Particle Accelerators, 1970, Vol. 1, pp. 187–198

APPLICATION OF PULSED SUPERCONDUCTING MAGNETS TO SYNCHROTRONS

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The behaviour of superconductors in variable fields is summarized. Some experimental results are given, concerning the behaviour of the coils and their losses; emphasis is put on electrical methods. Comments on the design of superconducting dipoles and quadrupoles are developed, and the main parameters of an experimental dipole are listed.

A step towards bigger machines could be the conversion of an existing machine; as an example, it is proposed to turn Saturne into a 15-GeV synchrotron.

Finally, some possible schemes using superconducting magnets in future plans for the European accelerator are sketched, taking into account the expected improvements in available amounts of power supply.

1. INTRODUCTION

The use of superconducting magnets for the design of circular accelerators would give a gain by a factor of 3 to 4 on the bending field and the focusing gradient. This means a reduction by about the same factor of the average radius of the machine and consequently a reduction in the cost of all the items which are an increasing function of the radius: tunnel, rf cavities, vacuum chamber, controls, etc.

On the other hand the power supply is more important and very likely more costly and the design of superconducting magnets as an accelerator unit is such a new problem that it is not reasonable to say today what would be the final cost of the magnet including its cryogenic aspects. The right answer will be obtained only after a detailed study which is in progress now in different laboratories. However, from the knowledge already available on dc magnets and the work of many groups on pulsed magnets it is possible to get preliminary conclusions and to make some interesting remarks on the future of the application of pulsed superconducting magnets to accelerators projects.

The two first applications one would think of are:

1. The conversion of existing machines by increasing the energy to save the important investments made in experimental areas.
2. The very-high-energy (TeV) machines. The existing projects (multihundred GeV) have radii of the order of a kilometer. A factor of 3 or 4 in the energy will certainly make it more difficult to find a suitable site.

In both cases, there are very many problems to be solved before a construction can be started. One of the most important of them is the behaviour of superconducting material in a variable field.

It is well known from dc magnet studies and experiments that the field variation gives heat production and temperature rise due to both permanent losses related to dB/dt, and flux jumps. These phenomena produce the degradation difficulty which has been overcome by the full stabilization which was used for all the coils made up to now. Recent work showed that the use of thin filaments will require much less stabilization and will lead to better results.

In the case of pulsed fields the same problem of permanent losses is much more important due to the higher desired dB/dt. The use of very thin filaments becomes an absolute necessity to reduce the losses to a level low enough to make the economical comparison favorable.

2. SUPERCONDUCTOR BEHAVIOUR IN VARIABLE FIELD

The typical field cycle which would be used in a superconducting accelerator is shown on Fig. 1.

Compared to dc magnets the field change will occur during more than half the time at a rate of 5 to 10 T/s.

The study of the field penetration in the bean critical state model theory shows,[1–3] that an electrical field will appear superimposed on a current density and will lead to losses. The behaviour can be illustrated in another way by looking to the flux density in the material subject to an outside varying magnetic field. In the simple case of a superconducting semi-infinite slab shown

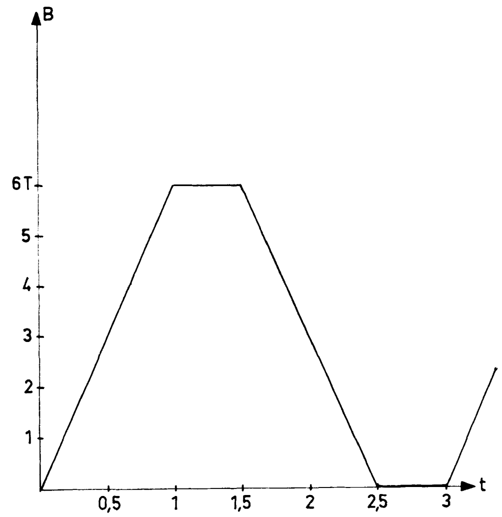

FIG. 1. Flux density versus time in a superconducting synchrotron.

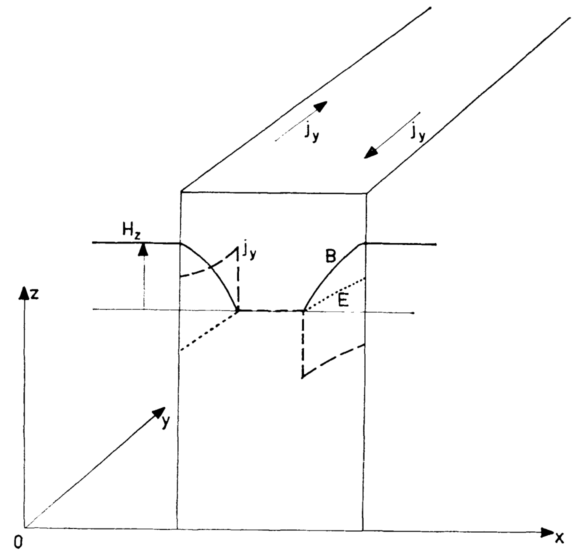

FIG. 2. Semi infinite slab for theoretical calculations.

in Fig. 2, the flux density penetration and the magnetization curve are represented on Fig. 3 for a cycle. The area of the closed curve $B(H)$ represents, as for a ferromagnetic material, the magnetization losses.

Computed from the expressions of the electrical field and the current density one gets for A, the losses per cycle and per unit of volume, the following result[3]:

$$A = \alpha a \left[\ln\left(\frac{B_0 + B_{\max}}{B_0}\right) + (j_m{}^2/\alpha^2) B_{\max}(B_0/3 + B_{\max}/4) \right] \quad (1)$$

in which α and B_0 are related to the critical current density by

$$j_c = \alpha/(B_0 + B);$$

$2a$ is the width of the slab, $B_{\max}$ is the maximum value of the flux density (assumed very large compared to the penetration value $2\mu_0 j_c a$), and j_m is the maximum critical current density.

Typically for $B_{\max} = 6$ T and $2a = 10\ \mu$, one gets 0.06 J/cm^3.

Formula (1) shows that the losses per cycle and per unit of volume are independent of the frequency, proportional to the slab thickness and function in a complicated way of the maximum field. For a given cycle and maximum field the only way to reduce the losses is the use of very thin filaments, of the order of 1 μ. To get a practical

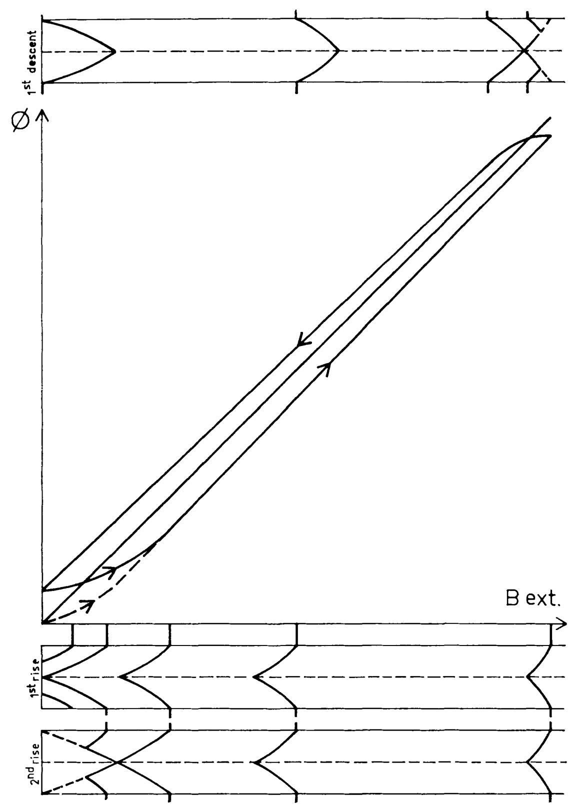

FIG. 3. Flux density penetration in semi-infinite slab for a whole synchtrotron cycle.

current for a coil, a very large number of filaments in parallel must be used and to be able to handle them, they must be imbedded in a strong matrix which will provide at the same time the stabilization. Unfortunately, it has been shown[4–6] that induced currents will circulate in the resistive matrix between filaments and will lead to supplementary losses and degradation effects. The physical phenomenon is illustrated on Fig. 4. A

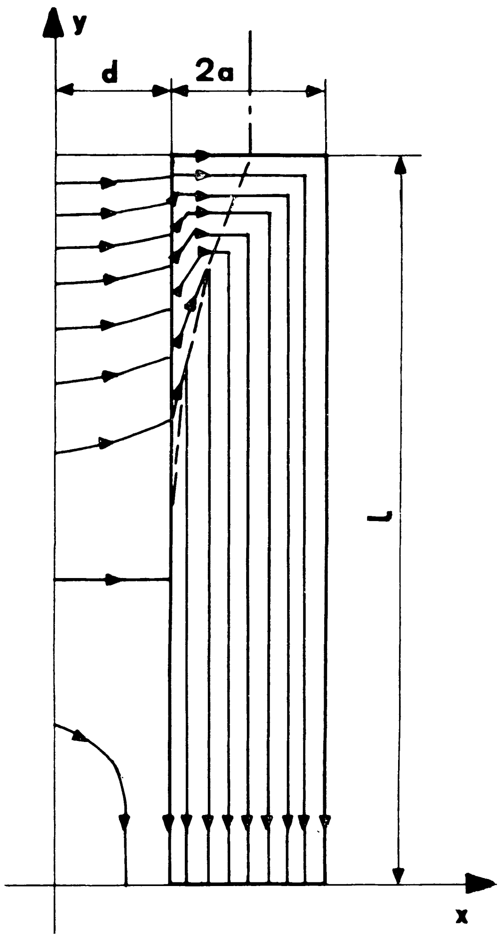

FIG. 4. Induced currents in two superconducting slabs in a resistive matrix.

critical length l_c of the slab will correspond to the case where the induced currents will fill the superconducting material to the critical current. l_c is given by[7]

$$l_c = \left[\frac{d}{(a+d)}\frac{\lambda a j_c \rho}{\mathrm{d}B/\mathrm{d}t}\right]^{1/2} \qquad (2)$$

in which ρ is the resistivity of the matrix, λ a coefficient depending on the shape and $2d$ the thickness of the resistive matrix.

If the very thin filaments are transposed with a pitch smaller than l_c, then formula (1) can be used to compute the losses in a small volume of superconductor subject to a given maximum field. For a given magnet with a known field map the losses will be computed from formula (1) extended to the general case taking into account the whole penetration cycle, and numerical integration.[8] Typically for a 6 T dipole having a useful circular aperture of about 10 cm diameter, with an average current density of 24 000 A/cm^2 and using correctly transposed filament of 4 μ, the magnetization losses would be $\sim$ 60 J/cycle · meter of length.

3. EXPERIMENTAL RESULTS

The experimental knowledge of the magnet losses can be obtained from magnetization cycle measurements on a sample or from direct coil loss measurements.

Magnetization measurements do not provide absolute values of losses and will be useful to check some parameter effects like maximum field, frequency and dimensions. Direct coil loss measurements will give an overall result including the additional effect of temperature rise due to bad cooling, conductor movement, etc. However, it seemed to us that one can get by this way more direct and practical results. We made most of our effort in this direction using the magnetization measurement only for comparison.

Measurements can be achieved by two methods. The calorimetric method by which the helium boil off due to losses is measured has been used at Brookhaven[9] and at the Rutherford Laboratory.[7] In the electrical method we measure by integrating the product of the voltage and the current in the coil, consequently are able to measure the energy which goes into and comes out of the coil, the balance being the total losses. This method is in use at Berkeley[10] and Saclay[11]. Our measurements, at Saclay[12] were made using more than 22 solenoids, the average characteristics of which are:

inside diameter	21 to 22 mm
outside diameter	90 to 120 mm
height	90 mm
maximum field	6 T
average current density	11 000 to 29 000 A/cm^2
repetition period	1 to 15 sec.

The superconducting conductor is made of Nb–Ti filaments imbedded in a copper matrix with a ratio of copper to superconductor of about 1/1 to 2/1. The diameters of the filaments varied from 300 μ to 28 μ, some of them were individually insulated and twisted with a large pitch, some were twisted directly in the copper matrix with differents values of pitch.

The results did not show extra degradation in pulsed conditions except for the coils which were badly cooled (small helium channel width). The loss measurements performed at different field levels are compared to the values obtained by using the theoretical expression numeratically integrated, knowing the field map of the coils.

The ratio of the measured losses to the calculated losses as a function of the field for some of the solenoids is shown in Fig. 5. It can be seen that the agreement between the theory and the experimental results is good to within a factor of 2. The coils which gave losses higher than expected are the coils with bad cooling. Repeated experiments with the same material but with larger channel width showed an important improvement. It appears also that a high tensile strain during winding improves the results.

No measurements have been done up to now with filament diameters below 25 to 30 μ. From a preliminary study,[13] it seems that surface currents will not alter the linear dependence of the losses on the filament size. Work is being done in many laboratories to obtain, in the near future, the loss levels for filament diameters of about 1 μ.

It is quite clear now that, from both points of view of degradation and losses, the cooling is a very important parameter. Any scheme, like impregnation, to hold the large forces during operation and prevent movement, must include special devices to extract the even low level of heat generated in the coil and to transfer it to the helium refrigerant.

The last point to be mentioned from the experimental results is that the losses were not a function of the cycling frequency when the twist pitch was slightly smaller than the critical value given by Eq. (2). This fact confirms the validity and the necessity of the transposition.

At this stage of the study, one is reasonably confident that steady progress will be made to

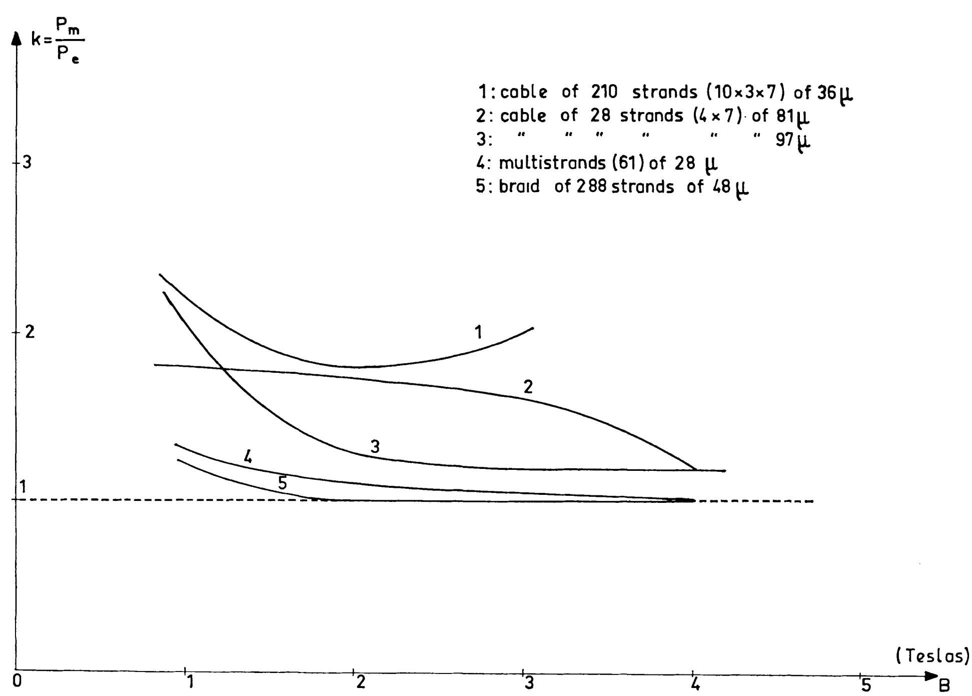

FIG. 5. Ratio of the measured losses to the computed losses in some solenoids using different conductor types.

reach soon the point where the technique of pulsed magnetic fields will be settled.

4. DIPOLE AND QUADRUPOLE PROJECTS

We assume initially that the accelerator will be of the separated function type. All the projects now being considered require an elliptical aperture, the size of which is typically of the order of 100 × 50 mm. For the dipoles such useful region can be obtained by different ways. The best known are illustrated in Fig. 6. The type II (intersecting

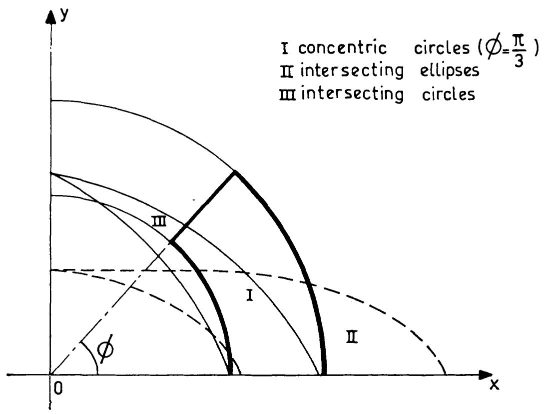

FIG. 6. Schematic coil shapes giving uniform field.

ellipses) would seem to be the most economic arrangement as it gives the field only in the useful space.

A preliminary study comparing type I and II from the point of view of the overall size, the stored energy and the area of the coil has been made.(14) The stored energy is the most important parameter for the power supply. The area of the coil is directly related to the quantity of superconducting material which will be used and the losses which one will get in the coil.

Figure 7 gives this comparison for the case of an aperture of 108 × 68 mm (the useful aperture is assumed to be 88 × 48 mm) for the stored energy W in the whole space assuming no iron shielding, for the area S of the coil, and for the horizontal size defined as the horizontal aperture plus the horizontal coil thickness. The abscissa indicates the current density with a range of 15 000 to 30 000 A/cm² which are reasonable present day values.

It appears that there is no evident difference between circular and elliptical coils and that increasing the current density improves the results very slightly for the stored energy and for the size and almost in a linear way for the coil area.

Another important fact is illustrated in Fig. 8 which gives the stored energy as a function of the inner diameter of a concentric circle type coil. The relationship between stored energy and inner diameter of the dipole is quite linear. It is important to point out that the difficult problem of the power supply, due to the very large stored energy in the coil, will not be solved by trying to design very small aperture machines.

The design of a dipole or quadrupole magnet for an accelerator has to solve a series of problems, which will take time and effort. The following points seem to be the most important.

1. Industrial production of conductor made of about 1 μ transposed filaments, having the right size and shape to transport many thousands of amperes, and which must be wound on a three-dimensional form with the right cooling and structural rigidity.

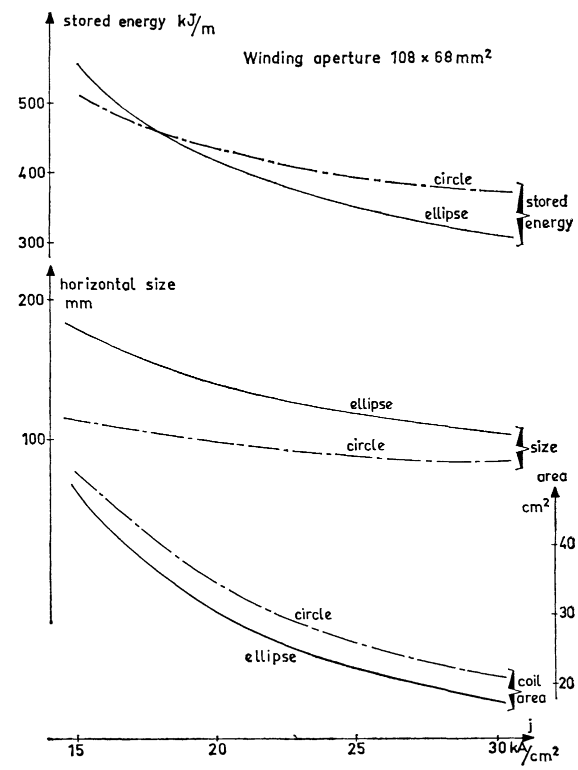

FIG. 7. Stored energy, size and coil area as a function of the current density for a typical circular coil.

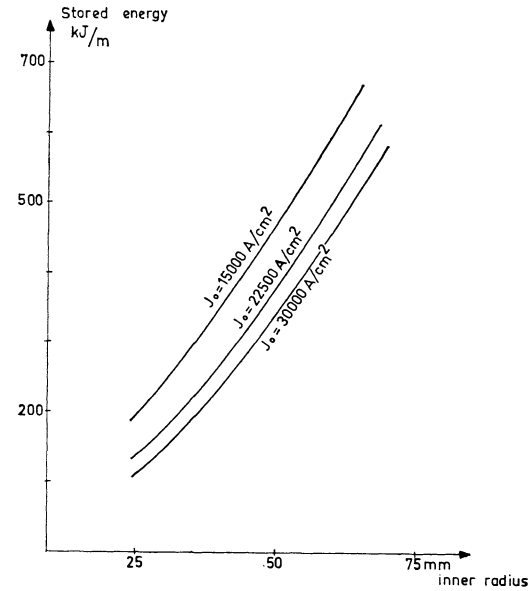

FIG. 8. Stored energy as a function of the inner radius for circular coils.

2. Computation of coil shapes and conductor tolerances to meet the desired field map.

3. Computation of end shapes easy to wind and giving the right field or gradient integrals along the trajectories.

4. Computation of the size and shape of the shielding to be installed close to the coil, even in the saturated state, to decrease the fringing field, the total ampere-turns, the stored energy and the losses, and with no effect on the field pattern.

5. Measurement and location of axes or symmetry planes to align units in the tunnel of an accelerator.

6. Study of a cryostat having a free inner cylindrical space at room or liquid helium temperature. The cryostat must be made of non-metallic materials to avoid eddy currents losses at low temperature.

7. Study of a reliable and economical liquid helium refrigeration system to cool a group of magnet units.

8. Study of the radiation effect on a superconducting magnet.

Moreover, all of the components of the accelerator must be thought of in a new way to take into account the smaller radius of the accelerator.

It is our opinion that, at the same time that theoretical and experimentai work is continued on losses, the construction of an experimental pulsed dipole will help to solve many of the problems and raise new and unexpected difficulties.

It was decided to built a dipole using an existing supply (150 V–4500 A) capable of supplying a stored energy of about 450 kJ in one second.

Assuming a horizontal aperture for the particles of 80 mm, the main parameters of the dipole were chosen as in Table I.

TABLE I

Main parameters of the dipole

Room temperature diameter	60 to 80 mm
Conductor inner diameter	100 mm
Conductor outer diameter	200 mm
Magnetic length	500 mm
Maximum central field	5 T
Stored energy	150 kJ
Maximum current	1500 A
Average current density	15 000 A/cm^2
Rise time	1.2 sec
Repetition period	6 sec
Estimated total losses with 4 μ filament	12 W
Estimated total losses with 10 μ filament	21 W

The three-dimensional shape of the coil is under consideration to give the right constant field and field integral in the volume and have an end that is easy to wind. It will include a special cooling device to extract the magnetization losses.

The coil will be surrounded by an iron shield of about 2 tons at room temperature, made of 1 mm sheets, which will have hysteresis losses of 6 W to 18 W depending on the Si percentage (4.5 per cent to 0 per cent respectively).

The cryostat, which will have a bore at room temperature, will be made of an insulating material to avoid extra losses at low temperature in the wall due to eddy currents.

The time schedule assumes about 18 months construction time and the first tests by the fall of 1971.

5. CONVERTING SATURNE INTO A 15-GeV MACHINE

The development towards an application to a large synchrotron like the 250/500 GeV European project goes through the construction of several model dipoles and quadrupoles. Moreover, before undertaking a large project, it would be wise to prove the validity of this new technique by building a model of a machine.

A good way of doing so would be to convert an existing machine. In this intention, we recently proposed[15] to turn Saturne, the Saclay 3-GeV weak-focusing machine, into a 15-GeV alternating-gradient superconducting synchrotron. It would be quite a useful test-bench, representing a 1/100 scale model of the European accelerator.

In the following paragraphs, a rough outline of the project is given.

5.1. *Basic parameters*

We choose a separated function lattice, as in every present project for big machines, since we intend to build a model. Besides, separate functions are more favourable in allowing a fairly free choice for locating short and long straight section. This flexibility is a strong argument in favour of separate functions. Moreover, the design of superconducting windings for combined functions would certainly introduce more difficulties.

The usual optimization procedure leads to the following list of parameters (see Table II).

TABLE II

Main parameters

Energy	15 GeV
Type of focusing	separated function
Radius of curvature	8.83 m
Wave number	3.75
Number of long straight sections	5
Number of periods	20
Dipoles: total number	30
equivalent length	1.85 m
Central flux density	6 T
Quadrupoles: total number	20 F + 20 D
equivalent length	0.3 m
gradients	− 53.0 T/m
	+ 55.7 T/m
β_{max}	12.4 m
Mean radius	22.6 m
Repetition period	2 sec

One of the 5 superperiods is sketched in Fig. 9. It includes 4 periods, which could accommodate 8 bending dipoles; but 2 of them are omitted, thus providing the free space needed for extraction channels, for the rf cavity and for injection.

The mean radius, equal to 22.6 m, is such that the ring fills the present Saturne hall width.

5.2. *The superconducting dipole*

For the presently most used material, namely Nb–Ti, it seems reasonable to fix the flux density at 6 T on the axis. On the other hand, it will be shown later that the half aperture is 5 cm. These

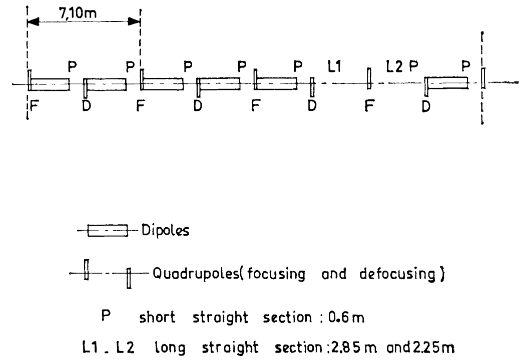

FIG. 9. Sketch of the 15-GeV synchrotron superperiod.

two values being fixed, other preliminary parameters follow as listed in Table III.

TABLE III

The superconducting dipole

Useful half-aperture		5 cm
Central flux density		6 T
Average current density		150 A/mm²
Winding: internal radius		6.0 cm
external radius		11.8 cm
Ampere-turns		1.62 . 10⁶
Magnetic shielding: internal radius		21 cm
external radius		46 cm
Stored energy: in internal volume		162 kJ/m
in winding		152 kJ/m
out of the winding		147 kJ/m
	total	461 kJ/m

With a conductor diameter of 4 μ and a suitable transposition, the magnetic losses may be of the order of 30 W/m and the overall dipole losses at 4.2 °K are 1.8 kW.

The stored energy for the whole machine amounts to 25 MJ, that is to say twice the value for the 3-GeV Saturne.

It is worthwhile to point out that this dipole is oversized for two reasons:

—The current density has been chosen at a conservative level.

—The magnetic shielding can be located closer to the windings and can work at a higher field.

Thus, most of the parameters in Table III ought to decrease during the course of the studies.

5.3. *Aperture*

As we shall see later, the horizontal half aperture in most of very high energy projects is of the order of 50 mm, and this is the reason why we choose this value. Moreover, it is very convenient in Saturne's case if one keeps the present 20-MeV linear accelerator as an injector. A brief account of the needed aperture is made in the following lines.

At injection, the aperture is made of the beam itself, closed orbit deviations, room for molecular diffusion and, in the horizontal direction only, synchrotron oscillations and sagitta.

The sagitta is related to the length of the straight elements in the dipole; when the total length (1.85 m) is divided in 2 or 3 parts, the half-sagitta amounts to 6 mm or to 2.7 mm (these rather large values are due to the small radius of curvature). One can also assume that the 'axis' follows the orbit; in that case, the sagitta drops down to zero.

To compute the beam size, one has to know the emittance at the injection energy of 20 MeV (energy of the present injector) and for the intensity of 110 mA needed to fill the ring in one single turn. Our estimates lead to a normalized emittance of $6\pi\ 10^{-6}$ rad·m. Taking a safety margin of 20 per cent into account for beam matching and miscellaneous errors, one gets 22.7 mm as beam radius.

The other terms, together with sagitta and beam size, give a total amount as follows:

horizontally : 50 mm
vertically : 38 mm (half dimensions)

5.4. *Intensity*

The pulse is foreseen with a rise time of 0.6 second and a flat top of the same duration; the total period is 2 seconds. Accelerating voltage is 25 kV (energy gain per turn: 12.5 keV) so one single cavity is enough. The space-charge limit has been evaluated at about 10^{12} protons.

This brief account shows that such a model would be of a convenient size, not too small to avoid nonscaling effects, not too big to stay reasonably cheap. It will be of the greatest interest to test on such a model the working conditions of superconducting elements with a beam.

6. POSSIBLE SCHEMES USING SUPERCONDUCTING MAGNETS IN FUTURE PLANS FOR THE EUROPEAN ACCELERATOR PROJECT

As it is well known, a design study for a large European proton synchrotron of 250/500 GeV has been made and, during this work, the idea of forecasting an eventual increase in energy by means of superconducting magnets was put forward.[16] In the following lines, some attention is devoted to a few possible modes of achieving this goal.

6.1. *The starting point*

To begin with, let us recall the main features of the 250/500 GeV project, as it appears under the name MR 29[17,18] Some significant parameters are listed in Table IV.

TABLE IV
The 250/500 GeV machine (MR 29)

	MR 29/A	MR 29/B
Energy	250	500 GeV
Type of focusing	separated functions	
Wave number	27.75	
Number of superperiods	6	
Number of periods	114	
Dipoles: total number	402	804
binding length	7.24 m	
flux density	1.8 T	
Quadrupoles: total number	114 F + 114 D	
quadrupole length	4.96 m	
gradient	6.05 T/m	12.1 T/m
β_{max}	133.8 m	
Mean radius	1456 m	

MR 29/B is foreseen to accommodate four bending magnets between two neighbouring quadrupoles; they are numbered B I to B IV and their useful apertures are shown in Table V.

TABLE V
Useful half-apertures of dipole magnets, in mm

	Hor.	Vert.
B I	60	18
B II	52	21
B III	44	24
B IV	37	28

In MR 29 A, only B I and B IV are installed; the maximum field being 1.8 T, the stored energy amounts to 53 MJ and the period of the magnetic pulse is 3.1 sec; the peak energy is 250 GeV.

To go to MR 29 B (500 GeV) one adds B II and B III, the stored energy becomes 104 MJ and the period is increased to 4.7 sec.

6.2. *Some possible schemes to achieve higher energies*

In a preliminary study different ways of introducing superconductivity as a future step for this project have been considered.[19]

(S 1)—A first scheme consists in putting in place, instead of the conventional B II and B III dipoles, a superconducting version of B II and B III. Using only these magnets, and thus switching off B I and B IV, one reaches 750 GeV with a maximum field of 6 T; the magnet length is 6.50 m, to be compared with 7.24 m in the conventional version; extra room will be used for magnetic shielding, cryogenics, etc. Stored energy, computed for circular coils having an inner diameter of 124 mm and 198 mm, respectively for B II and B III (so 20 mm are left for cryostat and coil forms) is 1265 MJ.

(S 2)—The previous scheme would certainly be considered only as a first step; in the final one, superconducting magnets would completely fill the ring, replacing all the conventional magnets. 1500 GeV would so be reached.

In that case, the circular apertures of B I to B IV dipoles are, respectively, 140, 124, 108 and 94 mm; total stored energy is now 2565 MJ.

(S 3)—In another type, MR 29 A is considered as a booster of 125 GeV, injecting into a 1500-GeV synchrotron built in the same tunnel. At the transfer energy, the beam radius is of the order of 1 mm; most of the necessary room is needed for closed orbit distortions. With a complete system of observations and corrections one should reduce closed orbit deviations to about 10 mm. We can then take a half-aperture of 15 × 15 mm in the large ring.

For dipoles with a circular aperture of 50 mm in diameter, the stored energy is 835 MJ. With these dimensions, there is no room for a slow resonant extraction. One is therefore limited to fast extraction, the slow extraction being possible from an additional storage ring.

(S 4)—At last, in order to provide the necessary room for slow extraction, the previous solution can be modified so that the useful half-dimensions become 45 × 15 mm. Coils have now a circular aperture of 110 mm in diameter, with a corresponding stored energy of 2350 MJ.

TABLE VI

Various superconducting solutions

	MR 29/A	MR 29/B	S 1	S 2	S 3	S 4	
Final energy	250	500	750	1500	1500	1500	GeV
Injection energy	8	8	8	8	125	125	GeV
Flux density	1.8	1.8	6	6	6	6	T
Useful dipole half-apertures	60 × 18	60 × 18		60 × 18			
		52 × 21	52 × 21	52 × 21	15 × 15	45 × 15	mm²
		44 × 24	44 × 24	44 × 24			
	37 × 28	37 × 28		37 × 28			
Stored energy	53	104	1265	2565	835	2350	MJ

Table VI summarizes these various solutions. One should take into account that S 3 needs a beam stretcher in order to obtain long external beam extraction, and it might therefore appear less attractive.

6.3. *Power and intensity considerations*

Let us now pay some attention to the power supply in the previous machines. The European network is able to provide a peak power such that about 100 MJ can be transferred in 1 sec into the magnets: that is the MR 29 requirement, valid for either MR 29 A or MR 29 B versions: for the latter, the rise time is doubled (1.8 sec instead of 0.9).

In a first step, we shall examine what kind of pulse we can get in the various solutions under the assumption that the peak power stays equal to the MR 29 one (115 MVA); in a second step, we shall increase this peak power, considering that some new possibilities will certainly occur over the next ten years.

(a) *Present peak power* (115 MVA). The various machines are listed in Table VII. The rise time is determined by the stored energy, and likewise for the fall time. Flat-top duration is 0.7 sec everywhere except for S 4, the larger aperture of which can accommodate 10-turn injection, so the injection process takes 16 sec, and the flat-top duration is increased by a factor of 10 to keep the extracted beam average intensity constant.

One notices the weak intensity given by solutions S 1, S 2, S 3, under this present peak power assumption.

(b) *Increased peak power* ($\geqslant$100 MVA). There are several reasons why one should not stick to too conservative peak power figures.

TABLE VII

Intensity for present peak power (115 MVA)

	MR 29/A	MR 29/B	S 1	S 2	S 3	S 4†	
Final energy	250	500	750	1500	1500	1500	GeV
Stored energy	53	104	1265	2565	835	2350	MJ
Injection time	0.8	0.8	0.8	0.8	0	16.0	sec
Rise time	0.9	1.8	21.5	43.5	14.1	40.0	sec
Flat top	0.7	0.7	0.7	0.7	0.7	7.0	sec
Fall time	0.7	1.4	16.7	33.9	11.0	31.1	sec
Period	3.1	4.7	39.7	78.9	25.8	94.1	sec
Relative intensity	100	66.0	7.8	3.9	12.0	32.0	

† 10-turn injection

—At the time when a superconducting machine is considered, the installed power of the network will have risen considerably.

—New types of power transfer systems will be developed.[20]

If one makes different assumptions about available peak power, one has to modify the figures of rise time and fall time in Table VII, getting Table VIII in which, for sake of simplification, only periods and relative intensity are shown (relative intensity 100 is for MR 28/A, present peak power); P_0 denotes the presently available peak power, used in previous estimates.

The corresponding curves are drawn on Fig. 10. For the S 4 machine, three variants are shown with, respectively, 5, 10 and 15 turns injected. The 5-turn machine gives a low relative intensity, when 10-turn machine is nearly as good as the 15-turn one.

6.4. *Two particular solutions*

Amongst these many solutions, let us take out two of them, indicated as SCM and HPM in Table VIII.

The slow cycling machine (SCM): the peak power is three times the present peak power; one has the following times

injection time	16.0
rise time	13.3
flat top	7.0
fall time	10.4
	46.7 sec

Such a period is rather lengthy; but it is with

TABLE VIII

Intensity for future peak power

(P_0 is the presently available peak power)

		S 1	S 2	S 3	S 4†	
$1 \times P^0$	period	39.7	78.9	25.8	94.1	sec
	relative intensity	7.8	3.9	12.0	32.9	
$3 \times P_0$	period	14.2	27.3	9.1	46.7	sec
	relative intensity	21.8	11.4	34.0	66.4	
					SCM	
$5 \times P_0$	period	9.1	17.0	5.7	37.2	sec
	relative intensity	34.1	18.2	54.4	83.3	
$10 \times P_0$	period	5.3	9.2	3.2	30.1	sec
	relative intensity	58.5	33.7	96.9	103.0	
			HPM			

† 10-turn injection

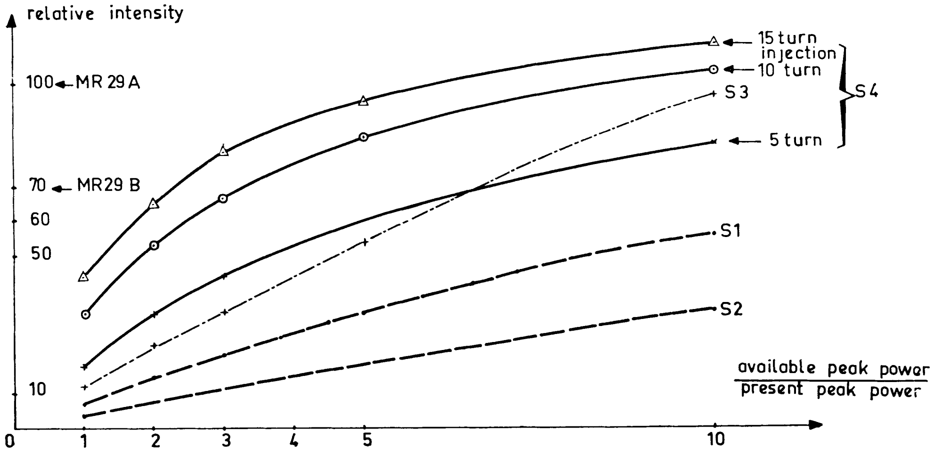

FIG. 10. Relative intensity as a function of the power supply for different superconducting synchrotrons.

10-turn injection, so the relative intensity is high, equal to the one of MR 29/B. The cycle of this machine is shown in Fig. 11; one has a possibility of using the booster at 250 GeV for physics experiments. Due to the long period, total magnetization losses are 7.7 kW at 4.2 °K.

The high power machine (*HPM*): the peak power is 10 times the present peak power, with the following times:

injection time	0.8
rise time	4.3
flat top	0.7
fall time	3.4
	9.2 sec

The period is shorter but since the injection is a single turn period one, the relative intensity drops to a half of the corresponding MR 29/B value.

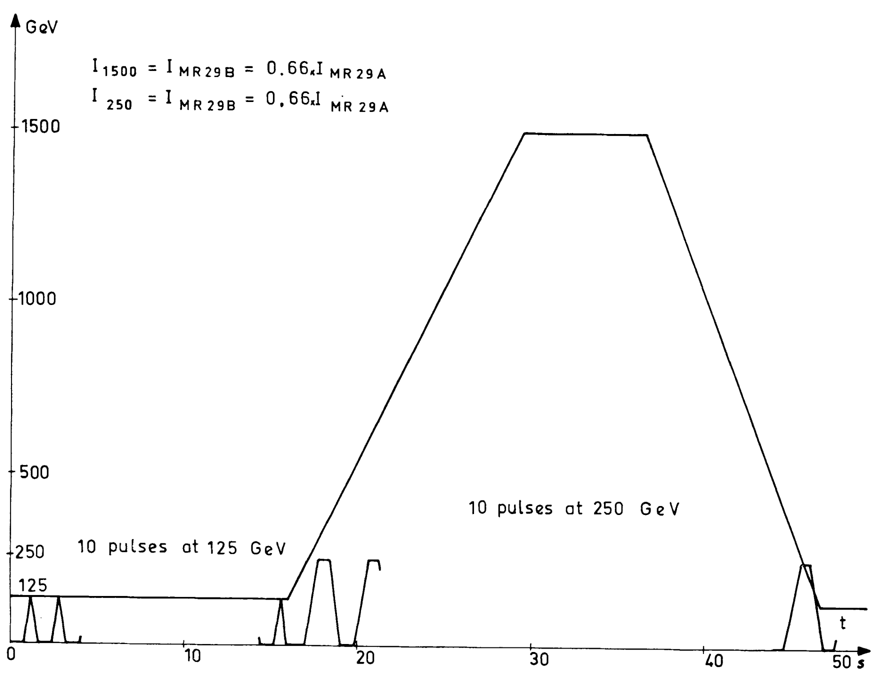

FIG. 11. Energy cycle of the S 4 type synchrotron.

Total magnetization losses have been evaluated at 39 kW at 4.2 °K.

One sees that for the same energy and the same mean intensity, within a factor 2, there are two ways for reaching that goal,

—either through a moderate peak power which gives a slow cycling machine (but with a 125-GeV injector and two beam transfers),

—or through a high peak power which leads to a machine quite comparable to existing projects as far as the cycle is concerned; such a project implies new power supply developments.

7. CONCLUSIONS

It has been shown from this preliminary study that

—the present development programme on superconductors, very encouraging, has to be carried further to very small filament diameters.

—a few dipole and quadrupole models have to show good magnetic and thermal tests,

—a model synchrotron must be built to prove that such a machine can be run safely and precisely.

No doubt such an attractive programme will cover the next ten years, leading to a major new step in pulsed magnet technology and opening the field to thousand-GeV synchrotrons.

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Received 24 April 1970