Assessment of Liquid Hydrogen Cooled MgB₂ Conductors for Magnetically Confined Fusion

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Abstract. Importantly environmental factors are not the only policy-driver for the hydrogen economy. Over the timescale of the development of fusion energy systems, energy security issues are likely to motivate a shift towards both hydrogen production and fusion as an energy source. These technologies combine local control of the system with the collaborative research interests of the major energy users in the global economy. A concept Fusion Island Reactor that might be used to generate H₂ (rather than electricity) is presented. Exploitation of produced hydrogen as a coolant and as a fuel is proposed in conjunction with MgB₂ conductors for the tokomak magnets windings, and electrotechnical devices for Fusion Island's infrastructure. The benefits of using MgB₂ over the Nb-based conductors during construction, operation and decommissioning of the Fusion Island Reactor are presented. The comparison of Nb₃Sn strands for ITER fusion magnet with newly developed high field composite MgB₂ PIT conductors has shown that at 14 Tesla MgB₂ possesses better properties than any of the Nb₃Sn conductors produced. In this paper the potential of MgB₂ conductors is examined for tokamaks of both the conventional ITER type and a Spherical Tokamak geometry. In each case MgB₂ is considered as a conductor for a range of field coil applications and the potential for operation at both liquid helium and liquid hydrogen temperatures is considered. Further research plans concerning the application of MgB₂ conductors for Fusion Island are also considered.

1. Introduction

Fusion research has entered a new era with the 2006 international decision to construct ITER with its long pulse capability using high field A-15 superconducting magnets. In addition, several countries are now constructing, or planning to have, domestic superconducting devices to explore steady plasma state operations and/or long pulse operations. Such devices include: SST-1 (India), EAST (China), KSTAR (Korea), W7-X (Germany) and NCT (Japan). These devices have been constructed from NbTi and will operate at magnetic induction no higher than 2.5-4 Tesla [1]. Such fundamental fusion magnet research is invaluable in helping to secure an optimum design for future demonstration DEMO...
power plants, but it is important to recognise that these various national projects are not on a trajectory towards a viable fusion power plant before 2050. At present the only machine lying on such a trajectory is the ITER experiment planned to commence operations in Cadarache, France in 2016 [2]. Despite the dominant position held by ITER and the science led approaches of various national projects, we posit that the time is now right to consider unconventional approaches to the commercialisation of fusion energy. In the ITER like design the superconducting magnet system represents a key component, contributing to about 30% of the (approximately €5billion) plant construction cost. Superconductivity costs must be reduced greatly if fusion reactors are to compete with mature low carbon electricity generation technologies, such as nuclear fission and wind power. Fusion planners must be sensitive to the risk of scarcity for key technological components such as high-field Nb-based conductors. Also there is a very important issue of mechanical and electrical cryostability of the Cable-in-Conduit Conductor (CICC), which scales with the size or the reactor. The strong effect of the transverse electromagnetic forces on the interstrand contact resistance, and consequently on the AC coupling losses, was discovered by the University of Twente during a combined AC loss with DC transport current experiment on a sub-size Nb₃Sn CICC in 1995. A few years later the effect was also observed in initial model magnet coils.

The mechanical properties of the cable bundle in terms of strand deformation are key characteristics for the conductor design. The Nb₃Sn strands are sensitive to strain and thus to deformation and so the cable stiffness significantly determines the final conductor performance. The aspect ratio of a tokomak (the ratio of the radius from the plasma centre to the tokamak axis / cross-sectional radius of the plasma), significantly influences machine investment cost. An increase of the toroidal magnetic field on the plasma axis could be beneficial to future fusion reactors and may help the economic viability of this new source of energy. The Compact Spherical Tokomak may become the solution to the lowering cost of the Fusion Reactor unit. It is also envisaged that the associated cryogenic plant also contributes to the so-called recycled power of the reactor: a part of the output electrical power, which is recycled for the reactor’s own needs. This part has to be minimized as it greatly affects the plant operational cost [3]. Central to conventional plans for fusion energy commercialisation is the notion that fusion will provide substantial stable base-load electricity supply. Secondary consideration has been given to other possible uses of fusion thermal energy. Such process-heat applications include the possibility of thermochemical production of commodities including, possibly, hydrogen for a future hydrogen economy. This could contribute to the difficult global challenge of reducing the carbon intensity of vehicle transport. Such an ambition would allow fusion to compete in an arena where few low-cost options exist. This situation contrasts with issues relating to the decarbonisation of electricity production where several mature technologies already exist.

Climate change is not the only driver for fusion energy. Over the timescale of the development of fusion energy systems energy security issues are likely to motivate a shift towards both hydrogen production and fusion as an energy source. These technologies combine local control of the system with the collaborative research interests of the major energy users in the global economy.

Fusion benefits from the fact that its fuels are abundant. Deuterium is readily obtained from seawater and tritium can be produced within a fusion reactor from lithium. Energy security should not be confused with fuel security however. For instance conventional approaches to fusion energy will require very large amounts of helium (a by-product of today’s fossil fuel economy) for cryo-pumping, heat transfer and most importantly for the cryogenic cooling of low-temperature superconducting magnets. The Fusion Island system might be used to generate H₂ (rather than electricity) as has been recently proposed [4, 5]. It suggests that a liquid hydrogen product from a fusion-for-hydrogen facility might provide a ready supply of cryogenic liquid hydrogen for 15-20K superconductor cooling. MgB₂ conductors would perhaps be suitable for the tokomak magnets windings, with electro-technical devices for Fusion Island’s infrastructure. Such developments may provide an opportunity to mitigate against the high costs of superconductivity in fusion, enhancing the technology’s cost competitiveness.

2. Hydrogen on Fusion Island
2.1 Helium replacement by Hydrogen

We are currently pursuing a study in to factors affecting future global helium resources. That study includes issues of supply, demand and their intersection via market prices in a System Dynamics framework [5a]. Today helium is obtained as a by-product of the global natural gas industry. Historically the United States has been a dominant player in global helium supply, but with the growth in liquefied natural gas many aspects of helium production are changing. Simultaneously demand growth is expected in sectors such as medical Magnetic Resonance Imaging systems and Brayton Cycle gas turbine applications, as would be required by High Temperature Gas-Cooled Fission power plants. There is perhaps a certain irony that the technologies of the late twenty-first century would appear, in many cases, to rely on a consumable item (helium) that is a product of the twentieth century natural gas industry. We see no cause for alarm, but we caution that the global fusion community, as a major future user of helium, should consider technological choices (such as hydrogen-based cryogenics) that hedge against helium-based uncertainties.

![Graph](image)

**Figure 1.** Yearly saving made by cooling the superconducting winding of the Fusion Island like reactors by LH2 rather than liquid helium. The assumption was made that reactors will be built progressively at the rate of 0.1 to 1 units/year starting from 2010 until 2060 with a consumption rate 55Mcf/year.

2.2 Hydrogen Cooling

Cryogenic cooling by liquid hydrogen (Tb~20.4K, Tm~14K) in the range 15-20K may necessitate operation with sub-atmospheric pressure and preferably liquid or slush (liquid-ice) phases. Considerable experience at slush hydrogen temperatures derives from the added heat of fusion and the avoidance of gas-liquid (two-phase) flow where pressure drop, boiling instability criteria and critical heat flux (CHF) issues can be problematic. CHF data have been examined extensively by Kandlikar [6] who notes the reduction in CHF in cryogens near Tc and Tm although, between these values, CHF is typically around 8W/cm².

An interesting method of avoiding the two-phase region is to exploit the tendency of cryogenic fluids to exhibit high wall superheats at the incipience of boiling [7]. By careful design and operation (to avoid boiling hysteresis) indefinite operation under superheated conditions at 1 bar would maintain a liquid phase throughout. Metal surface characteristics, fluid properties, and heat flux have been correlated to estimate the achievable wall superheat. However there are examples where it is considered that high current MgB2 conductors can be cooled directly by liquid hydrogen [8] but the impact of neutron flux and the formation of transient hot spots on bubble initiation would need to be carefully examined. For pulsed systems, as Iwasa at al [9] propose, the use of (oxygen free) solid nitrogen as a thermal buffer could be advantageous due to its higher specific heat. Ortho liquid hydrogen is unstable and catalytic conversion to the para form is usually undertaken before use.

3. MgB2 on Fusion Island

3.1 Neutron Irradiation

It is recognised that neutron irradiation in moderated doses improves the pinning and critical current density at higher magnetic field of most of Nb-based A-15 superconductors as well as MgB2[10,11]. It was predicted that particle fluxes for future fusion power plants exceed, by a factor of 30 or more, those expected for ITER [12]. Therefore use of A15 conductors such as Nb3Sn or Nb3Al will require a
long decommissioning process [13]. The very long decay times of Nb compounds imply that a significant radioactive waste inventory is unavoidable. The short lived nature of MgB$_2$ related nuclides would ensure that such hazards would decay to negligible levels on a manageable timescale[13] Figure 2. MgB$_2$ superconductors show remarkably shorter decay time than Nb-based superconductors, and its dose rate decreases below remote recycling levels within 50 years. However, the decay time behaviour of MgB$_2$ superconducting wires is determined by the volume fraction of stabilized Cu.

![Figure 2](image.png)

**Figure 2.** Decay behaviours of the dose rate for Nb$_3$Sn, NbTi, MgB$_2$, and CuMgB$_2$/Cu superconducting coils stabilized with Cu after 10 MW a/m$^2$ operation.

![Figure 3](image.png)

**Figure 3.** Critical current density of the Nb$_3$Sn conductors considered for ITER project. For comparison data for the ex situ/in situ MgB$_2$ data are presented for 4.2K.

3.2 Conductor

The (Mg+2B)$_{0.9}$(SiC)$_{0.1}$/(MgB$_2$)$_{0.9}$(SiC)$_{0.1}$/Cu composite conductor wire was synthesised by hot isostatic pressing (HIP) in a High Isostatic Pressure (HIP) chamber for 15 minutes at 750 °C, under argon at a pressure of 1.0 GPa [14]. The resulting critical current density is versus field is not better than Nb$_3$Sn up to 14 Tesla, Figure 3. However considering the high field $J_c(B)$ dependence of such composite MgB$_2$ wire it may provide the base for development of MgB$_2$ conductor working at 15K at high fields.

4. Fusion Island – Operational Considerations

The *Fusion Island* concept is motivated by a desire to explore possibilities for the most rapid and inexpensive route to the commercial application of fusion energy. We note the possibilities provided by pulsed operations of a tokamak with normal and superconducting magnets cooled to approximately 20K. To minimize engineering challenges we are considering tokamak concepts that lack a divertor for plasma cleaning. We see possible advantages in designing the tokamak with sacrificial components in mind and we are keen to avoid rotating turbo-machinery in the heat removal system, if at all possible. We consider the production of hydrogen to be a good first commercial use for fusion energy and we are considering the advantages of liquid hydrogen storage and supply chains. This liquid hydrogen might be able to provide the cryogenics necessary for tokamak magnet operation. We are considering several possible geometries and sizes of tokamak for such a development and we are most interested in schemes that might draw directly upon the ITER project, on the planned Ignitor machine and from spherical tokamaks, such as MAST in the UK. While a spherical tokamak would raise its own particular challenges, such as adequate magnet shielding, we are attracted by the potential that the central column might act as a plasma limiter and be designed as a re-used and recycled component replaced routinely and robotically during operations.
We note that implementation as a source of process heat for sulfur-iodine thermochemistry requires a high temperature (approximately 750°C) blanket and as such, Fusion Island would head in a direction different from the lower temperature ideas proposed for rapid and low-cost routes to fusion electricity generation. Below we present some initial thoughts concerning the possibility of a large spherical tokamak as a Fusion Island reactor. Rather than operate continuously we envisage that a Fusion Island hydrogen plant would operate in a regular pulsed mode on for instance a repeating 20 minute duty-cycle. The fusion process might follow the following sequence:

- Charge tokomak vessel with deuterium & tritium. For first demonstration plant tritium would be purchased, not made.
- Pellet charge additional fuel during fusion stage
- At relatively low B start to sweep the primary transformer and also to drive the Tokamak with external resonant RF input. Heat to fusion temperature quickly (~45s)
- Major coils are MgB$_2$ and copper cooled by LHe or LH$_2$
- Fusion starts ($t = 45s$) – vessel sealed - no pumping on vessel during fusion
- During fusion phase ramp up applied field to prolong the burn and to combat accumulation of He ash. Deliberately push plasma onto centre column
- At $t = 900s$, deliberately shutdown plasma fusion. Open gate valves to large turbo pumps and cryopumps. Routinely inspect centre column – and replace if necessary
- Pump for 300 s – base pressure $10^{-6}$ mbar – back to first step – recharge with fuel
- Regenerate cryopumps during next 900s burn phase
- Clean and reprocess exhaust gases for re-use
- Aim for ~70% duty cycle when running

We note that the use of a heavy metal liquid blanket would smooth temperature fluctuations for process heat applications and reduce difficulties associated with radiation damage to the blanket. We further note that the Fusion Island concept is less demanding in terms of fusion energy conversion (e.g. $Q \sim 5$) than might be expected for early electrical power applications ($Q \sim 50$). The notion that a Fusion Island process heat source might operate for approximately 15 minutes from every twenty there is the opportunity to store the heat in a heavy metal liquid blanket. It may even be possible to arrange for a heat exchanger directly from such a liquid metal cycle to the process heat needs of a thermochemical cycle. Some engineering care would of course be required to mitigate against the risk that the heat exchanger might perforate allowing liquid lead (for instance) to flow into the high temperature sulfuric acid of a sulfur-iodine cycle. Another concern is that a twenty-minute duty cycle will place large magneto-mechanical stresses on the reactor vessel and its associated components. Key engineering challenges lie here for the Fusion Island concept. The concept is currently being examined as well as issues of plasma confinement, plasma heating, prolonged plasma fusion and vessel evacuation. It is assumed that the plasma will be fired by the combination of a nearby 100MW conventional hydrogen gas turbine working in a continuous mode. It is expected that such a relatively standard technology would be the only source of electrical power to the entire Fusion Island facility. The Fusion Island reactor will not be engineered to produce any electricity. The hydrogen gas turbine (possibly combined cycle) will feed numerous electricity demands in sequence at the facility – including liquifiers and compressors. Electricity accumulation and storage will be provided by a large (approximately 300MW) flywheel using superconducting bearings integrated into the civil engineering of the fusion reactor building. Recently developed manufacturing technology of large bulk superconducting plates of MgB$_2$ which do not suffer from the granularity problem such as HTS may become very important magnetic bearings material for the flywheel considering that the temperature provided by liquid hydrogen will be at the level of 15-20K [16].

To reiterate, for simplicity we do not intend to generate electricity directly from the fusion process heat. We note that any fusion reactor requires an external source of electricity, such as that
from the proposed hydrogen combusting gas turbine, for black-start capability. Until reliability is established it is not expected that Fusion Island facilities will rely on externally supplied grid electricity. Key to the initiation of fusion is the ability to turn 100MWe from a gas turbine generator, by energy accumulation into the 300MWe to 400MWe required by a large-scale fusion reactor.

Conclusions

Looking ahead we are drawn to the conclusion that more work is required concerning liquid hydrogen technology for cryogenically cooled magnet applications using both superconductors and normal conductors. We regard such developments as potentially being of great benefit to low-cost fusion applications. We continue to suggest that the fusion research community should give more attention to the low-cost and rapid commercialisation of fusion physics. We believe that such opportunities could lie outside the electricity sector. The Fusion Island concept might provide the basis for a cost-competitive solution to the production of liquid hydrogen in bulk while simultaneously freeing early fusion plants from the demanding task of continuous high-reliability, electricity production. MgB₂ superconductors have the potential for application in conventional ITER-like designs as well as in the Fusion Island concept.

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