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# Active Zero Field Compensation

## A Comprehensive Manual

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# 1 Introduction

Muon spin rotation ( $\mu$ SR) experiments rely on the proper shielding of the sample region from unwanted magnetic fields originating e.g. from the earth's magnetic field or other external field sources within the PSI experimental hall. Up to now, this shielding has been achieved for the  $\mu$ SR spectrometers at PSI by three pairs of orthogonal coils mounted around the sample position which were manually set to a fixed current to compensate for static magnetic fields. The current through the compensation coils was calibrated on a regular basis every few weeks to maintain zero-field conditions at the sample. With this procedure a field stability of  $\pm 30$  mG has been obtained. In 2005, the COBRA solenoid of the  $\mu \rightarrow e\gamma$  experiment started operation in the  $\pi$ E5 area which is neighboring several  $\mu$ SR areas. The fringe fields of the COBRA magnet adds up to a level of a few Gauss depending on the excitation of the magnet. Additionally, the COMET magnet from the PROSCAN facility produces non-negligible stray fields at the GPS spectrometer also. Since stray fields of this order of magnitude severely disturb the  $\mu$ SR experiments, especially if the fields are time-dependent, a new *active zero-field compensation* device has been developed. In Figure 1 the general layout of the zero-field compensation (ZFC) equipment is shown.

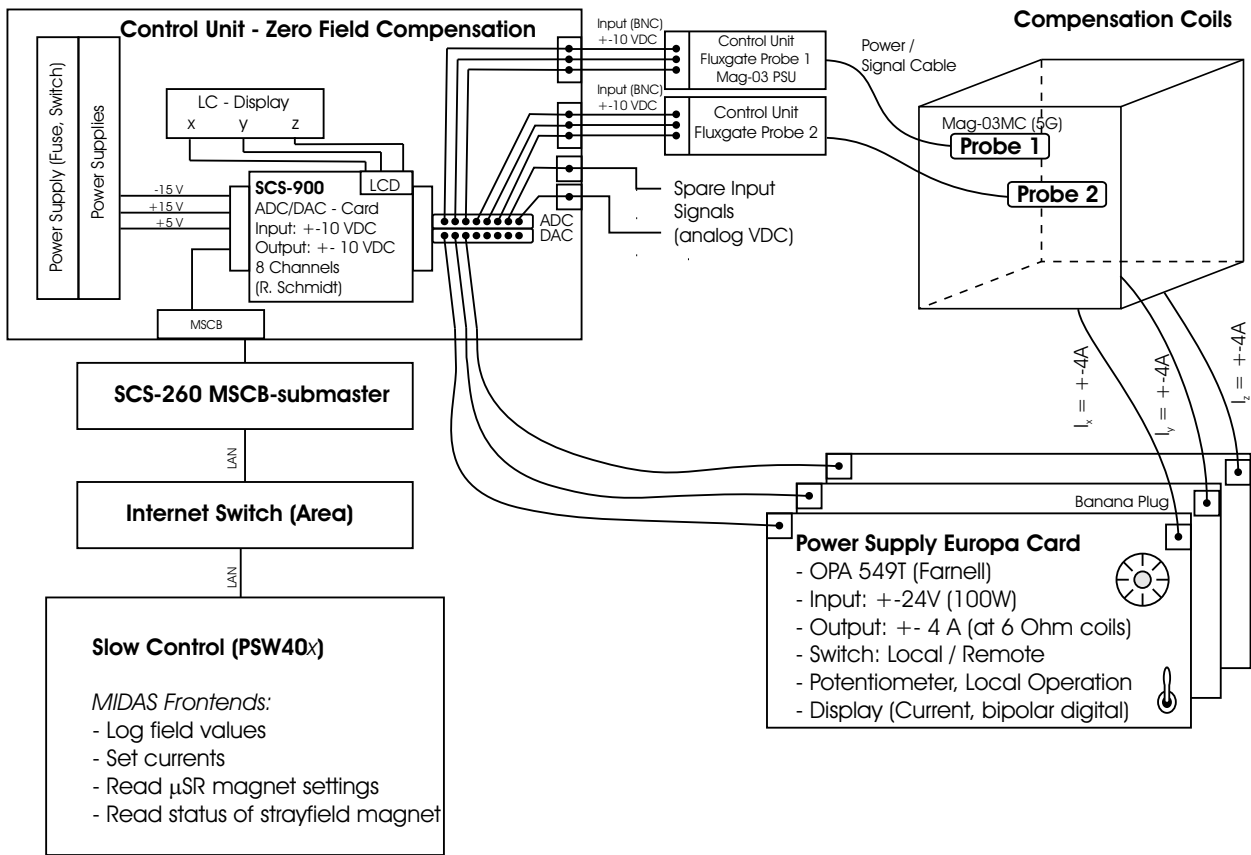


Figure 1: Schematic view of the ZFC equipment.

The new system utilizes the existing compensation coils with the corresponding currents being dynamically adjusted to account for the time-dependent disturbing fields. To measure these fields, a 3-axis fluxgate probe (Mag-03MC from Bartington Instruments) has been mounted near to the sample position. The three analog outputs ( $\pm 10$  V) of the field probe are connected to the data acquisition and control unit which is shown in Fig. 2. The signals are converted by a SCS-900 ADC/DAC card which has been developed at PSI. It communicates with the  $\mu$ SR slow control system via MIDAS slow control bus as well being developed at



Figure 2: Zero-field compensation control unit together with the 3-axis fluxgate probe.

PSI. A MIDAS frontend program which connects to the  $\mu$ SR run control program logs the measured field values and calculates the desired compensation currents. The current through the compensation coils is again controlled by the SCS-900 ADC/DAC card. The DAC outputs are amplified (using a newly designed scheme utilizing the OPA549T from Burr-Brown) thus providing a bipolar power supply with a maximum current of  $\pm 3$  A.

Tests at the GPS spectrometer show that the fringe fields from external sources within the experimental hall are effectively compensated by the new system and zero-field conditions on the level of a few mG are obtained.

## 2 Calculating the field at the sample position from the measured field outside the vacuum tube

The field outside the vacuum tube is measured by Probe1 and the field at the sample position is measured during the calibration process by Probe2. The field at Probe1 and Probe2 (if present) is given by the current through the compensation coils  $\vec{I}$ , the remanence of the  $\mu$ SR spectrometer  $\vec{c}_i$ , the orientation of the probes relative to the compensation cage (given by the linear transformations  $\mathbf{A}_i$ ), and the currents  $J$  in the COBRA and COMET magnets producing time-dependent stray fields  $\vec{h}_i(t, J)$  at the two probes. The following linear equations describe the sketched dependencies:

$$\vec{B}_1 = \mathbf{A}_1 \vec{I} + \vec{c}_1 + \vec{h}_1(t, J) \quad (1)$$

$$\vec{B}_2 = \mathbf{A}_2 \vec{I} + \vec{c}_2 + \vec{h}_2(t, J) \quad (2)$$

If no current is in the compensation coils ( $\vec{I} = (0, 0, 0)$ ) and no external fields in the experimental hall ( $\vec{h}_i(t, J) = (0, 0, 0)$ ), the two probes measure different remanent field  $\vec{c}_i$  due to the inhomogenous remanence fields of the  $\mu$ SR spectrometer and due to the (possibly) different orientation of the probes. The matrices  $\mathbf{A}_i$  and the vectors  $\vec{c}_i$  can be determined experimentally with a (semi-)automatic calibration procedure (see Section 5). The parameters  $\mathbf{A}_1$ ,  $\mathbf{A}_2$ ,  $\mathbf{A}_2^{-1}$  and the vectors  $\vec{c}_i$  as important input parameters for the control procedure are stored in the database under the following key:

/Equipment/ZFC/Settings/Devices/IN/DD/...

Please keep in mind that these parameters depend on the calibration and therefore on the correct setting of the calibration factor of the used probes. The calibration factors are stored in the database under:

/Equipment/ZFC/Settings/Devices/IN/DD/Probe1 Calibration Factor

/Equipment/ZFC/Settings/Devices/IN/DD/Probe2 Calibration Factor

It should be set, e.g. for a Bartington probe with 5 G range, to 0.5 Gauss/Volt.

The different orientation of the two probes can be described by the matrix  $\mathbf{R}$ , which describes the rotation of the two coordinate systems. Since the external stray fields from the COBRA and COMET magnet can be considered to be homogenous over the two probes, the following equation holds:

$$\vec{h}_2(t, J) = \mathbf{R}\vec{h}_1(t, J) \quad (3)$$

This, in principle, gives the opportunity to determine the orientation of the two probes with respect to each other by measuring  $\vec{h}_i(t, J)$  as a function of different  $J$ . Since we do not have access to the power supplies of COBRA and COMET every time we want to calibrate the relative orientation of the two probes, we try to align the probes as good as we can (with the axis parallel to each other). The rotation matrix  $\mathbf{R}$  can be inserted by hand into the database under the following key:

/Equipment/ZFC/Settings/Devices/IN/DD/Rotation R

In the real  $\mu$ SR experiment the Probe2 has (obviously) to be removed from the sample position. The control algorithm has to rely on measurements of  $\vec{B}_1$ . Combining Eq. (1), (2) and (3) the calculated field at the sample position  $\vec{B}_2^{calc}$  is given by

$$\vec{B}_2^{calc} = \mathbf{A}_2\vec{I} + \vec{c}_2 + \mathbf{R}(\vec{B}_1 - \mathbf{A}_1\vec{I} - \vec{c}_1) . \quad (4)$$

### 3 The ZFC Control

The set point for the field at sample position  $B_2^{set}$  in Gauss is stored in the database under the following key:

/Equipment/ZFC/Settings/Devices/IN/DD/Field Setpoint B2set (Gauss)

There are two different principle operation modes which can be selected by an ODB entry under the following key:

/Equipment/ZFC/Settings/Devices/IN/DD/Automatic (0,1)

0 User operation and 1 Automatic compensation

The control is done in three different ways depending on the mode entry in the ODB under:

/Equipment/ZFC/Settings/Devices/IN/DD/Mode (0,1,2)

The possible modes are:

0  $\equiv$  manual mode

1  $\equiv$  active compensation (ZF measurements only)

2  $\equiv$  table mode (LF and TF measurements)

The hierarchy of the different modes are depicted in the Figure 3.

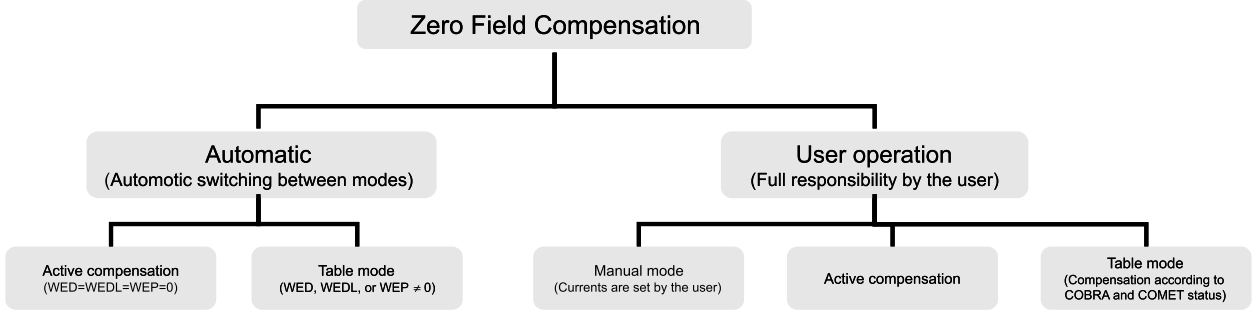


Figure 3: Hierarchy of the different control modes

### 3.1 Manual Mode

If the mode entry is set to 0, the current value for the compensation current  $\vec{I}$  will be fixed until it is changed in the ODB or the operation mode is changed to active or table mode.

### 3.2 Active Compensation

This mode can be used for ZF- $\mu$ SR measurements only. It stabilizes the field at the sample position to the value given by  $\vec{B}_2^{set}$  (usually  $(0,0,0)$  G). Since in a real measurement no field probe is at the sample position, the actual field at the sample  $\vec{B}_2^{calc}$  has to be calculated from the measured field at the Probe1 position  $\vec{B}_1$  according Eq. (4).

The control is done in an iterative manner. The new compensation current  $\vec{I}(t_{n+1})$  is calculated from the last  $\vec{I}(t_n)$  using the equation:

$$\begin{aligned} \vec{I}(t_{n+1}) &= \mathbf{A}_2^{-1} \left( \vec{B}_2^{set} - \vec{B}_2^{calc}(t_n) \right) + \vec{I}(t_n) \\ &= \mathbf{A}_2^{-1} \left( \vec{B}_2^{set} - \left[ \mathbf{A}_2 \vec{I} + \vec{c}_2 + \mathbf{R}(\vec{B}_1 - \mathbf{A}_1 \vec{I} - \vec{c}_1) \right] \right) + \vec{I}(t_n). \end{aligned} \quad (5)$$

This is very similar to a P-control loop but with the difference that the last term in the sum ensures that the desired field value is reached even if the first guess was not fully correct (similar to an I-term in the control loop).

### 3.3 Table Mode

The fields at the sample position is given by Eq. (2):

$$\vec{B}_2 = \mathbf{A}_2 \vec{I} + \vec{c}_2 + \vec{h}_2(t, J)$$

The matrix  $\mathbf{A}_2$  and the vector  $\vec{c}_2$  are stored (after the calibration) in the database. The homogenous stray field at the sample position is mainly produced by the COBRA and the COMET magnet:

$$\vec{h}_2(t, J) = \vec{h}_2^{COBRA}(t, J) + \vec{h}_2^{COMET}(t, J) \quad (6)$$

The status of these magnets is continuously monitored by the *strayfield* frontend, see Section 4. For the COBRA magnet, e.g., the current through the normal conducting coil ( $J_{NC}$ ) and through the superconducting coil ( $J_{SC}$ ) are stored in the database under the following key:

/Equipment/Cobra Status/Variables/Input

The field produced by the COBRA magnet is proportional to these current with the small offsets  $\vec{d}_{SC}$  and  $\vec{d}_{NC}$  and the proportionality constants  $\vec{f}_{SC}$  and  $\vec{f}_{NC}$ :

$$\vec{h}_2^{\text{COBRA}}(t, J) = \vec{f}_{SC} J_{SC} + \vec{d}_{SC} + \vec{f}_{NC} J_{NC} + \vec{d}_{NC} \quad (7)$$

The constants are calibrated once and then stored in the database under the following keys in the unit Gauss/StrayfieldSignal:

/Equipment/ZFC/Settings/Devices/IN/DD/Cobra SC Factor  
 /Equipment/ZFC/Settings/Devices/IN/DD/Cobra SC Offset  
 /Equipment/ZFC/Settings/Devices/IN/DD/Cobra NC Factor  
 /Equipment/ZFC/Settings/Devices/IN/DD/Cobra NC Offset

For the COMET magnet the database structure is equivalent (COMET 1, COMET 2).

Having the status of the COBRA and COMET magnet it is now possible to compensate for their stray fields without actually measuring these fields, e.g. in LF and TF  $\mu$ SR measurements. The currents through the compensation coils will be set according to the following equation (see Eq. 2):

$$\vec{I}(t) = \mathbf{A}_2^{-1} \left( \vec{B}_2^{\text{set}} - \vec{h}_2(t, J) - \vec{c}_2 \right). \quad (8)$$

## 4 Strayfield Status (COBRA, COMET)

The status of the COBRA and the COMET magnets are obtained via the internet through a broadcast mechanism. A broadcast device for each magnet, based and the SCS-260 LAN/MSCB adapter transmits the measured currents of COBRA (superconducting (SC) and normal conducting (NC) coil) and the COMET (Comet1 and Comet2). This multicast is received and stored in the ZFC database by the midas frontend *strayfield\_scfe* which needs the device driver *strayfield.c* and *strayfield.h*.

The present currents can be found in the DB under the following keys:

/Equipment/Stray Field/Variables/

The multicast group which is needed to receive the broadcast is stored in the database under the following key:

/Equipment/Stray Field/Settings/Devices/Stray Field/DD/MCAST\_GROUP\_COBRA  
 /Equipment/Stray Field/Settings/Devices/Stray Field/DD/MCAST\_GROUP\_COMET

This multicast group and a unique Mac-address is associated with the broadcast device. The list of the groups and addresses is administrated by S. Ritt.

## 5 Semi-Automatic Probe Geometry Calibration

At the moment it can be done only when COBRA and COMET are switched off! (ToDo: Introduce read back of COBRA and COMET status in this routine and compensate for it.)

In this section the procedure to obtain the parameters  $\mathbf{A}_1$ ,  $\mathbf{A}_2$ ,  $\vec{c}_1$ , and  $\vec{c}_2$  by a semi-automatic calibration is described.

Do the following steps:

1. Mount Probe1 outside the vacuum tube with the axis aligned along the axis of the compensation cage. (It does not matter in which direction  $x_1, y_1$ , and  $z_1$  is pointing as long as they are aligned along the three axis of the compensation cage.)
2. Put Probe2 at the sample position with the axis aligned along the axis of the compensation cage ( $x_2$ : longitudinal (upstream),  $y_2$ : vertical (top-bottom),  $z_2$ : horizontal (left-right)).
3. Connect the BNC-cables from the probes to the ZFC device.
4. Modify the rotation matrix  $\mathbf{R}$  in the ODB (/Equipment/ZFC/Settings/Devices/IN/DD/Rotation R) so, that the following relation holds (e.g. if the two probes are oriented in the same way this matrix is the unity matrix), also the direction is important, i.e. also the sign:

$$\begin{pmatrix} x_2 \\ y_2 \\ z_2 \end{pmatrix} = \begin{pmatrix} R_0 & R_1 & R_2 \\ R_3 & R_4 & R_5 \\ R_6 & R_7 & R_8 \end{pmatrix} \begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} \quad (9)$$

5. Check the probe calibration factors in the database (/Equipment/ZFC/Settings/Devices/IN/DD/Probe1 Calibration Factor and /Equipment/ZFC/Settings/Devices/IN/DD/Probe2 Calibration Factor). It should be  $ProbeRange = 10 \cdot f$ , e.g. for a 5G probe the calibration factor should be  $f = 0.5$ .
6. Check that COBRA and COMET are switched off and that the indoor crane does not pass the area during the calibration process.
7. Set the magnet for the small transverse field (e.g. in case of GPS the magnet WEP) to 100 G; wait a few seconds at this field and set it back to zero. This procedure leaves the apparatus in a well defined remanence situation.
8. Check that the ZFC frontend and the `zfc_control` program are running.
9. Set the probe geometry entry in the ODB (/Equipment/ZFC/Settings/Devices/IN/DD/Probe Geometry (0,1)) equal to 0. This will automatically start the calibration process.

The actual calibration process takes about 2 minutes. The device measures the values of  $\vec{c}_1$  and  $\vec{c}_2$  with the current  $\vec{I} = (0, 0, 0)$ . After this different currents are send through the compensation coils to experimentally determine all components of  $\mathbf{A}_1$  and  $\mathbf{A}_2$ .

*Check, that during the whole calibration process the field probes are in their range (no overrange). Otherwise the calibration will fail.*

After the calibration  $\mathbf{A}_1$ ,  $\mathbf{A}_2$ ,  $\mathbf{A}_2^{-1}$ ,  $\vec{c}_1$ , and  $\vec{c}_2$  are stored in the database under the following keys:  
 /Equipment/ZFC/Settings/Devices/IN/DD/...  
 and the control is set to manual mode.

## 6 The ZFC Hardware

### 6.1 OP-Amp Based Current Source

It is possible to exchange very easily the power supply card in case of a damage by another one. Attention: the cards are adjusted to amplify the DAC0, DAC1 or DAC2 values from the SCS-900 ADC/DAC-card by setting the corresponding jumper (solder it on the print) on the power supply card.

## 7 The ZFC Software

The software is based on midas-1.9.5 (updated). There is the *zfc* frontend setting up the database with all variables for the zero field compensation. The communication with the ZFC device (reading of field probes and setting compensation currents) is done through the *zfc* device driver.

The second frontend, *strayfield*, is recording the status of the two magnets in the experimental hall (COBRA and COMET) which produce a stray field at the  $\mu$ SR apparatus.

Finally, there is the control program *zfc\_control* which reads the database, calculates the required output currents, and writes the new outputs to the database.

The source files and their corresponding makefiles are stored on afs at the following location:

```

user: raselli
/afs/psi.ch/user/r/raselli/midas/musr-1.9.5/slowcont/zfc/zfc/Makefile.zfc
/afs/psi.ch/user/r/raselli/midas/musr-1.9.5/slowcont/zfc/zfc/zfc_scfe.c
/afs/psi.ch/user/r/raselli/midas/musr-1.9.5/drivers/device/zfc.h
/afs/psi.ch/user/r/raselli/midas/musr-1.9.5/drivers/device/zfc.c
/afs/psi.ch/user/r/raselli/midas/musr-1.9.5/slowcont/zfc/zfc/Makefile.strayfield
/afs/psi.ch/user/r/raselli/midas/musr-1.9.5/slowcont/zfc/zfc/strayfield_scfe.c
/afs/psi.ch/user/r/raselli/midas/musr-1.9.5/drivers/device/strayfield.h
/afs/psi.ch/user/r/raselli/midas/musr-1.9.5/drivers/device/strayfield.c
/afs/psi.ch/user/r/raselli/midas/musr-1.9.5/slowcont/zfc/zfc_control/MakefileSL5
/afs/psi.ch/user/r/raselli/midas/musr-1.9.5/slowcont/zfc/zfc_control/zfc_control.c

```

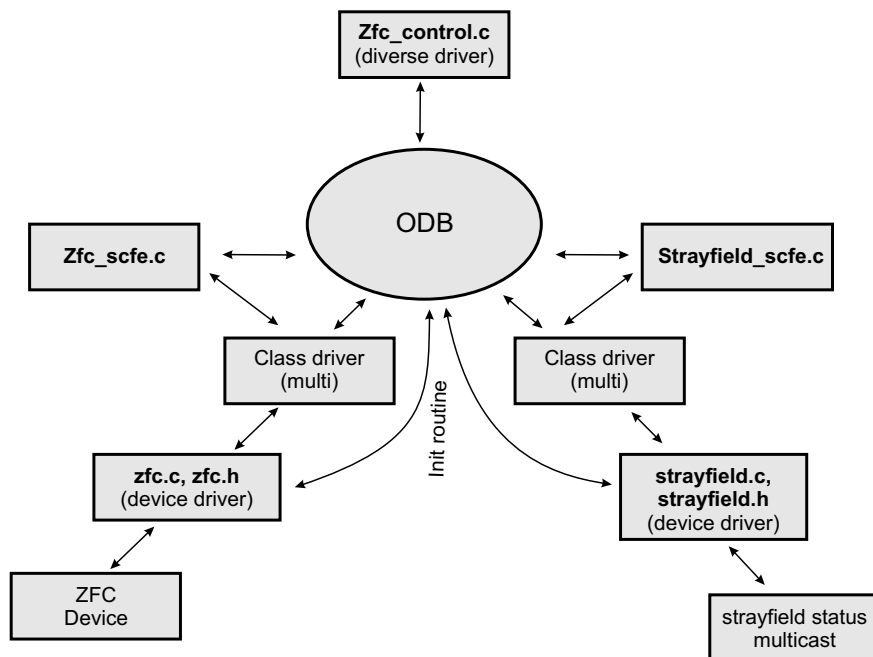


Figure 4: Relation and communication paths of the different ZFC software packages.



## 8 The ZFC Graphical User Interface

The GUI should display:

- $B2 = f * ADC$  (in Gauss)
- $R*B1$  (this is in the same coordinate system like B2 then)
- B2set
- COBRA and COMET currents
- automatic mode - non-automatic mode
- manual, active, table mode (maybe LED)

The GUI should have input possibilities for:

- automatic mode - non-automatic mode
- if non-automatic : manual, active, table
- Set point
- Start button semi-automatic calibration (password protected)