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N. A. Uckan

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N. A. Uckan

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ABSTRACT

In next-generation Engineering Test Reactors (ETRs), one major objective is envisioned to be a long-pulse or steady-state burn using noninductive current drive. At the high temperatures needed for efficient current drive, synchrotron radiation could represent a large power loss, especially if wall reflectivity ($\Re$) is very low. Many INTOR-class ETR designs [Fusion Engineering Reactor (FER), Next European Torus (NET), OTR, Tokamak Ignition/Burn Engineering Reactor (TIBER), etc.] call for carbon-covered surfaces for which wall reflectivity is uncertain. Global radiation losses are estimated for these devices using empirical expressions given by Trubnikov (and others). Various operating scenarios are evaluated under the assumption that the plasma performance is limited by either the density limit (typical of the ignition phase) or the beta limit (typical of the current drive phase). For a case with ≥90% wall reflectivity, synchrotron radiation is not a significant contribution to the overall energy balance (the ratio of synchrotron to alpha power is less than 10–20%, even at $<T_e> \sim 30$ keV) and thus should not adversely alter performance in these devices. In extreme cases with 0% wall reflectivity, the ratio of synchrotron radiation to alpha power may approach 30–60% (depending on the device and limiting operating scenario), adversely affecting the performance characteristics.

1. INTRODUCTION

In parallel with the International Tokamak Reactor (INTOR) studies,[1] four Engineering Test Reactor (ETR) design concepts[2] are being developed, one each by the European Community [the Next European Torus (NET)], Japan [the Fusion Engineering Reactor (FER)], the United States [the Tokamak Ignition/Burn Engineering Reactor (TIBER)], and the U.S.S.R. (OTR). The parameters of these concepts (listed in alphabetical order, following INTOR) are summarized in Table 1. Present efforts are focused on a new initiative, the International Thermonuclear Experimental Reactor (ITER). In all of these devices, one major objective is envisioned to be a long-pulse or steady-state burn using noninductive current drive, as expected in the ultimate fusion power reactor. At the high temperatures ($T_e \gg 10$ keV) needed for efficient current drive, synchrotron radiation could represent a large power loss, especially if wall reflectivity ($\Re$) is very low. Many fusion reactor designs, including the INTOR-class ETR (ITER) designs,[2] call for carbon-covered surfaces, for which wall reflectivity is uncertain. A smooth carbon surface may be highly reflective ($\Re \sim 0.9$–0.95, similar to metal surfaces). However, corrosion and redeposition of carbon could lead to a very low reflectivity (a perfect microwave absorber with $\Re \sim 0$). This raises the issue of whether an ETR with carbon walls operating at high burn temperatures will have significant synchrotron radiation losses.

In this report, global losses are estimated from the empirical models developed by Trubnikov[3] (and others[4,5]). The models are given in Sect. 2. Calculations are carried out for various operating scenarios (Sect. 3) under the assumption that performance is limited by either the density limit or the beta ($\beta_{crit} \sim I/aB$) limit. All of the ETR designs use a density limit in the form of the Murakami or Greenwald scaling[6] ($n_{max} \sim B/qR_o \sim I/a^2$) and a beta limit of the type given by the Troyon scaling[7] ($\beta_{crit} \sim I/aB$). However, the scaling coefficients and/or form factors used vary among the designs.[1,2] To provide some uniformity, the specific forms of these scalings[8] (see Table 1) developed in connection with the Compact Ignition Tokamak (CIT) studies are used in Sect. 3.

Table 1. ETR Machine and Plasma Parameters

	INTOR (IAEA)	FER (Japan)	NET (EC)	OTR (USSR)	TIBER (USA)
	Design Parameters[a]				
R_0 (m)	5.0	4.92	5.2	6.2	3.0
a (m)	1.2	1.32	1.35	1.5	0.834
κ	1.6	1.7	2.18[b]	1.5	2.22
δ	0.25	0.2	0.5[b]	0.3	0.4
B (T)	5.5	4.7	5	5.6	6
I (MA)	8.0	8.7	10.8	8.2	10
	Calculated Parameters				
$A = R_0/a$	4.2	3.7	3.8	4.1	3.6
V (m^3)	227	288	355	413	91
q_{cyl} ($\equiv q_*$)[c]	1.9	1.96	2.1	2.1	2.5
Density limit (10^{20} m^{-3})					
$<n_{mu}>$[d]	0.87	0.73	0.69	0.65	1.2
$<n_{GR}>$[e]	1.06	0.95	1.13	0.7	2.75
Beta limit ($3I/aB$ %)	3.64	4.22	4.8	2.93	6.0

[a] Design parameters are specified in Refs. 1 and 2. All other parameters are computed here based on these assumptions.

[b] Shape at null point.

[c] $q_* \approx (2.5a^2B_0/IR_0)[(1 + \kappa^2(1 + 2\delta^2)]$ at 95% flux surface.

[d] Murakami limit, where $<n_{mu}> = 1.5(B/q_*R_0)$.

[e] Greenwald limit, where $<n_{GR}> = 0.6[\kappa<J>] = 0.6(I/\pi a^2)$.

2. GLOBAL RADIATION LOSS MODELS

Global losses are estimated using empirical formulas developed by Trubnikov,[3] Yang,[4] and Rose.[5] Trubnikov gives a "universal" approximation formula that is represented in terms of a local emission rate times a dimensionless form factor Φ, which accounts for relativistic effects, geometry, and local and global reabsorption:[3]

$$P_S/V = [(\omega_p{}^2\omega_c{}^2)/(3\pi c^3)T]\Phi$$
$$\approx 6.2 \times 10^{-2} n_{20} T_{10} B^2 \Phi \quad (\mathrm{MW/m^3}) \qquad (1)$$

where $n_{20} = n_e/10^{20}\ \mathrm{m^{-3}}$, $T_{10} = T_e/10$ keV, and the magnetic field B is in tesla. The quantity Φ is a transparency factor (or radiation yield coefficient), which is defined as the fraction of the total synchrotron radiation energy that radiates away from a plasma without reabsorption. In all three cases, Φ can be represented as

$$\Phi = (g/\lambda^{1/2})(1 - \Re)^{1/2} \qquad (2)$$

where

$$\lambda^{1/2} = (a\omega_p{}^2/c\omega_c)^{1/2} = 77.7(n_{20}a/B)^{1/2} \qquad (3)$$

is the opacity coefficient, and a is the minor radius (in meters). Approximate analytic fits to the geometric and temperature correction factor g by Trubnikov (T), Yang (Y), and Rose (R) are

$$g_T = 0.16 T_{10}{}^{3/2}[1 + 5.7/A(T_{10})^{1/2}]^{1/2} \qquad (4a)$$
$$g_Y = 0.30 T_{10}{}^{1.1}[1 + 0.034(5 - A)]^3 \qquad (4b)$$
$$g_R = 0.08 T_{10}{}^{7/4}(1 + T_{10}/20.4) \qquad (4c)$$

where $A = R_o/a$ is the aspect ratio.

The effect of wall reflection is to decrease the losses by a factor $(1 - \Re)^{1/2}$, as indicated in Eq. (2). The exact value of the reflection coefficient depends on the wavelength of the dominant radiation harmonics emitted by the plasma, the particular material structure of the first wall, corrosion and redeposition of the material, and the specific reflective portion of the first-wall design. For metal surfaces $\Re$ is typically high, around 90–98%, depending on the wall deterioration and penetrations.

In the temperature range of interest ($\langle T \rangle \sim$ 10–30 keV) for ETRs, the power losses estimated from the Trubnikov and Yang expressions are in reasonable agreement. At these temperatures, estimates from the Rose expression are very low, as has been noted before.[9] For all three models, Table 2 compares the net power loss (for $\Re = 0$) for the five ETR devices of Table 1 at average electron temperatures of 10, 20, and 30 keV. Because of the differences in size, field, and current, the capabilities of devices operating at a given density (or beta) level will vary substantially (see Table 1). In Table 2, the expressions are evaluated at an average density corresponding to the Murakami limit in each device. For 90% wall reflectivity, the total radiation emission is reduced by approximately a factor of 3 from the values given in Table 2. At 10 keV, the total radiated power is small, ranging from ~2–3 MW in FER and TIBER to ~4–5 MW in OTR. The radiation power density is $\sim 12 \pm 2$ kW/m^3 in all devices, except TIBER, in which it is about a factor of 2 higher. At 30 keV, power losses are significant, about a factor of 10–15 higher than those at 10 keV.

In the absence of wall reflection ($\Re = 0$), the results obtained from global formulas, such as those given by Eqs. (1)–(4), are found to be in reasonable agreement with the full transport calculations for both the radiation profile and total energy loss.[9] For $\Re \sim$ 0.9–0.98, it is found in Ref. 9 that, although the global models still provide a good estimate for the total loss, the radial dependences of the losses are grossly different from those obtained from the full transport calculations. Basically, the radiation from the hot core plasma is found to be much larger than predicted simply by the $(1 - \Re)^{1/2}$ scaling, and most of the radiated energy is reabsorbed in the outer parts of the plasma. This redistribution of energy within the plasma is likely to affect the plasma temperature profile and related phenomena. Analysis with full radiation transport calculations is beyond the scope of this work.

Table 2. Synchrotron Power Loss (MW): Comparison of Models

($\Re = 0$)

T (keV)	Model	INTOR	FER	NET	OTR	TIBER
	T	2.8	2.2	3.0	4.1	2.0
10	Y	3.6	2.9	3.9	5.4	2.8
	R	0.9	0.7	0.9	1.3	0.6
	T	14.3	11.0	15.2	21.1	10.5
20	Y	15.6	12.1	17.1	23.1	11.7
	R	6.2	4.9	6.8	9.1	4.6
	T	37.7	28.8	39.7	55.4	27.5
30	Y	36.8	28.5	38.4	53.3	27.2
	R	20	15.5	20.3	29.7	14

3. ESTIMATES AT THE DENSITY AND BETA LIMITS

Although the absolute magnitude of the radiated power (or power density) is important, a better insight into its impact on plasma performance can be gained when it is compared to other terms in the overall energy balance, such as the alpha (P_A), the bremsstrahlung (P_B), or the current drive (P_{CD}) power. In this section, these comparisons are made using only the Trubnikov formalism.

3.1 Comparison to Alpha and Bremsstrahlung Powers

The bremsstrahlung and alpha power densities are evaluated assuming a square-root-parabolic density profile and a parabolic temperature profile with $T_e \approx T_i \approx T$. For $Z_{eff} \approx 1.5$ ($\Delta Z_{eff} \approx 0.1$ due to thermal alphas and $\Delta Z_{eff} \approx 0.4$ due to oxygen impurity), simplified expressions are (in MW/m^3)

$$P_B/V \approx 2.6 \times 10^{-2} n_{20}{}^2 T_{10}{}^{1/2} \approx 4 \times 10^{-2} \beta^2 B^4 (T_{10})^{-3/2} \qquad (5)$$

$$P_A/V \approx 0.18\ (n_{20} T_{10})^2 \alpha(T) \approx 0.28 \beta^2 B^4 \alpha(T) \qquad (6)$$

where $\beta \approx 0.8 n_{20} T_{10}/B^2$ is the volume-average plasma beta, n is the volume-average electron density, and T is the density-weighted average temperature. In Eq. (6), the D-T fusion reaction rate parameter $<\sigma v>$ is approximated as $<\sigma v> \sim T^2\alpha(T)$, where $\alpha(T)$ is a weak function of temperature for $T \sim$ 8–25 keV. [Typically, depending on the profiles, $\alpha(T) \approx 1$ for 8 keV $\leq T \leq$ 15 keV and $\alpha(T) \approx (1.5/T_{10})^t$ with $t \sim$ 0.25–0.5 for 15 keV $\leq T \leq$ 25 keV.] For the assumed profiles, the Trubnikov expression (in MW/m^3) can be rewritten as

$$P_S/V \approx 1 \times 10^{-2} (T_{10})^{5/2} n_{20} B^2 [(1 + \chi)/\lambda]^{1/2} (1 - \Re)^{1/2}$$

$$\approx 1.3 \times 10^{-2} (T_{10})^{3/2} \beta B^4 [(1 + \chi)/\lambda]^{1/2} (1 - \Re)^{1/2} \qquad (7a)$$

or

$$P_S/V \approx 1.3 \times 10^{-4} (B T_{10})^{5/2} (n_{20}/a)^{1/2} (1 + \chi)^{1/2} (1 - \Re)^{1/2}$$

$$\approx 1.5 \times 10^{-4} T_{10}{}^2 B^{7/2} (\beta/a)^{1/2} (1 + \chi)^{1/2} (1 - \Re)^{1/2} \qquad (7b)$$

where χ is a part of the geometry and temperature correction factor g [see Eq. (4a)] that accounts for the field inhomogeneity $(2a/R)$ and Doppler broadening $[\Delta\omega/\omega = (2\pi T/m_e c^2)^{1/2}]$ of the emission spectrum, $\chi = (2a/R_o)/(\Delta\omega/\omega) \approx <5.7/A T_{10}{}^{1/2}>$.

Equations (5)–(7) are evaluated at either the density ($<n_{mu}>$ or $<n_{GR}>$) or the beta (β_{crit}) limit for each ETR. Table 3 compares the synchrotron losses (for $\Re = 0$) at these limits.

Table 3. Synchrotron Power Loss (MW) at the Density or Beta Limits ($\Re = 0$; Trubnikov Model)

T (keV)	P_S at limit	INTOR	FER	NET	OTR	TIBER
	$<n_{mu}>$	2.8	2.2	3.0	4.1	2.0
10	$<n_{GR}>$	3.1	2.5	3.8	4.3	3.1
	β_{crit}	3.5	2.7	4.4	5.5	3.1
	$<n_{mu}>$	14.3	11.0	15.2	21.1	10.5
20	$<n_{GR}>$	15.8	12.5	19.3	21.9	15.9
	β_{crit}	12.8	9.9	15.8	19.9	11.1
	$<n_{mu}>$	37.7	28.8	39.7	55.4	27.5
30	$<n_{GR}>$	41.6	32.9	50.7	57.5	41.5
	β_{crit}	27.4	21.1	33.9	42.7	23.8

Relative magnitudes of the synchrotron emission and the alpha and bremsstrahlung powers are given at the density limit in Table 4 and at the beta limit in Table 5. At the density limit (Table 4), P_S/P_A ~ 8–10% at 10 keV and ~ 25–30% at 30 keV in all devices except OTR, where it is about 50% higher than the others primarily because of the large (aB) and low beta. At the beta limit (Table 5), at 10 keV, P_S/P_A ranges from about 3% in TIBER and NET to ~4% in FER, ~5% in INTOR, and ~6% in OTR, primarily because of the differences in (aB) and current (I), i.e., β_{crit}. Corresponding values at 30 keV are about an order of magnitude higher. Note that, neglecting variations in χ with geometry (A) and temperature, we have:

$$P_S/P_A \propto [T^2/\alpha(T)](1/\beta)^{3/2}(1/aB)^{1/2} \qquad (8)$$

At $n \sim <n_{mu}> \sim B/q_* R_o$, this yields

$$P_S/P_A \propto [T^{1/2}/\alpha(T)](aB)(q_* A)^{3/2}$$

$$\propto [T^{1/2}/\alpha(T)](aB)[f(\kappa)/\beta_{crit}]^{3/2} \quad (9a)$$

where $f(\kappa) \propto (1 + \kappa^2)$. At $\beta \sim \beta_{crit} \sim I/aB$, the relationship is

$$P_S/P_A \propto [T^2/\alpha(T)](aB)(I)^{-3/2} \propto [T^2/\alpha(T)](\beta_{crit} I^{1/2})^{-1} \quad (9b)$$

Table 4. Powers Evaluated at the Murakami Density Limit
($\Re = 0$; Trubnikov Model)

T (keV)	Powers	INTOR	FER	NET	OTR	TIBER
	P_S (MW)	2.8	2.2	3.0	4.1	2.0
10	P_S/P_B	0.65	0.6	0.75	1.0	0.65
	P_S/P_A (%)	9.2	8.4	10.5	14.7	9.4
	P_S (MW)	14.3	11.0	15.2	21.1	10.5
20	P_S/P_B	2.4	2.0	2.7	3.4	2.4
	P_S/P_A (%)	12.6	11.4	14.6	19.4	13.1
	P_S (MW)	37.7	28.8	39.7	55.4	27.5
30	P_S/P_B	5.1	4.4	5.7	7.4	4.9
	P_S/P_A (%)	26.0	22.9	29.3	38.7	25.4

Table 5. Powers Evaluated at the Troyon Beta Limit
($\Re$ = 0; Trubnikov Model)

T (keV)	Powers	INTOR	FER	NET	OTR	TIBER
	P_S (MW)	3.5	2.7	4.4	5.5	3.1
10	P_S/P_B	0.35	0.29	0.23	0.4	0.2
	P_S/P_A (%)	5.1	4.1	3.2	6.0	2.8
	P_S (MW)	12.8	9.9	15.8	19.9	11.1
20	P_S/P_B	3.5	3.0	2.4	4.3	2.0
	P_S/P_A (%)	19.2	16.0	12.6	23.4	10.7
	P_S (MW)	27.4	21.1	33.9	42.7	23.8
30	P_S/P_B	13.8	11.3	9.2	16.7	7.6
	P_S/P_A (%)	48.3	40.2	32.3	59.2	27.0

Comparisons for arbitrary temperatures at either the beta or the density limit may have some shortcomings: an evaluation for a given temperature along one of these limits may violate the other one. Such difficulties arise, for example, in evaluations at high temperatures for a given density limit or at low temperatures for a specified beta limit. For the results given in Table 4 [$n \sim \langle n_{mu} \rangle$], all devices exceed their Troyon beta limit at 30 keV, and all but TIBER and NET exceed the β limit at 20 keV. Similarly, for $\beta \sim \beta_{crit}$ (Table 5), all devices exceed their Murakami density limits by a factor of ~1.5–2 at 10 keV. To eliminate such cases, one last comparison is made in Table 6, where synchrotron emission and relative powers are evaluated at a point that satisfies both (density and beta) limits simultaneously.

Table 6. Powers Evaluated at Both the Beta and Density Limits
($\Re = 0$; Trubnikov Model)

Limit	Powers	INTOR	FER	NET	OTR	TIBER
β_{crit} and $<n_{mu}>$						
	P_S (MW)	8.2	6.5	18.5	15.7	13.9
	P_S/P_B	1.6	1.4	3.1	2.8	2.9
	P_S/P_A (%)	11.4	9.9	15.1	18.0	13.7
β_{crit} and $<n_{GR}>$						
	P_S (MW)	5.7	4.0	7.4	13.7	3.0
	P_S/P_B	0.8	0.6	0.6	2.2	0.2
	P_S/P_A (%)	7.9	6.1	5.6	15.5	2.7

At $n \sim <n_{mu}>$ and $\beta \sim \beta_{crit}$, net emission from these devices varies by a factor of 3, ranging from ~6.5 MW in FER (the lowest) to ~18.5 MW in NET (the highest). Emissions from OTR and TIBER (~15 ± 1 MW) and those from FER and INTOR (~7.5 ± 1 MW) are comparable (within ±10%). Emission per unit volume is lowest in FER, which differs by a factor of 2 from NET, primarily because of the differences in temperatures at these simultaneous limits (~16 ± 1 keV in FER, INTOR, and OTR; and ~22 keV in NET and TIBER). P_S/P_A differs by a factor of about 2; it is ~10% in FER (the lowest) and ~18% in OTR (the highest).

As noted in Table 6, the results are somewhat different at $n \sim <n_{GR}>$ and $\beta \sim \beta_{crit}$. Overall the emission is lower (by about 30–40% in INTOR and FER, by about a factor of 2.5 in NET, and by nearly a factor of 4.5 in TIBER) compared to the previous case, primarily because of the lower temperatures at the Greenwald limit (~12–13 keV in FER, INTOR, and NET; ~16 keV in OTR; and ~10 keV in TIBER). Note the T^2 scaling of the losses [Eq. (7)]. P_S/P_A differs by a factor of a little over 5, being ~3% in TIBER (the lowest) and ~15–16% in OTR (the highest). These features can easily be seen from the equations [Eqs. (5)–(9)]. Noting that the temperatures ($T \sim T_*$)

corresponding to $n \sim n_{mu}$ or n_{GR} and $\beta \sim \beta_{crit} \sim I/aB$ are $T \sim T_{*mu} \sim q_* A I \sim aBf(\kappa)$ or $T \sim T_{*GR} \sim aB \sim q_* A I / f(\kappa)$, we can rewrite Eqs. (8) and (9) as

$$P_S/P_A \propto I^{1/2}(aB)(q_* A)^2 \propto (aB)^3[f(\kappa)]^2(I)^{-3/2}$$
$$\propto [(aB)/(\beta_{crit})]^{3/2}[f(\kappa)]^2 \qquad (10)$$

at $n \sim n_{mu}$, $\beta \sim \beta_{crit}$, and $T \sim T_{*mu}$; and

$$P_S/P_A \propto I^{1/2}(aB)(q_* A)^2 \propto (aB)^3(I)^{-3/2} \propto (aB/\beta_{crit})^{3/2} \qquad (11)$$

at $n \sim n_{GR}$, $\beta \sim \beta_{crit}$, and $T \sim T_{*GR}$. Variations in χ and $\alpha(T)$ with T and A are neglected in Eqs. (10) and (11).

3.2 Comparison to Current Drive Power

The current drive efficiency γ is defined as

$$\gamma = n_{20} I(\mathrm{MA}) R_o(\mathrm{m})/P_{CD}(\mathrm{MW}) \approx (T_{10}/60)(J/P) \qquad (12)$$

where P_{CD} is the (absorbed) current drive power and (J/P) is the dimensionless current drive efficiency, which typically has values around 10–40, depending on the current drive scheme.[10] In general, (J/P) is not constant; it depends on temperature and other physical quantities. Here, for simplicity and to ease comparison, we assume (neutral-beam-like or lower-hybrid-like) a value around (J/P) ~ 20, which yields

$$P_{CD}(\mathrm{MW}) \approx 3(n_{20} I R_o/T_{10}) \approx 3.75\beta B^2 I R_o/T_{10}^2 \qquad (13)$$

The current drive efficiency γ improves nearly linearly with temperature (the power requirement scales as $1/T^2$ at constant beta), whereas the synchrotron radiation increases as T^2. Table 7 compares the required current drive power and net synchrotron emission at the beta limit. For $\Re = 0$, at the high temperatures needed for efficient current drive (T ~ 25–30 keV), the synchrotron emission exceeds the current drive power in all devices except TIBER. At 30 keV, the ratio P_S/P_{CD} is ~1.25 in NET and FER, ~1.5 in INTOR, ≥2 in OTR, and ~0.9 in TIBER.

Table 7. Synchrotron and Required Current Drive Powers Evaluated at the Troyon Beta Limit ($\Re = 0$; Trubnikov Model)

T (keV)	Powers (MW)	INTOR	FER	NET	OTR	TIBER
20	P_S	12.8	9.9	15.8	19.9	11.1
	P_{CD}	41.3	37.5	63.2	43.8	60.7
30	P_S	27.4	21.1	33.9	42.7	23.8
	P_{CD}	18.4	16.7	28.1	19.5	27

4. DISCUSSION AND SUMMARY

Synchrotron radiation could represent a large power loss in plasmas that either have high magnetic fields (CIT-like devices) or operate at higher temperatures (steady-state reactors or ETR-like devices), especially when the wall reflectivity $\Re$ is low. Recent evaluations have shown that synchrotron radiation losses appear tolerable in CIT-like designs with toroidal fields in the range of 10–13 T.[11] In these devices, ignition typically occurs below 10 keV and below n_{mu}, and the losses at $\Re \sim 0$ differ by only a few megawatts from those at $\Re \sim 0.9$. Similar calculations for much higher field (~20-T) compact ohmic ignition experiments have shown that ohmic ignition may be prevented if wall reflectivity is very low ($\Re \sim 0$).[12]

For ETR-like devices, the results of this paper for a case with $\Re \geq 0.9$ show that synchrotron radiation is not a significant contribution to the overall energy balance (P_S/P_A < 10–20%, even at $\langle T_e \rangle \sim 30$ keV) and thus should not adversely affect performance. In fact, this loss process could provide a positive benefit in passive thermal burn control. In extreme cases with 0% wall reflectivity, however, synchrotron radiation may approach or exceed the current drive power requirements ($P_S \geq P_{CD}$) with P_S/P_A approaching 30–60% (depending on the device and limiting operating scenario), adversely affecting the performance characteristics. Given the magnitude and important deleterious consequences of these losses on the possibility of high-Q, noninductive current drive operation of any ETR, it may be worthwhile to verify or modify the results presented in this paper with more detailed radial transport code calculations that incorporate energy transport by synchrotron radiation, such as those considered in Refs. 9 and 11.

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