CHAPTER – VII

COMPARISON OF CORONAL AND NON-CORONAL EFFECTS
IN STARTUP PHASE OF TOKAMAKS

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References
1. Introduction

In this chapter we discuss the coronal and the non-coronal behaviour of impurities during plasma evolution in startup phase of a typical tokamak. This study is carried out numerically by using a zero-d code (time evolution of spatially averaged quantities) with oxygen as a typical impurity.

The time evolution is obtained for both cases: (i) the coronal radiative loss and (ii) the non-coronal radiative loss. The externally applied loop voltage (source of energy) is identical in the two cases. A comparative study indicates that, in the latter case the radiative loss is much higher. Since a comparatively higher fraction of input energy is radiated away, we find that non-coronal effects ultimately predict lesser plasma temperature (and hence current). Also, low-ionized charge states of oxygen are also shown to survive up to much higher temperatures. Implications of the results on radiation-barrier, loop-voltage optimization and impurity related diagnostics are discussed.

1.1 The startup phase physics

The startup phase of a tokamak consists of following two crucial stages: (i) the breakdown of working gas into plasma-ions and electrons (ionization) and current initiation by an externally applied loop voltage, and (ii) the rise of current and temperature to a quasi-steady state by heating the plasma (e.g. by ohmic or Joule heating). Such that it
overcomes the impurity-radiation barrier.

A variety of physical processes are involved during the startup phase. Typically an external loop voltage is applied by a transformer action, the plasma torus acting as the secondary winding. The ionization of the filling gas and the charge exchange collisions between the ions and the neutrals are the important atomic processes initially, as the plasma density builds up with time. The current driven by the toroidal electric field increases plasma temperature by Joule heating. The lowered resistivity of the plasma (due to increased temperature) allows simultaneous increase of plasma current and temperature. The discharge evolution is strongly controlled by the local energy balance and its evolution. The loss of energy occurs primarily by heat transport and the radiation from impurities.

In a realistic tokamak plasma impurities arise quite commonly as a result of outgassing from the vessel walls and interaction of the plasma with the vessel wall and other metallic objects like limiter/divertors etc. At low temperatures, characteristic of startup, the low-z impurities like carbon and oxygen radiate so strongly that radiative power loss almost equals the input power. For an ohmically heated plasma, one therefore needs a higher loop voltage so that plasma receives more energy than it loses by radiation. However a demand for higher loop voltage can result in lessening the total discharge duration. This is due to the fixed number of volt-seconds or 'flux swing' through the ohmic transformer, e.g. the total available volt-seconds for
Radiative loss directly affects the design and optimization issues of the external power supply systems. Radiation loss arises typically due to the following processes: (i) line-radiation, (ii) radiative recombination (iii) di-electronic recombination (iv) charge-exchange and (v) bremsstrahlung. Line-radiation is the strongest contributor to radiation loss and arises from electron-impact excitation and spontaneous decay of the excited state of the impurity atom/ion. Charge states with three or more electrons radiate very strongly. When plasma becomes hot enough to "burn" or ionize these states completely into helium-like (or higher), the radiation drops dramatically. Other loss mechanisms, then shape the discharge evolution. A "radiation-barrier" therefore exists which plasma must "burn" through. Some of these points have already been noted in chapter II.

1.2 Motivation and aim

In the present work we wish to examine plasma and impurity evolution and compare results of two cases, when radiative loss is coronal and non-coronal. The non-coronal effects are due to time variations and finite confinement times of impurity atoms/ions in the plasma.

Time-varying effects were studied earlier by Galushkin et al. [2] where an instantaneous influx of impurities, into a plasma with given temperature and density was assumed. Additional effects due to spatial inhomogeneity of plasma
density and temperature were examined by Gervids and Krupin for the TM-3 tokamak [3]. With a view for futuristic devices, the startup phase of large tokamaks like TFTR was examined by Hawryluk and Schmidt [4] in an elegant zero-d model for the coupled plasma and impurity evolution. Albert carried out similar studies for the ASDEX tokamak [5]. Numerical studies on impurities carried out at the Princeton Plasma Physics Lab., U.S.A. were reviewed by Hulse [6]. In a plasma with temperature $T = 50 \text{ eV}$ and density $n = 2 \times 10^{14} \text{ cm}^{-3}$, it was shown that oxygen radiation takes about 0.7 milliseconds to reach its coronal value (starting with neutral oxygen at $t = 0$). In another numerical work with $n$ and $T$ as fixed, several impurities were examined in detail by Carolan and Piotrowicz [7]. Time required to relax to coronal equilibrium was shown to be several milliseconds for typical values of $n \approx 10^{13} \text{ cm}^{-3}$ and $T \approx 20 \text{ eV}$ with low-Z impurities like oxygen. Effects due to charge exchange between impurity ions and plasma neutrals were also discussed [6,7]. The non-stationary plasma conditions, typical of the startup phase in tokamaks were considered by Abramov & Krotova [8]. Total radiation from oxygen, as well as line intensity of the ion ($\lambda = 1032 \text{ A}$) were modelled by taking experimentally measured $n(t)$ and $T_e(t)$ on the TFR tokamak [9]. Radiation was shown to be enhanced due to non-stationary conditions, compared to coronal expectations.

The question one would like to ask is: what is the effect of non-coronal radiative power loss on the start-up evolution? We seek to answer this question in this chapter.
The earlier study of Hawryluk and Schmidt [43] focussed on startup scenario with design and technology aspects of large tokamaks. The coupled plasma and impurity evolution was examined but coronal and non-coronal effects were not compared due to the qualitatively different aim of their study. The studies by Huke, Carolan et al., and Abramov et al. [6-8] compared the coronal and the non-coronal radiation but did not evolve plasma self-consistently, i.e. \( n(t) \) & \( T(t) \) were assumed. In this work, we consider both, the self consistent plasma and the impurity evolution and the comparison of coronal and non-coronal results. It is shown later that the evolution is quite strongly modified by comparatively larger radiation in the non-coronal case.

2. Model equations and assumptions

In this section we discuss the model to describe startup evolution and the various physical processes it accounts for.

In the startup phase, the discharge evolution is decided by its energy balance, which is primarily affected by the radiative energy loss. A zero-d description of this phase is adequate to illustrate the basic physical issues here [4,5,11-14].

In the investigations presented in earlier chapters we had used a Two Ion Model for the radiation calculation. In the present work, we consider all the charge states of the given impurity. Since several equations are involved a space and time dependent problem is much more difficult to solve. In the zero-d model here the effects of diffusion are in a sense, taken care by using known confinement times for the
various species involved.

We wish to examine the effects of time variations and finite confinement times (non-coronal effects) in detail. We therefore consider a simple but a standard zero-d model for plasma evolution as considered by Hawryluk et al. [4] and Sharma et al. [13,14] (runaway effects are not considered here). Such a model is discussed below.

2.1 Particle Balance

The plasma is created in the tokamak chamber by ionizing the neutral gas (hydrogen is considered here) which is filled into the vessel at some specified pressure, typically ~ 0.3 millitorr. Initially some electrons are present in the gas say due to preionization. With the external loop voltage these electrons get accelerated and ionize the neutral gas. The ion (proton/density $n_i$ in the presence of neutrals with number density $n_o$ and electron density $n_e$ is given by

$$\frac{d}{dt} n_i = n_e n_o S_{ion} - \frac{n_i}{r_p}$$

(1)

where $S_{ion}$ is the ionization rate coefficient of hydrogen and $r_p$ is the ion confinement time. From a fit to experimental and theoretical data [15,16] $S_{ion}$ is given by

$$\log_{10} S_{ion} = -3.054x - 15.72 \exp(-x) + 1.603 \exp(-x^2)$$

for $T_e < 50$ eV

$$= -0.515x - 2.563/x - 5.231 \text{ for } T_e > 50 \text{ eV}$$

Here $x = \log_{10} \left( \frac{T_e}{k_B} \right)$ with $T_e$ expressed in electron-volts.
If the impurity (oxygen, $z = 8$) density for ion "j" (charge $z_j = j-1$) is written as $O_j$, the electron density is given by the charge neutrality condition,

$$n_e = n_1 + \sum_j z_j O_j$$

(2)

Though the neutral gas consists initially of molecular hydrogen, the time development of the dissociation process is not discussed here as it does not affect the discharge significantly [111]. However the energy spent in dissociation is accounted for in the overall energy balance discussed in the next subsection.

The neutrals fill the volume $V_v$ of the vacuum chamber, whereas the plasma volume $V_p$ is defined by the location of the limiter. Consequently the equation for neutrals is

$$\frac{dn_O}{dt} = -\frac{dn_j}{dt} + \Gamma$$

(3)

where $\Gamma$ is the amount of hydrogen gas coming into the vacuum vessel, say, by gas puffing.

2.2 Energy Balance

In the scenario we shall consider the external power supply is from the ohmic heating. In this a current, carried primarily by electrons is set up and heats electrons. The electrons lose their energy in processes like: neutral gas ionization, collisional transfer to ions, ionization and excitation of impurity atoms/ions and loss due to finite energy confinement time. The ions, on the other hand gain energy from the electrons and lose it by charge transfer.
collisions with neutrals and also due to the finite energy confinement time. We can therefore write the energy balance equations as:

\[
\frac{3}{2} \frac{d}{dt} \left( n_e T_e \right) = \eta J^2 - \dot{W}_{\text{ion}} n_e n_0 S_{\text{ion}} - Q_{\text{le}} - P_{\text{rad}} - P_{\text{ion}}
\]

\[
- \frac{3}{2} n_e T_e / \tau_{ee}
\]

\[
\frac{3}{2} \frac{d}{dt} \left( n_i T_i \right) = Q_{\text{le}} - \frac{3}{2} n_i T_i n_0 S_{\text{cx}} - \frac{3}{2} n_i T_i / \tau_{ki}
\]

where temperatures are in energy units. The resistivity is the spitzer resistivity \[15,17]\)

\[
\eta = m_e \nu_{ee} / n_e e^2
\]

where

\[
\nu_{ee} \tau_{ee} = \nu (Z_{\text{eff}}) = 0.457 Z_{\text{eff}}^{1.077+Z_{\text{eff}}} + 0.29 Z_{\text{eff}}
\]

defines \(\nu_{ee}\) and

\[
\tau_{ee} = \frac{3 m_e^{1/2} T_e^{3/2}}{4 (2\pi)^{1/2} n_e e^4 \ln \Lambda_e} ; Z_{\text{eff}} = \left[ \frac{n_i + \sum_j z_j^2 \rho_j}{n_e} \right]
\]

\(\tau_{ee}\) is the electron-electron energy relaxation time. An electron loses energy in the dissociation of a hydrogen molecule, and the excitation and ionization of the resulting hydrogen atoms. We write this loss of energy \(W_{\text{ion}}\) which typically has a value of about \(10\) eV \[4\]. The energy transfer between electrons and ions is given by

\[
Q_{\text{le}} = 3 n_e \left( T_e - T_i \right) / 2 \tau_{ei} = 3 m_e n_e \left( T_e - T_i \right) / m_i \tau_{ee}
\]

where \(\tau_{ei} = (m_i / 2 m_e) \tau_{ee}\).

The radiative power loss \(P_{\text{rad}}\) is calculated as
\[
\text{Prad} = n_e \sum_{j=1}^{n} R_j
\]

where \( R_j \) is the total radiation rate (erg cm\(^{-3}\) sec\(^{-1}\)) as obtained from Jensen et al. [18], and Post et al. [19]. The total radiation rate consists of line radiation, radiative and dielectronic recombination and bremsstrahlung as discussed earlier. The power lost in ionization of the impurity atoms/ions is given by

\[
P_{\text{ion}}^0 = \sum_{j=1}^{n} \gamma_j n_e \left( S_j^0 - r_j n_e^{O_{j+1}} \right)
\]

where \( \gamma_j \) is the ionization potential and \( r_j \) are the three-body recombination (inverse process of ionization, typically negligible for the parameters of interest) coefficients.

The loss of ion energy by charge exchange with neutral (assumed to be cold) is given with a charge exchange rate coefficient [15]

\[
S_{\text{cx}} = \sigma_{\text{cx}} v_{\text{rel}}, v_{\text{rel}} = (8T_1/m_1)^{1/2}
\]

and

\[
\sigma_{\text{cx}} = \left[ 7.6 \times 10^{-8} - 1.06 \times 10^{-8} \log_{10} \left( \frac{1}{2} m_1 v_{\text{rel}}^{2} (\text{ev}) \right) \right] \left( \text{cm}^2 \right).
\]

The energy confinement time is actually decided by complicated process from the zero - d point of view. The energy confinement as such is not clearly understood as it is known to be decided by anomalous processes. We therefore allow ourselves a choice here, e.g. various scaling laws can be used. Some standard choices which have been used are given

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The electron energy confinement time $\tau_{ke}$ is obtained from the scaling law [20]

$$\tau_{ke} \text{ (sec)} = 5 \times 10^{-19} n_e \text{ (cm}^{-3}) a^2 \text{ (cm}^2)$$

(10)

The ion energy confinement time is given by

$$\tau_{ki} = \left( \frac{a}{2.5} \right)^2 \frac{1}{K_{nci}}$$

(11)

where the neoclassical ion thermal conductivity $K_{nci}$ is given by [15]

$$K_{nci} = \frac{0.68}{1 + 0.36 \nu_i} \frac{Z_{\text{eff}}^2 n_{ip}^2 (r/R)^{1/2}}{r_i}$$

$$+ \frac{Z_{\text{eff}} \rho_{ip}^2}{r_i} \left[ 1 + \frac{1.6 r^2 R^2}{R^2 B_T^2} \right]$$

and is evaluated at $r = a/2$. $\rho_i$ and $\rho_{ip}$ are the ion Larmor radii in the toroidal ($B_T$) and poloidal ($B_p$) magnetic fields respectively. Also,

$$\nu_i^* = \left( \frac{Z_{\text{eff}} B_T}{r_i B_p} \right) \left( \frac{R^3 T_i/n_i}{m_i} \right)^{1/2}$$

and

$$r_i = \left[ \frac{3}{4n_e e^4 m_i} \right] \left( \frac{m_i T_i}{\pi} \right)^{1/2}$$

is the ion energy relaxation time. When $\tau_{ki}$ above exceeds $\tau_{ke}$ we take $\tau_{ki} = \tau_{ke}$. However, during the startup phase the $\tau_{ki}$ neoclassical estimate above can be an overestimate as magnetic surfaces are not well formed. Experimentally the $\tau_k$ is calculated from the global energy balance equation.
where \( P \) is the power input and \( W \) is the total thermal energy of the plasma. In the steady-state (\( \frac{dW}{dt} \approx 0 \)) the measured values of \( W \) & \( P \) can give an estimate of \( r_e \) [20]. In the startup phase the radiated power is significantly large, often close to the ohmic power input

\[
P = V I_p - \frac{d}{dt} \left( \frac{1}{2} L_p I_p^2 \right)
\]

where \( V \) is the externally applied loop voltage, \( I_p \) and \( L_p \) are the plasma current and inductance respectively (see next subsection for detail). We can then define \( r_e \) from Eq. (12) as

\[
r_{\text{re}} = \frac{W_e}{P - P_{\text{rad}} - \frac{dW_e}{dt}}
\]

where the quantities on the r.h.s. are evaluated at the previous time step of integration.

2.3 **Plasma Circuit Model**

The plasma formation and heating are also accompanied by initiation and buildup of plasma current. The space averaged or the zero-d model here the Ohm's-law for plasma simply describes plasma as a current filament with some constant resistance \( R_p \) and an inductance \( L_p \). The current buildup is then given by

\[
L_p \frac{dI_p}{dt} + R_p I_p = V
\]

with the inductance as given by
Here \( R \) and \( a \) are the major and minor radii of the toroidal plasma and \( \frac{2\pi R}{C^2} \) is the internal inductance with \( \zeta \approx 1 \) for the broad current profiles considered here [22].

The voltage is taken to a specified function of time. A simple exponentially decreasing time variation with three time scales has been considered. The shape of \( V(t) \) is shown in the relevant figures later. The basic idea here is to model the energy as in a typical tokamak with ohmic heating.

2.4 Impurity Model

Let us now discuss the model for impurities. The atomic processes governing the density evolution of impurities are: ionization; radiative, dielectronic and three-body recombinations; and auto-ionization. The population \( O_1 \) of neutral oxygen fills the vacuum vessel, whereas the populations \( O_k \) (\( k = 2, 9 \)) of the ionized species is confined to the plasma volume. The time evolution is given by

\[
\frac{dO_1}{dt} = V_p \left[ -n_e O_1 S_1 + n_e O_2 \left( \alpha_2 + \gamma_2 n_e \right) \right. \\
+ \left. \sum_{k=2}^{a} O_k/r_{pc} \right]
\]  

\[
\frac{dO_k}{dt} = n_e S_{k-1} O_{k-1} - n_e \left[ S_k + \alpha_k + \gamma_k n_e \right] O_k \\
+ n_e \left[ \alpha_{k+1} + \gamma_{k+1} n_e \right] O_{k+1} - O_k/r_{pc}
\]

\( k = 2, 8 \)
and

\[ \frac{dO_9}{dt} = n_e S_{88} - n_e \left[ \alpha_9 + \gamma_9 n_e \right] O_{9} - O_{9}' / \tau_{po} \]  

(18)

In these equations the confinement time of all the charge states is taken to be \( \tau_{po} \) for simplicity and is calculated by

\[ \tau_{po} (ms) = 0.075 \alpha_m R^{0.75} Z_{eff} / q \]  

(19)

following detailed experimental scaling by Harmer et al. [23]. Here \( \alpha_m \) is the hydrogen mass and \( q \) is the safety factor at the limiter. The escaping ions are recycled as neutral oxygen.

Atomic rate coefficients are as follows: \( S_k \) is the ionization rate coefficient \( \text{(cm}^3 \text{ s}^{-1}) \) from the state \( k \) to the state \( k+1 \); \( \alpha_k \) is the sum of radiative and dielectronic rate coefficients \( \text{(cm}^3 \text{ s}^{-1}) \) and \( \gamma_R \) is the three body recombination rate coefficient \( \text{(cm}^6 \text{ s}^{-1}) \).

The atomic physics data is taken from the well known Average-Ion-Model (AIM) of Jensen et al. [18], Post et al. [19], for ionization, all the recombinations. The auto-ionization process is modeled as discussed by Jordan [24] and Kato [25]. A comparative study of several atomic physics models for ionization and recombination by Deshpande et al. [26] indicates that in general, AIM overestimates the ionization potentials for the low-z impurities. This results in a reduction of the ionization rate. This situation can be improved [27] by using ionization potentials as given by Lotz [28]. We call this model AIML, where only ionization rates...
have changed from the original AIM. Rates for radiative processes mentioned earlier in the introduction to this chapter are also taken from AIM.

The startup evolution is then examined by using both, AIM and AIML separately and comparing the results, as discussed in the next section. The equations for the oxygen charge state densities above constitute our non-coronal model of impurities. When ionization and recombination effects are so large that \( \frac{d}{dt} \) and \( \frac{1}{\tau_{po}} \) terms are negligible, one obtains the familiar "coronal" or "ionization"-equilibrium (CE). In the CE the net flow between the adjacent charge states is zero in

\[
\alpha_{k+1} o_{k+1} = S_k o_k
\]

so that

\[
o_{k+1} / o_k = S_k / \alpha_{k+1}
\]

(three body recombination is not included here). The ratio of charge states is a function of temperature alone [19]. From CE one can readily obtain \( o_k / \sum_{k=1}^{9} o_k \), \( k=1,9 \) as a function of \( T_e \) through ionization and recombination rates. The radiative power loss in coronal equilibrium is then calculated by using these densities in the expression (7) for \( P_{rad} \). The evolution so obtained is called the coronal run of zero-d. The non-coronal run of zero-d is performed by using the densities as obtained by solving the impurity equations above at each time steps, to calculate \( P_{rad} \).

We therefore solve the zero-d evolution equations for
the coronal and non-coronal radiation for both AIM and A1ML atomic data sets.

3. Results

Let us now discuss the results of the zero-d evolution of plasma and the impurities. We have solved these equations with ADITYA [1] parameters as an example. For this tokamak, the parameters are $R = 75\, \text{cm}$, $a = 25\, \text{cm}$, $B_r = 15\, \text{kilo Gauss}$, $B_p = 2\, \text{kilo Gauss}$, Max. plasma current $I_p = 250\, \text{kAmp}$, and safety factor $q(a) = 2.5$. The equations are numerically integrated on the DEC-10 computer, to obtain $n_e, n_i, T_e, T_i, I_p$ and $\Omega_k$'s with several other parameters.

In Fig. 1 we display the coronal and non-coronal evolution of the plasma temperature & the toroidal current with a given voltage (V-loop) waveform (discussed earlier). The coronal run predicts much higher $T_e$ and $I_p$ compared to the non-coronal runs. Results are displayed for both AIM and A1ML data sets. A change of ionization data (A1ML) affects the duration of radiation barrier more noticeably in the non-coronal case. This is seen by comparing the initial "flatness" of curves for coronal run (AIM with A1ML). In the coronal runs this time duration of about 5 ms around $t = 0$ is unchanged from AIM to A1ML. The change is quite significant for the corresponding comparison with non-coronal runs. This initial plateau arises due to the large radiative loss which keeps the plasma temperature low. After the plasma "burns" through the $T_e$ and $I_p$ rise quite sharply and eventually approach a quasi-steady state. We conclude that in the non-coronal case, one would be required to put more energy so
that identical final values for $T_e$ & $I_p$ are attained. This implies a greater volt-second consumption for the non-coronal case.

In Fig.2(a), (b) & (c) we show the behaviour of oxygen charge states $[O_1, O_2, O_3$ in 2(a), $O_4, O_5, O_6$ in 2(b) and $O_7, O_8, O_9$ in 2(c)]. The fractional densities are plotted for the entire temperature range through which plasma evolves. The curves for these densities show a strong shift to higher temperatures in the non-coronal case. Compared to coronal the non-coronal densities survive up to quite high temperatures. This result has the following implication on the interpretation of impurity related diagnostics on tokamaks. The emission lines from these ions of oxygen are often observed as a function of time during discharge evolution. The coronal and non-coronal evolutions predict different temperatures up to which these ions survive in the plasma.

In Fig.3 we compare the coronal and non-coronal cases. Consistent with previous study by Carolan [7] the non-coronal run indicates lesser ionization of oxygen impurities, at a given temperatures, compared to the coronal case. This happens due to the fact that plasma evolves rapidly, leaving insufficient time for ionization and relaxation to CE. Finite confinement time also affects this relaxation.

The important result on enhanced radiation at higher temperatures due to the effects discussed above is displayed in Fig.4. The total oxygen density is written as $n_1$ on these diagrams. This result, again is consistent with that of Carolan's [7].
4. Conclusion

We have studied the startup phase evolution by a zero-d code. The evolution is obtained with both, coronal and non-coronal calculation of radiative power loss, and, compared for the two cases. The loop voltage as a function of time is kept identical in both cases.

Due to rapid time variations and finite confinement time the impurity densities and radiative power losses deviate from their coronal estimates strongly. The average charge $\langle z \rangle$ is lower and radiated power is consequently higher for the non-coronal evolution. As a result, the plasma temperature (and current) is comparatively lesser at a given instant of time.

In summary, the non-coronal effects are quite important as the realistic startup conditions involve rapid time variations as well as recycling (finite confinement time) effects. For medium sized tokamaks like ADITYA [1] the non-coronal effects can modify the energy balance to alter the total volt-second consumption in startup phase. The interpretation of emission lines for plasma diagnostics must also take these effects into account, as various charge state survive higher (than coronal) temperatures.
References

12. J.Sheffield in "Tokamak Start-up" (Ed. by H.Knoepfel)


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Fig 1 Time evolution of $T_e$ and $I_p$ for coronal and non-coronal radiated powers.
Fig 2(a) Fractional densities of oxygen charge states: $O^+_1$, $O^+_2$, $O^+_3$ as a function of temperature.
Fig 2(b) Fractional densities of oxygen charge states: $O^4, O^5, O^6$ as a function of temperature.
Fig 2(c) Fractional densities of oxygen charge states: $0_1, 0_{II}, 0_p$ as a function of temperature.
Fig 3 Average charge, \langle z \rangle, for coronal and non-coronal cases.

\( m^{26} \)
Fig 4 Radiative power loss (total) for coronal and non-coronal cases. $n_e$ is the total oxygen density.