Pbar Note #606

Magnetic pressed-powder cores for sweep magnet

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Due to the highly unusual requirements placed on it, the sweep magnet is radically different in design from any other magnet at Fermilab, both in terms of its spiral conductor arrangement and the use of powder cores in the magnetic circuit. It has successfully operated for millions of pulses on the bench. This report describes the properties of the magnetic cores and the expected effects of the extreme environment of the target station.

MARS and CASIM calculations of energy deposition downstream of the target, supported by measurements on the high-voltage test module, show significant heating of iron and ferrite magnet test cores downstream of the target. Total heating increases linearly with proton beam intensity, and is a strong function of the radius of the magnet core.

Four magnetic materials were considered for use in the return yoke, before choosing the powder core material.

1. Ferrites. Ferrites have poor thermal conductivity, a low Curie temperature, a low saturated magnetic flux density, and exhibit short-term radiation effects [Ref. 1]. It would be necessary to operate a ferrite-core magnet with a large inner radius to minimize beam heating, and a large outer radius to minimize magnetic field in the core. Maintaining adequate cooling under these conditions would be very difficult. They are unacceptable for use in the sweep magnet.
2. Tape-wound cores. A stack of tape-wound cores could be used as the return yoke. However the fact that the magnetic field lines need to twist on entering the cores from perpendicular to parallel to the direction of the tapes causes excessive losses in the magnetic field.
3. Silicon-steel laminations. A stack of thin laminations with thickness .004" or less is a potential candidate for the return yoke. These laminations typically have insulation strength of 1 - 2 V per lamination, or 250 V/inch for .004" laminations. Expected voltage per lamination for .004" laminations is in the range 2 - 4 V, which may exceed the strength of the insulation. Each magnet requires over 5000 laminations. Difficulties are expected in preparing and stacking the thin laminations.
4. Powder cores. There are three candidate magnetic powder core materials. These are 2-81 Molybdenum Permalloy (MPP), High-flux (50Ni-50Fe), and Sendust (85.5Fe - 9.5Si - 5Al). The one chosen for the prototype magnet is MPP, because it has the lowest losses. These cores are cheap and assembly is simple. Their relatively high thermal conductivity and Curie temperature (> 400 deg C) significantly simplify the thermal restrictions compared to ferrites. The thermal stresses are small and can be contained by press fitting the cores in a water-cooled nickel housing. This design provides a stable rigid structure under any conceivable thermal or mechanical stress. Nickel was chosen for the housing because it has the same thermal expansion coefficient as the MPP cores.

Estimated beam thermal power is 54 Watts per core at 1 x 10^{13} protons per pulse and a 1.5-sec rep rate, or a total power of 1944 Watts for 36 cores. The expected temperature gradient from core ID to OD is about 5 degrees Centigrade.

The cores have an inorganic ceramic-type insulation, and all three types are manufactured by essentially the same process. In the case of MPP the process is to first produce the powder by embrittling the permalloy powder by the addition of a few thousandth of a percent of sulfur. The powder is then mechanically comminuted. A small amount of talc is added to the powder before it is heat treated between 630 and 760 deg-C. The heat-treated powder is coated with an inorganic insulating mixture of sodium silicate, magnesium oxide, colloidal clay, and kaolin. Zinc stearate is added as a pressing lubricant, and the mixture is pressed at 1650 MPa (240 ksi) into the shape of the desired core. Cores are heat treated at 630 deg C to relieve the stresses introduced during pressing without impairing the insulating properties of the coating. [Ref. 2]

The cores chosen for the prototype were μ=125 MPP cores. However the μ=60 cores have significantly lower electrical losses, and are mechanically stronger than the μ=125 cores. From visual inspection of the (Magnetics) cores, it appears that the cores with μ of 60 and lower have finer grains of magnetic material than those of 125 and higher. One would expect a finer-grain material to have greater mechanical strength and lower losses. Figure 1 shows the results of a tensile strength test. A mechanical test of the other types of cores was not done. However the Sendust material does appear to be more brittle than the MPP.

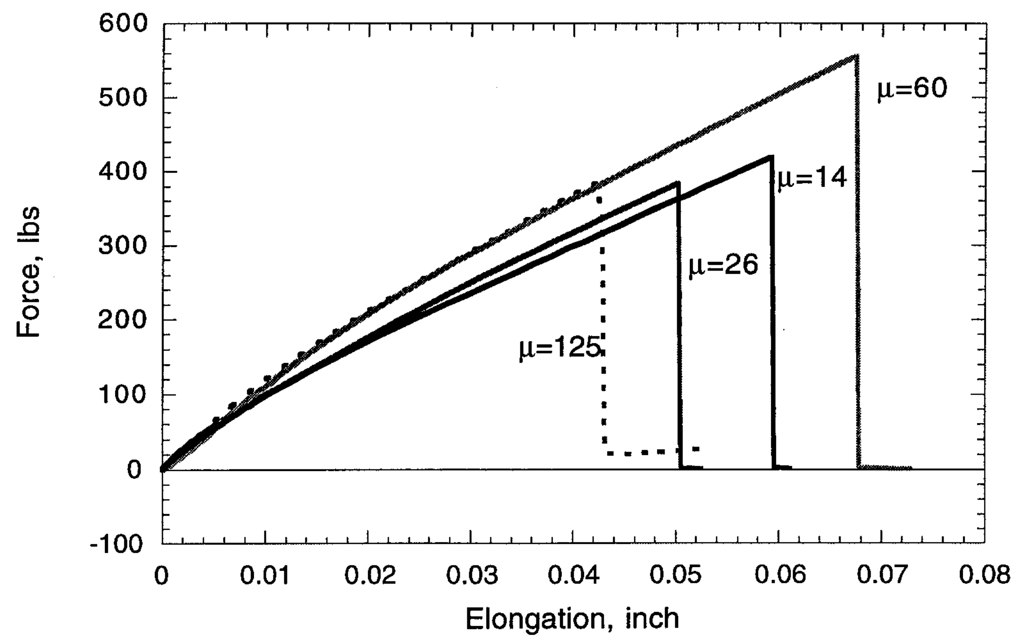

Figure 1. Tensile strength test of several MPP cores. OD = 3.063", ID = 1.938", height = 0.500". The test was done by Kurnaev and Cherepakhin.

Since the amount of electrical insulation in the magnetic circuit is proportional to $1/\mu$, the μ=60 cores have more than twice as long a path length of insulation as the μ=125 cores. In fact, this amount of insulation compares favorably to that typically present in silicon-steel laminations. Figure 2 shows the effect of μ of the cores on magnet current required to achieve a given axial field. The effect is small -- the current required for μ=60 is 1% higher than for μ=125. Magnets to be built in the future should use the μ=60 cores. The structure and properties of the cores from the two manufacturers are quite similar, but we prefer the Magnetics cores over the Arnold cores because the paint on the Magnetics cores is easily removed by immersing them in boiling hot water.

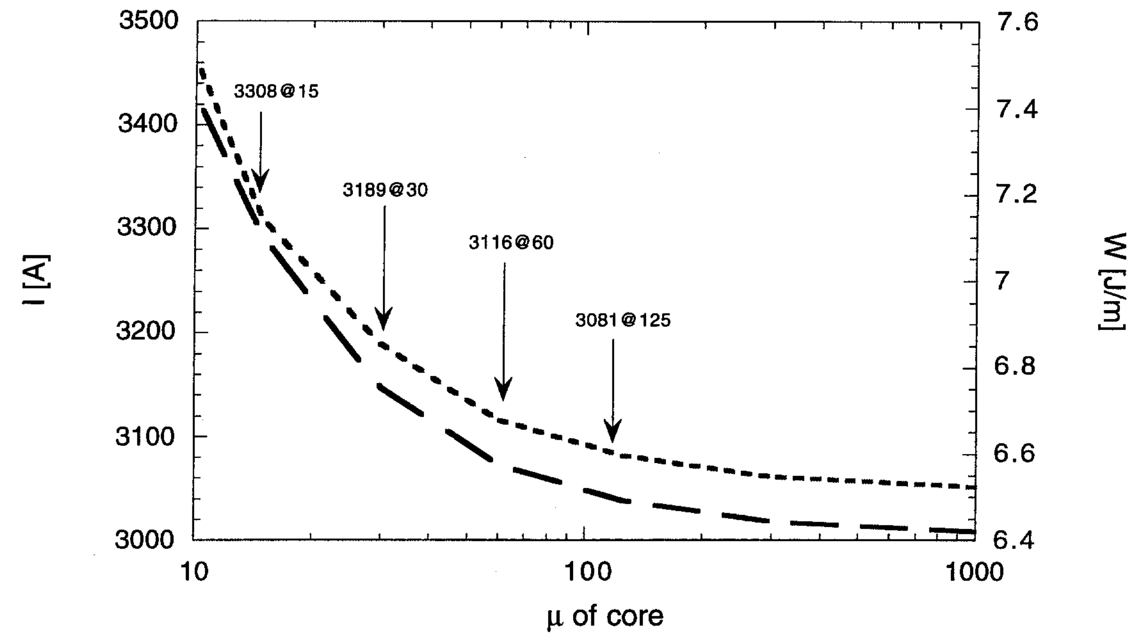

Figure 2. Effect of μ of core on sweep magnet current (upper curve) and stored energy (lower curve) corresponding to a field on axis of 2 kG, from a POISSON calculation.

Ref. 3 discusses the effects of radiation on magnetic materials. Table 1 reproduces a portion of Table 7.5 of Ref. 3, where $R/\mu Lf$ = core loss factor = $2\pi/\mu Q = aB + ef + c$, c = residual loss coefficient, a = hysteresis loss coefficient, e = eddy current loss coefficient.

Table 1

Effect of irradiation with 2 x 10^{18} fast neutrons/cm^2

Material		μ	a	e	c	R/μLf
MPP	before	123	1.5	20	10	500
	after	122	1	40	10	1000
Sendust	before	175	10	5	180	500
	after	195	11	30	20	1100

In the measurement, the loss factor increased a factor of two in both cases. The cores showed some degree of recovery toward their pre-irradiation properties after 10-month storage at room temperature. In addition, tests with other magnetic materials showed the rate of deterioration slows down above 1 x 10^{18} neutrons/cm^2, possibly implying a saturation level of fluence beyond no further damage occurs.

We expect 10^{12} neutrons/cm^2/pulse (10^{11} fast neutrons/cm^2/pulse) in target station operation [Ref. 4]. So the results listed in the table correspond to roughly 1 month to 1 year of operation, assuming 1 million pulses per month.

The major components of the core are nickel, iron, and molybdenum. Nickel and iron (in the form of stainless steel) have been used successfully in target station components. On the other hand, molybdenum has not been used in the target station, to my knowledge. The Reactor Handbook states that molybdenum has a low thermal neutron capture cross section and has attractive properties for nuclear reactors. So it should not be a problem either. A 125μ MPP core was unaffected by radiation in a test at the Booster extraction septum to 1 MRad both in terms of magnetic properties, and mechanical properties (swelling).

A further irradiation test by Hiep Le in the target station is planned for a MPP core and a High-Flux core. A small Sendust core will also be tested. The test will determine whether there is any swelling, which could be dangerous in a press-fit core, and whether there is any significant deterioration in magnetic properties (magnetic permittivity and high-frequency losses). A test stand for sensitive measurement of the high-frequency magnetic properties of the cores has been completed and is located in the cage.

Q measurements

Two large cores have been prepared for installation in the target vault for radiation test. Both are 60 mu powder cores from Magnetics. The first is an MPP core #55867, marked MPP 60 +8. The second is a high flux core #58867, marked HF 60 +0. Tests of the cores showed that the Q of the MPP core is about 21 and the Q of the high flux core is about 12 in the vicinity of 700 kHz. The measured and predicted (from Magnetics powder cores catalog) values for Q are in reasonable agreement for the MPP core, but the actual losses are lower for the HF core than predicted by the catalog. The reason for this fact is not clear. They both compare favorably with the measured Q of the 125 μ core in the prototype magnet, which is Q=7.

Table 2
Mechanical properties of the cores:

	high flux	MPP
height	0.500	0.511
OD	3.093	3.091
ID	1.932	1.930
weight	259.8 g	273.9 g

The size measurements were made with the kapton insulation and steel band in place. The weights were of a pair of fresh cores, not the ones prepared for test. An additional sendust core of smaller size, National Arnold #MS130060-2 was also prepared for test. The paint was not removed and a steel band was not placed around the core. A core of the same size as the other cores was not immediately available for test. Measured Q was 21.

The cores are double wrapped on each side (6 turns, 12 wraps) with #20 magnet wire. Insulation is 0.3-mil kapton film. The cores have a steel band around the outside to simulate the press-fit nickel tube around the cores.

Tests to be done after radiation exposure:
1. Check for mechanical damage, any evidence of swelling or shrinkage of the core material.
2. Do electrical tests with the test stand as below
(a) Resonant frequency and amplitude
(b) Effect of a pulsed bias current on resonant field and amplitude.
Performance before the radiation test are shown in the figures below, and summarized in the spreadsheet "MPP cores Q measurements". Performance should not be appreciable different in the test. The droop near the end of the current pulse is probably due to saturation of the Pearson 110A current monitor. Note that the MPP core shows some deterioration in mu at peak current (about 3 kG field). There is little effect of pulsed bias current on mu of the high-flux core.

The circuit is contained in a series of boxes and looks like this:

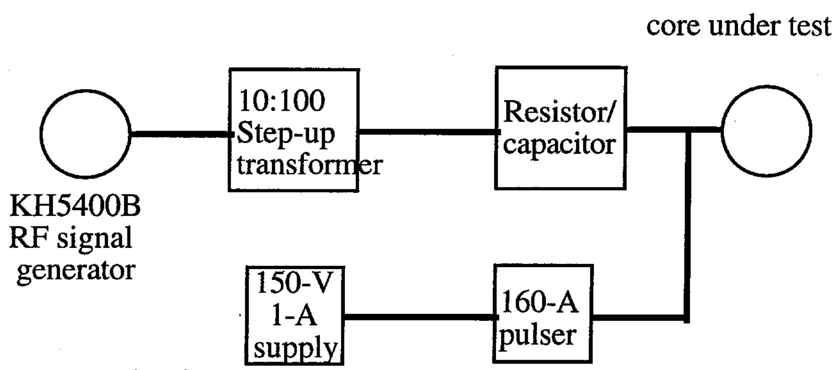

Figure 3. Test circuit.

Solid lines represent RG-58 cables with bnc terminations. The series resistor is $R_s = 5$ kOhm, to isolate the resonant circuit from the signal generator. The value of the capacitor which resonates with the core is 0.0165 µF. The current pulser is teed into the circuit in parallel with the rf circuit. When measuring the rf voltage at the output end of the step-up transformer, use a high-impedance scope probe, to avoid loading down the signal. When measuring high-field performance, pulse about once every 10 seconds to allow the pulser capacitor (1300 µF) to charge up.

The Q of the resonant circuit is determined by measuring the transformer secondary voltage V_0 impressed on the series resistor R_s and the voltage V_{core} across the core under test at resonance. The effective resistance of the resonant circuit at resonant frequency f was calculated by

$$R_{eff} = R_s \frac{V_{core}}{V_0}$$

and the Q of the circuit was calculated by

$$Q = 2\pi f R_{eff} C$$

Table 3 shows the results of the measurements. An air-core inductor made of copper tubing was used to determine the Q of the circuit independent of the cores. The second Magnetics #55866 core was the core irradiated in the Booster. Note that the μ=60 cores have higher Q than the μ=125 cores, which in turn have higher Q than the μ=300 core tested.

Table 3
Bench test results for several cores.

vendor	core	type	μ	# turns	V_0	V_{core}	f [kHz]	Q
	copper tubing				92.8	9.52	729	43.2
Magnetics	#55866	MPP	125	4	127	2.54	713	7.5
"	#55866 (radiated)	MPP	125	4	126	2.2	724	6.7
"	#55867	MPP	60	6	94.4	5.32	699	21.6
"	#58867	HF	60	6	92.8	2.96	717	12.3
"	#55104	MPP	300	4	133	1.92	500	3.8
Arnold	#MSS13 6060-2	Sendust	60	6	97	4.78	778	20.9
"	#A07106 5-2	MPP	60	6	94	5.2	696	21.1

MPP is the nominal choice for the core material, because of its low losses. This test will determine whether it continues to perform acceptably after a large dose of radiation. If there is any deterioration in the MPP core performance, hi-flux core appears to be a good alternative. Its advantage is the absence of molybdenum, and operation at higher field -- the effective μ of MPP starts to drop when magnetic field is in the 3 kG range. We may need to operate up to 6 kG in the core. (Peak field in the core is higher than field on axis because of the geometry of the magnet.) An acceptable core Q is quite low - Q of 1 is roughly the lower limit (most of the energy in the magnet circuit is in the air gap, not in the core). The mechanical strength and properties of the two cores should be quite similar, because they have the same binder, etc. The Sendust core is to some extent a compromise between the two large cores in properties. The peak field is higher than MPP, and losses are comparable to MPP. But Sendust may not be mechanically as strong as MPP.

References

1. FM Bieniosek, Summary of results for the beam sweep test module, Pbar Note #556 (6/1/1995)
2. Materials Handbook, vol. 7: Powder Metallurgy (American Society for Metals, 1984), p. 644
3. CW Chen, Magnetism and metallurgy of soft magnetic materials, Dover, 1986.
4. FM Bieniosek, Consequences of a lithium lens failure, Pbar Note # 550 (2/16/1994)

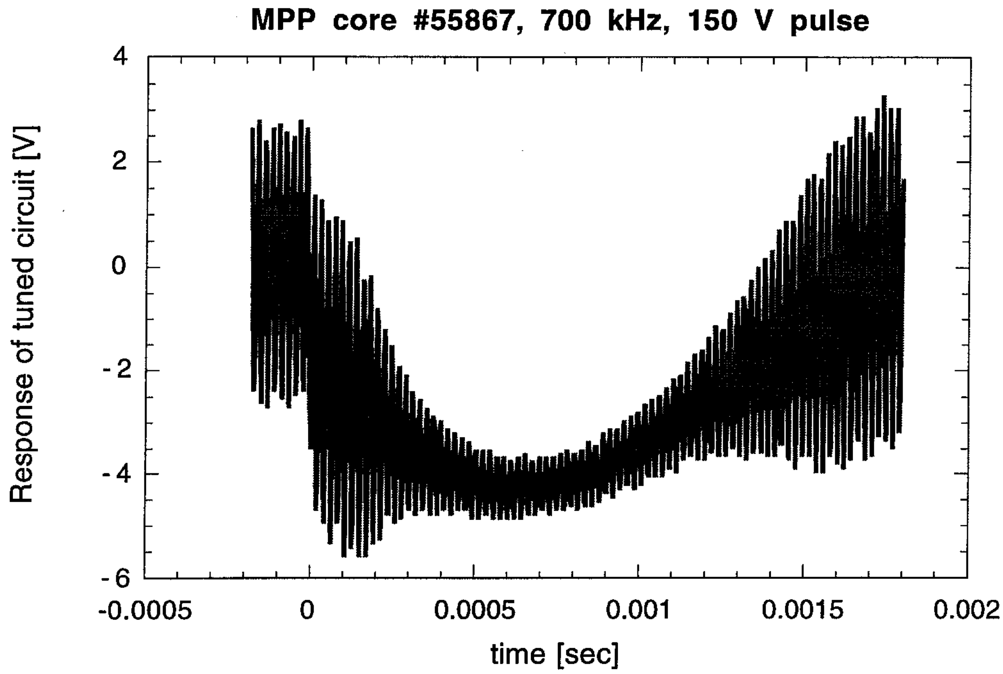

Figure 4. Response of MPP core to 160 A current pulse at resonance, 700 kHz.

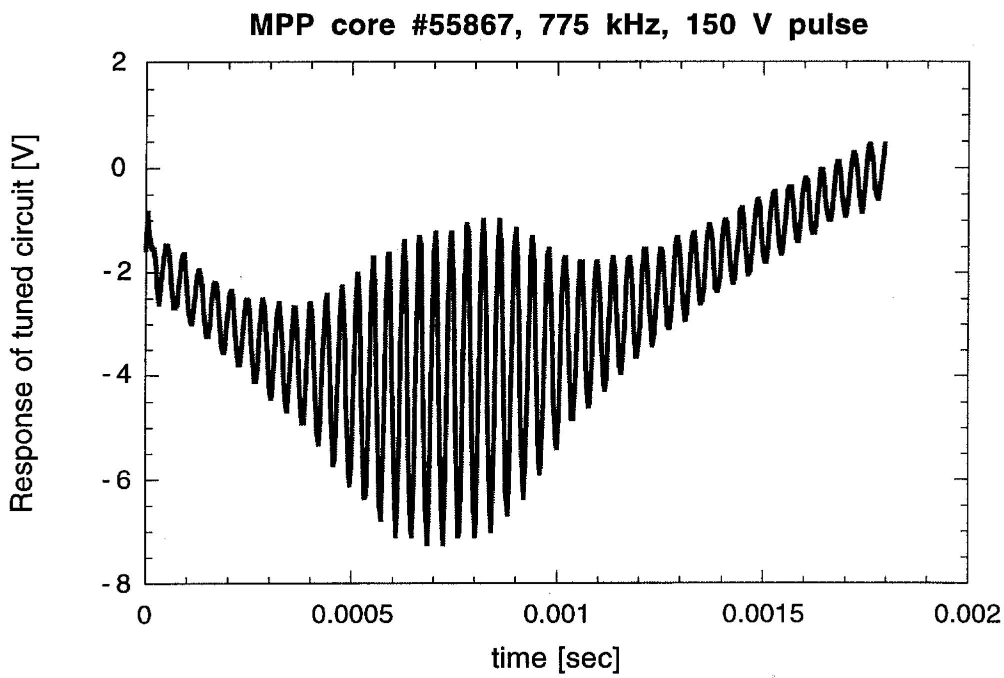

Figure 5. Response of MPP core to 160 A current pulse at 775 kHz.

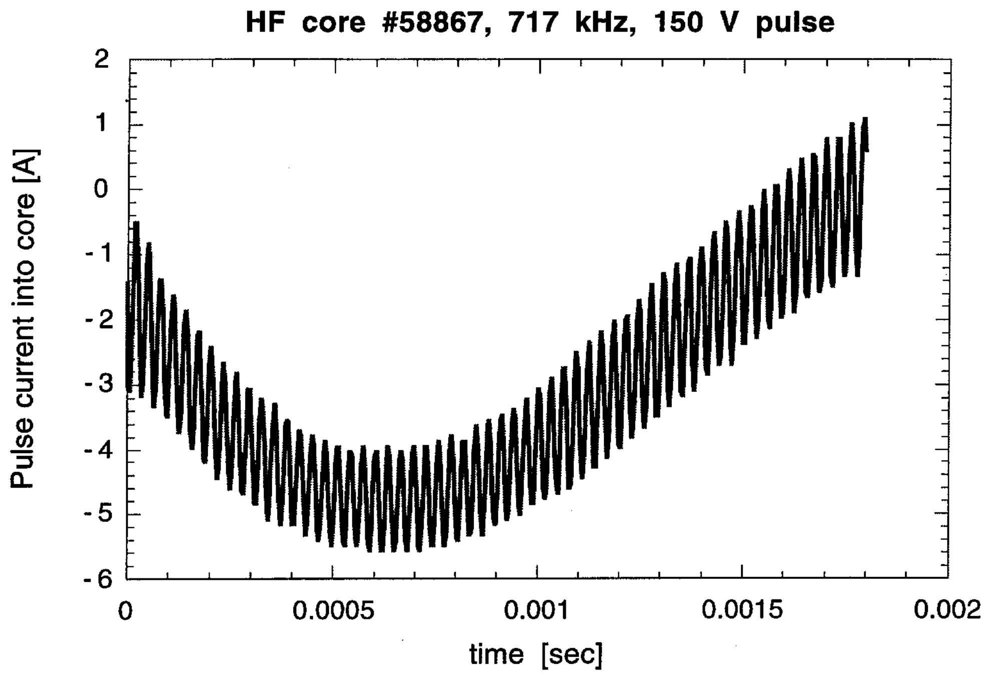

Figure 6. Response of HF core to 160 A current pulse at resonance, 717 kHz.

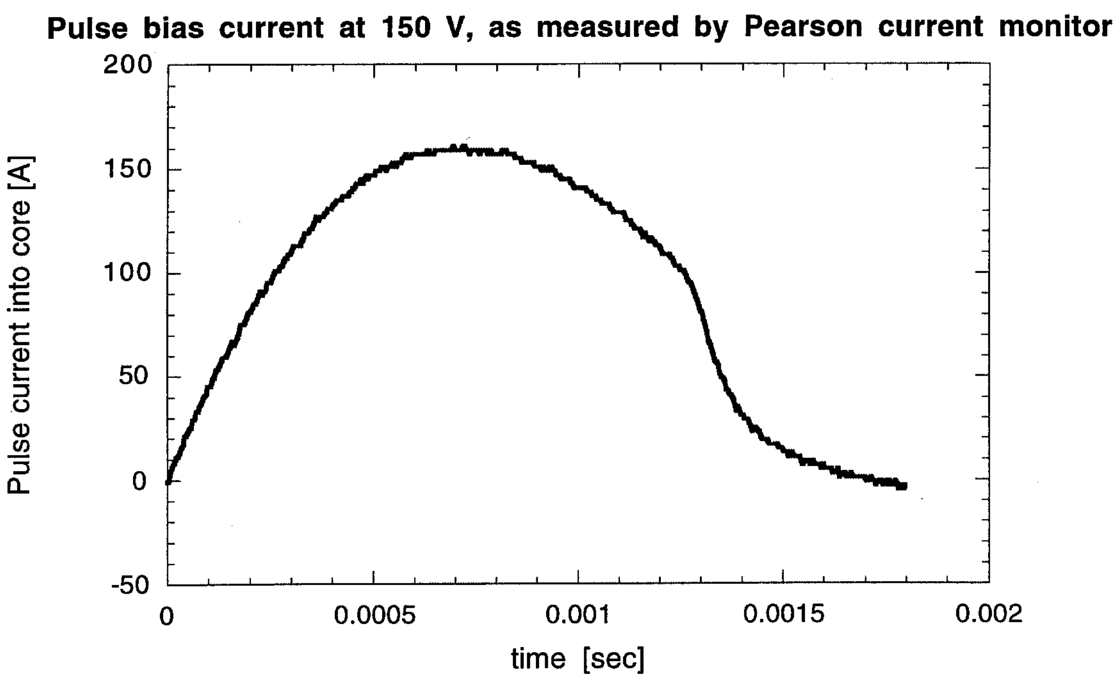

Figure 7. Pulse bias current waveform.