SAND2014-XXXXR
LDRD PROJECT NUMBER: 173659
LDRD PROJECT TITLE: Ferrite Solutions for Electromagnetic Shock Lines
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ABSTRACT:

The goal of this work is to develop tools and test procedures for identifying ferrites suitable for use in shock line applications.

Electromagnetic shocklines have been used to provide fast rising voltage pulses for many applications. In these applications a slow rising pulse is injected into the line where currents drive the ferrites into saturation leading to a fast rising output pulse.

A shockline's unique capabilities could be applied to new detonator configurations. A properly conditioned voltage pulse is critical for fire set applications. A carefully designed shockline could provide a passive solution to generating a fast rising voltage pulse for the fire set.

Traditional circuits use ferrites operating in a linear regime. Shock lines push the ferrites well into the nonlinear regime where very few tools and data currently exist. Ferrite material is key to the operation of these shock lines, and tools for identifying suitable ferrites are critical.

This report describes an experimental setup to that allows testing of ferrite samples and comparison to models with the goal of identifying optimal ferrites for shockline use.

INTRODUCTION:

One of the simplest shockline configurations is that of a ferrite loaded coaxial transmission line. Most of the volume between the center and outer conductors is filled with ferrite material. A high amplitude pulse is injected into one end of the line. As the pulse propagates into the line, the ferrite material is driven into saturation (hence nonlinear) by the pulse's high azimuthal magnetic field. The velocity of propagation is hence a function of amplitude since the material's relative permeability is being driven to 1. Since the low amplitude rising portion of the pulse sees an effective permeability that is higher than the later high amplitude portion, the wavefront steepens and forms the electromagnetic shock front.

Shockwave Propagation
The normalized shock velocity can be expressed as [1]:

$$v_s = \frac{1}{\sqrt{1+\frac{I_m}{I_s}}}$$

where

$$I_m = (1 - m_0) \cdot 4\pi \cdot \eta \cdot \frac{M}{p}$$

In this case the velocity is normalized by the maximum velocity achievable on the saturated line. I_s is the shock current, M is the saturation magnetization, m_0 is the initial relative ferrite magnetization, η is the ferrite filling factor , and p = H/I is the geometric factor relating the magnetic field, H, to the current, I. Note that the shock velocity is a function of both the drive level (V_s, I_s) and the initial magnetization (m_0).

An effective shock permeability [2] can be defined as:

$$\mu_s = \frac{1}{v_s^2}$$

This results in some simple relationships between the shock voltage and current (i.e., the magnitudes of the voltage and current discontinuities at the shock front) and the shock velocity and shock impedance:

$$Z_s = \frac{V_s}{I_s} = \sqrt{\mu_s} * Z_0 = \frac{Z_0}{v_s}$$

where Z_0 is the characteristic impedance of the saturated line.

Model

The nonlinear line is modeled as a simple L-C ladder network. In this case, the inductors are ferrite loaded and the nonlinearity results from current driven magnetic fields effecting the ferrite's magnetization and hence the inductance of the circuit.

Kirchoff's equations are coupled with a reduced form of the Landau-Lifshitz-Gilbert (LLG) equation [3] which models the nonlinear magnetization in the line as follows [4] :

$$KCL: \quad i_n = \frac{du_n}{d\tau} + i_{n+1}$$

$$KVL: \quad u_{n-1} = u_n + \frac{d}{d\tau} i_n + \eta \frac{d}{d\tau} m_n$$

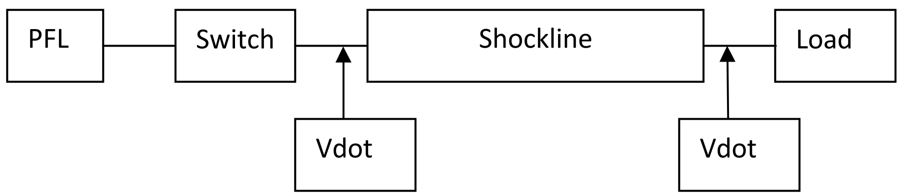
$$LLG: \quad \frac{d}{d\tau} m_n = q(1 - m_n^2) i_n$$

Where: L_0 and C_0 are the basic ladder line elements, $i_n = I_n / I_*$, $v_n = V_n / V_*$, $m_n = M_n / M$, M is the ferrite magnetization, $I_* = M/p$, $V_* = I_* * Z_0$, $q = (\alpha \gamma_0 M \tau_0)(1 + \alpha^2)$, η is the filling factor of the inductor by the ferrite, α is the ferrite dissipation coefficient, $\tau_0 = \sqrt{L_0 C_0}$, L_0 and C_0 are the basic ladder line elements, and $\gamma_0 = 1.76x10^7 \ Oe^{-1} s^{-1}$ is the gyromagnetic ratio of the electron.

Each LC unit cell yields equations relating voltage, current and magnetization resulting in approximately 3N coupled 1st order ordinary differential equations to solve. MATLAB's Runge-Kutta routine was used to solve the set of equations.

EXPERIMENTAL SETUP:

A block diagram of experimental setup is shown below:



The shockline is driven by a simple coaxial pulse forming line (PFL). The PFL is initially charged and then switched into the line. The pulse propagates thru the line and is absorbed in the load. In this case the load consists of a "get lost" cable that is long enough to time isolate any reflections from an imperfect termination of the cable. The performance of the shockline is monitored by Vdot's located at the input and output of the line.

The shockline constructed as a ferrite loaded coaxial transmission line (see figure below).

It consists of:

Outer conductor:	brass tubing - 36" x 0.25"OD x 0.184"ID x 0.032" wall
Inner conductor:	14AWG magnet wire, 0.068"OD
Ferrite beads:	MetaMagnetics MX8, 0.500"L x 0.132"OD x 0.072"ID
Insulation:	2 layers of 4mil Kapton tape

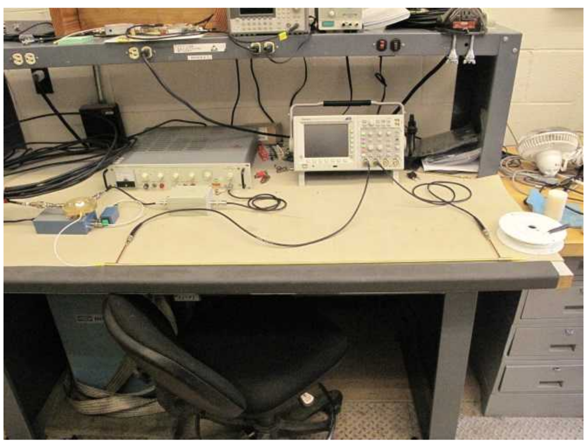
The ferrites were purchased from MetaMagnetics and have the properties summarized below.

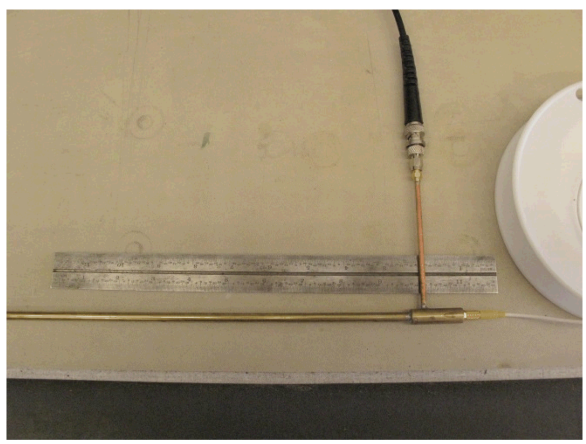
$4\pi M_S$ (Gauss)	3300
ε_r	14
$\tan \delta_\varepsilon \times 10^{-4}$	<10
ΔH (Oe)	120
μ_i	2100

Other test bed components include:

Teledyne Reynolds high voltage connections (600 series)
PFL - 50 ft of ¼ Heliax cable
PFL charging supply: 0-3 kV
Switch - 15 kV Gigavac relay
Get loss line - 90 ft of Teledyne Reynolds Type L coax terminated in 50 ohms
Scope - Tektronix TDS3054C (5 GSample/sec, 500 MHz)
Data acquisition software - Voss Scientific DAAAC

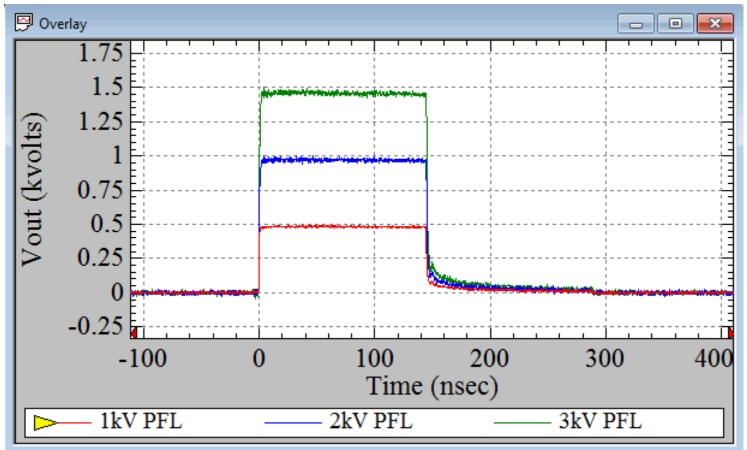
The photographs below show the table top testbed and a close-up of the Vdot arrangement at the output end of the shockline.





RESULTS AND DISCUSSION:

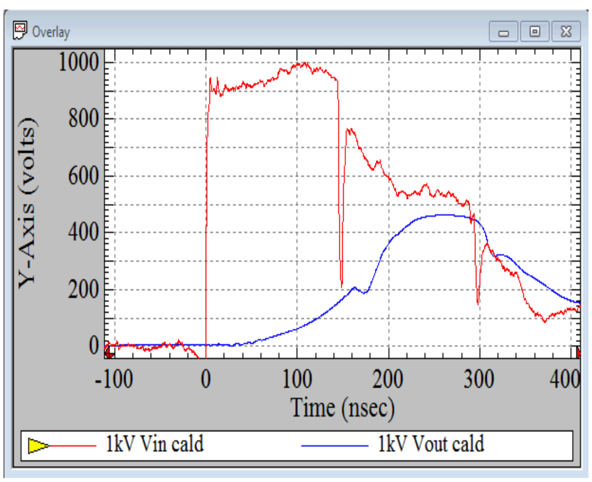
The shockline was exercised at three different drive levels and compared with the model. The figure below shows the output of the PFL into a matched 50 ohm termination.

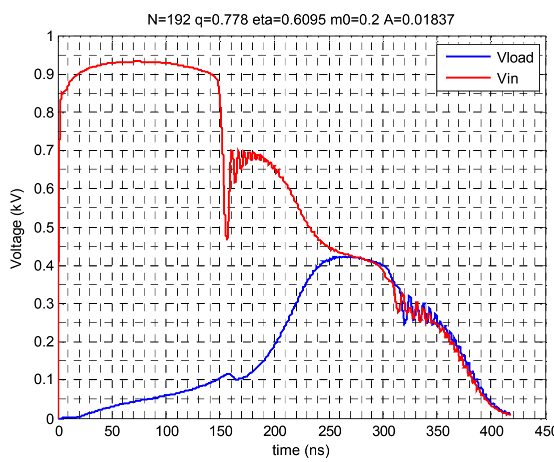


As expected, the voltage delivered to a matched load is just half of the charge voltage (e.g. for the blue 2kV charge case, approximately 1 kV is delivered to the matched load). The duration of the pulse is 145 ns which is set by the length of the PFL.

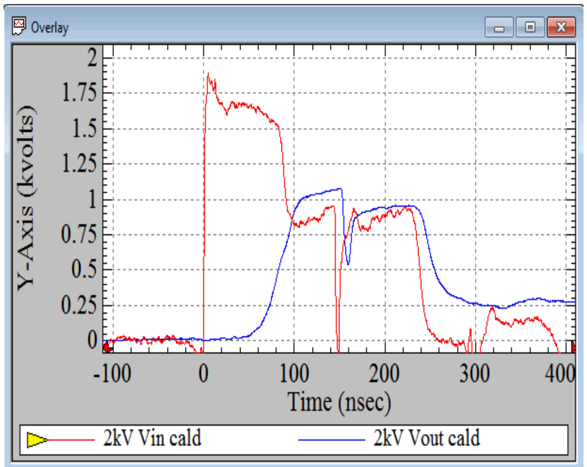
The following figures compare the measured performance of the line with that predicted by the model. The figures on the left are numerically integrated signals from the input and output Vdots. On the right is shown waveforms predicted by the model.

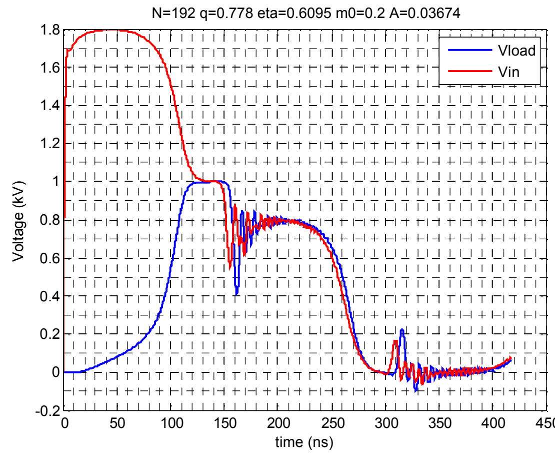
1kV PFL charge:



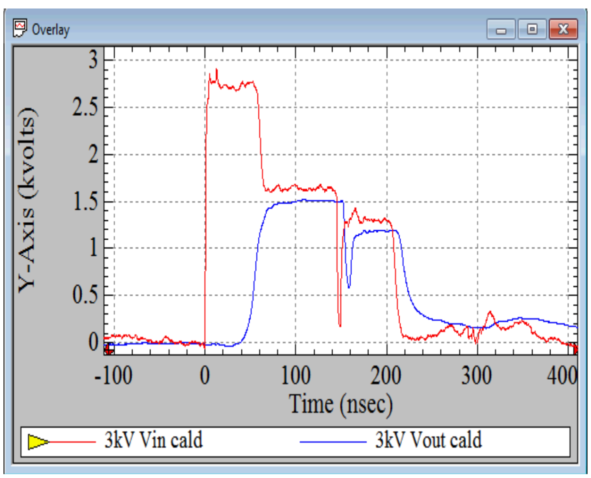


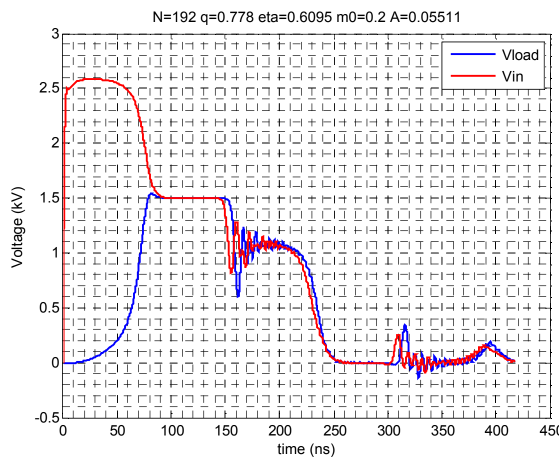
2kV PFL charge:





3kV PFL charge:





One of the first observations is that the waveforms are far from the simple square pulses that would be seen into a matched load. The shockline does not present a matched impedance to the PFL and hence reflections are set up. In the same sense, the wave exiting the PFL is not matched to the 50 ohm get “loss line”, again resulting in reflections. These various mismatches result in relatively complex waveforms.

An added intricacy of the nonlinear line is that the shock parameters are a function of drive level. As can be seen above, the waveshapes vary as the drive level increases. The shock impedance drops as the drive increases resulting in different reflection magnitudes. Also, an expected result can be seen in the propagation delay through the shockline. As the drive level increases the delay drops from ≈ 200ns to 70 ns.

The model successfully captures many of the shockline propagation characteristics (delay, voltage magnitudes, etc.). However, the predicted risetimes are slower than that observed. The model's accuracy could be improved by incorporating a more sophisticated form of the LLG equation which models the ferrites magnetization dynamics. Dolan [5] has used a 3D version of the equation to better model fast rising pulses in ferrite media. This code refinement would also allow for modeling effects of applying a dc magnetic bias to the ferrite which has been shown to decrease risetimes.

ANTICIPATED IMPACT:

Shocklines are potentially useful for pulse conditioning in connection with fire set applications. Another application is in generation of high power microwaves (HPM). Over the duration of this LDRD, there has been active interaction between org 5443 personnel with AFRL's (Air Force Research Laboratory) HPM group on our common interest in shocklines. This has led to AFRL funding SNL (at a $70k level) for an initial quick look at advanced shockline concepts that may be of benefit to both organizations.

CONCLUSION:

A test bed has been constructed that allows characterization of ferrite based shocklines. A circuit model that includes basic ferrite nonlinearity physics has been used to compare with experimental data. Having a model allows quick exploration of different parameters to identify optimal shockline designs. Comparisons between measurements and model predictions show good but not excellent agreement. Refinement of the how the ferrite magnetization dynamics is incorporated into the model should be pursued as a method of improving agreement. Future experimental efforts should include increased drive voltages to generate faster shocks. Also, the facilities are now in place to allow for quick relative characterization of various ferrite samples. This testbed and modeling capability should enable rapid development of future shockline designs.

REFERENCES:

1. M. Belyantsev, A. I. Dubnev, S. L. Klimin, Yu. A. Kobelev, and L. A. Ostrovskii, "Generation of radio pulses by an electromagnetic shock wave in a ferrite-loaded transmission line", Tech. Phys., vol. 40 (8), pp. 820-826, 1995.
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4. A. M. Belyantsev and A. B. Kozyrev, "Influence of local dispersion on transient processes accompanying the generation of rf radiation by an electromagnetic shock wave", Tech. Phys., vol. 43 (1), pp. 80-85, 1998.
5. J. E. Dolan, "Simulation of shock waves in ferrite-loaded coaxial transmission lines with axial bias", J. Phys. D: Appl. Phys., 32, pp1826-1831, 1999.