SECONDARY BEAM MAGNETS FOR THE 200-BEV ACCELERATOR--CONVENTIONAL OR SUPERCONDUCTING?*

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Summary

To exploit fully the capabilities of the 200-BeV Accelerator, many experimental beams must be set up concurrently, and many magnets will be required. The great stiffness of secondary-particle beams having momenta around 100 GeV/c requires long magnets to provide reasonable focal lengths and deflections. The result is a very expensive system of dc beam-transport magnets, and a large expenditure for electric power.

Recent spectacular advances in the technology of superconducting (SC) magnets have led us to consider the economics of replacing conventional magnets with equal numbers and kinds of SC magnets. We find the total capital-plus-operating costs of the two systems to be equal, within the accuracy of the analysis.

We have, however, compared an optimized system of conventional magnets with a nonoptimized system of SC magnets. Perhaps we would get more physics per dollar with different sizes and numbers of SC magnets. We have not placed a dollar value on one of the major advantages of SC magnets--their higher magnetic-field capability. In some cases the higher fields offer no advantage, in others the advantages might be dramatic. Some beam lines may be shortened about in proportion to the increase in field. The result is less shielding and better usage of the rather expensive facilities. Better measurements can be made on particles having short lifetimes. The development of new SC devices, for example, separators and detectors, will be bolstered by the presence of other SC and cryogenic systems and capabilities.

We feel that vigorous pursuit of the technology of SC devices is essential to fullest utilization of the 200-BeV Accelerator.

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Experimental Areas

There are three experimental areas: a relatively small internal-target area, and two large expandable external-proton-beam (EPB) areas. At each of the four target stations in the EPB areas there is a system of large pulsed "target magnets" (Fig. 1). Radiating from the target magnets are strings, some as long as 3500 ft, of dc magnets, which we are considering replacing by SC magnets.

List of Conventional dc Magnets

Table I lists 164 conventional magnets intended to satisfy the needs of the experimenters for a few years after completion of the accelerator.[1] The bending magnets have the conductors adjacent to the aperture, and most are H-type (Fig. 2). Some C-type magnets are provided for locations where the yoke of the H-type magnets would interfere with an adjacent beam. Conventional 4-in. and 8-in. quadrupoles are provided. In addition, there are a smaller number of special quadrupoles for use where beams are close together. The 164 magnets in the list are considered assigned to experimenters. An additional 20% are unassigned.

SC Magnet Design

To achieve the high fields of which SC magnets are capable, we must abandon the conventional iron-core configurations. One can produce a uniform or quadrupole field inside a cylinder having any desired shape of cross section by a suitable distribution of longitudinal currents on the surface of the cylinder. The characteristics can be described by very simple equations for cylinders of circular or elliptical cross section. The stray fields must be minimized where beams are close together. Beth has shown how a second current sheet placed some distance outward from the main one can be used to cancel completely the external field.[2] We will adopt this scheme for this study, but iron shielding could be used. For our bending magnets, the dimensions of the outer current sheet result in doubling the total ampere-turns. One kind of shielded quadrupole has a shield coil with twice the major axis of the main coil and requiring multiplying the total ampere-turns by a factor of 4/3. The other kind has a more closely-fitting secondary coil and requires doubling the ampere-turns.

Whereas solenoids are capable of producing fields greater than 100 kG, for transverse-field magnets of the size under consideration the structural problems become limiting at around 50 kG. For quadrupoles the structural problem is less severe, but a maximum field of 50 kG seems reasonable. Higher fields will not reduce the number of ampere-feet of conductor needed to produce a magnet of given focal length or bending power, and will only aggravate the problem of achieving a reasonable current density.

Superconducting magnets may have the unhappy characteristic of "quenching" if the current is excessive, or if the magnets are otherwise mistreated. In a small magnet no harm is done, but in a large magnet a quench might damage the magnet. The conductor may be "stabilized" to decrease this effect only at the expense of a low overall current density. In large or low-field magnets, current densities as low as a few thousand A/sq cm are tolerable. On very small high-field magnets, current densities of the order of 50 000 A/sq cm are necessary and have been attained. For our purposes, we have assumed current densities of from 5 000 to 25 000 A/sq cm, with the actual value depending on the stored energy. Somewhat lower values could be tolerated, but the geometrical proportions would become grotesque. Some means of switching the energy into an external resistor in the event of quenching will probably be necessary. Figure 3 shows some of the proposed magnets.

List of Equivalent Supermagnets

A list of SC magnets equivalent to those in Table I is presented in Table II. The equivalence between the two sets is established by the following rules: (a) each conventional magnet has its SC counterpart; (b) lengths of the SC magnets decrease in inverse proportion to their higher fields; (c) quadrupole aperture diameters and bending-magnet aperture heights are the same in the two sets; and (d) bending-magnet aperture widths are made to clear a beam bent through a given angle.

Cost Estimate

Operating Costs

For the optimization of the accelerator, the operating expense has been taken as the average rate of expenditure multiplied by 10 years, and we will use the same basis. This is not to say that the accelerator will have a useful life of only 10 years. If we purchase an annuity with the calculated operating cost and pay for the operation with payments from the annuity, then at an interest rate of 7%, for example, the payments will continue for 20 years.

Conventional Bending Magnets

The width of the yoke is selected so the field averaged across the yoke does not exceed that in the aperture. The coil width is selected to minimize the total cost of the magnet and auxiliaries.[3] Cost vs weight data for many yokes and coils were graphed[4] and the results used in this study.

Conventional Quadrupole Magnets

Weights and power requirements were scaled from data from a large number of magnets,[5] and similar cost vs weight graphs were used to estimate costs.

SC Magnets

Conductor costs are based on discussions with several manufacturers and reflect the opinion that future costs may be much less than current costs. We have used a scale of unit costs varying from 3.0 \$/(1000 A ft) at a current density of 25 000 A/sq cm to 1.2 \$/(1000 A ft) at 10 000 A/sq cm for the main coils, and a little less for the shield coils, which operate in a smaller field. The costs of coil hardware and dewar were estimated with the help of our shop people. On the average, the cost of the conductor accounts for about 80% of the total cost of the magnet.

Electric Power Cost

Power cost is estimated as follows:[6] (duty factor) x (total nameplate power) x (power cost rate) x (time) = (0.22) x (64 000 kW) x (0.0055 \$/kWh) x (10 x 365 x 24 h) = \$6 800 000.

ac Power Distribution

A detailed estimate for the entire system prorated for the dc magnets resulted in an estimated cost of \$1 490 000. The cost of the system for the SC magnets is estimated to cost about one-fourth of this, namely, \$370 000.

dc Power Supplies

For conventional magnets the cost is estimated as follows: (power rating of the 164 assigned magnets) x (installed power supply rating/rating of assigned magnets) x (power supplies owned/power supplies installed) x (unit capital cost) x (allowance for maintenance and connection to magnets) = (64 000 kW) x (0.8) x (1.05) x (70 \$/kW) x (1.20) = 4 530 000.

Power supplies for the SC magnets are required to be capable of a 10% change of current in 15 sec at 70% rated current. Thus, the power (kW) = 0.07 x stored energy (kJ). The cost is then (0.07) x (146 000 kJ) x (80 \$/kW) = \$820 000.

Cooling Water System

Cost is estimated as follows: (cooling capacity/assigned magnet rating) x (assigned magnet rating) x (unit cost) = (0.65) x (64 000 kW) x (20 \$/kW) = \$832 000, including operating costs.

Utilities Distribution Facilities

Large areas must be serviced so the system is bound to be expensive. We estimate \$3.0 million for the conventional magnets and \$0.5 million for the SC magnet system.

Refrigeration System for SC Magnets

The cost of the 4^{o}K refrigeration system associated with the SC magnet system is a major part of the cost of the entire system. Strobridge, Mann, and Chelton have considered various kinds of systems and estimated relative costs of systems likely to be most satisfactory. They considered, for example, the use of a central refrigerator (cold-gas return), a central liquefier (warm-gas return), and individual refrigerators on each magnet. Transporting the liquid from a central liquefier by portable dewar was compared with using transfer lines. They arrived at three systems, each costing less than \$10 million, and one as low as \$7.1 million. We will adopt \$8.5 million as a practical value. Their analysis covered only major items likely to affect the comparison of the various systems, so we will add 25% to cover minor items which were not included in their study. Since their study was made the ground rules have been changed somewhat. We estimate that 148 magnets will require constant refrigeration, compared with the 130 magnets in the NBS study.

8.5 x 1.25 x 148/130 = \$12.1 million

Total Costs

Costs for the two systems are shown in Table III. The difference in total cost is probably within the accuracy of the analysis.

References

1. 200-BeV Accelerator Design Study, Lawrence Radiation Laboratory Report UCRL-16000, Vol. I, June 1965, p. XII-13.

2. R. A. Beth, Brookhaven National Laboratory Internal Report AADD-110, June 1966.

3. R. B. Meuser, Lawrence Radiation Laboratory Engineering Note M3817, Sept. 14, 1966.

4. R. B. Meuser, Lawrence Radiation Laboratory Engineering Note M3382A, Aug. 4, 1964.

5. R. B. Meuser, Lawrence Radiation Laboratory Engineering Note M3371, July 21, 1964.

6. R. B. Meuser, Duty Factor for the dc Experimental Magnets, in Lawrence Radiation Laboratory Report UCRL-16830, Vol. 3, 200-BeV Accelerator: Studies on Experimental Use (to be published).

7. T. R. Strobridge, D. E. Mann and D. B. Chelton, National Bureau of Standards NBS-9259, Oct. 1966.

Table III. Relative costs of conventional and superconducting magnet systems.

	Costs (10^6): Conventional magnets	Costs (10^6): Superconducting magnets
Magnets	6.1	11.4
Electric power	6.8	a
ac Power distribution	1.5	0.4
dc Power supplies	4.5	0.8
Cooling water system	0.8	---
Utilities distribution facilities	3.0	0.5
Refrigeration system	---	12.1
	22.7	25.2

a. Included in refrigeration system

Table I. Characteristics of conventional magnets.

Magnet type		Aperture (in.)	Length (in.)	Field (kG)	Septum width (in.)	Per magnet Power (kW)	Per magnet Cost ($1000)	Quant.	Total Power (kW)	Total Cost ($1000)
Quadrupole	Low-power	4 diam	60	11	4	217	5.6	20	4340	112
		4 diam	120	11	4	435	8.3	20	8700	166
		8 diam	60	11	8	217	13.1	20	4340	262
		8 diam	120	11	8	435	23.7	20	8700	474
	High-power	4 diam	120	10	1	750	9.0	8	6000	72
		8 diam	120	10	2	750	12.0	8	6000	96
	Septum	8 diam	160	10	~0	500	50.0	8	4000	640
Bending	C	4 x 12	80	20	13	218	36.2	5	1090	181
	H	4 x 12	80	20	28.5	194	28.4	10	1940	284
	H	4 x 12	160	20	28.5	319	48.2	15	4785	723
	C	8 x 16	80	20	15	410	59.3	5	2050	297
	H	8 x 16	80	20	35	354	51.5	10	3540	515
	H	8 x 16	160	20	35	564	85.0	15	3460	1275
							Totals:	164	63945	5097

Table II. Characteristics of superconducting magnets.

Magnet type		Aperture (in.)	Length (in.)	Field[a] (kG)	Septum width (in.)	Stored energy (kJ)	Cost ($1000)	Quant.	Total cost ($1000)
Quadrupole	Unshielded	4 diam	24	27.8	4.1	160	23.7	10	237
			48	27.8	4.1	320	41.3	10	413
	Shielded	4 diam	24	27.8	7.4	171	29.8	10	298
			48	27.8	7.4	342	51.4	10	514
	Shielded, compact	4 diam	48	27.8	5.0	214	68.3	8	546
	Unshielded	8 diam	20	33.3	4.9	370	29.3	10	293
			40	33.3	4.9	740	48.6	10	486
	Shielded	8 diam	20	33.3	10.2	390	37.3	10	373
			40	33.3	10.2	780	60.7	10	607
	Shielded, compact	8 diam	40	33.3	7.0	490	81.0	8	648
Bending	Unshielded	4 x 9	32	50	7.0	1045	47.9	5	240
			64	50	7.0	2090	78.9	5	395
	Shielded	4 x 9	32	50	9.0	1320	75.4	10	754
			64	50	9.0	2640	121.5	10	1215
	Unshielded	8 x 14.5	32	50	10.5	1950	48.0	5	240
			64	50	10.5	3900	57.5	5	288
	Shielded	8 x 14.5	32	50	14.0	2810	72.1	10	721
			64	50	14.0	5620	123.3	10	1233
						Totals:		164	9501

a. Field at edge of aperture is tabulated.
Field at coil is 50 kG.

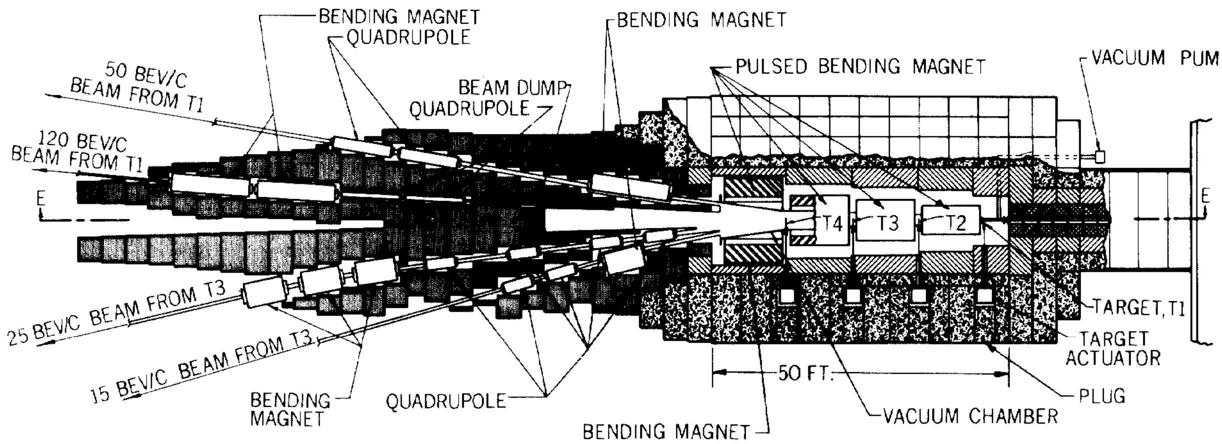
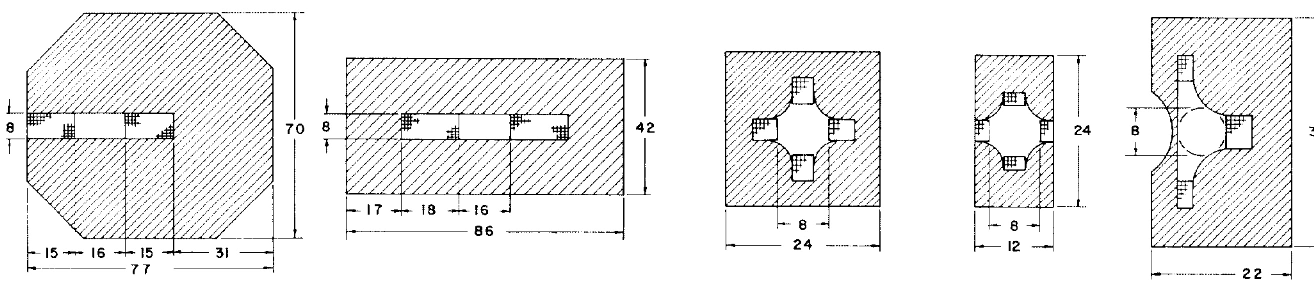


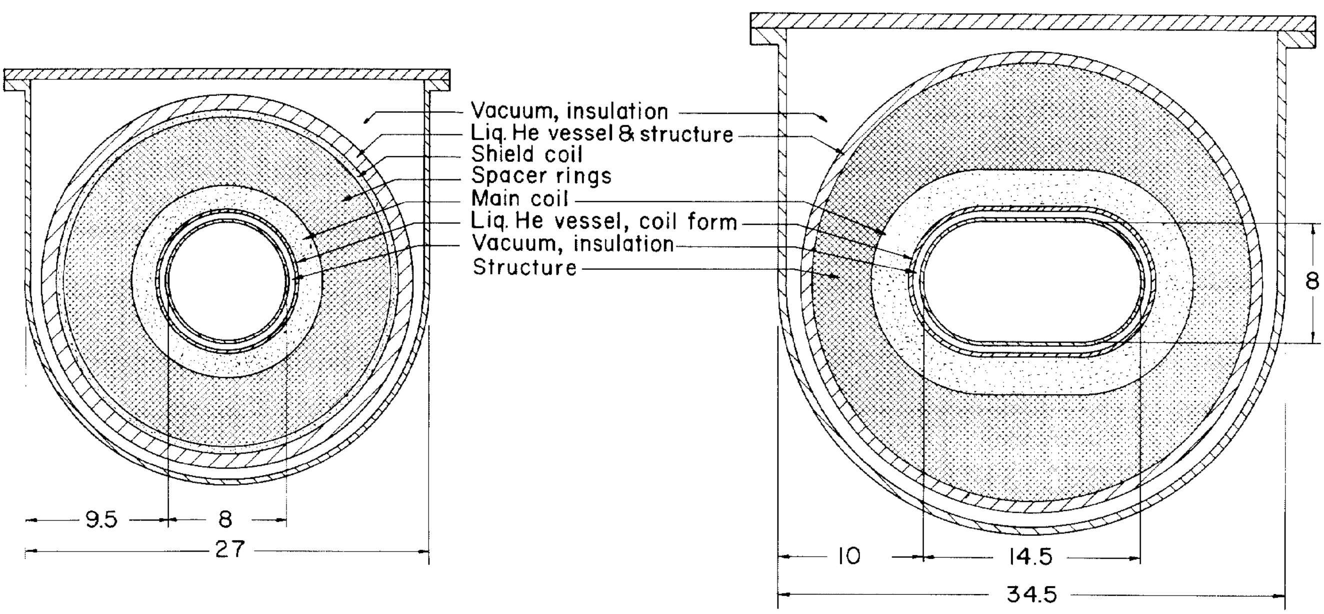
Fig. 1. Typical EPB target station.



C-type H-type Low power High power Septum

8 x 16-in. bending magnets 8-in. quadrupoles

Fig. 2. Cross sections of conventional magnets.



8-in. shielded quadrupole 8 x 14.5-in. unshielded bending magnet

Fig. 3. Cross sections of superconducting magnets.