Smaller & Sooner – Exploiting high magnetic fields from new superconductors for a more attractive fusion energy development path

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Abstract. The recent industrial maturation of high-temperature, high-field superconductors opens up a faster and cheaper development path for fusion energy by enabling reactor-level performance at smaller scale. The current fusion energy development path, based on large volume moderate magnetic B field devices is proving to be slow and expensive. A development effort is underway on new superconductor magnet technology development, and accompanying plasma physics research at high-B, that will open up a viable and attractive path for fusion energy development. This path would feature smaller volume, fusion capable devices that could be built more quickly than low-to-moderate field designs based on conventional superconductors. This strategy would also permit the testing of multiple confinement configurations while distributing technical and scientific risk among smaller devices.

1. **Introduction**

Scale is a significant hindrance to the development of magnetic fusion energy (MFE). Scale refers to the physical size, cost and/or thermal power of the individual D-T devices required to confront the acknowledged and integrated, problems of economic fusion reactors: suitable materials, continuous availability, and large net fusion energy gain. The combination of large scale, moderate B, and known tokamak physics leads to the assumption of large risk in single projects. This situation, dictated largely by B field limits, is extremely unfavorable for the development steps required for fusion. Indeed, the present fusion energy development path, based on large volume moderate magnetic B field devices is proving to be slow and expensive with many projections moving fusion energy well past 2050; a timescale which seems unacceptable in light of the need for massive deployment of carbon-free energy and electricity.

It seems timely to evaluate a newly available high-B fusion development path that would feature smaller volume, fusion capable devices that could be built more quickly than low-to-moderate field designs based on conventional superconductors. The strategy is self-evident: fusion's worldwide development could be accelerated by using several small, flexible devices rather than relying solely on a single, very large device. These would be used to obtain the acknowledged science and technology knowledge necessary for fusion energy beyond achievement of high fusion plasma gain. Such a scenario would also permit the testing of multiple confinement configurations while distributing technical and scientific risk among smaller devices and fusion funding countries. Higher field and small size also allows operation away from well-known operational limits for plasma pressure, density and current. The advantages of this path have been long recognized – earlier U.S. plans for burning plasma experiments (e.g. Burning Plasma Experiment (BPX) [1], Fusion Ignition Research Experiment (FIRE) [2]) featured compact high-field designs, but these were necessarily pulsed due to the use of copper coils. There have also been substantial international efforts using high magnetic field with a prime example being the IGNITOR [3] program. While these approaches are recognized as scientifically valid, the use of copper coils provides significant technical challenges (cooling, electricity use, pulsed power, etc.) and has an image problem of appearing to access fusion conditions with a technology (copper) that is irrelevant for fusion power plants.

2. **A new high-field strategy for magnetic fusion**

The recent industrial maturity of high-temperature, high-field superconductor tapes underpins this new approach; these tapes offer a truly “game changing” opportunity for magnetic fusion when developed into large-scale coils (Fig. 1). The most important feature of the REBCO (Rare-Earth Barium Copper Oxide) superconductors is that they have almost no degradation of their critical current versus magnetic field. This feature opens up a design space of peak field on coil ~23 T that was previously inaccessible with Nb_3Sn superconductor. The limitation on B field is almost solely due to the allowed stress in the coil, but that limitation can be overcome with effective coil engineering. For example, small-bore REBCO coils have already achieved >26 T peak field by exploiting the high tensile strength of REBCO tape and using standard cryogenic steel for structure [4]. This new technology appears to be poised to fundamentally change the manner in which we design superconducting coils for magnetic fusion.

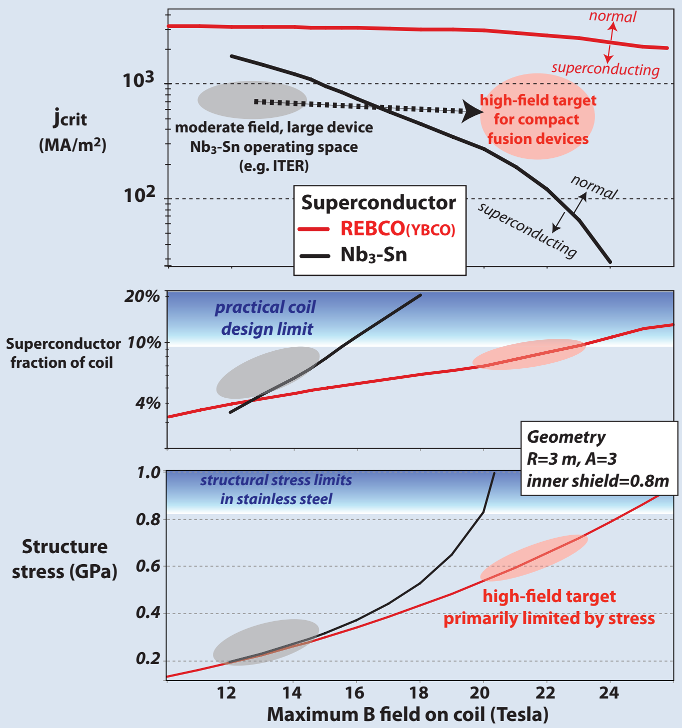


Fig. 1. Comparison of Nb_3Sn and REBCO superconductors vs peak B field at 4 K. (Top) Critical current density (Middle) Required sudperconductor fraction in coil to achieve B field for given geometry assumptions (Bottom) Peak stress in structural material (i.e. non-superconductor) of coil. Shaded regions indicate practical limits to coil design REBCO critical currents obtained from http://fs.magnet.fus.edu/~lee/plot/plt.htm

In addition to high B field, the superconductor tape form and higher operating temperatures also open up the possibility of demountable superconducting magnets in a fusion system, providing a modularity that vastly improves simplicity in the construction, maintenance, and upgrade of the coils and the internal nuclear engineering components required for fusion’s development. A specific example of this approach is the ARC (Affordable Robust Compact) pilot conceptual design [5] – a JET-sized device with B=9.2 tesla at plasma to produce 500 MW of fusion power and ~200 MW net electricity by combining demountable coils and a novel liquid immersion blanket (Fig. 2). The design of ARC highlights several generic strategic advantages of the high-field approach enabled by the new REBCO technology: high power density necessary for economic fusion and robust core scenarios from operational limits.

3. **Scale and magnetic field in the challenge of fusion development**

Large scale is a risk to fusion devices and MFE development, but this risk can be strongly reduced by high magnetic field. The construction of ITER, with its ~1000 m^3 core, has raised our awareness to the risks in cost and schedule of such a large device. The present estimate provided by the US Secretary of Energy [6] is that ITER construction and commissioning achieve burning plasma ca. 2035, ~30 years after the start of the project. ITER will cost the U.S. at least 4 billion dollars as a 9% partner. While the science mission and motivation for ITER to achieve the burning plasma state continues to be strong, it is simply larger than any other fusion device constructed by about a factor of ten in mass and volume.

The design challenge for tokamaks is to produce steady-state/equilibrated fusion power and neutrons in a reasonable size device. The design challenge can be summarized by consideration of the governing 0-D equations for tokamaks. The fusion power (P_{fusion}) over the wall/blanket surface area, S, at fixed tokamak aspect ratio and shaping is given by

$$\frac{P_{fusion}}{S} \sim \frac{\beta_N^{\ 2}}{q^2} R\, B^4 \qquad (1)$$

Sufficient power density is an obvious requirement for both economic fusion power plants and for a fusion nuclear science facility. By fixing the power density, the other basic requirement of fusion power gain is set by the triple product and can be described by

$$nT\tau_E \sim \frac{\beta_N H_{89}}{q} R^{1.3}\, B^3 \qquad (2)$$

With fixed dimensionless plasma parameters (normalized beta, confinement and safety factor) Eqs. 1-2 illustrate a design choice between high magnetic field B and linear size R. Both these parameters have limits: R must be of sufficient size to accommodate a neutron blanket/shield of ~1 m depth, while B is limited by either the stresses in the toroidal field coils (~B^2) or the intrinsic B limit of the superconductor. In the case of ITER, B is primarily limited by its Nb_3Sn superconducting limit (Fig. 1) and a peak field on coil ~11-12 T which was the maximum achievable with that technology in the mid-1990's at the time of ITER's design [7]. In considering burning plasmas the other critical parameter is the empirical Greenwald density limit; the fusion power is effectively set by the tokamak's operating density because the temperature is fixed by the minimum in the Lawson criterion [8].

$$\frac{P_f}{V} \sim n^2 \le n_{Gr}^2 \sim \left(\frac{B}{q\,R}\right)^2 \qquad (3)$$

Thus to meet ITER's fusion power/gain mission, the major radius was required by the tokamak performance rules to be large: R=6.2 m (ITER, Q=10, P_f=500 MW) or R=8 m (ITER-EDA, ignited, P_f=1000 MW). Importantly ITER must operate at the density limit due to its maximum B value and its large R. This is the direct consequence of the density limit being highly punitive to large R tokamaks (Eq 3); designs which go to larger R than ITER face the combined risk of having poor power density, low safety factor and operating above a disruptive density limit (e.g. ITER-EDA was designed to operate 30% above the density limit).

Thus ITER represents the world fusion community's best attempt at achieving fusion energy gain at the smallest size possible with Nb_3Sn superconductors within known plasma performance and just below the density limit. Yet an under-appreciated risk in ITER has been its large size: scaling R by a factor of 2 from previous DT devices (JET, TFTR) entailed an increase in volume and cost by about an order-of-magnitude. Subsequently ITER requires both large-scale international resource pooling and fusion engineering/components at a scale never attempted before. While not the sole cause, these two factors must certainly be significant contributing to the ~30 year timescale between the start of the ITER project and its first burning plasma. Tellingly, this ~30 year time is also a large step in the construction times compared to the JET and TFTR, which were completed in ~5 years. So while the delays in ITER are disappointing, the fusion community would be remiss in not learning its lesson regarding the risk of developing fusion energy in large scale devices; with perhaps the biggest risk being the fact being that the world has a single project in pursuit of fusion energy gain based on magnetic confinement.

4. **A high field, compact strategy for magnetic fusion development**

An examination of Eqs 1-3 provide an obvious strategy of exploiting high magnetic fields to reduce the risk of large scale and/or plasma physics limits, as we develop the scientific and technical basis for fusion. This is not a new insight of course, and was the basis for the design of many high-field, copper-coil, burning plasmas. The recent development of REBCO superconductors, and their successful deployment in small coils at $B > 25$ T, provides a new opportunity to explore and optimize the high-field approach. One such example has been the ARC (Affordable Robust Compact) conceptual design [5] which we use here to illustrate the attractive design features for an aspect ratio ~ 3 tokamak using REBCO (other groups such as Tokamak Energy and PPPL are exploring the REBCO's use in lower aspect ratio tokamaks with similar conclusions).

The ARC design study primarily focused on evaluation of the engineering limits of using REBCO for large-bore coils. Generally the two biggest challenges to the high-field compact approach are stress limits in coils and the space requirements for neutron moderation and shielding. Results from numerical analysis were similar to that shown in Fig. 1, namely a peak field on coil of ~23 T was achievable within the stress limit of the structural steel of the coil, with a factor of two margin to the critical current limit of the REBCO [5]. In addition, neutron transport simulations were used to show that adequate shielding of the coils could be obtained with an inner shield/blanket build of ~0.7 m using a FLiBE liquid blanket and specialized inboard shielding materials. These engineering limits provided a 9.2 T on axis B-

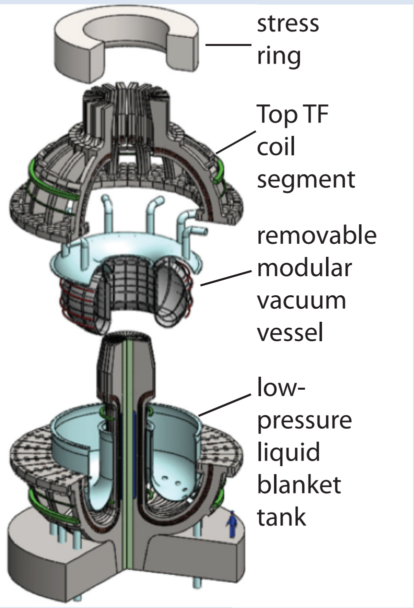
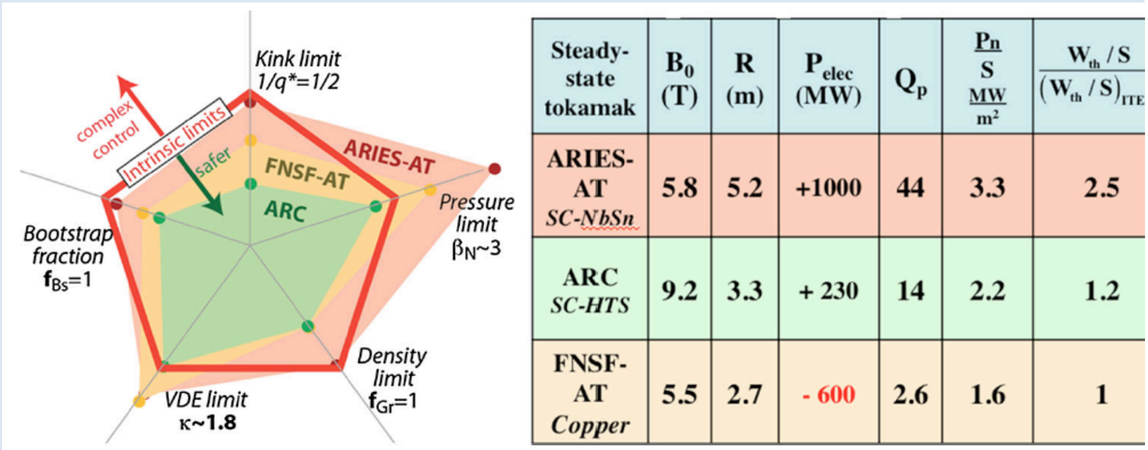


Fig. 2 ARC is a JET-sized fusion pilot with demounted TF coils allows for modular replacement of internal components and an immersion liquid blanket [5]

field in ARC with R~3.2 m.



Steady-state tokamak	B_0 (T)	R (m)	P_{elec} (MW)	Q_p	$\frac{P_n}{S}$ $\frac{MW}{m^2}$	$\frac{W_{th}/S}{(W_{th}/S)_{ITE}}$
ARIES-AT *SC-NbSn*	5.8	5.2	+1000	44	3.3	2.5
ARC *SC-HTS*	9.2	3.3	+ 230	14	2.2	1.2
FNSF-AT *Copper*	5.5	2.7	- 600	2.6	1.6	1

Fig. 3. (Left) Operating points and intrinsic limits presented on a polar plot for steady-state US burning plasma designs ARIES-AT [11], FNSF-AT [12] and ARC [5]. (Right) Engineering parameters of designs including net electricity production (+) or consumption (-).

Insights gained about the advantages the high-field approach epitomized by ARC are as follows:

1. *Performance vs. Cost/Scale*: The B^3 - B^4 dependence for fusion performance (Eqs. 1-2) requirements allows *both* high energy gain and power density in much smaller devices, i.e. with ARC ~ 10 times smaller than ITER in volume, while producing fusion energy at the same level of 500 MW. The small scale of ARC, essentially that of JET, also bodes well for more rapid construction and deployment based on historic precedent.

2. *Operational Robustness*: Just as importance as cost, high-field compact tokamaks can operate far from all intrinsic disruptive kink, pressure, density, and shaping limits, and use normalized plasma regimes (β_N, H, q) already integrally demonstrated in present devices. This stands in stark contrast to high power density, moderate B, large size tokamak reactor designs which are forced to operate close to, or in excess of, known operational limits as illustrated for the ARC design by Fig. 3. All burning plasmas feature high plasma energy density, so the ability to avoid damaging disruptions and transients by operating far from limits is highly advantageous, if not necessary.

3. *Tokamak Steady-State Physics*: High-gain, robust steady-state, featuring significant external control of the current, can arise from small size and high-B. This approach combines moderate bootstrap current fractions (~60%) by exploiting a high safety factor and moderate β_N operational point simultaneously compatible with avoiding disruptive limits. This high-B, high safety factor approach is accompanied by improvements in external current drive efficiency at high-B using through accessibility gains with Lower Hybrid current drive, and by decreasing the plasma's volume to surface ratio at small R.

4. *Heat Exhaust* While the high volumetric power density of high-B compact devices is attractive (or necessary in power plants) this also brings into question the power exhaust limits with this strategy. However the recently discovered upstream heat flux scaling $q_{//} \sim P_{heat} B / R$ is punitive to large scale devices. Fusion devices are designed to a specific neutron power loading of the blanket, i.e. $P_n / S \sim P_{heat} / R^2$ is a fixed requirement.

Combining these requirements reveal $q_{//} \sim R\left(1+5/Q_p\right)B$ providing the insight that smaller R is *desirable* for limiting upstream heat flux density at fixed B; while large R and small Q<5 are clearly unfavorable. At fixed gain Q_p, the use of scaling laws (Eq. 2) provides another constraint on the relationship between size and scale, namely $R \sim 1/B^{2.5}$. Combining this constraint into the upstream heat flux relations reveals $q_{//} \sim B^{-1.5}$, i.e. that the high-field approach in fact decreases parallel heat flux. This somewhat counter-intuitive result simply arises from the fact that heat width does not scale explicitly with size but rather with magnetic field; so building large R devices is punitive when trying to achieve a target power loading and energy gain. The advantage of compact high-field is even more substantial than this, because high density operations are possible (Eq. 3) and this is a well-established route to providing dissipative boundary and divertor plasmas.

5. **Magnet engineering challenges and opportunities with REBCO**

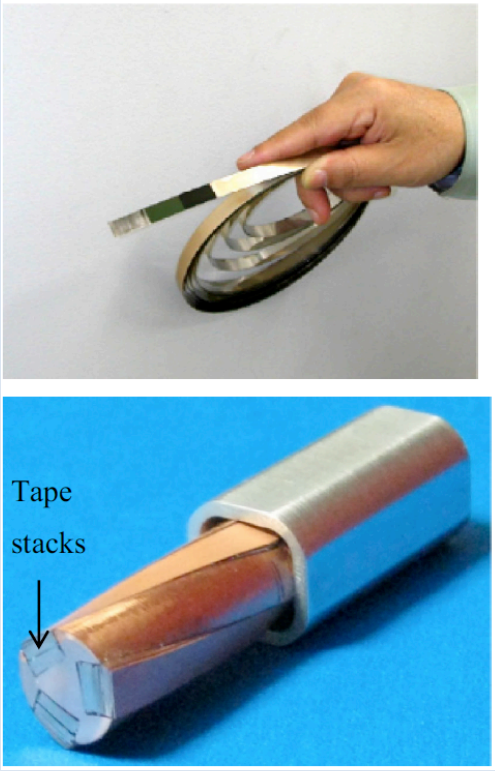


Fig. 4. (Top) REBCO superconductors are made in long lengths as thin, flat tapes. Primarily composed of stainless steel, the tapes have high mechanical strength and thermal robustness (Bottom) Example of conductor produced with REBCO tape stack, with copper stabilizer and SS jacket. This example is Twisted Stack Tape Conductor [13]

REBCO is a material of enormous promise for high temperature and high field applications ready for exploitation. *This is a revolutionary material with the potential for raising field, current density, and operating temperature simultaneously, while lowering refrigeration requirements.* Achievement of these goals would offer a realistic vision for making an economical future commercial fusion reactor. REBCO has already been used for demonstration at fields > 30 T in small bore solenoid geometries. Such conductors do not yet have either the strength or the low AC loss requirements of present fusion conductors such as Nb_3Sn or NbTi but are showing significant progress in development. REBCO has little to no degradation of critical current density, j_{crit}, at B_{coil} > 20 Tesla, in contrast to Nb_3Sn, which has an exponential decrease in j_{crit} vs. B (Fig. 1). This feature allows a smaller quantity of REBCO to be used in SC coils to access higher peak field on coil, i.e. the conductor remains in the superconducting state at very high B field because in a coil the $B_{coil} \sim j$. The strong decrease in j_{crit} in Nb_3Sn n limits ITER to $B_{coil} \sim 11$ T at the inner high-field side leg of the toroidal field coil, resulting in a maximum B field on axis ~ 5.3 T. REBCO SC can double the field to $B_{coil} \sim 22$-23T, $B_0 \sim 9$-10 T, simply because at this field the REBCO has ~100 times the j_{crit} of Nb_3Sn. Simply stated, REBCO superconductors present a quantum leap in SC performance at high B.

In addition to their outstanding properties at high B field, REBCO SC are produced in the form of extremely strong, flexible, thin, flat tapes (Fig. 4) which allows for joints and demountability, i.e. the ability to take the SC coil apart and put back together. REBCO joints have been tested at small scales and have been studied conceptually for implementation in the Vulcan design [9]. More recently work has indicated several viable pathways to the engineering design of the demountable joints [10]. This work used both small scale experiments and modeling to show that the resistance in the joints between SC tapes is sufficiently small when operated at ~20 K, that power consumption is reasonable (e.g, in ARC the joints consume < 1 MW of electricity). Most importantly, demountable TF coils provide ready access to the interior components of the tokamak (Fig. 2). Vertical removal and replacement of the interior components, such as used in Alcator C-Mod is an enormous advantage to assembly and installation over sector maintenance. The ARC study exploited those advantages to provide innovative solutions to heat exhaust and blanket design [5]. Thus new REBCO magnets will touch on most aspects of fusion device design. This should not be surprising for *magnetic* fusion.

6. **References**

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