Pbar Note #605

Magnetic pulse compression for the beam sweeping system

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0. Introduction.

Early conceptions of the beam sweeping system envisioned a linear circuit to drive the sweep magnet. [Ref. 1,2] They involved very high charge voltages, high power switches, fast high-voltage pulse transformers, and very large circulating currents flowing over long cables between the power supply and the sweep magnet. The introduction of a nonlinear element, saturating magnetic reactors, allowed a dramatic reduction in the voltages, circulating currents, and more generally in the cost and risk of the sweeping system [Ref. 3].

Pulse compression by saturating magnetic reactors is an old idea, first developed for use in radar modulators during WW II [Ref. 4]. Tapes of annealed, grain-oriented 50% nickel-50% iron material with a square B-H loop were developed for this purpose. With the advent of metallic glasses in the past 20 years interest has grown in these reliable, repetitive high power solid-state switches [Ref. 5], but they require careful application because of the subtle problems associated with this still-developing technology. The most serious recurrent problem is that of interlamination insulation. This note describes our recent research effort to identify and characterize switch materials appropriate for our system.

Metglas is an amorphous metallic glass material, manufactured by the Allied-Signal Corporation, which has unique applications in the field of pulsed power because of its high saturation magnetic flux density, high resistivity, and low cost of raw material. We considered two Metglas materials for the output reactor in this project. These are Metglas 2605 SC, which consists of $Fe_{81}B_{13.5}Si_{3.5}C_2$ and Metglas 2605 CO, which consists of $Fe_{67}Co_{18}B_{14}Si_1$. Although the 2605 CO material has higher losses and is more expensive than the 2605 SC material, it has two important advantages. First it has the highest saturation flux density (B_{sat}) of any amorphous alloy commercially available. This fact is important because the size of a switching reactor for a given volt-seconds and inductance requirement scales as the square of $B_{sat.}$ [Ref. 6] The value of B_{sat} for 2605 Co material is 1.80 Tesla, and for 2605 SC material is 1.61 Tesla, according to Allied-Signal sales brochures. The second advantage is that the sensitivity of the 2605 CO material to mechanical stress is much lower than for 2605 SC material. The magnetic anisotropy energy is 1000 J/m^3 for the 2605 CO material, but only 100 J/m^3 for the 2605 SC material [Ref. 7]. As discussed below, the high sensitivity of the 2605 SC material associated with its small magnetic anisotropy energy is a major restriction in the packing factor that is practically obtainable.

1. Radiation effects.

At the expected radiation levels at the top of the target module, no significant radiation-induced changes in properties of magnetic materials occurs[Ref. 8]. Although the work of Ref. 8 was performed before Metglas material was developed, its properties should also be relatively insensitive to radiation damage, since it is an amorphous material.

The major drawback of the 2605 CO material is that it contains 18% cobalt. The cobalt ^{59}Co will capture neutrons in the target vault forming ^{60}Co which is a strong gamma emitter with a half-life of 5.27 years. Boron (14%) in the material will strongly absorb many of the neutrons, but since cobalt has a sharp neutron absorption resonance at 100 eV, a significant fraction of the neutrons will interact with the cobalt to form ^{60}Co. It is difficult to quantify the amount of induced radioactivity in the cobalt. Following is a rough order of magnitude estimate. It has been estimated that the neutron flux close to the target will be 2 x 10^{12} neutrons/cm^2/sec. [Ref. 8] If the neutron attenuation through the steel target modules is 10^{-5}, then the integrated flux at the Metglas reactor over a 10-year lifetime is on the order of 10^{15} neutrons/cm^2. If the core has a surface area of 1000 cm^2, and all of the incident neutrons are absorbed by the cobalt, there will 10^{18} interactions. At a distance of 1 foot, this corresponds to 10^{14} ^{60}Co gammas per cm^2. The ^{60}Co gammas have an energy of about 1 MeV, with an absorption length of 20 g/cm^2. This corresponds to a residual dose of about 1 J/g or 10^5 Rads over 10 years, or 1 Rad/hr. If only 10% of the incident neutrons interact with cobalt the residual radiation will be in the range of 100 mrad/hr. Thus, since there is some concern about the possible buildup of residual radiation in the target vault, the cobalt-based 2605 CO material was not further considered for use in this project.

Two materials, kapton and mylar, were used for insulation of the cores. Mylar maintains its strength up to a dose of 5 x 10^8 Rads, and kapton is about 50 times less sensitive to radiation than mylar [Ref. 9]. Both of these materials should be relatively unaffected by the expected lifetime radiation dose on top of the target module (10^7 Rads) [Ref. 3].

2. Insulation

Tape-wound cores require insulation between the cores to hold off the loop voltage induced on each lamination by the dB/dt. The pulsed interlamination voltages in our reactors is about 0.6 V turn to turn in the first stage reactor, and 2.4 V in the second stage reactor. A number of insulation techniques for Metglas cores have been used from time to time, with varying degrees of success [Ref. 10]. A simple insulation technique that manufacturers apply is a dip coating of magnesium methylate, which is then thermally polymerized into a thin MgO film. This process generally provides acceptable insulation up to 2 V with Fe/Ni tape cores, although it is sensitive, for example, to the annealing temperature, and to the presence of burrs on the edges of the tape material. It has been less successful with Metglas cores. We find that the MgO insulation breaks down in Metglas cores for pulsed interlamination voltages lower than 0.6 V, possibly as low as 0.1 V. The reason for this poor performance is not known, but may be related to the relatively rough surface of the Metglas, or to the difference in annealing conditions between Metglas and Fe/Ni tapes. Placing the cores in oil has been used with some success in the past, but we are unable to use oil because of the radiation levels in the target vault. As a result the Metglas cores are only useful for our application when cowound with an insulating film.

3. Manufacturing

The Metglas material chosen for the cores was the 2605 SC material.

The first set of sample cores purchased from Allied-Signal was wound with 0.3-mil (8 micron) kapton insulation. Kapton maintains it strength at the annealing temperature of the Metglas, typically 220 - 280 deg C, so that the cores were wound with the kapton insulation before annealing and then annealed in place. Unfortunately Allied was unable to produce cores with the desired square loop. After discussions with Carl Smith (formerly at Allied-Signal) and Lou Reginato of LBL, we discovered that this was a known problem that Allied-Signal had simply forgotten. The kapton damages the magnetic properties of the Metglas material because the differential thermal expansion and contraction of the Metglas and Kapton stresses the material. The two surfaces are sufficiently rough that they stick together under tension and warp due to differential thermal contraction. The magnetic properties of the 2605 SC Metglas are very sensitive to stress because the magnetic anisotropy energy [Ref. 11] is small. Bending stresses easily rotate the direction of magnetization out of the ribbon direction when the magnetic anisotropy energy is small. The effect is to twist the B-H characteristic from the ideal square loop to an elongated loop. However, despite the less-than-ideal B-H characteristics of these cores (usable volt-second area of about 32 mV-sec (3 cores, 4 turns), compared to the design goal of 40 mV-sec, they were successfully used in initial tests of the system [Ref. 3].

After investigation of this problem was completed, a second set of sample cores was purchased from Allied-Signal. These cores were first wound and annealed without insulation, then unwound inside out and rewound with 3-micron mylar insulation. This is a difficult procedure since the Metglas becomes brittle after annealing, but it is the accepted procedure for manufacturing annealed Metglas pulse cores. Although the process of winding and rewinding the cores generally causes a slight deterioration in squareness of the B-H loop, measurements of these cores show that they are acceptable for our requirements. The measured volt seconds for a 5-A reverse bias current is at least 2.9 mV-sec per core per turn. These cores have a 16% smaller cross section than the original cores, to reduce the output inductance of the reactor. However the complete second stage reactor has a larger volt second area of 36 mV-sec (3 cores, 4 turns). A complete set of cores for the second stage specified to be manufactured in the same manner as the best of the three sample cores is now being manufactured at Allied-Signal.

4. Failure of the original second stage reactor.

The original second stage reactor was assembled utilizing three of the (kapton insulated) Metglas cores, potted in Sylgard. It failed after 3 million test pulses at full operating voltage (3 kV charge). Extensive tracking was observed through the outer (roughly) 100 layers of Kapton and Metglas. Multiple breakdowns occurred through the Sylgard insulation between the cores and the conductors. Regions of charred Sylgard slowly grew during the course of the test until failure of the reactor occurred when the charred region extended across the full gap. Investigation of the cause of this failure led to the conclusion that it occurred because of parasitic magnetic coupling between the conductor winding and the cores.

In the original reactor design, the simple 4-turn conductor winding was wound around the cores in a single direction toroidally. Effectively it acted as a 1-turn primary of an air-core transformer, and the Metglas tape winding, which has over 1000 turns, inductively coupled to this current, acted as the secondary of the transformer. Very large voltages were induced across the full Metglas winding. In a test with 80 V loop voltage, the induced voltage measured across the core was as much as 800 V. The voltage across the Metglas winding oscillated with a frequency of about 50 kHz, which corresponds roughly with the capacitance and inductance of the structure. This interpretation was verified by winding two 4-turn conductors on opposite sides of the core. The two conductor windings were connected in parallel such that the flux was in the same direction and energized. When the terminals were properly positioned to cancel out each other's inductive effect on the core winding, no parasitic induced voltage was observed. In practice we were able to greatly alleviate the problem by placing each core inside a .060" wall aluminum can. The can shorted the parasitic magnetic coupling in the toroidal direction, so the only coupled magnetic flux was the flux that could penetrate through the aluminum wall. A gap was left open on each can to support the azimuthal inductive voltage drop. After removing the damaged portions of the cores, the reactor was rebuilt. After 4 million test pulses (to date) the modified reactor with aluminum cans has had no problem. We plan to use both aluminum cans and the double winding technique (Figure 1) in the second stage reactor in the production system. It is interesting to note that the large parasitic oscillations were observed only with the Metglas core with film insulation; the amplitude was very small in similar tests with a Ni-Fe tape core with MgO insulation.

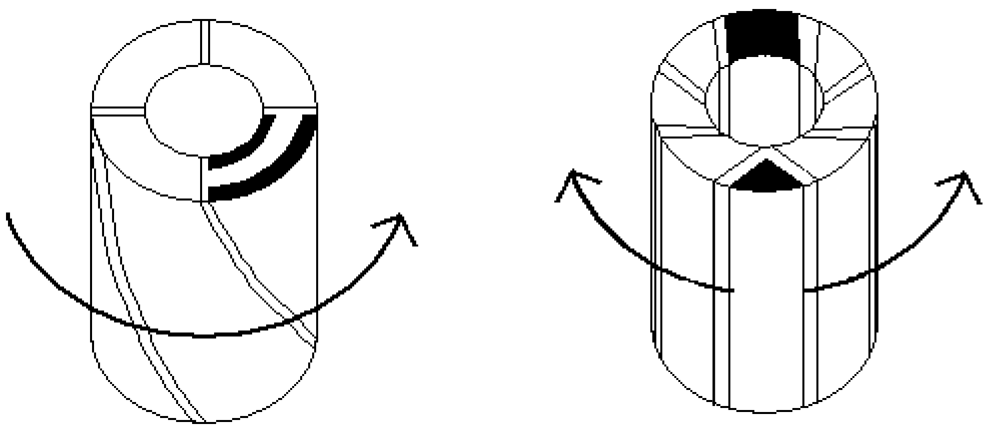

Figure 1. Sketch of reactor windings. These windings each enclose three Metglas cores. On the left is a schematic of the original reactor winding. The connections to the external circuit are colored, and the toroidal direction of current flow is as indicated. The toroidal current flow generated a toroidal loop voltage in each turn of the cores. On the right is the modified reactor winding. The toroidal current flow in the two parallel windings is in opposite directions, so there is no net toroidal loop voltage induced on the cores. An additional advantage of this winding arrangement is that the full voltage drop is distributed across the reactor rather than appearing across adjacent turns.

5. First stage reactor.

Loop voltage and dB/dt in the first stage reactor are 1/4th of those in the second stage reactor. Although it is possible to use the same cores in the first stage as we are using in the second stage, we investigated other core materials to lower costs and reduce our dependence on a single supplier.

We considered and tested four other core materials for the first stage.
1. 1-mil Magnetic Metal pulse anneal Fe-Ni tape ('Square 50') cores. These cores performed well. We plan to use these cores in the first stage reactor. The Magnetic Metals cores are well proven technology, the packing factor of these cores is higher than the Metglas cores, and the cost is lower. The Magnetic Metals cores have been pulse tested for 1 million pulses at 1.8 V/lamination, much higher than the requirement for operation in the first stage (0.6 V/lamination).
2. 1-mil silicon steel cores (Magnetic Metals). These cores performed satisfactorily. Volt seconds are slightly higher than the Square 50 material, and insulation was adequate. Although the silicon steel cores are much cheaper than the Square 50 cores, we chose the Square 50 material, because it has lower losses, and sharper switching characteristics (a more square B-H loop).
3. 1-mil Deltamax (a Fe-Ni tape), from National Arnold. The Deltamax material is nominally the same material as Magnetic Metals Square 50 but the insulation strength was

poor. The cores had excessive jitter, due to interturn breakdowns, in service in the first stage reactor. One core was tested independently and broke down at 1.7 V/lamination. These cores were deemed unacceptable.

4. 1-mil 2605-SA1 Metglas cores, manufactured by National-Arnold using an Allied-Signal Metglas material with similar magnetic properties to that of the 2605 SC material chosen for use in the second stage. The insulation was a magnesium methylate coating. The insulation strength was found to be only slightly better than that on Metglas cores with MgO insulation. One core broke down in a test at 0.4 V/lamination, the other at 1.2 V/lamination. They were also deemed unacceptable.

6. Magnetic measurements of the cores.

Pulse test of the cores were performed by replacing the sweep magnet in the sweep system power supply by the core under test, and applying a pulsed voltage across the core. The current through the core was measured by a Pearson current monitor, and the loop voltage was picked up with a single wire loop and integrated by an analog integrator.

Metglas cores were tested with a single turn. Typical voltage and current traces are shown in Figure 2. Peak loop voltage was 3.0 kV, or 2.7 V/lamination. Results for the three new mylar-insulated Metglas cores, and for one of the kapton-insulated core are listed in Table 1. The increase in volt seconds of the cores for increasing DC bias current agrees well with the DC B-H loops provided by Allied-Signal (Fig. 3). At least 5 A will be available for DC bias in the sweeping system. Of the mylar insulated cores the trend was clear that increasing the packing factor, corresponding to increasing the winding tension and more material in the core, tended to reduce the usable volt-second area. The trend continues with the older kapton-insulated core, which was very tightly wound, again indicating the decrease in remanence due to the sensitivity of the Metglas material to stress. The dimensions of the new cores is 3.125" ID x 5.375" OD x 2.00" height; the dimension of the old kapton-insulated cores is 2.78" ID x 5.40" OD x 2.00" height.

Table 1
Volt-second measurements for the Allied-Signal Metglas cores for various DC bias currents

core	weight	packing factor	volt-second area [mV-sec]				
			I-bias= 0 A	1 A	2 A	5 A	18 A
1	2495 g	0.70	2.81	2.87	2.93	3.02	3.18
2	2685	0.75	2.74	2.80	2.88	2.98	3.13
3	2740	0.765	2.74	2.79	2.84	2.92	3.06
kapton	2780	0.62	2.59	2.62	2.66	2.74	2.95

Pulsed B-H loops for the Metglas cores are shown individually in Figures 4-7 for three bias currents. The magnetic field B in the plot is the magnetic flux divided by the cross section of the cores. To determine the field in the Metglas, divide the plotted field by the packing factor. All the Metglas cores were pulsed at roughly the same dB/dt. The curves represent about 1-1/2 complete oscillation, at varying loop voltages, and B = 0 Tesla represents the starting point of the pulse. The curves don't form a perfect closed loop because loop voltage is not the same at the end of the curve as it is at the beginning of the pulse. The width of the pulsed B-H loop is much wider than the width of the DC B-H loop, i.e., the losses are higher. Losses increase with the loop voltage (or dB/dt), so the loop is widest when loop voltage is largest. Figure 8 shows the effect of dB/dt on the shape of the B-H loop. Figure 9 summarizes all the pulsed B-H loop measurements on the Allied-Signal Metglas cores.

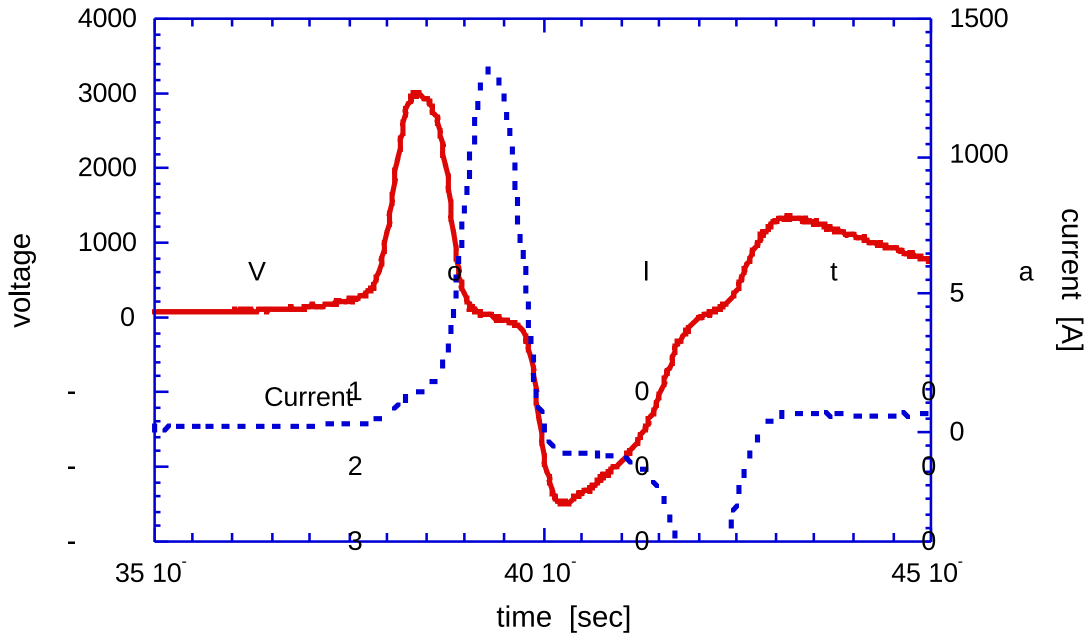

Figure 2. Typical loop voltage and current in the pulse tests.

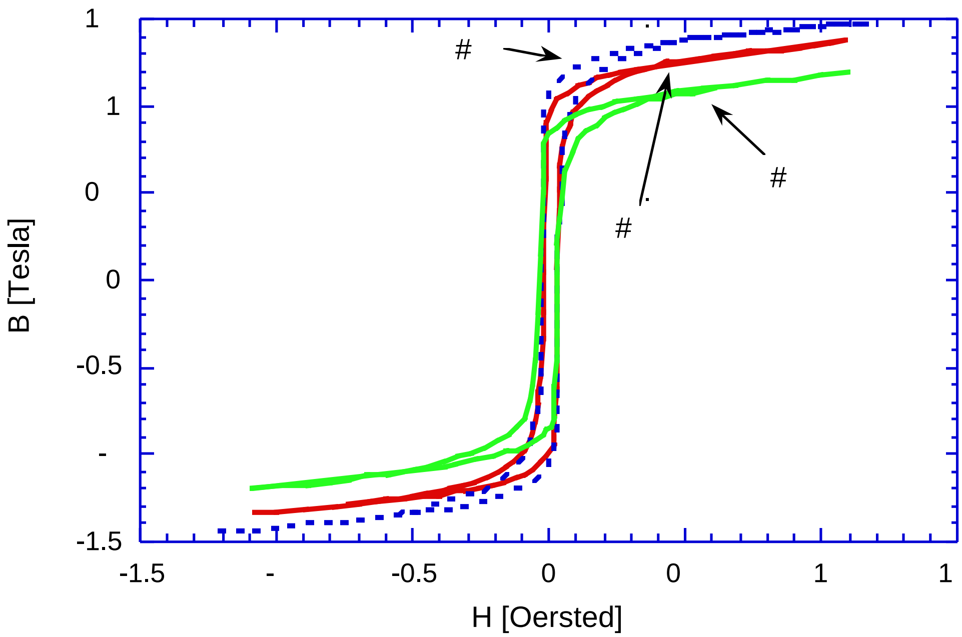

Figure 3. DC B-H loops for the core material provided by Allied-Signal for the three sample Metglas 2605 SC cores.

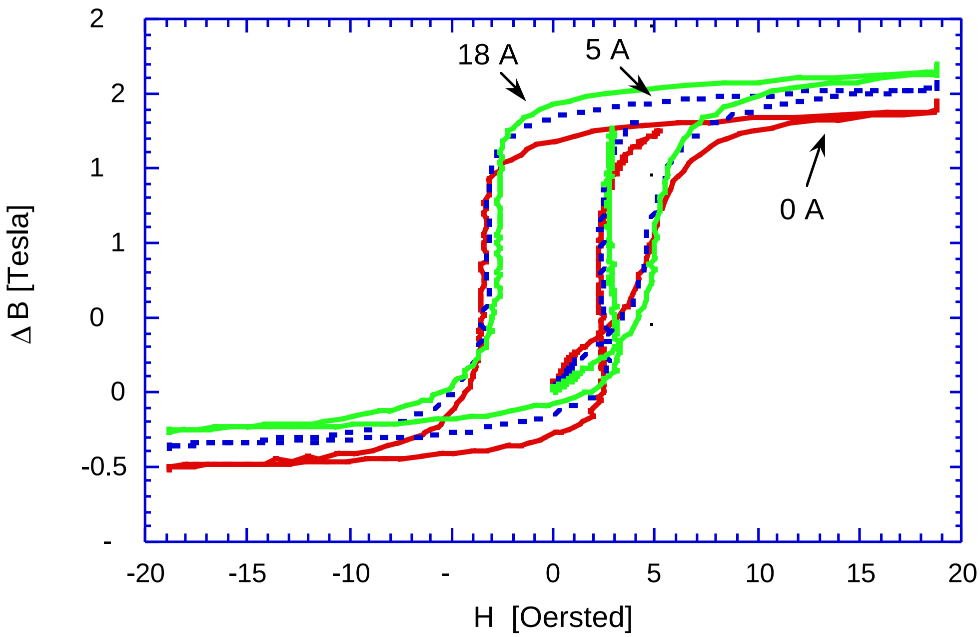

Figure 4. Pulsed B-H loops for Metglas core #1 for three bias currents: 0 A, 5 A, and 18 A. The packing factor is 70%, and the peak dB/dt in the Metglas is 2.96 T/μs.

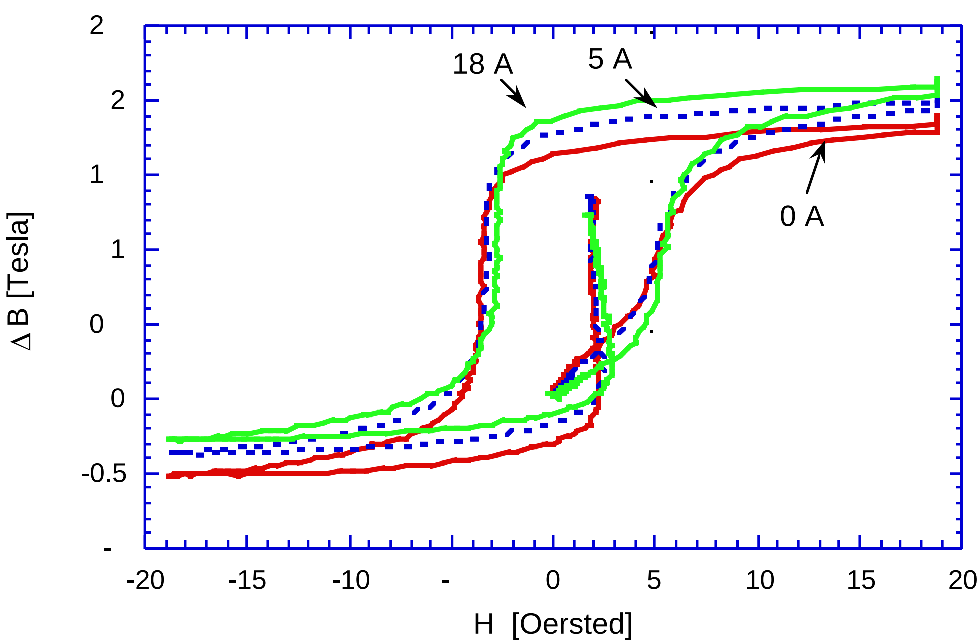

Figure 5. Pulsed B-H loops for Metglas core #2 for three bias currents: 0 A, 5 A, and 18 A. The packing factor is 75%, and the peak dB/dt in the Metglas is 2.76 T/μs.

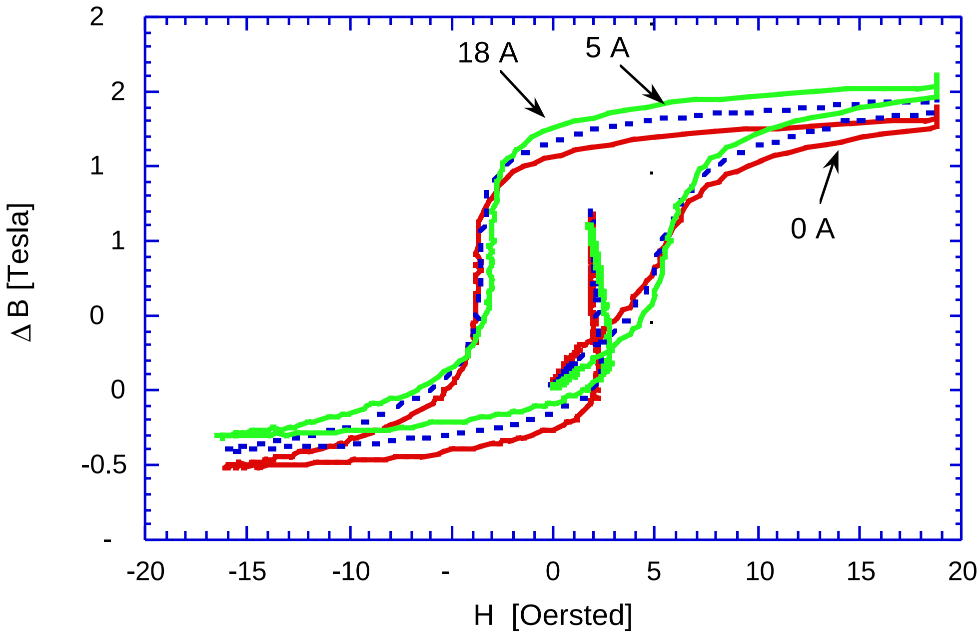

Figure 6. Pulsed B-H loops for Metglas core #3 for three bias currents: 0 A, 5 A, and 18 A. The packing factor of 76.5%, and the peak dB/dt in the Metglas is 2.71 T/μs.

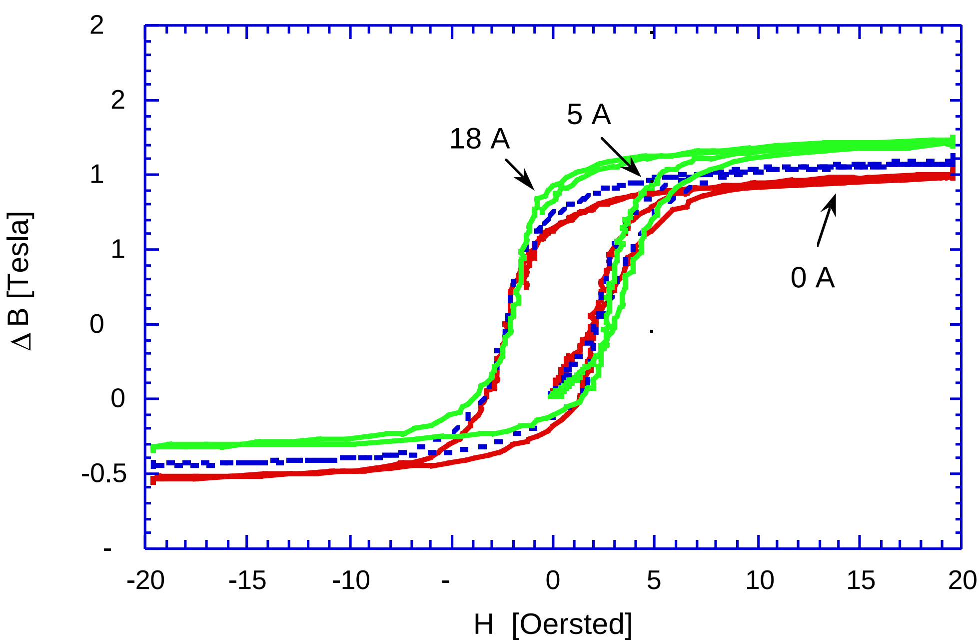

Figure 7. Pulsed B-H loops for Metglas core with kapton insulation for three bias

currents: 0 A, 5 A, and 18 A. The packing factor of 62%, and the peak dB/dt in the Metglas is 2.87 T/µs.

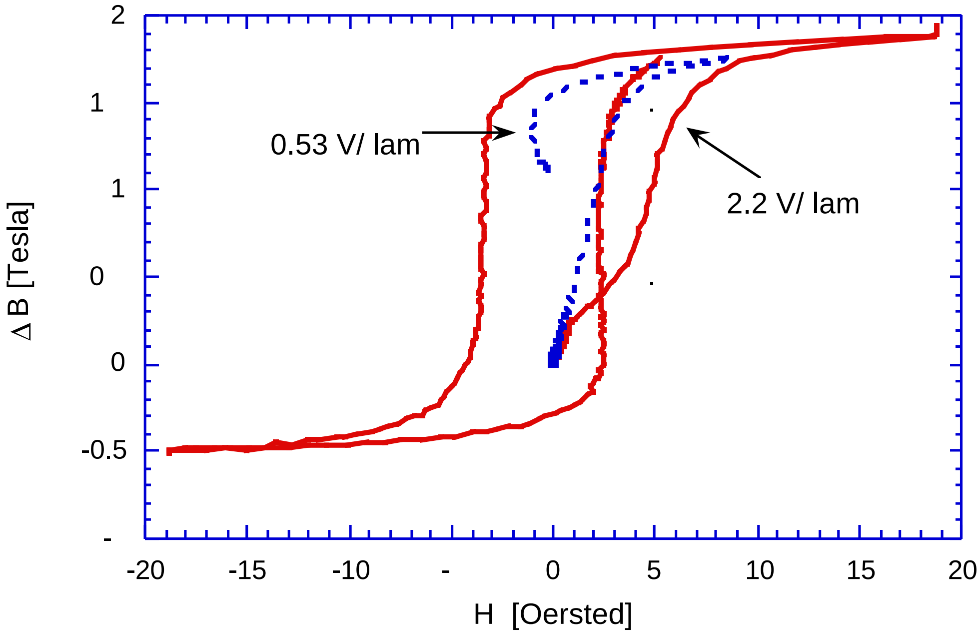

Figure 8. Shape of B-H loop for Metglas core #1 with bias current = 0. The peak dB/dt for the two curves are approximately 2.9 T/µs and 0.7 T/µs.

In addition to the reduction in flux swing (or volt-second area) for the tighter-wound cores, there is some increase in loop area between core #1 to core #3. This may represent some additional mechanical damage to the Metglas or to the fragile 3-micron mylar insulation when the cores are tightly wound. The core with the smallest loop area is the core wound with 8-micron kapton insulation, which is much stronger than the mylar insulation. If core losses are due to intermittent turn-to-turn shorts, they represent a problem because they can lead to jitter in output pulse timing. A requirement of the project is that jitter must be within a 40-ns window.

Two sets of Magnetic Metals cores were tested. The dimensions of the cores were 3.00" ID, 4.50" OD, and 1.50" tape height. They were tested using 4 turns in the circuit, instead of 1 turn, as used in the Allied-Signal Metglas tests, to better match the output impedance of the power supply.

Figure 10 shows the current and voltage waveforms and Figure 11 shows the pulsed B-H loop for a Magnetic Metals Square-50 core. The shape of the curve differs from the Metglas core curves because the magnetic properties of the material and the current and voltage waveforms are different. The loop is very square -- B-H loops are essentially independent of the bias current. This test was at 2.2 V/lamination. The B-H loops were larger than the Metglas cores, indicated higher losses in the core. Two cores were tested -

they showed virtually identical characteristics. DC resistance of the tape winding from end to end was 47 Ohms and 61 Ohms. No difference in switch performance was noted between the core in a plastic case, and one wrapped in copper shielding, to simulate the aluminum can to be used to house the cores.

Figure 12 shows the current and voltage waveforms and Figure 13 shows the pulsed B-H loop for a Magnetic Metals Silicon steel core. Measurements were performed at 0.53 and 2.2 V/lamination. The curve is not as square as the Square-50 material - although the full flux swing is larger than for Square-50, the volt-second area was comparable, and a function of bias current. Also the losses were slightly greater than for the Square-50 material. There was a large difference in the resistance of the winding from end to end, 100 Ohms for core #1 and 15 Ohms for core #2. The difference may indicate the presence of interturn shorts in one of the cores, although, surprisingly, no significant difference in performance was noted.

Two National-Arnold Metglas cores were tested. They exhibited intermittent breakdown throughout comparable tests. Results were complicated. One core broke almost immediately, at 0.4 V/lamination. The other core was subjected to an endurance test of 40,000 pulses at 0.5V/lamination. Insulation significantly deteriorated, with increases in front-porch current and intermittent breakdowns. Finally a test at 1.2V/lamination completely destroyed the core - there was no initial voltage holdoff. Figures 14 and 15 show the current and voltage pulse, and the B-H loop before and after the endurance test and 1.2-V test.

Test results from a National-Arnold Deltamax core are shown in Figures 16 and 17.

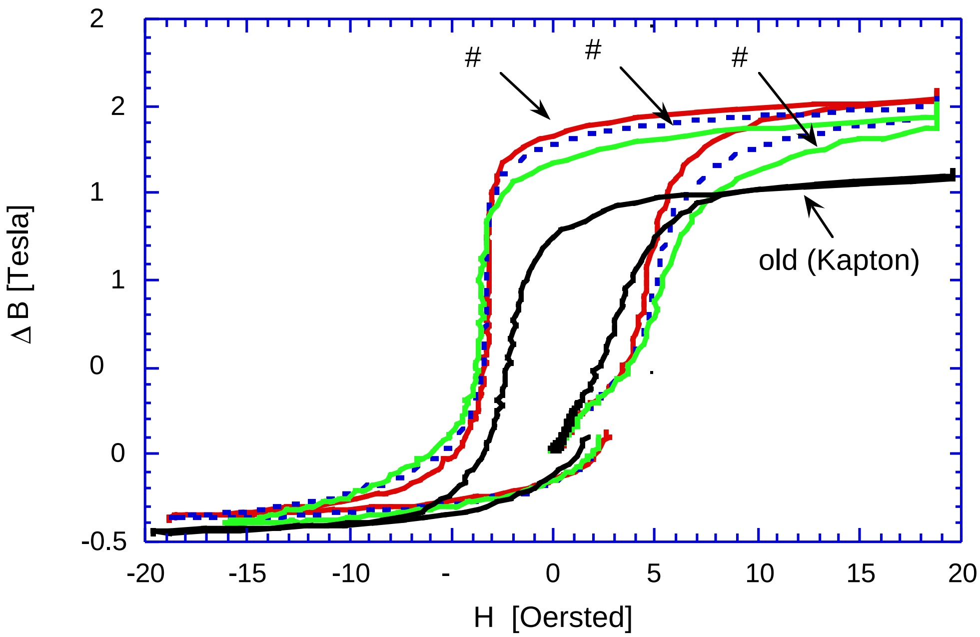

Figure 9. Pulsed B-H loops at 5-A bias current for all Allied-Signal Metglas cores tested.

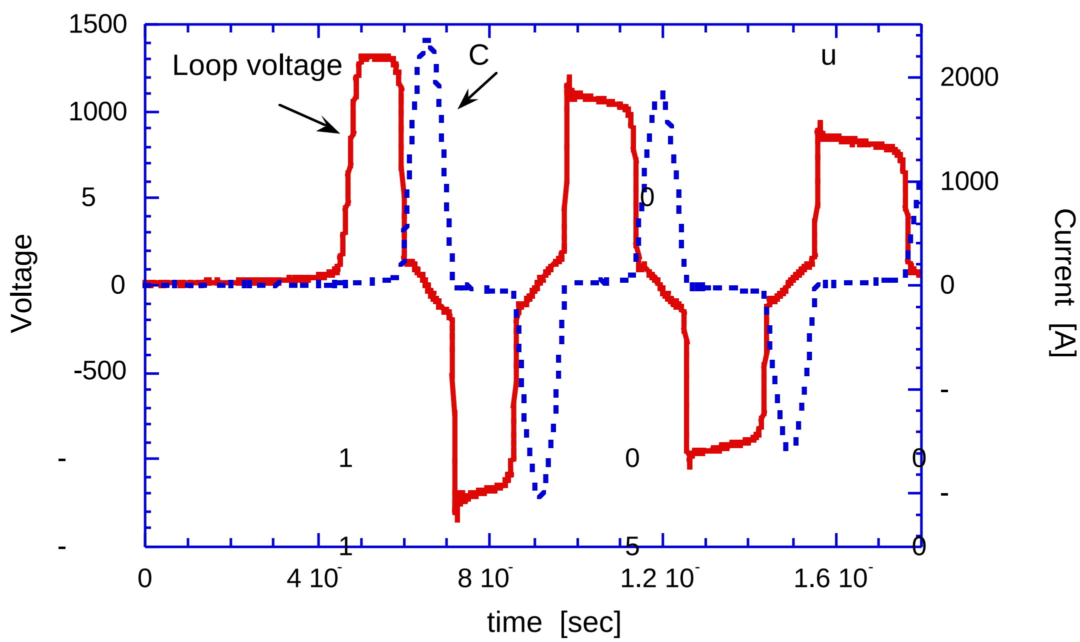

Figure 10. Current and voltage waveforms for a Magnetic Metals .001" Square-50 tape-wound core #1 at peak dB/dt of 2.24 T/μs.

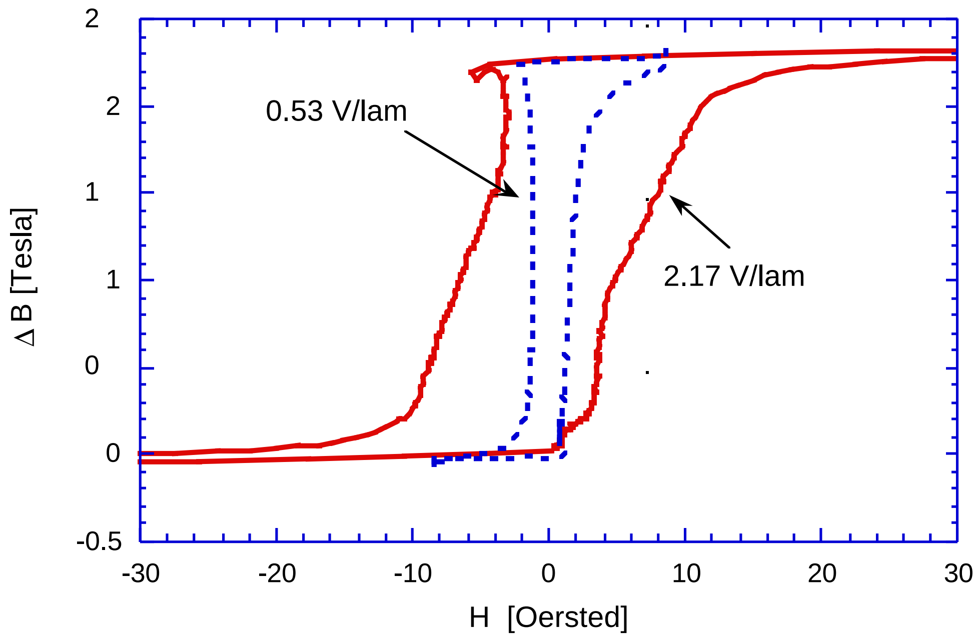

Figure 11. Pulsed B-H loop for a Magnetic Metals .001" Square-50 Ni-Fe tape-wound core, with no bias current. For a packing factor of 80%, the peak dB/dt in the core material is 2.24 T/μs and 0.55 T/μs.

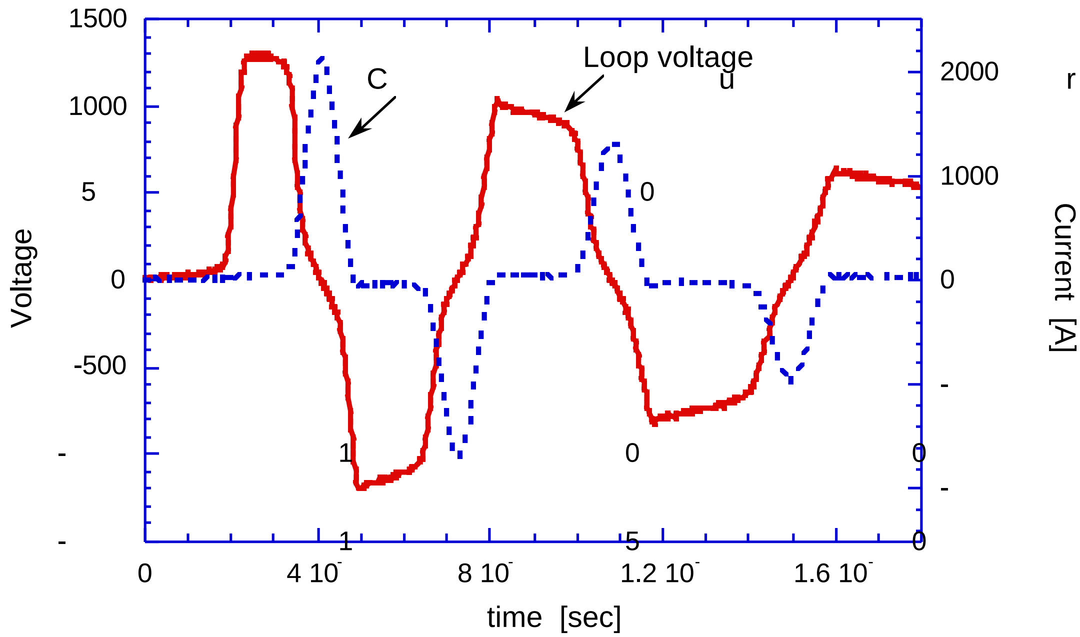

Figure 12. Current and voltage waveforms for a Magnetic Metals .001" Silicon steel tape-wound core #1 at peak dB/dt of 2.24 T/μs.

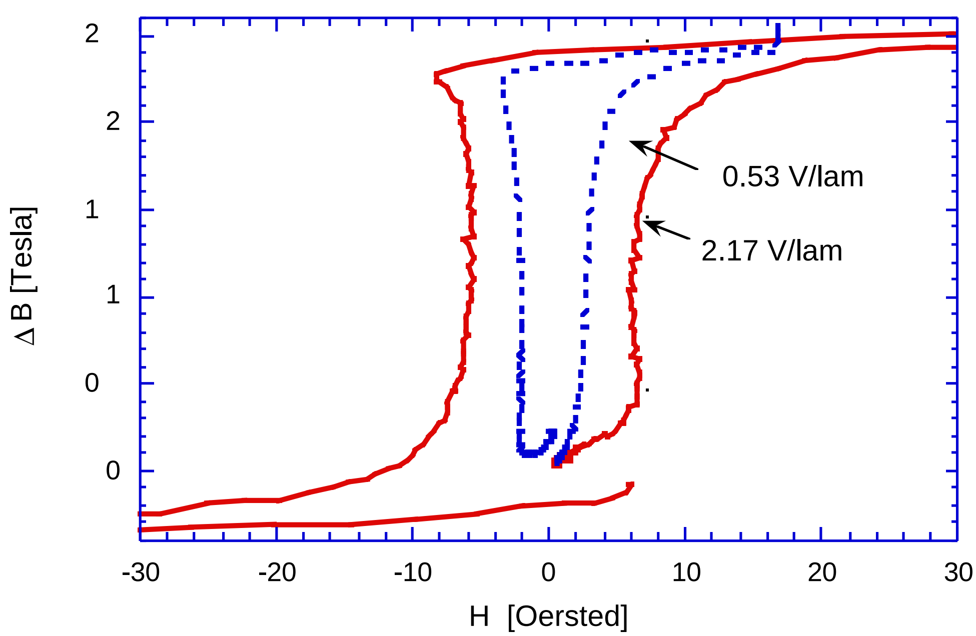

Figure 13. Pulsed B-H loop for Magnetic Metals .001" Silicon steel tape-wound core #1, with no bias current, for two different pulse voltages. For a packing factor of 80%, the

peak dB/dt in the core material for the two cases are 0.55 T/μs and 2.24 T/μs.

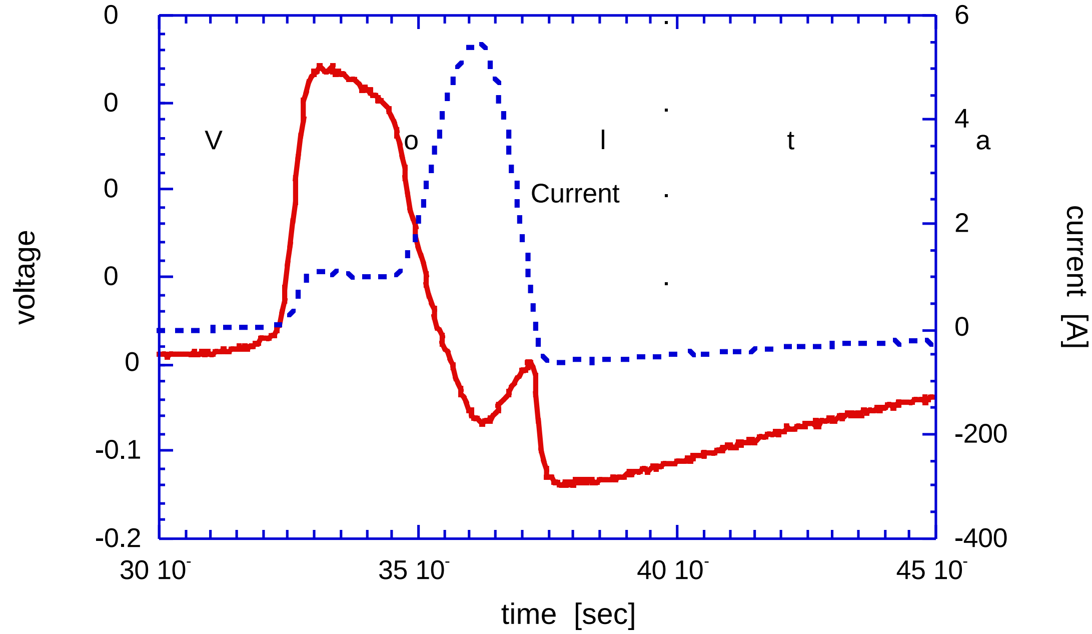

Figure 14. Current and voltage in the National-Arnold Metglas tests.

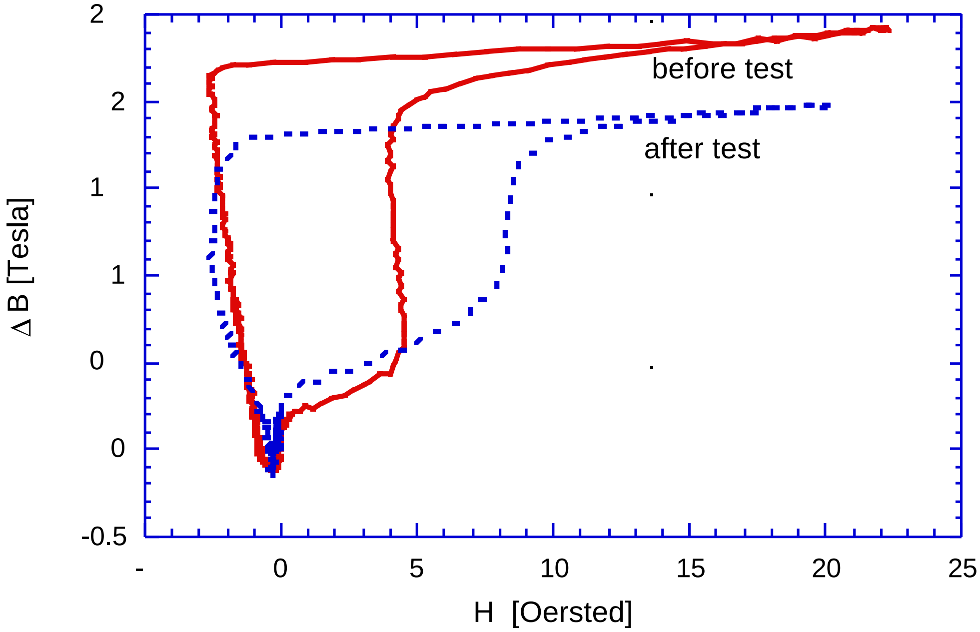

Figure 15. B-H loop before and after endurance test in National-Arnold Metglas core. Loop voltage = 0.7 V/lamination, dB/dt = 0.87 T/μs.

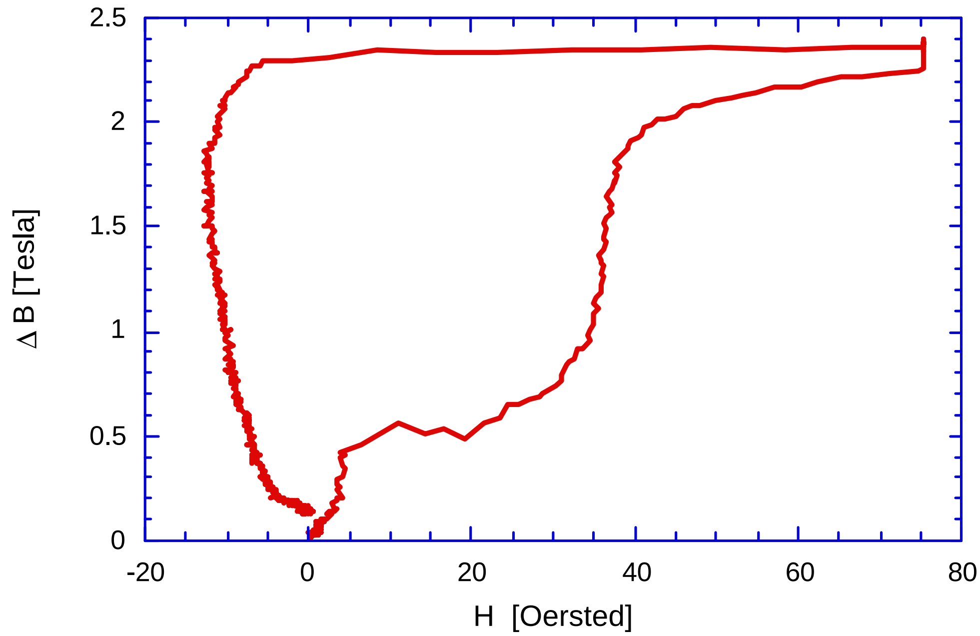

Figure 16. Pulsed B-H loop for a National-Arnold .001" Deltamax core at 1300 V peak

loop voltage, or 1.6 V/lamination (2.0 Tesla/μs). The core usually broke down at this level.

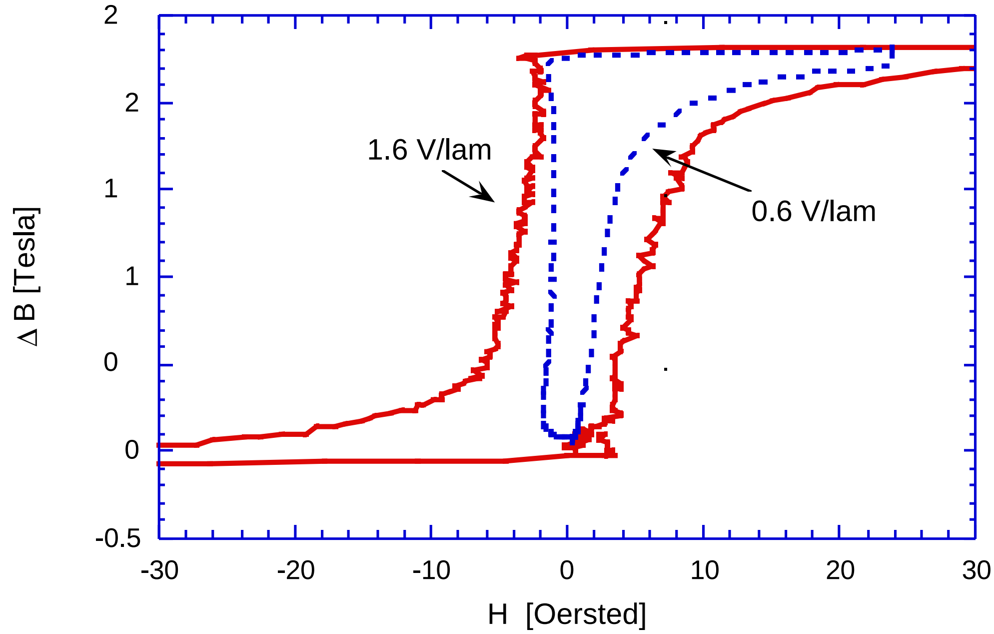

Figure 17. Pulsed B-H loop for a National-Arnold Deltamax core at loop voltages of 0.6 V/lamination, and during one of the rare occasions when it did not break down at 1.6 V/lam.

Magnetic energy is given by

$$U = \frac{1}{2}\int B \bullet H \, dv$$

where the integral is over the volume. For a core, the hysteresis energy loss in a unidirectional current pulse is the area under the B-H curve for H > 0, i.e., the energy loss per unit volume is:

$$du = \frac{1}{2}\int H(B)\, dB$$

The cores were tested at switching rates appropriate for the first stage (about 0.6 T/μs) and for the second stage (about 2.2 to 2.9 T/μs). The dB/dt tended to be higher for the Metglas core material, partially due to its lower packing factor. The core volume of the first reactor (4 cores with dimensions 5.25"OD, 3.25" ID, 1.50" height) is 1.313 x 10^{-3} m^3. The core volume of the second (Metglas) reactor (3 cores with dimensions 5.125" ID, 5.375" OD, 2.00" height) is 1.477 x 10^{-3} m^3. The energy losses calculated by integrating the area under the B-H loops (above) for various cores are listed in the tables below. Table 2 shows Metglas core losses per cubic meter of core volume (not volume of Metglas tape) at high dB/dt. Table 3 shows switching losses for the three core type deemed acceptable. The core materials chosen for the switching reactors are underlined. The total energy in the circuit is 45 J for (maximum) 3 kV charge.

Table 2

Core losses for the Metglas cores at several bias currents

Core	I=bias=0 A	5 A	18 A
1	315 J/m^3	352 J/m^3	411 J/m^3
2	353	397	475
3	370	411	479
kapton	135	155	251

Table 3

Volt seconds and magnetic switching losses for the three acceptable core materials

Core material	Volt seconds (per turn)	low dB/dt (first stage)	high dB/dt (second stage)
3 cores Metglas (#1)	9.0 mV-sec	0.18 J	<u>0.52 J</u>
4 cores .001" Square 50	9.3	<u>0.27 J</u>	0.88 J
4 cores .001" Si steel	9.7	0.43 J	1.05 J

Conclusions

We have identified core materials for use in the sweeping system that we are confident will perform reliably in the sweeping system. The Metglas cores have the lowest losses, and possibly the best insulation, when wound with mylar film. They appear to be the best choice for use in the second compression stage. The Magnetic Metals Square 50 cores have a slight advantage over the Silicon steel cores, but both are acceptable for use in the first stage. The performance of the tape cores appears to be strongly dependent on the supplier, even for nominally comparable tapes. The Metglas cores require careful cowinding with mylar film, and should be wound with as little tension as possible, to avoid damaging the Metglas tape and the insulating film.

References

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