

Reliability and Performances Improvements of the SPHINX Machine Based on the 1 Microsecond LTD Technology¹

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Abstract – The SPHINX machine developed at Centre d'Etudes de Gramat (CEG) is based on the 1 microsecond LTD technology. Since May 2004, it operates with 16 branches of 8 LTD stages each and is used for implosion of Z-pinch loads in direct drive mode. At a charging voltage of 50kV, the stored energy is 1.3MJ and the machine has shown a very good reliability which allowed every experiment on ~4MA, ~700ns implosion of nested wire-arrays described in references [3] to [5]. Parallel to these experiments, improvements on LTD stages have been achieved on test-beds up to 70kV charging voltage, leading to a new design of stages, named LTD05. Sphinx machine has been upgraded with 128 such LTD05 stages in October 2005. Details are given on LTD05 design, on electrical and electrostatic simulations and on experimental results. Other modifications on premagnetizing and triggering systems are described and a status on improved performances and reliability of the complete Sphinx system is given.

1. Introduction

The Sphinx machine configuration at 50kV charging voltage and 1.3MJ stored energy has been described in [1]. This configuration used since May 2004 for implosion of Z-pinch loads in direct drive mode has shown very good reliability; results obtained on ~4MA, ~700ns implosions of Aluminum nested arrays are given in [2] to [5].

Parallel to these Z-pinch experiments, several improvements described here were conducted to reach reliable operation of the LTD generator up to the 70kV nominal charging voltage. The Sphinx machine configuration since October 2005 is shown on Fig. 1.

2. Microsecond LTD stage improvement

Each LTD stage has 2 multigap-multichannel (MMCS) switches, giving 256 switches for the whole Sphinx generator. These switches operate in dry air, at atmospheric pressure. Previous LTD-04 switches showed hazardous prefires and breakdowns for charging voltages $V_{ch} > 50kV$. The main modifications

made with the LTD-05 switch are shown on Fig. 2 and Fig. 3.



Fig. 1 Sphinx machine, 16m diameter, 3m height 16 branches, 8 LTD-05 stages per branch

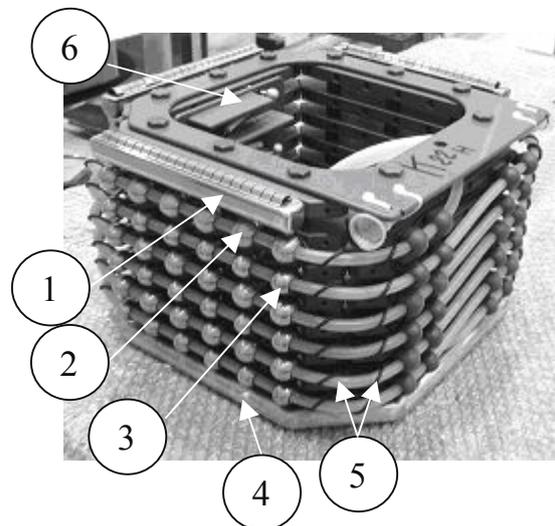


Fig. 2 LTD-05 switch; 7gaps-18channels (1: ground electrode; 2: $\varnothing 23$ -spheres row; 3: $\varnothing 21$ -ovoids row; 4: high-voltage electrode; 5: trigger cable with esistive $\varnothing 2$ -string; 6: resistive bridge with new dielectric insulation)

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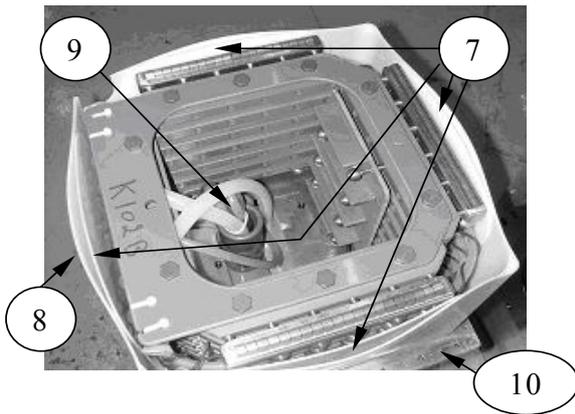


Fig. 3 : LTD-05 switch inside dielectric insulation (7: new PEHD foils; 8: former PEHD box; 9: new dielectric insulation of the trigger-cable connection; 10: capacitor body)

- The high density polyethylene (PEHD) insulation between the spheres electrodes and the return current path (switch case at ground) was increased from 3.5mm to 5.5mm, adding a 2mm thick PEHD foil (7) on each sides of the square switch and re-shaping the high voltage plate (4). As shown on Fig. 4 this modification lowers E-field in these regions thus reducing electrostatic charges on the dielectric surfaces. For example, from LTD-04 to LTD-05 design maximum E-field is reduced from 760kV/cm to 370kV/cm in the PEHD insulation between the 70kV plate (4) and the ground.

- Each of the 7 gaps of the switch was increased from 5.5mm to 6.5mm by re-machining half of the $\varnothing 23\text{mm}$ spheres to $\varnothing 21\text{mm}$ ovoids (3). This allows to reduce maximum E-field in gaps; between the 70kV plate (4) and the first row this reduction is from 23kV/cm for 5.5mm gap to 18kV/cm for 6.5mm gap.

- The resistive bridge (6) allows an homogeneous distribution of voltage between gaps. The insulation of this bridge was improved adding anti-corona spheres and PVC separations between the 100M Ω resistors. Voltage distribution between channels was improved by reduction of the resistance of the $\varnothing 2\text{mm}$ string (5).

- The insulation of the trigger cable connection (9) was modified to avoid surface tramping and breakdown between this HV cable and the LTD 'convolute'.

These improvement studies were supported by circuit and 2D plus 3D electrostatic simulations, and by tests on two test beds composed of 1 and 4 LTD stages.

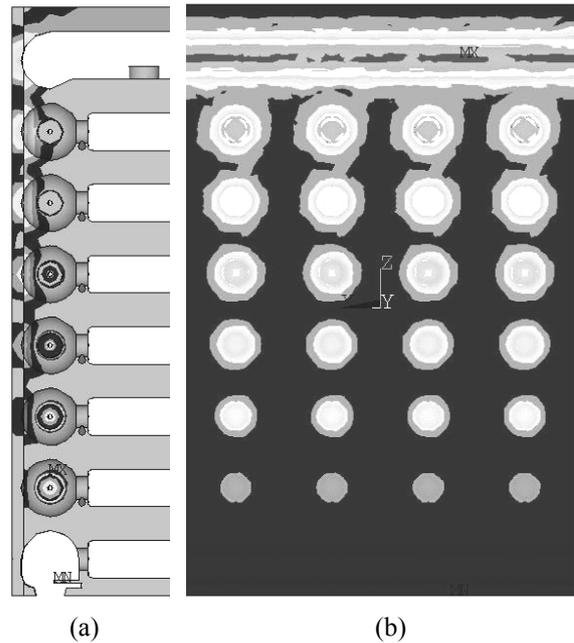


Fig. 4 : Example of a 3D-electrostatic simulation (a) : Efield > 30kV/cm along 1 channel; (b) : Efield topology on the PEHD surface contacting the electrodes

The equivalent scheme of a single stage is shown on Fig. 5. Compared to previous LTD-04 design, the increased on total inductance is less than 5% and is due to an increase of each switch inductance from 6nH to 9.4nH.

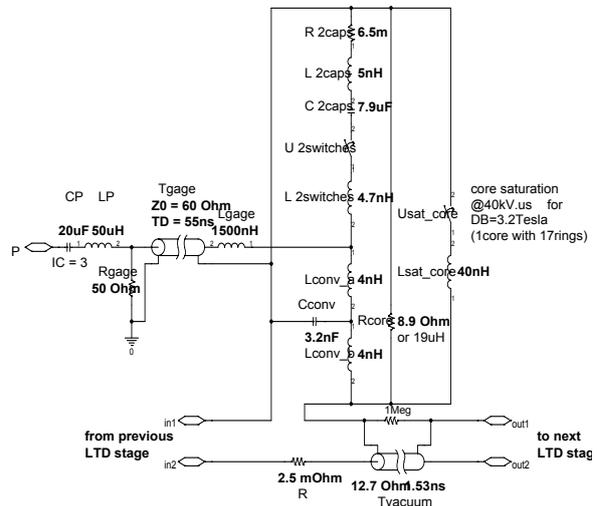


Fig. 5 : Electrical scheme of a single LTD-05 stage

The final LTD-05 design showed a good reliability at the nominal 70kV charging voltage: after more than 500 test bed shots and without any maintenance, LTD-05 stages showed no pre-fires and no damages.

3. The Sphinx machine with LTD-05 stages

The Sphinx machine has been upgraded with 128 such LTD05 stages (16 branches of 8 stages) and shots at 60kV charging voltage on Aluminum Z-pinch loads began on October 2005.

Pre-magnetizing system

As described in [1], the magnetic cores of LTD stages are pre-magnetized during the shot sequence. A $60\mu\text{s}$ rise time pulse is sent through the 60Ω cable (see point P on Fig. 5) around each core and the main LTD pulse starts when this pre-magnetization current reach its maximum $\sim 1.5\text{KA}$. The polarity of these two pulses is opposite so that the Hysteresis swing is maximum $\Delta B \sim 3.9\text{Tesla}$ and the core, which cross section is $7.4 \cdot 10^{-4} \text{ m}^2$, can withstand a Volt.Second integral of $49\text{kV} \cdot \mu\text{s}$ before saturation. To insulate the core circuit and the load circuit during the pre-magnetization, a self-closing vacuum surface switch named 'P-switch' is installed on the ground side (opposite to the load) of each coaxial LTD branch.

Several problems appeared during first shots on the LTD-05 upgraded Sphinx. Some of them were due to minor defaults on LTD switches assemblies; they affected only few stages and were easily solved. More awkward were breakdowns occurring mainly on the LTD stages located on ground side. The analysis showed that these breakdowns were due to over-voltages created during closing of the P-switches. A redesign allowed to reduce the jitter and the closing delay of the 16 P-switches, so reducing the overvoltages and breakdown risks. This modification improved a lot the reliability of the machine for further shots.

New pre-magnetizing generator

Despite this good result, it was decided to develop a new pre-magnetization system which will be on line from June 2006. A new compact generator has been built to generate a (1.5KA , $18\mu\text{s}$ rise time, single polarity) pulse on each core. This generator is based on 2 parallel LTD stages modified with single gap, single channel switches and liquid resistors. The pre-magnetizing pulse is applied several hours before the shot, before connection of the load, on the ground side of the inductive support (see Fig. 1 & point P on Fig. 6) and distributes through the convolute to the cores. To close the pre-magnetizing circuit, the 16 P-switches are replaced by fixed short-circuits, giving the benefit during the shot to suppress the over-voltage risks described previously. With this system, the cores pre-magnetized at $-B_r$ have a $\Delta B \sim 3.2\text{Tesla}$ Hysteresis swing and can withstand a Volt.Second integral of $40\text{kV} \cdot \mu\text{s}$ before saturation.

Prepulse generator for wire-arrays pre-heating

Thanks to the new pre-magnetizing generator, the former system can be removed or used for other application. This system is composed of 8 generators, each of them associated to 2 LTD branches, and can be triggered independantly. Each generator gets itself several outputs which are connected to the point P of LTD stages (see Fig. 5). As all P-switches are now short-circuited, main part of the discharge current goes to the low impedance circuit of the Z-pinch load. Measurements, also fitted by circuit simulations, show that these generators can deliver, for each of the 16 lines, a prepulse up to 1.3kA with a $50\mu\text{s}$ rise time in the load. Choosing the number of generators, the number of outputs, the charging voltage and the triggering time, this allows a large range of possible prepulses, going from few 100A to 20 KA, with rise times from few μs to $60 \mu\text{s}$ before the main LTD pulse.

First results of Aluminum nested wire-arrays using this prepulse for wires pre-heating are given in [4] and [5].

Triggering system

The trigger system fires each of the 256 LTD switches. Triggering operation of the LTD switch is based on a pulsed distortion of the electrical field between gaps, created by a controlled discharge of the HV trigger cable (5) going through the spheres electrodes (see Fig. 2). As the only trigger energy is the energy stored in the HV cables, this system is compact, simple and reliable. The complete system is based on a 2 steps switches cascade described in [1]. The "trig-trig" switch and the 16 "trigger" ones are identical and are based on the same technology as LTD switches. Trigger cables are charged at 55kV in about 30s with an independent high voltage power supply. The "trig-trig" and "trigger" switches are been improved: reduction of gaps from 9 to 7, better repartition of impedance between the channels. First improvements made on the 16 trigger switches has shown, within each branch a reduction of the spread from 20ns to 10ns between closing time of the 8 LTD stages. These modifications, when completed on June 2006, should allow to improve significantly the global jitter of all LTD switches, with a spread between the 16 lines reduced from 50 ns to less than 30 ns.

4. Status on Sphinx performances

A simplified electrical scheme of the Sphinx generator is given in Fig. 6. The values with LTD labels are the equivalent capacitance, inductance and resistance of the 256 LTD-05 stages distributed in 16 parallel branches of 8 stages.

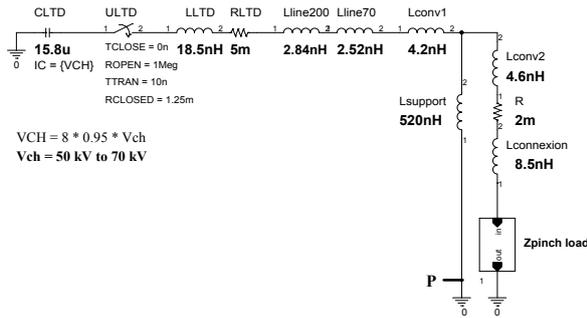


Fig. 6 :Simplified electrical scheme of the complete Sphinx generator with 16 branches and 8 LTD-05 stages per branch.

The Fig. 7 compares experimental data on nested aluminum wire-arrays loads with a 700ns implosion time. The new LTD-05 stages allow an increasing of charging voltage from 50kV to 60kV which gives for these 2 shots a maximum current going from 4MA to 4.6MA and a radiated energy $E > 1\text{keV}$ from 17kJ to 27kJ with a FWHM around 50 ns. More details on Z-pinch loads, with results on radial and axial radiated powers and analysis of the influence of a prepulse for preheating wires are presented in [4] and [5].

Up to now, around 10 successive shots at 60kV charging voltage have been done without maintenance of the new LTD-05 stages and showed no defaults. This analysis of Sphinx generator reliability at $V_{ch}=60\text{kV}$ will continue while improving the wire-arrays loads and testing a new 200mm triple gas-puff load. If reliability is confirmed on the whole generator as it was on test-beds, first shots at $V_{ch}=70\text{kV}$ will be starting to improve the Sphinx performances.

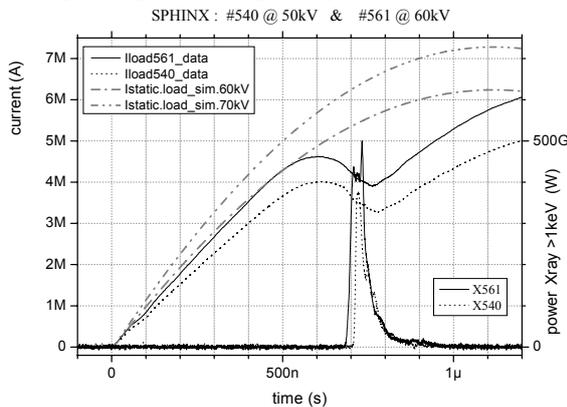


Fig. 7 : Sphinx current and Xray>1keV radiated power for an Aluminum nested wire arrays load. (solid lines : shot at $V_{ch}=60\text{kV}$; dot lines : shot at $V_{ch}=50\text{kV}$; grey lines : simulation at $V_{ch}=60\text{kV}$ and $V_{ch}=70\text{kV}$ for a static 1.3nH, 15mΩ load)

At 60kV charging voltage, the Sphinx generator stores 1.8MJ and reach 4.6MA on a 700ns wire-array load, which would correspond to a 6.2MA, 1.1μs discharge on a static load (see the grey line simulation on Fig. 7 for a 1.3nH,15mΩ load). At $V_{ch}=70\text{kV}$, the stored energy will be 2.5MJ, reaching 5.4MA on a 700ns load and 7.3 MA on a same static load.

An other short term way to improve performances is to add LTD stages. The architecture of the machine is designed to accept up to 10 stages per branch and LTD values on the equivalent scheme of Fig. 6 can be easily modified to analyze the new coupling with a z-pinch load. The configuration with 9 LTD-05 stages per branch will be on line on June 2006 and should be increased to 10 stages on 2007 depending on funding.

5. Conclusion

Improvements made on microsecond LTD stages now allows to fire routinely the Sphinx machine at 60kV charging voltage, giving 1.8MJ stored energy and 4.6MA on a 700ns implosion time load. These new LTD-05 stages will allow during next months to continue the increase of performances by going to 70kV charging voltage and 9 stages per branch. The objective is to validate the reliability of Sphinx machine in this new configuration by the end of 2006.

For the longer term, several independent or combined options are under study for further increase of Sphinx performances : current multiplier, 500ns rise time LTD stages with new capacitors, 1μs to few 100ns power amplifier and LTD stages working at $V_{ch}=90\text{kV}$.

References

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