

Electrical characterization of S/C conductor for the CMS solenoid

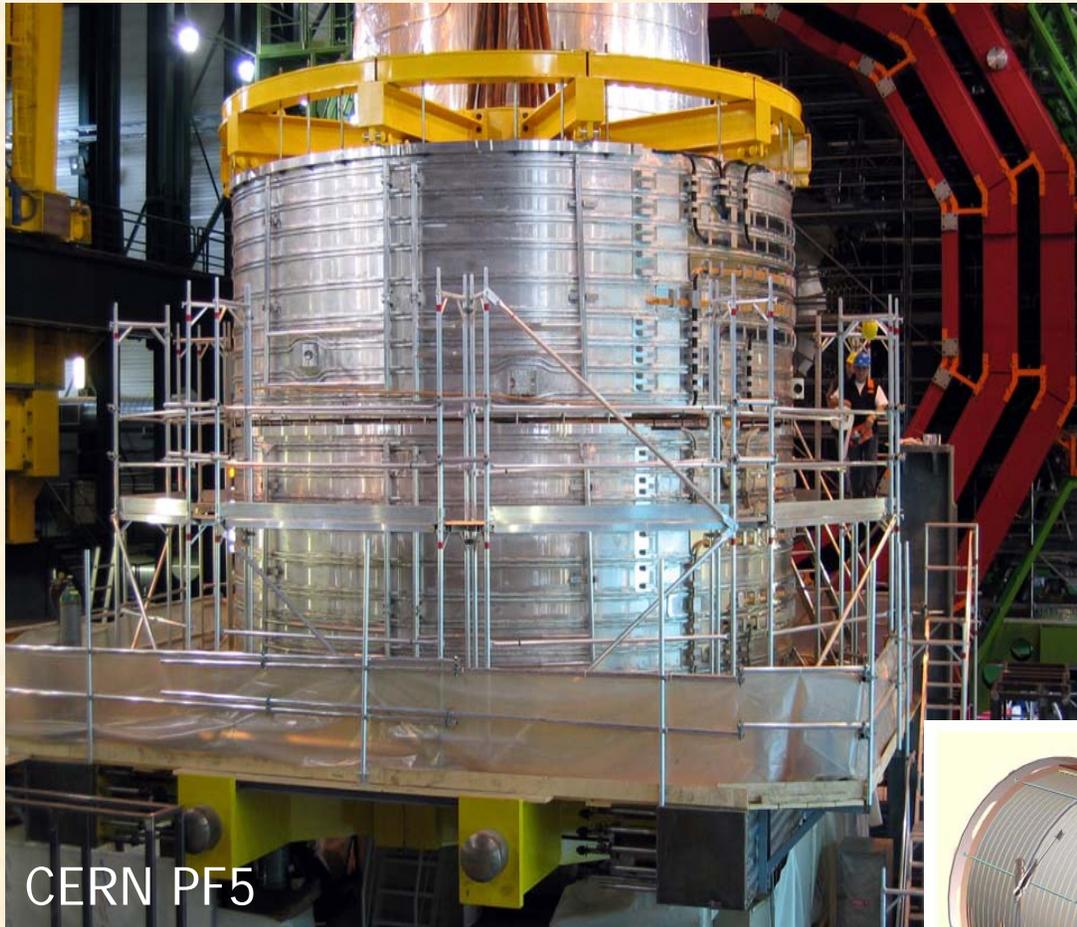


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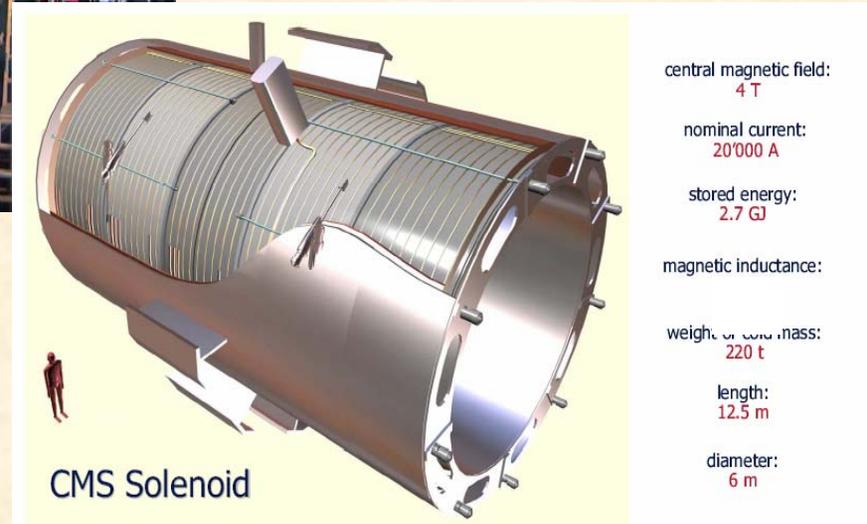
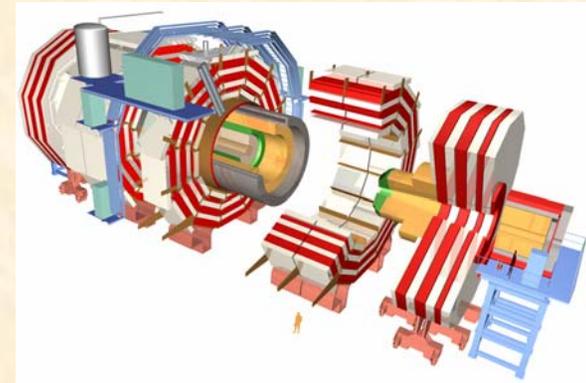


F. Kircher-CEA Saclay
B. Curè-CERN Switzerland

CMS-Compact Muon SOLENOID



**Solenoid: 5 modules
CB±2, CB±1 & CB0
4 layers each
Central magnetic field: 4T**



Intro

Conductor

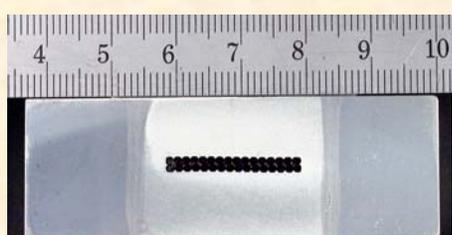
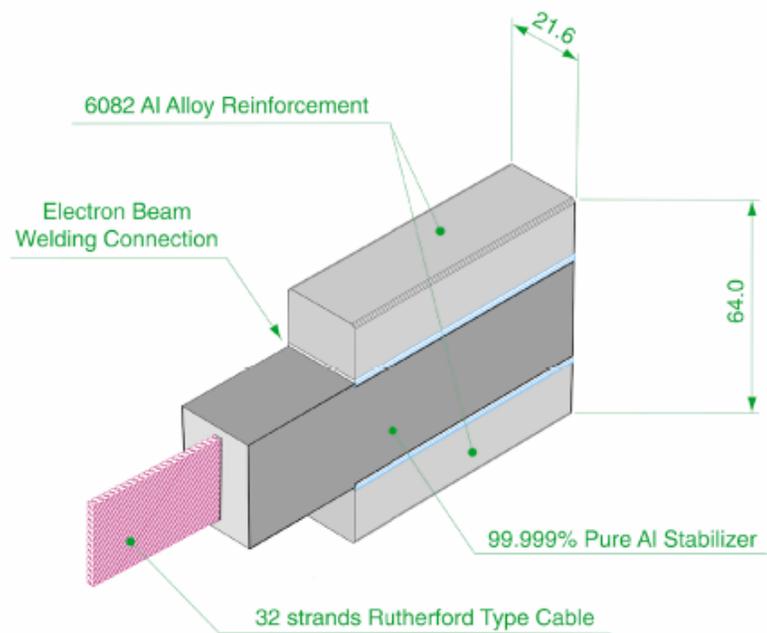
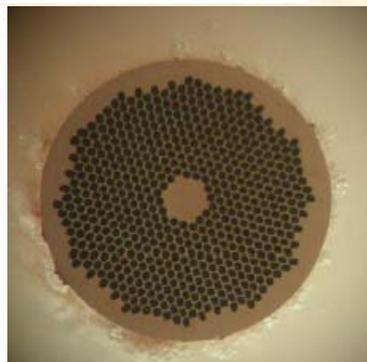
Meas System

Ic statistics

Joints

Concl

Strand Specifications	Parameters
Strand Diameter (Cu+Barrier)/Nb-Ti ratio	1.280 ± 0.005 mm 1.1 ± 0.1
Filament diameter	< 40 μm
Number of Filaments	□ 552
Strand Unit length	2750 m
Strand Minimum Critical Current I_c (Criteria : 5 T, 4.2 K, 10 μV/m)	1925 A



Strand → Cabling → Co-extrusion → EB-welding

21 conductors, 2250 m each

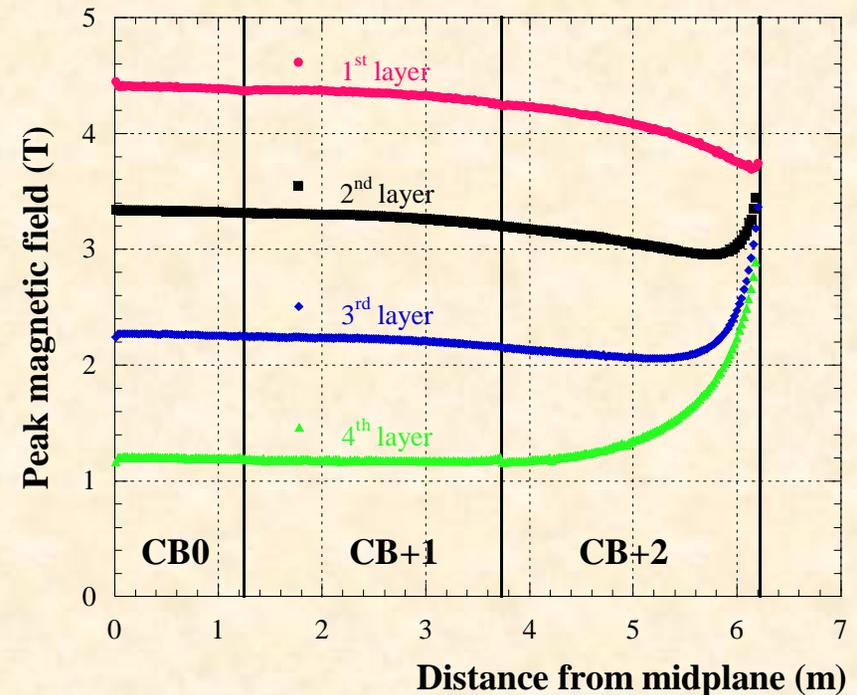
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Importance of I_c survey

-quality control during the multi-step conductor fabrication \rightarrow degradation control

- $I/I_c \sim 1/3 \rightarrow$ large enthalpy margin

-analysis of field distribution on the layers for each module \rightarrow choice of the "best" conductor



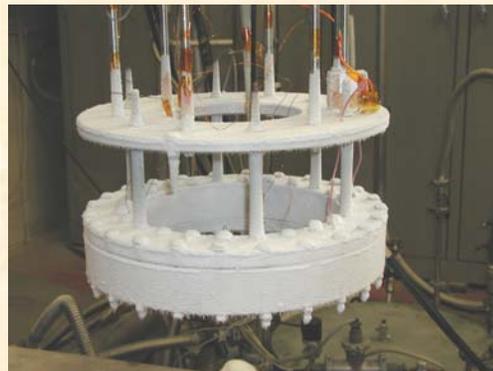
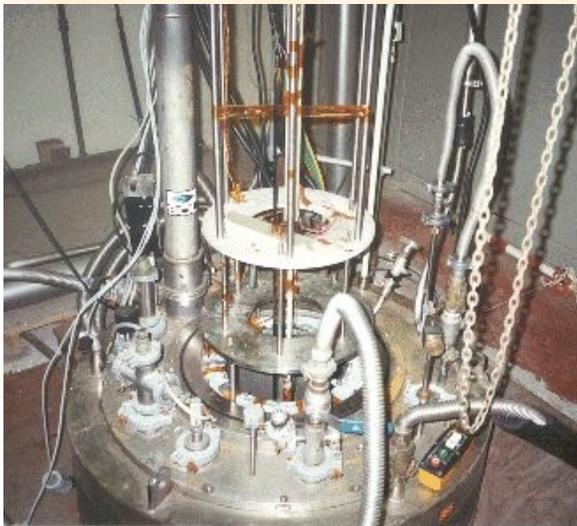
Layer/Module	B (T) CB±2	B (T) CB±1	B (T) CB0
1	4.2	4.3	4.4
2	3.4	3.2	3.3
3	3.2	2.2	2.3
4	2.9	1.2	1.2

Where and how:

CEA-Saclay: critical current measurement
single strands in the CHRISTIANE
facility

Infn-Genova: critical current measurement of
the finished conductor in Ma.Ri.S.A
facility

Property	Single strand	32-Strand Cable
Diameter/ Dimensions (mm)	1.28	20.63 × 2.24
Cu/Sc ratio	1.1/1	1.1/1
Number of NbTi filaments	500 to 700	32 × (filaments in one strand)
Twist pitch (mm)	45	180-190
Sample holder Ic measurement	Straight /hairpin Direct	Circular Transformer



Measurements
at 4.2 K & 5T

Intro

Conductor

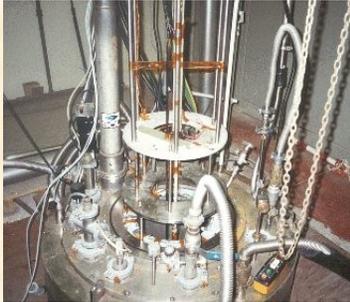
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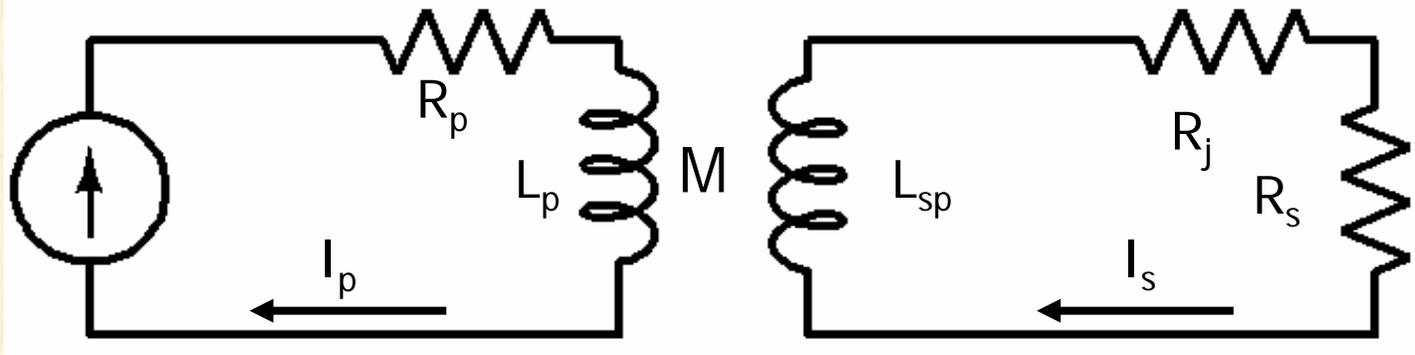
Infn-Genova: *direct transformer method*



Ma.Ri.S.A.



CMS conductor



Primary

Number of turns	4176
L_p (H)	6.4
I_p (A)	<970

Secondary

L_s (μ H)	0.88
I_s (A)	100000
Amplification	720

How to compare?

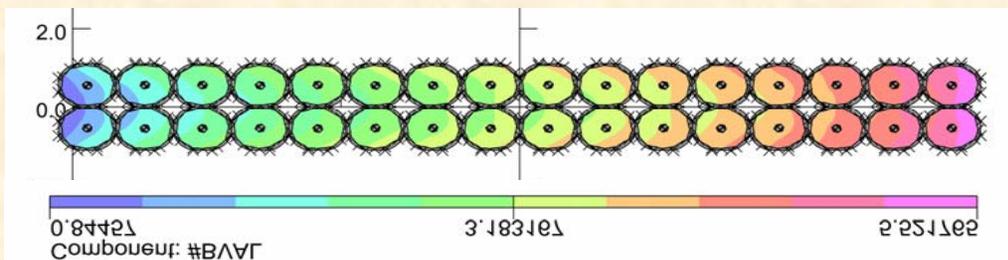
Definition of I_c without ambiguity

Voltage Criterion, $0.1 \mu\text{V}/\text{cm}$

Definition of critical field

Not unique

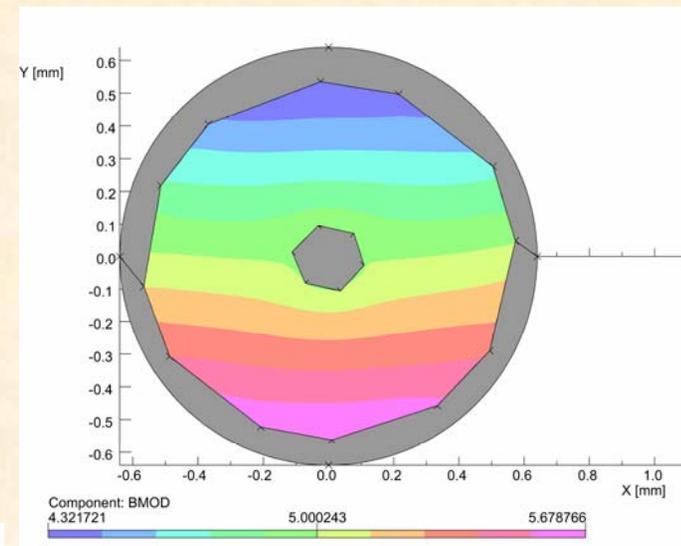
- Self-field
- Complex field distribution in multi-strand cables



Rutherford cable

$$B_{\text{ext}} = 3.18 \text{ T} + \text{Self-field}$$

$$I = 1860 \times 32 \text{ A}$$



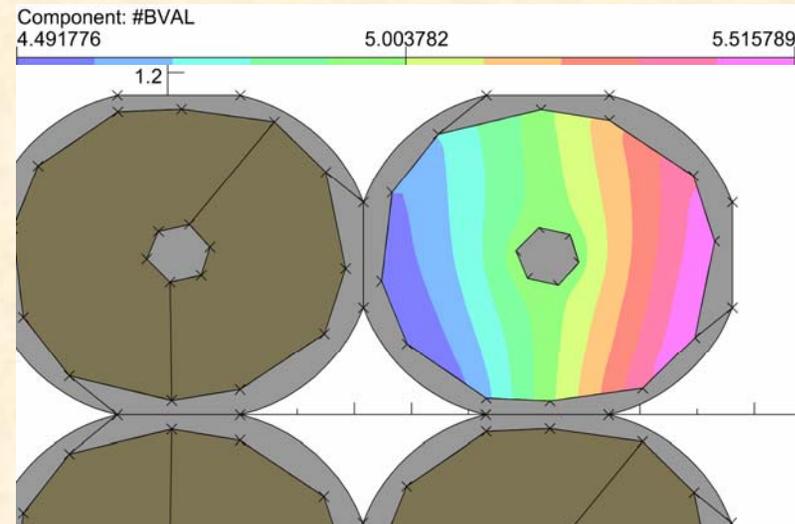
Single strand

$$B_{\text{ext}} = 5 \text{ T} + \text{Self-field}$$
$$I = 1860 \text{ A}$$

How to compare?

Apply an external field so that the strands in the cable at higher field experience a mean field equal to that of the single-strand distribution .

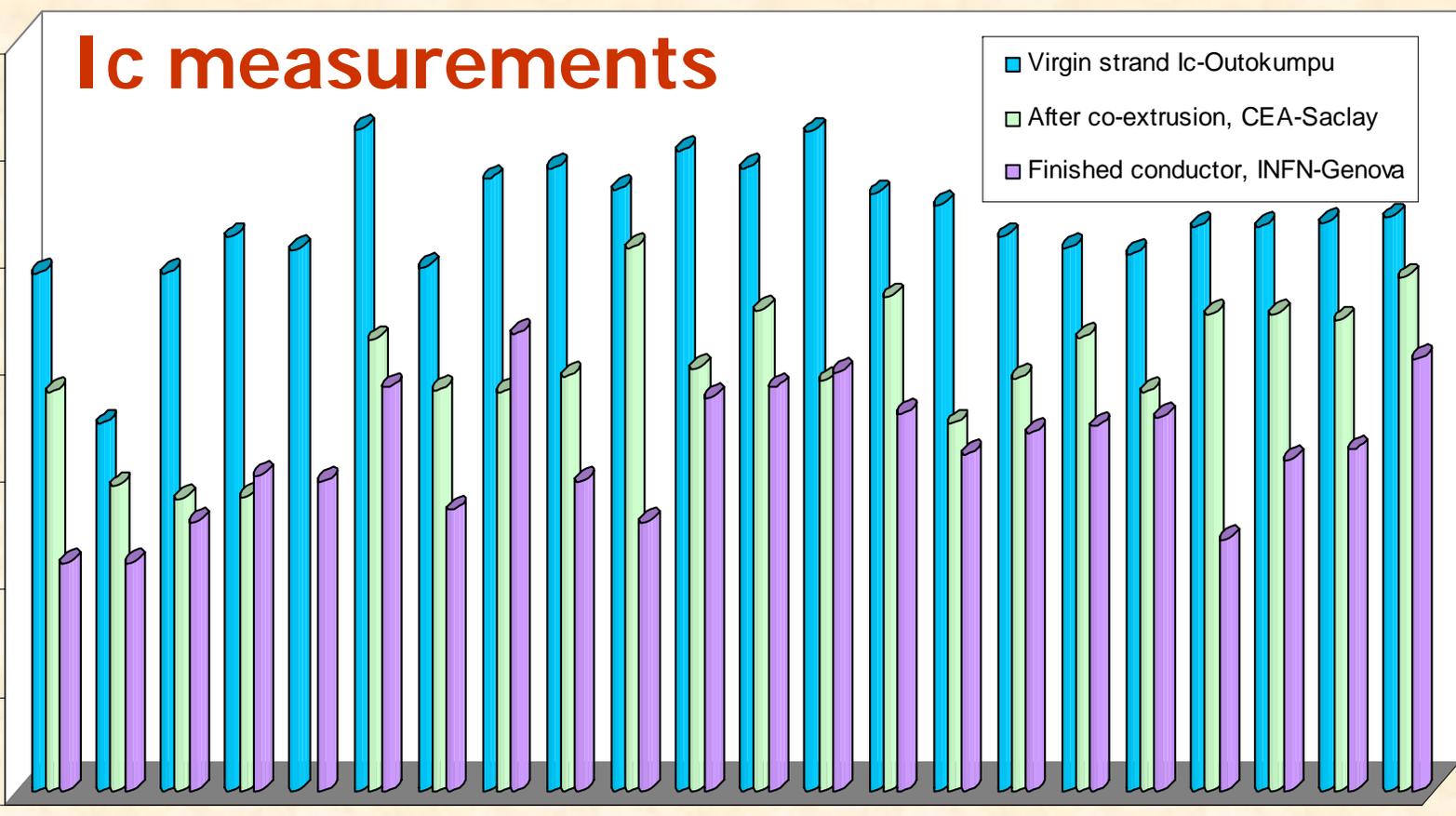
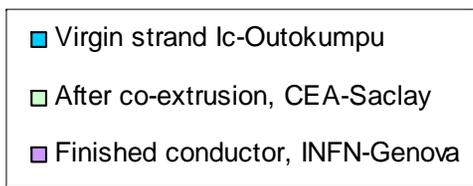
$$B_{\text{ext}} = 3.17 \text{ T}$$
$$B_{\text{mean}} = 5 \text{ T}, B_{\text{peak}} = 5.52 \text{ T}$$



We made in Ma.Ri.S.A. some measurements on co-extruded samples to compare our results with the critical current of single strands. There is a very good agreement; the max difference is within the error value of 2%.

2100
2050
2000
1950
1900
1850
1800
1750

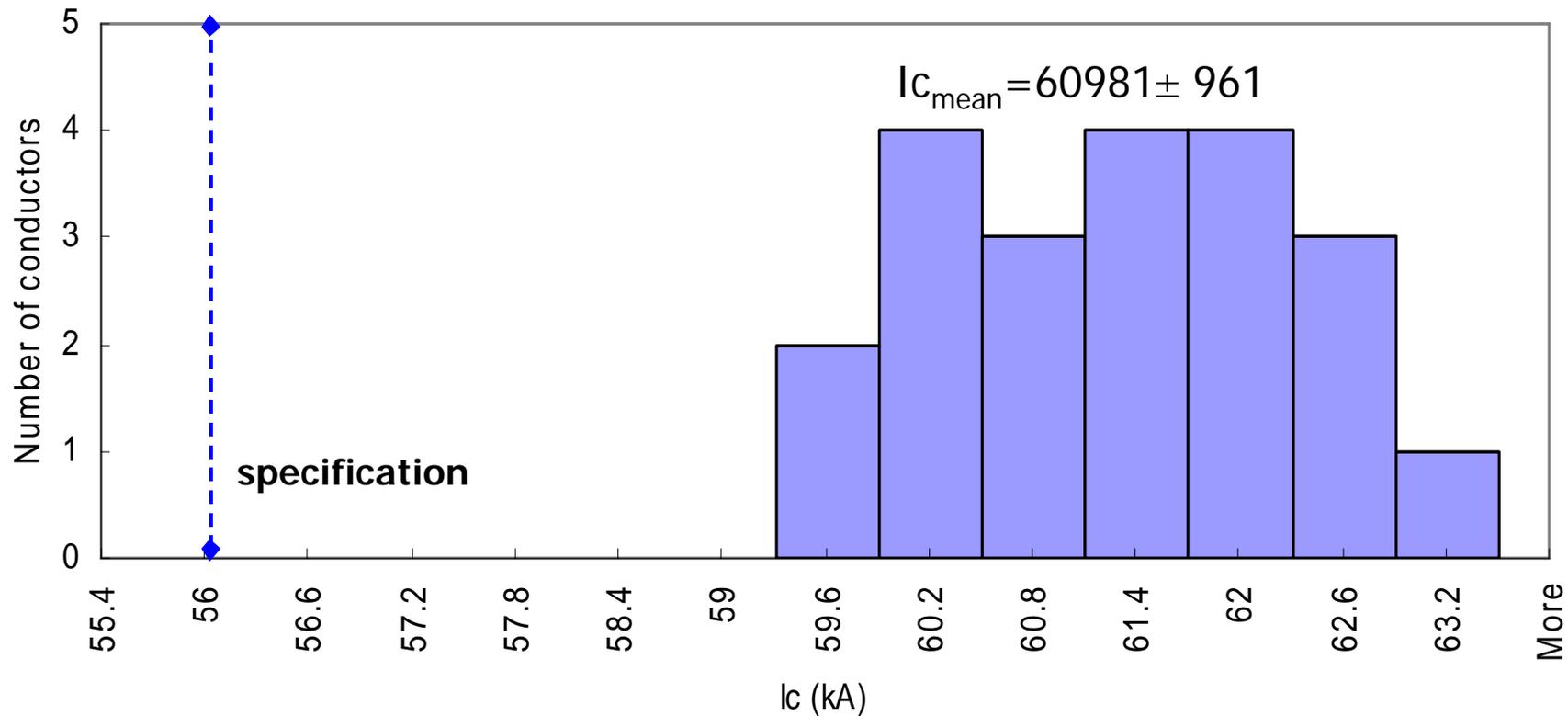
Ic measurements



	Ic (A) Virgin	Ic (A) Coextruded	Ic strand (A) Conductor ring	Total degradation
ebw01-cms02	1991	1936±23	1856	-6.8%
ebw02-cms01	1921	1892±17	1856	-3.3%
ebw03-cms03	1991	1886±14	1875	-5.8%
ebw04-cms04	2008	1887±21	1897	-5.5%
ebw05-cms05	2002		1894	-5.0%
ebw06-cms08	2058	1960±30	1938	-6.0%
ebw07-cms06	1994	1937±30	1881	-5.7%
ebw08-cms07	2035	1936±71	1963	-3.6%
ebw09-cms09	2040	1943±15	1894	-7.0%
ebw10-cms10	2030	2003±21	1875	-7.4%
ebw11-cms12	2048	1947±1	1933	-5.7%
ebw12-cms13	2040	1974±27	1938	-5.0%
ebw13-cms14	2057	1941±55	1945	-5.4%
ebw14-cms15	2028	1980±14	1926	-5.0%
ebw15-cms16	2023	1921±15	1907	-5.8%
ebw16-cms17	2008	1942±22	1917	-4.6%
ebw17-cms19	2003	1961±19	1920	-4.2%
ebw18-cms20	2000	1936±12	1924	-3.9%
ebw19-cms18-t2	2013	1972±17	1867	-7.3%
ebw19-cms18-t1	2013	1972±17	1904	-5.5%
ebw20-cms21	2015	1969±18	1909	-5.3%
ebw21-cms22	2017	1989±24	1951	-3.3%

Ic spec per strand=1750 A
4.2 K & 5 T

Max degradation, -7.4%
Min degradation, -3.3%

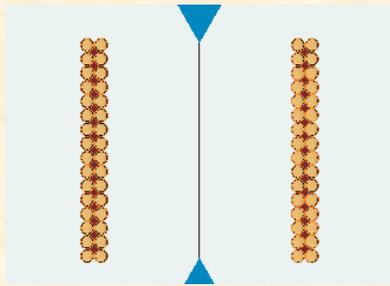


I_c spec = 56 kA at 5 T and 4.2 K

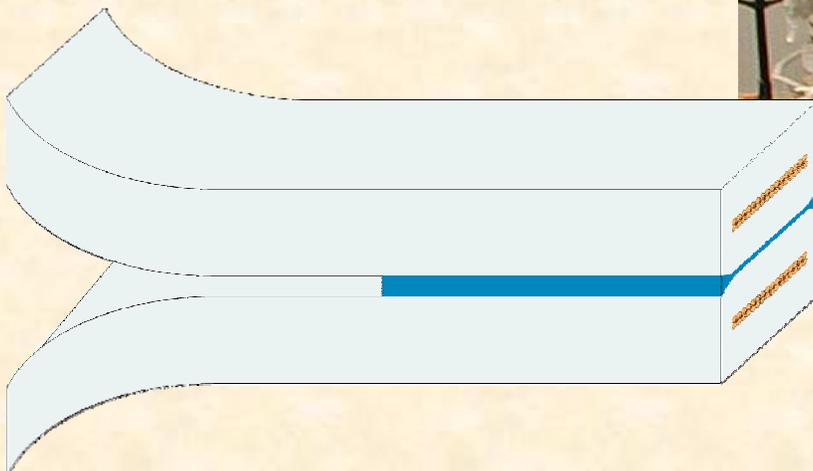
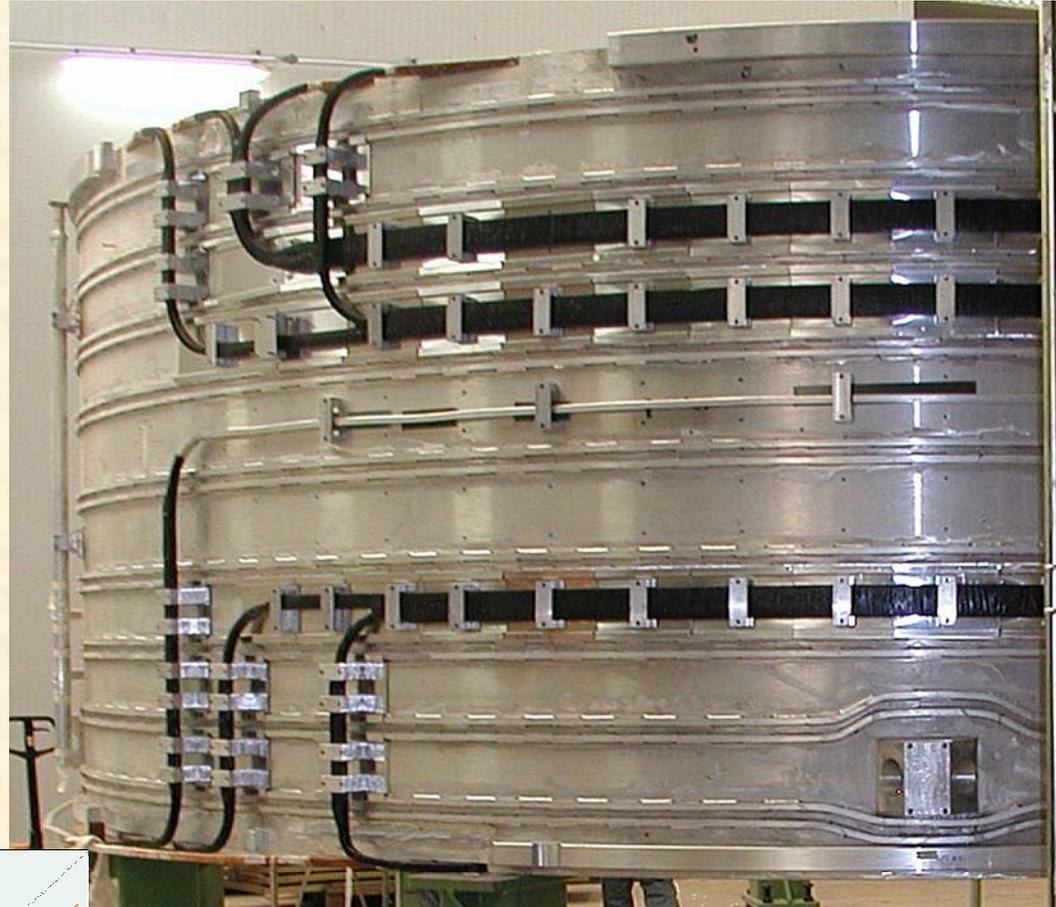
All conductors have critical current higher than the spec value from a minimum of 6% to a maximum of 11% .

Electrical characterization of joints

R_j required $< 10^{-9} \Omega$



TIG joint



Praying hands configuration

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Ansaldo Superconduttori procedure

- 3 mm deep chamfer, 45° angle
- One pass, fore-heating at 120 °C, max temperature 320 °C
- Spot welding

INFN tests on round samples in *shaking hands* configuration

$$R_j = 4.9 \cdot 10^{-9} \Omega$$

on a 28 cm long joint → need 140 cm



CEA tests on straight samples in *praying hands* configuration

$$R_j = 7.8 \cdot 10^{-10} \Omega$$

on a 99.3 cm long joint → need 78 cm

Joints are welded two meters long to be very safe!

Conclusions

We have electrically characterized the S/C conductor for the CMS solenoid at CERN.

All the conductors used for winding the magnet have a critical current at least 6% higher than the specification value. The total degradation from the virgin strand to the finished conductor is in the worst case 7.4%.

We have qualified the method used for making the electrical joints between layers in a single module and between modules and bus-bars.

Both round and straight samples were measured. According to these measurements, it has been decided a conservative length of two meters corresponding to a resistance of $3.8 \cdot 10^{-10} \Omega$ with an external field of 1 T.