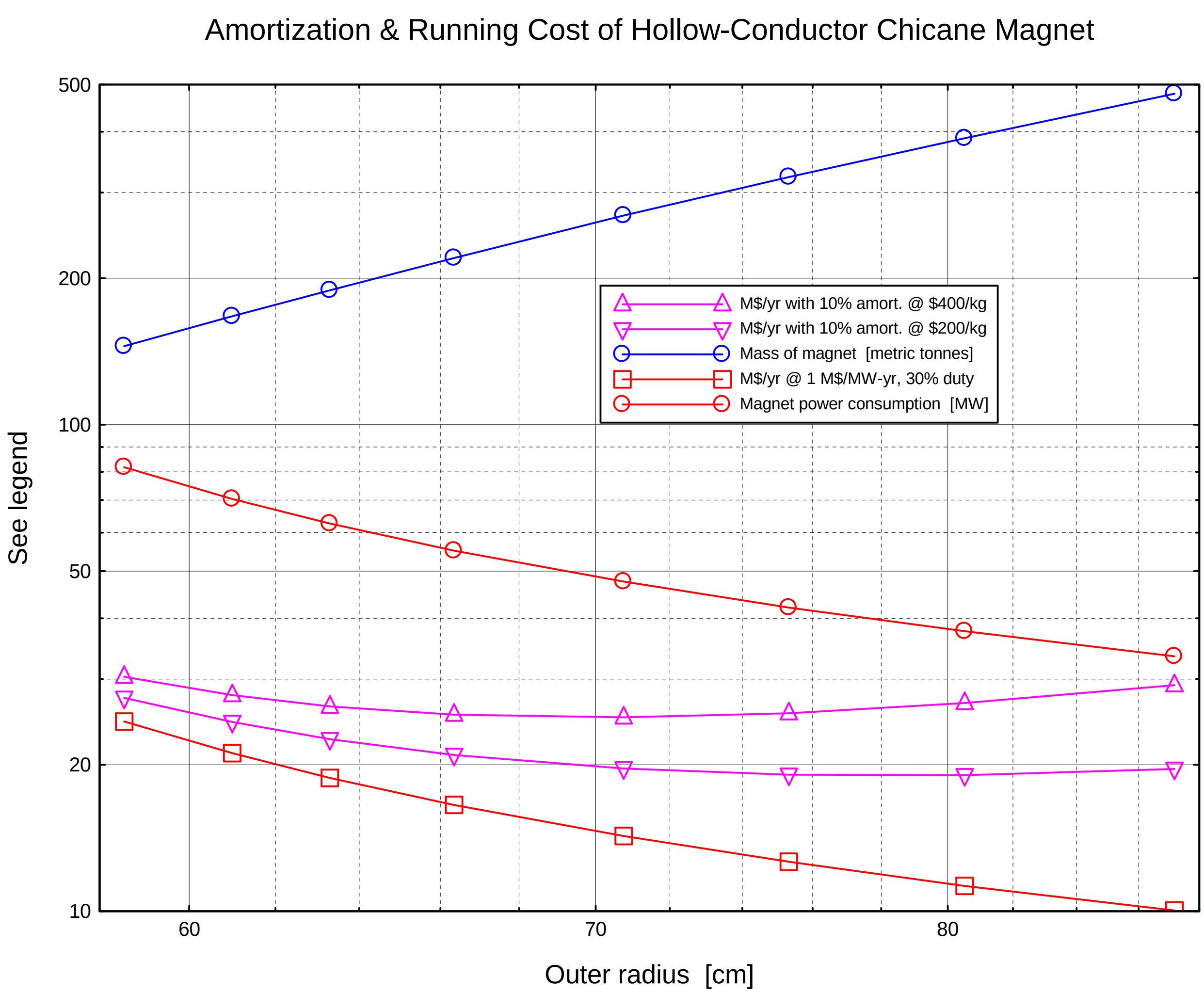
Amortization & Running Cost of 1.5-T Magnets for 50-meter Chicane

Bob Weggel
Magnet Optimization Research Engineering, LLC
Particle Beam Lasers, Inc
March 1, 2013

This report explores the optimization of magnets for a 1.5-T chicane fifty meters long with a magnet inner radius of 43 cm. Resistive magnets, as expected, are unappealing. The graph below shows that even with an outer radius as large as 87 cm the magnet would consume 34 MW if built with radiation-resistant hollow conductor. Assuming power at 1 M$ per MW-yr (11.4 cents per kW-hr), the magnet would incur a running cost of 34 M$/yr at a duty cycle of 100%, or 10 M$/yr at 30%. The minimized total yearly cost is 19 M$/yr if the duty cycle is 30%, the unit cost of fabrication is $200/kg, and the amortization rate is 10% per year. The optimum magnet has an outer radius of 78 cm, a mass of 350 metric tons, and consumes 40 MW. Doubling the unit cost of fabrication cost to $400/kg increases the cost to 25 M$/yr and shifts the optimum to 70 cm, 250 tonnes and 49 MW.



Mass, power consumption, and amortization, running & total cost of 1.5-T chicane magnets of JHF-like conductor.

The remainder of this report explores the economics of superconducting magnets for the chicane. The operating cost has two components: 1) amortization of the investment in conductor and fabrication, and 2) electrical power for refrigeration. The unit cost assumed for fabrication is \$400/kg, based on the \$400-\$500/kg total cost, including conductor, for several multimillion-dollar superconducting magnets at the National High Magnetic Field Laboratory.

Conductors considered were NbTi, Nb_3Sn, MgB_2 and YBCO. For each conductor a graph of $I_c(B|T)$, the critical current vs. field at fixed temperature, allowed the generation of a curve fit of $I_c(T|B)$. For the chicane, the analysis assumes B = 2 T (not 1.5 T), to introduce a generous 4:3 allowance for the field ratio of maximum ambient field to on-axis field.

For NbTi the unit cost is based on a reported value of \$1/kA-m at 7 T, 4.2 K, which the graph of $I_c(B)$ reveals to equate to \$0.60/kA-m at 5 T, 4.2 K. The fitting equation, normalized to [5 T, 4.2 K], is $i_c \equiv I_c(T|B{=}2T)/I_c(4.2K,5T) = 4.109 - 0.495$ T. This evaluates to 2.03 at 4.2 K; therefore, the unit cost at [2 T, 4.2 K] is \$0.60/2.03 = \$0.30/kA-m. At (6.0, 7.2, 8.0] K, i_c evaluates to [1.14, 0.55, 0.15] and therefore predicts respective unit costs of [0.53, 1.10, 4.03] \$/kA-m.

For Nb_3Sn the unit costs derive from a reported value of \$4.60/kA-m at 10 T, 4.2 K, where I_c = 290 A. Combined with a fitting equation $I_c(T,B{=}2T) = 1910 - 130$ T, the respective unit costs predicted at [6.0, 8.0, 10.0, 12.0, 13.5] K are [1.18, 1.53, 2.19, 3.81, 8.61] \$/kA-m.

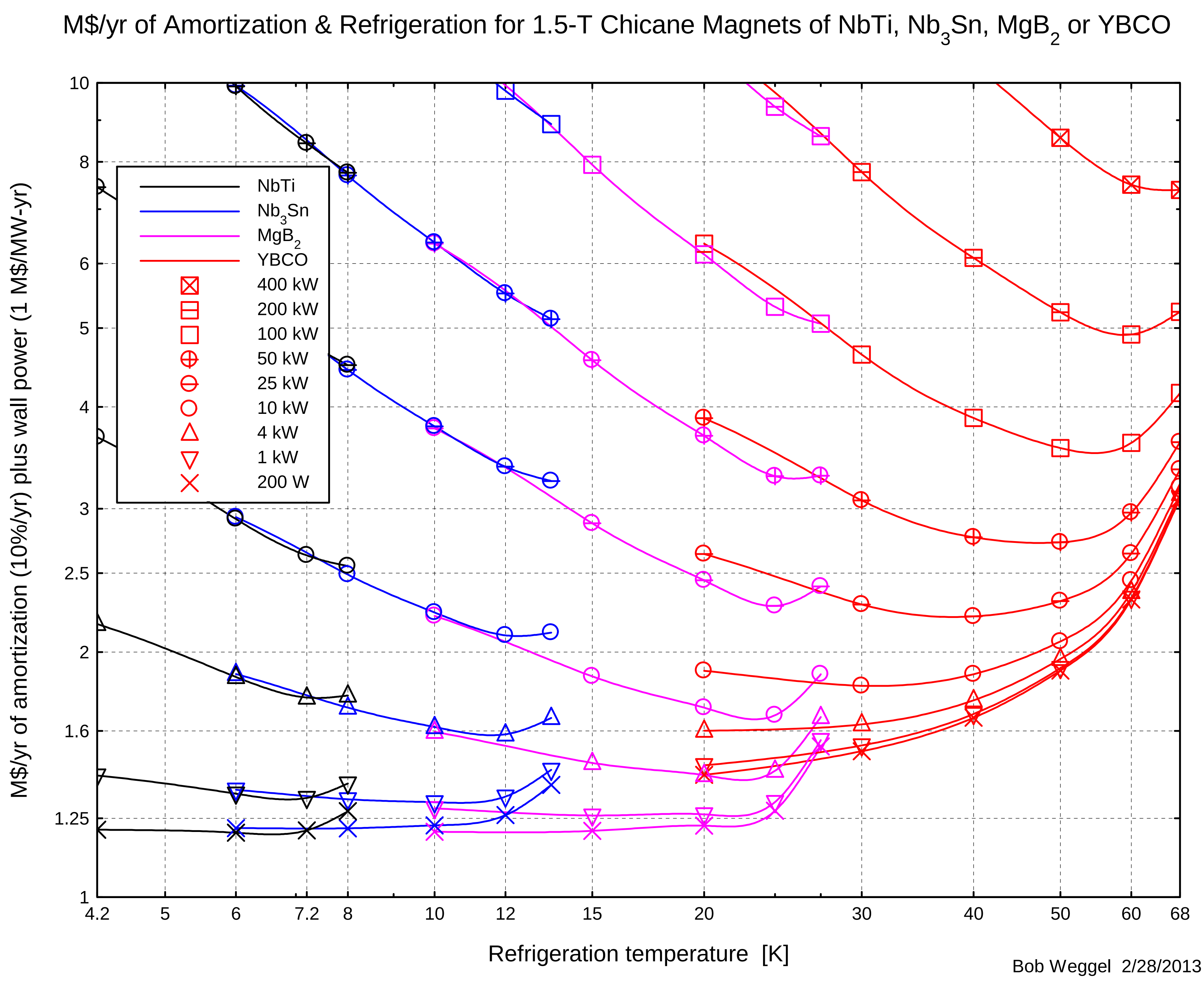
For MgB_2 the base value of unit cost is \$1.50/m, which equates to \$7.50/kA-m at 1 T, 20 K, where I_c = 200 A. This value is one projected for a few years hence, embodying a five-fold improvement in either current capacity or price (from scaled-up production). The fitting equation $I_c = 342.6 - 9.49\,T - 0.0919\,T^2$ predicts respective unit costs at [10, 15, 20, 24, 27] K of [1.26, 1.67, 2.58, 4.85, 15.5] \$/kA-m.

For YBCO the unit costs derive from a cost of \$25/m for tape 4-mm wide that in a PBL/BNL magnet of 100-mm bore carried 150 A at 35 K in an ambient field of 5.5 T (and 250 A in an ambient field of 9.2 T at 4.2 K, which post-test analysis suggests could have been allowed to rise to 12 K before the magnet would have quenched). The fitting equation $I_c(T,B{=}2T) = 673.8 - 20.0\,T + 0.236\,T^2 - 0.00114\,T^3$ predicts respective unit costs at [20, 30, 40, 50, 60, 68 K] of [10.4, 14.7, 21.0, 30.9, 48.6, 80.4] \$/kA-m. Although YBCO is much more expensive than the other three superconductors, it nonetheless is competitive for this chicane because of the reduction in refrigeration power that arises from the higher permissible operating temperature, which greatly reduces the amount of wall power needed for refrigeration.

The refrigeration is needed to remove heat deposited in the magnet by protons, muons and muon-decay particles. The particles have a heating power of ~500 kW, and some of the particles are so energetic as to have penetrating power far beyond the capacity of shielding likely to fit in the magnet bore. **Can the magnet be sufficiently transparent that particles can transit without depositing much heat? Or, can shielding greatly reduce the power deposited?** If not, economics strongly favors refrigeration at a temperature that is cryogenically favorable.

Refrigeration at 4.2 K requires a refrigeration-power ratio q of ~300; to remove 0.5 kW at 4.2 K requires ~150 MW of wall power, which costs ~150 M\$/yr at a duty cycle of 100%. Superconductors such as MgB_2 and YBCO can generate 1.5 T economically at temperatures of at least 25 K and 60 K, respectively, reducing the refrigeration-power ratio to ~40 at 25 K and ~12 at 60 K. A convenient curve fit is $q = [t-1]/[r+(1-r)\,t^{-2}]$, where [t–1] is the power ratio for perfect Carnot efficiency for the temperature ratio $t \equiv T_{warm}/T_{cold}$, and r = 0.28 gives a good fit to the data for 100-kW refrigerators given in Fig. 5 on p. 227 of Y, Iwasa's *Case Studies in Superconducting Magnets*.

My analysis looked at NbTi over the temperature range 4.2-8 K; Nb_3Sn at 6-13.5 K; MgB_2 at 10-27 K; and YBCO at 20-68 K. The graph below reveals that NbTi is economically appealing only if the deposited power is no more than a few hundred watts. Nb_3Sn is edged out by NbTi when $P \leq 200$ W and by MgB_2 if $P \geq 200$ W. MgB_2 is good for power levels between 200 W and 25 kW. Below 1 kW any refrigeration temperature between 10 K and 23 K will do; at 25 kW, operation is most economical with a refrigeration temperature between 20 K and 27 K. For power depositions above 25 K, the conductor yielding the most economical operation is YBCO. With a power deposition of 25 kW, operation can be economical at any temperature between 30 K and 50 K. At 100 kW, operation is most economical at 48 K to 60 K. At 400 kW, the best temperature range is 60-70 K.



M$/yr of Amortization & Refrigeration for 1.5-T Chicane Magnets of NbTi, Nb_3Sn, MgB_2 or YBCO
M$/yr of amortization (10%/yr) plus wall power (1 M$/MW-yr)
Refrigeration temperature [K]
NbTi
Nb_3Sn
MgB_2
YBCO
400 kW
200 kW
100 kW
50 kW
25 kW
10 kW
4 kW
1 kW
200 W
10
8
6
5
4
3
2.5
2
1.6
1.25
1
4.2
5
6
7.2
8
10
12
15
20
30
40
50
60
68
Bob Weggel 2/28/2013