Developing a Robust Compact Tokamak Reactor by Exploiting New Superconducting Technologies and the Synergistic Effects of High Field

D. Whyte, MIT

Steady-state tokamak fusion reactors would be substantially more robust and compact if the achievable magnetic field, B, could be roughly doubled from its present limitation of B~5-6 T to B~10 T. All reactor studies show two criteria for a fusion reactor since together they obviously dictate fusion's economic viability:

1) Adequate fusion power areal density ($P_f / A_{blanket} \geq 4\ MW\ m^{-2}$) and

2) High fusion (Q>25) and electrical (Q$_e$~5) gain.

However, observing that even a simple burning plasma experiment ITER (R~6.2 m, Q=10, $P/A < 1\ MW\ m^{-2}$, Q_e=0), which clearly underperforms as a fusion reactor, will cost ~25B$ strongly motivates us to decrease as much as possible the linear size (R) and therefore the cost (~R^3) of prototype reactors and Fusion Nuclear Science Facilities. Robustly non-disruptive scenarios are also necessary because the plasma thermal pressure (p_{th}), which determines the fusion power density ($\propto p_{th}^2$), will be $p_{th} \sim 1\ MPa$ in all reactor designs [1], i.e. a factor of 4-5 larger than in ITER where damage from disruptions/instabilities seems already unacceptable.

Therefore it is also clear that the *development schedule* of fusion power would be greatly accelerated if reactors could be designed with two extra criteria

3) Smaller size/volume, total power output and expense, and,

4) For the tokamak concept, robust steady-state operation.

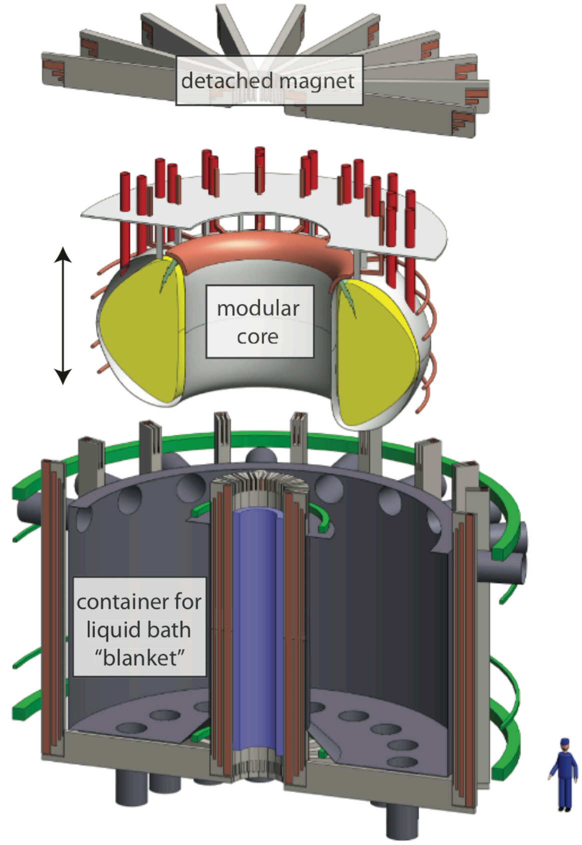
The only way to satisfy all of these criteria is to increase B which can be seen from the simplified relationships

$$\frac{P_f}{A_{blanket}} \sim \left(\frac{\beta_N^2}{q^2}\right) R\, B^4 \quad , \quad \left(\frac{\beta_N H}{q^2}\right) R^{1/2} B^3 \geq C_{Ignition}$$

that determine power density and gain/ignition respectively at fixed geometry (see appendix for derivations at fixed aspect ratio and shaping). The bracketed terms contain dimensionless plasma physics parameters of the normalize pressure limit (β_N), kink safety factor (*q*) and confinement quality (*H*). For robustness, the bracketed terms should decrease compared to standard reactor designs (e.g. ARIES [2]). These designs routinely violate the intrinsic β_N limit by a factor of two and push q down to is minimum value against the kink (q) limit: Why? Because due to the available B strength the only way to make the device size "reasonable" (R~6 m, volume < 10^3 m^3), yet meet criteria 1-2, is to increase the bracketed terms, thus incurring large, and possibly unacceptable, disruption risk. The good news is that due to the strong power-dependencies on B a modest factor of two increase in field can decrease the size R a factor of two, thus decreasing the volume/unit-cost eightfold, yet simultaneously allowing the bracketed terms, and the disruption risk, to also decrease by nearly an order of magnitude!

This highly attractive route for fusion energy development has been made feasible by breakthroughs in superconductors (SC) which provide the approximately power-free B. Standard niobium-tin SC, such as used in ITER, are limited to maximum field on coil ~11 T due to intrinsic superconducting limits. However, commercial high-temperature SC (HTSC) tapes have been developed in the last decade which do not exhibit this intrinsic limit if cooled to T < 20K, opening up the possibility that the coil's maximum field is limited only by the stress in the structural material ($\propto B^2$). Perhaps equally important as access to higher B, the tape form of the SC also opens the possibility of designing SC coils that can be taken apart, i.e. demountable tape-to-tape conducting joints are engineered with low total resistance such that the cooling required for the coils remains negligible in the reactor power balance.

High field, demountable SC coils would be transformative to tokamak design, maintenance/ repair and blanket design. This is illustrated by a recent reactor conceptual design based on the use of this new HTSC technology (see figure). Analysis showed that peak field on coil ~21 T was within the SC and structural limits, providing on-axis 9.2 T for a small size (R~3.3 m, R/a=3) high gain/power density (Q=30, P/A~0.7 MW m^{-2}) reactor. The design features robust, already demonstrated physics parameter ($\beta_N \sim 2.3$ below the intrinsic limit, safety factor q_{95}~6 well away from kink limit), enabled by the ~doubling of $B_{coil,max}$. However the design also indicated important *synergistic* wins between high field, small R and demountable coils.



The main components of a proposed fusion power plant are shown. Using novel technologies, a modular design is possible which eases construction and maintenance.

- Small size + demountability allows the vacuum vessel (VV) "core" to be a single modular component, constructed off-site, and inserted as a single unit because its small volume allows for single unit lift.
- Thus allowing for a simplified high-temperature liquid blanket (molten salt in this design) surrounding the core, removing all solid components from the breeding blanket design.
- Thus solid material damage is then limited to only the core ~cm thick VV and plasma-facing components…there are no dpa limits in liquids!
- Thus decreasing the solid waste by x25-50 compared to ~0.5 m solid blanket.
- Aspect ratio is not set by sector maintenance but rather tradeoffs in core, current drive and coil shielding (appendix). An aspect ratio of ~3 was found to provide the best core performance per unit surface area, access to non-inductive scenarios while providing long lifetimes for the SC coils.
- High field improves RF accessibility, and its small size limits volume average temperature to ~10 keV. Thus lower hybrid RF provides extremely efficient and robust mid-radius current drive; ~ 20-25% of total current, factors of three more external current control than in standard designs
- Higher relative control of the current profile and operating away from intrinsic limits, provides for a highly robust steady-state scenario with low recirculating power → Fusion power ~500 MW, net electric power ~ 200 MW (for this particular design).
- The core is the only replaceable component and is relatively small-size and modular leading to the possibility that the device can be its own Fusion Nuclear Science Facility.

Recommendation

I would not claim we have made a definitive reactor design, nor have we ensured the engineering of the new coils could be achieved. Rather we have demonstrated that demountable, high-field SC coils would be transformative to magnet fusion's development and should be heartily pursued. We are a community dominated by plasma physicists. But for fusion's development it seems to make a lot of sense to start moving the risks from exotic core plasma physics (high β_N, disruptions) to the engineering of high-field, demountable magnets enabled by these new SC. The gains of such advancement appear profound towards core robustness, steady-state, fusion material development, and maintenance. Most importantly they lead to a smaller, sooner, simpler fusion development path.

References

[1] Compilation of reactor designs found in fire.pppl.gov/sofe03_meade_poster.pdf

[2] Compilation of ARIES design studies at aries.ucsd.edu

Appendix

We derive core performance dependencies (note that constants are liberally dropped throughout). The volumetric fusion power density (e.g. MW m^{-3}) in the range of T~5-25 keV is given by

$$p_{fusion} = \frac{n^2}{4} R(T)_{DT}\, kQ_{DT} \sim n^2 T^2 \sim p_{th}^2 , \qquad [1]$$

where R is the DT rate coefficient, (which varies as T^2 from T~5-25 keV), n is density, T is temperature and p_{th} is the thermal fusion pressure. The normalized plasma pressure is expressed through beta to relate it to the magnetic field static pressure with

$$\beta \equiv \frac{2\mu_o\, p_{th}}{B^2} \;,\; \beta_N \equiv \beta\left(\frac{\epsilon RB}{I}\right) \qquad [2]$$

where $\epsilon \equiv a/R$ is the inverse aspect ratio, I is the plasma current and β_N is the "normalized" beta that actually expresses the intrinsic pressure limit of the plasma, with its typical limit being $\beta_N \leq 2.5-3$ (This is the so-called "no-wall" limit since exceeding it requires close conducting shell wall stabilitzation and/or active feedback to control MHD. While these conditions have been demonstrated in tokamaks the plasmas are less robust, i.e. prone to disruptions). The other most important operational core limit is the kink limit dictated by the safety factor which for a shaped plasma (κ is elongation) is

$$q \sim 5\frac{BR}{I}\epsilon^2\left(1+\kappa^2\right) \qquad [3]$$

which must stay above ~2 to avoid a hard kink-limit disruption. As its name implies, raising the safety factor q contributes greatly to the robustness of the plasma (but the design tradeoff is that the plasma current is needed for confinement),

It is convenient to recast thermal pressure in terms of normalized beta, the kink safety factor and B field

$$p_{th} \sim \beta B^2 \sim \frac{\beta_N \epsilon\left(1+\kappa^2\right)}{q} \qquad [4]$$

The volumetric and areal power density are then respectively given by

$$p_{fusion} \sim \frac{\beta_N^2 \epsilon^2 (1+\kappa^2)^2}{q^2} B^4 \quad \text{and} \quad \frac{P_f}{A_{blanket}} \sim \frac{p_{th}^2 V}{A} \sim \frac{\beta_N^2 \epsilon^3 (1+\kappa^2)^2}{q^2} RB^4 \qquad [5]$$

Between T~10-20 keV the Lawson ignition criterion is well approximated (within 10%) that the product of thermal pressure and energy confinement time, τ_E , is $p_{th}\tau_E \geq 1\, MPa \cdot s$. A generic energy confinement scaling law is

$$\tau_E \sim \frac{H\ I\ R^{3/2}}{P} \sim \frac{H\ \epsilon^2 B\ R^{5/2}}{q\ P} \quad [6]$$

where H is the confinement quality factor and P is total heating power (MW). Near ignition the heating power is the alpha power and therefore just 1/5 of the fusion power so P~P_f. At *fixed* total fusion power P_f we combine [4] and [6] to express the ignition condition

$$p_{th}\tau_E \sim \frac{\beta_N \epsilon\left(1+\kappa^2\right)}{q} B^2 \left[\frac{H\ \epsilon^2 B\ R^{5/2}}{q}\right] \sim \frac{\beta_N H \epsilon^2\left(1+\kappa^2\right)}{q^2} R^{5/2} B^3 \quad [7]$$

Which we can further simplify by noting that for economic reasons power density is effectively a constant for reactor designs $P_f / A \sim 4-5\ MW\ m^{-2}$ (actually pinned by the plasma heat exhaust limits, please refer to the white paper of Lipschultz and Whyte on boundary plasma challenges) so that for fixed total fusion power (as for [7]) then $A \sim R^2\epsilon$ is effectively a constant and therefore

$$\frac{\beta_N H \epsilon\left(1+\kappa^2\right)}{q^2} R^{1/2} B^3 \geq C_{ignition} \quad [8]$$

where $C_{ignition}$ is the numerical constant to satisfy Lawson/ignition. At fixed shaping (ϵ, κ) the criteria listed in the main text are recovered from [5] and [8] respectively giving

$$\frac{P_f}{A_{blanket}} \sim \left(\frac{\beta_N^2}{q^2}\right) R\ B^4 \quad , \quad \left(\frac{\beta_N H}{q^2}\right) R^{1/2} B^3 \geq C_{Ignition} \quad [9]$$

It is clear from [5] and [8] that increasing inverse aspect ratio and elongation can improve fusion performance. This is balanced by considering that the limitation (SC or structural) on the plasma B is set by the maximum field allowed on coil ($B_{coil,max}$), and so is also set by geometry due to the 1/R dependence on B

$$B = B_{coil,\max}(1-\epsilon) \quad \text{or} \quad B = B_{coil,\max}(1-\epsilon-\frac{\Delta_b}{R}) \quad [10]$$

including the required inner blanket width, Δ_b ~ 1 m for shielding of the SC coils. This leads to simple but illustrative relationships from [5] and [8]

$$p_{fusion} \sim \frac{\beta_N^2}{q^2} B_{coil,\max}^4 \left\{\epsilon^2 (1-\epsilon-\frac{\Delta_b}{R})^4 (1+\kappa^2)^2\right\}$$

$$\frac{P_f}{A_{blanket}} \sim \frac{\beta_N^2}{q^2} R B^4 \left\{\epsilon^3 \left(1-\epsilon-\frac{\Delta_b}{R}\right)^4 (1+\kappa^2)^2\right\}$$

$$\frac{\beta_N H}{q^2} R^{1/2} B^3 \left\{\epsilon \left(1-\epsilon-\frac{\Delta_b}{R}\right)^3 \left(1+\kappa^2\right)\right\} \geq C_{ignition}$$

where the curl brackets contain purely geometric factors. For small size (R < 4 m) and allowed elongation due to vertical stability ($\kappa \sim 5\epsilon$) one finds these terms are maximized for $\epsilon \sim 0.3-0.4$. While this simple example cannot capture the complexities of geometric optimization nonetheless it indicates that it is desirable to have geometry choices which are not primarily dictated by sector maintenance (which typically pushes $\epsilon \sim 0.25$ for ARIES SC designs) but rather by balances in the core performance and vertical stability.