Laboratori Nazionali di Frascati

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# MAGNETIC MEASUREMENTS ON THE GUN FOCUSING SOLENOID

*B. Bolli, S. Ceravolo,M. Esposito, F. Iungo, M. Paris, M.Preger,*
*C. Sanelli, F.Sardone, F. Sgamma, M. Troiani, P.Musumeci°,*
*G.Bazzano*, D.Bianculli*, I. De Cesaris**

*INFN-LNF*
*° Università di Roma“la Sapienza”*
**Fondazione CNAO*

## Abstract

The electrical and magnetic measurements on the SPARC gun solenoid are reported. A magnetic measurements procedure used to evaluate the shift of the solenoid magnetic axis, with respect to the mechanical axis, is also described.

**Picture 1 : The SPARC Gun focusing solenoid**

## 1. Introduction

The SPARC gun focusing solenoid for emittance compensation, shown in Picture 1, is made up of four coils independently powered interleaved with massive iron plates that together with the end-caps constitute the magnet yoke. It was designed and originally tested in the Particle Beam Physics Laboratory of UCLA and was then delivered to Frascati in June 2005 where it was tested to verify the Magnetic field intensity and uniformity at different excitation currents. Since these measurements evidenced an anomalous behaviour of the solenoid magnetic axis, a dedicated set of measurements was performed in September 2005.

## 2. Electrical Measurements

The power supply used for all measurements is FUG model NTN 10500 – 35, whose specification are given in appendix.

### *2.1 Resistance – Volt-Ampere method*

The resistance of the magnet was measured by means of the Volt-Ampere method at room temperature using a voltmeter Fluke mod. 77. The current reading was given by the power supply.

- Measure at $T_{amb}$ = 21 °C:

V = 0.508 V
I = 5 A

corresponding to a DC resistance of $R_{Room} = 0.102\ \Omega$.

- Measure at thermal regime:

$V = 29.41$ V
$I = 249.9$ A

corresponding to a DC resistance of $R = 0.118\ \Omega$.

### *2.2 Inductance and resistance at different frequencies*

The inductance and resistance was also measured by means of a LCR meter, HP mod. 4284 A, at different frequencies. Results are shown in Figure 1. The corresponding DC values can be extrapolated from these data. Table I lists the measured values.

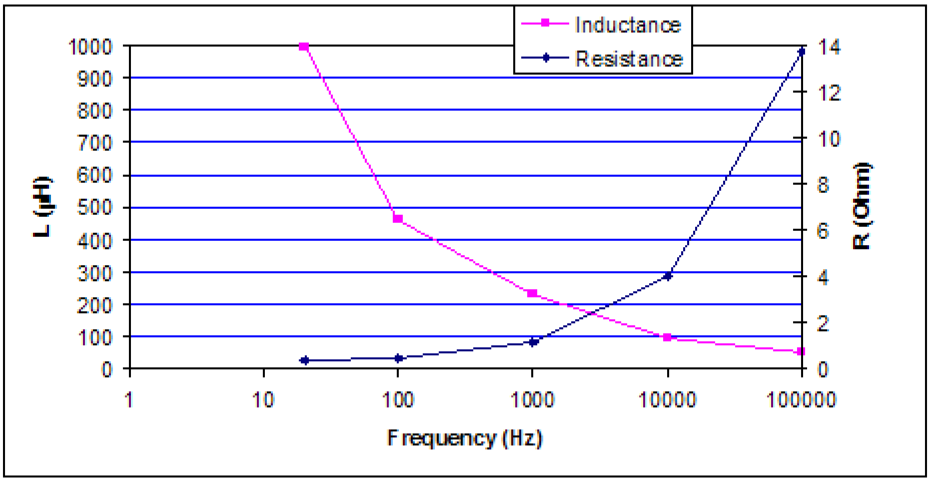



**Figure 1: Gun focusing solenoid resistance and inductance versus frequency**

Table I – *Resistance and inductance versus frequency*

| **Frequency (Hz)** | **R (Ω)** | **L (µH)** |
|---:|:---:|:---:|
| 20 | 0.39 | 996.6 |
| 100 | 0.48 | 462.8 |
| 1 k | 1.14 | 230.2 |
| 10 k | 4.01 | 95.2 |
| 100 k | 13.75 | 50.6 |

## 3. Thermal Measurements

Three sets of measurements, with three different values of feeding current, have been performed.
For each measurement the hydraulic and thermal parameters were.

| | |
|---|---|
| Room temperature: | 21°C |
| Pressure drop: | 0.15 MPa |
| Water flow: | $0.11 \cdot 10^{-3}$ $m^3/s$ |

The following instrumentation was adopted:

Thermometers: PT100 (four)
Paper recorder: Yokogawa LR 400

Temperature was acquired in three points on the magnet: on the iron yoke, on coil 1 and on coil 4. The fourth PT-100 recorded the room temperature (approximately 21°C) which is used as reference.
Temperature values are collected electronically (via GPIB through a dedicated VI) instead of being recorded on paper and are shown in Figure 2, Figure 3 and Figure 4 together with the best fit curve on the experimental data.
Note that coil1 is the first one in the hydraulic circuit, while coil4 is the last (i.e. it receives hotter water) and this explains the difference in equilibrium temperature reached by the two.

The data obtained for the coils and yoke are fitted with the following expression:

$$T = T_{Inf} - \Delta T \cdot \exp(-t/\tau).$$

Fit parameters $T_{Inf}$ (the temperature asymptotic value), $\Delta T$ and $\tau$ are reported in Table II, together with the linear correlation coefficient R. They were obtained with KaleidaGraph fit routine.

Table II – *Fit coefficients for coils and yoke thermal characterization*

| ***Coil 1*** | **I = 100 A** | | **I = 200 A** | | **I = 250 A** | |
|---|---|---|---|---|---|---|
| **$T_{Inf}$ [°C]** | 23.67 | ± 0.03 | 37.3 | ± 0.1 | 47.7 | ± 0.1 |
| **ΔT [°C]** | 2.6 | ± 0.2 | 16.0 | ± 0.4 | 27.1 | ± 0.3 |
| **τ [min]** | 13.0 | ± 1.5 | 15.1 | ± 0.6 | 16.6 | ± 0.4 |
| **R** | 0.898 | | 0.985 | | 0.996 | |
| ***Coil 4*** | **I = 100 A** | | **I = 200 A** | | **I = 250 A** | |
| **$T_{Inf}$ [°C]** | 24.76 | ± 0.03 | 42.9 | ± 0.1 | 55.8 | ± 0.1 |
| **ΔT [°C]** | 3.7 | ± 0.2 | 21.5 | ± 0.4 | 35.9 | ± 0.3 |
| **τ [min]** | 13.0 | ± 1.0 | 14.5 | ± 0.5 | 14.5 | ± 0.2 |
| **R** | 0.944 | | 0.989 | | 0.998 | |
| ***Yoke*** | **I = 100 A** | | **I = 200 A** | | **I = 250 A** | |
| **$T_{Inf}$ [°C]** | 26.45 | ± 0.04 | 50.6 | ± 0.1 | 67.6 | ± 0.2 |
| **ΔT [°C]** | 5.5 | ± 0.1 | 31.9 | ± 0.2 | 50.6 | ± 0.4 |
| **τ [min]** | 29.8 | ± 1.2 | 30.8 | ± 0.4 | 37.3 | ± 0.7 |
| **R** | 0.988 | | 0.998 | | 0.998 | |

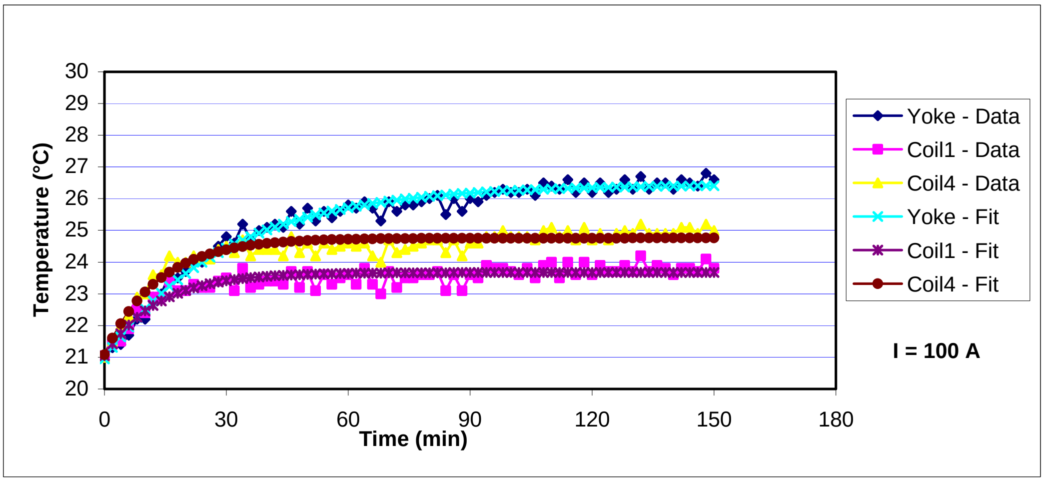



**Figure 2: Temperature increase with I = 100 A**

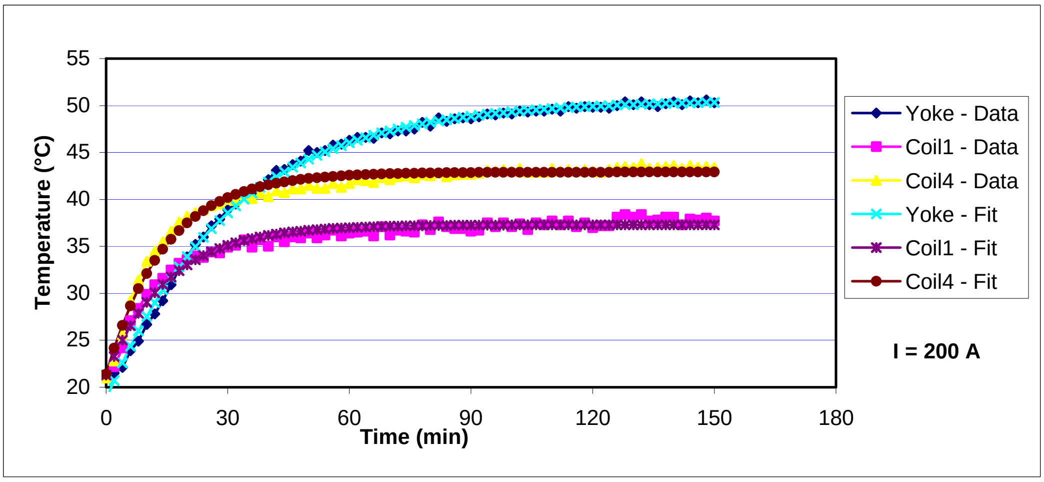



**Figure 3: Temperature increase with I = 200 A**

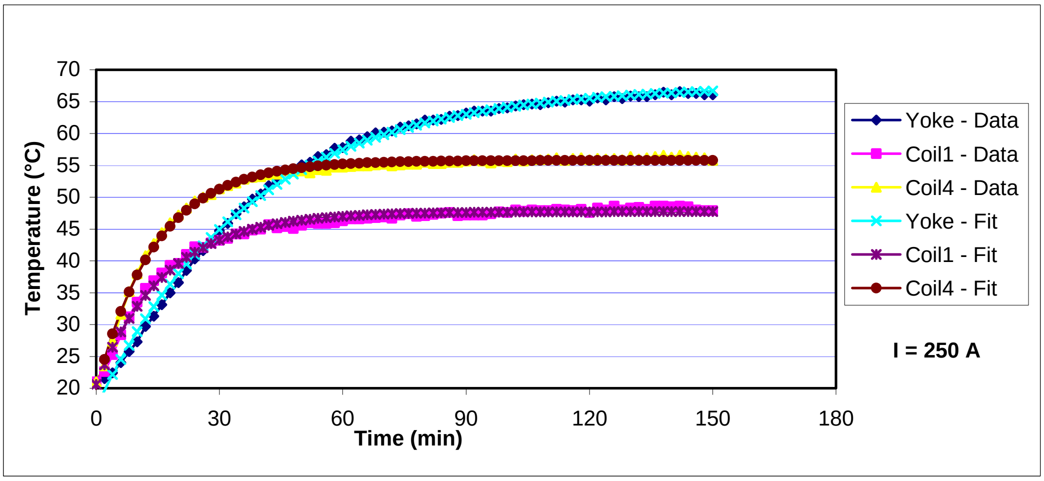
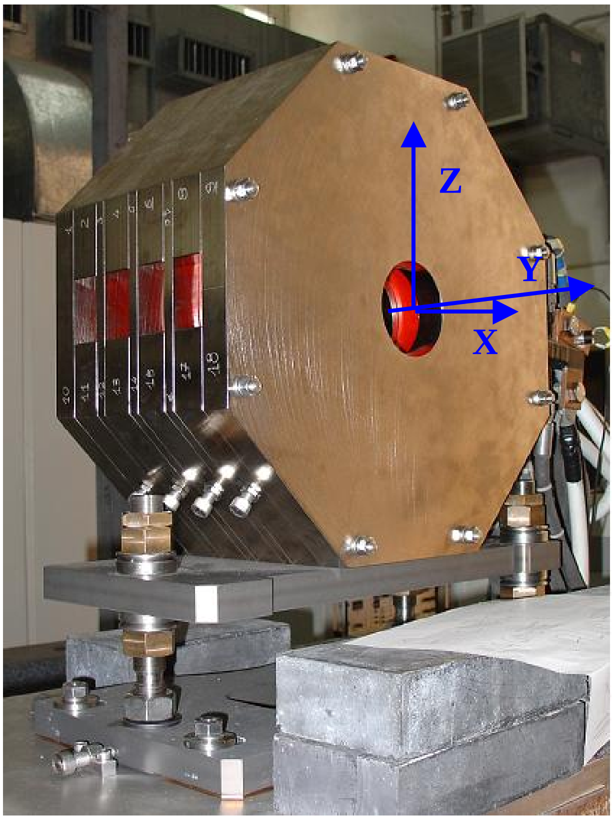



**Figure 4: Temperature increase with I = 250 A**

# 4. Magnetic Measurements




**Picture 2 : Reference system for the hall probe measurements of the solenoid.**

Magnetic measurements were performed between June, 23rd and July, 7th. Unfortunately data acquired in this period were affected by a systematic error of 1.2 mm on the vertical coordinate (*z*) due to alignment problems and were for this reason discarded.
Therefore, between September, 22nd and September, 27th, 2D and 3D measurements were repeated.

The reference frame used for the hall probe measurements is given in picture 2 . Please note that in our convention the *z* coordinate corresponds to the vertical axis, the *y* coordinate to the longitudinal axis (the beam direction) and the *x* coordinate to the transverse (horizontal) axis.

## *4.1 $B_Y$ versus I*

The dependence of the magnetic field with the excitation current was measured *before* the solenoid was realigned and was not repeated afterwards. The Hall plate used was model DTM-141 from Group3, with a resolution of 0.05 gauss.

The axial component $B_Y$ of the magnetic induction was measured in the mechanical centre of the solenoid (and therefore with a systematic error on Z, as explained before), current settings were from 0 A to 300 A with current step of 15 A.

Figure 5 shows the data collected. A linear fit of these data provides:

$$B_Y \text{ [gauss]} = 19.43 \text{ [gauss } A^{-1}] * I \text{ [A]} .$$

Neglecting the first point (I= 0 A), the formula reconstructs the measured data with an average relative error of $4 \cdot 10^{-4}$ and maximum relative error $1.2 \cdot 10^{-3}$ (at the minimum current setting considered).

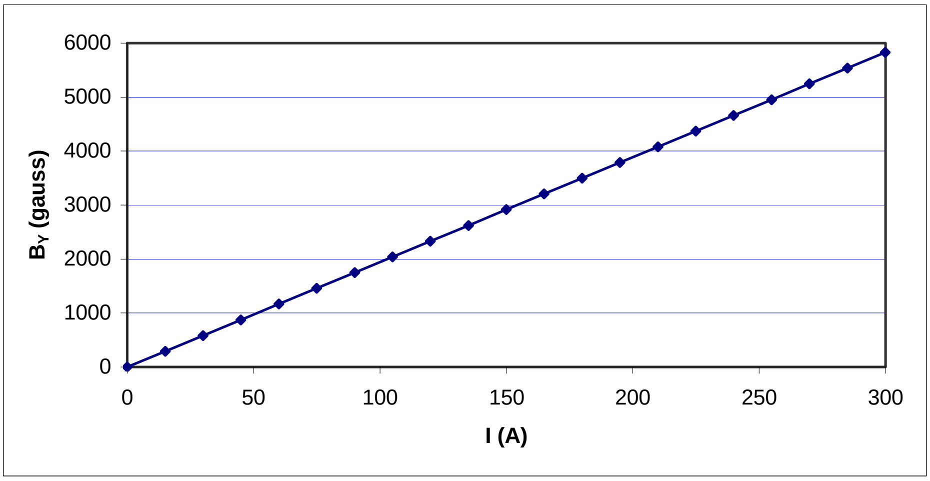



**Figure 5: Longitudinal component of the magnetic field in the solenoid centre (with systematic error on the vertical position) as a function of the excitation current**

### *4.2 Residual field*

The residual field along the longitudinal (*y*) axis was recorded immediately after powering the magnet to the maximum current (i.e. 300 A) and then switching the power supply off.
The acquisition mesh was:

$Y \in [-350 \text{ mm} ; + 350 \text{ mm}]$ ; step: 5 mm
X = 0
Z = 0 [1]

In Figure 6 the measured $B_Y$ is shown.

The two asymmetric peaks (3 gauss and 2.7 gauss) occur in position Y = ± 55 mm, which lie approximately in the middle of coil 1 (+ 55 mm) and coil 4 (- 55 mm).

[1] As discussed before, these data are affected by an alignment error on the vertical coordinate of approximately 1.2 mm

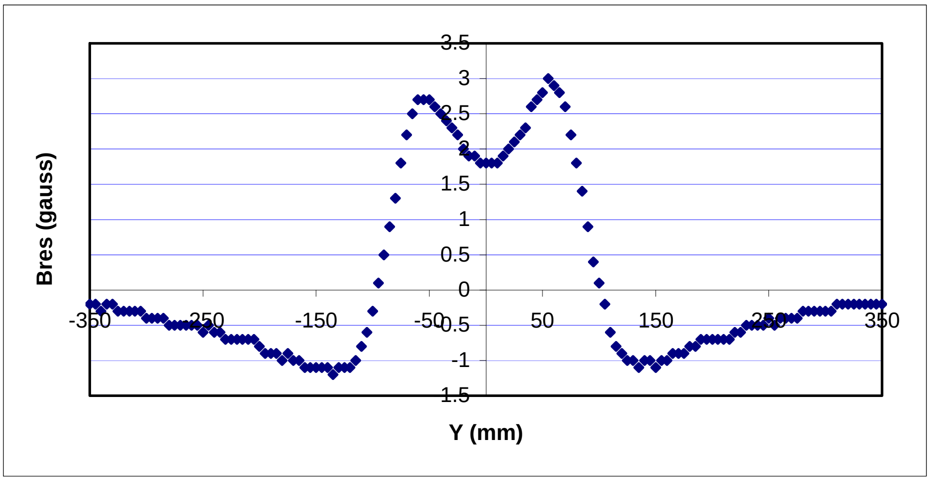



**Figure 6: Residual field on the solenoid mechanical axis.**

### *4.3 Coil centring and magnetic axis*

The solenoid coils have screws that enable, to some extent, to adjust their position inside the yoke. A set of measurements was dedicated to the coil centring, the goal being the minimization of the magnetic axis deviation from the mechanical one.

The alignment group checked and corrected the magnet position before the measurements and also a different Hall plate was used: DTM-151 from Group3, with a resolution of 0.001 gauss.

A common procedure to centre solenoid coils relies on the acquisition of the radial component of the field; however our system only allows the measure of the longitudinal component and this is the procedure we followed:

⇨ Operate the four coils in “single mode” i.e. power one single coil at a time at the nominal current $I_{Nom}$ = 140 A

- Place the probe on the solenoid mechanical axis at a Y coordinate corresponding to the centre of the coil which is now powered
- Scan a small transverse (*x* ; *z*) area measuring the $B_Y$ component
- Analyse the grid of value collected to obtain (with a parabolic fit) the coordinates $(X ; Z)_{Centre}$ of the field minimum point (see Figure 7 for an example of the data collected)
- Move the coil (with its positioning screws) to bring the field minimum towards the mechanical axis
- Repeat the field scanning and analysis
- If necessary move the coil again, until $(X ; Z)_{Centre} \approx (0 ; 0)$
- Power the next coil and repeat the procedure

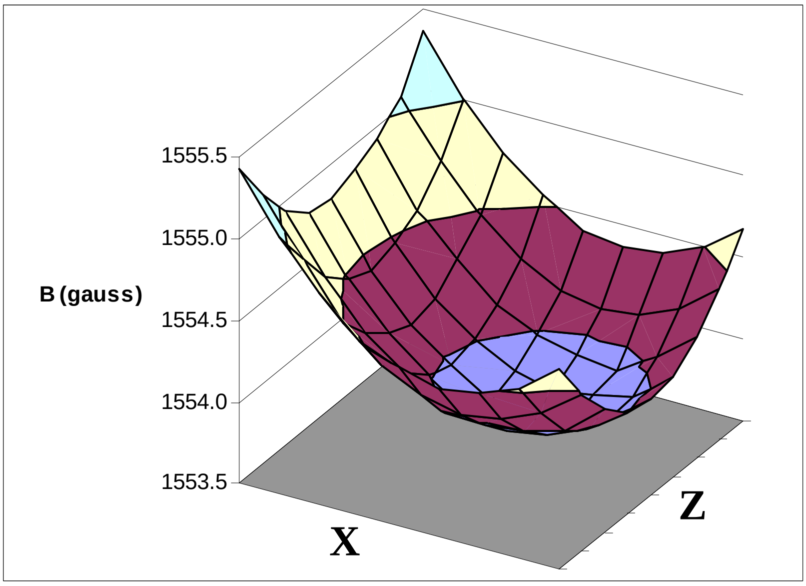



**Figure 7: Example of 2D scanning of the field – Coil B in "single mode"**

Once all the single coils have been checked and moved

⇨ Operate the four coils in "series mode" i.e. power all the coils in series at the nominal current $I_{Nom}$ = 140 A

- Scan the four coil area as made before and check the final positions of the centres

In our reference system the *y* coordinate of the four coils are:

$Y_{Coil1}$ = +61 mm
$Y_{Coil2}$ = +21 mm
$Y_{Coil3}$ = -21 mm
$Y_{Coil4}$ = -61 mm

The area covered with the scan is

$X \in$ [-1 mm ; +1 mm] ; step: 0.25 mm
$Z \in$ [-1 mm ; +1 mm] ; step: 0.25 mm

Once the procedure was completed the centres position has been retaken both in single and series mode, as a counter-check (see Table III). The $X_{Centre}$ and $Z_{Centre}$ values obtained are reproduced within a ± 0.07 mm interval, which is better than half the mesh step.

With respect to the procedure described before we faced the following problems:

I. The outer yoke limits the coil movement with the positioning screws. For this reason we could not bring the field minimum points on the mechanical axis. We decided instead to align the four points on a line parallel to the mechanical axis.
II. Coil A and Coil D, the outer coils, are closer to the yoke end-caps so, with respect to the inner coils B and C, are surrounded by thicker iron plates. Their behaviour is therefore iron-dominated and the positioning modification with the screws results even more inefficient.

III. Although operating in single mode we were able to position the four minimum points on a line parallel to the mechanical axis (within a 0.1 mm tolerance), once the solenoid is powered in "series mode" the centres coordinates change significantly. See Table III for quantitative details.

In Figure 8 and Figure 9 we can see a comparison of the centres coordinates obtained in the two mode, for x and z respectively. Note that the value $Z_{Centre}$ (series mode n.1) = -0.13 mm is most likely spurious, since the other three measurements assign a positive sign to this parameter.
On the *x* coordinate, the effect of the series connection of the coils is a tilt of the magnetic axis. On the contrary, on the *z* coordinate the effect is a distortion of the axis.
This suggest that in the alignment phase the solenoid should be positioned in such a way to compensate the horizontal tilt and average the vertical displacement of the axis.

Table III – *Coordinates of the field minima obtained with fit on data*

| | **Single mode** Meas. n1 | | **Single mode** Meas. n2 (*counter-check*) | | **Series mode** Meas. n1 | | **Series mode** Meas. N2 (*counter-check*) | |
|---|---|---|---|---|---|---|---|---|
| **Y** (mm) | **X** (mm) | **Z** (mm) | **X** (mm) | **Z** (mm) | **X** (mm) | **Z** (mm) | **X** (mm) | **Z** (mm) |
| -61 | 0.37 | 0.16 | 0.41 | 0.17 | 0.53 | -0.13 | 0.58 | 0.15 |
| -21 | 0.36 | 0.08 | 0.35 | 0.21 | 0.35 | 0.37 | 0.42 | 0.47 |
| 21 | 0.36 | 0.06 | 0.33 | 0.15 | 0.32 | 0.44 | 0.23 | 0.40 |
| 61 | 0.30 | 0.01 | 0.32 | 0.14 | 0.16 | 0.30 | 0.17 | 0.27 |

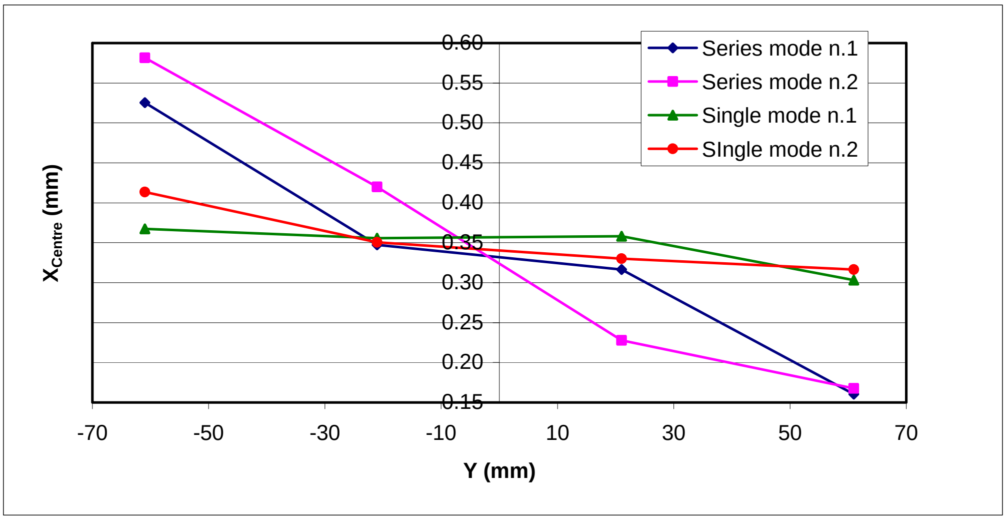



**Figure 8: Comparison of the $X_{Centre}$ values measured with coils operated in single and series mode.**

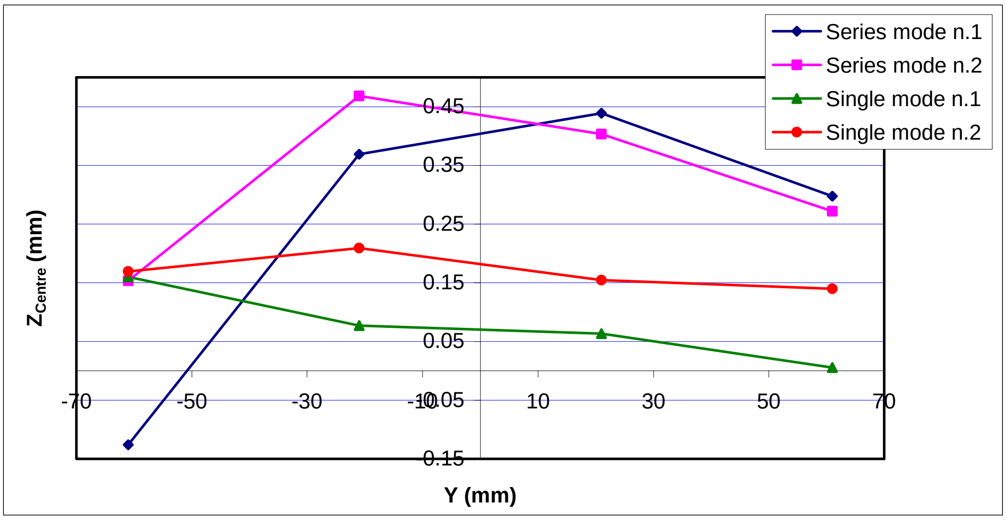



**Figure 9: Comparison of the $Z_{Centre}$ values measured with coils operated in single and series mode.**

### *4.4 3D mapping*

At the end of the magnetic axis measurement a full three dimensional scan of the magnetic field inside the solenoid was completed at the nominal current $I_{Nom}$ = 140 A.
The mesh was:

$X \in$ [-10 mm ; +10 mm] ; step: 5 mm
$Z \in$ [-10 mm ; +10 mm] ; step: 5 mm
$Y \in$ [-350 mm ; +350 mm] ; step: 10 mm

Note that these coordinates always refer to the mechanical axis frame.

Figure 10 reports the longitudinal profile of $B_Y$ along the mechanical axis.

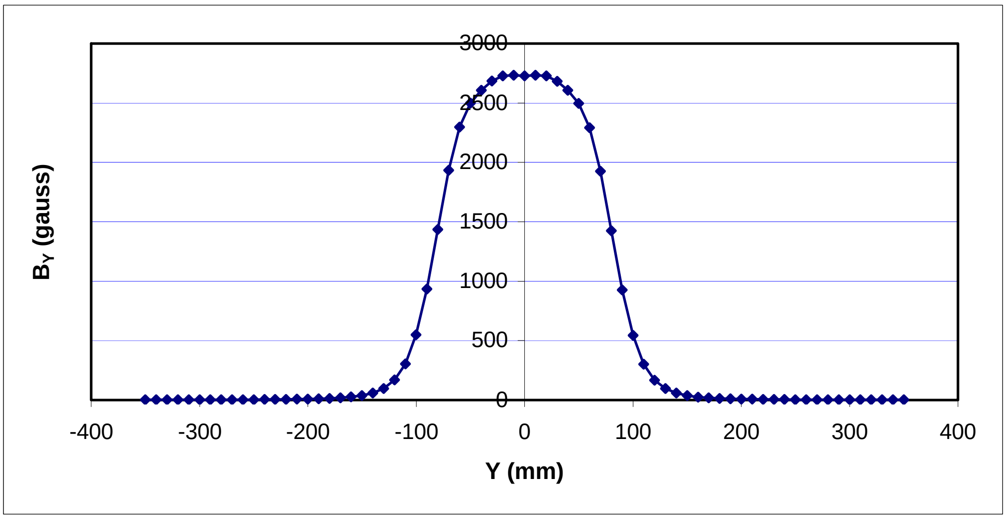



**Figure 10: Longitudinal profile of the axial ($B_Y$) component of the field – I = 140 A**

The expected maximum value (at the solenoid mechanical centre) at 140 A, according to the relation in paragraph 4.1, is

$$B_{Ymax}(140\ \mathrm{A}) = 19.43 \cdot 140 \sim 2720\ \mathrm{gauss}$$

The measured value is instead 2726 gauss, about 0.2% higher.

Further analysis based on the 3D field map have been made by other groups within the SPARC collaboration and are therefore reported in dedicated notes.

## 5. Appendix – Power supply specifications

Fug NTN 10500 – 35

Linear regulated power supply

Voltage: 0 – 35 V
Current: 0 – 300 A

| | |
|---|---|
| **Setting range:** | from approx. 0,1% to 100% |
| **Reproducibility**: | $\pm 1 \times 10^{-4}$ |
| **Setting resolution (potentiometer)**: | $\pm 1 \times 10^{-3}$ |
| **Residual ripple:** | $<1 \times 10^{-4}$pp + 10 mVpp |
| **Recovery time:** | |
| Voltage control: | <50µs for load changes from 10% to 100% or from 100% to 10% |
| Current control: | <500 ms for load changes causing an output change of less than 10% of the rated voltage<br>Units with >65V output voltage will switch off for a short time at high and fast load changes. |
| **Setting time at nominal load:** | 100 ms to 500 ms for changes of the output voltage from 10% to 90% or 90% to 10% |
| **Discharging time constant for output without load:** | approx. 2sec. to 60sec., depending on type |
| **Deviation:** | |
| for ±10% mains voltage variation: | $<\pm 1 \times 10^{-5}$ |
| for no load / full load: | $<2 \times 10^{-4}$ |
| over 8 h under constant conditions: | $<\pm 1 \times 10^{-4}$ |
| within the temperature range: | $<\pm 1 \times 10^{-4}$ / K |