RACER (Ring ACceleratEd Reactor)

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ABSTRACT

A fusion reactor concept is described in which a low-beta plasma is supplied with D-T fuel, heating, and inductive energy using high-speed plasma rings injected from both ends into a central chamber. A large plasma current is slowly built up over time using modest injection hardware. The concept appears to be more attractive than current magnetic and inertial fusion approaches.

INTRODUCTION

The RACE (Ring Acceleration Experiment) machine at LLNL [1], performed in the 1980s, and its successor, MARAUDER [2] were coaxial guns capable of accelerating dense plasma rings to over 2000 km/sec with injection efficiencies over 25%. At this velocity, if D-T were used instead of hydrogen, ion temperatures of up to 50 keV could be achieved after slowing down and thermalizing. Thermalized electron temperatures, on the other hand, would be only a few eV initially. Therefore, unlike ohmic heating, this approach could first heat the ions directly, which would make more effective use of allowable plasma pressures when starting up.

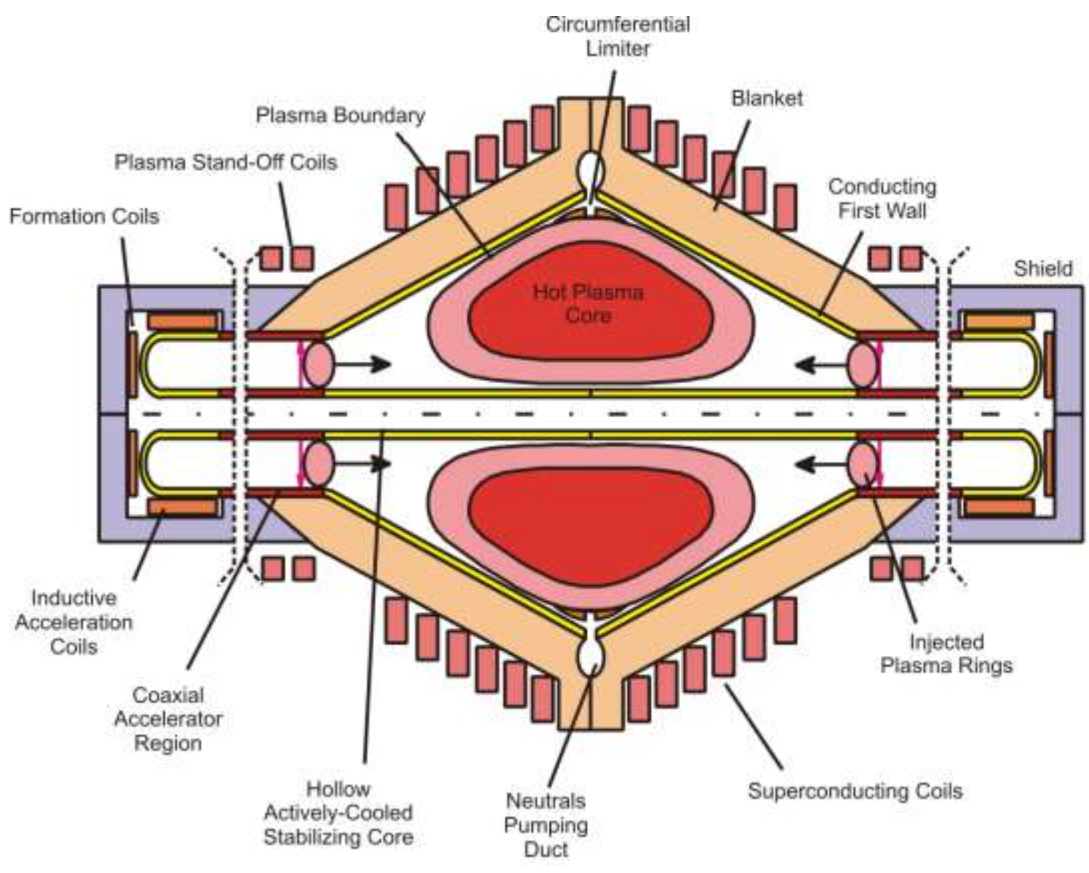

Fig. 1. Reactor concept with spheromak main plasma and both inductive and coaxial plasma ring accelerators.

That there is interest in compact torus injection is shown by the number of experiments conducted in the past and recently [3-6]. There have also been some interesting reactor studies as well [7,8]. The purpose of this article is to add some innovations to this body of knowledge.

GENERAL DESCRIPTION

A cross-section of the reactor concept is shown in Fig. 1 above. It is cylindrically symmetric, and the left and right halves can be slid apart for maintenance access. The plasma is surrounded by conical conducting first walls and neutron-absorbing blankets. Outside the blanket are superconducting coils that keep the confining plasma current from expanding outward. The coil fields are stronger at the ends to keep the current centered in the chamber. A central passive core, which is hollow, actively-cooled and electrically conducting, helps stabilize the plasma vertically. There is no current in that core.

To each side of the main plasma are the injectors. These supply D-T fuel in plasma rings at very high velocity. The embedded currents in these rings merge with the main plasma current and slowly build it up. Inductive acceleration first brings the plasma rings up to a few hundred km/sec. Then the coaxial accelerators take over and bring the rings to about 1600 km/sec.

The injector system requires capacitor banks of several megajoules each for plasma formation and for acceleration. Pulse rates around 20 Hz are needed. Based on results from RFP-type experiments [9], these parameters appear feasible.

THE LOW-BETA MAIN PLASMA

The main plasma could be a spheromak (some toroidal flux) or field-reversed mirror (poloidal flux only). In either case it is low beta (ratio of plasma pressure to magnetic pressure). The result is a very high plasma current (about 60 MA) at the fusion power densities needed. The external coils keep this current, and the plasma, firmly in place, much like toroidal fields that stabilize the plasma in tokamaks.

The plasma sketched in Fig. 1 shows an inner and outer boundary. This is an artifact used in the calculations to approximate density and temperature profiles. The inner hot core is assumed to have uniform density and temperature throughout and is taken to be the useful reacting plasma volume. The outer section is taken to have no particles.

Energy confinement in spheromaks has been low, probably because the experiments have been small. It is expected that the large plasma current in this concept will provide better confinement. However, some energy losses may be preferred to none. Fusion ignition may actually be undesirable because then control is lost and a thermal excursion could occur. Instead, it is preferred that some external heating is needed to maintain an optimum plasma temperature (about 13 keV) while not requiring too much recirculating power.

REACTOR PARAMETERS

The reactor concept shown in Fig. 1 is intended to produce 500 MW of electricity for sale. Up to 150 MW(e) is used to start up the reactor. During startup, the power is taken from the grid. It may also be necessary to add power during the steady state burn, depending on plasma transport losses. Then the power is supplied by the plant electric generator. The gross electricity generated would be as high as 650 MW(e). This amounts to 23% recirculating power. Much higher than that would adversely affect plant economics.

The plasma rings fired into the main plasma supply everything needed to keep it going: fuel, heating, and inductive energy. The main plasma is of course resistive, especially at the beginning. In this simple analysis, it is assumed that 99% of the thermal and inductive energy delivered is dissipated as heat in the plasma. That still leaves one percent to build up the main plasma density and current.

The end result is a very long startup time, about 11 hours. This is actually advantageous because the superconducting coils, whose fields must follow the poloidal field, take time to charge up, as does starting up the power plant.

The energy used for startup, about 1700 kW-hr, must be purchased. The cost of this (~$170 K at $0.10/kW-hr) is recoverable in only about six hours of selling the 500 MW(e) of electricity at half that rate. After startup, operation is steady state indefinitely.

It is assumed that the same 150 MW(e) is needed during steady state, although most likely it will be considerably lower.

The reactor parameters are selected to be rather conservative, increasing the chance of success. In addition to the 500 MW(e) for sale, other fixed parameters are poloidal beta, 10%, and average neutron wall loading, about 2 MW_n/m^2.

The poloidal beta is about half that already achieved [5]. The second requires some discussion: High neutron wall loadings for a given power no doubt produce a smaller reactor. However, this is at the cost of higher magnetic fields, higher heat fluxes and material thermal stresses, more frequent blanket changeouts due to neutron damage, and possibly poorer plasma confinement due to the smaller size. The wall loading used here is comfortable for a reactor plant, with blanket changeouts expected to occur about once per decade.

The total thermal power assumes 40% power conversion efficiency and 10% blanket neutron energy multiplication. The result is a required1625 MW(th) total, about 1200 MW of neutron power. This conversion efficiency is readily achieved with a steam plant having a peak steam temperature of 540°C (1000 °F) and a condensing temperature as high as 66 °C (150 °F). This efficiency is 70% of the ideal Carnot efficiency (about the same as existing plants). The high condensing temperature could allow plant siting in remote areas where cooling water is scarce.

A reasonable major radius, R, and plasma radius out to the limiter, a, is chosen: R = 4 m and a = 2.67 m. That gives an aspect ratio R/a = 1.5, which is common for spheromaks and allows room for a central stabilizing core. Taking the useful hot first wall area to be out to the end of the injectors and the limiter, and using a 30° cone angle, that area is 575 m^2. This gives an average neutron wall loading of 2.1 MW_n/m^2, as desired.

There is the question of the proper cone angle. The one chosen gives a prolate plasma, which might be tilt unstable. It is hoped that the central core will provide some stability. Recent experiments, however, have shown the prolate shape to be stable after merging [6].

Plasma density and temperature profiles are unknown at this point. However, because everything enters the edge of the plasma, one would expect reasonably flat density, temperature, and current density profiles. In this analysis, actual expected profiles are approximated by flat out to 0.6a with density and temperature values equal to that on axis. Outside of 0.6a all values are taken to be zero. This gives a useful reacting plasma volume of 257 m^3. The neutron power density is then 1200 MW_n/257 m^3 = 4.7 MW_n/m^3.

As mentioned above, it is assumed that the steady state burn could be made slightly subignited so that the injectors can be used to control plasma temperature. The optimum temperature, where $\langle\sigma V\rangle/T^2$ is maximized, is 13.6 keV for D-T. The term $\langle\sigma V\rangle$ is the fusion cross section at that temperature in m^3/sec. Dividing it by T^2 represents the fusion power density for a given plasma pressure in the 10-20 keV temperature range. Running at the best $<\sigma V>/T^2$ is significant because all of the investment is going into creating this pressure.

In this analysis, it is assumed that $T_i = T_e$ and plasma densities $n_i = n_e$. However, the injectors provide initial high values of T_i after thermalization at the edge of the plasma with negligible T_e, while ohmic heating heats the electrons in the center. Therefore, in reality, only detailed analysis will show the actual temperature profiles over time.

The plasma pressure at the temperatures above is 0.88 MPa. The corresponding plasma density for the power density above is $n_i = 2\times10^{20}\ m^{-3}$. With 10% beta, the confining pressure from the plasma current is 8.8 MPa.

This gives a plasma current of 63 MA and a poloidal field at the plasma edge of 4.7 T. This is the field that must be supplied at the limiter by the superconducting coils in order to prevent that current from expanding. The fields at the end coils are higher. At the moment, they are taken to be 7.0 T, a little below the maximum for NbTi superconductors.

The center and edge coil radial thicknesses are 1.2 m and 1.0 m, respectively, giving average hoop stresses for each of about 63 MPA (9 ksi). It is important for the sake of reliability to have moderate stresses like these in superconducting coils because they are difficult to repair, and failure can be catastrophic.

Repeating a key point: The high plasma current is not a major concern because the hardware needed to create it is modest. Rather than one swing of a large ohmic heating coil, many plasma rings with internal currents are rapidly injected to achieve that current. And even though the current is large, the magnetic fields needed to contain it are within the scope of existing superconducting technology. In addition, those superconducting coils are simple non-interlocking circular solenoids.

PLASMA CONFINEMENT TIME

At steady fusion burn, the alpha power is about 300 MW. This power is entirely absorbed into the plasma and then migrates out of it. Losses are Bremmstrahlung radiation, 61 MW, and alpha power transport through particle conduction, convection, and charge exchange.

In steady state, this alpha power transport is the difference between these two, 239 MW. A transport energy confinement time at steady state of $\tau_e = 0.8$ sec is needed, which is not unreasonable.

INJECTORS

The coaxial injectors are taken to be 10 m long, somewhat longer than the 6 m in the RACE experiment. This gives an average accelerating force on the plasma rings, 70 kN, equal to the inductive force holding the plasma ring together, taken to be $E_{mag}/(2a_{ring})$. This acceleration, about 10^{10}-g's, has shown to be acceptable by experiment [2]. The outer and inner electrode radii are 1.67 m and 0.55 m respectively.

Stability of the plasma ring is helped during acceleration by the fact that the electrodes have some electrical resistance. Should a part of the plasma try to advance ahead of the rest, the local accelerating current would reduce locally due to that longer, and more resistive, section of the electrode.

The plasma ring poloidal beta is taken to be 20%, twice the main plasma. The argument is that, under acceleration, it is confined and cannot go anywhere except down the tube. Ring plasma ion density is taken to be $2\times10^{19}\ m^{-3}$, lower than in the RACE experiment.

Plasma temperature during acceleration is assumed to be 100 eV. At the 20% beta, this requires a ring plasma current of 0.25 MA. The resulting inductive energy per ring is 77 kJ. Taking the RACE injection efficiency of 25%, the 150 MW(e) of peak recirculating power delivers 37 MW of injected power. The total energy injected (thermal + inductive + kinetic) per ring pair (i.e., both sides) is 1.6 MJ per injection.

With that 37 MW of total power injected, the pulse rate can be as high as 37/1.6 = 23 Hz. The total energy in the main plasma (inductive + thermal) once it reaches steady burn is 15 GJ. Assuming only one percent of the injected total energy is used to build that up, and the rest goes to heat, then at least 940,000 pulses are needed to reach steady state current and density. As said earlier, this takes about 11 hours.

MERGING OF PLASMA RINGS INTO MAIN PLASMA

It is expected that the plasma rings will merge into the main plasma and not bounce back or blow past each other [13]. This has been shown experimentally in the T-3 and SSX machines for moderate plasma ring velocities [3,5]. But magnetic reconnection and relaxation of the main plasma will dissipate some of the injected magnetic energy into heat [4].

No information has been found regarding merging of spheromaks at very high-velocities. However, there is an attractive force between the rings and the main plasma current (remember that all currents are in the same direction).

LIMITER

Because of the injection ports at both ends, divertors there do not appear feasible. Instead, a large circumferential limiter (see Fig. 1) is used to define the plasma boundary. The heat load on this limiter is made up of particle transport, Bremmstrahlung radiation and some neutron heating.

The limiter would be divided into many panels. Only one set would be fixed. The others would articulate radially by means of bimetallic strips, depending on their temperature, so as to evenly distribute the heating.

The limiter material needs to be capable of a heat load up to about 1.5 MW/m^2 (150 W/cm^2). However, it does not have to be at high temperature. Even 300°C is sufficient to make use of this heat. For example, It can be used to preheat feedwater in a steam power conversion system, eliminating the need for most of the steam extractions from the turbine stages. In fact, all the plasma facing components can be at this modest temperature and still get 40% conversion to electricity.

There are new materials coming available that could be used for the limiter. A very interesting one is DSC-Al, developed for diesel engine pistons [10], which are subjected to heat loads reaching 5 MW/m^2. The material is made up of pure aluminum interspersed with 35% aluminum oxide nanoparticles.

Table 1 gives some mechanical and thermal properties of DSC-Al at 300°C. It's thermal conductivity is very high. And its thermal expansion coefficient is about the same as stainless steel, allowing the latter to be used for attachment structure. DSC-Al appears capable of large scale production at reasonable cost.

No information is available about damage in DSC-Al from energetic neutrons. However, the material has very fine microstructure, which could be helpful. Also, with irradiation occurring at fairly high temperature, in-situ annealing may occur. At any rate, the limiters are readily accessible for rapid replacement.

Similarly, sputtering of this material by energetic plasma particles is unknown. Again though, the fine microstructure and high alumina fraction may help, as might the cloud of thermalized neutral particles expected to surround it.

TABLE 1. PROPERTIES OF DISPERSION-STRENGTHENED ALUMINUM DSC-AL AT 300°C (FROM REF. 10)

Coeff. of expansion, 10^{-6}/°C	18.3
Thermal conductivity, W/m-K	114
Density, gm/cc	3.09
Young's Modulus, GPa	117
Ultimate tensile strength, MPa	190
0.2% yield strength, MPa	165
Fatigue strength, 10^8 cycles, MPa	61

THE IMPURITY ISSUE IN THE INJECTORS

An issue with the RACE experiment was mass build up in the plasma due to sputtering of the electrodes from the plasma ring itself [11]. This seems to occur because particles in the plasma rings have very high axial momentum but little radial momentum. The resultant momentum vector is at a glancing incidence to the electrode wall. Sputtering from such shallow angles is especially severe [12], and is akin to chiseling away of the surface.

Electrons have low sputtering; so it is doubtful that the accelerating current would be a problem in this regard.

An attempt at reducing sputtering could be the following: The plasma stand-off coils shown in Fig. 1 would supply a weak axial magnetic field that is compressed between the electrically-conducting electrodes and the high-speed electrically-conducting plasma rings, as suggested in Fig. 2 below.

This hopefully would keep the energetic plasma particles off the electrode walls. The magnitude of this field needs to be determined, probably by experiment, as well as its interaction with other fields. This field compression should work best at the higher speeds, where it is needed the most.

Low-Z coatings on the electrodes may still be needed, however. Pure boron might be attractive: It is low-Z and electrically conducts at high temperature.

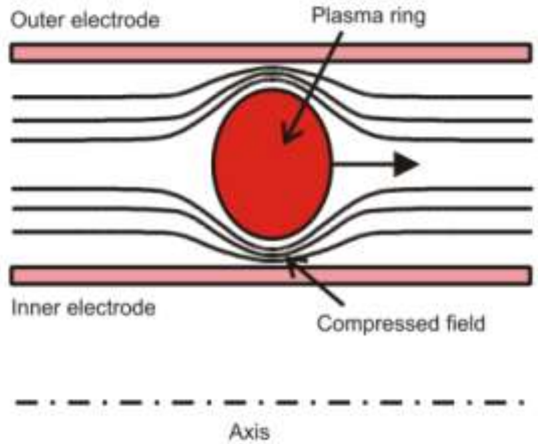

Fig 2. Use of weak axial magnetic fields to reduce impurity generation.

ADDING DYNAMIC COMPRESSION

A modification to the geometry shown in Fig. 1 might be having the plasma rings go into converging cones before reaching the main chamber [1]. This would slow and compress the rings, increasing both ion and electron temperatures, thereby reducing the resistivity in the main current. It might also assure that the plasma rings do in fact merge.

SUMMARY

It is hoped that this concept offer a more attractive approach to nuclear fusion power plants. If the currently dominant confinement methods, tokamaks, stellarators, and laser inertial fusion, showed promise of commercial viability, this task would be superfluous. But this seems to be not the case.

The RACER concept is attractive for power reactors because it is, or has:

- Cylindrically symmetric, facilitating design, manufacture, and maintenance
- Steady state
- Acceptable recirculating power
- Moderate-field, well-shielded circular superconducting coils
- High plasma current built up using pulsed moderate hardware
- Fuel, heating and inductive energy supplied by very high-speed plasma rings
- Moderate neutron wall loading
- Low beta with resulting better confinement and stability
- Some basis in experimental results

While the reactor parameters are given throughout the body of this document, for convenience they are also summarized in Table 2 below.

TABLE 2. SUMMARY OF REACTOR PARAMETERS

Electricity for sale	500 MW(e)
Recirculating power	up to 150 MW(e)
Poloidal beta at steady state	10%
Neutron wall loading at steady state	2.1 MW_n/m^2
Major radius	4 m
Plasma radius to limiter	2.67 m
Aspect ratio	1.5
Plasma chamber cone angle	30°
Reactor OD to outside of coils	19.5 m
Reactor length up to injector channels	18.4 m
Reactor total length	~50 m
Electrical power conversion efficiency	40%
Blanket neutron energy multiplication	1.1
Total thermal power	1620 MW
Neutron power	1200 MW
Alpha power	300 MW
Optimum steady state plasma temperature	13.6 keV
Ave density n_i and n_e each	2×10^{20} m^{-3}
Bremsstrahlung power	61 MW
Assumed Z_{eff}	3
Required energy confinement time with no auxiliary heating	0.8 sec
Limiter surface area	175 m^2
Limiter heat flux	1.5 MW/m^2
B field at midplane	4.7 T
B field at ends	~7 T
Center S/C coil radial thickness	1.2 m
End S/C coil radial thickness	1.0 m
Average hoop stress all coils	63 Mpa (9 ksi)
Inductive accelerator length	~3 m
Coaxial accelerator length	10.5 m
Outer electrode radius	1.67 m
Inner electrode radius	0.55 m

Plasma ring major radius	1.11 m
Plasma ring plasma radius	0.56 m
Max ring injection velocity	1600 km/sec
Plasma ring max acceleration	1.2×10^{10} g's
Max injection rate	up to 23 Hz
Time to startup with 99% losses	11 hours
Min injection pulses for startup	940,000
Total purchased energy for startup	1700 kW-hr

SUGGESTED FUTURE WORK

If there is further interest in this concept, it would be good to repeat the above analysis in order to verify it. The software used here was EES (Engineering Equation Solver) from University of Wisconsin.

After that, future analytical work should include detailed magnetics analyses including steps along the ramp-up to steady burn, including a time-dependent analysis of the plasma power balance with the inclusion of auxiliary heating if needed.

Some of this was done in the past [7], with Fortran 77, with different parameters using an assumed energy confinement scaling law. It was found during this effort that enough control parameters exist to adjust electrical output to meet changing demand.

It would be good to analyze a slow ramp-up to determine the minimum energy confinement needed to keep plasma temperature, and current, climbing; and then compare that with possible confinement scaling laws.

If the above tasks continue to show promise, possible experiments could include (1) the idea of using weak magnetic fields to limit impurities in a coaxial accelerator and (2) a small version of the configuration shown in Fig. 1 to learn about magnetic reconnection and merging at high plasma ring velocities, and (3) the stability of prolate geometries with a central conducting core.

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