HFM

High Field Magnets

Status of High Field Magnet development at CIEMAT

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Outline

- Introduction
- SMART-Lab: a new facility for high field magnets
- ISAAC: a common coil model magnet with existing coils
- DAISY: a 14 T common coil magnet demonstrator
- Conclusions

HFM plans at CIEMAT

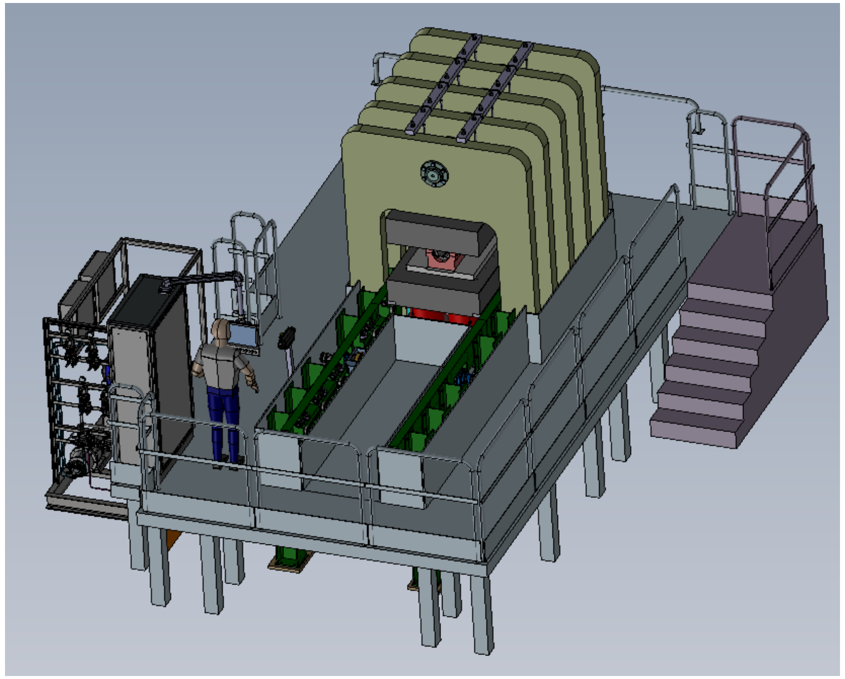
- **CIEMAT** is contributing to the **High Field Magnet (HFM)** program led by **CERN**.
- CIEMAT is working on high field magnets based on **common coil** topology, profiting from the lessons learned from EuroCirCol collaboration.
- The target is to develop a prototype magnet able to provide **14 T** at the aperture.
- In a first step, CIEMAT is working on a model magnet (**ISAAC**) using existing coils produced by CERN. The aim is to learn about mechanics of high field magnets in common coil configuration. **ISAAC** means **I**nvestigating **S**uperconducting **A**ssembly to **A**ddress **C**ommon coil mechanics.
- In a second step, we are developing **DAISY**: **D**emonstrator for **A**ssembly **I**nnovations in **S**uperconducting common coil technolog**Y**. It honours Margarita Salas, an outstanding Spanish biologist (*daisy* is translated into Spanish as *margarita*).
- DAISY coils will be the first ones made with Nb_3Sn cable in the new CIEMAT magnet laboratory (**SMART-Lab**: **S**uperconducting **MA**gnet **R**esearch and **T**echnology **Lab**oratory).

- Two halls of building 31 have been completely refurbished. The laboratory will be fully **operational** by the end of 2025.
- Layout based on the **927 Laboratory** at **CERN** (special thanks to Juan Carlos Pérez).
- About 1000 m^2 divided in four volumes:
  - **Underground**: workshop and storage
  - **Main hall**: winding machines, metrology, impregnation, reaction furnace.
  - **Magnet assembly hall**: vertical press, magnetic measurements, magnet assembly.
  - **First floor**: offices

SMART-Lab main hall

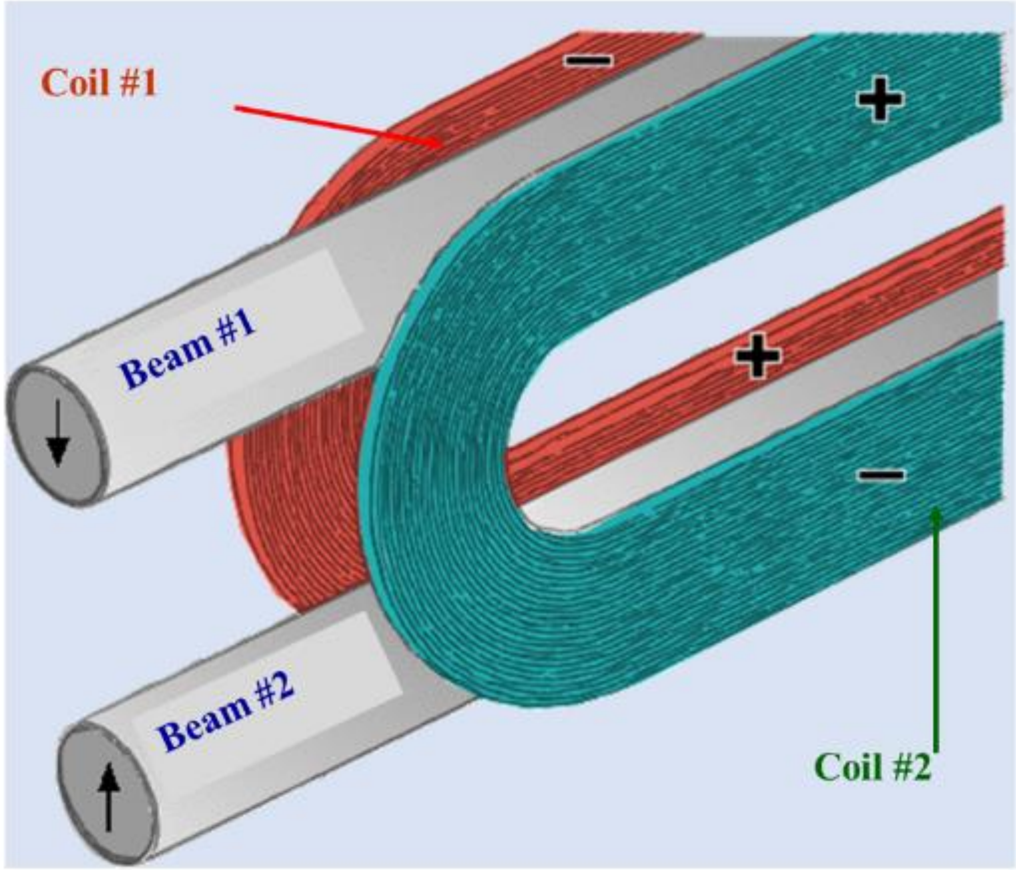
- The largest machines are the reaction furnace and the vertical press.
- The **reaction furnace** is being commissioned.
- The **vertical press** is in fabrication, with expected delivery by September.

Reaction furnace



Vertical press

A reminder: common coil magnet



Courtesy: R. Gupta (BNL)

- It is a topology proposed by **Ramesh Gupta** (BNL).
- It is only valid for **dipoles**, not for higher order magnets.
- It is always a **double aperture magnet**, where the apertures are contained in the same vertical plane.

Outline

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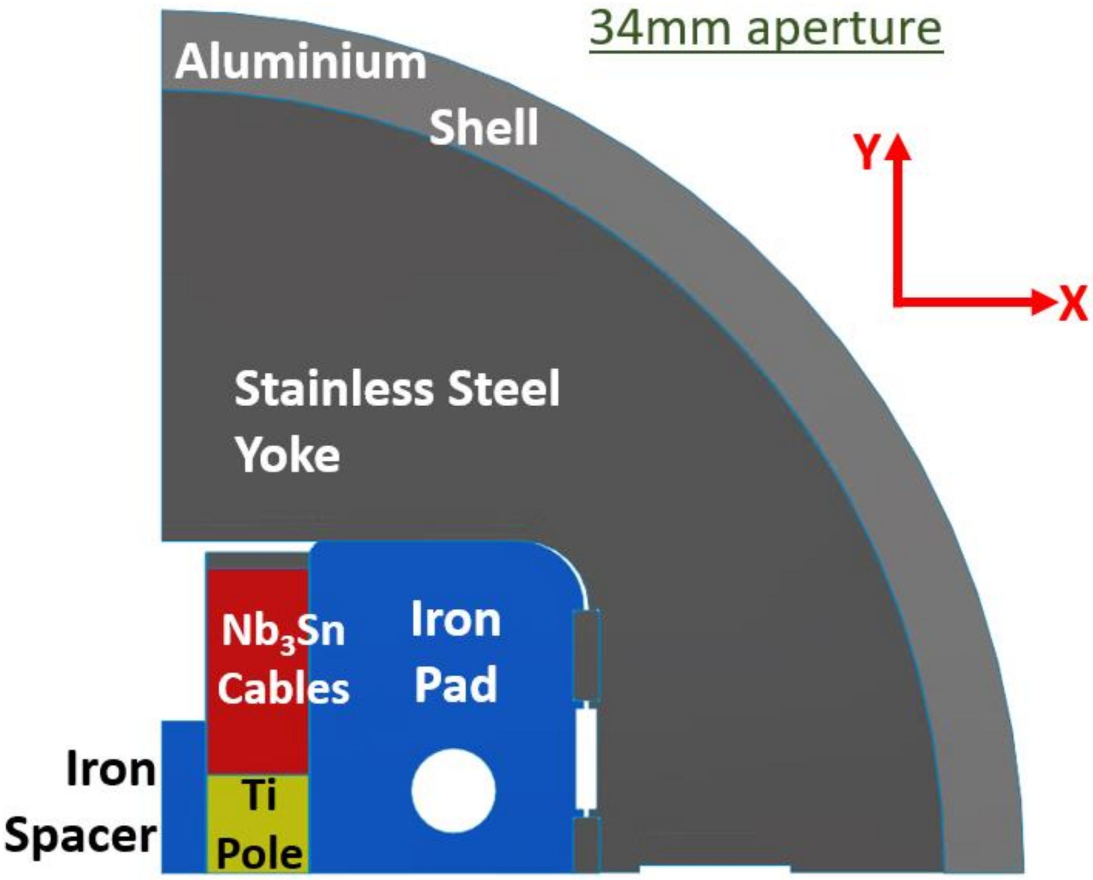
ISAAC design baselines

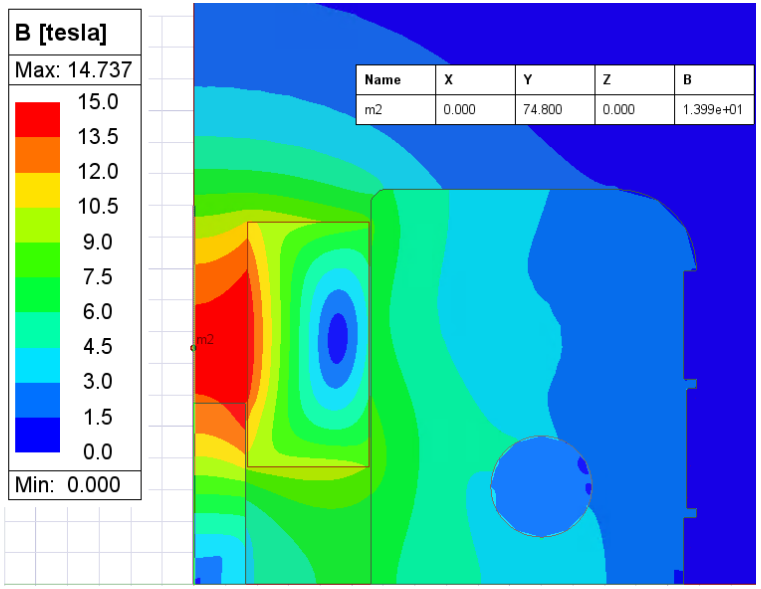
- Main goal: learn for the 14 T demonstrator (**DAISY**) with **existing coils**, mostly on **mechanics**
  - Existing RMC coils made at CERN with MQXF strand
  - Provide ≈14 T in the 34-mm aperture (100% load). 50-mm aperture is possible to test insert HTS coils.
  - **No horizontal preload**: coils can be placed closer to the aperture
- Horizontally-split iron to hold large horizontal EM forces. Assembly with **bladder and keys**, slight **preload** just to keep contact between parts (@RT). In a **second step**, we could not use any shell.
- Goal: To have a horizontal **coil displacement** due to the EMF **below 0.5 mm** to reduce:
  - The impact on field quality and magnitude (0.5 mm -> 1% less field in the aperture)
  - The possibility of sudden coil movements (quench)



ISAAC 2D Magnetic Design

Parameter	Conf.#1		Conf.#2		Units
Aperture	34		50		mm
Nominal current	19340		20728		A
	Roxie	Maxwell	Roxie	Maxwell	
Magnetic length	0.55	-	0.55	-	m
WorkPoint on LoadLine	100.6	-	100.4	-	%
Stored energy	1049	-	1357	-	kJ/m
Aperture Field	14.04	13.99	12.74	12.70	T
Peak Field	14.85	14.74	14.45	14.32	T
Field ratio	1.06	1.05	1.13	1.13	-
F_x (Q1)	6.56	6.40	5.98	5.83	MN/m
F_y (Q1)	0.45	0.44	0.85	0.83	MN/m

Parameter	Conf.#1	Conf.#2	Units
Aperture	34	50	mm
Nominal current	16264	19410	A
Aperture Field	12	12	T
WorkPoint on LoadLine	85.5	94.3	%

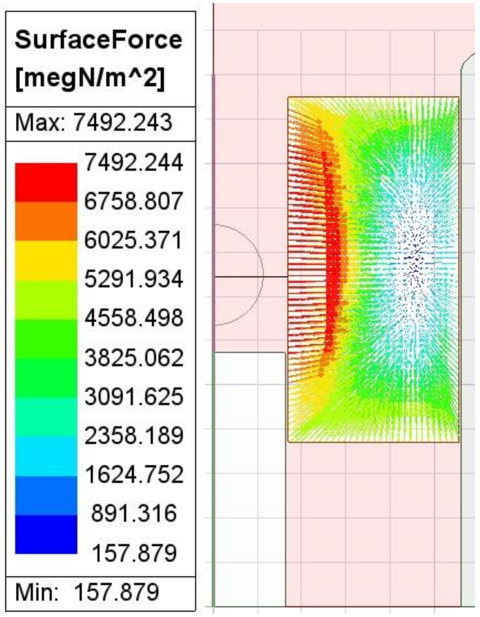


Field (B)

34mm aperture

Coil Cable EMF

34mm aperture

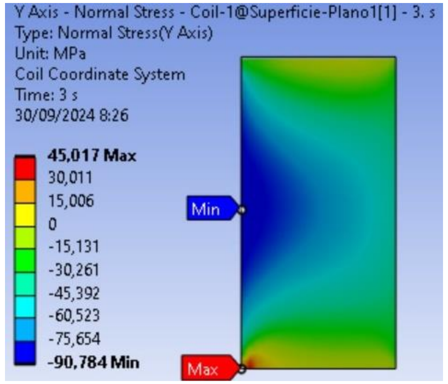


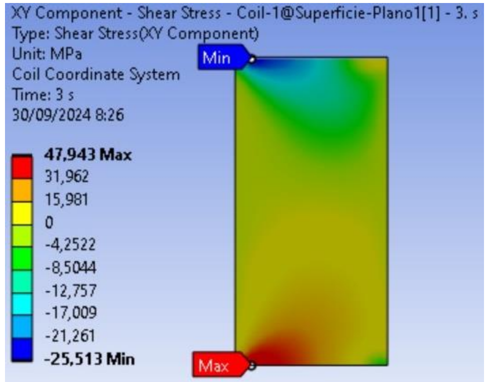
- Protection with **dump resistor** (30 ms delay + Vmax 1000 V): hot spot temperature:
  - 201 K for 34 mm aperture
  - 291 K for 50 mm aperture

ISAAC 2D Mechanical Design

Components without preload @ RT

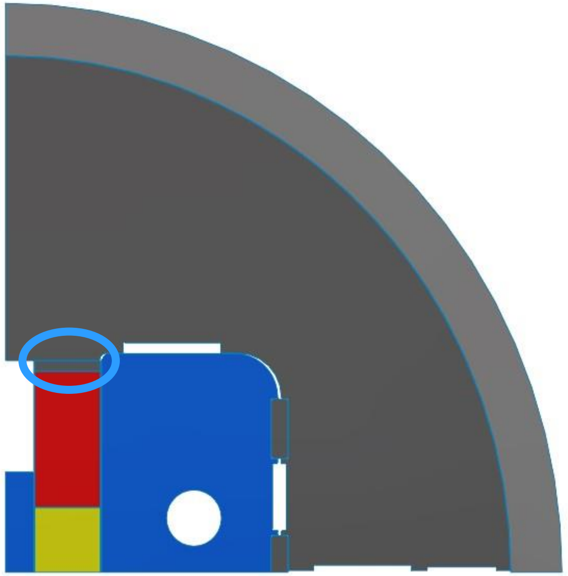
	Coil Stress				
	X stress	Y stress	Shear Stress	VM stress	
Max	**30,0 MPa**	14,1 MPa	14,0 MPa	36,8 MPa	Cooling
Min	-14,0 MPa	-24,9 MPa	-16,4 MPa	0,6 MPa	
Max	**95,1 MPa**	**45,0 MPa**	**47,9 MPa**	113,9 MPa	Cooling + EMF
Min	-101,3 MPa	-90,8 MPa	-25,5 MPa	4,1 MPa	





Main concern: **Pole turn detaching** due to **Vertical (Y)** and **Shear Stress**

More info @ "Mechanical Design of a Common Coil Magnet with RMC Coils (ISAAC)" doi: 10.1109/TASC.2025.3537063



Vertical preload @ RT

Vertical interference @RT: 0.2mm

(this is NOT our original target: free horizontal movement of the coil)

	Coil Stress				
	X stress	Y stress	Shear Stress	VM stress	
Max	**29,7 MPa**	-36,6 MPa	16,3 MPa	81,5 MPa	Cooling
Min	-18,8 MPa	-82,2 MPa	-17,3 MPa	43,6 MPa	
Max	**56,2 MPa**	-1,8 MPa	43,3 MPa	132,7 MPa	Cooling + EMF
Min	-98,2 MPa	-136,3 MPa	-34,2 MPa	30,0 MPa	

Only compressive vertical stress (no tension)

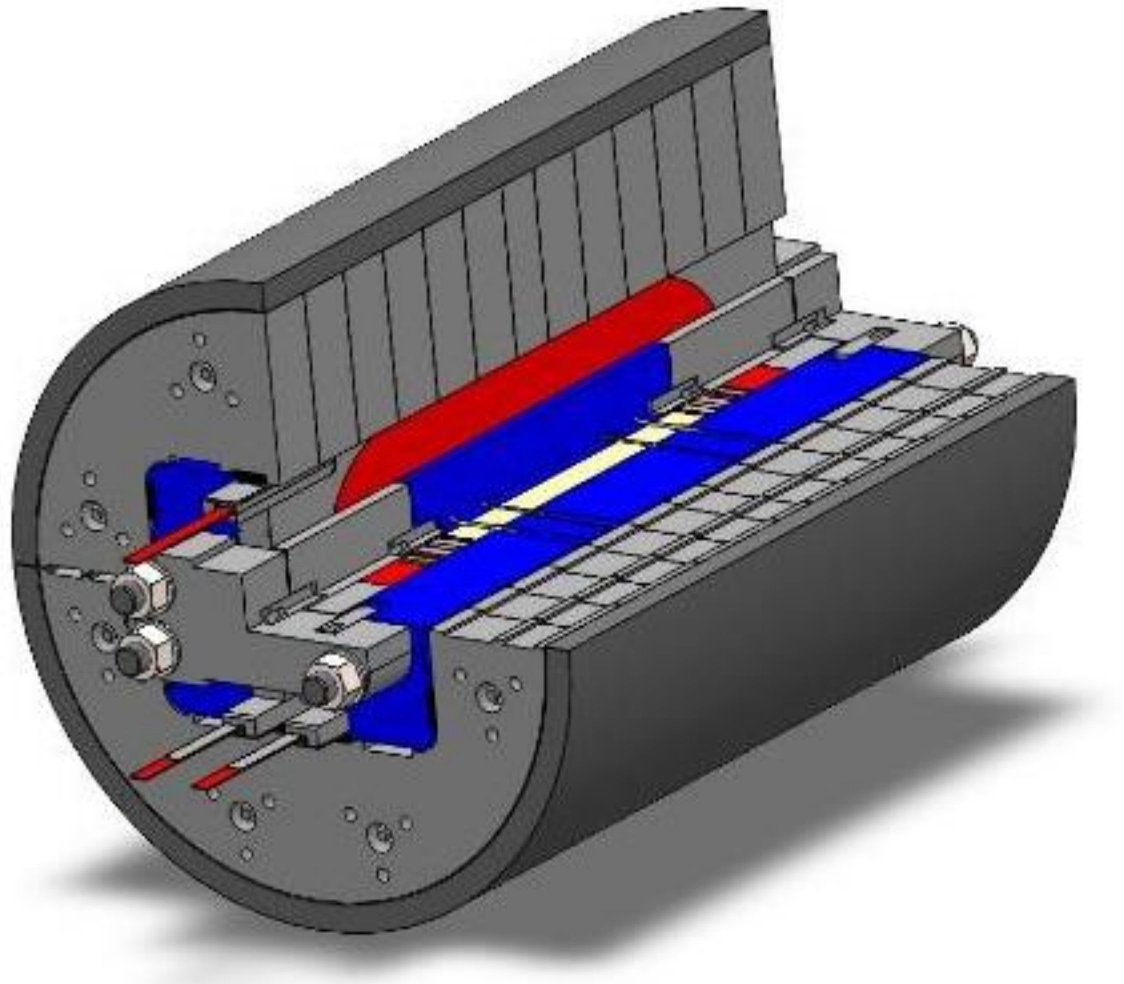
Maximum shear stress is slightly **reduced**

Horizontal tension **stress** is **reduced**

VM equivalent stress is 133MPa (**below** the limit of **150MPa**)

ISAAC Engineering design

- Iron pad has the same length than the coils, but iron central spacer is shorter.
- Off-centering EM forces on that central spacer
- Sliced stainless steel pad
- One single shell
- Stainless Steel rods to provide axial preloading and rigidity



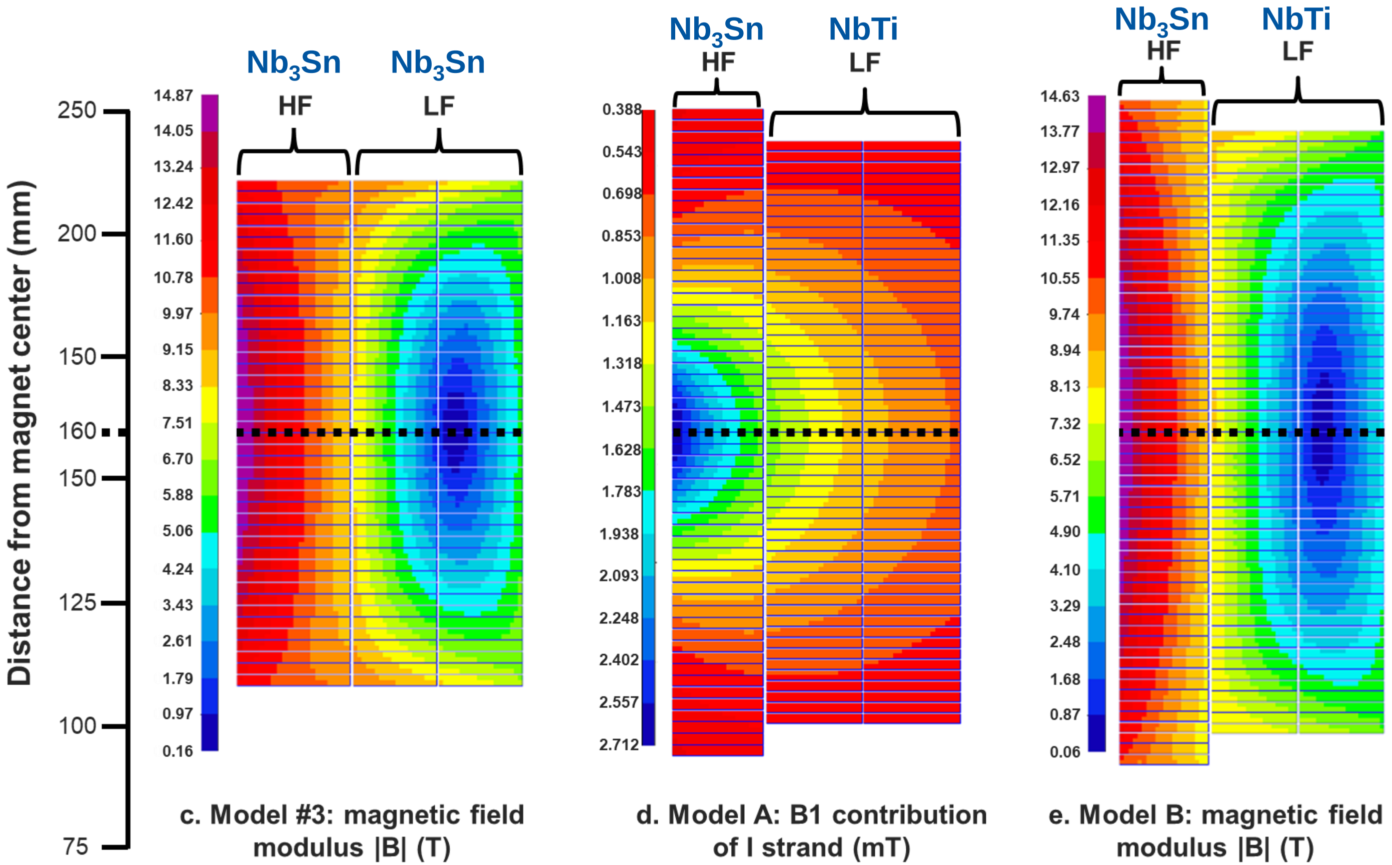
Next steps:
Manufacturing: July 2025
Assembly: September 2025
Power test: October 2025

DAISY

DEMONSTRATOR FOR ASSEMBLY INNOVATIONS IN SUPERCONDUCTING COMMON COIL TECHNOLOGY

DAISY motivation

- The target is a **14 T dipole** in common coil configuration.
- **Nb_3Sn** is considered the best cable choice for this field.
- A common coil dipole is well suited to use NbTi in the low field region (**hybrid magnet**):
  - Decrease superconductor cost
  - Reduce coil fabrication complexity
  - Reduce AC losses
  - Reduce magnetic instabilities
  - Mechanically, NbTi is not so easy to be degraded

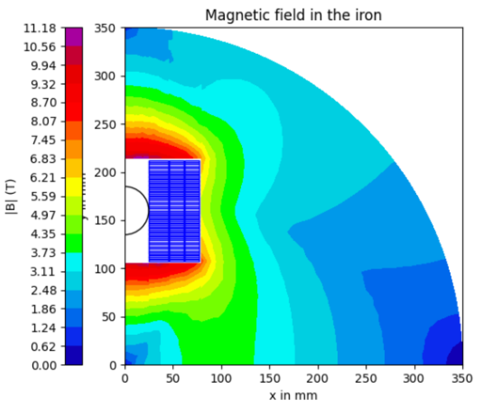


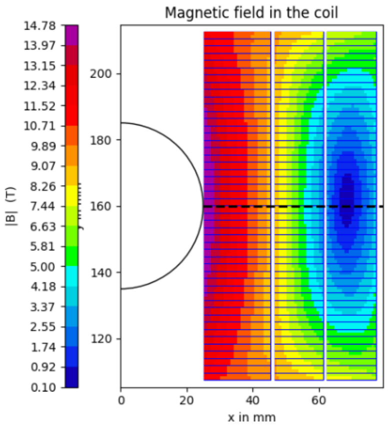
c. Model #3: magnetic field modulus |B| (T)

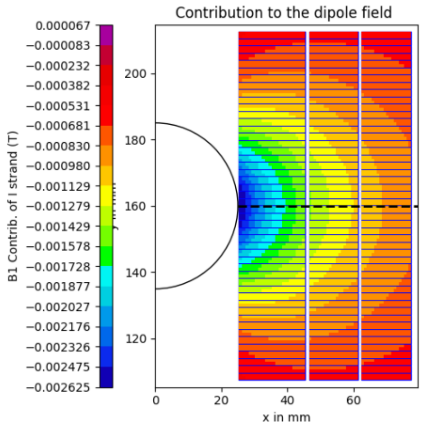
d. Model A: B1 contribution of I strand (mT)

e. Model B: magnetic field modulus |B| (T)

Minimum amount of superconductor







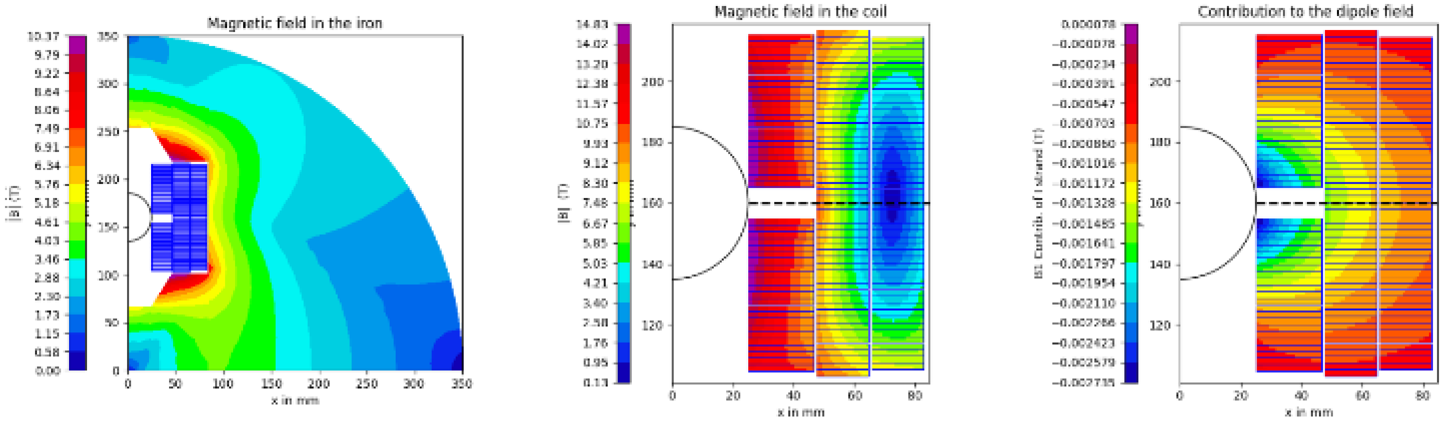
REF01 will be our reference model:

- No field quality: solid coil blocks
- Large multipole variation with the current: iron is close to aperture
- But… **Maximum superconductor efficiency**

Parameters	Units	REF01
Material used	-	Nb_3Sn
Nominal current	A	13476
Loadline margin	%	19.9
Temperature margin	K	4.43
Equivalent coil width	mm	50.7 (26.8+23.8)
Max. Temp (Dump: 1000 V, 40 ms)	K	264
b3 / a2 / max. multipole	units	251 / -30 / -2 (b5)
Inc. b3 / a2 / max. increment	units	-228 / 30 / 2 (b5)
Nb_3Sn strand consumption	km	18.1
NbTi strand consumption	km	-
Nb_3Sn length compared to REF01	%	0
Nb_3Sn length compared to equiv. SN	%	-

*All models for 320 mm of intrabeam distance and 14T in a 50 mm aperture.
Maximum hot spot temperature below 270 K.

Field quality without pole coils



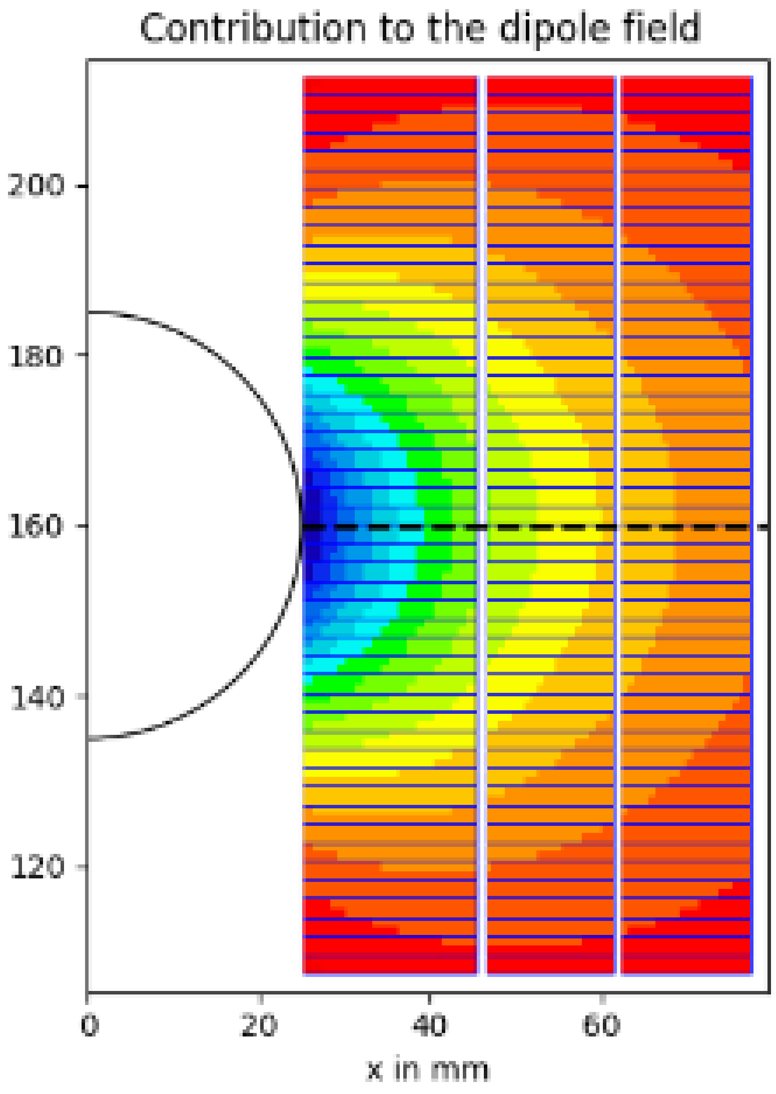
Parameters	Units	REF01	REF02
Material used	-	Nb_3Sn	Nb_3Sn
Nominal current	A	13476	14723
Loadline margin	%	19.9	19
Temperature margin	K	4.43	4.3
Equivalent coil width	mm	50.7 (26.8+23.8)	55 (27+28)
Max. Temp (Dump: 1000 V, 40 ms)	K	264	266
b3 / a2 / max. multipole	units	251 / -30 / -2 (b5)	134 / -35 / -40 (b5)
Inc. b3 / a2 / max. increment	units	-228 / 30 / 2 (b5)	-9 / 35 / 6 (b5)
Nb_3Sn strand consumption	km	18.1	20.5
NbTi strand consumption	km	-	-
Nb_3Sn length compared to REF01	%	0	13
Nb_3Sn length compared to equiv. SN	%	-	-

REF02 is an intermediate step:

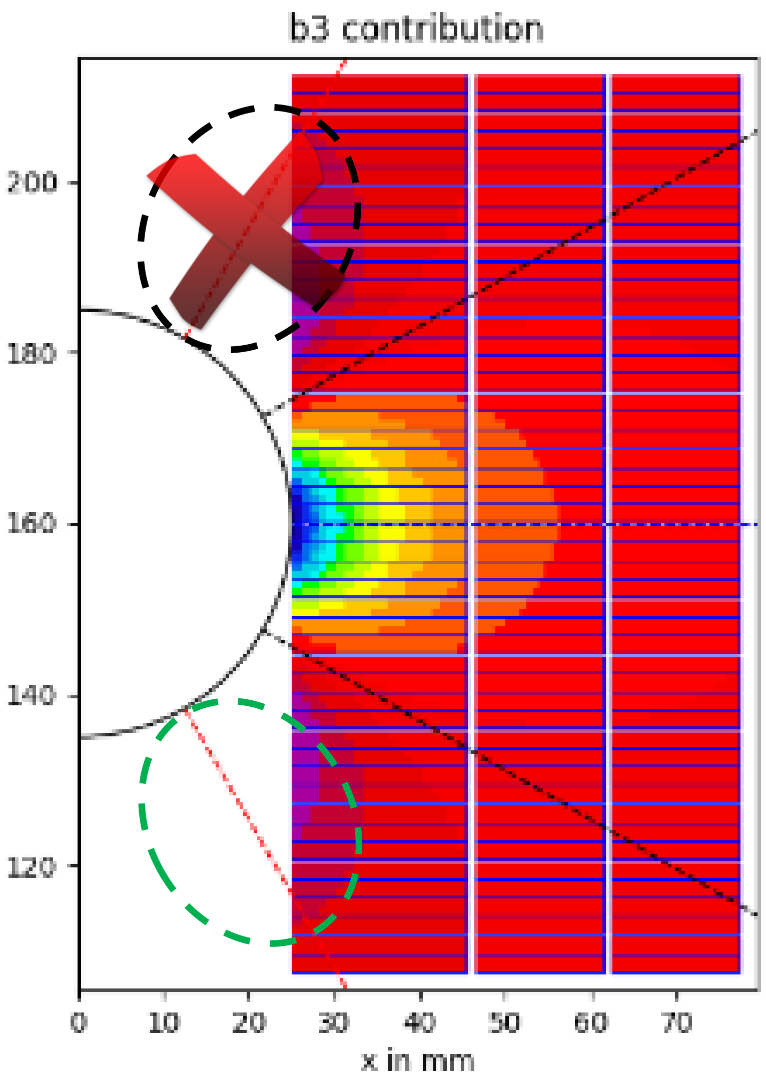
- **Better field quality, but not good enough**: 10 mm gap at midplane of HF coil
- Multipole variation with the current is decreased
- 55-mm coil equivalent width: 13% more Nb_3Sn
- Next step is to improve field quality

*All models for 320 mm of intrabeam distance and 14T in a 50 mm aperture. Maximum hot spot temperature below 270 K.

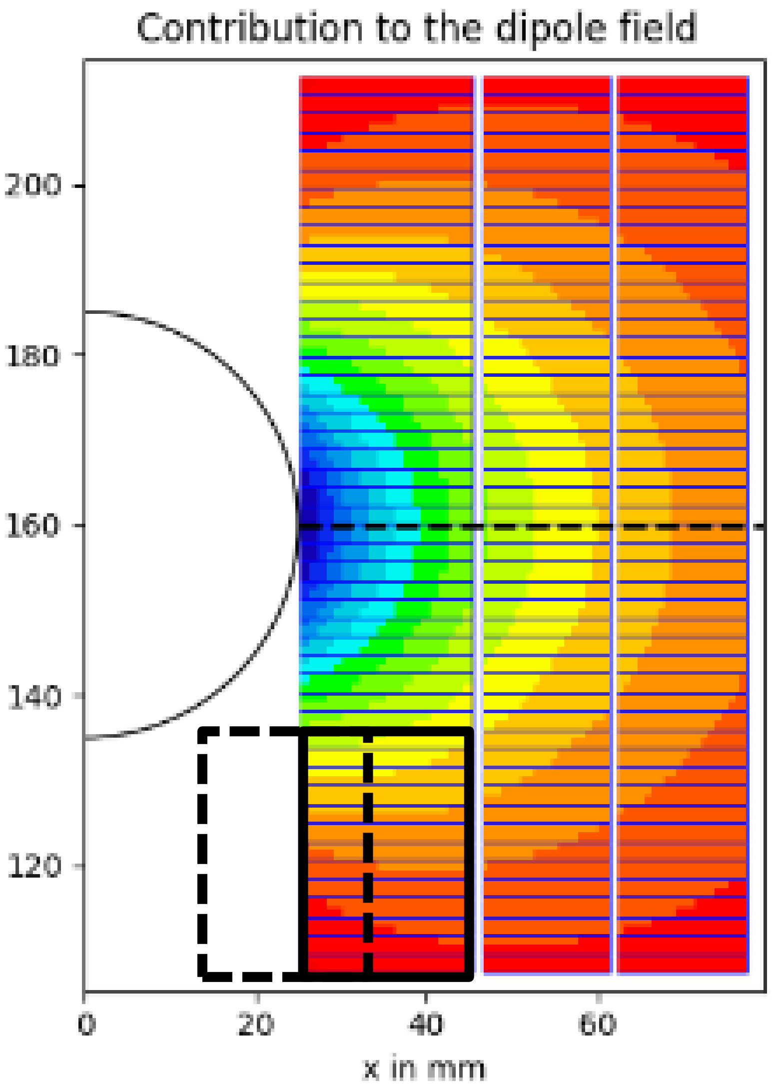
Field quality in a common coil magnet: dealing with a large sextupole

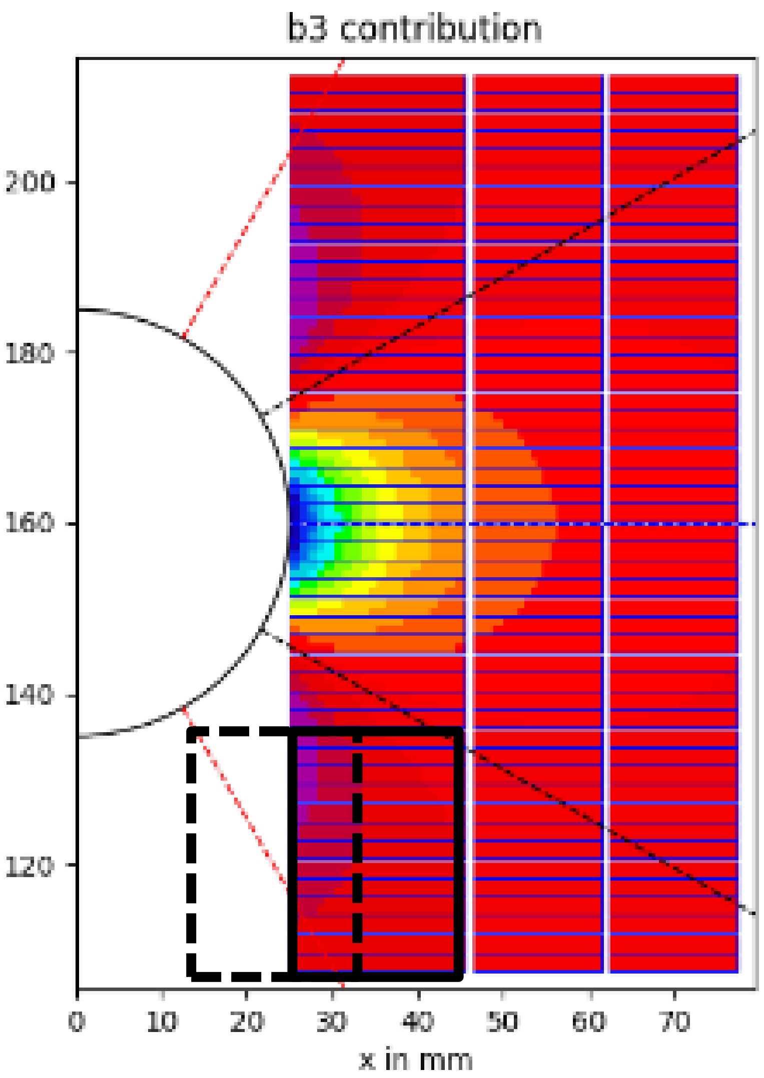


- Midplane region is the cause of the large b_3 in the common coil, but removing those cables has a strong impact on efficiency.
- Contribution of cables to b_3 decreases sharply with radial distance.
- Another option is to place cables in the highlighted areas by means of ancillary coils.
- To avoid non-planar ancillary coils the upper region should be discarded.



Field quality in a common coil: What if…?





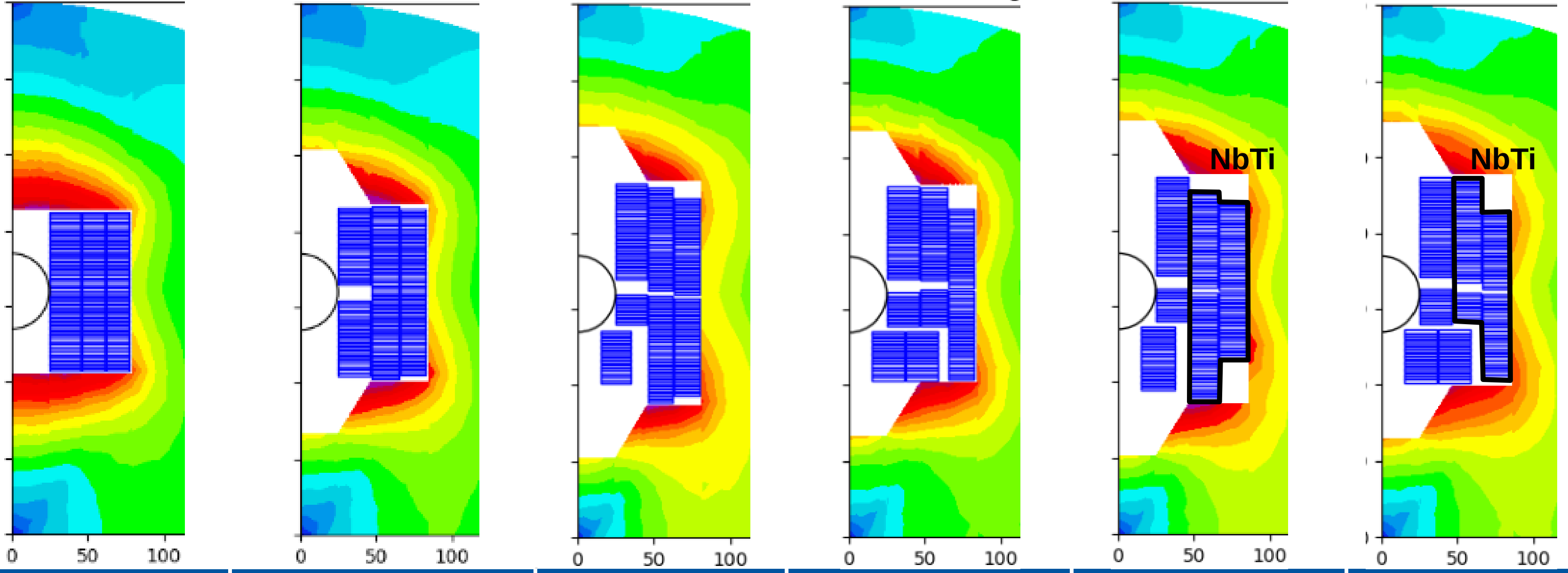
…we move the lower turns towards the aperture?

- Sextupole compensation should be more efficient
- Based on asymmetric common coils proposed by PSI

D. Araujo, B. Auchmann, A. Brem, T. Michlmayr, A. Haziot and E. Ravaioli, "Electromechanical Design of Nb3Sn Stress Managed Asymmetric Common-Coils". Article DOI: 10.1109/TASC.2025.3532906.

Comparing these models with the previous ones

- Good field quality
- Low multipole variation with current
- **The hybrid options save a significant amount of Nb_3Sn!!!**
- Temperature margin at NbTi is around 2K, more than current LHC main dipoles (1.3K)

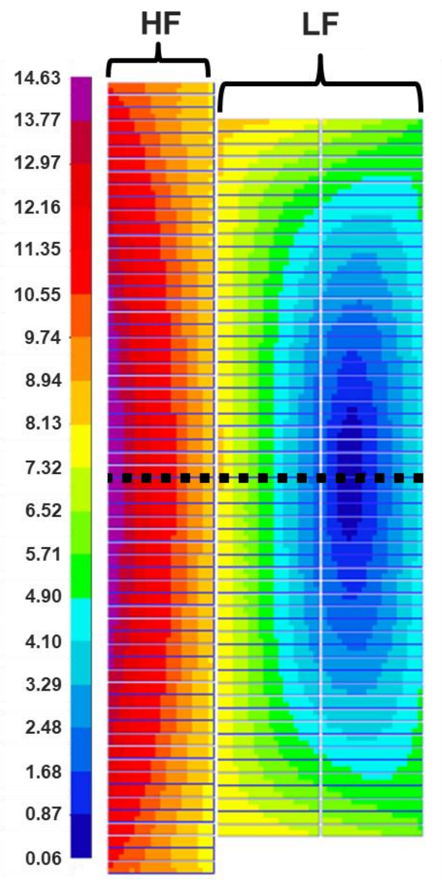


Parameters	Units	REF01	REF02	SN_1	SN_2	HYB_1	HYB_2
Material used	-	Nb_3Sn	Nb_3Sn	Nb_3Sn	Nb_3Sn	Nb_3Sn + NbTi	Nb_3Sn + NbTi
Nominal current	A	13476	14723	13701	14649	15359	15425
Loadline margin	%	19.9	19	20	19.8	19	19.4
Temperature margin	K	4.43	4.3	4.45	4.42	2.05	2.13
Equivalent coil width	mm	50.7 (26.8+23.8)	55 (27+28)	59 (29.3+29.7)	58.4 (30+28.4)	61.1 (32.4+28.7)	60.5 (31.6+29)
Max. Temp (Dump: 1000 V, 40 ms)	K	264	266	287	245	157	153
b3 / a2 / max. multipole	units	251 / -30 / -2 (b5)	134 / -35 / -40 (b5)	4 / -13 / 13 (a6)	11 / -12 / -11 (b5)	12 / -12 / 13 (a6)	7 / 2 / 12 (a6)
Inc. b3 / a2 / max. increment	units	-228 / 30 / 2 (b5)	-9 / 35 / 6 (b5)	-4 / 29 / 3 (a4)	10 / 25 / 7 (a4)	-2 / 4 / -3 (a6)	6 / 34 / 7 (a4)
Nb_3Sn strand consumption	km	18.1	20.5	22.94	22.79	9.64	11.6
NbTi strand consumption	km	-	-	-	-	11.72	10
Nb_3Sn length compared to REF01	%	0	13	27	26	-47	-36
Nb_3Sn length compared to equiv. SN	%	-	-	-	-	-58	-49

*All models for 320 mm of intrabeam distance and 14T in a 50 mm aperture

DAISY: design guidelines

- **DAISY** will be our **first common coil magnet demonstrator**:
  - We propose not featuring accelerator field quality, but addressing the challenge of mechanics of a hybrid magnet.
  - It will have a high field coil with a single layer of Nb_3Sn cables and a double pancake coil with NbTi cables.
- **Schedule**:
  - Calculations: June 2025
  - Cable orders: July 2025
  - Manufacturing drawings: October 2025
  - Tooling: March 2026
  - Coil fabrication: September 2026
  - Magnet assembly: November 2026
  - Magnet test: January 2027
- In a **second step**, we would target a hybrid common coil magnet performing accelerator field quality.



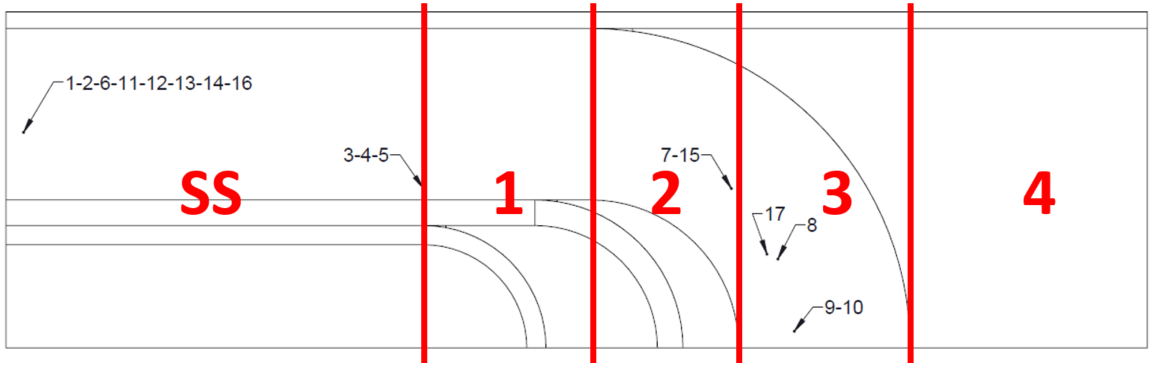
Conclusions

- **CIEMAT** is contributing to HFM Programme by means of common coil magnets.
- **ISAAC** is a model magnet made using existing RMC coils. Mechanics is based on a low preload concept. Magnet test is foreseen for next autumn.
- We have explored the space design of common coil magnets providing 14 T in a 50 mm aperture at 1.9 K.
- We have found very promising results for **hybrid magnets** using Nb_3Sn and NbTi coils.
- **DAISY** will be our first common coil magnet demonstrator. We propose not featuring accelerator field quality, but addressing the **mechanics** of a hybrid magnet.
- In a **second step**, we would target a hybrid common coil magnet performing accelerator field quality.

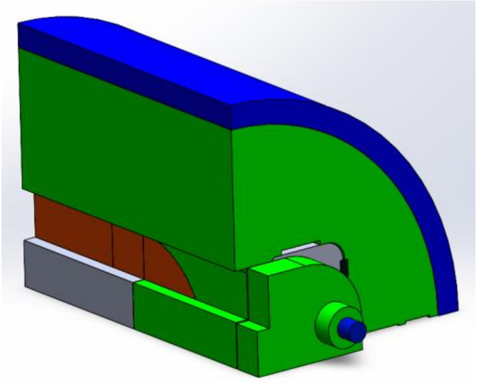
Extra slides

ISAAC 3D Design: Iron

- The spacer and the pad can be made of iron. **Which length?**
- If the spacer is made of iron, it should not be longer than the pad. When the peak field is at the straight section, the margin on the load-line increases.
- The stored magnetic energy decreases with more iron volume.
- A full iron pad provides better support to the large outwards horizontal EMF.



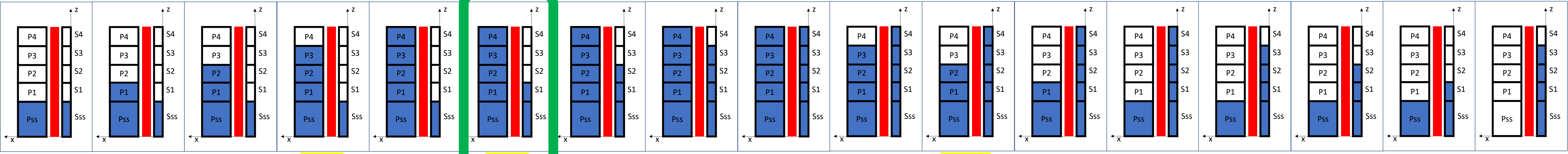
Case	Nominal current (kA)	Aperture Field in SS (T)	Peak Field (T)	Peak Field Loc.	Field Ratio	Transfer Function (T/kA)	Load line (%)	Stored Energy Q1 (kJ)	Fx Structure (kN)
#1	19.340	13.912	14.660	SS	1.054	0.719	99.6	76.06	1508.88
#2	19.040	13.763	14.502	SS	1.054	0.723	98.4	74.38	1461.93
#3	18.804	13.626	14.382	SS/1	1.055	0.725	97.5	73.13	1423.10
#4	18.663	13.547	14.315	SS/1	1.057	0.726	97.0	72.61	1407.84
#5	18.754	13.599	14.370	SS/1	1.057	0.725	97.4	73.52	1443.50
#6	18.665	13.525	14.249	SS	1.054	0.725	96.7	72.81	1408.69
#7	18.604	13.480	15.225	2	1.129	0.725	101.5	72.32	1382.28
#8	18.557	13.460	14.392	3	1.069	0.725	97.2	71.96	1351.00
#9	18.508	13.462	14.499	3	1.077	0.727	97.7	71.82	1345.53
#10	18.509	13.390	14.266	3	1.065	0.723	96.5	71.13	1321.44
#11	18.635	13.464	14.186	SS	1.054	0.723	96.3	71.65	1334.09
#12	18.859	13.596	14.326	SS	1.054	0.721	97.3	72.87	1368.68
#13	19.147	13.738	14.477	SS	1.054	0.717	98.4	74.52	1410.68
#14	19.152	13.751	14.490	SS	1.054	0.718	98.5	74.57	1411.07
#15	19.190	13.780	14.847	2	1.077	0.718	100.4	74.87	1444.02
#16	19.253	13.830	14.574	SS	1.054	0.718	99.1	75.35	1472.37
#17	19.904	13.415	14.366	3	1.071	0.674	98.9	79.30	1518.37



The best-balanced design option is Case #6.

- **Pad entirely made of iron**
- **Short spacer made of iron** (SS+S1)

More info @ "Mechanical Design of a Common Coil Magnet with RMC Coils (ISAAC)" *doi: 10.1109/TASC.2025.3537063*



Case #1 | Case #2 | Case #3 | Case #4 | Case #5 | Case #6 | Case #7 | Case #8 | Case #9 | Case #10 | Case #11 | Case #12 | Case #13 | Case #14 | Case #15 | Case #16 | Case #17

ISAAC 3D Design: coil stress

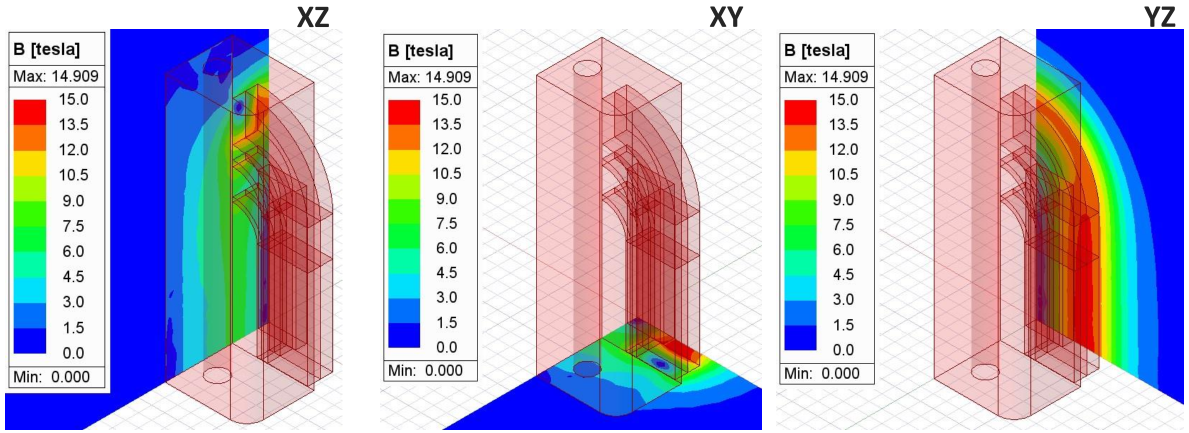
Nominal current: 19340 A

Vertical preload: 0.2 mm interference

Aluminium rods with **25kN pretension** each

	Coil	Spacer	Pad
Fx	2,02 MN	-28,63 MN	-36,99 MN
Fy	0,42 MN	58,30 MN	-13,26 MN
Fz	0,30 MN	-24,15 MN	-64,92 MN
Total F	2,08 MN	29,32 MN	39,83 MN

EMF per quadrant

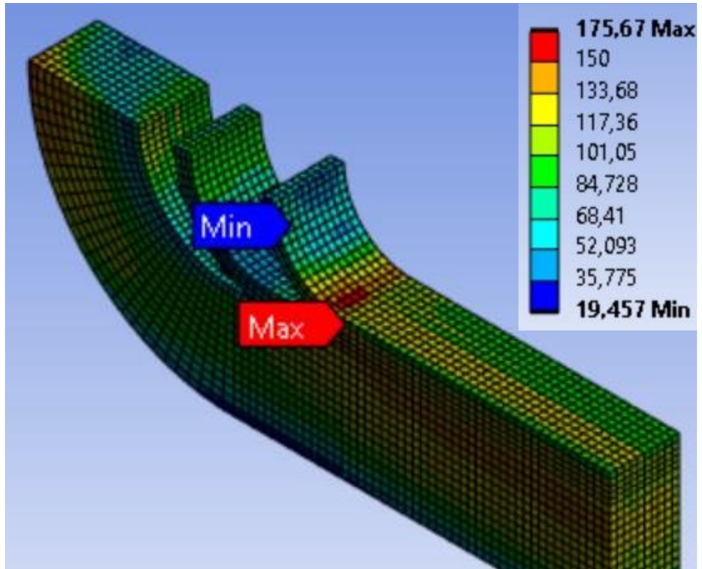


@RT: -120 MPa <-> 20 MPa

@Cold: -150 MPa <-> 20 MPa

	COIL				
	X stress	Y stress	Z stress	VM stress	
Max	2,7 MPa	-5,0 MPa	-0,5 MPa	**20,1 MPa**	RT Assembly with Rod Pretension
Min	-14,7 MPa	-26,4 MPa	-10,6 MPa	3,3 MPa	
Max	**50,1 MPa**	-2,7 MPa	**54,2 MPa**	**133,2 MPa**	Cooling
Min	-8,6 MPa	-131,4 MPa	-75,6 MPa	**22,1 MPa**	
Max	**68,6 MPa**	**64,5 MPa**	**141,1 MPa**	**175,7 MPa**	Cooling + EMF
Min	-104,3 MPa	**-167,3 MPa**	-73,5 MPa	19,5 MPa	

Coil Stresses over limits only in some located areas (bonded to coil parts)



Equivalent VM (MPa)

	COIL SHEAR STRESS								
	Planar surfaces		1st Block surfaces		2nd Block surfaces		3rd Block surfaces		
	XY	XZ	XY	XZ	XY	XZ	XY	XZ	
Max	2,1 MPa	1,9 MPa	2,0 MPa	0,3 MPa	2,3 MPa	0,2 MPa	4,7 MPa	2,0 MPa	RT Assembly with Rod Pretension
Min	-0,7 MPa	-1,0 MPa	-0,5 MPa	-0,2 MPa	-0,1 MPa	-0,4 MPa	-0,2 MPa	-1,2 MPa	
Max	0,4 MPa	28,0 MPa	22,5 MPa	31,4 MPa	10,9 MPa	7,3 MPa	32,2 MPa	7,1 MPa	Cooling
Min	-43,2 MPa	-28,1 MPa	-15,5 MPa	-31,8 MPa	-13,2 MPa	-10,7 MPa	-14,5 MPa	-8,6 MPa	
Max	0,4 MPa	44,2 MPa	44,3 MPa	42,0 MPa	29,6 MPa	25,3 MPa	**54,9 MPa**	**52,5 MPa**	Cooling + EMF
Min	**-64,9 MPa**	-32,3 MPa	-18,9 MPa	-22,8 MPa	-16,9 MPa	-29,3 MPa	-26,0 MPa	-36,6 MPa	

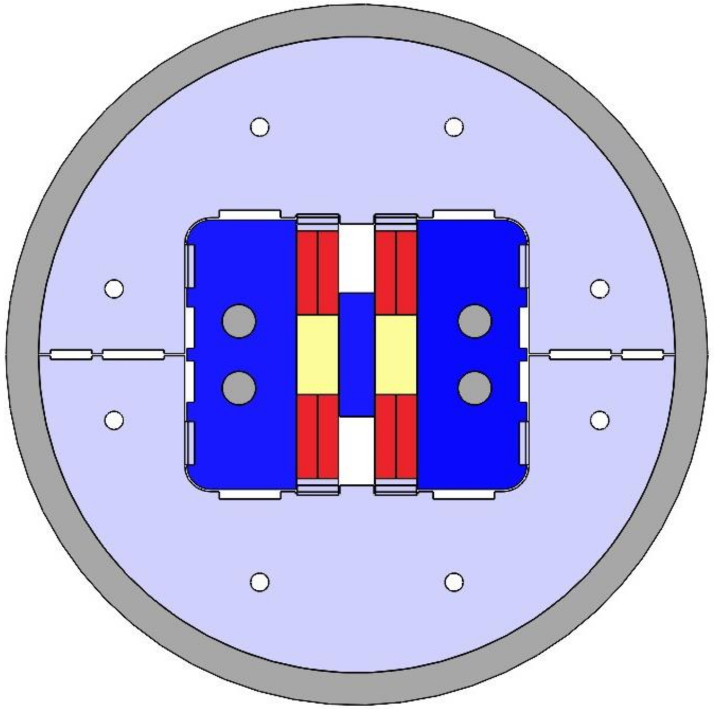
@RT & Cold:

-45 MPa <-> 45 MPa

	COIL DISPLACEMENT DUE TO EMF		
	X	Y	Z
Max	**0,27 mm**	0,03 mm	**0,21 mm**
Min	0,14 mm	**-0,05 mm**	0,00 mm

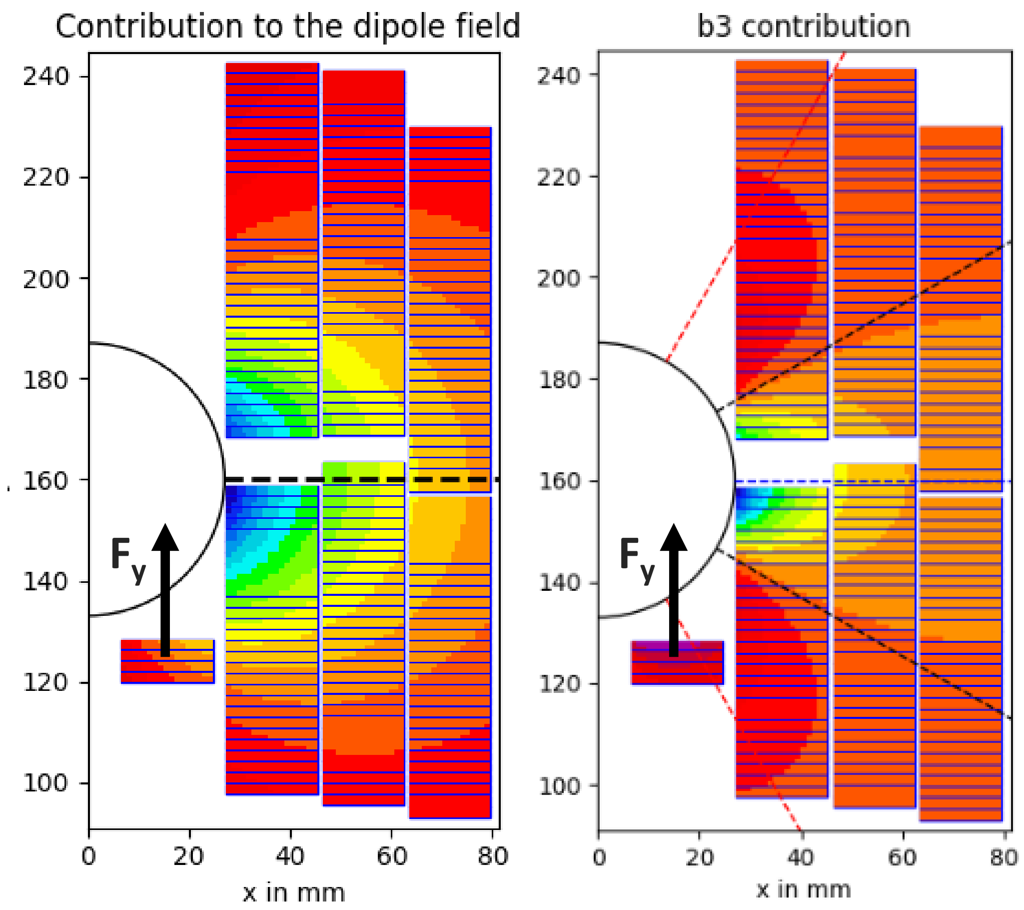
ISAAC Learned lessons (up to now)

- **Horizontal preload** over the coil is difficult to apply, but a stiff support structure allows small coil displacement.
- Most of the horizontal electromagnetic forces are hold by the **yoke** (different from other magnet configurations running in parallel).
- **Glued titanium pole** induces large shear and horizontal stresses at pole turn. No simple way to reduce them.
- **Short intrabeam distance** decreases superconductor efficiency and induces repulsive vertical forces, that is, tensile stress at pole turn.
- Off-centering forces on **central spacer** are difficult to hold.
- **Axial preload without contact at coil loading plate** induces large shear stresses at glued pole turn.
- **Slow learning curve**: common coil magnets look simple, but…



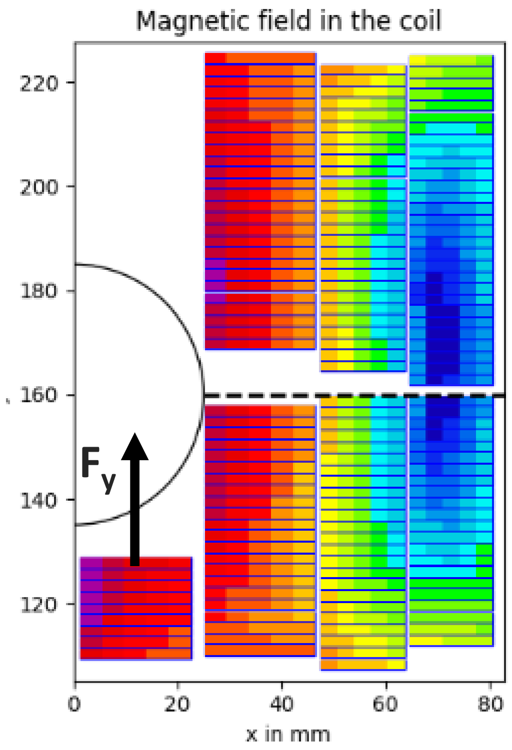
Field quality in a common coil: exploring the asymmetric field quality coil

D. Araujo, B. Auchmann, A. Brem, T. Michlmayr, A. Haziot and E. Ravaioli, "Electromechanical Design of Nb3Sn Stress Managed Asymmetric Common-Coils". Article DOI: 10.1109/TASC.2025.3532906.



Mechanics!! This additional coil feels a force towards the aperture. Some support structure is required.

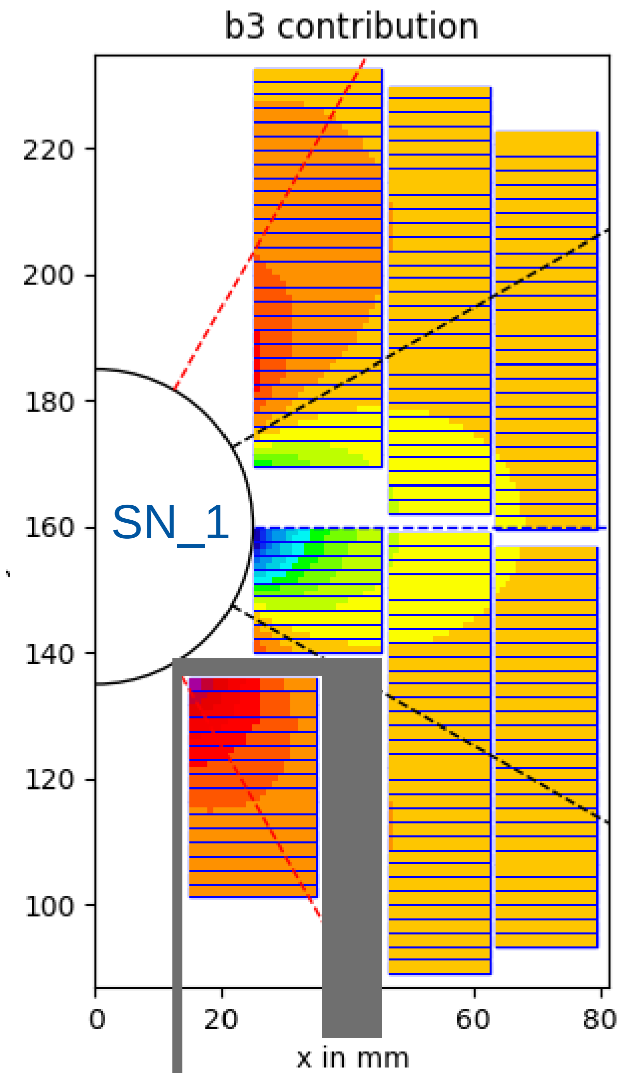
The sextupole can be compensated with this coil but the midplane gap is still large, losing efficiency.

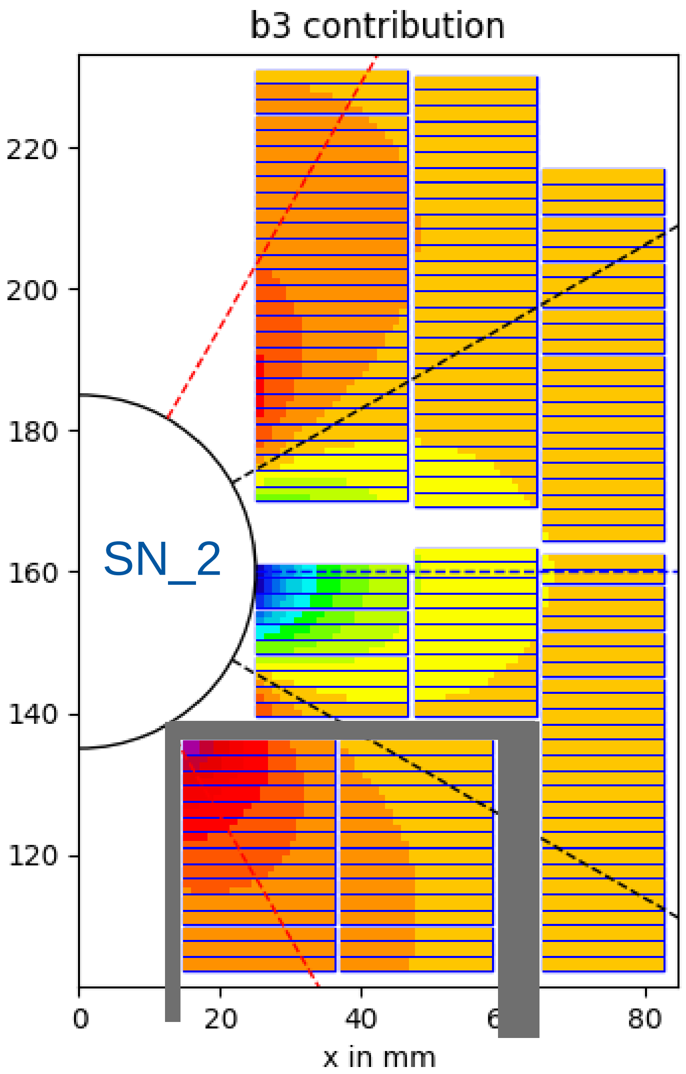


Only few strands hit the maximum b_3 contribution region and the block has a low contribution to the main field

If the cable needs to be wide, it is very near the vertical axis where all the magnetic flux is concentrated, leading to high peak field/load and low efficiency.

Field quality in a common coil: What if…?





…we move the lower turns towards the aperture?

- Sextupole compensation should be more efficient
- Main field efficiency is lost in the gap around the pole coil, but it is further from the aperture.
- A casing could hold the EM forces.