High-voltage measurement for the BIPM x-ray generators

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ABSTRACT

In an x-ray tube, a spectrum of x-rays is produced when an electron beam hits a target. The electron beam is produced from a filament heated by an electrical current, and the electrons are accelerated by a high voltage (for example up to 250 kV) applied between the cathode and the anode. The intensity of the x-ray beam is determined by the heating current in the filament whereas the x-ray spectrum depends on the high voltage, the material used for the target (tungsten and molybdenum are used at the BIPM) and the target angle. This report describes the arrangement that has been put in place to measure the high voltage for the low- and medium-energy facilities at the BIPM.

1 – Introduction

Following the installation of replacement x-ray tubes and high-voltage generators at the BIPM it was evident that, to monitor the stability and the repeatability of the low- and medium-energy systems, there was a need to measure the high-voltage output from the generators. To make such a measurement, three nominally identical high-voltage dividers (HVD) were constructed, each one able to operate up to an input voltage of 160 kV and dividing by a factor of approximately 10 000. Each divider must be calibrated and, to this end, a study of the behaviour of the resistors was made over a large range of input voltages. Finally, to maximize accuracy, the temperature coefficient of each high-voltage divider was measured.

2 – Aims and realization of a divider

2.1 Aims

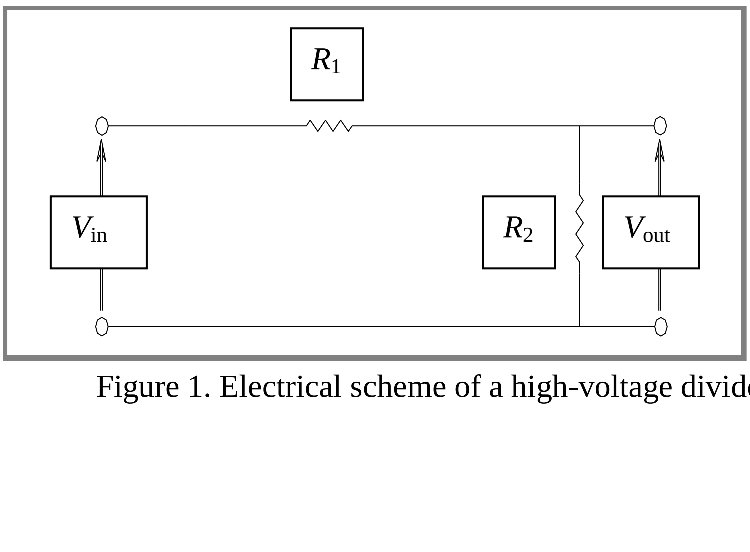
Each HVD was designed to divide an input voltage in the range from 3 kV to 160 kV by a factor of about 10 000 with an accuracy of a few parts in 10^4.

The choice of components was strongly influenced by ready availability, the need for long-term stability and the final cost of the equipment. Operating at such high voltages, the design had to comply with a high level of safety, not only for users of the equipment but also regarding connection to the high-voltage generators. All of the components had to be easily serviceable and the effect of the dividers on the generators had to be evaluated and minimized.

2.2 Realization

2.2.1 Electrical scheme

The electrical scheme for a HVD is shown in Figure 1. It comprises essentially two resistors R_1 and R_2; R_1 is composed of a chain of 1000 resistors in series, grouped in sets of 100 on ten printed circuit boards (PCB) and R_2 is a set of ten resistors of the same type mounted in parallel on a PCB at the output.



Divider ratio :
$V_{in} / V_{out} = 1 + (R_1 / R_2)$
$R_1 = 1000R$, $R_2 = R / 10$
$V_{in} / V_{out} = 100\ 01$

Figure 1. Electrical scheme of a high-voltage divider (HVD).

2.2.2 Choice of resistors

In view of the required long-term stability, precision metal film resistors were chosen. Each has a maximum voltage of 250 V, a low voltage coefficient (typically $<1 \times 10^{-6}$/V) and a low temperature coefficient, of 15×10^{-6}/K. The nominal resistance value R = 147 kΩ was chosen to ensure a high input impedance, which is around 147 MΩ. The choice of identical resistors for R_1 and R_2 is expected to increase stability because thermal effects and ageing should tend to cancel. A chain of a 1000 resistors was chosen for R_1 to minimize the voltage on each resistor and therefore to reduce the total voltage effect (only R_1 sees the high voltage). To determine the residual effect of the high voltage on the HVD, a divider model was constructed and studied (as described in section 3.1).

2.2.3 Housing and connections

Each HVD is installed in a stainless steel container constructed at the BIPM. The container is connected to ground to minimize electrical noise and assure electrical safety, and is equipped with two R24 type high-voltage connectors and a BNC connector for the low-voltage output. A holder for a temperature probe is incorporated.

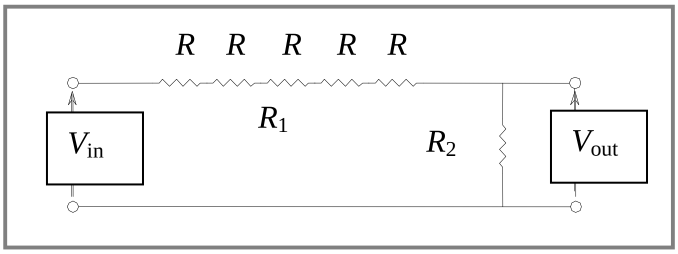
2.2.4 Insulation

To assure the high-voltage insulation, all resistors are submerged under insulating oil, type Shell Diala G. This mineral oil has an electrical rigidity of around 80 kV cm^{-1}, which is around ten times greater than the maximum voltage inside the divider and thus offers a significant margin of security.

3- Calibration

3.1 Realization of a model divider

The fundamental problem to resolve is that no calibrated voltage supply is available at the BIPM for the operating range up to 160 kV. The HVD can therefore be calibrated only at relatively low voltages, up to 5 kV, where the voltage across each resistor is very much smaller. To study the effect that higher voltages on each resistor might have on the divider calibration made at low voltages, a model divider was constructed from a smaller number of identical resistors. This model was used to study the behaviour over a range of voltage levels from 3 V to 160 V per resistor, which is equivalent to an input voltage on the HVD of 3 kV to 160 kV. The electrical scheme for the model divider is shown in Figure 2. All resistors are of the same type as used in the HVD. The resistor R_1 is composed of five resistors in series and R_2 is a single resistor.



Divider ratio :
$V_{in} / V_{out} = 1 + 5R / R'$
$R = 147\ \mathrm{k}\Omega,\ R_2 = 1\ \mathrm{k}\Omega$
$V_{in} / V_{out} = 736$

Figure 2. Electrical scheme of the model divider.

3.2 Determination of correction factors

3.2.1 Experimental value

Figure 3 shows the ratio of the input over the output of the model divider for a well known input voltage of between 3 V and 160 V, plotted as a function of the voltage across each resistor. Two regions of voltage per resistor are identified: one where the HVD will be calibrated, with input voltages from 3 kV to 5 kV (indicated in red on the left-hand side of Figure 3), and one where the medium-energy x-ray HVDs will be operated, with generator voltages from 50 kV to 160 kV (indicated in green on the right) .

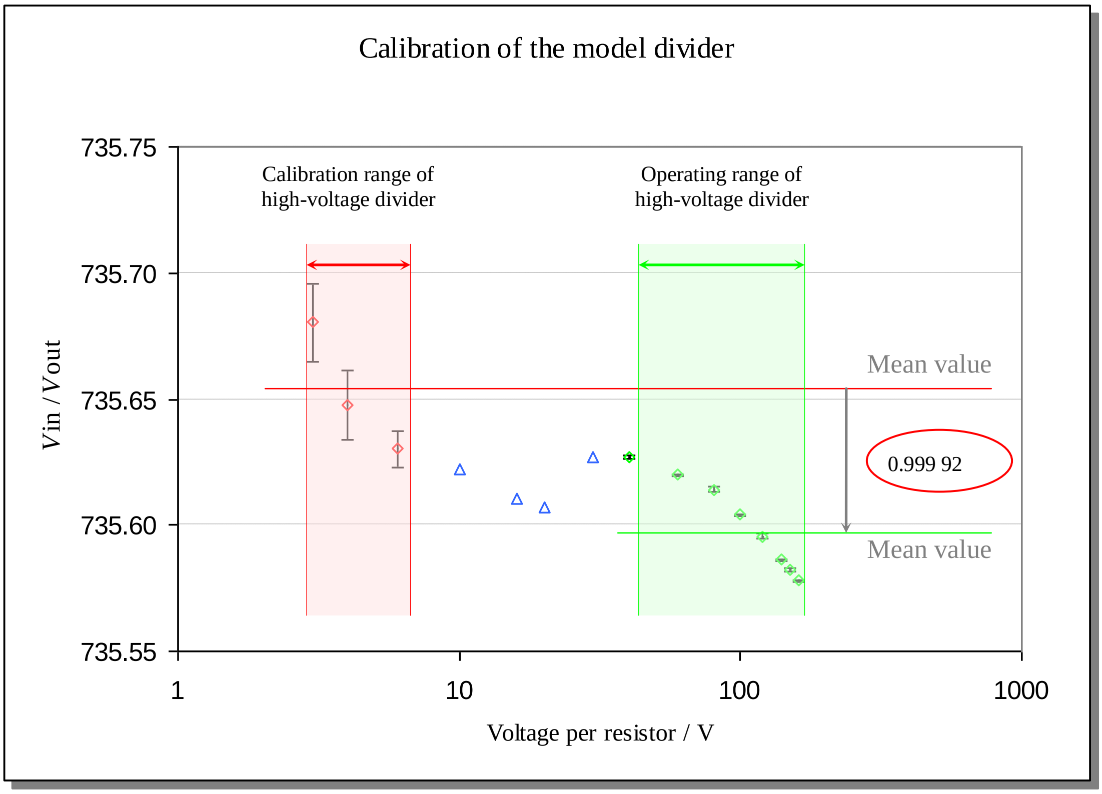


Figure 3. Calibration results for the model divider

The behaviour of the model divider shows very little dependence on voltage, the total variation being around 2 parts in 10^4. A small correction factor (k_{volt}) can be applied to correct a result obtained in the range from 3 kV to 5 kV to the value appropriate for the range over which the HVD will be used. This correction factor is evaluated from the difference between the mean value obtained over the calibration region and the mean value between 50 kV to 160 kV, representing the operating range of the HVD; for the medium-energy x-rays this gives $k_{\mathrm{volt}} = 0.999\ 92\ (4)$ and for the low-energy x-ray range from 10 kV to 50 kV it gives $k_{\mathrm{volt}} = 0.999\ 95\ (4)$.

3.2.2 Theoretical value

To support the values determined by the model, estimates were calculated using the manufacturer's data for the voltage coefficient. The high voltage applied at the input of the HVD is seen only by R_1, therefore the voltage coefficient of the resistor (VCR) can be applied to this series of resistors. As shown in Figure 1 the divider ratio is

$$V_{\mathrm{in}} / V_{\mathrm{out}} = 1 + (R_1 / R_2)$$
$$R_1 = 1000R,\ \ R_2 = R / 10$$
$$V_{\mathrm{in}} / V_{\mathrm{out}} = 100\ 01$$

We can now express the divider ratio

$$V_{\mathrm{in}} / V_{\mathrm{out}} = 1 + (R_1 / R_2) \times k_{\mathrm{volt}}$$

where

$$k_{\mathrm{volt}} = 1 / (1 + (\mathrm{VCR} \times V_{\mathrm{r}}))$$

VCR = $0.7(3) \times 10^{-6}$ / V (manufacturers spec $<1 \times 10^{-6}$ / V)
$V_{\mathrm{r}} = V_{\mathrm{in}} / 1000$ (V_{r} = voltage across each resistor)

Correction factor at 30 kV
$k_{\mathrm{volt}} = 1 / (1 + (1 \times 10^{-6} \times 30))$ $k_{\mathrm{volt}} = 0.999\ 98\ (1)$

Correction factor at 100 kV
$k_{\mathrm{volt}} = 1 / (1 + (1 \times 10^{-6} \times 100))$ $k_{\mathrm{volt}} = 0.999\ 93\ (3)$

The results are in agreement with the measured values within the uncertainties, although this simple model does not explain the structure of the results in Figure 3.

3.3 Determination of the temperature coefficient

When the HVD is used for medium-energy x-rays, the voltage applied at the input can reach 125 kV, in which case the power dissipated by the divider is about 100 W. Under these conditions the oil temperature can rise from room temperature at 20 °C to 27 °C during a normal day's use, and the temperature coefficient must therefore be considered. To determine this effect, each of the medium-energy x-ray HVDs was calibrated at a series of temperatures as the system warmed up under operation. Figure 4 shows the calibration results for the HVD RI DIVNEG003 as a function of temperature and Figure 5 those for RI DIVPOS004.

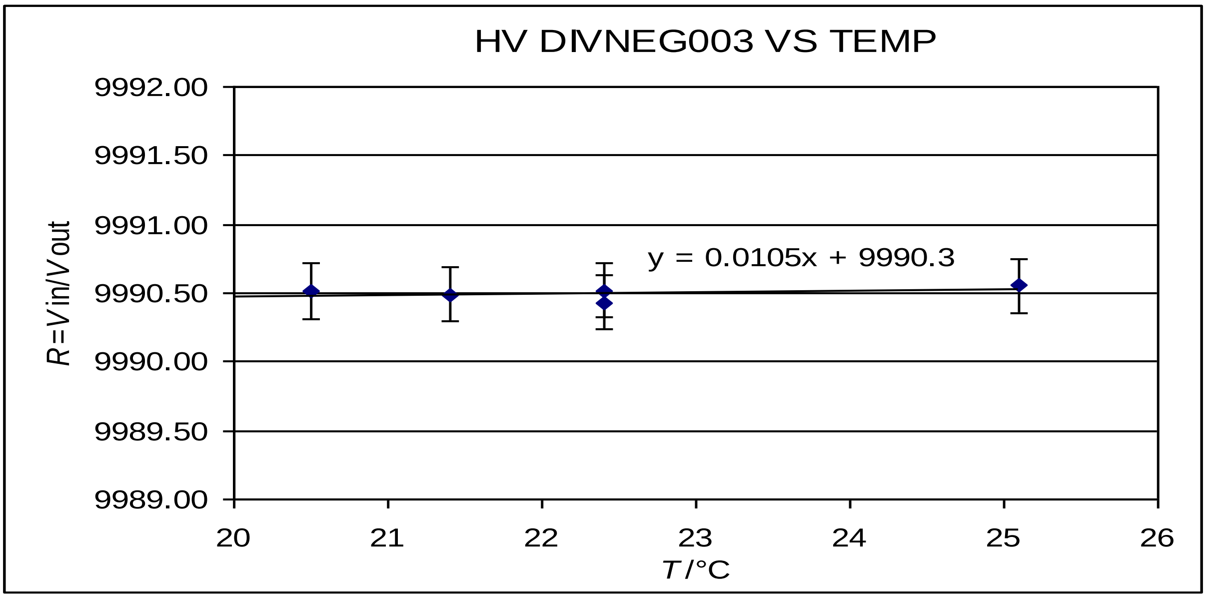


Figure 4. Calibration of DIVNEG003 as a function of temperature.

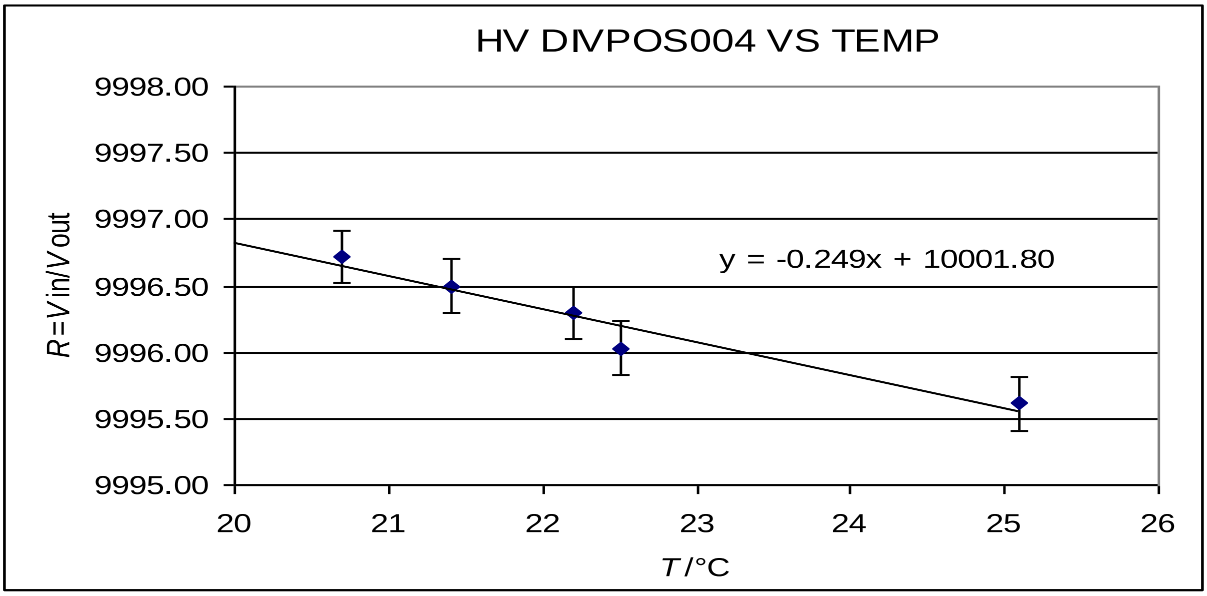


Figure 5. Calibration of DIVPOS004 as a function of temperature.

Although the two dividers are nominally identical, it is clear that their behaviour with temperature is quite different. The hypothesis that temperature effects should cancel for resistors R_1 and R_2 appears not to hold for one of the dividers, and it might be that some other component of the divider is responsible. A temperature correction can be evaluated; the divider ratio $D(T) = V_{in}/V_{out(T)}$ will be determined using the function:

$$D(T) = D_{20} + (-0.25\ (T\ /°\mathrm{C} - 20))$$

where $D(T)$ is the divider ratio at temperature T, D_{20} is the calibrated ratio at 20 °C and T is the temperature at which the HVD is used.

3.4 Stability

Figure 6 shows the results of calibrations for one divider made over a period of 7 years. The larger uncertainty bar for the first measurement indicates a slight instability that disappeared after the first few weeks of use.

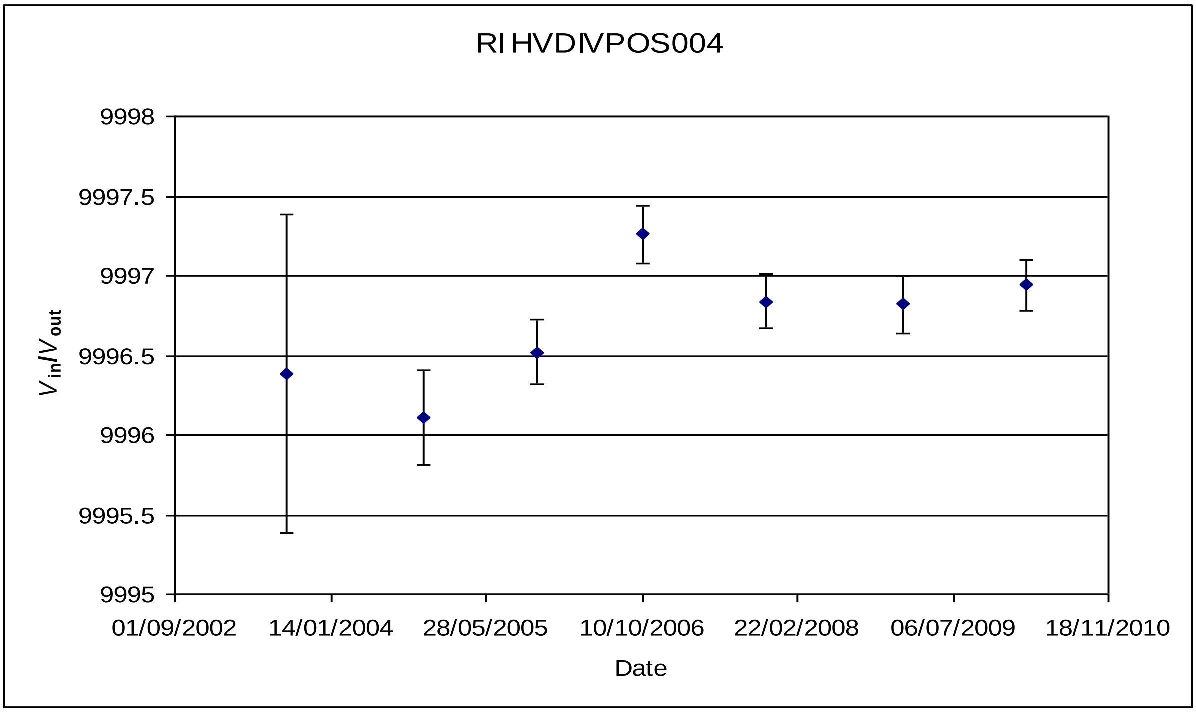


Figure 6. Calibration of HVDIVPOS004 (used in the medium-energy x-ray facility)

4- Conclusion

A voltage divider has been designed and constructed at the BIPM to measure the high voltage of the x-ray generators applied to the x-ray tubes used for dosimetric measurements. The divider is calibrated at low voltages and the extrapolation to high voltages is obtained within the design level of 1 part in 10^4. The stability of the high voltage divider has been demonstrated over a period of 7 years and is in constant use to provide feedback on the quality of the x-ray dosimetry measurements. The equipment now forms part of the quality management system of x-ray measurements at the BIPM.