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Economic Studies of Superconducting Magnets and their Refrigeration for the CERN II North Experimental Area

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ECONOMIC STUDIES OF SUPERCONDUCTING MAGNETS AND THEIR REFRIGERATION FOR THE CERN II NORTH EXPERIMENTAL AREA

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Abstract

Experimental areas for large proton-synchrotrons may be designed by using either normally conducting or superconducting magnets. The superconducting alternative is studied for both, primary and secondary beams in the proposed North Experimental Area of the CERN 300-GeV synchrotron. The requirements for helium refrigeration systems are specified in both cases. The refrigeration for the secondary beams may be quite different from the one used in the beam line magnets. Cost estimates are given for the refrigeration system and the magnets themselves in dependence on field level and magnet aperture.

Ökonomie supraleitender Magnete und ihres Kühlsystems für die Nord-Experimentierfläche des CERN II-Beschleunigers

Zusammenfassung

Experimentierflächen für große Protonen-Synchrotrone können alternativ mit normalleitenden oder supraleitenden Magneten zur Strahlführung ausgestattet werden. Für die vorgesehene nördliche Experimentierfläche am 300 GeV-Synchrotron in CERN wird die supraleitende Alternative für den primären Protonenstrahl und sekundäre Strahlen untersucht. Die Anforderungen an die Kältesysteme werden in beiden Fällen spezifiziert; dabei zeigt sich, daß die Eigenschaften der Kühlung in Sekundärstrahlen erheblich von denen des Primärstrahls abweichen können. Kostenabschätzungen für die Kühlung und die Magnete selbst werden mit der Feldstärke und der Magnetapertur als Parameter durchgeführt.

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Refrigeration for Superconducting Magnets in the CERN II Experimental Area

by Michael A. Green
5 May 1972

This report discusses the refrigeration of superconducting magnets in the north experimental area of CERN II. This report describes the equipment necessary to cooldown, and keep cold superconducting dipoles and quadrupoles operating in various primary and secondary beams. A primary beam is a proton beam from the machine which has not been targeted. The definition of a primary beam is further restricted to those proton beams which are in tunnels located between the SPS ejection system and the target stations. The secondary beam is defined as those beams which have been targeted (usually not protons) and lie in the experimental area between the target and the last piece of experimental detection equipment. The refrigeration system for the superconducting magnets in the secondary beams may be quite different from the refrigeration used in the beam line magnets.

1. Other studies on refrigeration for superconducting magnets

A number of studies have been made on refrigeration systems for superconducting magnets in accelerator experimental areas. The National Bureau of Standards study[1] of 1966 pointed out a number of difficulties which could occur in a system of refrigeration involving a large number of magnets. This report studied bulk liquid transfer systems, systems using a large central refrigerator, and systems using individual refrigerators. The report presented a great deal of important data which is still useful today.

A 1968 study by LRL Berkeley and 500 Incorporated[2,3] (now Crogenic Technology Incorporated) was based on three experimental areas which had 10 different beams. The beam lines came from LRL[4] and CERN[5] experimental area studies in 1966 and 1967. The LRL-500

Incorporated report only considered refrigeration of superconducting magnets in secondary beams. That report came to the conclusion that a system which consisted of a number of small refrigerators supplied from a central compressor station was best from a technical and economic standpoint. This study has one major flaw; the refrigeration required for a pair of magnet leads was improperly estimated.

A 1969 paper by Strobridge[6] further updated cost estimates for cryogenic refrigeration plants. In 1970, Green[7] showed that the small unit concept was still valid for a spread out secondary beam system. This paper corrected the estimate given for electrical lead refrigeration which was given in the LRL-500 Incorporated paper. The paper also related some of the difficulties that can be encountered in the operation of a system of small refrigerators. A really cheap flexible transfer line for refrigeration was presented also.

The author is also aware of a study that was made either at CERN or by the French. This report suggested that periodic liquid transfers could be made through long transfer lines from a bulk liquid storage system and liquifier to various magnets. The gas was to be recovered cold from the magnets and used in the liquifier. The author sees little difference between this system and a central refrigerator.

Previous studies have shown that the operation of a superconducting magnet on a closed cycle refrigerator is quite different from the operation of the same magnet on transferred liquid[8]. The use of direct closed cycle refrigeration has an important effect on cryostat design [9] and the design of the magnet itself. The density of magnets in a given area has an important effect on the type of cryogenics system that should be employed. In general, an area that is densely packed with magnets, whose position is considered permanent, will use a few large refrigerators to supply cooling. However, if the magnets are widely spaced and the magnets may be moved, then small refrigerators are attractive. These refrigerators may be connected to central helium compression system for improved reliability.

2. Refrigeration for the Primary Beam Transport System

In the absence of definitive data, certain assumptions have been made:

1) The primary beam transport system is assumed to transport beams which have an energy of 1000 GeV or less.
2) The primary beam transport system consists of a beam dump splitter magnet, bending magnets to transport the beam to the earth's surface (two sets, one to bend the beam up and a second to bend the beam level), and a beam splitting system which supplies primary beam to three target stations (see figure 1).
3) Most of the transport quadrupoles are assumed to be conventional because adequate space is available for conventional quadrupoles.
4) The dipole magnets are assumed to be superconducting when the primary beam energy is 1000 GeV. Only the beam switch yard dipole magnets are superconducting when the maximum primary beam energy is 400 GeV.

The preceding assumptions may not be valid, though they provide a basis for making a determination of the type of refrigeration system needed to supply superconducting magnets which may lie between the north area extraction points and the targets.

The vertical bends in the tunnel from the extraction point to the target will be determined by the use of conventional (1.8T) magnets at 400 GeV. Therefore, when a conversion of the machine to 1000 GeV is made, superconducting (4.5T) magnets will be used for the vertical bends. In the absence of other data, an angle of 85 mrad has been assumed for each of the vertical bends. This is the equivalent of 10 main ring magnets or their superconducting replacements. These magnets are assumed to be pulsable at the same rate as the superconducting ring.

At 1000 GeV, the refigeration for the first vertical bend can be supplied by the refrigeration system used to feed the superconducting synchrotron. The additional refrigeration required, including transfer lines, is about 400 to 500 watts at $4.5^{o}K$. The second vertical bend located about 450 m downstream from the first vertical bend has about the same refrigeration requirement (without long transfer lines). The refrigeration of the second vertical bend comes from the same source as the refrigeration for the primary beam switch yard. The beam switch yard is assumed to switch the beam to three different targets. The system is assumed to consist of 14 dipoles and 12 quadrupoles; pulsibility, while not required, is desirable. Two sets of leads are required for the dipole magnets and three sets of leads are required for the quadrupole magnets. The total estimated refrigeration requirement for the beam switch yard area is about 650 watts. This refrigeration is needed in a length of about 60 meters. The second vertical bend is located within 100 meters of the switch yard. Therefore, it is reasonable to put the switch yard and the second vertical bend on the single refrigerator with a capacity of about 1100 watts. A transfer line from the first vertical bend to the second vertical bend would require an additional 300 to 400 watts of cooling plus the transfer line itself. As a result, one gains economically by using a separate refrigerator for cooling the switch yard and the second vertical bend.

The 400 GeV machine may have superconducting magnets in the primary beam line. Because of the additional problems encountered when one tries to refrigerate the first vertical bend, both vertical bends are assumed to consist conventional magnets. The beam switch yard is assumed to be superconducting; the number of dipoles in the switch yard is reduced to 6, the number of quadrupoles remains at 12. The estimated refrigeration for the 400 GeV beam switch yard is about 500 watts, which would be supplied by a single refrigerator located outside the shielding.

The preceding remarks on primary beam line refrigeration requirements take into consideration the fact that the quadrupoles are conventional and that the magnets within the target station are also conventional. Table 1 gives an estimate of the refrigeration required in the primary beam lines of the north area, if the energy of the machine is 1000 GeV or 400 GeV. A more accurate estimate of refrigeration requirements will require more detailed information.

3. Refrigeration of the Secondary Beam Transport System

This section of the report describes the refrigeration problems associated with a system of magnets which has the following characteristics:

1) The magnets or groups of magnets are often separated by distances of 40 meters or more.
2) Clumping of bending magnets will be common, pairing of quadrupoles is also common.
3) The magnet position is not to be considered permanent, even though some experimental setups are expected to remain in place for many months (even years).
4) Beam transport magnets , their power supplies, and their equipment should be standardized for maximum flexibility and economy in the experimental area.
5) In many areas, the required shielding is not very thick. As a result, the operation of the refrigeration system near the magnets may be seriously considered.

The LRL-500 Incorporated reports of 1968 favor the small refrigerator concept in the secondary beams of an experimental area. That concept is still valid today (1972), but with some modifications:

1) Selection of the lead currents is important; on one hand, the lead current can't be too low because of the high winding cost of the magnet and the high inductance of the magnet; on the other hand, the lead current can't be too high because of the increased refrigeration required for leads (this refrigeration is 10 to 15 watts per 1000 Amps per lead pair. This number includes the refrigeration required because the lead gas doesn't return through the refrigerator heat exchanger).
2) It makes a great deal of sense to put quadrupole doublets in a single cryostat.
3) Large groups of bending magnets and quadrupoles can be run off of one or more large refrigerators, if they are close together.

This report recommends that magnets in the secondary beam lines be run off of refrigerators capable of delivering from 40 to 100 watts. Reliable refrigerators which can operate unattended over this range are well within today's technology. It should be noted that a refrigerator meeting the above criteria, which is sufficiently reliable for experimental area use, is available today from at least one manufacturer. The refrigerators should, in most instances, be run from a central compressor system. Gas to and from these compressors could be delivered along a beam line through rather conventional room temperature piping. It should be noted that the size of this piping is not greatly different from what might be required to transport cooling water to a system of conventional magnets with the same bending and focusing strength.

The central compressor station is a source of compressed gas for the refrigerators. Helium gas repurification and recovery also take place at the compressor station. The compressor stations can be located some distance from the experiments, just as cooling towers for conventional magnets are today. The largest source of failure of helium refrigerators in the size range suggested here has been compressor failure. Consolidation of compression facilities permits one to provide the redundancy necessary for reliable operation. It should be noted that the odd magnet or two which are located long distances from the central compressors can be cooled by refrigerators which have portable trailer mounted compressors.

In absence of data on the layout of the CERN II experimental area, we must make a number of assumptions in order to make a rough cost estimate of the secondary beam line refrigeration system. Let us assume the following:

1) The secondary beam lines consists of 100 - 200 quadrupole and dipole magnets of various strengths scattered over an area which is 1.5 km long and 150 m wide. About two-thirds of these magnets are quadrupoles.

2) Large spectrometer magnets, spark chamber magnets, and bubble chamber magnets will have their own refrigerators; hence, they are not considered a part of the beam transport refrigeration

system.

3) Quadrupoles are assumed to occur in doublets (two quadrupoles per cryostat). The dipoles are built one to a cryostat or are at least with segmented cryostats with one dipole per segment.

4) The refrigerators are separated from the magnets by no more than 30 meters of flexible or semi-flexible transfer line (this system has been used with good success at LRL Berkeley . Flexible transfer lines will also form an integral part of the Karlsruhe refrigeration transfer system.).

5) Two quadrupole doublets (about 90 watts) or two dipole magnets (90 - 100 watts) can be cooled from one refrigerator. The number of magnets to be cooled is a function of the transfer line length and the number of magnets located close to the refrigerator.

6) The warm compressed gas piping is assumed to run next to the beam line.

7) The refrigerator cold boxes are located outside the shielding in high radiation areas.

Table 2 presents an estimate of the refrigeration required for a quadrupole doublet and a dipole section. The stated heat loss estimate is rough, but from it a reasonable cost estimate can be obtained.

For a 1000 GeV experimental area, let us assume that all of the quadrupoles are in 67 doublets; the 66 dipole magnets are often grouped. One can make the assumption that 80 refrigerators (including spares) are required for an experimental area consisting of 200 magnets. One may also assume that the average length of flexible transfer line required is about 15 meters per magnet. Let us assume that one purchases 150 such lengths including spares. The compressed gas for the 80 refrigerators is assumed to be supplied by two compressor stations; each capable of delivering enough helium gas to run 2500 watts worth of small refrigerators (500 grams/sec if today's machines are used). In addition, 4 helium compressor trailers are assumed to supply the refrigerator used for the odd magnets. Each trailer is assumed to have enough gas capacity to run one refrigerator at a rating of 100 watts (20g/sec).

The 400 GeV experimental area is assumed to have 50 quadrupole doublets and 35 dipole magnets. I assume that 60 refrigerators are required including spares. I assume that there ible transfer line sections with an average length of 15 meters. I assume that only one compressor station exists in the 400 GeV experimental area. This compressor station supplies enough gas to run 3500 watts worth of small refrigerators. In addition, I assume that the 4 helium compressor trailers used in the 1000 case are used in the 400 GeV area as well. The number of magnets does not go down linearly with energy because a certain number of focusing and bending elements are requred just to perform an experiment.

Three helium pipes must be run in the experimental area. One pipe supplies warm compressed helium to the refrigerator; a second returns the gas to the compressor. This pipe also carries warm gas from the magnet leads and gas expelled from the magnet during cooldown. The third pipe recovers impure helium gas from the experimental floor.

4. Preliminary Cost Estimate

Preliminary cost estimates of beam transport systems made a number of years ago by Meuser[10] indicated that the capital cost per Tm of bending was the same or lower for a system of superconducting magnets as compared to a system of conventional magnets; this is still true today. The operating cost of the superconducting magnet system can be expected to be substantially lower than for the conventional magnet system. The a.c. magnets being developed at the three GESSS laboratories can be used as models for d.c. beam transport magnets because the technical requirements for a good d.c. beam transport magnet are not greatly different from a pulsable magnet, (the primary difference is the magnet current).

The cost of the refrigeration system for the primary beam transport system is shown in Table 3. The refrigeration cost for the first vertical bend in the 1000 GeV case is an extension of the superconducting synchrotron refrigeration system. It represents the cost of extending a 10 to 20 kw refrigerator by 500 watts. The cost of the beam switch yard and second vertical bend refrigeration is based on costs quoted in reference 6. These costs are high by today's standards. The 400 GeV primary beam transport system refrigeration cost is only for the switch yard refrigeration system.

Tables 4 and 5 give a cost estimate for refrigeration in a 400 GeV and a 1000 GeV beam transport area. It should be noted that one could supply each refrigerator with its own compressor and purification. The total cost of such a system for the experimental area would be about 22 Million Sw Fr for the 1000 GeV system and about 17 Million Sw Fr for the 400 GeV system. One, however, would increase the operating cost because the central compressors would be cheaper to maintain than many small compressors scattered about the site. Table 6 presents a rough estimate of the yearly operating cost of refrigeration in the primary and secondary beam transport systems.

5. Conclusions

Refrigeration can be supplied to the primary and secondary beams of the north area of the SPS for from 14 Million Sw Fr (400 GeV peak beam energy) to 20 Million Sw Fr (1000 GeV peak beam energy). The yearly operating cost of system varies from 2.5 to 3.0 Million Sw Fr depending on the primary beam energy. These numbers apply to a system of magnets which generates 530 to 1000 Tm of bending and 1.5 1.5 - 2 × 10^5 Tm/m of focusing. The average capital cost of refrigeration per dipole or per quadrupole doublet is around 150000 Sw Fr (about 0.8 - 1.2 × 10^4 Sw Fr / Tm of bending). One should compare this cost with the power supply and cooling system cost for a like amount of conventional bending or focusing.

The unit cooling cost, 150000 Sw Fr per cryostat, is relatively independent of the magnet useful aperture over a range of aperture diameters from 40 to 120 mm. The cost of refrigeration begins to climb as the magnet useful aperture goes above 120 mm. The cost of refrigeration does not vary a great deal over a range of magnet design fields from 3.5 to 5.5 T. As one increases the design dipole or quadrupole pole field beyond 6 T, The magnet size grows rapidly. This will increase the unit cost of refrigeration.

Figure 1 An Overall Layout of the North Experimental Area

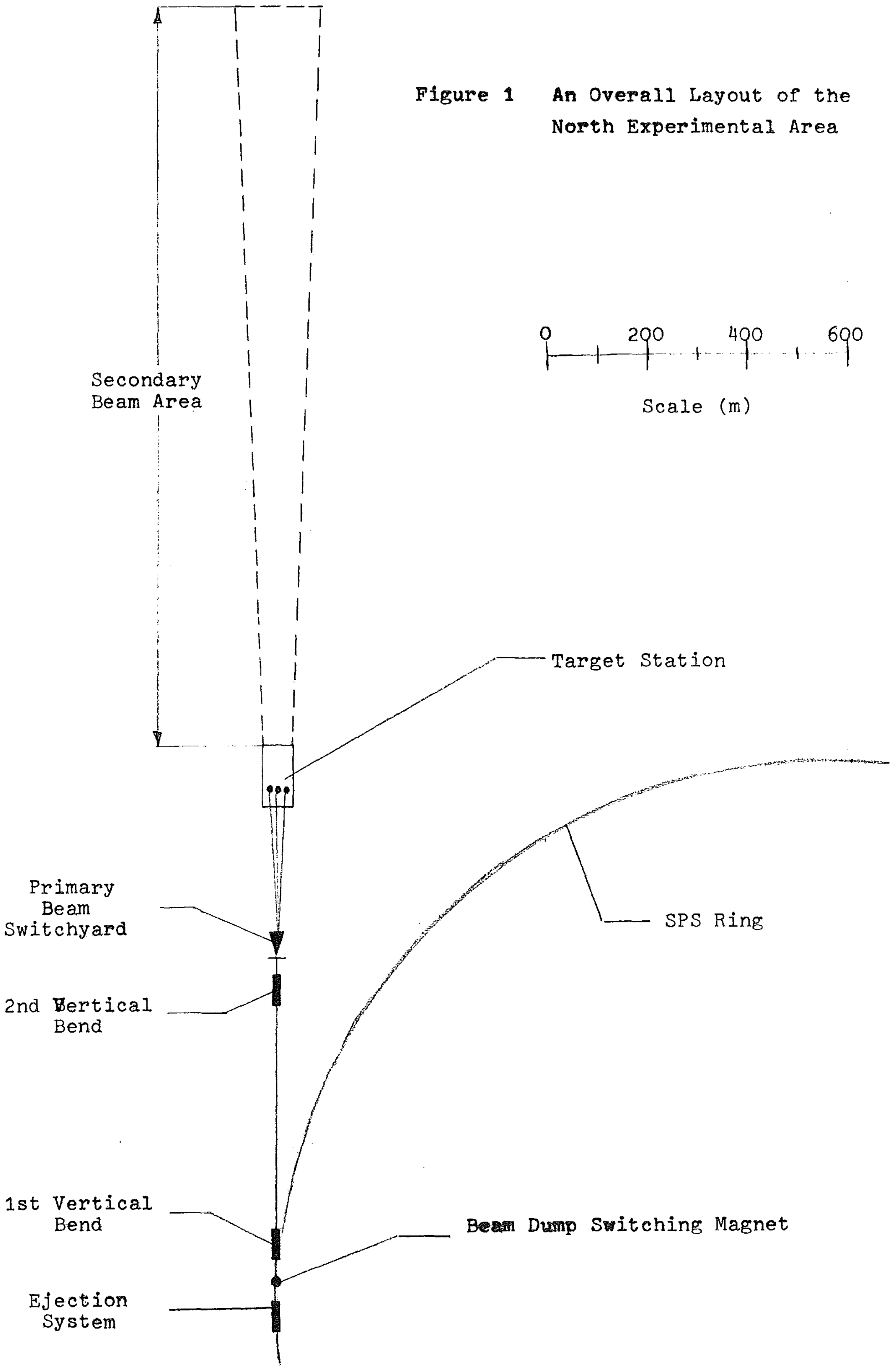

Table 1 Estimated Refrigeration Requirements for the Primary Beam Transport System

	400 GeV	1000 GeV		
	Beam Switch Yard	1st Vertical Bend	2nd Vertical Bend	Beam Switch Yard
Heat Leaks through the Supports 2.5W/magnet	45 W	25 W	25 W	65 W
Heat Leaks through the Superinsulation[+]	100 W	100 W	95 W	160 W
Electrical Lead Refrigeration 12W/1000A pair	50-125 W	5000A leads 120 W	5000A leads 60 W	depends on current 50-125 W
Transfer Line Heat Leak 1W/meter	75-100 W	50 W	75-100 W	75-100 W
A.C. Loss and Cooldown	80-100 W	100-150 W	100-150 W	100-150 W
Total Load	350-470 W	395-445 W	355-435 W	450-600 W
Installed Refrigeration Capacity	500 W	475 W	450 W	650 W
Installed Capacity for the 2nd Vertical Bend plus the Beam Switch Yard			1100 W	

[+] No nitrogen temperature shields are assumed

Table 2 Estimated Heat Loads for Various Element in a Beam Transport System

	2-3 meter long Quadrupole doublet 500A leads for each quadrupole	Single Dipole Section 4 meter long Room Temperature leads 1000A
Heat Leaks through the Supports	5 watts	3 watts
Heat Leaks down the Necks and through the Superinsulation+	3-6 watts	6-10 watts
Electrical Lead Cooling	12-14 watts	12-15 watts
Loss during Charging and Cooldown Allowance	10 watts	10 watts
Total Heat Load	30-35 watts	31-38 watts
Purchased Refrigeration Required	40 watts	40 watts

\+ No nitrogen temperature shields are assumed

Table 3 Refrigeration Cost for the Primary Beam Transport System

a) 400 GeV Primary Beam Transport System

Component	Cost of the Refrigeration	
	1st Vertical Bend	2nd Vertical Bend and Beam Switch Yard
Refrigerator and Compressor		740 000 Sw Fr
Transfer Lines		40 000 Sw Fr
J-T Valves and Control System		20 000 Sw Fr
Total for Components		800 000 Sw Fr
Total for 400 GeV Primary Beam Transport Area		800 000 Sw Fr

b) 1000 GeV Primary Beam Transport System

Component	Cost of the Refrigeration	
	1st Vertical Bend	2nd Vertical Bend and Beam Switch Yard
Refrigerator and Compressor	280 000 Sw Fr	1 140 000 Sw Fr
Transfer Lines	20 000 Sw Fr	80 000 Sw Fr
J-T Valves and Control System	40 000 Sw Fr	80 000 Sw Fr
Total for Components	340 000 Sw Fr	1 300 000 Sw Fr
Total for 1000 GeV Primary Beam Transport Area		1 640 000 Sw Fr

Table 4 Refrigeration Cost for the 400 GeV
Secondary Beam Transport System

Component	Cost (Thousands of Sw Fr)		
Compressor Stations			
Compressors	2000		
Purification	420		
Gas Storage	300		
Cooling and Power Distribution	560		
4 km Distribution Piping	1520		
Total per Station	4800	1 Station	4800
Portable Compressors Trailer-mounted	140 000 Sw Fr / Trailer		560
60 Refrigerators	125 000 Sw Fr / Refrigerator[+]		7500
110 Transfer Lines (average 15 m long)	4 000 Sw Fr / Transfer Line[++]		440
Total for the Secondary Beam System			13300

[+] Today a refrigerator meeting the above specification costs 170 000 Sw Fr without compressors or 270 000 Sw Fr with compressors and purification. The price above is based on quantity buying.

[++] LRL made a transfer line of this type for less than 140 Sw Fr/meter. Vacuum Barrier quotes a price of 5 000 Sw Fr for a 15 m long flexible transfer line[12].

Table 5 Refrigeration Cost for the 1000 GeV Secondary Beam Transport System

Component	Cost (Thousands of Sw Fr)		
Compressor Stations			
Compressors	1 440		
Purification	420		
Gas Storage	250		
Cooling and Power Distribution	400		
3 km Distribution Piping	1 140		
Total per station	3 650	2 Stations	7 300
Portable Compressors Trailer-mounted	140 000 Sw Fr / Trailer		560
80 Refrigerators	125 000 Sw Fr / Refrigerator[+]		10 000
150 Transfer Lines (average 15 m long)	260 Sw Fr / m or 4 000 Sw Fr / line[++]		600
Total for the Secondary Beam System			18 460

[+] Today a refrigerator meeting the above specification costs 170 000 Sw Fr without compressors or 270 000 Sw Fr with compressors and purification. The price above is based on quantity buying.

[++] LRL made a transfer line of this type for less than 140 Sw Fr/meter. Vacuum Barrier quotes a price of 5 000 Sw Fr for a 15 m long flexible transfer line[12].

Table 6 Yearly Operating Cost for Refrigeration for the Primary and Secondary Beam Transport Systems at 400 GeV and at 1000 GeV

	Yearly Operating Cost (Thousands of Sw Fr)	
	400 GeV	1000 GeV
Electric Power 0.04 Sw Fr/kw hr 400 GeV 2500 kw 1000 GeV 3400 kw	900	1200
Labor for Normal Operation (5 shifts, including Holidays and Weekends) 50 000 Sw Fr/Man yr. 400 GeV 3 men/shift 1000 GeV 4 men/shift	750	1000
Labor for Maintenance (day shift only) 400 GeV 3 men 1000 GeV 4 men	150	200
Replacement Parts	300	400
Helium Gas Makeup	100	100
Liquid Nitrogen, other Materials	100	100
Total Operating Cost	2300	3000
Operating Cost based on Reference 2	2700	3600
Operating Cost Range given in Reference 9	1900 - 5600	2600 - 7600

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Cost of Superconducting Dipole Magnets for an Experimental Area

Michael A. Green

The five tables which are attached explain the process for calculating the cost of a superconducting magnet system for the experimental area. The details of how the costs presented in Tables 2 through 5 were calculated is discussed in a full report which will come out later. Tables 1 through 4 compare the parameters and costs for nine different 4 meter long dipole magnets. The central induction varies in steps of 3.6, 4.5, and 5.4 T; the magnet coil aperture varies in steps of 50, 100, and 150 mm.

Table 1 shows the parameters of the nine magnets. Table 2 explains the process for calculating superconductor cost. Table 3 tabulates the major cost components which make up the magnet cost. Table 4 tabulates the cost of the major components of a superconducting magnet system. These include the magnet, the magnet cryostat, the magnet power supply, and the magnet refrigeration system. The last column in Table 4 shows the cost per Tm of bending. One should build magnets which have a central induction of around 4.0 to 4.5 T, if the magnet system is to be of minimum cost.

Table 5 compares the capital and operating cost of conventional and superconducting experimental area magnet systems. The conventional system must include the magnet, the magnet power supply, and the magnet cooling system.

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12. Private Communication with Norman E. Weare of Vacuum Barrier Corporation, 4 Barten Lane Woburn, Massachusetts 01901, USA represented in Europe by Kabelmetal, D 3000 Hannover, Postfach 260.

Table 1 Coil Ampere Turns and Ampere Meters for 4 Meter Long Dipole Magnets with Central Inductions of 3.6, 4.5, and 5.4 T and Coil Aperture Diameters of 50, 100, and 150 mm

Coil Central Induction (T)	Coil Aperture Diameter (mm)	Useful Aperture Diameter (mm)	Peak Induction in Coil (T)	Overall Coil Current Density[*] (A/cm^2)	Coil Thickness[+] (cm)	Ampere Turns of Conductor	Ampere Meters of Conductor[++]
3.6	50	35	4.0	2.4×10^4	1.72	3.26×10^5	2.68×10^6
	100	80	4.0	2.4×10^4	1.72	4.85×10^5	4.07×10^6
	150	120	4.0	2.4×10^4	1.72	6.90×10^5	5.81×10^6
4.5	50	35	5.0	2.0×10^4	2.79	4.32×10^5	3.57×10^6
	100	80	5.0	2.0×10^4	2.79	7.12×10^5	6.01×10^6
	150	120	5.0	2.0×10^4	2.79	9.92×10^5	8.55×10^6
5.4	50	35	6.0	1.7×10^4	4.13	6.40×10^5	5.31×10^6
	100	80	6.0	1.7×10^4	4.13	9.90×10^5	8.38×10^6
	150	120	6.0	1.7×10^4	4.13	13.42×10^5	11.58×10^6

[*] A cos θ coil is assumed; current density applies at $\theta=0$; the change in current density with field is correct when IMI, Airco, or Supercon materials are used.

[+] A cos θ coil has a uniform coil thickness.

[++] The dipole length is 4 meters; round ends are assumed.

Table 2 Super conductor Cost for 4 Meter Long Dipole Magnets with Central Inductions of 3.6, 4.5, and 5.4 T and Coil Apertures of 50, 100, and 150 mm

Dipole Central Induction (T)	Dipole Coil Aperture (mm)	Ampere Meters of Conductor	Superconductor[+] Cost Factor (Sw Fr/Am)	Coil Superconductor Cost (Sw Fr)
3.6	50	2.68×10^{6}	2.0×10^{-2}	0.54×10^{5}
	100	4.07×10^{6}	2.0×10^{-2}	0.81×10^{5}
	150	5.81×10^{6}	2.0×10^{-2}	1.16×10^{5}
4.5	50	3.57×10^{6}	2.4×10^{-2}	0.86×10^{5}
	100	6.01×10^{6}	2.4×10^{-2}	1.44×10^{5}
	150	8.55×10^{6}	2.4×10^{-2}	2.06×10^{5}
5.4	50	5.31×10^{6}	2.8×10^{-2}	1.49×10^{5}
	100	8.38×10^{6}	2.8×10^{-2}	2.35×10^{5}
	150	11.58×10^{6}	2.8×10^{-2}	3.25×10^{5}

[+] The price of fine filamented (8-12 µ filaments) NbTi superconductors is from 4×10^{-3} US \$/Am to 1.3×10^{-2} US \$/Am (1.5×10^{-2}-5×10^{-2}Sw Fr/Am) at a wire induction of 5 T. It should be noted that the price from IMI consistantly falls at the upper end of this scale $8\times10^{-3}$to 1.3×10^{-2}US \$/Am and the Airco and Cryomagnetics falls at the lower end of the scale. All prices are based on small lots, say 10^{6} to 3×10^{6} ampere meter of superconductor. The price per ampere meter of a given conductor is inversely proportional to it's critical current.

Table 3 The Cost of a 4 Meter Long Superconducting Dipole Magnet as a Function of Central Induction (3.6, 4.5, and 5.4 T) and Magnet Coil Aperture (50, 100, and 150 mm)

Magnet Central Induction (T)	Magnet Coil Aperture (mm)	Magnet Superconductor Cost (Sw Fr)	Magnet Conductor Winding and Potting Cost (Sw Fr)[*]	Magnet Bore Tube Assembly and Test (Sw Fr)[+]	Magnet Iron Cost (Sw Fr)[++]	Total Magnet Cost (Sw Fr)[**]
3.6	50	0.54×10^5	0.27×10^5	0.2×10^5	0.2×10^5	1.21×10^5
	100	0.81×10^5	0.41×10^5	0.25×10^5	0.4×10^5	1.87×10^5
	150	1.16×10^5	0.58×10^5	0.3×10^5	0.8×10^5	2.84×10^5
4.5	50	0.86×10^5	0.43×10^5	0.2×10^5	0.3×10^5	1.79×10^5
	100	1.44×10^5	0.72×10^5	0.25×10^5	0.6×10^5	3.01×10^5
	150	2.06×10^5	1.03×10^5	0.3×10^5	1.2×10^5	3.79×10^5
5.4	50	1.49×10^5	0.75×10^5	0.2×10^5	0.5×10^5	2.94×10^5
	100	2.35×10^5	1.18×10^5	0.25×10^5	0.9×10^5	4.68×10^5
	150	3.25×10^5	1.63×10^5	0.3×10^5	1.7×10^5	6.88×10^5

[*] This cost estimate is based on the winding cost of two large Berkeley magnets. The average winding cost was $1\text{-}1.3\times10^{-2}$ Sw Fr/Am; production magnet cost should be much lower.

[+] This cost is based on Berkeley experience, a cost of $5000 to $10,000 per magnet for bore tube and assembly. If the magnet is mass produced, these costs will be substantially lower.

[++] This cost is based on a price of 8 Sw Fr/Kg for finished iron cores.

[**] The total price does not include engineering and development. Add a contingency allowance of 40%.

Table 4 The Cost of the Magnet System for a 4 Meter Long Superconducting Dipole Magnet as a Function of Central Induction (3.6, 4.5, and 5.4 T)

Magnet Central Induction (T)	Coil Aperture (mm)	Magnet Cost (Sw Fr)	Magnet Cryostat Cost ** (Sw Fr)	Magnet Power Supply Cost + (Sw Fr)	Refrigeration System Cost ++ (Sw Fr)	Total Magnet System Cost (Sw Fr)	Superconducting Magnet System Cost per Tm (Sw Fr)
3.6	50	1.21×10^5	0.8×10^5	0.2×10^5	1.5×10^5	3.71×10^5	2.58×10^4
	100	1.87×10^5	0.9×10^5	0.2×10^5	1.5×10^5	4.47×10^5	3.11×10^4
	150	2.84×10^5	1.0×10^5*	0.2×10^5	1.5×10^5	5.54×10^5	3.85×10^4
4.5	50	1.79×10^5	0.8×10^5	0.2×10^5	1.5×10^5	4.29×10^5	2.38×10^4
	100	3.01×10^5	0.9×10^5	0.2×10^5	1.5×10^5	5.61×10^5	3.11×10^4
	150	3.79×10^5	1.0×10^5*	0.24×10^5	1.5×10^5	6.53×10^5	3.63×10^4
5.4	50	2.94×10^5	0.9×10^5	0.2×10^5	1.5×10^5	5.54×10^5	2.56×10^4
	100	4.68×10^5	1.0×10^5	0.2×10^5	1.5×10^5	7.38×10^5	3.42×10^4
	150	6.88×10^5	1.0×10^5*	0.38×10^5	1.5×10^5	9.76×10^5	4.52×10^4

* It is probable that the iron will lie outside the cryostat.

** Based on cryostat cost quoted to the KFK, some allowance has been made for quantity production.

\+ Cost based on a minimum price of 5000 US \$ or 0.25 US\$/watt whichever is higher; this is based on Berkeley experience. Ripple requirement $\leq 2\times10^{-4}$. Mass produced power supplies could be less expensive.

\++ Unit refrigeration system cost given in the refrigeration system report BSG Notiz 72/7.

Table 5 A Comparison of the Cost of 18 Tm of Bending using Superconducting and Conventional Magnets in an Experimental Area

	Superconducting Magnet	Conventional Magnet
a) Magnet Parameters		
Number of Magnets	1	2
Magnet Induction	4.5 T	1.8 T
Length of Magnet	4.0 m	5.0 m
Aperture of Magnet	100 mm Φ	100×240 between poles
Type of Magnet	cos θ	Window Frame
Iron Weight	-----	19.6 Tons*
Copper Weight	-----	5.2 Tons**
Power Requirements to Produce 1.8 T	44 kw	440 kw
b) Magnet System Capital Cost (Sw Fr)		
Magnet	3.01×10^5	2.98×10^5
Magnet Cryostat	0.9×10^5	-----
Magnet Power Supply	0.2×10^5	$4.4\times10^{5+}$
Refrigeration System	1.5×10^5	-----
Water Cooling System	-----	$1.68\times10^{5++}$
Total Capital Cost for 18 Tm	5.61×10^5	9.06×10^5
Capital Cost per Tm	3.11×10^4	5.03×10^4
Cost Range for 18 Tm of bending	$4.0-8.0\times10^5$	$7.7\times10.5\times10^5$
c) Magnet Yearly Operating Cost (Sw Fr)		
Power Cost	0.15×10^{4} §	1.5×10^5
Labor Cost	0.15×10^4	0.1×10^5
Total Yearly Cost	0.3×10^4	1.6×10^5

* Iron cost is 0.50 US $/lb (4.2 Sw Fr/kg) including assembly.

** Copper current density 600 A/cm^2 (the optimum for minimum capital cost is 400 A/cm^2. Beam transport magnets which run at lower induction much of the time have higher than optimum current densities); copper cost is 5.00 US $/lb (42 Sw Fr/kg)

\+ Power supply cost 1000 Sw/Fr/kw based on German costs.

++ Cooling system cost complete is 380 Sw Fr/kw installed. This is based on Berkeley costs.

§ Power cost 0.01 US $/kw hr (0.038 Sw Fr/kw hr).