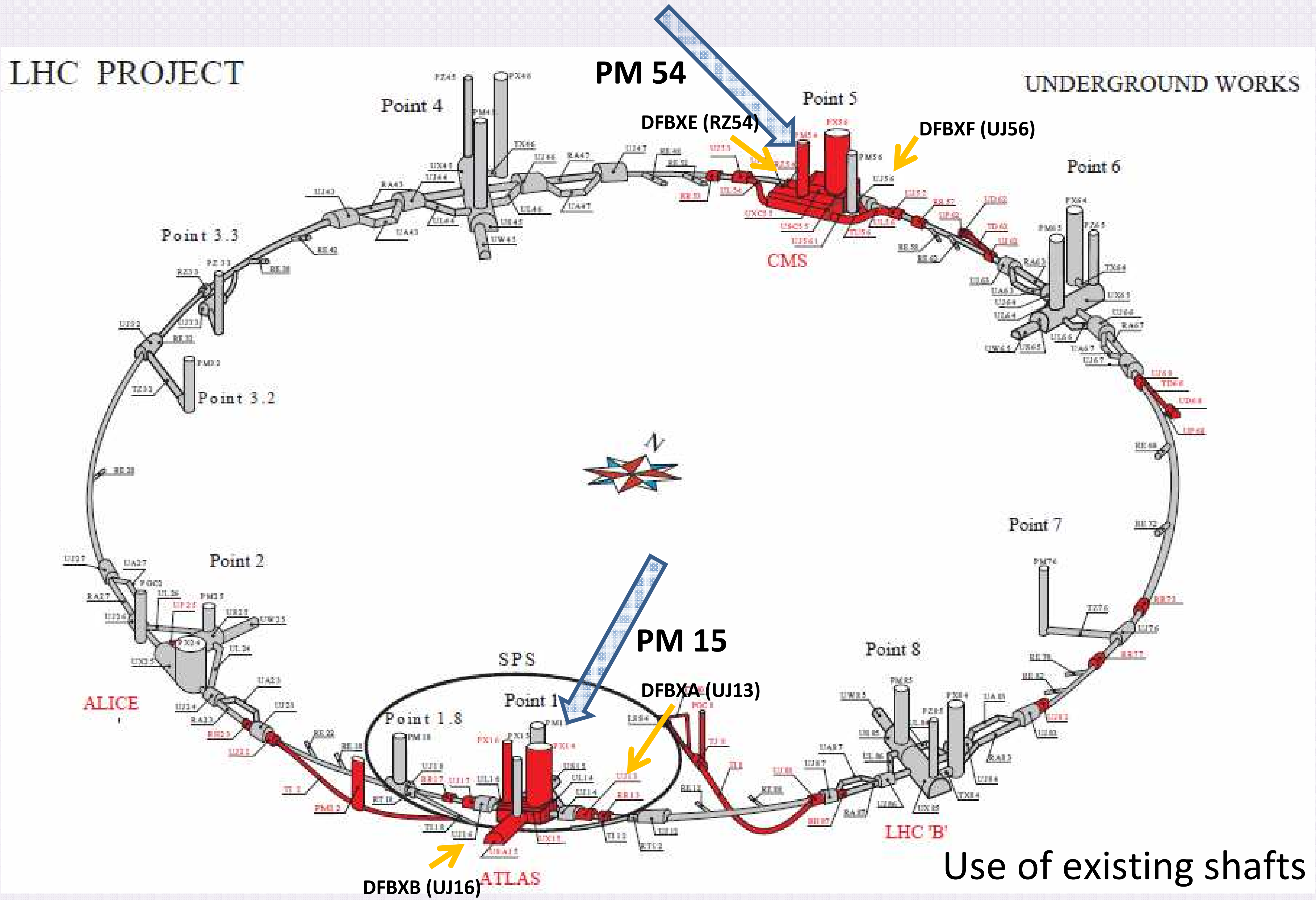
48 cables rated at 600 A per link

P7: Integration in LHC Tunnel



J. P. Corso

P1 and P5: Surface Installation



PM 54

DFBXE (RZ54)

DFBXF (UJ56)

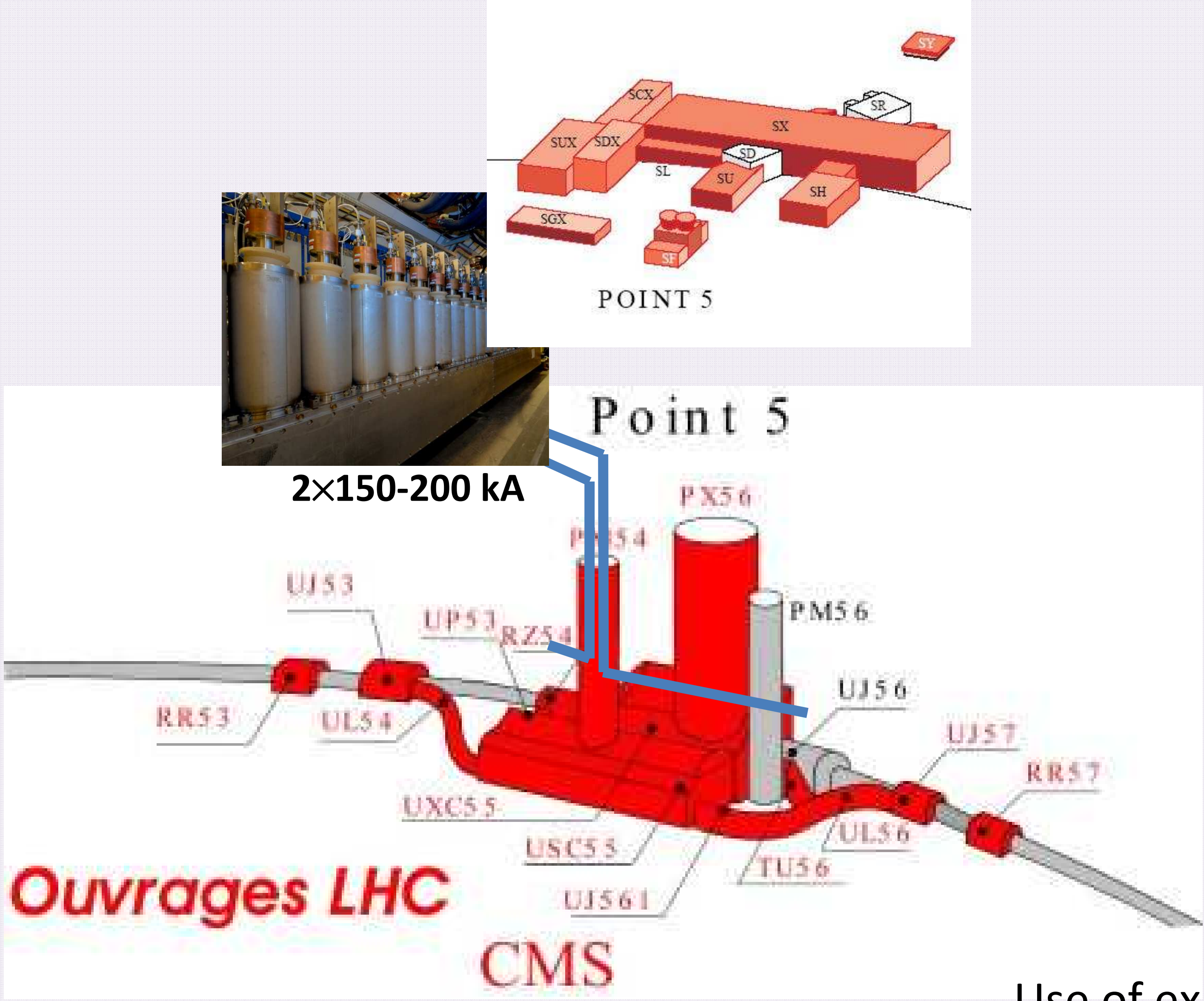
PM 15

DFBXA (UJ13)

DFBXB (UJ16)

Use of existing shafts

P1 and P5: Surface Installation

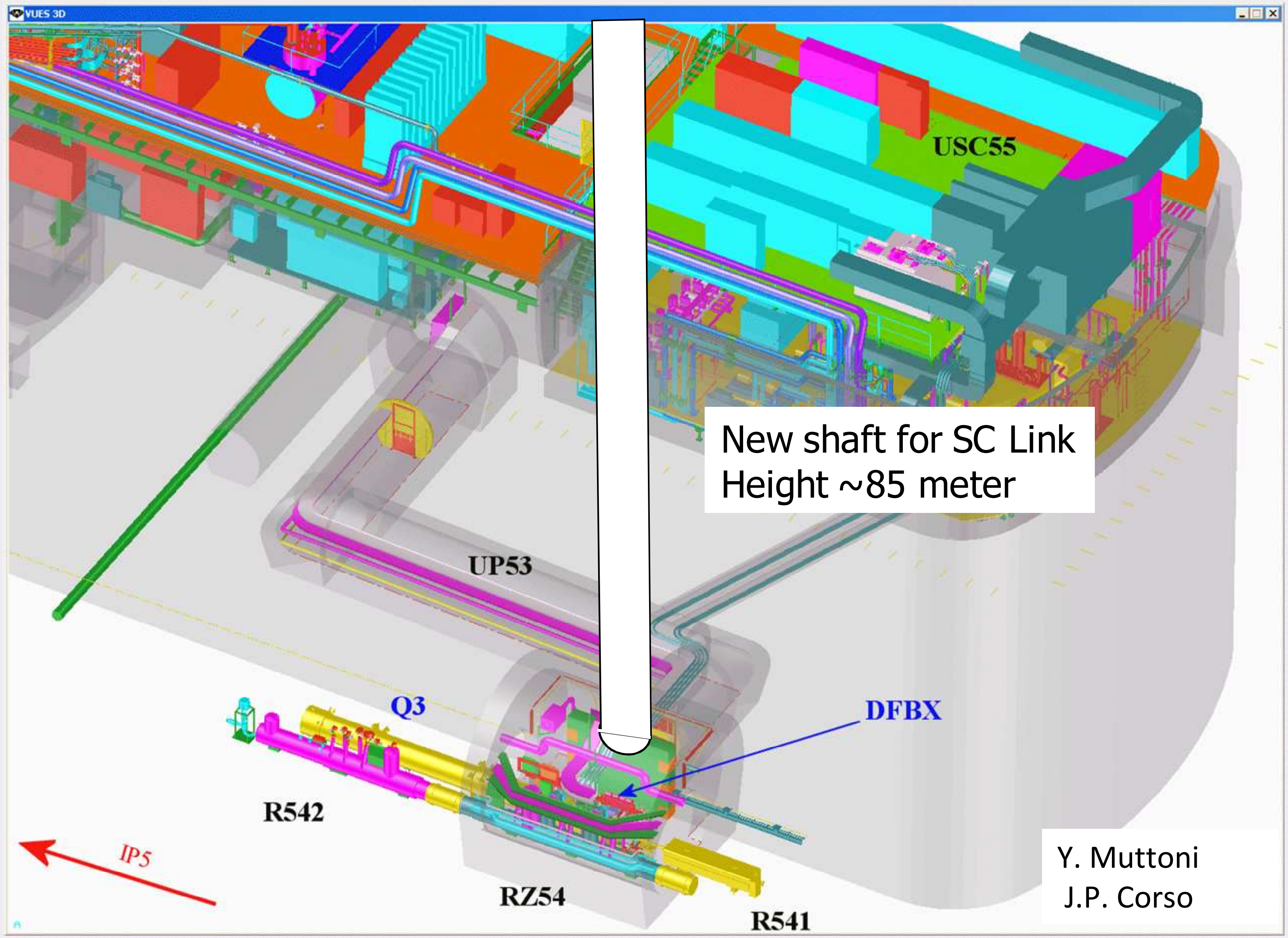


2×150-200 kA

Use of existing shafts

P1 and P5: Surface Installation

Point 5



New shaft for SC Link
Height ~85 meter

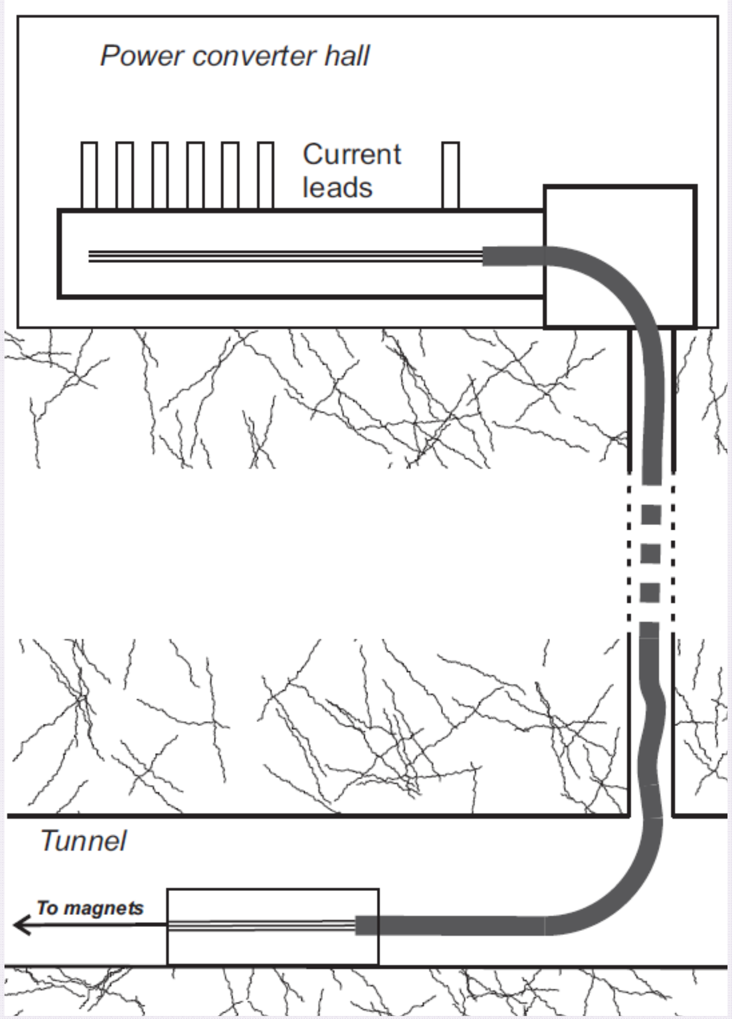
Y. Muttoni
J.P. Corso

Requirements

- Transfer of up to ~ |200| kA via multiple cables feeding different magnet circuits – the cables shall be thermally and electro-magnetically decoupled

- Total length: up to 500 m, with a significant vertical transfer – about 80 m

- Use of available He cryogenics – He gas at 5 K, 20 K and 50 K



HTS cables for power transmission

1) **AC** cables for operation in the network
2) **First** and **second generation HT**S conductors
3) **LN_2** cooling
4) Cables operated at max. up to about **4000 A max**
5) One or **max three cables** in the cryogenic envelope
6) **Horizontal** transfer
7) **High-voltage**

SC links for the LHC machine

1) Quasi-**DC** operation
2) Study of **MgB_2** potentials
3) **GHe** cooling
4) Cables operated at **up to 20 kA**
5) Multi-cable (~ **50 high-current cable**) assemblies
6) **Horizontal + Vertical** (~ 80 m) transfer
7) **1.5 kV – 2 kV** electrical insulation

Conductors

MgB_2, **YBCO** and **Bi-2223**

MgB_2: good electrical properties at the fields (<1 T) and temperatures (≤ 25 K) of interest for this application.
Low cost

YBCO : superior mechanical properties, higher operating temperature

BSCCO 2223: well known conductor, higher operating temperature

Conductors Specification

		Φ (mm)	W (mm)	Th (mm)	Tmax (K)	Ic (‡) (A)
(†)MgB_2	wire	< 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

(†) bending radius $R_B \leq 80$ mm

(‡) at applied field $B \leq 0.5$ T

Cabling of reacted wires

MgB_2 round wire

- Choice of **round wire** for high-current cables. Possible use of tape for low-current applications (< 1 kA)
- **Development** of MgB_2 round wire in close collaboration with Columbus Superconductors
- Production at Columbus of several wires round with **different architectures** (optimization of barrier, number of filaments, filaments size,…)
- Definition of final wire geometry and **first fully successful characterization** at CERN of short lengths of conductor in July 2012
- Finalization of wire characteristics (implementation of stabilization, reduction of diameter of wire, increased number of filaments,…) and production of long unit lengths of conductor (> 1km) at Columbus

Laboratory – Industry Collaboration

Current Ratings and Conductor Needs

Number of links and quantity of conductor:

2 at LHC P7
Itot~ 30 kA/link
50 cables rated at **600 A**

~150 km of conductor

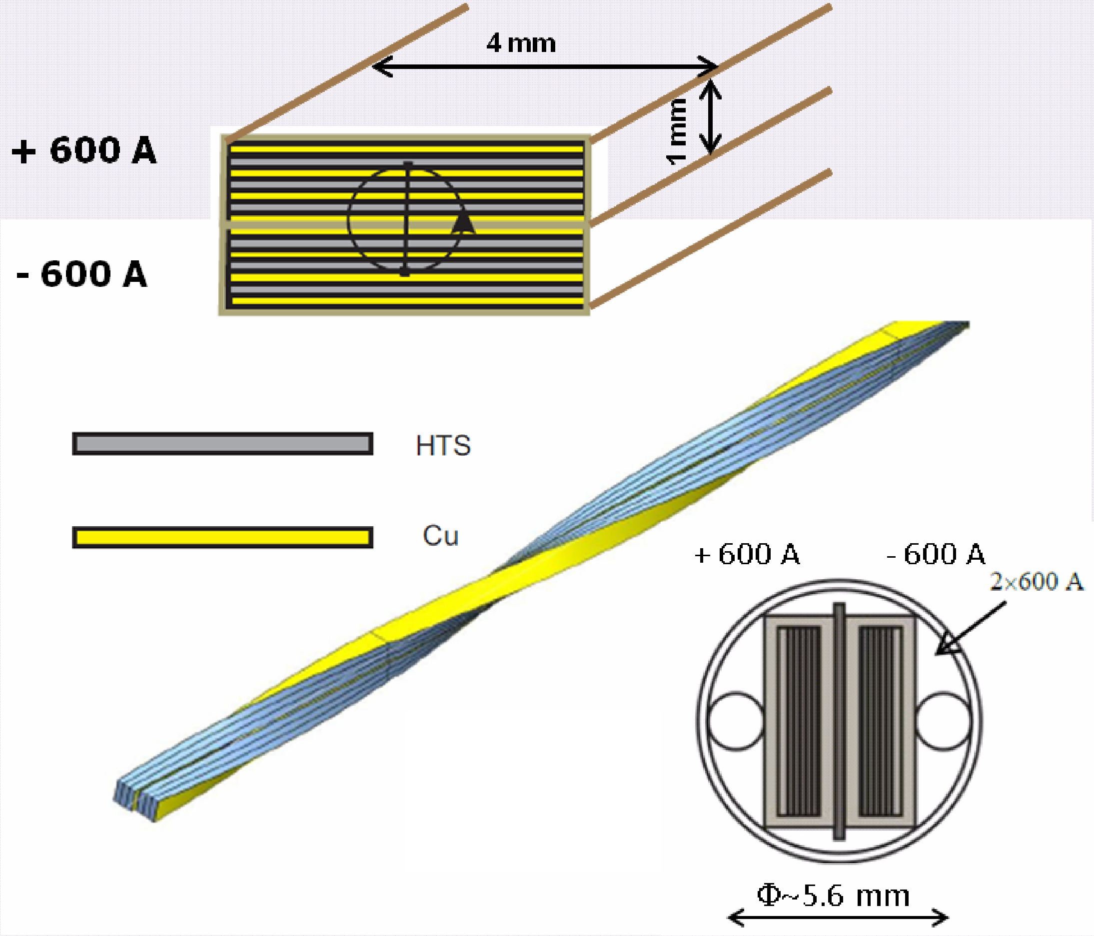
4 at LHC P1
4 at LHC P5
Itot up to 190 kA/link
Up to **50 cables** rated at **120 A**, **600 A, 3000 A**, **6000 A**, **13000 A** and **20000 A**

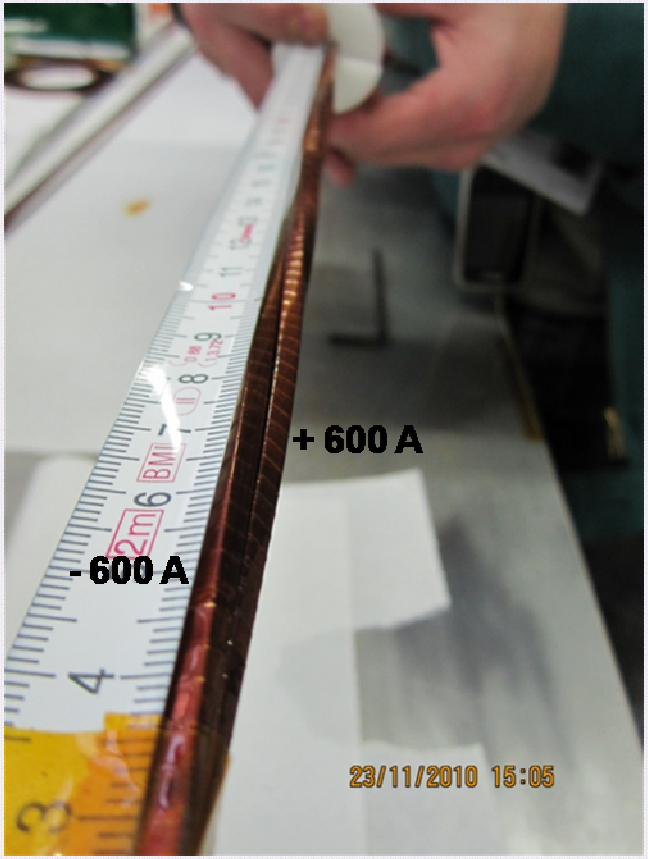
~850 km of conductor

Ltot ~ 1000 km of conductor for series production

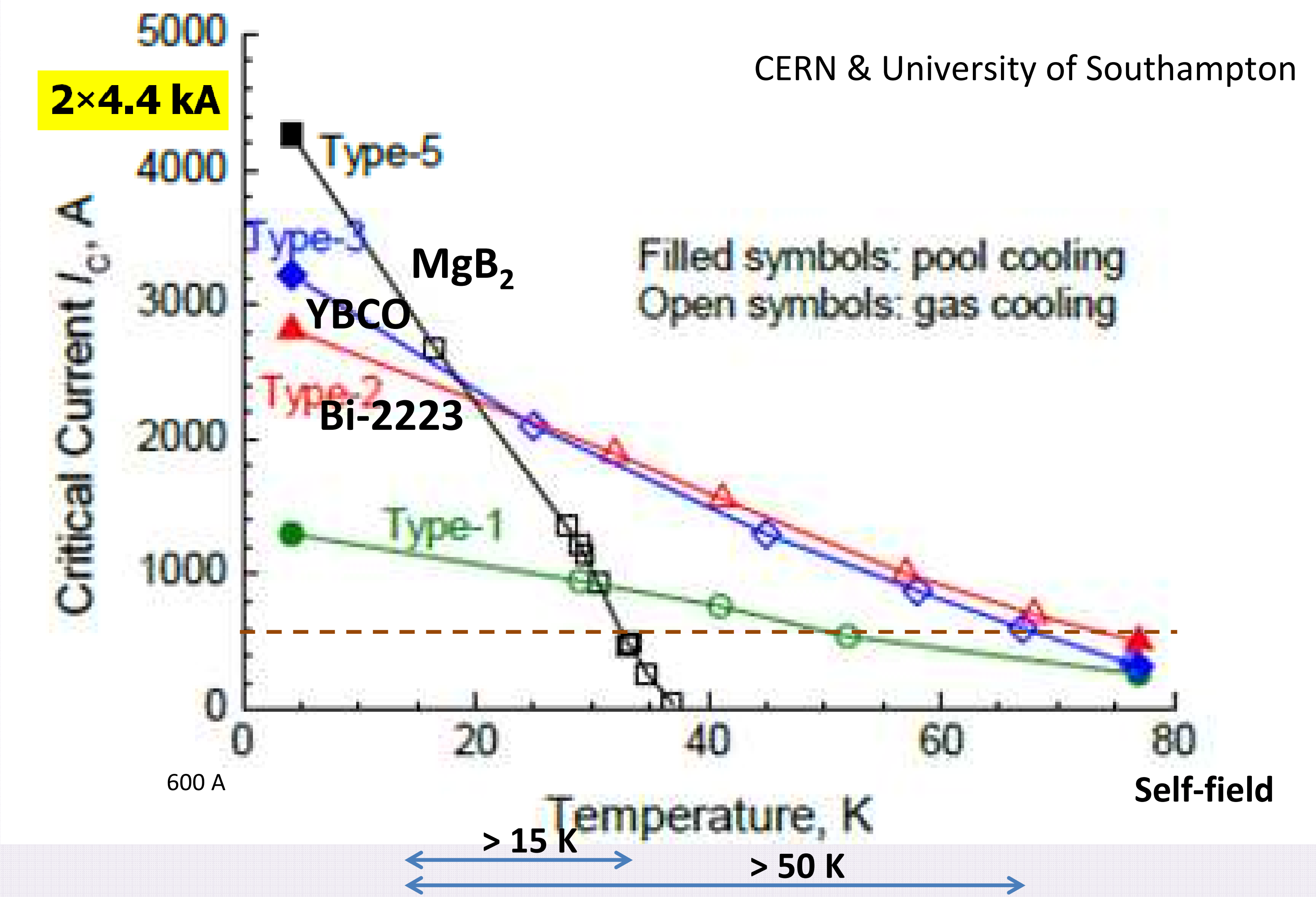
Cable for electrical transmission (1 kA range)

Twisted-pair cables made from tapes





Cable Development (1 kA range)



CERN & University of Southampton

2×4.4 kA

MgB_2

YBCO

Bi-2223

600 A

Self-field

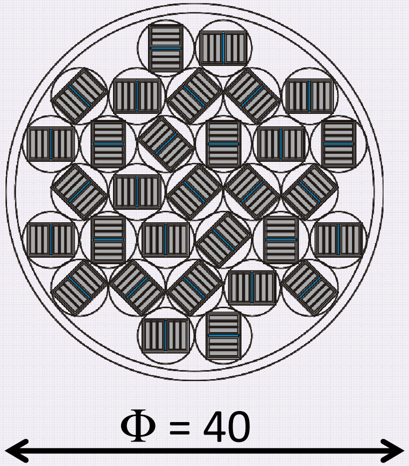
> 15 K

> 50 K

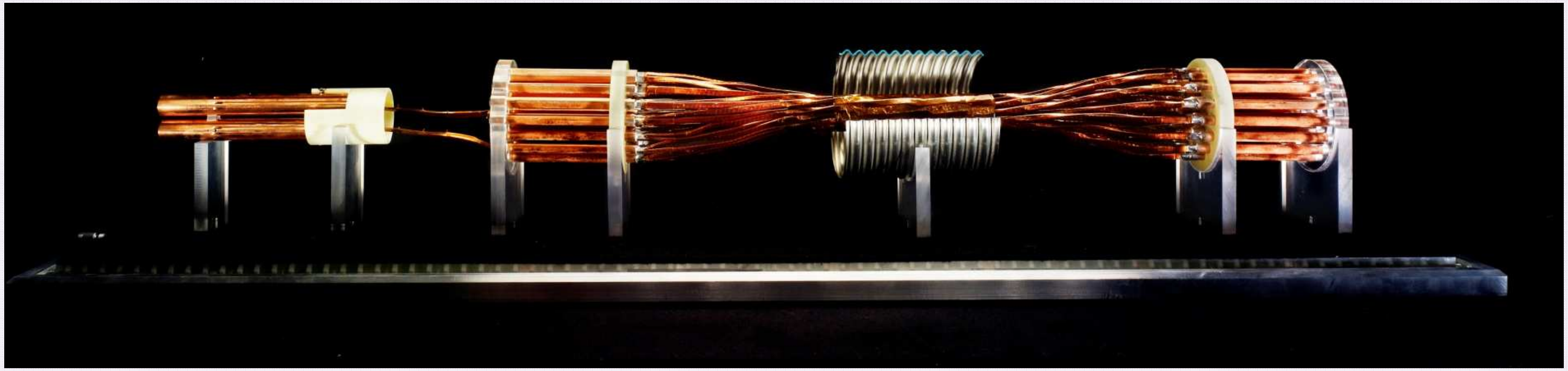
Measurements performed on cables 2 m long

Multi-Cable Assembly

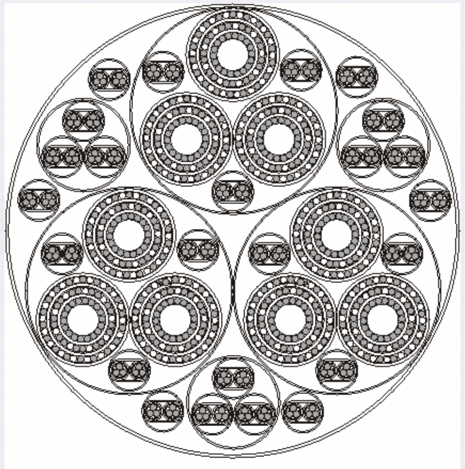
25 × 2 × 600 A (2 × 15 kA)



30 kA
~2 kg/m
~ 150 m_{HTS}/m_{cable}



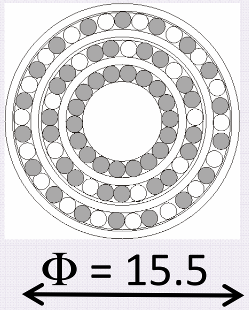
High-Current Cables



Φ = 75

27 cables 6000 A
48 cables 600 A
Itot = **190 kA @ 20 K**
(~2 × 95 kA)

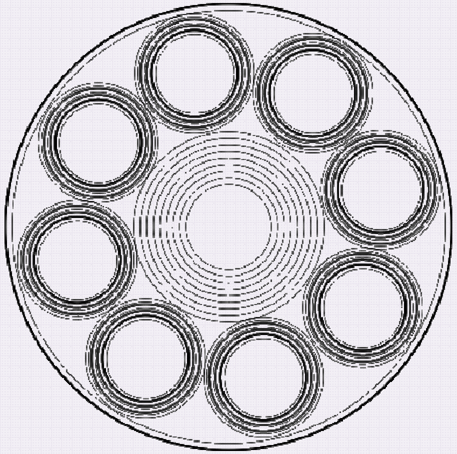
3 × 6 kA



Φ = 15.5

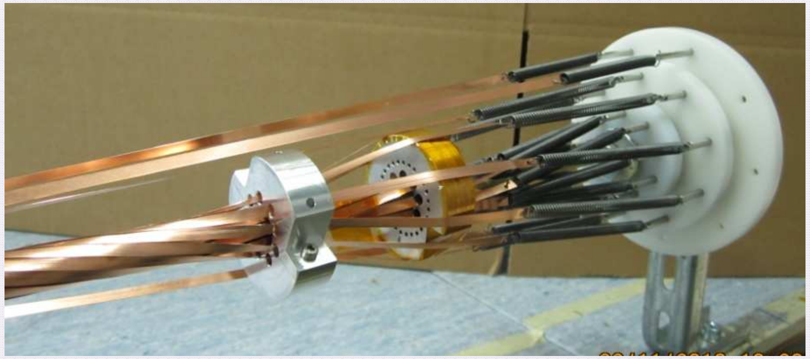
~**7 kg/m**

~ **900 m_{HTS}/m_{cable}**

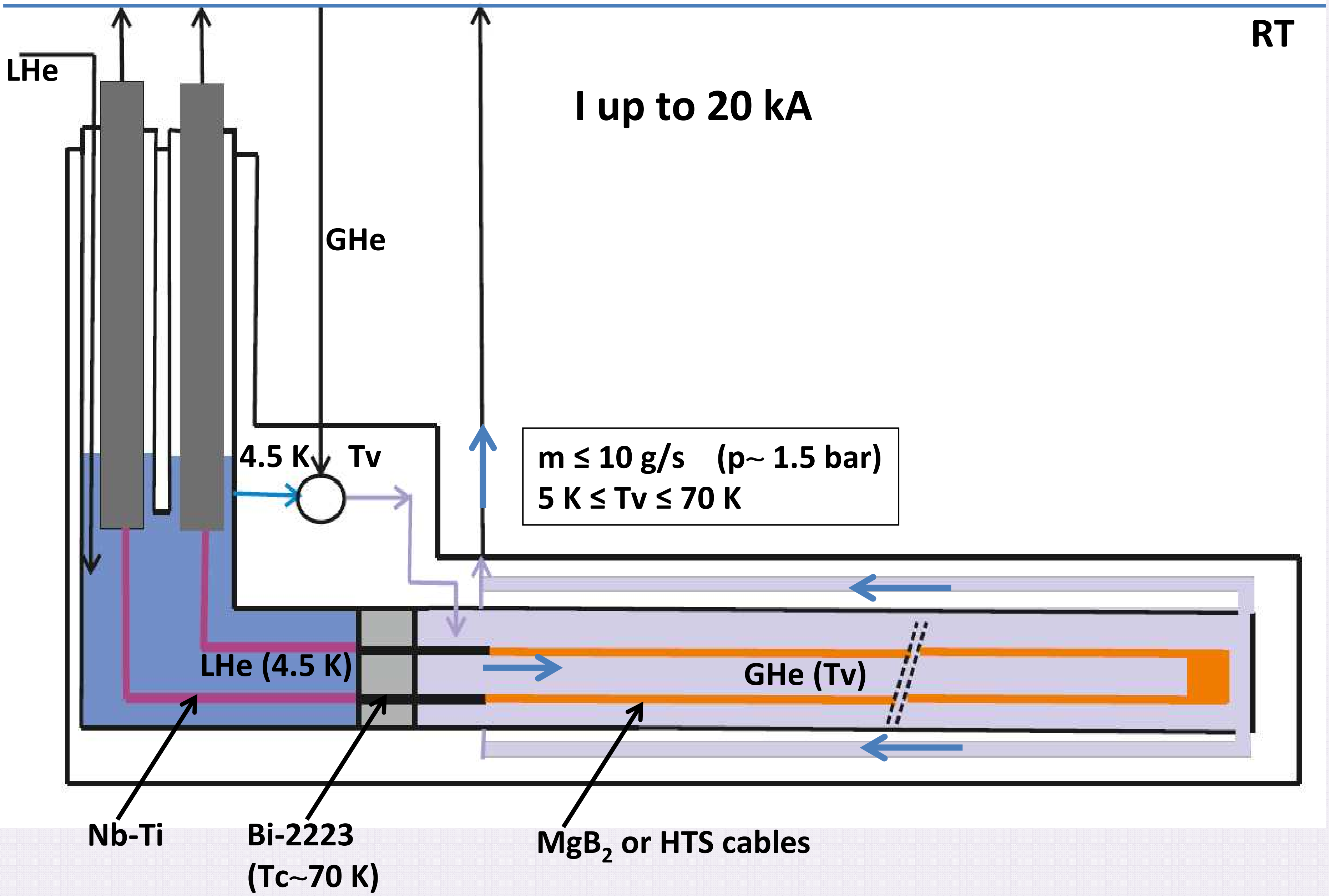


Φ =70

24 × 6000 A
42 × 600 A
Itot = **169 kA & 20 K**
(~ 2 × 84.5 kA)



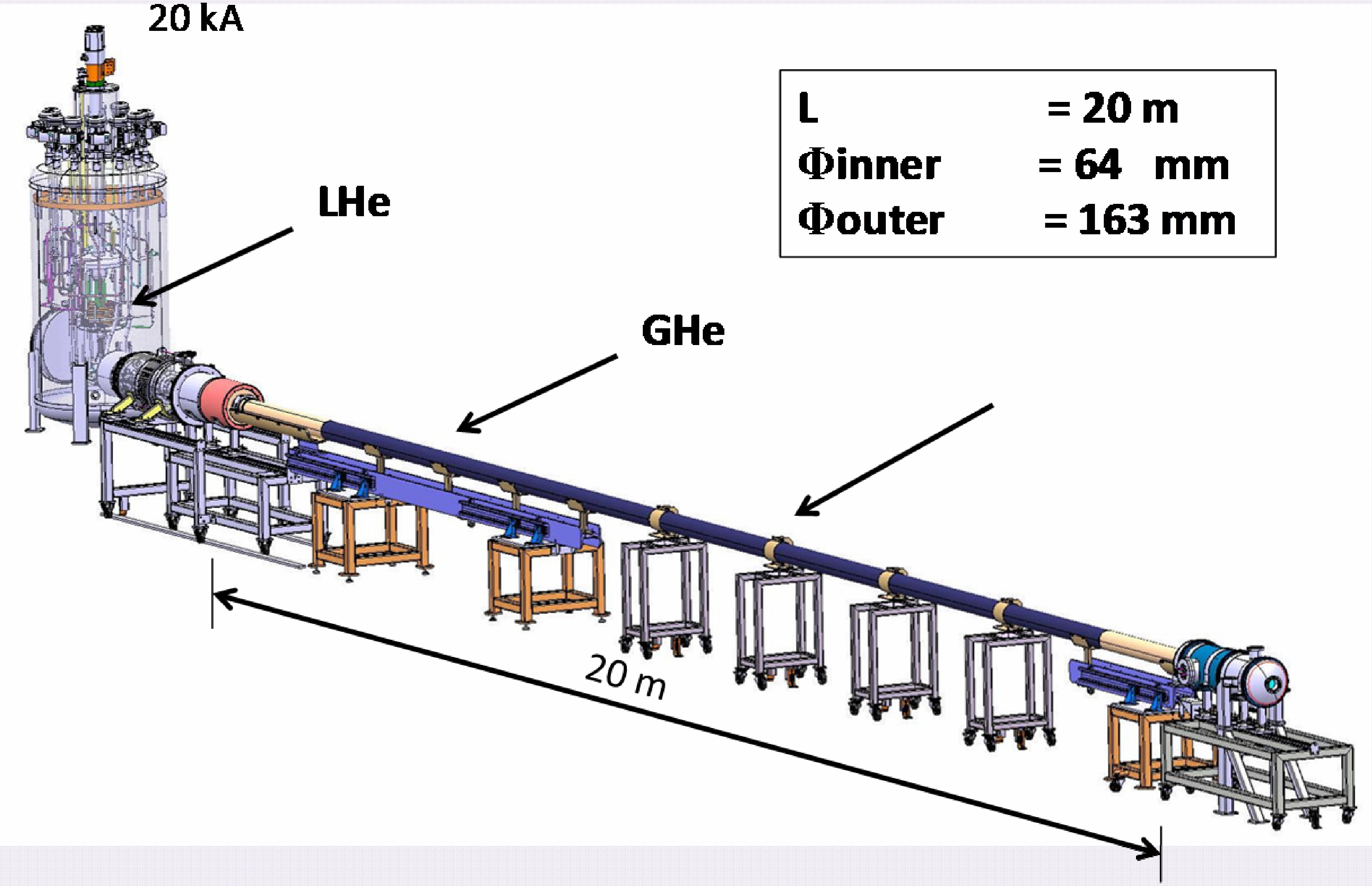
CERN Test Station



I up to 20 kA

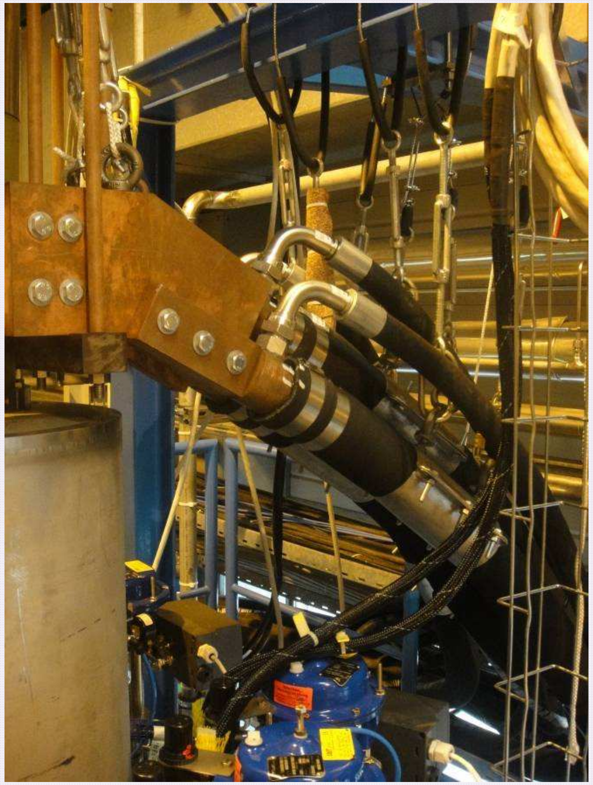
m ≤ 10 g/s (p~ 1.5 bar)
5 K ≤ Tv ≤ 70 K

CERN Test Station



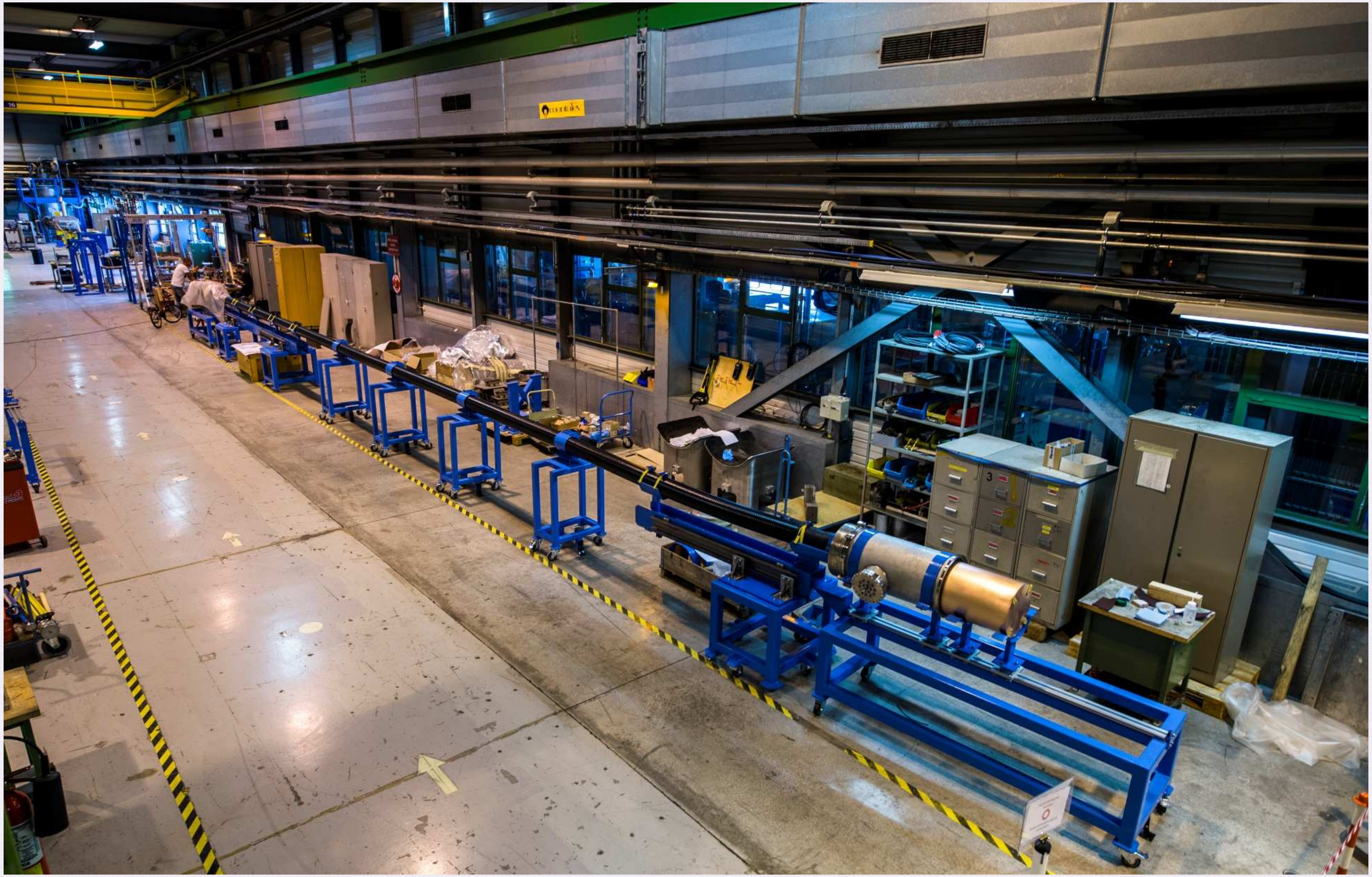
L = 20 m
Φinner = 64 mm
Φouter = 163 mm


H ~ 4 m
FRAGILE



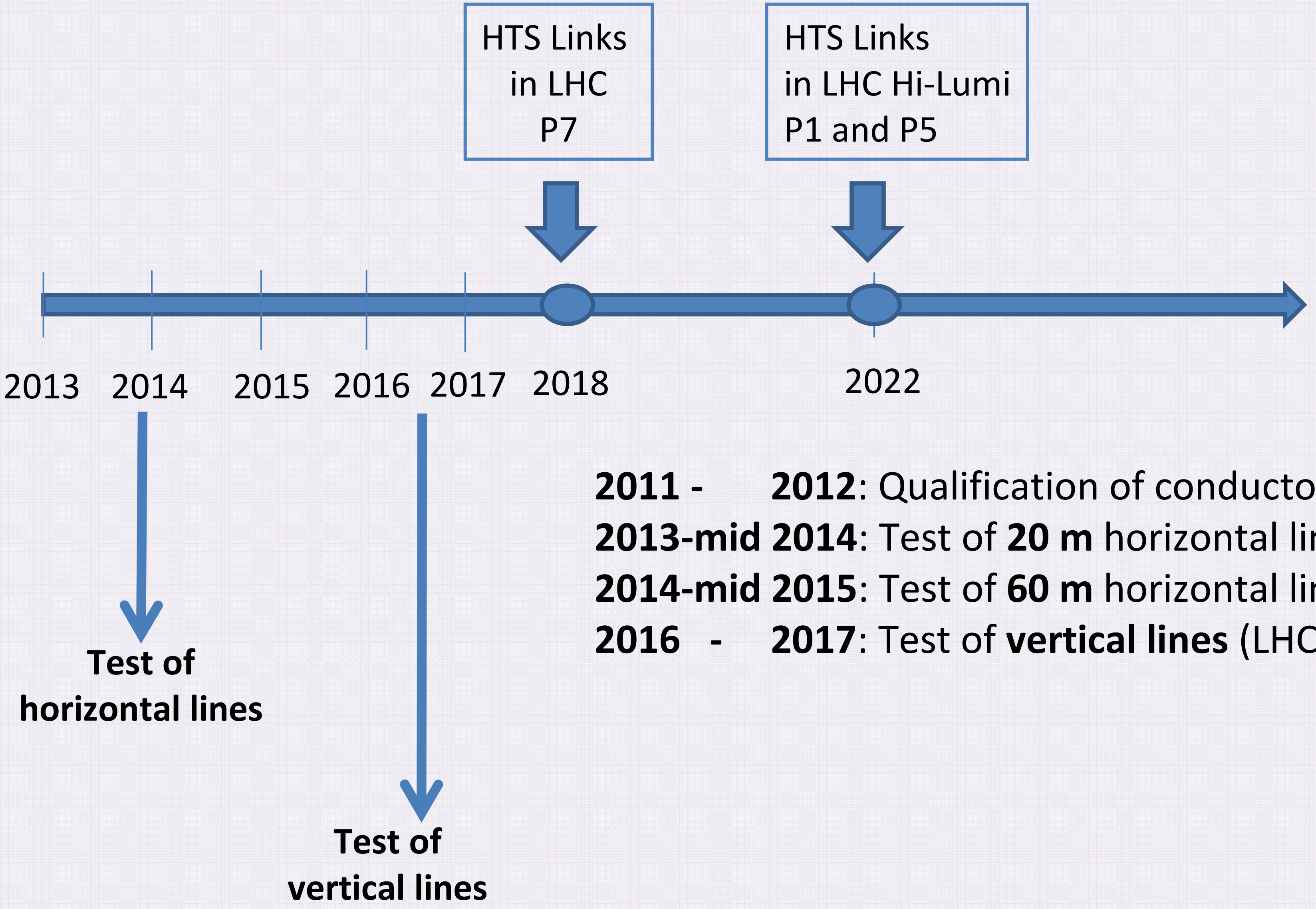

VELAN
VELAN

CERN Test Station



Test station at CERN commissioned and operational

Timeline


HTS Links
in LHC
P7

HTS Links
in LHC Hi-Lumi
P1 and P5

Test of horizontal lines

Test of vertical lines

2011 - 2012: Qualification of conductor
2013-mid 2014: Test of **20 m** horizontal lines
2014-mid 2015: Test of **60 m** horizontal lines
2016 - 2017: Test of **vertical lines** (LHC shaft)

Conclusions

- **Superconductivity** plays a major role in the field of **HE physics**

- For magnet applications, the work-horse conductor has been **Nb-Ti**. Requirements for higher fields define the present and future R&D effort at CERN on **A15** and **HTS** conductors and associated devices

- Successful **R&D** development of superconductors and of superconducting devices is the result of a **close collaboration between academia**, **laboratories** and **industry**. This applies from the very early stage of the development up to the final phase of series production. A **symbiotic relationship** that enables technology and science to progress, and that made the construction of the LHC machine and the new physics findings possible

Thanks for your attention !