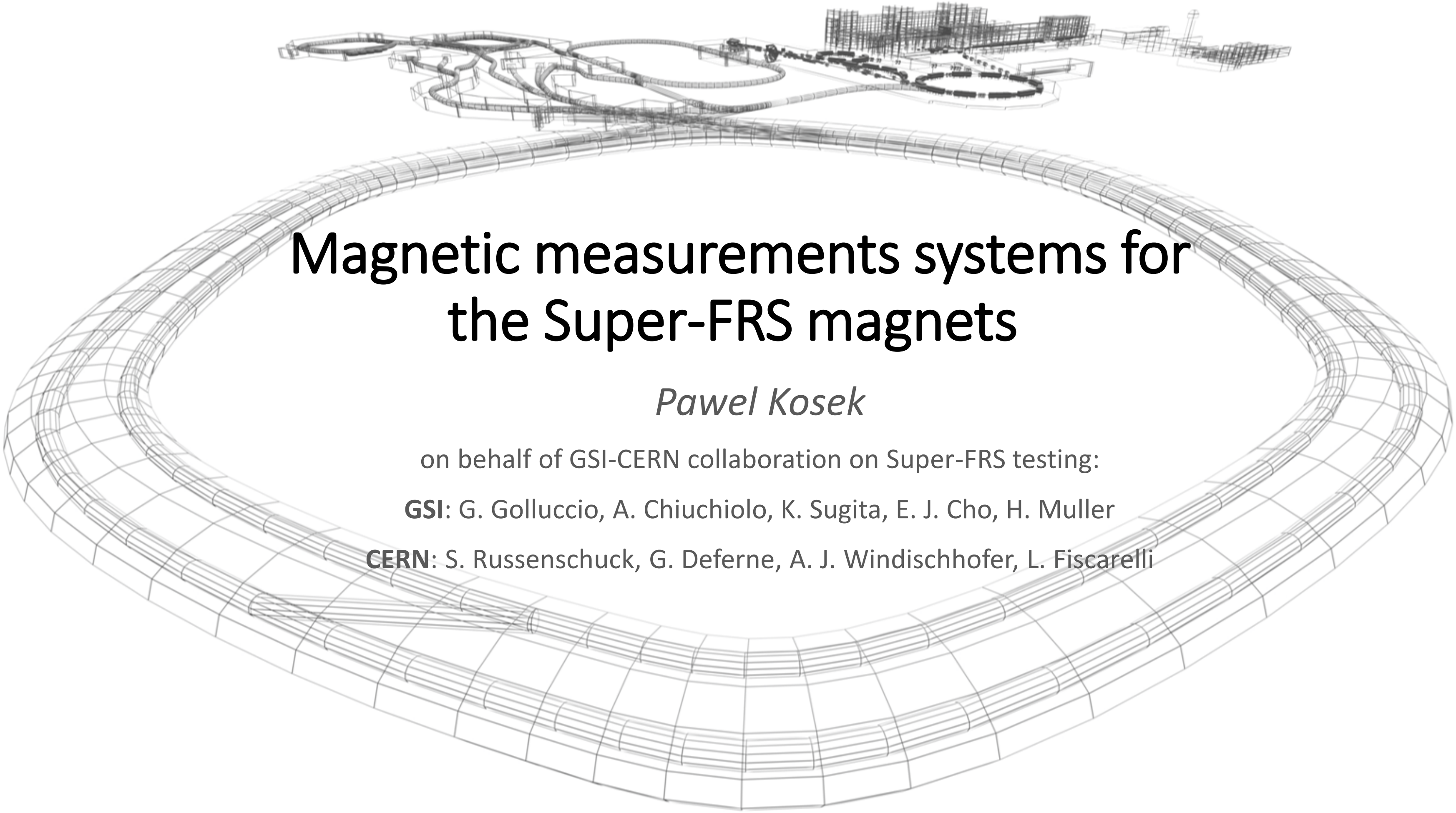


# Magnetic measurements systems for the Super-FRS magnets

*Pawel Kosek*

on behalf of GSI-CERN collaboration on Super-FRS testing:

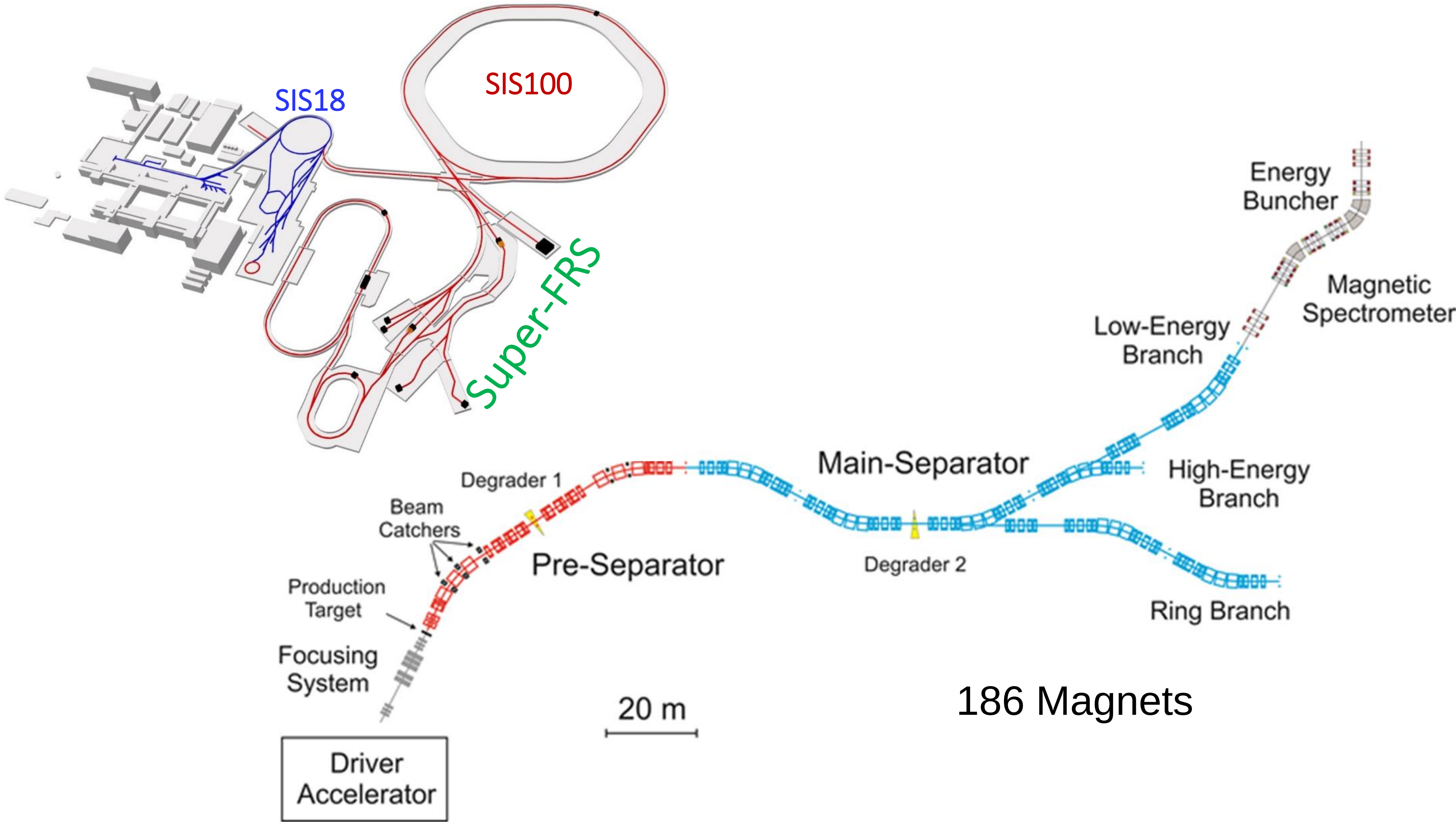
**GSI**: G. Golluccio, A. Chiuchiolo, K. Sugita, E. J. Cho, H. Muller

**CERN**: S. Russenschuck, G. Deferne, A. J. Windischhofer, L. Fiscarelli

# Outline

- Super-FRS Project overview
  - About Super-FRS
  - Test Facility at CERN
  - Magnets
- Magnetic Measurements
  - Measurement requirements
  - Measurement Devices
    - Rotating coil
    - Single stretched wire
    - Translating Flux-meter
- Summary

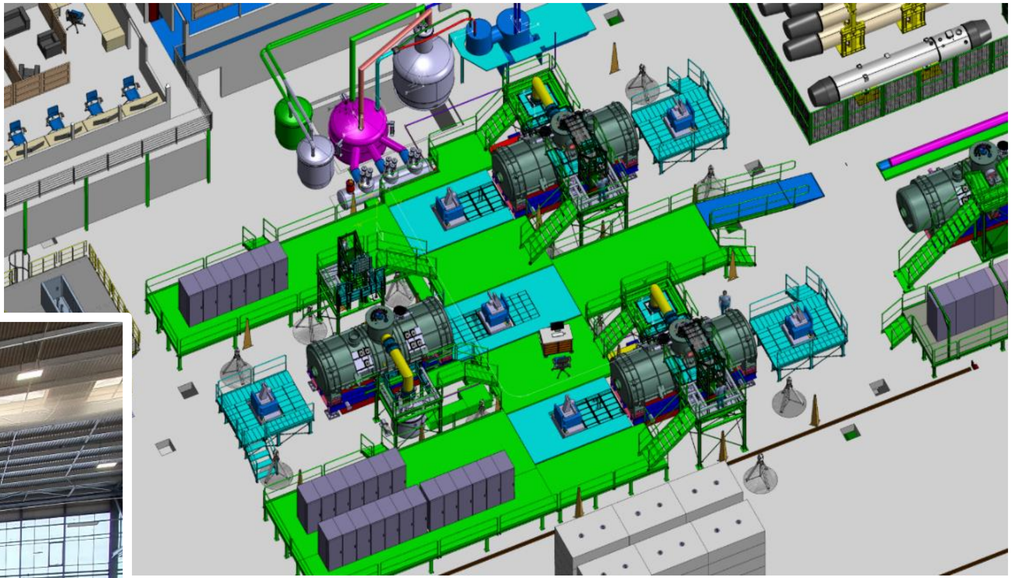
# Super FRagment Separator



186 Magnets

# Test Facility @ CERN (B.180)

- 3 test benches for cold (4K) testing
- 9 power converters for individual magnet powering + energy extraction
- Preparation area



# Multiplets

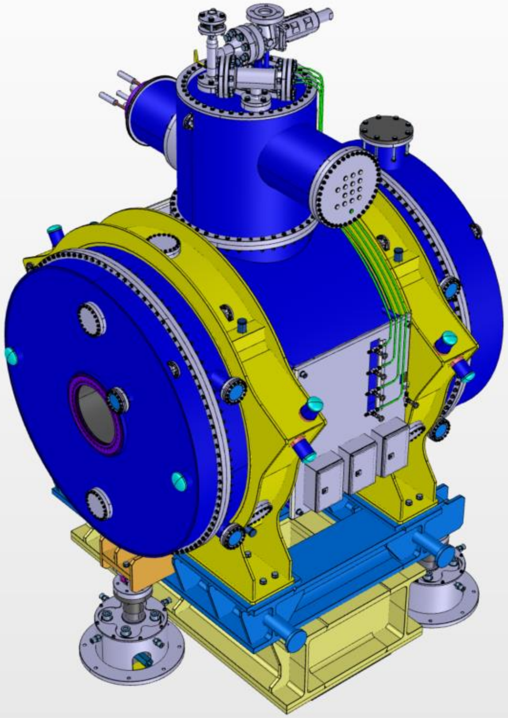
- 7+1 short multiplets (SM)
- Standard configuration:

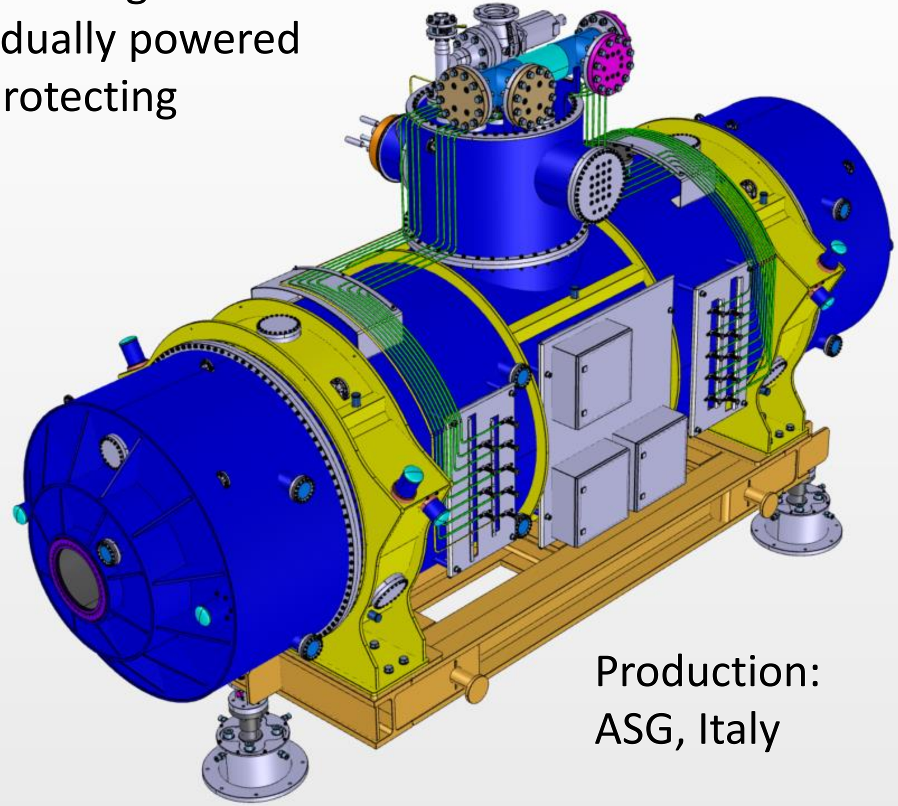
1x Quad + 1 x Hex

- 2.6 m long

- Super-ferric
- Warm bore (192 mm)
- DC each magnet individually powered
- Self protecting

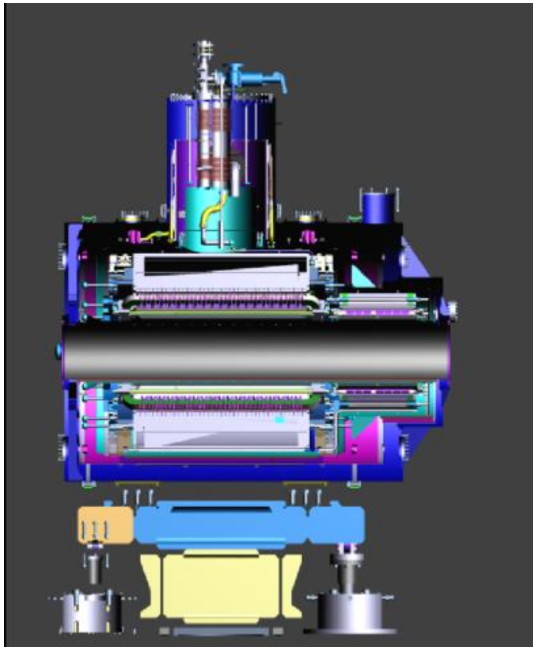
- 24+1 long multiplets (LM)
  - Up to 9 magnets (quadrupoles, sextupoles, octupoles, steerers)
  - 7 m, 6.5m, 6m long, 60 ton



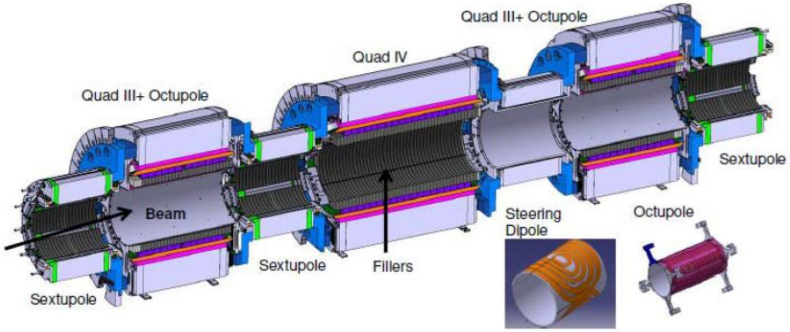


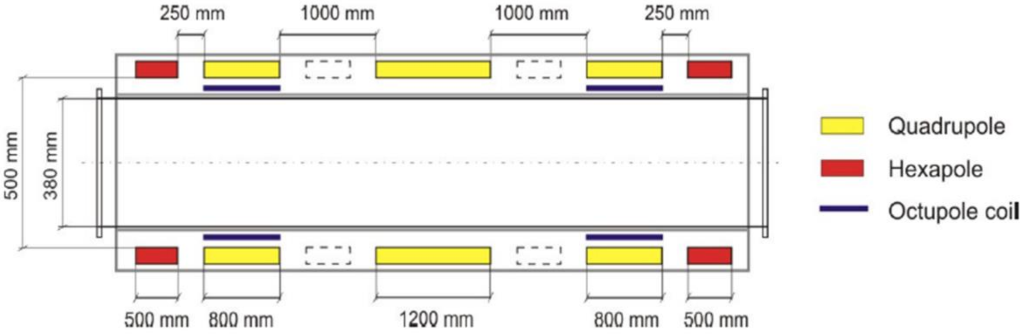
Production:
ASG, Italy

# Multiplets’ Magnets



| | Quad III (SQ) | Quad IV (LQ) | Sextupole | Octupole | Steering dipole |
|---|---|---|---|---|---|
| Number of magnets | 44 | 32 | 39 | 42 | 13 |
| Length of iron (mm) | 800 | 1200 | 500 | - | 500 |
| Pole tip radius (mm) | 250 | 250 | 237 | - | 250 |
| Warmbore radius (mm) | 192 | 192 | 192 | - | 192 |
| Outer radius of yoke (mm) | 701.4 | 701.4 | 420.85 | - | 405.8 |
| Integrated gmax (Tm/mn-1) | 8 | 11.5 | 20 | 84 | 0.1 |
| Ramp time (s) | 120 | 120 | 120 | 120 | 120 |
| Imax(A) | 300 | 300 | 291 | 160 | 280 |
| Inductance @Imax (H) | 16 | 21 | 0.88 | 0.097 | 0.62 |
| Stored energy @Imax (kJ) | 664 | 952 | 37 | 1.3 | 2.6 |
| Number of layers | 26 | 26 | 22 | 2 | 1 |
| Number of turn/layer | 48 | 48 | 11 | 18 | 5 Blocks |
| Bpeak in the conductor @Imax (T) | 4.2 | 4.2 | 1.9 | 0.2 | 1 |
| Magnet weight (ton) | 8 | 12 | 2.5 | 0.125 | 1.6 |
| Integrated Field Quality at 190 mm | ±1.0*10-3 < 0.8 gmax | | ±5.0*10-3 | ±8.0*10-3 | ±8.0*10-3 |
| | ±6.0*10-3 > 0.8 gmax | | | | |





# Dipoles

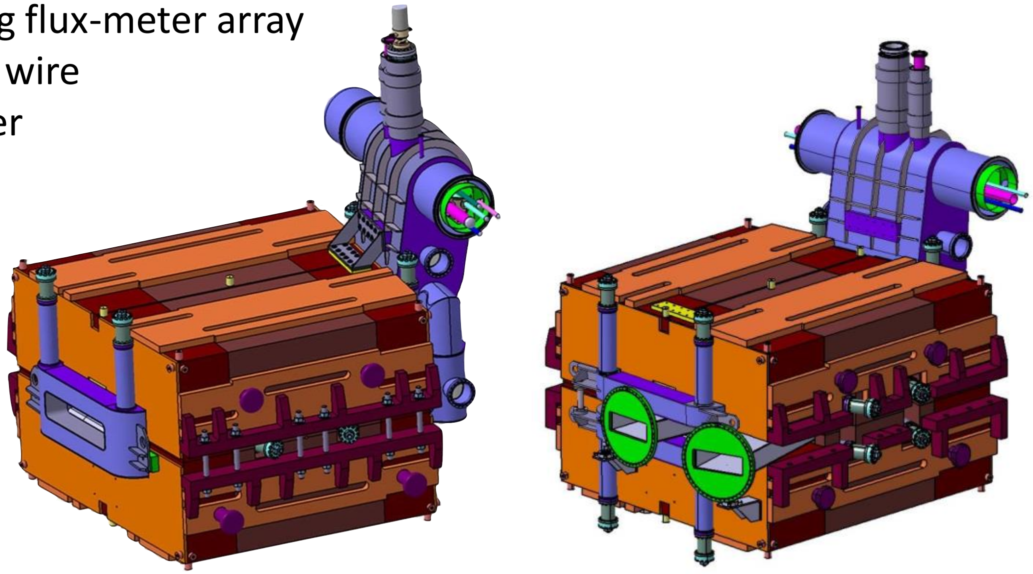
- 3 units - dipole type 2 [11 degree bending angle]
- 18 units - dipole type 3 [9.75 degree bending angle]
- 3 units - branching dipole [9.75 bending angle]

- Warm iron, SC coil
- Aperture ±190mm x ±70mm
- Weight: 50 to 60 ton

Measurement devices:

- Translating flux-meter array
- Stretched wire
- 3D Mapper

| **Dipoole type 3** | |
|---|---|
| Central field at Inom (T) | 1.6 |
| Integral field at Inom (Tm) | 3.403 |
| Integral field at Imin (Tm) | 0.319 |
| Magnetic length (mm) | 2127 |
| total measurement length (mm) | 4000 |
| Bending angle ° | 9.75 |
| Curvature radius (mm) | 12.5 |
| Aperture width (mm) | ±460.85 |
| Aperture height (mm) | ±85 |
| Good Field region width (mm) | ±190 |
| Good Field region height (mm) | ±70 |
| Acceptance criteria of field quality on the GFR boundary (Units of the integral field) | ±3 |
| Rise time to Inom (s) | 120 |



Production:
Elytt, Spain

# Magnetic measurements

**Goals**:

- Integral field measurements:
  - Conformity to QA SAT parameters
  - Magnet to magnet reproducibility
  - Localization of the magnetic field for installation purposes (fiducialization)
- Local measurements and field errors:
  - Measurement in the 2D region and integral
  - Only for the first of series
  - Verify mechanical assembly tolerances

**Challenges**:

- Large dimension of the Good Field Region
  - 170 mm radius for quadrupoles
  - 380 x 140 mm for dipoles
- Extended fringe field
- No possibility of standard calibration procedures
- Tight requirements of accuracy and fiducialization

| | | | |
|---|---|---|---|
| Field Quality | Quads | Current levels | 5 |
| | | Integral field homogeneity | $\pm 5*10^{-5}$ |
| | | Absolute integral field accuracy | $\pm 5*10^{-4}$ |
| | Multipoles | Absolute integral field accuracy | $\pm 1*10^{-3}$ |
| | | Integral field homogeneity | $\pm 2*10^{-4}$ |
| Fiducialization | Quads and multipoles | Angle (mrad) | <0.5 |
| | | Axis (mm) except steerers | 0.2 |

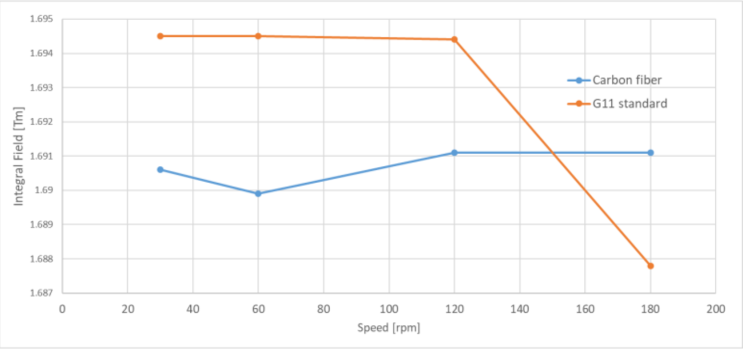
# Carbon fiber shaft (prototype)

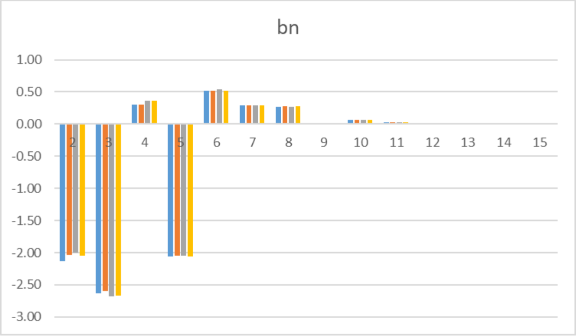
Carbon Fiber structure

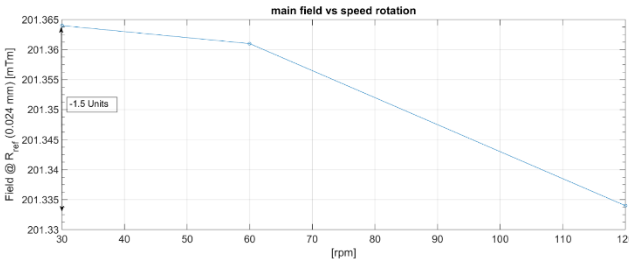
- Support structure for PCB
- rigidity
- weight reduction

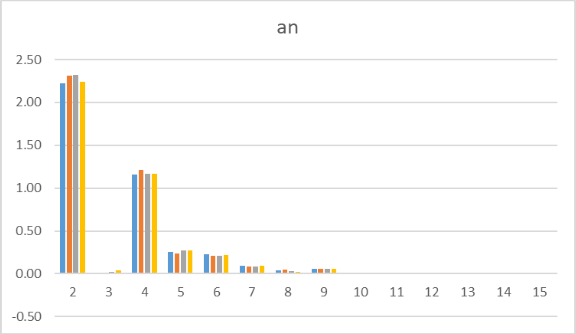
Test Program

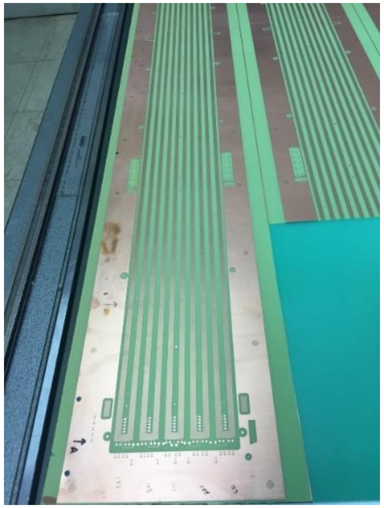
- Test on different bearings
- Test of eddy currents in the carbon shell:
- measure in standard bucking configuration the quadrupole with the shaft centered at various speeds
- Comparison with standard coil
- Test at cold @2.6 T

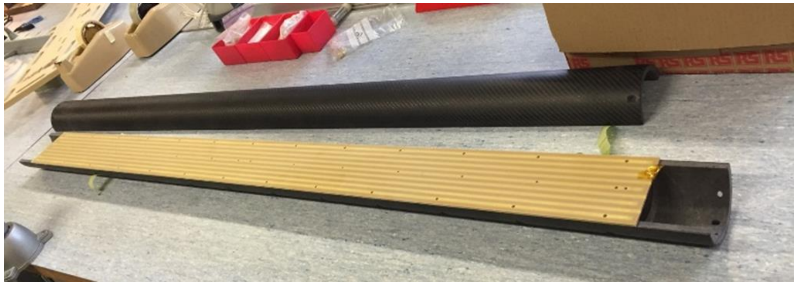






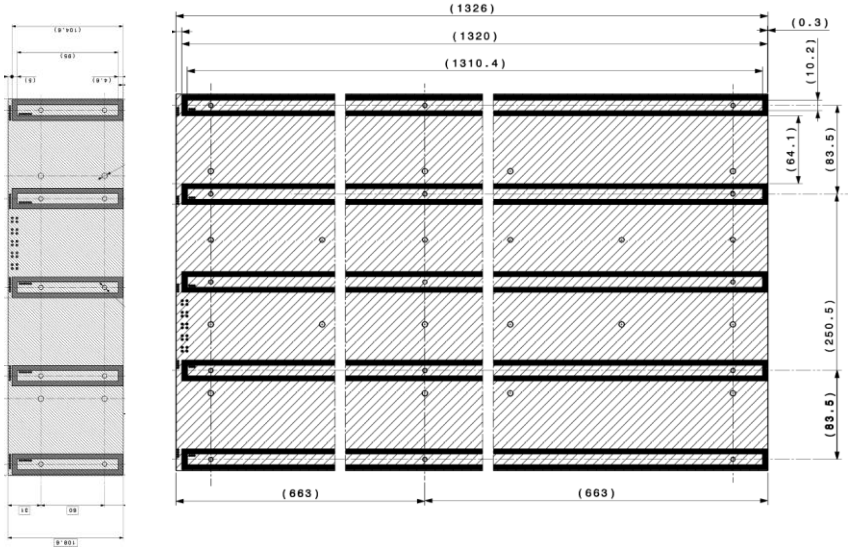


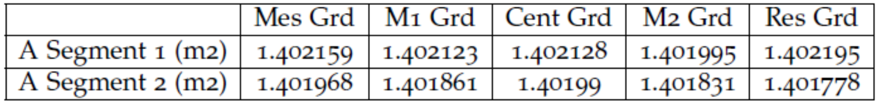




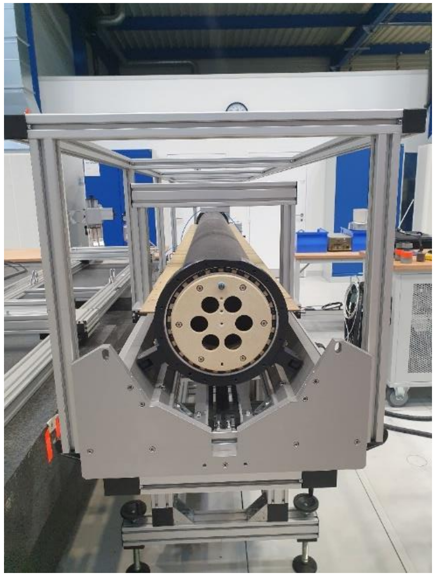
# Rotating shaft - design

- 3 PCBs, radial, 5 coil configuration:
  - External coil radius of 167mm
  - Bard thickness : 3.373 mm
  - 6 layers, 12 windings each **= 72 turns**
  - 2 long segments: **1315.2 mm** (coil) ;1326 mm (board), surface ~1.40 $m^2$ each
  - 1 short segment, length: **104.6mm** (coil); 108.6 mm (board)
  - Theoretical bucking ratios dipole and quadrupole in range of 10000.
  - Surface calibration on reference dipole – designed value: 1.402 $m^2$





| | Mes Grd | M1 Grd | Cent Grd | M2 Grd | Res Grd |
|---|---|---|---|---|---|
| A Segment 1 (m2) | 1.402159 | 1.402123 | 1.402128 | 1.401995 | 1.402195 |
| A Segment 2 (m2) | 1.401968 | 1.401861 | 1.40199 | 1.401831 | 1.401778 |



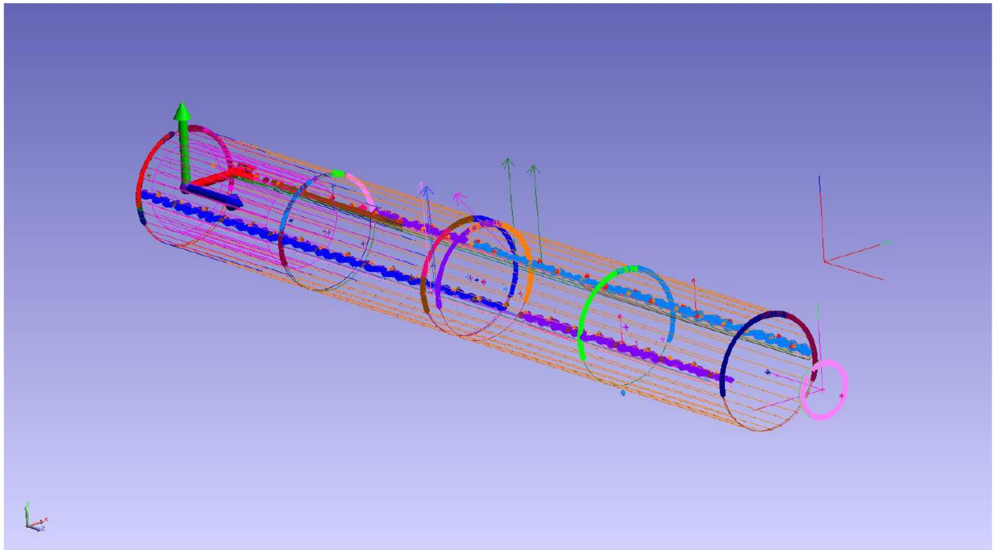
# Rotating coil evaluation

- Mechanical Measurements of the PCB boards
- Magnetic Measurements on the span of few months done on calibration quadrupole (0.5 m long, ~0.5 Tm/m, 170mm pole radius)
- Different configurations of DAQ system:
  - Multiple FDIs vs single FDI
- Assessment of gradient and harmonics:
  - Speed variation
  - Rotation direction
  - Longitudinal position
  - Current level
  - Transversal position

- Dipole and quadrupole Filed angle
- Theoretical vs real bucking ratios

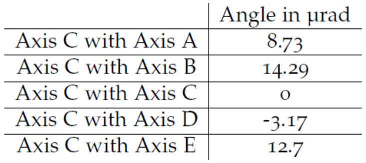
# Mechanical measurements of PCB

- No calibration devices for radius or angle for shaft this size
- Metrology report - measurement of reference holes + X-ray scan of the printed coil to the reference holes



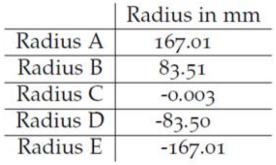
Laser tracker map:

- Static (flatness)
- Dynamic – center of the rotation – sag of the shaft is in accordance with simulated value (60µm)



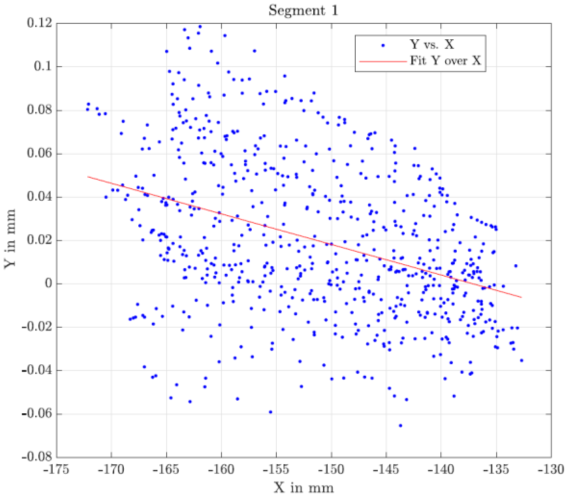
| | Angle in µrad |
|---|---|
| Axis C with Axis A | 8.73 |
| Axis C with Axis B | 14.29 |
| Axis C with Axis C | 0 |
| Axis C with Axis D | -3.17 |
| Axis C with Axis E | 12.7 |

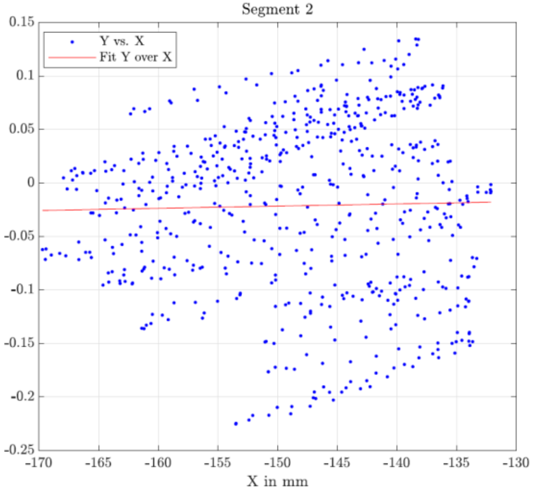
Table 2.1: Angles between axes

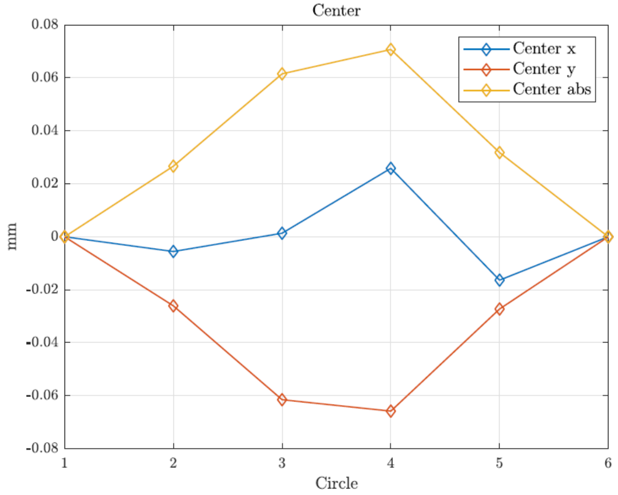


| | Radius in mm |
|---|---|
| Radius A | 167.01 |
| Radius B | 83.51 |
| Radius C | -0.003 |
| Radius D | -83.50 |
| Radius E | -167.01 |

Table 2.2: Radii of axes

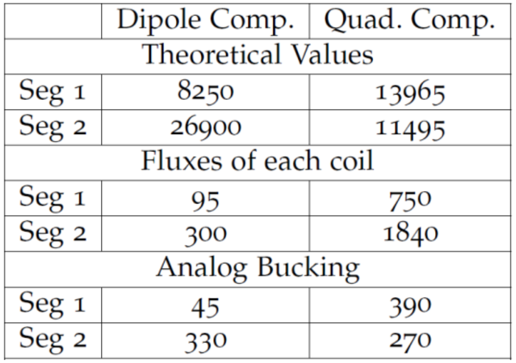




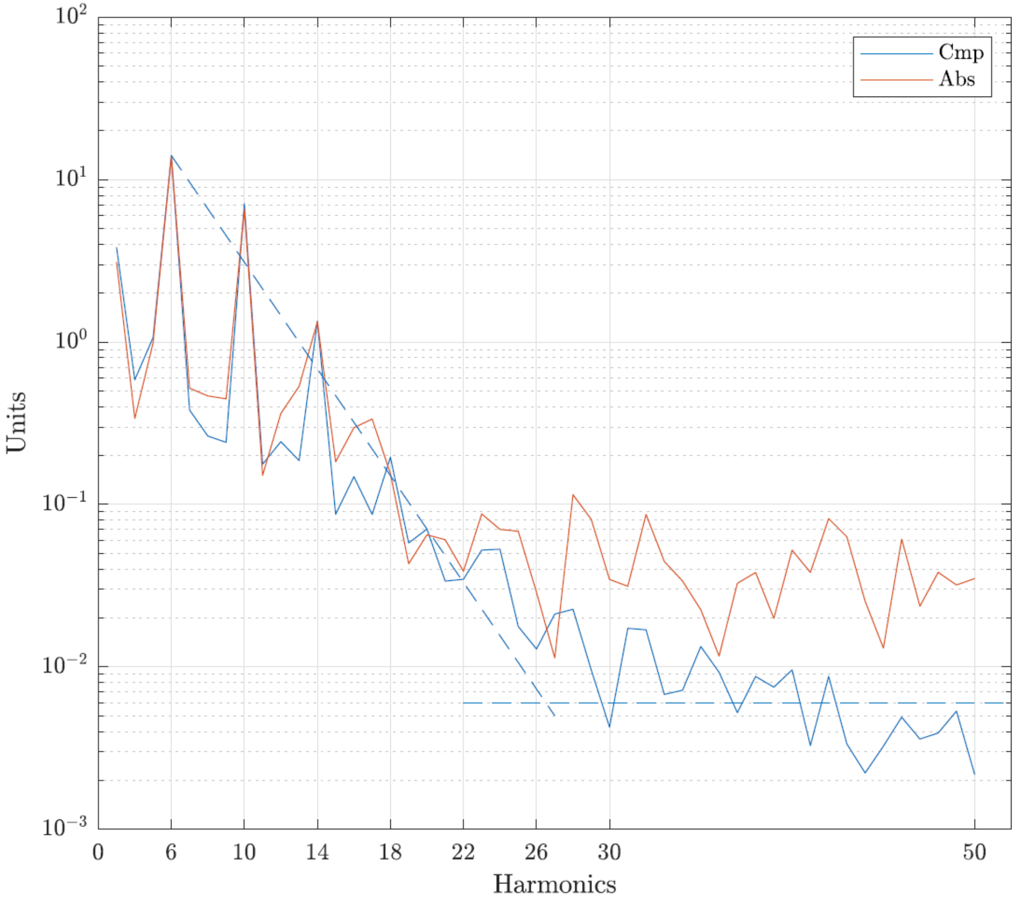


# Harmonics –Noise analysis

- Higher harmonics lost in the noise floor (10^-8 Vs)
- Up to 18th harmonic recognizable
- Noise floor on compensated signal approximately order of magnitude lower then on absolute
- Quadrupole compensation analog A-B-C+D
- Even though compensation not great:

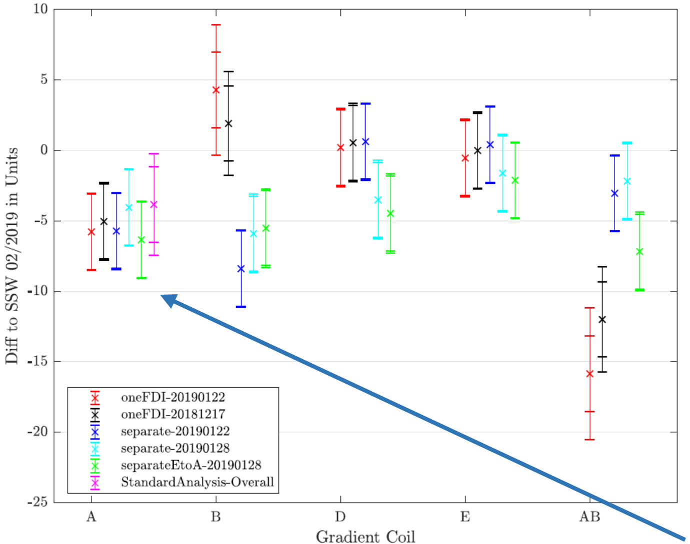


| | Dipole Comp. | Quad. Comp. |
|---|---|---|
| Theoretical Values | | |
| Seg 1 | 8250 | 13965 |
| Seg 2 | 26900 | 11495 |
| Fluxes of each coil | | |
| Seg 1 | 95 | 750 |
| Seg 2 | 300 | 1840 |
| Analog Bucking | | |
| Seg 1 | 45 | 390 |
| Seg 2 | 330 | 270 |

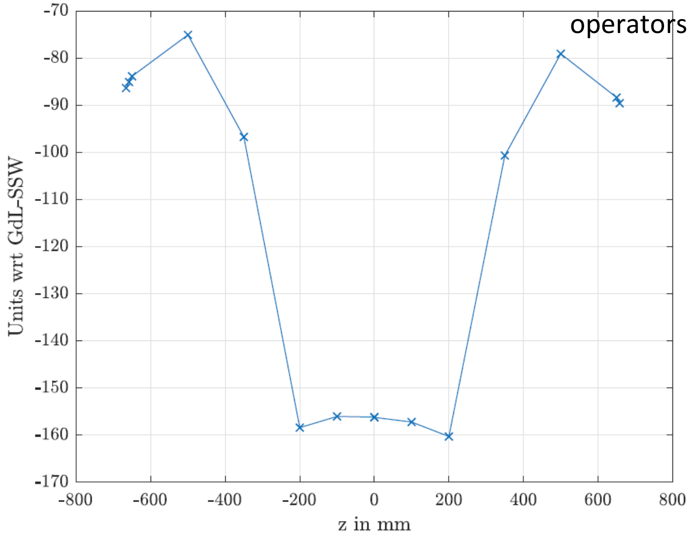


# Rotating coil - Gradient measurement

- “Standard” rotating coil configuration: 2nd harmonic and coil distance gives the gradient (“Measurement” or “A” coil)
- “Gradient Coil”: Coil A – Coil B and distance between them (analog or digital)
- Also from individual coils (except central) and their respective radii
- Missing field in the gap:
  - numerical simulation or local “center field measurement” and theoretical gap length
  - Central field from previous measurement
  - Comparison with SSW
- Longitudinal variation corresponds to simulation

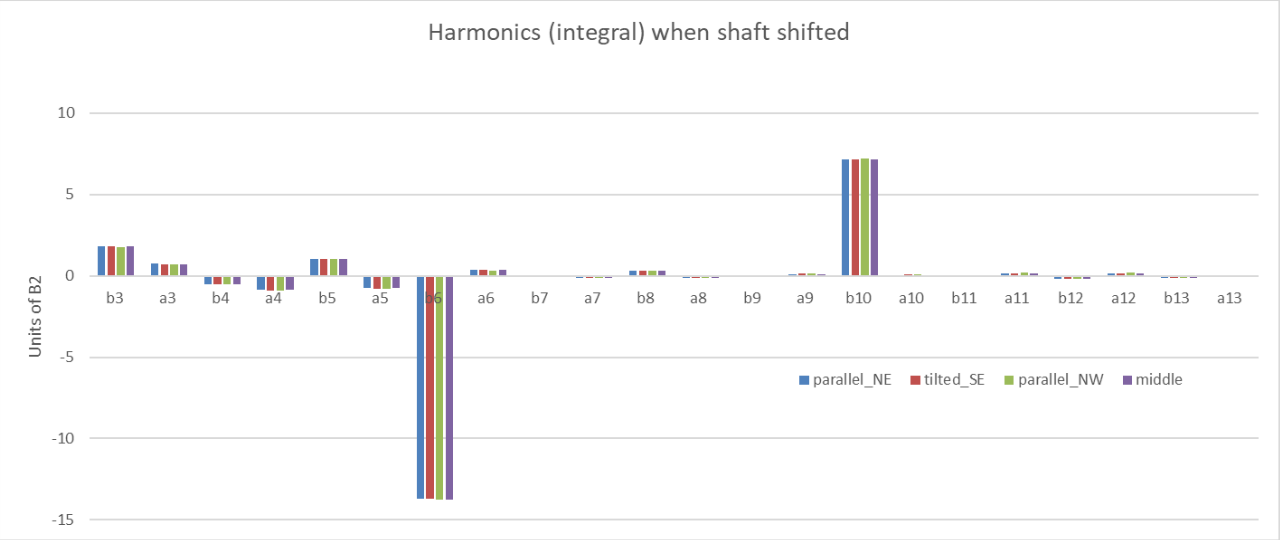


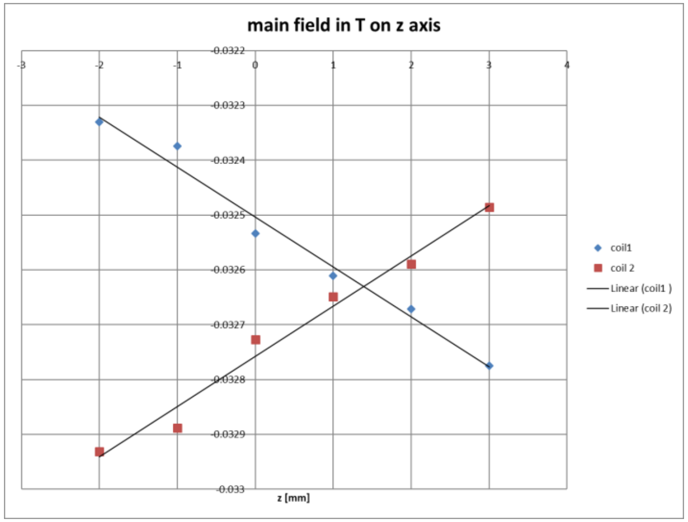
Different connection setups operators, month apart

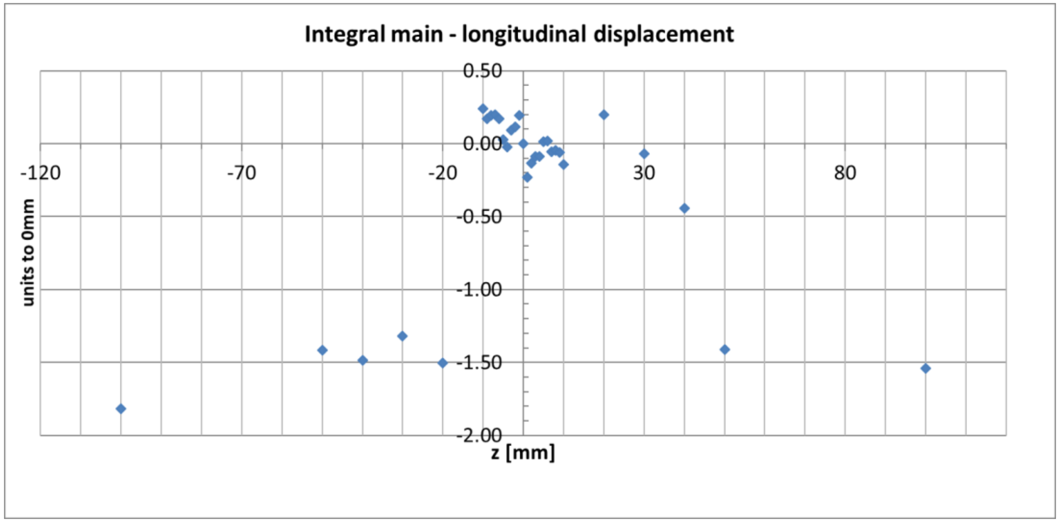


# Shaft position variation

- Sensitivity to longitudinal position (magnet symmetry)
- Positioning repeatability
- Main field :
  - 0.5 unit @+-20mm
  - 2 units @+-100mm

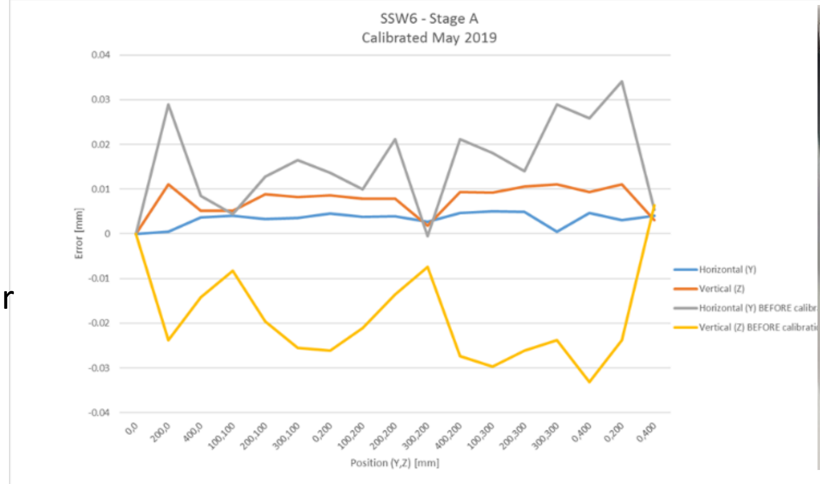


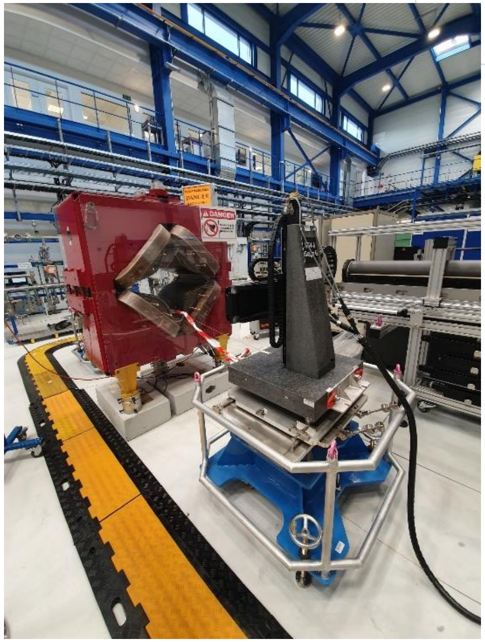


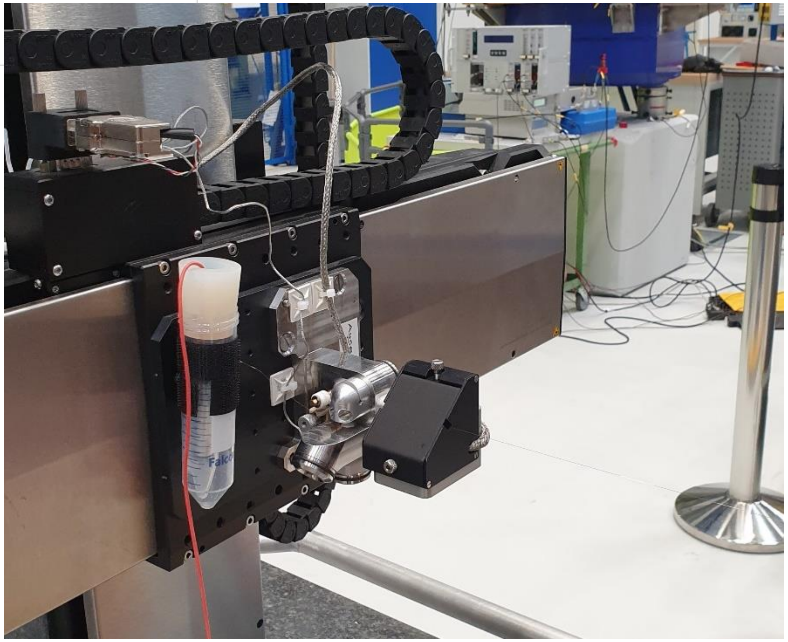


# Stretched wire

- 400 mm stroke
- Absolute positioning accuracy 1um
- Movement error better than 0.01mm
- Optical vibrations sensor
- Wire tension sensor
- CuBe wire 0.1mm
- Ceramic ball bearings







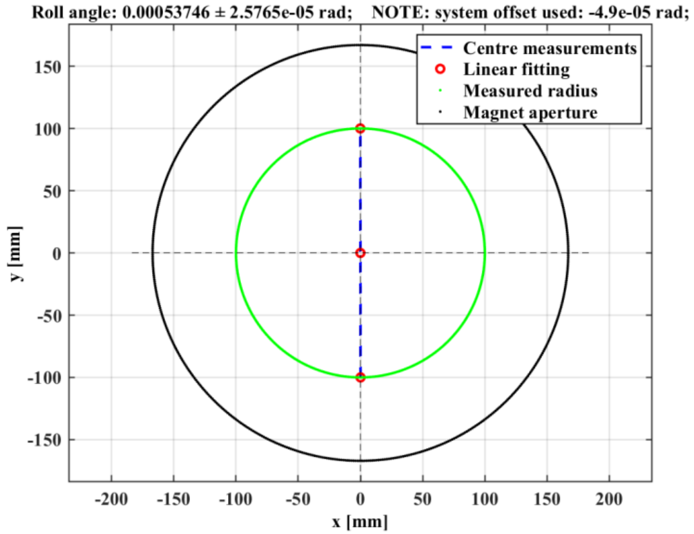
# SSW evaluation – center localization

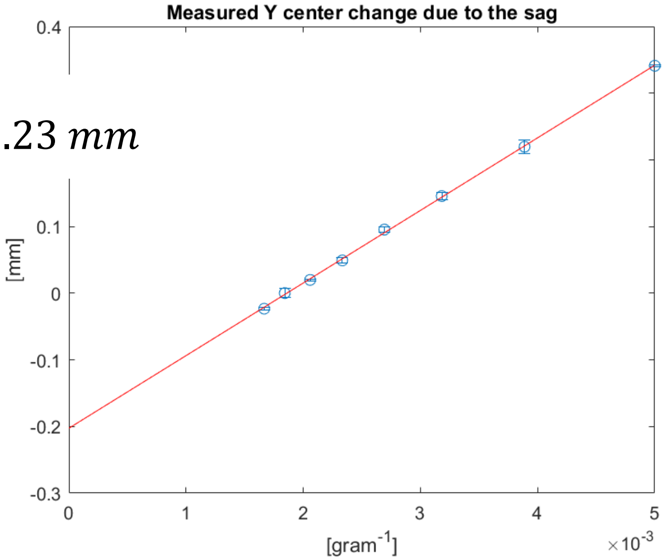
- Co-directional stages movement – 4 steps (2 directions forth and back)

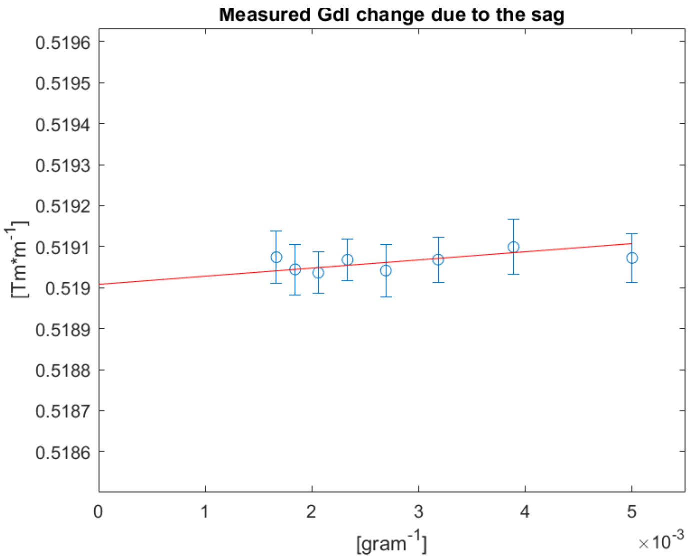
$$center = -\frac{\Delta x}{2}\,\frac{(\Phi_1 - \Phi_3)}{(\Phi_1 + \Phi_3)} = -\frac{\Delta x}{2}\,\frac{(\Phi_2 - \Phi_4)}{(\Phi_2 + \Phi_4)}$$

- Counter-directional movement for pitch and yaw
- Precision @2σ better than 0.01mm
- Sag correction @ 3.5 m stages distance

$$h = -\frac{\lambda_m g\, L^2}{8T} = -\,0.23\ mm$$



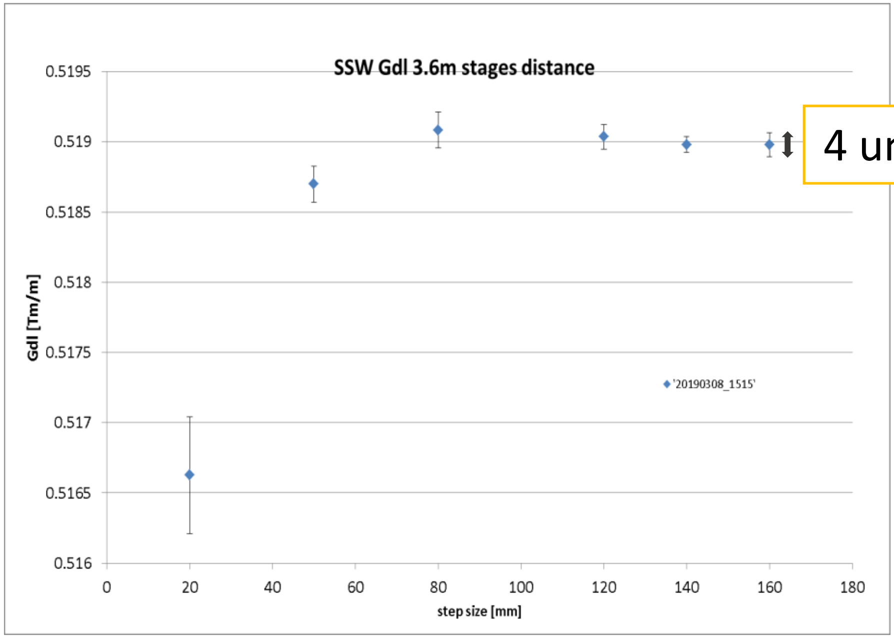




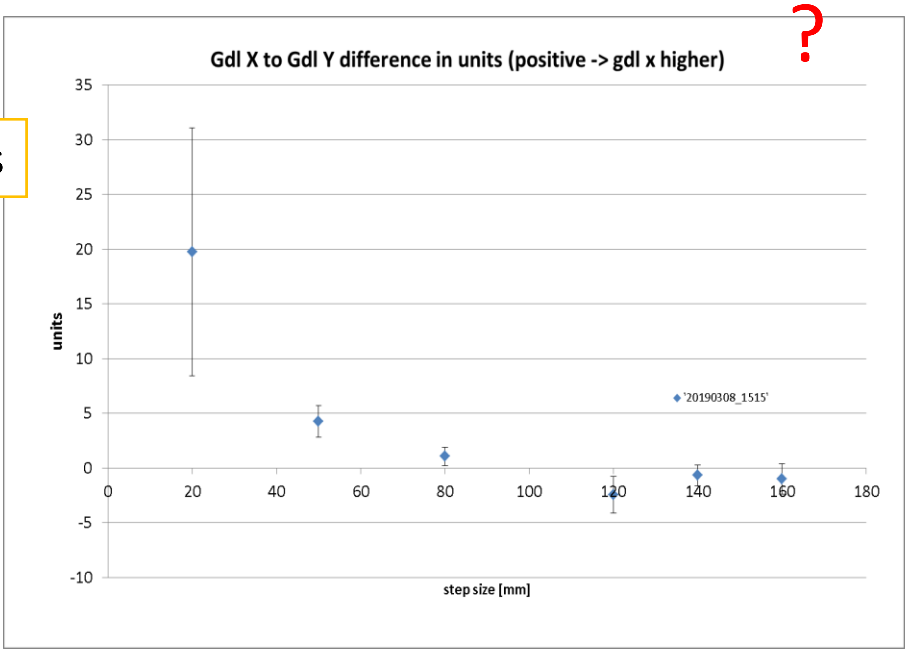
# SSW evaluation - gradient

- Comparison to rotating coil (shaft gap calibration)
- Dependency on step size (poor S/N) Gdl@400A = 0.519 Tm/m (~1/16 of nominal Gdl for SQ)
- X and Y plane movement difference
- Effect on mainfield because of harmonics <1 unit

| | Value | Uncertainty | Unit |
|---|---|---|---|
| Gap total | 6.5 | +-0.1 | mm |
| Gdl in the center (QIMM) | 0.738517 | +-0.00005 | T/m |
| Gdlin the gap | 0.0048 | +-0.0001 | Tm/m |
| Gdl– Rotating Coil (no gap) | 0.514057 | +-0.00004 | Tm/m |
| Gdl– Rotating Coil (with gap) | 0.518857 | +-0.00005 | Tm/m |
| Gdl SSW | 0.51898 | +-0.0002 | Tm/m |
| Difference SSW to Rotating coil (in units) | -2.4 | ~ +-3 | 10^-4 |



4 units



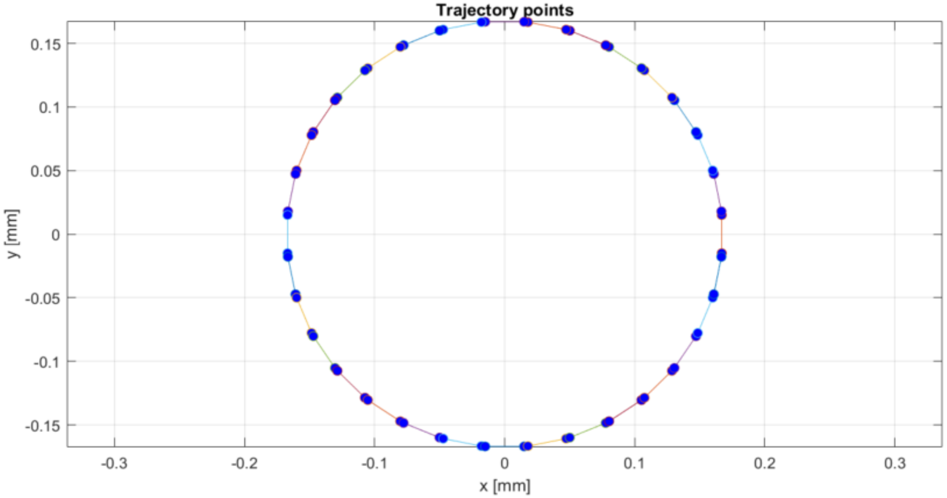
# SSW evaluation - harmonics

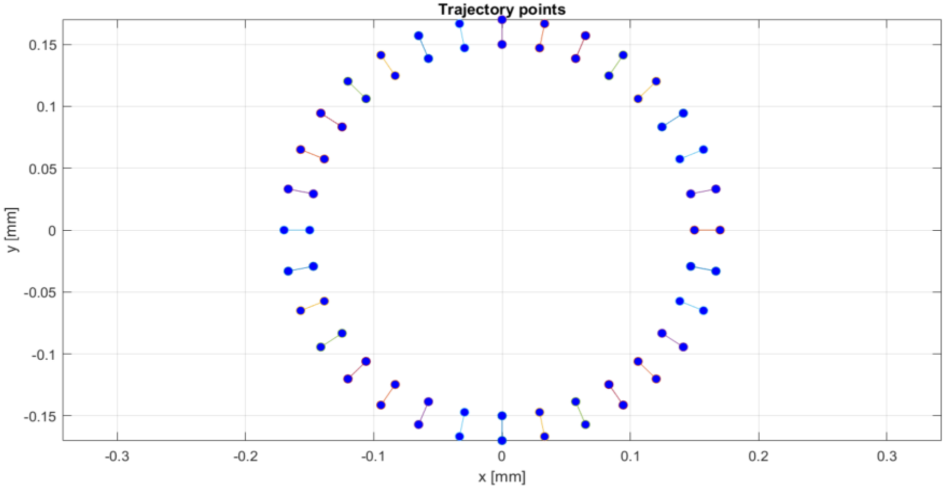
- Circular trajectory
- 32 steps
- Tangential coil-like movement: 167mm radius, 30mm steps
- Radial coil-like movement- 20 mm steps, smaller radius -> extrapolation to 167mm (but also errors)

- Standard Fourier expansion Harmonics analysis

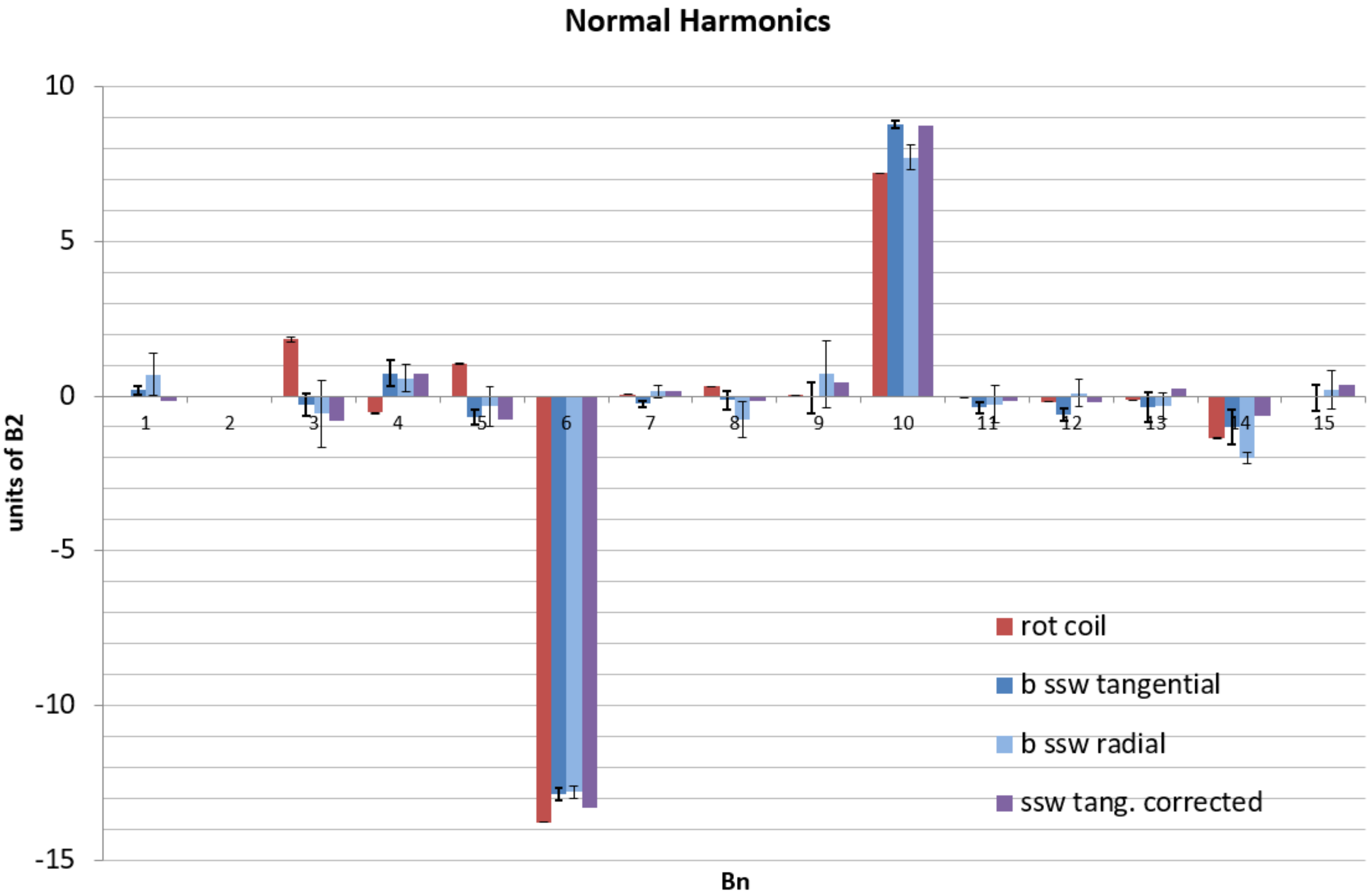
$$\kappa_{tang} = \frac{\left(R_{ref} + \frac{\Delta z}{2}\right)^n - \left(R_{ref} - \frac{\Delta z}{2}\right)^n}{n}$$

$$\kappa_{rad} = \frac{2i}{n}(R_{ref})^n * \sin\left(\frac{n * \Delta\theta}{2}\right)$$

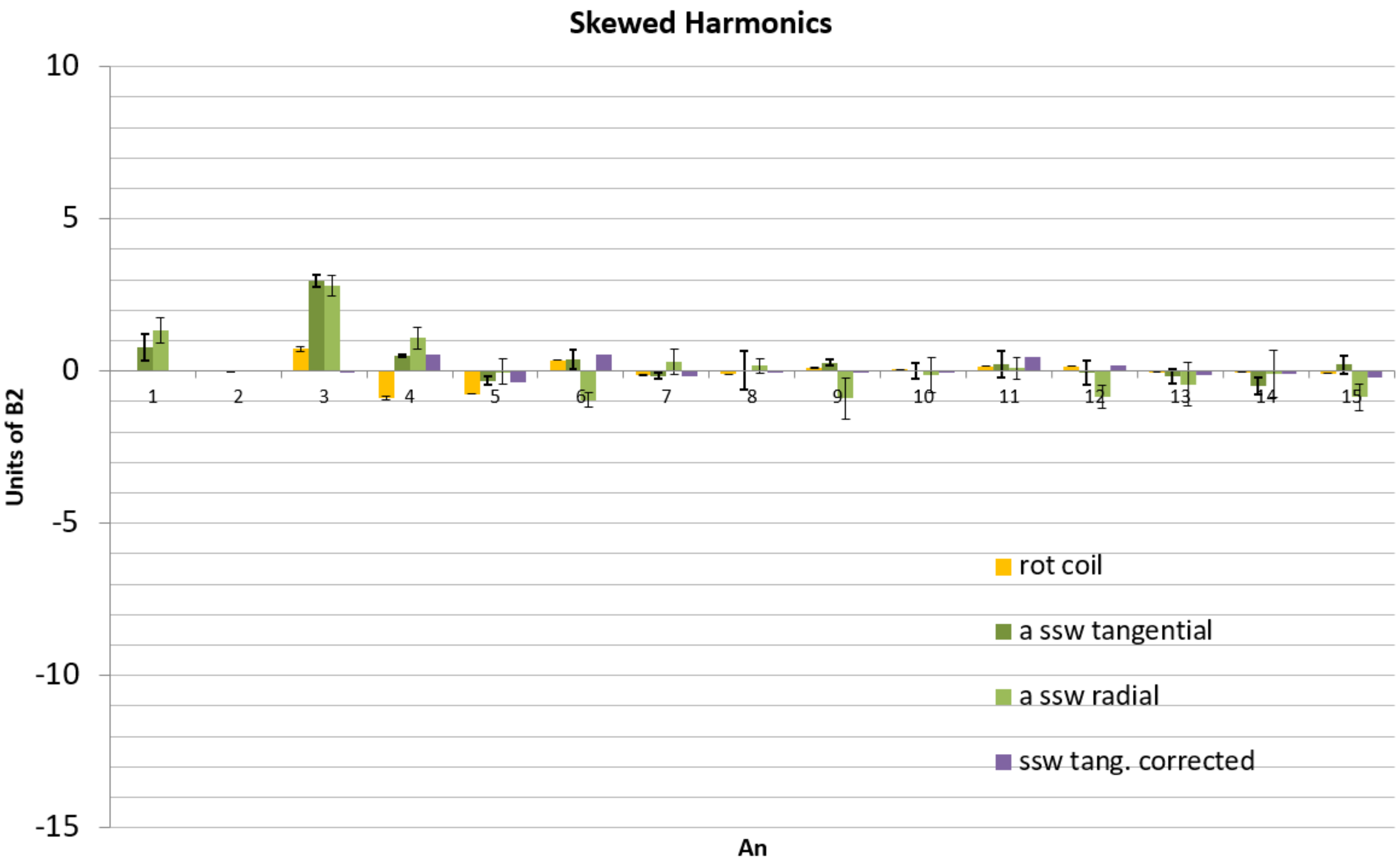




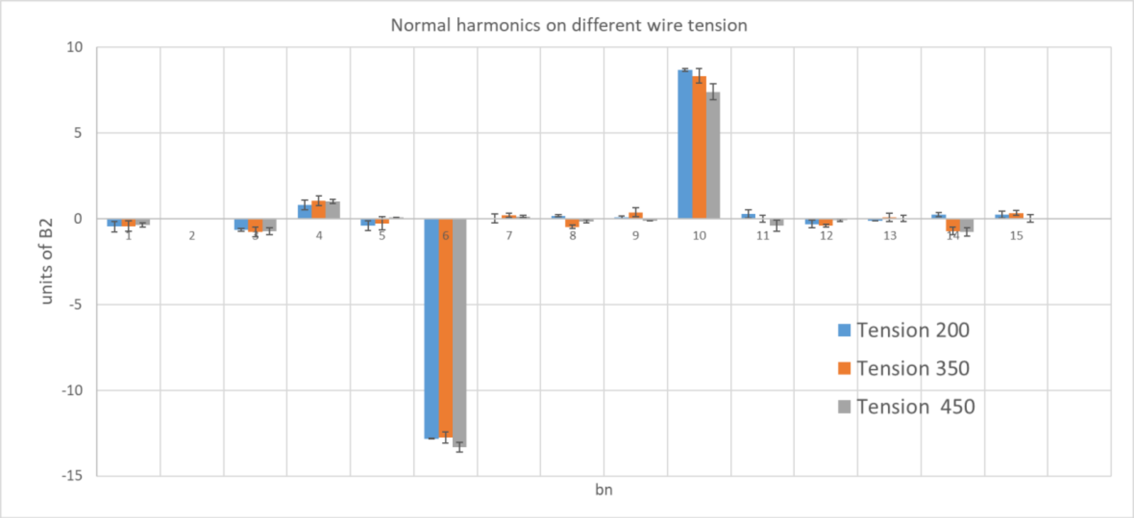
# SSW evaluation - harmonics

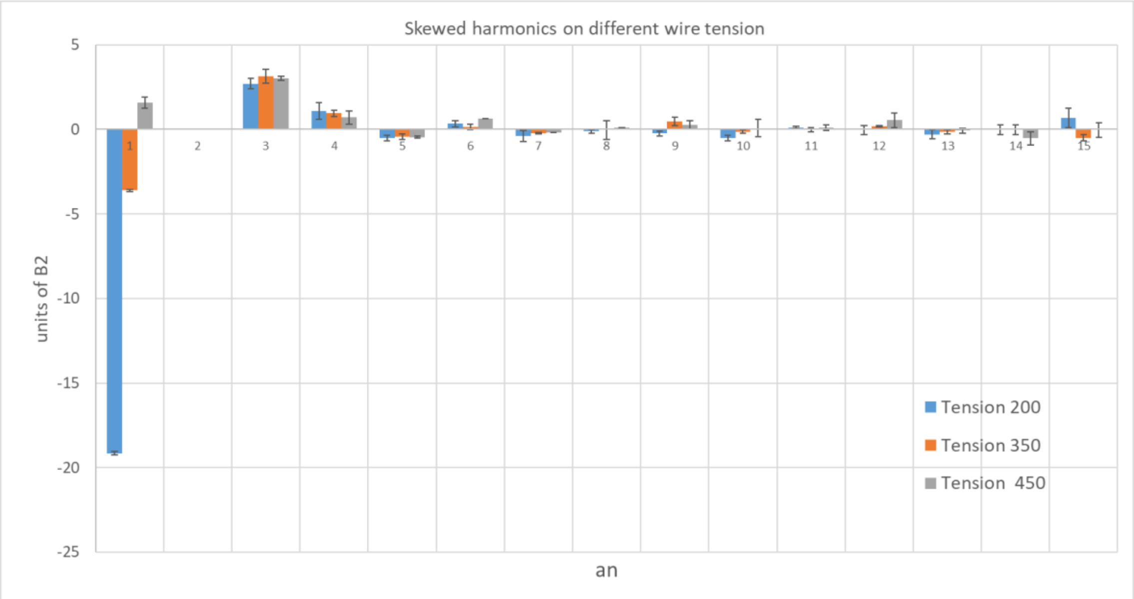


# SSW evaluation - harmonics



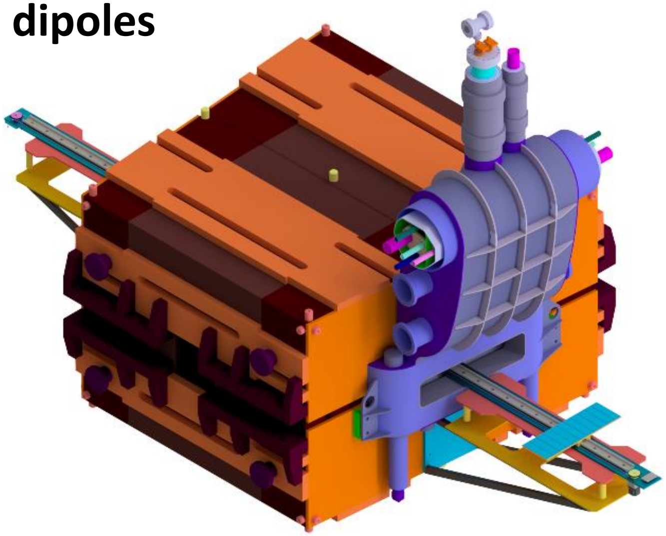
# SSW harmonics – sag effect





# Translating Flux-meter

**New 4 m measurement length translating fluxmeter for dipoles**



Based on the prototype build in 2015

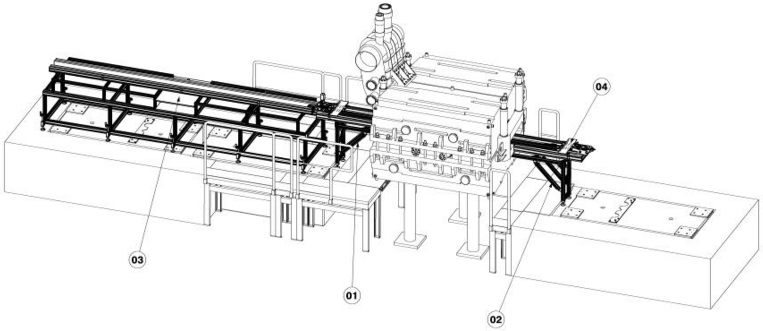
PCB plate with

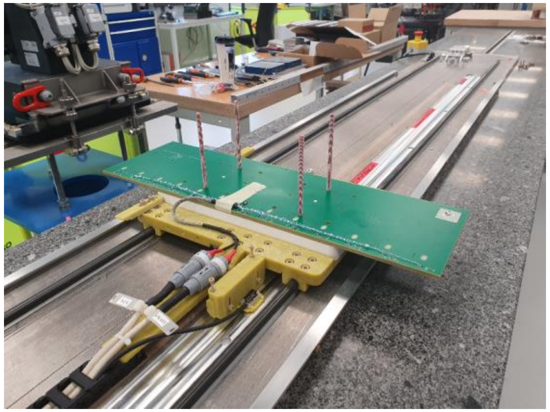
- 13 coils of 0.6 m$^2$ (w=28mm l =110 mm)
- 1D Hall probe for offset adjustment

Aluminium structure

- Guiding system
- Non magnetic linear encoder (5 µm resolution)

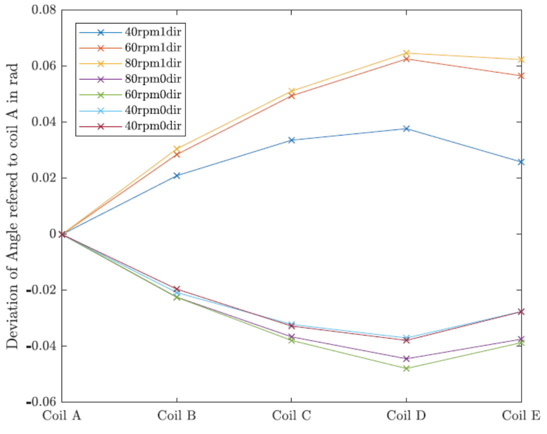
- Construction in progress…



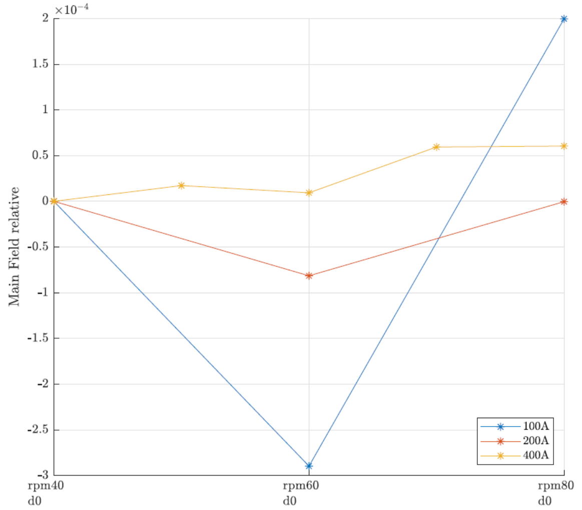


Thank you!

# Additional slide 2



(a) Angle of the dipole component at different speeds and rotation directions.



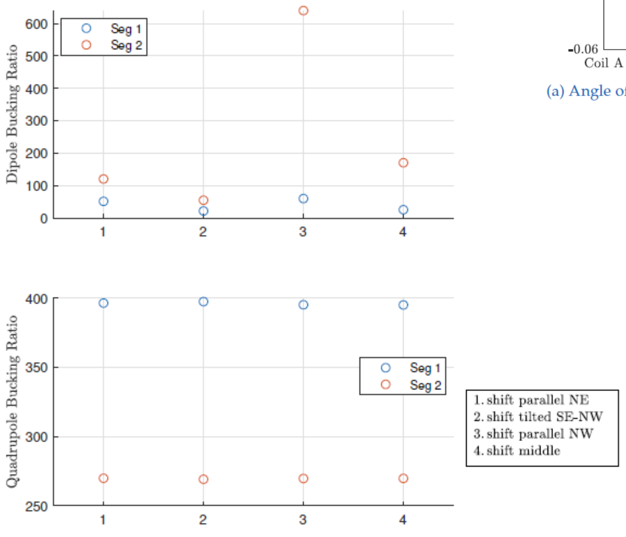
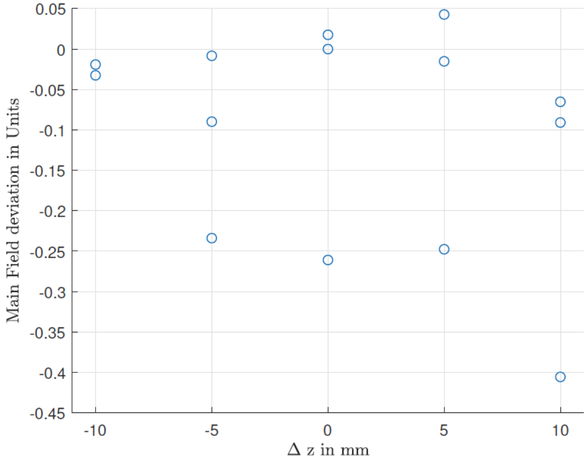


Figure 1.24: Different transversal positions and their effect on the bucking ratio



# Additional slide 3 - 3D Mapper

**3D mapper for dipole**
3D with 3000 x 1000 x 1000 mm stroke mapper and 3D hall probe sensor

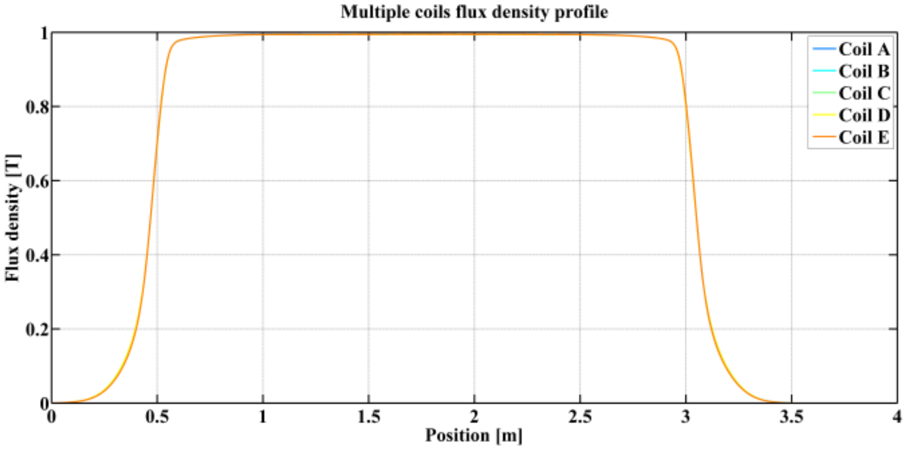


Figure 7.14: The magnetic flux profile for the 5 coil array.

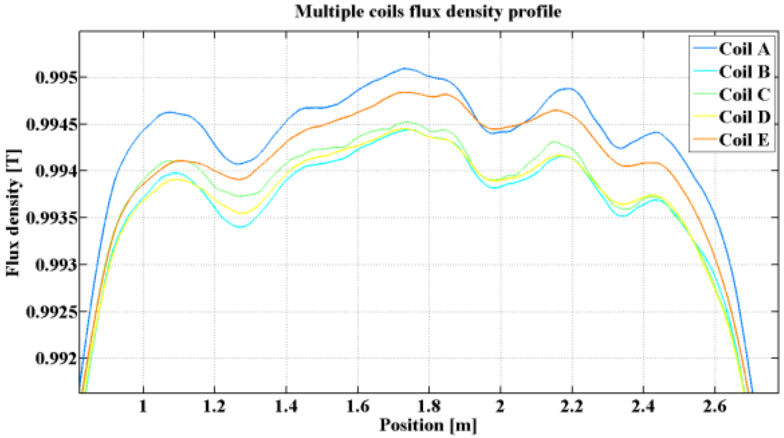


Figure 7.15: A close-up of the upper part of the field profile. Every coil profile is drawn with a different colour.

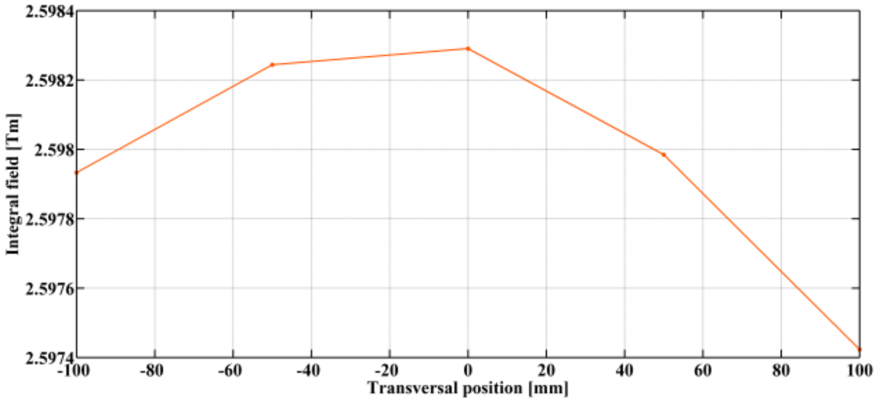


Figure 7.17: The integral homogeneity plot