Fusion Reactor with Electrodynamic Confinement

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Abstract

Thermonuclear plasma confinement can be significantly improved using the reaction of electrical conductors to the variable magnetic fields created by the plasma. In this way the magnetic fields can be confined in some well defined space and with it the plasma itself. Also many plasma instabilities are restricted in development by the dynamic of plasma and its fields.

1 Introduction

The fusion reactor described here has the purpose to generate usable energy from the fusion reaction between the hydrogen isotopes, mainly between deuterium and tritium which require a lower temperature than other reactions. It is based on an improved version of tokamak magnetic confinement, using electrodynamic suspension and stabilization of plasma in a toroidal chamber that has a high electrical conductivity metallic shell around the plasma column. The currents induced in this conductive layer produce the electrodynamic suspension of plasma relative to the walls. Rather than using a stationary confinement, in this case a dynamic confinement is used, with variable currents and magnetic fields that produce the reactive field expulsion from the conductive layers. This produces the confinement of the magnetic field and subsequent the confinement of plasma. A dynamic system, together with a suitable geometry of the high conductivity confinement shell, offers multiple benefits.

One such benefit is the magnetic levitation of plasma inside the conductive shell due to the reactive field expulsion. Because of the good electrical conductivity of the high temperature plasma and of the confinement shell, the oscillating magnetic field created by the current flowing along the z axis of plasma, will be expelled from the high conductivity shell and from plasma, the field lines being forced to close in the space between the plasma surface and the inner surface of the shell. This will squeeze the field in that space and will keep the plasma away from the walls even against significant forces. The metallic confinement shell will react to changes in plasma position and will stabilize it inside its walls.

Another benefit is the reduction of particle escape at the plasma surface. The limited magnetic penetration time will confine the current in a relatively thin layer at the plasma surface. This is the transition layer from the inner plasma pressure and density to the outer vacuum, with the plasma surface being less diffuse and better delimited compared with a stationary regimen. The electric field induced along the z axis in combination with the azimuthal magnetic field will prevent the charged particles to leave the plasma surface.

Also cyclic changes of azimuthal magnetic field direction combined with cyclic plasma compression and expansion will limit the evolution of instabilities which have longer evolution time. A magnetic field along the z axis created by a toroidal coil will stabilize the plasma against fast evolving instabilities like localized pinches. This magnetic field will also increase the rigidity of the plasma and by changing its intensity we can modulate the compression ratio.

2 The confinement system

The structure of principle of the system is shown in figure 2.1.

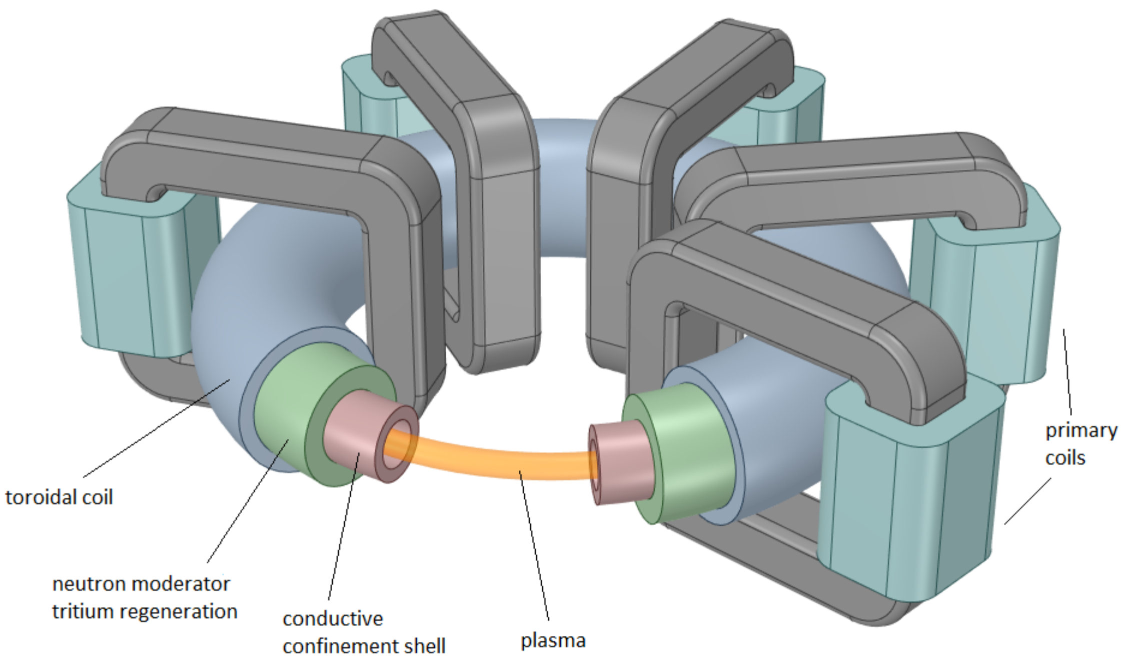

Figure 2.1: Electrodynamic confinement the structure of principle

Because the toroidal plasma ring has a cylindrical symmetry, we will use a cylindrical coordinate system, with the z axis along the toroidal ring of plasma, the r radius transversal on the z axis, the azimuthal φ angle around the z axis. Now the z axis is following the toroidal curvature, however locally we approximate this with a straight z axis cylindrical coordinates. Any component along the z axis will be named “axial", along r radius will be named “radial", revolving with the φ angle around the z axis will be named “azimuthal". To prevent that the metallic confinement shell to be induced with toroidal currents by the primary coils variable magnetic field, the toroidal shell will be assembled from segments electrically insulated between them. In this way a close electrical path similar to the plasma column is avoided and the plasma column is the only secondary turn for the primary coils.

2.1 Electrodynamic suspension and stabilization

The variations in the azimuthal magnetic field will induce currents in the metallic confinement shell placed around the plasma column, currents that will create their own magnetic field that will oppose and expel the inductive magnetic field from the metal. For this the material of the metallic shell must have a high electrical conductivity and no ferromagnetic properties, like Cu for example. Because the magnetic field has no divergence, the azimuthal field lines are forced to close in the space between the plasma outer surface and the inner surface of the confinement shell. In this way it will create an electrodynamic suspension or levitation of plasma column inside the metallic shell. This will prevent the plasma to go close to the shell walls and also will limit the local bending of the plasma column. Virtually the azimuthal magnetic field around the plasma column is confined between the plasma surface and the walls, both being of high electrical conductivity. The azimuthal magnetic field created by the axial current through plasma, must change the direction periodically, with a high enough frequency, to create the suspension effect of the plasma column inside the metallic confinement shell. This will produce a series of compression, during the current increase, followed by expansion during the current decrease, then the current change the direction and repeat the compression expansion cycle but with a reversed azimuthal magnetic field this time. To change the current direction with the required frequency, several sources of alternating voltage with the average value of zero will be used. This can be implemented using static switching devices or multipolar rotary generators if the frequency is low enough. The equivalent electrical circuit is presented in figure 2.2.

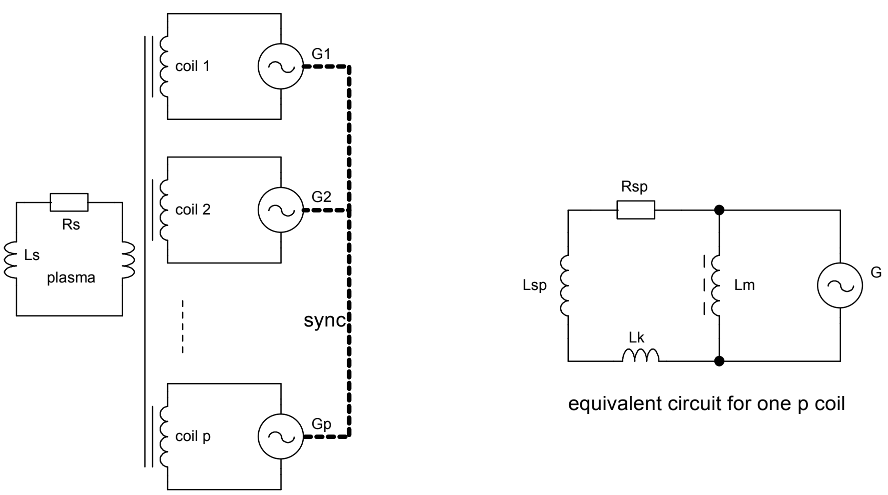

Figure 2.2: Equivalent electrical circuit

We will consider that we have a number of p primary coils, every one supplied with alternating voltage from a source. All these generators will be driven synchronously. The voltage wave form can be sinusoidal (for the case of rotary generators), rectangular/trapezoidal or sinusoidal (for the case of a static switched mode source). The plasma ring act like a short-circuit turn and is induced with a voltage and current by the oscillating magnetic field of all primary coils, but in the same time it has its own inductance L_s the effect of its own magnetic field which is not coupled with the magnetic cores (mainly the field bellow the inner surface of the confinement shell). We can represent an equivalent circuit with all the elements reflected in the primary side of every coil, with L_{sp} the reflected inductance of plasma, L_k the additional leakage inductance, L_m the magnetization inductance of one primary coil. We can write for the voltage induced in the plasma ring

$$u_s = -\frac{d\Phi_{sum}}{dt} = -p \cdot \frac{d\Phi_p}{dt} \quad (2.1)$$

in the same time the voltage induced in one of the primary coils is

$$u_p = -N_p \cdot \frac{d\Phi_p}{dt} \quad (2.2)$$

where N_p is the number of turns of the primary coil. So the voltage ratio will be

$$u_s = u_p \cdot \frac{p}{N_p} \quad (2.3)$$

For every magnetic field line passing through one of the magnetic cores, we have the Ampere equation

$$\oint H dl = N_p i_{ptot} + i_z = N_p i_m \quad (2.4)$$

where i_m is the magnetization current reflected in the primary coil, i_z is the axial current through plasma, so for the primary current we can write

$$i_{ptot} = -\frac{i_z}{N_p} + i_m = i_p + i_m \quad (2.5)$$

only the magnetization current effectively create a magnetic field line that encircle both current loops (primary and secondary), the rest of the currents primary i_p and secondary(plasma) i_z are reflected currents and their magnetic fields cancel each other, the minus sign indicate exactly this cancellation. So for the reflected currents, neglecting the direction of flow we have

$$i_z = i_p N_p \quad (2.6)$$

with this we can also verify the conservation of reflected energy $u_s i_z = u_p i_p p$. A magnetic field line that do not encircle both current loops but only one is produced by the entire current that it encircle and do not contribute to the reflection of energy, but contribute to the uncoupled inductance $L_k + L_s$.

Any impedance from the secondary(plasma ring) is reflected in all the primary coils as

$$Z_{sp} = \frac{u_p}{i_p} = \frac{u_s}{i_z} \cdot \frac{N_p^2}{p} = Z_s \cdot \frac{N_p^2}{p} \quad (2.7)$$

because $Z = R + j\omega L$ (here j is the imaginary unit), we can also write

$$L_{sp} = L_s \cdot \frac{N_p^2}{p} \quad (2.8)$$

$$R_{sp} = R_s \cdot \frac{N_p^2}{p} \tag{2.9}$$

The electrodynamic stabilization inside the conductive shell is illustrated in figure 2.3. In the normal position the azimuthal magnetic field is equal around the plasma and magnetic forces are canceling each other. When the plasma position is shifting toward one of the walls, the magnetic field on that side become stronger because it is repelled out from the conductive wall due to the induction of eddy currents. This will create a difference of forces that will push the plasma back into the normal position.

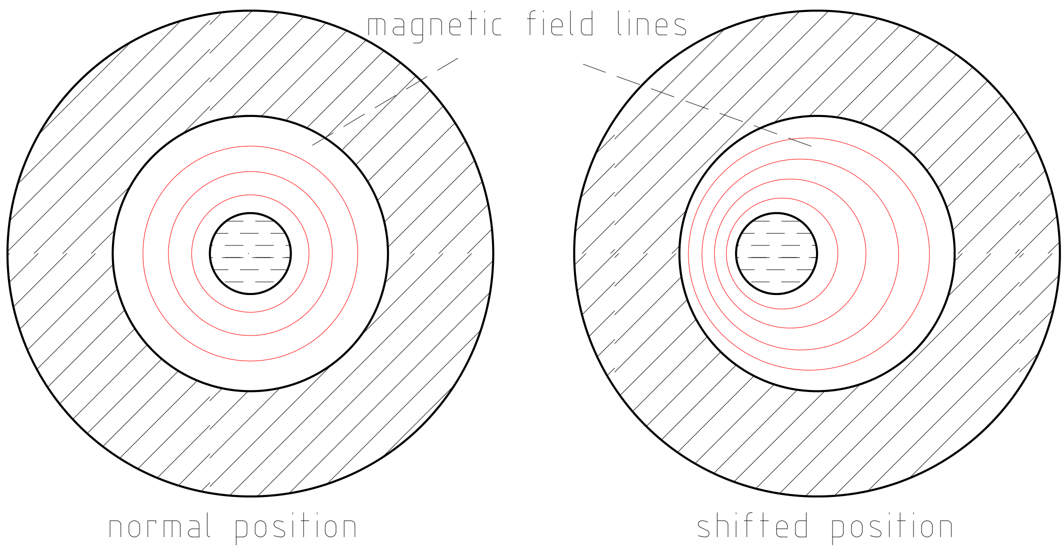

Figure 2.3: Plasma levitation inside the metalic shell

The penetration depth of a sinusoidal varying magnetic field in a conductive medium is limited in a layer close to the surface by the induction of eddy currents in the conductive medium

$$\delta = \frac{1}{\sqrt{\pi \mu \sigma f}} \tag{2.10}$$

where δ is the penetration distance into conductive material where B decrease e times from the surface, σ is the material electrical conductivity, μ is the magnetic permeability, f is the frequency of oscillations of the magnetic field. The thickness of the metallic wall must be at least several times bigger than δ, the magnetic field at distance x inside the conductive medium metal or plasma will decrease exponentially

$$B_x = B_s \exp\left(-\frac{x}{\delta}\right) \tag{2.11}$$

where B_s is the field at the surface.

To avoid to short circuit the plasma ring in the presence of the induced axial electric field, the high conductivity metallic shell must be assembled from multiple tubular segments over the length of the torus.

These segments must be connected together with an insulation interface between them to prevent the circulation of a toroidal current. However the localized axial currents are able to circulate inside every segment and in this way to expel the azimuthal

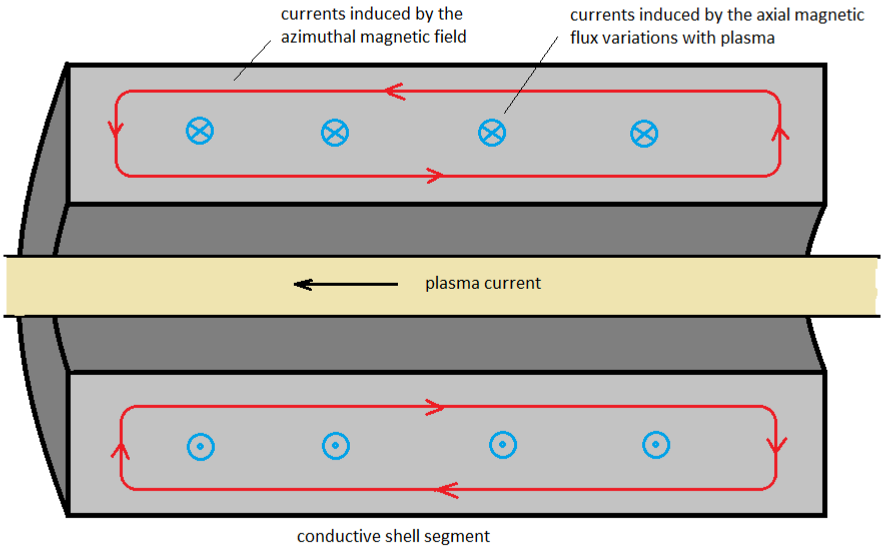

Figure 2.4: Section view through one segment of the conductive shell

magnetic field from inside. Also they will allow the circulation of azimuthal induced currents by the axial magnetic field. Because these currents can be relatively high and also because of the plasma radiation, a significant amount of heat will be produced inside these segments and an active cooling using some electrical insulating fluid must be used to keep them at a low enough temperature.

The confinement and compression of plasma is done primarily by the azimuthal magnetic field created by the induced current along the z axis of plasma, while the plasma shape and particles motion is additionally stabilized and confined by the axial magnetic field created by the toroidal coil. As we will se later this axial field while is created by a stationary current, is also “frozen" inside plasma and its value will change with the plasma radius.

2.2 Magnetic pressure

The plasma is subjected to the action of two magnetic fields, the azimuthal field created by the current induced in the plasma by the primary coils (the axial current) and the axial field created by an external coil placed along the z axis of the torus. As a result we will have two magnetic pressures exerted on the plasma surface by these fields, in addition to the particles pressure from inside the plasma. Because at high temperature the plasma has a very good electrical conductivity and also because the axial current from the plasma and its azimuthal magnetic field change with a relatively high frequency, the axial current will flow in a relatively thin layer at the surface of plasma. In consequence the azimuthal magnetic field will be null inside the plasma and will be present only in the exterior of plasma and in the transition layer close to the surface where the current is flowing. The thickness of this transition layer is comparable with the penetration distance of the magnetic field. Another effect of high conductivity of plasma is the behavior of the axial magnetic field, it will be frozen inside plasma during the relatively short time of a half period of the cycle. The thickness of the transition layer from the internal to the external field will be again comparable with the penetration distance. In consequence both magnetic pressures are built up inside the transition layer located at the plasma surface, being balanced by the particles pressure from inside the hot plasma.

The magnetic pressure appear only in areas where are current density components, so only in areas where the magnetic field change. In figure 2.5 is illustrated the transition layer at the surface of plasma where the magnetic pressure is build.

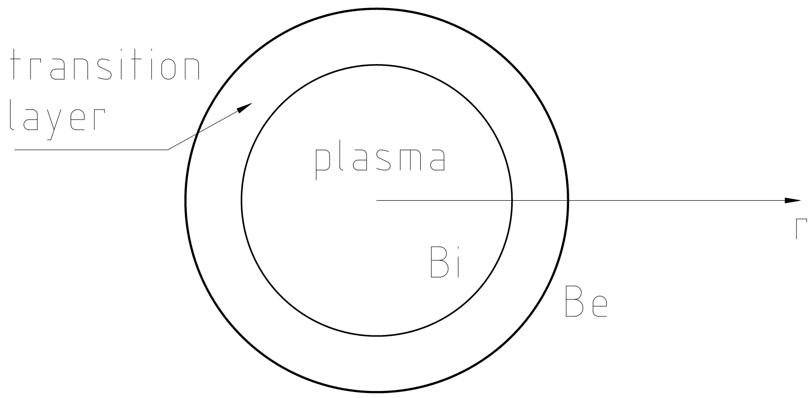

Figure 2.5: Magnetic pressure in the transition layer of plasma

The volume density of the magnetic force, equal with the inverse of the magnetic pressure gradient, is

$$\vec{f_m} = \vec{j} \times \vec{B} = -\nabla p_m + \vec{f_{mt}} \tag{2.12}$$

we also have $\mu_0 \vec{j} = \nabla \times \vec{B}$ and replacing in 2.12 result

$$-\nabla p_m + \vec{f_{mt}} = \frac{1}{\mu_0}\left(\nabla \times \vec{B}\right) \times \vec{B} = -\frac{1}{2\mu_0}\nabla\left(\vec{B}\cdot\vec{B}\right) + \frac{1}{\mu_0}\left(\vec{B}\nabla\right)\vec{B} \tag{2.13}$$

where the first term is the magnetic pressure

$$p_m = \frac{B^2}{2\mu_0} \tag{2.14}$$

the second term $(B\nabla)\,B$ is the magnetic tension force density and is important only in the case of some deformations of the plasma column and field lines. The magnetic pressure produce forces only over surfaces with a gradient of magnetic field pressure with the field lines parallel to the surface, like in the case of the plasma transition layer. The compressing magnetic pressure over this transition layer will be

$$p_m = \frac{1}{2\mu_0}\left(B_e^2 - B_i^2\right) \tag{2.15}$$

where B_i and B_e are the magnetic field inside and outside the plasma. This magnetic pressure has two major components, the azimuthal magnetic pressure and the axial magnetic pressure. However the direction of action of these pressures is radial, but we will just name them after the field that produce them.

The azimuthal magnetic field from the inside of plasma under the transition layer will be null, the external field just on the external surface of plasma will be at its maximum value

$$B_{\varphi s} = \frac{\mu_0 i_z}{2\pi a} \tag{2.16}$$

where a is the radius of the plasma column. The azimuthal magnetic pressure become

$$p_{m\varphi} = \frac{B_{\varphi s}^2}{2\mu_0} = \frac{\mu_0 i_z^2}{8\pi^2 a^2} = \frac{\mu_0 i_z^2}{8\pi S_i} \tag{2.17}$$

this is the pressure below the inner limit of the transition layer, $S_i = \pi a^2$ is the radial section area of the plasma. In the transition layer the azimuthal pressure decrease progressively from its maximum value (on the inner limit of the layer) to zero (on the outer limit). In consequence some of the particles close to the outer surface of the plasma, being exposed to a low pressure and receiving thermal energy from the inner particles, will have the tendency to escape from plasma. Because of the magnetic fields the particles will move on a circular path, eventually returning back into plasma. Additionally the variable magnetic fields created by the primary coils and the variable azimuthal magnetic field will induce an electric field along the z axis. Inside plasma and at the plasma surface, the electric field induced by the primary coils will be balanced by the electric field induced by the variation of the azimuthal magnetic field of the plasma, the remaining field will compensate the voltage drop on the plasma resistivity. This axial electric field at the surface of plasma will always have the direction of the z current, as such the escaping particles will be accelerated by it, they will interact with the azimuthal magnetic field and the resultant Lorentz force will prevent the particles to leave the plasma surface. This is true at the plasma surface and very close to it, further away from the surface in the radial direction, the electric field induced by the primary coils is no longer fully balanced by the azimuthal magnetic field variation. As a result far away from the plasma surface the electric field will be more intense and will have the same direction as the z current only during the plasma compression, during the expansion will have an opposite direction to the z current, so any charged particles here during the expansion stage will be pushed toward the tube walls and toward the plasma surface during the compression stage.

The axial magnetic field is created from exterior by the toroidal coil using a constant current, so that in a stationary plasma it will be constant and slightly weaker inside the plasma because of the plasma diamagnetism. In our case of dynamic plasma this diamagnetism is no longer important because the inner field will compress and relax with the plasma. When the radial plasma section crossed by the axial magnetic field, change with the radius change, the inner magnetic flux will change and because of the plasma high conductivity, an azimuthal current will be induced that will try to keep the inner flux constant close to the average value for the cycles. This current will circulate in the transition layer close to the surface. This is the cause that produce the frozen effect of the axial magnetic field inside the plasma of high conductivity. A similar effect appear inside the confinement shell that is also highly conductive and its segments allow for an azimuthal current to close around it. So while the magnetic field created by the toroidal coil is constant outside the conductive shell, inside it and especially inside the plasma this field will be changed by the change in the plasma radial section, but only if these changes evolve fast compared with penetration times. For the magnetic field inside the plasma we have

$$B_{zi}S_i = B_0 S_1 = const \tag{2.18}$$

where S_i is the radial section of the plasma, B_0 is the field created by the toroidal coil, S_1 is the average value of the plasma radial section. The axial magnetic pressure will be both positive (compressing) and negative (expanding). We can write for it

$$p_{mz} = \frac{1}{2\mu_0}\left(B_{ze}^2 - B_{zi}^2\right) \tag{2.19}$$

where B_{zi} is the axial field inside the plasma, B_{ze} is the field outside the plasma up to the confinement shell, B_0 is the average axial field created by the toroidal coil. Because the magnetic flux inside the plasma column is constant, with the change of the plasma radius the surface of the circular crown between the plasma outer radius and the inner radius of the shell will also change. This will produce a change in the magnetic flux passing through this circular crown and as so the entire flux passing through the inner section of the confinement shell will change. This will induce azimuthal currents around the conductive shell that will keep the flux constant.

$$B_{ze}S_e = B_0 S_2 = const \tag{2.20}$$

where S_e is the circular crown surface, S_2 is the average value of the crown surface. During compression when $S_i < S_1$ the axial magnetic field inside the plasma will be higher than the field outside it and the axial magnetic pressure will oppose compression and also will stabilize the plasma. During expansion when $S_i > S_1$ the axial magnetic field inside the plasma will be lower than the field outside it and the axial magnetic pressure will oppose further expansion. Replacing in 2.19 we have

$$p_{mz} = \frac{B_0^2}{2\mu_0}\left(\frac{S_2^2}{S_e^2} - \frac{S_1^2}{S_i^2}\right) = \frac{B_0^2}{2\mu_0}\left[\frac{(S_0 - S_1)^2}{(S_0 - S_i)^2} - \frac{S_1^2}{S_i^2}\right] \tag{2.21}$$

where $S_0 = S_1 + S_2 = S_i + S_e$ is the inner radial section of the confinement shell. The equilibrium of pressures on the plasma surface is

$$p_{th} = p_{m\varphi} + p_{mz} \tag{2.22}$$

where p_{th} is the particles thermal pressure, equal with the sum of the thermal pressure of ions and electrons

$$p_{th} = n_i k T_i + n_e k T_e \tag{2.23}$$

As can be observed the confinement shell has influence over both magnetic fields inside it, azimuthal and axial and by this will have a strong contribution to the plasma confinement and stability, both against displacement toward the walls and against the kink deformations.

2.3 Plasma polarization

One aspect that must be taken into consideration is the possibility that the plasma column can become electrically charged relative to the metallic shell, through exchange of charged particles. This will produce a radial electric field between the plasma surface and the tube walls, field that will produce attraction forces between the two. Once the plasma column is out of its central position inside the tube and closer to a wall than to the other side wall, on the closer distance the radial electric field will become stronger and its forces will become unbalanced with the tendency to push the plasma into the tube wall if the electrical charge built in plasma become high enough. The plasma will have the tendency to become charged by the electrons emitted by the metallic shell under the influence of the radiation emitted from plasma, also ions and electrons escaping from plasma may reach the wall transporting electrical charge.

To eliminate this problem we can use injectors of ions and electrons into plasma. Some injectors will accelerates positive ions of deuterium and tritium into plasma, the others will accelerates electrons into plasma. The amount of ions and electrons injected will be controlled by a system that measure the intensity and direction of the radial electric field and take action to keep it to a minimum. In the same time this injection system ca be used to supply the plasma with new nuclei of deuterium and tritium to replace the ones that has been converted to helium, also will play a role in the initial formation and heating of the plasma. Together with a method of extracting the helium and other heavy impurities from plasma, will allow for continuous running of the fusion reaction.

2.4 Pinch and kink instabilities

These are fast evolving instabilities that must be compensated by the magnetic fields, while others slower evolving ones are restricted by the relatively short time of one compression cycle, combined with the change of azimuthal field direction in the next cycle.

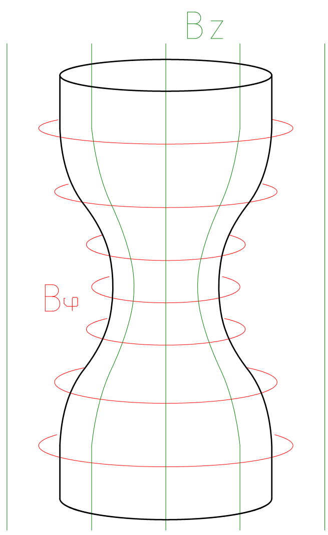

Figure 2.6: Localized pinch deformation

The pinch instability (figure 2.6) appear as a local reduction in the radius of the plasma column, that in turn lead to the local increase of the azimuthal magnetic field and its pressure which trigger a further propagation of the deformation. It is stabilized by the axial magnetic field. The inner axial field is pinched with the plasma and this lead to its increase and the increase of the inner axial pressure. In the same time the axial field on the exterior of plasma will decrease because of the local geometry of the pinch. Also in the pinched area the magnetic tension forces will push to straighten the field lines. From equations 2.17 and 2.21 we can observe that while the axial current remain constant, the azimuthal magnetic pressure will change slower with the inner section surface of the plasma column than the axial magnetic pressure, so if the axial magnetic field from inside the plasma is strong enough the pinch will be stable. For very small deformations the condition of stability is

$$\left|\frac{dp_{mz}}{dS_i}\right| \geqslant \left|\frac{dp_{m\varphi}}{dS_i}\right| \tag{2.24}$$

after derivation we have

$$\frac{B_0^2}{\mu_0}\left(\frac{S_2^2}{(S_0 - S_i)^3} + \frac{S_1^2}{S_i^3}\right) \geqslant \frac{\mu_0 i_z^2}{8\pi S_i^2} \tag{2.25}$$

When the plasma is at its maximum radius the axial current is zero and the particle pressure is balanced only by the axial pressure which now is positive and compressive. Here the plasma is stable because the azimuthal field is zero. When the plasma is at its minimum radius the azimuthal magnetic field will be maxim and this is the point of maximum instability, so if the condition 2.25 is satisfied for $S_i = S_{min}$ then the plasma will be pinch stable for the entire cycle. If the pinch is stable at very small deformations, it will be also stable for bigger deformations because of the additional tension forces.

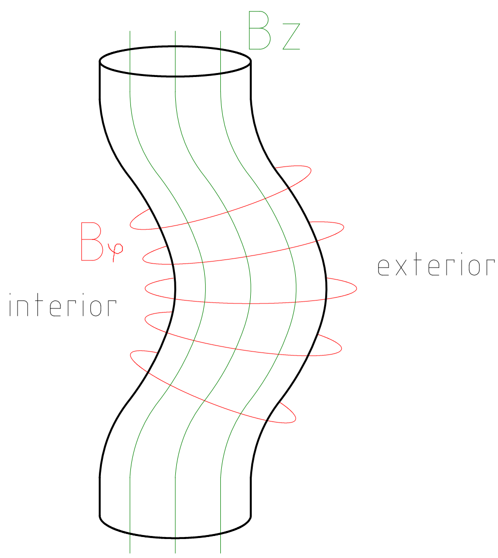

Figure 2.7: Localized kink deformation

The kink instability (figure 2.7) appear as a local bending of the plasma column, that in turn lead to the increase of the azimuthal field on the interior of bending compared to the field on the exterior of it, the difference in azimuthal magnetic pressures will push the deformation even further. It is stabilized by the conductive shell through the expulsion effect and also by the axial magnetic field from inside the plasma column. The conductive shell will change the value of azimuthal magnetic field around the deformation (see figure 2.3) until the unbalance will be eliminated and the deformation will no longer progress any further. The inner axial magnetic field lines will follow the bend of the plasma column by the induction of additional azimuthal currents in plasma at the area of deformation. These currents will bend the field lines which are shorter on the interior of the bend so the field here is stronger than the field on the exterior of it. This will create a difference in the axial magnetic pressures that will push the deformation back. In addition the tension forces of the bent field lines will push the deformation back. In the case of kink deformation, both the conductive shell and the axial magnetic field have an active role in stopping the deformation, the conductive shell is more effective for large deformations, while the axial field for small ones. Consequently with stronger axial field produced by the toroidal coil come better stability but also more plasma rigidity and less compression.

In time the plasma has the tendency to develop flute instability into a helicoidal deformation following the combined field lines of azimuthal and axial field. However in this case if the cycle time is too small for a significant evolution of flute deformation, because in the next cycle the direction of the azimuthal field will be changed and that will change the helicoidal direction of rotation, the previous evolution of any helicoidal deformations will be supressed and the situation will repeat the next cycle. Also all instabilities driven by the diffusion of the magnetic field into plasma, will be supressed as well because of the absence of such a diffusion.

3 Thermonuclear plasma

The plasma column is composed of hydrogen isotopes deuterium and tritium but also some amount of helium will result as a byproduct of fusion. The ionization energy of hydrogen from its ground state is 13,6 eV which for 3 degrees of freedom correspond to a temperature of 105250 K. The plasma will be at temperatures much higher than this so it will be completely ionized. Helium ionization energy for the first electron is 24,6 eV which correspond to a temperature of 190380 K almost double than H but still way bellow typical thermonuclear temperatures, so it also will be completely ionized. In consequence we will have a gas of charged particles, positive charged nuclei (ions) and negative charged electrons. The processes of compression and expansion are slow compared to maxwellization times so that the Maxwell-Boltzmann distribution remain valid during their evolution.

3.1 Debye length

The screening length of the electric field created by the individual charged particles in plasma. Valid in the condition that all charged particles have a Maxwell-Boltzmann distribution. In our case of interest we consider the presence in plasma of electrons, ions of hydrogen(deuterium and tritium) and ions of helium with $Z_a = 2$, the Debye length [4] is

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k}{q_e^2 \left(\frac{n_e}{T_e} + \frac{n_i}{T_i} + \frac{Z_a^2 n_a}{T_a}\right)}} \tag{3.1}$$

where k is the Boltzmann constant and n is the particle density for electrons, ions of hydrogen, alpha particles (helium nuclei) respectively. If we neglect helium concentration $n_a \simeq 0$, electrons and ions temperatures equal $T_e = T_i = T$ the Debye length become

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k T}{q_e^2 (n_e + n_i)}} \tag{3.2}$$

For a time interval small enough that the ions redistribution movement can be neglected, we have only electrons screening with

$$\lambda_{De} = \sqrt{\frac{\varepsilon_0 k T_e}{q_e^2 n_e}} \tag{3.3}$$

being the electronic Debye length.

3.2 Plasma frequency

The high temperature plasma is electrically neutral having equal numbers of positive and negative particles so that the total electric charge is zero. However in reality small deviations from neutrality exist, both at a large scale as plasma polarization and at a small scale as local separations between the ions and electrons. When such localized separation occur a local electrical restoration force appear that will restore neutrality. Because of the particles mass, this takes a specific time to happen, correspondingly a frequency can be associated with it called plasma frequency. For our case the plasma frequency [4] is

$$\omega_p = \sqrt{\frac{q_e^2}{\varepsilon_0}\left(\frac{n_e}{m_e} + \frac{n_i}{m_i} + \frac{Z_a^2 n_a}{m_a}\right)} \tag{3.4}$$

where m is the mass of the electrons, ions and alpha. Because the mass of the ions is much higher than the mass of electrons, the plasma frequency can be approximate as

$$\omega_p = \sqrt{\frac{q_e^2 n_e}{\varepsilon_0 m_e}} \tag{3.5}$$

which means that the movement of electrons is almost entirely responsible for neutrality restoration. Plasma absorption of electromagnetic radiation is influenced by the plasma frequency, the plasma is opaque for radiation with frequency $\omega \ll \omega_p$ and is transparent for $\omega \gg \omega_p$.

3.3 Electrical conductivity

Because is completely ionized the plasma has a good electrical conductivity that will increase with the temperature. The positive nuclei of hydrogen (ions) and their electrons will be separated and will move free, forming a gas of particles that interacts with each other. The electrons being much more light and fast than ions, will carry almost all the current, with the positive ions carrying a much smaller amount. Such a plasma will have some electrical resistance because of the Coulomb collisions between the moving electrons and the ions that are much slower and move in the opposite direction (figure 3.1). On average electron-electron collisions momentum transfer is neglected because all electrons are drifted in the same direction by the electric field.

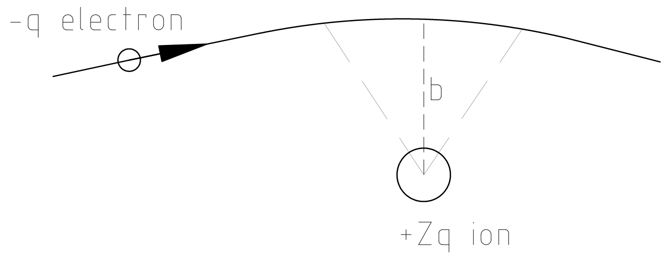

Figure 3.1: Coulombian interaction ion-electron

Most Coulomb interactions in hot plasma are characterized by a small scattering angle. On average after a number of such interactions and a corresponding time interval the electron will lose(transfer) its momentum in the direction of the electric field, this will be the electron-ion momentum transfer time τ_{mei} and will have a momentum transfer collision frequency ν_{mei}. In consequence the electron will have an average drift velocity in the direction of electric field

$$v_d = \frac{q_e E}{m_e} \cdot \tau_{mei} \tag{3.6}$$

where $q_e m_e$ are the charge and mass of the electron. The current density in plasma is

$$j = n_e q_e v_d \tag{3.7}$$

where n_e is the electrons density. The electrical conductivity is

$$\sigma_e = \frac{j}{E} = \frac{n_e q_e^2 \tau_{mei}}{m_e} \tag{3.8}$$

The momentum transfer collision frequency for electron-ion interactions [4, 8] is

$$\nu_{mei} = \frac{1}{\tau_{mei}} = \frac{\sqrt{2\pi} Z_i^2 q_e^4 n_i \ln \Lambda}{12\pi^2 \varepsilon_0^2 \sqrt{m_e} (kT_e)^{3/2}} \tag{3.9}$$

where $Z_i = 1$ for a hydrogen plasma, $\ln \Lambda$ is the Coulomb logarithm for electron-ion collision, the result of integration between the minimum and maximum of the impact parameter b.

For a high temperature plasma $b_{max} = \lambda_D$ and b_{min} is limited by the larger value from the classical or the quantum limit. In the classical limit the interaction potential energy must be less than the kinetic energy

$$b_{minc} = \frac{Z_1 Z_2 q_e^2}{4\pi\varepsilon_0 m v^2} \tag{3.10}$$

where v is the relative velocity and m is the reduced mass of the two particles

$$m = \frac{m_1 m_2}{m_1 + m_2} \tag{3.11}$$

The quantum limit is the limit where the quantum effects become important

$$\hbar = m v b_{minq} \tag{3.12}$$

For electron-ion and electron-electron collisions b_{min} is limited by the quantum effects for temperatures from 0.5 MK up. In this case the quantum limited Coulomb logarithm for electrons become

$$\ln \Lambda_{qe} = \ln\left(\frac{b_{max}}{b_{min}}\right) = \ln\left(\frac{\lambda_D m_e v_e}{\hbar}\right) \tag{3.13}$$

with the electron thermal velocity

$$v_e = \sqrt{\frac{3kT_e}{m_e}} \tag{3.14}$$

for electrons in plasma, considering $n_i = n_e$ and $T_i = T_e$ we have

$$\ln \Lambda_{qe} = \ln\left(\sqrt{\frac{3}{2}} \cdot \frac{kT_e}{\hbar \omega_p}\right) \tag{3.15}$$

For the case of plasma ion-ion collisions the b_{min} is limited by the classical condition for temperatures up to 1000 MK. For $T_i = T_e$ we have the classical limited Coulomb logarithm for ions

$$\ln \Lambda_{ci} = \ln\left(\frac{12\pi n_i \lambda_D^3}{Z_i}\right) = \ln\left[\frac{6\pi\,(\varepsilon_0 kT)^{3/2}}{Z_i q_e^3 \sqrt{2n_i}}\right] \tag{3.16}$$

Considering the condition of quasi neutrality $n_i = n_e$, the conductivity become

$$\sigma_e = \frac{12\pi^2 \varepsilon_0^2\,(kT_e)^{3/2}}{\sqrt{2\pi m_e}\, q_e^2 \ln \Lambda_{qe}} \tag{3.17}$$

This expression of conductivity remain independent of the current density if the thermal movement of electrons dominate over the drift movement $v_e \gg v_d$. When the drift velocity of electrons become comparable and larger than the thermal velocity, the conductivity start to increase with the current density. We may take into account the increased conductivity by adding the drift kinetic energy of electrons to their thermal energy

$$\frac{3}{2} kT_e + \frac{m_e v_d^2}{2} \tag{3.18}$$

So that the electrons temperature in the presence of drift will become

$$T_{ed} = T_e + \frac{m_e v_d^2}{3k} \tag{3.19}$$

with the drift velocity given by the eq. 3.7.

In the presence of a magnetic field inside plasma, the plasma charged particles movement perpendicular to magnetic field direction will be deflected. The electrical conductivity along the magnetic field lines will be unmodified $\sigma_{\parallel} = \sigma_e$, but the conductivity perpendicular to the field lines will be reduced

$$\sigma_{\perp} = \frac{\sigma_{\parallel}}{1 + \left(\frac{\omega_{ce}}{2\pi\nu_{mei}}\right)^2} \tag{3.20}$$

where ω_{ce} is the cyclotron frequency of electrons. The transverse conductivity remain reduced as long as the circular movement of particles around the field lines remain undisturbed, that is far away from plasma edges. At the plasma edges the transverse conductivity will increase back to the normal parallel conductivity.

3.4 Thermal bremsstrahlung

This radiation is produced by the coulomb collisions and braking of charged particles in plasma, also known as free-free radiation because both particles are free moving before and after the interaction (figure 3.1). The radiant energy from the interaction between particles of the same type (electron-electron and ion-ion) is negligible compared with the contribution from the ion-electron interaction. Considering a maxwellian velocity distribution for electrons, the spectral emission power per unit volume is

$$\frac{dP_{br}}{d\nu dV} = C_1 \cdot \frac{Z^2 n_z n_e}{\sqrt{T_e}} \cdot \exp\left(-\frac{h\nu}{kT_e}\right) \cdot G \tag{3.21}$$

where C_1 is a constant, ν is the frequency of the emitted radiation, n_z is the concentration of the ions with Z charges, G is the Gaunt factor of correction that is related with the Coulomb logarithm

$$G = \frac{\sqrt{3}}{\pi} \ln \Lambda \tag{3.22}$$

From 3.21 result that the emitted spectra is continuous up to a photon energy comparable with the average thermal energy of electrons and then decrease rapidly to higher frequencies. So the cutting off upper frequency will be

$$\nu_{max} = \frac{kT_e}{h} \tag{3.23}$$

The plasma has a good transparency for the frequencies of this radiation that are higher than plasma frequency, so most of the power emitted will escape from the volume of plasma to the walls of the metallic shell. The total radiated power over all frequencies per unit volume in our case will be

$$\frac{dP_{br}}{dV} = C_2 \left(n_i + Z_a^2 n_a\right) n_e \sqrt{T_e} \cdot \overline{G} \tag{3.24}$$

where $\overline{G}$ is the Gaunt factor averaged over frequencies. For thermonuclear plasma we can consider $\overline{G} \simeq 1.2$ and $C_2 = 1.4 \cdot 10^{-40}$ [SI] [1, 4]. In the condition of good plasma confinement, this radiation represent the main way of energy loss form plasma. Also if we determine the maximum frequency of the bremsstrahlung, then we can get the electrons temperature inside plasma.

3.5 Cyclotron movement

In the presence of a magnetic field B in plasma (like the axial magnetic field), the charged particles ions and electrons will start to rotate around the magnetic field lines. Because the plasma has some density, this rotation movement will be disturbed by collisions, however most collisions are soft. Considering a maxwellian distribution and the Lorentz force that act over the charge and the centrifugal force, we have

$$\frac{mv^2}{r_c} = qvB \tag{3.25}$$

Because of the rotation around the magnetic field lines the parallel velocity is not contributing, the average thermal velocity of rotation will be

$$v = \sqrt{\frac{2kT}{m}} \tag{3.26}$$

For electrons the cyclotron radius

$$r_{ce} = \frac{\sqrt{2m_e kT_e}}{q_e B} \tag{3.27}$$

from $v = \omega r$ the electrons cyclotron frequency

$$\omega_{ce} = \frac{q_e B}{m_e} \tag{3.28}$$

And similar for ions

$$r_{ci} = \frac{\sqrt{2m_i kT_i}}{Z_i q_e B} \tag{3.29}$$

and

$$\omega_{ci} = \frac{Z_i q_e B}{m_i} \tag{3.30}$$

The cyclotron frequency only depend on the magnetic field and the particle mass and is much higher for electrons than for ions.

This rotation being accelerated movement will produce the emission of cyclotronic radiation with the corresponding frequency. The radiated power is much smaller than bremsstrahlung power and in addition the metallic shell will reflect this radiation back into plasma further reducing the power loss through cyclotronic radiation. The cyclotronic frequency of the emitted radiation can be used to determine the value of the magnetic field from plasma.

3.6 Maxwellization times

The maxwellization time can be approximate with the inverse of the momentum transfer collision frequency. We will have four distinct maxwellization times: electron-electron, ion-ion, electron-ion and ion-electron [4]. The electron-electron maxwellization time will be

$$\tau_{mee} = \frac{1}{\nu_{mee}} = \frac{12\pi^2 \varepsilon_0^2 \sqrt{m_e}\,(kT_e)^{3/2}}{\sqrt{\pi}\, q_e^4 n_e \ln \Lambda_{qe}} \tag{3.31}$$

The ion-ion maxwellization time

$$\tau_{mii} = \frac{1}{\nu_{mii}} = \frac{12\pi^2 \varepsilon_0^2 \sqrt{m_i}\,(kT_i)^{3/2}}{\sqrt{\pi} Z_i^4 q_e^4 n_i \ln \Lambda_{ci}} \tag{3.32}$$

For electron-ion maxwellization time we have

$$\tau_{mei} = \frac{1}{\nu_{mei}} = \frac{12\pi^2 \varepsilon_0^2 \sqrt{m_e}\,(kT_e)^{3/2}}{\sqrt{2\pi} Z_i^2 q_e^4 n_i \ln \Lambda_{qe}} \tag{3.33}$$

And for ion-electron maxwellization time

$$\tau_{mie} = \tau_{mei} \cdot \sqrt{\frac{m_i}{m_e}} \tag{3.34}$$

The ions maxwellization time is much larger than the electrons time. As an example for a hydrogen plasma with $T_e = T_i = 50\,\mathrm{MK}$, $n_i = n_e = 1 \cdot 10^{22}\mathrm{m}^{-3}$, we have 0.97$\mu$s for electron-electron, 0.69μs for electron-ion, 56μs for ion-ion, 47μs for ion-electron maxwellization times. Electron-ion collisions contribute to the maxwellization of both ions and electrons. The total maxwellization time for electrons will be given by

$$\frac{1}{\tau_{me}} = \frac{1}{\tau_{mee}} + \frac{1}{\tau_{mei}} \tag{3.35}$$

and for ions

$$\frac{1}{\tau_{mi}} = \frac{1}{\tau_{mii}} + \frac{1}{\tau_{mie}} \tag{3.36}$$

These maxwellization times are much smaller than typical cycle times of the axial current.

3.7 Thermalization of fast charged particles

Because the plasma stay compressed only for a limited amount of time in each cycle, we are interested in the thermalization time of fusion byproduct nuclei in plasma. In the case of a deutrium-tritium plasma the electrically charged byproduct is helium-4 also known as alpha particle. In our case we have alpha particles with $Z_a = 2$ mass m_a and an initial energy ϵ of 3.5 MeV released into plasma. These particles will transfer energy to both ions and electrons, so we have two thermalization processes [4].

In the case of thermalization on ions, the alpha velocity is much bigger than the ions thermal velocity for most of the thermalization process

$$v_a = \sqrt{\frac{2\epsilon}{m_a}} \gg \sqrt{\frac{3kT_i}{m_i}} \tag{3.37}$$

In this case the thermalization time on ions can be approximate with

$$\tau_{ai} = \frac{8\pi\varepsilon_0^2 m_i \epsilon^{3/2} \sqrt{2m_a}}{(m_i + m_a)\, Z_a^2 q_e^4 n_i \ln \Lambda} \tag{3.38}$$

Because of the high kinetic energy of the alpha particle, the Coulomb logarithm in this case will be limited by the quantum condition for energy above approximate 200 keV and is limited by the classical condition bellow this energy. Also in this case we can approximate the relative velocity with the alpha velocity. For the quantum limit we have

$$\ln\Lambda_{qai} = \ln\left[\frac{\lambda_D m_i \sqrt{2\epsilon m_a}}{\hbar(m_i+m_a)}\right] \tag{3.39}$$

for the classical limit we have

$$\ln\Lambda_{cai} = \ln\left[\frac{8\pi\varepsilon_0\lambda_D m_i\epsilon}{Z_a q_e^2(m_i+m_a)}\right] \tag{3.40}$$

For the thermalization on electrons, the alpha velocity is much smaller than the electrons thermal velocity

$$v_a \ll \sqrt{\frac{3kT_e}{m_e}} \tag{3.41}$$

In this case the thermalization time on electrons can be approximate with

$$\tau_{ae} = \frac{6\pi^2\varepsilon_0^2 m_a\sqrt{2\pi}\,(kT_e)^{3/2}}{\sqrt{m_e}Z_a^2 q_e^4 n_e \ln\Lambda} \tag{3.42}$$

For a high enough temperature, the Coulomb logarithm will be always limited by the quantum condition $\ln\Lambda = \ln\Lambda_{qe}$ (3.15). The total thermalization time through both of these processes is given by the

$$\frac{1}{\tau_a} = \frac{1}{\tau_{ai}} + \frac{1}{\tau_{ae}} \tag{3.43}$$

As an example for a plasma with $T_e = T_i = 50\,\mathrm{MK}$, $n_i = n_e = 1\cdot10^{22}\mathrm{m}^{-3}$, for alpha particle initial energy 3.5 MeV, thermalization time on ions will be $\tau_{ai} = 67$ ms (this time is dependent of alpha particle energy and will decrease during the process), thermalization time on electrons will be 3.9 ms (independent of alpha particle energy). The cycle time usually will be comparable with the total thermalization time, so only some of the plasma heating from the alpha particles will happen around peak compression. This will make possible that some of the alpha energy to be directly converted (with the cycle thermodynamic yield) into electric energy, however this is not an important aspect for D-T reaction since alpha energy in this case is around 15% of total energy released.

The dominant path of thermalization is to electrons, then this energy is shared with ions through temperature equilibration. Considering that both ions and electrons have a maxwellian distribution and $n_i = n_e$, the temperature equilibration time [4] will be

$$\tau_{eq} = \frac{3\pi\varepsilon_0^2\sqrt{2\pi}m_e m_i}{n_i q_e^4 \ln\Lambda_{qe}}\cdot\left(\frac{kT_e}{m_e}+\frac{kT_i}{m_i}\right)^{3/2} \tag{3.44}$$

In our example the equilibration time, for $T_e \approx T_i$ will be 1.6 ms comparable with thermalization time.

3.8 Compression and expansion

During the cyclic changes of the axial current, the azimuthal magnetic pressure will increase from zero to a maximum value and then back to zero, to increase again for the opposite direction of the axial current. This will produce cyclic compression and expansions of the plasma together with the axial magnetic field from inside of it. In these processes the plasma will behave like a gas composed from two particles ions and electrons, it form a thermodynamic system that is under a resultant magnetic pressure equal with its thermal pressure given by 2.23. Because the pressure value of the plasma will change relatively fast, little heat will be exchanged during these small periods and the plasma will suffer a series of adiabatic transformations between the extreme values of its pressure. This will determine a corresponding change of the plasma volume and its temperature. Considering the plasma as an ideal gas, we have the equations

$$pV^{\gamma} = const \tag{3.45}$$

and

$$TV^{\gamma-1} = const \tag{3.46}$$

between plasma perticles pressure, volume and temperature.

$$\gamma = \frac{C_p}{C_V} = 1 + \frac{2}{f} \tag{3.47}$$

is the adiabatic index, with f the number of degrees of freedom. Both ions and electrons have 3 degrees of freedom so they will have $\gamma = 5/3$. Assuming that p_1 is the plasma thermal pressure when $S_i = S_1$, during the cycle the plasma thermal pressure will be

$$p_{th} = p_1 \left(\frac{S_1}{S_i}\right)^{\gamma} \tag{3.48}$$

This particle thermal pressure must be balanced during the cycle by the sum of magnetic pressures (eq. 2.22).

4 Energy balance

In a thermonuclear plasma of high temperature, the amount of energy produced by fusions reactions is proportional with plasma density, temperature and the type of reaction involved. To have a positive energy output, this fusion energy must exceed the energy lost through plasma radiation (see 3.4), and any additional energy loss in the system. Under the influence of thermal movement the nuclei from plasma will suffer repeated coulomb collisions between them, if in such a collision the two nuclei have enough thermal energy to overcome the electric repulsive force and are getting close enough a process of nuclear fusion will happen. This define a limit cross section for the approaching nuclei, inside which a nuclear fusion reaction will happen. If we consider one nucleus, the number of reactions per second is dependent by the number of other nuclei it meet inside the cross volume defined by the cross section moving with the thermal velocity $\sigma_r v$. Because the reaction cross section is dependent on the approaching velocity of the two nuclei, the cross volume per second must be integrated over velocity distribution to obtain the reactivity or average cross volume per second

$$\langle \sigma_r v \rangle = \int_0^{\infty} \sigma_r v f(v) dv \tag{4.1}$$

In the case of thermonuclear reactions a maxwellian distribution for velocity end energy is considered. In the temperature range of 15...390 MK (2...50 keV) the reactivity for deuterium-tritium D-T reaction is 40 to 100 times higher than for D-D or T-T reactions [5]. This indicates that the D-T reaction is the most favorable in this temperature interval. Also indicates that in a D-T plasma the D-D and T-T reactions are happening at a very small rate compared with the D-T reactions which will be dominant. In table 1 are presented the reactivity at various temperatures and corresponding thermal energy $3/2kT$.

keV (MK)	D-T	D-D (1+2)	T-T
1 (7.7)	$5.48 \cdot 10^{-27}$	$1.52 \cdot 10^{-28}$	$3.28 \cdot 10^{-28}$
2 (15)	$2.62 \cdot 10^{-25}$	$5.42 \cdot 10^{-27}$	$7.09 \cdot 10^{-27}$
3 (23)	$1.71 \cdot 10^{-24}$	$2.95 \cdot 10^{-26}$	$3.03 \cdot 10^{-26}$
4 (31)	$5.58 \cdot 10^{-24}$	$8.46 \cdot 10^{-26}$	$7.46 \cdot 10^{-26}$
5 (39)	$1.28 \cdot 10^{-23}$	$1.77 \cdot 10^{-25}$	$1.4 \cdot 10^{-25}$
6 (46)	$2.42 \cdot 10^{-23}$	$3.09 \cdot 10^{-25}$	$2.26 \cdot 10^{-25}$
7 (54)	$3.98 \cdot 10^{-23}$	$4.81 \cdot 10^{-25}$	$3.29 \cdot 10^{-25}$
8 (62)	$5.94 \cdot 10^{-23}$	$6.89 \cdot 10^{-25}$	$4.47 \cdot 10^{-25}$
9 (70)	$8.26 \cdot 10^{-23}$	$9.32 \cdot 10^{-25}$	$5.79 \cdot 10^{-25}$
10 (77)	$1.09 \cdot 10^{-22}$	$1.21 \cdot 10^{-24}$	$7.22 \cdot 10^{-25}$
15 (116)	$2.65 \cdot 10^{-22}$	$2.96 \cdot 10^{-24}$	$1.56 \cdot 10^{-24}$
20 (155)	$4.24 \cdot 10^{-22}$	$5.16 \cdot 10^{-24}$	$2.51 \cdot 10^{-24}$
25 (193)	$5.59 \cdot 10^{-22}$	$7.6 \cdot 10^{-24}$	$3.51 \cdot 10^{-24}$
30 (232)	$6.65 \cdot 10^{-22}$	$1.02 \cdot 10^{-23}$	$4.54 \cdot 10^{-24}$
35 (270)	$7.45 \cdot 10^{-22}$	$1.28 \cdot 10^{-23}$	$5.57 \cdot 10^{-24}$
40 (309)	$8.02 \cdot 10^{-22}$	$1.54 \cdot 10^{-23}$	$6.6 \cdot 10^{-24}$
45 (348)	$8.43 \cdot 10^{-22}$	$1.81 \cdot 10^{-23}$	$7.63 \cdot 10^{-24}$
50 (387)	$8.7 \cdot 10^{-22}$	$2.08 \cdot 10^{-23}$	$8.65 \cdot 10^{-24}$

Table 1: Reactivity [m^3/s] (source [6])

For energies up to 25 keV (190 MK) the D-T reactivity in [m^3/s] can be approximate with

$$\langle\sigma_{dt} v\rangle = \frac{1.44 \cdot 10^{-13}}{T^{2/3}} \cdot \exp\left(-\frac{3944}{T^{1/3}}\right) \tag{4.2}$$

were T is the plasma temperature in [K]. In an unit volume per second, for every deuterium with density n_d we will have a number of reactions with tritium nuclei with density n_t encountered inside the average cross volume. The fusion power released per unit volume will be

$$\frac{dP_{dt}}{dV} = \langle\sigma_{dt} v\rangle\, n_d n_t \epsilon_{dt} \tag{4.3}$$

where ϵ_{dt} is the amount of energy released per one D-T fusion process.

One deuterium and one tritium nucleus will undergo the fusion reaction

$$\mathsf{D}^2 + \mathsf{T}^3 \longrightarrow \mathsf{He}^4 + \mathsf{n} + 17.6\text{MeV} \tag{4.4}$$

that produce a helium-4 nucleus and a neutron and will release 17.6 MeV of energy. This energy is distributed as kinetic energy, 3.5 MeV on the He nucleus and 14.1 MeV on the neutron. Because the helium nucleus have a positive electric charge, it will suffer Coulomb collisions with the plasma ions and electrons and most of its kinetic energy will be transferred to plasma, heating it up in compensation of some if not all the energy lost through bremsstrahlung. The neutron, on the other hand, being electrically neutral will interact very little with plasma, will pass through the metallic shell (losing some kinetic energy here) and will transfer most of its energy in the moderator placed around the stabilization shell. This energy can be converted then into electricity (with a steam turbine for example). The slowed down neutron can be captured by a lithium-6 isotope to regenerate back the tritium used, through the reaction

$$\mathsf{Li}^6 + \mathsf{n} \longrightarrow \mathsf{He}^4 + \mathsf{T}^3 + 4.8\text{MeV} \tag{4.5}$$

that also release additional 4.8 MeV of energy. In this way the tritium will be recirculated and the nuclear fuel actually used is deuterium and lithium-6, producing a total of 22.4 MeV of energy on every pair of reactions. Not all neutrons resulted from the reaction 4.4 will be captured by lithium-6, some of them will be lost. To keep producing enough tritium some neutrons multiplication must be employed. If some lithium-7 is introduced in the moderator, then it can react with fast neutrons as follows

$$\mathsf{Li}^7 + \mathsf{n} - 2.47\text{MeV} \longrightarrow \mathsf{He}^4 + \mathsf{T}^3 + \mathsf{n} \tag{4.6}$$

reaction that consume some energy from the incoming neutron, produce one tritium nucleus and also a new neutron that can enter into a lithium-6 reaction producing an additional tritium. In addition to this a neutrons multiplier and reflector like beryllium can be used.

For the reactor to produce more energy than consume, the produced energy must compensate for the bremsstrahlung loses and for the additional dissipation in coils, driving generators, etc. The alpha heat released in plasma by the helium nuclei, together with the Joule heat, count for the compensation of the plasma loses through radiation and other ways, while the rest of energy is converted into electricity with a limited efficiency of about 40%. The conversion of plasma radiation loses into electricity is limited by the temperature of the metallic shell used for confinement and stabilization. This layer electrical conductivity decrease with the increase of its temperature, also will increase its emission of impurities into plasma. As a consequence is preferable to keep this layer at a low temperature, but from the energy efficiency point of view is better to be at a temperature closer to the temperature of the moderator. In any case the energy released into plasma as alpha heat and as Joule heat from the axial current, cannot be higher than the total loses from plasma otherwise the plasma will overheat. So we can say that its maximum energy production is reached when alpha heat and Joule heat equal the plasma loses mainly through bremsstrahlung. Bellow this point the plasma need additional heating, above this point it need additional cooling. However in this case, because most of the energy is produced during the temperature peaks, the level of energy can be easily controlled through the amplitude of the axial current that influence both the Joule heat and the compression ratio, and also through the axial magnetic field that will influence the compression ratio. For example for a D-T plasma the alpha heat will balance the bremsstrahlung at about 35 MK, if the level of loses from plasma are double to that of bremsstrahlung the required temperature increase at about 45 MK. In this example a constant temperature was considered. In our case we have a pulsed working regimen, the average power per cycle must be considered and this depend of driving parameters and the peak of temperature.

We can define the driving ratio as being the ratio between the azimuthal magnetic pressure and the plasma particle thermal pressure, at the maximum of compression i.e. at the maximum of the driving current. We need a driving ratio bigger than 1 to have a strong enough modulation of the axial magnetic field, with all the advantages. At a low driving ratio that is smaller than 1, the reactor will start to behave more like a tokamak confinement system with additional stabilization.

5 Conclusion

The thermonuclear plasma can be effectively confined by confining its own magnetic field in a limited space. This space is limited by using a magnetic expulsion wall in the form of a metallic shell in combination with an alternating axial current to create a permanent variable magnetic field so that the expulsion effect become permanent. This is contrary to the typical tokamak systems where the plasma current flow in the same direction and after the initial dynamic evolution ends and become stationary, the plasma lose the stability and the confinement. In addition an alternating current always keep changing the conditions from plasma, like the magnetic field direction, the radius and temperature, the behavior of the axial magnetic field, preventing in this way the development of instabilities. So rather than being just a stationary magnetic confinement system, in this case is an electrodynamic one, where the plasma column is kept inside a conductive tube in a way similar to the electrodynamic levitation. Also the system allow for a continuous run of the reactor.

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