Smaller & Sooner: Exploiting High Magnetic Fields from New Superconductors for a More Attractive Fusion Energy Development Path

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ORIGINAL RESEARCH

Smaller & Sooner: Exploiting High Magnetic Fields from New Superconductors for a More Attractive Fusion Energy Development Path

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Abstract The current fusion energy development path, based on large volume moderate magnetic B field devices is proving to be slow and expensive. A modest development effort in exploiting new superconductor magnet technology development, and accompanying plasma physics research at high-B, could 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. 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 gain. Such a scenario would also permit the testing of multiple confinement configurations while distributing technical and scientific risk among smaller devices. 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 US plans for burning plasma experiments (compact ignition tokamak, burning plasma experiment, fusion ignition research experiment) featured compact high-field designs, but these were necessarily pulsed due to the use of copper coils. Underpinning this new approach is the recent industrial maturity of high-temperature, high-field superconductor tapes that would offer a truly "game changing" opportunity for magnetic fusion when developed into large-scale coils. 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. Our conclusion is that while tradeoffs exist in design choices, for example coil, cost and stress limits versus size, the *potential* physics and technology advantages of high-field superconductors are attractive and they should be vigorously pursued for magnetic fusion's development.

Keywords Magnetic fusion · Magnets · High temperature superconductors · Tokamak

Background

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.

A new generation of superconducting (SC) tapes puts within reach loss-free conductors with peak magnetic field on coil B >20 Tesla, nearly double those allowed by "standard" Nb_3Sn superconductors such as used in ITER.

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Access to new superconductor technology, to approximately double their present B limits, would thus be a "game-changer" for fusion reactor design and fusion *development*. While the use of new SC tapes would be generically attractive for magnetic fusion, it is particularly acute for tokamaks, the present leading concept for achieving burning plasmas and high gain:

1. *Performance versus Cost/Scale* The B^3–B^4 dependence for fusion performance requirements allows *both* high energy gain and power density in much smaller devices, i.e. on the order of 10 times smaller than ITER in volume, while producing fusion energy at the 100's of MW level. All of these features are highly attractive for the *development* of fusion energy and may also be crucial for its eventual commercial realization.
2. *Operational Robustness* Just as critically, 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.
3. *Tokamak Steady-State Physics* High-gain, more robust steady-state, featuring significant external control of the current, can arise from small size and high-B. This approach combines bootstrap current from high safety factor and moderate β_N plus the associated improvements in external current drive efficiency at high-B. In particular this exploits radio-frequency current drive techniques that thrive at high-B field and reactor core plasma conditions. Accompanying steady-state physics research issues are identified as being plasma power exhaust, divertor physics and radio-frequency (RF) current drive at high-B field.

The superconductors, in the form of thin, flat tapes, also enable demountable toroidal field coils. A strong synergy exists between the high-B, smaller size, and demountable coils, allowing for simplified and improved fusion engineering choices: e.g. immersion liquid blankets, single-phase high temperature cooling, and a modular vacuum vessel, which becomes the only replacement item in the reactor, greatly reducing solid waste. These concepts are combined in an example Fusion Nuclear Science Facility FNSF/Pilot design called Affordable, Reliable, Compact (ARC) [1] to produce a high net energy gain fusion system with margin to operating limits, greatly reduced materials concerns, and improved maintainability.

Advantages of High Magnetic Field for Fusion Development

Any convincing strategic plan will evolve based on critical knowledge recently gained; magnetic fusion is no different. Indeed, the past decade following the launch of the ITER project has provided new insights into the MFE development challenges.

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 $\sim$1000 m^3 core, has raised our awareness to the risks in cost and schedule of such a large device. The present estimate [2] is that ITER construction and commissioning will require $\sim$30 years to achieve burning plasmas. ITER will cost the US 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. While the delays and high cost of ITER are disappointing, we would be remiss to not learn the lessons gained by the exercise of trying to build and operate an experimental fusion device at ITER scale. Indeed, a recent strategy along these lines has been to consider a FNSF [3, 4] that provides integrated nuclear testing of components but at a much smaller size than ITER in order for its cost and schedule to be reasonable for the US to build. The design challenge is obviously to produce steady-state fusion power and neutrons in a small size facility. The design challenge can be summarized by considering the governing equations (e.g. [5]) for tokamak fusion. The fusion power P_{fusion} (and neutron) loading over the wall/blanket surface area S at fixed tokamak aspect ratio and shape is given by

$$\frac{P_{fusion}}{S_{wall}} \sim \frac{\beta_N^2}{q_*^2} R B^4 \quad (1)$$

while the thermal fusion power gain via the triple-product can be described by

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

at fixed P_{fusion}/S. The RHS of these equations are organized into dimensionless plasma physics parameters (blue font), linear size R (black) and on-axis magnetic field B (red).

These relationships indicate that in order to reduce size compared to ITER ($R_{ITER} = 6.2$ m, volume $\sim 10^3$ $m^3 \propto R^3$) the design must either increase the normalized plasma physics parameter or the magnetic field. However there is a sharp difference between these two choices. In particular decreasing *safety factor*, q_*, or increasing β_N inherently place the tokamak plasma at a higher risk of disruption and other limiting magnetohydrodynamics (MHD) events, for example edge localize modes (ELMs). Simultaneously, the damage to surrounding material surfaces from such transient events becomes nearly intolerable because such devices *must* have high absolute pressure (plasma energy density) in order to attain the required fusion power density. This is well known by ITER's concerns for disruption and ELM damage. An FNSF, Pilot plant or reactor will have to deal with the same issues. The better choice, if available, is clearly to increase B, the magnetic field strength, because this keeps the tokamak away from physics operating limits while strongly reducing the device's size through the B^3–B^4 dependencies in Eqs. 1–2. This is not a new result: for example, two previous US designs (Burning Plasma Experiment (BPX) [6] and Fusion Ignition Research Experiment (FIRE) [7]) used B $\sim$10 T, approximately double ITER's B field, to achieve a burning plasma at R < 3 m and thus 1/10th the plasma volume of ITER (Fig. 1). However the magnet technology available at the time of those designs forced a decision between long-pulse, large-volume, B $\sim$ 5 T and short-pulse, small volume, copper B $\sim$ 10 T devices. The advent of new superconductor technology allows, for the first time, the possibility to have both: steady-state and small-volume high B field ($\sim$10 T on axis). This is exemplified by the recent ARC design [1] shown in Fig. 1 with parameters compared to FIRE [7].

Boundary Physics and Discharge Sustainment Issues May Be Alleviated at High Field and Small Size

Boundary physics understanding has considerably evolved in the past decade, providing better constraints in dealing with several critical issues

(a) The heat exhaust problem and the associated plasma-material interaction (PMI) issues are even more challenging than previously believed for ITER/FNSF/reactor devices. It is now known that the upstream heat exhaust width organizes inversely to poloidal field [8] and the divertor plasma pressure is limited by B-field pressure [9]. In general these organizations with B compel exploration of the boundary and PMI physics in high-B toroidal devices that match reactor B in order to best access the appropriate range of divertor plasma physics regimes.

(b) The lack of intrinsic size scaling in the upstream heat flux $q_{//}$ is punitive to large scale devices at low plasma energy gain Q_p. As shown in [10] the scaling is $q_{//} \sim P_{heat}B/R$ where P_{heat} is total plasma heating power (alpha + external). Fusion devices for an FNSF [3, 4] or energy mission [11] are always designed to a specific neutron power loading of the blanket, i.e. $P_n/S \sim P_n/R^2$ is a requirement. Therefore the heat flux can be recast as $q_{//} \sim R(1 + 5/Q_p)B$. This relationship provides the somewhat counter intuitive 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. Finally one can use the triple product (Eq. 2 derived at fixed P/S) with fixed plasma physics parameters to estimate R $\sim$ $1/B^{2.3}$, i.e. higher B enables smaller size to achieve the required gain, resulting in $q_{//} \sim B^{-1.3}$. This generically indicates the attractiveness and complementarity of small-size and high-B, although it should be cautioned that the relation between R and B is made more complicated by the sizing requirements of the $\sim$1 m thick blanket. It is noted that heat exhaust is more problematic for envisioned reactors that have high total power output due to economy of scale costing arguments for the cost of electricity. This optimization will likely need to be re-examined in light of better physics understanding of the SOL. In the nearer term, developing fusion "pilots", i.e. devices which don't consider economies of scale, then the small, high-B approach is favored for heat exhaust.

(c) Transient heating of plasma-facing surfaces from instabilities like disruptions and large ELMs is intolerable in ITER, FNSF and reactors. Such damage also reduces the quiescent heat removal capacity of the surfaces. This requires that burning plasma tokamak scenarios be far from operational and disruptive limits, which can only be accomplished in tokamaks by using high B field.

(d) RF launcher structures used for current drive in FNSF face an extremely hostile environment and present concepts are unlikely to survive. A novel approach to solving the launcher PMI issues is to

	FIRE	ARC
R (m)	2.14	3.2
B_o (T)	10	9.2
Q_p	>10	>10
Steady-state	No	Yes
Tritium breeding	No	Yes
$Q_{electric}$	0	~4

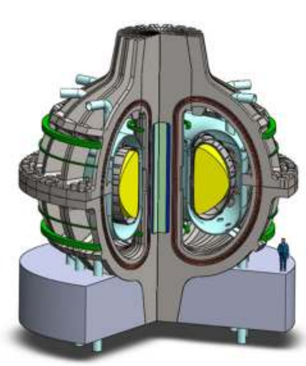


Fig. 1 (*Left*) Main parameters for the FIRE [7] and ARC high-field burning plasma designs (*right*) cutaway of ARC [1]

place them adjacent to the quiescent SOL plasma on the high-field side HFS [1, 12] at small major radius. Testing this solution, critical to sustaining steady-state plasmas with RF current drive, requires a facility with built-in access to the HFS and high local B field to match the appropriate local RF physics conditions [10].

Proposed Initiatives

Three national initiatives centered around new REBCO (Rare Earth Barium Copper Oxide) high-temperature superconductors (HTS) high B-field technology and high-B boundary/RF physics [Advanced Divertor Experiment (ADX)] are proposed. These initiatives address a wide range of critical gaps as identified by the Fusion Energy Sciences Advisory Committee (FESAC) 2007 Greenwald report [13] as shown graphically in Fig. 2.

The REBCO-HTS magnet initiative seeks to produce reliable, economic high-B magnets for FNSF/Pilot/reactors based on newly available commercial technology. Simultaneously the second initiative addresses integrated fusion materials testing by developing demountable superconducting coils vital to nuclear component replacement in an FNSF, Pilot and reactor. In parallel, physics issues dealing with boundary heat exhaust, PMI and RF launchers and integrated high-field scenarios are addressed with the ADX initiative which, unique among present world experiments, provides high-fidelity experimental matching of the expected absolute range of boundary plasma conditions in an FNSF/reactor [10]. A summary of the initiative's timeline, cost, and research goals is shown in Fig. 3. For a relatively modest investment, the US can be prepared to answer critical design questions on an attractive, realistic superconducting FNSF/Pilot design in 10 years. The third issue would be detailed system studies and concept development for a high-field FNSF or Pilot Plant. Such a device would bridge the gap to a pre-commercial demonstration power plant.

Advancing Fusion Magnet Technology

Magnet systems are the ultimate enabling technology for magnetic confinement fusion devices. Powerful magnets are required for plasma confinement, and, depending on the magnetic configuration, DC and/or pulsed magnetic fields are required for plasma initiation, Ohmic heating, inductive current drive, plasma shaping, equilibrium, and stability control. Almost all design concepts for power producing commercial fusion reactors rely on superconducting magnets for efficient and reliable production of these magnetic fields.

Background on Fusion Magnets

Although the majority of past and present magnetic fusion experimental devices use normal resistive magnets, design concepts for commercial fusion reactors generally rely on superconducting magnets for efficient and reliable operations. The overall electrical power requirement for large superconducting magnets, including refrigerators to maintain the cryogenic temperatures, is extremely small compared with power dissipation of comparably sized resistive magnets. The electrical power difference between superconducting and resistive magnets increases with increasing magnetic fields and magnet size, or where long pulse

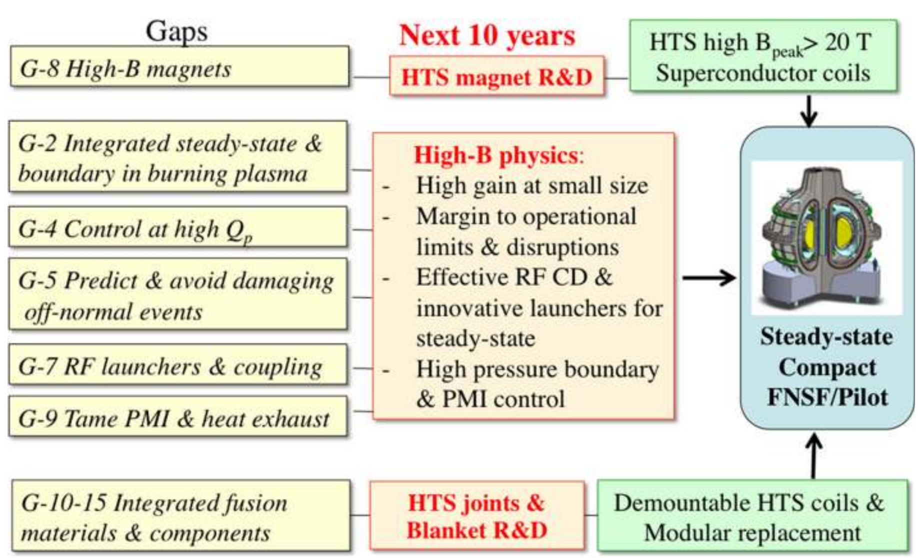


Fig. 2 Summary of gaps from FESAC 2007 [13], proposed research initiatives over the next 10 years towards an attractive steady-state compact superconducting FNSF or Pilot that can produce net electricity

Foundations	Year 1-3	Year 4-7	Year 8-10	FNSF options
Transport		H_{98} OK, no X-point MARFE		Disruptivity vs. performance assessment
Stability			ELM-free stationary ped.	
Wave-particle	Design HFS launch: LHCD & ICRF	Install, assess PMI & coupling	High η_{CD}, j profile control	Valid RF model & launchers
PMI	Design divertors PMI diagnostics	Install divertors, q// vs. B physics	Integrated q// PMI solution @ high pressure	Heat exhaust/ PMI solutions Solid vs liquid
Long Pulse				
Plasma sustainment		CD efficiency f(B) on HFS	Disruption rates away from limits	Current control toolkit
B-field sustainment	Prototype HTS conductor & joints	Wound coils /w joints	B>20 T jointed coil demo	Cu vs. HTS FNSF or Pilot?
Materials	Erosion resistant high-Z PFC	Study: modular replacement	High-T, high-Z, low E_{ion} divertor	Modular replacement

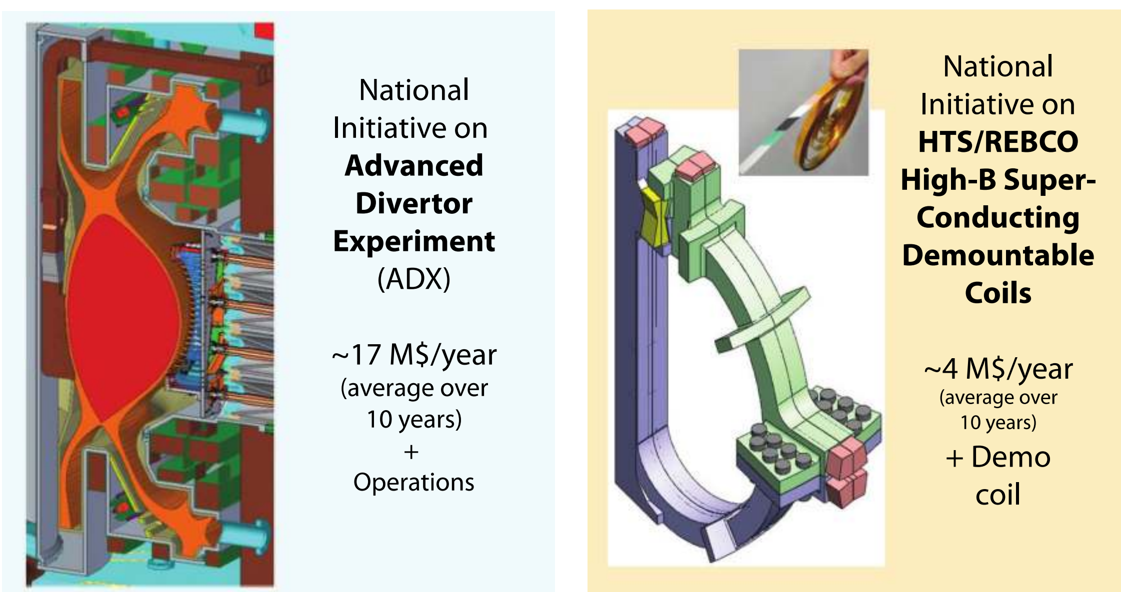


Fig. 3 Proposed ADX [10] and high-B SC coils initiatives to FES Foundation and Long-Pulse research thrusts. Timeline of research goals through a 10 year research plan culminate in critical and attractive design options for FNSF/Pilot

length or steady state operation is required. Because the magnet system forms the core of the fusion device, the chosen magnet technology defines the operational limits of the plasma, as well as the core machine size and cost. Magnet limitations constrain the design of new experimental facilities as well as design and evaluation of commercial reactors. For magnetic fusion to be attractive as a clean and efficient power source, the magnet systems, must offer very high performance, acceptable first cost, low operating and maintenance costs, and high reliability.

The present state of the art in fusion superconducting magnet systems is ITER. Yet the Low-Temperature-Superconductor (LTS) technology for ITER was developed in the 1990s. This technology has been used successfully in model coils and in smaller fusion experiments. In fact, all superconducting fusion systems in operation or under construction (EAST, KSTAR, SST-1, LHD PF coils, Wendelstein 7-X, ITER) [14–18] use the Cable-in-Conduit-Conductor technology invented and developed in the US in the 1970s [19].

Magnet design for fusion applications requires multidisciplinary engineering skills including applied superconductivity, mechanical engineering, electrical engineering, materials science, and engineering design. It encompasses electromagnetics, cryogenics, structural analysis, power systems and circuits, specialized instrumentation, and complex magnet system modeling. If the US is to be an active participant in a fusion energy future beyond ITER, it is imperative that it remains a leader in fusion reactor design, engineering, construction, and operation. To do so it must reestablish and maintain a solid base of scientists and engineers with the necessary skills and experience, and at the same time educate and train the next generation of professionals who will be needed to carry on the fusion program.

New Superconductor and Magnet Innovations

Superconductor performance limits have increased dramatically in the last few years with the development of so-called "high-temperature superconductors" (HTS). The use of HTS could significantly change the economic and technical status of superconducting magnets. Some types of HTS materials, in particular yttrium barium copper oxide (YBCO) exhibit very high critical currents at temperatures well above that of boiling liquid nitrogen at 77 K as compared with the commonly used LTS (NbTi and Nb_3-Sn), which must operate at temperatures near liquid helium (~4 K). Some yttrium is often substituted by Zirconium, or doped with other rare earth (RE) elements such as Gadolinium (Gd) to give even higher performance, and thus these conductors are called REBCO. More importantly, if HTS is operated at lower temperatures than liquid nitrogen, it exhibits critical current density much higher than the LTS conductors at extremely high magnetic fields making them feasible for use in SC magnets with peak field significantly greater than 20 T, as shown in Figs. 4 and 5.

REBCO/YBCO 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. Recent demonstrations at the National High Magnetic Field Laboratory—Florida State University (NHMFL-FSU) showing fields of more than 35 T [20], and studies at the Massachusetts Institute of Technology (MIT) indicate that HTS magnets make demountable magnets a feasible option for future devices [21].

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} versus B (Fig. 4). 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

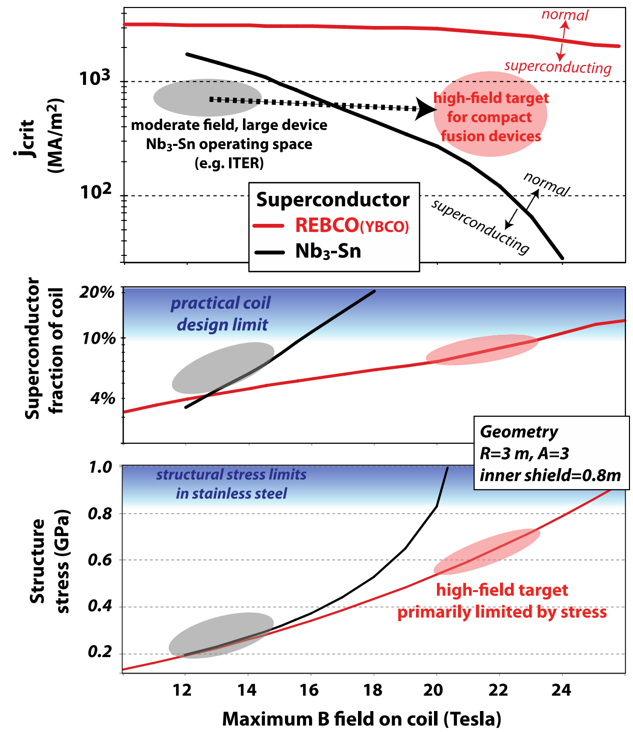


Fig. 4 Comparison of Nb_3Sn and REBCO versus B field. (*Top*) Critical current (*middle*) required superconductor fraction in coil to achieve B field for given geometry assumptions (*bottom*) Peak stress in structural material (i.e. non-superconductor) of coil. *Shaded regions* indicate practical limits to coil design REBCO critical currents obtained from http://fs.magnet.fus.edu/~lee/plot/plt.htm

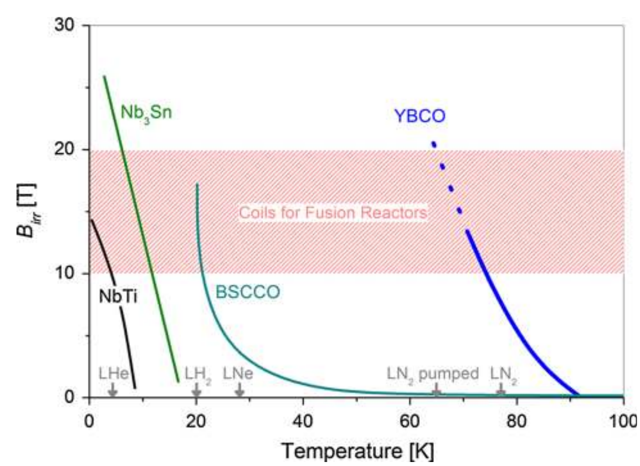


Fig. 5 Critical field as a function of temperature for several LTS and HTS materials. YBCO exhibits very high critical magnetic field when compared with the LTS conductors at temperatures between 20 and 77 K [34]

B field because in a coil the $B_{coil} \sim j$. The strong decrease in j_{crit} in Nb_3Sn 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 $B_0 \sim 5.3$ T. REBCO SC can double the field to $B_{coil} \sim 22$T, $B_o \sim 10$ T, because at this field the REBCO has ~100 times the j_{crit} of Nb_3Sn. As seen schematically in Fig. 4 the REBCO has such high margin that more structure can be placed in the coil which then helps to handle the larger jxB-induced stresses. Structure yield strength ~1 GPa, and conductor strain, eventually limit B_{coil} in REBCO-based coils rather than j_{crit}. It must be noted that existing tokamaks (e.g. C-Mod) and burning plasma designs (BPX, FIRE) have successfully dealt with such mechanical stresses. *REBCO tapes now makes very high field operation feasible in a superconducting tokamak*.

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. 6) 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. VULCAN is a small tokamak proposed for PMI studies [22]. The study indicates that the resistance in the joints between SC tapes is sufficiently small when operated at 20K that power consumption is reasonable. More importantly, demountable TF coils provide ready access to the interior components of the tokamak (Fig. 7). Another important feature of demountable coils is that even relatively short lengths of REBCO can be used to build the magnets, effectively increasing conductor production yield, and lowering conductor cost.

There are primarily three ways in which advances in magnet technology can lower the cost of experiments and fusion power production: (1) by providing conductor and magnet performance which substantially increases or optimizes the physics performance so as to allow a smaller or simpler device, e.g. significantly increased current density and magnetic field, (2) by lowering the cost of the superconductor and magnet components and/or assembly processes, and (3) by optimizing the configuration of the magnet systems, so that the cost of other fusion subsystems may be reduced. The advent of new REBCO technology enables all three of these paths. The US fusion program should develop magnet technologies that are specifically focused on lowering the cost and increasing the availability/reliability of the magnets required in fusion power systems [23, 24]. The replacement of a failed toroidal field coil or a major poloidal field coil in a fusion reactor is considered to have such a negative impact on reactor availability (several years) that coil failure should not be a credible event.

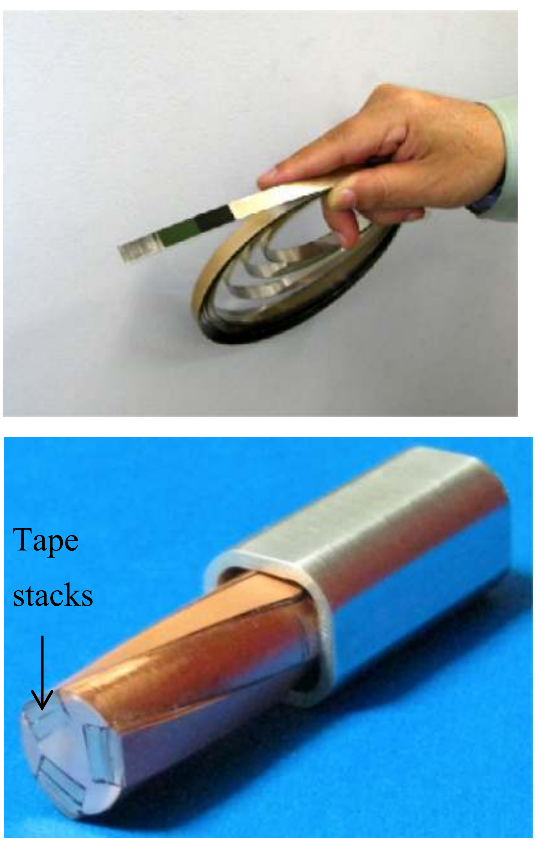


Fig. 6 (*Top*) REBCO superconductor are made in long lengths as thin, flat tapes. Their critical current density is anisotropic for in-plane and out-of-plane magnetic fields. (*Bottom*) An example of REBCO conductors for use in coils, here using the example of Twisted Stack Tape Conductor

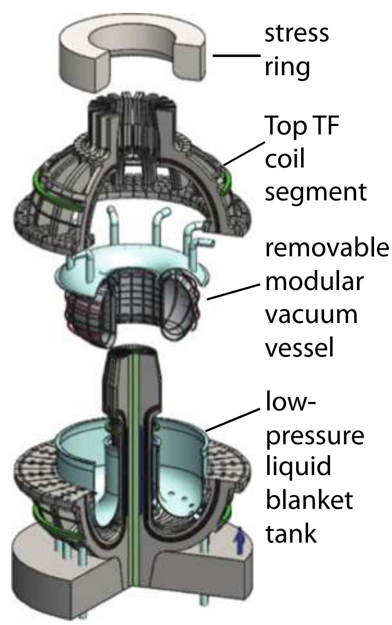


Fig. 7 ARC with demounted TF coils allows for modular replacement of internal components and an immersion liquid blanket [1]

Magnet R&D

The US fusion program should lead an effort to advance beyond the State-of-the-Art in LTS magnet technology. Physics progress has been and will continue to be impressive, but fusion is a futile effort if the required engineered systems are not available at a reasonable cost with adequate performance. The physics results of high-field HTS coils will be shared, but the knowhow to build the components will rest with the teams that develop them. Thus, the foremost requirements of the magnet systems for an attractive reactor (high performance, high reliability and availability, and acceptable cost) form the basis for the necessary magnet development program, and provide the guidelines for future research and development.

A focused HTS magnet development program should be a coordinated efforts ranging from lab-scale R&D, prototype component development, prototype magnet tests, and eventually integration into a next-step device. The proposed program will significantly expand the fusion magnet development effort, which is presently very modest, and engage fusion magnet experts across US universities, national laboratories, and industries. This research will require funds for procurement of HTS materials, insulation, and structural materials as well as for fabrication of components, prototypes, and the test program. It should be noted that while Department of Energy (DOE)-sponsored superconductor technology for electric power utility applications has in the past yielded great progress, there are fundamental differences between these applications and fusion magnets. This proposed thrust would leverage ongoing R&D on HTS but would focus on HTS fusion magnet research specifically, not on development of the superconductor tapes themselves. Importantly a large majority of the R&D steps noted below can be done on a relatively fast timescale because it does not require magnets at the size used for fusion confinement devices. Based on the maturity of the HTS manufacturing, the history of developing Nb_3Sn technology for ITER [25] and the recent rapid progress in prototyping high-B solenoid magnets >25 T, we estimate that with sufficient resources the R&D program could be completed in 4–5 years.

Specific R&D Elements of Magnet R&D

A structured research and development program should consist of the following elements:

Element 1—HTS wire/tape characterization program

The goal of the HTS materials characterization program is to quantify the performance of high current tapes that can tolerate the fusion environment. The REBCO/YBCO superconductor is made with thin-film technology and can only be made in long lengths as thin, flat, tapes, as shown in Fig. 6. Due to the tape geometry, the critical current density, J_c, is often anisotropic, with J_c values much lower for magnetic fields perpendicular to the flat face of the tape when compared with magnetic fields parallel to the tape.

Characterization of this material must be done in fusion relevant operating conditions of high magnetic field and current and in the temperature range 4.2–77 K with emphasis in the 20–50 K range. In addition the program should keep abreast of new developments and improvement in REBCO technology, for example the recent discovery that the inclusion of Zr in the tape significantly reduces the anisotropy [26] while pushing the critical current density to extraordinarily high values. In addition the program should include irradiation testing of the newer material.

One disadvantage of REBCO tapes is their high magnetization loss in changing magnetic fields. This is not much of a problem for the TF coils which are operated in steady state. If HTS conductors are needed to be operated as poloidal field coils, either low loss solutions for the tapes and multi-tape conductors must be developed or other types of superconductor must be used. Another type of superconductor under development is a multifilament wire from MgB2 which would be suitable as a PF coil conductor [27].

Element 2—High current conductors/cables development program

The goal of a HTS research cable program is the production and test of high engineering current *conductors* in long lengths through cabling, bundling, or stacking of a large number of tapes. For fusion applications, cables with 50–100 kA are desired driven by coil protection. Recent laboratory work has demonstrated feasibility, for untwisted stacks for up to 100 kA [N. Yanagi, S. Ito, Y. Terazak, Design and Development of High-Temperature Superconducting Magnet System with Joint-Winding for the Helical Fusion Reactor, Nucl Fusion v55, n 5, p 053021 (7 pp.), May 2015] and for transposed tapes so far to 5–10 kA level [28], but there is a challenge to expand this work to the 50–100 kA level. One approach being studied is Twisted Stacked Tape Conductor (TSTC) concept, illustrated in Fig. 6.

Element 3—Development of advanced magnet structural materials and structural configurations

Structural materials and structural concepts optimized for use with HTS material need to be explored. It is possible that conventional cryogenic materials can be used. In contrast to ITER magnets made with Nb_3Sn, heat treatment of the superconductor and the structure is not required. For cost and manufacturing ease, the exploration of structural material improvements and of advanced manufacturing techniques will yield quantitative reductions in magnet fabrication complexity and assembly. This is an area that has received little attention and where even limited resources may yield substantial gains.

Rapid prototyping, or "additive manufacturing", can be used to create near net-shape components directly from Computer Aided Design (CAD) solid models. One potential use is to manufacture the structural plates of the magnet with features needed for assembly and manufacture. Multiple material deposition heads create the coil structure in a timely manner to near net shape such as internal coil grooves and attachment features. The fabrication cost of fusion magnet structures with this technology has been estimated to be a small fraction of traditional fabrication methods. Flexible HTS tapes integrated into grooves in structure with complex shapes could also ease the manufacture of magnets with 3-D geometry such as helical devices, or other alternate configurations.

Element 4—Development of cryogenic cooling methods for HTS magnets

Cooling methods for HTS conductors need to be investigated. Present performance of HTS materials at 77 K results in critical fields that are far too low for fusion applications. The critical field of HTS, however, increases very rapidly with diminishing temperature. Alternative coolants and cooling methods include flowing helium gas, single or two-phase liquid hydrogen, liquid neon, and subcooled nitrogen and nitrogen-eutectics.

Operation at higher temperature also allows for savings in the cryostat, as higher heat loads can be accepted with a reduced ($\sim 1/10$) refrigeration penalty. In addition, it is possible to absorb substantially higher nuclear heating at higher operating temperature. The heating constraints on the magnets can then be virtually eliminated. The problem of radiation damage to the superconductor and the insulation, however, still remain.

Element 5—Development of magnet protection devices and methods specific to HTS magnets

Operation at relatively high cryogenic temperatures, e.g. 20–50 K requires reconsideration of superconductor stability, quench detection and magnet protection. This is because the heat capacity of the conductors, structure, and cryogenic fluid are orders of magnitude higher than those for a magnet operating in liquid helium. In general this is a positive feature but it changes the nature of quench protection.

Passive and active quench protection methods need to be investigated. One such method is the possibility of using RF fields to simultaneously quench a substantial portion of the magnets through the use of eddy current heating (or by introducing magnetization hysteresis losses in the SC) [29]. These quench protection means are not needed for LTS magnets at liquid helium temperature because of their significantly faster quench propagation, even in the presence of helium coolant. Fast quench propagation does not occur with HTS materials.

The overall design philosophy for off-normal conditions and faults in HTS fusion magnets would also have to be rigorously developed, to guarantee protection against credible operational events. Design and analysis codes should be revised specifically for fusion magnets operating at these higher temperatures, and confirmed by comprehensive laboratory testing as has been done in the past for liquid helium LTS magnets.

Element 6—Development of advanced radiation tolerant insulating materials

There has been substantial effort in the fusion community to develop radiation resistant insulators. Progress has been made in the development of both organic and hybrid insulators. The main characteristic of these insulators is the presence of a liquid phase that can penetrate through the coil winding, filling the voids, and impregnating the coil elements and the insulation sheets. The use of HTS can substantially change the direction of this work, opening new avenues for development of superior insulation systems. For the case of HTS material directly deposited on a substrate, it would be possible to subsequently deposit thick layers of ceramics that can serve as insulation. Ceramic insulators should survive ~ 100 times higher radiation dose than organic insulators.

Means of transferring loads between plates of the magnet need to be investigated, to take full advantage of this structural potential, since the plates cannot be impregnated with epoxy resin. The use of large plates eases the application of the ceramic insulation, with insulated windings on the plates, and planar insulation between plates. Alternatively, the conductors could be encased or wrapped in a ceramic insulation material. In addition recent work [30] has started to explore high-field magnets that do not use ceramic insulators, but rather rely on the steel structure of the tape to act as a form of insulator at cryogenic temperatures.

It should be noted that, although radiation damage to the magnet insulation presently limits the operating service life of the magnet system, there is reason to predict that improvements in organic and inorganic (including ceramic) insulating systems could extend the damage limit beyond that of the superconducting material, for both low temperature and high temperature superconducting materials. At this time there does not seem to be any physical path to extend the radiation damage limit for the superconductor.

Element 7—Integration of conductor with integrated structure, insulation, and cooling

The options described above need to be integrated into a fabrication technique that takes into consideration the requirements of the superconductor, coolant, structure, insulation and assembly. There are synergisms between these requirements that can substantially benefit fusion plasmas, as described above. The possibility of additive manufacturing, with HTS deposited on a structure with built-in cooling passages and then coated with ceramic insulation, can substantially decrease magnet cost while simultaneously enabling operation at higher performance (field, fusion power, pulse length). Alternatively, a method of winding HTS in grooves on plates and then insulating them needs to be developed. The coolant geometry may be different, in that the conductors may be able to carry the coolant themselves, as is the case with Cable-In-Conduit-Conductors (CICC).

Element 8—Development of joints for demountable coils

The ability to operate at relatively high cryogenic temperatures and the use of relatively simple structural configurations provide very high stability that, in turn, allows consideration of demountable joints. Demountable high temperature superconducting coils promise unique advantages for tokamaks and alternate configurations. They would enable fusion facilities in which internal components can be removed and replaced easily and remotely, a major advantage for the difficult challenges of Reliability, Availability, Maintainability and Inspectability (RAMI).

To date, there has been very limited investigation of demountable superconducting magnets (Fig. 8). The use of HTS allows for relatively high resistance joints with modest cryogenic power consumption when compared with joints in LTS coils. The use of tapes also facilitates certain types of joints such as lap joints, where surfaces of the tapes are pressed together for a non-permanent joint. It will typically be necessary to add support structure to minimize tensile stresses across the joint region, as the joint has limited load-carrying capabilities. One additional issue that needs to be addressed is cooling of the joint region. The accumulated joint region has the largest cryogenic load of the magnet, larger than the current leads or thermal radiation, and it is deposited in a small volume. The joints need to be effectively cooled. Although it is preferable to cool the joint directly, other cooling options should be studied. This activity is linked to Element 4.

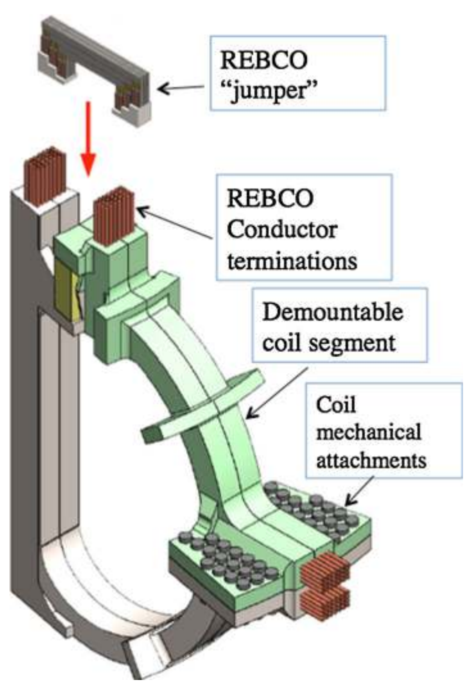


Fig. 8 Conceptual design example for TF coil with a demountable segment, superconductor jumpers and low resistance joints

Element 9—Coil fabrication technology

Attractive solutions generated in Elements 1–8 need to be integrated and demonstrated by building prototype magnets of different configurations, e.g. planar coils, solenoids, 3-D coil geometries, etc. These must then be operated under full-scale operating conditions to the extent that they can be simulated in a prototype coil test facility. The most promising and useful magnet designs would then be incorporated into new magnetic fusion research facilities.

Opportunities for International Collaboration on Fusion Magnet Development

Outside the United States there are teams that are beginning R&D programs to develop advanced magnet technologies for use in the next major machines to be designed and built in anticipation of a future DEMO. Most of these programs are beginning to focus on HTS magnet technology. An informal group has begun to focus and coordinate research efforts with the goal of using international collaboration to make the most efficient use of limited programmatic resources, and to share major testing facilities, which are limited in number and expensive to operate. This group is called HTS4Fusion Working Group, and at this time has about 30 participants from the US, Japan, England, Italy, Germany, Switzerland, Austria, India, and Russia, representing about 15 different research institutions and universities. It expects to add members from Korea, China, and France shortly. The HTS4Fusion program would benefit immensely from formal sponsorship, organization, and coordination by our respective governmental funding agencies.

ARC Design Concept: Exemplifying the New Approach

The access to high-B demountable superconductors is a "game-changer" for FNSF/Pilot design. For illustrative purposes we examine here features of the recent ARC design study [1], although there are likely to be many more possibilities with the new magnet technology. ARC

(Figs. 1, 7) is basically a 9.2 T JET-sized tokamak that produces ~500 MW of fusion power, with a liquid blanket allowed by the demountable coils. ARC is self-sufficient in tritium, and can produce ~200 MW with an overall plant electricity gain ~4.

The key design parameters of ARC are shown in Fig. 1 and Table 1. Like FIRE, the plasma core scenario of ARC exploits the high B field (9.2 T) to achieve excellent absolute fusion performance at realistic normalized plasma performance. This can be understood by examining Eqs. 1 and 2, the ~ doubling of B provides a factor of B^3–B^4 ~ 8–16 to both halve R *and* decrease the normalized plasma parameters. Thus the core scenario required for ARC, as denoted in Table 1, has already been achieved in present tokamaks with simultaneous achievement of normalized gain, plasma shaping, Greenwald faction and fully non-inductive sustainment at edge safety factors near 7 (for example see [31]). In this way, high-B inherently addresses most of the control and steady-state gap issues (Fig. 2).

The ARC high-B design is also intentionally designed far from operational and disruptive limits. This stands in marked contrast to other FNFS/reactor designs as shown graphically in Fig. 9. Designs based on Nb_3-Sn superconductors [11] or cooled copper coils [3, 4] are limited to peak field <13 T (B_0 ~ 5.5 T for aspect ratio ~3.5–4 typical of AT designs). In order to achieve the necessary fusion power density (Eq. 1) for their missions, these designs must operate right at or above intrinsic limits (left plot of Fig. 9). While a single one of these limits may be traversed in single-effect trials in present devices, simultaneous complex control of these limits is extremely risky, and perhaps not possible, in a self-heated burning plasma. The consequences of losing control are calamitous to plasma-facing components because of the necessary energy density (or pressure) in these plasmas; all FNSF/reactor designs have disruption damage threats equal to or surpassing ITER (last column in Fig. 9). By using high-B technology, the transient damage gap (Fig. 1) is principally addressed by the most obvious strategy: operate far from the intrinsic limits.

Another attractive feature of ARC is large external control of the current profile at high gain, Q ~ 14 (Fig. 9) by combining modest bootstrap fraction (~60 %) and efficient current drive using high-field side Lower Hybrid Current Drive. Control of 40 % of the current and q profile allows for relatively easy stability and transport modification, in contrast to the <10 % current control in low-field AT reactor designs (Fig. 9).

Access to high gain, Q_p, is also critical because the power exhaust challenge becomes much more difficult at low gain (Fig. 10). For a given neutron loading, necessary to meet the FNSF mission, the wall/divertor heating increases strongly below Q ~ 10. This forces lower neutron wall loading and higher divertor loading in FNSF-AT because of its low gain, Q_p ~ 2.6.

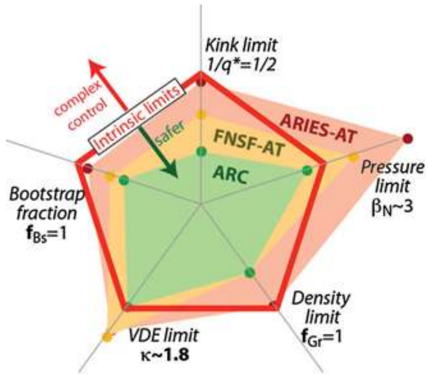
The development of the REBCO-based coils directly addresses the magnet gap [13]. Beyond access to high-B, coil demountability will have a profound design impact. First, the TF coils themselves can be modularly maintained and repaired (Fig. 7). Second, as with other FNSF designs [3, 4], demountability allows for modular replacement of internal components providing integrated testing of nuclear components. However in stark contrast to the Cu coil FSNF designs, the ARC SC coils only require ~1 MW of electricity for the joints/cooling, while the Cu FNSF designs consume an enormous ~400–500 MW of electricity (Fig. 9). Simply the installation and dissipation of this electric/thermal load may make Cu-based FNSF impractical, while the use of SC coils opens the possibility of net electricity production at the ~200 MW level as a Pilot fusion power plant.

Demountabilty has also enabled the use of a liquid immersion blanket to simplify the overall nuclear technology required for ARC [1]. Nonetheless component

Table 1 Parameters of ARC exploiting high-field, high-temperature REBCO superconductors

FNSF/pilot requirement for ARC	Achieved	Required initiative
R ~ 3 m, V ~ 100 m^3	TFTR, JET, JT-60	
B ~ 9 T in tokamak with demountability	C-Mod, FTU	
Peak B ≥ 22 T with REBCO SC + demountability	–	National REBCO coil R&D program
β_N ~ 2.6	Multiple tokamaks	
Normalized gain	Multiple tokamaks	
$G_{89} \sim \beta_N H_{89}/q_{95}^2 \sim 0.15$		
Non-inductive @ q_{95} ~ 7	DIII-D, C-Mod, JT-60	
Non-inductive @ q_{95} ~ 7 + n_{20} ~ 2 + RF launcher	–	ADX
Heat exhaust $q_{//}$ ~ PB/R ~ 150	~60 in C-Mod	ADX
Q > 10		ITER, ARC, FNSF

Fig. 9 (*Left*) Polar plot of operating and control limits for different FNSF/reactor burning plasma ARIES-AT [11], FNSF-AT [3] and ARC [1] (*right*) operating design parameters including net electricity production (+) or consumption (−) and thermal energy density normalized to ITER in order to quantify the disruption damage threat



Steady-state tokamak	B_0 (T)	R (m)	P_{elec} (MW)	Q_p	$\frac{P_n}{S}$ $\frac{MW}{m^2}$	$\frac{W_{th}/S}{(W_{th}/S)_{ITER}}$
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

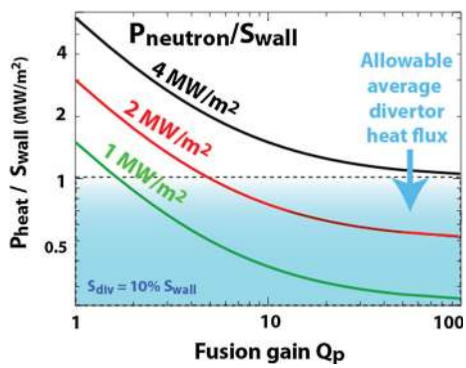


Fig. 10 Global heat loading versus fusion gain at various neutron wall loading for an FNSF mission

testing in the modular vacuum vessel is completely allowed in ARC.

High-B Physics Research to Address Boundary and RF Gaps

It is apparent that access to high-B demountable SC coils addresses many fusion development gaps. This motivates a national initiative to develop these coils based on REBCO HTS superconductor technology as described above in "Magnet R&D" section. It is reasonable to expect significant progress towards this capability in the next decade with rather modest investments, such that it can be applied to any FNSF/Pilot design.

By far the largest gap towards the successful design and implementation of FNSF/Pilot is taming heat exhaust and PMI. This is generically true of any FNSF/reactor design, which all feature large steady-state parallel heat flux [9]. A related issue is RF current drive and PMI on launchers, for which solutions are not presently in hand. These both compel a national initiative, ADX, to address boundary, PMI and RF physics issues (Fig. 3). The key feature of ADX is that it provides the high-fidelity experimental access to FSNF/reactor matched boundary plasma conditions by a combination of high B-field (up to 8 T) and high power density. For example the parallel heat flux and divertor plasma pressures are both matched absolutely to FSNF/reactor scenarios decreasing the reliance on extrapolation with models. These conditions cannot be accessed simultaneously by either low-B tokamaks or linear plasma devices [32]. ADX also features innovative solutions to boundary problems with access to various extended-volume divertors [10] and high-field side RF launchers [33].

Summary

A *new "game changing" opportunity* that could significantly advance the economic and technical status of superconducting magnets is now viable, namely the use of so-called HTS. The use of these materials enables an attractive fusion development path because high magnetic field operation of a tokamak leads to smaller size, increased margin to operational limits with lower risk of disruptions and efficient RF current drive for steady state operation. HTS can be used, in fact, with any magnetic field configuration including 3-D shaped devices. Revolutionary new HTS materials such as REBCO/YBCO are sufficiently advanced for next-step fusion applications. Success in this program can potentially revolutionize the design of magnetic fusion devices for very high performance in compact devices with simpler maintenance methods and enhanced reliability. A program of magnet technology development, high field tokamak physics and fusion system studies would provide the scientific and engineering underpinnings needed to exploit the opportunity provided by the new conductor technology. These high-B initiatives, undertaken in the next 10 years on relatively modest budget profiles, will lead to attractive and realistic design options for FNSF and Pilot.

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