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SIMULATION STUDY OF NANOSECOND PULSE POWER BASED ON GYROMAGNETIC NONLINEAR TRANSMISSION LINE

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Abstract

On-axis injection mode is planned to use in the Southern Advanced Photon Source (SAPS), which requires high quality to injection pulsed power supply. Gyromagnetic nonlinear transmission line (GNLTL) is introduced as a pulse compressor to meet the needs for pulse width. In this paper, 3-D finite element model is established based on Landau-Lifshitz-Gilbert equation and Maxwell's equations. The influence of geometrical sizes and bias magnetic field to output pulse is analysed for better design of NLTL. A prototype was built with nanosecond pulse width and sub-nanosecond rise time to verify the simulation.

INTRODUCTION

The Southern Advanced Photon Source (SAPS) is a projected mid-energy fourth generation synchrotron light source Which is planned to built in Guangdong Province, in China [1]. The transverse on-axis swap-out injection scheme is considered to be applied in SAPS which posed high demands on the kicker and pulsed power [2]. Table 1 shows the preliminary targets for the pulsed power.

Table 1: The Target Parameters for the Pulsed Power

Voltage	Rise time	Fall time	Width
16.3kV	2.55 ns	1.81 ns	4.79 ns

Gyromagnetic nonlinear transmission line (GNLTL) provides a possible option to get such a narrow pulse [3,4]. In this paper, we established a 3-D finite element model for the GNLTL, and build a prototype to explore the pulse sharpening effect of GNLTL.

THEORETICAL GROUNDS

The structure of the GNLTL includes an inner conductor, an outer conductor, insulating medium, ferrite magnet rings and a coil. A two-dimensional structure diagram of the GNLTL is shown in Fig.1.

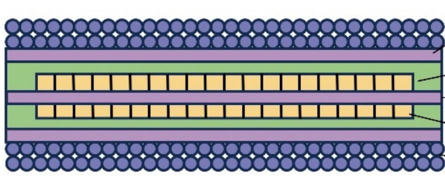

Figure 1: Structure of the GNLTL.

The ability of the GNLTL to compress a pulse is generated from the no-linear characteristic of ferrites which can be explained by the precessional motion of magnetic moment. Landau and Lifshitz firstly proposed the equation to describe this precession which is called Landau-Lifshitz equation [5]:

$$\frac{\partial M}{\partial t} = \gamma\mu_0 M \times H_{eff} + \frac{\alpha\gamma\mu_0}{|M|} \times (M \times H_{eff}) \tag{1}$$

Where M is the magnetic moments of ferrites, γ is the electron gyromagnetic ratio which is close to 2, μ_0 is the permeability of vacuum, H_{eff} is the effective magnetic field, and α is the phenomenological damping factor.

In this article, only the external magnetic field generated by the bias coil and the input pulse are considered, so H_{eff} can be expressed as:

$$H_{eff} = H_0 + H_p \tag{2}$$

Where H_0 is the magnetic field caused by the bias coil and H_p is the magnetic field caused by the input pulse.

The first term on the right side of Eq. (1) describes the precession of the magnetic moment and the second term represents the damping. To accommodate a larger damping coefficient, Gilbert modified the damping term as [6]:

$$R = \frac{\alpha}{M_s}\left[M \times \frac{\partial M}{\partial t}\right] \tag{3}$$

Where *R* represents the damping term, and M_s is the saturation magnetization. The equation with Gilbert damping term is called Landau-Lifshitz-Gilbert (LLG) equation.

It is difficult to get the analytical solution of LLG equation in three dimensions. However, in COMSOL Multiphysics, the numerical solution can be computed by finite element method (FEM).

The input pulse propagates through the transmission line in the TEM mode. This process can be solved by the Time-Dependent Transient Electromagnetic (TEMW) physics interface in COMSOL according to the Maxell equation [7]:

$$\nabla \times \frac{(\nabla \times A)}{\mu_r} + \mu_0\sigma\frac{\partial A}{\partial t} + \mu_0\frac{\partial}{\partial t}(\varepsilon_r\varepsilon_0\frac{\partial A}{\partial t}) = 0 \tag{4}$$

Where *A* is the magnetic vector potential, μ_r is the relative permeability, ε_r and ε_0 is the relative permittivity and permittivity of vacuum, and σ is the electrical conductivity.

Combining the above equations, the numerical solutions of the electromagnetic field in the GNLTL can be solved

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and the output voltage can be computed by integral of electric field on the output port.

MODELING AND VALIDATION

A 3-D FEM model of the GNLTL is established in COMSOL Multiphysics. The inner and outer conductor are made up of aluminium alloy. Transformer oil is chosen as the insulating medium. The ferrite is selected to be made of NiZn for its good high-frequency characteristics. The total length of the GNLTL is 500 mm, and the ferrite is 470 mm long. The external diameters of the inner conductor, ferrite and insulation are 7 mm, 13 mm and 14 mm, respectively.

A prototype of the GNLTL with the same material and parameters is designed and tested to verify the model. The ferrite in the prototype consists of 94 NiZn magnet rings with the size of 13×7×5 mm. The bias coil is wound with 1470 turns of copper wire. A nanosecond high voltage pulser based on magnetic switch and semiconductor opening switch has been developed as the input power of the GNLTL [8]. Fig.2 shows the overview of the experiment system.

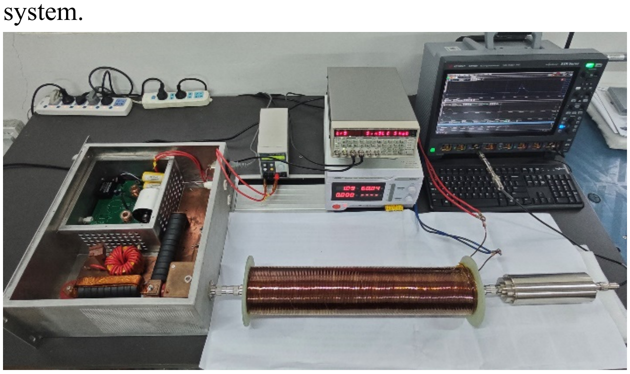

Figure 2: Overview of the experiment system.

The input pulse, simulation output and experiment output are shown in Fig. 3.

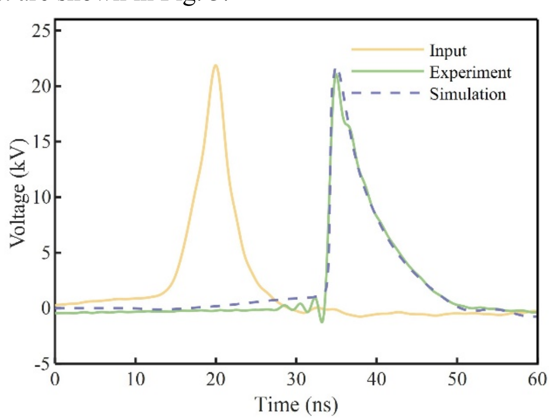

Figure 3: Waveform of input, experiment output and simulation output.

Compared to the experiment, the left bottom of the simulation output is smoother which is more similar to the input pulse, and the simulation result shows a little higher peak voltage than the experiment one. Both of the simulation and experiment shows an excellent sharpening effect on the rising edge. The rise time of the input pulse is compressed from 4.8 ns to 0.9 ns after passing the GNLTL. While it should be noted that the falling edge is extended from 4.7 ns to 10.7 ns.

ANALYSIS OF THE SHARPENING EFFECT OF THE GNLTL

Based on the model established in Sec. III, the outputs at different length of the GNLTL and different bias magnetic field are simulated to analyse their influence to the output waveform.

Influence of the GNLTL length

When the bias magnetic field is set to keep in 20 kA/m, the simulation outputs of different GNLTL length from 200 mm to 1000 mm is shown in Fig.4.

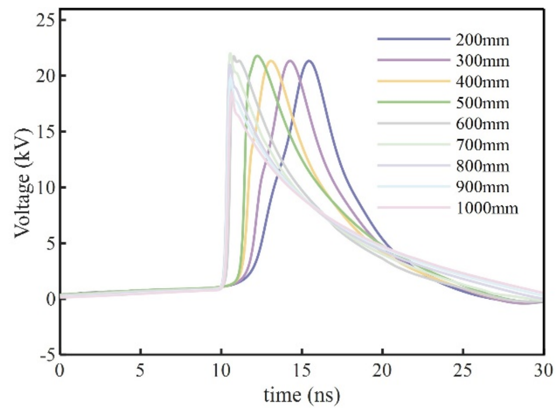

Figure 4: The simulation output waveform at different GNLTL length.

As the figure shows, when the length is too short, the GNLTL nearly has no effect to the input pulse. With the increase of the length, the rise time of the pulse decreases gradually, but when the length reaches to 600 mm, the rise time has no significant decreases with the length keeping increasing. Moreover, when the length reaches to 1000 mm, the peak voltage decreases to 18 kV. An excessively long GNLTL not only does not help with faster pulse sharpening, but also leads to a decrease in amplitude.

Influence of the bias magnetic field

At the length of 500 mm, the simulation outputs at different bias magnetic field from 20 to 100 kA/m is shown in Fig.5.

When then bias magnetic field is 20 kA/m, The GNLTL shows obvious sharpening effect on the rising edge. With the bias magnetic field increases, the rising edge becomes slower and the falling edges becomes faster. When reaching to 100 kA/m, the output waveform is nearly similar to the input pulse which means the GNLTL has no effect to the pulse edge at high bias magnetic field. It can be explained by the precession of magnetic moment of the ferrite. When the bias magnetic field is much larger than the magnetic field generated by the input pulse, the total external magnetic field is similar to the bias magnetic field, and the orientation of the magnetic moment will be hardly changed by the input pulse. The GNLTL is more like to an ordinary transmission line which will not change the waveform.

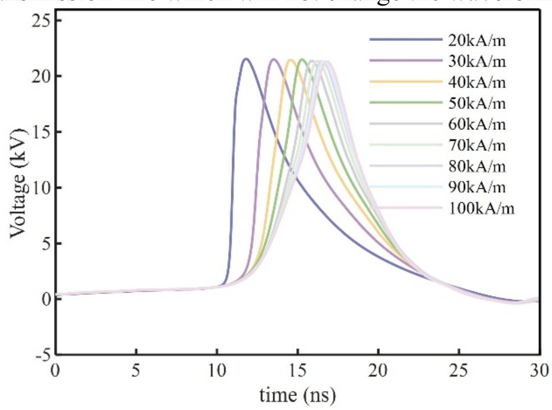

Figure 5: The simulation output waveform at different bias magnetic field.

CONCLUSION

In this paper, finite element method is employed to establish a 3D model of the GNLTL, and a prototype is designed and tested to validate this model. The influence of the GNLTL length and the bias magnetic field to the output waveform are analysed. Both the simulation and experiment show the GNLTL has obvious sharpening effect to the rising edge, and the rise time can be compressed to less than 1 ns. The rise time and peak voltage has been satisfied with the requirement parameters of the injection kicker in SAPS, but the falling edge extends with the compression of the rising edge. The falling edge cannot be compressed solely through the GNLTL. We will maintain our focus on the sharpening of the falling edge in our next stage of research.

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