Magnetic Field Energy in Polywell IEC Systems

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In any fusion system utilizing magnetic fields, electrical energy is stored in these fields during their operation. If normal conductors (e.g. copper alloys, et al) are used for the windings of the magnetic coils producing these fields, this stored magnetic energy will naturally dissipate at the rate of ohmic heating inherent in coil operation. Since such coils must be designed with sufficient cooling to handle this ohmic heal load, there is no possibility of catastrophic failure of such systems due to coil or current shorting; the coils are already "shorted" in normal operation.

However, many magnetic fusion power systems, especially those using large fields over large volumes, have been designed to use superconducting magnets in order to reduce drive power requirements and thus improve system power balances. In such systems, coil failures can cause the stored magnetic energy to be dumped precipitously as ohmic heating in "normal-going" superconductor coils, potentially leading to coil material meltdown. If the coil inductance is (or becomes) sufficiently small during failure, this can even result in quasi-explosive vaporization of coil material.

The stored magnetic energy in such systems is thus a very large hazard and potential source of system catastrophe. Typically stored energy in large scale superconducting magnetic fusion systems (e.g. large tokamaks) is of the order of 10^{12} joules (10^6 MJ; 4 MJ is equivalent to energy content of 1 kg of high explosive).[1] It is thus of interest to estimate the stored magnetic energy in Polywell IEC systems, to assess this as a source of hazard in fusion power operation. The total *B* field energy is simply:

$$E_B = \int_0^\infty \frac{\left[B(r)\right]^2}{8\pi} 4\pi r^2 dr \qquad (1)$$

where the *B* field is given by the "rollover" equation:[2]

$$B(r) = B_0 \langle r \rangle^m \left[\frac{2}{1+\langle r \rangle^{m+2}}\right] \qquad (2)$$

for polyhedral field configurations with spatial index *m*. Here $\langle r \rangle = (r/R)$. The field index varies with the order of the polyhedron, as shown in Table 1, below.

Table 1 — B Field index for Various Polyhedral Configurations

Polyhedral System	Field Index, *m*
Octahedron (truncated tetrahedron)	2
Truncated cube	3
Truncated dodecahedron	4

As an example, consider the truncated cube system, with m = 3 Then equations (1) and (2) give:

$$E_B = 2B_0^2 R^3 \int_0^\infty \left[\frac{\langle r \rangle^8}{\left(1+\langle r \rangle^5\right)^2}\right] dr \qquad (3)$$

Numerical integration of equation (3) shows that $E_B \approx 2.0 B_0^2 R^3$. It is found that approximately 90% of this *B* field energy is stored beyond $\langle r \rangle = 1.15$, external to the system, that the region from $0.85 < \langle r \rangle < 1.15$ contains roughly

9% of the energy, and that only the remaining 1% is stored within the system at <r> < 0.85.

For a numerical example take $B_o = 7.5 \times 10^3$ Gauss and $R = 4.5$ m (characteristic of a thermal-conversion ^{3}He-half-catalyzed DD system at 500 MWe net power). In this system, $E_B = 1000$ MJ, about 10^{-3} of that stored in a typical large scale magnetic (M&M/LTE) tokamak fusion system. If the device here is made smaller in size to $R = 2.1$ m, for example, the stored energy will drop by a factor of ten. In general, it is found that E_B in IEC/EXL systems is between 1/100 and 1/1000 of that found in large superconducting M&M systems. Further, since many IEC/EXL systems can use normal conductors, no hazard exists at all in these systems.

As a final example of a superconducting IEC system consider a $p^{11}B$ reactor with $R = 3.0$ m and $B = 1.7 \times 10^4$ G. This gives $E_B = 1600$ MJ. If a magnet coil cooling failure occurs over a length x, the coil can "go normal" in the region of this failure. The superconductor will exhibit an initial finite resistance R_o over this region.

Local ohmic heating of coil material here will propagate at a rate set by the balance between the electrical inductive decay time $t = L/R_o$ (L is the coil inductance) and the thermal capacity heating time of the coil material. This latter is very small for operation at the coil temperatures required for use of conventional superconductors (e.g. NbTi).

The result is that the thermal heating proceeds initially at the rate set by the initial R_o due to the local cooling failure, but at an ever-increasing rate until all of the coil has gone normal, with final resistance $R_f >> R_o$. The coil heating rate in the last stages of this process reaches its highest values because of the great decrease in inductive decay/heating time constant, due to the increased resistance R_f (because $\delta x \rightarrow$ total coil winding length).

For the $p^{11}B$ example given above, assuming a coil of radius $R_B = 3.0$ m requires a coil current of 1.8×10^7 ampere-turns to produce the specified B field. Use of NbTi in a 60:40 NbTi:Cu matrix results in a coil cross-section of 600 cm^2, of which 240 cm^2 is Cu and 360 cm^2 is NbTi. The d.c. resistance (for a normal conduction path) of this coil (due entirely to the copper) is $R_c = 1.5 \times 10^{-5}$ ohms over its complete winding circumference, or $R_c = 1.3 \times 10^{-8}$ ohm/em, and its inductance is $L = 8 \times 10^{-6}$ H (henries). Thus the fast heating time is ≈0.53 sec for the entire coil. Initially the heating time per unit length is $\tau = 1060/\delta x$ seconds, where δx is the conductor segment length that has "gone normal."

If cooling fails over a one meter coil section the initial e-folding heating time is thus τ_o = 10.6 seconds, during which time energy would be dumped into this coil section at a rate of about 150 MJ/second. Neglecting heat conduction over this time, the coil material would be vaporized within 3.5 to 5 seconds.

However, what actually happens is that the heat conduction propagates the "gone-normal" zone at a rate of about 0.2-1.0 m/second, until the entire coil is normal and the final heating rate is at its maximum at ca. 2900 MJ/second over the complete coil volume. But the stored energy is only $E_B \approx 1600$ MJ, thus the maximum temperature rise of the complete coil is limited to less than 450°C, well below the coil material melting point. In this case, then, even coil cooling failure and going-normal will not lead to any catastrophic or hazardous failure.

Conversely, in a system with $B = 2 \times 10^5$ G (20 T), such as those characterizing large M&M tokamak systems,[3] the stored energy densities are all higher by the B^2 ratio of ≈ 100-400x and the magnetic field volumes are higher by about 10x, giving a stored energy of order 1000-4000x that for comparable IEC systems. Since the magnet coil material volume is about 10-40x greater for the tokamak M&M system, the net result is a greater heating potential by a factor of about 100-200x for the large superconducting system. Such large magnetic fusion systems thus can suffer catastrophic failures which are impossible for small IEC/EXL systems.

References

[1] The ARIES-I Tokamak Reactor Study, Final Report, 1991, UCLA-PPG-1323, Volume I, Section 1.4, "Magnet Engineering"

[2] Robert W. Bussard and Katherine E. King, "Phenomenological Modeling of Polywell/SCIF Multi-Cusp Inertial-Electrostatic Confinement Systems," Technical Report EMC2-1191-02, presented at APS Plasma Physics Division Meeting, Tampa, FL, November 1991

[3] F. Najmabadi, R. W. Conn, and the ARIES Team; "The ARIES-II and ARIES-IV Second-Stability Tokamak Reactors," Fusion Technology, Volume 21, No.3, Part 2A, May 1992, p. 1721 ff.