DEVELOPMENT OF A 1 MV ULTRA-FAST LTD GENERATOR*

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Abstract

A 1 MV linear transformer driver (LTD) generator has been manufactured by ITHPP and SEIV, and delivered to CEA/DIF/Polygone d'Expérimentation de Moronvilliers, in order to demonstrate the capability of this technology for flash X-ray radiography applications. This generator is composed of 10 cavities; each cavity includes 16 bricks representing two capacitors (GA 35436, 100kV, 8nF) and one multi-gaps air pressurized switch. To reduce the resistive losses in the switches, the inter-electrode gaps have been reduced from 6 mm in initial design to 4 mm, and the dry air pressure has been slightly increased. Each cavity has been tested individually on an automated testbed using a low inductive resistive load (~1.2nH) and extensive diagnostics, including a set of sixteen capacitive probes in front of each switch to control their timing sequence. The cavities deliver more than 100kV at ±100kV charging voltage into a matched load of 0.55-0.6Ω in a ~70-ns FWHM pulse. Around 300 shots have been made on each cavity (to condition the switches) before their integration into the generator.

The 10 cavities are stacked in series on a stiff metal frame and can move on rails with precise and reproducible mechanical alignment. Compression of the cavities is provided by the design of this frame. The center cathode of the output MITL is a 3.5 m long straight conductor that is cantilevered and hold on a support, moving on rails, to allow easy and fast insertion and removal. All the subsidiaries are also integrated on a dedicated lateral support, so the whole generator is movable on these main rails.

A high voltage trigger generator with 20 outputs (2 trigger cables per cavity) has been used to trigger the cavities synchronously with a very low jitter. The premagnetizing pulse is applied globally to all the cavities cores through the MITL cathode by using a movable contact under vacuum that is pneumatically controlled. The whole system is computer controlled and allows easy, reliable and safe remote operation.

The generator has been successfully tested with a large area ~6 Ω e-beam diode, in more than one thousand shots at full charge voltage. It proves to be very reproducible (a few percent) and has a very low jitter (<2ns, 1σ over 20 consecutive shots).

I. DESIGN OF THE STAGE

A new superfast LTD stage prototype, able to deliver a 75ns FWHM voltage pulse into a ~0.5-0.6 Ω matched load with ~20 GW output power, had been developed previously and was described in detail in [1]. This prototype design has been used as a basis for the definition of the 10 operational stages able to be stacked in series to build a 1MV generator in order to demonstrate the capability of this technology for flash X-ray radiography applications. Each cavity consists of sixteen "bricks" in parallel located evenly around the axis. Each brick includes 2 storage capacitors (GA 35436, 100kV, 8nF), one multi-gap air pressurized switch, and the output connectors. To reduce the resistive losses in the switches [2], the inter-electrode gaps have been reduced from initial 6 mm to 4 mm, and the operating pressure has been slightly increased (for ~1 bar). The lengths of the corona needles have been also adapted to have an optimized voltage distribution inside the switch. The ferromagnetic core consists of 6 rings made from Fe-Si3% tape which is 50 µm thick and 18 mm wide. The turns in the ring are insulated by a 10 µm thick insulating film and are potted in epoxy after winding. A cross-section of ~55 cm²

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provides a ~17 mV.s volt second integral with passive premagnetization resulting in quite low current loss [3].

The cavities are made of stainless steel output electrodes, an aluminum body, and a polycarbonate vacuum interface used to assemble the inner electrodes of the stage (see Fig. 1). Liquid resistors are used for charging and triggering, and insulation is provided by mineral oil. The switches are purged after each shot by using a vacuum reserve. The outside diameter of the body is 1.6 m and the equivalent length per stage is 214 mm.

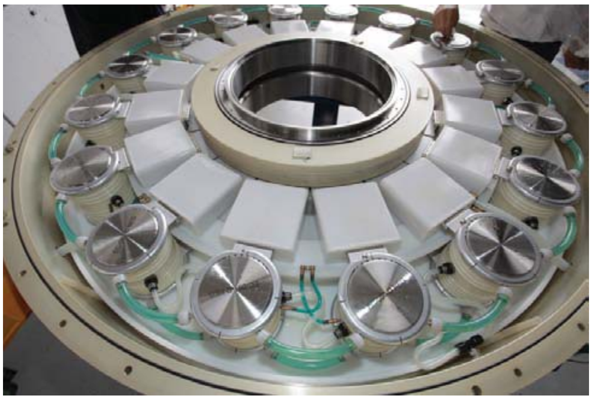

Figure 1. Picture of an opened cavity.

II. TESTBED OF THE STAGES

Each cavity has been tested individually on an automated testbed using a very compact and low inductive KBr resistive load (~1.2nH) in order to keep the stage output performances at their nominal values. The resistor can be inserted as a single element inside the stage and contacts the output electrodes by means of the finger stocks. High voltage withstand of the insulators is provided in that case thanks to SF6 at atmospheric pressure. The stage is equipped with a dedicated diagnostic flange equipped with 16 capacitive dividers (V-dots), to control the timing sequence of the switches and possible self-triggering, and 3 B-dots for core loss current measurement. One voltage (capacitive divider) and current (Rogowsky coil with damping resistors [4]) monitors are also placed on the resistive load. Each stage has been fired ~300 shots to condition the switches and control their proper operation. During the ~3000 shots done, only 7 prefires of one of the switches have been observed without any other defaults. At a matched load of ~0.6 Ω, the measured output performances are Vmax=~106 kV, Imax=~177 kA, FWHM=71 ns, Icore~15 kA (~8.5%), P=~19 GW, E=~950 J (~72% of Estored). When the load resistance was changed to 0.9 Ω, the output voltage and FWHM were increased to 124 kV and 75 ns, respectively, with a current of 130 kA (Fig. 2).

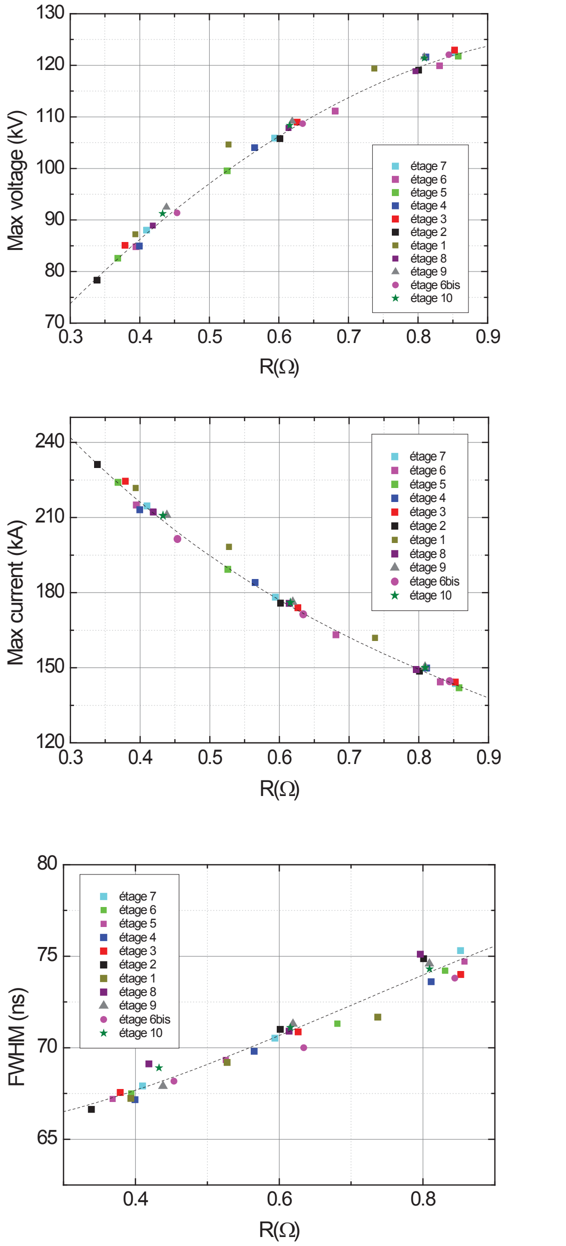

Figure 2. Synthesis of the output parameters (V, I, FWHM) of the 10 stages.

The spread of the switch closure has been measured by the 16 capacitive monitors to be less than 4-5ns, with 3.9 bars relative pressure in the switches. The typical jitter of the stage, between the trigger pulse and the output voltage, is less than 0.5 ns (1σ definition over 50 shots).

III. DESCRIPTION OF THE GENERATOR

The 10 stages are stacked in series on a stiff metal stand (designed to have a deformation less than 0.2 mm with the nominal loading of the cavities weight: ~750 kg with oil) and compressed from the diode side (see Fig. 3). This conception is similar to the one used by HCEI for the 1MV generator delivered to SNL in 2004 [5].

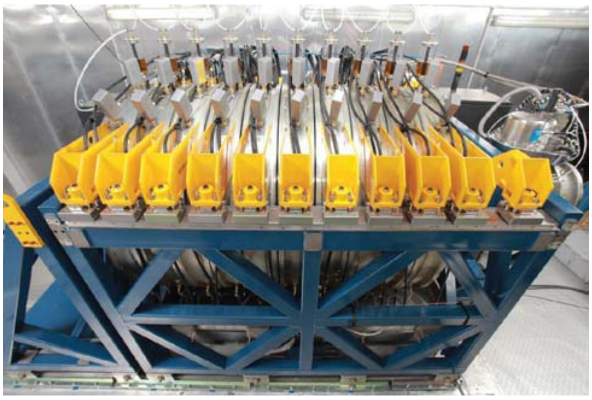

Figure 3. Overall view of the 1MV generator made by 10 LTD cavities stacked in series on a metal stand

The stages can move on rails with a precise and reproducible alignment. An external stand with position measurements of the inner electrode relatively to a central reference is used to settle the little trolleys (with X,Y,Z and tilt adjustments) that support the stages before assembly on the generator. The design of the rails on the stand, using V-shaped and flat guide rails, allows the reversal of the output polarity of the generator (by reversal of the stages) without realignment of the stages.

The cathode is a 3.5 m long straight aluminum conductor, cantilevered from the back, and hold on a support that can move on rails to allow easy insertion and removal from the inside of the stacked cavities. A view of the cathode out of the 1MV generator is shown in Fig. 4. The generator is ended by a ~1m long extension line where locates the cryopump providing secondary vacuum inside the central coaxial line and increasing the distance between the stages and the future possible radiographic diodes that may generate pollution and debris. The diameter of the center conductor was defined by using the Creedon's model [6], in order to provide at the output of the 10^{th} stage an operating impedance in establish regime of ~6Ω, which is matched with the large area diode impedance used to test the generator. The line has a 10.45 Ω vacuum impedance with an outer bore diameter of 469 mm.

Figure 4. View of the cathode and its support moving on rails outside from the generator.

All the subsets of the generator are integrated on a lateral support that can move with the generator along its rails (Fig. 5).

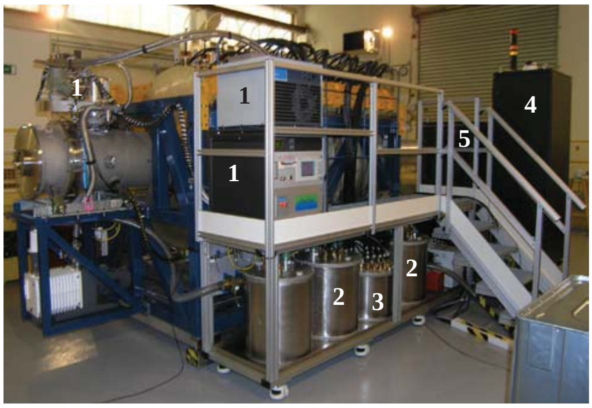

Figure 5. View of the subsets of the 1MV generator (1 - vacuum systems, 2 - HV distribution and dump, 3 - HV trigger, 4 - command-control, and 5 - acquisition bay) integrated on a lateral support.

IV. SUBSETS OF THE GENERATOR

The premagnetization of the cores (~4-6 kA, T/4~50 μs) is made by a 2 polarities generator on a single stage, and by a single polarity one for the 1MV generator. In the last case, the premagnetizing current is injected around the cores of all the cavities thanks to a movable contact under vacuum that comes in contact with the cathode prior to the shot (pneumatically controlled). This system operates at 2-3 kV charging voltage and its capacitors are discharged by HV thyristors. A series inductance on the outputs is used to protect the electronics from the HV pulse during firing of the stage, and allows keeping it connected to the stage for passive or active premagnetization (for individual tests).

A 20 outputs high voltage trigger is used to trigger synchronously all the stages (2 cables per stage). The trigger is charged to 100kV whatever is the charging voltage of the generator. This provides reliable firing of the generator from ±100 kV down to ±40kV (with similar reproducibility and jitter). This trigger generator is made of 5 GA 35404 caps (100 kV, 20 nF) and 3 single polarity LTD like switches (5 gaps) providing low inductance and fast rise time of the output pulse on the 20 HV cables.

The triggering of the first 20-kV gap of the switches in the trigger generator is made by grounding the first switch electrode by using a thyratron or thyristors system with a very low jitter (<1.5ns 1σ, over 20 shots for both systems). The faster thyratron closure compared to the one of the thyristor, as it can be seen in Fig. 6, decreases the trigger jitter from ~2 ns to ~1 ns (1σ, 20 shots). But the thyristors HV grounding switch appears as a simple, reliable, very low jitter and low cost alternative compared to the more sophisticated thyratron ones.

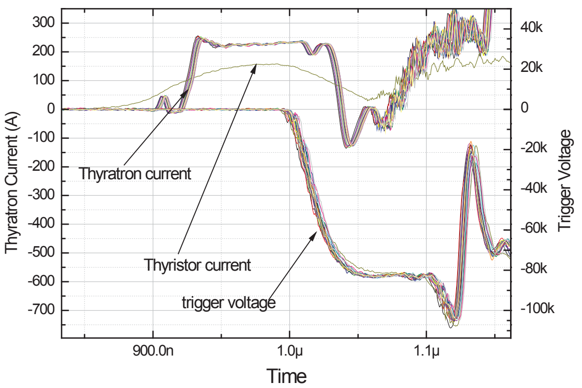

Figure 6. Graph showing the overall jitter of the thyratron discharge currents and trigger output voltages over 20 shots.

The 1MV LTD generator is fully remotely computer controlled (fiber optics links) excluding the vacuum system, that has an independent control system, and the oil filling that is manual.

V. TESTS RESULTS

In ITHPP, about 1300 shots have been done on a large area e-beam diode (~4Ω, 6Ω and high impedance with MITL self limited mode) before the generator was delivered to CEA. During these tests, the output voltage on each stage has been controlled by a differential measurement on each electrode of the cavities thanks to external resistive dividers with high bandwidth (~60MHz, 3dB high cut-off frequency). Cathode and anode B-dot probes can be moved along the generator to measure the currents at different locations. One self integrating Rogowsky coil was used also for the anode current measurement downstream the 10^{th} stage. Capacitive dividers have also been used to measure the output voltage inside the vacuum line but these shown to be reliable at low voltage without electronic emission from the cathode only.

At a ~4Ω low diode impedance, the current measurements show a negligible electronic current and the experimental data can be reproduced very precisely with a circuit model using the geometrical impedance of the line. The proper operation of the capacitive monitors in that case has been used to check the calculation of the output voltage thanks to the sum of the voltage pulses on each stage and an inductive correction, as it can be seen in Fig. 7.

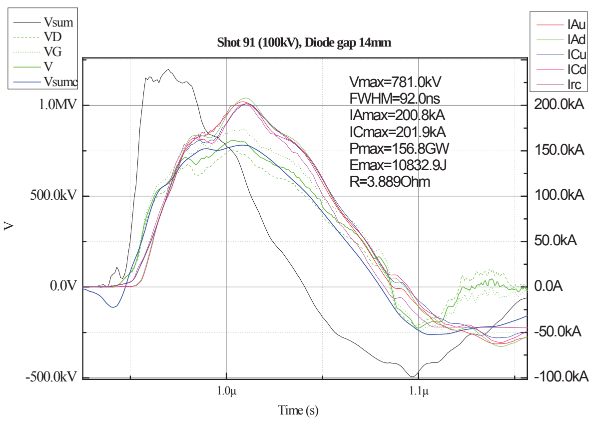

Figure 7. Graph of the comparison of the measured voltage (in green, VD, VG) by 2 capacitive monitors, and mean value (V) compared to the calculated one (Vsumc in blue) from the sum of the stages voltage (Vsum in black) and generator currents (right axis).

At higher load impedance close to matched mode (~6Ω), an electronic current was visible at the beginning of the shots but has tend to decrease due to conditioning of the MITL along the shots. The estimated electronic emission threshold appears in that case to be close to 290 kV/cm. Typical experimental data are shown in Fig. 8. The maximal calculated voltage is then above 1.1 MV with a pulse width of 92 ns (87 ns on the diode anode current), and the peak anode current reaches ~172 kA. The cathode current has moved from 145 kA at the beginning to the same peak value as the anode current after some tenth of shots. The pulse width is clearly degraded compared to the single stage tests due to the high inductance of the single diameter cathode which was used in these tests.

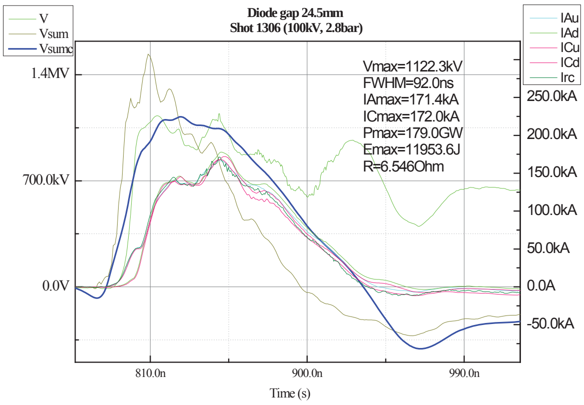

Figure 8. Graph of the typical output data of the 1MV generator on a 6 Ω large area diode (IAu,d and ICu,d anode and cathode current, upstream: after stage 10 and, downstream: just before the diode).

To increase the voltage stress on the stages, the generator has been also tested on higher impedance by using the self limited mode of the MITL (~8 Ω, 70-mm gap in the diode). These tests have proved the good behavior of the stages and of their vacuum interfaces at higher voltage and larger emission from the cathode. The signals for this case are given in Fig. 9, they demonstrate the loss front on the anode currents, and a significant electronic current in the extension line downstream from the 10th stage, up to the diode (~40 to 45kA).

In case of the prefire of one switch in a stage, the charging voltage on the whole generator was decreased by ~10%, this stage was rapidly recharged by the nine others. The stage with the prefiring switch discharges around the core, and do not initiate the triggering of the neighboring stages. So, no any parasitic voltage can be measured on the diode in such case. The charging may so continue up to 100 kV (computer controlled) and the shot has nominal performances (in a usual reproducibility range). The prefiring stage can only be identified from the cavities voltage measurements by a slightly bigger voltage reversal than the others due to a beginning of the core saturation at the end of the pulse (2nd discharge seen by the core without resetting).

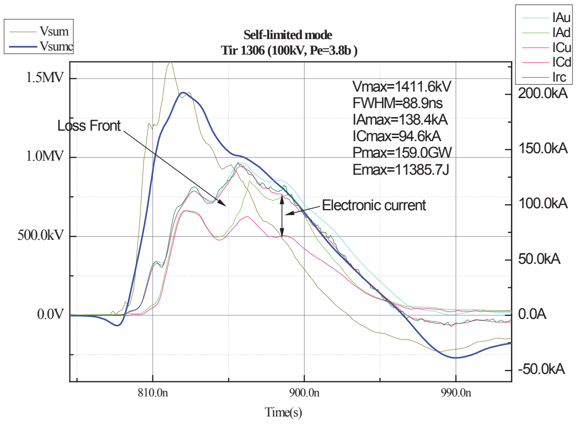

Figure 9. Graph of the typical output data on the 1MV generator in self limited MITL mode (~8Ω)

The decrease of the operating pressure from 3.8 bars to 2.8 bars does not change significantly the switch prefire probability (~1/30 during ITHPP tests). Figure 10 shows the superposition of the Si-PIN diode signal used to control the X-ray pulse in front of the diode in 20 consecutive shots (100 kV, 6 Ω and 3.8 bars in the switches). The pulse width is 65 ns and the overall jitter (from the 30 V triggering pulse) is 2.2 ns (1σ, or ~9 ns min-max).

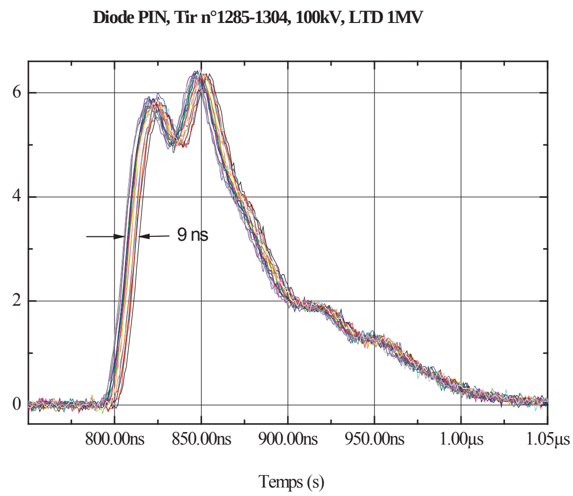

Figure 10. Superposition of the X-ray pulses on 20 consecutive shots at 3.8bars pressure in the switches

Contrarily, the decrease of the operating pressure significantly improves the reproducibility and reduces the jitter of the whole generator (to less than 1.4 ns at 2.8 bars). This effect is clearly put in evidence in Fig. 11 that compares 20 X-ray consecutive pulses (corrected in time from the trigger pulse) at 3.8 and 2.8 bars. The reproducibility of the generator is so improved by that change from ±2% to ±1%.

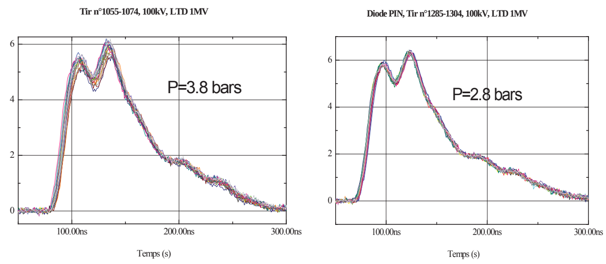

Figure 11. Comparison of 20 consecutive X-ray pulses at 3.8bars and 2.8 bars pressure in the switches.

V. CONCLUSION

A 1MV, 6Ω LTD generator has been developed, manufactured and tested for delivery to the French Atomic Energy Commission (CEA). The LTD technology and its subsets have proved to be reliable, reproducible and having very low jitter. The overall and compact integration of the generator allows it to be movable, and its mechanical design facilitates its operation and maintenance. A triggering system with high reliability and very low jitter has been developed and can be easily adapted to trigger a larger system in a controlled way (transit time delayed, group delayed or any specific sequence).

Different MITLs (tubular, with 2 steps and conical) have been designed, simulated and their proper operations have been controlled and checked [7].

So, this 1MV demonstrator tends to prove that this ultra-fast LTD technology appears as a good candidate for the development of future, medium to high voltage, fast radiography pulsers.

VIII. REFERENCES

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