

DEVELOPMENT OF A SUPERCONDUCTING PROTECTION SWITCH FOR THE HERA P-RING.
DESIGN STUDY AND DEMONSTRATION MODELS

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Abstract

The electrical circuit of the HERA p-ring is divided in octants whereby in the case of a quench the current has to be commutated to dumping resistors. A straightforward method would be to use a conventional switching device and stationary loaded current feedthroughs. This approach results in a notable helium consumption of at least 150 L/hr due to the continuous energy loss in the large number of high current leads. An alternative is to apply superconducting switches which enables to keep the main circuit at 4 K while during a quench the current is forced to flow through instantaneously loaded leads and the dumping resistors. The main specifications of the required switches are: current of 6.5 kA, minimum off-resistance 12 Ω , energy absorbed 1 MJ and self protecting. In this paper the various design and feasibility aspects of superconducting switches for this application are discussed. It appeared that the requirement of being passively protected against a self-quench is the most critical one.

Introduction

The main circuit of the HERA proton ring [1] which is now under construction at DESY Hamburg consists of dipoles and quadrupoles connected in series. The dipole part which contains the main part of the stored energy is divided into octants. Figure 1 shows the proposed schematic layout of the dipoles and

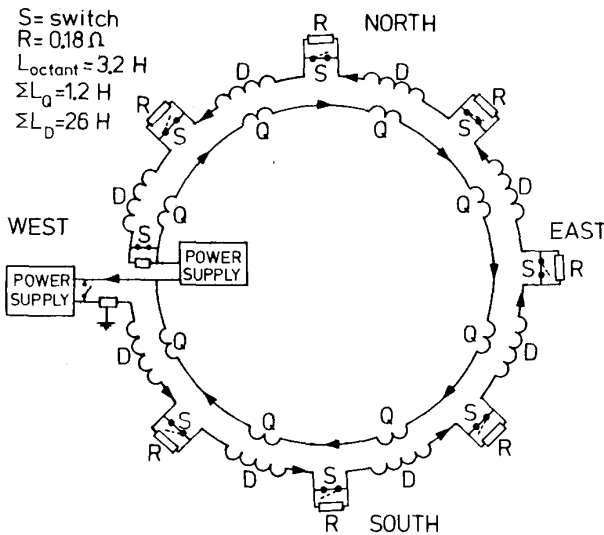


Fig. 1. Proposed scheme of the electrical circuit of the HERA proton ring.

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quadrupoles. The stored energy in an octant is 68 MJ whereas the energy in the quadrupole section amounts to 22 MJ. After the event of a quench in a main magnet the circuit current of 6.5 kA maximum has to be switched to dumping resistors in order to prevent damage to the coil structure and the conductors. The current decay is achieved by opening eight switches simultaneously, one in each octant, rather than to use a single switch for the entire ring. The limitation of the maximum circuit voltage is the main advantage of this circuit arrangement.

In the proposed scheme the switches and resistors are at room temperature and are connected to the octants via stationary loaded current leads. These sixteen leads will cause a helium consumption of between 150 and 200 L/hr at an operating current of 6 kA and approximately 60 % of that during zero current. Although this heat load is small compared to the cooling requirements of the entire machine, it is large enough to consider alternatives. The application of superconducting switches is a serious alternative. It would reduce the helium evaporation due to the leads to a negligible level because the main circuit of the ring including the switches can now be kept at 4 K. In this case the leads can be optimized for pulsed operation. For convenience both alternatives are illustrated in figure 2.

The application of a superconductor as a switch has been investigated for as long as practical superconductors have existed. Besides their possible use as protection and power switches in superconducting coil systems [2-4] they are also applied as persistent mode switches using different design specifications. A third field of application is superconducting rectifiers in which they can act as the rectifying elements [5]. However, each application sets its own requirements.

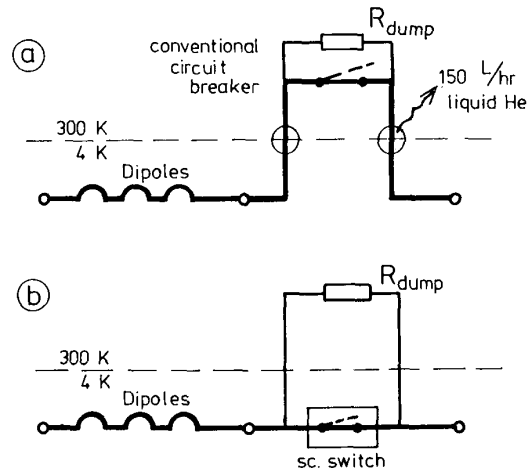


Fig. 2. Electrical circuits of an octant illustrating both alternatives:
(a) using a conventional switch at 300 K;
(b) using a superconducting switch at 4 K.

The main technical specifications required for the HERA protection switches are:

- ▷ max. current $I_s = 6.5$ kA at $\partial I_s / \partial t \leq 100$ A/s,
- ▷ cryogenic energy loss in the switch ≤ 1 MJ,
- ▷ reliable in stationary operation,
- ▷ by preference it should be protected passively against a self-quench,
- ▷ dielectric strength of 5 kV,
- ▷ fast triggering and reproducibility ≤ 1 ms.

The electrical circuit

One octant of the ring consists of a series of dipole coils and a superconducting protection switch which is shunted by a dumping resistor as indicated in Fig. 3. This large resistor is located outside the cryogenic system and consists of several meters of metal pipe. Its inductance of 100 μ H maximum is the dominant inductance in the dumping circuit since the inductance of the switch can be made negligibly small (from 0.1 to 10 μ H max.). The dumping resistor has a resistance of 0.18 Ω and limits the voltage difference across the switch to about 1.2 kV. The main decay time constant of the current in the ring will remain below 18 seconds provided the switches in the octants operate simultaneously.

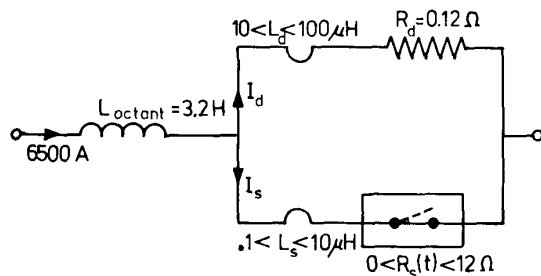


Fig. 3. The electrical circuit of one octant. The values of the components are indicated.

The off-resistance of the switch has effect on the desired cryogenic energy loss as well as on the allowable temperature rise in the switch. The design value for the tolerable loss in the switch W_s is 1 MJ while the stored energy in an octant is 68 MJ. The required off-resistance R_s now becomes $R_s \geq R_d W_d / W_s = 12 \Omega$ where W_d is the dumped energy. The resistance ratio of 0.18 to 12 implies that 1.5 % of the current remains in the switch. The maximum time constant in the commutation circuit of switch and resistor is $(L_s + L_d) / R_d = 0.5$ ms. This means that during a very fast opening of the switch by a current pulse (opening time in μ s range) the current transfer rate is lowered by the inductance of the dumping resistor, while after a self-quench of the switch the current transfer rate will mainly be determined by the resistance rate (relatively low velocity).

The current and energy distribution can be simulated assuming a certain time dependence for the increase of the resistance in the switch as for example $R_s(t) = R_{s-max}(1 - e^{-t/\tau_s})$ where $R_{s-max} = 12 \Omega$ and τ is the characteristic time constant. As an example Fig. 4. shows the influence of the switch resistance rate on the current commutation and the momentary dissipation in the switch during the first 5 ms. Knowledge about the time dependence of the switch resistance is essential to evaluate the temperature rise in the switch. This must remain well below 500 K to prevent annealing or even a burn-out of the conductor.

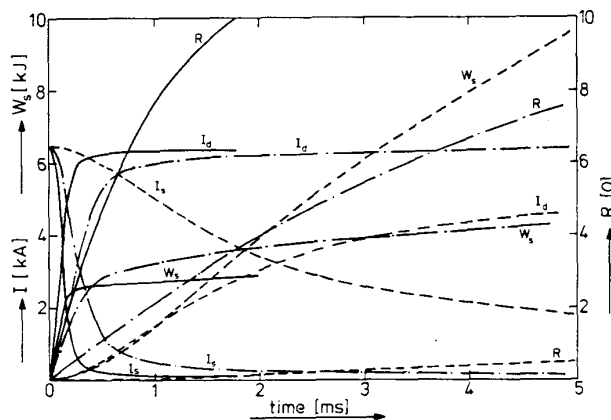


Fig. 4. Simulation of the current redistribution between switch (I_s) and dumping resistor (I_d), and the heat generated in the switch (W_s). Parameter is τ_s , the time constant with which the off-resistance grows. τ_s is 1 (), 5 () and 125 ms () respectively.

Design and construction aspects

- Essential design aspects of the switches are:
- ▷ the type of cabled conductor having a high resistivity and at the same time a stable operation;
 - ▷ the method of triggering to open the switch;
 - ▷ the method of conductor packing to obtain a minimum volume and inductance but a sufficiently high break-down voltage;
 - ▷ the heat conduction mechanism to meet the enthalpy requirements; and
 - ▷ the method of protecting the switch against a burn-out after the occurrence of a self-quench,
 - ▷ the production has to be practical and economical.

The conductor

An essential property of a superconductor for application in a superconducting switch is its high resistivity to achieve an off-resistance with an acceptable length of conductor. As strand material in a high current cabled switch conductor one could use:

- ▷ a pure NbTi wire, film or tape;
- ▷ a multifilamentary NbTi wire having a matrix of $\text{Cu}_{70}\text{Ni}_{30}$;
- ▷ a NbTi multifilamentary wire having a Cu matrix which is (partly) removed by etching.

The use of NbTi tape has a lot of disadvantages although it has a high resistivity ($\approx 70 \times 10^{-8} \Omega\text{m}$) compared to the usual matrix material as CuNi ($\approx 36 \times 10^{-8} \Omega\text{m}$). Problems arise with the stability in self-fields (use very thin foils, $\leq 10 \mu\text{m}$), the non uniform current density and the electrical insulation. Moreover to obtain 6 kA at 1000 A/mm^2 , one has to use a tape of 600 mm width or 120 tapes of 5 mm in parallel. A full transposition of several tapes can hardly be obtained. Therefore the use of round multifilamentary wires is preferred. They can easily be connected in parallel with full transposition. A typical strand-wire has a diameter of 0.3 mm, a matrix/NbTi ratio of about 1, a filament diameter near 10 μm in order to achieve adiabatic stability and a normal resistance of 6 Ω/m . The critical current will be about 240, 180 and 130 A at 0.5, 1.0 and 2.0 tesla respectively.

With a suitable strand wire several types of cables can be made. During the past years we made for superconducting rectifier switches [5] several cables with strand numbers up to 720 for currents up to 40 kA [7]. The smaller ones were twisted while the larger ones are braided cables. However, a braid has a small metal filling factor so we started tests to investigate flat cables closely packed in a non-inductive way. In general we found for the maximum current in copper-nickel matrix cables under low field or self-field conditions an empirical criterion for the maximum achievable current. It states $I_N = N^{0.8} \times I_1$, in which I_N is the stable maximum current through N strands and I_1 is the maximum current through a single strand wire at a low current rate [7].

Switch geometry

The number of possibilities to arrange non-inductive switch elements is enormous. For this project investigations have so far concerned a few sub-sized cables made of the mentioned strand wire, see table 1. They were produced to investigate the influence of the internal geometry of the non-inductive switch element on the maximum current measured as function of the current rate. With exception of a toroidal-shaped switch the test switches have a solenoidal geometry and were made by winding the cable in a non-inductive way with a few layers on small cores. The switches were wet wound or potted with STYCAST 2850FT resin. Without mentioning all the construction details a few results will be presented here. In figure 5 the measured maximum current in a strand under self-field conditions is indicated as a function of the current rate. The best results are obtained with the small 6-strand round cable and with the 28-strand flat cable of which 10 meter was wound in several layers to obtain an almost perfect non-inductive arrangement as well as equal magnetic fields on all wires. Six equal elementary switch units made of the six strand cable were connected in parallel. It appeared that the maximum current per strand was less than in the single unit. This could be explained by checking the maximum current of all the six units separately. Differences up to 40 % were found (0.7 -1.0 kA at 1 A/s in a strand, in a self-field of 0.9 mT/A). This implies that the maximum current of the parallel connection is determined by 6 times the smallest maximum current of a certain unit. The differences are probably caused by production tolerances which are extremely important in connection with copper-nickel matrix wires [9]. As a consequence the winding technique and impregnation procedures are very critical.

Table 1. Survey of cables used in test switches. All cables have the same strand wire.

cable	number of strands	shape	size mm or mm ²
1	6 x 1	round, twisted	1.0
2	3 x 3 x 3	round, twisted	1.5
3	27	flat ¹	8.9 x 0.33
4	28	flat ²	9.2 x 0.33
5	50	flat ²	16.5 x 0.33

1 : all strands have the same current direction, used for a single layer toroid in which the magnetic field should be the same at all strands.

2 : adjacent strands have opposite current direction.

Triggering mechanism

Switching with superconductors is achieved by control of the normal to superconducting transition. The transition can be initiated either by a heating or

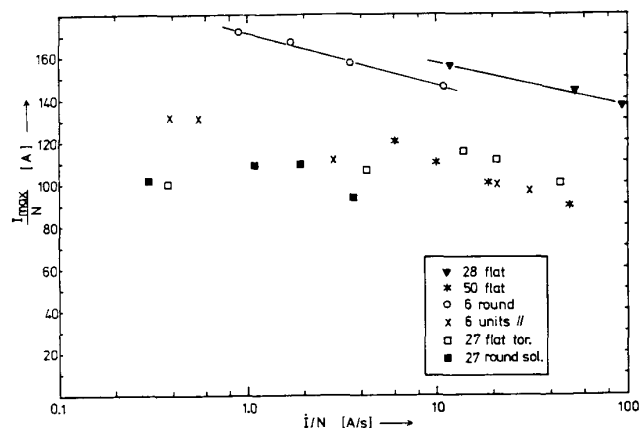


Fig. 5. Measured maximum current in the strands of switch cables used in 6 test switches, versus the current rate in the strands.

a magnetic field pulse on the conductor or by an over-current pulse through the conductor. The easiest method is to apply an array of heating elements which can create a very large number of normal spots. This results in a delay time of about 1 ms where after the switch can be opened within a few milliseconds [5]. A very fast transition (1-10 μ s) can be obtained by introducing an over-critical current in the conductor by means of a symmetrical discharge of capacitors [2-4]. In our case both the thermal and over-current triggering are feasible since the time constant of the main ring is large enough. Moreover if one requires a self-protecting switch then the introduction of a single spot is in principle enough to trigger the switch safely. The final choice will be made when the reproducibility of the switching times in both methods of switching has been investigated.

Passive and active protection

The desire to construct a self-protecting switch is the main design problem since it requires precise and reliable knowledge about the normal zone propagation phenomena in copper-nickel matrix wires and cables. For example, consider the first milliseconds after the occurrence of a self-quench. On this time scale local adiabaticity can be assumed and the heating process can be described by the thermal

$$\text{load integral: } \int_0^t J^2(t) dt = \int_4^T C(T)/\rho(T) dT = K(T),$$

where C and ρ are the heat capacity and the resistivity of the normal spot and K is a constant for a certain permissible final temperature. For 300 K a value of 1.2×10^{15} is found for a usual copper-nickel matrix wire. This implies that at an average current density of 2000 A/mm^2 in the wire the allowable time constant is 0.6 ms! In terms of our typical switch wire of 0.3 mm this means that at a current of 70 A, which is about half the critical current at 2 tesla, the switch has to be almost open within 1 ms! It is impossible to achieve such a fast resistance rate with a common thermal propagation of the normal zone. In figure 6 the measured and calculated normal zone propagation in the 0.3 mm strand wire is shown as function of current and magnetic field. It appears that the velocity measured in a single wire is almost linear with the current density. Moreover they can be predicted with a sufficient accuracy. The velocity lies between 10 and 25 m/s in the relevant current range of 40 to 90 A.

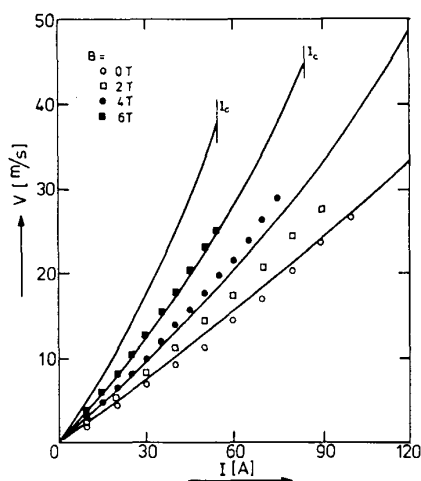


Fig. 6. Normal zone propagation velocity in a typical switch wire having a CuNi matrix and 574 filaments NbTi. Wire diameter 0.3 mm. Comparison of measured (dots) and calculated (lines) velocities at 0, 2, 4 and 6 tesla.

Extremely large propagation velocities have been observed in a 6-strand cable with copper-nickel matrix wires of 0.13 mm. The cable was applied in a superconducting transformer [9]. Figure 7 shows the measured resistance rate and current decay in the current range of 96 to 129 A. One observes resistance rates of $4 \times 10^5 \Omega/s$ which corresponds to a velocity of approximately 100 km/s! A second conclusion is that the velocity decreases very fast with the current.

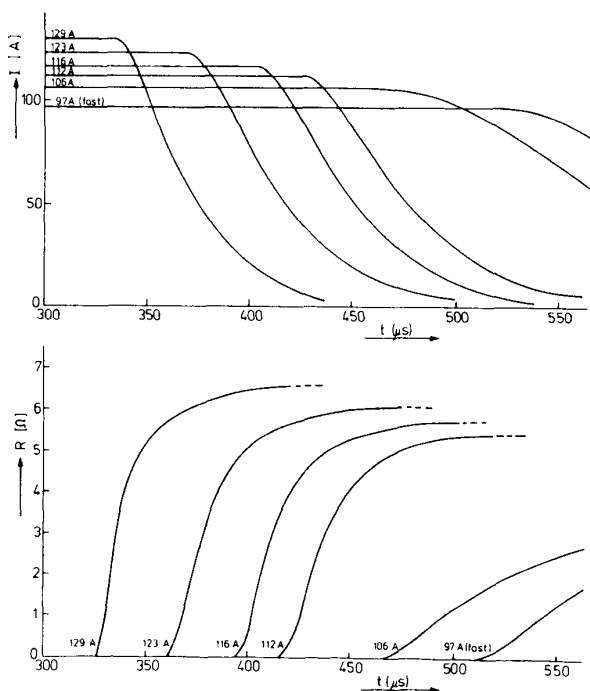


Fig. 7. Current decay and resistance rate versus time. Example of a very fast propagation in a cable with CuNi matrix wires (6 strands of 0.13 mm).

Below 90 A the velocity falls to the usual values as predicted by thermal propagation theories. The explanation for the fast quenches is related to the fact that it is not a single wire which is involved but a cable. A quench will start first in a single wire after which the current is commutated to the neighbouring wires in which the critical current is exceeded provided the current is high enough. In turn the neighbours will quench etc. In fact the cable is switched to the normal state by over-currents which are generated by the commutation processes between the strands. At the same time it implies that one cannot guarantee the high resistance rate at low currents and therefore it is doubtful whether one can rely on the explained phenomenon. On the other hand this effect is the only one that could cause passive protection of a switch against a self-quench. It is likely that the effect can also occur between several switch units operating in parallel provided the inductances are negligibly small. Further investigations are in progress.

Conclusions

The production of a special type of superconducting switches for the HERA proton ring will probably present no problems as far as it concerns the development of the conductor, the switch structure, the enthalpy and heat conduction requirements to absorb the 1 MJ of energy. However the demand of being self-protecting makes it necessary to continue the investigations of the propagation process in multistrand cables made of copper-nickel matrix superconductors. It is still uncertain whether it remains necessary to apply an active protection scheme to enable safe operation of the switch.

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