

## **Fusion Technologies for Tritium-Suppressed D-D Fusion**

White Paper prepared for FESAC Materials Science Subcommittee

M. E. Mauel<sup>1</sup> and J. Kesner<sup>2</sup>

<sup>1</sup>Dept of Applied Physics and Applied Mathematics, Columbia University

<sup>2</sup>Plasma Science and Fusion Center, MIT

December 19, 2011

### **Summary**

The proposal for tritium-suppressed D-D fusion and the understanding of the turbulent pinch in magnetically confined plasma are new developments in fusion science that create an alternate and potentially advantageous technology pathway. Tritium-suppressed D-D fusion eliminates the need to breed fuel from lithium, reduces the damage from 14 MeV neutrons, and allows structural materials now qualified for fission systems to be used for fusion. The turbulent pinch gives scientists the ability to design magnetic confinement systems that control the direction of the turbulent particle and heat flux. In a levitated dipole, plasma profiles become highly peaked, and plasma energy confinement can significantly exceed particle confinement. Additionally, because a levitated dipole confines plasma at near unity beta, in steady-state, and without toroidal magnetic field coils, large plasma confinement volume does not incur high system cost. Experiments and simulations indicate that the levitated dipole can meet the physics requirements for tritium-suppressed D-D fusion, and the reduced neutron heating from advanced fuels makes plausible the technology of self-powered cryogenic cooling of an internal superconducting coil. However, tritium-suppressed fusion in general and the levitated dipole fusion concept in particular require the development of high-field, high-strength, and high-temperature superconductors that exceed the performance of today's Nb<sub>3</sub>Sn superconductors.

Because the technology pathway for tritium-suppressed D-D fusion is different from the pathway for steady-state D-T/Li fusion power and because the pursuit of multiple technology pathways enhances the likelihood of successful fusion energy development, our nation's strategy for fusion technology development should include research that advances high-field, high-strength superconducting magnet technology and continues the exploration of fusion based on the tritium-suppressed D-D fuel cycle.

### **Introduction**

In the U.S., Sheffield and co-authors [*Sheffield, 2002; Sawan, 2002; Sheffield; 2008*] and, in Russia, Khvesyuk and Chirkov [*Khvesyuk, 2002; Chirkov; 2006*] independently proposed tritium-suppressed D-D as an alternate technology pathway to fusion power. Sheffield characterizes D-D as the "ultimate fusion cycle" because it's fuel is plentiful on Earth and avoids the need to breed tritium from lithium. Tritium-suppressed fusion goes beyond the usual view of the D-D fuel cycle by removing the tritons created by fusion in the plasma before they fuse with deuterium. By removing the tritons, the flux of damaging 14 MeV neutrons is alleviated without significant impact on

the plasma power balance. For a fusion reactor with  $5 \text{ MW/m}^2$  power flux, removal of tritium results in a factor of two reduction of neutron displacement damage and, most significantly, a 20 to 100 fold reduction in He producing transmutations [Sheffield, 2008]. When more than 90% of the tritium is removed from a D-D fusion reactor, structural materials qualified for fission can be used for fusion. Tritium suppressed D-D fusion avoids the need to develop structural materials for the first wall of a D-T/Li fusion reactor, which has been described [Zinkle, 2005] as “arguably the greatest structural materials development challenge in history.”

When the removed tritons are permanently stored and later re-injected as  $^3\text{He}$ , the plasma Lawson confinement parameter ( $n\tau_E$ ) needed for high gain is ten times larger than needed for D-T/Li fusion. (See Figure 1.) The plasma temperature must be twice as high ( $T \sim 40 \text{ keV}$ ). With full  $^3\text{He}$  recycling, 94.4% of the energy released from tritium-suppressed D-D fusion consists of charged particles (two  $^4\text{He}$  and three protons), and the energy from these particles sustain the fusion burn. Only 5.6% of fusion energy is released in the form of 2.45 MeV neutrons.

Tritium-suppressed D-D fusion with recycled  $^3\text{He}$  requires significant tritium storage to provide recycled  $^3\text{He}$  fuel. One GW-year (total released fusion energy) consumes 90 kg of deuterium, 22 kG of  $^3\text{He}$  produced by fusion within the plasma, and 22 kg of  $^3\text{He}$  produced from tritium’s radioactive decay. With a half-life of 12.3 years, 410 kg of tritium must be safely and permanently stored for each GW-year of tritium-suppressed D-D fusion. (In contrast, one GW-year of D-T/Li fusion energy consumes 56 kG of tritium, and the on-site tritium inventory will be less than the storage requirements for tritium-suppressed D-D fusion. However, tritons must be continuously accessible and cannot be permanently stored for a D-T/Li fusion reactor.) For both D-T/Li and tritium-suppressed D-D fusion power, international control of tritium, including monitoring at gram-levels, will be required to prevent proliferation [Kalinowski, 1995].

There have been several studies of the configurations and requirements for fusion using advanced fuels like D-D and D- $^3\text{He}$ . Fusion reactors using advanced fuels will be significantly larger than those using D-T/Li fuel and require challenging confinement and stability parameters [Nevins, 1998; Stott, 2005]. Although D- $^3\text{He}$  tokamak fusion reactors are large and require advanced performance, they benefit from full-lifetime walls, improved safety, and the possibility of highly efficient direct conversion of fusion produced radiation to electricity [Kulcinski, 1992]. Examples of large tritium-suppressed D-D fusion devices are: a tokamak with 84 MA of plasma current and a 9 m major radius [Sheffield, 2008] and a high-beta spherical tokamak with 150 MA of plasma current and a 4.5 m major radius [Chirkov; 2006]. All of these designs require high-field superconducting magnets beyond today’s capabilities.

Besides being large and requiring advanced magnets, advanced fueled reactor concepts require removal of tritium and other fusion products without energy confinement degradation. Ignition with advanced fuels cannot occur when the confinement time of charged fusion products exceeds five times the confinement time for energy. Fusion with advanced fuel becomes easier, when energy confinement time is *longer* than the confinement time of particles. Wave resonant pumping, like “alpha-channeling” [Fisch, 1999] or drift-resonant pumping [Khvesyuk, 2002], has been suggested as one possible mechanism to remove tritons [Sheffield, 2008]. “Channeling”

means fusion products should be removed after their energy is deposited into the plasma but well before causing fuel dilution.

Recent observations and simulations of turbulent mixing in the levitated dipole are exciting, in part, because they indicate dipole plasma confinement can meet these challenging requirements. Energy is confined longer than particles because particles naturally cool as they diffuse from the central high-pressure region to the cooler edge scrape-off-layer (SOL). This relative confinement property occurs in dipole geometry, because the turbulent diffusion rate for both particle number and entropy density,  $P\delta V'$ , are identical [Kesner, 2011] and there is no dynamical separation between trapped and circulating particles. Additionally, the large plasma confinement volume required for tritium-suppressed D-D fusion does not incur high system cost in the dipole fusion concept because large toroidal field coils are not required for plasma stability. The high-beta and favorable confinement properties of the magnetic dipole make it well suited for tritium-suppressed D-D fusion.

### **Magnetically-Levitated Dipole Confinement and the Turbulent Pinch**

Hasegawa introduced the levitated dipole concept based on understanding gained from satellite observations of magnetospheric plasma [Hasegawa, 1987]. More than 50 journal articles and twelve invited talks have presented research documenting the physics of high-temperature plasma confinement by a levitated dipole.

Two experiments have studied high-beta, steady-state plasma confinement with magnetically-levitated superconducting dipoles. The LDX device, located at MIT, is the largest, consisting of a 0.66 m diameter, 1.2 MA dipole made from Nb<sub>3</sub>Sn superconductor [Zhukovsky, 2005; Garnier, 2006]. The RT-1 device, located at the University of Tokyo, consists of a 0.50 m diameter coil made from high- $T_c$  Bi-2223 superconductor and carrying 0.25 MA [Yoshida, 2006]. Steady-state plasma discharges are maintained with low-power ECRH (10-50 kW). Recently, low-power ICRH experiments have begun at RT-1 [Yano, 2011]. LDX is ready now to begin ICRH experiments at powers up to 1 MW [Mauel, 2010].

These experiments show stable, steady-state confinement with peak plasma beta approaching unity [Garnier, 2006; Garnier, 2009; Saitoh, 2010] with centrally-peaked pressure profiles that are consistent with theoretical predictions [Garnier, 1999].

The turbulent pinch has been directly observed in both LDX [Boxer, 2010] and RT-1 [Saitoh, 2010]. These observations show that transport phenomena observed in magnetospheres [Walt, 1971] also occur in laboratory dipole devices. MHD [Pastukhov, 2005; Kouznetsov, 2007] and gyrokinetic simulations [Kobayashi, 2010] are consistent with experimental observations.

The verification of the turbulent pinch is important because the pinch dynamics sets the pressure and density profiles. Both gyrokinetic simulations [Kobayashi, 2010] and measurements of global energy confinement [Boxer, 2010] indicate the turbulent pinch drive both heat and particles to insure that plasma profiles are strongly peaked. The central plasma temperature is very high while the edge temperature is low. The centrally peaked profiles are robust during modulations of heating power or gas fueling [Kesner, 2010]. The turbulent pinch is also important to the understanding of tokamak [Baker, 1998; Hoang, 2003; Angioni, 2009] and stellarator discharges [Tanaka, 2010].

Understanding and controlling the turbulent pinch in tokamaks may lead to improved operating modes for D-T/Li fusion [Whyte, 2010].

Several conceptual design studies have examined advanced-fueled dipole reactors, and these studies identified key requirements: high plasma beta (exceeding 100% at maximum), high plasma energy confinement (exceeding particle confinement), large overall size, and superconducting magnets more advanced than presently possible. As was first suggested by Dawson, recent dipole reactor studies [Teller, 1992; Kesner, 2004] use fusion radiation to provide cryo-cooling power to maintain the temperature of the superconducting dipole in steady state. The calculated neutron heating power to the levitated superconducting ring is small, and only a small fraction of the fusion power would need to be diverted for on-board refrigeration.

Advanced high-field magnets, beyond today's capabilities, are essential to the development of a tritium-suppressed D-D fusion reactor because the plasma pressure cannot exceed the magnetic pressure generated by the superconducting dipole. If advanced, high-field, high-strength superconducting magnets could be developed, studies conclude that a dipole fusion reactor would have attractive features: steady state, high reliability, improved safety and reduced neutron activation, relatively low capital and maintenance cost.

### **Technology Research Needs for Tritium-Suppressed D-D Fusion**

The technology research needs for tritium-suppressed D-D fusion are: (1) high-strength superconducting magnetic technology, (2) compact cryogenic systems that are self-powered from fusion radiation, (3) high temperature first-wall materials, (4) efficient plant-scale detritiation systems, (5) permanent tritium storage that meets all safety and environmental standards, and (6) fusion engineering systems studies that provide the basis for a demonstration fusion power plant based on tritium-suppressed D-D fusion. High-strength superconducting magnetic technology is critical to tritium-suppressed D-D fusion and is the technology need with highest priority. High-strength superconducting magnetic technology, high temperature first-wall materials, and detritiation systems are also technology systems common to D-T/Li approaches to fusion.

#### *(1) High-Strength, High-Field Superconducting Magnets*

High-strength, high-field superconducting magnets are required for tritium-suppressed D-D fusion [Kesner, 2004; Sheffield, 2008]. Peak field at the conductor should exceed 25 T; hoop stress should exceed 4 GPa in the magnet support structure; active quench protection would be required [Kim, 2008; Markiewicz, 2008]; and magnet stored energy would reach 10 GJ. The required dipole current is at least 30 MA in a coil made from an advanced high  $T_c$  superconductor [Bromberg, 2011] and having a diameter exceeding 15 m.

While these magnet requirements are extremely challenging, promising developments indicate that superconductors meeting the requirements for tritium-suppressed D-D fusion might be possible. A 30 T magnet has been designed using  $\text{YBa}_2\text{Cu}_3\text{O}_7$  (Y123) conductor with a measured 27 T transition temperature at 77 deg K [Watanabe, 2008]. Commercial second generation (2G) high  $T_c$  superconductors have demonstrated critical fields that exceed 27 T [Hazelton, 2009]. High strength composite materials have been made using carbon nanotubes [Coleman, 2006], demonstrating a

structural material with 200 GPa modulus and 50 GPa strength capable of reducing strain within high-field magnets.

*(2) Compact Cryogenic Systems Self-Powered from Fusion or Beamed Radiation*

Levitated dipole magnets will require on-board cryogenic systems that are powered from fusion or beamed radiation. Estimates of neutron heating to a shielded levitated coil using MCNP4C [Briesmeister, 2000] indicate that much less than 1% of the neutron power impacting the coil is deposited into the cold superconductor, and the on-board cryogenic system must remove less than 5 kW of neutron power in addition to thermal conduction power. With a high temperature superconductor and reasonable efficiency, the refrigerators require approximately 1 MW of on-board power. Thermal electric power [Kesner, 2004] or high-efficiency rectenna, like those considered for the Apollo D-<sup>3</sup>He tokamak reactor design [Kulcinski, 1992], could be used for this purpose. Alternatively, power could be beamed to the on-board refrigerator from a coherent source. Rectenna and thermo-electric power systems are now commercially available.

*(3) High-Temperature First-Wall Materials*

High-temperature first wall materials, like tungsten, will be needed for the outer, plasma-facing material boundary of the levitated magnet. Tritium-suppressed D-D design studies calculated that the steady first-wall temperature may reach as high as 1900 deg K in order to radiate the inward heating of the levitated dipole. Because the dipole is fully enclosed by the plasma, the dipole is “fully recycling”, with zero net inward particle flux, and the plasma density rises near the coil to act like a radiative divertor and to reduce first-wall erosion.

*(4) Plant-Scale Detritiation Systems*

As is also required for D-T/Li fusion reactors, a key requirement for tritium-suppressed D-D fusion is detritiation. Tritium must be continuously removed from plasma effluent along with protons, alpha particles, and other impurity species.

*(5) Inherently Safe Permanent Triton Storage*

Recycling <sup>3</sup>He to burn in the fusion chamber significantly improves gain and plant effectiveness. Unlike D-T/Li fusion reactor, the tritium extracted from a tritium-suppressed fusion plant will be stored permanently. For a 500 MW fusion plant, 200 kG of tritium must be stored, generating 30 kW of decay heat and producing 20 g of <sup>3</sup>He daily. These relatively large quantities of tritium must be cooled and stored permanently in inherently safe and environmentally secure on-site facilities.

*(6) Fusion Engineering and Systems Studies*

Tritium-suppressed D-D fusion is a promising new approach to fusion power that has not yet benefited from detailed engineering and systems studies. To guide the technical and scientific development of tritium-suppressed D-D fusion, detailed fusion engineering and systems studies should be used to identify design trade-offs and specify key requirements that must be demonstrated through research.

## The R&D Pathway to a Tritium-Suppressed D-D Fusion Demo

The FESAC recommended plan to develop fusion energy [Goldston, 2002] from our present state of knowledge to a fusion Demo calls for the pursuit of “technically credible alternate science and technology pathways that are judged to reduce the risk substantially or to offer substantially higher payoff (*i.e.* breakthroughs)”. Tritium-suppressed D-D fusion using a high-current levitated dipole magnet improves the likelihood of successful fusion energy development because it eliminates the need to breed fuel from lithium, reduces the damage from 14 MeV neutrons, and allows structural materials now qualified for fission systems to be used for fusion.

The R&D pathway leading to a tritium-suppressed D-D fusion demo is paced by two parts: (1) a fusion performance experiment large enough to establish all required confinement physics, and (2) a magnet technology program leading to high-field, high-strength superconductors. These two activities can be done in parallel. The cost for this fusion development pathway may be significantly lower than the fusion development pathway for D-T/Li fusion using tokamaks and stellarators because (1) it avoids the expensive qualification of fusion materials for 14 MeV neutrons and (2) it does not require the construction of fusion experiments with large superconducting toroidal field coils.

### *(1) Fusion Performance Experiment*

The LDX and RT-1 experiments are now ready to study high-power (up to 1 MW) confinement in fusion-relevant, steady-state, high-beta plasma. However, fusion performance studies require a larger device that can be built using today’s Nb<sub>3</sub>Sn superconducting magnet technology in a scaled experiment.

Figure 2 illustrates the design parameters for a magnetically-levitated superconducting dipole scaled from the LDX experiment located at MIT. When a 4 m diameter levitated dipole is energized to approximately 15 MA, it can be heated with approximately 10 MW and achieve  $Q_{DT} \sim 1$  when used with D-T gas. The superconducting magnet would operate below 1 GPa hoop stress and require active quench protection [Kim, 2008; Markiewicz, 2008] in contrast to the passive quench protection used on LDX.

The overall size of the scaled fusion-performance experiment would be large. It would require a vacuum chamber equal in diameter to the Space Power Facility (SPF) located at NASA’s Plum Brook Facilities in Sandusky, OH. However, because this large confinement volume does not require a toroidal field, the overall cost and engineering complexity would likely be much less than an equivalent, superconducting  $Q_{DT} \sim 1$  tokamak or stellarator.

Like LDX, the superconducting dipole in a fusion performance device would not be refrigerated. 14 MeV neutrons from D-T fusion would limit experiments to half-hour pulses. Nevertheless, these half-hour pulses are sufficiently near steady-state conditions that experiments would establish the energy and particle confinement properties (*e.g.* fusion alpha confinement time) necessary for tritium-suppressed D-D fusion.

### *(2) Magnet Technology Program*

At the same time as the fusion performance of the levitated dipole will be tested experimentally, an aggressive research program should be underway aimed at very high-field and high-strength superconducting magnets. This program would accelerate existing

high-field, high-temperature magnet science and technology research for fusion. The objective of stable, high-energy superconducting magnets would motivate the integrated study of high-strength materials (like high-strength, high-modulus graphene-based material composites) and next generation high  $T_c$  superconductors. Advancements in superconductors can be tested in relatively small research magnets.

## Recommendation

As recommended in the FESAC fusion development plan [Goldston, 2002], the pathway to Demo should provide for “breakthrough” developments that significantly improve the fusion end product. The U.S. plan for fusion technology development should include multiple technology pathways that will reduce the risk of failure and maximize the possibility of technology “breakthroughs”.

We believe the proposal for tritium-suppressed D-D fusion and the recently discovered favorable confinement and stability properties of the magnetically-levitated dipole are new developments in fusion science that create an alternate and potentially advantageous technology pathway for fusion. Although tritium-suppressed D-D fusion requires the development of high-field superconductors that exceed the performance of today’s magnets, credible magnet technologies exist (like YBCO conductors supported with carbon-nanotube composite materials) that may meet these challenging requirements.

Because the technology pathway for tritium-suppressed D-D fusion is different, and may have operational advantages, as compared with steady-state D-T/Li fusion power and because the pursuit of multiple technology pathways enhances the likelihood of successful fusion energy development, our nation’s strategy for fusion technology development should include research that advances high-field, high-strength superconducting magnet technology and continues the exploration of fusion using the tritium-suppressed D-D fuel cycle.

## References

Angioni, *et al.*, “Particle pinch and collisionality in gyrokinetic simulations of tokamak plasma turbulence,” *Phys Plasmas*, 2009 vol. 16 (6) p. 060702

Baker and Rosenbluth, “Density profile consistency and its relation to the transport of trapped versus passing electrons in tokamaks,” *Phys Plasmas*, 1998 vol. 5 (8) pp. 2936-2941

Boxer, *et al.*, “Turbulent inward pinch of plasma confined by a levitated dipole magnet,” *Nature-Physics*, 2010 vol. 6 (3) pp. 207-212.

Briesmeister J.F. (ed) 2000 “MCNP4C: Monte Carlo N-particle transport code system,” Oak Ridge National Laboratory Report CCC-700.

Bromberg, *et al.*, “Status of High Temperature Superconducting Fusion Magnet Development,” *Fusion Sci Technol* (2011), pp. 635–642.

Chirkov, “Possibility of utilizing the D-3He fuel cycle with 3He production in a spherical tokamak reactor,” *Tech Physics*, 2006 vol. 51 (9) pp. 1158-1162.

Coleman, Khan, and Blau, "Small but strong: A review of the mechanical properties of carbon nanotube-polymer composites," *Carbon*, 44 (2006) pp. 1624-1652.

Fisch and Herrmann, "A tutorial on alpha-channeling," *Plasma Phys Contr F*, 1999 vol. 41 pp. A221-A228

Garnier, *et al.*, "Design and initial operation of the LDX facility," *Fusion Eng Des*, 2006 vol. 81 (20-22) pp. 2371-2380.

Garnier, *et al.*, "Confinement improvement with magnetic levitation of a superconducting dipole," *Nucl Fusion* 49, 055023 (2009).

Goldston, *et al.*, "A plan for the development of fusion energy," *J Fusion Energ*, 2002 vol. 21 (2) pp. 61-111.

Green, "Quench Protection and Design of Large High-Current Density Superconducting Magnets," *IEEE Trans. on Magnetics*, vol. 17 (1981) pp. 1793-1798.

Hazelton and Selvamanickam, "SuperPower's YBCO Coated High-Temperature Superconducting (HTS) Wire and Magnet Applications," *Proc. IEEE*, 97, 1831-1836 (2009).

Hoang, *et al.*, "Particle pinch with fully noninductive lower hybrid current drive in Tore Supra," *Phys Rev Lett*, 2003 vol. 90 (15) p. 155002

Kalinowsk and Colschen, "International Control of Tritium to Prevent Horizontal Proliferation and to Foster Nuclear Disarmament," *Science & Global Security*, 1995, vol. 5, pp. 131-203

Kesner, *et al.*, "Helium catalysed D-D fusion in a levitated dipole," *Nucl Fusion*, 2004 vol. 44 (1) pp. 193-203

Kesner, *et al.*, "Stationary density profiles in the Levitated Dipole Experiment: toward fusion without tritium fuel," *Plasma Phys Contr F*, 2010 vol. 52 p. 124036

Kesner, Garnier, and Mael, "Fluctuation driven transport and stationary profiles," *Phys Plasmas*, 2011 vol. 18 p. 050703.

Khvesyuk, *et al.*, "Ash Pumping From Mirror and Toroidal Magnetic Confinement Systems," *Fusion Technol*, 1995 vol. 27 pp. 406-408.

Kim, *et al.*, "Detect-and-Activate-the-Heater Protection Technique for YBCO Coils," *IEEE T Appl Supercon*, 2008 vol. 18 (2) pp. 1337-1340.

Kobayashi, Rogers, and Dorland, "Particle Pinch in Gyrokinetic Simulations of Closed Field-Line Systems," *Phys Rev Lett*, 2010 vol. 105 p. 235004.

Kouznetsov, Freidberg, and Kesner, "Quasilinear theory of interchange modes in a closed field line configuration," *Phys Plasmas*, 2007 vol. 14 (10) p. 102501.

Kulcinski, *et al.*, "Summary of Apollo, a D-<sup>3</sup>He Tokamak Reactor Design," *Fusion Technology*, vol. 21 (1992) pp. 1779.

Markiewicz, "Protection of HTS Coils in the Limit of Zero Quench Propagation Velocity," *IEEE T Appl Supercon* **18**, 1333–1336 (2008).

Mauel, *et al.*, "High Power RF Heating in the LDX Experiment," *BAPS.2010.DPP.NP9.27*, 2010.

Nevins, "A review of confinement requirements for advanced fuels," *J Fusion Energy*, 1998 vol. 17 (1) pp. 25-32.

Pastukhov and Chudin, "Self-Consistent Turbulent Convection in a Magnetized Plasma," *JETP Letters*, 2005 vol. 82 (6) pp. 356-365.

Saitoh, *et al.*, "Formation of High-beta ECH Plasma and Inward Particle Diffusion in RT-1," *J Fusion Energ*, 2010 vol. 29 (6) pp. 553-557.

Sawan, Zinkle, and Sheffield, "Impact of tritium removal and He-3 recycling on structure damage parameters in a D-D fusion system," *Fusion Eng Des*, 2002 vol. 61-2, 561-567.

Sheffield, Batchelor, Zinkle, and Sawan, "Reference scenario for an advanced deuterium power plant system," *Fusion Engineering*, SOFE2002, 2002 pp. 252-255

Sheffield and Sawan, "Deuterium-fueled power plants with tritium suppression," *Fusion Sci Technol*, 2008, vol. 53 (3) pp. 780-788.

Stott, "The feasibility of using D-<sup>3</sup>He and D-D fusion fuels," *Plasma Phys Contr F*, 2005 vol. 47 (8) pp. 1305-1338.

Tanaka, *et al.*, "Particle Transport of LHD," *Fusion Science & Techn.*, 2010 vol. 58 p. 70.

Teller, *et al.*, "Space Propulsion by Fusion in a Magnetic Dipole," *Fusion Technology*, vol. 22 (1992) pp. 82.

Walt, "Radial Diffusion of Trapped Particles Induced by Fluctuating Magnetospheric Fields," *Space Sci Rev*, 1971 vol. 12 (4) pp. 446.

Watanabe, *et al.*, "Compact Design of a 30 T Superconducting Magnet Incorporating YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> Coated Conductor Tapes and Pre-reacted Nb<sub>3</sub>Sn Strand Cables," *Appl. Phys. Express*, 2008 vol. 1 p. 101703

Whyte, *et al.*, "I-mode: an H-mode energy confinement regime with L-mode particle transport in Alcator C-Mod," *Nuclear Fusion*, 2010 vol. 50 p. 105005.

Yano, *et al.*, "Preliminary Results of ICRH on the RT-1 Magnetospheric Device," *BAPS.2011.DPP.UP9.82*, 2011.

Yoshida, *et al.*, "First Plasma in the RT-1 Device," *Plasma and Fusion Research*, 2006 vol. 1 pp. 008-008.

Zinkle, "Advanced materials for fusion technology," *Fusion Eng Des*, 2005 vol. 74 (1-4) pp. 31-40.

Zhukovsky, *et al.*, "First integrated test of the superconducting magnet systems for the Levitated Dipole Experiment (LDX)," *Fusion Eng Des* **75-9**, 29–32 (2005).

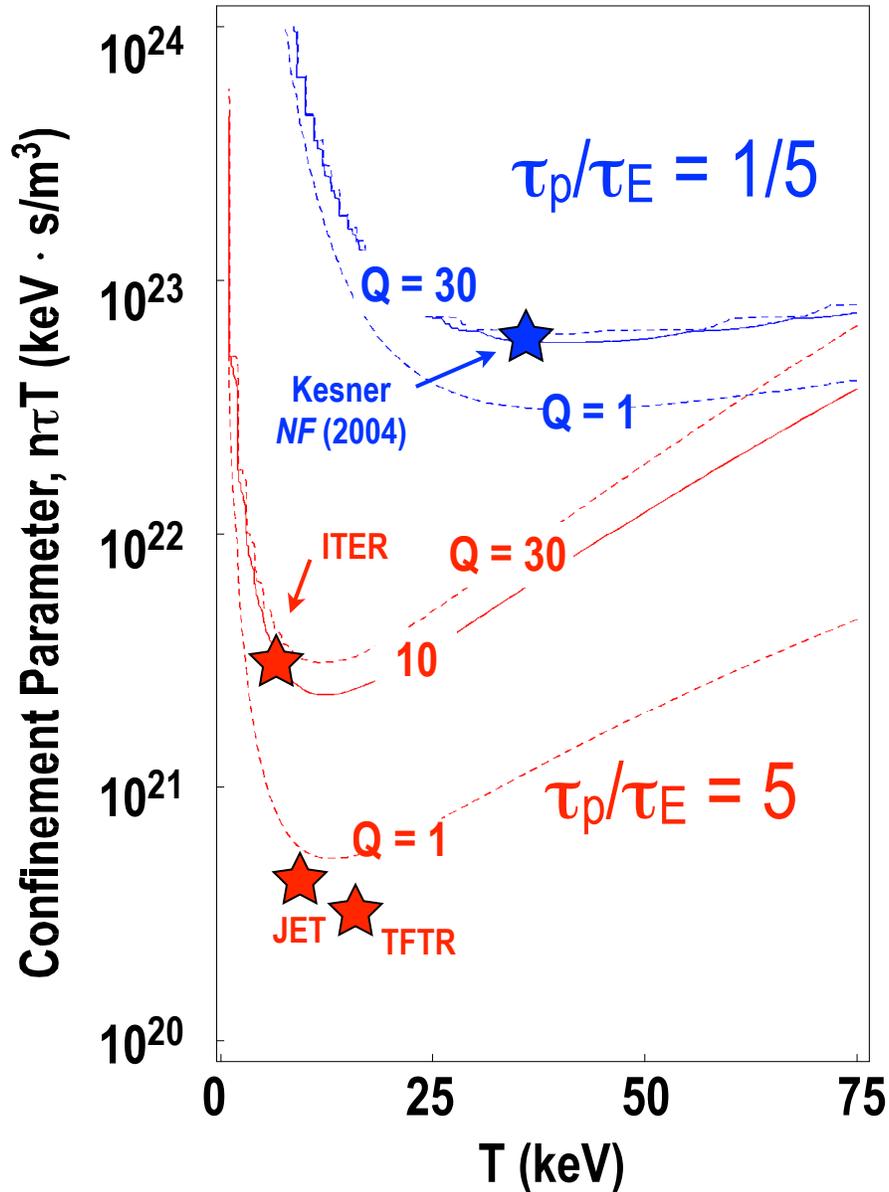


Figure 1. Fusion gain,  $Q$ , as a function of the confinement product and ion temperature. For D-T/Li fusion (red), the particle confinement time was taken to be five times longer than the energy confinement time. For tritium-suppressed D-D fusion (blue), the particle confinement time was five times *less* than the energy confinement time. The ITER base-case scenario and target parameters for a dipole fusion reactor [Kesner, 2004] are indicated along with the TFTR and JET achievements.

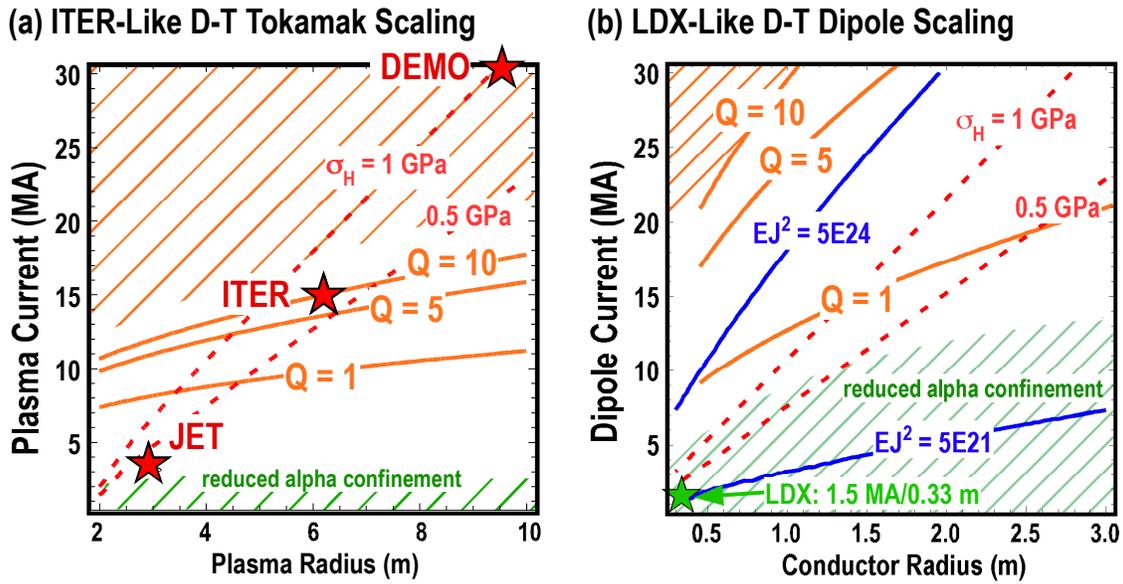


Figure 2. Scaled engineering parameters and fusion  $Q_{DT}$  for long-pulse D-T fusion experiments. (a) Scaling for ITER-like tokamak fusion showing the requirements for very large current and size to achieve high power. (b) For fixed dipole radius, the confining magnetic field increases linearly with the dipole current. A modest gain,  $Q_{DT} \sim 1$ , fusion performance experiment could be built within today's engineering constraints: hoop stress below 1,000 MPa and magnet energy below the quench "burnout limit",  $EJ^2 > 5 \times 10^{24} \text{ J MA}^2/\text{m}^4$  [Green, 1981]. Building a superconducting dipole with a 4 m diameter levitated dipole energized to 15 MA,  $Q_{DT} \sim 1$  (energy breakeven) can be achieved, demonstrating the plasma confinement parameters required for tritium-suppressed fusion.