# PHASE COMPARISON OF HIGH CURRENT SHUNTS

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***Abstract***

In the framework of Task 3.3 a new type of phase comparator has been built for comparing the phase of shunts for currents between 10 A and 100 A and frequencies from 500 Hz to 100 kHz. The comparison between existing shunts has been organized and the measurements were performed at INRIM. The results of the relative measurements have shown a good repeatability. The method for the evaluation of the reference value was based on similar shunts and derived by extrapolation.

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# Introduction

A co-operation activity for improving the traceability in power and power quality measurements was undertaken.

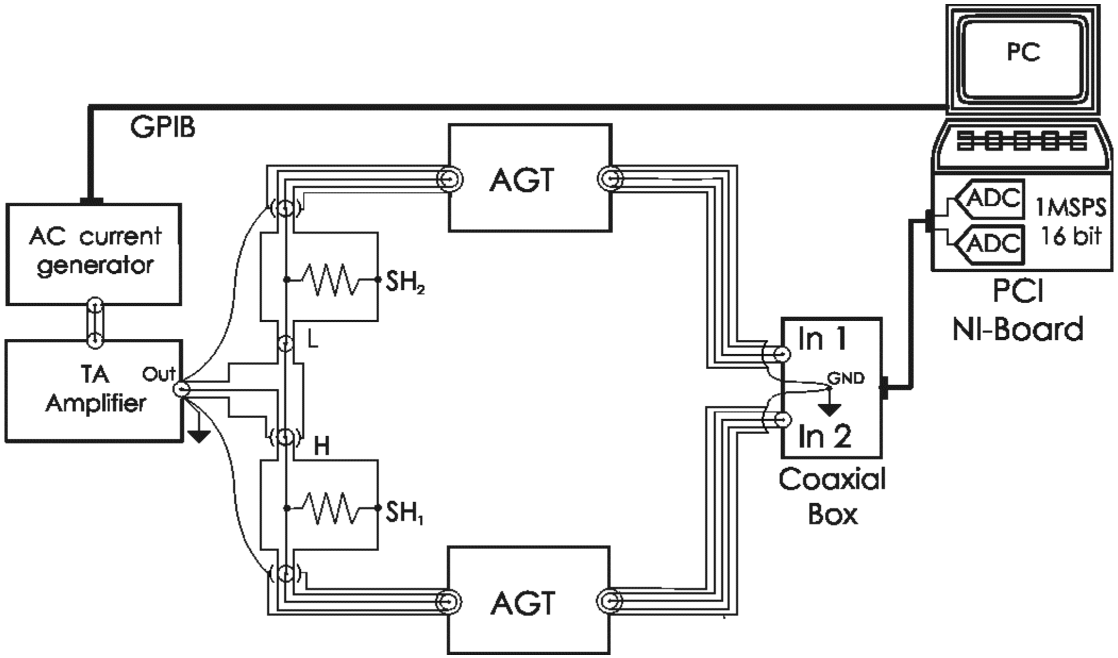
For current measurements the project aimed at developing shunts for different current ranges, with high stability of impedance with load current, temperature and time, starting from the technology already available.

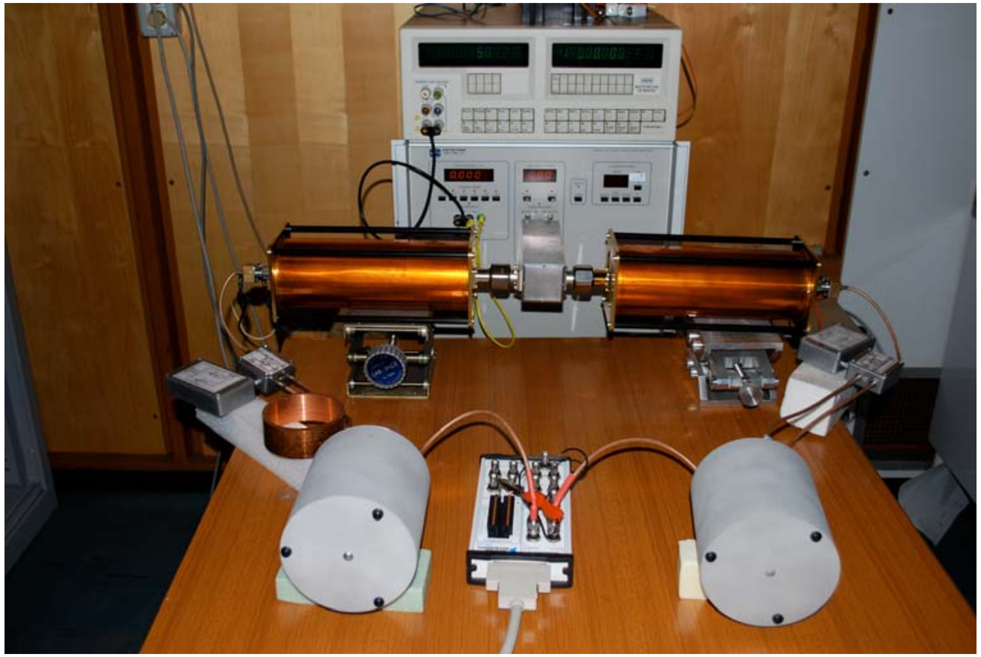
Analytical models can lead to proper design and optimization of these shunts, however there is always the need of experimental verifications. So, the measurement of the impedance components of the shunts and their changes with frequency has been pursued.

For this purpose, a phase comparator operating for frequencies up to 100 kHz has been built. A preliminary characterization on existing shunts, in the range form 10 A to 100 A, built by some laboratories taking part in the project was performed. This comparison was useful to establish a connection between the analytical models and the resulting devices. Now, the measurements are applied to the characterization of the shunts produced in the project.

# Phase comparator

A phase comparator was built for the measurements of phase differences between two shunts.



Basic circuit of the phase comparator. $SH_1$ and $SH_2$ denote the two shunts being compared. Two active guarded transformers (AGTs) are employed as wideband decoupled precision transmitters.

The current generator was assembled by connecting a calibrator in the ac voltage function that supplies a transconductace amplifier.

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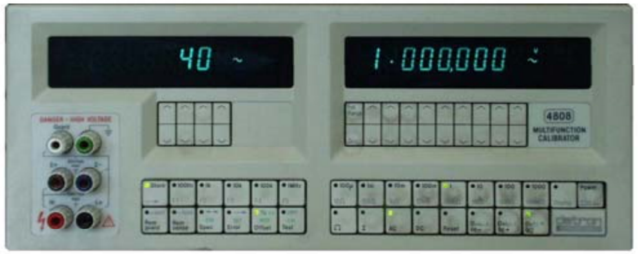
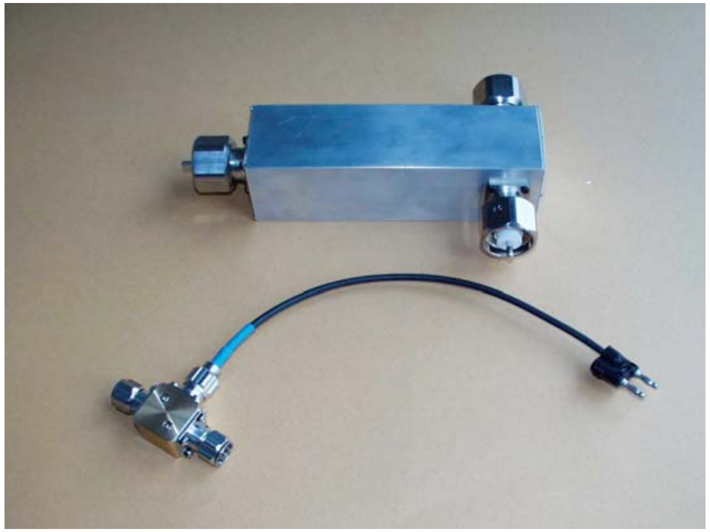
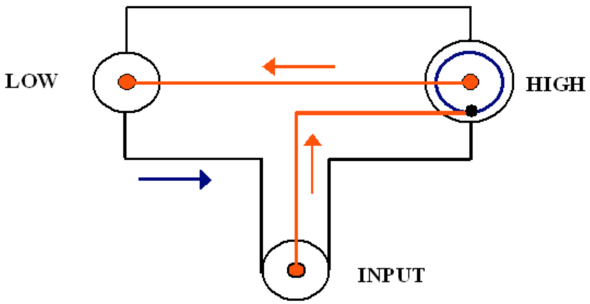
# Generation of the current

The system for the current generation was assembled by connecting a calibrator in the ac voltage function that supplies a transconductace amplifier. The ac current for every measurement point is produced at the output of the transconductance amplifier. The input was driven by the calibrator, automatically set to the proper voltages and frequencies directly by the computer via IEEE-488 bus.



By means of suitable current nodes, the ac current is supplied to the two shunts under comparison connected electrically in series.



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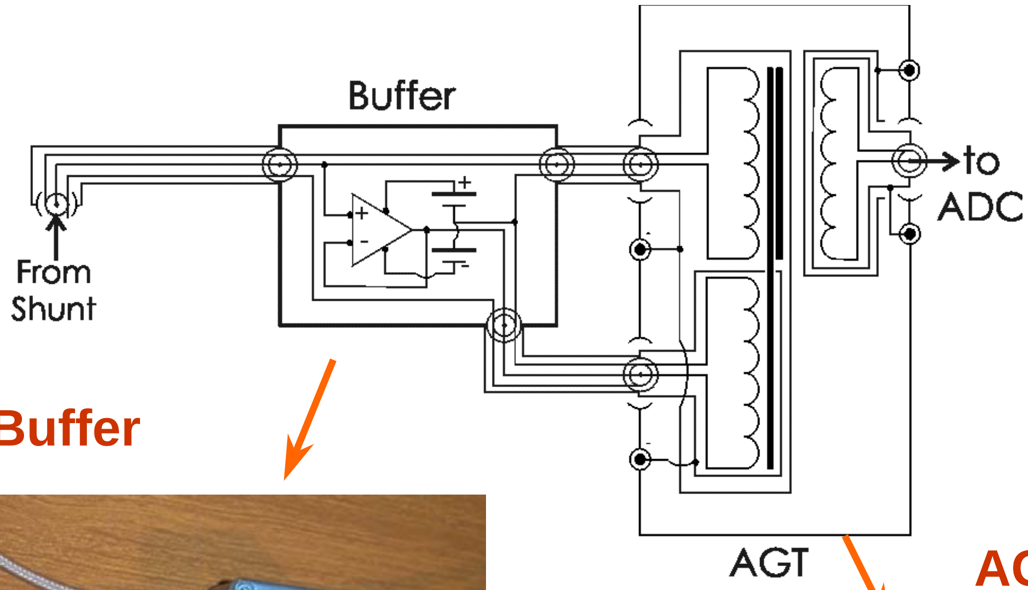
# The active guarded transformers (AGT)

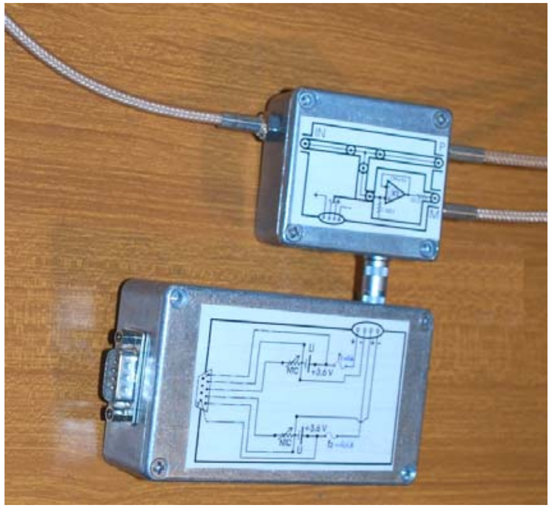
Two AGTs are employed to transmit the voltage between the output of the shunts and the inputs of the phase detector. These transformers are of identical construction and made as a special type of double stage transformers.

One of the core acts as the magnetizing element and the winding is driven by a buffer.

In this way, the primary winding only requires a negligible current. So, the impedance seen by the output of the shunt is high.




**Buffer**



**AGT**


For wideband operation nanocrystalline cores were employed and all the windings are limited to 30 turns. The resulting bandwidth of the transformer is between 100 Hz (at 1 V rms) and more than 2 MHz - 500 kHz for phase under 5 mrad.

# The digital phase detector

The first prototype of the digital phase detector was built by means of a commercial board put inside the controlling computer.

ver. 1 with NI 6733

ver. 2 with NI PCI-5922

A software program for acquiring and processing the samples was developed in MATLAB .

- The program sets the initial current and the frequency.
- After the stabilization, for each frequency the program acquires a selected number of bursts of nominally simultaneous samples.
- The samples for the two signals are stored on the internal memory of the board and then transferred to the hard disk.
- The transitions from the negative to positive value are identified and, a first frequency of the signal is evaluated.
- The mean values $A_m$ and the rms of the fundamental of the signal, supposed to be sinusoidal, are evaluated and these values, through a best fit approximation, are employed for a more accurate guess of the period.
- The 4 parameters sine fit is applied and the frequency and the sine and cosine components are further adjusted. Eventually, the phases in the two channels are computed by means of the 3 parameters sine fit.

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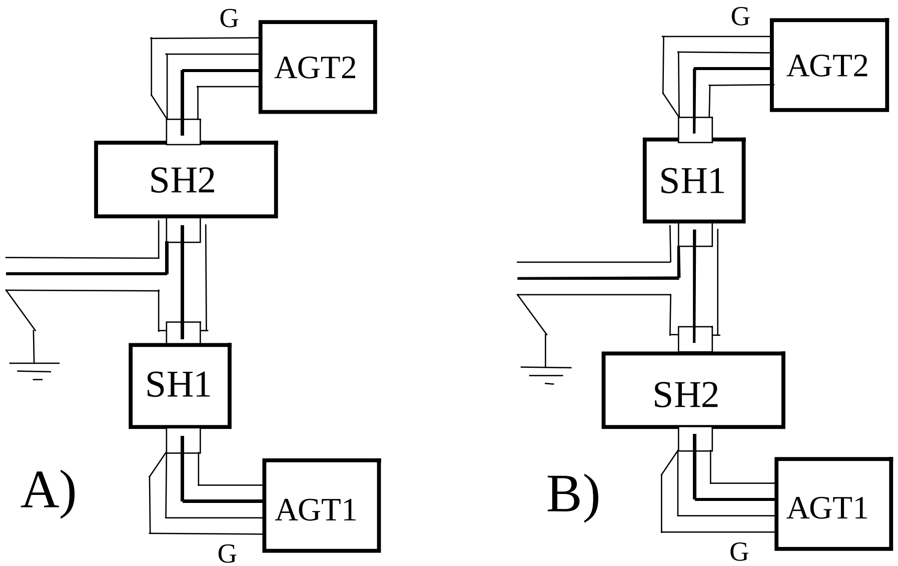
# Comparison - measurement procedure

- For each couple of shunts, they are firstly put in series, as in Fig. A).
- Three sets of measurement samples are taken for each current and for each frequency planned for this couple of shunts. (38 bursts of 20000 consecutive samples for both voltages at the outputs of the two shunts. The sample rate is 800 kSample/s.
- The two series of data are acquired and stored in the computer and, then, the controller of the phase comparator evaluates the values of the phase differences for every burst.
- The same shunts are put in series in the reversed order, shown in Fig. B). Then, three other sets of measurements are taken with the same methodology as before.
- After the measurement, the phase differences for each burst are stored in a file and a first processing is performed., which evaluates the mean values for each measurement set and the related standard deviations.



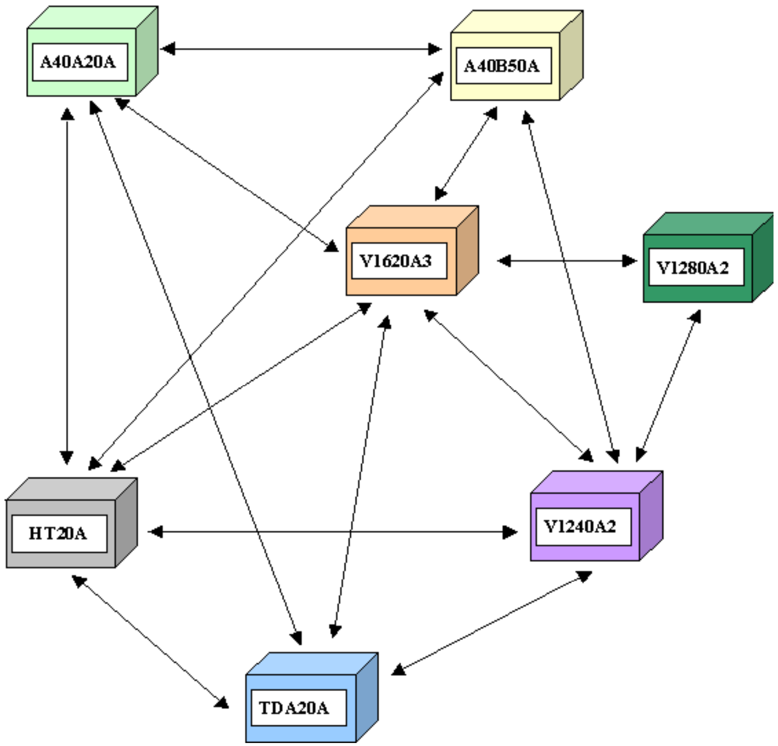

Connections of the shunts SH1 and SH2 in the two successive measurements for the compensation of the systematic errors.

$$\alpha_{SH2} - \alpha_{SH1} = \frac{\Phi_A - \Phi_B}{2}$$

$$\varepsilon = \frac{\Phi_A + \Phi_B}{2} - \pi$$

# Data processing

The differences of the phases between two shunts are the starting point for the data processing, which is aimed at consolidating the results by the coherence principle (in all closed loops, the sum of the phase differences is zero). These additional constraints allow to adjust the resulting values by means of a suitable optimization performed by a best fit.




Example of the set of measurements performed at 10 A

The data are organized in groups – one group for each current value – and diagram of the comparison links id derived. For each frequency, the values are adjusted by a best fit. The evaluation of the uncertainty is made a priori from the means of the variance divided by the number of degrees of freedom. A successive evaluation can be made a posteriori from the standard deviation of the displacements.

For linking the phase differences of the shunts with different nominal current a typical step-up procedure is utilized. Some shunts are associated to two measurement groups, which allows to link the value of the phase difference, between measurement made at different current. In the step a specific shunt is assumed to have the same phase difference at the two currents with an additional uncertainty evaluated by the relative changes of the shunts measured at the two currents.

# Results of the first measurement round

Relative phase of the shunts under comparison, relative to the shunt assumed as a reference (V16A20A3 at 10 A).
(values in mrad , MF = metal foil, CL = cage-like,
O = other type)

| | Type | I | 500 Hz | 1 kHz | 2 kHz | 5 kHz | 10 kHz | 20 kHz | 50 kHz | 100 kHz |
|---|---|---|---|---|---|---|---|---|---|---|
| B7A10A | MF | 10 | 0.000 | -0.002 | -0.005 | -0.004 | 0.004 | 0.016 | 0.03 | 0.01 |
| CMI10A1 | CL | 10 | 0.011 | 0.015 | 0.024 | 0.057 | 0.111 | 0.218 | 0.52 | 1.02 |
| JVNT10A | CL | 10 | 0.002 | -0.002 | -0.008 | -0.018 | -0.036 | -0.073 | -0.20 | -0.42 |
| MU10ASIQ | CL | 10 | -0.006 | -0.016 | -0.034 | -0.084 | -0.167 | -0.335 | -0.84 | -1.64 |
| TDA20A | O | 10 | 0.129 | 0.255 | 0.502 | 1.221 | 2.385 | 4.694 | 11.62 | 23.13 |
| A40A20A | O | 20 | 0.030 | 0.051 | 0.072 | 0.100 | 0.123 | 0.12 | -0.09 | -0.69 |
| A40B50A | CL | 20 | 0.019 | 0.036 | 0.071 | 0.169 | 0.328 | 0.65 | 1.61 | 3.15 |
| HT20A | O | 20 | 0.036 | 0.072 | 0.142 | 0.355 | 0.729 | 1.53 | 3.91 | 7.75 |
| TDA20A | O | 20 | 0.127 | 0.254 | 0.502 | 1.220 | 2.384 | 4.69 | 11.61 | 23.09 |
| V1240A2 | MF | 20 | -0.002 | -0.004 | -0.007 | -0.011 | -0.014 | -0.01 | -0.01 | 0.07 |
| V1280A2 | MF | 20 | 0.003 | -0.002 | 0.002 | 0.003 | 0.005 | 0.02 | 0.09 | 0.46 |
| A40B50A | CL | 50 | 0.020 | 0.038 | 0.073 | 0.171 | 0.334 | 0.67 | 1.64 | 3.18 |
| CS1D0701 | CL | 50 | 0.031 | 0.058 | 0.114 | 0.284 | 0.551 | 1.03 | 2.21 | 4.04 |
| CS2D0702 | CL | 50 | 0.028 | 0.057 | 0.113 | 0.280 | 0.546 | 1.04 | 2.25 | 4.15 |
| V1280A2 | MF | 50 | 0.001 | 0.003 | 0.006 | 0.006 | 0.010 | 0.03 | 0.11 | 0.42 |
| CS1D0701 | CL | 100 | 0.033 | 0.062 | 0.12 | 0.30 | 0.58 | 1.08 | 2.28 | |
| CS2D0702 | CL | 100 | 0.030 | 0.061 | 0.12 | 0.30 | 0.58 | 1.09 | 2.33 | |
| V1280A2 | MF | 100 | -0.001 | -0.001 | 0.00 | -0.01 | -0.02 | -0.02 | 0.04 | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| U (k=2) | | 10 | 0.005 | 0.005 | 0.006 | 0.005 | 0.005 | 0.020 | 0.03 | 0.04 |
| U (k=2) | | 20 | 0.010 | 0.010 | 0.008 | 0.008 | 0.025 | 0.05 | 0.06 | 0.15 |
| U (k=2) | | 50 | 0.011 | 0.016 | 0.015 | 0.012 | 0.028 | 0.06 | 0.09 | 0.26 |
| U (k=2) | | 100 | 0.017 | 0.020 | 0.03 | 0.04 | 0.07 | 0.12 | 0.21 | |

From the results of the comparison between the shunt from 10 A and 100 A, information about the phases of the different shunts could be derived.
At 10 A, which was the best measurement point, given the large number of shunts and measurements between them, the expanded uncertainty of the phase differences was less than 6 μrad up to 10 kHz and less than 40 μrad at 100 kHz.
The uncertainty increases respectively to about 30 μrad and 260 μrad at the same frequencies for the shunts measured at 50 A.

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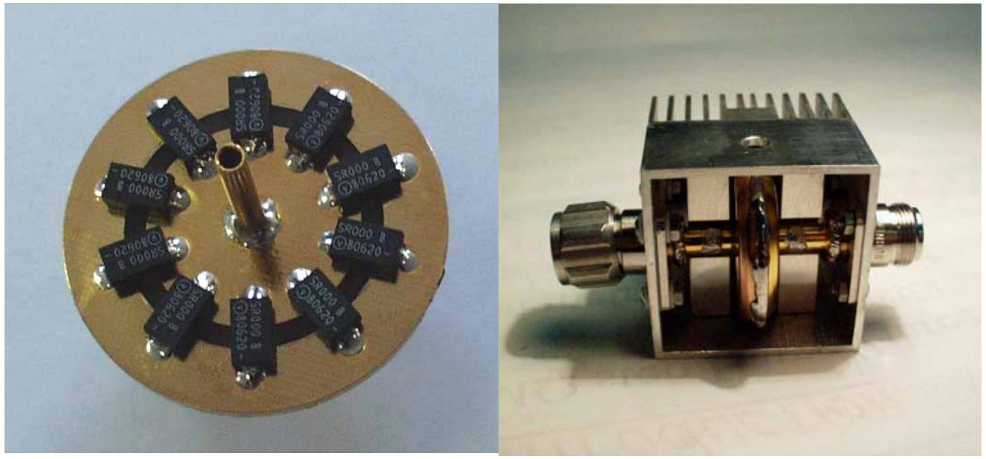
# Phase reference

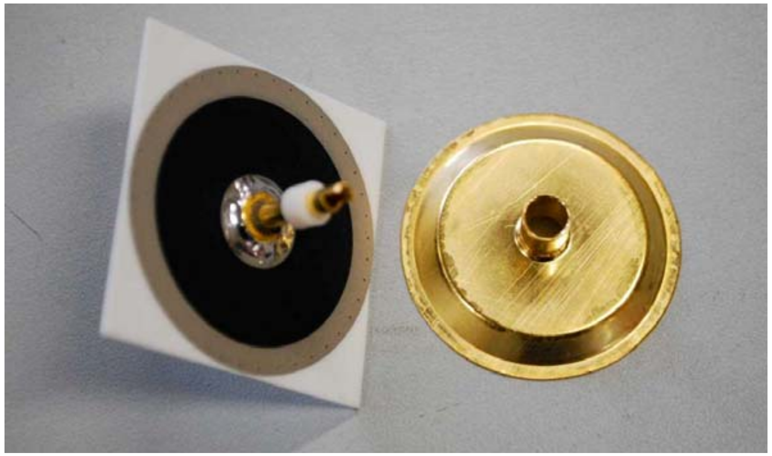
The absolute phases of the shunt V1620A3 at 10 A, taken as a reference, was evaluated by using a step-down procedure for the steps 5 A, 2 A, 1 A and 0.5 A.

The determination of the absolute value of the reference was accomplished by considering that there were three types of shunts of identical structure ( R respectively of 0.5 Ω, 1 Ω, 2 Ω).

From the identical internal construction the same value of the inductance L was assumed, even if the contribution of the inductance of the resistive elements are not negligible. The reference value was computed by supposing that, for all couple of shunts of this type and with different resistances, the absolute values is obtained from the relative ones, considering their time constants proportional to 1/R.



Internal structure of the first set of shunts to evaluate the reference



Internal structure of the new set of shunts to evaluate the reference

# Conclusions

- A wideband phase comparator for high current shunts was built and tested at INRIM.
- Tests performed on different elements of the comparator showed that, even if the constitutive elements (digital phase comparator – AGTs) have phase shift not negligible, their stability and the compensation of the procedure improve the accuracy of the phase determination of at least an order of magnitude.
- By means of the comparator a set of shunts were compared and the values obtained, showed that the results are accurate, stable and repeatable.
- The phase values for a set of 10 A to 100 A shunts have been measured up to 100 kHz and the values obtained seem to be stable in time and linear as a function of the frequency.
- This comparison, and the other tests, were performed for characterizing the shunts already built. The data collected have been useful, within the project, for identifying the models that are more suitable for the different current ranges and for improving the design of the shunts.
- The results have been useful, with an improved phase comparator and a new determination of the reference, to characterize the prototype of the shunt built in the project.
- By using the method of the evaluation by extrapolation developed for this comparison, with metal film shunts it is possible to improve the accuracy of the absolute determination of the phases.