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Large superconducting magnet systems for plasma and fusion applications

W. Heinz

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Große supraleitende Magnetsysteme für Plasma- und Fusionsanwendungen

W. Heinz

Kernforschungszentrum und Universität Karlsruhe
Institut für Experimentelle Kernphysik
7500 Karlsruhe, Postfach 3640
Bundesrepublik Deutschland

Zusammenfassung

Die gegenwärtige Situation in der Fusionsforschung ist durch das Vertrauen in die Lösung der plasmaphysikalischen Probleme charakterisiert. Daher ist es notwendig, den technologischen Entwicklungen mehr Aufmerksamkeit zu widmen, um die Machbarkeit der Schlüsselkomponenten eines Reaktors zu demonstrieren. Wegen der notwendigen Abmessungen des reagierten Plasmas besteht die einzige wirtschaftliche Lösung für den magnetischen Einschluß in der Verwendung supraleitender Magnete. Beim magnetischen Einschluß werden 3 Konzepte verfolgt: toroidale Systeme (Tokamaks), offene Systeme (Spiegelmaschinen) und gepulste Reaktorkonzepte (Θ-Pinch).
Die Arbeiten zu supraleitenden Magnetsystemen und der gegenwärtige Stand dieser Technologie werden beschrieben. Es werden Konzeptüberlegungen und Probleme großer Magnetsysteme (Stabilität, magnetische Kräfte, Kühlmoden, Sicherheitsfragen) diskutiert. Neuere Ergebnisse der experimentellen Arbeiten in Karlsruhe werden berichtet. Schließlich werden die Grundzüge des amerikanischen und europäischen Programms dargestellt.

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W. Heinz
Kernforschungszentrum und Universität Karlsruhe
Institut für Experimentelle Kernphysik
7500 Karlsruhe, Postfach 3640
Federal Republic of Germany

Summary

The present situation in fusion research is characterized by the confidence that the problems of plasma physics can be solved. So more attention has to be paid to technological developments to demonstrate the feasibility of the key reactor components. Because of the necessary dimensions of the reacting plasma the only economic solution for magnetic confinement of plasma will be superconducting magnets. Three major approaches are being pursued: toroidal systems (tokamaks), open systems (mirror machines), and pulsed reactor concepts (theta pinch).

Work on superconducting magnet systems and state of the art of superconducting magnet technology are described. Conceptual design consideration and problems of large magnet systems (stability, magnetic forces, cooling modes, safety) are discussed. Recent results of experimental work at Karlsruhe are reported. An outline of American and European programs is given.

1. Introduction

The energy crisis has distinctly demonstrated to everybody the dependence of our modern social system upon energy. There are finally two ways to reduce this dependence: to reduce the growth rate of energy consumption and to develop new and everywhere available energy resources such as solar energy, geothermal energy etc.

The energy consumption of the world has been increasing geometrically with a doubling rate of 15 years (10 years in industrial societies) and cannot be stopped abruptly. Primary power consumption in 1975 was corresponding to 8 to 9 TW and probably will climb to 30 TW sometime in the 21st century. That corresponds to about 2 kW/capita in 1975 and 5 kW/capita sometime after the year 2000. Even in case that mankind will succeed to approach zero growth rate by that time, a tremendous increase in absolute energy consumption must be foreseen. Nevertheless, this figure might be far too optimistic. The corresponding figures for 1975 are already 4 kW/capita in Western Germany and 10 kW/capita in the United States.

Conventional energy resources such as coal, oil or even uranium to be burnt in light water reactors cannot meet the steadily growing demand up to the total power expected even in the first half of the next century. Therefore it is necessary to develop and live with advanced nuclear fission and fusion power reactors prior to other long term solutions.

2. Fusion reactors

2.1 Fusion reactions

For about 25 years controlled thermonuclear reactions have been studied. Fusion reactors are based on the fusion of light atomic nuclei: D Deuterium, T Tritium and ^{3}He Helium 3. The main reactions are listed in table 1.
The physical and engineering task is to demonstrate the simultaneous maintenance of certain parameters like plasma temperature and density for periods which make a positive energy balance feasible. Typical parameters for a D-T reaction are $kT \approx 4$ keV (1 keV $\hat{=}$ $11.6 \cdot 10^{6}$ K), $n \approx 10^{20}\ m^{-3}$, $\tau \approx 1$ s. At these values, the energy release due to controlled reactions should exceed the unavoidable energy

losses and the energy consumption to start and maintain the 'burning'. The released energy is the kinetic energy of the charged or uncharged reaction products. The energy losses are radiation losses, mainly bremsstrahlung.

Not all the reactions listed are equally useful. The D-T-reaction is the most promising one for a fusion power cycle. Its cross-section is two orders of magnitudes bigger than those of the other two reactions mentioned (maximum 1 barn at 10 keV) (Fig. 1). But tritium is not to be found in nature in an amount which is worth mentioning. It has to be produced by a tritium-breeding cycle in the reactor itself (Table 1). Lithium resources necessary for this breeding are huge and their equivalent is comparable to uranium and thorium reserves to be burnt in fast breeders, but nevertheless resources are limited. The α-particle remains within the plasma, depositing its energy to electrons and ions. Only neutrons of 14.1 MeV are available for thermal energy conversion. No direct energy conversion into electric power is possible. Therefore the efficiency of a D-T-reactor does not exceed that of a fission reactor or a conventional power plant.

D-D-reactions do not need any breeding and deuterium is available everywhere in natural water. Thus fuel resources become unlimited. In the D-^{3}He-reaction all reaction-products are charged so that direct conversion to electric power with greatly enhanced efficiency and therefore negligible thermal pollution becomes possible. However, ignition temperatures in both reactions are higher and power densities reduced. Leaving aside all specific elements of a fusion power plant except the plasma and thermal conversion system, Lawson [2)] has calculated the condition for energy-breakeven of a D-T-reactor per unit volume of plasma. This is the condition for 100 % circulating power and no net plant output, that is the electrical output of the thermal converter is able to sustain burning conditions taking into account D-T-reaction energy and bremsstrahlung losses only. The Lawson criterion at temperatures somewhat above D-T-ignition ($T \approx 5$ keV) is commonly taken as a measure of achieving 'scientific feasibility'. The criterion says that the product of density of the reacting plasma n times confinement time τ has to exceed 10^{20} sec/m^3:

$$n\tau \geq 10^{20} \text{ sec/m}^3 .$$

The ALCATOR-group has recently announced that they are only a factor of 10 below that value.

2.2 Why fusion?

The energy needs of the world in the future are so great that all sources of energy should be seriously studied. Besides solar energy which is the most attractive candidate but might not be adequate to the European situation, only nuclear energy - fission and fusion - can meet the long term needs. The present understanding is that both systems are complementary rather than alternatives. Fast breeder reactors may form the basis of future power generating plants. Fusion is at present at a much earlier stage but offers the possibility of several longterm advantages:

- it is intrinsically 'cleaner' because the ultimate fusion products are non-radioactive and harmless,
- radioactive fuel inventory is minimal,
- for physical reason no uncontrolled nuclear runaway can occur,
- safeguarding against misuse is easy,
- the principal 'fuels' for a D-T-reactor, deuterium and lithium, are comparable with the reserves of uranium and thorium; fuel is practically unlimited for D-D-reactors.

The only serious radioactive problem will be the safe enclosure of the reactor tritium, whilst the radioactivity produced by neutron irradiation in the structural material is expected to be comparable with that in a fission reactor. But there are tremendous technological problems unsolved.

3. State of fusion research

3.1 Magnetic confinement systems

Besides laser fusion which is not considered here three different magnetic confinement system may possibly lead to a fusion reactor:

- magnetic mirror
- theta-pinch and
- tokamak.

Mirror machines are devices with open-ended magnet geometry, the plasma being established in a magnetic well. The escape of plasma along field lines is limited by the 'magnetic mirror'. The magnet geometry is of the baseball or Yin-Yang type (Fig. 2). Because of the simple plasma geometry physics is fairly good understood, but confinement experiments are still far away from the Lawson criterion. The 'mirror-magnet' calls for very high magnetic fields and superconductors with highest critical fields.

Theta-pinch devices have a toroidal magnet geometry. The plasma is compressed and shock-heated by rapid discharge of a capacitor bank or storage coil into a one-layer toroidal coil confining the plasma (Fig. 3). Huge amounts of energy have to be stored. A superconducting storage coil or a superconducting homopolar generator may present economic and technically attractive alternatives for the indispensable storage device of a theta-pinch reactor.

The tokamak principle is shown schematically in Fig. 4. A steady helical magnetic field is produced by superposition of the fields of the toroidal field coils and the plasma current. This plasma current is induced by transformer coils and has to be maintained during operation to provide the helical field together with plasma heating. Pulsed operation of the tokamak will be the rule.

Additional poloidal field coils act as stabilizing and divertor coils. The stabilizing coils produce a vertical field to compensate the field asymmetry due to the bending of the plasma axis. The divertor coils shall permit the escape of ion impurities from the border zone of the plasma. They may be located within or outside the toroidal main field coils. The toroidal field coils will be superconducting d.c. coils. All poloidal field coils will be pulsed (field rise about 1 T/s) and it will depend on size and economy of the system whether they are superconducting or resistive coils. A schematic view of the torus cross-section is shown in Fig. 5.

3.2 State of tokamak experiments

The tokamak confinement system was first developed in the U.S.S.R. and is now considered as the most promising one. Therefore I will restrict myself to this type. The progress of tokamak research may be seen from Fig. 6. The arrow represents the expected figure for the Joint European Torus JET which is supposed to be built in the near future.

Of two other big machines, the T-10 of Kurchatov Institute, Moscow, has come into operation recently and the Princeton Large Tokamak PLT will follow soon. Even bigger machines like T-20 or JT 60 are proposed. Main parameters are listed in Table 2.

3.3 Need for a fusion technology

Approaching the Lawson-curve will unavoidably lead to bigger and bigger magnet systems due to scaling laws for power breakeven. Power reactors will have magnet coils of about 20 m bore diameter and a stored energy of the whole magnet system which exceeds 200 GJ: that is more than two orders of magnitude above existing ones (Table 3).

The load of the first wall due to D-T-reaction neutrons and plasma radiation is as low as 1 to 2 MW/m^2 in conceptual design studies. Nevertheless, a lifetime of less than 2 years is expected. Selection of wall material or remote handling for replacing wall sections is by no means neither a solved problem nor the only technological one which is on the critical path to an economical power reactor.

At present people are getting more and more concerned about the necessity to soon tackle crucial technological developments besides physics problems. One of these developments, which has come into focus, is superconducting technology. For a power reactor, superconductivity is indispensable and even the dimensions of future plasma experiments are such that they require superconducting magnets. The toroidal magnet system of a post-JET-experiment may well be superconducting. The time scale of such an experiment and the gap in size and complexity which has to be bridged from present to future technique calls for development programs which are starting now.

4. Technology of superconducting magnets

4.1 State of the art

4.11 Conductor

Two types of superconductors are in use for superconducting magnets: Alloys of niobium and titanium and compounds with a β-tungsten or A-15 crystal structure. The present technical interest for magnet applications is concentrated on NbTi50 (about 50 % of titanium by weight) and Nb_3Sn or V_3Ga. All are produced as multifilamentary wires.

Superconducting NbTi filaments are embedded into a copper matrix or for a.c. applications into a copper matrix with resistive barriers of cupro-nickel. Their thickness is typically 5 to 50 µm. One conductor strand contains up to 1000 filaments. The critical temperature is 9.5 K, the upper critical field 14.5 T. By cold working, dislocations are produced which act as pinning centers. The dislocation density is as high as $10^{12}/cm^3$. The critical current is of the order of $2 \cdot 10^5$ A/cm^2 at 5 T. The conductor is ductile and can be produced in great lengths.

Nb_3Sn and V_3Ga are intermetallic compounds. Their crystal structure is complex (A-15 structure) and sensitive to disturbances. They are extremely brittle. The critical temperature of Nb_3Sn is 18.2 K, the upper critical field 24.5 T, and the critical current is typically that of NbTi at 5 T, but considerably higher at higher fields: $5 \cdot 10^4$ or $5 \cdot 10^3$ A/cm^2 at 10 resp. 18 T. V_3Ga exceeds the critical current of Nb_3Sn above 15 T, but the other characteristic values, including price, are less favourable.

There are two different procedures to produce multifilamentary Nb_3Sn wires: the bronze route and surface diffusion route. The first uses niobium-rods embedded in tin-bronze. The composite is worked down to its final size and then heat-treated to form a Nb_3Sn layer between the bronze and the rods. In the second process, the composite is worked down to final size and then given a surface coating of tin. It is heated to an intermediate temperature to allow the tin to diffuse into the composite and finally to react to Nb_3Sn.

Other very promising high temperature superconducting materials are known which give critical fields exceeding 40 T or critical temperature up to 23.5 K. Future development will show whether they will become technically feasible.

During past years sustained progress has been made in the development of improved composite superconductors. The development started with intrinsically stable multifilament NbTi conductors for d.c. applications. The typical number of filaments is about one to several hundred filaments with filament sizes between 20 to 50 μm.

Then pulsed applications for proton synchrotron magnets came into focus and initiated the corresponding conductor development. A.c. losses occur due to hysteretic, eddy current, and coupling losses. These losses can be considerably reduced by subdividing the conductor into thin filaments (typically 5 to 10 μm) and providing resistive barriers (usually of cupro-nickel) to supress transverse current flow between single filaments. Finally, the conducting wire is tightly twisted about its own axis to prevent additional filament coupling and thus additional losses by the varying transverse field. The matrix contains pure copper for stabilizing reasons, the copper to superconductor ratio is about 1. A 10 μm filament will carry 50 mA; 10^5 individual filaments of niobium-titanium have to be composed to form a superconducting cable of 5 kA.

Usually such a cable is composed of a large number of individual strands each containing a modest number of individual filaments (say 1000). Solid conductors are formed by combining clusters of filaments (say 1000) to form a wire consisting of 10^4 or more individual filaments. Several of these wires may form a cable of appropriate (e.g. rectangular) shape. Niobium-titanium conductors and cables with low losses and inherent stability are now commercially available for high currents.

Magnets wound from these conductors may undergo a quench when stable operation conditions are violated. This may not be allowable for big magnets with large amounts of stored energy. So all magnet systems of a considerable size use cryostatically stabilized conductors where the ratio of copper to superconductor exceeds 10 to provide sufficient copper for a current bypass in case of a quench without disturbing magnet performance. In addition, the cooling has to be sufficient not to increase the temperature in normal conducting mode above the critical temperature. No standardized cryostatically stable conductors exist, they require individual solutions to individual magnet systems.

In the last year conductors made of β-tungsten-compounds (Nb_3Sn and V_3Ga) became commercially available, too. They are more expensive (typically a factor of 3 to 5) than NbTi-conductors and sensitive to mechanical deformations. In bulk form, Nb_3Sn breaks at a tensile strain of about 0.2 %. In filamentary form this value is certainly better than this and manufacturers report of minimum bending radii for their Nb_3Sn or V_3Ga wires of about 250 times the conductor diameter, that is the wire can be bent or otherwise mechanically strained to about 0.5 %. The winding procedure has to be adapted to these demands.

Without any additional precautious no pure copper will exist in the wire as the tin is very diffusive. However, copper may be necessary to perform the very useful two functions of stabilizing the composite and protecting it from burn out at quench in a magnet. So, islands of pure copper or clusters of filaments in bronze, grouped in a copper matrix, are foreseen. The copper is protected from the bronze by a diffusion barrier of tantalum or some other metal.

Circular and rectangular wires with several thousand filaments typically 5 μm thick and outer conductor dimensions of about 1 mm are commercially available in several km lengths. Conductors with up to about 10^5 filaments have been produced in laboratory style. The next step will be to develop cables of several strands, with appropriate dimensions, mechanical and electrical properties such as full transposition, additional copper or aluminum stabilization and mechanical reinforcement.

4.12 Magnet technology

Superconducting magnet technology with NbTi conductors is established for both d.c. and a.c. applications. A lot of magnets for different projects have been built and successfully operated all around the world. The superconducting magnet technology is one of the major technological breakthroughs of the last 5 to 10 years. Nevertheless, a lot of problems is left, especially for large superconducting magnet systems.

There are three routes of magnet technology:

- very high field magnets ($\geq$ 15 T)
- medium size magnets as economical alternatives to conventional systems
- very huge magnets or magnet systems.

Very high field magnet systems have been built as hybrid systems with a resistive core magnet and a superconducting envelope increasing the central field, or with a superconducting insert made of Nb_3Sn ribbon or V_3Ga multifilamentary conductors. A 16.5 T magnet at 3 K with a clear bore diameter of 25.7 mm made of Nb_3Sn ribbon as well as a 25 T hybrid system with a resistive inner coil and a superconducting outer coil producing 7 T have been successfully operated [7, 7a].

Medium size magnets are considered and have already been used for a great variety of applications. The outstanding developments have been made for levitated trains and high energy accelerators. There is a great industrial interest in superconducting alternators and ore separation.

Our laboratory is engaged in these developments.
Magnets of medium size make us of inherently stable con-

ductors and will experience quenches in case of disturbances affecting stability.The main problem for the designer is therefore to prevent such disturbances. The conductor used is flexible and has to be held in proper position during operation. On the other hand, it will experience magnetic forces and undergo thermal contraction during cooldown. Compacting and fixing the winding package is an absolute necessity to achieve the desired field configuration and avoid conductor movement which might induce disturbing field components. In many cases the coils are impregnated by epoxy resins thus fixing individual windings but at the same time preventing the direct access of the helium to the conducting wire. Appropriate design of cooling channels or heat drains has to be ensured taking into account thermal conductivity and heat transfer through the complex winding structure.

A special problem is encountered in impregnated coils (the effect is much less pronounced in mechanically clamped coils): current degradation or training when the magnet is energized for the first times. The critical current value or even the design value which may be well below critical current value is only gradually achieved by a series of premature quenches. Sometimes several hundred of quenches are necessary. After training the magnet reaches its design value at once. The causes of training are manifold: conductor movement, heat release due to degeneration of mechanical stresses, cracks within the resin, dislocations or rearrangements within the conductor. More work has to be done to achieve full understanding of and finally avoiding the effect. The effect is more pronounced in complicated winding configurations than in simple coil configurations.

The present state of magnet technology is characterized by the fact that many superconducting magnets are used all around the world mainly in research laboratories for very different kinds of applications without any special knowledge besides the instruction manual. There are solenoids with a field homogeneity of 10^{-5} in the useful bore, dipole and quadrupole magnets for charged particle beam lines more compact and powerful than conventional iron magnets but equally accurate and reliable: field accuracy is 10^{-3} without auxiliary correcting coils and fields between 4 and 6 T are commonly used. The development of pulsed magnets has achieved the design goal of accelerator requirements: field accuracy and level as mentioned, field rise time 1 to 10 s, losses as low as 10 W/m, long term operation of several 10^{5} pulses without any degradation or fatigue. Levitation of test carriers on the track has been achieved by superconducting magnets. An example which demonstrates design considerations, construction concepts, and successful operation of superconducting magnets will be reported elsewhere [8]: Two quadrupoles for a hyperon beam experiment 1.1 resp. 1.4 m long with a peak field of 4.2 T in the coil and a field gradient of 156 T/m, and a total loss at helium temperature including current leads of about 5 W each (Fig. 7).

The state of very huge magnet systems is well known. Each of these magnet systems requires a specific design. The common feature is that all these magnet designs make use of fully stabilized conductors. Most of the very large magnets are bath cooled, that means the superconducting coil is immersed into liquid helium. A few use forced cooling by supercritical helium [9,10]. The technological progress may conveniently be demonstrated by showing the Lubell-diagram of the last International Cryogenic Engineering Conference [11] which shows stored energy vs. time for all the large superconducting magnets (Fig. 8). A less steep slope is expected for more complicated magnet systems such as toroidal field configuration. Nevertheless no insurmountable difficulties are seen when proceeding to larger magnets with present techniques.

A new task has arisen from the fact that Nb_3Sn and V_3Ga superconducting multiflament conductors have become available. Magnet technology using these conductors is at the very beginning but already promising results have been obtained [12,13,14]. A small coil made by Siemens and Vakuumschmelze has achieved a maximum field of 13 T at the Nb_3Sn-coil in a background field of a 7 T NbTi-coil. Development of Nb_3Sn-technology for large magnet systems especially for fusion applications will be a challenge of the future.

4.13 Fusion oriented magnet work

Plasma confinement systems are of "open" or "closed" type corresponding to the course of magnetic field lines with respect to the plasma volume. An advantage of open geometry is that the coil can be designed to make the field lines curve away from the plasma thus producing a "minimum B" magnet well and creating a hydromagnetically stable confinement which allows high plasma densities. Two types of coil configurations producing these fields have been built using superconducting coils: the baseball II coil in a neutral injection experiment at Lawrence Livermore Laboratory [15] and mirror quadrupole coils in the IMP experiment of Oak Ridge National Laboratory [16].

The baseball II coil has 1.2 m bore, produces a maximum field of 5.5 T at the conductor and stores 10 MJ of magnetic energy. The conductor used is a NbTi composite multicore conductor.

A schematic view of the mirror quadrupole of the IMP experiment is shown in Fig. 9. The circular mirror coils use NbTi fully stabilized multicore conductor, the quadrupole coils are Nb_3Sn tape conductor stabilized with an interwound high-purity aluminum strip. The coils generate a central field of about 2 T with a maximum field of 5.9 T at the NbTi coils and of 8.2 T at the Nb_3Sn quadrupole coils. The total energy stored in the coil system is 2.4 MJ, the total length of the system about 1.1 m.

The next mirror experiment MX, proposed to follow baseball, will use Yin-Yang type coils, which may be considered as technically and economicly improved versions of baseball coils and which may have the potential to fit reactor requirements. The superconducting route will concentrale on this coil configuration.

If the field lines remain within the vacuum system, we have a "closed" confinement geometry. Such a configuration is usually created by a strong toroidal field to which are added either helical windings (stellarator) or a current along the axis of the torus, e.g. the plasma itself, in tokamak devices.

Outstanding experiments were made with levitated superconducting rings buried within the plasma, e.g. [17,18]. The superconducting ring has to float to avoid mechanical supports or current leads which would quickly dissipate the plasma. Both the levitated field and vertical field to confine and stabilize the plasma are produced by superconducting coils. The Culham device has a ring of 60 cm major diameter × 9 cm minor diameter carrying a current of 0.5 MA. It is levitated by superconducting coils, the largest of which is about 1.2 m in diameter. All coils are made of NbTi multifilament conductor and are vacuum impregnated in epoxy resin. The LLL levitron has an 80 cm major diameter × 9 cm minor diameter ring wound with Nb_3Sn tape. Similar devices have been studied at Garching and Princeton.

A superconducting toroidal system is the NASA Lewis "bumby torus" magnet facility [19]. It consists of 12 superconducting coils each with 22 cm inner diameter and capable of producing 3 T on their axis. The coils are equally spaced around a major radius of 0.76 m. The system has successfully been operated and exceeded design values. It is used to study plasma heating and confinement problems.

A stellarator coil for the Wendelstein VII experiment has been built by Siemens and tested. Finally, Wendelstein VII was built with normal conducting coils, it is nearing completion now. The mean coil diameter of the superconducting prototyp coil is 1.04 m, maximum field in the torus was designed to be 6.2 T, total stored energy is about 2 MJ. The superconducting coil has been successfully operated in a simulated torus environment and exposed to pulsed fields with field components up to 0.5 T with a current rise of 5 ms (100 T/s) simulating the transient field components produced by the helical stellarator windings [20].

The most advanced plasma technology experiment using a superconducting torus is carried out at Kurchatov Institute, Moscow [21]. A superconducting tokamak T-7 is being constructed and nearing completion during this year. Major diameter of the plasma chamber is 2.5 m (outer diameter 4 m), and its minor diameter 0.7 m. Plasma diameter is 0.6 m. The plasma current will be 0.5 MA. The superconducting magnet system is made of 48 coils grouped in 8 sections. Mean coil diameter is 1 m. The conductor is a fully stabilized hollow conductor cooled by supercritical helium. The torus structure is made of aluminum. The toroidal central field is 3 T and stores about 20 MJ of magnetic energy. First plasma experiments are foreseen for 1977.

The other magnetic confinement approach is the high field, high-β theta pinch in which a plasma is heated by compression in a single-turn pulsed coil using a capacitive or inductive energy storage system. The confining coil will not be superconducting but economics of energy storage may call for superconducting storage coils rather than capacitors. Adequate developments are going on at several places including Los Alamos, Efremov Institute Leningrad, and Karlsruhe. A storage experiment ESPE 2 has been carried out at Karlsruhe using a superconducting storage coil and a superconducting power switch (Fig. 10) [22]. The maximal stored energy is 220 kJ which can be discharged in a few msec allowing power pulses up to 62 MW at 50 kV. The objective of the experiment is to study high voltage properties of cryogenic components, high efficency and reversible energy transfer schemes, and magnet system protection allowing fast extraction of the stored energy. Another experiment TESPE is under construction. It is a toroidal system consisting of six coils which will store 5.8 MJ. Major torus diameter is 1 m, inner coil bore 0.4 m. The coils will create a central field of 5 T, maximum field at the coil is designed for 8 T. The conductor is niobium-titanium. An artists view on TESPE is given in Fig. 11. TESPE is a technology experiment allowing to study mechanical, thermal and electrical behaviour of torus configurations and checking predictions made by adequate computer calculations: such as force distribution, quench behaviour, heat and energy transfer. The cooling concept foresees forced cooling with supercritical helium in cooling channels. The device will be an intermediate step to a toroidal system with 3 m diameter coils.

4.2 Superconducting magnet development programmes

4.21 Size and problems of next generation magnets

The objective of any fusion-oriented superconducting magnet development programme is to prove the feasibility of these magnets for a fusion reactor magnetic confinement system. However, already the set of plasma experiments which will follow the present experiments under design or construction (Post-JET-experiments) will require superconducting magnets for economic reason. From Table 2 it may be seen that coil radii of 3 m for JET and even 5 m for T-20 are foreseen.

A Post-JET experiment is not yet specified but is expected to have a toroidal magnet system with a bore ranging from 5 to 10 m, a peak magnetic field at the windings of 8 to 12 T, and stored energies of 20 to 50 GJ. Pulsed fields of the order of 1 T in the toroidal winding and 5 T in the poloidal windings will be experienced, with rise times less than 1 second.

Reactor dimensions may be seen from Table 3 where results of conceptual design studies are given. The main field coils are assumed to be D-shaped which may be dictated by the plasma shape. The size is far beyond present state of the art (two orders of magnitude). The poloidal field windings have necessarily to be superconducting in a reactor whilst for a POST-JET-experiment it is not yet clear whether a normal or superconducting solution will be selected. That may depend on the position of these coils inside or outside of the main coil cross section.

The choice of the conductor - niobium-titanium or niobium-tin - will depend on future developments of both plasma physics and superconducting technology. Niobium tin or other high field and high temperature superconductors will be favoured for two reasons: 1) the power rate P of a fusion reactor is proportional to the square of plasma density which under certain similarity assumptions, is in turn proportional to the square of the magnetic field B, thus $P \propto B^4$; 2) the higher critical temperature will allow increased operation temperature and thus reduced refrigeration cost or offer a wider safety margin and thus contribute to overall reactor safety.

A major problem of fusion reactor magnets will be mechanical. The main field coils will experience axial compressing forces and radial forces directed to the torus center. Bending forces due to the radial inhomogeneity of the field act on the coil shape; D-shaped coils will minimize these forces. The interaction with the pulsed poloidal fields will lead to dynamic loads on the main coils. Finally, large asymmetric forces will be developed in case of a failure of one or more coils. Reinforcement will be a major part of the coil design.

Another major problem is coil protection. Huge amounts of stored energy have to be handled safely. Both passive devices such as external resistive shunts acting as energy dumps and active devices may be considered. External or internal energy dissipation may be foreseen. The integrity of coils must be insured under all possible circumstances.

Further problems are listed to show the range of required developments: conductor development and test; selection and investigation of refrigeration and cooling concepts; coil design especially with respect to coil protection;development of economic and reliable steady state toroidal and pulsed poloidal coils; radiation effects on superconducting coils, structural and insulating materials; minimizing a.c. losses and dynamic mechanical loads; power supply including superconducting storage devices (storage coils or homopolar machines). Large and expensive test facilities for large coil tests have to be built.

4.22 Superconducting magnet development programme

The main objectives will be: to develop, design, fabricate, and test reliable magnet systems for larger plasma experiments, for experimental test and power reactors. In particular for tokamaks, large volume toroidal and reliable pulsed superconducting magnets have to be developed. For mirror machines the high field route (> 10 T) is of distinct interest. For pulsed magnet systems like in theta-pinches and tokamak poloidal field systems superconducting storage devices may present economic alternatives.

The United States ERDA has initiated a programme [23] which covers all these objectives. The tasks are distributed amongst national research laboratories. The programme is a long termed one (up to the year 2000) and includes two experimental power reactors of several 100 MW_{th} and a full size demonstration power reactor. Its final goal is to demonstrate a capability for commercial fusion power.

The first planning has its target in 1981 to show the feasibility of superconducting coils for an experimental tokamak power reactor and a fusion engineering research facility FERF for a mirror machine.

A similar but less ambitious programme is under discussion within EURATOM. It will comprise a period of 7 to 8 years and is aiming at a demonstration magnet which either could be a complete toroidal assembly of magnets of approximately 3 metres bore with poloidal windings or a single large coil, or cluster of coils, of approximately 6 metres bore with simulation of toroidal effects and poloidal fields.

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Nuclear fusion reactions relevant for fusion reactors

$D + T \rightarrow {}^{4}He\ (3.52\ MeV) + n\ (14.06\ MeV)$

$D + D \rightarrow {}^{3}He\ (0.82\ MeV) + n\ (2.45\ MeV)$

$\rightarrow T\ (1.01\ MeV + p\ (3.03\ MeV)$

$D + {}^{3}He \rightarrow {}^{4}He\ (3.67\ MeV) + p\ (14.67\ MeV)$

Tritium-breeding reactions with Lithium

${}^{6}Li + n = {}^{4}He + T + 4.80\ MeV$

${}^{7}Li + n = {}^{4}He + T + n - 2.47\ MeV$

Table 1: Main fusion and tritium-breeding reactions.

Device	Country	Plasma current (MA)	Major radius (m)	Mirror radius (m)	Torus central field (T)
T-10	USSR	0.8	1.5	0.35	5.0
PLT	USA	1.4	1.3	0.45	4.6
JT-60	JAPAN	3.0	3.0	1.0	5.0
JET	EUROPE	4.8	3.0	1.25 - 2.10*)	3.5
T-20	USSR	6.0	5.0	2.0	3.5

*) noncircular coils

Table 2: Main parameters of major tokamaks considered.

	TEPR (Argonne[3])	UWMAK 2 (Wisconsin[4])	PFPP (Princeton[5])	FERF (Livermore[6])
Electr. power output (MW_{el})	20 - 50	1700	2000	
Plasma torus dimension				
Major radius (m)	6.25	13	10.5	
Minor plasma radius (m)	2.1	5	3.25	
Coil bore dimensions (height × width) m^2	12 × 8	28.3 × 19.25	19 × 12	
Superconductor	NbTi + Cu	NbTi + Cu	Nb_3Sn	Nb_3Sn
Central field (T)	3.5	3.67	6	
Peak field (T)	7.5	8.30	16	12
Number of coils	16	24	48	2
Stored energy (GJ)	15.6	223	250	2.5
Wall load due to neutrons and plasma radiation (MW/m^2)		1.2		
Mean ion temperature (keV)	10	11	30	

Table 3: Main parameters of proposed power reactors and large scale demonstration experiments. UWMAK 1 (University of Wisconsin tokamak) and PFPP (Princeton Fusion Power Plant) are conceptual design studies of power reactors with a thermal power of 5000 MW. TEPR is a design study for a Tokamak Experimental Power Reactor (comparable to POST-JET-data). FERF-data refer to a Yin-Yang type mirror magnet experiment (Fusion Engineering Research Facility).

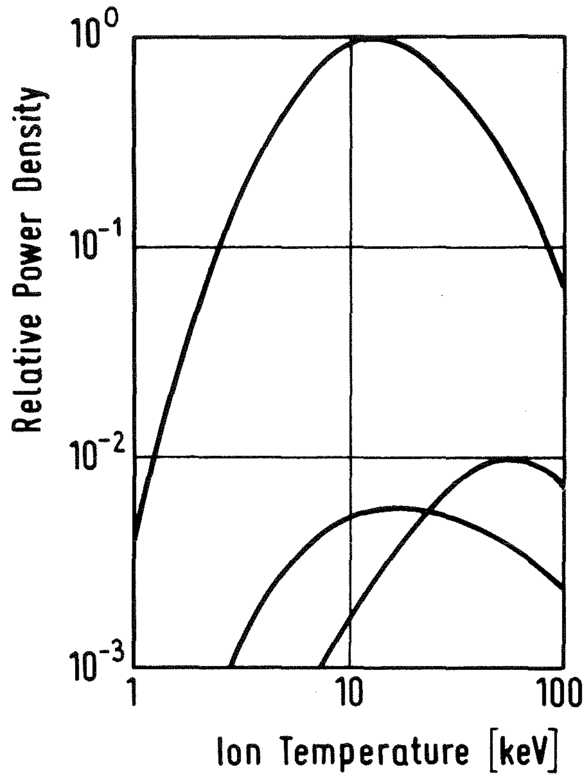

Fig. 1: Relative fusion power density (after Knobloch[1])

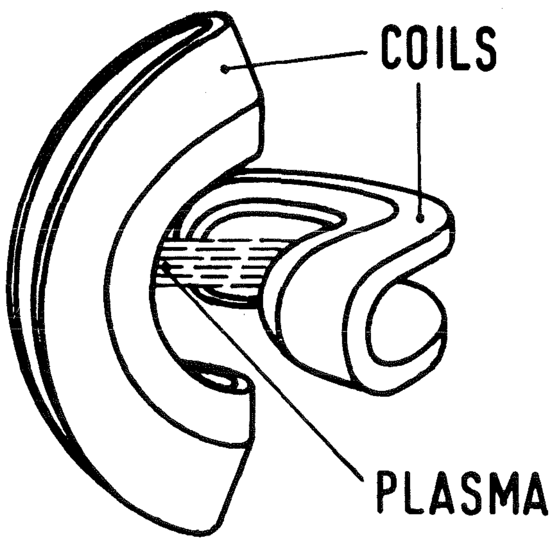

Fig. 2: Principle of Yin-Yang-type field coils

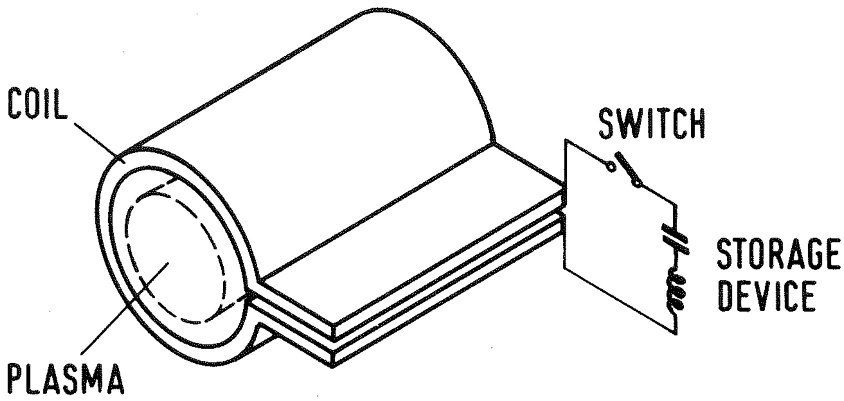

Fig. 3: Principle of a theta pinch coil system

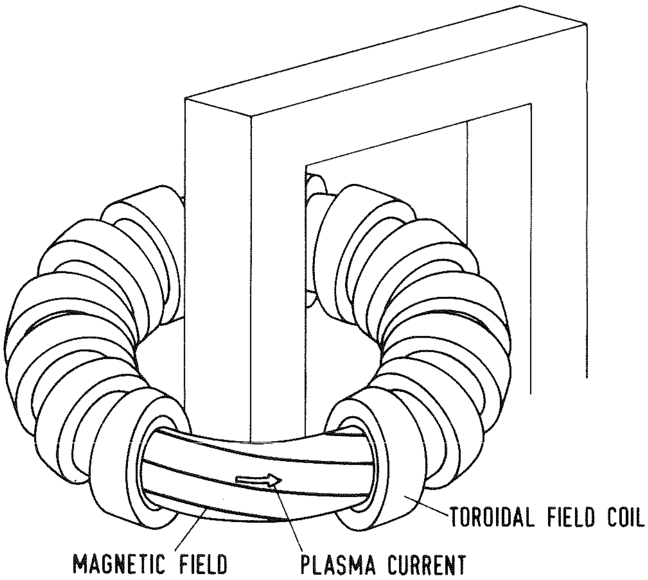

Fig. 4: Tokamak principle

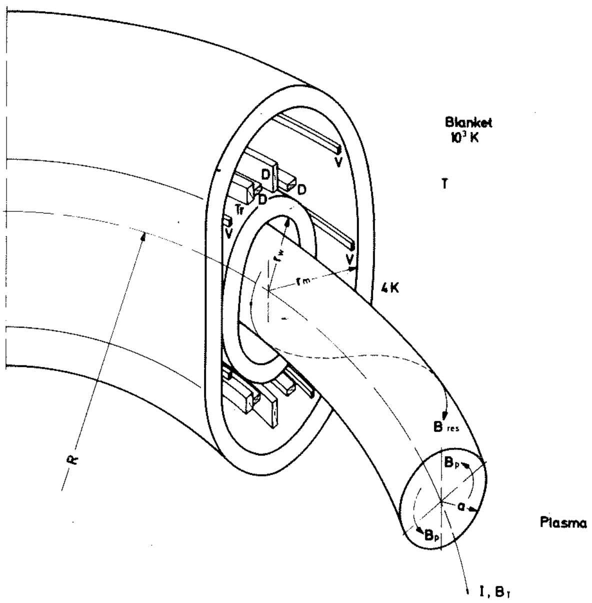

Fig. 5: Schematic view of magnet torus cross section

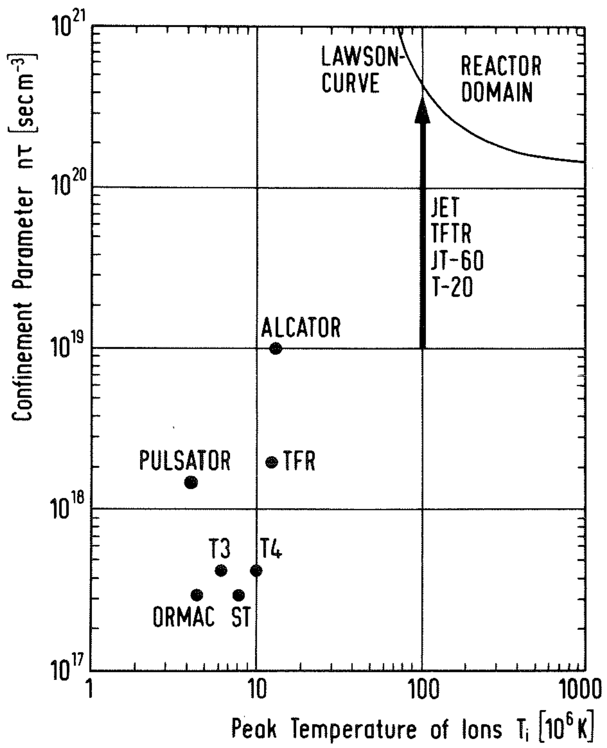

Fig. 6: Performance of different plasma experiments together with the Lawson curve

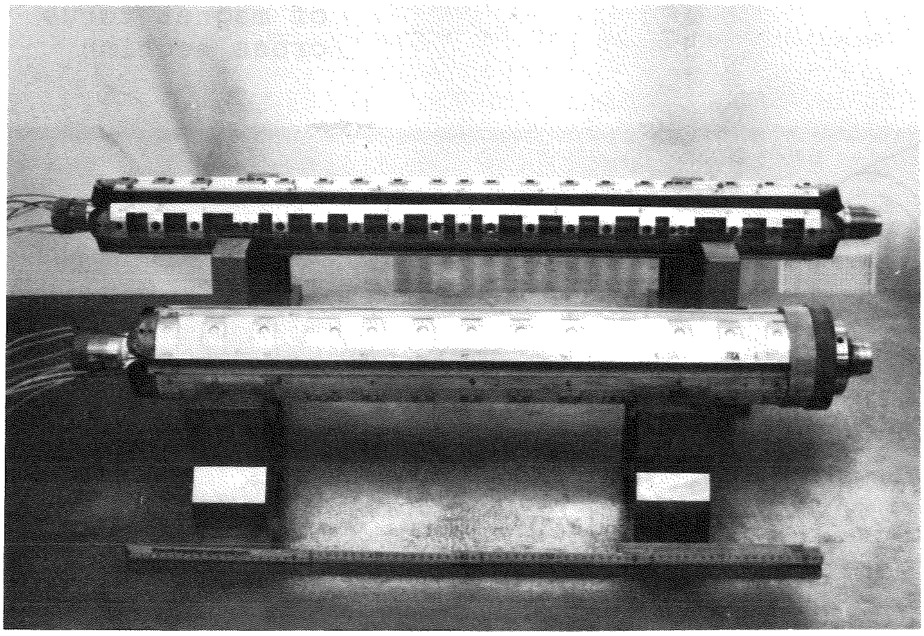

Fig. 7: Two superconducting quadrupole coils for a hyperon beam line

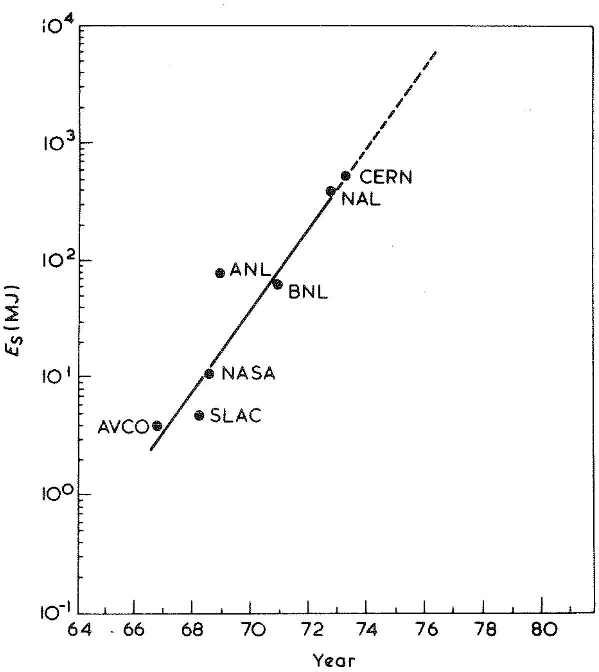

Fig. 8:

Technological progress of superconducting magnets as indicated by stored energy vs. time for all the large superconducting magnets

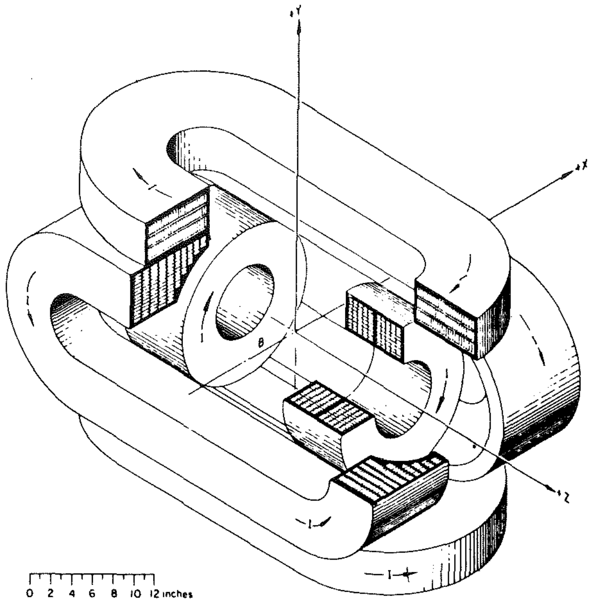

Fig. 9: Schematic view of the mirror quadrupole of the IMP experiment

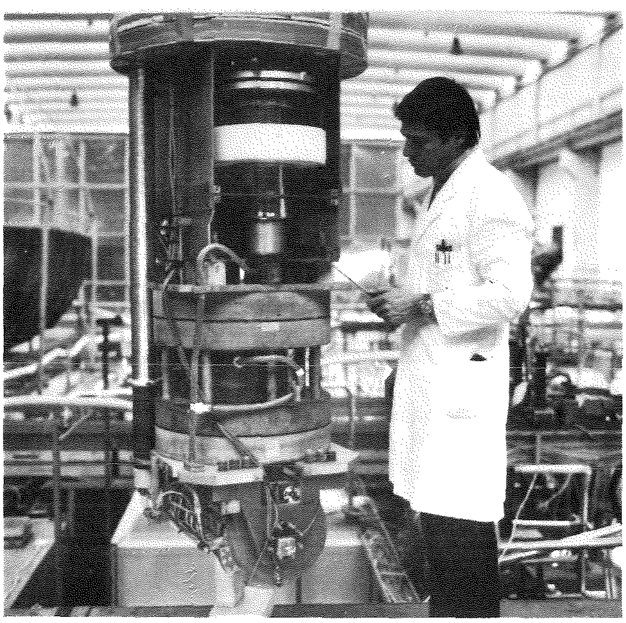

Fig. 10:

View on energy storage experiment ESPE 2 with storage coil and s.c. switch coil

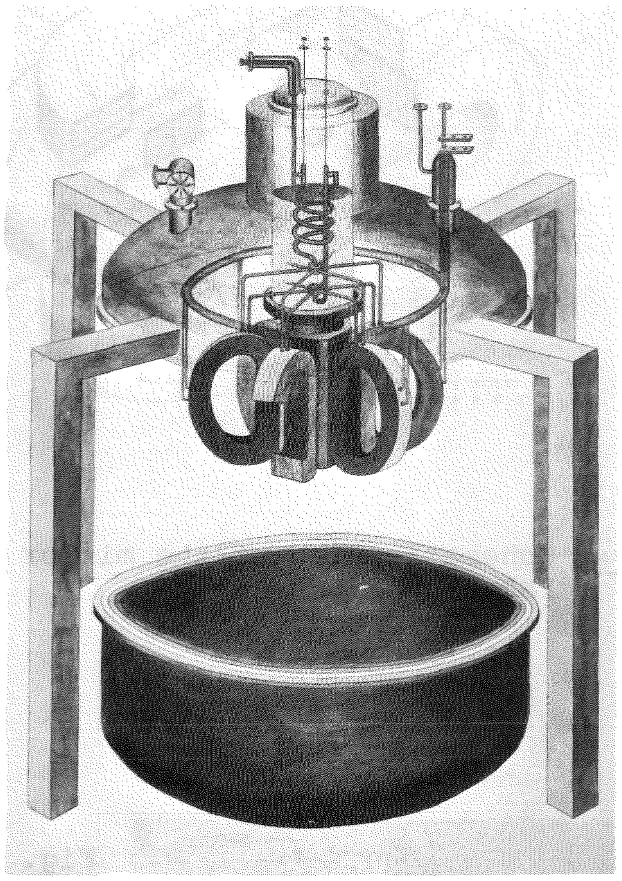

Fig. 11: Artist view on the toroidal magnet system TESPE