VIP

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Preliminary Test of a VIP-upgrade Target Prototype

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Abstract.
In order to realize the upgrade of the VIP experiment it is needed a more efficient copper target, capable of circulating a higher current. A simple water-cooled prototype has been realized and tested, with current densities in excess of 375 A/mm^2. Its electrical and thermal behavior are analyzed and discussed. Moreover, the realization of an even more performant version of the copper target will be proposed.

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1. INTRODUCTION

The Pauli Exclusion Principle (PEP) is a consequence of the spin-statistics connection [1] and plays a fundamental role in our understanding of many physical and chemical phenomena, from the periodic table of elements, to the electric conductivity in metals, to the degeneracy pressure, which makes white dwarfs and neutron stars stable, just to cite few ones. Although the principle has been spectacularly confirmed by the number and accuracy of its predictions, its foundation lies deep in the structure of quantum field theory and has defied all attempts to produce a simple proof, as nicely stressed by Feynman [2].

Given its basic standing in quantum theory, it seems appropriate to carry out precise tests of the PEP validity and, indeed, in the last fifty years, several experiments have been performed to search for possible small violations [3–8]. Often, these experiments were born as by-products of experiments with a different objective (e.g., dark matter searches, proton decay, etc.), and most of the recent limits on the validity of PEP have been obtained for nuclei or nucleons.

Concerning the violation of PEP for electrons, Greenberg and Mohapatra [9] examined all experimental data which could be related, directly or indirectly, to PEP, up to 1987. In their analysis they concluded that the probability that a new electron added to an antisymmetric collection of N electrons might form a mixed symmetry state rather than a totally antisymmetric state is $\leq 10^{-9}$. In 1988, Ramberg and Snow [10] drastically improved this limit with a dedicated experiment, searching for anomalous X-ray emitted by transitions of electrons in copper from 2p to 1s level, with 1s already occupied by 2 electrons, that would point to a small violation of PEP in a copper conductor. The electrons were brought in copper by a circulating current. The result of the experiment was a probability $\leq 1.7\times10^{-26}$ that a new electron circulating in the conductor would form a mixed symmetry state with the already present copper electrons.

We have set up an improved version of the Ramberg and Snow experiment, the VIP experiment, with a higher sensitivity apparatus [11] by using high resolution Charge Coupled Devices (CCD) as soft X-rays detectors [12], and decreasing the effect of background by a careful choice of the materials and sheltering the apparatus in an underground laboratory. The VIP setup was installed at the Gran Sasso underground laboratory (LNGS) in 2006 and took data since then.

The limit obtained by VIP is a probability of violation of PEP by electrons $<5\times10^{-29}$. Presently we are considering the upgrade of the VIP setup, by using triggerable Silicon Drift Detectors, an external veto system, a more compact geometry and higher current circulating in the copper target.

The present document reports on a preliminary design, realization and test of the copper new target. Some problems were met, and a new test is foreseen, to go even higher with the current.

2. THE VIP EXPERIMENTAL METHOD

The experimental method, originally described in [10], consists in the introduction of electrons into a copper strip, by circulating a current, and in the search for X-rays resulting from the 2p →1s anomalous radiative transition that occurs if one of the new electrons is captured by a copper atom and cascades down to the 1s state already filled by two electrons of opposite spin. The energy of this transition, calculated by using a multiconfiguration Dirac–Fock method with an estimated error e <10 eV [13], would differ from the normal K_α transition by about 300 eV (7.729 keV instead of 8.040 keV), providing an unambiguous signal of the PEP violation. The measurement alternates periods without current in the copper strip, in order to evaluate the X-ray background in conditions where no PEP violating transitions are expected to occur, with periods in which current flows in the conductor, thus providing "fresh" electrons, which might possibly violate PEP. The fact that no PEP violating transitions are expected to be present in the measurement without current is related to the consideration that any initial conduction electron in the copper that was in a mixed symmetry state with respect to the other copper electrons, would have already cascaded down to the 1s state and would therefore be irrelevant for the present experiment. The rather straightforward analysis consists in the evaluation of the statistical significance of the normalized subtraction of the two spectra, with and without current, in the energy region where the PEP violating transition is expected.

VIP used a cylindrical target [14] where a current of 40÷50 A was circulated, with a maximum current density of about 3.5 A/mm^2.

3. THE VIP UPGRADE

The present VIP setup exhausted its capacity to obtain a substantial improvement in the limit on PEP.

So, what we are planning in order to arrive at an important gain is to built a new setup, keeping some useful elements of the present setup (the DAQ/Slow Controls and shielding for example), but to rebuild its core.

We propose to do the following:

- use a much more compact system, with a higher acceptance

- use a more efficient copper target, capable of circulating a higher current

- use faster, triggerable, X-ray detectors

- reduce background by means of better shielding

Aim of this report is the description of a high current VIP copper target prototype and the analyses of the measures done.

4. THE WATER-COOLED COPPER STRIP PROTOTYPE

The need to flow a large current trough a copper foil as thin as possible to improve the X-ray emission is a key ingredient in upgrading the VIP experimental setup. This could be done using a water-cooled conductor.

For this purpose, we build the simple prototype shown in figure 1.

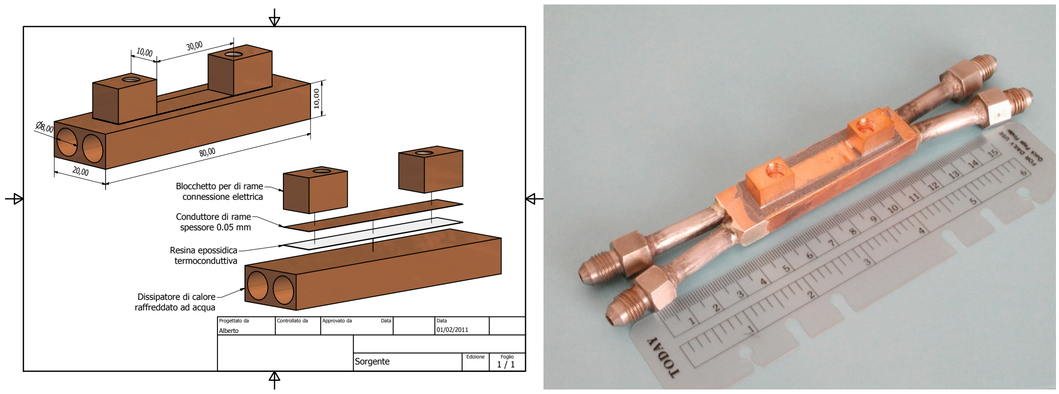

Figure 1

On a copper brick, with an embedded water-cooling circuit, a thin copper strip is bonded with a thin layer of thermal conducting epoxy resin. For electrical connections two copper terminals, with threaded holes, brazed on the strip, are foreseen. Moreover, the strip is electrically insulated from the cooling brick.

The dimensions of the copper strip are 10 mm wide, 30 mm long, 40 μm thick, while the cooling brick is 80 mm long, 20 mm wide and 10 mm thick, with two 8 mm diameter longitudinal holes.

To estimate the power dissipated in the strip, let's start calculating its electrical resistance:

$$R = \rho \frac{l}{S}$$

that, using actual values for:

$\rho = 1.72 \cdot 10^{-8}$ Ωm (copper resistivity)

$l = 0.03$ m

$S = 0.01 \times 4 \cdot 10^{-5}\ \text{m}^2 = 4 \cdot 10^{-7}\ \text{m}^2$

yields

$R = 1.3 \cdot 10^{-3}\ \Omega$

Such a value is relatively small, but if a large current flows trough the strip the dissipated power cannot be neglected.

The power P dissipated in the strip when a current I flows is:

$P = RI^2$

That, for a current $I = 250$ A, yields $P = 81$ W.

This value could easily be dissipated by a simple water cooling, providing a **good** thermal contact between the strip and the cooling brick.

Using the COTRONICS special high temperature epoxy resin DURALCO 133, whose thermal conductivity value from data sheet is 5.8 $\text{Wm}^{-1}\text{K}^{-1}$, to bond the copper strip on the cooling brick, should satisfy the requirement of a good thermal contact and, due to its high electrical resistivity of about 10^4 Ωm, the electrical insulation from the copper brick too.

Bonding the 10×30 mm^2 copper strip to the cooling brick with a thin layer of 0.2 mm of epoxy resin a thermal conductivity of about 8.7 WK^{-1} can be obtained. In this case, a power load of about 80 W should yield about 9 °C of temperature rise.

5. DESCRIPTION OF MEASUREMENT

The measurement have been carried out in the LNF Magnet Measurement Facility in Frascati in which a computer controlled electromagnet power supply, used as high current source, and a water-cooling system are available.

The power supply is a FuG, NTN series, 35V, 350A, with a precision of ±0.2% of nominal value.

The cooling system has been trimmed to deliver a water flow of about 2.3 l/minute, the water temperature was 23.1 °C.

A preliminary test, done with an electronic multimeter, to verify the resistance between strip and cooling brick yields a value of 3.7 kΩ. This result is fully compatible with the purpose of the present test. Considering that the copper strip resistance is about 1.3 mΩ, it is possible to say that all the current flows trough the strip.

Similar assumption applies for what concern the heat flow. It is possible to say that the heat flows almost entirely trough the epoxy resin that bonds the copper strip to the cooling brick. To verify this, let’s consider the longitudinal copper strip thermal conductivity Λ of the strip mid point toward the two electrical cable terminations:

$$\Lambda = \lambda \frac{S}{l}$$

that, using actual values for:

λ= 400·W m^{-1} K^{-1} (copper thermal conductivity)

and considering that the mid point of the copper strip is connected to electrical cable terminations on both sides

$l = 0.015$ m

$S = 2\times0.01\times 4\cdot10^{-5}\ m^2 = 8\cdot10^{-7}\ m^2$

yields

$\Lambda = 0.02\ WK^{-1}$

This value is small compared to thermal conductance of epoxy resin and, for the purpose of this technical note, can be neglected.

To perform the measures a simple connection, whose schematic diagram is shown in figure 2, has been implemented.

The computer controlled DC Power Supply (PS), feeds the current (*i*) to the VIP copper target (*r*), generating a voltage (*V*) across *r*.

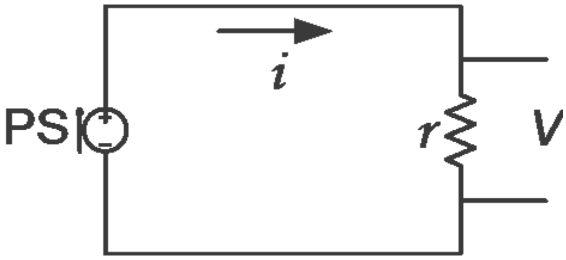

Figure 2

Figure 3 shows the VIP test prototype connected to the water cooling system with four flexible hoses, two on the right for inlet and two on the left for outlet. The electrical connections are the two grey cables, coming from the top of the picture.

Figure 3

The measures have been carried out feeding into the copper strip a series of increasing current values *i* and recording the corresponding voltage values *V*, measured with a digital multimeter set on 300 mV full scale range, and the temperature *T* of the copper strip, measured with a digital thermometer, whose K type thermocouple sensor where in contact with the copper strip itself.

In table 1 the values of measured current, voltage and temperature are reported.

Current *i* [A]	Voltage *V* [mV]	Temperature *T* [°C]
10,000	15,000	23,300
50,000	74,100	30,600
75,000	114,50	41,900
100,00	160,80	59,200
125,00	216,60	84,200
150,00	288,40	125,50
175,00	393,00	203,80

Table 1

The first current value was 10A, to check if all was OK, then the measure has been done starting from 50A, with 25A steps, up to a maximum value of 150A. The 175A value has been recorded later, just for curiosity, with slightly different cooling conditions.

6. DISCUSSION

The aim of this test is to verify if the cooling is efficient, measuring the temperature rise of the prototype copper strip versus flowing current and to see which is the maximum current that is possible to flow in the strip, remaining in a safe region. Moreover it is possible to calculate, using the measured values, the power load, the strip electrical resistance, the current density and the thermal resistance between copper strip and cooling brick.

In figure 4 is reported the plot of the copper strip temperature versus current, beside a parabolic fit of the data. The agreement between measured data and fit is quite good.

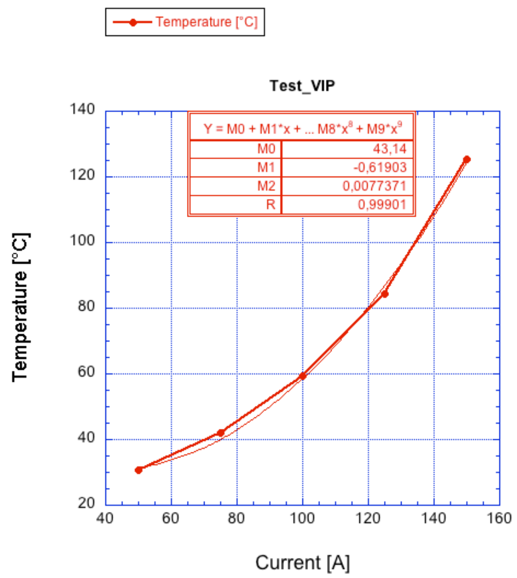

Figure 4

The quadratic relation between flowing current and temperature is a consequence of the fact that temperature should be linearly correlated to dissipated power, and the power is a quadratic function of the current: $P=i^2/r$

Now, it is possible to calculate dissipated power P, strip resistance r, current density j and thermal conductance k, using measured values of current i, voltage across the strip V and temperature T.

The relations are the following:

$P=V\cdot i$

$r=V/i$

$j=i/S$

$k=P/(T-T_0)$

Where S is the copper strip cross section and T_0 is the water cooling temperature.

The results are shown in Table 2.

Current *i* [A]	Voltage *V* [mV]	Temperature *T* [°C]	Power *P* [W]	Resistance *r* [mΩ]	Current Density *j* [A mm^{-2}]	Thermal Conductance *k* [W K^{-1}]
10,000	15,000	23,300	0,15000	1,5000	25,000	0,75000
50,000	74,100	30,600	3,7050	1,4820	125,00	0,49400
75,000	114,50	41,900	8,5875	1,5267	187,50	0,45678
100,00	160,80	59,200	16,080	1,6080	250,00	0,44543
125,00	216,60	84,200	27,075	1,7328	312,50	0,44313
150,00	288,40	125,50	43,260	1,9227	375,00	0,42246
175,00	393,00	203,80	68,775	2,2457	437,50	0,39230

Table 2

The plot in figure 5 shows the relation between temperature and power. The linear fit is in a very good agreement with measured data. This confirms the good quality of the measure and the approximation that all the generated heat flows trough the epoxy resin. To confirm this later point, it is possible to estimate the heat flow trough the copper strip itself. The copper thermal conductivity $\lambda = 390\ Wm^{-1}K^{-1}$, thermal conductance of the strip can be obtained from the following relation:

$$k_s = \lambda \frac{S}{l}$$

where:

$\lambda = 390\ Wm^{-1}K^{-1}$, is the copper thermal conductivity

S is the strip cross section

l is the strip length

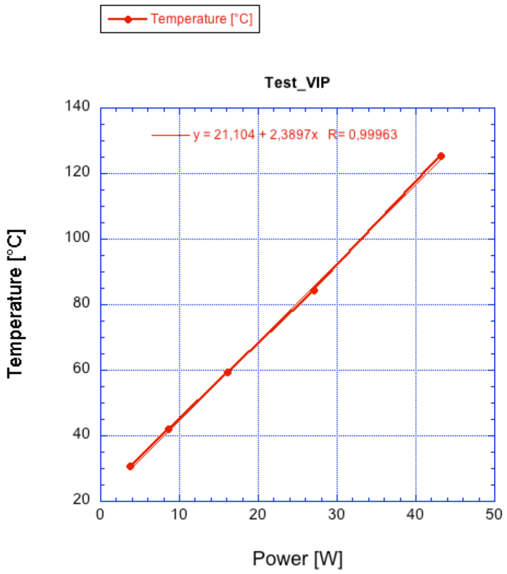

Figure 5

At this point it is evident the disagreement between the expected value of the temperature rise and the measured one. Indeed, using the relation

$T_c = T_0 + P/k$

And substituting for k the expected value of 8.7 WK^{-1}, we obtain the values shown in figure 6.

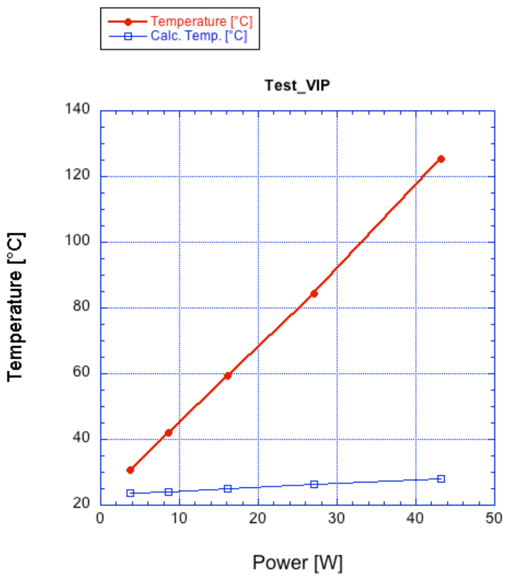

Figure 6

It seems that the actual thermal conductance is much worst than the expected one, calculated starting from thermal epoxy characteristics.

Figure 7 shows the values of thermal conductance obtained from the measures of temperature and dissipated power.

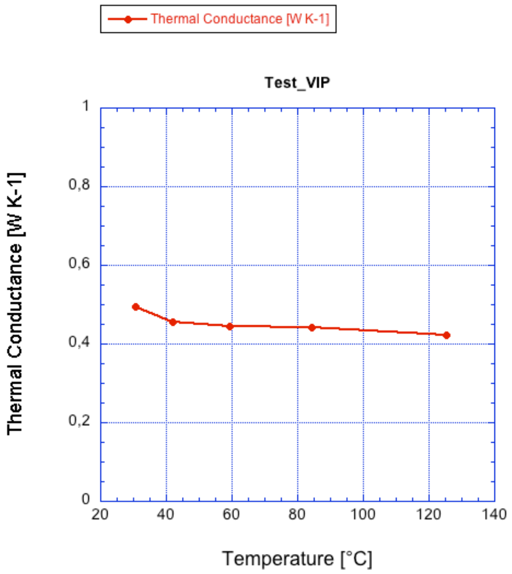

Figure 7

The measures give a mean value of about 0.45 WK^{-1} for thermal conductance between copper strip and cooling brick. This value is about 20 times smaller than expected. This discrepancy could be explained to the fact that the epoxy resin used for bonding the copper strip to the cooling brick has past its expiration date.

7. CONCLUSIONS

A simple prototype of a water cooled copper strip has been realized and tested in laboratory. The aim of this test is to increase the maximum current density that is possible to flow in the strip, remaining in a safe region. Even if the thermal conductivity is higher than expected, probably due to a bad epoxy resin, the current density that can flow trough the copper target, with a small temperature rise (about 7 °C @ 50 A) is 125 A/mm^2, this is a quite good value and is much more higher than the previous VIP setup value of 3.5 A/mm^2.

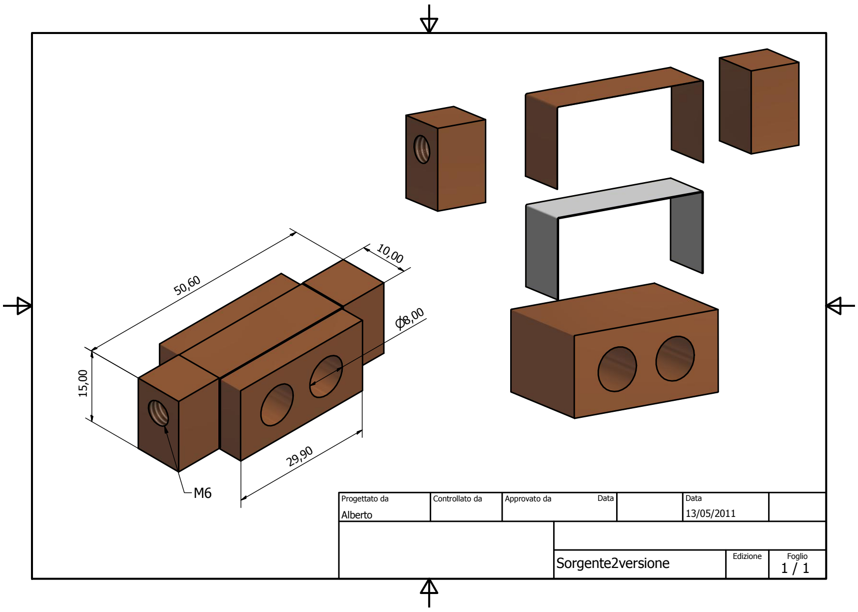

Figure 8

The good results obtained with the prototype described in this document lead us to go ahead toward a further increase in the current density, with a target temperature rise as low as possible. We propose the realization of a second prototype, using proper epoxy resin, a more compact size copper target, that will be compatible with the VIP setup, and a better cooling system. Figure 8 shows a simplified drawing of this new prototype.

8. ACKNOWLEDGEMENTS

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