Persistent current magnetization effects in the EuroCirCol designs for the FCC-hh 16 T magnets

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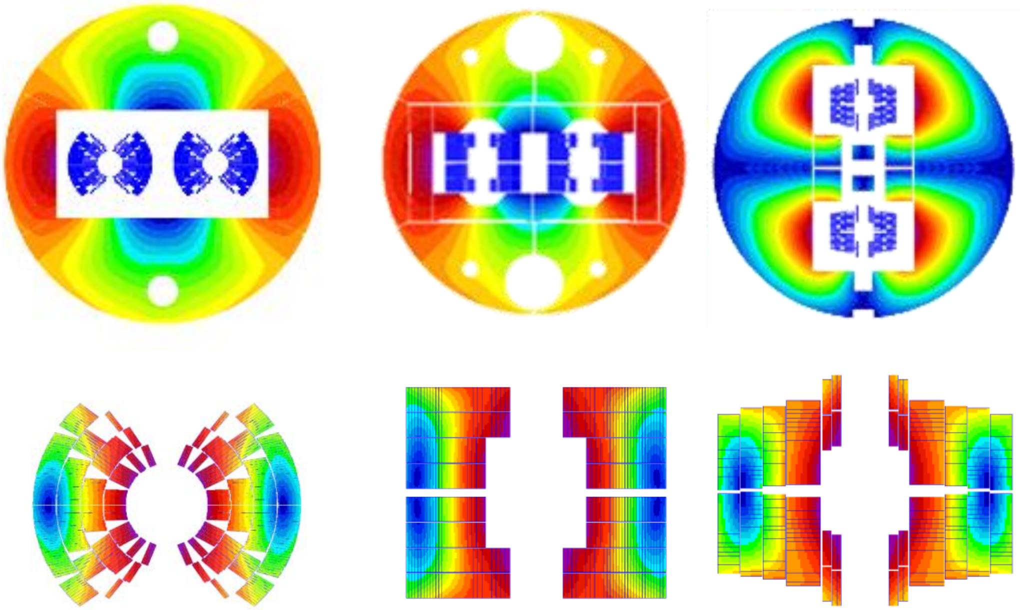
Introduction

- Within EuroCirCol Program, WP5, three different magnet design options were explored [1].
- 16 T operating field, different coil configuration:
  - Cos-theta (INFN), [2]
  - Block (CEA), [3]
  - Common-coil (CIEMAT), [4]
- In 2018, the persistent currents effects at injection for the different coil configurations were explored EDMS 2036614
  - Here we summarize the outcome of the study performed at the time



Magnetic cross section of the cosθ [2], block [3] and common-coil [4] designs.

[1] Tommasini, Status of the 16 T Dipole Development Program for a Future Hadron Collider, IEEE Transactions on Applied Superconductivity (Volume: 28, Issue: 3, April 2018)

[2] V. Marinozzi et al. "Conceptual design of a 16 T cosθ bending dipole for the future circular collider" IEEE Transactions on Applied Superconductivity (Volume: 28, Issue: 3, April 2018)

[3] C. Lorin M. Durante H. Felice M. Segreti " Design of a Nb 3 Sn 16 T block dipole for the future circular collider " IEEE Transactions on Applied Superconductivity (Volume: 28, Issue: 3, April 2018)

[4] 10. F. Toral J. Munilla "Magnetic and mechanical design of a 16 T common coil dipole for FCC" IEEE Transactions on Applied Superconductivity (Volume: 28, Issue: 3, April 2018)

Field quality at injection

- Field quality at injection energy is dominated by the persistent current effects, which mainly depend on:
  - Strand magnetization, which depends on
    - Sub-element diameter (d_{sub})
    - Critical current density (non-Cu) (J_c)

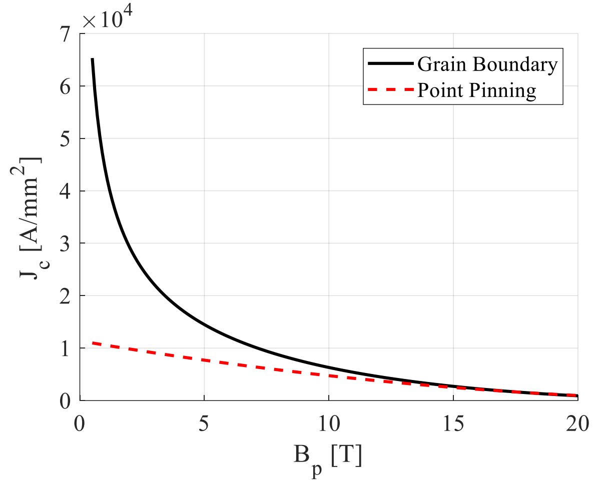
$$M(B) \propto d_{sub} \cdot J_c\,(B) \cdot \frac{1}{\lambda + 1}$$

- FCC targets: D_{eff} = 20 μm; J_c > 1500 A/mm^2 at 16 T , 4.2 K
- To my knowledge, the focus today is in increasing J_c
  - The strands being explored for HFM program so far have a D_{eff} 50-60 μm [5], the reduction of the filament size will be pursuit in a second stage of the development phase
  - Other groups are also working on strand development to reach FCC spec (see for example [6])

[5] S. C. Hopkins, et al., "Design Optimization, Cabling and Stability of Large-Diameter High Jc Nb3Sn Wires," in IEEE Transactions on Applied Superconductivity, vol. 33, no. 5, pp. 1-9, Aug. 2023, Art no. 6000609, doi: 10.1109/TASC.2023.3254497.
[6] Xingchen Xu, et al., "High critical current density in internally-oxidized Nb3Sn superconductors and its origin ," Scripta Materialia,Volume 186,2020,Pages 317-320,
ISSN 1359-6462, https://doi.org/10.1016/j.scriptamat.2020.05.043.

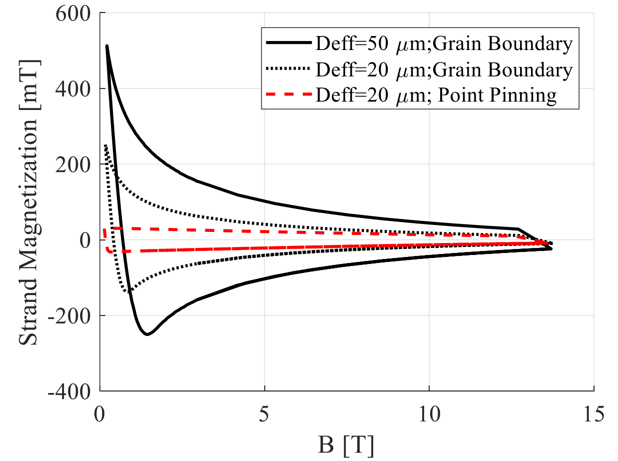
Cases considered for strand magnetization

- Cases considered for strand magnetization:
  - D_{eff} = 50 μm, grain boundary pinning (state of the art technology)
  - D_{eff} = 20 μm, grain boundary pinning
  - D_{eff} = 20 μm, artificial pinning to reduce magnetization at low field
    - Remark: today this is an ‘academic case’, and we are reducing the current margin at low field
  - D_{eff} = 20 μm, half of the artificial pinning efficiency



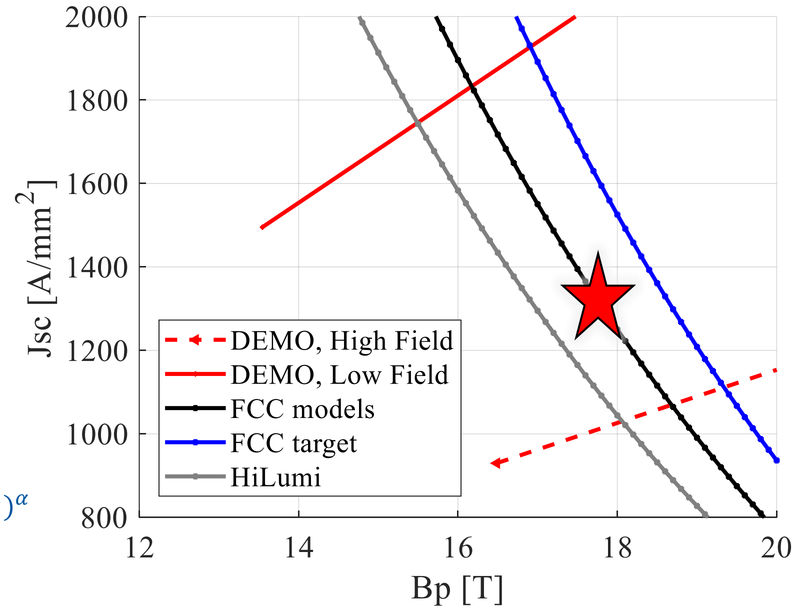
$$J_c = \frac{C(T)}{B_p} b^{0.5}(1-b)^2 \qquad B_{c2}(T) = B_{c20}(1-t^{1.52}) \qquad C(t) = C_0(1-t^{1.52})^{\alpha}(1-t^2)^{\alpha}$$

Pinning method	Grain Boundary	Grain Boundary	Point Pinning
Effective filament diameter, D_{eff} [μm]	50	20	20
p [--]	0.5	0.5	1
q [--]	2	2	2
T_{c0} [K]	16	16	16
B_{c20}[T]	29.38	29.38	29.38
α	0.96	0.96	0.96
C_0[A/mm²T]	1.03*267845	1.03*267845	1.03*338485
Cabling degradation [%]	3	3	3



Critical Current Density

- Today, the strands available for HFM are:
  - halfway between HiLumi and FCC targets in terms of Jc (consistent with EuroCircol choice for models construction)
  - Similar to HiLumi in terms of Deff (≈ 50 μm)



$B_{c2}(T) = B_{c20} \cdot (1 - t^{1.52})$; $J_C = \frac{C(t)}{B_p} \cdot b^{0.5} \cdot (1-b)^2$; $C(t) = C_0 \cdot (1 - t^{1.52})^{\alpha} \cdot (1 - t^2)^{\alpha}$

	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

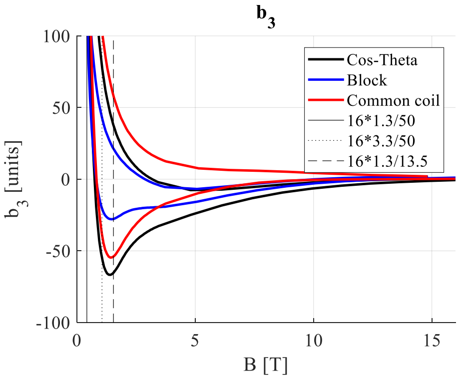
Cases considered for injection energy

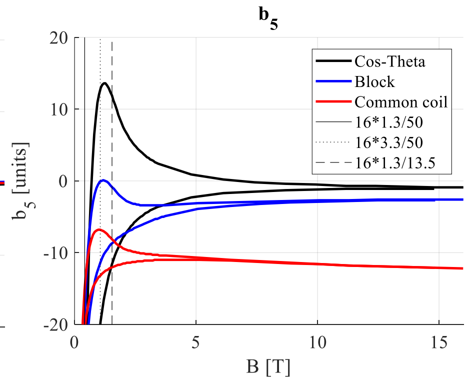
1. 0.45 TeV, HE-LHC (13.5 TeVx2 collision energy)
2. 0.90 TeV , HE-LHC (13.5 TeVx2 collision energy)
3. 1.30 TeV , HE-LHC (13.5 TeVx2 collision energy)
4. 3.30 TeV , FCC (50 TeVx2 collision energy)
5. 1.30 TeV , FCC (50 TeVx2 collision energy)

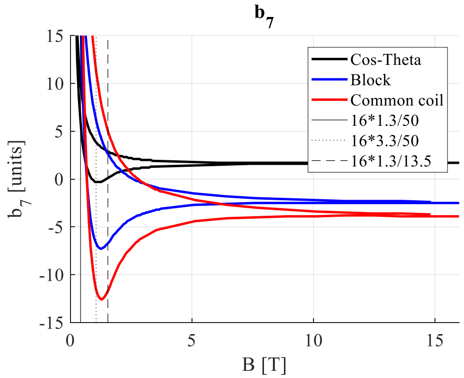
Today, I focus on cases 4 and 5

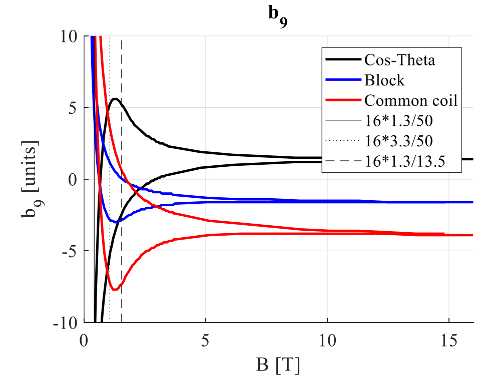
Sensitivity to coil design

- Assumed strand magnetization: D_{eff} = 50 µm, FCC target J_c
- Coil geometry plays a role in strand magnetization
  - Strand magnetization effects in the block coil geometry are about a factor two smaller than in the cos-theta and common coil design.
  - The only harmonic where the persistent current effects are significant lower for the cos-theta design is b_7.
- Today we are far from having a reference magnet cross-section, so we should talk more about a range than an actual number

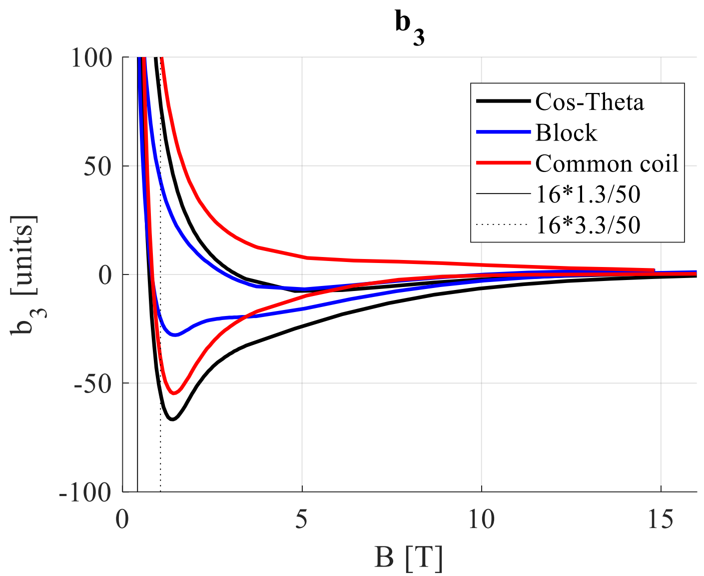


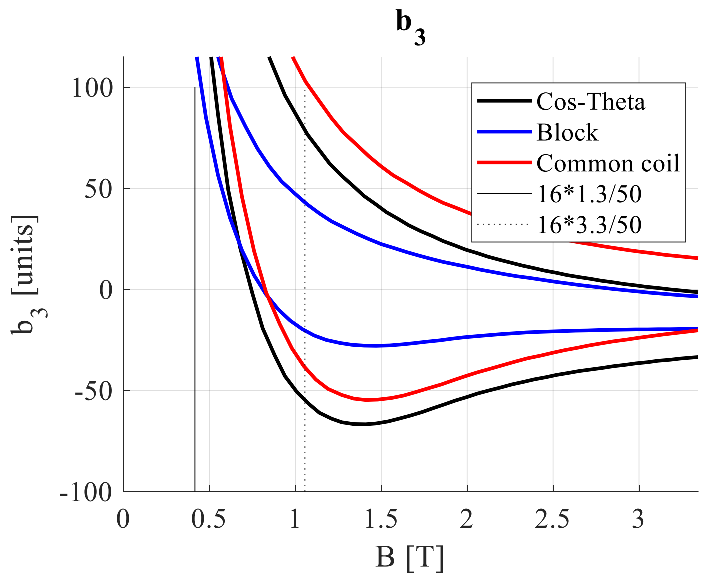






Sensitivity to coil design – zoom at injection





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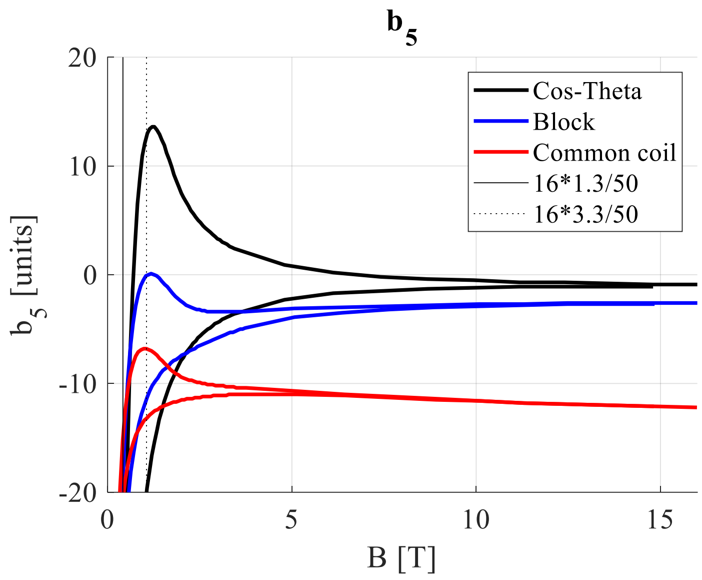

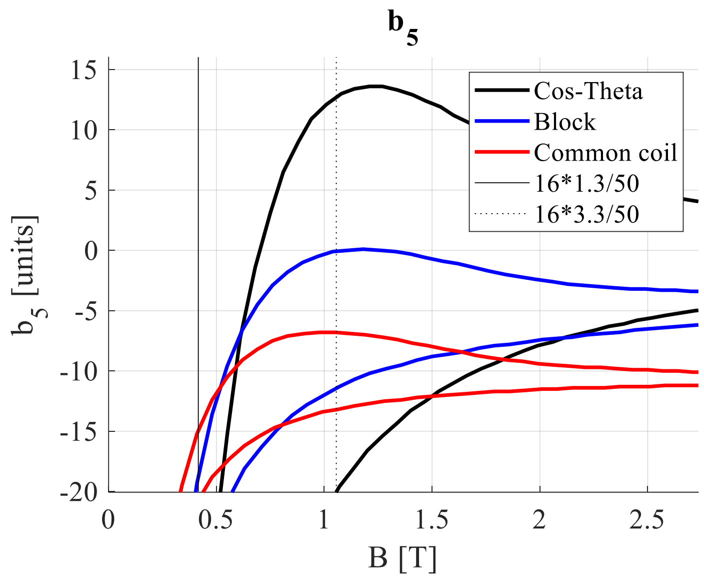

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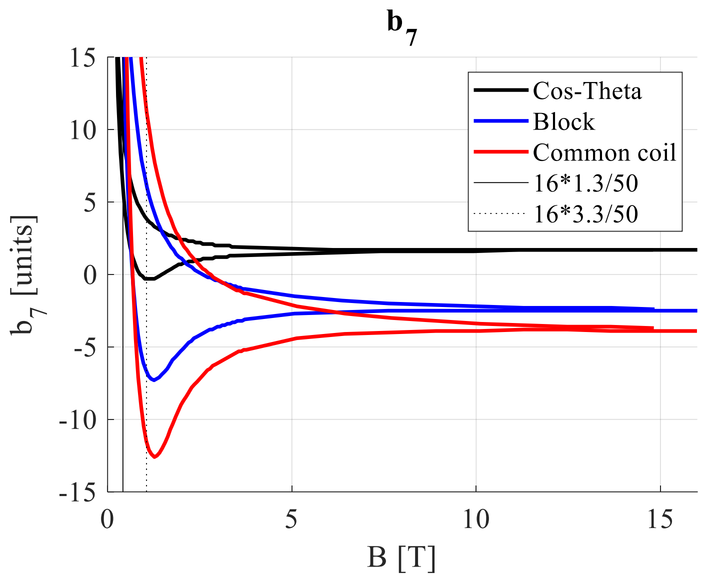

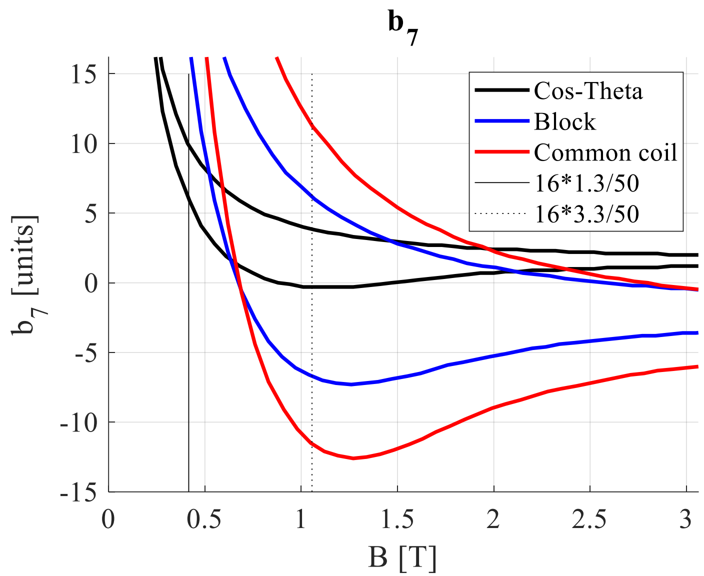

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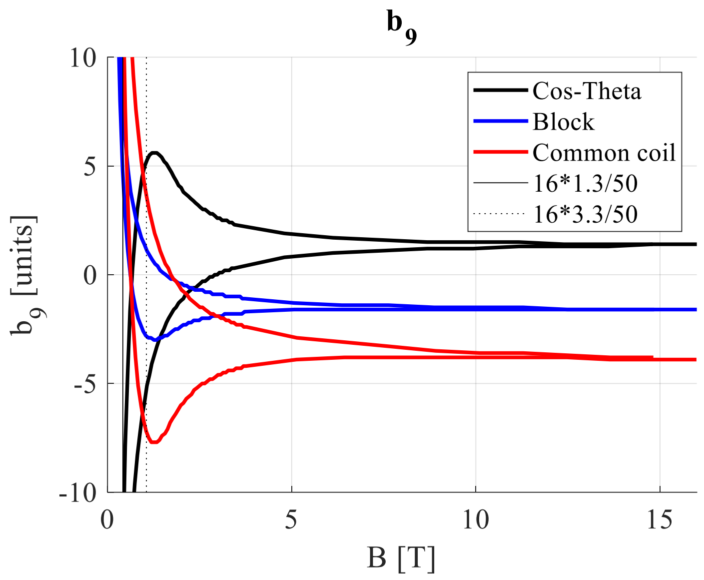
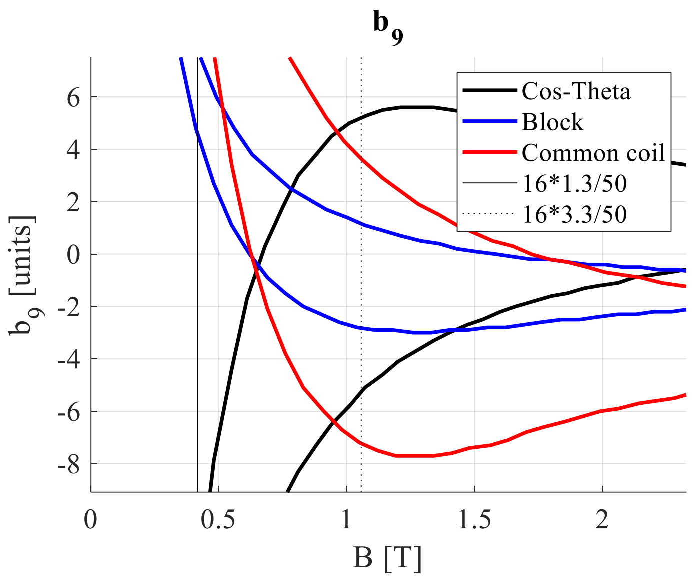
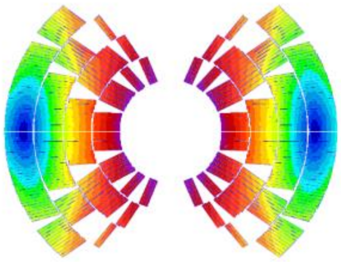
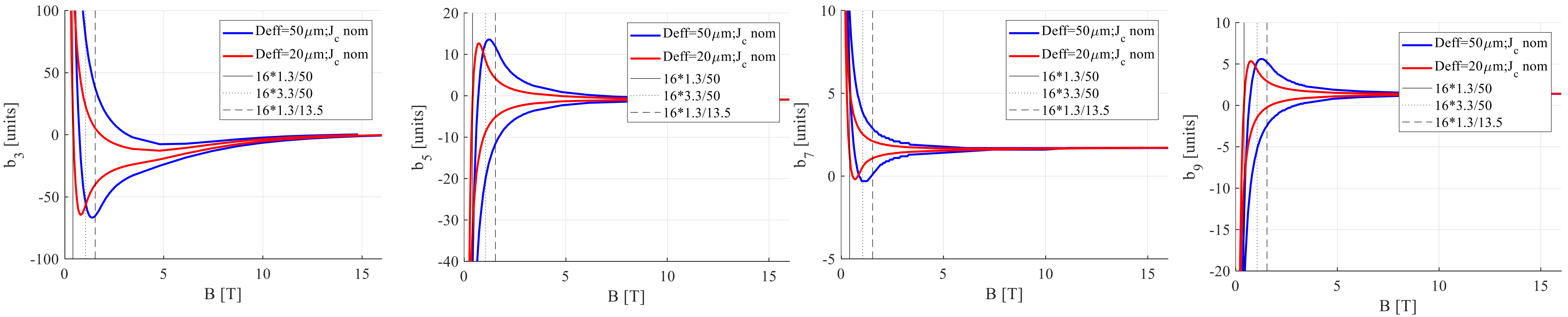




Sensitivity to filament size



- From now on, we will focus on the cos-theta magnet
- The reduction of the filament size from 50 to 20 µm reduces the width of the hysterics loop and the penetration field



Field errors at injection for the cos-theta magnet, for three different injection energies. 1.3 TeV (and 3.3 TeV) injection in the FCC (B_{inj} = 0.4 T (and B_{inj} = 1 T)) and 1.3 TeV injection in the HL-LHC machine (B_{inj} = 1.5 T).

Strand Technology	Jc	D_{eff}, µm	B1, T	b3	b5	b7	b9	b11
Grain Boundary	Nominal	50	0.416	209.4	-41.9	6.0	-13.2	0.7
			1.056	-55.0	12.8	-0.3	5.2	0.9
			1.541	-65.4	11.7	0.1	5.3	1.0
Grain Boundary	Nominal	20	0.416	14.6	-1.2	1.2	0.5	0.8
			1.056	-56.8	8.6	0.6	4.3	1.0
			1.541	-39.8	4.1	1.1	2.9	1.0

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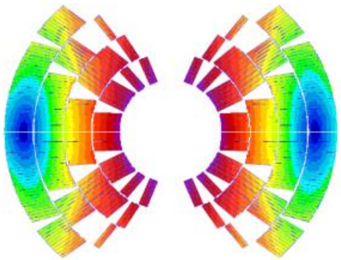
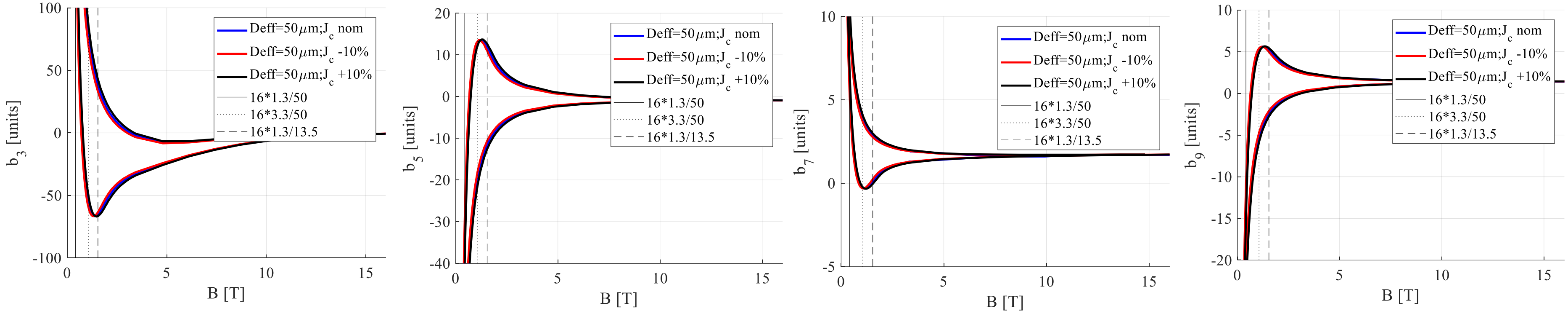
Sensitivity to J_c



- When injecting in the very steep region, very sensitive to the different parameters affecting magnetization



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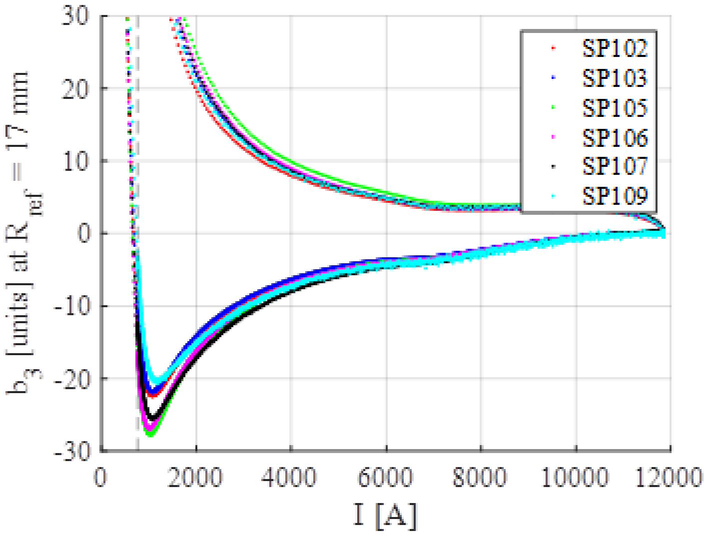
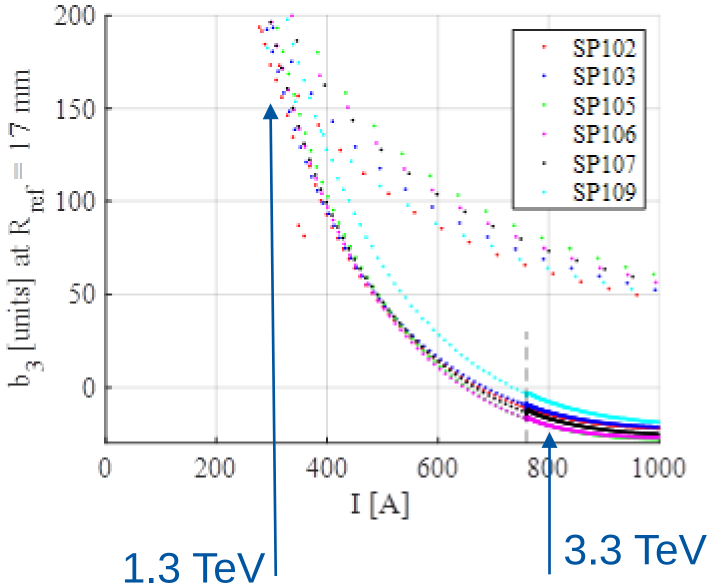
Grain Boundary	+ 10 %	50	0.416	216.0	-42.9	6.1	-13.6	0.7
			1.056	-49.3	12.0	-0.3	4.9	0.8
			1.541	-66.7	12.6	0.0	5.4	0.9
Grain Boundary	- 10 %	50	0.416	160.4	-31.2	4.7	-9.7	0.7
			1.056	-59.4	13.2	-0.3	5.4	0.9
			1.541	-63.2	10.9	0.3	4.9	1.0

Reproducibility – 11 T

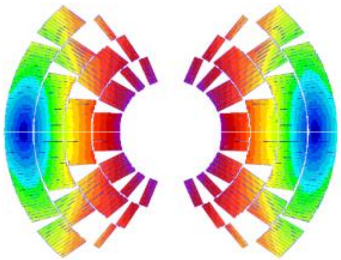
- In the 11 T short model programs (different conductors were explored, in a series production one expect to haver more uniform parameters):
  - Spread at 1.3 TeV eq. energy ≈ 50 units
  - Spread at 3.3 TeV eq. energy ≈ 15 units



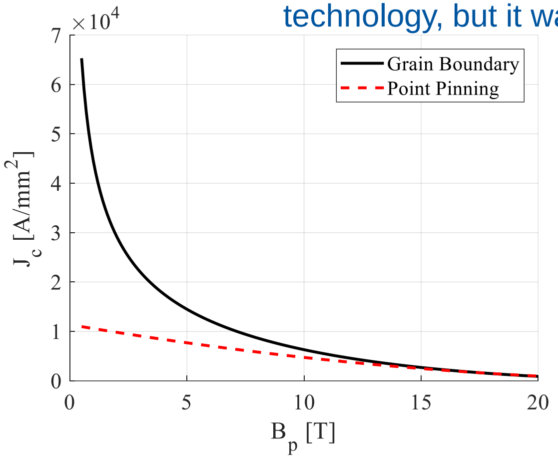
b_3 swing for the 11 T short models

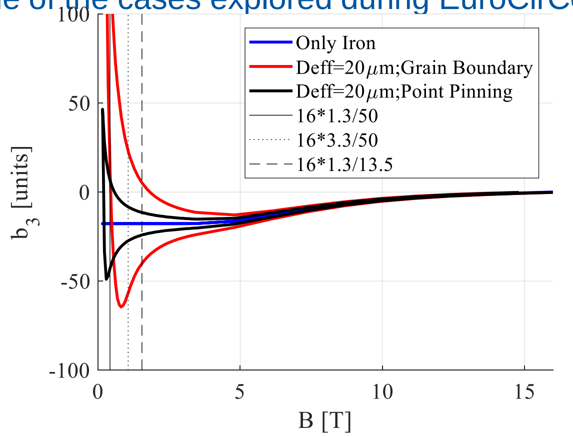


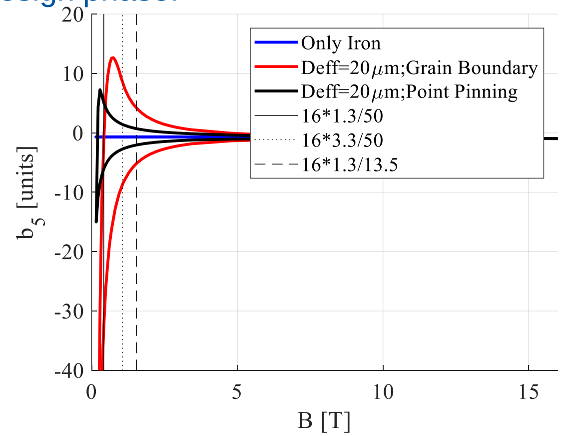
Sensitivity to strand magnetization



- We can drastically reduce the field errors are injection, reducing Jc at low field, what we 'called' point pinning
  - Please, keep in mind that this is an academic case for the moment, today we don't have the wire technology, but it was one of the cases explored during EuroCirCol design phase.







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Point Pinning	Nominal	20	0.416	-42.9	5.1	0.9	3.2	1.0
			1.056	-27.3	1.4	1.4	2.0	1.0
			1.541	-24.0	0.7	1.4	1.8	1.0

Conclusion

- Today we don’t the element to prove that a 1.3 TeV injection is viable
  - From the magnet perspective, it will be driven by the conductor development, but the final choice in terms of magnet cross-section/field will also play a role
  - Smaller filaments mean higher price and lower current density, so today they are contradictory requirements