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PLASMA-GUN FUELING FOR TOKAMAK REACTORS

by

David A. Ehst

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Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

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ABSTRACT

In light of the uncertain extrapolation of gas puffing for reactor fueling and certain limitations to pellet injection, the snowplow plasma gun has been studied as a fueling device. Based on current understanding of gun and plasma behavior a design is proposed, and its performance is predicted in a tokamak reactor environment.

1. Introduction - Reactor Fueling Requirements

Plasma fueling is crucial to the success of long pulse or steady state fusion reactors and may prove especially challenging for closed-field devices such as tokamaks. Many means have been proposed to fuel large plasma devices,(1) and the present report focuses on one method, plasma gun injection, which holds considerable promise for tokamak application.

It appears desirable to have a centrally peaked plasma density profile in a tokamak reactor for several reasons. Various studies have shown the advantage of peaked densities for enhancing the fusion power production.(2,3) Also, peaked density profiles appear to be important to the success of various steady state current generation techniques, viz., the bootstrap effect,(4) lower hybrid driven surface current equilibria,(5) and Alfvén wave current generation.(6) The goal of the present study is the design of a fueling system which is capable of maintaining a peaked plasma density profile and which can be adapted to STARFIRE, a conceptual commercial reactor.(7) Figure 1 is the fuel ion production required to maintain a plasma density profile $n(r) = n_0\ [1-(r/a)^2]^{1.1}$, where a = 1.90 m is the effective limiter radius for STARFIRE. This source profile is inferred from a one-dimensional plasma transport simulation; the results in Fig. 1 assume neoclassical ion transport without a Ware drift mechanism.(8) Note that the ion production rate near the center is required to be about one per cent of the edge production in order to attain this peaked profile.

Gas puffing has successfully maintained peaked profiles in most experimental tokamaks, and, due to its simple implementation, it would be the most attractive choice for fueling reactor-scale tokamaks. However, neutral gas transport calculations (see, for example, the discussion in Ref. 8) do not reproduce experimental profiles, and there is, consequently, some apprehension in extrapolating this technique to large devices. Moreover, recent results from some large tokamaks suggest that fairly flat profiles may result from gas puffing.(9) Prudence dictates that alternate fueling schemes to gas puffing be studied in order to insure the successful fueling of reactors. A preliminary survey of a variety of alternatives led us to concentrate on pellet injection and plasma guns.

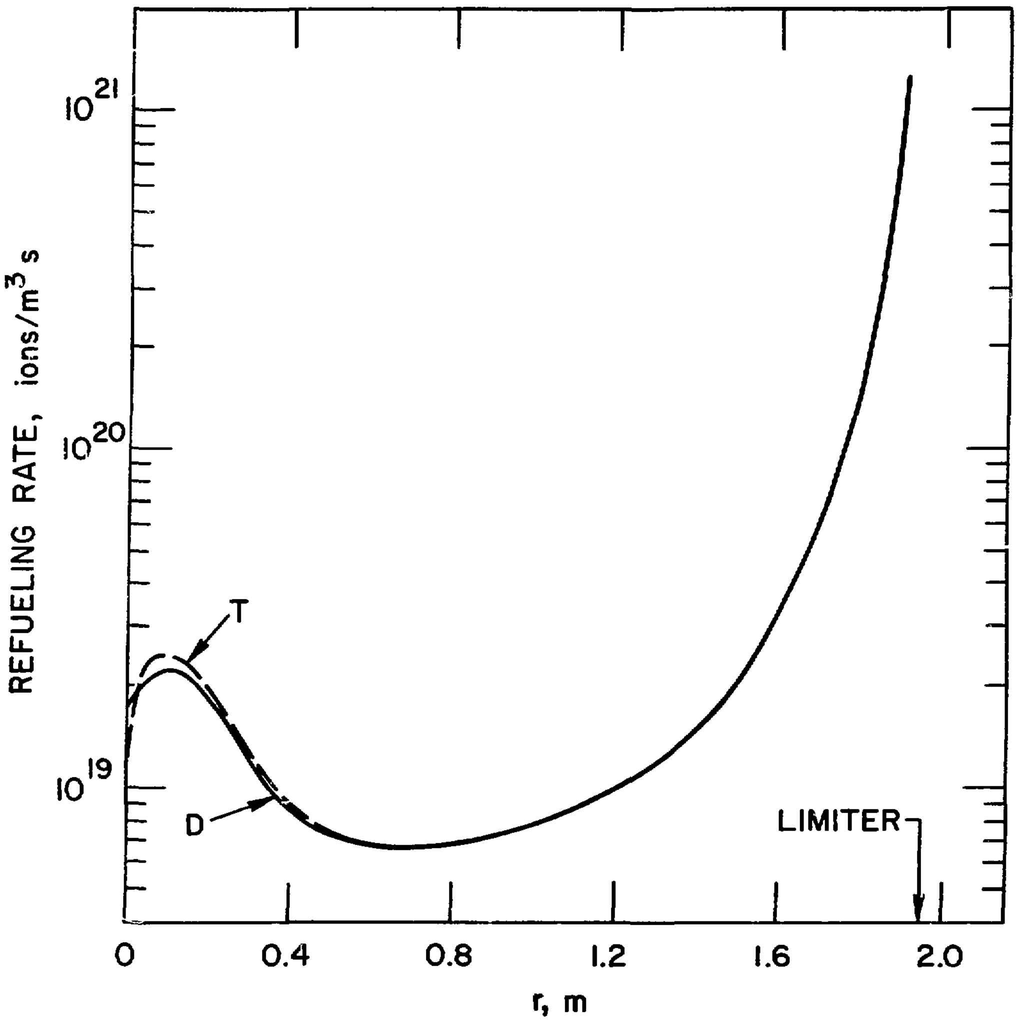

Figure 1. Deuterium/tritium source profile including recycling and external fueling to obtain steady state $n_{DT} = n_0[1-(r/a)^2]^{1.1}$; WHIST code, with neoclassical ions.

The large particle recycling rate at the first wall (90% reflection of hydrogen) in STARFIRE leads to a high fractional burn (41%) with a total external DT fueling requirement of $S_{DT} = 6.03 \times 10^{21}\ s^{-1}$. This corresponds to a fueling rate of 1.30 kg/d of tritium, with 0.54 kg/d of tritium consumed. The lowest permissible duty factor for pulsed injection occurs approximately for pulses spaced temporally by $\Delta t = 1$ s, corresponding to $N \equiv S_{DT}\ \Delta t = 6.03 \times 10^{21}$ fuel particles per pulse. For STARFIRE, a low density reactor (the average fuel density is $\bar{n}_{DT} = 0.806 \times 10^{20}\ m^{-3}$), this yields a density change of $N/(\bar{n}_{DT}V) = 9.6\%$, and we expect larger N values would lead to undesirably large density fluctuations. With this limitation on N we will discuss fuel penetration for pellets in Sec. 2 and for plasma guns in Sec. 3. Calculations suggest that pellets fail to fuel the central region, while plasma guns promise good penetration.

2. DT Pellet Injection

Solid DT ice has a particle density of $5 \times 10^{22}\ cm^{-3}$, so a spherical pellet of initial radius $\rho_0 = 0.31$ cm delivers the maximum number of particles ($N = 6.0 \times 10^{21}$). The pellet ablation theory of Parks[(10)] appears to agree well with experimental tests,[(11)] and, from Table II of Ref. 11, the model predicts a 0.3 cm pellet launched at 9000 m/s will only penetrate 0.42 m into a device with $n_e = 3.3 \times 10^{20}\ m^{-3}\ [1-(r/\tilde{a})^2]^2$, where the distance to the magnetic axis is $\tilde{a} = 0.63$ m. Pellet ablation is a strong function of electron temperature, and for STARFIRE a much broader $T_e(r)$ profile is assumed:[(8)] $T_e = 23\ keV\ [1-(r/\tilde{a})^2]^{0.3}$. Consequently pellet ablation near the plasma surface is much more severe in STARFIRE than for the TNS case quoted above. [For example, in STARFIRE, $T_e\ (r/\tilde{a} = 0.83) = 15.8$ keV, while for the TNS example in Ref. 11, $T_e = 15.8$ keV at $r/\tilde{a} = 0.33$.] This broader T_e profile and the greater $\tilde{a}$ (= 1.12 m) for STARFIRE lead us to believe pellet velocities far in excess of 9000 m/s will be required to deposit fuel near the magnetic axis. Since such high speeds seem unrealistic,[(12)] we must conclude that pellet injection will not satisfy the fueling requirements outlined in Sec. I.

3. Plasma Gun Fueling

Ott and Manheimer[(13)] discuss the conditions required for ionized plasma beams to cross vacuum field lines and magnetized plasma, which are, respectively,

$$\omega_{pf}^2 >> \Omega_f^2 \quad (1)$$

$$n_f E_f \geq B^2/2\mu_0 \quad . \quad (2)$$

The subscript f denotes the fuel ions supplied by the gun, ω_p is the plasma frequency, Ω the cyclotron frequency, E the average particle kinetic energy, n the density, and B the magnetic field strength. We assume the plasma gun is located on the outboard (low field) side of the plasma (see Fig. 2) and must cross a vacuum field with $B \approx 4.6$ T. Equation (1) is satisfied for fuel densities exceeding 4.5×10^{10} cm^{-3}, a condition readily achieved with a coaxial gun of the Marshall design.[14-16]

The second condition is more demanding; in order to penetrate to the magnetic axis, where B = 5.2 T, the fuel energy density must exceed 10.8 J cm^{-3}. It is generally desirable to keep E_f as low as possible to reduce the power requirements for plasma fueling, so Eq. (2) points to the necessity of injecting very dense fuel beams. Routine operation of plasma guns can produce densities in the 10^{17} cm^{-3} range,[15] and guns operated in the deflagration mode have formed well focused, pinched plasma with densities as high as 10^{18} cm^{-3}.[17] The plasma focus, a related device with higher filling pressure and reversed electrode polarity, normally produces densities well above 10^{19} cm^{-3}.[18] If a pulsed gun can be operated to produce high purity, low divergence plasma with $n_f = 5 \times 10^{17}$ cm^{-3}, such a gun would be ideal for our application. This performance, which is a small extrapolation from present-day results, appears attainable, and we assume this n_f value for our remaining calculations. Consequently, from Eq. (2), the gun ions must have energies $E_f \gtrsim 140$ eV.

Normally Marshall guns produce 99% of the ions with $\sim$ 100 eV energies, but about 1% of the ions have $\sim$ 10 keV energies. For fueling purposes this 10 keV component represents a gun inefficiency since it contains half the plasma energy but contributes negligibly to the particle injection rate. Assuming, therefore, a gun efficiency of $\eta = 0.5$, the total energy expenditure of the gun per pulse is $U \equiv N E_f \eta^{-1} = 270$ kJ. This energy is near the range for which the Beta II gun has been designed at Lawrence Livermore National Laboratory,[19] and, with an injection period of $\Delta t = 1$ s, it represents

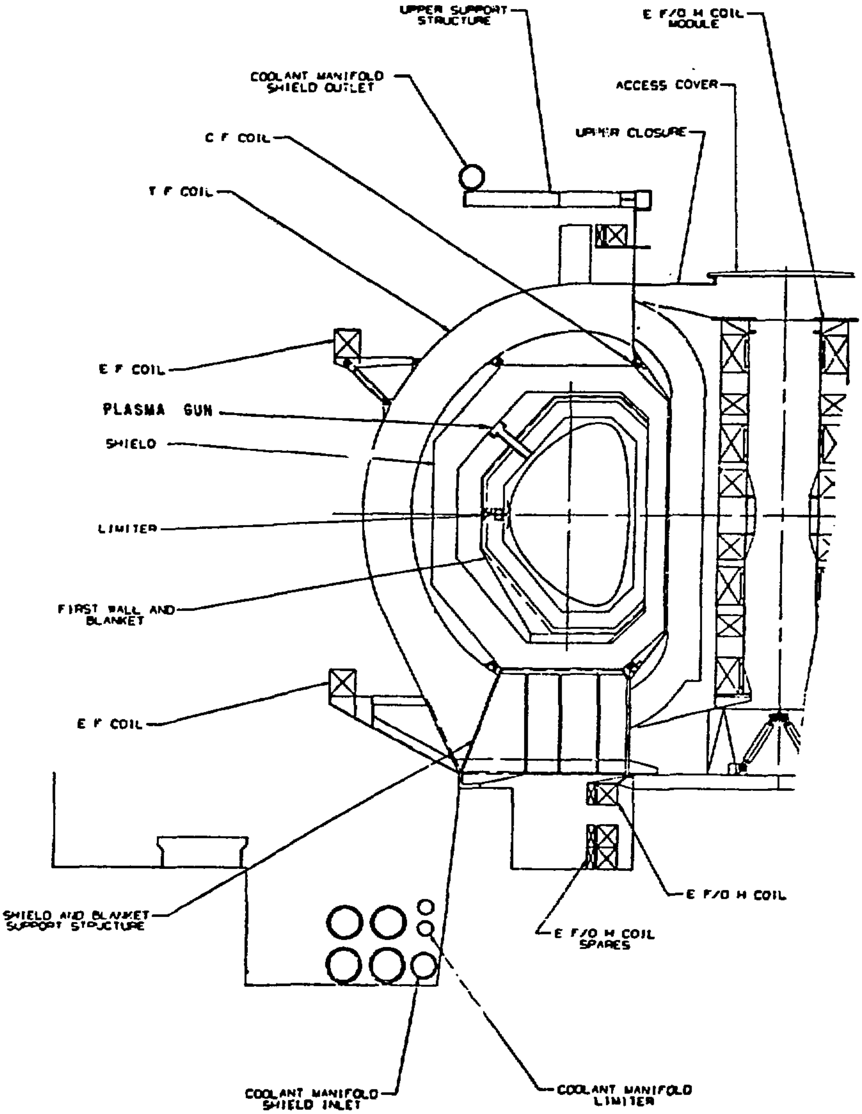

Figure 2. STARFIRE design showing outboard location of plasma gun.

a time averaged power requirement of $P \equiv U/\Delta t = 270$ kW for fueling the tokamak reactor. Even with inefficiencies in the electric power supply system this is a negligible impact on the plant's power balance, since STARFIRE produces 1400 MW of gross electric power.

Figure 3 shows the design, similar to the Beta II gun, which we propose. The radius of the hollow center cathode is $r_1 = 7.5$ cm, the outer electrode has a radius $r_2 = 10.0$ cm, and the overall length is $L_1 = 140$ cm. Prior to the current discharge 112 cm^3-atm of molecular DT is introduced midway down the barrel. This fills the gun volume, producing an average pressure of ~ 4.4 torr, a gas density of $\rho \equiv 1.3 \times 10^{-6}$ g/cm^3. Marshall has developed a scaling law which relates gun performance to the discharge voltage:[14]

$$V = U\ (12.53\ L_1 r_1 \sqrt{\rho}\ )^{-1}\ , \tag{3}$$

where U is in joules, L_1 and r_1 are in centimeters, ρ is in g/cm^3, and where V is the voltage in volts. Evaluating this, we find that a voltage $V \equiv 18$ kV is required to produce satisfactory operation. This is a voltage typical of present experimental gun operation.

An estimate of the neutron flux in the gun can be made by examination of previous calculations. Figure 4 is based on data from Ref. 20 which show the flux attenuation in a 20 cm diameter cylindrical penetration of a typical tokamak blanket. The upper curve in the figure represents the flux in a vacuum duct, and the lower curve approximates the flux in a coaxial gun where we have reduced the flux at 140 cm, ad hoc, by 25% to account for neutron capture in the cathode. The ceramic insulator separating the electrodes is a BeO gasket of radius $r_3 = 20$ cm and thickness $L_2 = 3$ cm, and we roughly approximate the flux at the gasket by reducing the flux at 140 cm by the solid angle subtended by the gasket surface, $L_3/2r_3 = 0.075$. The overall attenuation at the insulator is, thus, $\sim 1.5 \times 10^{-4}$. STARFIRE has an average neutron wall load of 3.7 MW/m^2 with a first wall neutron flux $\sim 1 \times 10^{19}$ $m^{-2}s^{-1}$, so, assuming plant availability of 75%, the fluence in the BeO from one year of operation is $\sim 3.6 \times 10^{22}$ m^{-2}. From the radiation damage data compiled in Ref. 21 we conclude the insulators will survive about a decade before replacement is necessary. More accurate calculations are needed in order to refine the lifetime estimate.

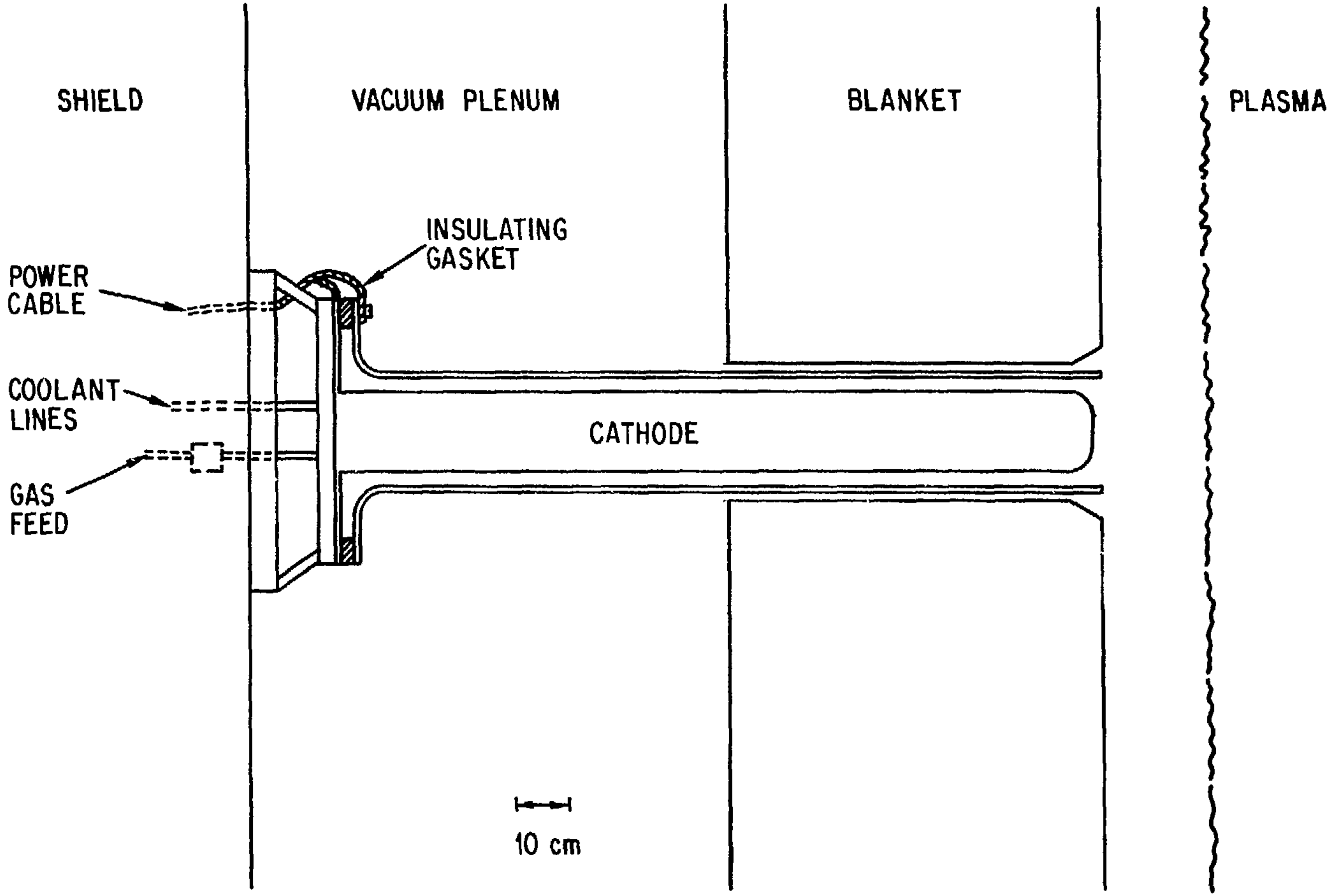

Figure 3. Detail of Marshall gun.

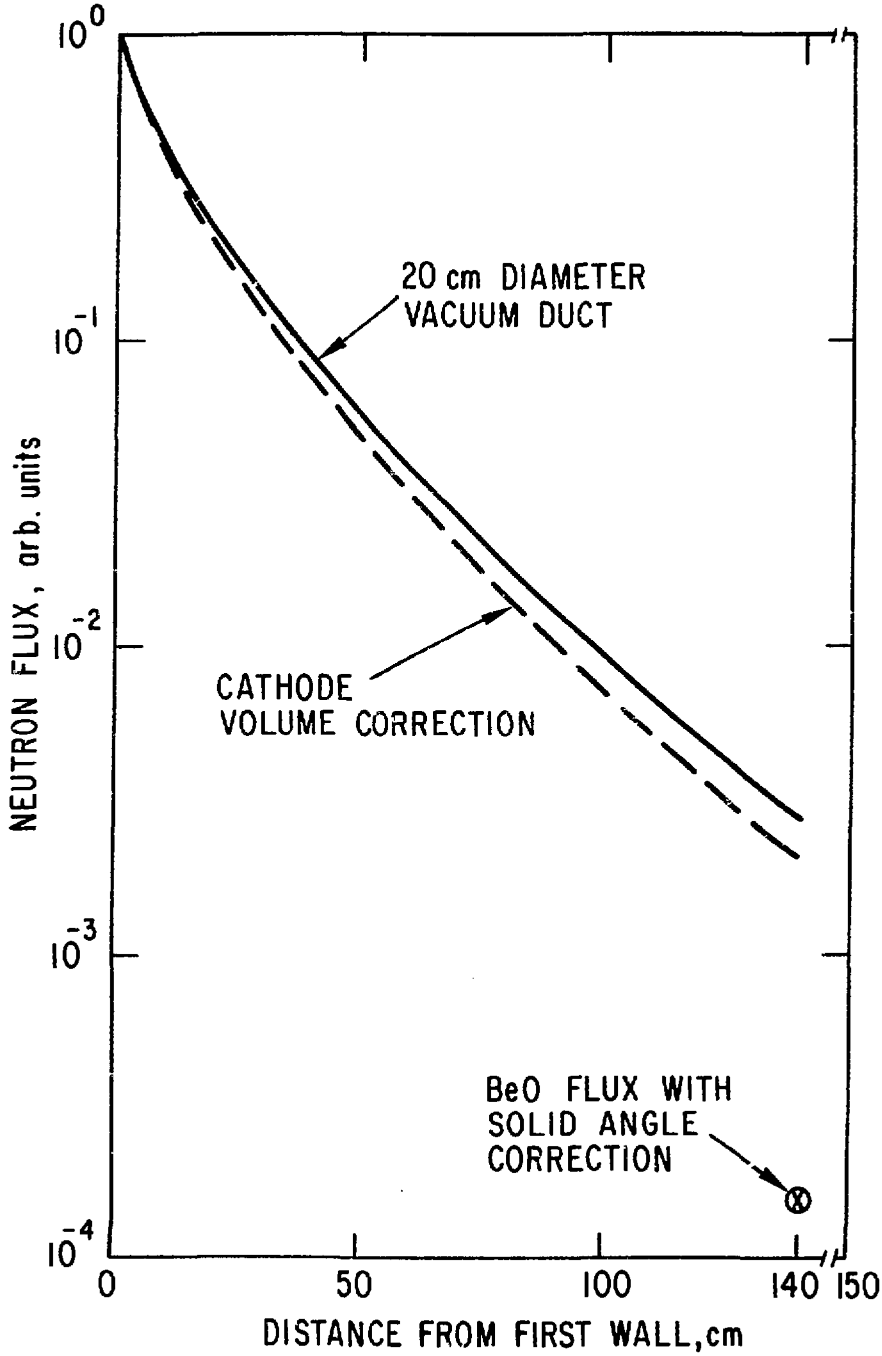

Figure 4. Neutron attenuation along gun axis.

From the gun's inductance ($L = 0.08\ \mu H$) we estimate the gun current as $I = \sqrt{2U/L} = 2.6$ MA, which yields a transient magnetic field $B_\theta = \mu_0 I\ (2\pi r_1)^{-1} = 7.0$ T near the cathode. This B_θ is about the same strength as the static toroidal field, and care must be taken to assure proper gun operation in such a strong field perpendicular to the gun axis. It was found to be difficult to magnetically shield the gun from the background field without seriously affecting the toroidal field in the plasma region.

Assuming a current rundown lasting $\sim 10\ \mu s$, the electrodes are heated resistively on the surface to a skin depth ~ 0.023 cm. If we specify that three guns be mounted on the reactor, this will provide system redundancy to guarantee high reactor availability; it will permit periodic repair, if necessary, during regularly scheduled blanket maintenance periods; and it will reduce each gun's duty factor, requiring $3\ \Delta t = 3$ seconds between an individual gun's shots. Thus, although the instantaneous electrode resistive heating is large ($\propto I^2$), the time averaged power dissipated is much lower [$\propto I^2 \times (10\ \mu s/3s)$], amounting to only $\sim 0.9\ W/cm^2$. Based on analysis of similar reactor structures(22) we predict about 20 W/cm^3 of nuclear heating in the gun structure, and another $\sim 0.9\ W/cm^2$ of surface heating is expected from charge exchange neutrals and bremsstrahlung radiation. This amount of heating power may be readily removed by continuously cooling the electrodes with water.

Of greater concern is possible cathode sputtering and vaporization from energetic particle bombardment during the discharge of the gun. Cathode erosion and impurity generation can be minimized by properly programming the gas injection and current discharge in the gun,(23) and the detrimental effects of impurity generation can be lessened by the judicious choice of cathode materials (e.g., low-Z metals such as beryllium).

4. Discussion

For a number of reasons plasma guns may prove to be the best fueling devices for tokamak reactors. They are compact, have no moving parts, have a simple design, and appear to provide reliable operation. An additional asset to reactor compatibility is the fact that the plasma gun requires a low pressure gas supply rather than a reservoir of hydrogen liquid or slush. Consequently, the inventory of tritium vulnerable to accidental release is kept at the minimum possible level. Guns suitable for reactor fueling appear to be a straightforward extrapolation from present experimental guns. Two areas requiring additional research are gun performance in strong perpendicular magnetic fields and operation with minimal impurity injection.

An experiment[(24)] has been done on the Large Wisconsin Octupole to test gun injection into a tokamak-like device, and the test confirmed good plasma penetration characteristics. In light of the successful test on the low-field octupole (0.03 T) and in view of the attractive engineering features of plasma guns, it seems desirable to test gun operation in stronger field (multi-tesla) tokamaks.

Acknowledgements

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