REQUIREMENTS ON SC MATERIALS, STRANDS AND CABLES FOR THE FUTURE NEEDS

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- **Future Needs**
- **Some Considerations on magnet design**
- **Can we make the best use of the high current densities in SC**
- **Motor winding type**
- **How to compensate the larger filament size**
- **Materials**
- **Critical current densities and Inter-strand resistance**
- **Characteristics of conductors for various magnet types**
- **Conclusions**

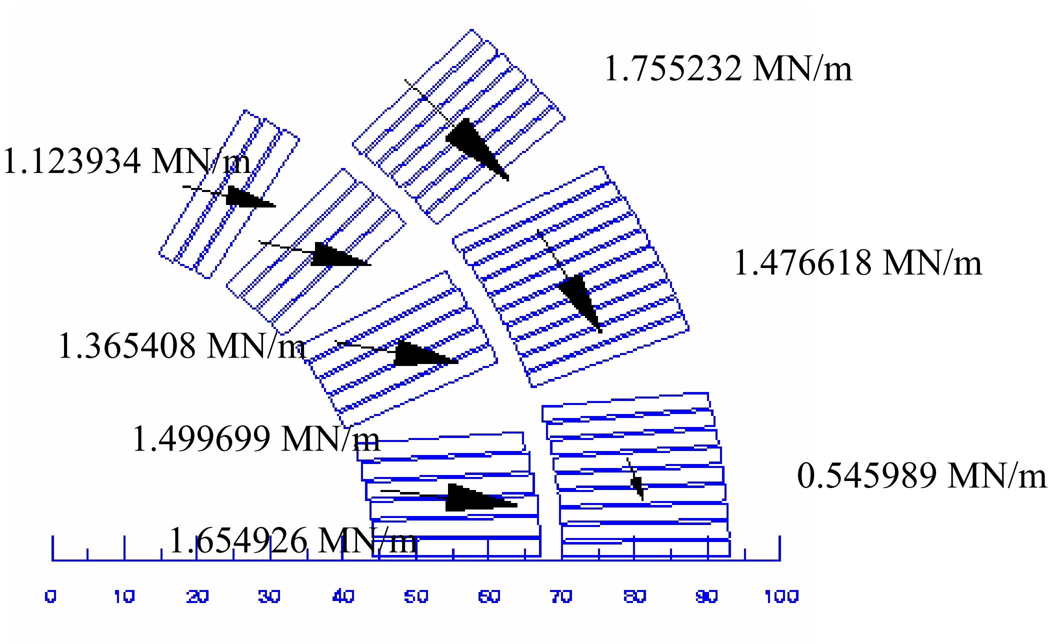
FUTURE NEEDS

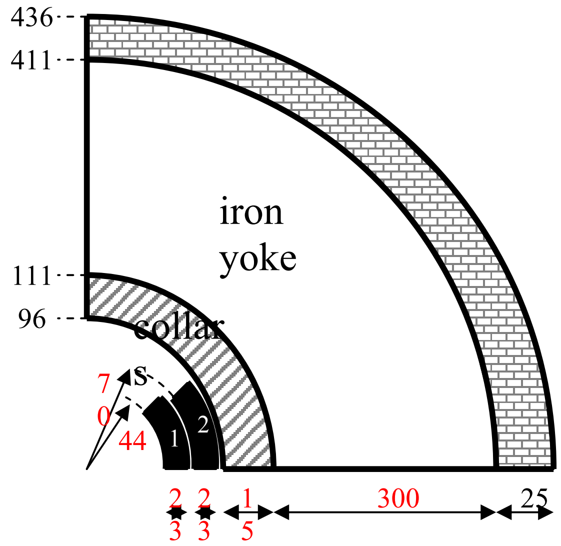
- High field magnets in the range 10 to 15T,in a large aperture bore up to 88mm and in lengths of circa 10m

- Pulsed magnets at 0.5T/s to 5T/s for fields 2 to 6T, in large aperture bore (50 to 100mm)and lengths up to 10m

- Low field 2T magnets. The past experience has shown that the SC magnets have to use the maximum current capacity to reach a low cost per Tm. This presentation will not deal with the low field SC magnets.

Some considerations on magnet design





➢ Some considerations on magnet design

- We do not know the limits of the cosθ magnet design. They offer a good field quality in large apertures but can be limited by stresses maximum at the mid-plane. The pressure vary as :

$$P_\theta=-j.(R/2)[B_1+B_0.(r_2-R/r_2-r_1)+ B_0.(R^3-r_1^3)/3R^2(r_2-r_1)] \cos^2\theta$$

- At 15T, j=1500A/mm2,the e.m compressive stresses are 150MPa on the inner layer and 160MPa on the outer layer in a 88mm bore dipole. Moreover, the inner layer forces are transmitted to the external structure through the outer layer.

- $P_\theta \sim B_{coil}.j \sim K_{supra}$. The azimuthal pressure does not vary much with field in dipoles which use at the best the current carrying capacities.It is mainly depending on the superconductor characteristics.The azimuthal pressure is higher with Nb3Sn.

- To the e.m stresses, it has to be added the stresses due to the structure deflection $\sigma_{\theta,M}$ under the main horizontal forces which vary from 7MN/m to 15MN/m when the field goes from 12 to 15T. $\sigma_{\theta,M}$ is compression on the mid-plane,tension at the upper angle.
- At high field ,the mechanical structure has to be more rigid.
- NbTi magnets have more" nervous" cables and need a prestress which has to be added during by the assembly.The Nb3Snwindings,after reaction,are less reactive. They could need less pre-stress?
- The axial forces are as high as 1.8MN for a stored energy of 1.8MJ/m.

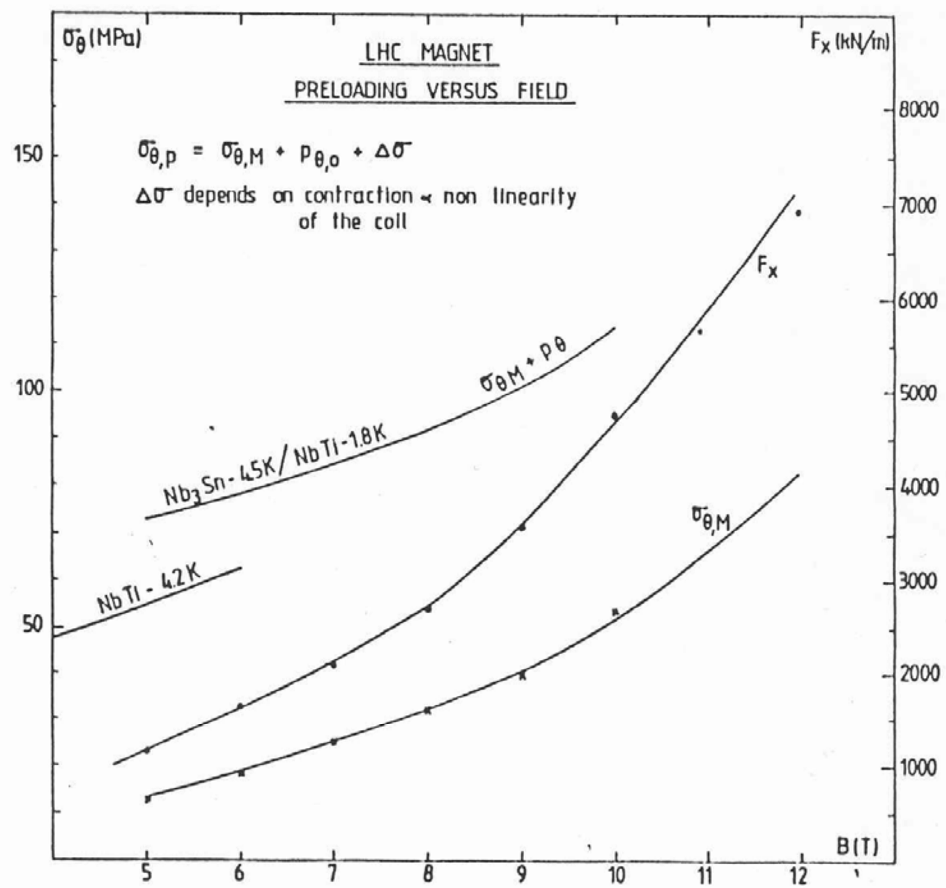
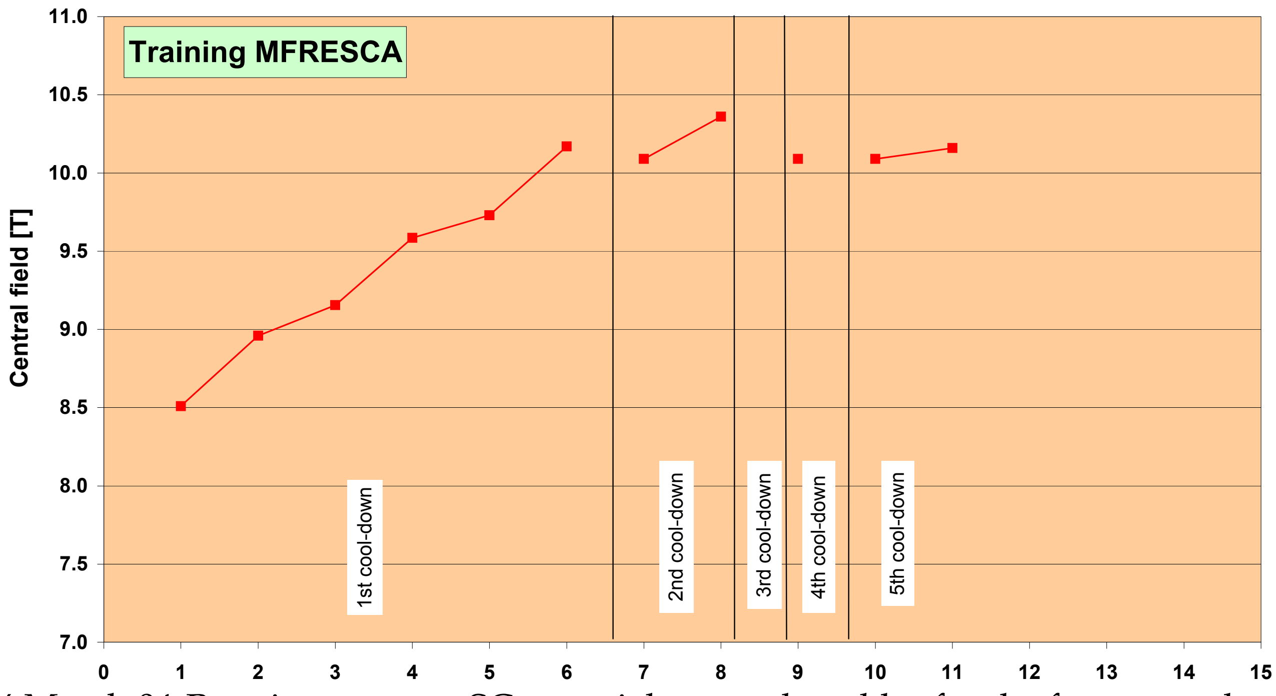


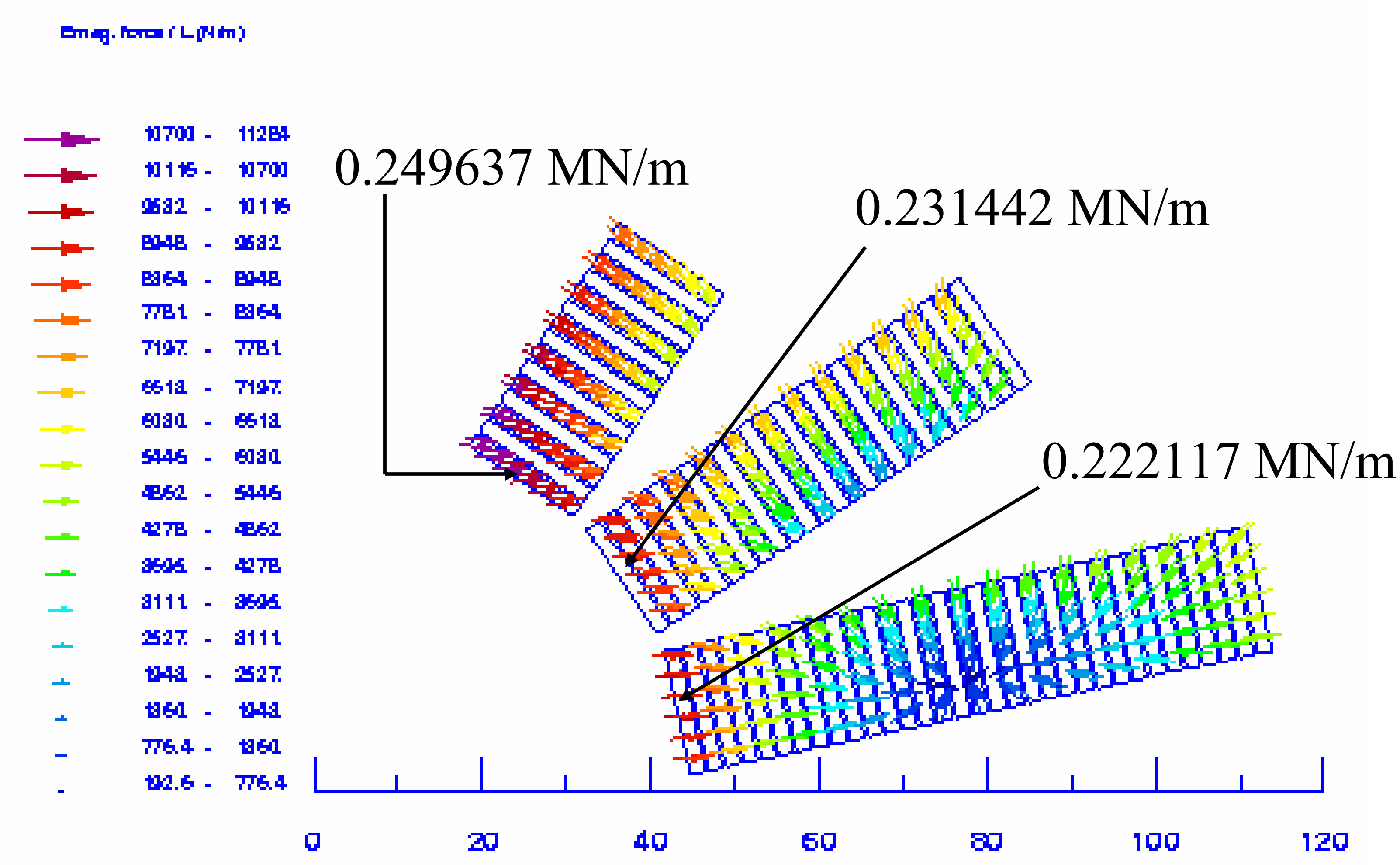
Fig. 8b - Horizontal resultant of the electromagnetic forces and preloading

Can we use the high current density in SC

- A 11T, Nb3Sn magnet has been built with success by Twente
- With NbTi at 1.9K,we have built ,in industry the magnet MFRESCA reaching the cable short sample limit like in (jc =1100A/mm2 at 11T,Fx=3.8MN/m).
- LBNL has built a magnet reaching 16T



MOTOR DESIGN: Is it worthwhile to look at other structures?.



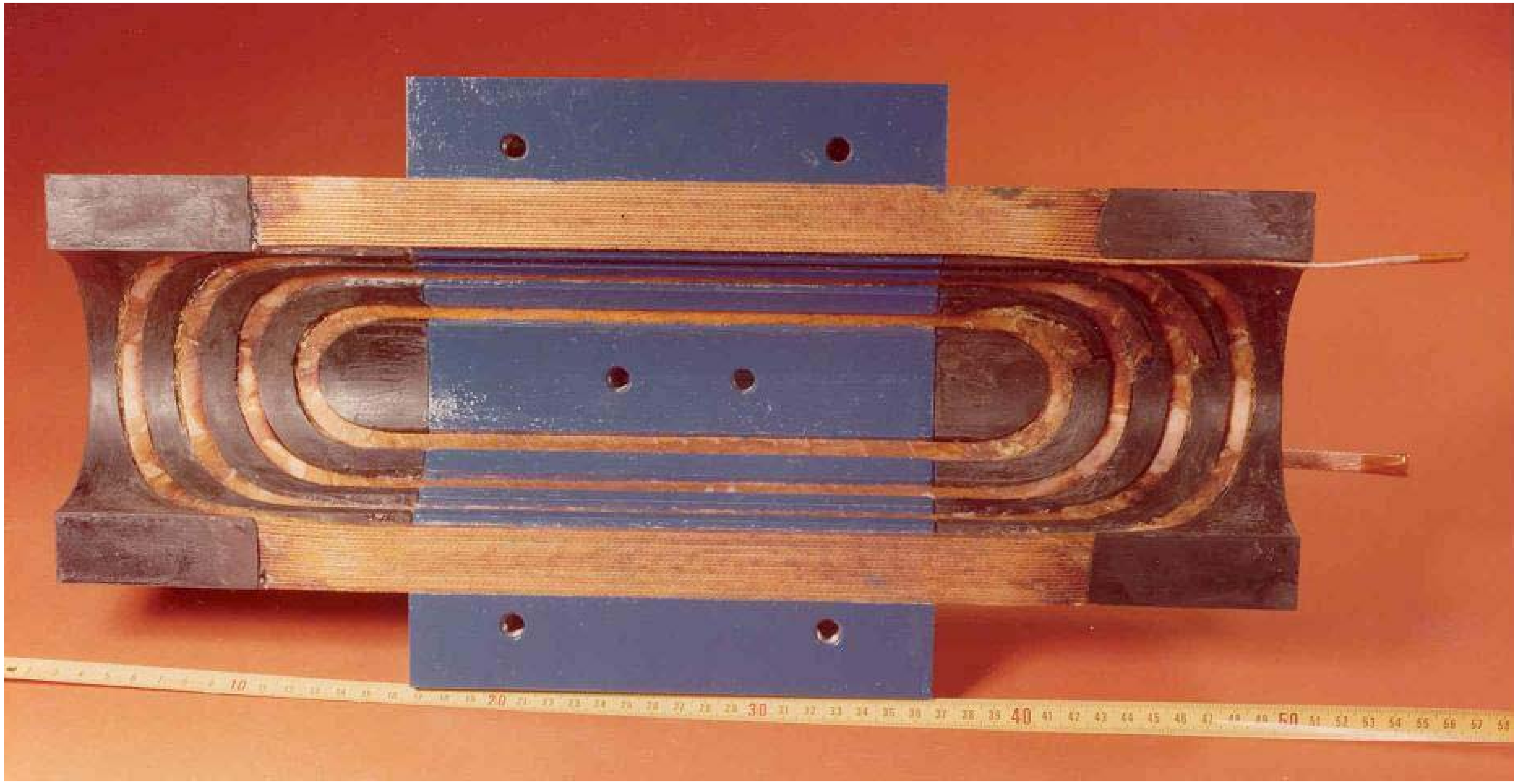
- This design already tested by J.Perot at Saclay.

- The compressive stresses applied **on rectangular cables of smaller width(14mm)** are around 150MPa.The moderated azimuthal stresses are sustained by a metallic structure closed to the winding .Bladders could be inserted if necessary.

- The distribution of field inside the coils make the magnet less sensitive to the inter-strand losses.

- The coil ends offer a real mechanical challenge to the designers.The hard bend could be tolerable with a cable having 87%filling factor.

- The NbTi cables needs prestress.The Nb3Sn are perhaps less demanding in prestress.



Motor type dipole made by J.Perot at Saclay

How to compensate the field harmonics for larger filament size

The Nb3Sn filaments have an effective diameter larger than 30 μm leading to high magnetization effects at low field. If we express the field components in the winding by:

$B_r=[B_1+B_0(r_2-R/r_2-r1)+B_0\ (R^3-r_1^3/3R^2(r_2-r_1)]\sin\theta$

$B_\theta=[B_1+B_0(r_2-R/r_2-r_1)-B_0\ (R^3-r_1^3/3R^2(r_2-r_1)]\cos\theta$

where $B_1$and B_0 are respectively the iron contribution and the coil contribution to the main field.

By inserting a paramagnetic material in the coil winding, it is then possible to generate magnetic currents which will be in opposition to the sc diamagnetic currents.

$\mathbf{j'_z=dM_\theta/dr - dMr/d\theta}$

At 5T,an iron wedge in the inner layer of the 15T magnet will still generate a sextupole of 25 units

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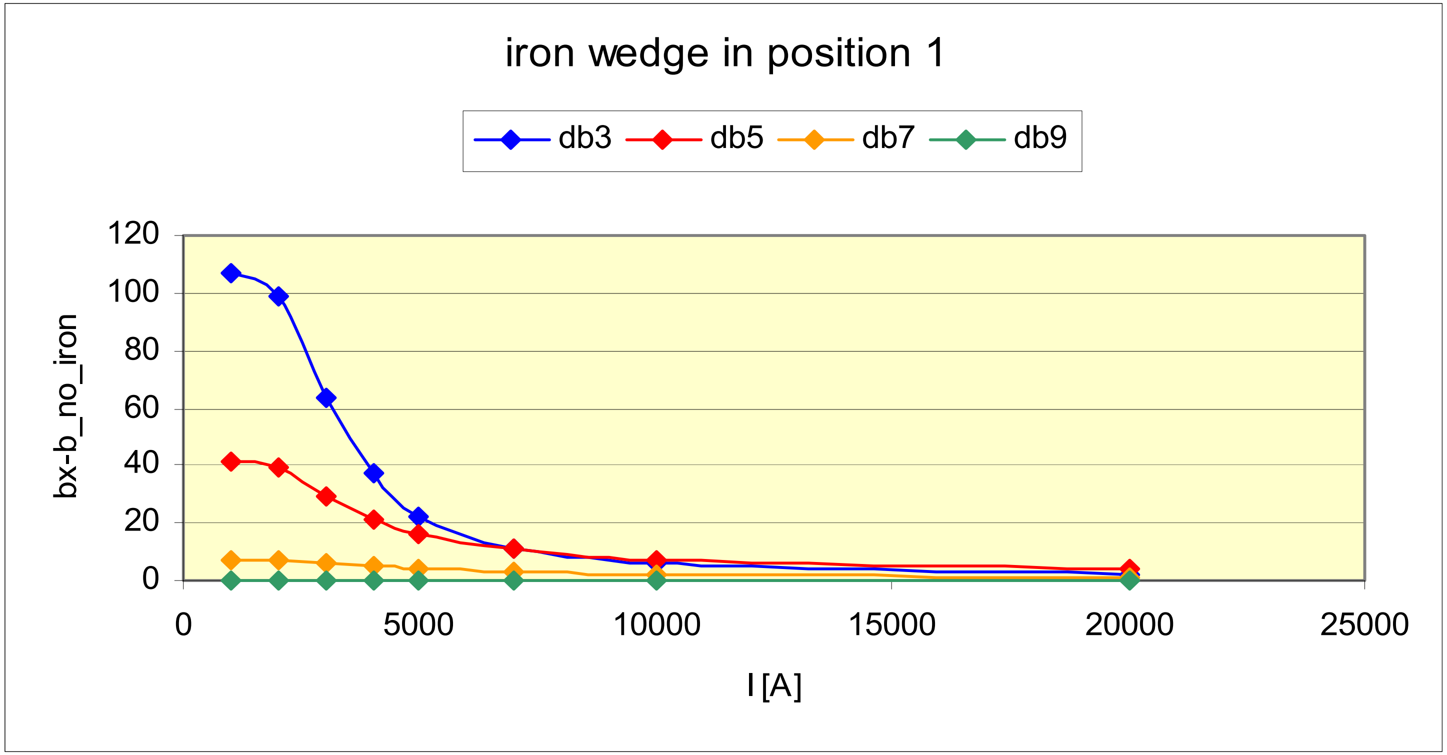


Multipoles due to iron wedge to compensate the diamagnetic effects
(apart from spool pieces)

SC MATERIALS

Axiome is that it is feasible to build a good magnet at a field X when a current density between 1000-2000A/mm2 is obtainable at the field X.

The Materials at our disposal for the programme until 2010 are the following:

Material	Max Field(T)	Status	Long magnets	AC
Nb3Sn	15-16	In good progress	To be proven with the 3% volume exp.	Rc
NbTi	10	Stable process	proven	suitable
NbTiTa	11-12	To be made	classical	suitable
HTS		R&D	?	?
MgB2		R&D	?	?

Other speakers will treat the material aspects.

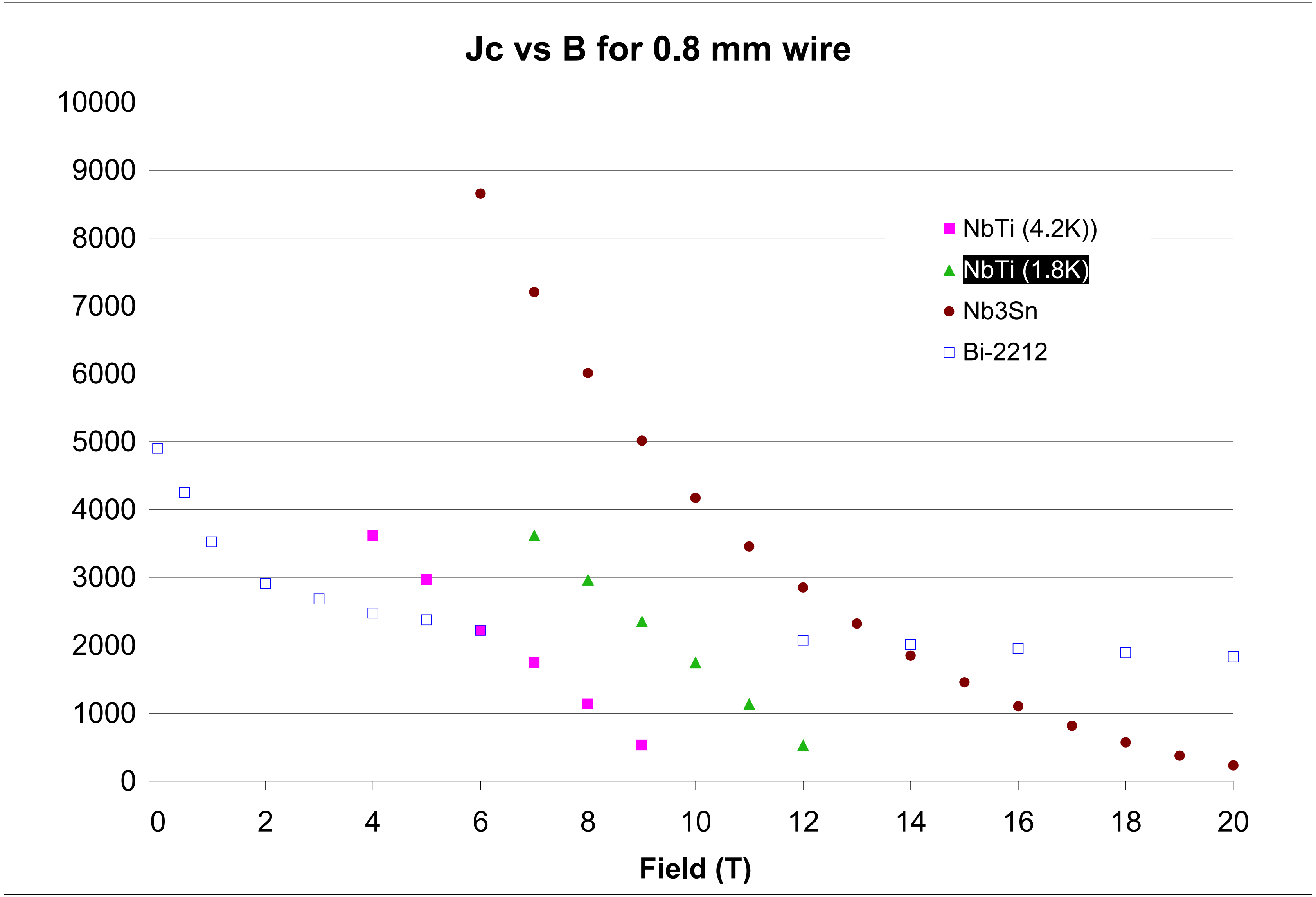
Critical current density

The values of critical current densities for the magnet design can be as shown in S.Gourlay plot:

NbTi **1200A/mm2 at 11T**

NbTiTa **1200A/mm2 at 12T (to be proven)**

Nb3 Sn **1500 A/mm2 at 15T,3000A/mm2 at 12T**


Jc vs B for 0.8 mm wire
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
2
4
6
8
10
12
14
16
18
20
Field (T)
NbTi (4.2K))
NbTi (1.8K)
Nb3Sn
Bi-2212

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INTER_STRAND RESISTANCE

The inter-strand resistance has a major impact on the ac losses. The cable losses vary with the square of the cable aspect ratio and are very important for wide flat cables (23mm for a 15T magnet)

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The values of Rc are governed by:

Coating material, strand deformation, coating rugosity , local pressure.

Coating Materials and Rc values

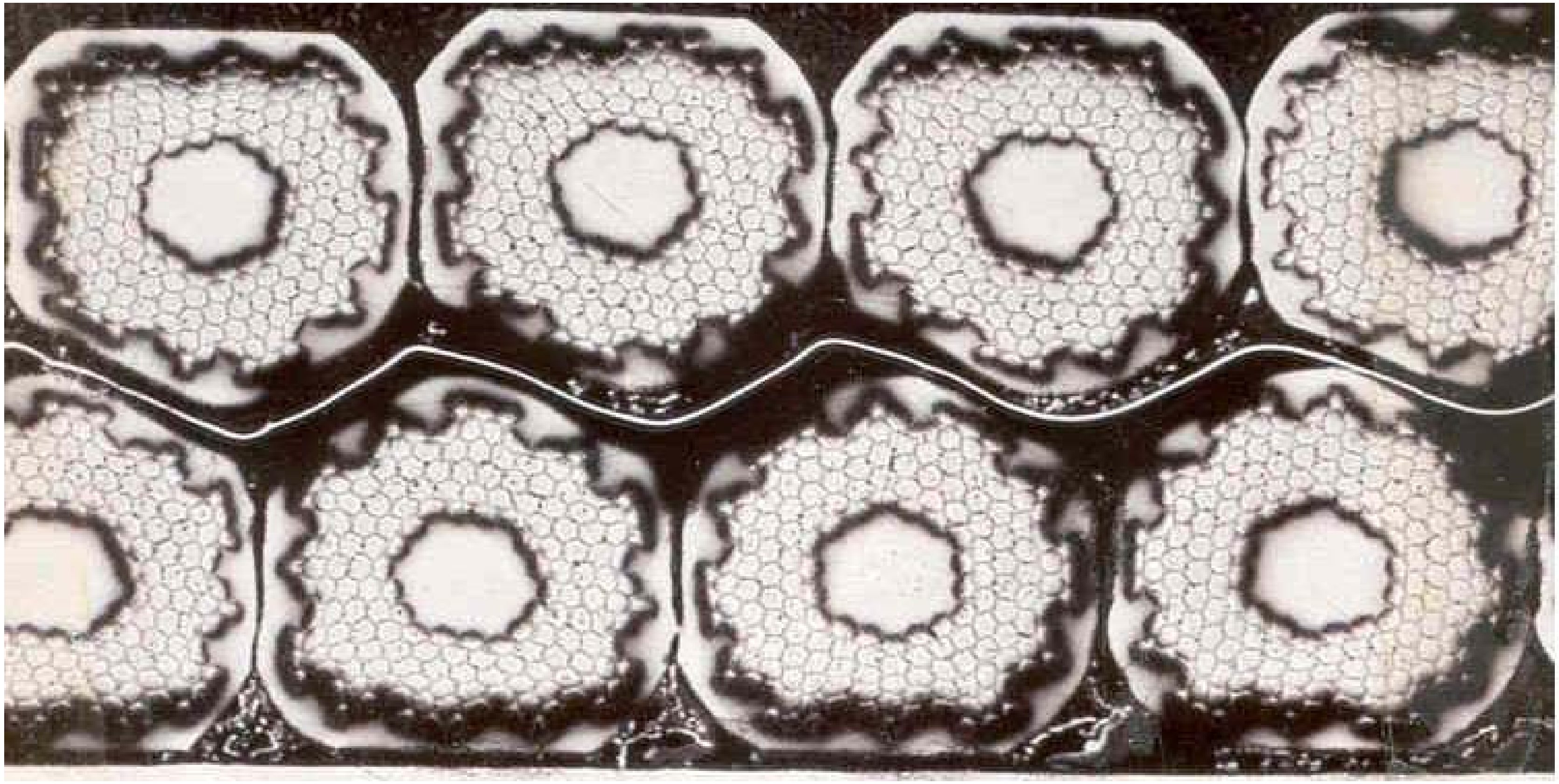
SnAg 10-50μΩ (after a cable heat treatment at 200 °C),not usable at 700°C

Sn Ni 100-500μΩ,could be used at 700°C

Ni 500-μΩ(Rutherford cable has been made)

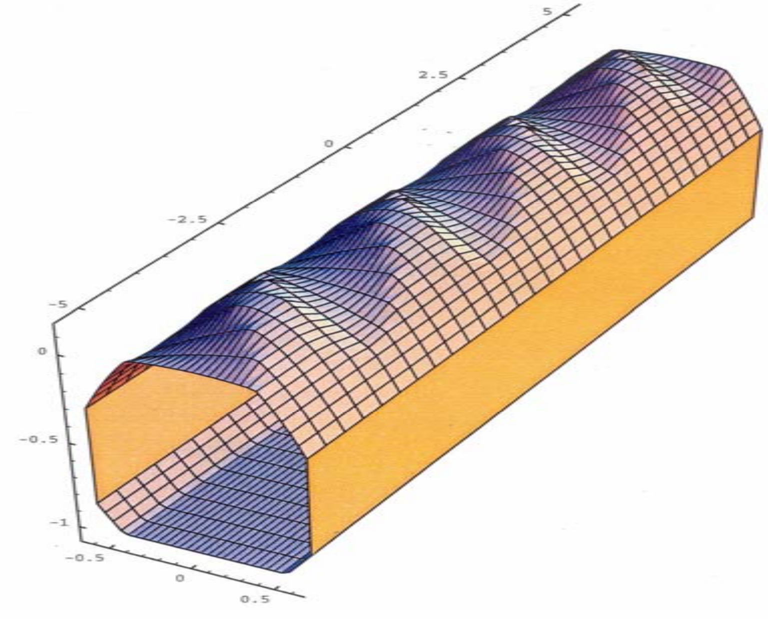
Cr 700μΩ(?)

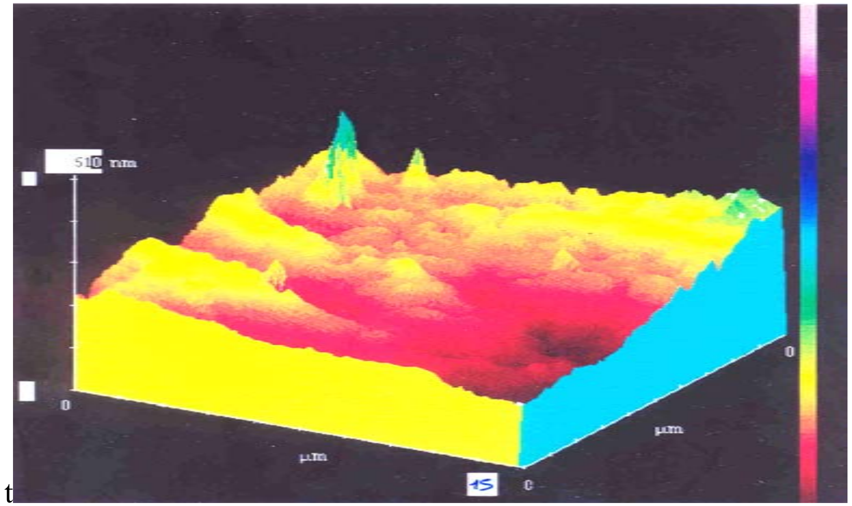
Cored cables Cables with a Stainless Steel or Ta core : 1Ω



$\mu\Omega.mm^2$

10	**SnAg**	**(soft coating ⇒ creeps)**
100	**SnNi**	
500	**Ni**	**(hard coating ⇒ cracks)**
	ZnNi	**(Ni oxidized preferentially to Zn)**
1000	**Ni+NiP**	
	Zn	**(thick oxide layer)**
10^4	**passived Zn**	**(Oxide layer)**
10^6	**Oxidized Cu**	





<u>strand deformation and surface topology</u>

AC MAGNET   RANGE 5T in 25 sec(0.2T/s)

Material :NbTi

They are like TEVATRON magnets,using a Zebra cable.

At CERN a magnet using a Rutherford cable impregnated with SnIn alloy to reduce the cable losses has been buit(5T in 25 sec).

The cooling is circulating sub-cooled helium.

Magnet technology known

AC magnet Range 5T/sec (e.g GSI)

Material:NbTi

Strand dimension :~ 0.8mm

Strand filament size: 3 μm in a copper matrix (The dominant origin of losses is the hysteresis losses). For finer filaments :CuMn matrix
Twist pitch 10-15 mm

Cored cables

Cooling by Cu drains or holes in insulation(GSI)

Needs high current (10-20kA) to reduce self-induction and reduces the impact on the mains for long machines.

Magnet technology known

DC high field magnets- up to 10.5 T

Material NbTi at 1.9K

Jc 1100 A/mm2 at 11T
Filament size 5-7 μm

Cable compaction 88-90%
3% of helium II allows for enthalpy

Known technology for the magnet constuction
.
At superfluid helium, losses up to 10mW/cm3 are accepted by the system

DC High field magnet - up to 12T

Material NbTiTa at 1.9K to be developed.

The material must be high homogeneity and is sensitive to the fabrication process. No real systematic attempt has been conclusive to obtain high Jc(after Mc Inturff&Larbalestier)

Jc 1200 A/mm2 at 1.9K

Filament size 5-7μm

Cable as for NbTi at 1.9K

Known technology for the magnet constuction.
At superfluid helium, losses up to 10mW/cm3 are accepted by the system

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DC high field magnet at 4.2K range 15-16T
Material : Nb3Sn ITD , Nb3Sn PIT

Raw Material :NbTa,NbTi Barriers Nb,Ta

Jc 1500A/mm2 at 15 T,3000A/mm2 at 12T

Final filament size : 40-50μm to avoid flux jumps.Process to reach >24% Sn homogenous over the reacted cross-section

Copper matrix with a fine sub-division for dynamic stability,

Cu/Sc >1.25 for magnet protection RRR copper >70(annealing of strands)

Magnet needs quench heaters for quench distribution on the coils

Volumic expansion at reaction of 3%. Cable before reaction should have a reduced compaction to reduce effect on cable mid-thickness
Temperature margin: at 13T :1.4K at 12T :2.6K

- **Conclusions**
- The conclusions refer to the quenching magnet field.The operation field has to take into consideration oter factors like beam losses,..
- The tools exist for the design of magnets for the future needs.
- The tools exist for the calculations of the strand and cable characterics effect on the magnets.
- The NbTi material is well known and is usable for magnets up to 10.5T.
- The NbTiTa material should be developped to gain 1T and build long magnets with a known technology.

- The Nb3Sn has made enormous progress thanks to the efforts in USA.

- Field up to 16T has been reached.We sould be able to build large bore magnets with Nb3Sn in the range 12-16T following the wind and react route.The construction of long magnets is still challenging.