Simple and compact capacitive voltage probe for measuring voltage impulses up to 0.5 MV

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The paper describes a simple and compact 0.5 MV high-voltage capacitive probe developed in common by Université de Pau (France) and Loughborough University (UK). Design details are provided, together with a simple and straightforward methodology developed to assess the characteristics of high-voltage probes. The technique uses a 4 kV pulsed arrangement combined with results from a 2D electric field solver and a thorough PSpice circuit analysis. Finally, a practical example of high-voltage measurement performed using such a probe during the development phase of a high power microwave generator is provided. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3690906]

I. INTRODUCTION

Modern pulsed power applications of high power microwave (HPM) technology require simple, compact, and if possible inexpensive high-voltage probes for the reliable measurement of impulse voltages with amplitudes of about 0.5 MV inside relatively small oil-filled containers. Although the literature dedicated to high-voltage probes is vast, there are few examples of *compact* probes for such high-voltage amplitudes. Some of the work describes high-performance probes, which are however complicated and expensive,[1,2] while others present probes specifically designed for a particular pulsed power arrangement,[3,4] including the measurement of voltage impulses along transmission lines.[5] Those which correspond to the present requirements are all made using aqueous resistors, usually in the form of pure demineralised water doped with $CuSO_4$ and contained inside dielectric cylinders.[6,7] Such probes are however very sensitive to ambient temperature and require regular service. When the measurement is performed with the probe immersed in oil, experience shows that, at least during the development phase of a high-energy pulsed power system, it is preferable to avoid the presence of conductive liquids inside the oil tank. For example, the generation of strong mechanical shocks by an accidental electrical breakdown may induce cracks in the dielectric wall of the probe, with the conductive liquid mixing with large amounts of specialty oil.

The paper introduces a simple design of a compact 0.5 MV probe termed Half-Megavolt, developed jointly by the Université de Pau (France) and Loughborough University (UK). Results are presented from an experimental study of the frequency response obtained using a simple high-voltage arrangement. Full details of the technique used to assess the high-voltage probe are presented, including both a 2D electric field analysis and a PSpice-based study of the complete arrangement. Finally, results obtained with the probe when used in a HPM application are provided.

II. HIGH-VOLTAGE PROBE DESIGN

A. High-voltage arm

The high-voltage arm in Figure 1 comprises a collection of $N = 5$ metallic (aluminium) discs, parallel-mounted and kept in place by a plastic bar, with the radius of curvature of the top disc being 5 mm and only 3 mm for all the other discs. Because the probe is made as compact as possible, no electric field grading rings are used to ensure a homogeneous field along the structure of the high-voltage arm, which makes the probe relatively sensitive to metallic objects in their proximity. Because the high-voltage arm has cylindrical symmetry, an electrostatic analysis of the probe immersed in transformer oil of permittivity of 2.25 was made using Ansys Maxwell 2D software.[8] The resulting capacitance matrix is provided in Table I, data which is later used in the PSpice analysis. In Table I the capacitance of each disc with respect to ground, C_{ii}, $i = 1, \ldots, N$ is shown on the diagonal with the various mutual capacitances between discs, C_{ij}, $i \neq j$, $i, j = 1, \ldots, N$ filling the rest of the table.

B. Low-voltage arm

The low-voltage arm of the Half-Megavolt probe is shown in Figure 2 and comprises 20, 200 V, 1 nF low-inductance capacitors type NP0.[9] These miniature capacitors are one of the most stable ceramic capacitors commercially available, with a temperature variation of no more than ±0.3% between −55 °C and +125 °C and they also have no measurable variation of capacitance with frequency up to at least 10 MHz and no hysteresis effect. Based on the manufacturer data sheet, the equivalent series self-inductance of one capacitor was estimated as 0.9 nH. The number of parallel-mounted capacitors has been used as means of adjusting the probe attenuation factor as close as possible to 10 000. The

FIG. 1. (Color online) Half-Megavolt probe. The high-voltage arm is visible at the top of the assembly and the low-voltage arm is mounted on the base.

FIG. 2. (Color online) Half-Megavolt probe. The low-voltage arm is mounted at the base with the end cap of the shield opened for inspection.

BNC output has a 50 Ω series resistor to adapt the impedance to the double-shielded 4 m coaxial cable and, as presented later, due to the very small currents (μA) flowing through the low-voltage arm the electromagnetic shielding of all low-voltage arm components is of paramount importance. More details are given below related to the PSpice analysis.

With the divider housed inside a metallic oil container, the output shielded cable usually passes through the lateral wall using a coaxial grounded feedthrough. In all experiments reported here however, the metallic containers were without a lid, allowing the cable to be straightforwardly connected to the oscilloscope.

III. EXPERIMENTAL PROGRAMME

A. Methodology

Standard methods for obtaining the frequency response of a high-voltage probe, having an attenuation of 10 000, are not easy to implement and the alternative methodology adopted here is far more straightforward. A very fast impulse generator is required, together with a high-performance lower voltage sensor having a known frequency bandwidth much larger than that of the high-voltage probe under study. The two are mounted in parallel and the response to a fast voltage impulse is recorded. By comparing the two FFTs obtained, a conclusion can be reached regarding the frequency response of the high-voltage probe under study. Separately, using the matrix of capacitances, a full analysis of the high-voltage probe together with the test circuit can be performed via PSpice software. This analysis provides a theoretical prediction of the frequency response, which can then be compared with the experimental data to assist in improving the probe design. The calculation with PSpice also provides the potential distribution on all of the discs of the probes following the application of the fast voltage impulse. This information is then fed back into an electrostatic solver to provide the precise electric field distribution, which in turn is used to evaluate the maximum voltage the probe can withstand.

TABLE I. Capacitance matrix for Half-Megavolt probe (pF).

i	*j* = 1	2	3	4	5
1	6.6033	11.726	0.86738	0.36129	0.1295
2	11.726	2.9439	11.168	0.57391	0.15767
3	0.86738	11.168	3.1147	11.1	0.434
4	0.36129	0.57391	11.1	4.0019	10.742
5	0.1295	0.15767	0.434	10.742	39.237

B. Simple, low-cost, and very fast 4 kV pulser

Very fast, low-voltage pulsers are available at a reasonable cost, but the present output from the high-voltage probes for a transistor-transistor logic (TTL) signal is only of the order of 250 μV. For a very much higher voltage output, of the order of a few kV, very fast pulsers can be extremely expensive. In what follows, a simple and low-cost pulser is presented with the overall electrical scheme of the arrangement used to obtain the frequency response being presented in Figure 3. This includes a 26 kV output voltage micro-transformer having approximate dimensions of 40 × 20 × 15 mm and driven by a 470 nF capacitor charged to 300 V and discharged using a thyristor. The resulting high-voltage impulse charges a coaxial cable pulse forming line of length $l = 55$ cm, which in turn is discharged by a spark gap in air at atmospheric pressure and mounted inside a cylindrical coaxial structure that accurately maintains the line impedance.[10] The output measured by a very fast voltage sensor embedded in the coaxial cable[11] is very fast, having a rise time of 250 ps as shown in Figure 4. The voltage impulse delivered to the load by the present arrangement has however a rise time of 4.5 ns, as it is affected by the self-inductance of the connection to the high-voltage probes when these are mounted in the oil tank.

C. Experimental arrangement and frequency response results

The calibration of the high-voltage probe was performed using a 250 MHz, 4 kV sensor, type Agilent 10076B.[12] The

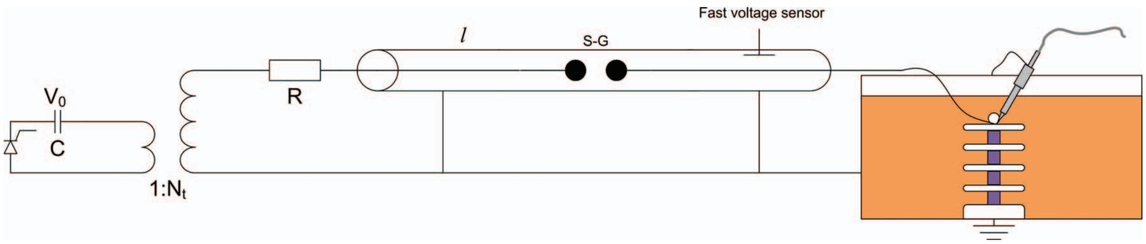

FIG. 3. (Color online) A 4 kV pulser arrangement with the voltage probe mounted inside an oil tank C = 470 nF, V_0 = 300 V, N_t = 66, R = 1 kΩ, and l = 55 cm.

practical implementation of the electrical scheme of Figure 3 is presented in Figure 5. Typical voltage impulses measured during tests are presented in Figure 6, with the ringing observed around 2 ns period being excited by the very fast rising edge of the input signal. The FFT of a typical calibrator signal has a bandwidth exceeding –20 dB for up to 85 MHz, which is certainly adequate for the accurate characterization of the probe. The resulting attenuation as a function of frequency is presented in Figure 7. The results indicate that the probe has a ±3 dB bandwidth up to about 55 MHz.

D. PSpice analysis of the Half-Megavolt probe and determination of the maximum voltage that can be safely measured

Based on the data in Table I, a PSpice model for the Half-Megavolt probe was developed as shown in Figure 8. This was used to provide a theoretical prediction of the frequency response, which is compared with experimental findings in Figure 7.

The PSpice model was also used to obtain the precise voltage applied on each of the high-voltage arm discs (from upper to lower) for 1 V input: 1V, 590 mV, 362 mV, 176 mV, and 100 μV. Once the voltage distribution on the discs of the high-voltage arm is known, the information can be used as initial data for the electrostatic solver, with the resulting electric field distribution being presented in Figure 9. The electric field data can then be used, as shown later, to estimate the maximum voltage that can confidently be applied to a probe. For example, for a 0.5 MV voltage impulse applied to the Half-Megavolt probe, the corresponding electric field calculated as $E_{0.5}$ = 250 kV/cm is generated on a total equivalent surface A = 43 cm^2. Application of the well-known Charlie Martin formula for the electric field breakdown E_b (in kV/cm) in oil[13]

$$E_b = 480 t^{-1/3} A^{-0.067} \tag{1}$$

for an impulse having a duration t of 0.5 μs (t is the time for which the voltage impulse exceeds 60% of the peak voltage) gives in this case E_b = 470 kV/cm, with a 50% probability of breakdown. This last result (i.e., $E_b > E_{0.5}$) indicates that the Half-Megavolt probe can certainly be used to measure voltage impulses up to *at least* 500 kV.

E. Proximity effect

In practice, the probe is usually placed in a metallic tank filled with oil, with various metallic components possibly mounted nearby. As these may perturb the internal electric field of the probe, it is important to estimate their minimum distance from the probe at which the calibration of the probe is unaffected.

Figure 10 presents the results of a theoretical study of the proximity effect on the Half-Megavolt probe. The probe is relatively sensitive; a metallic cylinder of diameter 510 mm mounted coaxially and connected to ground at a distance of 200 mm from the probe can change the attenuation by 4.4%.

F. Lesson learned

A very important lesson concerning the electromagnetic shielding of the low-voltage arm components was learnt

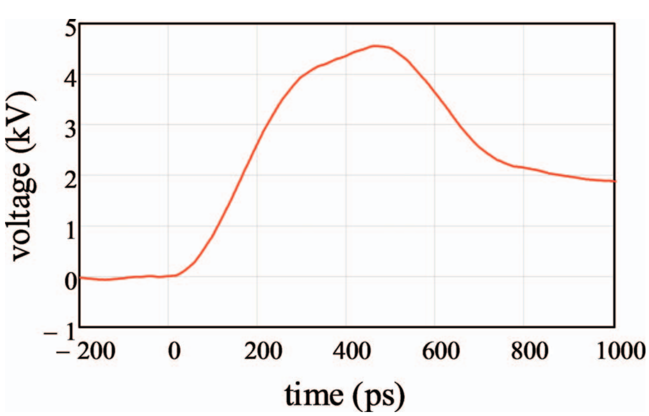

FIG. 4. (Color online) A 4 kV pulser output having a rise time of 250 ps.

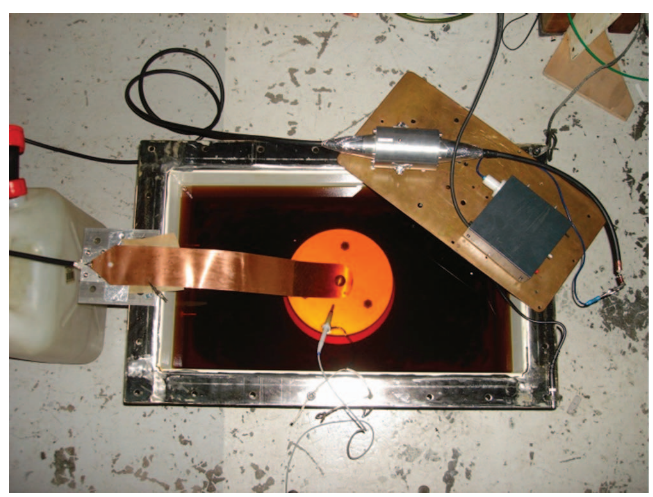

FIG. 5. (Color online) Practical arrangement for experimental determination of the frequency response of the Half-Megavolt probe.

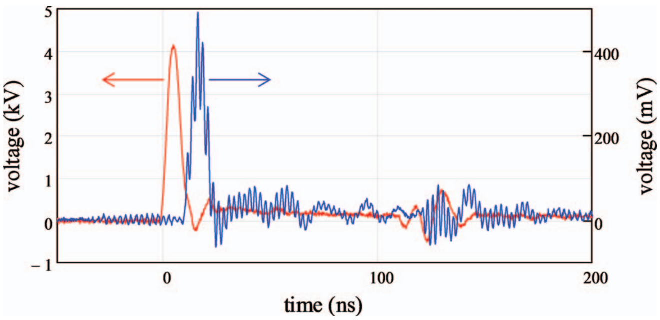

FIG. 6. (Color online) Typical signals recorded from the tests on the Half-Megavolt probe. The calibrator signals are in kV, while the probe signal is in mV, as recorded on the oscilloscope; the time origins differ mainly because of the very different coaxial cable lengths for connection to the oscilloscope.

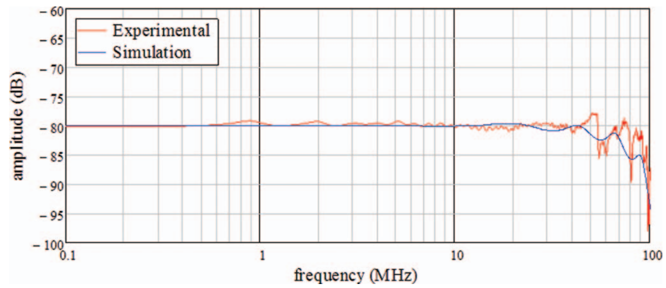

FIG. 7. (Color online) Frequency response for the Half-Megavolt probe (attenuation –80 dB, i.e., 1:10 000). The corresponding theoretical prediction (smoother curve) is also shown.

during the development of the Half-Megavolt probe. A preliminary study of the divider, made using a network analyser, highlighted that unwanted resonances may be produced by an improper shielding and further experiments using the arrangement shown in Figure 3 made these evident. Without the end cap of the shield (see Figure 2), the probe has a bandwidth of less than 25 MHz (Figure 11(a)). With the end cap in place, the bandwidth is much larger, reaching 52 MHz (Figure 11(b)). Finally, by improving the quality of the electrical contacts between the end cap and the cylindrical shielding box, the bandwidth was further improved to 55 MHz (Figure 11(c)).

IV. AN EXAMPLE OF PRACTICAL USE OF THE HALF-MEGAVOLT PROBE

A broad range of modern industrial applications requires compact high-power ultra-wideband (UWB) generators and a system developed at Pau University uses an innovative and very compact resonant transformer to drive a dipole antenna. The complete pulsed power source, termed MOUNA,[14] comprises a set of batteries, a dc/dc (300 V/10 kV) converter to

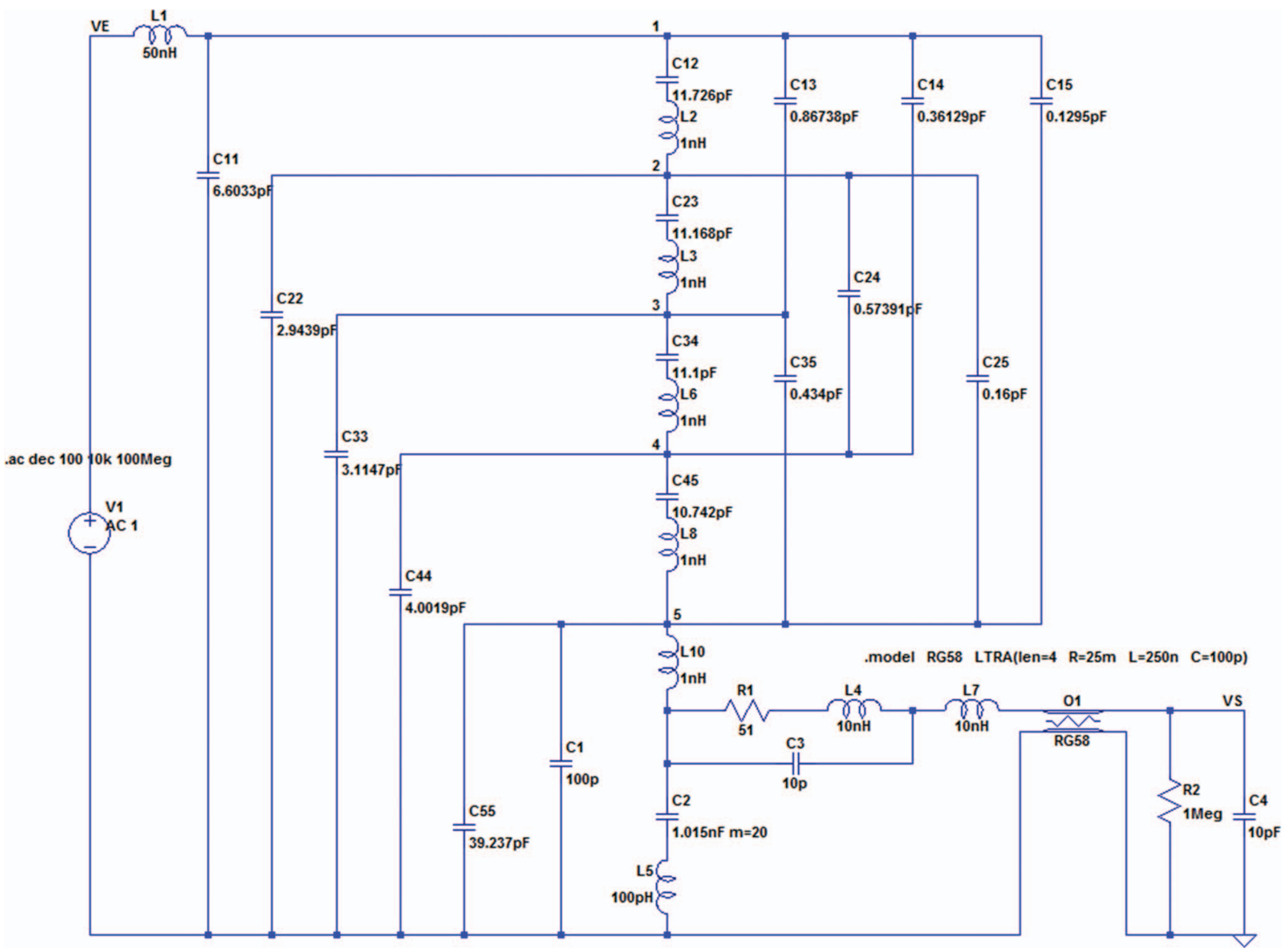

FIG. 8. (Color online) PSpice model for the Half-Megavolt probe, including the arrangement of Fig. 3.

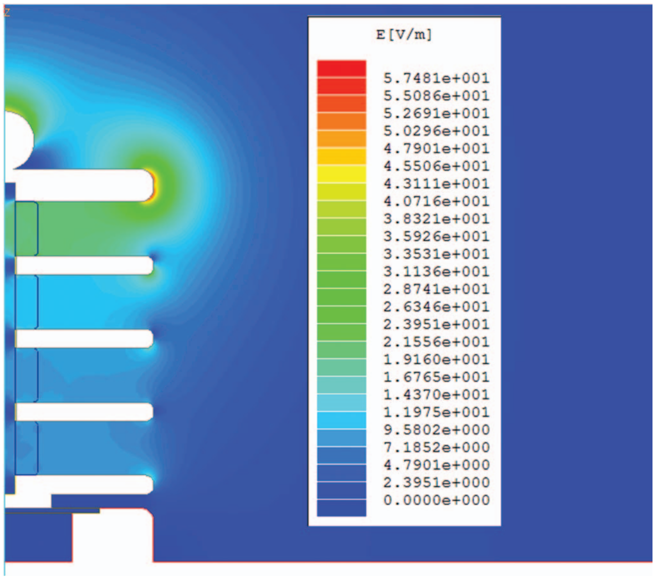

FIG. 9. (Color online) Map of electric field produced for 1 V applied on the Half-Megavolt probe. Because of symmetry only the right hand side is shown.

charge four capacitors, four synchronised spark gap switches, a resonant transformer generating 600 kV/300 ns pulses, and an antenna.

The total volume of the pulsed power source is less than 20 l and the complete system is housed inside a metallic container, filled with transformer oil and degassed using vacuum technology. A very compact high-voltage probe was necessary to measure the very high voltage pulses inside oil during the developmental programme *in a volume limited to only 1.5 l*. Apart from the volume, the main characteristics required for the probe were a bandwidth of more than 12 MHz (i.e., ten times larger than the maximum frequency to measure) and a maximum measurable voltage of at least 600 kV. As far as the authors are aware, *there is no commercial probe available having such characteristics*, making the development of the Half-Megavolt probe an important feature of the developmental programme. Figure 12 presents a photograph of the MOUNA pulsed power generator, mounted inside its metallic container and coupled to an 80 pF capacitive load, simulating the dipole antenna during the developmental tests. The capacitive load has a similar design to that used in the construction

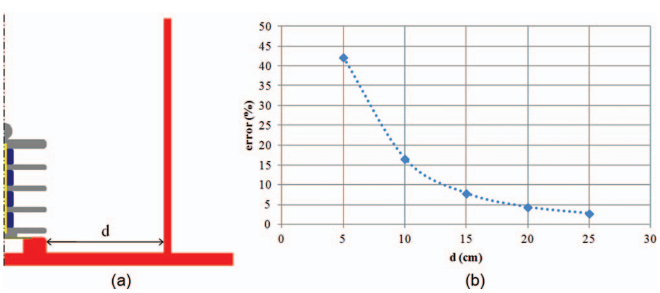

FIG. 10. (Color online) The influence of a metallic cylinder connected to ground on the probe attenuation (a) schematic indicating the distance d between the probe and the cylinder (b) estimated error introduced in the probe attenuation by the cylinder.

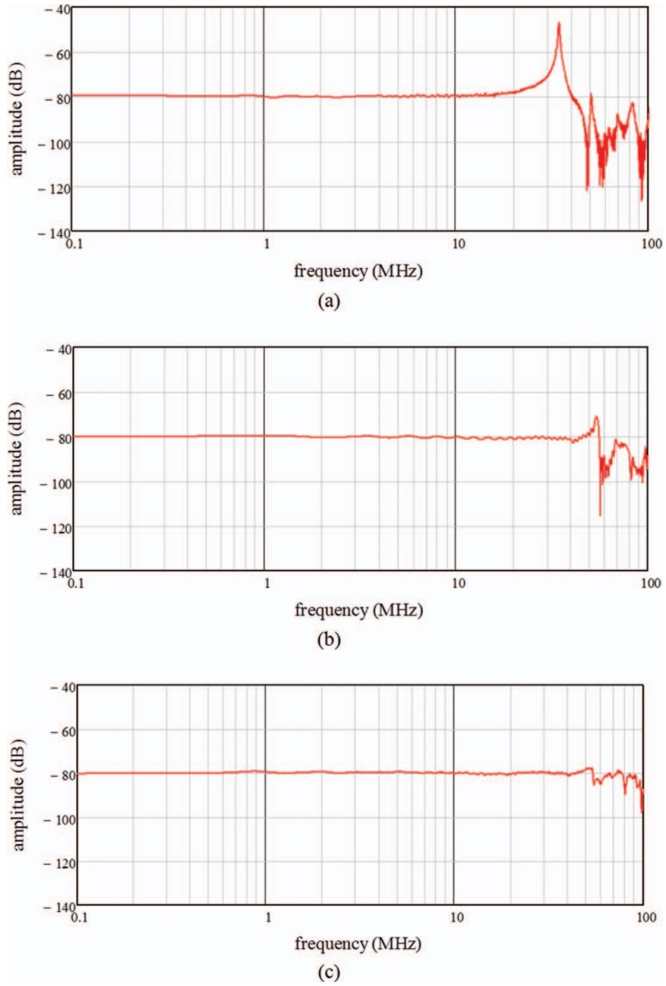

FIG. 11. (Color online) Frequency response for Half-Megavolt probe with the low-voltage arm: (a) unshielded, (b) shielded, and (c) shielded with improved electrical connections.

FIG. 12. (Color online) MOUNA: a compact and fully autonomous Half-Megavolt generator. The arrangement was used during the developmental tests with the assembly housed in a metallic oil-filled container. The Half-Megavolt probe is located towards the upper right corner and measures the voltage across a passive capacitive load (80 pF, located on the lower right) simulating the antenna. The load has a similar design to the high-voltage arm of the probe.

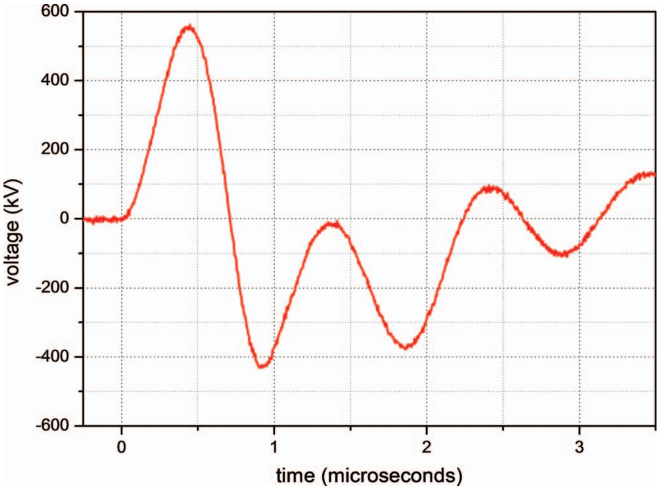

FIG. 13. (Color online) MOUNA output pulse measured by the Half-Megavolt probe during developmental tests.

of the high-voltage arm of the Half-Megavolt probe shown in Figure 1. A typical MOUNA output voltage measured by the Half-Megavolt probe is presented in Figure 13. For an input voltage of only 9.5 kV, the maximum generated load voltage reaches 555 kV, having a rise time of only 265 ns. An oil peaking switch can be added to the system in order to sharpen further the output pulse.

V. CONCLUSIONS

A very compact high-voltage capacitive probe, based on a novel design, having a bandwidth of many tens of MHz and capable of measuring up to about 0.5 MV proved to be extremely useful during the developmental phase of a HPM generator and in other pulsed power applications where the load is immersed in oil.

ACKNOWLEDGMENT

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