Magnets design for Soleil Upgrade

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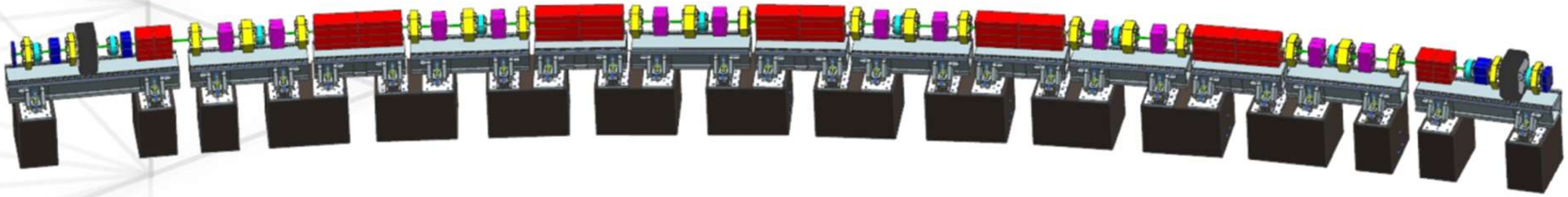
SOLEIL UPGRADE PROJECT: TOWARDS 4th GENERATION SYNCHROTRON LIGHT SOURCE

SOLEIL SYNCHROTRON UPGRADE

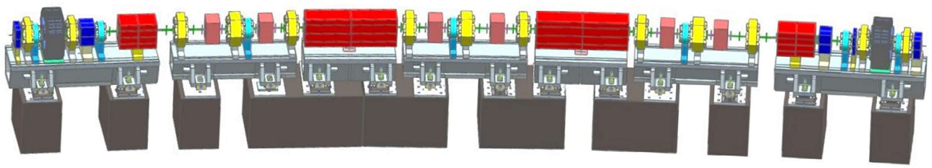
Key features:

1. 80 pm.rad / 2.75 GeV / 354 m.
2. 20 straight sections (4 of ~8 m; 8 of ~4.2 m and 8 of ~2.7 m).
3. Large photon spectrum (far IR to hard X-rays).
4. Non-standard MBA lattice: 12 x 7BA + 8 x 4BA.
5. NEG coated very small vacuum chamber diameter = 10 mm.
6. Extensive use of permanent magnets.
7. Miniaturization.
8. Off-axis injection.
9. High performance Multipole Injection Kicker (MIK).
10. Energy Savings.

7BA cell



4BA cell



CDR Reference magnets lattice

- *Dipole in red*
- *Reverse Bend in magenta*
- *Quadrupole in blue,*
- *Sextupole in yellow*
- *Octupole in cyan*

SOLEIL SYNCHROTRON UPGRADE

Magnets For SOLEIL Upgrade at One Glance

Number of magnets

Total number : **1296**

Number of types : **41** types + 7 x Superbend (SB) with 3 T or 1.7 T magnetic field

Compactness: distance between magnets very short (50 mm and in one location down to 30 mm yoke-to-yoke)

Extensive use of:

1. **PM design**
   - Dipole with transverse gradient
   - Quadrupole
   - Reverse Bend
2. **Combined function magnets**
   - dipole with transverse gradient
   - Sextupole + dipolar correctors
   - Octupole + normal and skew quadrupole

Harmonics : under discussion and iterations

Magnetic measurements: usual methods such as Stretched wire and Hall probe

Type		Gap or diameter [mm]	Dev[mrad]	Lmag[mm]	B[T]	B'[T/m]	Nbr	Tot
Permanent Magnet	Short dipole							
	DNC1	23	41.8	430	0.893	-17.7	22	40
	DNC2	23	39.9	430	0.851	-17.7	16	
	DNC3	23	41.9	430	0.893	-22.01	1	
	DNC4	23	42	430	0.895	-22.01	1	
	Long dipoles							
	DNL1	19	68.2	947	0.551/1.2/0.551	-21.57	58	76
	DNL2	19	65	947	0.551/1.2/0.551	-21.57	16	
	DNL3	19	68.7	947	0.551/1.2/0.551	-21.57	1	
	DNL4	19	66.3	947	0.551/1.2/0.551	-21.57	1	
	Long ReverseBend							
	DIL1	21	-3	140	-0.197 (-2.5 mm)	80.85	118	152
	DIL2	21	-2.9	140	-0.188 (-2.3 mm)	80.85	32	
	DIL3	21	-3.7	140	-0.242 (-3.0 mm)	80.85	1	
	DIL4	21	0.2	140	+0.015 (+0.18 mm)	80.85	1	
	Short ReverseBend							
	DIC1	18	-1	100	-0.092 (-0.8 mm)	120	24	40
	DIC2	18	-0.95	100	-0.088 (-0.7 mm)	120	16	
	Quadrupole QF	16		54 to 94		120	150	162
	and QD	21		146 to 216		80	12	
			Mech.Length(mm)		Integrated strength			
Electromagnet	Sextupoles	21	60		300 T/m		12	408
		16	60		520 T/m		108	
		16	80		680 T/m		192	
		16	110		920 T/m		96	
	Octupoles	16	60		6000 T/m²		204	216
		21	60		3500 T/m²		12	
	Normal Corr quad	16	60		0.6 T	0.15	192	192

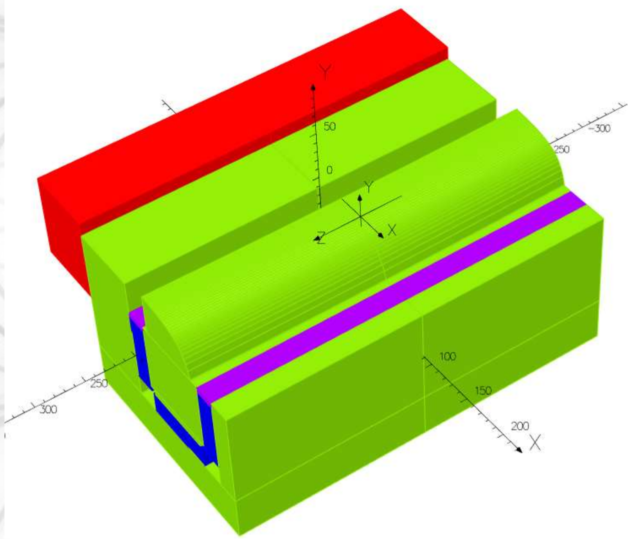
PM Dipoles

Dipoles Parameters

- Permanent Magnet in Sm_2Co_{17} (PM) + Low Carbon Steel (LCS)
- ThermoShim for temperature stability

- 40 short dipoles
- Size : 396 mm (L) x 302 mm (l) x 394 mm (H)
- Gap 23 mm for the short dipole

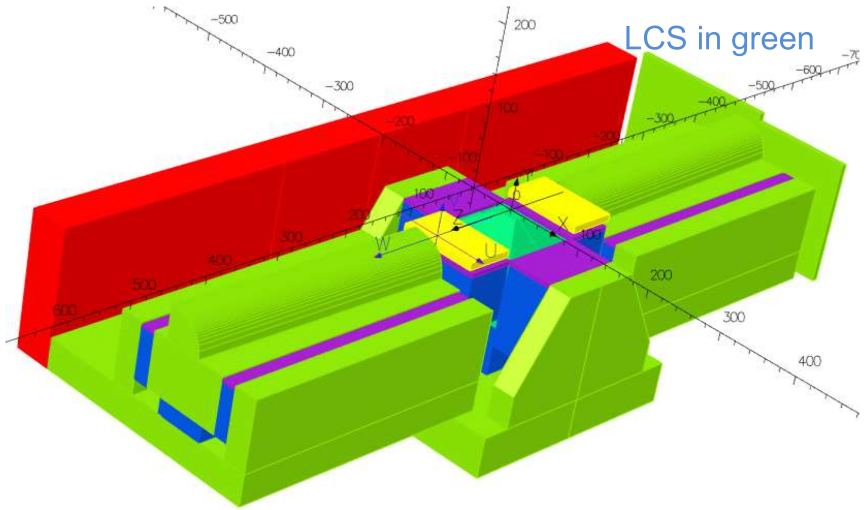
- 76 long dipoles
- Size : 925 mm (L) x 390 mm (l) x 439 mm (H)
- Gap 19 mm for the long dipole



ThermoShim
in purple

Moving Yoke in red (MY)

PM in blue



Floating poles in yellow

LCS in green

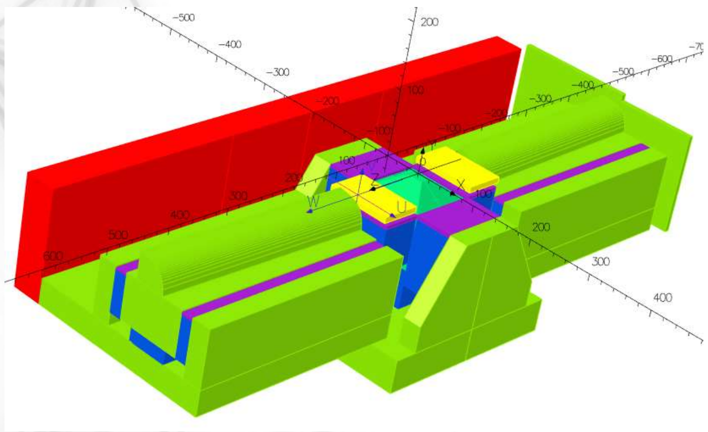
Progress report Dipole

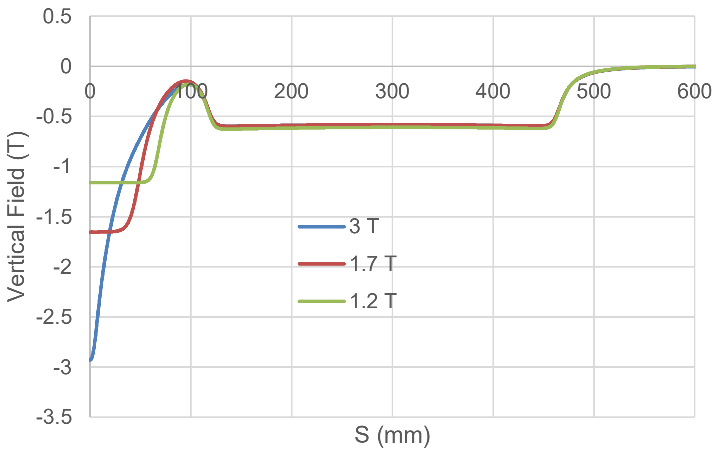
Long Dipole (76) :

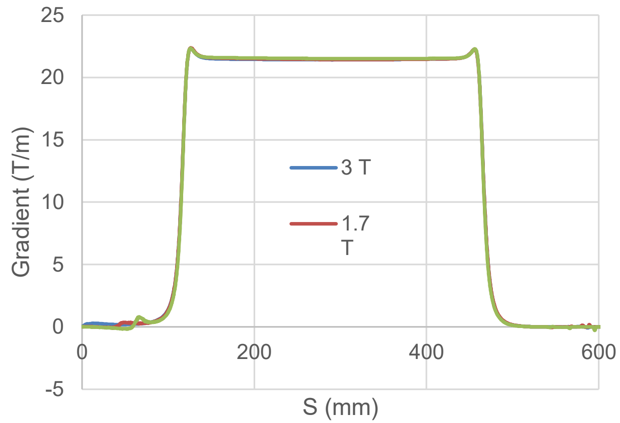
- Three Parts (Two Dipole/Quadrupole poles + Central pole)
- Four different deviation angles
- Fine tuning of the deviation angle by radial displacement
- Straight pole for the Dip/Quad Part (DQ pole)
- Adjustment of the Integrated gradient with floating pole

- Central field 1.2 T or 1.7 T or 3 T
- One quadrupolar strength (21 T/m)
- Adjustment of Gradient with the Moving Yoke (MY)
- Central pole Low carbon steel except Permendur for 3 T

→ As there is just one quadrupolar strength, the PM block size will be the same for all the long dipoles

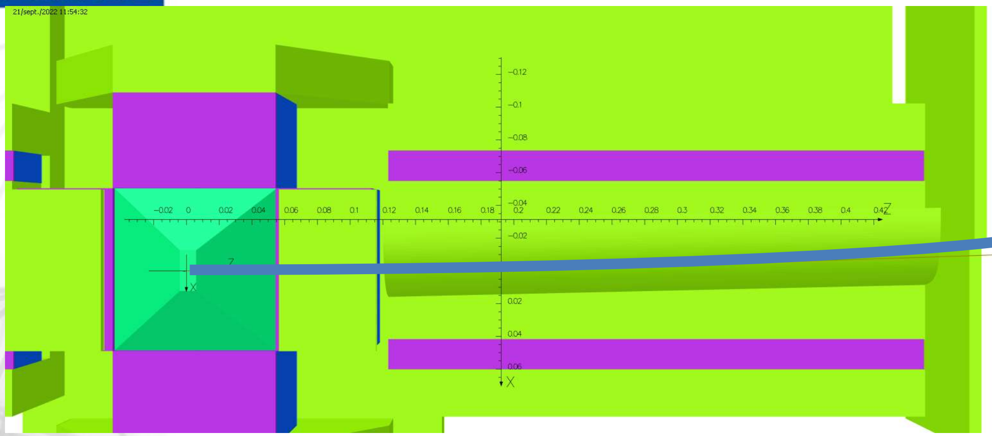






	1.2 T	Bn (Unit) @ 5mm	1.7 T	Bn (Unit) @ 5mm	3 T	Bn (Unit) @ 5mm
B_Integral	-0.611 (T.m)	10000	-0.612 (T.m)	10000	-0.614(T.m)	10000
G_Integral	15.442 (T)	-1264	15.419 (T)	-1260	15.514 (T)	-1263
S_Integral	4.4 (T/m)	-2	-20.4 (T/m)	8	-65.8 (T/m)	27
O_integral	-5732 (T/m²)	12	-5702(T/m²)	12	-4411 (T/m²)	9

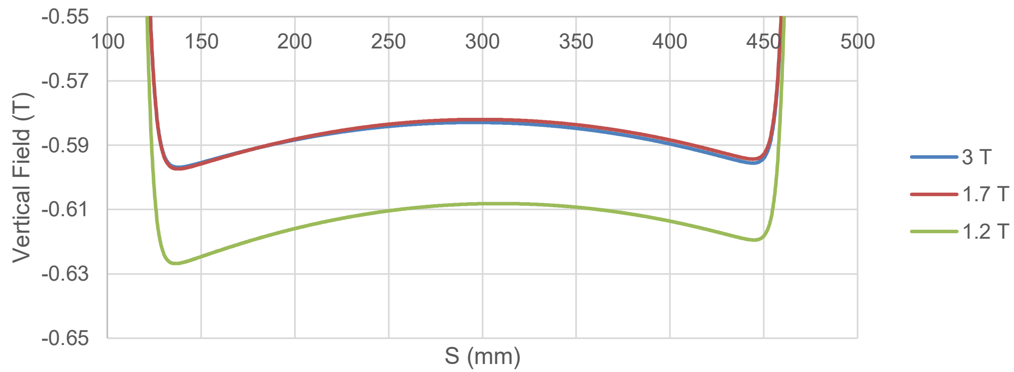
Adjustment of the DQ pole



Trajectory is computed in Tosca/post processor (with 0.25 mm step)
The deviation angle is deduced from the trajectory
For the harmonic content, an 2D-harmonic analysis of the magnetic potential at each point of the trajectory is done. We cumulate the harmonics to get:

- Integrated gradient (B2)
- Integrated sextupole (B3)
- Integrated octupole (B4)

The deviation angle and the integrated gradient input quantities for the Optimiser to get the right pole shape, magnet's block size, DQ pole orientation (Y axis) and DQ pole position (X axis)



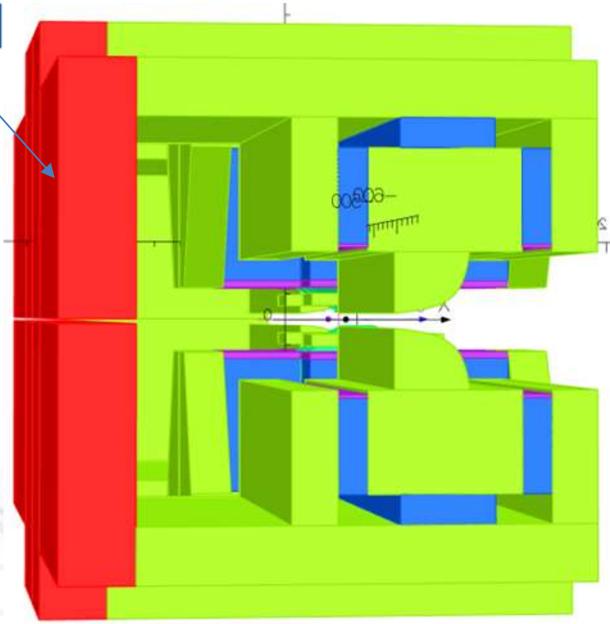
Although the pole is straight, the field variation along the trajectory is only 20 mT.

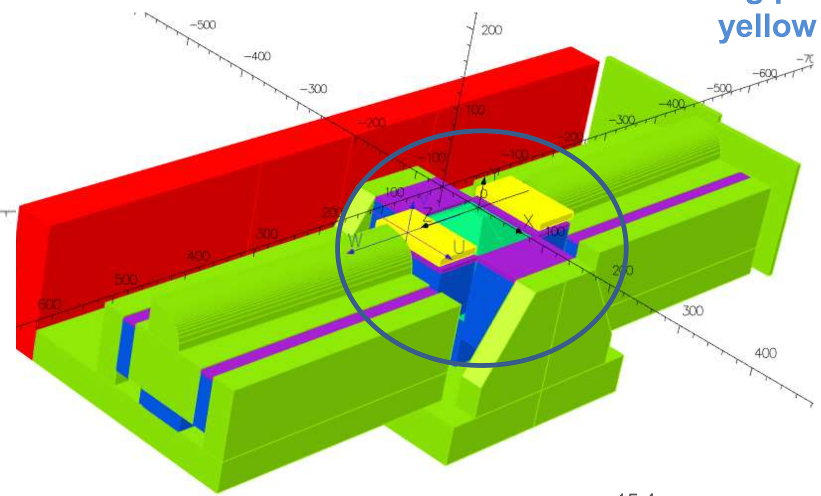
SOLEIL SYNCHROTRON UPGRADE

Long dipole: Tuning scheme

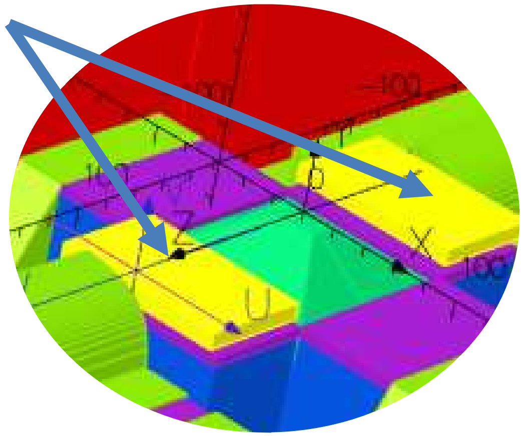
Moving Yoke

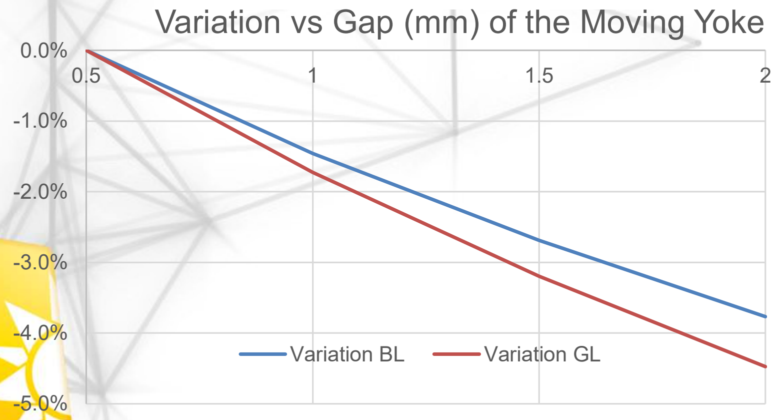
variable gap





Floating poles in yellow

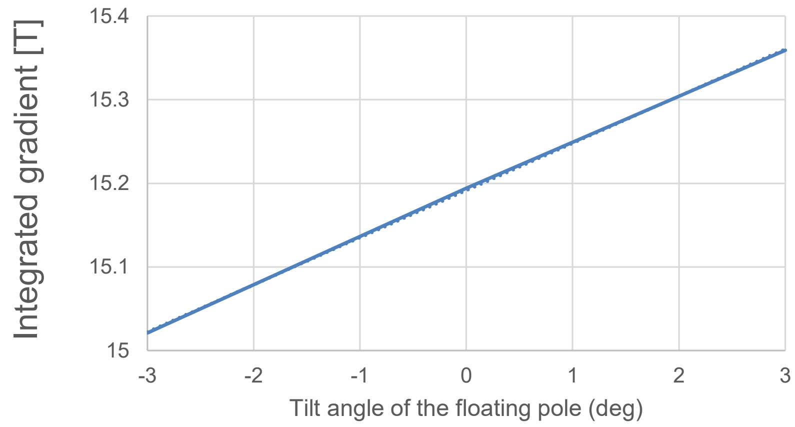




By changing the Gap of the moving yoke:

- **~3%.mm^{-1} Gradient integral variation**
- **~2%. mm^{-1} Vertical field integral variation**

By changing the lateral position of the dipole one can adjust the vertical field integral only (~2%. mm^{-1}) due to the gradient.



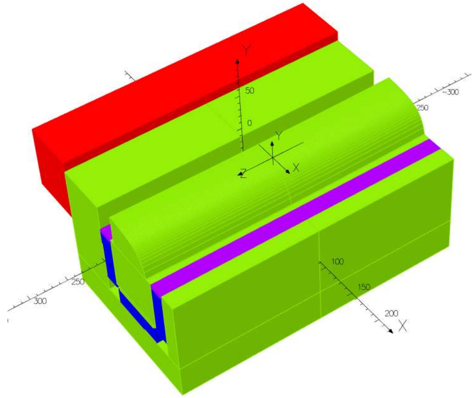
- **Tilting the floating poles around the beam axis changes the gradient integral (~0.3%.deg^{-1})**
- **The vertical field integral not impacted**

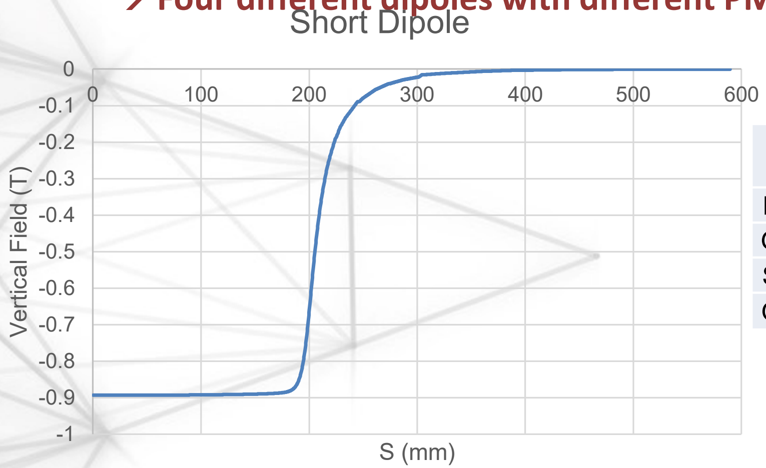
Short Dipole

Short Dipole (40) :

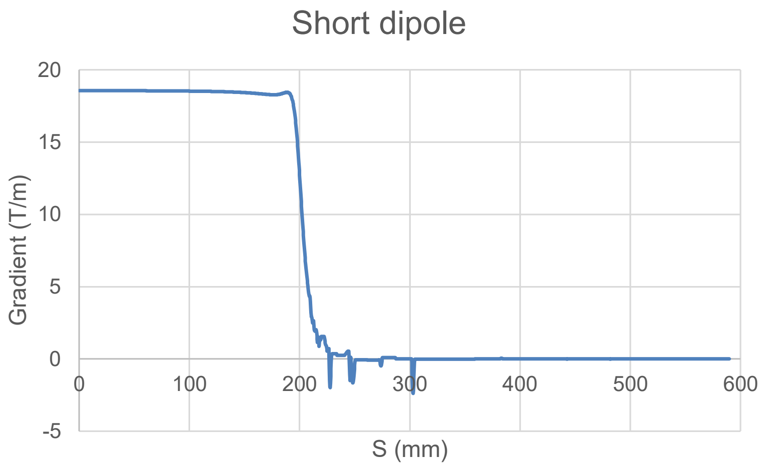
- Four different deviation angles
- Two quadrupolar strengths (17.7 T/m and 22.0 T/m)
- Adjustment of Gradient with the Moving Yoke (MY)
- Fine tuning of the deviation angle by radial displacement and magnetic short circuit
- Curved poles following the E-beams trajectory (may change)

→ Four different dipoles with different PM block size and pole shape

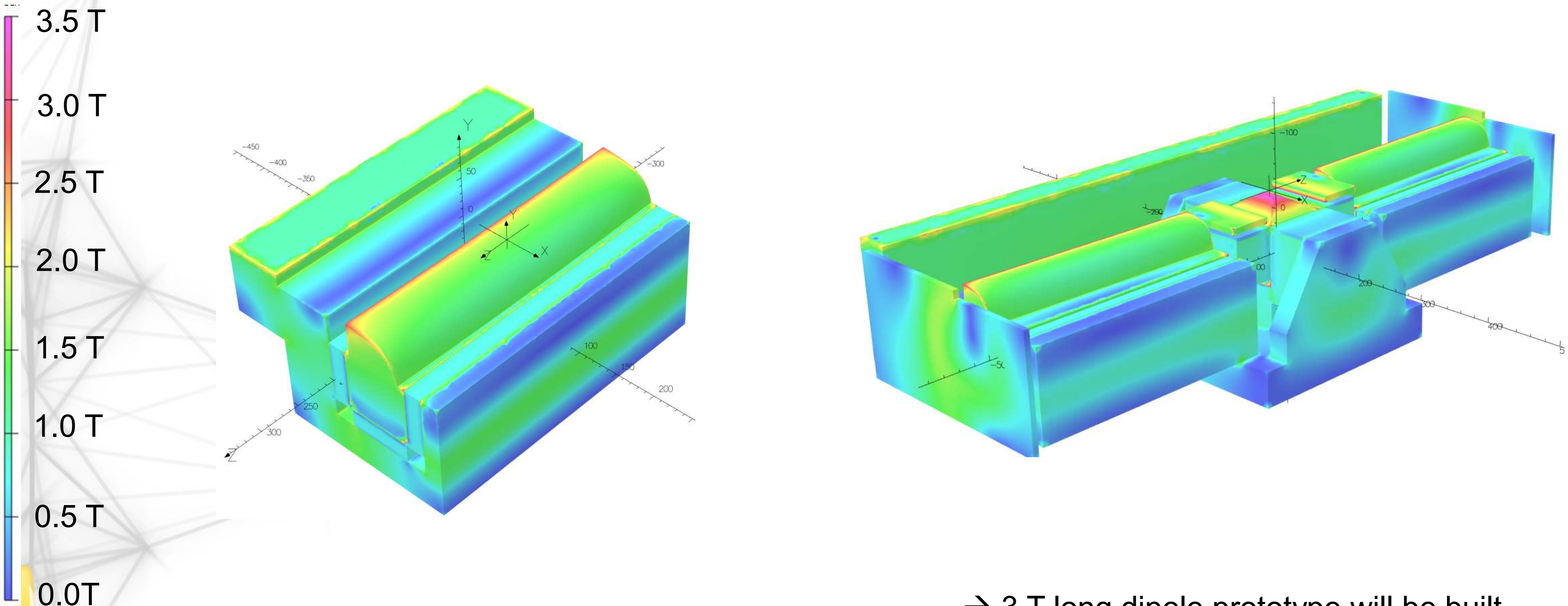




	Short dipole	Bn (Unit) @ 5mm
B_integral	-0.374 (T.m)	10000
G_Integral	7.646 (T)	-1021
S_Integral	-23.571 (T/m)	16
O_integral	-2436.516 (T/m²)	8

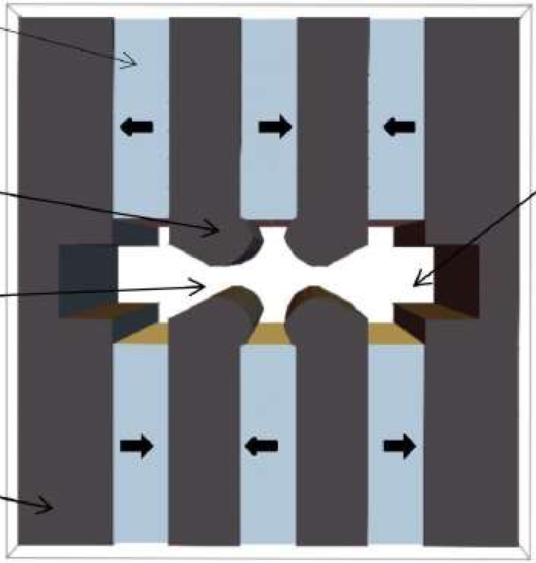


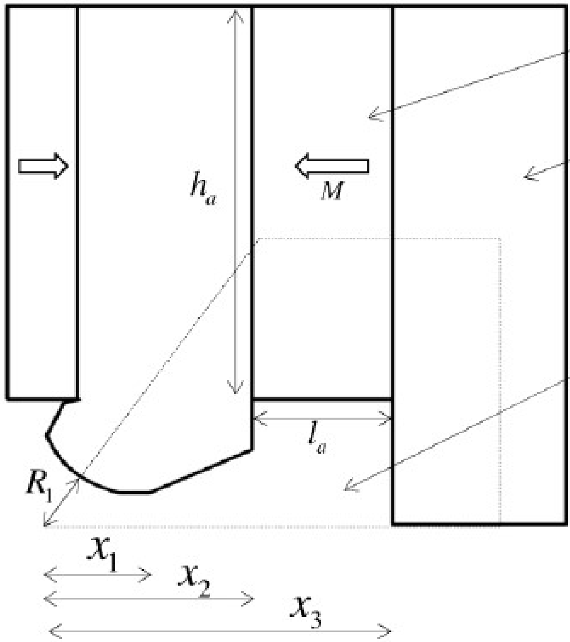
Dipoles



→ 3 T long dipole prototype will be built next year

Proposed Quadrupole/ReverseBend





$$G = \frac{B_r l_a}{\frac{R^2}{2} - \frac{x_1{}^2 l_a}{h_a}\left(\frac{1}{2} + \frac{x_3}{x_1 - x_3} \times ln\left(\frac{x_3}{x_1}\right)\right)}$$

Br [T]	R [mm]	x1 [mm]	x3[mm]	La [mm]	Ha [mm]	G [T/m]
1.1	8	10.1	60	20	60	239.4

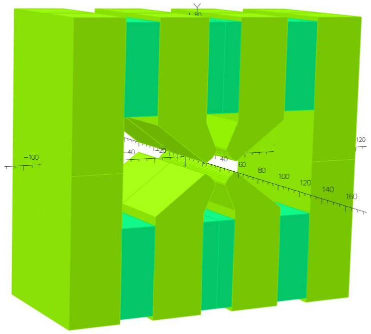
Hybrid high gradient permanent magnet quadrupole,P. N'gotta, G. Le Bec, and J. Chavanne, Phys. Rev. Accel. Beams 19, 122401 – Published 20 December 2016

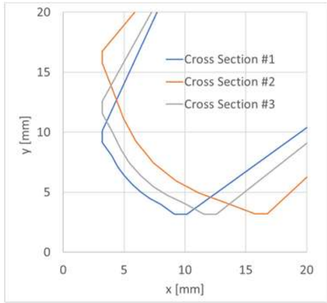
G ≈240 T/m
μ=∞

A idealistic value but 160 T/M reachable with classical BH curve of the steel

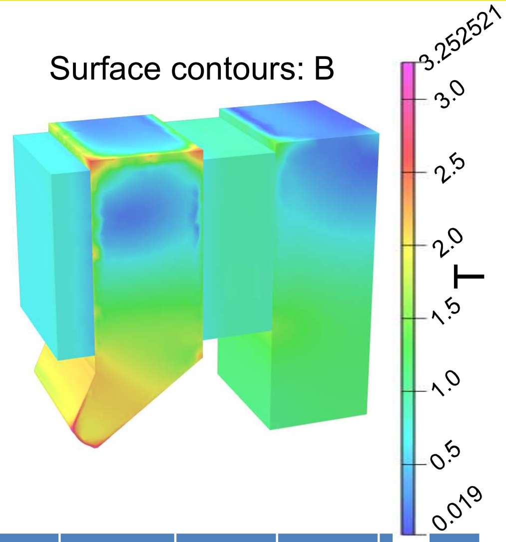
Quadrupole/ReverseBend

- Lattice includes 19 different Quadrupoles (162) and ReverseBends (192)
- Fixed gradient quadrupole and reversebend
- 3 different pole cross-sections
- Length adjusted to match lattice requirements
- Reversebends are quadrupoles with an offset
  - <0.8 mm for short ReverseBend (DIC)
  - 0.18 mm to 2.45 mm for long ReverseBend (DIL)





	Width [mm]	Height [mm]
Profil #1	180	165
Profil #2	180	191
Profil #3	180	165

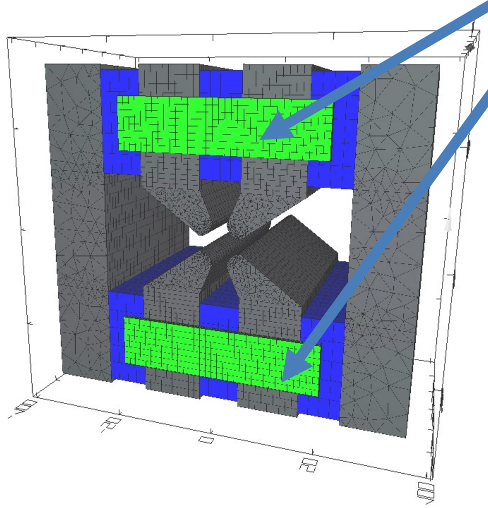


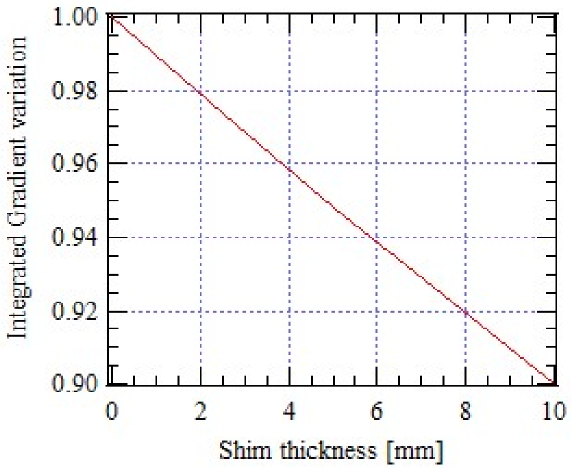
Name	QD10	QD17	QD13	QD12	QD04	QD15	QD07	QD06	QD09	QF11	QF16	QF05	QF14	QF08	QF01	QF03	QD02	DIL	DIC
Number	2	2	4	2	16	2	16	32	16	4	4	32	2	32	4	4	4	152	40
Cross-section	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3
Integrated gradient [T]	6.51	6.53	6.98	8.29	8.34	8.38	8.47	9.26	9.5	9.79	9.82	10.78	11.21	11.27	11.72	15.02	17.28	11.32	12.02
Yoke length [mm]	49.07	49.22	52.34	61.42	61.76	62.06	62.67	68.14	69.76	71.77	72	78.6	81.57	81.96	124.43	158.63	182.03	120.31	105.49
Aperture diameter [mm]	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21	21	21	21	18
Radius at which bn is computed [mm]	5	5	5	5	5	5	5	5	5	5	5	5	5	5	8	8	8	8	6
b4	-5	-5	-5	-4.8	-4.8	-4.8	-4.8	-4.7	-4.7	-4.7	-4.7	-4.6	-4.5	-4.5	-3.8	-3.5	-3.3	-3.9	-2.6
b6	-4.1	-4.1	-3.4	-1.8	-1.8	-1.7	-1.6	-0.8	-0.6	-0.3	-0.3	0.4	0.7	0.8	-0.4	2.4	3.8	-0.82	5.81
b8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-0.2	-0.2	-0.2	0
b10	-2	-2	-2	-2	-2	-2	-2	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	0.9	0.8	0.7	0.9	1

Work in progress to reduce the number of families

- Use of the lattice quadrupole EM correctors to reduce the number of families
- Optimization of the quadrupoles longitudinal position in the lattice
- Include in the mechanical design provisions to adjust the integrated gradient at the assembly (work to be done in collaboration with beam physicists)
  - Add shims at the quadrupole ends

Shim: 100mm x 25 mm x thickness

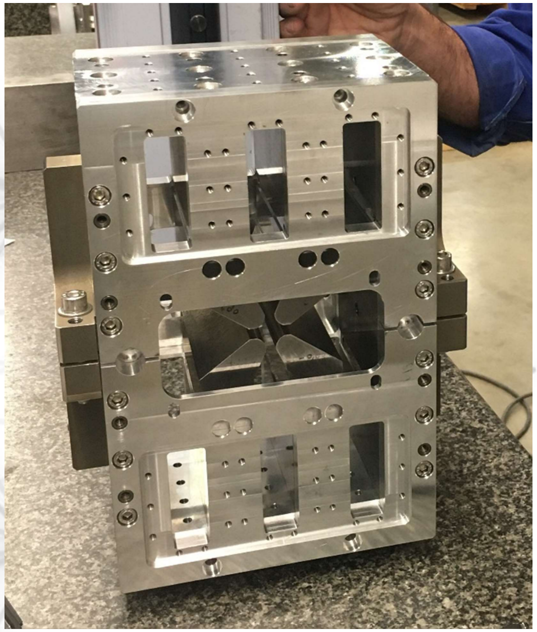




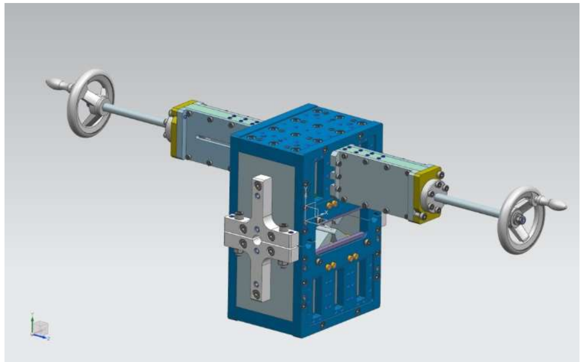
10% variation

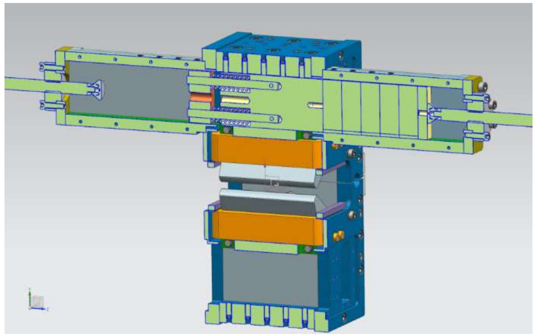
Quadrupole/ReverseBend

A first quadrupole prototype initiated in early 2020
- Non optimized profile to exhibit specific harmonics (b4 and b6)
- Include coils for heating

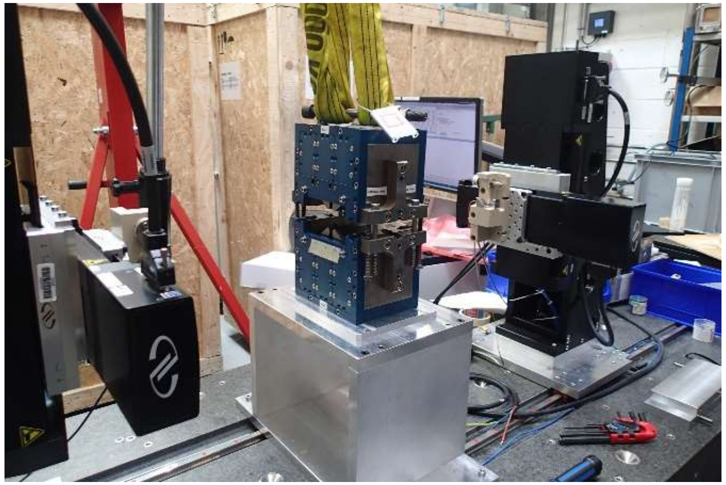


Empty yoke received from the vendor





Tooling for the insertion of PM blocks in the yoke
→ Less than 4 hours for the 30 PM blocks



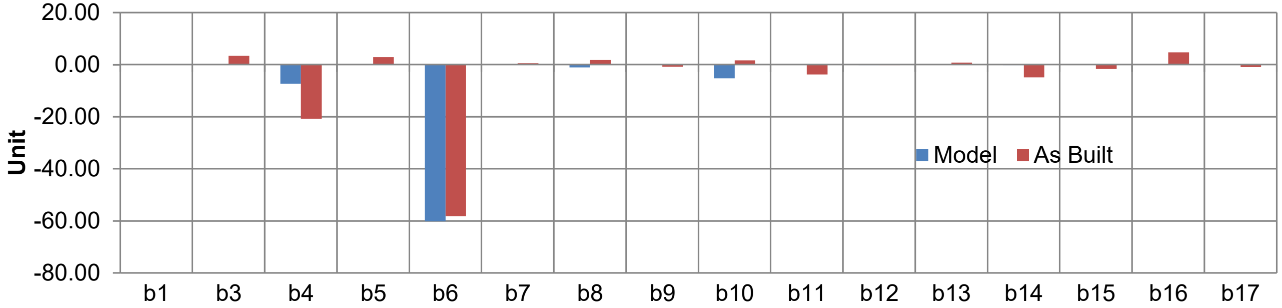
Ready for magnetic measurement

Quadrupole/ReverseBend

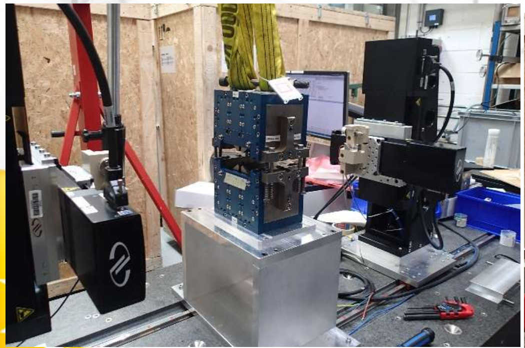
A first quadrupole prototype initiated in early 2020

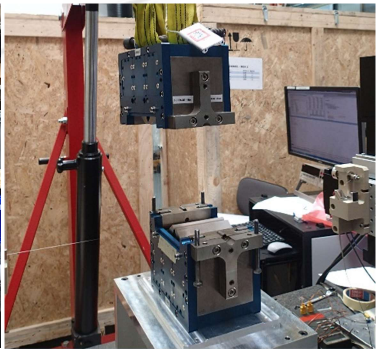
- 0.5% difference between b2 measured (56.819Tmm) and computed (57.077 Tmm)
- 2 units difference between b6 computed (-60) and measured (-58)

Norm. Harm.	b1	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	b15	b16	b17
Measured	0.3	3.4	-20.8	3.0	-58.4	0.7	1.9	-0.8	1.7	-3.7	-0.1	0.9	-4.9	-1.6	4.8	-0.8
Model	0.0	0.0	-7.3	0.0	-60.1	0.0	-1.0	0.0	-5.2	0.0	-0.1	0.0	-0.1	0.0	0.0	0.0



Open-up the quadrupole top from bottom part on the magnetic measurement bench

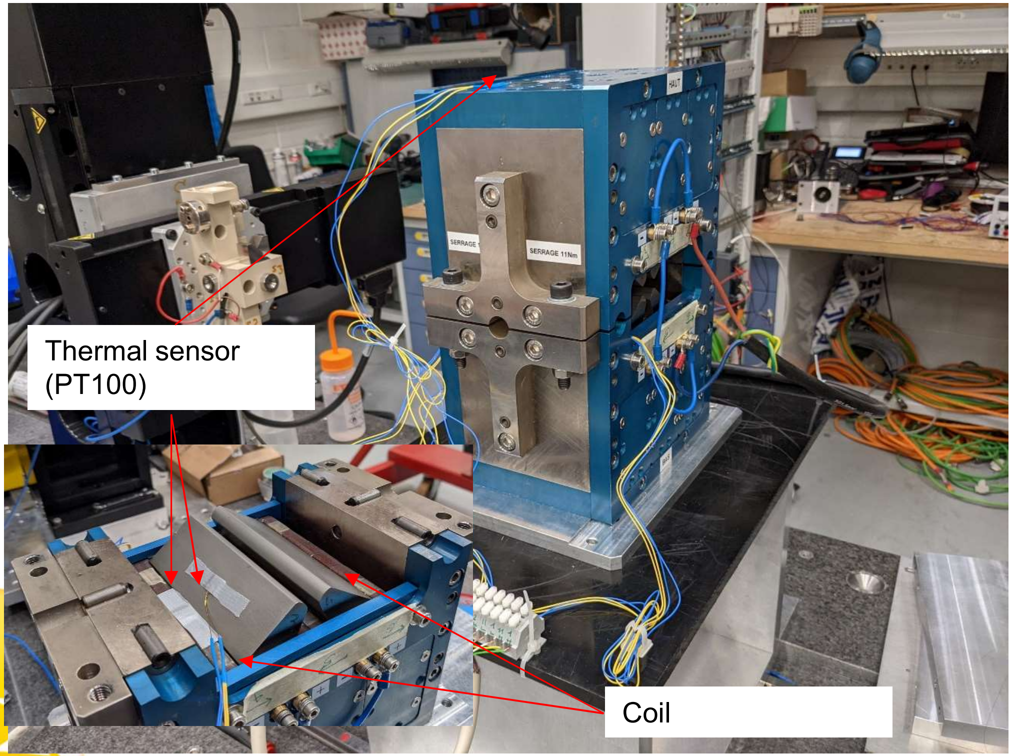


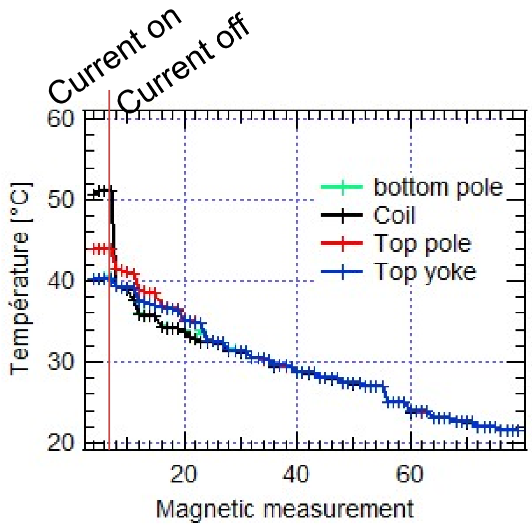


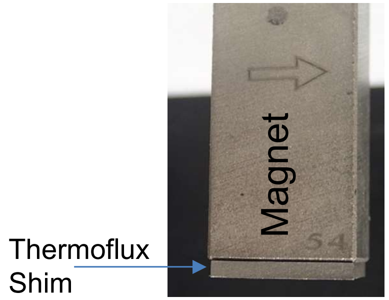
	Horizontal Center		Vertical Center	
	Ave. over 10 meas.	Stand. Dev.	Ave. over 10 meas.	Stand. Dev.
Opening #1	0 µm	2 µm	0 µm	4 µm
Opening #2	-1 µm	2 µm	3 µm	7 µm
Opening #3	-1 µm	1 µm	1 µm	3 µm

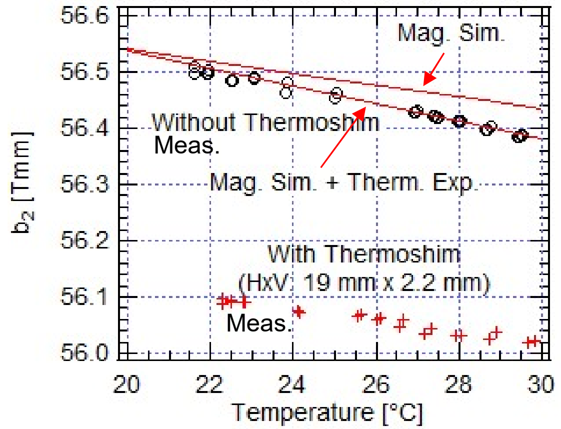
Quadrupole/ReverseBend

- Experimental validation of thermoflux shims:
  - Turn on the current (7 A) in the quadrupole coils to heat the quadrupole up to 40 °C
  - Turn off the current and periodic magnetic and thermal measurements performed during the cooling of the quadrupole



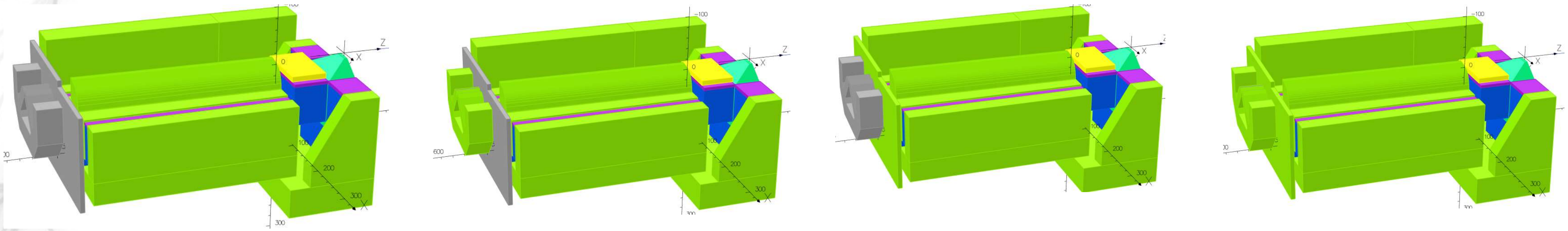




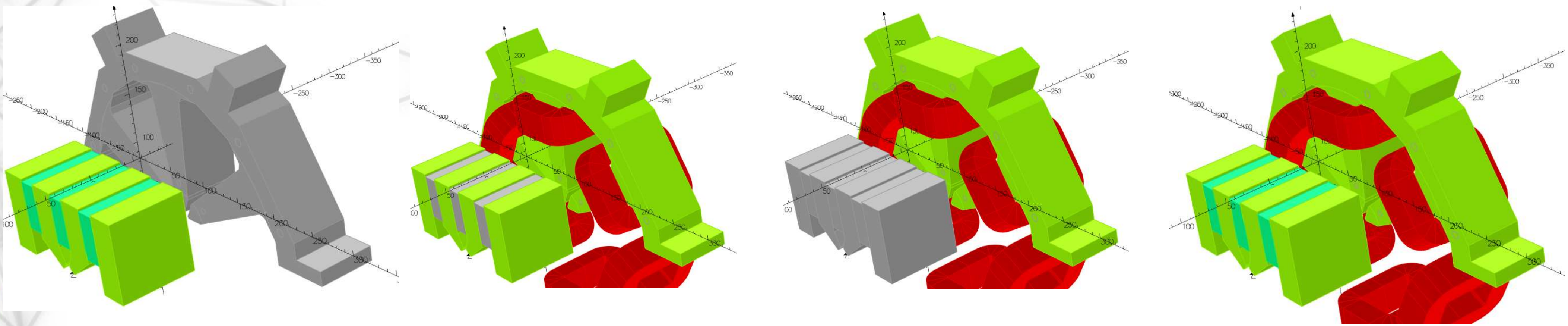


- As temperature varies, thermal expansion of the mechanical structure adds to the magnet remanence variation
- From simulation, a 1.5 mm thick shim expected to compensate for remanence variation
- From measurement ~7.2 mm thick thermoflux shim necessary to compensate for both thermal expansion and remanence variation

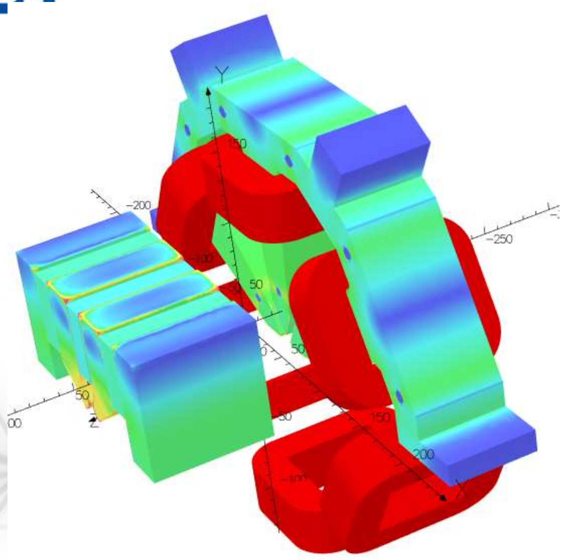
Cross talk first results

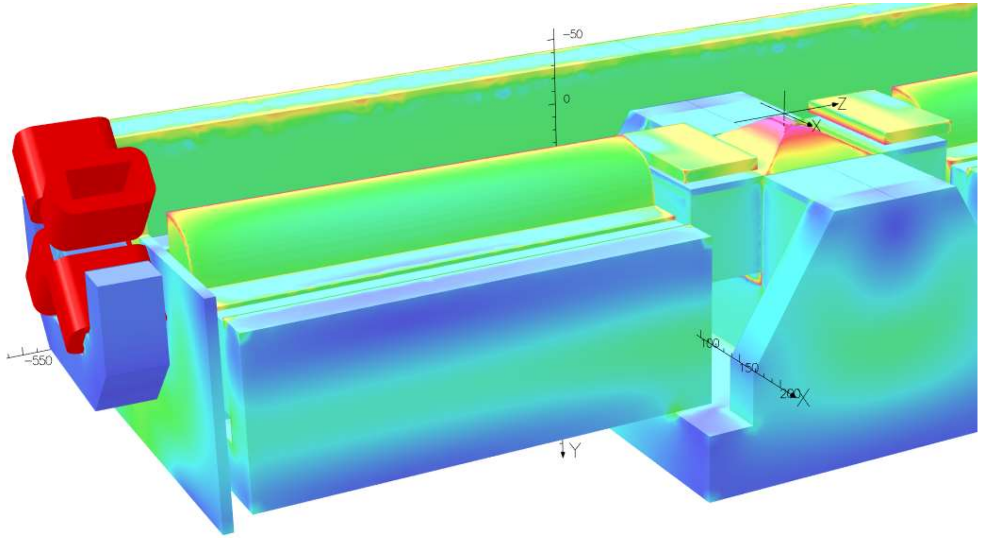


In order to avoid any mesh effect, the material of the different part are switched from “AIR” TO “ STEEL”



Cross talk first results





Distance between quad yoke and the sextupole yoke is 56 mm

- Small variation of the quadrupole strength (-0.1%).
- Small variation of the sextupolar strength (-0.3%).
- Small dipole appears in the sextupôle

→ study need to be continued

Distance between dipole yoke and the quad corrector is 40.5 mm

→ Impact 1.6 % on the integrated dipole

→ Impact 0.8 % on the integrated quadrupole

- Insertion of shielding plate to reduce cross talk

→ Impact 0.04 % on the integrated dipole

→ Impact 0.003 % on the integrated quadrupole

We found out that it is mainly the presence of the yoke which create cross talk, the current of the coil has a minor effect

Thank you for your attention

Questions ?