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The dynomak: An advanced spheromak reactor concept with imposed-dynamo current drive and next-generation nuclear power technologies

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A high-β spheromak reactor concept has been formulated with an estimated overnight capital cost that is competitive with conventional power sources. This reactor concept utilizes recently discovered imposed-dynamo current drive (IDCD) and a molten salt (FLiBe) blanket system for first wall cooling, neutron moderation and tritium breeding. Currently available materials and ITER-developed cryogenic pumping systems were implemented in this concept from the basis of technological feasibility. A tritium breeding ratio (TBR) of greater than 1.1 has been calculated using a Monte Carlo N-Particle (MCNP5) neutron transport simulation. High temperature superconducting tapes (YBCO) were used for the equilibrium coil set, substantially reducing the recirculating power fraction when compared to previous spheromak reactor studies. Using zirconium hydride for neutron shielding, a limiting equilibrium coil lifetime of at least thirty full-power years has been achieved. The primary FLiBe loop was coupled to a supercritical carbon dioxide Brayton cycle due to attractive economics and high thermal efficiencies. With these advancements, an electrical output of 1000 MW from a thermal output of 2486 MW was achieved, yielding an overall plant efficiency of approximately 40%.

1. Motivation

An advanced spheromak reactor concept, henceforth called the dynomak, was formed around the recently discovered imposed-dynamo current drive (IDCD) mechanism on the steady, inductive, helicity injected torus (HIT-SI) experiment at the University of Washington. As opposed to other dynamo driven spheromak and reversed-field pinch (RFP) experiments that rely on driving the configuration unstable to provide cross-field current drive, IDCD perturbs and drives a stable spheromak configuration, possibly avoiding the severe confinement quality limitations present in other dynamo driven experiments [1]. Additionally, it has been suggested that this mechanism could provide plasma current profile control by tuning the imposed magnetic fluctuation profile via appropriate phasing of multiple inductive helicity injectors [1]. Lack of profile control has been suggested to be one of the main initiators of disruptions in tokamaks, and thus IDCD-enabled profile control could prove invaluable for tokamak reactor concepts as well [1]. Also, conventional current drive methods, namely neutral beam injection (NBI) and radiofrequency (RF) current drive, are inefficient when compared to the possible efficiency of IDCD [1]. With an efficient current drive scheme like IDCD, a lower bootstrap fraction tokamak or a spheromak configuration could be realized with a reasonable recirculating power fraction. It should be noted that the IDCD mechanism and the extrapolations from the university-scale experiment HIT-SI to the reactor-scale dynomak are speculative. In particular, core current drive via helicity injection in larger devices must be experimentally verified for IDCD to be considered a complete current drive solution for a fusion system; current drive within the core of a reactor-relevant plasma via IDCD has not been demonstrated. However, this study seeks to develop a vision for an IDCD-enabled fusion reactor system under the assumption that this current drive mechanism scales to reactor relevant regimes, providing sufficient current drive to maintain a constant $\lambda \equiv \frac{\mu_0 j}{B}$ profile within the last closed flux surface. IDCD will be used in this study to sustain a spheromak equilibrium with an ensemble of inductive helicity injectors.

A guiding philosophy behind this reactor concept was engineering simplicity and attractive reactor economics, and thus a spheromak configuration was chosen in an effort to minimize

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superconducting coil set requirements. This choice of configuration provided a more compact, low-aspect-ratio reactor concept (A = 1.5) when compared to typical tokamak and stellarator configurations [2]. Externally linked toroidal configurations suffer from compact size limitations partly dictated by the inboard $j \times B$ stress approaching unmanageable limits should high fields be used to approach economically attractive fusion power densities. Additionally, the inboard fast neutron flux limits the superconducting coil lifetime unless substantial neutron shielding is used, which typically comes at the expense of tritium breeding blanket materials. Without sufficient tritium breeding materials, an increase in reactor size is typically required to simultaneously achieve a sufficient TBR and an economical superconducting coil set lifetime. However, the simply connected spheromak topology and reliance on plasma currents to generate toroidal magnetic flux eliminates the mentioned structural and nuclear engineering limitations intrinsic to tokamaks and stellarators, allowing for the possibility of more compact, cost effective reactors.

Previous spheromak reactor concepts exploited high-β ($\beta \equiv (2\mu_o p)/B^2$) plasmas in very compact configurations with neutron wall loadings upwards of 20 MW m^{-2} for a proposed 1 GWe power plant [3], which are aggressive values when compared to more recent fusion reactor design studies [2,4] that benefit from a more substantive understanding of damage to materials in a deuterium-tritium (DT) fusion environment. Additionally, electrodes were used to inject helicity for spheromak sustainment in the aforementioned study, which results in open field lines that are effectively line-tied to the electrodes. Thus, this method of helicity injection effectively introduces a diverted magnetic topology [3], which is characteristic of most modern tokamaks that exploit H-mode. However, the use of a diverted topology focuses the plasma heat load, when it would be preferred from a materials engineering and first wall cooling standpoint to distribute the heat load uniformly on the plasma-facing first wall. The dynomak reactor system eliminates the necessity for a diverted topology using steady inductive helicity injection by not requiring electrodes. Thus, it is argued the plasma heat load will be distributed uniformly on the first wall, eliminating aggressive divertor cooling requirements.

While considering the economic attractiveness of fusion power, the ARIES-AT reactor study found that for 1 GWe power plants, economic improvements begin to saturate for increasing neutron wall loadings above approximately 4 MW m^{-2} [4]. While considering first wall cooling requirements using a uniform plasma heat load for the dynomak reactor concept, a neutron wall loading of 4.2 MW m^{-2} was chosen as an operating point. This low neutron wall loading, when compared to the previously mentioned spheromak reactor study [3], equates to a longer fusion power core (FPC) lifetime while optimizing reactor economics using the wall loading metric from the ARIES-AT study. It is an economic imperative for fusion energy to be competitive with conventional power sources to be considered as a replacement. The estimated overnight capital cost of the dynomak reactor concept will be argued to be competitive with fossil fuel energy sources. Using established materials will allow for an expedited NRC licensing process with a well developed pedigree of material performance in fission reactors; however, a fusion nuclear science facility (FNSF) will still be required. An FNSF is a necessary developmental step to study material degradation in a DT fusion environment and first wall plasma-material interactions. Lastly, it was sought to minimize the activation of surrounding reactor components to fully exploit one of the main advantages of fusion over fission: having only limited quantities of short-lived radioactive waste dependent on the choice of surrounding materials.

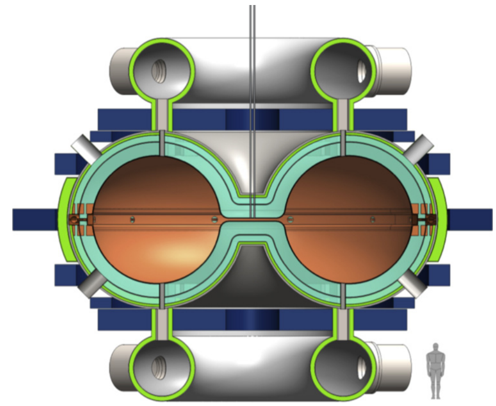

Fig. 1. A sliced rendering of the dynomak reactor concept, excluding the secondary power conversion cycle.

2. Dynomak overview

The dynomak is a high-β spheromak reactor concept that uses six inductive helicity injectors located on the outboard midplane to sustain a spheromak equilibrium with a nearly circular poloidal cross section. A molten salt mixture of LiF and BeF_2 commonly referred to as FLiBe is used as the first wall coolant, neutron moderator and tritium breeding medium [15]. The widespread usage of FLiBe is motivated by the engineering simplicity of using a single working fluid in the blanket system. A dual-chambered blanket system is used in the dynomak concept, which is depicted in turquoise in Fig. 1, and will be described in detail. The FLiBe exits the dynomak reactor through the depicted large pipes and couples to the secondary, supercritical CO_2 power conversion cycle.

The orange copper coils located near the outboard midplane in Fig. 1 exclude magnetic flux from the helicity injector region to ensure satisfactory injector operation. Due to the loss of blanket material in this region, an additional zirconium hydride neutron shield is placed in the outboard midplane region to supplement the zirconium hydride shield encircling the nearly doubly connected reactor vessel topology. Neutron shielding is depicted in green in Fig. 1. An insulating break is placed on the geometric axis on midplane, classifying this system as a spheromak and allowing for free creation of toroidal flux. Gas injection occurs in the insulating break region, which will expand major radially outward to fuel the reactor. Pumping channels on top and bottom are used to remove helium ash in an effort to maintain a helium fraction of less than 3%. Two, large pumping manifolds on top and bottom are depicted with ITER-developed cryosorption pumps oriented to avoid fast neutron beams emanating from the pumping channels. The high-temperature superconducting equilibrium coil set is depicted in blue, which utilizes yttrium barium copper oxide (YBCO) tapes operating at subcooled liquid nitrogen temperatures of approximately 65 K. This choice of superconducting material reduces the cooling power requirement when compared to more conventional niobium based superconductors that typically require liquid helium cooling. YBCO has been tested up to a fluence of 2.8×10^{22} m^{-2} at a temperature of 81 K, and no degradation of the critical current density was observed [5]. The threshold fast neutron fluence for the degradation of the critical current density of Nb_3Sn is approximately 3×10^{22} m^{-2}, and thus YBCO irradiation resistance may be as good or better than Nb_3Sn [5]. A higher tolerance to fast neutron damage of these superconductors would equate to a longer lifetime of these expensive components.