ILLINOIS INSTITUTE
OF TECHNOLOGY
Transforming Lives.Inventing the Future.

Adenrele Fapohunda
Engineering Department
Electrical Engineering
Illinois Institute of Tech
10 W. 33rd Street
Chicago, IL 60616

Supervisor:
David Wildman,
Accelerator Physics Center
Fermi National Accelerator Laboratory
Batavia, IL 60510-0500

August 10, 2007

Table of Contents

ABSTRACT:

This summer, I aim to test 20, 75kW peak power quad hybrids and 3, 400kW quad hybrids using a 8753E, 30 KHz - 6GHz Agilent Network Analyzer. I will also be attempting to make a combiner, which is needed to combine 2 individual 1200V voltages in series to make a 2400V output voltage. This will be useful in driving the meanders present in the chopper. In order to ensure that the voltage in the combiner is maximized, keeping in mind the losses in the cable, I will carry out some differential calculations incorporating the voltage and current laws.

I will also attempt to make some calculations for the fast phase shifter (FFS), such that we can achieve optimal uniformity in the field of the solenoid wound on the garnet ferrite of the FFS.

INTRODUCTION

The High Intensity Neutrino Source (HINS)

The aim of the High Intensity Neutrino Source (HINS) program at Fermilab is to develop a multi-mission linear accelerator (Linac), which is capable of accelerating H^- ions to 8 GeV while providing 2 MW at 30-120 GeV from the Main Injector and 0.5-2 MW at 8 GeV from the Linac. This effort is in primary support of the neutrino physics program here at Fermi National Accelerator Laboratory (FNAL).

The base design through 110 MeV requires multiple room temperature and super-conducting cavities to be driven by a single 325 MHz klystron. Usually, a single klystron is used to drive each cavity. As a first step in the HINS R&D program, Fermilab aims to construct the front end of the Linac, which will accelerate a beam to 60 MeV. The Linac's front end will be comprised of an H^- ion source; capable of a 1% duty factor (df), with a magnetic LEBT (low energy beam transport) followed by a commercial radio frequency quadrupole (RFQ) cavity.

Fermilab HINS brought about an increase in the need for accelerator based H^- ion sources to operate reliably with long pulse lengths and high duty factors. It is necessary to actively cool the ion source such that high operating temperatures and thermal stress linked with elevated duty factors can be avoided [1].

DESCRITPION OF THE VECTOR MODULATOR

The function of an **IQ Vector Modulator** is to simultaneously control the phase and amplitude of a microwave signal. This **Vector Modulator** device will convert a signal to a desired vector location.

The vector modulator, I worked with consisted of a quad hybrid with 2 phase shifters connected to ports 2 and 3 of the quadrature hybrids (QH).

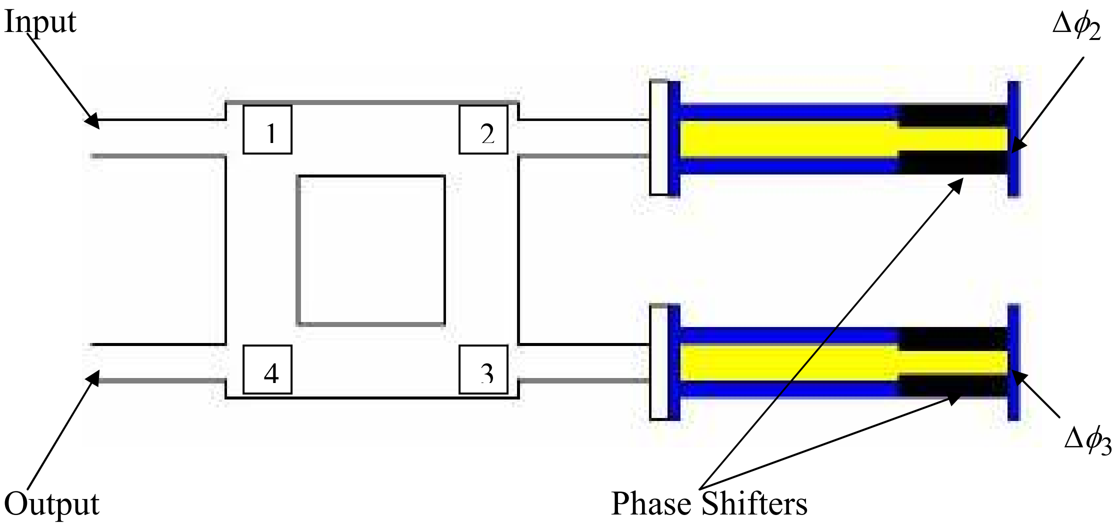


Fig. 1 The vector modulator

With $\Delta\phi = \dfrac{\Delta\phi_2 - \Delta\phi_3}{2}$

$$\phi = \frac{\Delta\phi_2 + \Delta\phi_3}{2}$$

Output power $\approx \cos^2(\Delta\phi)$

Phase Shift $\approx \phi + {}^{3\pi}\!/_{2}$

THE QUADRATURE HYBRIDS

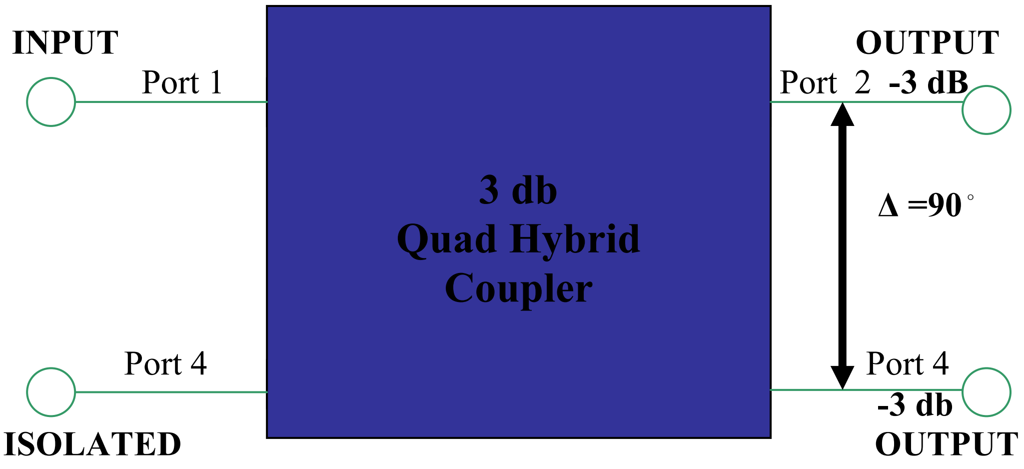


Fig. 2 Functional Block Diagram of the Quadrature Hybrid

The 90° Power Dividers/Combiners are four port networks capable of operating from 10 kHz to 40 GHz and available in a wide variety of package options. The Quad Hybrids I worked with this summer operated at 325MHz. The device can perform two complementary functions:

a) **Power Divider:** One function is to equally divide an input signal into two output signals while imparting to one of the outputs a 90° phase shift with respect to the phase of the other output. The outputs thus exhibit a quadrature relationship - their respective phases differ by one ‘‘quadrant’’ or simply 90°.

b) **Combiner:** The complementary function of the combiner is to combine two equal-amplitude, quadrature-phased input signals into a single output signal.

The quadrature hybrids also called quad hybrids are also known as 90° Power Dividers/Combiners, are reciprocal four port networks. Figure 2, above is a functional block diagram of a 3 dB quad hybrid coupler.

A signal applied to port 1 splits equally between ports 2 and 3 with one of the outputs exhibiting a relative 90° phase shift. Proper termination of ports 2 and 3 to matching 50Ω impedances leads to nearly all the signal in port 1 being transmitted to the loads connected to ports 2 and 3. , port 4 receives negligible power and is termed ‘‘isolated’’. However, if there is an impedance mismatch at port 2, then signal power reflected back from port 2 will be divided proportionally between ports 1 and 4. Power is not fed to port 3 [2].

Fig. 3 the Dielectric Quadrature Hybrid with connectors

TESTING THE QUADRATURE HYBRIDS

This summer, I successfully tested and measured 2 distinct types of quadrature hybrids.

(a) (20)75KW peak, 1KW average power and

(b) (3) 400KW peak, 5KW average power quad hybrids

The purpose of this test was to verify that the power split of the hybrids was -3db and that the phase difference between ports 2 and 3 was approximately 90°. In testing and measuring the quad hybrids, the following steps had to first be observed:

1) Calibrating the connecting adapters on port 1 and port 2,
2) Setting up the Network Analyzer for taking measurements and testing the hybrids,
3) Obtaining readings from the NA and analyzing the data.

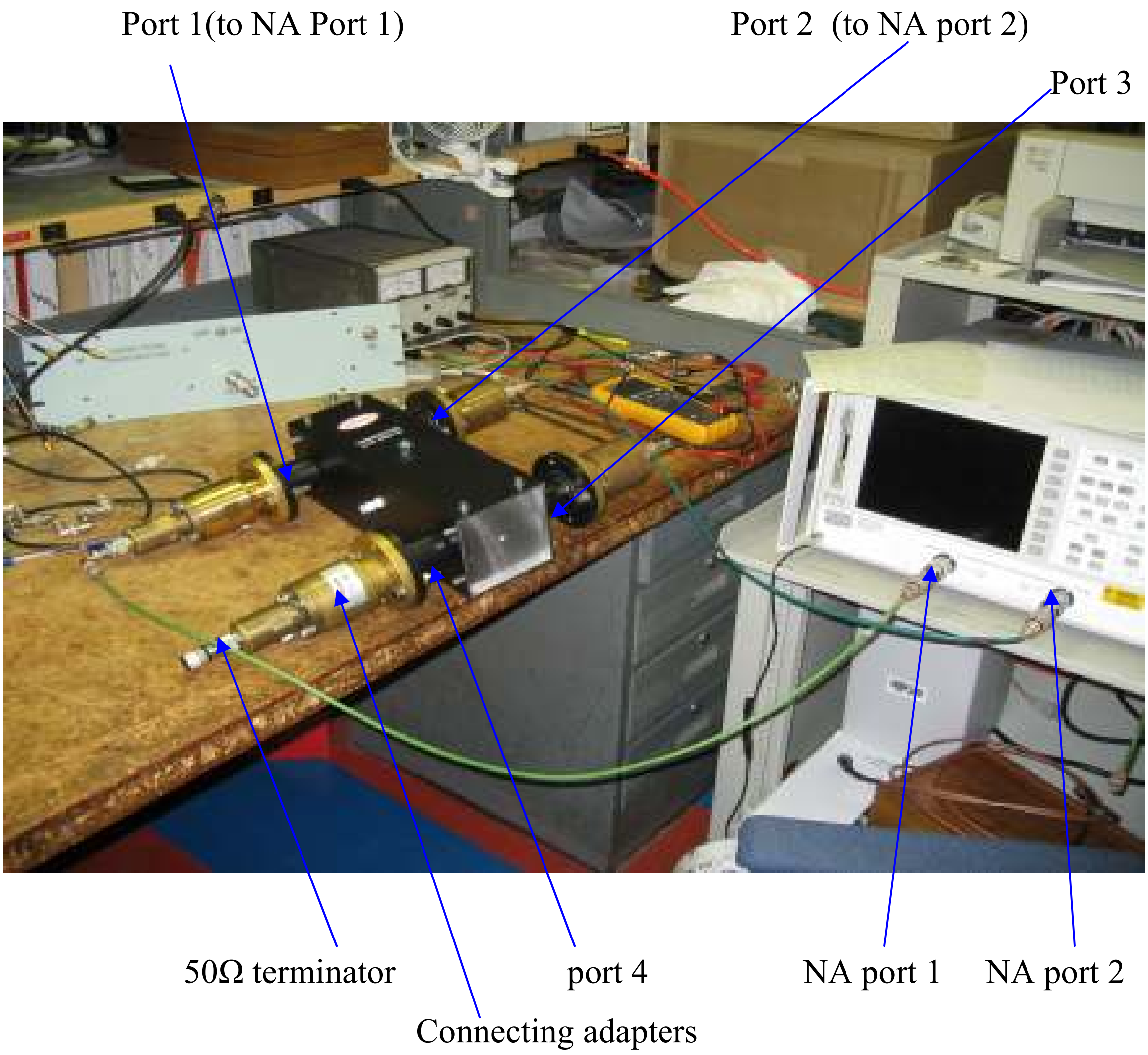


Fig. 4 The quad hybrid connected to the NA for testing

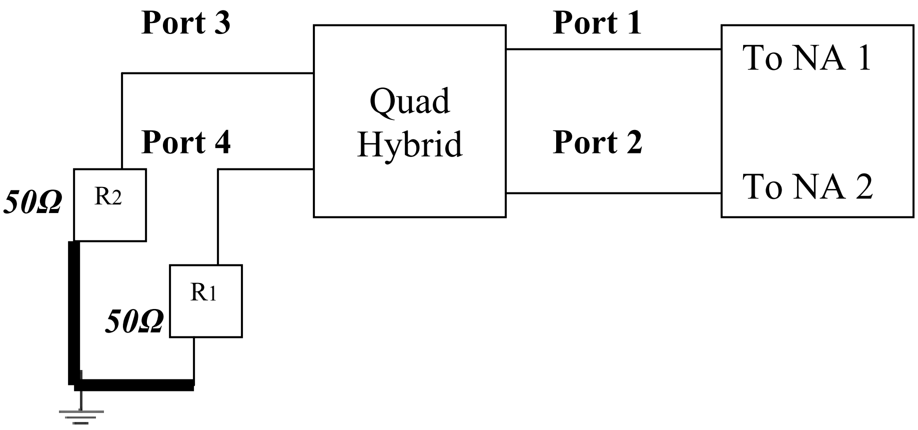


Fig. 5 Block diagram of connection of QH to NA for testing

Calibrating the connectors on the output ports of the 75Kw peak power Quad Hybrids

Before the two connecting adapters at ports 1 and 2 are connected to the hybrids, they must first be calibrated. In calibrating the two connectors, the two ends are brought together such that one connector points away (in the opposite direction) of the other one. Afterwards, they are tightly bolted together with a conductor in between them. This conductor acts to bridge the connection between both connectors and ensure that current flows through them both.

After this is achieved, the two ends of the connectors are connected via signal cables to ports 1 and 2 of the Network Analyzer (NA). Calibration commences by pushing the following commands/button on the NA

a) Calibrate
b) Calibrate Menu
c) Response
d) Thru

The two latter commands ensured that we got the frequency response of the connectors and test cables. After calibration, the connection is removed from the NA; the connectors are unbolted and connected to the ends of the various ports of the quad hybrids. The quad hybrids are now ready to be tested.

Calibrating the connectors on the output ports of the 400kw peak power Quad Hybrids

The process involved in calibrating the two connecting adapters of the 400kW QH is similar to the process used above to calibrate the 75kW peak power quad hybrids, with a difference in the positioning of the ports. Before they are bolted to the specific ports, ports 1 and 2 and first of all placed together with each ends facing the opposite pointing direction. A center conductor is placed between them after which they are bolted together. Ports 1 and 2 of the QH go to ports 1 and 2 of the NA. The adapters are calibrated by pushing the same commands as was done in the case of the 75KW QH. After this is done, the QH are set to be tested.

Fig. 6 400KW peak power quad hybrids

Fig. 7 Testing the quad hybrid using the Network Analyzer

Setting up the Network Analyzer for testing

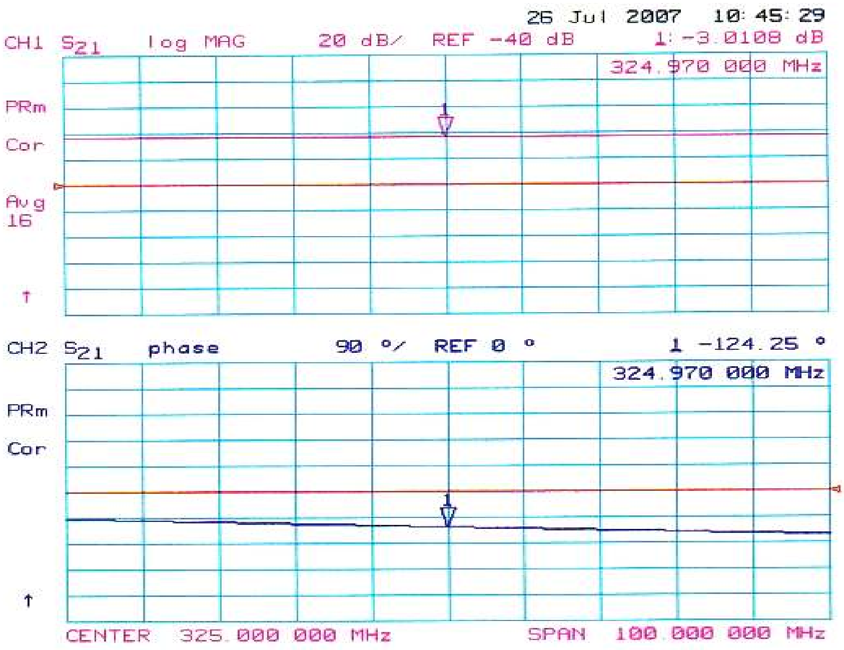
A network analyzer is an instrument used to analyze the properties of electrical networks, especially those properties associated with the reflection and transmission of electrical signals known as scattering parameters (S-parameters). Network analyzers are used mostly at high frequencies; operating frequencies can range from 9 kHz to 110 GHz. Special types of network analyzers can also cover lower frequency ranges down to 10 Hz.

In setting up the NA, a couple of things have to be done to ensure that the tests come out correctly. This does not have to be done in any particular order but it is important that they are done before testing. First, the center frequency of the NA is tuned to 325 MHz and the frequency span is set to about 100MHz (275 MHz to 375 MHz). Since we need to view both power output (dB) and the phase (degrees), we can set the NA to dual screen which allows Channel one and Channel two to be viewed on the same screen without switching back and forth between channels. The average is set to about 16 so that we can generate a more accurate data. This average is restarted for each time a new reading is taken. The measure is then set to S_{21} to measure the power flowing from port 1 of the NA through the device under test (DUT- the quad hybrid) back into NA port 2. Having done this, the NA is set to take readings.

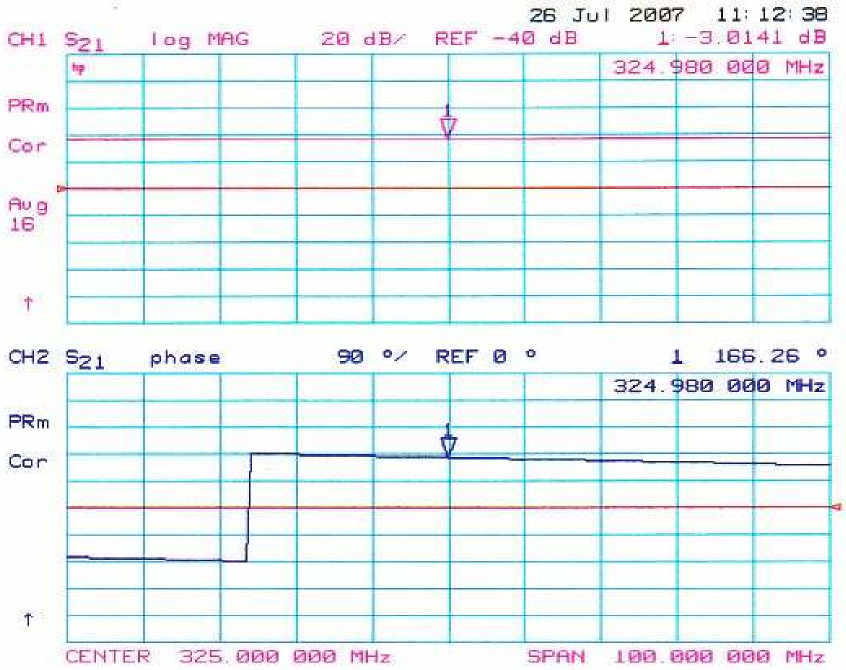
Obtaining readings from the NA and analyzing the data

After the connectors have been connected to the ports, a signal cable is connected from Port 1 of the quad hybrid (QH) to Port 1 of the NA. Another signal cable in connected from port 2 of the QH to port 2 of the NA. The remaining two ports (3 and 4) are each terminated with a 50Ω impedance. Using the preset values for the NA, the first data is obtained by restarting the average for the test. When the averaging is done, the values for the power (db) and the phase of the QH are recorded. The corresponding serial number of each QH is recorded along with the QH port number.

Having recorded the readings for port 2 of the QH (a better approach is to copy the data and print out a copy), we remove the terminator on port 3 of the QH and exchange it with the signal cables initially connected to port 2 of the QH. After this is achieved, the two terminations will be on port 4 and 2. Ports 1 and 3 of the QH are hence connected to ports 1 and 2 of the NA. This set of readings is again recorded or printed out. The phase difference is calculated from the values of the phase of port 1 and 2. *Graph 1-1* below shows a sample of one of the graphs generated for each port. The top portion of each graph holds the information we hold vital: the phase in degrees and the power in (db). The graph is followed by the tabulated readings procured from testing the 2 output ports of the 75KW peak power QH and the 400KW peak power QH



Graph 1-1 Port 1 sample plot for the Dielectric quad hybrid



Graph1-2 Port 2 sample plot for the Dielectric quad hybrid

SERIAL NO	PORT NO	PHASE IN DEGRESS	AMPLITUDE (DB)	PHASE DIFF. (360+port 2)- port 3
060701	Port 2	-99.386	-3.0154	90.214
	Port 3	170.4	-3.0332	
060702	Port 2	-99.391	-3.0168	89.669
	Port 3	170.94	-3.0169	
060703	Port 2	-99.621	-3.0079	89.049
	Port 3	171.33	-3.0155	
060704	Port 2	-98.258	-3.018	90.472
	Port 3	171.27	-3.0221	
060705	Port 2	-99.119	-3.0147	89.43
	Port 3	171.45	-3.0247	
060706	Port 2	-99.4	-2.999	89.47
	Port 3	171.13	-3.034	

060707	Port 2	-99.09	-3.0189	89.34
	Port 3	171.57	-3.0182	
060708	Port 2	-99.293	-3.0074	89.767
	Port 3	170.94	-3.0226	
060709	Port 2	-98.027	-3.0116	90.713
	Port 3	171.26	-3.0261	
060710	Port 2	-98.189	-30074	90.111
	Port 3	171.7	-3.021	
060711	Port 2	-99.003	-3.0119	89.787
	Port 3	171.21	-3.0306	
060712	Port 2	-99.374	-3.0236	89.036
	Port 3	171.59	-3.0089	
060713	Port 2	-98.858	-29945	89.672
	Port 3	171.47	-3.0241	
060714	Port 2	-100.26	-3.0092	88.94
	Port 3	170.8	-3.0147	
060715	Port 2	-98.812	-3.0069	89.928
	Port 3	171.26	-3.0562	
060716	Port 2	-99.007	-3.0278	89.533
	Port 3	171.46	-2.9965	
060717	Port 2	-98.796	-3.0307	89.904
	Port 3	171.3	-3.0296	
060718	Port 2	-99.223	-2.9959	89.537
	Port 3	171.24	-3.0408	
060719	Port 2	-99.717	-3.0179	88.823
	Port 3	171.46	-3.0181	
060720	Port 2	-98.49	-3.0154	90.35
	Port 3	171.16	-3.0301	

Table1 readings generated from measuring the 75KW peak power QH

Table 1 above shows the results obtained from testing/measuring the 75kW quad hybrid. As mentioned before, the test was carried out twice for each quad hybrid: once for each of the two output ports 2 and 3, and the phase difference between them was calculated by either representing the angles on the quadrant and finding the smallest angular difference between them, or by adding 2π to the value of port 1 and then subtracting the value of port 2 from it

Mathematically,

2π + (value of port 1) – (value of port 2) = phase difference

Below is the tabulated readings procured from testing the 2 output ports of the 400KW peak power QH.

SERIAL NO	PORT NO	PHASE IN DEGRESS	AMPLITUDE (DB)	PHASE DIFF. port 2- port 3
9876	Port 2	-82.734	-2.9781	89.776
	Port 3	-172.51	-3.0772	
9877	Port 2	-82.587	-2.9685	89.669
	Port 3	-172.68	-3.0892	
9878	Port 2	-82.448	-3.0026	90.692
	Port 3	-173.14	-3.0544	

Table 2 readings generated from measuring the 400KW peak power QH

Table 2 above represents the readings obtained from measuring the 400KW peak power QH. We can infer from this table that the output power of the system is approximately -3 db for both ports of each quad hybrid. The phase of the system should be approximately 90°.

SOLENOID CALCULATIONS FOR THE FAST PHASE SHIFTER

A phase shifter is a device used to adjust the transmission phase in a system. It can be fixed phase digital phase shifters or analog variable types. It can also be defined as a device that allows one to change the electrical length of a coaxial line.

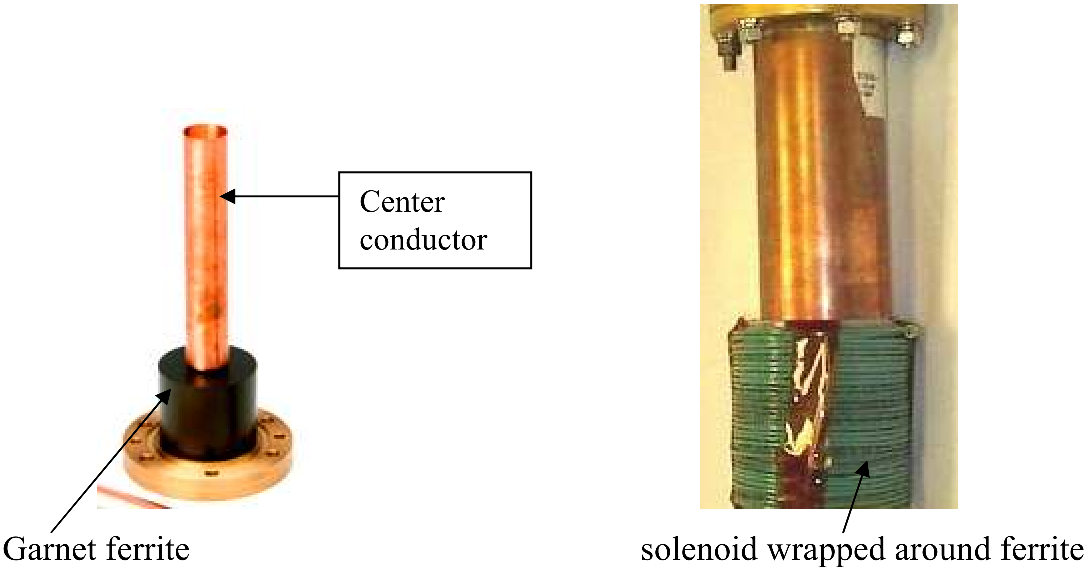


Fig. 8 3″OD X 0.5″ID X 2.5″ phase shifter

We are trying to get the magnetic field in the garnet ferrite as uniform as possible without having to make the solenoid infinitely long because the longer the solenoid, the greater the inductance, and consequently a slower phase shifter response. We calculate the approximate solenoid length that is appropriate to use for the fast phase shifter. To do this, we calculate the fields at the center and at the end of the ferrites. We know that the center is the point where magnetic field of the solenoid is strongest, getting weaker as it approaches the end. Hence, we calculate the ratio of the field at end, $B_{end,}$ to the field at the center, B_{cen}. The significance of this ratio is that it helps us to see how uniform the field is in the ferrite for a given solenoid length. Below is the calculation of the fields and the ratio

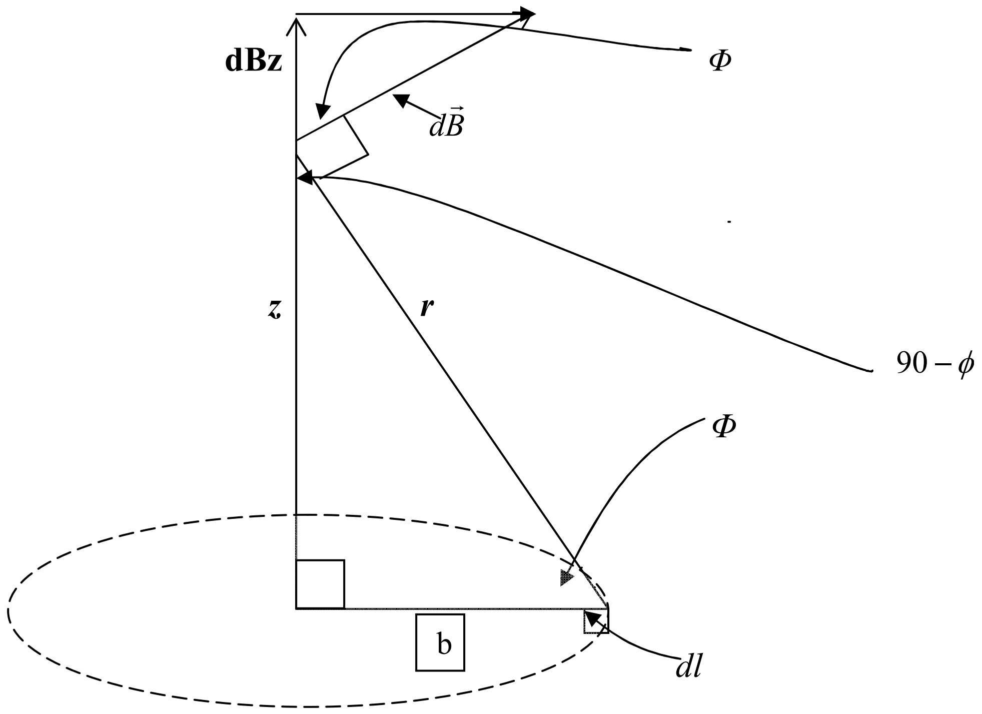


Fig. 9 calculating the field in one loop for the solenoid

$$dBz = \cos\phi dB$$

$$d\vec{B} = \frac{Id\vec{l} \times \hat{r}}{cr^2} = \frac{Idl}{cr^2}$$

$$dBz = \cos\phi \frac{Idl}{Cr^2}$$

$$Bz = \frac{\cos\phi I}{cr^2}\int dl$$

$$Bz = \frac{b}{r}2\pi bI * \frac{1}{cr^2}$$

$$Bz = \frac{2\pi Ib^2}{cr^3}$$

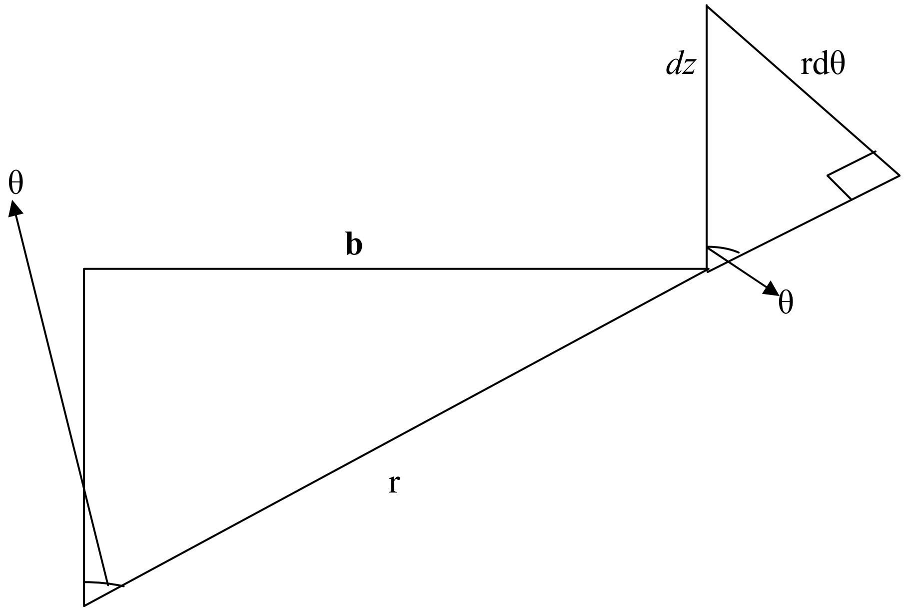


Fig. 10 calculating the field in n turns for the solenoid

$$\sin\theta = \frac{rd\theta}{dy}$$

$$dy = \frac{rd\theta}{\sin\theta}$$

$$dB = \frac{b^2 2\pi I_o nrd\theta}{cr^3 \sin\theta}$$

$$\sin\theta = \frac{b}{r}$$

$$Therefore\ dB = \frac{\sin^2\theta 2\pi I_o nd\theta}{c}$$

$$B = \frac{2\pi I_o n}{c}\int_{\theta_1}^{\theta_2}\sin\theta d\theta$$

$$B = \frac{2\pi I_o n}{c}[\cos\theta_1 - \cos\theta_2]$$

Having calculated the formula for B, we now go ahead and calculate the respective values for B_{cen} and B_{end}. The diagram below is the ferrite material (hollow cylinder) labeled to better help us understand what we are calculating

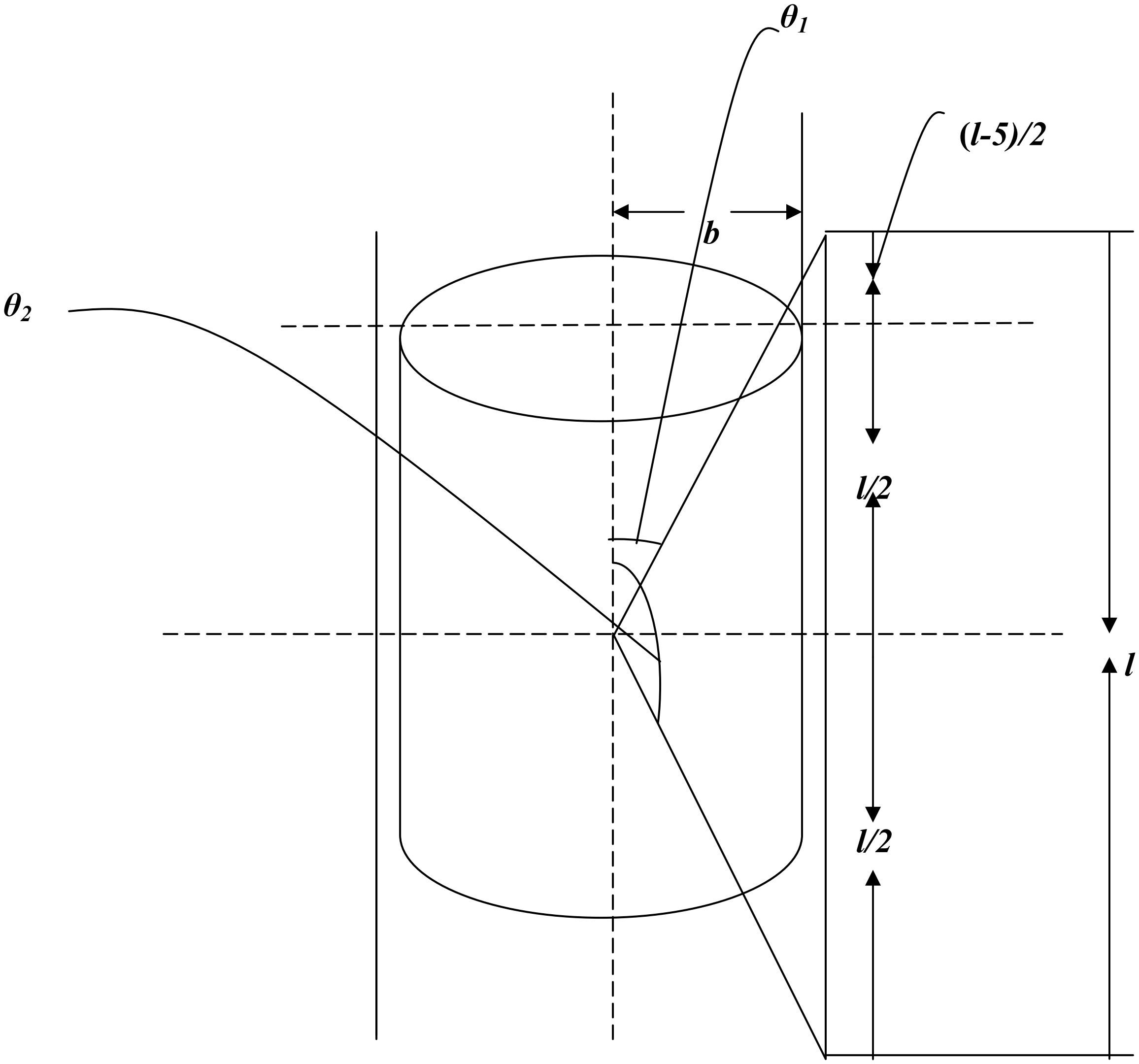


Fig. 11 ferrite with solenoid windings showing dimensions.

Fig. 11 above is the ferrite cylinder showing the solenoid windings of length *l*. When we calculate the field at the center, we calculate values of *b* for both 1.5 and 0.75 inches corresponding to the diameter of the two types of phase shifters. Similarly we calculate the length of the coil for each radius for *l* = 6 through 12 inches.

The equation for the field at the center for *b* = 1.5 and any *l* is given by (note this calculation was done by calculating the value of $\cos\theta_1$ and $\cos\theta_2$ from the above diagram. Its details has been skipped to optimize space in this paper)

For b = 1.5,

$$B_{cen} = \frac{2\pi I_o n}{C}\left[\frac{l}{\sqrt{9+l^2}} - \cos\left(180 - \cos^{-1}\left(\frac{l}{\sqrt{9+l^2}}\right)\right)\right]$$

For b= 0.75,

$$B_{cen} = \frac{2\pi I_o n}{C}\left[\frac{l}{\sqrt{2.25+l^2}} - \cos\left(180 - \cos^{-1}\left(\frac{l}{\sqrt{2.25+l^2}}\right)\right)\right]$$

For b = 1.5

$$B_{end} = \frac{2\pi I_o n}{C}\left[\frac{l-5}{\sqrt{l^2}\ +10l+34} - \cos\left(90 + \tan^{-1}\left(\frac{l+5}{3}\right)\right)\right]$$

For b= 0.75

$$B_{end} = \frac{2\pi I_o n}{C}\left[\frac{l-5}{\sqrt{l^2}\ +10l+27.25} - \cos\left(90 + \tan^{-1}\left(\frac{l+5}{1.5}\right)\right)\right]$$

Therefore for b = 1.5, the ratio of B_{end} to B_{cen}

$$\frac{B_{end}}{B_{cen}} = \frac{\frac{2\pi I_o n}{C}\left[\frac{l-5}{\sqrt{l^2}\ +10l+34} - \cos\left(90 + \tan^{-1}\left(\frac{l+5}{3}\right)\right)\right]}{\frac{2\pi I_o n}{C}\left[\frac{l}{\sqrt{9+l^2}} - \cos\left(180 - \cos^{-1}\left(\frac{l}{\sqrt{9+l^2}}\right)\right)\right]}$$

For b = 0.75, the ratio is

$$\frac{B_{end}}{B_{cen}} = \frac{\frac{2\pi I_o n}{C}\left[\frac{l-5}{\sqrt{l^2}\ +10l+27.25} - \cos\left(90 + \tan^{-1}\left(\frac{l+5}{1.5}\right)\right)\right]}{\frac{2\pi I_o n}{C}\left[\frac{l}{\sqrt{2.25+l^2}} - \cos\left(180 - \cos^{-1}\left(\frac{l}{\sqrt{2.25+l^2}}\right)\right)\right]}$$

Now that we have the ratio for both values of b, we substitute l for integer values of 6 to 12 inches. I used Microsoft Excel to generate the values of this ratio and consequently plotted the graph to compare both ratios.

For *b* = 1.5"

l in inches	B_{end}	B_{cen}	B_{end}/B_{cen}
6.0	1.280992	1.788854	0.716096
7.0	1.524843	1.83829	0.82949
8.0	1.681498	1.872658	0.89792
9.0	1.777802	1.897367	0.936984
10.0	1.838074	1.915653	0.959503
11.0	1.877299	1.929528	0.972932
12.0	1.903929	1.940285	0.981262

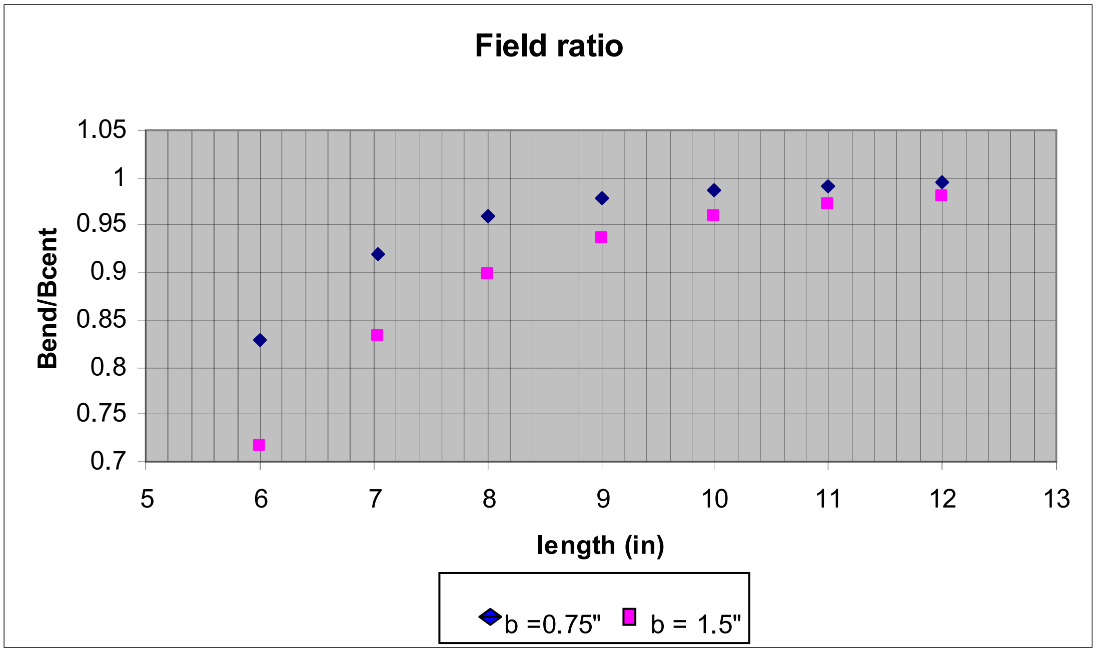
Table 4 readings generated for b = 1.5"

For *b* = 0.75"

l in inches	B_{end}	B_{cen}	B_{end}/B_{cen}
6.0	1.54553	1.86457	0.828894
7.0	1.792278	1.955605	0.916483
8.0	1.887836	1.965744	0.960367
9.0	1.930638	1.972788	0.978635
10.0	1.952863	1.977873	0.987355
11.0	1.965777	1.98166	0.991985
12.0	1.973932	1.984556	0.994647

Table 5 readings generated for b = 0.75"

Graph 2 below shows a graphic representation of B_{end}/B_{cen} against the length, *l*



s

Graph 2 plot of B_{end}/B_{cen} against length of solenoid

As mentioned before, we seek a ratio which is close to unity .As the solenoid length increases, its inductance L also increases slowing down the phase shifter response. A good compromise is to choose a length of 9”, where $\frac{B_{end}}{B_{cen}} = 0.95$. Increasing the solenoid length only gains a few percent in uniformity but increases L by 10-30%.

THE CHOPPER (NOT A MOTORCYLE)

The High Intensity Neutrino Source (HINS) Linac bunches are spaced at 325MHz- approximately 3.1ns. The Main Injector supplies an RF frequency of approximately 53MHz. We do not want bunches in the 53MHz separatrix because these bunches will not be accelerated hence approximately 1 out of every six bunches must be chopped out. Because 325MHz is not a multiple of 53MHz, it follows that two bunches might actually need to be knocked out instead of one bunch (the fifth or sixth bunch). This can be seen in the following figure which illustrates the timing of the 325 MHz bunches in red, and the phase of the 53MHz rf in black.

Bunches near the zero crossing point must be chopped out. Near t $\approx 19ns$, only one bunch is near the separatrix, whereas at t $\approx 55ns$, two bunches must be chopped out.

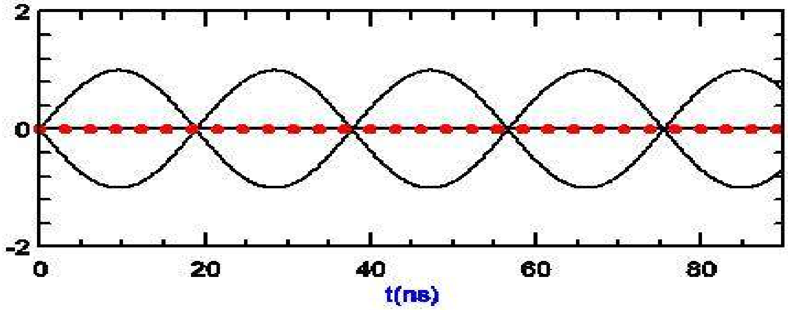


Fig. 12 Wave diagram showing the linac 325 MHz bunches

The task and responsibility of chopping out approximately every sixth bunch falls upon the chopper. It consists of two parallel plates which transmits pulses that deflect the beam. The pulses have a maximum width of approximately 5.5ns (including rise and fall time), 53MHz repetition rate, and a burst of 3ms @ 2.5Hz, or 1ms @10 Hz. Two pulsers are required to drive each 100Ω meander. This is achieved with help of the combiner- which will be discussed in detail in the next heading- in which two 1.2KV pulses are combined to form one 2.4 KV. The velocity of the pulse traveling along the chopper plates needs to match that of the beam so that the beam is deflected along the entire 50cm length of the chopper. This is achieved by using a serpentine or “meandering” trace pattern in the chopper plates.

$$\beta = \frac{\text{velocity of the beam}}{\text{velocity of light}} = \frac{2.19 \times 10^7\, m/s}{3.0 \times 10^8\, m/s} = 0.073$$

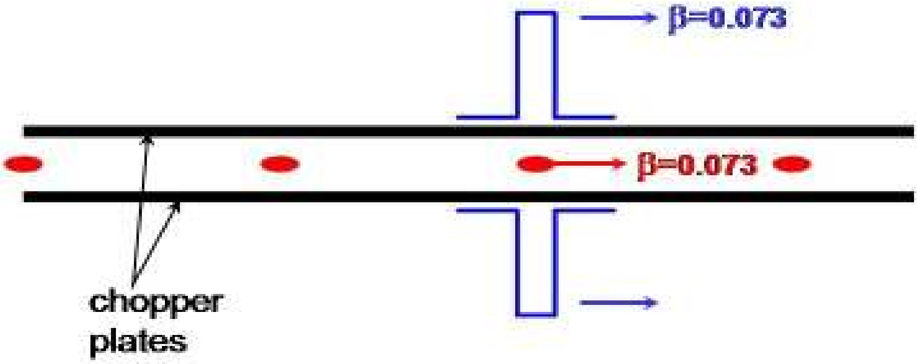


Fig. 13 Chopper plates showing pulse and beam movement

The beam is deflected by a traveling pulse (electric field) that has the same propagation velocity as the beam. Below is a picture of the single meander used in the chopper.

.

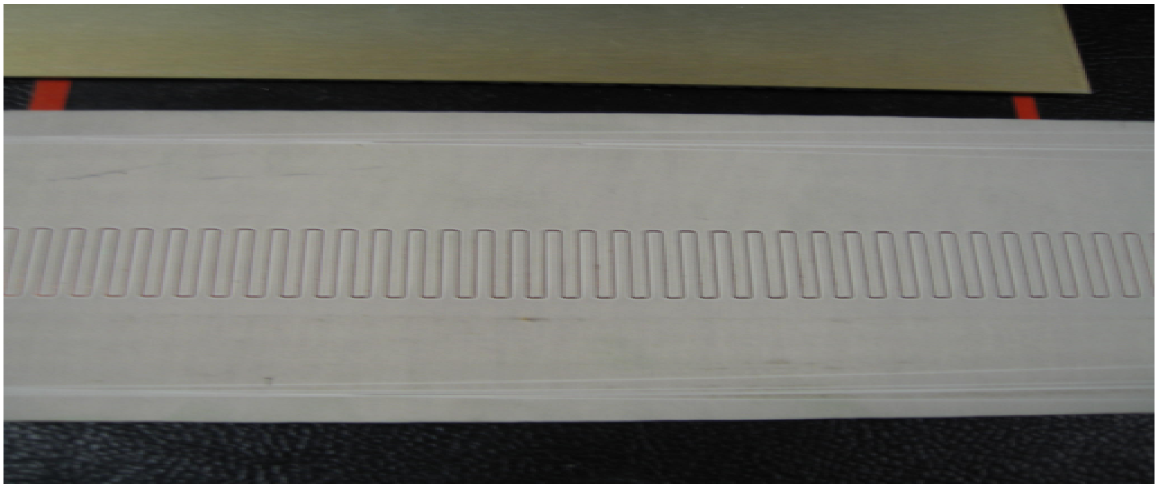


Fig. 14 Single Meander

THE COMBINER

The semi-arduous task of making the combiner:

The process of making the combiners, I must confess was not a very easy one. As straight-forward and as time efficient as it might seem, it was one which required a lot of care, time and precision. Having contributed to making this combiner, I can humbly say that the process was an arduous task, even though the instructions were pretty easy to follow.

The combiner is comprised of a 3/8 inch 50Ω superflexible foam dielectric cable (FSJ2-50) wound around (5) 1 inch thick Ceramic Magnetics MN60, MnZn toroidal ferrites (totals 5 inches).

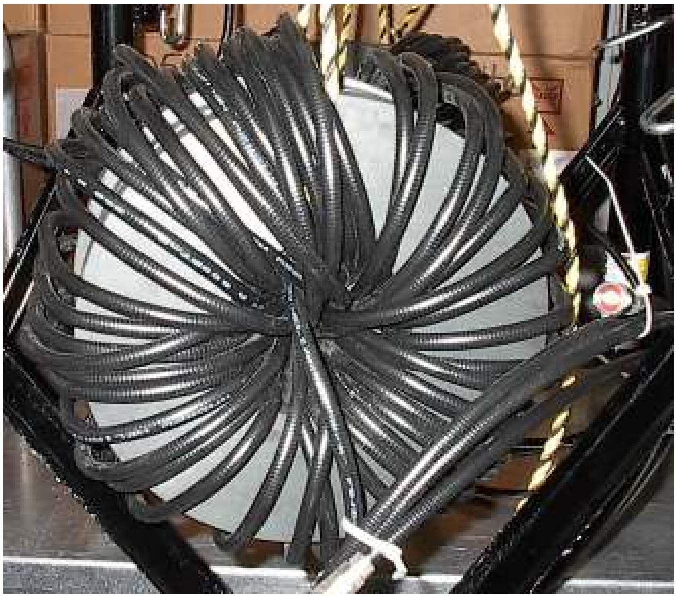
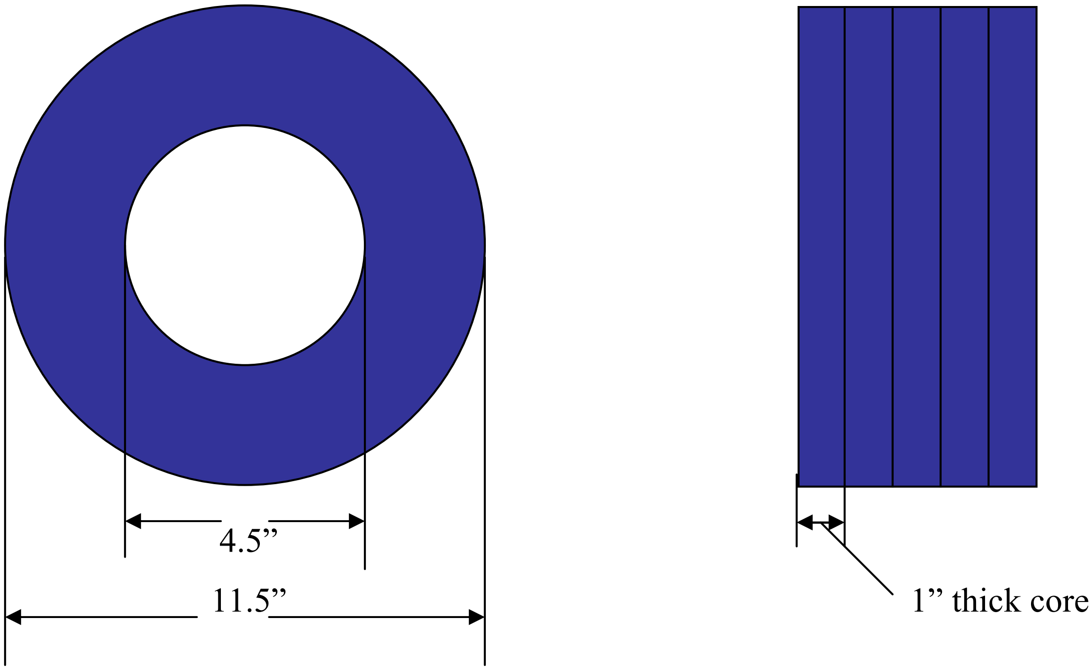


Fig. 15 The combiner



FRONT VIEW OF TORROID

SIDE VIEW OF TORROID

Fig. 16 Front and side view of the toroid

The toroids (comparable to the shape of a doughnut) have an internal diameter of 4.5”, external diameter of 11.5” and a thickness of 1”. In order to make this combiner, we had to ensure that the cable was not bent as this may damage the wire and increase the attenuation in the cable. Hence, in order to make one turn from a 97ft cable, I had to walk approximately 97ft across the room to make sure that the cable was not bent. Having done that, an equal distance is traveled back across the room and at this point the cable is inserted through the hole in the torpid and an approximate distance is walked across the room again to stretch the wire out, all the time trying as much as possible to keep the wire straight. As the number of turns increases on the toroid, the distance traveled across the room gradually reduces. Consequently, we get about 46 turns in our combiner from an initial cable length of 97ft. This piece of work took the combined effort of three individuals.

The use of the combiner

Two pulser voltages of 1.2KV each are combined using the combiner to generate 2.4KV for each of the meander plates in the chopper. Since 2.4KV is required to drive each meander, two combiners were built. The combiner accepts two voltages of 1200 volts, each of 50Ω impedance driven in parallel and connects them in series. This series connection is akin to adding each individual voltage to form one unique voltage. As we can see from Fig. 17 below, the combiner acts like an adder, summing up the individual input voltages, 1200V each, to obtain an output of 2400volts.

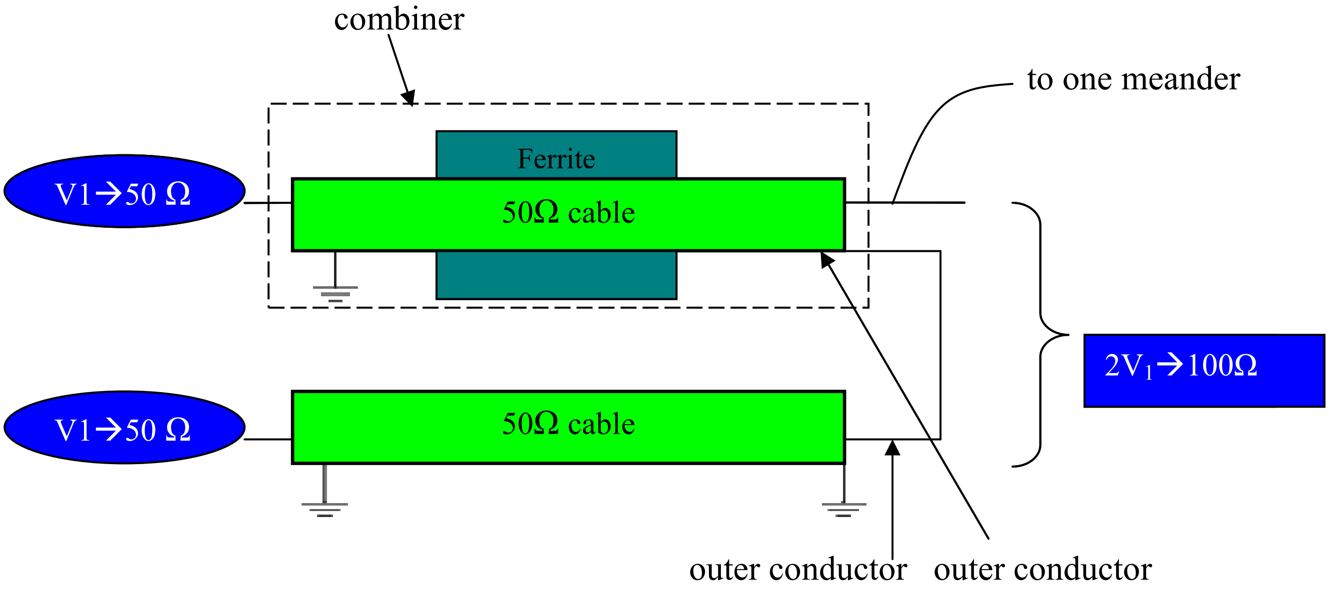


Fig 17. Block representation of the combination function of the combiner

$V_1 = 1.2KV$

The combiner can be tested by splitting and recombining the voltage (using a 500V pulser):

$$V_{out} = 95\% \, V_{in}$$

INDUCTOR CALCULATIONS FOR THE CHOPPER

We strive to maximize the output voltage of the combiner while keeping in mind that the loss in the cable increases with an increase in the length of the cable. In order to ensure that we get an approximate number of turns, N, which will generate this voltage, we perform the calculations below.

One draw back of this calculation is that we may not be able to reach this calculated value physically given the cable diameter and the internal diameter of the toroid. Hence, we will try to get as close to this number of N as is feasible.

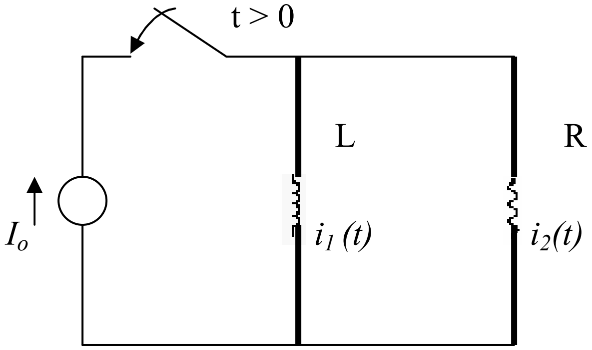


Fig. 18 A parallel R-L circuit

From Fig. 18 above, we can derive the equations 1 and 2 below

$$-L\frac{di_1(t)}{dt} = i_2(t)R \text{ ....} \textit{eqn 1}$$

$$i_1(t) + 1_2(t) = I_o \text{ ....} \textit{eqn 2}$$

Substituting in $i_2(t) = I_o - i(t)$ from *eqn 2* in *eqn 1*, we have

$$-L\frac{di_1(t)}{dt} = (Io - i_1(t))R \text{ ....} \textit{eqn 3}$$

$$\frac{di_1(t)}{I_o - i_1(t)} = -\frac{R}{L}dt$$

Let $i_1(t) = I$

Integrating both sides, we get

$$\int \frac{dI}{I_o - I} = \int \frac{-R}{L}$$

Let u = $I_o - I$

$\frac{du}{dI} = 1$ therefore $du = dI$

$$\int \frac{du}{u} = \ln|u|$$

$$\ln|I_o - I| = -\frac{Rt}{L} + C$$

$$-\frac{1}{R}\ln|I_o - I| = \frac{t}{L} + C \text{ ………………………} \textit{eqn 4}$$

At t= 0, I = 0, therefore $C = -\frac{1}{R}\ln|I_o|$

$$-\frac{1}{R}\ln|I_o - I| = \frac{t}{L} - \frac{1}{R}\ln|I_o|$$

$$-\frac{1}{R}(\ln|I_o - I| - \ln|I_o|) = \frac{t}{L}$$

$$(\ln|I_o - I| - \ln|I_o|) = -\frac{Rt}{L}$$

$$\ln(\frac{I_o - I}{I_o}) = -\frac{Rt}{L}$$

$$\text{I} = I_o(1 - e^{-\frac{Rt}{L}})$$

$$i(t) = I_o(1 - e^{-\frac{Rt}{L}}) \text{ …………………………} \textit{eqn 5}$$

Therefore, $V = i(t).R$

$$V(t) = V(1 - e^{-\frac{Rt}{L}}) \text{ ……………………………} \textit{eqn 6}$$

ESTIMATING THE LOSS FACTOR IN THE CABLE

$$V' = V(t) = V(k * l) \text{ ……………………………} \textit{eqn 7}$$

Where K is the loss in the cable per 100ft and l is the length of cable in question

We want to satisfy the following conditions

as t-→ 0, $f(l) = V' = V$ ……………………………….*condition 1*

as t-→ ∞, $f(l) = V' = 0$ ……………………………….*condition 2*

to determine the loss in cable of a specific length, we multiply k and l

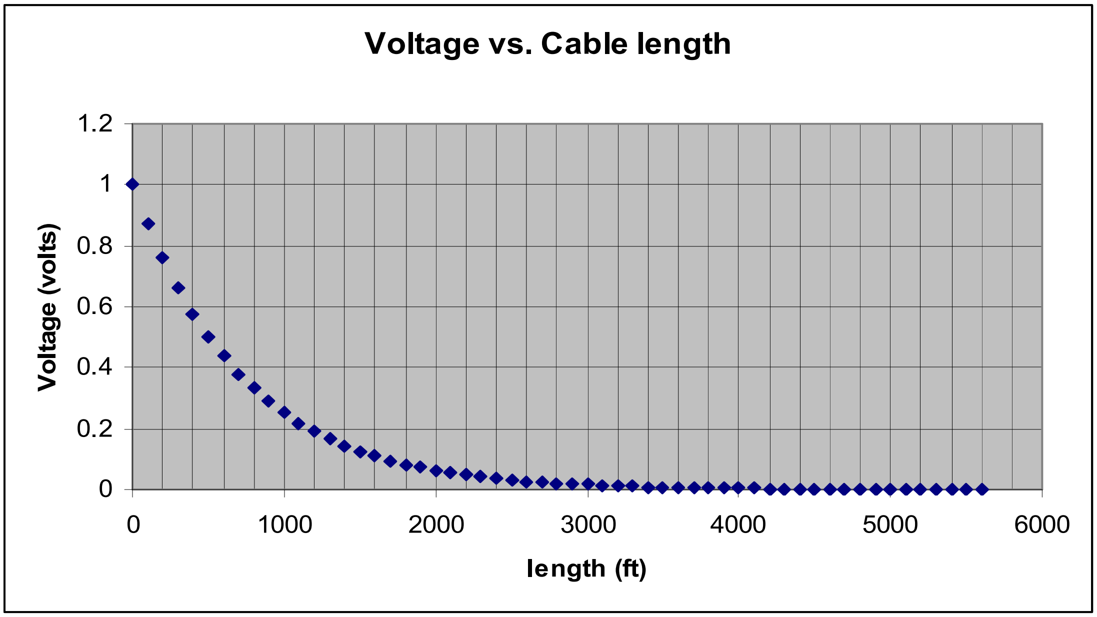
$k = \frac{-1.2db}{100ft}$, for a length l, the loss will be $\frac{-1.2db}{100ft} * l = 0.012ldb$

Converting db to voltage,

$$V' = V(10^{\frac{db}{20}}) = V(10^{\frac{-0.012l}{20}})$$

$V' = V(10^{-0.0006l})$ …………………………*eqn 8*

We verify that equation 8 satisfies the 2 conditions above by plotting a graph of V' with respect to length (we assume our V is initially 50 volts).

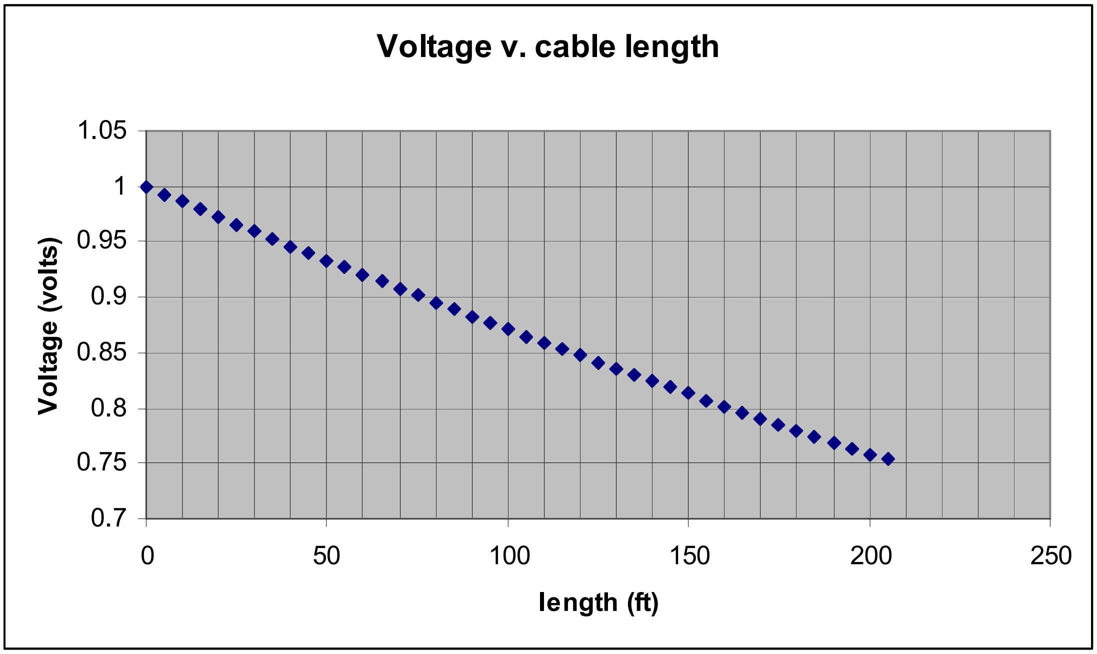


Graph 3-1 voltage in inductor against the length of cable.

Graph 3-1 above verifies that the determined loss factor meets the conditions and can hence be used in the pre-calculated *eqn 6*.

Having determined the right equation to determine the no of N, which will yield the maximum voltage for our inductor, we strive to represent the equation in terms of N, the no of turns.

Below is an expansion of the region for $0 \le l \le 205$



Graph 3-2 expansion of the region for $0 \le l \le 205$

We know that the loss in cable = -1.2db/100ft

With a 97ft wire, we made 46 turns around a 5 inch thick toroidal ferrite (1" each -→ 5 all together)

$$\text{Loss per turn} = \frac{loss}{length} * \frac{length}{turn} = \frac{-1.2db}{100ft} * \frac{97ft}{46turns}$$

= 0.0253db/turn

Therefore with N turns, we loss = 0.0253Ndb

Converting db to voltage, $10^{-\frac{0.0253N}{20}} = 10^{(-1.265*10^{\wedge}-3)\,N}$ ....*eqn 9*

The value above is the loss factor in terms of N. This value is multiplied with the equation we derived for the voltage (equation 6) so that we can get a precise voltage value with respect to time, t, putting into consideration the loss in the cable.

$$V(t) = V\,[10^{(-1.265*10^{\wedge}-3)\,N} * e^{\frac{-Rt}{L}}] \text{.......................................} \textit{eqn 10}$$

Where V is the voltage supplied to the system and L is the inductance of the system. We strive to represent L in terms of N, we know that

$$L = \ln(\frac{b}{a})(\frac{\mu}{\mu_o})2*10^{-9} * h(cm) * N^2(turns) \text{......................................} \textit{eqn 11}$$

b represents the external diameter of the toroid a represents the internal diameter of the toroid

h is the thickness of the toroid in (cm)

μ_o is permeability of free space (4π × 10^{-7} H/m), μ_r is the relative permeability of the material within the solenoid

$\mu_o = 4\pi * 10^{-7} H/M$

$\mu_r = 6000\mu_0$

Substituting the various values into equation 11, we get

$$L = \ln(\frac{11.5}{4.5})(\frac{6000\mu_o}{\mu_o})2*10^{-9}*12.7cm*N^2(turns) = 1.430*10^{-4}*N^2$$

Let C = 1.430 10^{-4}*

Therefore L = $C.N^2$ ………………………………*eqn 12*

To obtain the no of turns, N, that yields the maximum voltage, we find the derivative *V (t)* of with respect to N and equate to 0.

$$\frac{dV(t)}{dN} = 0$$

Substituting for L = $C.N^2$ into equation 10,

$V(t) = V[10^{(-1.265*10\text{^}-3)\ N} * e^{-\frac{Rt}{C}N^{-2}}]$…………..*eqn 13*

Let A = 1.265*10^{-3} and B = $\frac{Rt}{C}$

$V(t) = V(10^{-AN}).e^{-BN^{-2}}$ ……………………..….*eqn 14*

Representing 10^{-AN} as $e^{(A\ln|10|)N}$

$$V(t) = V[e^{-A\ln|10|N} * e^{-BN^{-2}}]$$

$V(t) = V[e^{-A\ln|10|N-BN^{-2}}]$…………………*eqn 15*

Differentiating *eqn 15* above with respect to N, we have

$$\frac{dV(t)}{dN} = 0$$

$$\frac{dV[e^{-(A\ln|10|N+BN-2)}}{dN} = 0$$

Differentiating we get

$$(-e^{-(A\ln|10|+B/N^2)}).(A\ln|10|-\frac{2B}{N^3})=0 \text{................eqn 16}$$

We know that the first part cannot be equal to 0, hence

$$(A\ln|10|-\frac{2B}{N^3})=0 \text{.........................eqn 17}$$

$$N^3=\frac{2B}{A\ln|10|} \text{.............................eqn 18}$$

Substituting for A and B in equation 18

$A = 1.265 * 10^{-3}$; $R = 50\ \Omega$; $t = 0.5\text{ms}$; $C = 1.430 * 10^{-4}$

Recall that $B = \frac{Rt}{C} = 174.825$

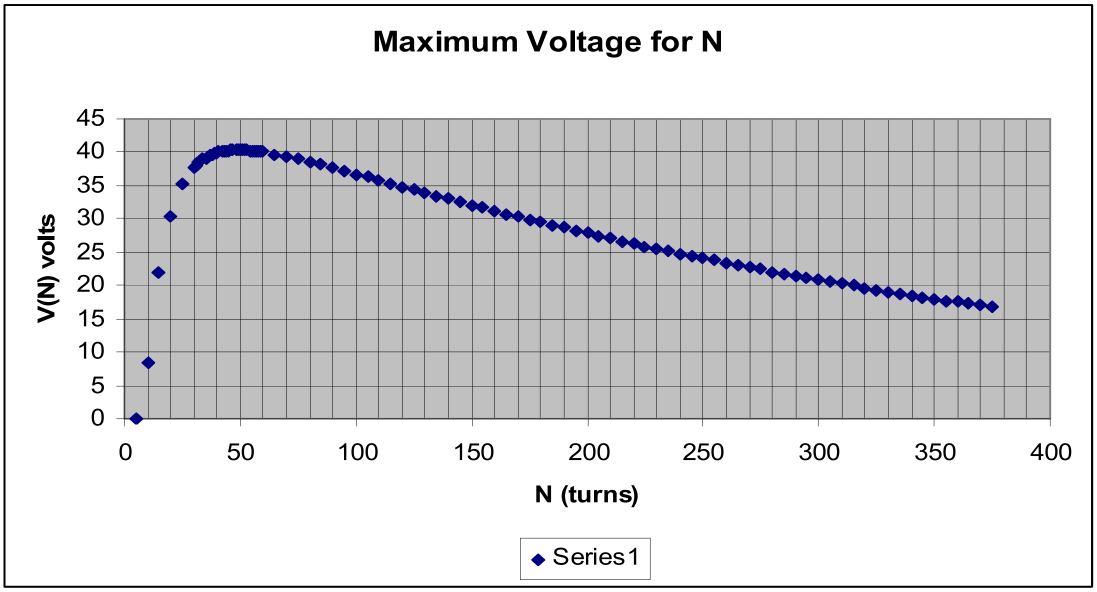
$N^3 = 120{,}040.3681$

$N = \sqrt[3]{120{,}040.3681}$

$N = 49$ (approx.)

Therefore with about 49 turns on the ferrite, the maximum voltage will be generated

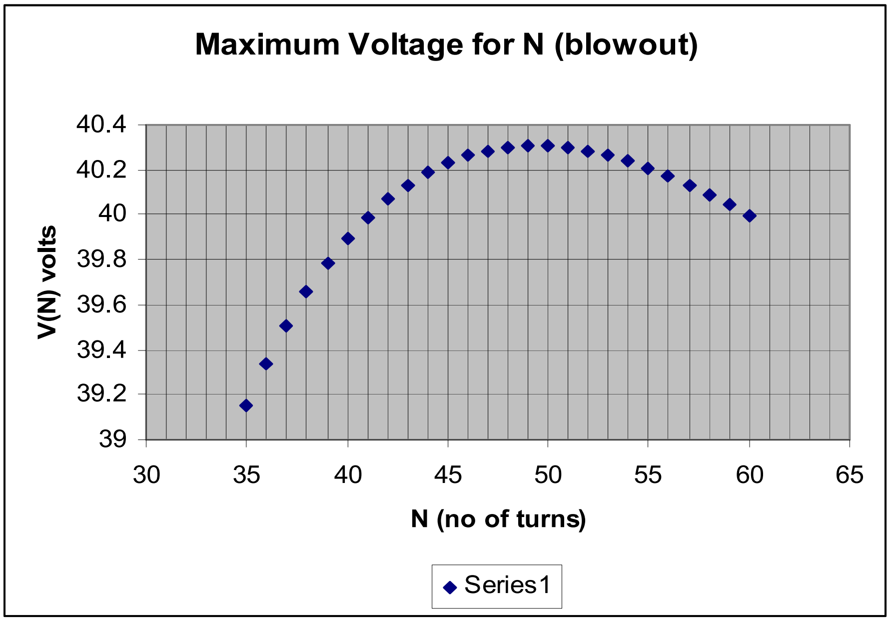
Below is the graph of *V (N)* with respect to *N*



Graph 4-1 plot of V (N) with respect to N

We can see that the graph above successfully verifies that at N = 49, a maximum voltage is obtained for the system.

Below is an expanded plot around the region N = 49



Graph 4-2 expansion of the region $35 \leq N \leq 60$

CONCLUSION

I successfully tested of 20, 75KW peak power QH and 3, 400 KW peak power hybrids.

I was part of a group that made 2 combiners using a 3/8 inch 50 superflexible foam dielectric cable (FSJ2-50) wound around 5 Ceramic Magnetics MN60, MnZn toroidal ferrites and achieved about 46 turns on it. This will be used to combine individual voltages needed to drive the meanders.

I was able to maximize the voltage in the combiner by calculating the optimum value of N, the number of turns, which will successfully give us the specifically sought maximum voltage. In calculating this, I considered the losses in the cable, which are proportional to an increase in the length of the cable.

The field calculation I made for the fast phase shifter helped us to identify the optimal length of solenoid that we required in each ferrite of both radiuses 0.75 and 1.5.

Finally, I analyzed the various graphs resulting from each of the test, measurement and calculations carried out.

ACKNOWLEDGEMENTS

I would first of all like to thank Almighty God for deeming me fit to return to the SIST Program and for the strength he adorned me with to go through this program without any problems. I would also like to thank the SIST committee for selecting me and giving me yet another opportunity to prove myself to them. More importantly, I would like to thank the duo of Dianne Engram and Elliot MCcrory for holding this program together and for making it possible for me to be here today, again. Immense kudos goes out to this hardworking duo for their relentless and praiseworthy efforts and work they do.

Also, I will like to thank my supervisor Dr David, for being ever so patient with me and explaining the details of every complicated set-up and equation. He, in my book deserves more than just a mere pat on the back or thumbs up; he deserves adulation for his great work! I also want to thank Dr. Robyn Madrak, who helped me out a lot in areas that posed as problems, especially during the time I was writing this paper. She was always there to fill in the loop-holes that were necessary to make the required bridge. I would also like to thank Joe Dey for his patience and assistance with every computer related question I had to ask him- both hardware and software. He and the rest of the Fermilab Accelerator Division made my work experience this summer a memorable one.

I would also like to thank Dr. Davenport for his help with the paper and presentation and with other more imperative areas akin to my stay at FERMILAB. I would also like to thank my mentors-David Peterson and Elliot McCrory for their time and advice. I would more importantly like to thank the entire group of SIST and GEM interns for making the summer a wonderful one-even though it could have been more eventful than it turned out.

To the directors, physicists, engineers, accountants and all other genres out here in this giant research laboratory, I thank you for making FERMILAB what it is and for

your immense contribution to the growth of science and technology to this great nation. Thank you FERMILAB!

REFERENCES

1) Douglas P. Moehs, Robert F. Welton, Martin P. Stockli, Jens Peters, James Alessi "Ion Source Choices - An H- Source for the High Intensity Neutrino Source" *http://lss.fnal.gov/archive/2006/conf/fermilab-conf-06-311-ad.pdf*

*2) ** Merrimac Inc., "Quadrature Hybrids, 90^o power divide/combiner 10KHz to 40KHz general information"* *http://www.merrimacind.com/rfmw/05intro_quadhybrids.pdf***

3) Robyn Madrak, "Fast Choppers/Fast Phase Shifters for HINS, Proceedings of Linac, Knoxville TN, 2006.

4) David Halliday and Robert Resnick (1981). Fundamentals of Physics (second Edition).NewYork: John Wiley & Sons Inc.

5) Tawwaz T. Ulaby (1997). Fundamentals of Applied Electromagnetics. Upper Saddle River, NJ: Prentice Hall

6) William H. Hayt, Jr. (1989). Engineering Electromagnetics (fifth edition). New-York McGraw-Hill, Inc.