Nuclear Fusion Energy 2025
Research project

Control the Magnetic Confinement of Fusion Plasma in a Toroidal Reactor With Alternating Current Drive

ALCUTOR

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- Proposal duration in months 72

Project summary

Nuclear fusion is a promising option to replace fossil and nuclear fission fuels as the primary energy source and can have an important role to play in addressing the climate change. The ALCUTOR is proposing a new approach to the thermonuclear plasma confinement by using alternating current (AC) in the plasma in a type of toroidal system and at frequencies that were never tried before, and also using automatic closed loop controlling and stabilization. This proof of concept is intended to test experimentally the new confinement system using regular hydrogen and helium plasma without nuclear reactions and neutrons. Our approach combine an electrically conductive wall around the plasma column with an alternating current induced along the plasma column. As a result of the induced eddy currents the wall will become repulsive to the plasma column and start working as a reactive magnetic vessel to the hot plasma. The AC nature of the current passing through the plasma column will also have a series of stabilizing effects on the plasma. The repeatedly rapid shift of the magnetic field lines limit the growing time of many instabilities which depend on the direction of these field lines. The plasma current itself will be repressed to the surface of the plasma column by the plasma high conductivity, this will prevent the volume flow of the plasma current, minimizing the resistive instabilities that come with it like the current filamentation and the magnetic islands. All these effects represent significant potential improvements over the state of the art magnetic confinement systems, like tokamak and stellarator, which lack such stabilizing effects.

Extended Synopsis of the scientific project

Nuclear energy including fusion is one of the best way to address the increased energy demand and to address the problem of accelerate climate change and its serious consequences. Benefits from fusion include: the relative abundance and low cost of fuel (deuterium and lithium), free of smoke and other emissions, the absence of high level radioactive waste. The biggest problem of experimental devices to produce energy from nuclear fusion reactions is related with thermonuclear plasma stability and confinement time. As a result the ratio between the energy produced and the energy consumption (energy efficiency or Q) is bellow 1. The objective of this research is to find better ways to increase plasma stability, heating efficiency and control. To achieve this we propose a new method and a new type of reactor design. The new method consist in using alternating current induced in the plasma in combination with a specially designed conducting wall around the plasma. Compared with the traditional state of the art devices (tokamak and stellarator) which use a stationary approach, this new device will benefit from many stabilizing electrodynamic effects produced by the new configuration. This may have the potential to go substantially beyond the state of the art devices in terms of plasma stability, confinement time and plasma heating, leading to better confinement and a higher triple product, that may open a new unexplored path to a practical energy source based on nuclear fusion.
Existing technologies like the tokamak and stellarator reactors (JET, JT60, etc.) while made significant progress, are still plagued by disrupting plasma instabilities, insufficient confinement, and low energy efficiency.

Limitations of traditional devices

The traditional reactors in magnetic confinement fusion technology are the tokamak and stellarator devices, which use strong magnetic fields to confine and stabilize the plasma required for fusion reactions. Another traditional approach is represented by the inertial confinement fusion technology which use strong laser pulses to rapidly heat a solid target to fusion temperatures, in the very short time interval while the hot plasma is confined by its own inertia. While the inertial confinement also made significant progress, it is plagued by a low overall energy efficiency and the inherent difficulty to scale up such a very short pulse system to a practical power plant. This is why currently the magnetic confinement is considered the most promising fusion technology for a potential scale up.
The currently used magnetic confinement technology, still struggle with major limitations:

1. Plasma instabilities – The common instabilities in tokamaks and stellarators, such as kink, plasma surface flutes, current filamentation and magnetic islands, will disrupt the magnetic confinement of plasma and lead to plasma dispersion and cool down. In particular resistive instabilities, driven by the plasma's electric conductivity increasing with temperature, lead to formation of current filaments and magnetic islands, which lead to serious disruptions.
2. Confinement time – The ability to keep the thermonuclear plasma in a state of high temperature and density is crucial to obtain a high triple product and a viable fusion technology. The triple product represent the product between the plasma temperature, density, and confinement time, and is a simple indication of efficiency of a fusion device. While a lot of progress has been done in this area, the currently used technologies are still insufficient and require significant improvements, and searches for new paths to open new possibilities in the area of plasma confinement, control and stability.
3. Energy efficiency – It is the ratio between the energy produced by the fusion reactions, to the energy injected in the system to sustain these fusion reactions. This involve not just the energy efficiency of the plasma itself (Q_{plasma}), but also the overall efficiency and technological implications to scale up the operation principle to a practical energy producing system. From this point of view the steady state operating devices are easier to scale up than pulsed devices.
4. Auxiliary heating systems – Traditional magnetic confinement reactors like tokamak and stellarator, need the use of auxiliary heating, like neutral beam injection (NBI) and radiofrequency heating (RF), to be able to reach a high enough plasma temperature. The tokamaks relies partly on auxiliary heating because its Joule heating is insufficient, while the stellarators relies entirely on auxiliary heating because they have no induced current and associated Joule heating. A problem with these auxiliary heating systems is that they still tend to be expensive and have low heating efficiency.

The ALCUTOR project proposes a shift in the operating principles from the traditional approaches, that have the potential to open a new way to address these problems, and may provide improved plasma confinement, stability and heating, compared with the state of the art traditional fusion technologies.

ALCUTOR device advantages

The ALCUTOR experimental device combine a toroidal magnetic field (like in tokamaks) with an alternating current (AC) of several hundreds of hertz induced in the plasma column, and a specially designed conductive shell (conductive wall) that form the reactor vessel. This current will create an alternating poloidal magnetic field around plasma column. This alternating poloidal magnetic field together with the conductive shell that form the reactor vessel will completely change the plasma behaviour and stability. Significant improvements are expected in comparison with traditional magnetic confinement systems based on tokamak and stellarator configurations.

A wall repulsion mechanism. The combination of using an alternating current in plasma and the conductive shell that form the reactor vessel will create a plasma repulsive magnetic wall. This is due to the secondary induction of eddy currents in the conductive wall by the alternating poloidal magnetic field. This shell must not short-circuit the induction system and for that it is composed from segments (like in fig.3) insulated between them. If the plasma column goes close to wall then a stronger repulsion will appear on that side that will push it back toward the equilibrium position. Because the alternation of the current will never stop this mechanism remain permanent in action.

The toroidal magnetic confinement devices like tokamak and stellarator use a toroidal-helicoidal magnetic field to confine the plasma with a magnetic lines geometry that have no or very slow variation in time and thus encouraging the growing of instabilities.

In the case of tokamak and stellarator reactors, the confinement vessel is created by the plasma diamagnetism only so it will follow the plasma with no permanent positional feedback and stabilization from the toroidal walls. So in this case we speak about a new plasma positional stabilization method that in addition involve many other phenomena that help to reduce or eliminate various plasma instabilities.

Better control of kink instability. The same wall repulsion mechanism also help the toroidal magnetic field to control better the kink instability, by pushing back the long kink deformations (with long λ) which are less effectively countered by the toroidal magnetic field alone, and thus reducing the maximum λ value that need to be stabilized by the toroidal magnetic field. The long kink deformations (longer than several times the inner radius of the conductive shell) are well stabilized by the repulsion exerted by the walls on the plasma column surface, while the short kink deformations are better stabilized by the toroidal magnetic field.

Improved plasma surface stability. The plasma column is kept confined by a combination of 2 magnetic fields, the toroidal field that go along the axis of the plasma column, and the poloidal field (called azimuthal for cylindric approximation) that is created by the current that pass through the plasma column. These 2 fields form a resultant helicoidal field around the plasma column. In the tokamak and stellarator reactors this helicoidal field rotate around the plasma in the same direction all the time because either the current through the plasma flow always in the same direction (tokamak), or the coils have a fixed geometry (stellarator). This constant geometry of the magnetic fields allow even the small instabilities to grow to create disruptions, compromising the plasma confinement.

One idea of improvement included in this proposal is the change of the geometry of the magnetic field lines periodically by the induced alternating current in the plasma column, so that the growing time at least for some of the instabilities to be limited. In this case the current through the plasma column change the direction periodically so that the helicoidal field also change its direction of rotation around the plasma, producing a variable magnetic geometry. There are instabilities that expand in time along or influenced by these helicoidal field lines, in our case because these lines change their geometry periodically the growing of these instabilities is limited in time to half the period of the plasma current frequency and so they do not grow enough to produce serious plasma disruptions.

Prevention of plasma flutes. This is one case of surface instability that is eliminated by the periodically changing direction of the resulting helicoidal magnetic field lines as explained above, since the flutes grow in time along these field lines. A second mechanism that work against the formation of plasma flutes is the repression of plasma current to the plasma surface, leading to the exertion of a higher Lorentz force on the top of the flutes.

Elimination of current filamentation. One of the most important aspect of using alternating current induced in the plasma column is that the current is repressed to a thin layer at the plasma surface. This will eliminate almost entirely the current flow through the volume of the plasma and with it the resistive instabilities associated with the volume conduction of the plasma current. This include the plasma current filamentation and the magnetic islands triggered by them, caused by the plasma conductivity increasing with temperature that will form filaments of high current which are self-enforcing by producing more heat and increased temperature along the filament path.

In the case of currently used tokamak devices, the plasma current flow in the same direction and in time it will penetrate in the plasma and will split into current filaments. The only protection in this case is the slow evolution of magnetic fields inside plasma of high conductivity and strong toroidal magnetic field. This is delaying the process for a few seconds but after that the plasma become prone to resistive disruptions. In the case of our proposed device, because the one direction current time is limited to half period, the current penetration in the plasma volume is limited close to the surface and the associated disruptive phenomena are eliminated. And this is not the only advantage of it.

Improved Joule heating of plasma. Since the current is repressed to the plasma surface then this current will flow through a much reduced area at the plasma surface circular crown delimited by the penetration distance into plasma. As a result the total electric resistance of the plasma column is increased (tens of times) and with it the amount of Joule heating. This eliminate the need for expensive auxiliary heating methods at least in the temperature range for D-T fusion reactions.
Can run continuously. Because the alternating current can be induced without interruptions, the plasma can be run and maintained at high temperature continuously, limited only by the development of disrupting instabilities and plasma accumulation of impurities.

Impact
The ALCUTOR project, depending on the experimental results, has the potential to generate significant impact, being emphasized by:

- the project have the potential to open a new path to thermonuclear plasma magnetic confinement, unexplored before that may speed up the process to a practical and economical energy source based on nuclear fusion reactions;
- the long term benefits of the project have the potential to help in combating the climate change, to reduce to a low level the problem of radioactive waste, and a reduction of the energy cost;
- the project can also help in the search for new and sustainable energy sources in the actual conditions of increased energy demands;
- if the experimental results are encouraging, a plan to continue this technology development will be devised, based on the project results, in this case a larger experimental reactor need to be build using D-T plasma and all auxiliary systems and targeting positive energy output.

The ultimate aim of the ALCUTOR is to generate the know how to be able to build power plants that will exploit the advantages of nuclear fusion process for clean and affordable energy production.

Comparison of proposed ALCUTOR with traditional systems

Characteristic	Tokamak	Stellarator	ALCUTOR
Operation	Pulsed only	Steady state	Steady state
Joule heating	Moderate - insuficient for D-T fusion	Poor - no induced currents	Very good - enough for D-T fusion
Wall repulsion of plasma	None or weak and of short duration	None	Permanent wall repulsion and stabilization
Pinch and kink instabilities control	Good - via toroidal magnetic field only (require higher toroidal fields)	Good - lack of plasma induced current	Good - via toroidal magnetic field in combination with wall stabilization
Plasma current filamentation prevention	No method - leading to magnetic islands and disruptions	No method - less problematic due to low currents	Eliminate the problem of filamentation for the induced current
Susceptibility to other resistive instabilities	High due to volume conduction of induced current	Low due to the lack of induced current	Low due to the lack of volume conduction for the induced current
Sensitivity of magnetic configuration to gradients and turbulence	Low due to the strong induced current drive but only for a short duration	High due to random currents drive that can upset its sensitive magnetic geometry	Low for an unlimited time due to a permanent and strong induced current drive that will be dominant
Slowly growing instabilities prevention	Poor due to the stationary magnetic field geometry	Poor due to the stationary magnetic field geometry	Good due to the variable geometry of the magnetic field
Power dissipation and auxiliary heating	Moderate dissipation in plasma Require auxiliary NBI and/or RF heating	Lower dissipation (no induced current) Relies entirely on auxiliary NBI and/or RF heating	Higher dissipation both in plasma and in shell Require less or no NBI and RF heating than tokamak

Project objectives
The objectives of ALCUTOR is to experimentally test the effects of alternating current drive on plasma confinement and stability, and then to scale up this newly developed technology for practical energy production from nuclear fusion reactions.