POSSIBILITIES FOR FUTURE LEVITATED OCTUPOLE UPGRADES

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Assuming a favorable outcome of the high power octupole experiments which are about to be done and a viable advanced fuel candidate, there will be considerable interest in scaling to higher field and longer pulse lengths. Although it has been assumed that a major and expensive (~ $28M) new device would be required, it behooves us to examine carefully the pssibility of meeting at least some of these objectives with relatively inexpensive ($\lesssim$ few $M) modifications of the existing octupole. The purpose of this note is to outline several such possibilities.

In order to increase the field without reducing the ring-to-wall distance in the bridge, a higher ring current is required. This will require a larger capacitor bank. Unfortunately, the existing iron core is barely adequate for the present 600 kJ bank. However, by reverse biasing the core, a factor of two increase in flux and hence in ring current is possible. Furthermore, because the machine is designed with close coupling between primary and continuity windings, and because the continuity windings were accurately tailored to match the wall current density, one can imagine operation with the core saturated if enough bank energy is available. An easy way to visualize this is to note that the magnetic energy density in the iron core is given by $B^2/2\mu$. For low fields, μ is large (several thousand μ_o), and so the core energy is negligible. When the core saturates, μ approaches μ_o, and a significant additional energy is required to maintain the core flux.

The energy requirement for a given ring current I_R can be estimated as follows. To the extent that the walls, rings, and continuity windings are perfect conductors, the magnetic flux change in the core is equal and opposite to the magnetic flux in the machine given by

$$\Phi = L_R I_R \tag{1}$$

where L_R is the ring inductance (0.71 μH for modest soak-in). The above equation, and all those that follow are in MKS units unless otherwise specified. The field in the core is given by

$$B = \Phi/A - B_r \tag{2}$$

where A is the cross-sectional area of the core (~ 0.58 m^2) and B_r is the dc reverse bias field in the core. The magnetizing force H can be determined from the B-H curve of the iron using the graph in Figure 1, which is the manufacturer's specification for Allegheny Ludlum A-L M-19 Transformer C. An approximate analytic fit, valid in the saturated region ($B \gtrsim 1.2$ tesla) is given by

$$B = \mu_o H + 2.41 + 0.148 \ \ell n \ (\mu_o H) \tag{3}$$

The fit is shown as a dashed line in Figure 1.

Neglecting the usually small energy stored in the reverse bias field in the core, the energy deposited in the core during a pulse is

$$U_c = A\ell \int_0^H BdH \qquad (4)$$

where ℓ is the major circumference of the core (~ 8 meters). From the analytic fit above, the energy can be calculated:

$$U_c = A\ell[\frac{1}{2}\,\mu_o H^2 + 2.26\ H + 0.148\ H\ \ell n(\mu_o H)] \qquad (5)$$

Acutally, the first term in the brackets, which dominates at large H ($\mu \to \mu_o$), is an overestimate since it assumes a uniform field throughout the volume of the core ($A\ell$) whereas, in reality, there would be a considerable fringing field outside the core. The $\mu \to \mu_o$ asymptotic limit can be calculated from the parallel inductance of four decoupled solenoids with dimensions equal to that of the primary windings (1 m dia. x 1 m long). The result is a reduction in the first term by a factor of ~ 1.84:

$$U_c = A\ell[0.27\ \mu_o H^2 + 2.26\ H + 0.148\ H\ \ell n(\mu_o H)] \qquad (6)$$

Combining equations (1)-(2), one can relate H to I_R as

$$L_R I_R/A - B_r = \mu_o H + 2.41 + 0.148\ \ell n(\mu_o H) \qquad (7)$$

The total energy required to achieve a given ring current is then given by

$$U = \frac{\Phi^2}{2L_R} + U_c \qquad (8)$$

This result is plotted in Figure 2 for a demagnetized core (B_r=0) and for a core with a reverse biase of B_r = 1.4 tesla. For small values of ring current, the core energy is negligible (iron core limit), but one pays an increasing energy penalty by operating the core into its saturated region. Also shown is the capacitor bank cost assuming 10¢/joule. As can be seen, it should be possible to achieve ring currents in excess of 3 MA for under $1M. This calulation may be slightly optimistic because resistive losses and leakage inductances have been ignored.

One concern is that the magnetic forces on the primary and continuity windings may be excessive. The magnetic pressure on the windings is given by

$$p = \frac{1}{2} \mu_o H^2 \qquad (9)$$

which has a value of 1.6 lb/in^2 for a 3 MA reverse biased case (μH_o=0.2655 teslas). Such a value certainly appears tolerable.

A circuit for reverse biasing the core to 14 kG would have to provide ~ 15 oersteds or 12 kA-turns or 133 A in our 90 turn primary. The most straightforward way to provide this is through an inductor with a sufficiently large value such that very little energy is robbed from the bank during the pulse. If we are willing to tolerate a loss of 10% of the energy that gets to the machine, the required inductance is

$$L = 10(90)^2 L_R = 57.5 \text{ mH} \qquad (10)$$

Although an iron core inductor might well be more economical, let's assume an air core inductor with a length of 2 meters (so as to fit in the space behind the wall). The optimum inductor has a diameter equal to 2.451 times its length (or 5 meters), and to get the required inductance in a single layer, we would need about 100 turns or ~ 5000 ft of wire. If we allow the inductor to dissipate 10 kW of power, which could be removed with forced air cooling, the coil resistance could be as high as 0.56 Ω, requiring the use of single 0 wire. The inductor would weigh less than a ton. The wire costs and the cost of the 75 V, 133 A power supply and switching circuitry would be a small fraction of the capacitor bank costs. This design is only meant to demonstrate feasibility, and considerable latitude in cost tradeoff remains.

All of the above considerations assume a relative flux loss due to field soak-in that is the same as we presently have at the peak of the 43 msec half sine wave (~ 34% usable flux). If we add capacitors to the bank at the same 5 kV as the present bank, the period will lengthen, and the energy loss will increase. We could go to a higher voltage bank, but then the primary insulation would have to be carefully examined and monitored. On the other hand, it may be desirable to lengthen the electrical pulse if the confinement of the high energy plasmas is as good as some hope. We are thus led to consider means to reduce the soak-in losses.

The most fundamental problem is the internal rings, and the most straightforward solution is to reduce their resistivity. For the same soak-in, the pulse length is inversely proportional to the square root of the resistivity. By going from aluminum to copper, one would gain a small factor of 1.3 in pulse length. If the copper were cooled to liquid nitrogen temperature (77 K at standard pressure) the factor would be about 4 (see Figure 3). A further improvement would result if the liquid nitrogen system were opeated at reduced pressure. In a levitated system, one would have to rely on the heat capacity of the rings to maintain the low temperature during the pulse. To see if this is reasonable, we can estimate the temperature rise in a inner ring (the worst case) during a pulse. Assume that each inner ring dissipates 1/3 of the total energy in the bank. Using the specific heat of copper (205 J/kg/^{o}C @80 K) and the estimated mass of a ring (1400 kg) gives a temperature rise of 1.2^{o}C/pulse per MJ of bank energy. Such a temperature rise seems tolerable for a bank of modest energy. Of course, one would have to remove the heat from the rings between pulses or between every few pulses. From the heat of vaporization of liquid nitrogen (161J/cm^3), one can calculate that 6.2 liters of nitrogen would be required/MJ/pulse in the steady state for all four rings. A more heroic solution to the pulse length limit is to use superconducting rings. Such a technological undertaking would be less formidable if a parallel superconducting bumpy torus effort were underway.

The soak-in at the walls is amenable to a number of possible solutions. First, one could imagine cooling the walls to liquid nitrogen temperature. A thin cryogenic copper liner could also be installed inside the machine. The liquid nitrogen requirement would be quite large, and experimental access would be inconvenienced, although there is precedent for operating machines in a cryostat (e.g. Alcator).

Second, one could make up the wall losses by means of a power crowbar. Such a crowbar would have to provide the order of 10 MW at a primary voltage of ~ 1000 volts for 1 MA of ring current. A power crowbar would further exacerbate the core saturation problem, however. Finally, one could imagine additional external windings, especially in the vicinity of the noses, perhaps using cryogenic copper. Some combination of these solutions could well provide a factor of 4 increase in wall soak-in time, making the wall losses compatible with the losses for a cryogenic copper ring.

Of course, lengthening the magnetic field pulse only makes sense if the energy confinement time of the heated plasma exceeds ~ 20 msec which we can presently accommodate. In that event, it would be necessary to extend the duration of the heating sources (neutral beams and ICRH, both of which are presently limited to 10 msec). This would be relatively straightforward, requiring only the purchase of additional capacitors and some improvements in the water cooling system. If the confinement time were $\gtrsim$ 100 msec then we could expect our 3.8 MW of auxiliarly heating to produce a temperature,

$$kT = \frac{P\tau}{3nV} \sim 2 \text{ keV} \qquad (11)$$

at $n = 5 \times 10^{13}$ cm^{-3}. Thus no additional auxiliary heating power would be required to reach what is generally considered "proof-of-principle" conditions. For the above parameters, at a ring current of 3 MA, one would have a beta of 6% in the outer bridge with ~ 12 proton gyroradii across the equal flux region.

In summary, it appears possible to roughly triple the magnetic field (ring current ~ 3 MA) and quadruple the pulse length (to ~ 100 msec usable time) at a cost that is at least an order of magnitude lower than the only slightly more ambitious (6 MA/200 msec) proposed multipole proof-of-principle experiment. If the confinement time scales favorably with field and temperature, plasma parameters close to those in PLT should be possible.

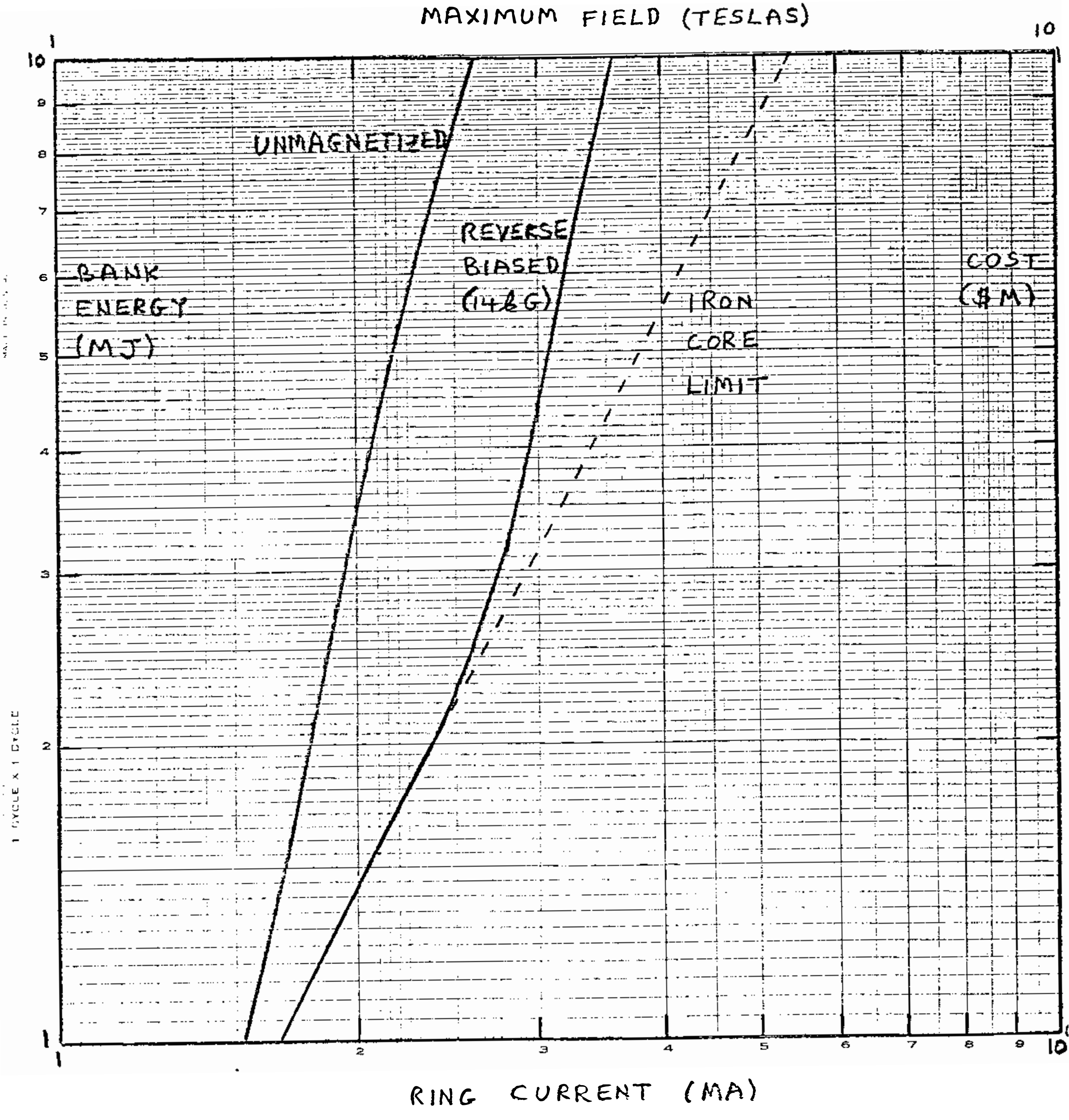
MAXIMUM FIELD (TESLAS)
1
10
10
9
8
7
6
5
4
3
2
1
UNMAGNETIZED
REVERSE
BIASED
(14kG)
BANK
ENERGY
(MJ)
IRON
CORE
LIMIT
COST
($M)
1
2
3
4
5
6
7
8
9
10
RING CURRENT (MA)
1 CYCLE X 1 CYCLE

FIGURE 2

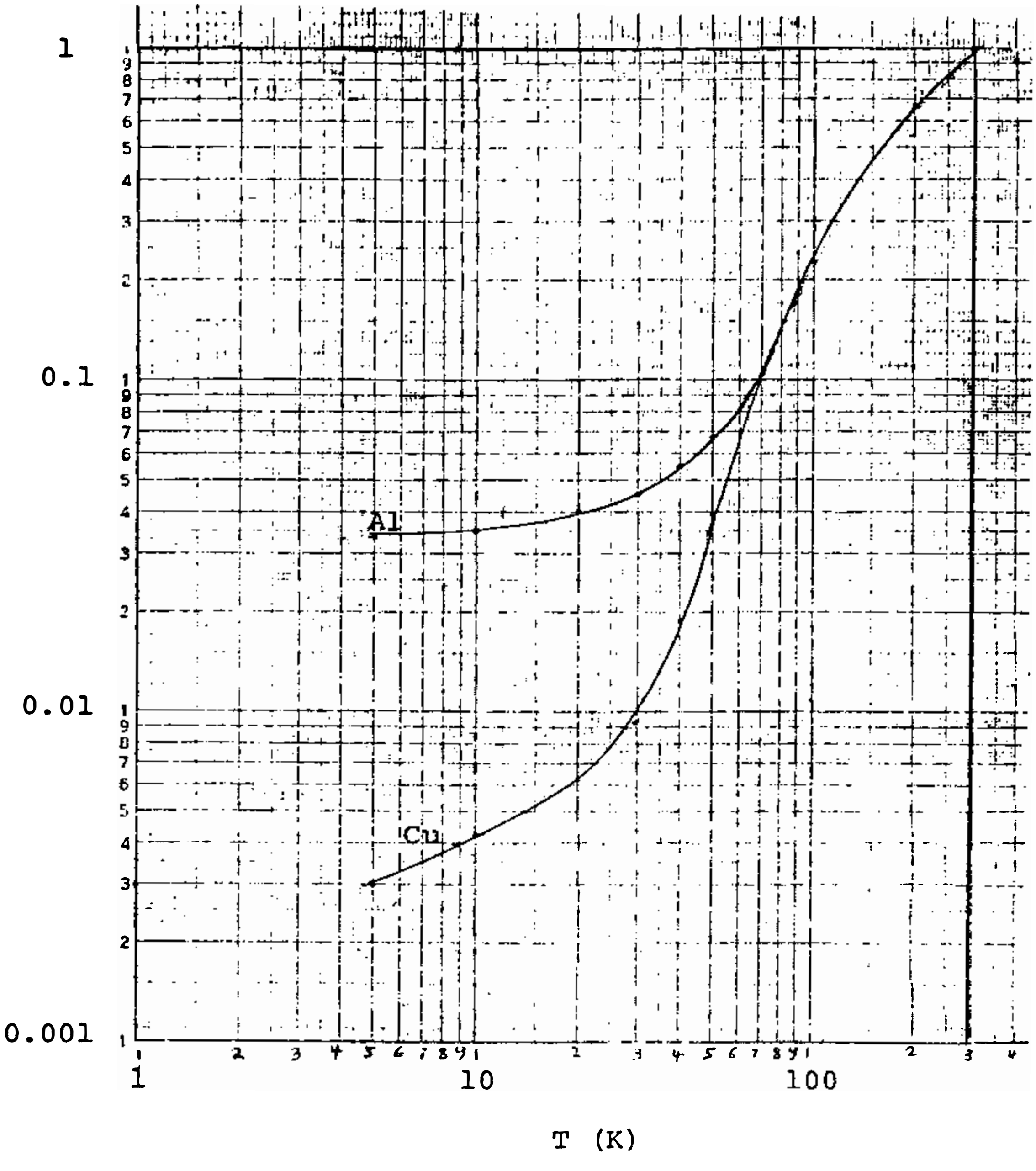

Fig. 3: Ratio of the electrical resistivities of Cu and Al at cryogenic temperatures to their resistivities at room temperature.