HFM

High Field Magnets Programme

HFM Forum

First Thoughts about a 4-layer Cos-theta Design

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Date: 30 May 2024

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INFN-CERN agreement proposal

- The INFN-CERN agreement proposal has been launched in the Nov. 2023 HFM general meeting
- Discussion for details is currently underway
- It will include, among other activities, the study and construction of a demonstrator **cos-theta dipole** for FCC-hh, to **14 T** field level
- The **INFN** activities are carried out in collaboration between **Milano** and **Genova**
- The construction will be realized in the new infrastructure at LASA of IRIS program (Supercond. Magnet Lab. - **SML**)

INFN-CERN agreement proposal

The proposal is a 6 years program with the following milestones:

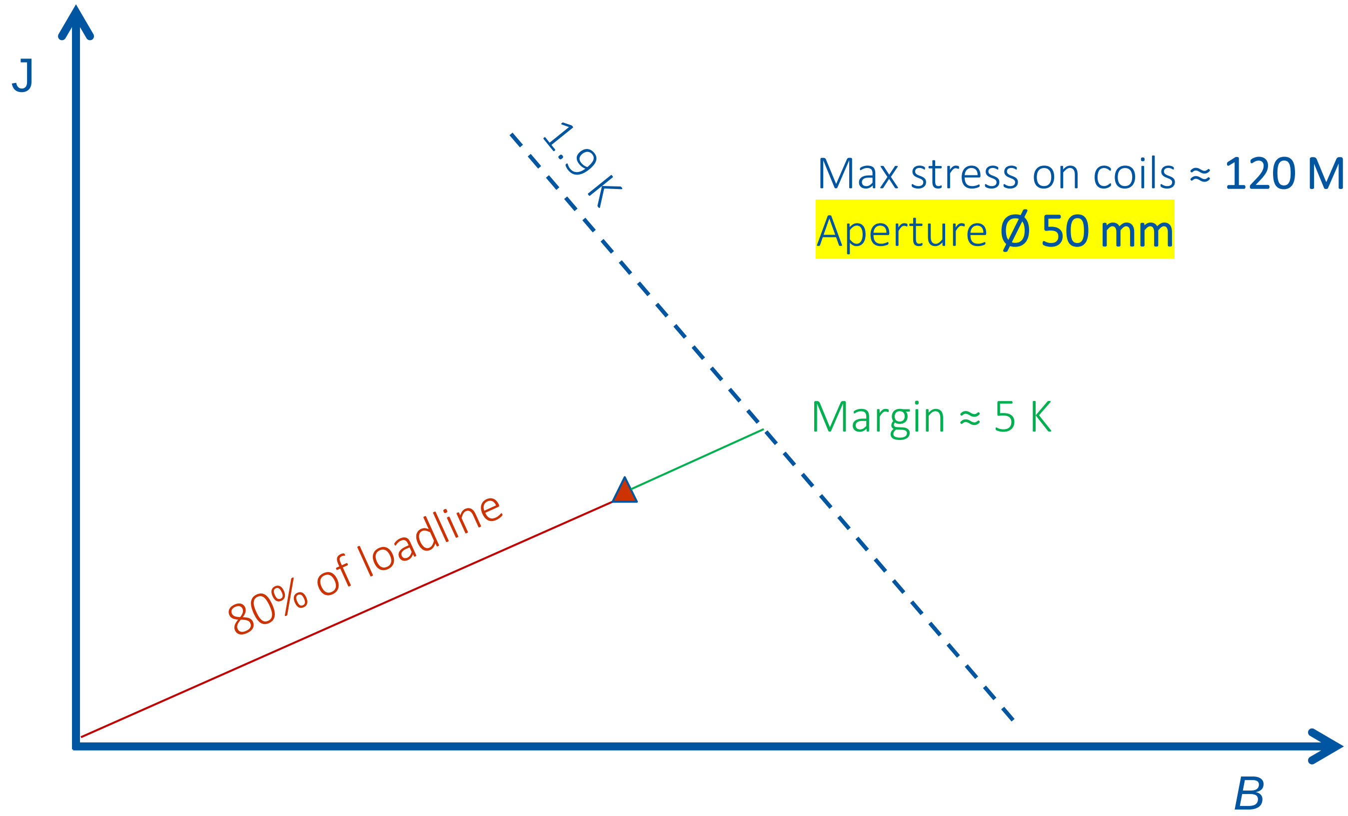
Milestones	**Months after agreement start**
Electromagnetic design and conductor choice	M6
Technical design report	M12
Coil engineering design report	M18
Winding test completion and tooling assessment	M24
Coil construction readiness review	M30
Manufacture of 1 dummy (copper) coil	M36
Magnet engineering design report	M42
Manufacture of 1 Nb_3Sn practice coil	M48
Manufacture of 2 Nb_3Sn coils	M54
Magnet assembly	M60
Manufacture of additional 2 Nb_3Sn coils	M66
Cold test at LASA at 4.5 K	M66
Cold tests at CERN with test report in collaboration with CERN	M72

INFN-CERN agreement proposal

- The e.m. preliminary design study has already started at LASA
  Master’s thesis – G. Attanasio
- The mechanical design is not considered in this study
  but reasonable assumptions are taken
- The target and criteria are coherent with HFM program
  see next slides

Technical requirements for dipoles

The HFM target is to fabricate dipoles of **14 T**

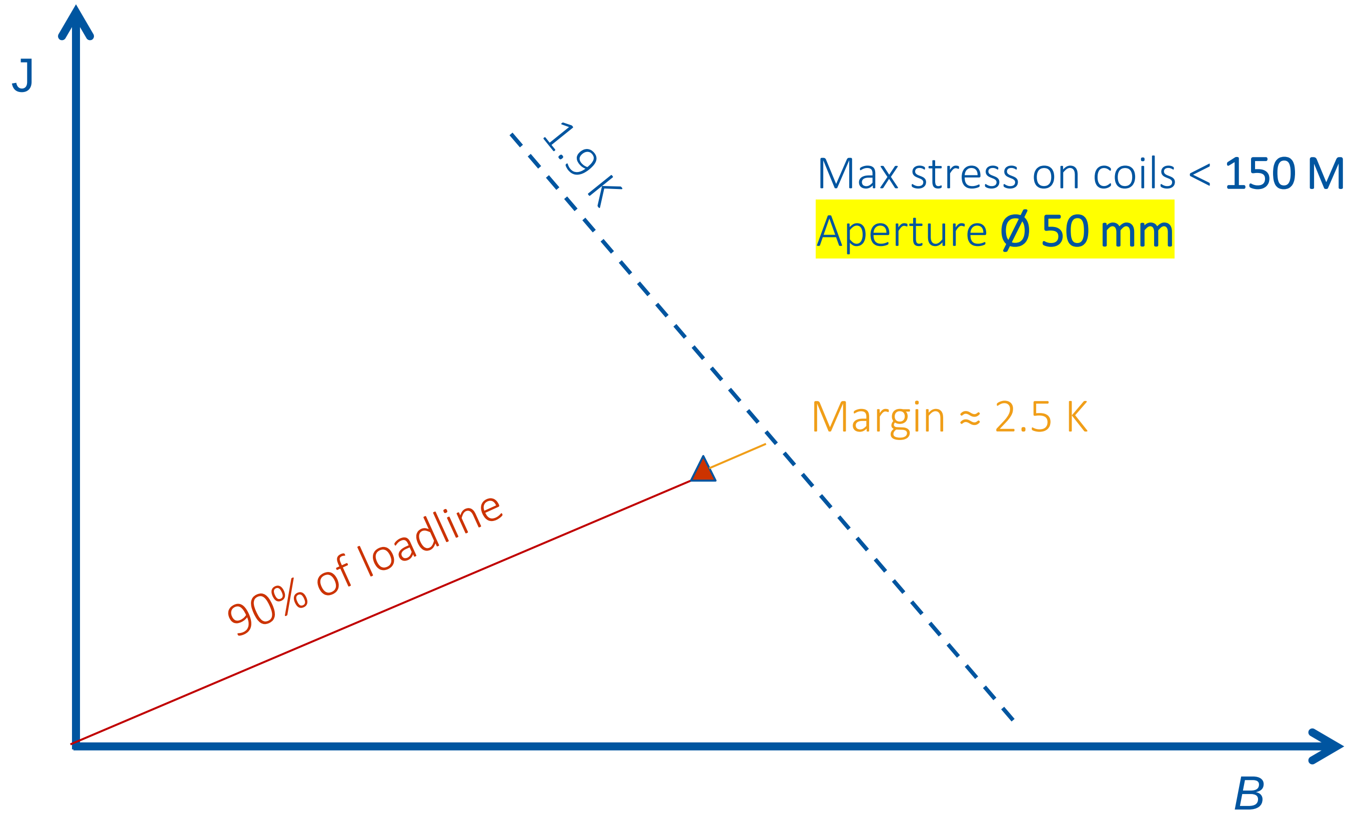


Max stress on coils ≈ **120 Mpa**

Aperture **Ø 50 mm**

Technical requirements for dipoles

Extra feature: explore the performance towards **16 T**



Max stress on coils < **150 Mpa**
Aperture **Ø 50 mm**

Technical requirements for dipoles

From analytic analysis with 60° sector coil
if we use Nb_3Sn ($J_{overall} \approx 400$ A/mm^2)

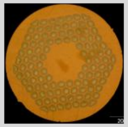
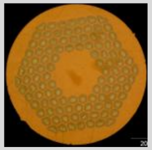
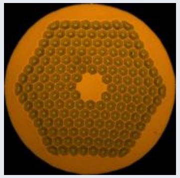
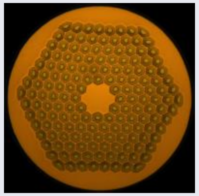
→ We need an equivalent coil width ≈ **50 mm**

(see E. Todesco, https://indico.cern.ch/event/915752/)

Possible Solution: 4-layer cos-theta (most efficient)

HFM Nb_3Sn conductor specs

RRP® Wire available for HFM programme

	HL-LHC		HFM	
	11 T dipole	**MQXF**	**ERMC-1**	**DEM-1.1**
				
Diameter (mm)	0.7	0.85	1.0	1.1
Layout	108/127		162/169	
d_s (µm)	45	54	58	64
Cu/non-Cu	1.15 ± 0.1	1.2 ± 0.1	0.9 ± 0.2	
Nb:Sn	3.6 (reduced Sn)		3.4 (standard Sn)	
Heat treatment	650 °C 50 h	665 °C 50 h	650 °C 50 h	665 °C 50 h

S. C. Hopkins et al.
doi: 10.1109/TASC.2023.3254497

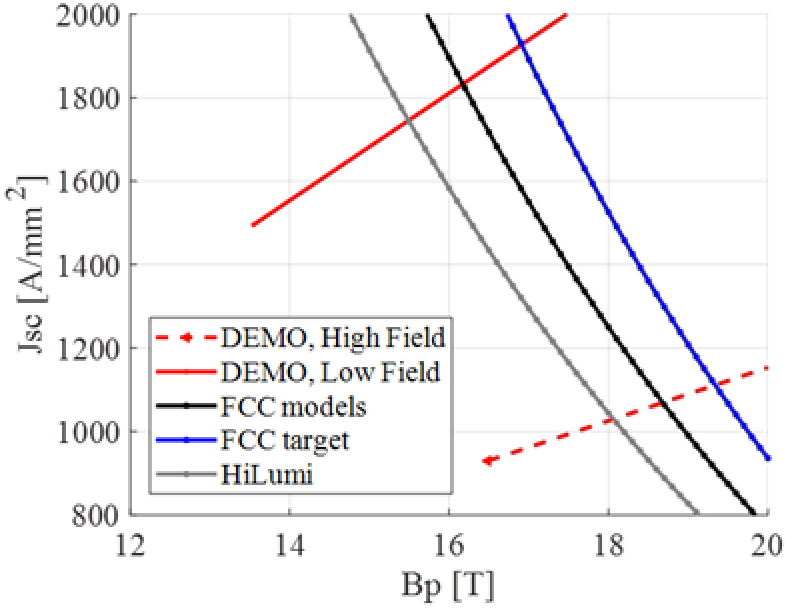
HFM Nb_3Sn conductor specs

Info received from A. Haziot

$$B_{c2}(T) = B_{c20} \cdot (1 - t^{1.52})$$

$$J_C = \frac{C(t)}{B_p} \cdot b^{0.5} \cdot (1 - b)^2$$

$$C(t) = C_0 \cdot (1 - t^{1.52})^{\alpha} \cdot (1 - t^2)^{\alpha}$$



	Hi-Lumi	FCC models	FCC target	HFM
T_{c0} (K)	16	16	16	16
B_{c20} (T)	29.38	28.8	29.38	29.38
α	0.96	0.96	0.96	0.96
$C_0 (A/mm^2T)$	188870	255230	275880	214462

J_c at 4.2 K	Hi-Lumi	FCC models	FCC target	HFM
12 T	2450	2880	3600	2800
16 T	1058	1236	1545	1200

Past examples of 4-layers magnet

Parameter	HF	LF
Strand diameter (mm)	0.750	0.480
N strands	37	47
Cu/No_Cu	0.43	1.00
Critical current density (A/mm^2)	515 (13.5 T, 4.22 K)	1519 (10.5 T, 4.22 K)
Overall current density (A/mm^2)	250	450
Cable width (mm)	14.45	11.63
Eq. coil width (mm)	44.8	
Cable mid thickness (mm)	1.369	0.873
Keystone angle (°)	0.000	0.000
N. turns	42	96
N. blocks	7	6

E. Todesco
https://indico.cern.ch/event/926968/

LBNL – D20 (1997)

Max Bore field

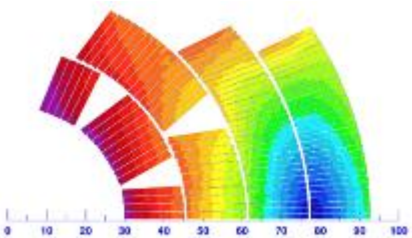
13.5 T @ 1.8 K

A. D. McInturff et al.
doi: 10.1109/PAC.1997.753158

Past examples of 4-layers magnet

Parameter	LF	HF
Strand diameter (mm)	1.0	0.7
N strands	28	40
Cu/No_cu	1.13	1.13
Critical current density (A/mm^2)	1500 (15 T, 4.22 K)	1500 (15 T, 4.22 K)
Overall current density (A/mm^2)	330	440
Cable width (mm)	15.10	15.10
Eq. coil width (mm)	52.3	
Cable mid thickness (mm)	1.870	1.319
Keystone angle (°)	0.805	0.805
N. turns	44	65
N. blocks	5	2

E. Todesco
https://indico.cern.ch/event/926968/



FNAL – MDPTC1 (2021)

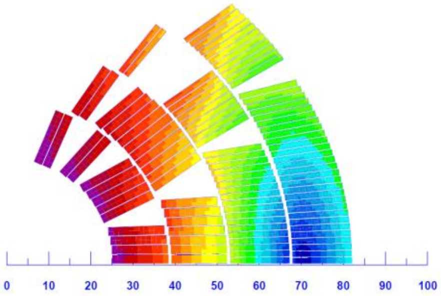
Max Bore field

14.5 T @ 1.9 K

A. V. Zlobin et al.,
doi: 10.1109/TASC.2021.3057571

Past examples of 4-layers magnet

Parameter	LF	HF
Strand diameter (mm)	1.1	0.7
N strands	22	38
Cu/No_cu	0.8	2.1
Critical current density (A/mm²)	High Performance 1500 (16 T, 4.22 K)	
Overall current density (A/mm²)	378	513
Cable width (mm)	13.2	14
Eq. coil width (mm)	48.3	
Cable mid thickness (mm)	1.870	1.319
Keystone angle (°)	0.5	0.5
N. turns	32	68
N. blocks	7	5



16 T EuroCircol study – INFN option (2019)

Bore field

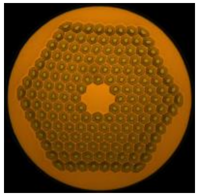
16 T @ 1.9 K

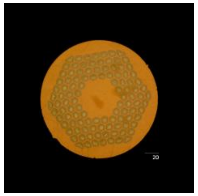
FCC-hh Conceptual Design Report,
https://doi.org/10.1140/epjst/e2019-900087-0

First studies on 4-layers magnet configurations – strand size

The best choice for grading is **Ø 1.1 mm** (HF) and **Ø 0.7 mm** (LF)
(from EuroCircol experience)

→ Already available in HFM

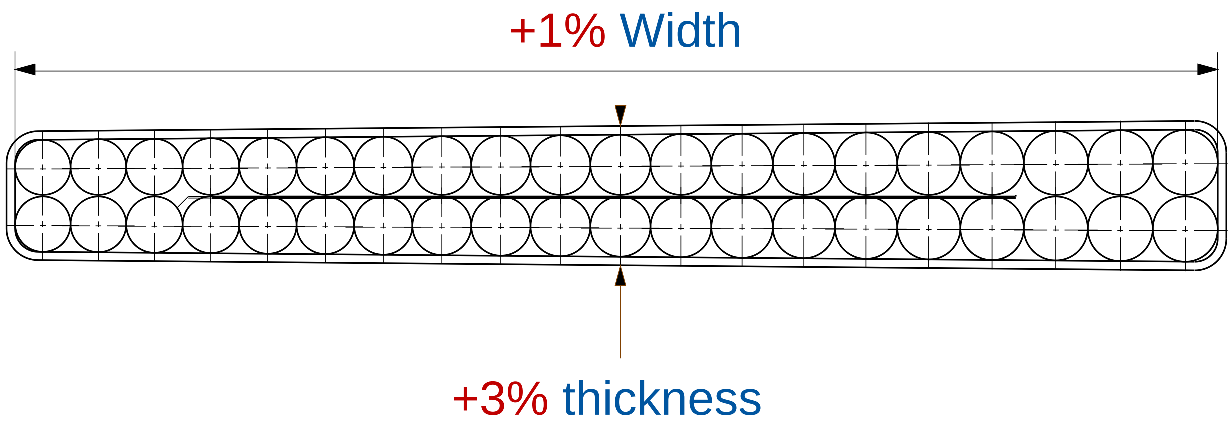




	High Field	Low Field
Diameter (mm)	1.1	0.7
Layout	162/169	108/127
d_s (µm)	64	45
Cu/non-Cu	0.9 ± 0.2	1.15 ± 0.1
Nb:Sn	3.4 (standard Sn)	3.6 (reduced Sn)
Heat treatment	665 °C 50 h	650 °C 50 h
J_c @16 T, 4.2 K (A/mm²)	1200	1058

First studies on 4-layers magnet configurations – HT cable expansion

- We design the cross-section considering the cable size increasing after heat treatment
  N. Andreev et al, https://doi.org/10.1063/1.1472635
- We set **guess values** based on Hi-Lumi experience
  D. Schoerling and A. V. Zlobin. Nb3Sn Accelerator Magnets: Designs, Technologies and Performance. Springer Nature, 2019.



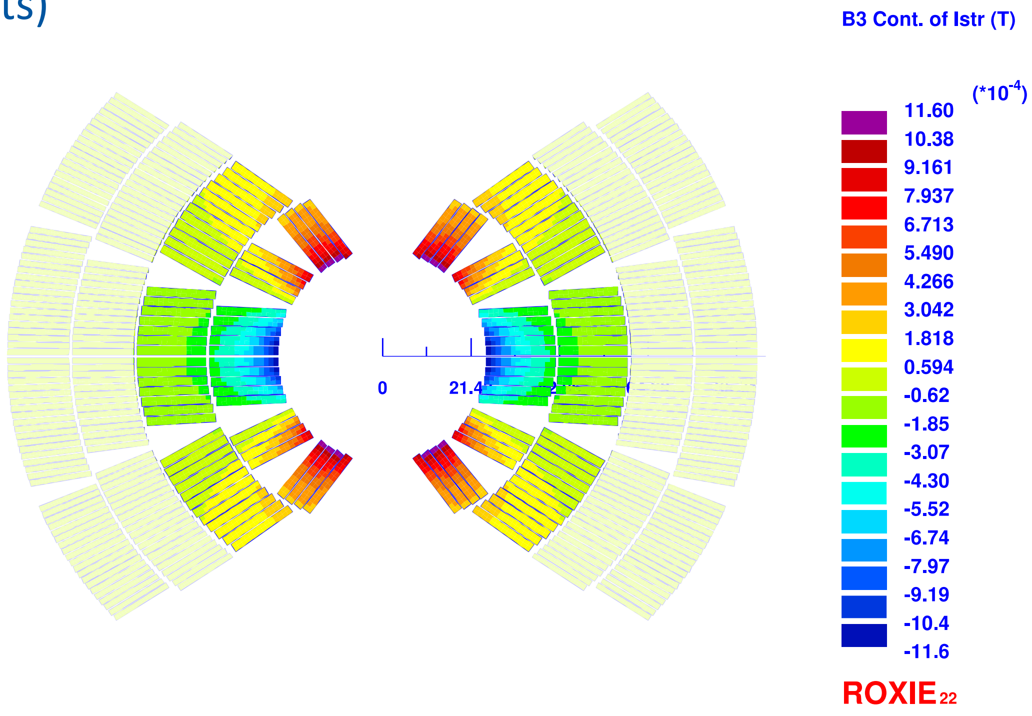
First studies on 4-layers magnet configurations – Cable design

	HF (layers 1-2)	**LF** (layers 3-4)
N° of strands	26	40
Strands diameter [mm]	1.1	0.7
Cu/Sc	0.9	1.15
Width [mm]	15.862	15.141
Inner thickness [mm]	1.911	1.216
Outer thickness [mm]	2.047	1.346
Keystone angle [°]	0.5	0.5
Insulation thick radial [mm]	0.150	0.150
Insulation thick azimuthal [mm]	0.150	0.150
Insulated cable filling factor [%]	35.40	29.44

Cables have to be considered bare and already reacted.

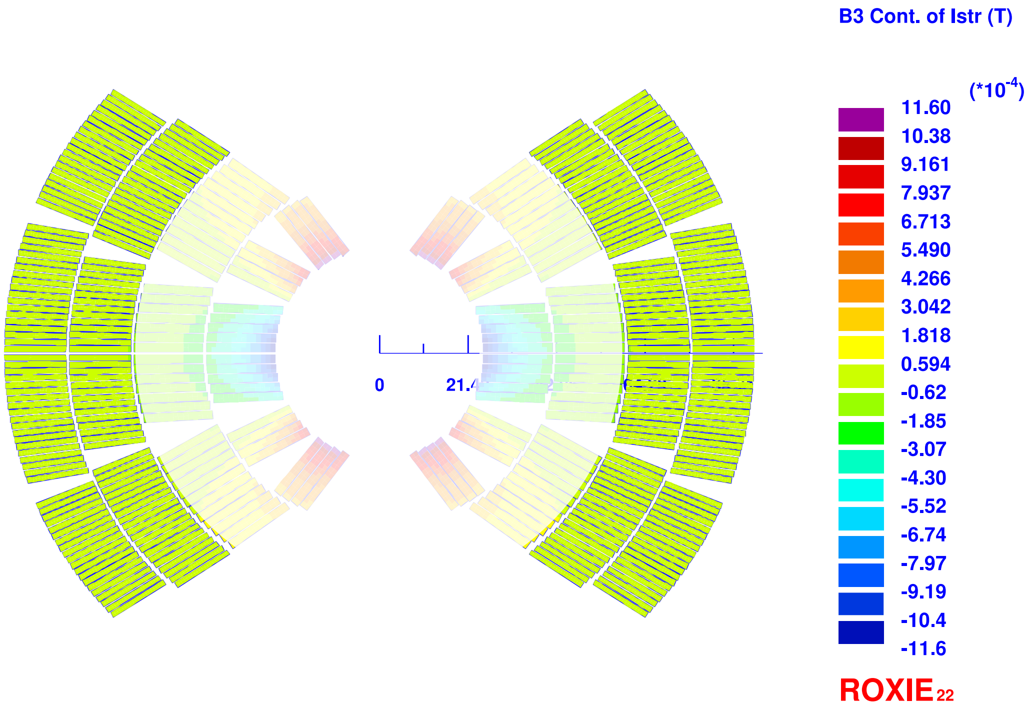
First studies on 4-layers magnet configurations – Optimization strategy

- The 1st and 2nd layers define the field quality
- Promising configurations are with 3 or 4 blocks in the 1° layer (as in the past magnets)



First studies on 4-layers magnet configurations – Optimization strategy

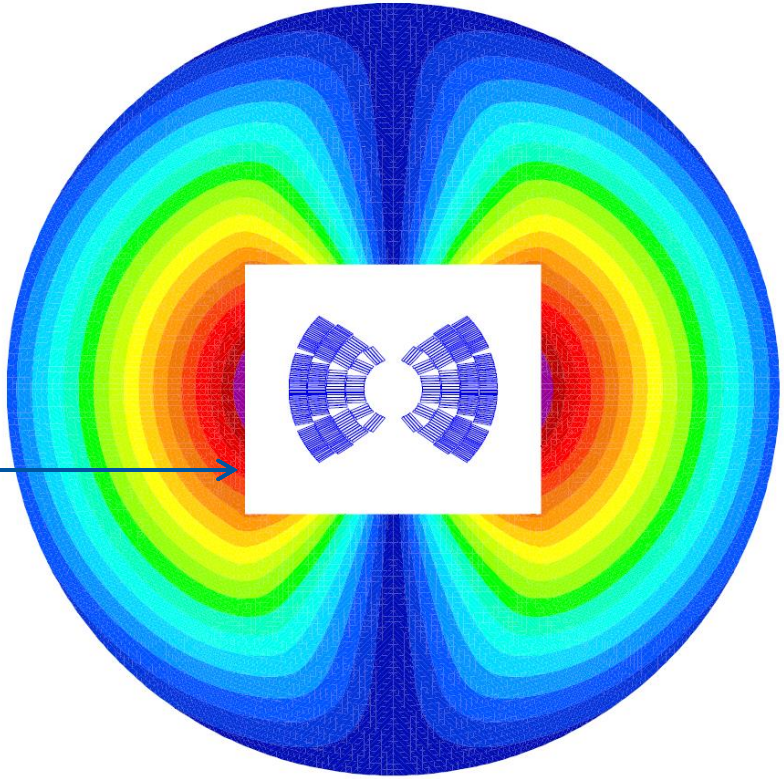
- The 3rd and 4th layers increase the bore field
  → few big blocks



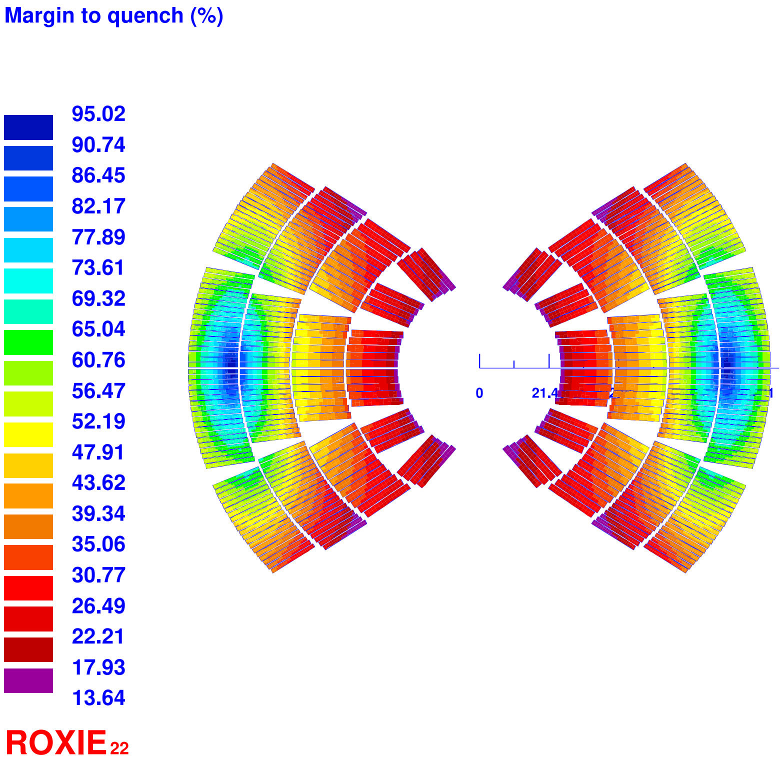
First studies on 4-layers magnet configurations – Iron yoke

The yoke is designed to set up the **bladder and key system**

Flat interfaces between iron and pads



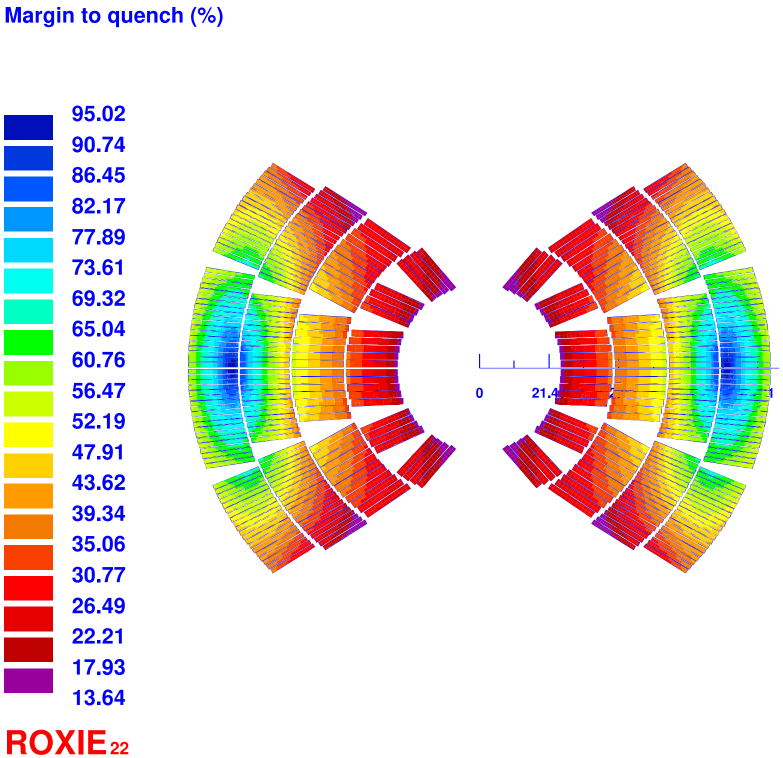
First studies on 4-layers magnet configurations – Case A (3 blocks IL)



Bore field 14 T	**HF**	**LF**
Peak field [T]	14.35	12.05
Temperature [K]	1.9	
j overall [A/mm^2]	273	412
j sc [A/mm^2]	774	1405
Loadline fraction [%]	77	79
Temperature margin [K]	4.99	4.66
Equivalent width [mm]	54.5	
N° of turn *(per quadrant)*	32	74

- The lower margin is on LF cable → fully exploited ($J_{overall}$ 412 A/mm^2)
- The HF cable is not fully exploited → strand number could be reduced from 26 to 24 (discarded to keep margins)

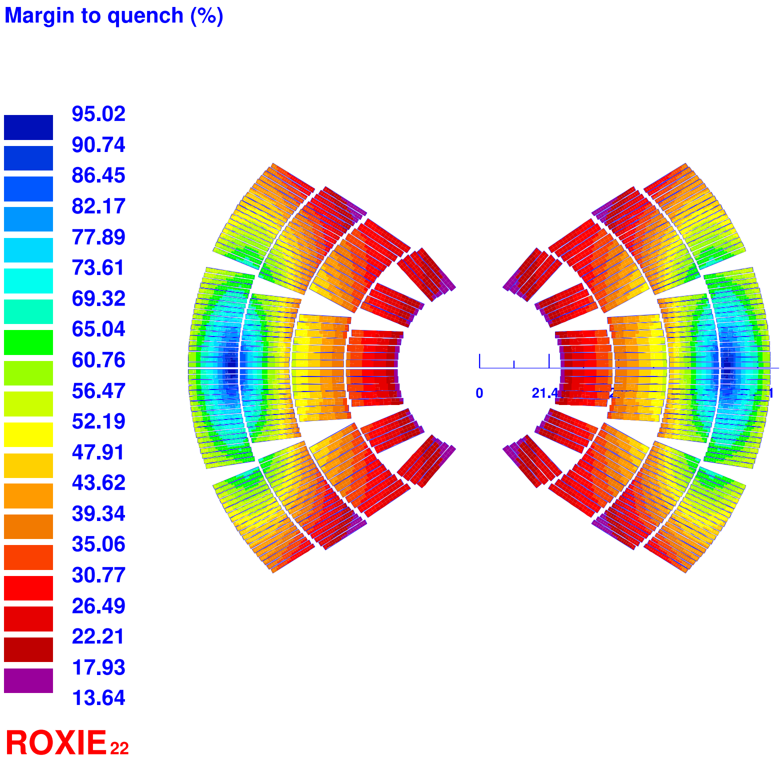
First studies on 4-layers magnet configurations – Case A (3 blocks IL)



Bore field 14 T	HF	LF
Peak field [T]	14.35	12.05
Temperature [K]	4.2	
j overall [A/mm^2]	273	412
j sc [A/mm^2]	774	1405
Loadline fraction [%]	84	86
Temperature margin [K]	2.69	2.36
Equivalent width [mm]	54.5	
N° of turn *(per quadrant)*	32	74

The margins are still safe at 4.2 K

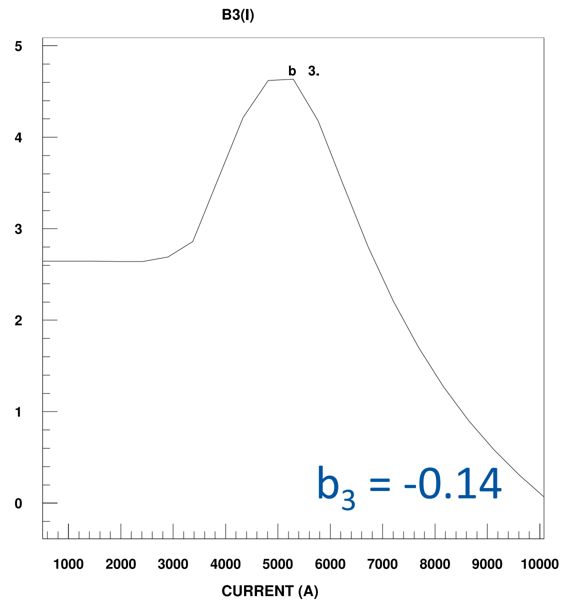
First studies on 4-layers magnet configurations – Case A (3 blocks IL)

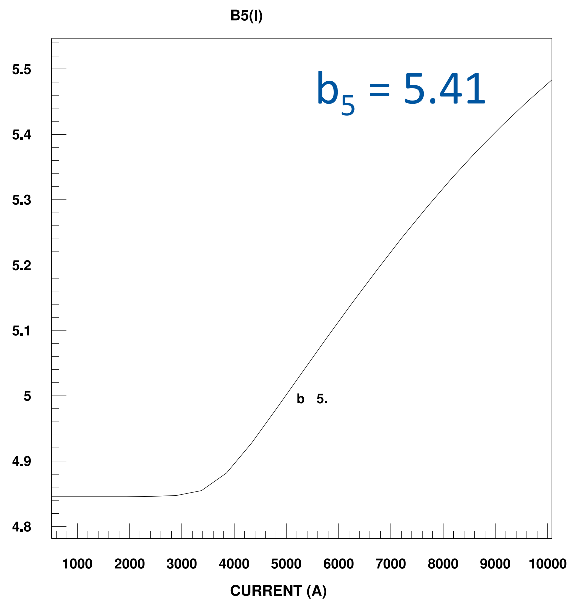


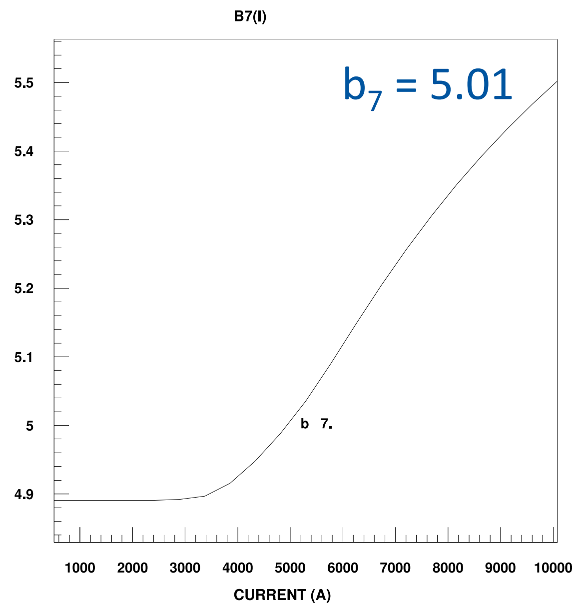
Bore field 15.8 T	**HF**	**LF**
Peak field [T]	16.21	13.68
Temperature [K]	**1.9**	
j overall [A/mm^2]	310	467
j sc [A/mm^2]	877	1594
Loadline fraction [%]	87	90
Temperature margin [K]	3.23	2.69
Equivalent width [mm]	54.5	
N° of turn *(per quadrant)*	32	74

Max. loadline working point at 90% (LF) → Bore field 15.8 T

First studies on 4-layers magnet configurations – Case A (3 blocks IL)

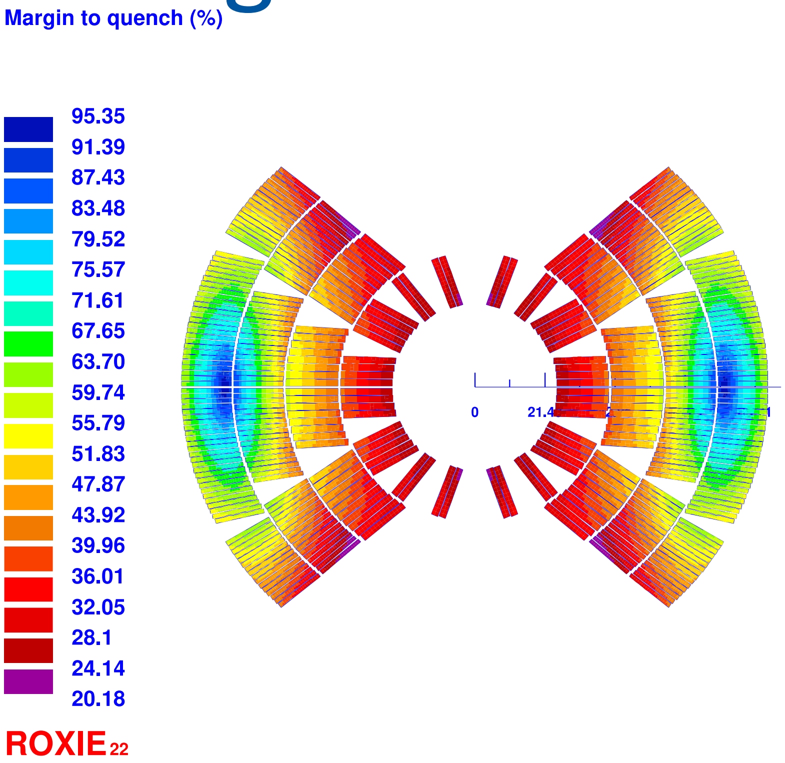






Inner layer with 3 blocks → more challenging to improve field quality

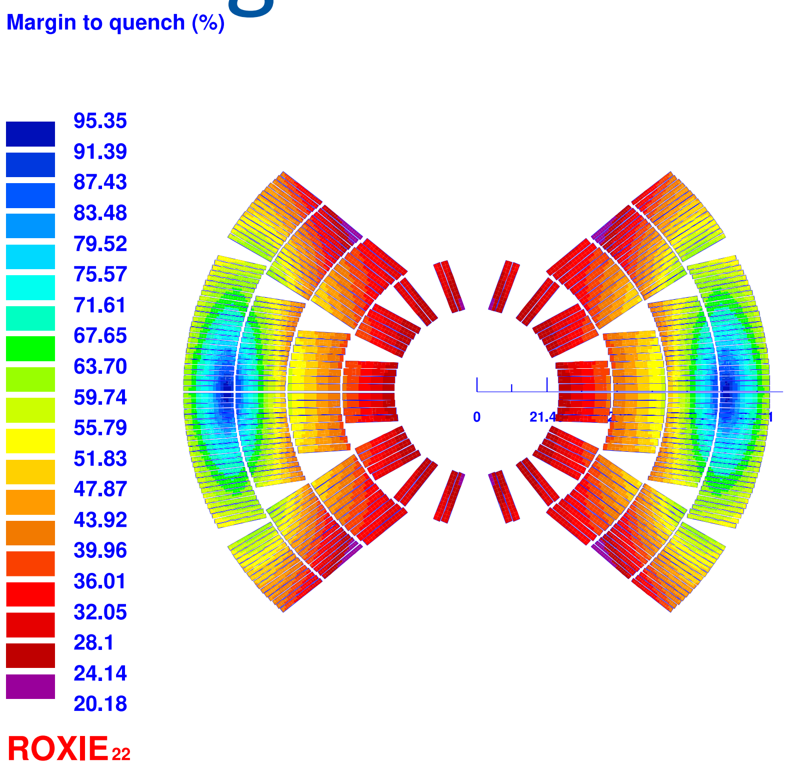
First studies on 4-layers magnet configurations – Case B (4 blocks IL)



Bore field 14 T	HF	LF
Peak field [T]	14.33	12.17
Temperature [K]	1.9	
j overall [A/mm^2]	348	409
j sc [A/mm^2]	768	1395
Loadline fraction [%]	77	80
Temperature margin [K]	5.02	4.57
Equivalent width [mm]	55.4	
N° of turn *(per quadrant)*	32	77

- The lower margin is on LF cable → fully exploited ($J_{overall}$ 409 A/mm^2)
- The HF cable is not fully exploited → strand number could be reduced from 26 to 24 (discarded to keep margins)

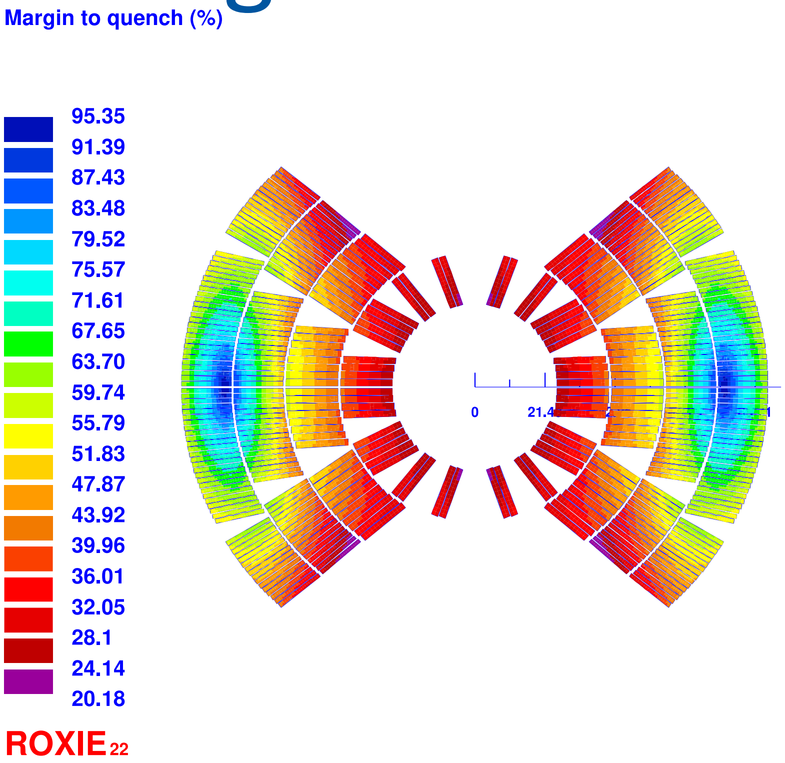
First studies on 4-layers magnet configurations – Case B (4 blocks IL)



Bore field 14 T	HF	LF
Peak field [T]	14.35	12.05
Temperature [K]	4.2	
j overall [A/mm^2]	273	412
j sc [A/mm^2]	774	1405
Loadline fraction [%]	84	87
Temperature margin [K]	2.72	2.27
Equivalent width [mm]	54.5	
N° of turn *(per quadrant)*	32	74

The margins are still safe at 4.2 K

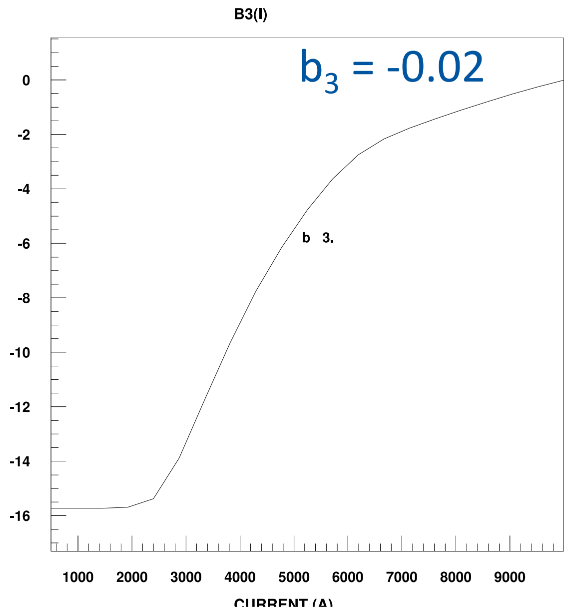
First studies on 4-layers magnet configurations – Case B (4 blocks IL)

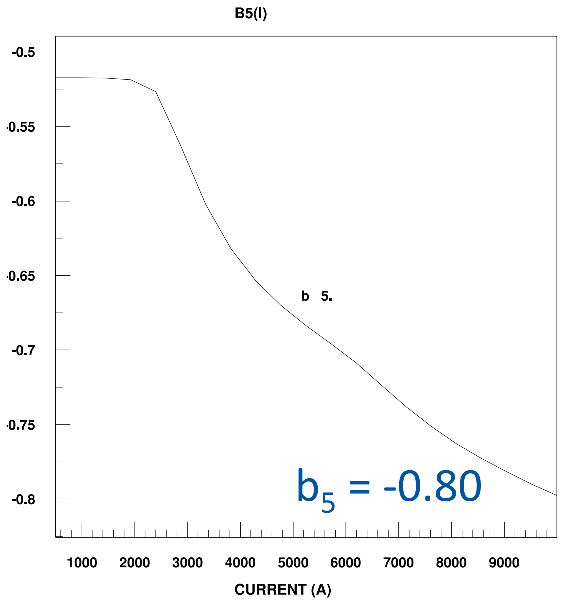


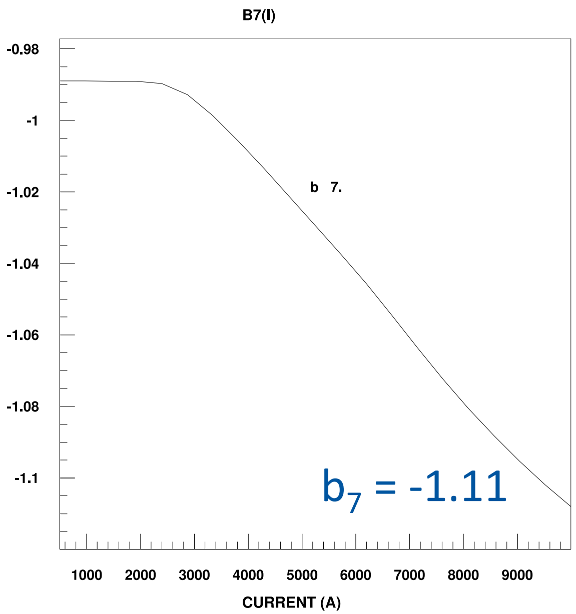
Bore field 15.7 T	**HF**	**LF**
Peak field [T]	16.12	13.68
Temperature [K]	1.9	
j overall [A/mm^2]	309	467
j sc [A/mm^2]	876	1591
Loadline fraction [%]	86	90
Temperature margin [K]	3.31	2.69
Equivalent width [mm]	54.5	
N° of turn *(per quadrant)*	32	74

Max. loadline working point at 90% (LF) → Bore field 15.7 T

First studies on 4-layers magnet configurations – Case A (3 blocks IL)

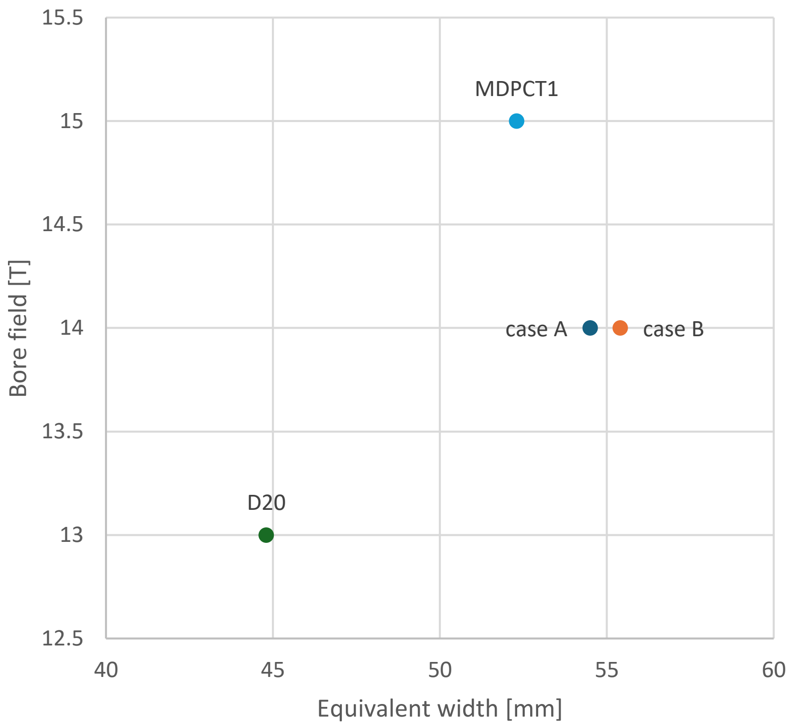


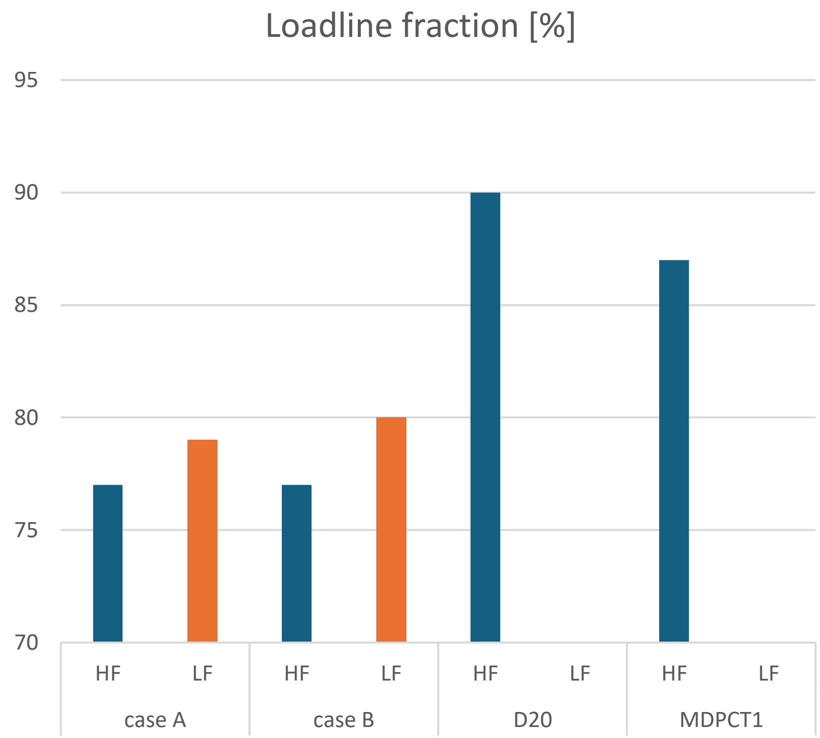




Inner layer with 4 blocks → easy to improve field quality

First studies on 4-layers magnet configurations – recap





The equivalent coil width is larger to have more margin

First studies on 4-layers magnet configurations – recap

	case A		case B		D20		MDPCT1	
	HF	LF	HF	LF	HF	LF	HF	LF
Bore field [T]	14		14		13		15	
Peak field [T]	14.35	12.05	14.33	12.17				
Temperature [K]	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
operating current [A]	10060	10060	9990	9990	5800	5800	10900	10900
j overall [A/mm^2]	273	412	348	409	250	450	330	440
j sc [A/mm^2]	774	1405	768	1395	507	1364	1056	1508
Loadline fraction [%]	77	79	77	80	90		87	
Temperature margin [K]	4.99	4.66	5.02	4.57				
Equivalent width [mm]	54.5		55.4		44.8		52.3	
N° of turn (per quadrant)	32	74	32	77	42	96	44	65
N. blocks	5	4	6	4	7	6	5	2
aperture [mm]	50	50	50	50	50	50	60	60
N° of strands	26	40	26	40	37	47	28	40
Strands diameter [mm]	1.1	0.7	1.1	0.7	0.75	0.48	1	0.7
Cu/Sc	0.9	1.15	0.9	1.15	0.43	1	1.13	1.13
Bare cable Width [mm]	15.862	15.141	15.862	15.141	14.45	11.63	15.1	15.1
Bare cable Inner thickness [mm]	1.911	1.216	1.911	1.216	1.369	0.873		
Bare cable Outer thickness [mm]	2.047	1.346	2.047	1.346	1.369	0.873		
Keystone angle [°]	0.5	0.5	0.5	0.5	0	0	0.805	0.805
Insulation thick radial [mm]	0.15	0.15	0.15	0.15				
Insulation thick azimuthal [mm]	0.15	0.15	0.15	0.15				
Insulated cable filling factor [%]	35.4	29.44	35.4	29.44				

Conclusion

- INFN-CERN agreement proposal is under discussion; meanwhile:
  1. We already started preliminary studies
  2. We are in the process of building a Superconducting Magnet Lab (SML) for fabricating short models
- We believe the state-of-art conductor allows us to build a 14 T dipole operating at 80% on LL @1.9 K
- First configurations have been found, considering also the past experiences in the community

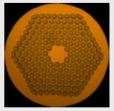
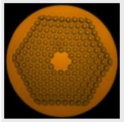
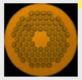
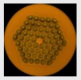
HFM

High Field Magnets

Programme

04/06/2024 – Review after the meeting

- The strand RRP Ø 0.7 mm used for Hi-Lumi is not available for the HFM programme, use the HFM one

	ERMC-1			DEM-1.1		
High Field 162/169		Diameter	1.0 mm		Diameter	1.1 mm
		Cu/non-Cu	0.9 ± 0.2		Cu/non-Cu	0.9 ± 0.2
		I_c at 4.22 K, 16 T	≥ 395 A		I_c at 4.22 K, 16 T	≥ 475 A
		d_{sub-el} (nom.)	58 µm		d_{sub-el} (nom.)	64 µm
	ERMC-0.7			**DEM-0.7**		
Low Field /91		Diameter	0.7 mm		Diameter	0.7 mm
		Cu/non-Cu	1.2 ± 0.2		Cu/non-Cu	1.8 - 0.2
		I_c at 4.22 K, 12 T	≥ 430 A		I_c at 4.22 K, 12 T	≥ 315 A
		d_{sub-el} (nom.)	54 µm		d_{sub-el} (nom.)	54 µm

- The stress limits reported in slides 7 and 8 must not be intended as targets
- The table in slide 30 must be completed with the following data (see next slide):
  1. Case A HFM and Case B HFM with the HFM RRP Ø 0.7 mm strand for the Low Field cable
  2. Eurocircol design with HFM strands

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	case A HFM		case B HFM		case A (11T LF)		case B (11T LF)		D20		MDPCT1		EuroCircol	
	HF	LF	HF	LF	HF	LF	HF	LF	HF	LF	HF	LF	HF	LF
Bore field [T]	14		14		14		14		13		15		14	
Peak field [T]	14.35	12.05	14.33	12.17	14.35	12.05	14.33	12.17					14.41	11.09
Temperature [K]	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
operating current [A]	10060	10060	9990	9990	10060	10060	9990	9990	5800	5800	10900	10900	9840	9840
j overall [A/mm^2]	273	412	348	409	273	412	348	409	250	450	330	440	313	425
j sc [A/mm^2]	774	1438	768	1428	774	1405	768	1395	507	1364	1056	1508	894	1480
Loadline fraction [%]	77	76	77	77	77	79	77	80	90		87		79	72
Temperature margin [K]	4.99	5.13	5.017	5.049	4.99	4.66	5.02	4.57					4.61	5.78
Equivalent width [mm]	54.5		55.4		54.5		55.4		44.8		52.3		49.5	
N° of turn (per quadrant)	32	74	32	77	32	74	32	77	42	96	44	65	32	68
N. blocks	5	4	6	4	5	4	6	4	7	6	5	2	7	5
aperture [mm]	50	50	50	50	50	50	50	50	50	50	60	60	50	50
N° of strands	26	40	26	40	26	40	26	40	37	47	28	40	22	38
Strands diameter [mm]	1.1	0.7	1.1	0.7	1.1	0.7	1.1	0.7	0.75	0.48	1	0.7	1.1	0.7
Cu/Sc	0.9	1.15	0.9	1.15	0.9	1.15	0.9	1.15	0.43	1	1.13	1.13	0.9	1.8
Width [mm]	15.862	15.141	15.862	15.141	15.862	15.141	15.862	15.141	14.450	11.630	15.100	15.100	13.596	14.420
Inner thickness [mm]	1.911	1.216	1.911	1.216	1.911	1.216	1.911	1.216	1.369	0.873				
Outer thickness [mm]	2.047	1.346	2.047	1.346	2.047	1.346	2.047	1.346	1.369	0.873				
Keystone angle [°]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0.805	0.805	0.5	0.5
Insulation thick radial [mm]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15						
Insulation thick azimuthal [mm]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15						
Insulated cable filling factor [%]	35.4	29.44	35.4	29.44	35.4	29.44	35.4	29.44						

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