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High energy X-ray emission driven by high voltage circuit system

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Abstract. The x-rays are produced by high voltage discharge applied inside plasma source interaction chamber; the control circuit system of high voltage is composed of a power supply and a LC-inverter. The goal of the project is based on the production of x-rays by a plasma to increase the efficiency of a classic x-ray tube with hot filament. Preliminary results of high energy x-rays emission, the layout and simulation with p-spice of the high voltage system are presented.

1. Introduction

Different applications of soft X-rays (~ 70 eV - 2 keV) and hard x-rays (~ 3 keV - 25 keV) in biological, radiobiological and in medical imaging field, have encouraged the development of X ray sources based on the production of plasma. The x-rays emission is due to plasma obtained focalizing an high power Nd-YAG laser beam on different targets [1].

Plasmas produced by focusing pulsed laser beams on solid targets are currently recognized as one of the most promising alternative to conventional (X-ray tubes) and to synchrotron X-ray sources.

Optimization of pulsed x-rays sources (~ 3 keV - 25 keV), due to the plasma electrons accelerated by an electric field, it is necessary to make x-rays source comparable with the most advanced current x-ray tubes (i.e. microfocus) for applications in the field of mammography and non-destructive inspection. There are many variables that allow us to get this optimization but the electrical parameters are especially the basis of the choice for the high voltage system configuration.

The reason to obtain a high voltage through a LC inverter is because of the system is working with high voltage in the discharge phase, but during the charge of the capacitors the system is isolated which is essential for the safety and average life of the electrical components.

The aim of the electrical simulation is to obtain phenomenological mathematical model using P-spice to understand the behaviour of the system and to check the condition of functionality optimizing the emission of x-rays. Orcad Pspice is a full-featured, native analog and mixed-signal circuit simulator [2].

2. Experimental Apparatus

The x-rays of the higher energy region (about 25 keV) is produced for bremsstrahlung effect. The relative configuration of the interaction chamber is shown in figure 1. The main feature is



to apply the High voltage (30–50 kV) from the target, on which the laser is focalized, (cathode) to the anode (such as metallic materials Mo or W) where x-rays are produced [1].

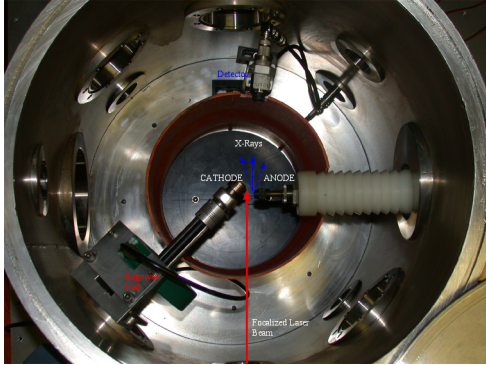


Figure 1. Interaction chamber (inside)

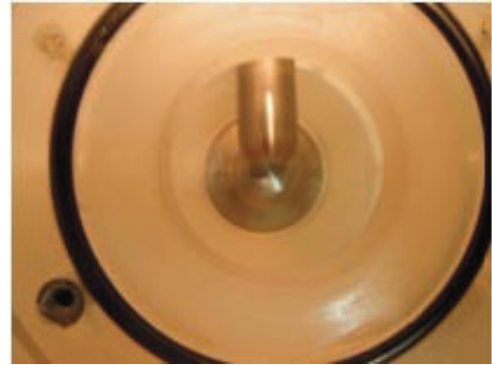


Figure 2. Spark Gap

The mechanism of x-rays production is based on the generation of a plasma obtained by focusing a laser beam NdYag (5J per pulse, duration 6 ns, 0.3 mrad divergence, 536 nm wavelength) on a target metal.

The apparatus for the High Energy X-rays generation is composed of interaction chamber in the vacuum (10^{-6} mbar) and two main circuits systems: a power supply that provides a maximum voltage of 40 kV and an LC-inverter circuit. From figure 1, Rogowsky loop is used to measure the intensity of the electronic current.

3. High Voltage System

High Voltage System is composed of following sub-circuits:

- High Voltage Power Supply
- Trigger circuit for Spark-Gap
- Trigger circuit for Thyatron
- LC Inverter

A customize high power supply is applied to spark gap for generating a discharge to produces x-rays. The Maximum voltage is around 40 kV. Spark Gap is a high power three-terminal switch which is used to be activated the discharge, shown in figure 2. It is composed of 3 poles: two poles are connected to the power supply and the central pole is connected to the output of the trigger circuit for spark gap.

A trigger circuit for Spark Gap (Figure 3) consists in a LC inverter and a Thyatron, which is used as high electrical power switch. The trigger circuit for Thyatron is shown in figure 4 and is used to generate the peak voltage sent to the Thyatron (Figure 5). The control signal of the Silicon Controlled Rectifier (SCR) (see figure 4) is obtained with a customize circuit as shown in figure 7. Moreover, a LC inverter (Figure 6) is used to activate the discharge by charging a couple of capacitors of $1.5 \mu\text{F}$.

The P-spice models consist in the design of the circuits with the following considerations:

- Spark Gap and Thyatron are simulated as a switch.
- Periodic Pulse Voltage is used to simulate the command of activation of the discharge.
- Standard P-spice models of passive and active components are used.

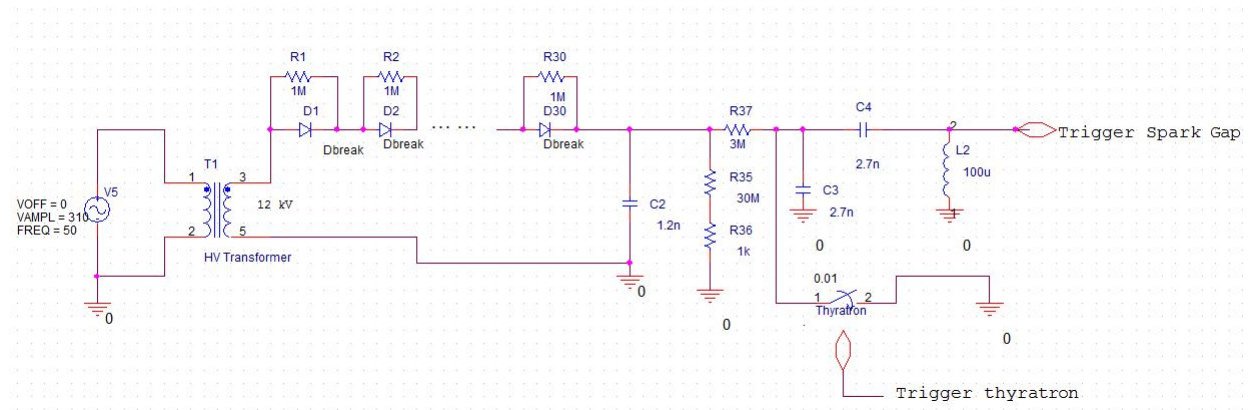


Figure 3. Trigger circuit for Spark Gap (Model)

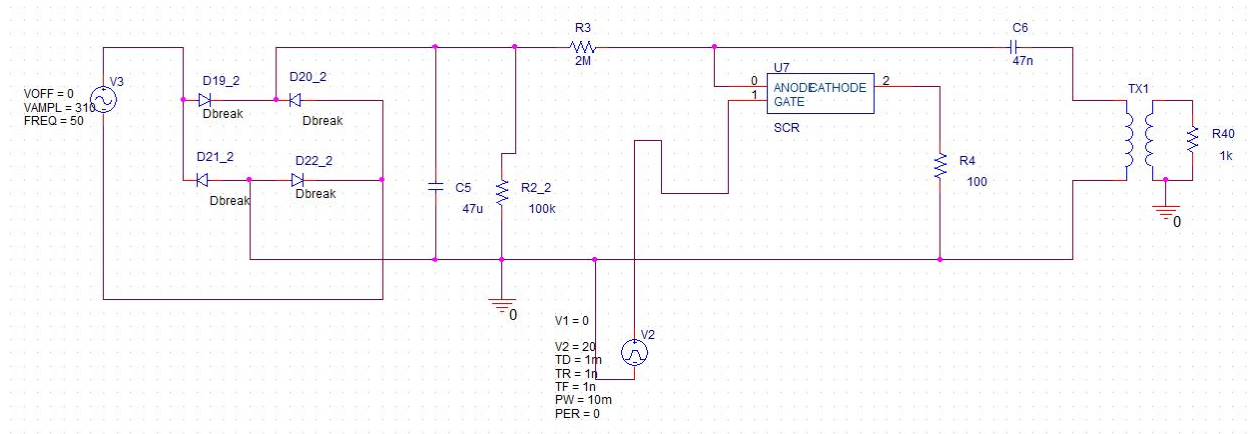


Figure 4. Trigger Circuit for Thyatron (Model)

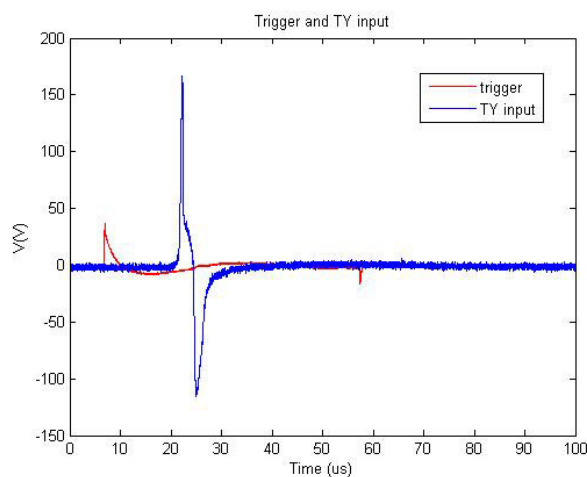


Figure 5. Output of trigger circuit for thyatron (blue line). In red line the control signal of SCR (Silicon Controlled Rectifier)

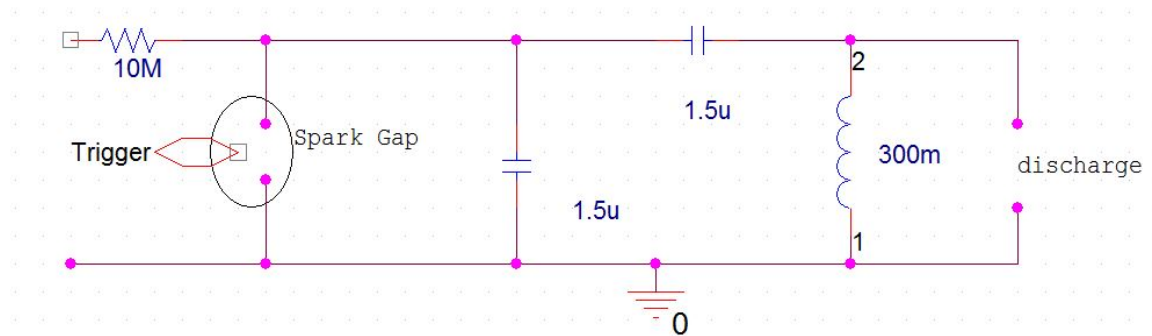


Figure 6. LC-inverter

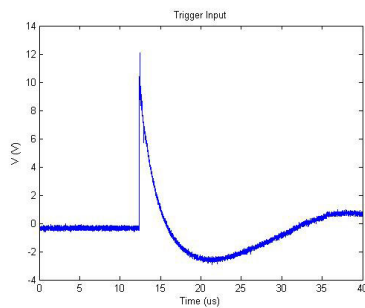


Figure 7. Control signal of SCR (Silicon Controlled Rectifier)

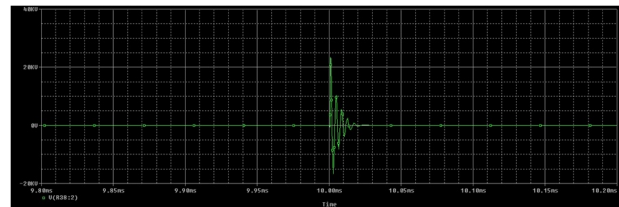


Figure 8. Output of trigger circuit for spark gap (Model)

From the p-spice analysis we can observe a signal with the maximum value around 20kV in the output of the trigger circuit for spark gap (Figure 8): if this value is higher, it could damage the system, in oppositely, the discharge can't be activated. It's important that the intensity in the output of the trigger circuit for spark gap is about 20 kV.

The LC-Inverter (Figure 6) is the most important circuit in the high voltage system to control the intensity of x-rays. In figure 9 the schematic representation of the p-spice model.

In figure 11 a typical voltage signal in output of LC inverter from P-spice simulation is shown. According to the experimental measurements (Figure 10), we obtained a similar signal with different damping due to the approximation of the model but with the same maximum value. All high voltage system is immersed in transformer oil (Figure 12) to isolate from the environment.

4. Preliminary results

From the results of p-spice model, we have tested the system by analyzing the emission of x-rays for iron target measured by photodetector from Quantrad system (diameter of 7.5 mm, absorption layer of 125 μm and dead layer of 0.3 μm). On the entrance window of photodetector, there is an aluminum foils of 12.8 μm thickness. The distance between photodetector and cathode is 10.5 cm. Transmission Profile of aluminum is shown in figure 13 where is visualized one energy peak at 1.5 keV with transmission from around 20% and reach to 100% for x-rays energies which is greater than 5 keV.

15 kV of power supply is applied in two poles of spark gap (which is the input of the circuit of figure 9); in according to the high voltage system the discharge voltage is around 25 kV. System Energy is estimated to be around 240 J. Inside the interaction chamber, we exposed films by

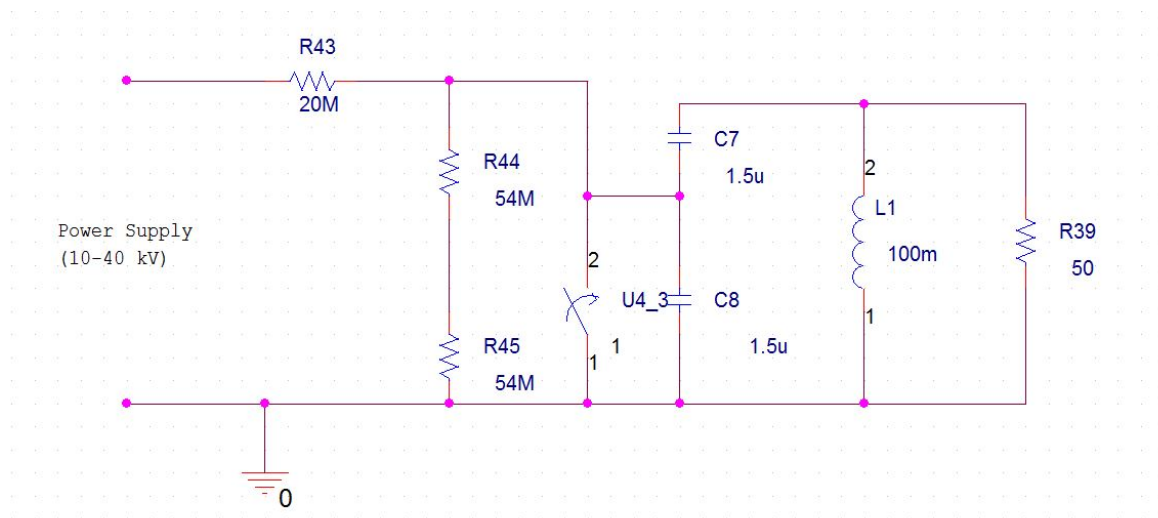


Figure 9. LC inverter - P-spice model

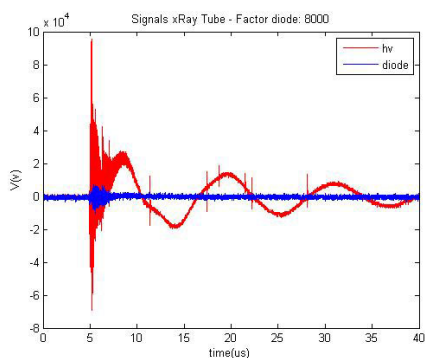


Figure 10. In red line output voltage of LC Inverter signal (Experimental)

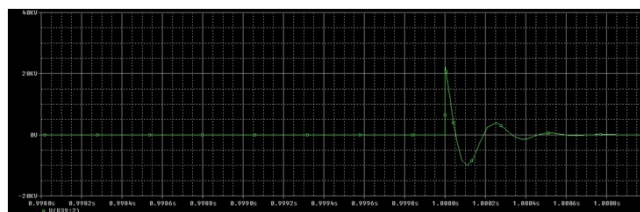


Figure 11. Output voltage of LC Inverter signal (Model)

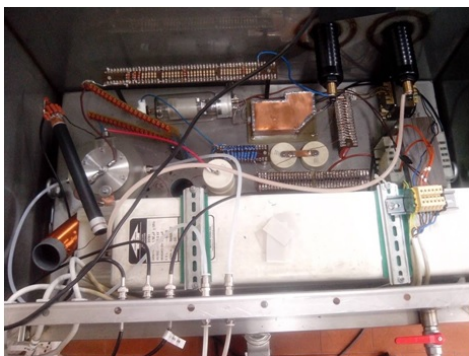


Figure 12. High Voltage system

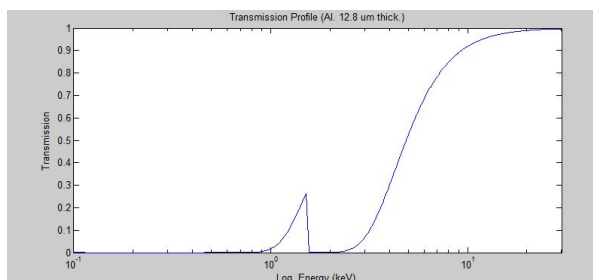


Figure 13. Profile Transmission of Aluminum (Thickness of 12.8 μm) [3]

Kodak (Film Dentaire ultra speed), to capture the samples of x-ray images (iron cross): one with aluminum foil of 12.8 μm thickness and another without aluminum foils. The x-ray images of iron cross are shown in Figure 14 where is noted a better image in the film with aluminum

foil; in fact, in the film without filter, it has a blurring due to all x-rays energies components (around keV and greater than 5 keV). Since x-ray image is formed with all energies components that have a different absorption coefficient, the image of the film is not well defined. While in the film filtered is selected by a spectra where K_α and K_β energies emission of iron are more intense.

In figure 15 is shown the signal of the photodiode and current intensity. The charge is measured around 0.07 nC.

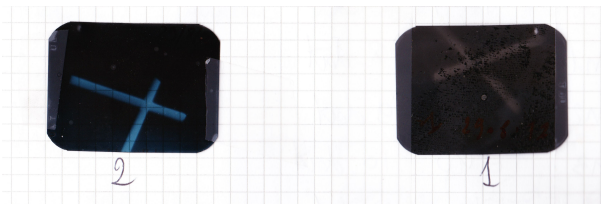


Figure 14. X-ray images captured using Films Dentaire by Kodak. Film without aluminum (1), Film with Aluminum (2).

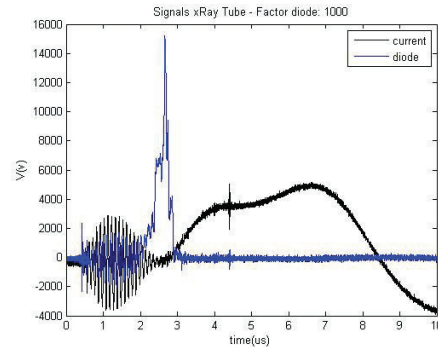


Figure 15. Output of photodiode (blue line) and current intensity (black line)

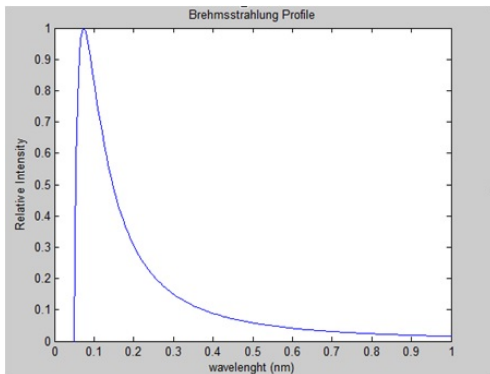


Figure 16. Standard Bremsstrahlung profile,
 $\lambda_{min} \cong \frac{12400}{25kV} = 0.049nm$

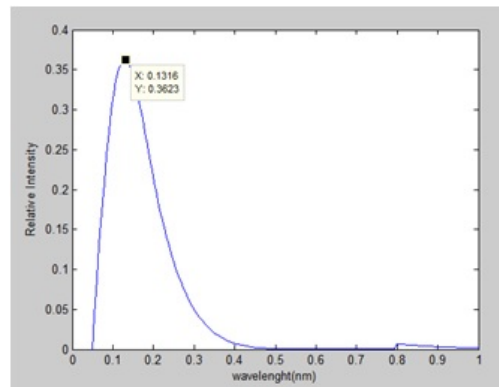


Figure 17. Complete Bremsstrahlung profile

According to the standard bremsstrahlung profile (Figure 16)

$$I \propto Z \left(\frac{1}{\lambda_{min}} - \frac{1}{\lambda} \right) \frac{1}{\lambda^2} \quad (1)$$

and taking into the consideration of the detector quantum efficiency, we have calculated the complete profile (Figure 17).

From these values, we have estimated the number of photons in the input of the photodiode of $\sim 10^8$. Considering the emission of x-rays on a 4π sr solid angle, the total number of x-rays photons emitted is $\sim 10^{12}$ [4].

From these analysis we can see that the number of emitted photons is comparable with present X-ray tubes [5] but with the difference that in our source, x-rays are emitted with a

time of the order of μs (figure 15), to be compared with the time of x-ray tubes traditional ranging from about 0.01 s to 10 s [5].

Another advantage of our High Voltage system is the LC-inverter; it allows to isolate the complete system during the charging phase which is essential for the safety of both people and electronic components.

5. Conclusions

The p-spice model presented is a mathematical tool to evaluate the electrical characteristics of the high voltage system to optimize the emission of x-rays. A possible future configuration will be to use an IGBT (Insulated Gate Bipolar Transistor) instead of Thyatron to compact the system and increase the energy.

The insulated-gate bipolar transistor or IGBT is a three-terminal power semiconductor device primarily used as an electronics switch and in the other devices are well-known used for combining high efficiency and fast switching.

In near future we will improve the synchronization of the system between trigger discharge with pulse laser beam. Moreover, we will examine x-rays emission by changing the distance from anode and cathode and power density of the laser [6].

6. Acknowledgement

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