COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL STUDIES OF A REFLEX TRIODE*

M. Karlssonξ**, F. Olsson, G. Filipsson, E. Edbom and B.O. Bergman**
Bofors Defence
SE – 691 80 KARLSKOGA, Sweden

T. Hurtig, P. Appelgren, M. Elfsberg, A. Larsson, C. Nylander and S.E. Nyholm
Swedish Defence Research Agency (FOI), Weapons and Protection Division
SE – 147 25 TUMBA, Sweden

Abstract

This paper presents a comparison of experimental and simulated results of a reflex triode driven by a compact Marx system. The experimental setup consists of a Marx system and a reflex triode together with a short output waveguide. A parametric study has been performed. The diagnostics used include current and voltage measurements and measurement of the magnetic field component of the microwave pulses using a B-dot probe.

The 3-dimensional particle-in-cell simulation code MAGIC is used to numerically study the system described above. A 1D model of the Marx system has been designed and this is connected to a 3D model of the reflex triode. Also included in this model is the output waveguide and part of the anechoic chamber used in the experiments. The simulated current, voltage and microwave radiation are compared to the experimental results and close qualitative agreements are usually found. Parameters like generated microwave power and microwave energy are also studied and presented in this paper.

I. INTRODUCTION

The objective of this paper is to gain basic understanding of the potential to generate high power microwave radiation from a reflex triode driven by a compact pulsed power system. The first step in this study was to create a feasible experimental setup including relevant diagnostics. The experimental setup consists of a compact Marx system and a reflex triode, both designed at Texas Tech University, USA [1, 2], together with a short output waveguide which ends inside an anechoic chamber. The Marx system consists of 20 stages, which can store 400 J of electrical energy at a nominal voltage of 20 kV per stage. The total length of the system is 1.5 m. The current in the circuit and the voltage over the reflex triode are measured together with the magnetic field component 2.55 m from the output of the waveguide inside the anechoic chamber [3].

A model of the Marx system, reflex triode, waveguide and part of the anechoic chamber is created in MAGIC [4]. From this model it is possible to simulate the current, voltage and magnetic field component in order to compare these simulated results with the experimental ones. If close agreements are found it may be possible to predict such parameters as generated microwave power, microwave energy and electromagnetic fields in the experiments. A future step is to use this model to optimize the geometry of a reflex triode driven by a compact pulsed power supply in order to achieve high energy efficiency.

II. EXPERIMENTAL SETUP AND RESULTS

The reflex triode is built into a eight inch, four way, stainless steel, vacuum cross. The anode has an effective diameter of 120 mm and consists of a woven stainless steel mesh that has been press fitted into a brass torus. The transparency of the anode is around 70 %. The cathode is made of a 90 mm diameter circular brass disk fitted with an emitting surface of velvet cloth or metal spikes. The radius of the emitting surface can be changed simply by fitting a new velvet cloth onto the brass cathode or, alternatively, by changing the number and configuration of metal spikes [3].

In the experiment presented here the emitting surface used was a velvet cloth with a diameter of 60 mm and the spacing between the anode and the cathode was 10 mm. A capacitive voltage divider was used to measure the voltage across the input terminals to the reflex triode and the cathode current was measured using a Pearson coil. Typical current and voltage traces are seen in Fig. 1(a, b). The output port of the reflex triode is fitted to a 400 mm long waveguide that ends inside an anechoic chamber

* Work supported by the Swedish Defence Materiel Administration (FMV) and the Swedish Armed Forces.
ξ email: magnus.u.karlsson@boforsdefence.se

0-7803-9189-6/05/$20.00 ©2005 IEEE.

Report Documentation Page			*Form Approved* *OMB No. 0704-0188*
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.			
1. REPORT DATE **JUN 2005**	2. REPORT TYPE **N/A**		3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Comparison Between Experimental And Numerical Studies Of A Reflex Triode**			5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)			5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Bofors Defence SE 691 80 KARLSKOGA, Sweden**			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**			
13. SUPPLEMENTARY NOTES **See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.**			
14. ABSTRACT **This paper presents a comparison of experimental and simulated results of a reflex triode driven by a compact Marx system. The experimental setup consists of a Marx system and a reflex triode together with a short output waveguide. A parametric study has been performed. The diagnostics used include current and voltage measurements and measurement of the magnetic field component of the microwave pulses using a B-dot probe. The 3-dimensional particle-in-cell simulation code MAGIC is used to numerically study the system described above. A 1D model of the Marx system has been designed and this is connected to a 3D model of the reflex triode. Also included in this model is the output waveguide and part of the anechoic chamber used in the experiments. The simulated current, voltage and microwave radiation are compared to the experimental results and close qualitative agreements are usually found. Parameters like generated microwave power and microwave energy are also studied and presented in this paper.**			
15. SUBJECT TERMS			

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

where measurements of the microwave field was performed using a B-dot probe to obtain the time derivative of the magnetic field component, orthogonal to the electron beam direction. This signal is then integrated to obtain the magnetic intensity as a function of time. The H-field and its spectral content can be seen in Fig. 1(c, d).

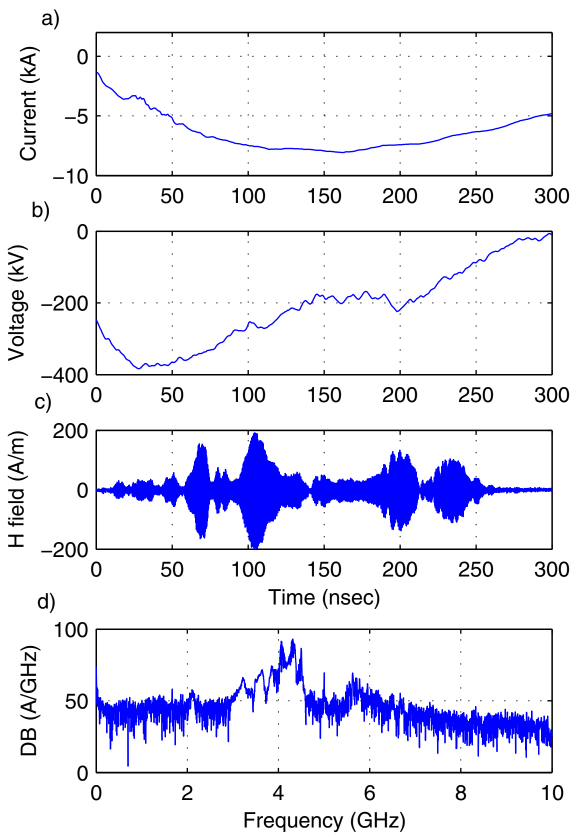

Figure 1. Cathode current (a), applied voltage (b), magnetic intensity (c) and spectrum of the magnetic intensity (d).

III. MAGIC SIMULATIONS

The 3D particle-in-cell simulation code MAGIC [4] is used to numerically study the system described above.

A. The MAGIC Model

One of the main objectives has been to create a fully integrated model which includes all the different sub-systems. For this reason it was necessary to construct a model in MAGIC for the Marx system. This model is based on a transmission line and consists of a charged capacitor in series with an inductor and a resistor. In addition to this a closing switch is connecting this 1D model of the Marx system with the rest of the model.

To validate the model of the Marx system it was connected to a 3D model of an infinite long transmission line with a characteristic impedance of 30 Ω. The capacitor in the Marx was initially charged to -420 kV and the voltage over the capacitor is shown in Fig. 2. This discharge curve is verified with good accuracy using other types of software such as PSpice.

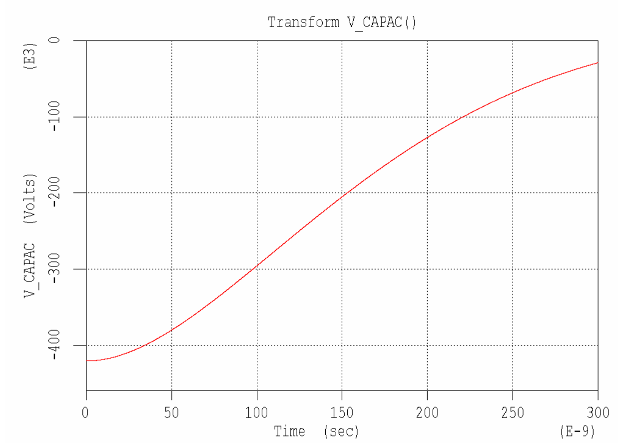

Figure 2. Voltage over the capacitor during a discharge into an infinite long 30 Ω transmission line.

The reflex triode, waveguide and part of the anechoic chamber are fully created in 3D and the basic geometry is shown in Fig. 3.

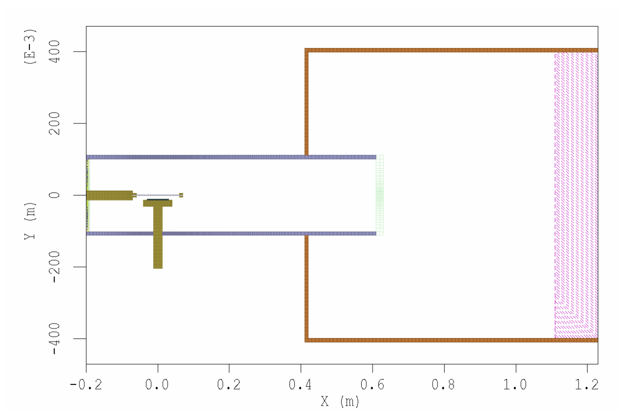

Figure 3. Basic geometry of the reflex triode.

This model is in general created by using most of the default values integrated into the emission and material models. The only exception is the anode grid which has been modeled as a foil.

It was not appropriate due to the required CPU time to include the entire anechoic chamber in the model and therefore the magnetic field was measured only 0.46 m from the end of the waveguide. In order to compare the simulated results to the experimentally measured ones at the distance 2.55 m a transformation was done. It was assumed that both points are in the far field region and under these conditions a simple 1/R-transformation can be done, where R is the distance from the waveguide end.

B. Simulation of the Reference Configuration

A reference configuration is defined by a set of values for the variables. The configuration chosen is:

- The anode-cathode gap is 10 mm.
- The diameter of the velvet emitter is 60 mm.
- The charged voltage is 21 kV per stage.

Fig. 4 and 5 shows the current and voltage over the reflex triode, respectively, for this reference configuration.

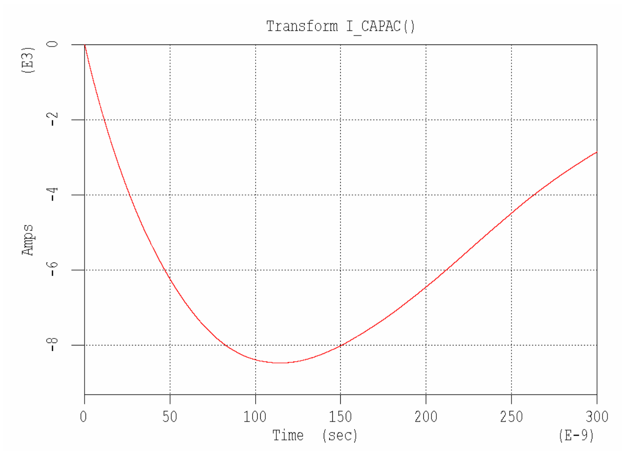

Figure 4. Simulated current.

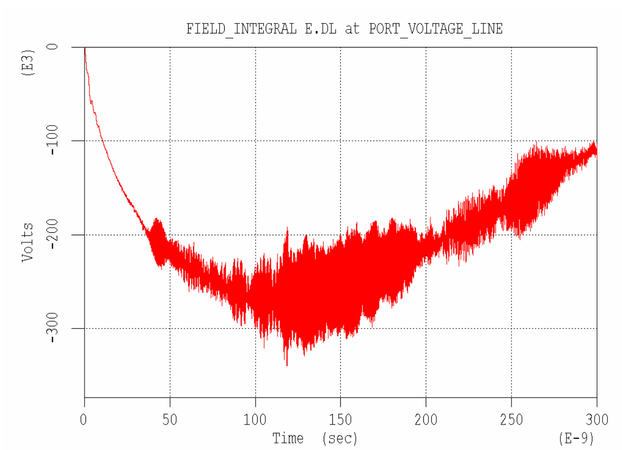

Figure 5. Simulated voltage over the reflex triode.

The peak current is around 8.5 kA and the maximum is reached after around 120 ns. The maximum voltage is around 280 kV and this value coincides in time with the maximum value of the current.

From the current and voltage curves it is possible to estimate the impedance of the reflex triode. This value is around 30-35 Ω during the interval 100-200 ns. The simulated results are in close agreement if compared to the experimental results.

The simulated magnetic field (vertical component) at 2.55 m from the end of the waveguide is shown in Fig. 6.

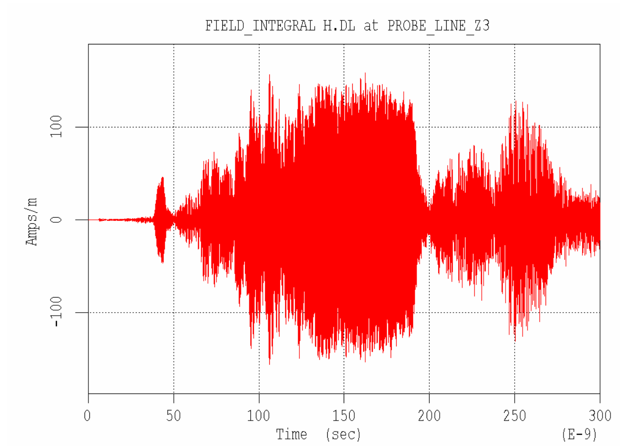

Figure 6. Simulated magnetic field at the position 2.55 m in front of the waveguide.

This curve bears in many parts a close resemblance to the curve measured in the experiments. The field increases slowly for the first 150-200 ns and then it falls abruptly. For the next 100 ns a couple of new field maxima are seen. The spectral content of the magnetic field is shown in Fig. 7.

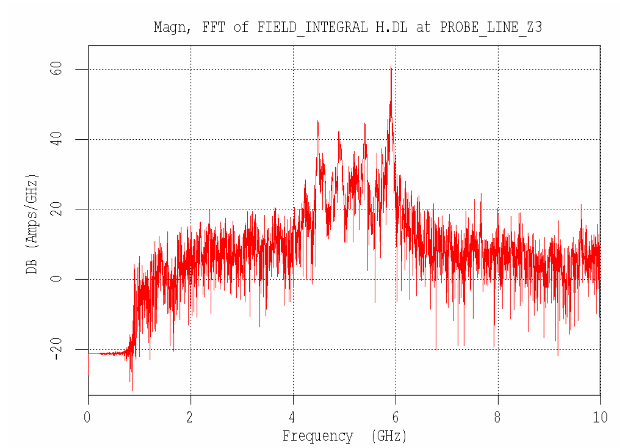

Figure 7. Frequency spectrum of the magnetic field.

Since there are, in general, close agreements between simulated and experimental results, it also seems possible to estimate and predict other parameters, which usually are hard to measure, from the simulated results. As an example the radiated power for the reference configuration is shown in Fig. 8.

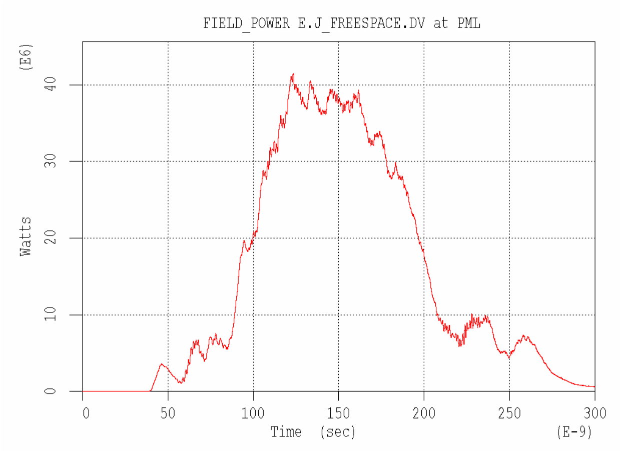

Figure 8. Simulated microwave power output.

The radiated energy during the first 300 ns is 4.2 J, for this case, and this corresponds to an energy efficiency of close to 1 %.

C. *Simulation of Other Cases*

Many different cases have been studied in order to get a basic understanding of the system and how to optimize the radiated power and energy efficiency. In this paper the study is restricted to the anode-cathode gap. Table 1 gives the maximum current, typical frequency and radiated peak power for the cases 10, 12 and 14 mm.

Table 1. Different anode-cathode spacing.

Distance [mm]	Max current [kA]	Freq. [GHz]	Power [MW]
10	8.5	4.9 (5.9)	40
12	7.0	4.5	35
14	5.8	3.9	20

For many of the simulations, as from the measurements, the power is usually distributed at a number of frequencies. For the reference configuration the main frequency is around 5.9 GHz. The distributions between the peaks are however in general rather unstable and dependent on the geometric surroundings inside the reflex triode. In order to compare the peaks between the different anode-cathode distances, and focus on the physics of the electron beam, it is probably the peak around 4.9 GHz (see Fig. 7) that corresponds to the main frequencies for the other two cases in Table 1. According to basic non-relativistic linear theory the frequency of a virtual cathode can be estimated by using

$$f_{osc} \approx \frac{5}{4 \cdot \pi} \cdot \frac{2}{3} \cdot \sqrt{\frac{e \cdot V_{gap}}{m \cdot d^2}} \quad \text{Hz} \qquad (1)$$

where e and m are the electron charge and mass, respectively [5]. V_{gap} is the voltage over the gap between the anode and the cathode and d is the spacing. If the simulated values are put into this equation the following result are obtained.

Table 2. Main frequency for different spacing between the anode and the cathode.

Distance [mm]	Simulated freq. [GHz]	Calculated freq. [GHz]	Measured freq. [GHz]
10	4.9	5.9	4.3
12	4.5	5.1	3.6
14	3.9	4.6	3.2

It is clear that the values for the same spacing are not the same for the three different cases. However the differences seem to be relatively stable and a constant correction term can be used to transfer the different values between the different cases.

IV. SUMMARY

A reflex triode driven by a compact Marx generator has been studied numerically and experimentally. The current, voltage and microwave radiation are compared and close qualitative agreements are generally found. Therefore it also seems possible to estimate and predict other parameters, which for many cases are hard to measure, from the simulated results.

The current compact system seems to be capable of generating tens of megawatt microwave power for more than a hundred nanoseconds. The frequency range is in general between 3 to 5 GHz and the energy efficiency is around 1 %.

V. REFERENCES

[1] M. Kristiansen et al., "Compact High Power Microwave/Vircator Efficiency Enhancement," Ref.#75811-1, Lubbock, USA, 2003.

[2] P. Appelgren, M. Akyuz, M. Elfsberg, A.Larsson and S. E. Nyholm, "Description of a Charger and Marx Generator System Including Initial Experiments and Numerical Simulations" presented at 2nd European Pulsed-Power Symposium, Hamburg, Germany, 2004.

[3] T. Hurtig, C. Nylander, P. Appelgren, M. Elfsberg, A. Larsson and S. E. Nyholm, "Initial results from experiments with a reflex triode powered by a Marx generator" presented at 15th IEEE Int. Pulsed Power Conference, Monterey, USA, 2005.

[4] B. Goplen, L. Ludeking, D. Smithe and G. Warren, "User-configurable MAGIC code for electromagnetic PIC calc.," Comp. Phys. Comm., vol. 87, pp. 54-86, 1995.

[5] V. L. Granatstein and I. Alexeff, High-Power Microwave Sources, Boston: Artech House, 1987, pp. 484-485.