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OPTIMUM CURRENT DENSITY IN THE MAGNET CONDUCTORS OF A 300 GeV PROTON SYNCHROTRON

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1. Introduction

The cost of an alternating gradient proton synchrotron is substantially influenced by the selected current density in the conductors of the excitation winding of the guiding magnet. Components mainly affected are : the magnet core, the coils, the power supply and the magnet cooling system. Since power costs represent an appreciable fraction of the running costs of the accelerator, these costs, capitalized over an appropriate period of time, should also be included in a study on the most economical design.

This report summarizes a study which has been made to determine the optimum current density in the main magnet conductor of a 300 GeV Proton Synchrotron presently under consideration at CERN. It is based on preliminary design data, but it is assumed that final data will not substantially change the result.

Magnets of the C-Type only are considered in the present study. The H Type has not been studied in detail because the lack of accessibility of the vacuum chamber and the extremely tight assembling tolerances represent serious drawbacks. Both water-cooled copper and aluminium conductors for the excitation coils have been included for.

It is assumed that the magnet would be supplied by two motor-flywheel-alternator sets and twelve mercury-arc power converters distributed at equal distances around the magnet ring.

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For the dissipation of the heat losses from the magnet coils various alternative cooling systems have been considered. Depending on the climatic conditions and the available water supplies of a proposed site, each of the considered plants, under certain conditions, shows advantages over the remainder. However, for the majority of possible sites in Europe it is considered that recooling with raw water will, - depending on certain technical and economic conditions, - provide the most satisfactory arrangement.

Components whose costs are comparatively small or not substantially influenced by the current density in the magnet coils, such as devices required for the "injection platform", or for compensating the ripple in the magnet voltage and current are not included in the present cost estimate. Excluded are also items whose cost depend more on the selected site rather than on current density, such as magnet supports, foundations for the magnet and the M.G. sets, and transport and erection costs.

The cost estimate was made for r.m.s. current densities in the range from 100 to 400 A/cm^2 for copper conductors and 100 to 300 A/cm^2 for aluminium conductors. All cost figures are based on recent information from prospective manufacturers of the equipment.

2. Parameters and Basic Assumptions

The following parameters were used in this study :

Kinetic particle energy	300 GeV
Magnet :	
Maximum magnetic field	12 kGauss
Peak amperetums	72 000
Peak stored energy in the magnet	68.5 MJ
Length of magnet units	6.10 m
Number of magnet units	864
Magnetic radius	840 m
Pole width	250 mm
Gap height at orbit radius	70 mm
Minimum gap	47 mm

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Magnet cycle :

Injection period	0.5 s
Current rise time (including 0.1 s front porch)	1.1 s
Flat top	0.7 s
Current fall time	0.9 s
Pulse repetition time	3.3 s

Basic Assumptions :

1. Rise and fall of the magnet current were assumed to be linear. This gives r.m.s. magnet currents and power losses which are somewhat higher than for the actual rise and fall of current. On the other hand the current during the "injection platform" is neglected which partly compensates the above error.
2. The stored energy in the magnet was assumed to be independent of the current density.

Further assumptions are made in Sections 3.3 and 3.4.

3. Estimated Cost vs. Current Density

3.1. Magnet Core

Design : C-type with excitation coils on the poles. Thin plates of low carbon steel press punched, and assembled by means of welded strips. Cross-section as shown below.

Cost estimates : The cost of the magnet core can be divided into two parts : material and manufacturing. The cost of the material is obviously proportional to the total weight of the raw steel plates. A fraction of the manufacturing cost is also proportional to the total weight of the plates to be handled and punched, while another part is only related to the number and to the length of the units.

Therefore, the cost of the core can be expressed by the formula :

$$C_{MC} = C_1 + W_i \cdot c_2 \tag{1}$$

where

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C_1 ... part of the manufacturing cost, independent of plate cross-section, within the considered limits;

W_i ... weight of the magnet steel in tons;

c_2 ... cost of material and manufacturing, per ton of steel plate.

$$W_i = 2 \pi r_m A_i \gamma_i \tag{2}$$

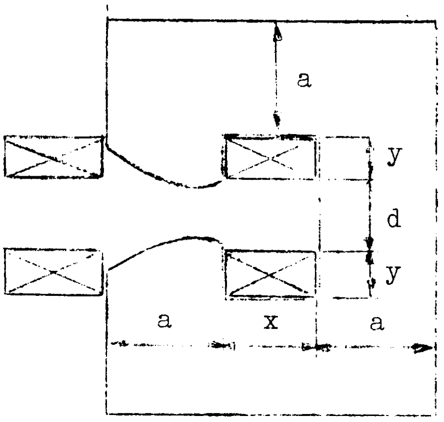
r_m ... magnetic radius

A_i ... magnet cross-section

γ_i ... specific weight of the magnet iron

$$A_i = (2a + x)(2a + 2y + d) \tag{3}$$

There is an optimum coil width to height ratio which gives a minimum iron cross-section.



The total conductor cross-section is

$$A_c = 2 fxy \tag{4}$$

from which follows

$$y = \frac{A_c}{2fx} \tag{5}$$

f ... filling factor

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By introducing (5) into (3) and differentiating we get

$$\frac{dA_i}{dx} = d + 2a - \frac{2a}{f} \frac{A_c}{x^2}$$

$\frac{dA_i}{dx} = 0$ gives

$$x = \sqrt{\frac{2a}{f(d + 2a)}} \sqrt{A_c} \quad \text{and} \quad y = \frac{1}{2} \sqrt{\frac{d + 2a}{2af}} \sqrt{A_c} \qquad (6)$$

By introducing (6) into (3) we get for the optimum plate cross-section

$$A_i = 2a (d + 2a) + 2 \sqrt{\frac{2a}{f} (d + 2a)} \sqrt{A_c} + \frac{1}{f} A_c \qquad (7)$$

The necessary total conductor cross-section is

$$A_c = \beta \frac{(NI)_p}{J} \qquad (8)$$

β ... ratio of r.m.s. to peak magnet current

$(NI)_p$ ... peak ampereturns

J ... r.m.s. current density in magnet conductor.

By introducing numerical values :

$a = 0.25$ m	$f = 0.5$
$d = 0.13$ m	$\beta = 0.63$
$r_m = 840$ m	$(NI)_p = 72\ 000$

$\gamma_i = 7.8$ t/m^3

into (2), (7) and (8) we get :

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$$W_i = 1.3 \cdot 10^4 + \frac{1.4 \cdot 10^5}{\sqrt{J}} + \frac{3.8 \cdot 10^5}{J} \quad \text{ton} \qquad (9)$$

In formula (1) the constants are :

$$C_1 = 22 \cdot 10^6 \text{ SFr. and } c_2 = 2 \cdot 10^3 \quad \text{SFr./ton}$$

therefore the cost of the magnet core is

$$C_{MC} = 22 \cdot 10^6 + 2 \cdot 10^3 W_i \qquad \text{SFr.} \qquad (1a)$$

Table 1 : Weight and Cost of the Magnet Core vs. Current Density

Current density A/cm^2	100	150	200	250	300	350	400
Weight $\cdot 10^3$ ton	30.8	26.9	24.9	23.3	22.4	21.6	21.0
Cost Mill.SFr.	83.6	75.8	71.8	68.8	66.8	65.5	63.9

3.2. Magnet Coils

Design : Flat pancakes of water cooled copper or aluminium conductor. Insulation impregnated under vacuum and cured in a mould. Three pancakes per coil.

Cost estimates : The cost of the coils can be divided into three parts :

a) conductor bar and coil winding;

b) insulation;

c) moulding, curing, tests.

The first part is proportional to the weight of the conductor, the second roughly to the square root of the weight, the third to the number of pancakes.

Therefore the cost of the coils can be expressed by the following formula :

$$C_{EC} = c_3 W_c + c_4 \sqrt{W_c} + c_5 P \qquad (10)$$

where :

W_c ... conductor weight in tons;

c_3 ... cost per ton of conductor bar for item a);

c_4 ... empirical coefficient for insulation cost;

c_5 ... fixed costs per pancake;

P ... number of pancakes.

$$W_C = L_C \cdot A_c \cdot \gamma_c \qquad (11)$$

L_C ... total length of coils;

A_c ... total conductor cross-section;

γ_c ... specific weight of conductor material.

$$L_C = \alpha \cdot 2 \cdot 2 \pi r_m \qquad (12)$$

α ... factor taking into account coil ends

$$A_c = \beta \frac{(NI)_p}{J} \qquad (8)$$

Introducing numerical values

$$\alpha = \frac{6.6}{6} = 1.1 \qquad r_m = 840 \text{ m}$$

$$\gamma_c = \begin{matrix} 8.9 \ \text{t/m}^3 & \text{for copper} \\ 2.7 \ \text{t/m}^3 & \text{for aluminium} \end{matrix}$$

into (11), (12) and (8) we get

$$W_C = W_{Cu} = \frac{4.77 \cdot 10^5}{J} \quad \text{ton for copper} \qquad (13a)$$

and

$$W_C = W_{Al} = \frac{1.45 \cdot 10^5}{J} \quad \text{ton for aluminium} \qquad (13b)$$

In formula (10) the constants are

$$c_5 = 830 \qquad P = 5200$$

$$c_3 = \begin{cases} 12.5 \cdot 10^3 & \text{for copper} \\ 17 \cdot 10^3 & \text{for aluminium} \end{cases}$$

$$c_4 = \begin{cases} 174 \cdot 10^3 & \text{for copper} \\ 282 \cdot 10^3 & \text{for aluminium} \end{cases}$$

if W_C is in tons

Therefore the cost is

$$C_{EC} = 830\,P + 12.5 \cdot 10^3\, \frac{4.77 \cdot 10^5}{J} + 174 \cdot 10^3 \sqrt{\frac{4.77 \cdot 10^5}{J}} \quad \text{SFr.} \qquad (14a)$$

for copper

or

$$C_{EC} = 830\,P + 17 \cdot 10^3\, \frac{1.45 \cdot 10^5}{J} + 282 \cdot 10^3 \sqrt{\frac{1.45 \cdot 10^5}{J}} \quad \text{SFr.} \qquad (14b)$$

for aluminium

Table 2 : Weight and Cost of Magnet Coils vs. Current Density in the Conductors

Current Density	A/cm^2	100	150	200	250	300	350	400
Weight	Copper Coils ton	4770	3180	2380	1910	1590	1360	1190
	Alum. Coils ton	1450	970	725	580	485	415	360
Cost	Copper Coils MSFr.	76.0	53.9	42.6	35.8	31.2	27.7	25.2
	Alum. Coils MSFr.	39.6	29.6	24.2	21.0	18.7	17.1	15.7

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3.3. Magnet Power Supply

Design : 2 Motor-flywheel-alternator sets

12 Power converter units distributed at equal distances round the P.S. ring, each unit consisting of two double-three phase sets in cascade.

Assumptions :

1. The driving motors will be equipped with Scherbius regulators;
2. The alternators will be hydrogen cooled and electronically excited;
3. The alternator voltage will be stepped up for transmission of the power to the distributed power converters.

Cost Estimate : The cost of the individual components of the magnet power supply depends in a different manner on the current density in the magnet coils and has therefore to be estimated separately.

The rating of the driving motors, the main alternators and the power converters is given in Table 3 below. It will be shown in a separate report how these ratings were determined. Cost figures are based on preliminary quotations from firms. They were determined from graphs giving the prices as a function of the rating.

Table 3 : Power Ratings and Cost of Components of the Magnet Power Supply vs. Current Density in the Magnet Conductors

A. Magnet with Copper Coils

Current Density A/cm^2	100	150	200	250	300	350	400
Motor Output Power MW	14.5	20.0	25.5	31.0	36.5	42.0	47.5
Alternator r.m.s. Power MVA	141	146	151	156	162	167	172
Converter Peak Power MW	156	162	168	174	180	186	192
Cost Motors + Transf. MSFr.	2.2	2.4	2.6	2.9	3.2	3.5	3.8
Cost Alternators + Transf. MSFr.	6.9	7.1	7.3	7.5	7.8	8.0	8.2
Cost Power Converters MSFr.	7.7	7.7	7.8	7.9	8.0	8.1	8.2
Total Cost MSFr.	16.8	17.2	17.7	18.3	19.0	19.6	20.2

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B. Magnet with Aluminium Coils

Current Density	A/cm^2	100	150	200	250	300
Motor Output Power	MW	21.5	30.5	39.5	48.5	57.5
Alternator r.m.s. Power	MVA	148	152	160	166	172
Converter Peak Power	MW	165	171	178	184	190
Cost Motors + Transformers	MSFr.	2.5	2.9	3.4	3.9	4.5
Cost Alternators + Transf.	MSFr.	7.2	7.4	7.7	8.0	8.3
Cost Power Converters	MSFr.	7.7	7.8	7.9	8.0	8.2
Total Cost	MSFr.	17.4	18.1	19.0	19.9	21.0

3.4. Magnet Cooling System

Design of the System : Four complete recooling plants distributed round the synchrotron, each plant consisting of a demineralized water/raw water heat exchanger, demineralizing plant, pumps, controls and piping.

Assumptions :

1. An adequate supply of raw water will be available at low cost, with an average yearly temperature of not more than about 11 to 12° C.

2. The raw water will be pumped into the site water distribution network, after treatment, from a water treatment plant situated at about 500 metres outside the machine ring perimeter.

   The raw water pipework will be laid in flat ground and will be of spun iron, with bitumen or concrete lining and bitumen sheathed.

3. The temperature difference of the demineralized cooling water passing through the magnet coils will be about 12° C. with an average temperature of 20° C. The maximum working pressure with a pressure drop across the magnet coils of 0.5 kg/cm^2, will be 10 kg/cm^2.

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Cost Estimate : Cost figures are given in Table 4 below.

Table 4 : Total Cost of the Cooling System vs. Current Density

Current Density A/cm^2		100	150	200	250	300	350	400
Cost of Cooling System MSFr.	Copper Coils	5.3	6.5	7.7	9.0	10.2	11.4	12.7
	Aluminium Coils	7.4	9.8	12.2	14.6	17.0	-	-

3.5. Total Capital Costs

The total of those capital costs which vary sensibly with current density are given in Table 5 below.

Table 5 : Total of those Capital Costs which depend sensibly on Current Density

A. Magnet with Copper Coils

Costs in Million SFr.

Current Density A/cm^2	100	150	200	250	300	350	400
Magnet Core	83.6	75.8	71.8	68.8	66.8	65.5	63.9
Magnet Coils	76.0	53.9	42.6	35.8	31.2	27.7	25.2
Magnet Power Supply	16.8	17.2	17.7	18.3	19.0	19.6	20.2
Magnet Cooling System	5.3	6.5	7.7	9.0	10.2	11.4	12.7
Total Cost	181.7	153.4	139.8	131.9	127.2	124.2	122.0

B. Magnet with Aluminium Coils

Costs in Million SFr.

Current Density A/cm^2	100	150	200	250	300
Magnet Core	83.6	75.8	71.8	68.8	66.8
Magnet Coils	39.6	29.6	24.2	21.0	18.7
Magnet Power Supply	17.4	18.1	19.0	19.9	21.0
Magnet Cooling System	7.4	9.8	12.2	14.6	17.0
Total Cost	148.0	133.3	127.2	124.3	123.5

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