Physics Issues for the Apollo Advanced Fuel Tokamak

G.A. Emmert and J.F. Santarius

October 1989

UWFDM-812

Presented at the 13th Symposium on Fusion Engineering, 2–6 October 1989, Knoxville TN; published in IEEE 89CH2820-9 (1990) 655.

Physics Issues for the Apollo Advanced Fuel Tokamak

G.A. Emmert and J.F. Santarius

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

October 1989

UWFDM-812

Presented at the 13th Symposium on Fusion Engineering, 2–6 October 1989, Knoxville TN; published in IEEE 89CH2820-9 (1990) 655.

PHYSICS ISSUES FOR THE APOLLO ADVANCED FUEL TOKAMAK

G.A. Emmert and J.F. Santarius
Fusion Technology Institute
University of Wisconsin-Madison
1500 Johnson Drive
Madison, WI 53706-1687

Abstract

A scoping study of a commercial D-^{3}He tokamak reactor, Apollo, is being carried out. The present design is for operation in the first stability regime and utilizes rectennas for direct conversion of synchrotron radiation to electricity coupled with synchrotron current drive. Very low neutron wall loading (0.1 MW/m^2) is obtained by suitable choice of the fuel mixture. Physics trade-offs leading to the chosen design point and critical issues, which include the removal of fusion generated ash, the need for high wall reflectivity for synchrotron radiation, and current drive, are discussed.

Introduction

The Apollo study is a scoping study of a D-^{3}He tokamak operating in the first stability regime and utilizing direct conversion of synchrotron radiation to electricity as well as synchrotron current drive to drive part of the plasma current. An overview of the Apollo design is presented in a companion paper [1] and engineering details are given in other papers [2-4] at this conference. In this paper we consider the modelling of the plasma and plasma-related critical issues that have emerged from the physics modelling.

Plasma Performance Modelling

The performance of Apollo with D-^{3}He fuel can be calculated using power balance considerations to get the fusion power produced and the losses from the plasma. The loss mechanisms of concern are radiation losses by bremsstrahlung and synchrotron radiation, and transport across the confining magnetic field by conduction and convection. The plasma density and temperature that can be confined by the magnetic field are determined by MHD equilibrium and stability requirements. The plasma pressure, which is of concern for MHD, is determined not only by the fuel plasma, but also by the energetic ions generated by fusion reactions, and by the accumulation of ash and impurities. The energy of the charged particles generated by the fusion reactions also helps to maintain the energy of the reacting plasma. Folding all these effects together provides a mechanism for estimating the performance of Apollo using D-^{3}He fuel.

A computer code, called DHE3TOK, has been developed in order to estimate the performance of a tokamak power reactor operating with D-^{3}He. The code is basically a zero-dimensional power balance code which calculates the ignition margin, M, defined as the ratio of the fusion power produced to the total losses, and the energy multiplication, Q, which is defined as the ratio of the fusion power to the external power injected into the plasma, for a given set of plasma conditions. The injected power is the power required to sustain the plasma conditions. For Apollo some injected power is required to maintain the plasma current, so that steady-state operation is achieved.

The plasma contains two fuel ion species (deuterium and ^{3}He) and three "ash" ion species (photons, alphas, and tritium). We also allow for a single impurity ion (e.g. oxygen), which is assumed to be fully stripped. Protons and alphas are produced primarily by the ^{3}He(d,p)^{4}He reaction. The D(d,p)T side reaction produces tritium which is important for evaluating the generation of 14 MeV neutrons.

The fusion power, P_f, is given by integrating the local fusion power density over the plasma. This calculation involves the Maxwellian-averaged fusion cross-section $<\sigma v>_f$, which depends on radius, r, through its dependence on the ion temperature and assumes the two ion species are Maxwellian at the same temperature. We include the accumulation of fusion produced ash (protons, tritons, and alpha particles); the ash density is determined by the balance of the production rate and the loss rate. The particle confinement time is taken to be the same for all ash species. The electron density is determined by quasineutrality.

The volume averaged plasma beta is given by the Troyon formula [5] with a coefficient determined by fits to MHD stability calculations and depends on the aspect ratio, elongation, current profile, and pressure profile. Included in the pressure are the effects of the various ion species, all of which are assumed to have the same ion temperature, the electrons, which have temperature $T_e(r)$, and also the pressure [6] of the hot ions generated by fusion reactions.

To determine the injected power required to sustain the plasma at a specified operating temperature, it is necessary to account for the various mechanisms by which the plasma loses energy. Bremsstrahlung radiation, with relativistic corrections [7], from the electrons is an important loss process, especially at low temperature and high density. Synchrotron radiation from the electrons is another form of radiation loss. While this is a classical process and is in principle calculable, it is a difficult radiation transport problem because the plasma is both a strong emitter and absorber of synchrotron radiation. We use a 'universal formula' developed by Trubnikov [8] to estimate the synchrotron power loss. Heindler et al. [9] has compared the Trubnikov formula with results from 1-dimensional transport calculations using the CYTRAN code. This comparison gave good agreement between the two if the volume averaging of the Trubnikov formula is done in a particular manner. Heindler et al. recommends using Trubnikov's formula as a local loss term and volume averaging the entire formula, rather than using the volume-averaged density and temperature in the Trubnikov formula. We have adopted their recommendation for the Apollo study.

The remaining energy loss process is transport across the magnetic field by conduction and convection. This is treated using empirical energy confinement times, which are obtained by regression analysis of experimental data on present tokamaks. A number of different confinement scaling expressions have been proposed [10]. It is difficult to recommend any particular scaling law for D-^{3}He reactor studies since the degree of extrapolation from the present database is rather large. The DHE3TOK code, however, requires some method for evaluating the power lost from the plasma by transport across the magnetic field. In this study, we use the Kaye-Goldston scaling law for this purpose with an enhancement factor of 2.5 to illustrate the confinement required relative to a well-known scaling expression. The enhancement factor can be interpreted as due to H-mode operation or to other improvements in confinement relative to this scaling expression. The DHE3TOK code has been benchmarked against the COLIF advanced fuels code and compares favorably with it.

An important consideration for advanced fuels is the accumulation of fusion produced ash in the plasma. "Ash" refers to the charged particles produced by the fusion reactions ^{3}He(d,p)^{4}He, D(d,p)T, and T(d,n)^{4}He. Ash (p, T, ^{4}He) accumulation reduces the allowed fuel density for a given beta and therefore reduces the fusion power density. Advanced fuels require good confinement in order to achieve ignition, but if the confinement is too good, then ash accumulation becomes a problem. In choosing the Apollo design point, we assume that we can control the particle confinement time, τ_p^a , of the ash separately from the energy confinement time, τ_E, of the fuel. Rather than specify the particle confinement time of the ash, we determine the required particle confinement time such that the density of the ash (protons, alphas, and tritium) of the plasma does not exceed 10% of the fuel density. If the ratio τ_p^a / τ_E is less than that suggested by the present experimental database (τ_p^a / τ_E about equal to 3), then some form of active ash removal is required.

The important plasma parameters for the basic Apollo-L2 design point (case B) and one variation (case A) are given in Table 1. Case B is the same as that in Ref. 1 and case A is a minor modification of case A in Ref. 1. Both cases have the same net electrical output power of 1200 MW. Case A assumes direct conversion of the synchrotron radiation using rectennas and conversion of the thermal power using a steam cycle, while case B assumes synchrotron conversion only, and discards the thermal power. In addition to the 10% ash accumulation, an oxygen impurity level of 1% is assumed. The net reflectivity of the first wall includes the effect of penetrations as well as absorption in the first wall itself.

Table 1. Key Plasma Parameters for Apollo

	A	B
Major Radius (m)	6.55	7.11
Aspect Ratio	2.5	2.5
Elongation	2.0	2.0
Plasma Current (MA)	72.2	80.1
q-psi (95% flux)	2.67	2.67
On-axis B Field (T)	9.56	9.75
H-mode Factor (KG)	2.5	2.5
τ_E (s)	24.0	23.4
τ_p^a (s)	16.0	13.2
Ion Density (10^{20} m^{-3})	1.54	1.07
Ion Temp. (keV)	51.3	70.7
Electron Temp. (keV)	65.0	80.0
Troyon Coefficient	3.25	3.25
Beta (%)	9.4	9.3
Net Synch. Reflectivity	0.92	0.95
Current Drive Power (MW)	44	40
Fusion Power (MW)	2336	2807

Ash Accumulation

As described above, the Apollo design point sets the allowed ash concentration to 10% of the fuel ion density and determines the particle confinement time of the ash required to achieve that value. In this section we consider the effect of varying the confinement time of the ash on the performance of Apollo, using the base design point as a starting point. Since the slowing down time of fast ions in the plasma is typically much less than the particle confinement time, we assume none of the fast ions are lost during the slowing down phase; their pressure is already included using the analysis of Ref. 4. Here we are concerned with the effect of the thermalized ash species. The equilibrium density of an ash species is given by the balance equation,

$$\int n_1 n_2 \langle\sigma v\rangle_{12}\, dV = \frac{1}{\tau_p^a} \int n_a\, dV$$

where τ_p^a is the particle confinement time of the ash and the subscripts 1 and 2 denote the species that react with cross-section $\langle\sigma v\rangle_{12}$ to form the ash species a. We assume that all ash species have the same particle confinement time.

Figure 1 shows the effect of increasing the ratio of τ_p^a / τ_E on the ash concentration for both cases A and B. The effect of τ_p^a / τ_E on the fusion power and the electrical output power is shown in Figure 2. As the ash accumulates, the fusion power drops and losses have to be reduced to hold the power balance on the plasma. We assume in this study that this is done by increasing the net reflectivity of the first wall (reducing the

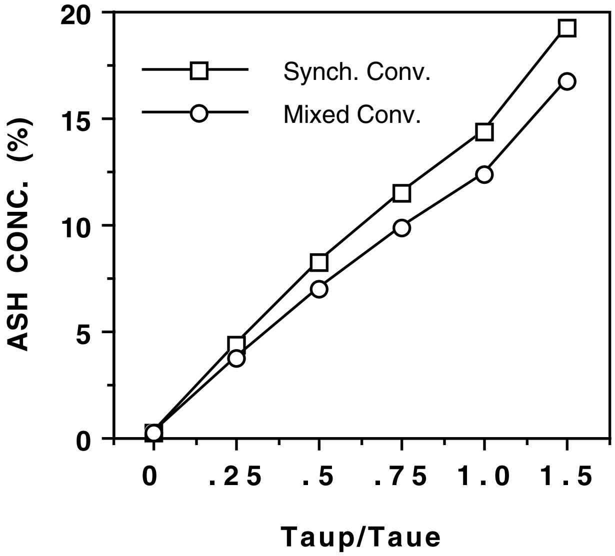

Fig. 1. Ash concentration versus τ_p^a/τ_E.

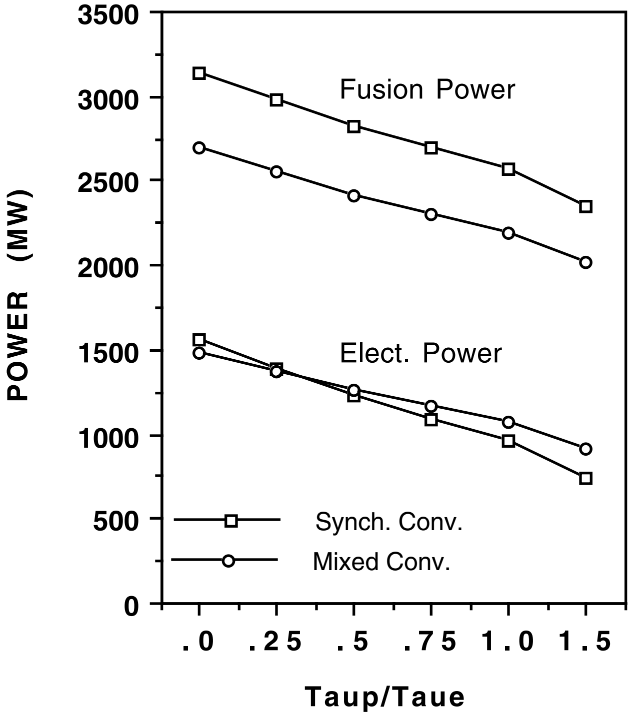

Fig. 2. Effect of ash concentration on the fusion power and the net electrical power.

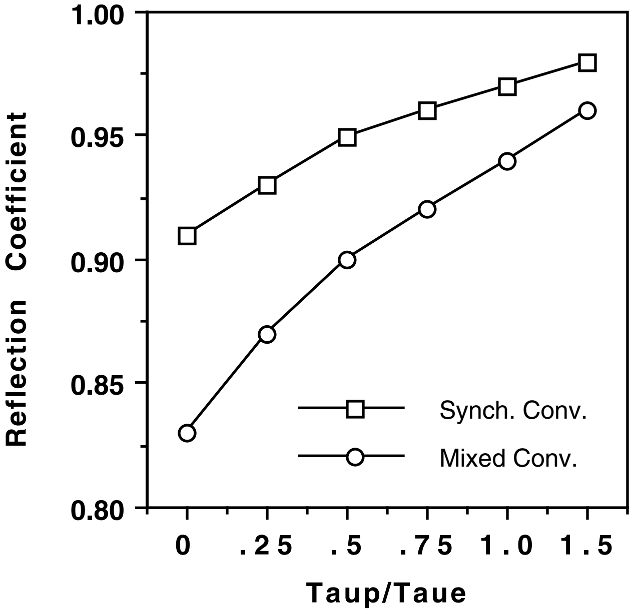

Fig. 3. Required synchrotron reflectivity for plasma power balance.

fraction of the first wall taken up by penetrations is one possibility). Figure 3 shows the required net reflectivity of the first wall versus τ_p^a/τ_E. These calculations show that the design point is very sensitive to ash accumulation; higher values of τ_p^a/τ_E cause the electrical power to degrade rapidly and lead to unrealistic requirements on the wall reflectivity. Case B is more sensitive to ash accumulation because it has a larger fraction of the energy lost by radiation and consequently needs a large $n\tau_E$ for power balance. If we were to use mixed thermal and synchrotron conversion for case B, then one could operate with τ_p^a/τ_E equal to 1.4 and still have a net electrical power of 1200 MW.

The small values of τ_p^a/τ_E needed for Apollo indicate that some form of active ash removal is needed. Since the ash is formed in the plasma core, the ash removal system must be effective there. Impurity removal systems which are effective only at the plasma boundary are not sufficient. Also, the ash removal system has to be species selective; it must not also decrease the confinement time of the fuel ions. One possibility is to use RF to induce stochastic transport of the protons and alpha particles. The protons have a different charge to mass ratio than the fuel so perhaps this can be done selectively. The alpha particles are more of a problem since they have the same charge to mass ratio as the deuterium. Since the protons and alpha particles are born at high energy, perhaps one can use RF resonating with a drift or bounce motion to induce stochastic transport without adversely affecting the fuel ions. Another possibility is that the fast ions may cause instabilities which induce stochastic transport. This has been analyzed to some extent for D-T plasmas [11]; the same analysis is also applicable to D-^{3}He plasmas.

Current Drive

The large plasma current (70-80 MA) in Apollo places a considerable demand on the current drive system. Part of the current is attributable to the bootstrap current, and part can be driven by synchrotron radiation, but the rest has to be driven by an external current drive system that requires power and reduces the net output of the plant.

The fraction of the total current attributed to the bootstrap current has been analyzed by Devoto, Fenstermacher, and Mirin [12] for the TIBER test reactor design. Applying their analysis to Apollo (case B) yields a bootstrap current fraction of 32%. Bootstrap currents have also been analyzed by Hsiao, Ehst, and Evans [13] for RF driven tokamak equilibria. Their analysis yields a 22% reduction in the required current drive power due to the bootstrap current. This differs from the bootstrap current fraction because of the different radial form of the bootstrap current density profile, the net current density profile, and the effectiveness of the RF system in driving current in the core versus near the edge. Neither analysis is directly applicable to Apollo, but they indicate that the fraction of the total current that can be attributed to the bootstrap current is in the range 20-30% for Apollo. This is a low bootstrap current fraction and arises because of the broad pressure profile required to maximize beta and because of the low poloidal beta.

Synchrotron current drive was first suggested by Dawson and Kaw [14]; they proposed a sawtooth-shaped first wall with a directional absorbtivity such that synchrotron absorption imparts a net momentum to the wall. The reaction back on the electrons is a net momentum which counters the momentum lost due to plasma resistivity and maintains the plasma current. In Apollo, we extract the synchrotron radiation by waveguides and convert it to electricity using rectennas. This waveguide system can be oriented to also extract net momentum from the radiation field and thus should be compatible with synchrotron current drive. Using an expression developed by Mau [15], which is based on the analysis of Fidone [16], we estimate that the current driven by synchrotron radiation is about 74 MA for case B of Apollo.

Using the above results for the bootstrap current fraction and for synchrotron current drive, we estimate for case B that the bootstrap current is about 20 MA and the total driven current is 94 MA, which exceeds the desired current of 80 MA. Consequently, the combination of bootstrap and synchrotron radiation can provide more than the required current. Of course, the current driven by synchrotron radiation can be reduced by appropriate design so that the net current is 80 MA. Furthermore, the current driven by bootstrap and synchrotron radiation should be designed to be less than the net current so that some external power is used to maintain and control the current. In the Apollo design, we assume 40 MW of external power is sufficient for this purpose. Problems requiring further analysis are consistency of the current profile with MHD equilibrium and time-dependent startup of the plasma current.

Acknowledgements

This research was supported by the Wisconsin Electric Utilities Research Foundation, the Electric Power Research Institute, Grumman Aircraft Corp., Grainger Electric Corp., and by Kernforschungsanlage Jülich, West Germany.

References

[1] G.A. Emmert, G.L. Kulcinski, et al., "Apollo-L2, An Advanced Fuel Tokamak Reactor Utilizing Direct Conversion", this conference.

[2] H.Y. Khater, M.E. Sawan, et al., "Activation and Safety Analyses for the D-^{3}He Fueled Tokamak Reactor Apollo," this conference.

[3] Laila El-Guebaly, "Shielding Design Options and Impact on Reactor Size and Cost for the Advanced Fuel Reactor-Apollo," this conference.

[4] L.J. Wittenberg, "Pellet Fueling of Helium-3 Enclosed in Li and Be Shells," this conference.

[5] F. Troyon, R. Gruber, et al., Plasma Phys. & Cont. Fusion, 26, 209 (1984).

[6] B. Deng and G.A. Emmert, "Fast Ion Pressure in Fusion Plasmas", University of Wisconsin Fusion Technology Institute Report, UWFDM-718 (1987).

[7] J. Rand McNally, Nuclear Fusion/Technology, 3, 9 (1982).

[8] B.A. Trubnikov, Reviews of Plasma Physics, 7, 1979 Plenum Press p. 345.

[9] M. Heindler, A. Nassri, W. Kernbichler, et al., "Synchrotron Radiation in Fusion Power Reactors", Sherwood Theory Meeting, San Antonio, Texas, paper 2C25, April 3-5, 1989.

[10] N.A. Uckan and the ITER Physics Group, "ITER Physics Design Guidelines" ITER-TN-PH-8-7, Oak Ridge National Lab., Jan. 1989.

[11] B. Coppi and F. Porcelli, "Plasma Oscillation Bursts and Scattering of Intermediate Energy Alpha Particles", Fusion Technology, 13, 447 (1988).

[12] R.S. Devoto, M.S. Fenstermacher, and A.A. Mirin, "Modeling of Neutral Beam Current Drive and Bootstrap Effects in a Tokamak Test Reactor" Lawrence Livermore Lab. Report UCRL-100599, Feb. 1989.

[13] M.-Y. Hsiao, D.A. Ehst, and K. Evans, Jr., "Bootstrap Currents in Radiofrequency Driven Tokamak Equilibria", Nuclear Fusion, 29, 49 (1989).

[14] J.M. Dawson and P.K. Kaw, Phys. Rev. Lett., 48, 1730 (1982).

[15] T.K. Mau, private communication.

[16] I. Fidone, G. Granata, and J. Johner, "Current Sustainment by Synchrotron Radiation in a Tokamak Device", Phys. Fluids, 31, 2300 (1988).