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# Transformer Recharging with Alpha Channeling in Tokamaks

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**Abstract.** Transformer recharging with lower hybrid waves in tokamaks can give low average auxiliary power if the resistivity is kept high enough during the radio frequency (rf) recharging stage. At the same time, operation in the hot ion mode via alpha channeling increases the effective fusion reactivity. This paper will address the extent to which these two large cost saving steps are compatible.

## 1. Introduction

Using radio frequency waves to drive the toroidal current in tokamak reactors is attractive as a means to achieve steady state tokamak operation, and there have been a variety of mechanisms proposed to drive this current [1]. The most successful technique to date is to drive these currents by lower hybrid waves [2]. In lower hybrid current drive (LHCD), the current is carried by a tail of superthermal electrons.

If other engineering issues were resolved, then the capability to operate the tokamak in the steady state with acceptable circulating power is thought to be the leading hope for economical fusion power. However, although the current drive effect may be efficient enough to allow economical fusion power with steady state tokamaks, its power cost is still large. The question has also been raised whether alpha particles might not damp the lower hybrid wave, interfering with the LHCD effect in working reactors [3, 4]. In addition, the penetration of high density plasma by lower hybrid waves is problematic, which reduces the parameter space in which the concepts can be applied (see, for example, [5, 6]). Hence, questions do remain as to whether the lower hybrid current drive effect will work near the plasma center, in an environment of alpha particle heating, or whether the current near the plasma center will have to be driven by some other means.

Should the LHCD effect not be sufficient to produce the full noninductive current, then other steady state current drive mechanisms may be necessary to supplement the current. In this respect, the electron cyclotron current drive effect may be used in the plasma center [7] and may also be used synergistically with the LHCD. Alternatively, lower phase velocity waves might drive electrons [8, 9] or with two ion species might heat ions to drive an electron current [10].

In any event, however the noninductive current is produced, there remains the issue of acceptable circulating power. Two categories of suggestions were advanced towards reducing the circulating power of non-inductive current drive techniques.

One suggestion was to have the current driven intermittently wherein either the density or the plasma resistivity would be a periodic function of time [11, 12]. This suggestion was advanced relatively early on as noninductive current drive techniques were first being considered, and then later further developed in the context of new current drive techniques [1]. In other words, consider that whatever the current drive source, there is a time of duration, $T_g$, during which the current is generated. This raises the current from its minimum value, $J_{min}$, to its maximum value, $J_{max}$. The generation stage is followed by a relaxation stage of duration $T_r$ in which there is no current drive, so that the current decays in an $L/R$ time, where $L$ is the tokamak plasma inductance and $R$ is the resistivity. The generation and relaxation cycles then repeat. The advantage of doing so is that, even as the current does not deviate much from its average value, the average power dissipation can be much less if the plasma parameters in the two stages are different.

Note that the particle and heat confinement times are of the order of a second in a tokamak reactor, whereas the $L/R$ time is about three orders of magnitude longer. Thus, the plasma particles can be exchanged many times, even as the current persists. Therefore, the current can be considered constant on the time scale on which the resistivity and other parameters can be changed.

The second suggestion towards reducing the circulating power was to use the alpha particles themselves as a source of free energy [13]. The idea is that the alpha particles, which mainly slow down on electrons, are born at high energy, and until they do slow down, this energy is in principle extractable. By extractable, we mean that the energy can be utilized without entropy production, making it available for conversion to other forms of energy such as by amplifying coherent waves. Thus, waves that might be utilized for driving current might be amplified in a plasma with a large component of energetic alpha particles. Because there are few alpha particles near the tokamak periphery, and many energetic alpha particles born near the plasma center, there is a population inversion that can be exploited.

The effect relies upon diffusion along constrained paths [13], or nearly constrained paths [14], in the joint phase space of position and energy, where, in diffusing in the rf fields, the alpha particles are ejected as they give up energy. Thus, by diverting alpha particle power to waves that drive current, the recirculating power needed to produce the waves is reduced. Waves thought best in producing this effect include the mode converted ion Bernstein wave [15, 16], which are best used in concert with other modes such as the toroidal Alfven eigenmodes [17, 18].

While both of these suggestions are speculative, they do address how lower recirculating power can be accomplished. For both suggestions, should they work, the potential cost savings can really be very substantial. What we address in this note is the extent to which these two suggestions might be compatible or synergistic. There are two basic ways in which they might be compatible: One way is to use the alpha channeling effect to assist in the current generation by reducing the wave power requirement. The other way is to use the alpha channeling effect to assist in the current relaxation, either by prolonging the relaxation or by increasing the fusion reactivity. These two ways, except for the fact that capital equipment might be shared, are essentially independent. so the benefits may be considered additive. However, since the plasma parameters are necessarily different in the two stages, the use of the channeling effect needs to be tailored specifically for each stage.

The basic equations for the noninductive overdrive are reviewed in § 2. The considerations for alpha channeling are noted in § 3. In § 4, we offer preliminary conclusions. The acknowledgment contains an important historical note.

## 2. Resistivity Oscillation

A more detailed and more general derivation is given in [1]. Here, we consider the regime in which the $L/R$ time is the longest time scale in either of the oscillatory stages. Thus, suppose that the $L/R$ time in the generation stage is $\tau_g$ (with $\tau_g \gg T_g$), and in the relaxation stage is $\tau_r$ (with $\tau_r \gg T_r$). The maximum current density $J_{max}$ occurs at the end of the generation stage and the minimum current density $J_{min}$ occurs at the end of the relaxation stage. For simplicity, let us assume that we are well into the overdrive regime, where the rf driven current density $J_{rf}$ is large compared to the actual current, so that $J_{rf} \gg J_{min}$. The rf driven current density $J_{rf}$ is defined as the plasma current were the rf on long enough for the current to achieve steady state, Under the assumption that the current density is periodic, the decay in the relaxation period must equal the rise in the generation period, so

$$J_{max} - J_{min} \approx J_{max} \frac{T_r}{\tau_r} \approx J_{rf} \frac{T_g}{\tau_g}, \tag{2.1}$$

where under the assumptions that $\tau_g \gg T_g$ and $\tau_r \gg T_r$ we also have the deviation in the current small, or $J_{max} \approx J_{min} \approx J_0$, where $J_0$ is the average current.

The rf power dissipated during the generation stage is $J_{rf}/\left\langle J/P_d \right\rangle_g$, where $\left\langle J/P_d \right\rangle_g$ is the current drive efficiency during the generation stage. Since the rf power is dissipated only in the current generation stage which lasts $T_g$, the energy expended during the generation cycle is just $[J_{rf}/\left\langle J/P_d \right\rangle_g] T_g$. However, the current is approximately constant throughout both stages, that is, $J_{max} \approx J_{min} \approx J_0$. Clearly, the average rf power used is minimized if the current is ramped up quickly and then used over a long time, such that $T_g \ll T_r$. It would also be advantageous to generate the current during a time when the efficiency $\left\langle J/P_d \right\rangle_g$ is large.

To be specific, using Eq. (2.1), assuming that $J_{max} \approx J_{min} \approx J_0$, it then follows that the ratio of relaxation times that gives periodicity is

$$\frac{T_r}{T_g} = \frac{J_{rf}}{J_0} \frac{\tau_r}{\tau_g} \gg 1, \tag{2.2}$$

and we have the average power dissipated as

$$\left\langle \frac{J}{P_d} \right\rangle_{avr} = \left\langle \frac{J}{P_d} \right\rangle_g \frac{\tau_r}{\tau_g}, \tag{2.3}$$

which is derived under the assumption that both $\tau_r/\tau_g \gg 1$ and $J_{rf}/J_0 \gg 1$.

Note that the peak power is larger if $J_{rf}/J_0 \gg 1$, except that the efficiency is calculated during the generation stage rather than the relaxation stage. Thus, in this technique the average circulating power may be decreased, even as the peak circulating power requirement is increased. However, in oscillating the resistivity, higher efficiencies in generating the current might not only reduce the average power needed, but also reduce the peak power needed.

Note also that there is substantial experimental evidence supporting the effects suggested here, even if the full implications have not been pursued. Transformer recharging with LHCD has been achieved in a number of experiments (for example, see [19, 20, 21]). Longer pulse tokamaks are encountering interesting effects associated with parameter variation at constant current, including temperature oscillations [22]. The efficiency coefficients governing the LHCD effect in the presence of a dc electric electric field, whether in the generation or relaxation stage, were determined on many tokamaks, but first in detail on the PLT tokamak [23].

## 3. Alpha Channeling in the Presence of Oscillating Resistivity

Let us now address the compatibility and synergy with the alpha channeling effect. Our approach in this paper is to indicate the possibilities in optimizing over several desirable features in tokamaks rather than to calculate precise optimizations or to somehow evaluate the degree to which these features are desirable. These desirable features include not only the low average current drive power, but also the fusion power density, the practicality of implementing the current drive mechanism, particularly the lower hybrid current drive mechanism, and the peak power requirements.

Near the maximum for the fusion reactivity of plasma, at constant pressure, there is the opportunity either to increase the temperature and decrease the density or vice versa. In current tokamak reactor designs, in order to accommodate higher current drive efficiency, there is the tendency to adopt the former approach, namely operation at slightly higher temperature [24]. However, theses considerations apply when $T_e = T_i$; for substantive deviation from equal temperatures, the reactivity can be more than doubled at constant plasma pressure [25].

Consider first the case of the higher temperature ARIES operating point of $T_i = T_e \approx 20\,\mathrm{keV}$, with plasma density $n \approx 1.24 \times 10^{20}\mathrm{cm}^{-3}$. With 75% of the alpha power diverted to ions, the operating point that more than doubles the fusion power density would be $T_i \approx 20\,\mathrm{keV}$, $T_e \approx 12\,\mathrm{keV}$, and $n \approx 1.75 \times 10^{20}\mathrm{cm}^{-3}$ [25]. Consider next the case of temperatures near the fusion power maximum, namely the ARIES operating point of $T_i = T_e \approx 15\,\mathrm{keV}$, with plasma density $n \approx 1.8 \times 10^{20}\mathrm{cm}^{-3}$. Here the fusion power density is increased by about 1/3 over the 20 keV case. However, in this case, with 75% of the alpha power diverted to ions, the operating point that almost doubles the fusion power density would be $T_i \approx 15\,\mathrm{keV}$, $T_e \approx 12\,\mathrm{keV}$, and $n \approx 2.15 \times 10^{20}\mathrm{cm}^{-3}$ [25]. What this illustrates is that an electron temperature of at least about 12 keV must be employed to attain a reasonable hot ion mode in plasma relevant to DT fusion reactors.

Here the alpha channeling effect is employed solely to increase the fusion power density at constant pressure, which allows, for example, the cost-savings opportunity to retain constant fusion power density but with lower magnetic fields. On the other hand, can the alpha channeling effect be employed to advantage when the tokamak parameters are varied? There are in fact opportunities both in the generation stage and in the relaxation stage. We consider these opportunities separately.

### 3.1. Current Generation Stage

In the current generation stage, it is advantageous of course to optimize the current drive efficiency. It is also advantageous to minimize the time required, and thereby the total energy expended in this stage. The time required to reach a given current density with the same rf driven current is proportional to the inductive time, $\tau_g \approx T_{eg}^{3/2}/Z_{ig}$, where $T_{eg}$ is the electron temperature during the generation stage and $Z_{ig}$ is the ion charge state during the generation stage; this time is short when the Ohmic conductivity is poor. Thus, it is advantageous that this regime feature high rf current drive efficiency but poor Ohmic conductivity.

In the absence of the channeling effect, the current generation stage should optimize not for the fusion power but for the current only. The fusion power is mainly produced in the much longer relaxation stage. But absent fusion power, there are not very many alpha particles anyway, so there is little to be gained by channeling the alpha particle energy. Hence, at first glance, it would appear that in the current generation stage the alpha channeling effect is essentially irrelevant.

However, do consider the following: The current generation stage features low density to optimize the noninductive current efficiency. It also features low electron temperature and high ion charge state to minimize the Ohmic conductivity. But the low electron temperature is also a feature of the hot ion mode. Moreover, note that in order to maintain large differences in the ion and electron temperatures, the plasma must not be too collisional, which means that it is advantageous that the density be kept low. Hence, the low density characteristic of the current generation stage also facilitates decoupling the electron from the ion temperature, so that the hot ion mode, $T_i > T_e$, can be maintained by the alpha channeling effect.

Thus, there appear to be two favorable limits in the current generation stage.

The first regime is simply to use this stage to recharge the current at low density and low temperature, say without substantive fusion production. In this regime, the alpha channeling effect will not be useful. However, since the operation will be at low density, the LHCD can be made very efficient. Moreover, the low density operation will avoid the issues of the lower hybrid wave penetrating the plasma center. By polluting the plasma with high charge state ions, the resistivity can be further increased, thereby shortening the time required for this stage. By optimizing for the current drive effect, both the average rf power and peak rf power requirements can be made small. Of course, in the much longer relaxation stage, significant fusion power will be produced in more dense and higher temperature plasma. It is inevitable in this scenario that the plasma pressure oscillates by a large amount. The plasma in the generation stage is used just to recharge the transformer. For example, for this stage in this regime one might have parameters such that $T_i = T_e \approx 5\,\mathrm{keV}$ and $n \approx 10^{19}\mathrm{cm}^{-3}$, with possibly an effective ion charge state of several.

The second possibility is to operate in the hot ion mode, at low density and low electron temperature, but high ion temperature. In this case, the high ion temperature means that substantive fusion power might be produced, so that enough alpha particle power can be channeled in turn to maintain the temperature differences. Here, it is advantageous to operate at higher ion temperatures. Thus, comparing to the ARIES scenario, instead of accommodating steady state current drive at electron temperatures as high as 20 keV, at lower electron temperature but lower electron density, the electron and ion temperatures can decouple. For example, at moderately low density, operation in the regime of 30 keV ions and 15 keV electrons becomes possible. The lower density means that the current drive effect will be more efficient, reducing both the average and peak power requirements. There is the further possibility that the amplified waves can themselves drive current, thereby making the current drive effective more efficient yet. Moreover, the lower density and electron temperature facilitates the LHCD effect at the plasma center. In this scenario, the plasma pressure oscillates by not a large amount, so that significant fusion power can be produced also in the current generation stage.

In sum, two favorable regimes are identified: In the first regime, with no alpha channeling, ion and electron temperatures are equal and low, densities are low, and little fusion power is produced. In the second regime, the alpha channeling effect enables the hot ion mode, with moderate electron temperature, but relatively high ion temperature, giving substantial fusion power, even if not quite as much fusion power characteristic of the longer current relaxation stage.

### *3.2. Current Relaxation Stage*

The current relaxation stage should be optimized for greater fusion power and for longer duration. Minimizing $Z_{ir}$, the ion charge state during the relaxation stage, achieves both. But high density gives high fusion power, while higher electron temperature gives longer inductive times. Absent the alpha channeling effect, the electron and ion temperatures would be about equal. Therefore, at constant pressure, taking into account the utility of long inductive times, the optimal operating point is at somewhat higher temperature and lower density than what optimizes for fusion power density only.

Since the fusion power density is large in this stage, useful effects might be accomplished by channeling the alpha particle power. First, the channeling effect could be used to eject quickly the fusion ash, thus increasing the ion reactivity and decreasing $Z_{ir}$. Second, this power could be used to prolong the discharge either by directly supporting a current drive effect or by damping on superthermal electrons, thereby increasing the so-called *hot* or non-thermal conductivity [26]. Third, there is a tradeoff in operating in the hot ion mode: the fusion power density is higher with energy more concentrated in ions rather than electrons, but the relaxation duration is shorter with lower electron temperature. To achieve both high fusion powers and long relaxation durations, it stands to reason that the optimal strategy would be a hot ion mode with modest temperature differential.

## 4. Conclusions

With rf recharging, the transformer coils can be replaced by rf sources. The advantages of alpha channeling include effectively higher fusion reactivity. Both transformer recharging and alpha channeling with rf waves hold promise for making fusion power significantly more economical. When used together, their effects can be synergistic. There are substantial advantages in employing the channeling effect to operate well into the hot ion mode regime in the current generation stage and somewhat into the hot ion mode regime in the current relaxation stage. More precise operating regimes could be identified if the engineering advantages were quantified.

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