# Magnets for SOLEIL II

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on behalf of SOLEIL II Project Team

SOLEIL SYNCHROTRON

SOLEIL II
La science éclaire l'avenir
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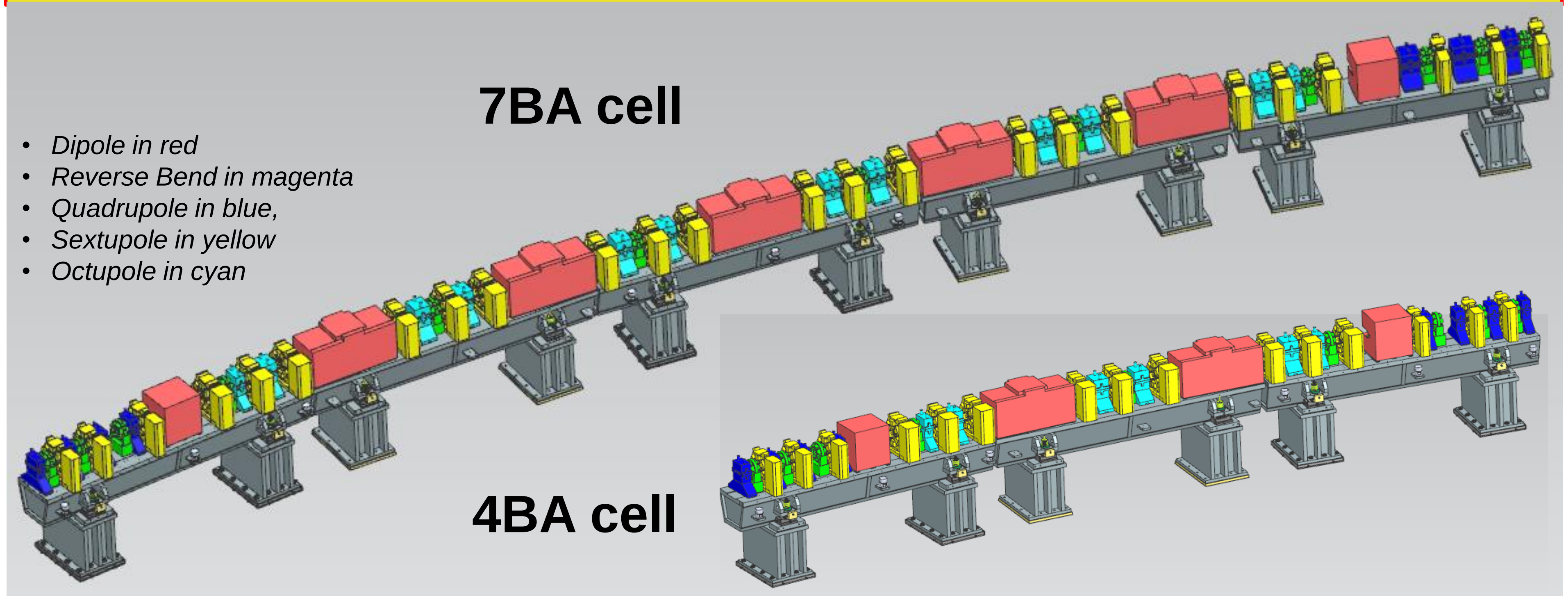
# SOLEIL II PROJECT: TOWARDS 4th GENERATION SYNCHROTRON LIGHT SOURCE

1. **80 pm.rad / 2.75 GeV / 354 m.**
2. **20 straight sections ( 2 of ~8 m, 4 of 4.2m, 4 of 3.7m, 2 of 3.5m and 8 of ~3.1m).**
3. **Large photon spectrum (far IR to hard X-rays).**
4. **Non-standard MBA lattice: 12 x 7BA + 8 x 4BA with symmetry 1.**
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. **Wide prototyping program (inc. 6 magnets)**
11. **Energy Savings.**

*Key features*




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

# SOLEIL II magnets at one glance

- **Number of magnets**
- Total number: **1277**
- Number of types: **41** types + 8 x Superbend with 3T, 1.7T, 1.2T peak field

1. **PM design**
   - Dipole with transverse gradient
   - Quadrupole
   - Reverse Bend

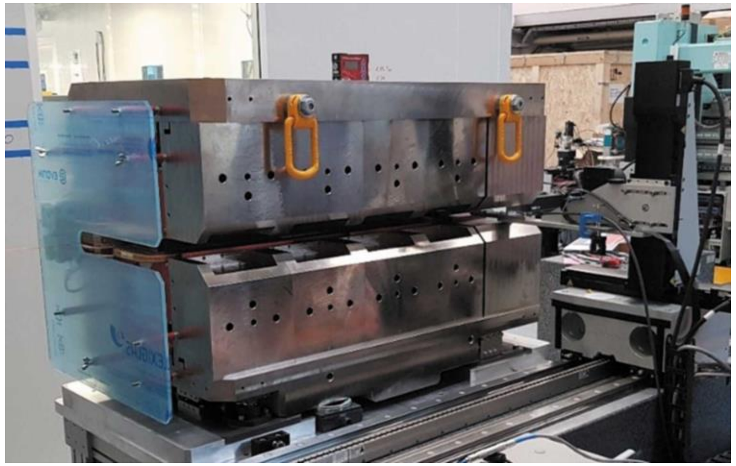
   SmCo magnets and low carbon steel (except the 3T pole made of Fe-Co alloy)
2. **EM design**
   - Normal Quadrupolar Corrector
   - Sextupole
   - Octupole

- Magnet doublets (sextupole/normal quadrupole corrector, sextupole/octupole)
- Harmonics : under discussion and iterations
- Magnetic measurements: usual methods such as Stretched wire and Hall probe

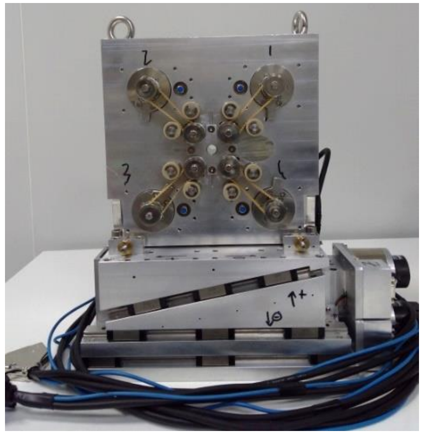
| | | Gap [mm] | Dev[mrad] | Lmag[mm] | B[T] | B'[T/m] | Nbr | Tot |
|---|---|---|---|---|---|---|---|---|
| Permanent magnet technology | Short dipoles | | | | | | | 40 |
| | DNC1 | 23 | 42.2206 | 430 | 0.893 | 17.7 | 22 | |
| | DNC2 | 23 | 40.0925 | 430 | 0.851 | 17.7 | 16 | |
| | DNC3 | 23 | 41.433 | 430 | 0.893 | 17.7 | 1 | |
| | DNC4 | 23 | 48.4646 | 430 | 0.895 | 17.7 | 1 | |
| | Long dipoles | | | | | | | 76 |
| | DNL1 | 22 | 68.8573 | 947 | 0.551/1.2 | 21.58 | 58 | |
| | DNL2 | 22 | 65.3867 | 947 | 0.551/1.2 | 21.58 | 16 | |
| | DNL3 | 22 | 69.0675 | 947 | 0.551/1.2 | 21.58 | 1 | |
| | DNL4 | 22 | 68.5013 | 947 | 0.551/1.2 | 21.58 | 1 | |
| | Long ReverseBends | | | | | | | 152 |
| | DIL1 | 21 | -3.4407 | 136.23 | -0.197 | 83 | 120 | |
| | DIL2 | 21 | -3.2673 | 136.23 | -0.188 | 83 | 32 | |
| | Short ReverseBends | | | | | | | 40 |
| | DIC1 | 18 | -0.8107 | 118.89 | -0.092 | 104 | 24 | |
| | DIC2 | 18 | -0.7699 | 118.89 | -0.088 | 104 | 16 | |
| | Chicanes | | | | | | | 3 |
| | CHIC2 | | -12.55 | 200 | -0.58 | 0 | 1 | |
| | CHIC3 | | 19.05 | 200 | 0.87 | 0 | 1 | |
| | CHIC4 | | -11.89 | 100 | -1.09 | 0 | 1 | |
| | Quadrupoles QF and QD | 16 | | 67 to 100 | | 120 | 128 | 162 |
| | | 21 | | 137 to 192 | | 80 | 12 | |
| | | 23 | | 87.5 to 130 | | 75 | 22 | |
| Electromagnet technology | | Bore diam. [mm] | Gap [mm] | Yoke Length[mm] | | Integrated strength | | |
| | Sextupoles (plus Horiz and Vert. Correctors) | 16 | 6.2 | 60 | | 550 T/m | 80 | 412 |
| | | 16 | 7 | 60 | | 550 T/m | 16 | |
| | | 21 | 6.2 | 60 | | 350 T/m | 10 | |
| | | 21 | 7 | 60 | | 350 T/m | 4 | |
| | | 21 | 10 | 60 | | 350 T/m | 14 | |
| | | 16 | 6.2 | 80 | | 680 T/m | 98 | |
| | | 16 | 7 | 80 | | 680 T/m | 74 | |
| | | 16 | 7.5 | 80 | | 680 T/m | 20 | |
| | | 16 | 6.2 | 110 | | 1000 T/m | 96 | |
| | Octupoles (plus Norm. and Skew Quadrupole Correctors) | 19 | | 60 | | 3300 T/m² | 142 | 162 |
| | | 21 | | 60 | | 3300 T/m² | 20 | |
| | Normal quadrupole correctors | 19 | 7 | 24 | | 1 T | 225 | 230 |
| | | 22 | 10 | 29 | | 1 T | 5 | |
| | | | | | | | total | 1277 |

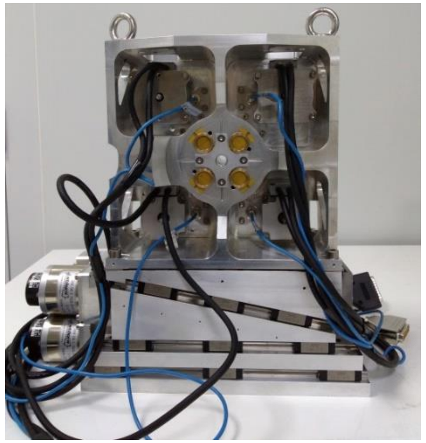
# Permanent magnets for SOLEIL II

## Besides undulator, PM Dipole and quadrupole magnet already built a SOLEIL



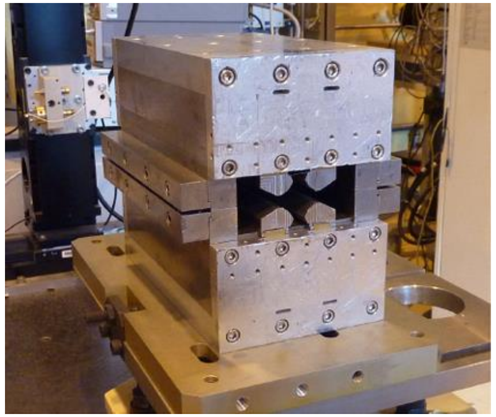
P. Brunelle and al. , « Development of a custom-made 2.8T permanent-magnet dipole photon source for the ROCK beamline at SOLEIL. » J. Synchrotron Rad. 30, p.695-707.





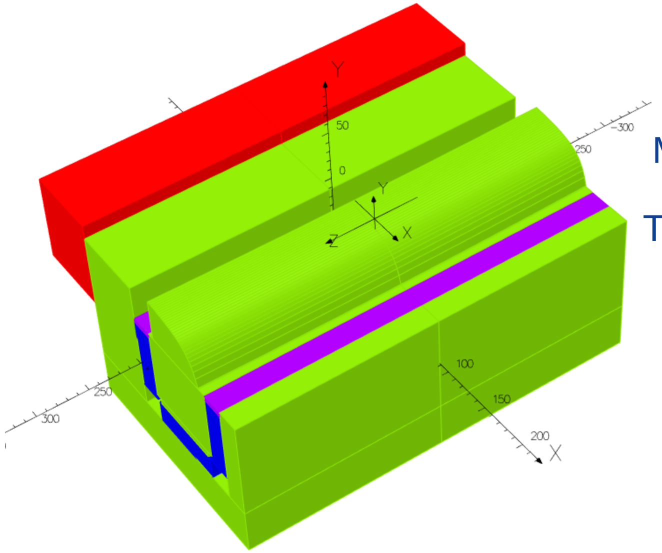
F. Marteau and *al.* Appl.Phys.Lett. 111 (2017) 25, 253503.

P. N'gotta, G. Le Bec,J. Chavanne
*Phys.Rev.ST Accel.Beams* 19 (2016) 122401



- For SOLEIL II quadrupole, geometry proposed by ESRF is preferred

# Dipoles

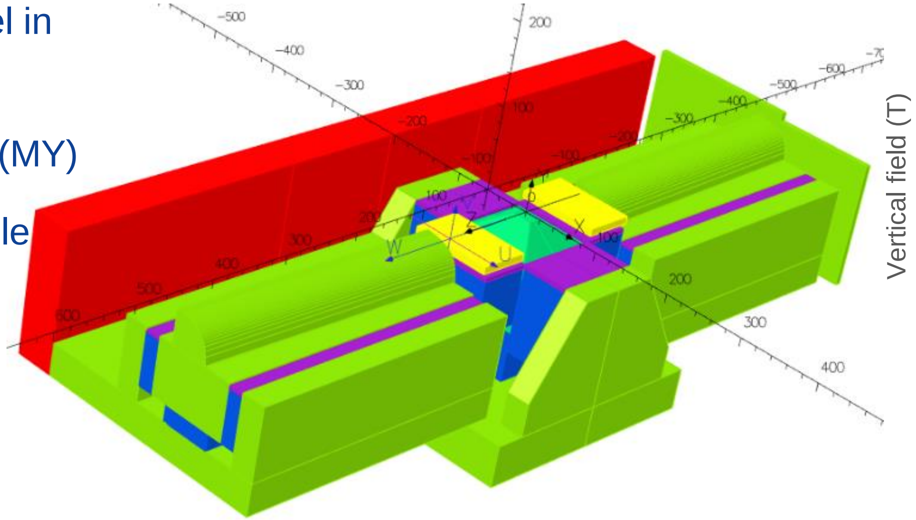


Low Carbone Steel in green

Moving Yoke in red (MY)

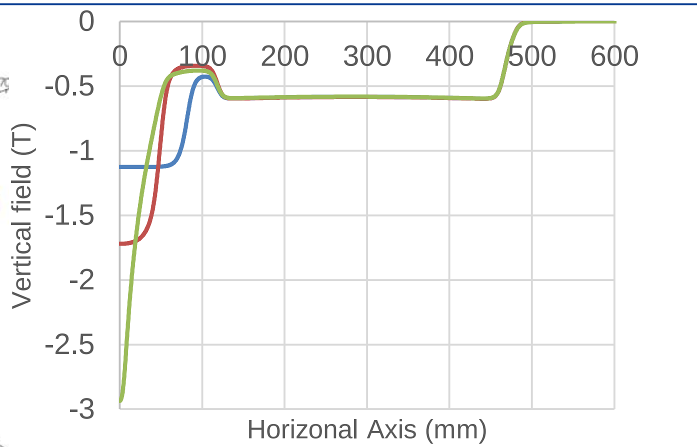
ThermoShim in purple

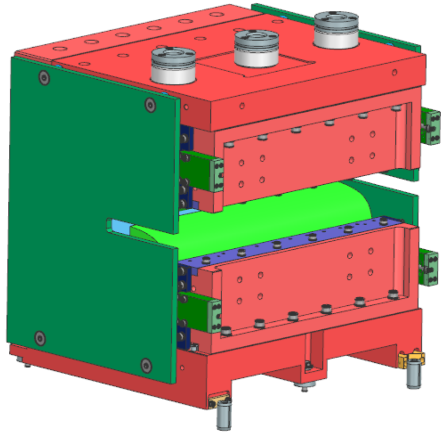
PM in blue



Short dipole

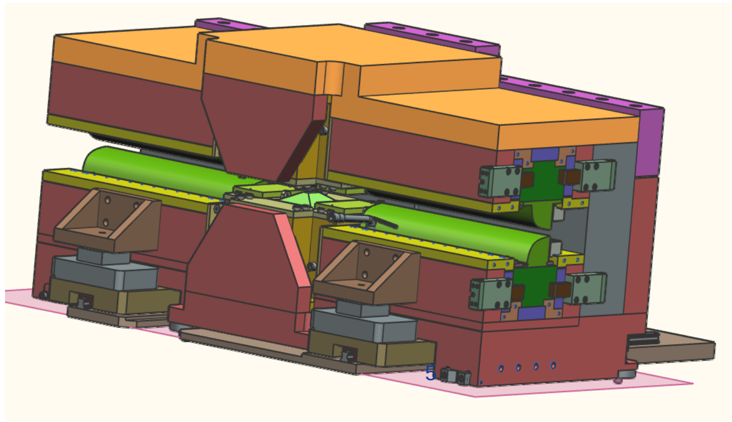
Long dipole



Details presented at Permalics https://indico.cells.es/event/1229/contributions/2077/attachments/1458/2787/perm_soleil.pdf

| | 1.2 T | Bn (Unit) @ 5mm | 1.7 T | Bn (Unit) @ 5mm | 3 T | Bn (Unit) @ 5mm |
|---|---|---|---|---|---|---|
| B_Integral | -0.6253 (T.m) | 10000.0 | -0.627 (T.m) | 10000.0 | -0.627(T.m) | 10000.0 |
| G_Integral | 15.301 (T) | -1223.5 | 15.380 (T) | -1225.9 | 15.320 (T) | -1222.1 |
| S_Integral | -39.125 (T/m) | 15.6 | -20.3 (T/m) | 8.1 | -129.56 (T/m) | 51.7 |
| O_integral | -6054 (T/m²) | 12.1 | 3962(T/m²) | -7.9 | -5437 (T/m²) | 10.8 |

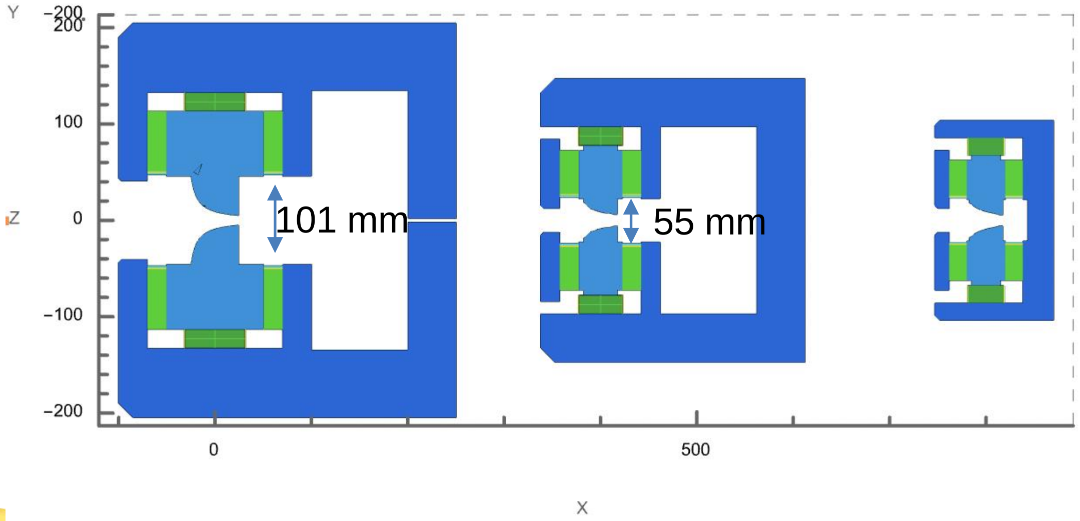


A long dipole with a 3T central pole and a short dipole are prototyped

- Magnet blocks delivered In October 2024
- Mechanical parts of the yoke to be delivered in December 2024
- Assembly to be done at SOLEIL in January 2024

# Dipole

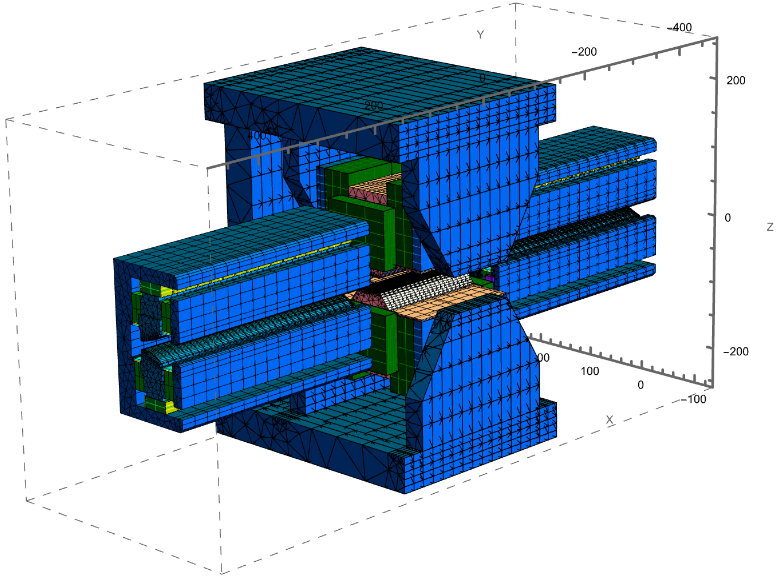
- Systematic octupolar component detrimental to the beam dynamics
- Unsuccessful attempt to correct the octupolar component by enlarging the width of the pole
- Design ala PETRA-IV proposed for the DQ part of the DNL

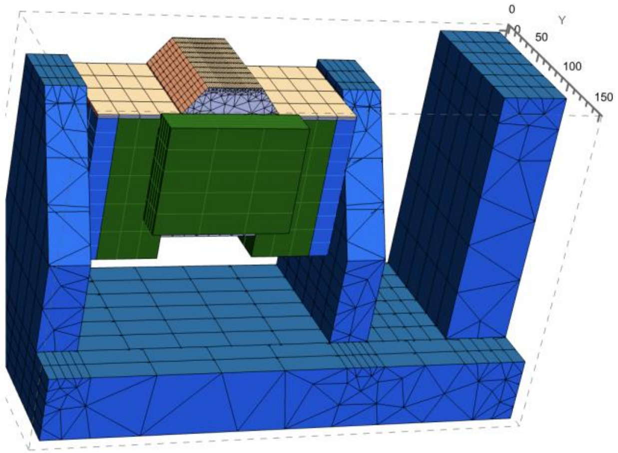


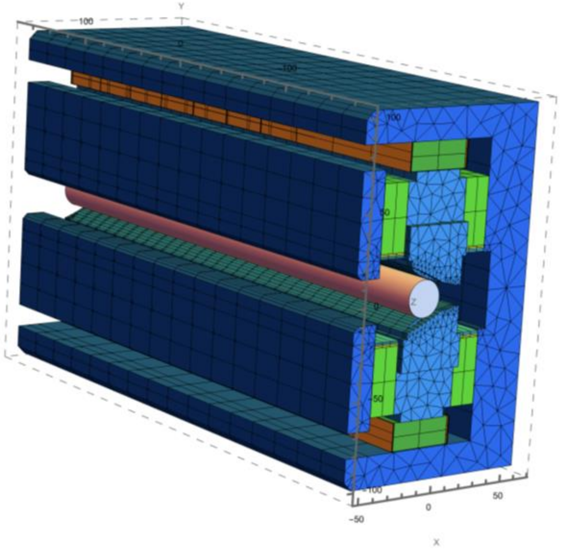

- 2D model
- narrower pole width
- Decoupled iron yoke (control residual sextupole term)
- Pole profile

# Magnetic design: Dipole

- Straight assembly for initial multipole analysis
- 3D model with the original 1.2T central pole (slightly curved pole face)
- DQ with specific end poles





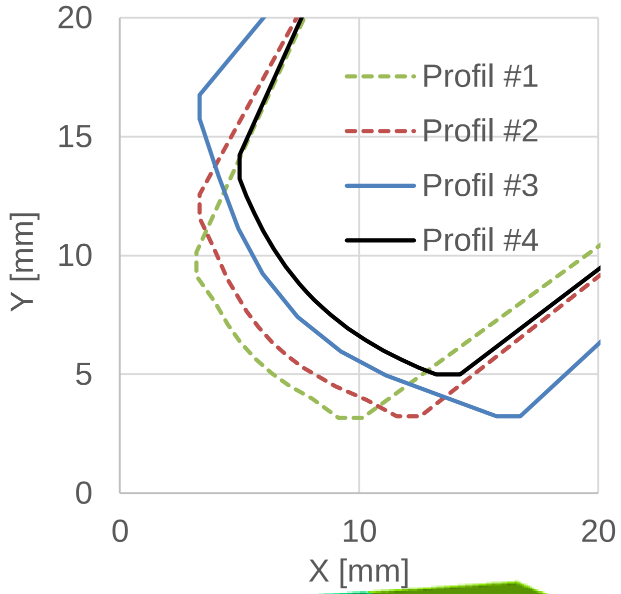


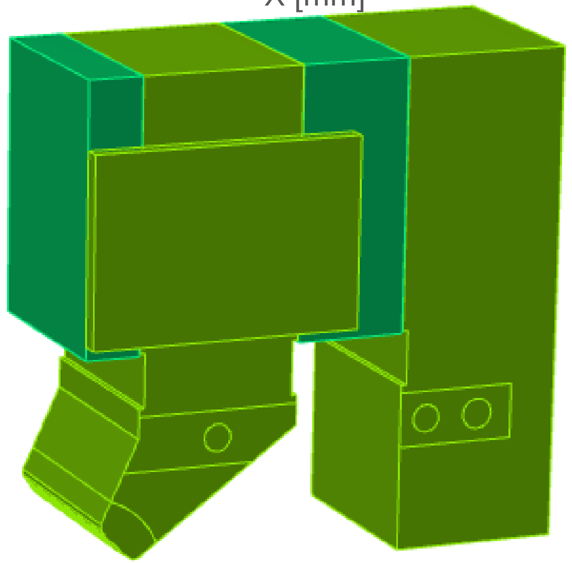
| Norm. bn @r=5mm | b1 | b2 | b3 | b4 | b5 | b6 | b7 | b8 | b9 | b10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Ori. DNL | 1 | -0.1184 | 7.338E-03 | 1.066E-03 | -2.674E-04 | -3.491E-05 | 3.232E-08 | 1.150E-06 | 3.652E-07 | -6.597E-08 |
| Prop. DNL | 1 | -0.1219 | -2.51E-05 | -6.41E-06 | -1.39E-04 | -1.70E-05 | -4.84E-06 | 5.42E-06 | -2.07E-06 | -6.69E-08 |

- A significant reduction of the sextupole and octupole contents in DNL seems feasible

# Quadrupole and reverse bend

- Lattice includes 25 different Quadrupoles (162) and ReverseBends (192)
- Fixed gradient Quadrupole and ReverseBend
- 4 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)
- Attempt to reduce the number of families with shims at the quadrupole ends to adjust the integrated gradient



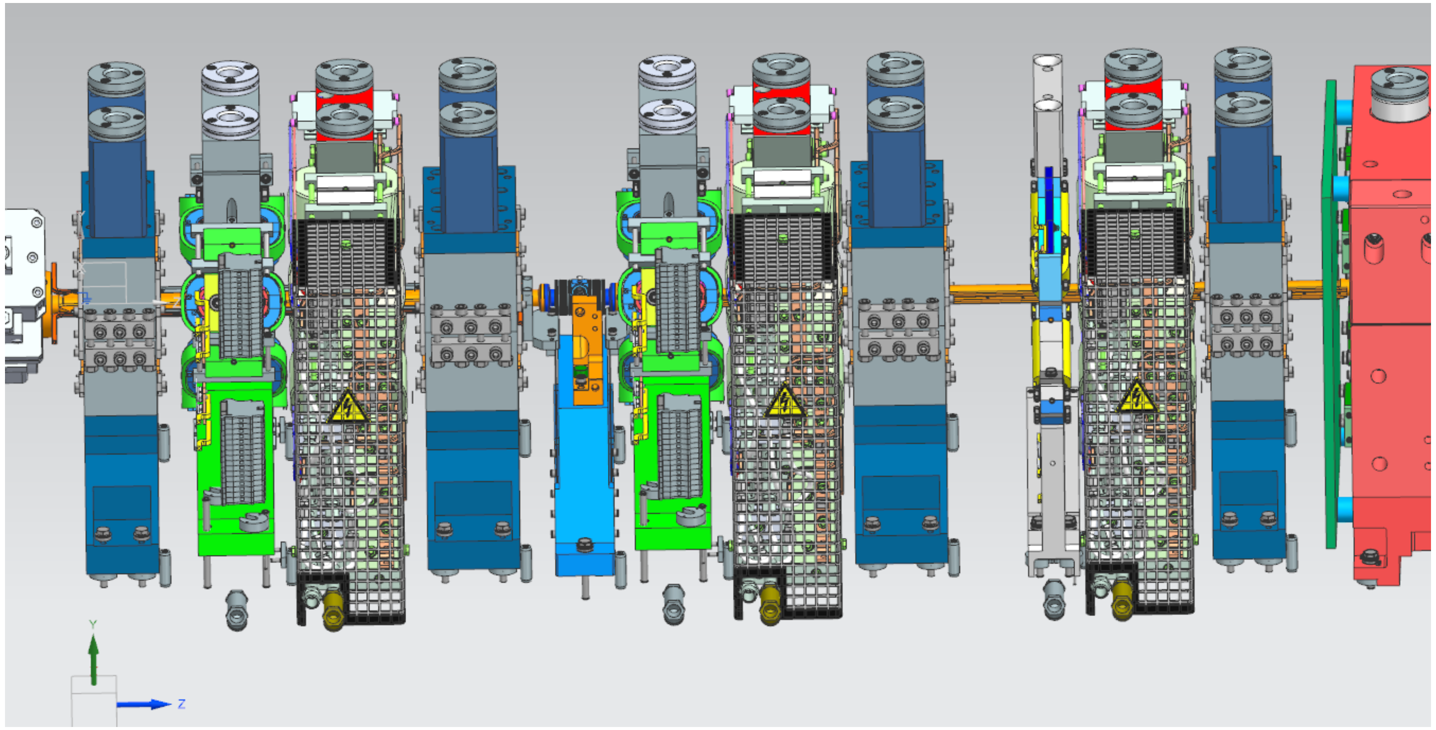



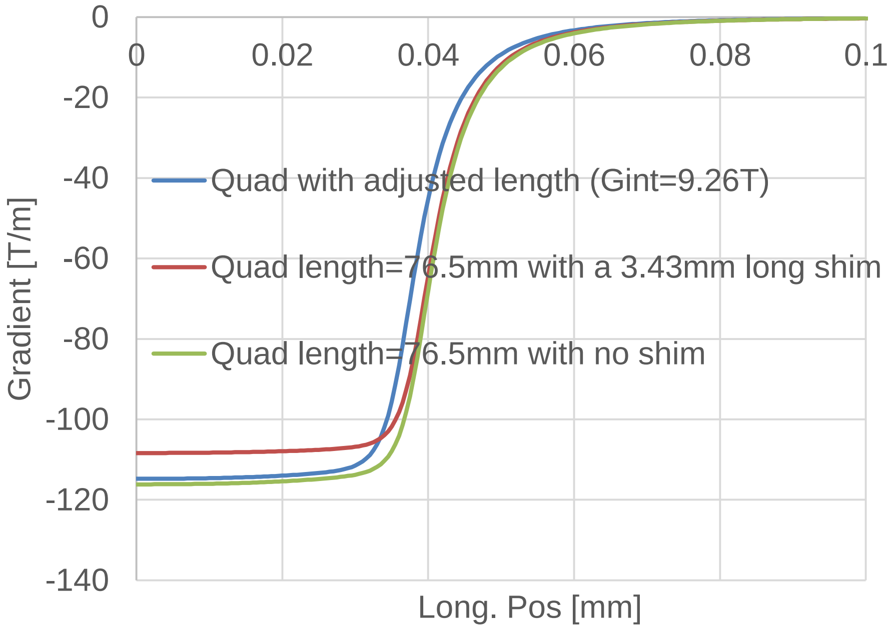
Details presented at Permalics https://indico.cells.es/event/1229/contributions/2077/attachments/1458/2787/perm_soleil.pdf

# Quadrupole and reverse bend

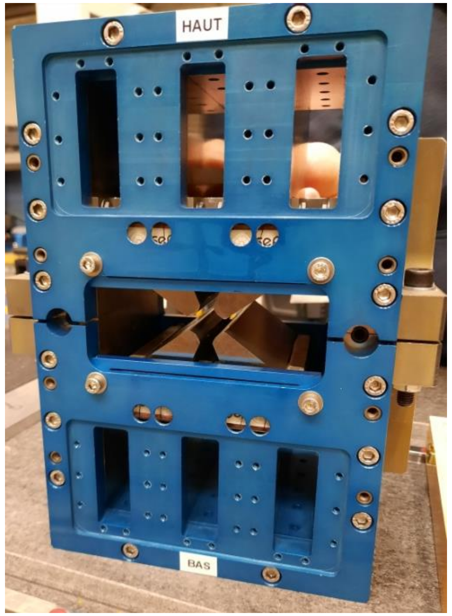
Exemple of quadrupoles with 16 mm aperture: 12 Qp families → 3 families

| Spec GL (T) | | -7.85 | -8.47 | -9.26 | 9.49 | -9.5 | -9.61 | -9.7 | 9.84 | 11.5 | 11.9 | 12.05 | 12.67 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Quantity | | 8 | 8 | 16 | 8 | 16 | 8 | 8 | 8 | 16 | 16 | 8 | 8 |
| Mech. Length when Gint {Quad} adj. to lattice [mm] | | 66.94 | 71.13 | 76.36 | 77.91 | 77.97 | 78.69 | 79.29 | 80.19 | 91.42 | 94.16 | 95.23 | 99.57 |
| Mech. Length when Gint {Quad+Shim} adj. to lattice | Quad [mm] | 66.5 | 66.5 | 76.5 | 76.5 | 76.5 | 76.5 | 76.5 | 76.5 | 97 | 97 | 97 | 97 |
| | Shim [mm] | 3.63 | 0.12 | 3.43 | 2.11 | 2.06 | 1.46 | 0.96 | 0.2 | 7.01 | 4.69 | 3.8 | 0.22 |



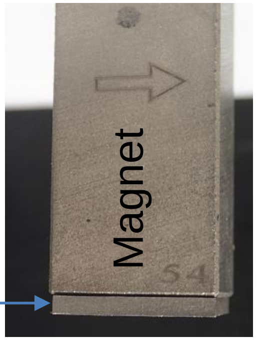



# Quadrupole prototype

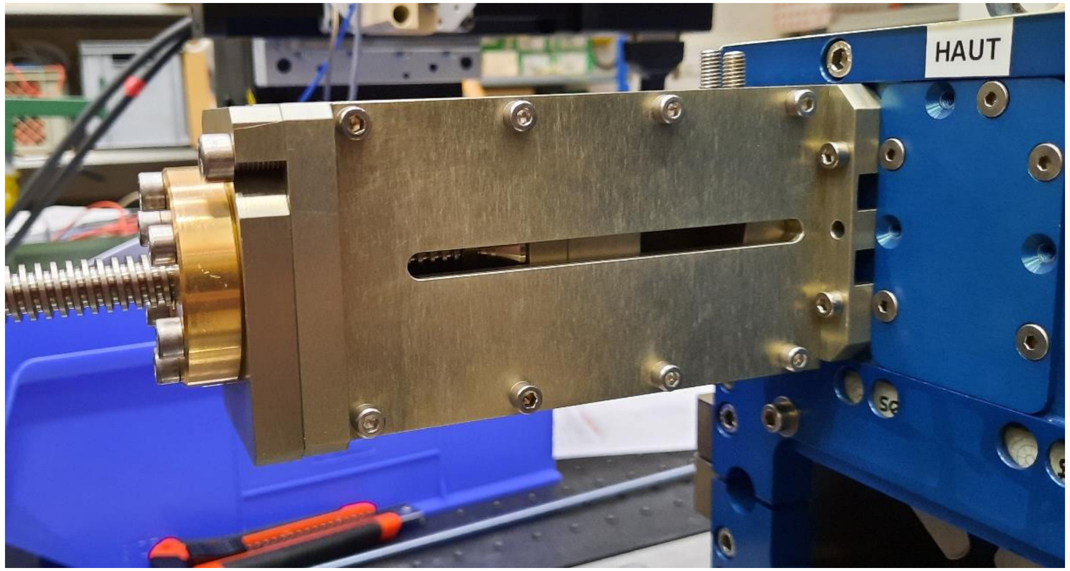


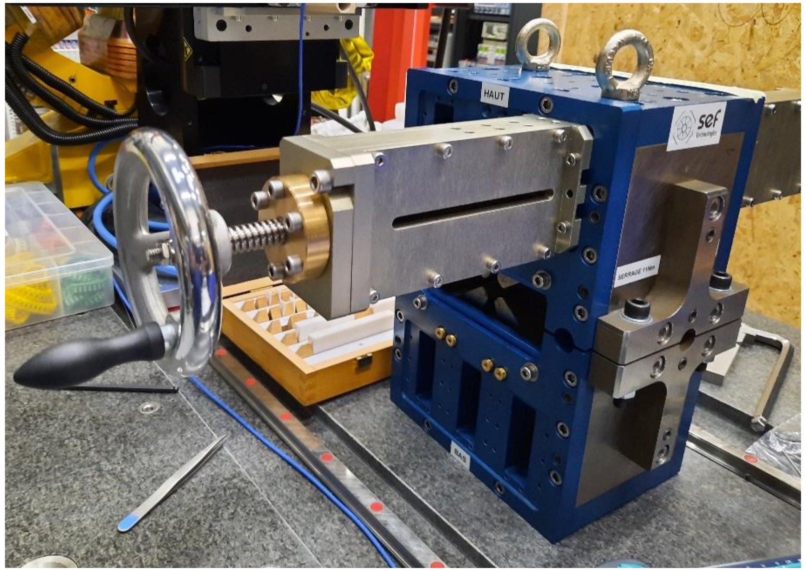

A first quadrupole prototype delivered at SOLEIL in early 2021

- 16mm aperture, 101.5mm long
- Include coils for heating
- Non optimized profile to exhibit specific harmonics (b4 and b6)
- A tight tolerance of 5µm specified on the pole tip
- Magnet block size 50 mm x 20(M) mm x 20.3 mm




Thermoflux Shim



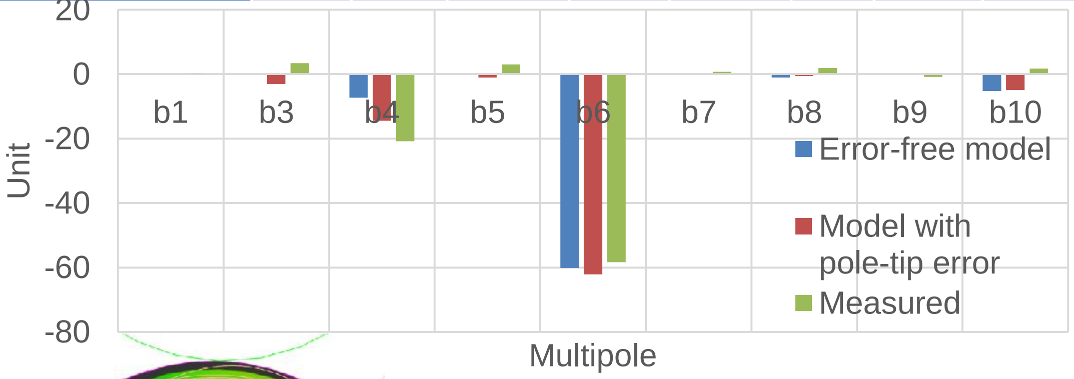



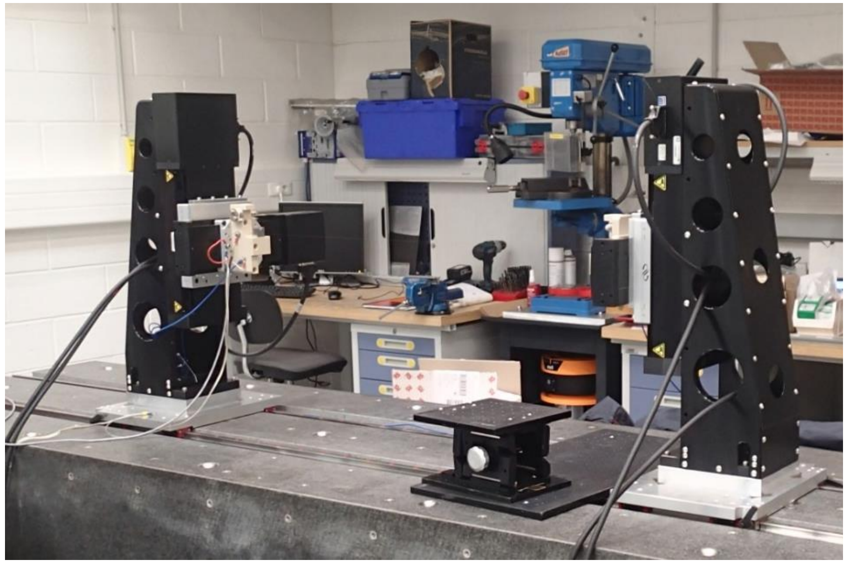
# Quadrupole prototype

- 0.5% difference between b2 measured (56.82Tmm) and computed (57.08 Tmm)
- 2 units difference between b6 computed (-60) and measured (-58)

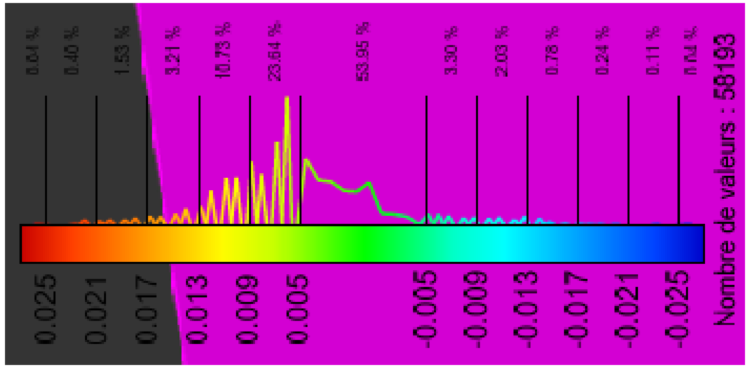
Multipole at r=5mm

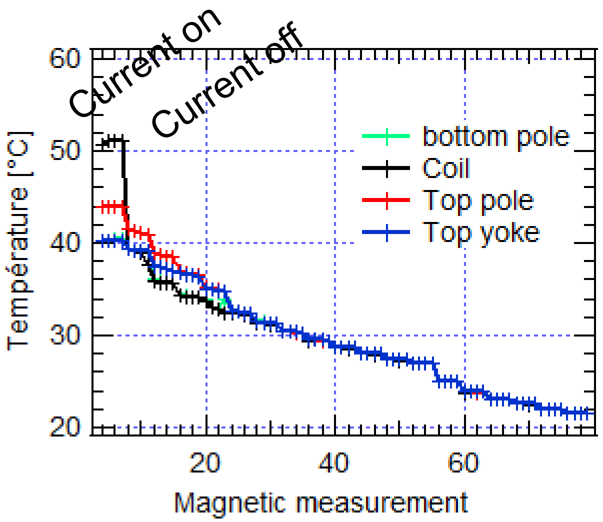
| Norm. Harm. | b1 | b3 | b4 | b5 | b6 | b7 | b8 | b9 | b10 |
|---|---|---|---|---|---|---|---|---|---|
| Error-free model | 0 | 0 | -7.3 | 0 | -60 | 0 | -1 | 0 | -5 |
| Model with pole-tip error | 0 | -3 | -14 | -1 | -62 | 0 | -0.6 | 0 | -5 |
| Measured | 0 | 3.4 | -21 | 3 | -58 | 1 | 1.9 | -1 | 1.7 |

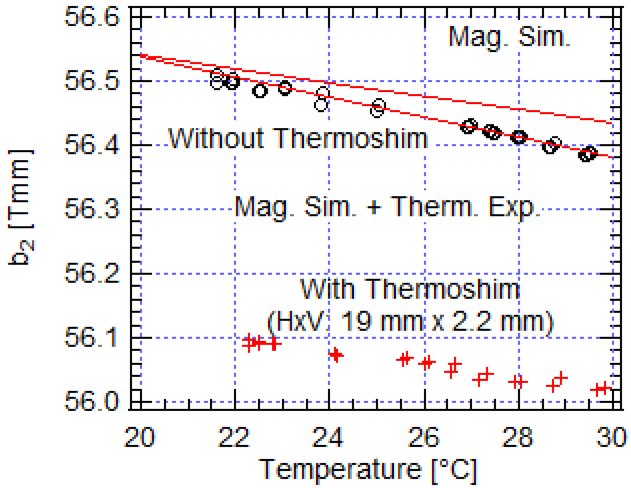


G. Le Bec, J. Chavanne and Ch. Penel, "Stretched wire measurement of multipole accelerator magnets", *Phys. Rev. Accel. Beams*, vol. 15, Feb. 2012, Art. no. 022401



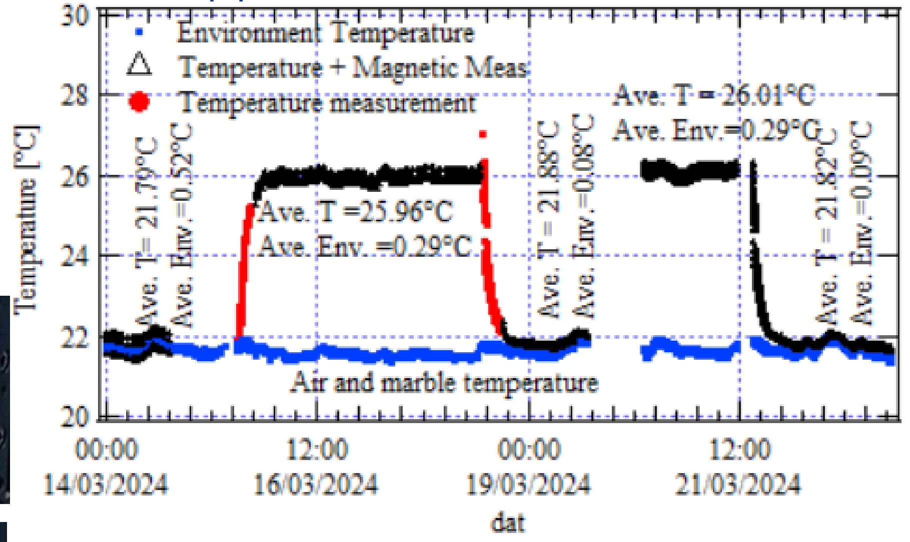



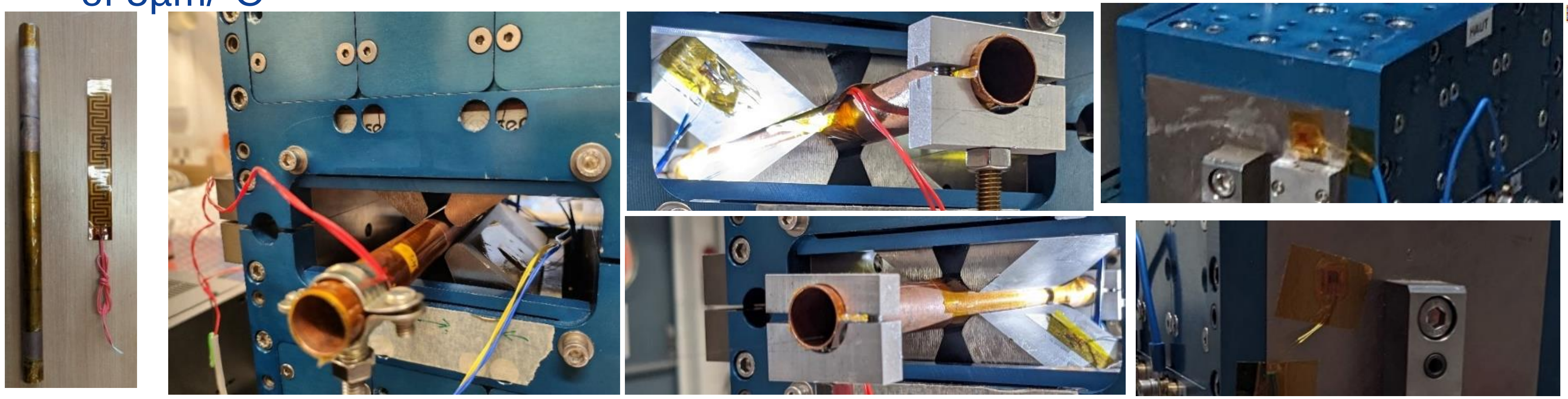



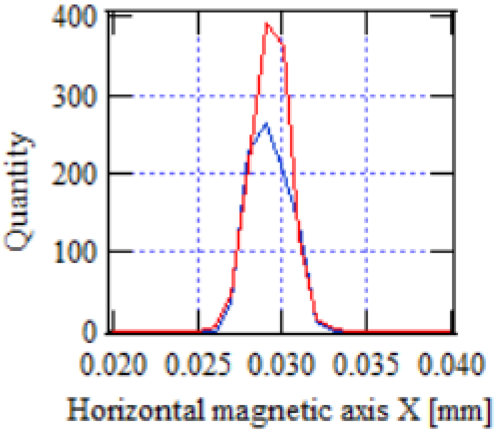
# Magnetic center and thermal dilatation

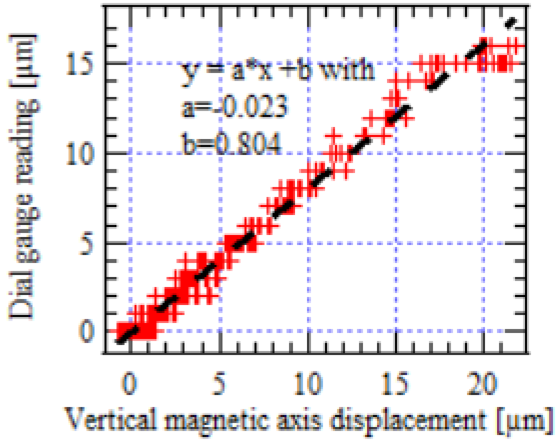
- Magnetic center computed from magnetic measurement
- Thermal expansion measured by dial gauges
- For a 4°C temperature increase of the quadrupole prototype #1, a 16µm mech. elongation (dial gauge) and a 20µm vertical axis shift are measured
- The vertical magnetic axis linearly varies w.r.t the temperature increase at a rate of 5µm/°C

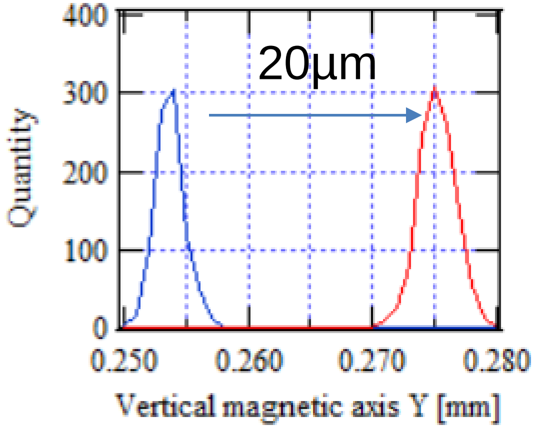
Cu pipe diam.: Øint =14mm/ Øext =15mm



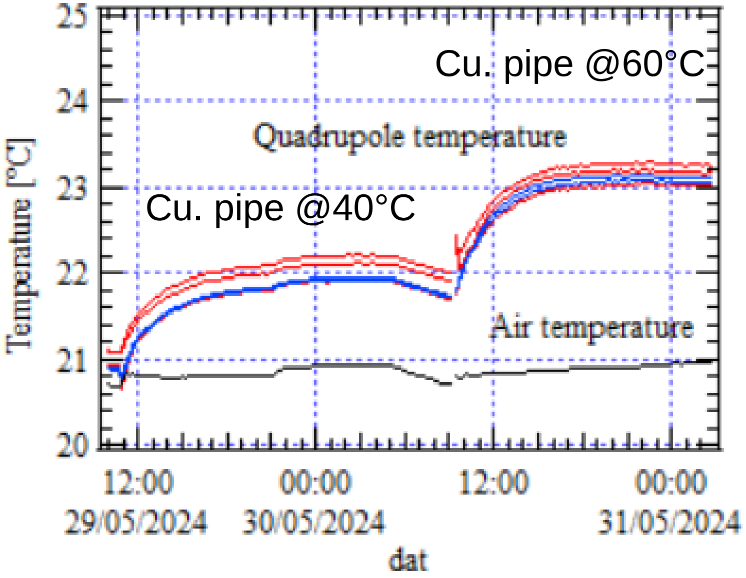






Cu pipe diam.: Øint =12mm/ Øext =14mm



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# Quadrupole prototype

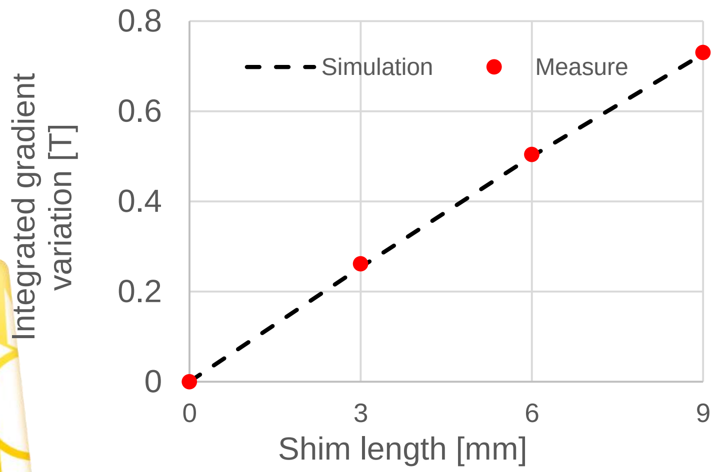
A second prototype delivered in March 2024

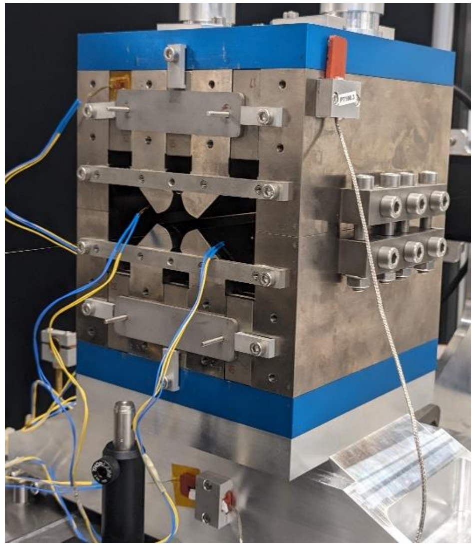
- To validate machining process on a 182.7mm long quadrupole
- Simplified design
- 21mm diameter aperture
- Manufacturer specialized in EDM selected, no prior experience in magnet
- Most of the parts were EDM machined

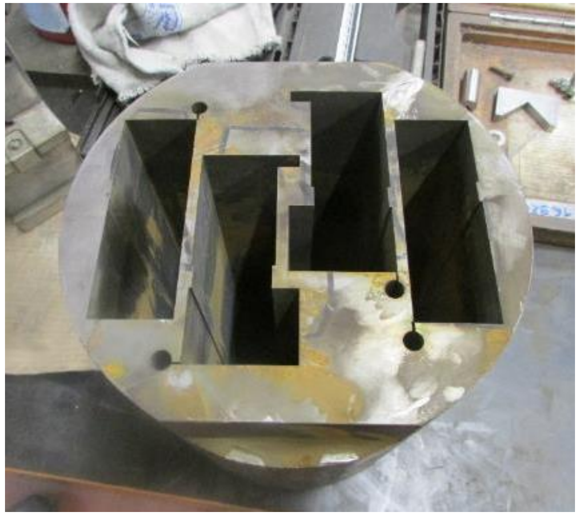
Multipole at r=8mm

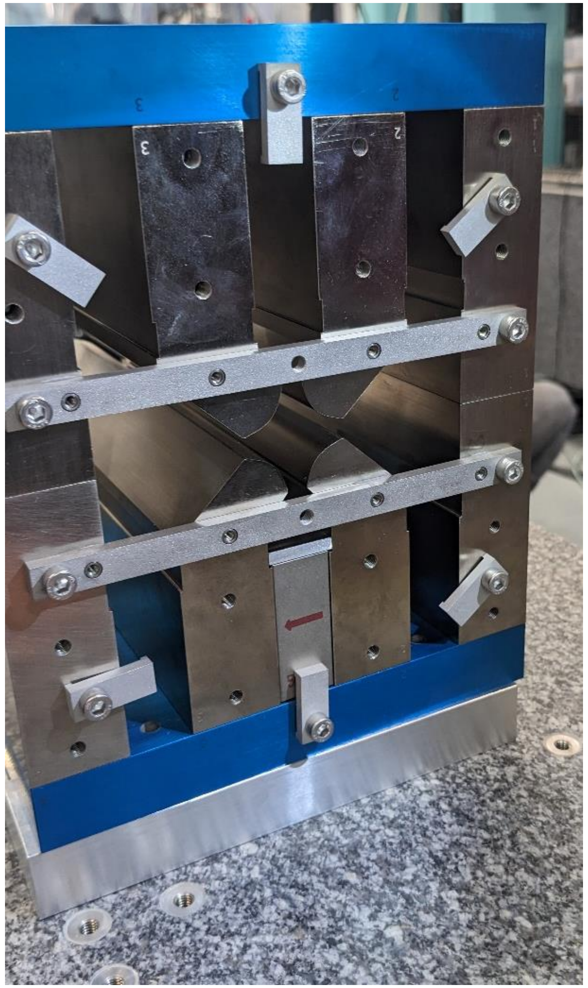
| harm. N | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| TOSCA | 0.00 | 10000 | 0.00 | -0.12 | 0.00 | -0.13 | 0.00 | 1.48 | 0.00 | 0.04 |
| Mesure | 1.16 | 10000 | 0.75 | 2.29 | -0.66 | -5.69 | -0.56 | 3.42 | -1.21 | -3.61 |

- 0.147% difference between expected and measured b2
- Few units on b4 and b6 hamonics



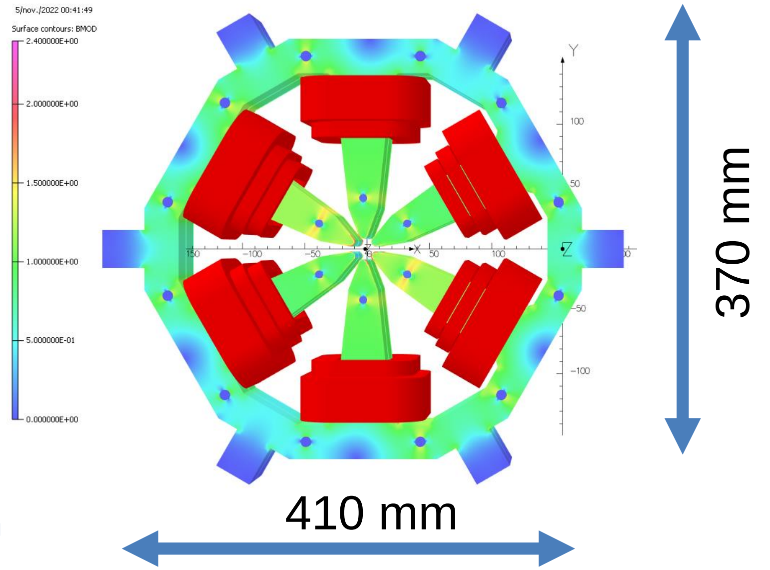





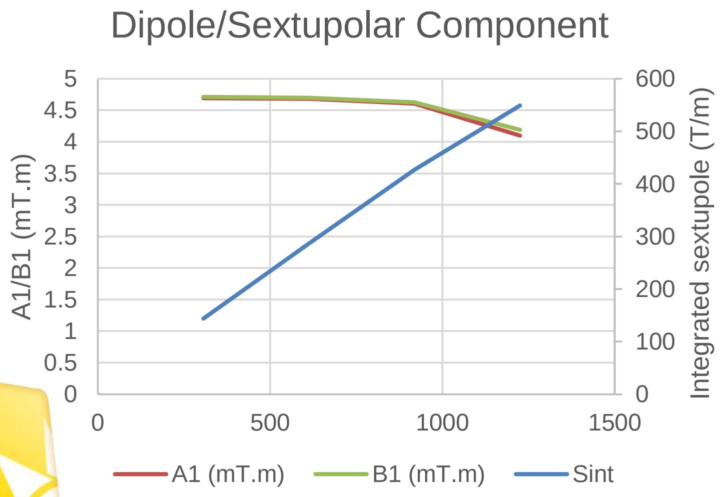


# Sextupole

- 9 types of sextupoles ( total number 412)
- Bore diameter : 16 mm and 21 mmn with a good field region : +/- 5 mm
- 3 Normal profiles with interpole distance 6.2 and 7 mm
  - 60 mm : sextupolar strength $(\frac{1}{2}B'')$ : 500 $T.m^{-2}$ to 8000 $T.m^{-2}$
  - 80 mm : sextupolar strength $(\frac{1}{2}B'')$ : 5300 $T.m^{-2}$ to 7300 $T.m^{-2}$
  - 110 mm : sextupolar strength $(\frac{1}{2}B'')$ : 6000 $T.m^{-2}$ to 8100 $T.m^{-2}$
- 1 profile with beamline notch with interpole distance 7.5 mm
- 1 profile with for canted section with 21mm diameter aperture and interpole distance of 10 mm
- 1 mrad Hor. And Ver. Dip. Cor



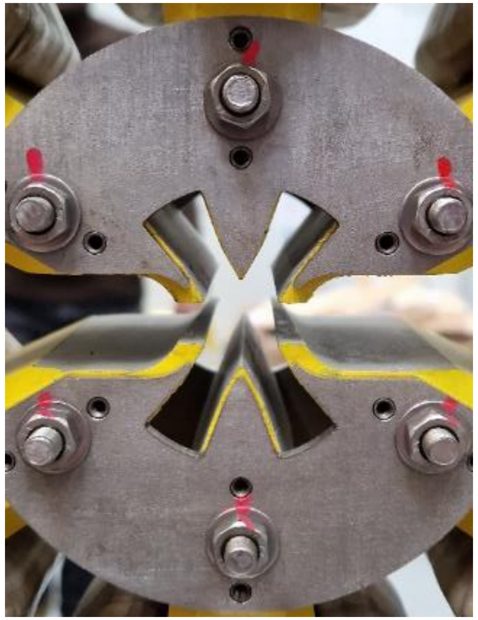
Sextupole magnetic design

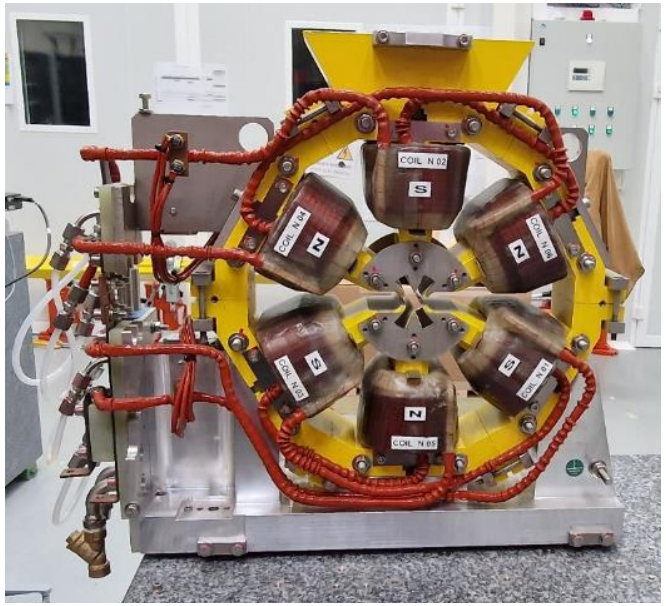


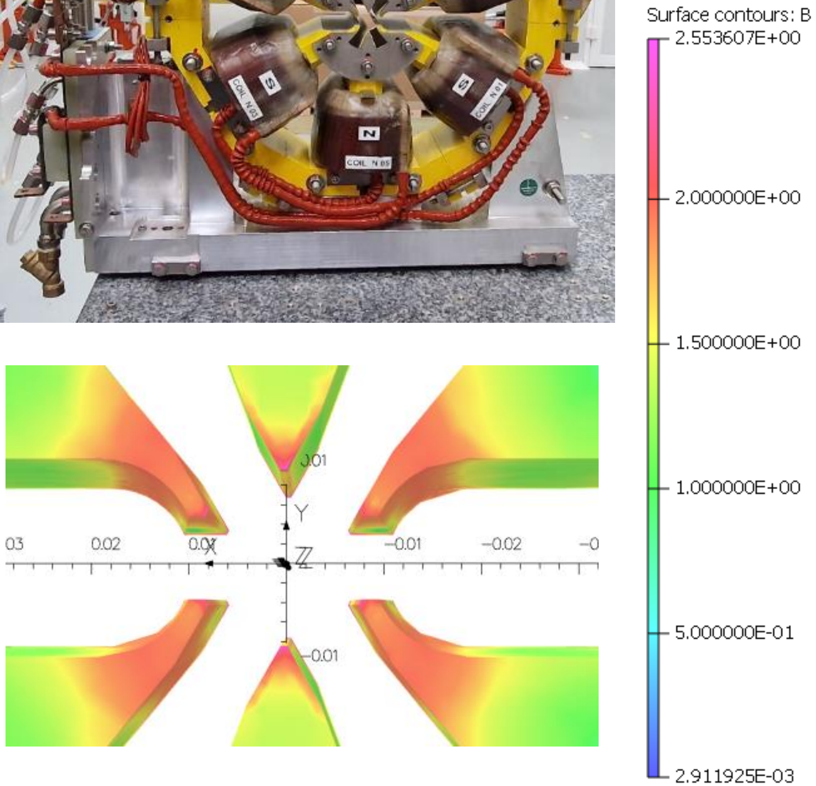

| Interpole [mm] 0 | Diam. [mm] | Length [mm] | Sint [T/m] | A.t | A | CH drop | CV Drop | Δ Sint / CH 100% | Δ Sint / CV 100% | B9 | B15 | B21 | Max. Hor. Cor. [mrad] | Max. Ver. Cor. [mrad] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | unit | | | | |
| 6.2 | 16 | 60 | 550 | 1300 | 40.6 | 5.9% | 4.8% | 1.5% | 1.1% | 143.6 | 1.4 | 0.1 | **0.99** | **0.90** |
| 6.2 | 16 | 80 | 680 | 1230 | 38.4 | 2.2% | 1.6% | 0.6% | 0.4% | 144.7 | 1.3 | 0.1 | 1.22 | 1.12 |
| 6.2 | 16 | 110 | 1000 | 1284 | 40.1 | 2.1% | 1.5% | 0.6% | 0.4% | 145.4 | 1.3 | 0.1 | 1.57 | 1.44 |
| 6.2 | 21 | 60 | 350 | 1900 | 59.4 | 39.1% | 35.7% | 2.2% | 1.8% | 7.2 | 0.1 | 0.1 | **0.81** | **0.74** |
| 7.0 | 16 | 60 | 550 | 1440 | 45.0 | 9.5% | 8.0% | 2.1% | 1.5% | 207.8 | 7 | 0.3 | **0.97** | **0.88** |
| 7.0 | 16 | 80 | 680 | 1350 | 42.2 | 3.5% | 2.7% | 0.9% | 0.6% | 209.5 | 7 | 0.3 | 1.19 | 1.09 |
| 7.0 | 21 | 60 | 350 | 1900 | 59.4 | 34.6% | 31.5% | 2.4% | 1.8% | 14.1 | 0 | 0 | **0.81** | **0.73** |
| 7.5 | 16 | 80 | 680 | 1600 | 50.0 | 29.7% | 39.2% | 9.1% | 2.1% | 235.9 | 9.6 | 0.5 | 1.17 | 1.04 |
| 10.0 | 21 | 60 | 350 | 2600 | 81.3 | 54.2% | 50.4% | 1.1% | 0.9% | 44.7 | 0.5 | 0 | **0.74** | **0.67** |

# Sextupole prototype

A sextupole prototype with notch was delivered to SOLEIL in October 2023



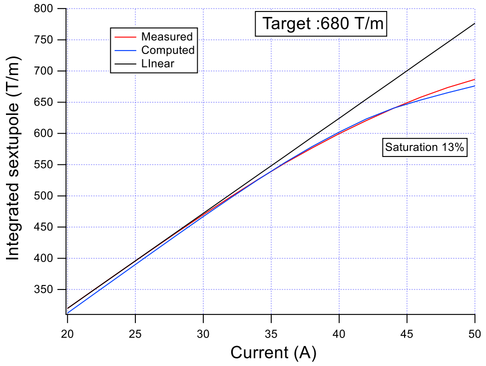


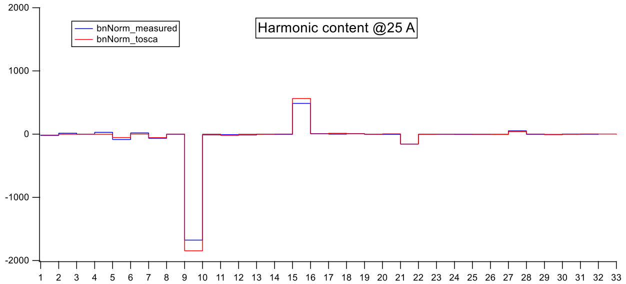



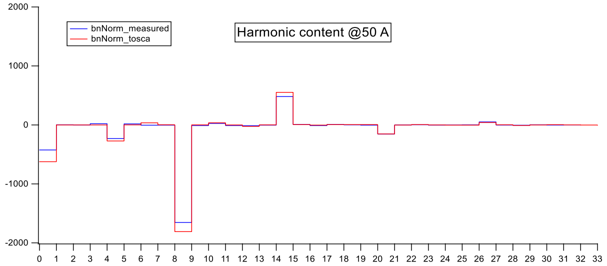

| Magnetic parameters | |
|---|---|
| Max. Ampere.turns | 9000 A.t |
| Max. Sextupolar strenght | 8200 T.m-² |
| Mechanical parameters | |
| Magnet Width | 410 mm |
| Magnet Height | 365 mm |
| Yoke Length | 80 mm |
| Steel weight | 33 kg |
| Electrical and hydraulical parameters main Coil | |
| Max. current | 47 A |
| Magnet voltage | 3 V |
| Magnet electrical power | 150 W |
| Water speed | 1. 72 m/s |
| Temperature increase | 1. 5 °C |
| Pressure drop | 6 bar |
| Hollow conductor for the main coil | |
| Conductor size | 5 x 5 mm² |
| Hole Diameter | 3 mm |
| Number of turns | 32 |
| Average turn length | 0.340m |

| Horizontal corrector | |
|---|---|
| Number of turns | 20/40 |
| Max. current | 10 A |
| Corrector voltage | 5 V |
| Corrector electrical power | 100 W |
| Vertical corrector | |
| Number of turns | 32 tours |
| Max. current | 20 A |
| Corrector voltage | 4.2 V |
| Corrector electrical power | 85 W |
| Conductor size | 5x0,8 mm² |

# Sextupole prototype



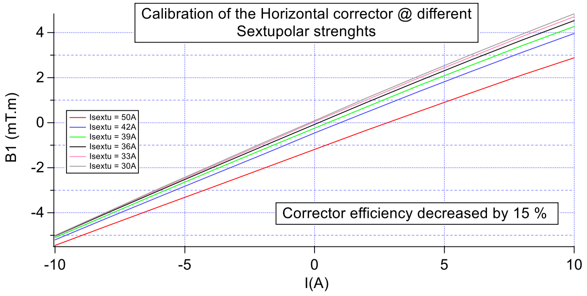



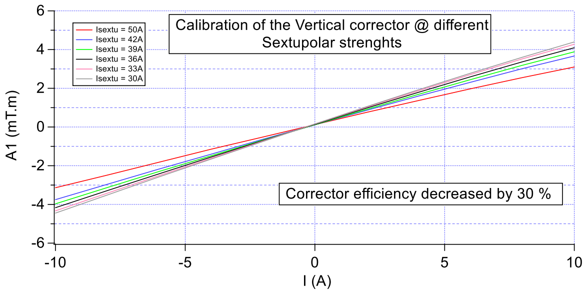

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 50 A | Measured | -425 | 2 | 10000 | 20 | -232 | 17 | -5 | -3 | -1655 | -11 | 25 | -12 | -15 | -3 | 482 | 6 | -11 | 7 | 0 | -4 | -155 |
| | Computed | -624 | -1 | 10000 | -1 | -273 | 1 | 35 | 2 | -1809 | 0 | 36 | -1 | -25 | 1 | 552 | 5 | -4 | 5 | 5 | 5 | -153 |
| | | | | | | | | | | | | | | | | | | | | | | |
| 25 A | Measured | -21 | 15 | 10000 | 28 | -86 | 19 | -66 | -2 | -1677 | -13 | -8 | -13 | 0 | -3 | 487 | 8 | 0 | 9 | -3 | -2 | -156 |
| | Computed | -14 | -1 | 10000 | -1 | -53 | 1 | -55 | 2 | -1846 | 0 | -20 | -1 | -1 | 2 | 564 | 5 | 13 | 6 | -1 | 5 | -157 |

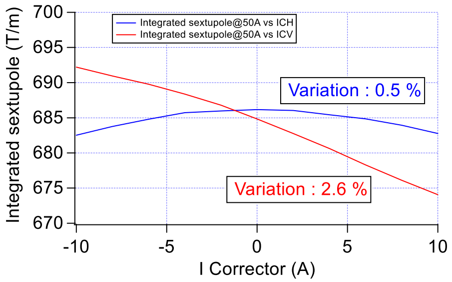
Harmonic content @ Rref = 7mm

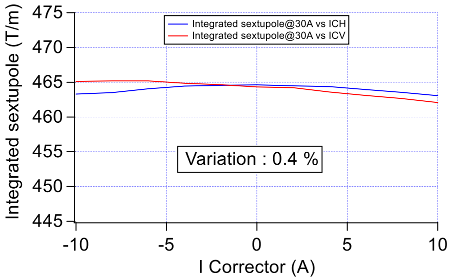
($b_n$ expressed in units of $10^{-4}$)

# Sextupole prototype



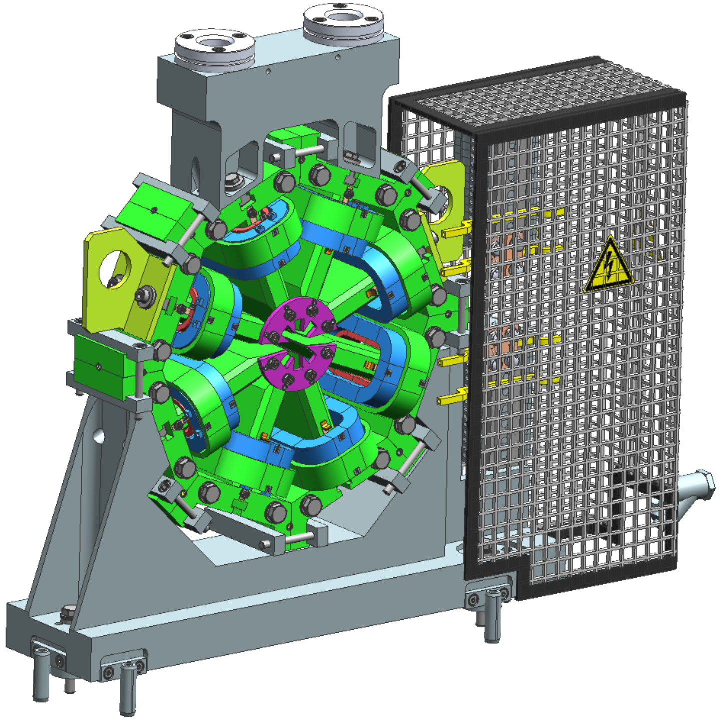
# Correctors

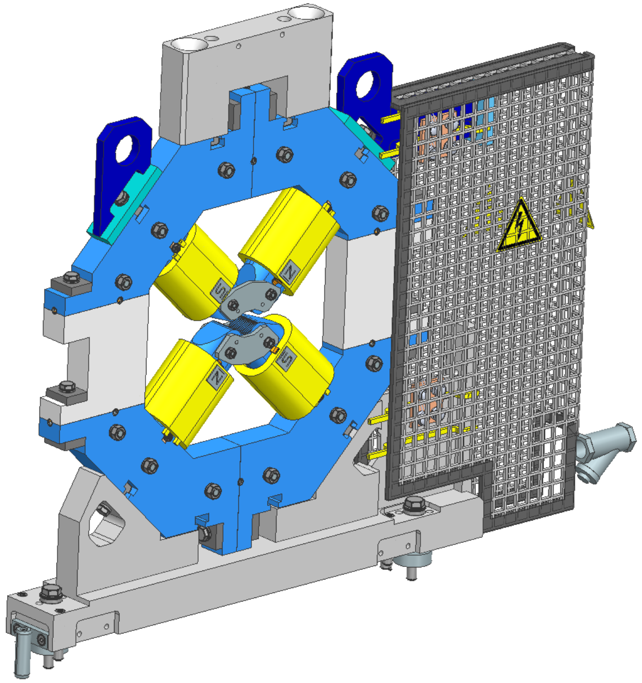
- 1 octupole and 1 quadrupole corrector to be prototyped
- Orders to be placed before 2025

| | Design 1 | Design 2 |
|---|---|---|
| Int. Grad. [T] | 1 | |
| Aperture diam. [mm] | 19 | 21 |
| Yoke Length [mm] | 24 | 29 |
| Gap [mm] | 7 | 10 |
| Ampere-Turn @1T | 1050 | 1100 |

3 coils per pole:

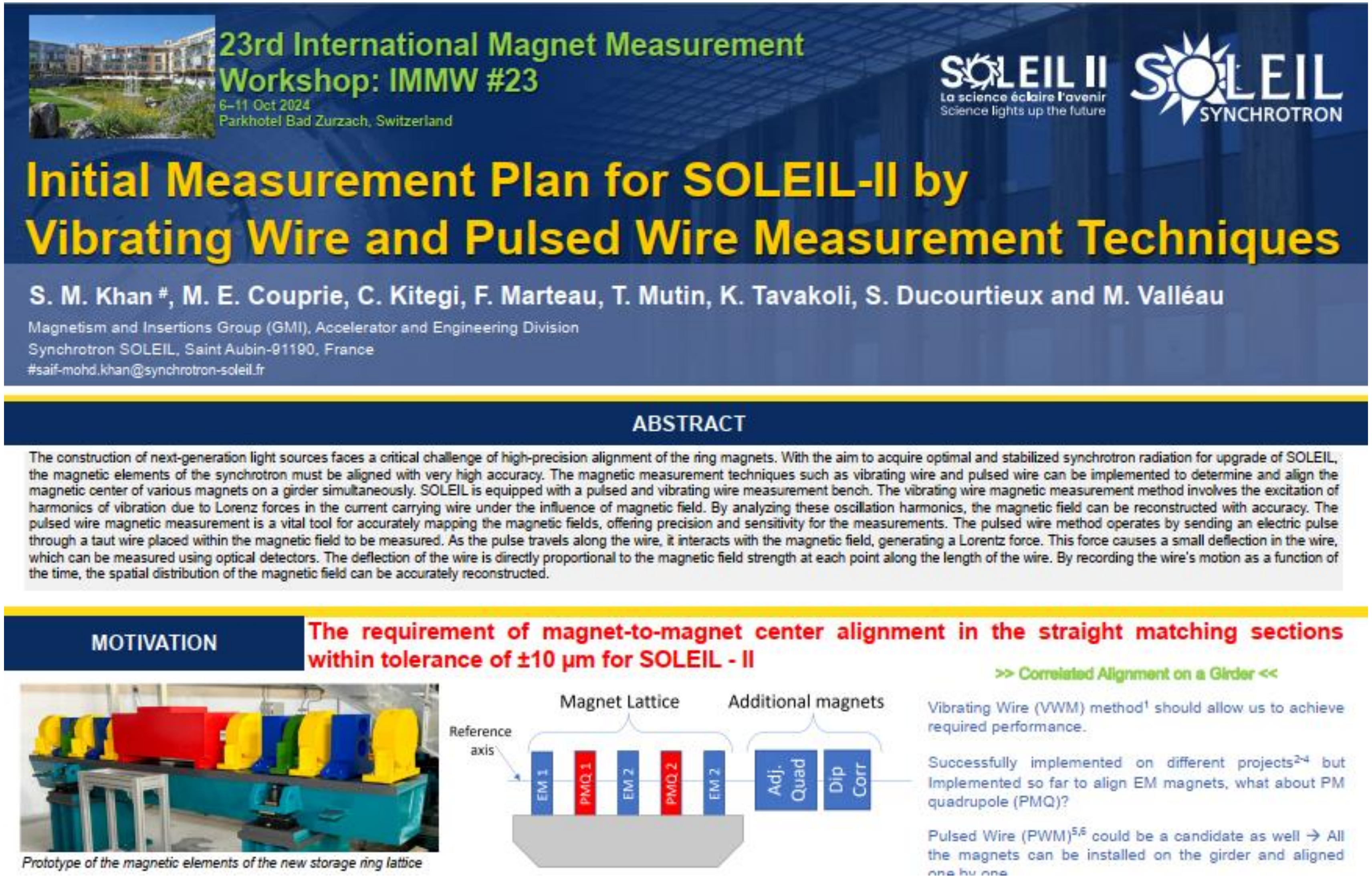
- Octupolar coils 120 At: 16 spires 5 x 0.8 mm² → 10 A
- Normal Quad coils 320 At (0.6T): 12 spires 5 x 5 $\phi$3 mm²→ 30 A
- Skew Quad coils 320 At: 16 spires 5 x 0.8 mm²→ 20 A





# "Correlated" Alignment on a Girder

- Tolerance on magnet-to-magnet center alignment tighten from ±25µm to ±10µm in matching straight sections.
- Such alignment tolerances already achieved with vibrating wire
- Dedicated poster by Saif Mohd KHAN on Wednesday



23rd International Magnet Measurement Workshop: IMMW #23
6–11 Oct 2024
Parkhotel Bad Zurzach, Switzerland

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SOLEIL SYNCHROTRON

## Initial Measurement Plan for SOLEIL-II by Vibrating Wire and Pulsed Wire Measurement Techniques

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### ABSTRACT

The construction of next-generation light sources faces a critical challenge of high-precision alignment of the ring magnets. With the aim to acquire optimal and stabilized synchrotron radiation for upgrade of SOLEIL, the magnetic elements of the synchrotron must be aligned with very high accuracy. The magnetic measurement techniques such as vibrating wire and pulsed wire can be implemented to determine and align the magnetic center of various magnets on a girder simultaneously. SOLEIL is equipped with a pulsed and vibrating wire measurement bench. The vibrating wire magnetic measurement method involves the excitation of harmonics of vibration due to Lorenz forces in the current carrying wire under the influence of magnetic field. By analyzing these oscillation harmonics, the magnetic field can be reconstructed with accuracy. The pulsed wire magnetic measurement is a vital tool for accurately mapping the magnetic fields, offering precision and sensitivity for the measurements. The pulsed wire method operates by sending an electric pulse through a taut wire placed within the magnetic field to be measured. As the pulse travels along the wire, it interacts with the magnetic field, generating a Lorentz force. This force causes a small deflection in the wire, which can be measured using optical detectors. The deflection of the wire is directly proportional to the magnetic field strength at each point along the length of the wire. By recording the wire's motion as a function of the time, the spatial distribution of the magnetic field can be accurately reconstructed.

### MOTIVATION

The requirement of magnet-to-magnet center alignment in the straight matching sections within tolerance of ±10 µm for SOLEIL - II

*Prototype of the magnetic elements of the new storage ring lattice*

Magnet Lattice
Additional magnets
Reference axis
EM 1
PMQ 1
EM 2
PMQ 2
EM 2
Adj. Quad
Dip Corr

>> Correlated Alignment on a Girder <<

Vibrating Wire (VWM) method[1] should allow us to achieve required performance.

Successfully implemented on different projects[2-4] but Implemented so far to align EM magnets, what about PM quadrupole (PMQ)?

Pulsed Wire (PWM)[5,6] could be a candidate as well → All the magnets can be installed on the girder and aligned one by one



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# Conclusions/next steps

- SOLEIL II lattice is complex, includes a lot of different magnet types
- Push further the magnetic design of DNLs as DQ magnets
- A new lattice that includes these dipoles will be released in early 2024
- Lattice not yet finalized
- Delivery of the dipole prototypes in December
- Order the prototype of the octupole and the quadrupolar corrector
- Measurement of the Crosstalk using sextupole and quadrupole prototypes