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Tokamak Reactor Concepts Using High Temperature, High Field Superconductors*

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ABSTRACT

Tokamak ETR and demo reactor design concepts using high temperature, high field oxide superconductors are described. Current densities in recently developed oxide superconductors appear at present to be very low and it is not clear whether practical magnets for fusion applications can be developed. However, if this development occurs the potential impact on tokamak design appears large. Significant reductions in cost, complexity and physics extrapolation could be possible by the combination of very high fields and liquid nitrogen operation. Illustrative parameters are given for an ETR device that has about the same plasma volume as TFTR. Parameters are also given for a demo device with approximately the same plasma volume as JET. If practical oxide superconducting magnets cannot be developed, a significant degree of the improvement due to high field operation might in fact still be realized using existing superconducting materials such as Nb_3Sn (Ta, Ti).

Introduction

Recent progress in oxide superconductor research opens up the possibility of magnets with much higher critical fields and temperatures[1,2]. Critical fields of greater than 20 T at liquid nitrogen temperature appear attainable, although, at present, only at very low current density. At liquid helium temperatures critical fields approaching 100 T may be possible. In this paper we consider tokamak ETR and demo reactor design using superconducting magnets with combined high critical field and temperature properties. Significant reduction in size, cost and complexity may be possible.

Potential Advantages

High Field Operation

High field magnet operation has been used to obtain a relatively high performance to cost ratio in the CIT design, reducing the cost of a short pulse ignition experiment. This approach should also be effective for devices with long pulse, high Q or ignited operation. The advantages of high field operation could be attainable with existing superconducting materials such as Nb_3Sn (Ta, Ti) [3,4,5] but could be extended with the oxides (Nb_3Sn and similar materials could provide fields of about 18 T at the toroidal field coil).

Both the minor radius and elongation needed to obtain a given value of $n\tau$ could be reduced by operation at high fields, resulting in a substantial decrease of the plasma volume. Operation at low beta could allow the plasma operating region to be closer to present experience and there could be a greater margin against the consequences of MHD instabilities. It could also reduce the complexity of the EF magnet system needed for plasma shaping and control. At sufficiently high fields it should be possible to use ohmic or ohmic-dominated heating to ignition.[6] This might result in reduced confinement degradation and increased confidence in using empirical confinement scaling laws. Auxiliary heating power requirements for startup could be substantially reduced or possibly eliminated.

Operation at high field could also be used to reduce the plasma current needed to provide a given value of $n\tau_e$. For example, if $n\tau$ is assumed to scale as $n\tau \sim B^2a/q \sim BIA$ where B is the field, a is the minor radius, I is the current and A is the aspect ratio[7] then a design with high B and A could be used to significantly reduce the plasma current. This reduction would lead to a decrease in current drive requirements and would be of particular importance for non-inductive current drive (where power requirements can be very large). The reduced current might also result in a reduction of the probability and consequences of disruptions.

It may also be possible to use high field operation to improve the efficiency of current drive. Lower hybrid current drive would be more efficient through improved wave accessibility. High field operation could also facilitate use of bootstrap current through operation at relatively high aspect ratio and lower toroidal beta.[8]

Another possibility is operation with advanced fuel mixtures. Use of high fields might provide the $n\tau$ and fusion power density needed for operation with tritium lean deuterium-tritium fuel mixtures, pure deuterium fuel or D-He^3. Ohmic or ohmic-dominated heating might be used to reach ignition in a deuterium-tritium plasma followed by a controlled thermal runaway to reach the temperatures needed for advanced fuel mixture operation.

High Temperature Superconductor Operation

Use of high temperature superconductors would result in a decreased shielding requirement for prevention of heating of the superconductor and could lead to a reduced shield thickness. Reduced shield thickness on the inboard side of the plasma would result in better utilization of the field at coil and a more compact design. For liquid nitrogen operation of the superconductor, the shielding needed to limit heating of the superconductor could be very modest. Consequently the shield thickness could be determined by damage to the insulator or the superconductor.

Operation at liquid nitrogen temperature or higher could lead to a simpler, more robust magnet design with greater thermal stability margins. The decreased thermodynamic load in transmitting forces from low temperature structures would allow simpler, stronger structures to be used to support, for instance, the overturning loads. In addition, it also might be possible to use demountable coils as in the copper magnet designs.

Liquid nitrogen operation might also allow the use of part of the cold structure of the toroidal field coil for shielding. The plasma-TF magnet distance could thus be reduced significantly.

Illustrative Design Concept

A possible magnet design approach using oxide superconductors might employ plates which combine the ceramic superconductor and normal conducting material of high strength. We will assume that by using such a combination the toroidal field magnet could be operated at an equivalent tensile stress of 800 MPA.

It will be assumed that the average current density in the magnet is 20-50 MA/m^2. The assumed current density in the oxide is 100-125 MA/m^2. This is one order of magnitude higher than has been achieved in the oxides. However, it may be possible to significantly improve the current carrying capacity of these materials. The low current carrying capacity may not be intrinsic to the lattice structure; for instance, it might be associated with an irregular macroscopic assembly of crystalline constituents separated by insulating constituents.

It will also be assumed that the superconductor can be operated at liquid nitrogen temperatures and that the thickness of the shielding on the inboard side is determined by damage to the insulator and/or superconductor. The insulator will be assumed to withstand a fluence of greater than 10^{20} neutrons/ cm^2 [9]. Possibilities for the insulator are polyimide alone or in combination with glass, mica-based materials or ceramic (for example, sprayed onto the metal component of the plate).

Illustrative ETR Designs

Illustrative parameters for a high field ETR design are given in Table 1. The confinement quality parameter B^2a is 58 T^2m. With these parameters the projected $n\tau$ should be sufficient for the high Q operation goal of the ETR. The magnetic field at the coil is 17 T and the field at the plasma is 10.3 T. The inboard warm shield thickness is 0.48 m, which should allow for about 1 yr of integrated fluence. Additional shielding is provided by the TF magnet casing. The major radius is 2.6 m, the minor radius is 0.55 m, and the elongation is 1.6 resulting in a plasma volume that is comparable to that of TFTR.

The plasma current is 3.9 MA. The combination of the modest current and the high field could lead to relatively modest current drive power requirements. The machine would have an OH transformer that could provide 300 seconds of current should it not be possible to use steady state drive. The elongation of 1.6 would be used to provide a divertor. The machine would be operated at $q \simeq 3.9$ and $\beta \simeq 4.4\%$.

More physics margin is possible in this type of design by incorporating more shielding into the liquid nitrogen cooled magnet structure and reducing the warm shielding. The thermal loading at liquid nitrogen temperature increases, however. For example, if the warm shield thickness were reduced in this way to 0.20 m then the minor radius could be increased to 0.65 m and B^2a could be increased to 76 T^2m.

Illustrative parameters for an ETR device operated at higher field are shown in Table 2. This device would have a large margin for ignition in confinement q and β. It might be possible to ohmically heat to ignition or at least to employ ohmic dominated heating. The ohmic heating power requirements are eased relative to a short pulse ignition device by the long startup time. This super high field ETR device would still have a relatively modest tokamak size and moderate cost.

Illustrative Demo Reactor Concepts

Table 3 gives illustrative parameters for a high field demo reactor concept. An inboard blanket-thickness of 0.35 m is assumed. The toroidal field magnet structure provides additional shielding for the insulator and superconductor. The device has a major radius of 3.5 m and a plasma volume that is comparable to that of JET. It would be substantially smaller and less expensive than present demo reactor concepts.

Table 4 gives parameters for a super high field version that might ohmically heat to ignition.

Conclusions

We have explored some of the possible implications of super high field, high temperature superconductors for tokamak development. A large range of other possibilities remains to be examined including hydrogen plasma confinement devices as well as other ETR and demo reactor design approaches. It is not clear whether simultaneous high field, temperature and current density oxide superconductor operation can be obtained and whether practical oxide superconducting magnets for fusion applications can be developed. Nevertheless, there is basis for optimism given the widebased approaches for making these materials. If such practical oxide magnets can be realized, the cost, complexity and degree of physics extrapolation of next step devices could be substantially reduced. If practical oxide superconducting magnets cannot be developed, a significant degree of the improvement due to high field operation might in fact still be realized using existing superconducting materials such as Nb_3Sn (Ta, Ti).

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Table 1. Illustrative Paramaters for High Field ETR

Major Radius (m)	2.6
Minor Radius (m)	0.55
Toroidal Field (T)	10.3
Maximum Field @ Coil (T)	17
Current Density in Oxide (MA/m^2)	100
Current Density in TF Coil (MA/m2)	30.1
Plasma-TF Coil Distance (m)	0.48
B^2a (T^2m)	58
<beta> (%)	2.8
Elongation	1.6
q	3.9
Plasma Current (MA)	3.9
Central Plasma Density (m^{-3})	$\leq 5.0 \times 10^{20}$
Central Ion Temperature (KeV)	17
Maximum Neutron Wall Loading (MW/m^2)	5.3
Total Fusion Power (MW)	484

Table 2. Illustrative Parameters for Super High Field ETR

Major Radius (m)	3.4
Minor Radius (m)	0.6
Toroidal Field (T)	15.3
Maximum Field @ Coil (T)	22.4
Current Density in Oxide (MA/M^2)	125
Current Density in TF Coil (MA/m^2)	27.8
Plasma-TF Coil Distance (m)	0.48
B^2a (T^2m)	140
<beta> (%)	1.5
Elongation	1.6
q	3.9
Plasma Current (MA)	5.1
Central Ion Temperature (KeV)	17
Central Plasma Density (m^{-3})	$\leq 5.7 \times 10^{20}$
Maximum Neutron Wall Loading (MW/m^2)	7.4
Total Fusion Power (MW)	972

Table 3. Illustrative Parameters for High-Field Demo

Major Radius (m)	3.5
Minor Radius (m)	0.70
Toroidal Field (T)	11.1
Maximum Field @ Coil (T)	18
Current Density in Oxide (MA/m^2)	125
Current Density in TF Coil (MA/m^2)	30.8
Plasma-TF Coil Distance (m)	0.65
B^2a (T^2m)	86
<beta> (%)	2.2
Elongation	1.6
q	3.9
Plasma Current (MA)	5
Central Plasma Density (m^{-3})	$\leq 4 \times 10^{20}$
Central Ion Temperature (KeV)	17
Maximum Neutron Wall Loading (MW/m^3)	4.3
Total Fusion Power (MW)	676

Table 4. Illustrative Parameters for Super-High Field Demo

Major Radius (m)	4.4
Minor Radius (m)	0.7
Toroidal Field (T)	16.6
Maximum Field @ Coil (T)	23.9
Current Density in Oxide (MA/m^2)	125
Current Density in TF Coil (MA/m^2)	23.5
Plasma-TF Coil Distance (m)	0.65
B^2a (T^2m)	192
<beta> (%)	1.2
Elongation	1.6
q	3.9
Plasma Current (MA)	5.8
Central Plasma Density (m^{-3})	$\leq 4.8 \times 10^{20}$
Central Ion Temperature (KeV)	17
Maximum Neutron Wall Loading (MW/m^2)	6.1
Total Fusion Power (MW)	1200