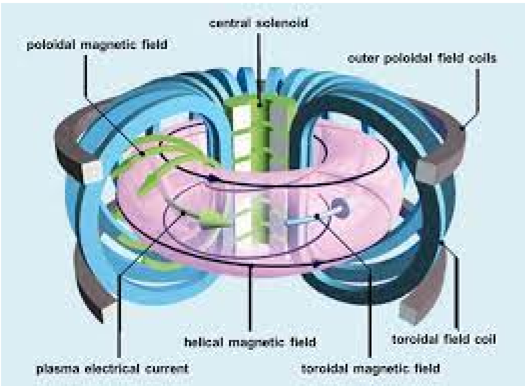
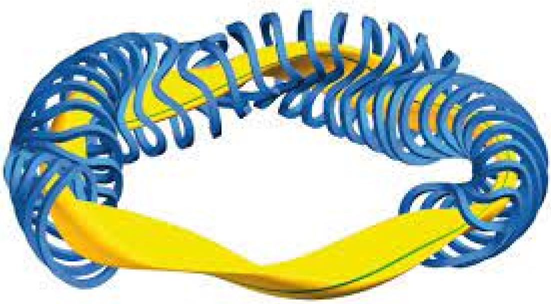
F4E Internship

ITER’s Nuclear fusion power plant

The International Thermonuclear Experimental Reactor (ITER) is located in Aix-en-Provence, and is an international project aiming to create the world’s largest nuclear fusion reactor which is intended to produce a higher output energy than its input. In spite of this, it will only be used as a laboratory for the experimental testing of plasma. The first reactor built for commercial use will be Demo, and its construction is intended to start after ITER will have proven that a Deuterium-Tritium plasma is sustainable.

Here we will firstly be exploring the different types of magnetic confinements, explaining why we chose a tokamak-like build over a stellarator build such as the Wendelstein.





We'll later take a keen interest in the systems responsible for the safety and diagnostics of the reactor, ensuring that everything is controlled and monitored.
Then we'll talk a little about the fusion reaction, the reactions that we’ll be using, why we use it, and whether it’s safer to operate than our modern day fission reactors.
Lastly we’ll see what is required to startup this technologically advanced machine, going later in-depth with calculation verifying that ECRH beams are heating the plasma the right way, and ensuring that they don’t start melting the tungstene walls.

The main difference between a stellarator and a tokamak is the obvious magnetic chamber, due to the shape of the superconducting coils. In a tokamak the superconducting coils are fitted both vertically and horizontally to control the “drift” created by the plasma's current. A force pushing upwards at the top of the reactor. In addition to this, the energy needed to power the tokamak increases over time, which means that after a certain period the input power will exceed the output, from which point the plasma will no longer be beneficial to produce energy. The stellarator, in contrast, tries to combine the magnetic fields from the horizontal and vertical coils with the help of helical coils, which unlike the tokamak design, will only need a stable amount of power to sustain. Unfortunately, it does come with a few inconveniences, the plasma held inside the reactor isn’t cylindrical as would be seen in a tokamak The plasma is twisted alongside the magnetic chamber, which is quite a demanding engineering feat. The stellarator might seem all in all a good candidate for nuclear fusion but unfortunately it's design is extremely complex. It could, perhaps, one day become a suitable design for a technologically advanced civilization, but for now we simply lack the technology and knowledge necessary for the development of such reactors.

Once the plasma is heated it rushes upwards towards the ceiling of the reactor which is an effect called "drift", if the plasma ends up touching the ceiling of the reactor, the amount of particles colliding into the beryllium wall will be sufficient to create a force powerful enough to lift the 23 000 ton machine for an instant before dropping back down and hitting the ground with a colossal amount of energy. An example of such an event happened in England, at the Joint European Torus (JET), where the impact was so powerful that seismographs nearby detected it as a small earthquake. Which is bearing in mind that it only weighs about 2,600 tonnes, about one tenth of ITER’s reactor. We call this consequence a "disruption", and it is considered to be the worst thing that can happen to a reactor since it can effectively destroy the reactor. Physicists and engineers however manage to control this drift and avoid these disruptions with the help of horizontal coils located both at the top and bottom of the reactor which are capable of powering themselves up and creating a repulsive force on the plasma preventing it from climbing any further. The system controlling this processes data at such a sufficiently rapid rate that it is capable of making millisecond adjustments, ensuring the plasma stays stable.

Other systems also prevent other types of dangerous accidents which could take place during the reaction, a tritium leak would be an example. Tritium being an unstable atom, which means that it is radioactive, is dangerous for the environment and its surroundings. Thankfully a clever system monitoring the pressure inside the valves, and the storage transporting the tritium, is able to close the entries and exits, making sure that these radioactive particles never escape.

Once the fusion is active a lot of highly energetic neutrons are emitted and need to be managed. Having this in mind, physicists plan to extract the neutrons' energy by using a circuit of water surrounding the reactor. When these neutrons collide with the water molecules, they break the molecular structure creating heat, the circuit of water then turns a turbine as a result of the water heating up and creating a convection. A magnet attached to the turbine then converts kinetic energy into electricity by alternating the magnetic field inside a coil. Physicists have also thought of pasting a small layer of uranium which could create fission allowing us to collect even more energy, however this still remains nothing but an interesting idea.

To monitor the plasma inside the tokamak reactor we have diagnostics which acquire information from the tokamak and monitor the behavior of the plasma. They achieve this with the help of a laser system called interferometry. It consists in shooting a laser into the reactor and measuring the phase shifts between a beam inside and outside the reactor. Using this method the diagnosticians can determine the density of the plasma. They can also gather information about the temperature emitted by the plasma and the energy released with the aid of spectroscopy, a graph exposing the different levels of temperature inside the reactor. This helps them evaluate where the plasma is hottest, and the location of possible impurities trapped inside the plasma.

In order to monitor the plasma in the machine IT experts have massive server rooms and supercomputers which allow them to process information and rapidly treat the data from instruments inside the reactor. The servers then distribute the information to CODAC where it is monitored and controlled by a team of diagnosticians.

We can achieve fusion using a deuterium-tritium reaction (DT), which then produces helium IV (3.5 MeV) and a neutron (14.1-14.7 MeV). We can also use a deuterium-deuterium (DD) reaction to create helium III (3.5 MeV) and a neutron (2.5 MeV) but we prefer the DT reaction because the neutron emitted is much more energetic than the DD reaction, using this to break lithium VI, creating helium IV and tritium. We then try to keep helium IV in the plasma as long as possible to extract as much energy as possible before it finally flies out and leaves the plasma. Unfortunately fusion has an important downside, tritium is a rare element to find on earth, and is very much needed to supply the nuclear reactor.

Due to the fact that fusion is a nuclear reaction some people start to worry whether it might explode since fission reactors have this infamous reputation. However fusion and fission are nothing alike, in nuclear fusion we put a lot of effort into maintaining the reaction, we try to sustain fusion for as long as possible. In fission however we try to limit the amount of reactions taking place, preventing it from getting out of control and exploding.The worst scenario that can happen in a tokamak, other than a disruption, would be encountering a problem preventing us from maintaining the reaction, which would simply halt the fusion reaction. In either case the plasma inside the reactor simply dissolves and nothing explodes. In the case of a disruption, physicists can measure the gravity of the impact and the damage it caused allowing space for solutions.

Before starting up the reactor physicists try to avoid any impurities, particles and atoms which make the fusion inside the plasma less efficient. Such particles are mostly obtained when the beryllium and tungsten on the walls release out-gases after being exposed to high temperatures. But other particles such as water can also be accumulating in the inactive nuclear reactor. It is predicted that for ITER the amount of water accumulated inside the tokamak can reach up to 1 liter, which is quite alarming knowing that the plasma must have an overall mass of about 1 gram of matter. To avoid any impurities the machine is subjected to something called "baking", a process which can take from a few days up to a full week heating the reactor to 200ºC or 320ºC. The metals inside the reactor create out-gases which are then extracted from the reactor with pumps making sure that all the impurities have been purged. After baking, the reactor is subjected to a Glow Discharge

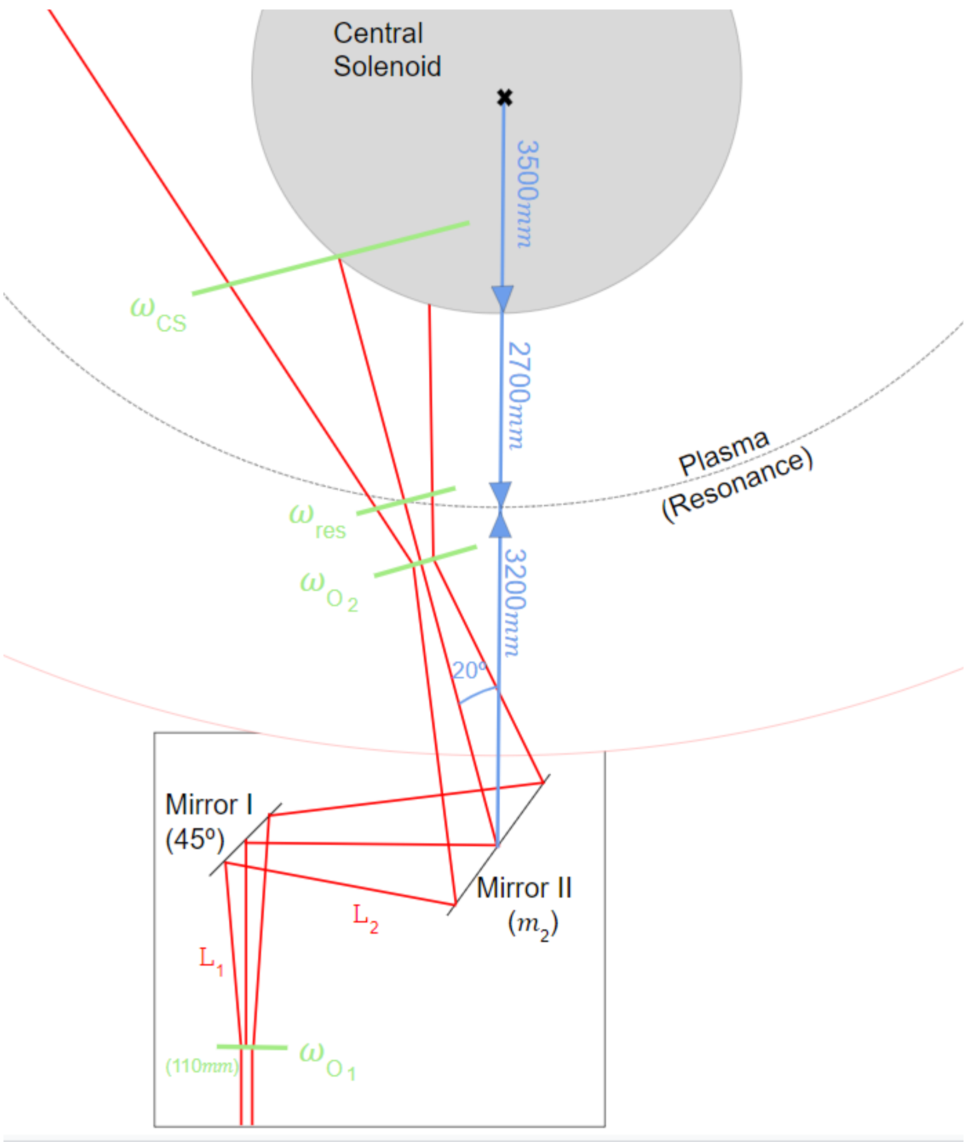
Cleaning(GDC) process which is a low energy plasma absorbing any impurities left behind.

To heat up the reactor and create the plasma we can use 3 different methods:

- Neutral Beam Injection (NBI) which consists of injecting highly energetic particles into the reactor which are then ionized after having collided with another particle giving them their energy and heating up the reactor.
- Ion Cyclotron Resonance Heating (ICRH) which sends electromagnetic waves into the reactor similarly to the way a microwave works. It excites the ions in the reactor, reducing the radius of their circular motion, thus increasing the temperature of the plasma.
- Electron Cyclotron Resonance Heating (ECRH) which sends electromagnetic waves into the reactor the same way the ICRH does, but targets the electrons instead of exciting the ions, creating more heat that way.

The ECRH can be described as gaussian beams, beams with a particular growth which we can calculate with the help of a few equations. In this section we'll try to verify that it is heating up properly within the tokamak, both for beams of $170GH_z$, and $104GH_z$. To simplify things we will only be doing the calculations for the $170GH_z$ beam.

Here's a little schematic of our situation. Our goal is to determine whether the focal length of the beams, at various points, emitted by the ECRH is enough to both heat the plasma and help physicists determine whether the walls are in danger of melting.



Let's start out by calculating the beam waist obtained on the second mirror, which is convergent and is responsible for sending the electrons in the tokamak.

Here we'll use an equation defining the width of the beam at a given point x:

$$\omega(x) = \omega_o \sqrt{1 + \left(\frac{2Z}{k\,\omega_o^2}\right)^2}$$

Where ω_o is width of the initial beam, Z the length to the given point x, and k the wavenumber of the beam's wavelength defined by :

$$k = \frac{2\pi\upsilon}{c}$$

Where υ, is the wave's frequency, and c, the celerity of light. Since :

$$k = \frac{2\pi}{\lambda} \text{ and } \lambda = \frac{c}{\upsilon}$$

Thus the beam's width at the second mirror m_2 :

$$\omega_{m_2} = \omega_{o_1} \sqrt{1 + \left(\frac{2(L_1+L_2)}{\frac{2\pi\upsilon}{c}\cdot\omega_{o_1}^2}\right)^2}$$

With Z being replaced by the sum of the lengths L_1 and L_2 since the angle of the first mirror is 45°.

Now let's proceed to calculate ω_{m_2} : $\omega_{o_1} = 110\cdot10^{-3}\,m$, $L_1 = 0.5\,m$, $L_2 = 0.9\,m$, $\upsilon = 170\cdot10^{9}\,Hz$, and $c = 3\cdot10^{8}\,m.s^{-1}$

$$\omega_{m_2} = 110\cdot10^{-3}\sqrt{1 + \left(\frac{2(0.5+0.9)}{\frac{2\pi\cdot170\cdot10^{9}}{3\cdot10^{8}}\cdot(110\cdot10^{-3})^{2}}\right)^{2}}$$

$$\omega_{m_2} \simeq 0.11023m$$

Thusω_{m_2} is about $110,23\ mm$ wide.

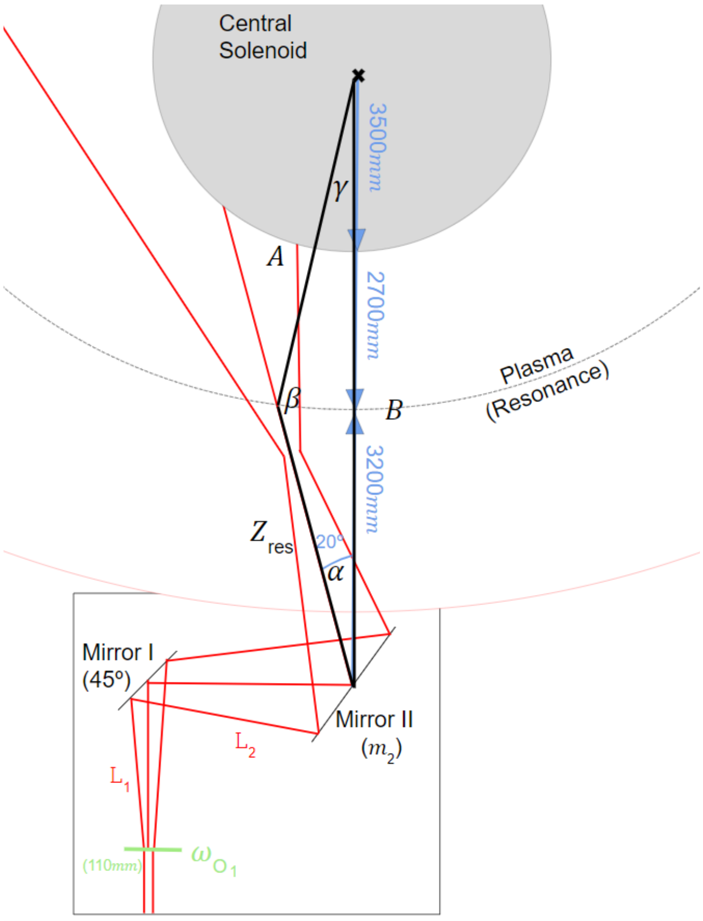
Now it's time to calculate the width of the beam at it's convergence point,ω_{o_2}.

This time however the beam is no longer divergent. The second mirror is curved inwards which means that once the initial beam scatters off the second mirror, it'll converge to ω_{o_2}. Due to this convergence we can not use the precedent equation to calculate it's width. To do so we need to refer ourselves to a different equation:

$$\omega_{o} = \frac{\omega_{m}}{\sqrt{1+\left(\frac{k\cdot\ \omega_{m}^{2}}{2\cdot Z_{res}}\right)^{2}}}$$

ω_{o}being the beam waist at the convergence width, $\omega_{m}$the beam waist at the mirror, and $Z_{res}$the length to the resonance.

To be able to use the formula we need to determine the length to the resonance. To do so we'll apply the Sine rule:



$$\frac{Z_{res}}{sin(\gamma)} = \frac{A}{sin(\alpha)} = \frac{B}{sin(\beta)}$$

Thus : $Z_{res} = \frac{A \cdot sin(\gamma)}{sin(\alpha)}$, and $sin(\gamma) = sin(180 - (\beta + \alpha))$,where

$\beta = sin^{-1}(\frac{B \cdot sin(\alpha)}{A})$

With $A = 6.2\ m$, $B = 9.4\ m$, and $\alpha = 20º$

$$\beta = sin^{-1}(\frac{9.4 \cdot sin(20)}{6.2})$$

$$\beta \simeq \{148, 8º; 31, 2º\}$$

Of the two calculated, the corresponding angle to our figure is$148, 8º$since$\beta$is much bigger than$90º$. After calculatingβwe can now calculateZ_{res}:

$$Z_{res} = \frac{A \cdot sin(180-(\beta+\alpha)}{sin(\alpha)}$$

$$Z_{res} = \frac{6.2 \cdot sin(180-(148.8+20)}{sin(20)}$$

$$Z_{res} \simeq 3.5\, m$$

Now that we've calculated the length to the resonance, let's apply the previous formula to calculate the beam waist at the convergence.

With $\omega_{m_2} = 110,23 \cdot 10^{-3}\, m$, $\upsilon = 170 \cdot 10^{9} H_z$,$c = 3 \cdot 10^{8} m.s^{-1}$, and

$Z_{res} = 3.5\, m$

$$\omega_o = \frac{\omega_m}{\sqrt{1+(\frac{k \cdot \omega_m^2}{2 \cdot Z_{res}})^2}}$$

$$\omega_{o_2} = \frac{\omega_{m_2}}{\sqrt{1+(\frac{\frac{2\pi\upsilon}{c} \cdot \omega_{m_2}^2}{2Z_{res}})^2}}$$

$$\omega_{o_2} = \frac{110,23 \cdot 10^{-3}}{\sqrt{1+(\frac{\frac{2\pi \cdot 170 \cdot 10^9}{3 \cdot 10^8} \cdot (110,23 \cdot 10^{-3})^2}{2 \cdot 3,5})^2}}$$

$$\omega_{o_2} \simeq 0.01761\, m$$

Thus the beam waist at the convergence is about $17.61\, mm$, which is nice to have calculated, yet we still don't know where this convergence is located relative to the second mirror,m_2.

To do so we'll try reversing the following equation to determine the length to the convergence beam waist. With Z_r being the Raleigh Range, defined by:

$$Z_R = \frac{\omega_o^{\ 2}\pi}{\lambda}$$

$$\omega = \omega_o\sqrt{1 + (\frac{Z}{Z_R})^2}$$

$$\Leftrightarrow \omega^2 = \omega_o^{\ 2}(1 + (\frac{Z}{Z_R})^2)$$

$$\Leftrightarrow \omega^2 = \omega_o^{\ 2} + \frac{\omega_o^{\ 2}Z^2}{Z_R^{\ 2}}$$

$$\Leftrightarrow \omega^2 - \omega_o^{\ 2} = \frac{\omega_o^{\ 2}(Z-Z_o)^2}{Z_R^{\ 2}}$$

$$\Leftrightarrow Z^{\ 2} = \frac{Z_R^{\ 2}(\omega^2-\omega_o^{\ 2})}{\omega_o^{\ 2}}$$

$$\Leftrightarrow Z = \frac{Z_R\sqrt{\omega^2-\omega_o^{\ 2}}}{\omega_o}$$

Once done we'll apply the equation substituting ω for ω_{m_2}.

$$Z_{o_2} = \frac{Z_R\sqrt{\omega_{m_2}^{\ 2}-\omega_{o_2}^{\ 2}}}{\omega_{o_2}}$$

However $Z_R = \frac{\omega_o^{\ 2}\pi}{\lambda}$ and $\lambda = \frac{c}{\upsilon} \Leftrightarrow Z_R = \frac{\omega_o^{\ 2}\pi\upsilon}{c}$

$$\text{Thus,} Z_{o_2} = \frac{\frac{\omega_{o_2}^2 \pi \upsilon}{c} \cdot \sqrt{\omega_{m_2}^2 - \omega_{o_2}^2}}{\omega_{o_2}}$$

Now let's proceed to calculate Z_{o_2}, with $\omega_{o_2} = 17,61 \cdot 10^{-3}\, m$,

$\omega_{m_2} = 110,23 \cdot 10^{-3}\, m$, $\upsilon = 170 \cdot 10^{9} H_z$, and $c = 3 \cdot 10^{8} m. s^{-1}$

$$Z_{o_2} = \frac{\frac{(17,61 \cdot 10^{-3})^2 \pi \cdot 170 \cdot 10^{9}}{3 \cdot 10^{8}} \cdot \sqrt{(110,23 \cdot 10^{-3})^2 - (17.61 \cdot 10^{-3})^2}}{17,61 \cdot 10^{-3}}$$

$$Z_{o_2} \simeq 3.4\, m$$

We now know the length Z_{o_2} to the convergence, relative to the second mirror, we can furthermore calculate the beam waist at the resonance using the previous equation:

$$\omega = \omega_o \sqrt{1 + (\frac{Z}{Z_R})^2}$$

Yet in order to make it work we need swap Z for ΔZ, being the difference in length between the new divergent beam waist, ω_{o_2}, and ω_{res}, with $\Delta Z = Z_{res} - Z_{o_2}$

$$\text{Thus,} \omega_{res} = \omega_{o_2} \sqrt{1 + (\frac{Z_{res} - Z_{o_2}}{Z_R})^2}$$

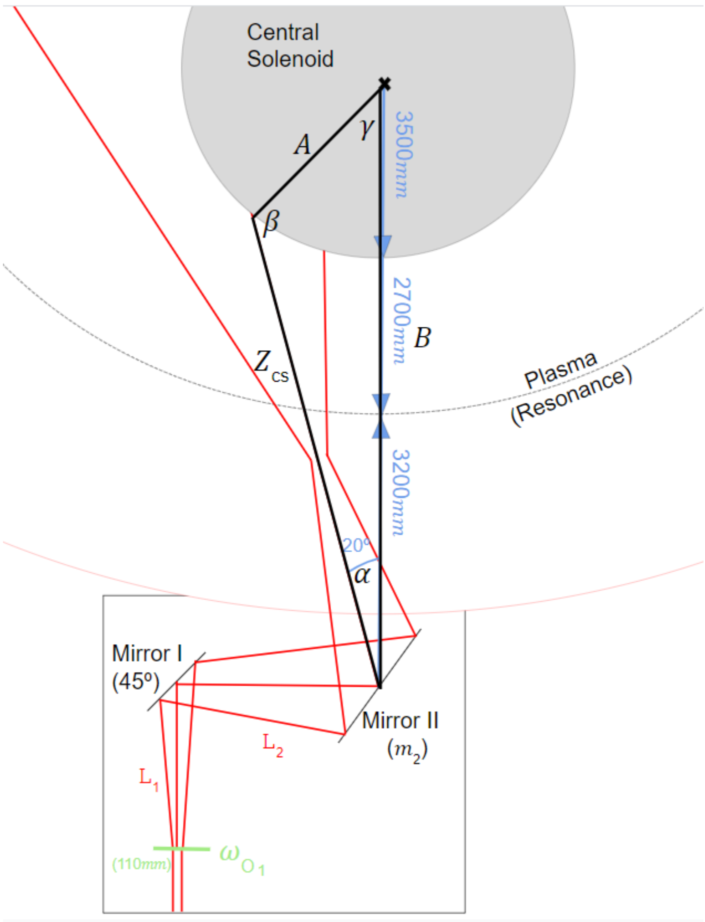
With $\omega_{o_2} = 17,61 \cdot 10^{-3}\, m$, $Z_{res} = 3.5\, m$, $Z_{o_2} = 3.4\, m$, and $Z_R = \frac{\omega_{o_2}^2 \pi \upsilon}{c}$

$$\omega_{res} = (17,61 \cdot 10^{-3}) \sqrt{1 + (\frac{3.5 - 3.4}{\frac{(17.61 \cdot 10^{-3})^2 \pi \cdot 170 \cdot 10^{9}}{3 \cdot 10^{8}}})^2}$$

$$\omega_{res} \simeq 0.01790\, m$$

The beam waist at the resonance is about$17,90mm$at the resonance.

Now let us calculate the beam waist at the Central Solenoid. Before doing so we'll need to, once more, apply the sine rule and calculate the length to solenoid relative to the second mirror,m_2.



$$\frac{Z_{cs}}{sin(\gamma)} = \frac{A}{sin(\alpha)} = \frac{B}{sin(\beta)}$$

Thus : $Z_{cs} = \frac{A \cdot sin(\gamma)}{sin(\alpha)}$, and $sin(\gamma) = sin(180 - (\beta + \alpha))$,where

$\beta = sin^{-1}(\frac{B \cdot sin(\alpha)}{A})$

With $A = 3.5\, m$, $B = 9.4\, m$, and $\alpha = 20º$

$$\beta = sin^{-1}(\frac{9.4 \cdot sin(20)}{3.5})$$

$$\beta \simeq \{113,3º; 66,7º\}$$

Of the two calculated, the corresponding angle to our figure is $113,3º$ since β is much bigger than $90º$. After calculating β we can now calculate Z_{cs}:

$$Z_{cs} = \frac{A \cdot sin(180-(\beta+\alpha)}{sin(\alpha)}$$

$$Z_{cs} = \frac{3.5 \cdot sin(180-(113,3+20)}{sin(20)}$$

$$Z_{cs} \simeq 7.45\, m$$

Now that we know the length to the central solenoid relative to the second mirror we can simply apply the previous equation to determine the beam's waist at that point.

$$\omega = \omega_o \sqrt{1 + (\frac{Z}{Z_R})^2}$$

Once again we swap Z for ΔZ, being the difference in length between the point of convergence and the central solenoid, relative to the second mirror, such as $\Delta Z = Z_{cs} - Z_{o_2}$.

Thus, $\omega_{cs} = \omega_{o_2} \sqrt{1 + (\frac{Z_{cs} - Z_{o_2}}{Z_R})^2}$

With $\omega_{o_2} = 17,61 \cdot 10^{-3}\, m$, $Z_{cs} = 7,45\ m$, $Z_{o_2} = 3.4\, m$, and $Z_R = \frac{\omega_{o_2}^2 \pi \upsilon}{c}$

$$\omega_{cs} = (17,61 \cdot 10^{-3}) \sqrt{1 + (\frac{7.45-3.4}{\frac{(17.61 \cdot 10^{-3})^2 \pi \cdot 170 \cdot 10^9}{3 \cdot 10^8}})^2}$$

$$\omega_{cs} \simeq 0.13038\, m$$

We finally conclude that the beam waist of the ECRH at the central solenoid is $130, 38\, mm$.

Special Thanks

Marc Henderson and his team of scientists for the assignment on gaussian beams, it was really helpful and I learned quite a lot about the subject.

Peter De Vrie for showing me the Work environment on the site as well as the many people you've made me encounter, further enhancing my knowledge about the plasma inside the reactor, and it's behavior.

Vitaly Krasilnikov for having cleared my doubts about the many functions of different types of fusion reactors, the behavior of the particle inside the tokamak, as well as the tools used to monitor the plasma.

Nicolas Ponce for the amazing tour around the many server rooms and the detailed explanations of what an important role IT serves at ITER

Romarick Darbourg for the detailed explanation about the functions of different buildings intervening in the creation of the plasma inside the reactor.

Laurent Schmiter for facilitating my training period in ITER

Cyril Lescure for the management of my training period.